Top flavour physics

Conference on Flavour Physics and CP violation

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on behalf of the ATLAS & CMS Collaborations

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Top quark overview

Main properties

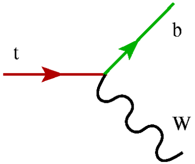
- Heaviest particle of SM: $\frac{1}{2}$ spin, $\frac{2}{3}e$, color charge
- Participates to all interactions
- "Natural" mass:

$$m_{\text{top}} = y_t \frac{v}{\sqrt{2}} \simeq 174\,\mathrm{GeV} \Longrightarrow y_t \sim 1$$

  - Privileged relationship with Higgs boson
  - Possible role in the EWSB mechanism
- Decay happens before hadronization can occur:

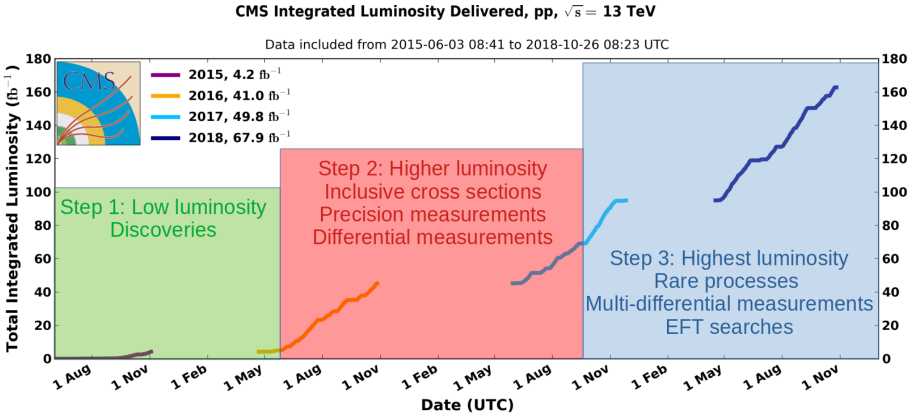
$$\tau_{top} = \frac{h}{\Gamma_{top}} \simeq \frac{h}{G_F m_{\text{top}}^3 |\mathrm{V}_{\mathrm{tb}}| \frac{2}{8\pi\sqrt{2}}} \simeq 2 \times 10^{-25} s$$

- Angular properties directly accessible through its decay products
- Weak interaction decay, dominantly to a W boson and a b quark



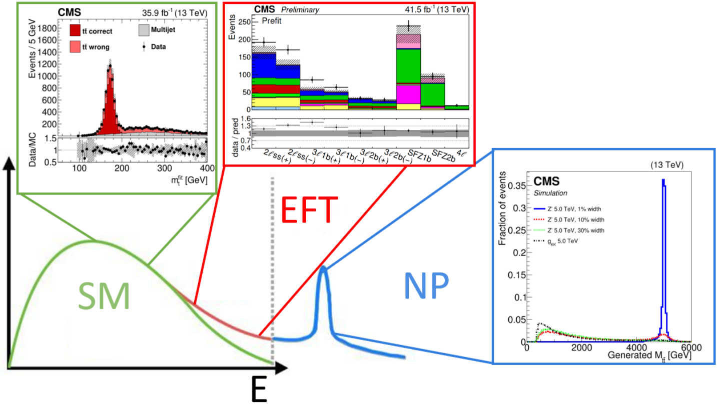
Introduction: Run-II prospect

- Very beginning of Run-II: (re)-discoveries of fundamental processes
- Middle of Run-II: precise measurements and accurate study of cross sections and other fundamental parameters
- Late Run-II: potential discoveries for new physics events ← we are here



