Tue 26 May at 12:30: It’s top time!
Top-quark theory review
The inception of the precision era

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Top-quark physics

Introduction

• The top quark is one of the main influencers in the HEP community and has many followers.

• Its appeal resides on the many different ways it can be studied:
  • Precision SM properties
  • Coupling to new states
  • Explore new interactions
Top-quark physics

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  • Precision SM properties
  
  • Coupling to new states
  
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Top-quark physics essentials I

Properties

All of the unique phenomenology of the top quark ultimately originates from its large mass (with respect to the b and the other quarks)

\[ m_t = \frac{y_t}{\sqrt{2}} v = 172.9 \pm 0.4 \text{ GeV} \Rightarrow y_t = 0.994 \pm 0.002 \]

• The dominant part of the top mass comes from EWSB ⇒ The only natural quark.

• It gives large corrections to EW observables and drives FCNC contributions.

• It points to a mass generation mechanism at low scales.

• It drives Higgs phenomenology and the Higgs potential at high scales.
Top-quark mass

\[ m_t^{\text{pole}} = 173.15 \pm 0.00200 \text{GeV} \]

[Andreassen et al. 1707.08124] [PDG 2019]

\[ y_t(M_t) = 0.93587 + 0.00557 \left( \frac{M_t}{\text{GeV}} - 173.15 \right) \ldots \pm 0.00200 \text{th} \]

[Hoang, 2004.12915] [Ravasio, 1810.10931] [Beneke et al. 1605.03609]
Top-quark mass

$\bullet \ m_t^{\text{pole}}$ is the goal of the direct measurement. Being colored the pole mass is an ambiguous quantity. Non-perturbative effects estimated via renormalon computations. The renormalon ambiguity associated to the pole mass is relatively small, order 100 MeV. However the ambiguity depends on the observable used (e.g. broad jets, smaller effects).

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- $m_t^{\text{MS}}$ short distance parameter that can be extracted from other top-related measurements. Other short distances versions exist that are tailored to specific observables.

[Hoang, 2004.12915][Ravasio, 1810.10931][Beneke et al. 1605.03609]

[Catani et al. 2005.00557]
Top-quark mass

$\bar{m}(\bar{m} = 163 \text{ GeV})$

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[Hoang, 2004.12915][Ravasio, 1810.10931][Beneke et al. 1605.03609]
The possibility of accessing a short distance mass (~potential mass) from $g g \rightarrow \gamma \gamma$ at the LHC has been put forward by [Kawabata & Yokoya, 1607.00990]. NLO (two-loop) computations have followed. 

$M_t^\text{match} \equiv M_t + B_t \, G(\bar{u}; \mathcal{E}) - M_{OC}$
Top-quark physics essentials II

Production at the LHC

- It has a multifaceted social life: it goes to parties mostly in pair, very often alone, rarely accompanied by movie-stars and friends. At the LHC, the top is produced via:
Precision SM Top Physics

Fixed-order computations

Cross section level

Amplitude level

LO

NLO

NNLO

\[ \frac{\alpha_W}{\alpha_S} = 0.1 \]
states. Production is almost as an estimate of the leading missing mixed QCD-EW higher orders. The advantage of the inclusion of EW by Sudakov logarithms, ⌃ purpose of the multiplicative approach is to estimate the size of argument still holds true. We show and discuss later in this section the size of almost all the photon-induced contribution arises form case of also contributes to depend on the photon PDF. The dominant photon-induced initial state is the consistent with the notation in the plots of the previous section. Term. The linear combination of NNLO QCD results and electroweak corrections can thus be defined as "EW corrections" we will refer to the quantity and those involving also EW corrections as purely QCD quantities as NNLO QCD-EW. In the regime where NLO QCD corrections are dominated by soft interactions and NLO, however, as it is suggested by its name, its size is in general subleading, so the previous contributions from the can be used due to the Heavy-light process, which we rename for convenience for convenience NNLO QCD-EW, which we rename for convenience for convenience.
Precision SM Top Physics
Fixed-order computations

Cross section level

Amplitude level

LO

NLO

NNLO

Cross section level

Amplitude level

LO

NLO

NNLO

Cross section level

Amplitude level

LO

NLO

NNLO

Cross section level

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Precision SM Top Physics
Fixed-order computations

Cross section level

Amplitude level

LO

NLO

NNLO

LO QCD

NLO QCD

NNLO QCD

QCD+EW

QCD+EW

\[ \alpha_s^2, \alpha_s \alpha, \alpha^2 \]

\[ \alpha_s^3, \alpha_s^2 \alpha, \alpha_s \alpha^2, \alpha^3 \]

\[ \alpha_s^4 \]

In the so-called "multiplicative approach", the terms are additive combinations of the LO, NLO, and NNLO amplitudes. The subleading EW contributions are also the stabilization of the scale dependence of the photon-induced contribution. As already discussed in ref. [1], the size is in general subleading, so the previous term is also the stabilization of the scale dependence of the photon-induced contribution. In order to help the reader and be as close as possible to the common notation, we further define the quantity...
Precision SM Top Physics
Fixed-order computations

Cross section level

LO

NLO

NNLO

Complete NLO (C-NLO) ≡ all blobs at NLO level

Estimated from NLO EW via multiplicative scheme
Precision SM Top Physics

The path

“Rules of thumb at the LHC”:

• Predictions must be calculated at least to NLO QCD to control the central value.

• NNLO QCD provides control on the uncertainties stabilizing the perturbative expansion.

• NNLO QCD is expected to be of the same order as NLO EW $\alpha_s^2 \sim \alpha_W$, yet EW corrections grow large and negative at high energies (Sudakov logs).

• Universal, all-order terms that are potentially large for some observables (logs or 1PI loops for propagators) need to be resummed. These typically lead to improvements in precision and accuracy.
Top-quark physics essentials III

Width

• It decays semi-weakly in $5 \cdot 10^{-25}s$, $\Gamma_t \simeq 1.5$ GeV $\Rightarrow$ it does not spin flip nor hadronises.

• Thanks to L-handed nature of the weak interactions the direction of lepton is 100% correlated to the spin direction $\Rightarrow$ we can measure its spin $\Rightarrow$ EPR type measurements in $t\bar{t}$ production.

• 3-body decay + spin of the top gives enough independent momenta to build CP-odd observables $\Rightarrow$ look for extra CP violation.

• $V_{tb} = 0.99911 \pm 0.00003$ (3 generations)
  $V_{tb} = 0.988 \pm 0.024$ (direct) [CMS 2004.12181]
Off-shell effects
\( t\bar{t} + X \)

- Inclusion of off-shell effects is a very challenging technical task: many diagrams, needs consistent treatment of the width, difficult phase space integration, higher-point integrals,…
- These can be important for very precisely measured final states where selection cuts force one or both tops off-shell.
- A famous case is the overlapping between \( t\bar{t} \) and \( tWb \).
- Another problem is the interface with the parton shower.

- \( tj \) [Frederix et al. 1907.12586] QCD/EW and QCD+PS
- \( t\bar{t}Z \) [Bevilacqua et al. 1907.09359] QCD
- \( t\bar{t}W \) [Bevilacqua et al. 2005.09427] QCD
- \( t\bar{t}\gamma \) [Bevilacqua et al. 1912.09999][Bevilacqua et al., 1809.08562][Bevilacqua et al., 1803.09916] QCD
- \( t\bar{t}j \) [Bevilacqua et al. 1710.07515][Bevilacqua, 1609.01659][Bevilacqua, 1509.09242] QCD
- \( t\bar{t}H \) [Denner et al. 1612.07138] EW/QCD (dileptonic)
- [Denner and Pellen, 1711.10359] QCD (semileptonic)
- [Denner et al. 1607.05571] EW (dileptonic)
- [Denzo et al. 1607.04538] QCD+PS (dileptonic)
- [Denner, 1207.5018] QCD (dileptonic)
# Precision SM Top Physics

## Status of the SM predictions

<table>
<thead>
<tr>
<th>SM</th>
<th>QCD</th>
<th>EW</th>
<th>Complete</th>
<th>Res</th>
<th>Off-Shell</th>
<th>NLO+PS</th>
<th>+jets</th>
<th>+ jets merging LO</th>
<th>+jets merging NLO</th>
</tr>
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<tbody>
<tr>
<td>$t\bar{t}$</td>
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<td>NLO</td>
<td>NLO</td>
<td>NLO</td>
<td>NLL</td>
<td>NLO QCD</td>
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<td>✓</td>
<td>✓</td>
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<td>NLO</td>
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<td>✓ (1 NLO ALL)</td>
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<td>NLO</td>
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<td>NLL</td>
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<td>✓ (1 NLO ALL)</td>
<td>✓ (✓)</td>
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<tr>
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<td>NLO</td>
<td>X</td>
<td>NLO QCD</td>
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<td>✓</td>
<td>✓ (1 NLO ALL)</td>
<td>✓ (✓)</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>NLO</td>
<td>NLO</td>
<td>NLO</td>
<td>NLO</td>
<td>NLL</td>
<td>NLO QCD</td>
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<td>✓ (✓)</td>
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<td>✓</td>
<td>✓ (1 NLO ALL)</td>
<td>✓ (✓)</td>
</tr>
<tr>
<td>$t\bar{t}t\bar{t}$</td>
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<td>X</td>
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<td>✓ 1 jet NLO QCD</td>
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<td>✓ (✓)</td>
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<tr>
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5F scheme assumed. When in ( ) is being/can be done.
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<td>NNLO</td>
<td>NLO</td>
<td>NLO</td>
<td>NNLL</td>
<td>NLO QCD</td>
<td>NLO (QCD and EW)</td>
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<td>up to 5 NLO QCD</td>
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</tr>
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<td>NNLL</td>
<td>NLO QCD</td>
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<td>(+1 NLO ALL)</td>
<td>✓</td>
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</tr>
<tr>
<td>$t\bar{t}Z$</td>
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<td>NLO</td>
<td>NLO</td>
<td>NNLL</td>
<td>NLO QCD</td>
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<td>(+1 NLO ALL)</td>
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<td>$t\gamma$</td>
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<td>(+1 NLO ALL)</td>
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<td>NLO</td>
<td>NLO</td>
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<td>(+1 NLO ALL)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$t\bar{t}t\bar{t}$</td>
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<td>NLO</td>
<td>NLO</td>
<td>NLL</td>
<td>X</td>
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<td>LO</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>$tj$</td>
<td>NNLO</td>
<td>NLO</td>
<td>NLO</td>
<td>NNLL</td>
<td>NLO QCD</td>
<td>NLO (QCD and EW)</td>
<td>✓</td>
<td>1 jet NLO QCD</td>
<td>✓</td>
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<tr>
<td>$t\bar{t}Z$</td>
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<td>X</td>
<td>✓</td>
<td>(1 jet NLO QCD)</td>
<td>✓</td>
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</tr>
</tbody>
</table>