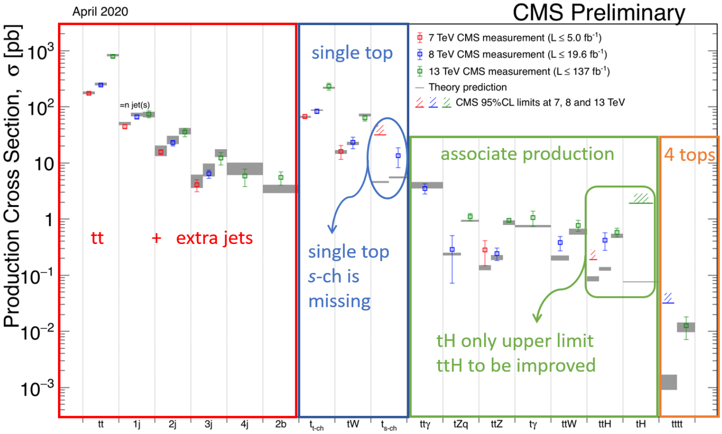
Analyses' typologies

- Precision SM measurements: better exploiting cross section to derive fundamental parameters, inclusive and differential top quark mass measurements, differential angular properties
- Effective field theory (EFT) searches: deviation from SM expectation
- Searches for new resonances: resonant effects due to new particles



Cross sections measurements: CMS

- Many cross sections measured with Run-II data → values of measured cross sections cover 4 orders of magnitude!
- Several final states analyzed; inclusive, differential and multi-differential cross sections studied.



Cross sections measurements: ATLAS

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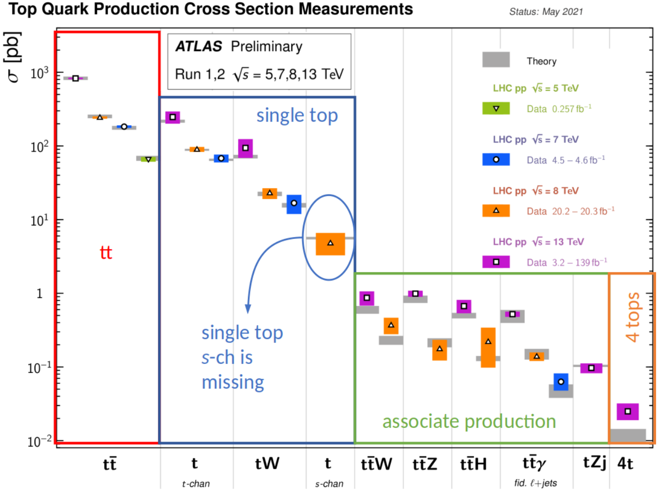
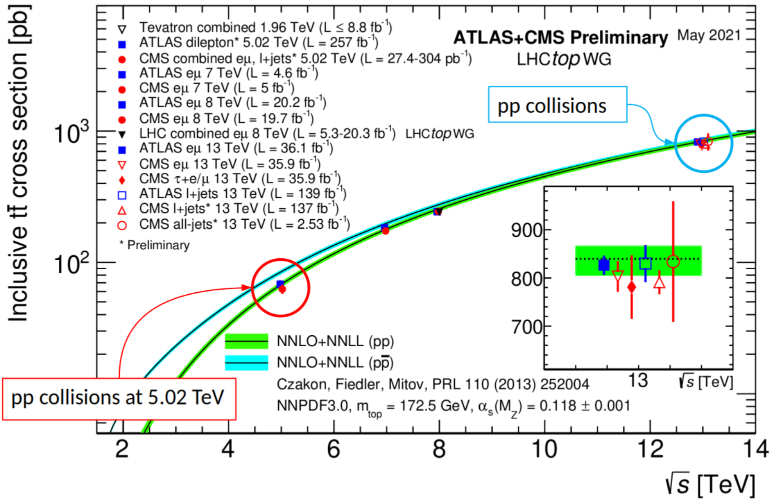


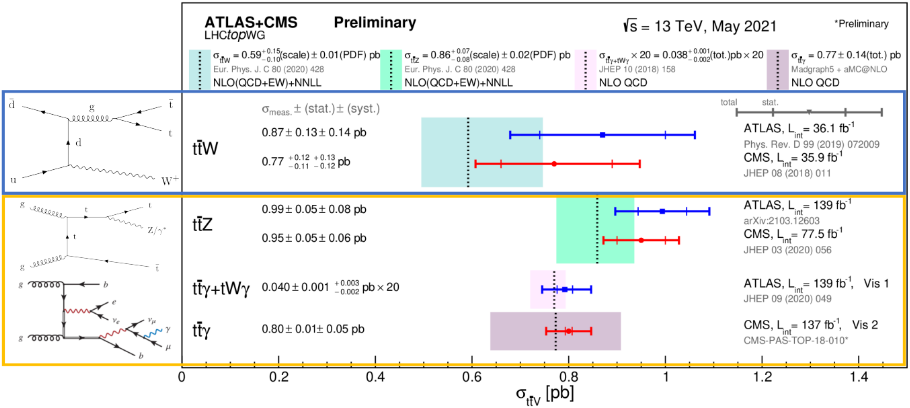
$t\bar{t}$ cross sections

Let's focus on top pair production.
A lot of measurements at 13 TeV but also at 5,02 TeV by exploiting pp collisions data