$tj$ at complete NLO and off-shell in the talk by Davide Pagani  
Study of $ttW$ at complete NLO the talk by Ioannis Tsinikos  
Study of $ttZ$/gamma at NLO QCD off-shell the talk by Giuseppe Bevilacqua
Precision...what for?
Searching for new interactions with an EFT

The matter content of SM has been experimentally verified and there is no evidence for light states. SM measurements can be interpreted as searches for deviations from the dim=4 SM Lagrangian predictions.

\[ \mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \ldots \]

**BSM goal of the precision LHC programme: determination of the couplings of the SMEFT lagrangian.**
Precision...what for?
Searching for new interactions with the SMEFT

Tree level sensitivity
Top-X final states

Loop sensitivity
Top-X couplings without the top or the X*

*Paraphrasing [Henning et al., 1812.09299]
Top-quark physics essentials IV

The SM\(^\text{EFT}\)

- New interactions among SM particles can be systematically parametrized in the context of the SM\(^\text{EFT}\). Directly related to the top fields, at dim=6

\[
\mathcal{L}^{(6)}_{SM} = \mathcal{L}^{(4)}_{SM} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i + \ldots \Rightarrow \text{Obs}_i = \text{Obs}_i^{SM} + M_{ij} \cdot \frac{s}{\Lambda^2} c_j
\]

2QBs

\[O^{ij}_{u \gamma} = \bar{q}_i u_j \gamma \phi \phi,\]
\[O^{ij}_{D} = (\phi \gamma \bar{D}_\mu \phi)(\bar{q}_i \gamma \gamma^\mu q_j),\]
\[O^{ij}_{u} = (\phi \gamma \bar{D}_\mu \phi)(\bar{u}_i \gamma \gamma^\mu u_j),\]
\[O^{ij}_{D} = (\phi \gamma \bar{D}_\mu \phi)(\bar{q}_i \gamma \gamma^\mu u_j),\]
\[O^{ij}_{W} = (\phi \gamma \bar{D}_\mu \phi)(\bar{q}_i \gamma \gamma^\mu q_j),\]
\[O^{ij}_{D} = (\phi \gamma \bar{D}_\mu \phi)(\bar{u}_i \gamma \gamma^\mu u_j),\]
\[O^{ij}_{D} = (\phi \gamma \bar{D}_\mu \phi)(\bar{q}_i \gamma \gamma^\mu q_j),\]
\[O^{ij}_{W} = (\phi \gamma \bar{D}_\mu \phi)(\bar{u}_i \gamma \gamma^\mu u_j),\]
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\[O^{ij}_{W} = (\phi \gamma \bar{D}_\mu \phi)(\bar{u}_i \gamma \gamma^\mu u_j),\]
\[O^{ij}_{D} = (\phi \gamma \bar{D}_\mu \phi)(\bar{q}_i \gamma \gamma^\mu q_j),\]
\[O^{ij}_{W} = (\phi \gamma \bar{D}_\mu \phi)(\bar{u}_i \gamma \gamma^\mu u_j),\]

2Q2L

\[O^{ijkl}_{ij} = (\bar{l}_i \gamma^\mu l_j)(\bar{q}_k \gamma^\mu q_l),\]
\[O^{ijkl}_{ij} = (\bar{l}_i \gamma^\mu t_j)(\bar{q}_k \gamma^\mu t_l),\]
\[O^{ijkl}_{ij} = (\bar{l}_i \gamma^\mu t_j)(\bar{u}_k \gamma^\mu u_l),\]
\[O^{ijkl}_{ij} = (\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l),\]
\[O^{ijkl}_{ij} = (\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_l),\]
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\[O^{ijkl}_{ij} = (\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l),\]

2Q2q-4Q

\[O^{ijkl}_{ij} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma^\mu q_l),\]
\[O^{ijkl}_{ij} = (\bar{q}_i \gamma^\mu u_j)(\bar{q}_k \gamma^\mu u_l),\]
\[O^{ijkl}_{ij} = (\bar{u}_i \gamma^\mu q_j)(\bar{u}_k \gamma^\mu q_l),\]
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\[O^{ijkl}_{ij} = (\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma^\mu u_l),\]
\[O^{ijkl}_{ij} = (\bar{u}_i \gamma^\mu q_j)(\bar{u}_k \gamma^\mu q_l),\]

which, assuming \(U(2)_q \times U(2)_u \times U(2)_d\), corresponds to 42 degrees of freedom (11x4Q, 14x2Q2q, 9x2QBs, 8x2Q2L)
## SMEFT