Discovery of $t\bar{t}V$ associate production

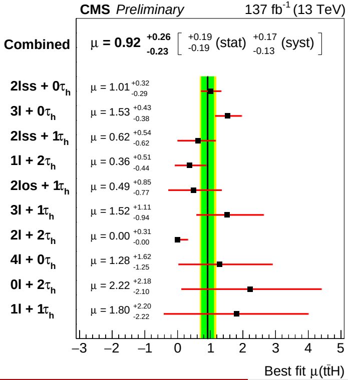
- Rarer processes investigated thanks to the amount of data and new analysis techniques.
- Among them associate production of top quark pairs and vector bosons are the most relevant.



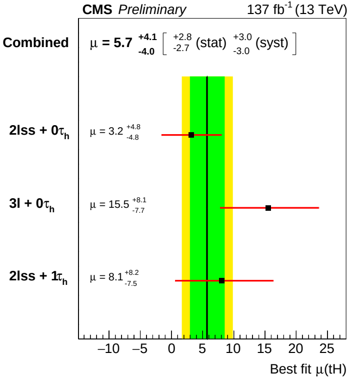
Top-Higgs associate production

- $t\bar{t}H \rightarrow$ magnitude of y_t $\quad$ $tH \rightarrow$ sign of y_t $\quad$ Eur. Phys. J. C 81 (2021) 378
- $H \rightarrow WW$, $H \rightarrow ZZ$, $H \rightarrow \tau\tau$ and $t \rightarrow$ all
- 10 different signatures depending on lepton multiplicity
- Signal to background discrimination with machine learning techniques
- Results given in term of SM expectation
- Confidence interval at 95%: $-0.9 < y_t < -0.7$ or $0.7 < y_t < 1.1$