Processes and (some) operators

<table>
<thead>
<tr>
<th>NLO</th>
<th>Process</th>
<th>$O_{tG}$</th>
<th>$O_{tB}$</th>
<th>$O_{tW}$</th>
<th>$O^{(3)}_{\varphi Q}$</th>
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More on SMEFT with top and Higgs in the talk by Peter Galler
SMEFT
A few recent examples

1. $t\bar{t}$ at threshold at NNLO with Coulomb resummation
2. $t\bar{t}Z$ C-NLO+NNLL vs loops
3. $tZj$ C-NLO
4. $t\bar{t}t\bar{t}$ C-NLO see additional material
**SMEFT**

**$t\bar{t}$ threshold production**

---

**Figure 1:** Theoretical predictions compared with the CMS data in the di-lepton channel [42].

---

**Summary**

In this paper, we describe a combination among four calculations for the differential cross sections in $t\bar{t}$ production: the NNLO QCD calculations, the NNLL QCD threshold resummation, the NNLL QCD resummation for boosted top quarks, and the complete-NLO predictions of QCD and EW origin. This is the first time that such a complicated combination appears in the literature. The outcome represents the state-of-the-art prediction for $t\bar{t}$ differential distributions within the SM, which includes all sets of corrections available at the moment. Numerical results are presented for the invariant-mass distribution, the transverse-momentum distribution as well as rapidity distributions. We compare our predictions with the CMS measurements in the di-lepton channel at the 13 TeV LHC with an integrated luminosity of 35.9 fb$^{-1}$, and find overall good agreements.

---

**Acknowledgements**

L. L. Yang and X. Wang are supported in part by the National Natural Science Foundation of China under Grant No. 11575004, 11635001 and 11975030. D. J. S. is supported under the ERC grant ERC-STG2015-677323. The work of D. P. and I. T. is supported by the Alexander von Humboldt Foundation, in the framework of the Sofja Kovalevskaja Award Project “Event Simulation for the Large Hadron Collider at High Precision”. The work of A. M. and A. P. is supported by the European Research Council Consolidator Grant NNLOforLHC2 and by the [Czakon et al. 1901.08281]

---

A significant undershooting of our best theory with respect to data in the first $m(t\bar{t})$ bin

---

When produced almost at rest and in a color singlet the $t$ and $\bar{t}$ tend to form a (pseudo) bound state ⇒ enhancement of the x-sec

---

[Czakon et al. 1901.08281]

[Hagiwara et al., 0804.1014]
A very much refined analysis confirms the expectations of Hagiwara et al.

Coloumb resumption leads to a visible shift in the right direction that is stable under radiative corrections.
SMEFT

Top Yukawa coupling from $t\bar{t}$

The behavior at threshold could be affected by the exchange of a Higgs or a Z-boson. [Kuhn et al.,1305.5773]

This can give a bound on the value of the Yukawa coupling. A first analysis performed by CMS finds $y_t/y_{t}^{SM}$ value to be $1.07 \pm 0.34 -0.43$ with an upper limit of 1.67 at the 95% confidence level.

Q: How are these results affected by the new calculations?
SMEFT

$tZj$: Experimental status

TH (NLO):

$\sigma(tZq)^{\text{NLO}} = 75.87(4)^{+2.2\%}_{-6.4\%} \pm 1.2\% \text{ fb}$

[Degrande et al. 1804.07773]

([Campbell et al. 1302.3856])

$\sigma(pp \rightarrow tZq \rightarrow t\ell^+ \ell^- q) = 111 \pm 13 \text{ (stat)} +^{11}_{-9} \text{ (syst) fb}$

[CMS 1812.05900]

$\sigma(tZq) = 97 \pm 13 \text{ (stat.)} \pm 7 \text{ (syst.) fb}$

[ATLAS, 2002.07546]
SMEFT

$tZj$ and $tHj$: NLO complete corrections and 4F vs 5F

New calculation being performed including the C-NLO corrections to $tZj$ and $tHj$ and a comparison between 4F and 5F schemes.

The upshot is an extremely good control/understanding of rates of distributions.

[Pagani, Tsinikos, Vryonidou to appear]
**SMEFT**

$tZj$ ($tHj$): the interplay of operators/processes

- Rich interplay between EFT operators from different sectors
- Different energy growth and interference with the SM
- Four fermion interactions also present

**tW**

[HWW]

$\mathcal{O}_{\phi W} : \varphi^{\dagger} \varphi \ W_{i}^{\mu \nu} W_{ij}^{\mu}$

[TGC]

$\mathcal{O}_{W} : \epsilon^{ijk} W_{i, \mu \nu} W_{j, k, \rho} W_{\mu \rho}$

[Wtb vertex]

$\mathcal{O}_{\varphi W} : i (\varphi^{\dagger} \overleftrightarrow{D}_{\mu} \varphi)(\overline{Q} \gamma^{\mu} \sigma_{i} Q)$