$t\bar{t}H$ associate production

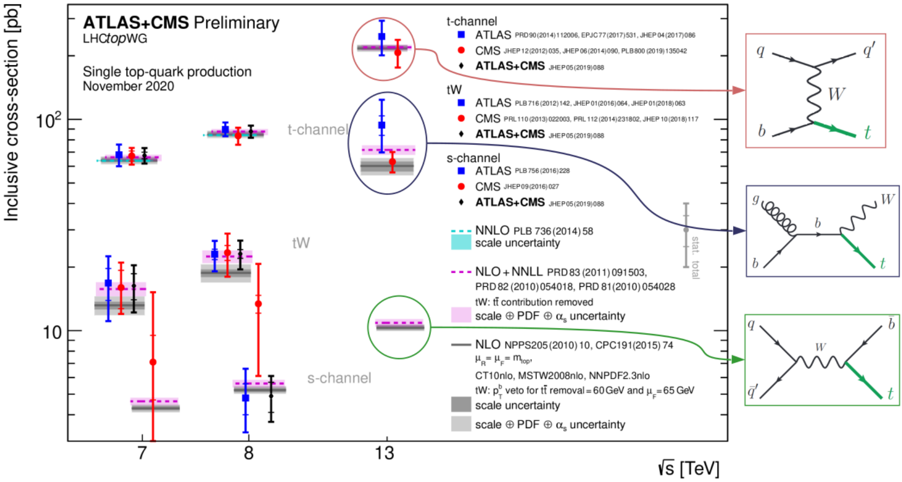


tH associate production



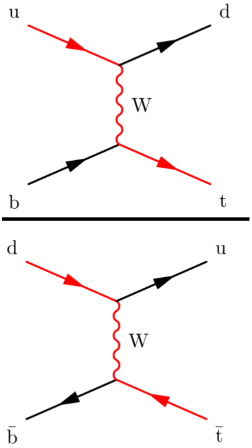
Single top quark cross sections

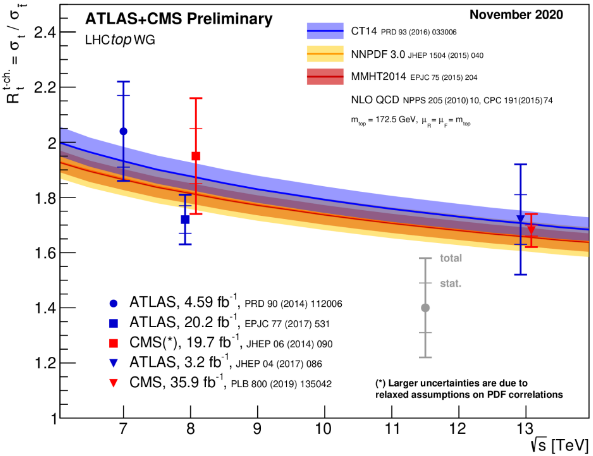
Single top quark production has been precisely measured.
The only missing is the s-channel production.



t-channel production

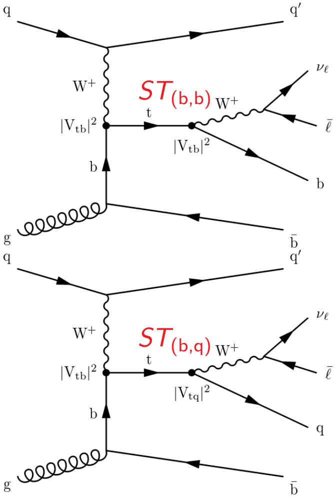
- Highest cross section for single top production
- Cross section as a function of the charge → ratio
- Golden channel for measurement of CKM matrix elements





CKM matrix elements

- Single top events indicated for CKM matrix elements measurements
- 1 high-pt isolated e/μ, $N_{jets} \geq 2$, $N_{b-tags} \geq 1$
- Several BDTs to discriminate signals $ST_{(b,b)}$ and $ST_{(b,q)}$



SM assumption

By assuming: $|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2 = 1$

$$|V_{tb}|^2 > 0.970$$
$$|V_{td}|^2 + |V_{ts}|^2 < 0.057$$

BSM scenario

Presence of additional quark families:

$$|V_{tb}|^2 = 0.988 \pm 0.051$$
$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$$

Phys. Lett. B 808 (2020) 135609

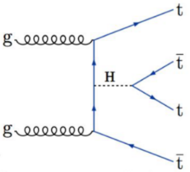
4 top quarks production **NEW**

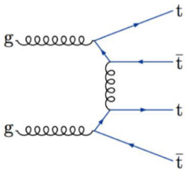
- Predicted by SM $\rightarrow$ enhancement by many BSM scenarios
- Not observed yet: very rare process $\sigma_{t\bar{t}t\bar{t}} = 12$ fb
- Sensitive to magnitude and CP properties of the Yukawa coupling tH [1, 2]
- Final state: 4 W bosons and 4 b quarks

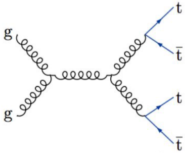
Eur. Phys. J. C 80 (2020) 1085

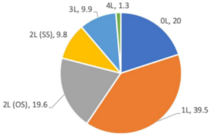
- Clean channel 2 leptons same sign (SS) + 3 leptons

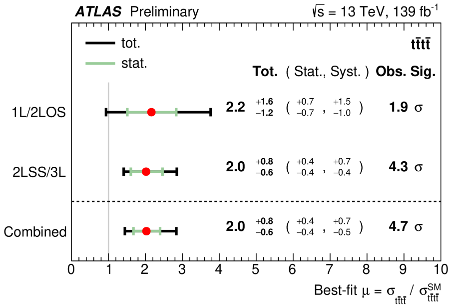
$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5(stat)^{+5}_{-4}(syst) = 24^{+7}_{-6} \text{ fb}$$







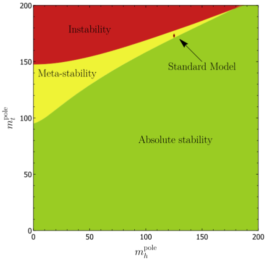




Top quark mass

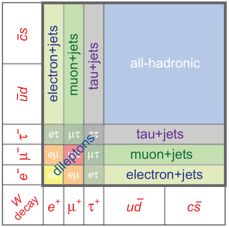
Why is it important?

- Key input for EW precision tests
- Crucial interplay with the Higgs and α_S
  - EW vacuum stability
- Cosmological consequences
- Challenging for experiments and theory
  - theory ambiguities on m_t^{MC} vs. m_t^{pole}



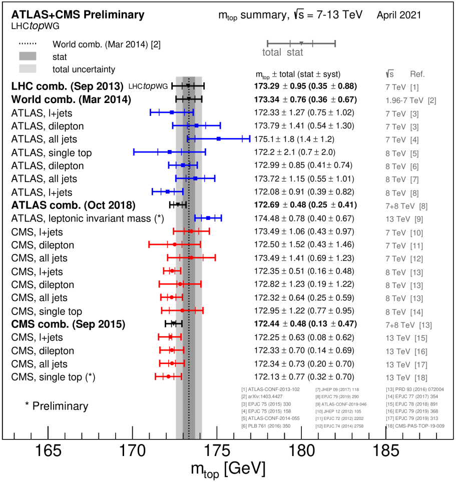
How can it be determined?

Top Pair Decay Channels



- Direct measurements:
  - observable dependent on m_t
- Indirect measurements:
  - property $f(m_t^{pole})$
- Many decay channels, many experimental observables $\rightarrow$ combination

Top quark mass measurements



Links to complete list of top mass measurements: ATLAS and CMS

- Measurements performed in several different final states: all-had ℓ+jets ℓ+jets $\ell\ell$
- Multi-differential measurement with simultaneous extraction of top quark mass, α_S and PDFs:

  Eur. Phys. J. C 80 (2020)
- Measurement from boosted topology (top quark decay in single jet):

  Phys. Rev. Lett. 124 (2020)
- Almost all top quark mass determinations have uncertainty below 1 GeV

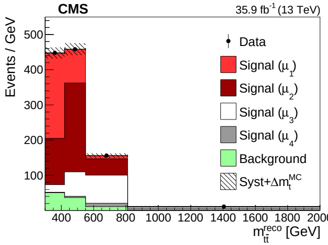
Running top mass

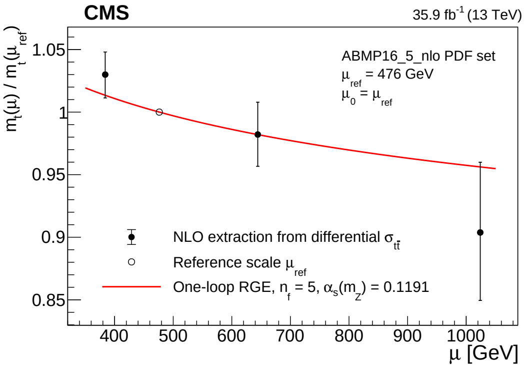
NEW

- Running mass equation: $\mu^2 \frac{dm(\mu)}{d\mu^2} = -\gamma\left(\alpha_S(\mu)\right) m(\mu)$
- 2 opposite flavour leptons final states
- m_t extracted from $d\sigma/dm_{t\bar{t}}$ at parton level

4 bins in $m_{t\bar{t}}$

Bin	$m_{t\bar{t}}$ [GeV]	Fraction [%]	μ_k [GeV]
1	<420	30	384
2	420–550	39	476
3	550–810	24	644
4	>810	7	1024





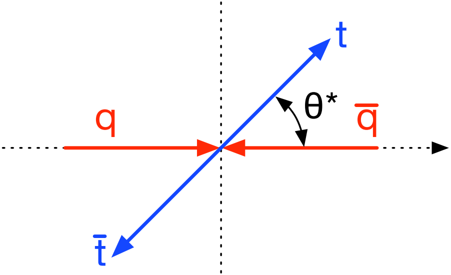
Phys. Lett. B 803 (2020) 135263

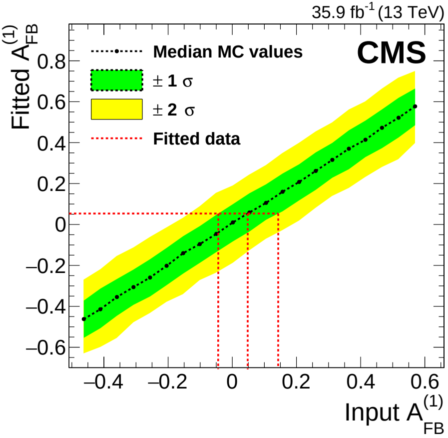
Forward-backward asymmetry **NEW**

- 1 isolated lepton (μ or e)
- Several variables simultaneously fitted to distinguish between $q\bar{q}$ and gg or qg productions