[Contact terms]

$\mathcal{O}_{\varphi b} : i (\varphi^{\dagger} \overleftrightarrow{D}_{\mu} \varphi)(\overline{b} \gamma^{\mu} t)$

$\mathcal{O}_{t_{\varphi}} : (\varphi^{\dagger} \varphi) (Q t) \bar{\varphi}$

$\mathcal{O}_{t_{W}} : i (\varphi^{\dagger} \overleftrightarrow{D}_{\mu} \varphi)(\bar{t} \gamma^{\mu} t)$

$\mathcal{O}_{t_{B}} : (Q \sigma_{\mu \nu} t) \bar{\varphi} B_{\mu \nu}$

Accessing the $bW \rightarrow tH$ & $bW \rightarrow tZ$ sub-amplitudes
SMEFT
tZj: LHC sensitivity

Effects of operators with coefficients set at the boundaries of current exclusions
SMEFT

$t\bar{t}Z$ experimental results

[Broggio et al., 1907.04343]

$\sigma_{t\bar{t}Z} = 810.9(2)^{+89.2(+11.0\%)}_{-77.8(-9.6\%)} + 19.1(+2.4\%) - 19.1(-2.4\%)$

[CMS 1907.11270]

$\sigma(t\bar{t}Z) = 0.95 \pm 0.05 \text{ (stat)} \pm 0.06 \text{ (syst)} \text{ pb}$
Two independent approaches available one using SCET and the other res in Mellin space. Give compatible results. For $t\bar{t}Z$ extremely good control of QCD uncertainties in total rates and main distributions, at better than 10% percent.
SMEFT

t\bar{t}Z operators: trees and loops \( gg \to HZ, \, gg \to ZZ, \, t\bar{t} \)

SMEFT computations at NLO in QCD are available for \( t\bar{t}Z \) too. A natural way to test the couplings of the Z-boson to the top. However, comparable sensitivity can be obtained from high \( p_T \) tails in loop induced processes such as \( gg \to HZ \), where only the top loop contributes, \( gg \to ZZ \) and also \( t\bar{t} \) close to threshold, as recently suggested.

\[
O_{\phi Q}^{1} = (\phi^\dagger D_\mu \phi)(\bar{Q}\gamma^\mu Q) \\
O_{\phi Q}^{3} = (\phi^\dagger i D_\mu \phi)(\bar{Q}\gamma^\mu r Q) \\
O_{\phi t} = (\phi^\dagger i D_\mu \phi)(r\gamma^\mu t)
\]

See also [Englert et al., 1410.5440] [Englert et al., 1603.05304] [Azatov et al., 1608.00977] [Bylund et al., 1601.08193] [Martini and Schultze, 1911.11244]

More details and insights in the talk by Till Martini
**SMEFT**

Global fits in the top sector

- Already now and without a dedicated experimental effort there is considerable information that can be used to set limits. Fits dedicated to the top sector:
  - TopFitter (Global, LHC+Tevatron, LO)  
    - Buckley et al., 1506.08845
  - SMEFiT (Global, LHC,NLO)  
    - Hartland et al., 1901.05965
  - EFTfitter (Partial, LHC+Flavor, LO)  
    - Bissmann et al., 1909.13632
  - SFitter (Global, LHC,NLO)  
    - Brivio et al., 1910.03606

- Several flat directions can be lifted with specific observables, also exploiting NLO effects.

- Combination with EW and Higgs data is needed to constrain all operators entering the all processes.
Global fit in the top + Higgs @ NLO

The top sector is connected to both the EW and Higgs sectors and therefore a really global approach is needed. A total of 24 additional operators are needed in addition to the 42 giving 66 operators.

Robustness and convergence of the fitting procedure is being explored right now (starting with a smaller number of operators).

[Courtesy of Eleni Vryanidou, from Ethier et al., work in progress]
Conclusions & Outlook
The inception of the precision era

• The top quark is special, i.e. is the only standard quark in the standard model. It plays an important role and its electroweak behaviour could be a gateway to new physics.

• Tremendous improvements in the accuracy/precision of SM predictions have been achieved, opening a new realm of opportunities.

• The top-quark campaign of precision measurements at the LHC is entering a new phase measuring at unprecedented precision the main production channels and accessing for the first time rare final states.

• A far reaching approach to interpreting SM measurements is to constrain the top interactions by employing an EFT.

• Predictions are now available at NLO accuracy in QCD and constraints start to be obtained in a global way.

• Busy future ahead with even more room for TH/EXP collaborations.
Acknowledgements

Thanks to:

• Davide Pagani, Eleni Vryonidou, Ioannis Tsinikos for discussions and precious material.

• Rikkert Frederix and Carlo Oleari for useful discussions.
Additional material

TH calculations
Rare processes
$t\bar{t}\gamma$ in ATLAS

TH (NLO): \[ \sigma = 39.50^{+0.56}_{-2.18} \text{(scale)} +1.04^{+1.18}_{-1.18} \text{(PDF)} \text{ fb} \]

EXP: \[ \sigma = 44.2 \pm 2.6 \text{ fb} \]

[Bevilacqua et al., 1803.09916]

More details and insights in the talk by Giuseppe Bevilacqua.
Single-top t-channel
Status

NNLO QCD
[Brucherseifer et al. 1404.7116]
[Berger et al. 1606.08463]
[Berger et al., 1708.09405]

NLO QCD+PS
[MadGraph5_aMC@NLO]
[POWHEG]

1+jet NLO QCD+PS
[POWHEG]

NLO+QCD+OS+ PS+EW
[Frederix et al. 1907.12586]
Single-top t-channel
Complete NLO+OS calculation

Complete NLO corrections to the $pp \rightarrow \nu_e JJ J$ contribution to the t-channel signature, in the five-flavor-scheme, where $J$ is a fully democratic (EW) jet.

More details and insights in the talk by Davide Pagani.
Associated top production
$t\bar{t}H, t\bar{t}V, t\bar{t}VV, t\bar{t}t\bar{t}$

$t\bar{t}V, t\bar{t}H$ production at pp colliders at NLO in QCD

$\sim 0.5 - 3$ pb

$t\bar{t}V, t\bar{t}t\bar{t}$ production at pp colliders at NLO in QCD

$\sim 2 - 10$ fb

MadGraph5_aMC@NLO
## NLO (QCD+EW) + NLL \( t\overline{t}W^+ \)

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[Broggio et al., 1907.04343]
NLO (QCD+EW) + NLL
t\bar{t}H

### Combined scales

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[Broggio et al., 1907.04343]
**NLO (QCD+EW) + NLL**

\[ t\bar{t}Z \]

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<td>+117.32(−24.2%)+11.05(−2.3%)</td>
<td>0</td>
</tr>
<tr>
<td>NLOWQCD</td>
<td>+110.1(−14.2%)+17.9(−2.4%)</td>
<td>0.79(2)</td>
</tr>
<tr>
<td>NLO</td>
<td>+110.1(−14.2%)+17.9(−2.4%)</td>
<td>0.87(2)</td>
</tr>
<tr>
<td>nNLOWQCD</td>
<td>+42.3(−3.7%)+19.3(−2.4%)</td>
<td>0.96(4)</td>
</tr>
<tr>
<td>nNLO</td>
<td>+41.3(−3.5%)+19.5(−2.4%)</td>
<td>1.03(4)</td>
</tr>
<tr>
<td>NLOWQCD+NNLL</td>
<td>+89.4(−11.1%)+19.0(−2.4%)</td>
<td></td>
</tr>
<tr>
<td>NLO+NNLL</td>
<td>+89.2(−11.0%)+19.1(−2.4%)</td>
<td></td>
</tr>
</tbody>
</table>

[Broggio et al., 1907.04343]
SMEFT

Linear vs quadratic

At the fitting level the squared can have an important effect, as there are no flat directions in the fit with the squares:

In general without knowing the effect of the squares one is left in the dark about the meaning/reliability of the fit.

Always provide constraints using i) linear and ii) linear+squared terms

[Brivio et al., 1910.03606]
**SMEFT**

$t\bar{t}Z$ couplings from loops in $t\bar{t}$

\[ Q_{33}^{qg1} = \left( \varphi^+ i \bar{D}_\mu \varphi \right) (\vec{p}_L \gamma^\mu t'_L), \]

\[ Q_{33}^{qg3} = \left( \varphi^+ i \tau^I \bar{D}_\mu \varphi \right) (\vec{p}_L \tau^I \gamma^\mu t'_L), \]

\[ Q_{33}^{qu} = \left( \varphi^+ i \bar{D}_\mu \varphi \right) (\vec{p}_R \gamma^\mu t'_R), \]
SMEFT
Top-philic scenario

• Same flavour symmetries as baseline scenario

• Assumes new physics couples more strongly to 3rd-generation LH doublet and RH up-type singlet (+ bosons)

\[
\begin{align*}
&c_{tq}^{[I]}, &c_{\varphi Q}^-, &c_{\varphi Q}^3, &c_{\varphi t}, &c_{tW}^{[I]}, &c_{tZ}^{[I]}, &c_{tG}^{[I]}, \\
&c_{tq}^{[I]} &\text{and} &c_{tW}^{[I]} &\text{appear proportional to } y_b \\
c_{QQ}^1, &c_{QQ}^8, &c_{Qt}^1, &c_{Qt}^8, &c_{Qb}^1, &c_{Qb}^8, \\
c_{QDW} = c_{Qq}^3 = c_{Qt}^3, \\
c_{QDB} = 6 c_{Qq}^{1.1} = \frac{3}{2} c_{u1}^1 = -3 c_{Qq} = -3 c_{Qd} = -2 c_{Ql}^{(e)} = -c_{Qe}, \\
c_{tDB} = 6 c_{tq}^1 = \frac{3}{2} c_{tq}^1 = -3 c_{td} = -3 c_{tb} = -2 c_{tl}^{(e)} = -c_{te}^{(e)}, \\
c_{QDG} = c_{Qq}^8 = c_{Qu}^8 = c_{Qd}^8 = c_{Qb}^8, \\
c_{tDG} = c_{tq}^8 = c_{tu}^8 = c_{td}^8 = c_{tb}^8.
\end{align*}
\]