JHEP 06 (2020) 146

$$A_{\rm FB} = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$$





$$A_{\rm FB}^{(1)} = 0.048^{+0.095}_{-0.087}\,({\rm stat})^{+0.020}_{-0.029}\,({\rm syst})$$

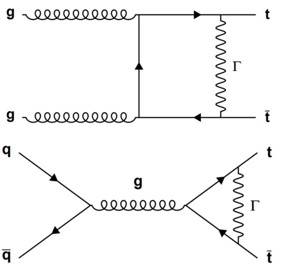
Yukawa coupling

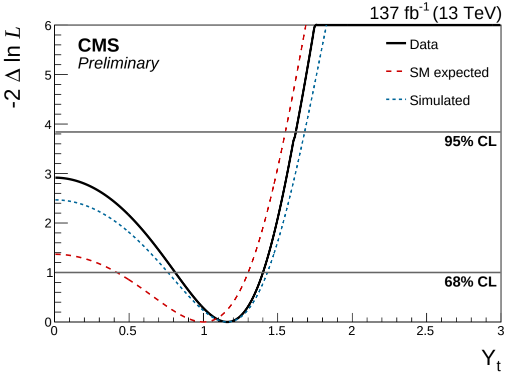
NEW

- Weak force mediated corrections $\sim \mathcal{O}(\alpha^2 \alpha_{weak})$
- t and $\bar{\mathrm{t}}$ with small relative velocity, $\sigma_{t\bar{t}}$ sensitive to Yukawa coupling
- 2 high-pt isolated e/μ, $N_{b-tags} \geq 2$
- No full kinematic reconstruction due to the presence of 2 neutrinos
- Proxy variables $M_{b\ell} = M(b + \bar{\ell} + b + \ell)$ and $|\Delta y|_{b\ell} = |y(b + \bar{\ell}) + y(b + \ell)|$

Phys.Rev.D 102 (2020) 092013

Weak virtual corrections





Top quark portal to New Physics

After 26 years the top still is, together with the Higgs, our best gateway to the TeraWorld!

Strategies:

- Precision SM top-quark properties measurements
- Search for non-SM top-quark interactions
- Searches of top-quark partners and other states

Needs:

- High precision predictions (NNLO in QCD and NLO EW) for key SM observation
- A consistent and complete model-independent framework = EFT

Credits to F. Maltoni

Effective field theories' approach

The EFT is a flexible framework for undertaking indirect probes of higher energy scales physics.

- An EFT is a low-energy approximation for a more fundamental theory involving interactions at a mass scale Λ.
- The effective Lagrangian can then be written as:

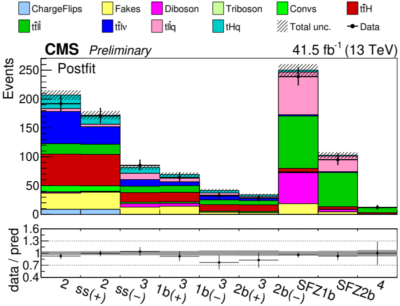
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- $\mathcal{L}_{SM}$ is the SM Lagrangian, $\mathcal{O}_i^{(d)}$ are the effective operators of dimension d, and c_i^d are dimensionless parameters known as Wilson coefficients (WCs)
- Dimension-five operators produce lepton number violation, these operators are neglected
- Dimension-six operators provide the leading contribution from new physics.