• 34 parameter basis reduced to 19 free parameters

Reducing the number of dofs leads to an improvement of the bounds as could be expected. The pattern, however, is not always trivial.
**SMEFT**

$t\bar{t}t\bar{t}$: the power of 4

The cross section depends on $y_t$ to the fourth power. It does not depend on $\Gamma_H$, since the Higgs is off-shell.

$$\kappa_t \equiv \frac{y_{Htt}}{y_{Htt}^{SM}}$$

$$\sigma(t\bar{t}tt) = \sigma^{SM}(t\bar{t}tt)_{g+Z/\gamma} + \kappa_t^2 \sigma^{SM}_{int} + \kappa_t^4 \sigma^{SM}(t\bar{t}tt)_H$$

In combination with the measurement of $t\bar{t}H$ both $y_t$ and $\Gamma_H$ can be determined.

$$\sigma(pp \to t\bar{t}H \to t\bar{t}xx)$$

$$\mu_{t\bar{t}H}^{xx} \equiv \frac{\sigma}{\sigma^{SM}} = \frac{\kappa_t^2 \kappa_t^2}{R_\Gamma}$$

$$R_\Gamma \equiv \frac{\Gamma_H}{\Gamma_H^{SM}}$$

100 TeV

$$0.962 \leq \kappa_t \leq 1.031$$

$$0.91 \Gamma_H^{SM} \leq \Gamma_H \leq 1.08 \Gamma_H^{SM}$$

for $\mathcal{L} = 30 \text{ ab}^{-1}$
**SMEFT**

$t\bar{t}t\bar{t}$: the power of 4

**Blue band:** LO calculation rescaled to the SM C-NLO predictions.

95% confidence level limit of $|y_t/y_t^{SM}| < 1.7$
SMEFT
$t\bar{t}t\bar{t}$: the power of 4

\[ \mathcal{O}_T = \frac{ct}{2M^2} (H^\dagger \tilde{D}^\mu H)^2 \]
\[ \mathcal{O}_{WB} = \frac{g^2}{M^2} H^\dagger \sigma^a H B_{\mu\nu} W^a_{\mu\nu} \]
\[ \mathcal{O}_B = \frac{ig^2}{2M^2} (H^\dagger \tilde{D}^\mu H) \partial^\mu B_{\mu\nu} \]
\[ \mathcal{O}_W = \frac{ig^2}{2M^2} (H^\dagger \sigma^a \tilde{D}^\mu H) D^\nu W^a_{\mu\nu} \]

\[ \hat{S} = 4 \left( c_{WB} + \frac{c_W}{3} c_{t}\right) \frac{m_t^2}{M^2} \]
\[ \hat{W} = c_{2W} \frac{m_t^2}{M^2} \]
\[ \hat{Z} = c_{2G} \frac{m_t^2}{M^2} \]

\[ \mathcal{O}_2W = -\frac{c_{2W}}{4M^2} (D^\mu W^a_{\mu\nu})^2 \]
\[ \mathcal{O}_2B = -\frac{c_{2B}}{4M^2} (\partial^\mu B_{\mu\nu})^2 \]
\[ \mathcal{O}_2G = -\frac{c_{2G}}{4M^2} (D^\mu G^a_{\mu\nu})^2 \]

\[ \hat{T} = \frac{c_T}{5} \frac{m_t^2}{M^2} \]
\[ \hat{Y} = c_{2B} \frac{m_t^2}{M^2} \]
\[ \hat{H} = c_\square \frac{m_t^2}{M^2} \]

[Englert et al., 1903.07725]
LO2 and LO3 are large and have also large cancellations. NLO2 and NLO3 are mainly given by ‘QCD corrections’ on top of them, so they are large and strongly depend on the scale choice, at variance with standard EW corrections. Accidentally, relatively to LO1, NLO2+NLO3 scale dependence almost disappear.
Figure 11. The $p_T(t_1)$ distribution in $t\bar{t}t\bar{t}$ production. See the caption of Fig. 9 for the description of the plots.
72. The top quark background contributions which are top-quark pair production and W boson production in association with heavy flavour jets. They find $\sigma_s = 4.8^{+1.6}_{-1.3} (\text{stat.}) + 1.6^{−1.3}_{−1.6} (\text{syst.}) \text{pb}$ with a signal significance of 3.2 standard deviations [116], which provides first evidence for $s$-channel single-top production at 8 TeV. The signal is extracted through a maximum-likelihood fit to the distribution of a multivariate discriminant defined using boosted decision trees to separate the expected signal contribution from background processes. At 7 TeV and 8 TeV, CMS uses $5.1 \text{ fb}^{−1}$ and $19.3 \text{ fb}^{−1}$, respectively, and analyzes sleptonic decay modes by performing a maximum likelihood fit to a multivariate discriminant defined using a Boosted Decision Tree, yielding cross section of $\sigma_s = 7.1^{±1.1} \text{ pb}$ and $\sigma_s = 13.4^{±1.7} \text{ pb}$, respectively, and a best fit value of $2.0^{−0.9}_{±0.8}$ for the combined ratio of the measured $\sigma_s$ values and the ones expected in the Standard Model [117]. The signal significance is 2.5 standard deviations. Both, ATLAS and CMS, also measured the electroweak production of single top-quarks in association with a Z boson, see section C.2.4 of this review.

![Figure 72.2: Measured and predicted single top production cross section from Tevatron energies in $\sqrt{s}$ collisions to LHC energies in $\sqrt{s}$ collisions. Tevatron data points at $\sqrt{s} = 1.96 \text{ TeV}$ are from Refs. [96,97]. The ATLAS and CMS data points at $\sqrt{s} = 7 \text{ TeV}$ are from Refs. [98, 100, 108, 109, 115, 117]. The ones at $\sqrt{s} = 8 \text{ TeV}$ are from Refs. [101, 102, 110, 111, 116, 117]. The ones at $\sqrt{s} = 13 \text{ TeV}$ are from Refs. [104, 105]. Theory curves are generated using [5, 8, 9].](image-url)
Precision top physics

High-$p_T$ tops in $t\bar{t}$

[CMS, 2020]

Shapes ok. Rates are significantly smaller than predicted.
Running top mass
CMS measurement

The interpretation of the CMS analysis has been put into question in [Catani et al. 2005.00557] where no evidence for the running is found.
Precision top physics

$t\bar{t}$ Asymmetries CMS and ATLAS

\[
\frac{d\sigma}{dx}(qq) = \frac{\alpha s}{\pi m_W^2} \left[ 2 - \beta^2 + \beta \gamma_{c} e^2 + \alpha (1 - \beta \gamma_{c} e^2) + 2 \left[ 2 - \frac{2}{3} \beta^2 + \alpha \left( 1 - \frac{1}{3} \beta^2 \right) \right] A_{FB}^{(1)} \right].
\]
Precision top physics
Differential $t\bar{t}$ distributions

Figure 11: Absolute (left) and normalized (right) differential cross sections at the parton level as a function of $p_T(t)$ with $t$ in the lower (upper) and $H^+$ in the upper (lower). The data are shown as points with light (dark) error bars. The theoretical predictions include POWHEG P8 [FxFx], NNLO QCD+NLO EW, Powheg v2+Pythia8, and MG5 P8 [FxFx]. The ratios of the various predictions to the measured cross sections are shown.

Panel in each plot shows the ratio of the theoretical prediction to the data. The left and right plots correspond to absolute and normalized measurements, respectively. The lower and upper panels of the left plot are compared to theoretical predictions with beyond NLO precision. The left panel in each plot shows the ratio of the theoretical prediction to the data.

[CMS, 1803.08856]
Precision top physics

W-helicity fractions

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{4} (1 - \cos^2 \theta^*) F_0 + \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{8} (1 + \cos \theta^*)^2 F_R \]

F_0 = 0.693 \pm 0.014
F_L = 0.315 \pm 0.011

ATLAS+CMS, \sqrt{s} = 8 \text{ TeV}

LHCtopWG

Theory (NNLO QCD)
PRD 81 (2010) 111503 (R)

Data (F_R/F_L/F_0)

ATLAS 2012 l+jets, \text{ L}_{\text{int}} = 20.2 \text{ fb}^{-1}
EPJC 77 (2017) 264

CMS 2012 e+jets, \text{ L}_{\text{int}} = 19.8 \text{ fb}^{-1}
PLB 762 (2016) 512

CMS 2012 \mu+jets, \text{ L}_{\text{int}} = 19.8 \text{ fb}^{-1}
PLB 762 (2016) 512

CMS 2012 single top, \text{ L}_{\text{int}} = 19.7 \text{ fb}^{-1}
JHEP 01 (2015) 053

ATLAS+CMS, \sqrt{s} = 8 \text{ TeV}
LHCtopWG
Rare processes

$t\bar{t}W$ background to $t\bar{t}H$ needs to be scaled up in ATLAS analysis

Normalisation factors for several important irreducible and reducible backgrounds are determined by the fit (see Section 6). Of particular interest are the three measured normalisation factors for the $t\bar{t}W$ background in the 2$\ell$SS and 3$\ell$ event categories: $\lambda_{t\bar{t}W}^{SS} = 1.56^{+0.30}_{-0.28}$, $\lambda_{t\bar{t}W}^{3\ell} = 1.26^{+0.19}_{-0.18}$, and $\lambda_{t\bar{t}W}^{3\ell} = 1.68^{+0.30}_{-0.28}$. They are consistent with each other and systematically above unity, indicating a preference of the data for a higher value of the $t\bar{t}W$ cross section than the updated $t\bar{t}W$ theoretical cross section (see Section 3). Because the $t\bar{t}W$ modelling uncertainties are constructed to only affect the shapes of distributions while the total yield is fixed, the normalisation factors represent a scaling factor for $t\bar{t}W$ events selected in this analysis. Uncertainties to extrapolate the $t\bar{t}W$ scaling factor to the inclusive phase space are not included.

[ATLAS, 2019]

More details and insights in the talk by Ioannis Tsinikos