New physics with EFT approach

NEW

- Associated top quark production with a H, W or Z boson
- 16 dimension-six operators simultaneously studied
- Detector-level observables to enhance sensitivity to all operators



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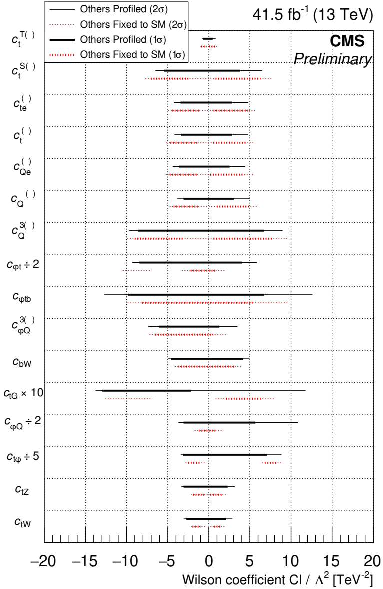
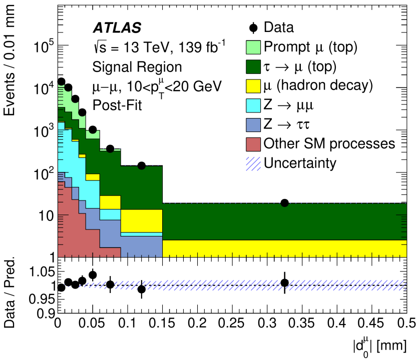


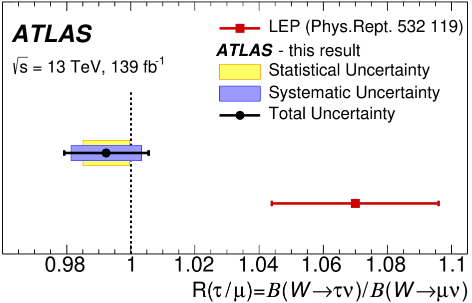
Lepton couplings universality **NEW**

- Lepton-flavour universality: $W\ell$ coupling not dependent from the ℓ's mass
- Important test of the SM: LEP result → 2.7σ tension
- W→ $\tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau\nu_\tau$ and W→ $\mu\nu_\mu$ processes, to extract $R(\tau/\mu)$
- Secondary vertex used to discriminate τ and μ

arXiv:2007.14040



$$R(\tau/\mu) = 0.992 \pm 0.013$$



Open channels and potential for Run-III

(Re)-discovery at 14 TeV

- single top *s*-channel
- SM top+Higgs associate production
- 4-top production

Precision SM measurements

- top quark mass
- Yukawa coupling
- multi-differential including higher-p_T regime

Direct searches

- resonant top+X production for exotic final states
- non-resonant (EFT) top+X production at growing p_T spectra

Conclusions

- Many properties of the top quark measured with high precision
- Top mass is one of the most important: direct and indirect measurements with uncertainties below 1 GeV
- Large amount of collision data allows measurements of rare processes to test the SM predictions for the first time:
  - 4 top quarks production
  - Direct measurement of $|V_{td}|^2 + |V_{ts}|^2$
  - Lepton flavour universality
- Many BSM models can be tested with differential and multi-differential measurements
- No deviation from the SM predictions is observed but the top quark sector is one of the most interesting for BSM physics manifestation
- Many other studies ongoing: stay tuned

BACKUP

On top mass definition

In the on-shell (o.s.) and $\overline{\text{MS}}$ schemes $S^R(p)$ can then be expressed in terms of pole and $\overline{\text{MS}}$ masses, respectively, as follows:

$$S^R_{\text{o.s.}}(p) \simeq \frac{i}{\not{p} - m_{\text{pole}}} \;,\; S^R_{\overline{\text{MS}}}(p,\mu) \simeq \frac{i}{\not{p} - m_{\overline{\text{MS}}}(\mu) - (A-B)m_{\overline{\text{MS}}}(\mu)}$$

The relation between top-quark pole ($m_{\text{t}}^{\text{pole}}$) and $\overline{\text{MS}}$ ($m_{\text{t}}(m_{\text{t}})$) masses was calculated up to four loops in and reads:

$$\begin{aligned} m_{t,\text{pole}} &= \bar{m}_t(\bar{m}_t)\left[1 + 0.4244\,\alpha_S + 0.8345\,\alpha_S^2 + 2.375\,\alpha_S^3 + (8.615 \pm 0.017)\,\alpha_S^4 + \mathcal{O}(\alpha_S^5)\right] \\ &= [163.508 + 7.529 + 1.606 + 0.496 + (0.195 \pm 0.0004)]\ \text{GeV}. \end{aligned}$$

For further details see arXiv:1903.06574

The pole mass is closer to what we measure at colliders through invariant mass of the top decay products.