Top cross-section measurements and rare $t\bar{t}X$ processes

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Introduction

- Heaviest particle in Standard Model
- Produced in copious numbers at LHC!
  - $t\bar{t}$ production: $\sim 120M$ events @10 Hz for $\sqrt{s} = 13$ TeV
- Allows for precise tests of SM
- Interesting properties (interacts strongly with Higgs sector, …)

Also see talks by Thomas Stevenson, Massimiliano Grazzini, James Howarth, Ashley Parker, Adrian Salas, & Nicolas Chanon!

This talk highlights a few of the latest ATLAS & CMS top cross section and $t\bar{t}X$ measurements
Overview

1) pair production
   main production process, sensitive

2) single-top production
   good EWK probe

3) associated production
   rare tests of SM

xsec summary plot
**$t\bar{t}$ production**

1) **pair production**

2) **single-top production**

3) **associated production**

**Highlights: pair production**

- early Run 3 $\sigma_{t\bar{t}}$ measurement at 13.6 TeV
- early Run 3 $\sigma_{t\bar{t}}$ and $\sigma_{Z\rightarrow ll}^{\text{fid.}}$ measurement at 13.6 TeV
- inclusive/differential $\sigma_{t\bar{t}}$ at 13 TeV
- search for violation of Lorentz invariance in $t\bar{t}$
- boosted $t\bar{t}$ jet substructure differential $\sigma_{t\bar{t}}$

**NEW!**

Also see talks by Mohammed Faraj, Kathryn Coldham, Federica Colombina, & Carmen Diez Pardos!
### $t\bar{t}$ Production

- **Dominant production mode at LHC**
- **→ Allows for precise probes of SM!**

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\sigma_{t\bar{t}}$ (NNLO + NNLL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 TeV</td>
<td>$833.9^{+29.4}_{-36.6}$ pb (4.4%)</td>
</tr>
<tr>
<td>13.6 TeV</td>
<td>$923.6^{+32.1}_{-40.4}$ pb (4.4%)</td>
</tr>
</tbody>
</table>

(LHCPhysics)

(LHC Physics)
inclusive \( t\bar{t} \) production

**CMS-TOP-22-012**

- Summer 2022 inclusive \( \sigma_{t\bar{t}} \)
- 1 or 2 leps (e/\( \mu \)) +jets
- First early Run 3 results @ 13.6 TeV!

\[
\sigma(pp \rightarrow t\bar{t}) = 882 \pm 23 \text{ (stat+syst)} \pm 20 \text{ (lumi)} \text{ pb}
\]

**ATLAS-CONF-2023-006**

- 2022 inclusive \( \sigma_{t\bar{t}} \) & fiducial \( \sigma_Z \)
- OS \( e\mu \) + b-jets
- First early Run 3 results @ 13.6 TeV!

\[
\sigma(pp \rightarrow t\bar{t}) = 859 \pm 4 \text{ (stat)} \pm 22 \text{ (syst)} \pm 19 \text{ (lumi)} \text{ pb}
\]
\[
\sigma(pp \rightarrow Z^{\text{fid.}}) = 751 \pm 0.3 \text{ (stat)} \pm 15\text{(syst)} \pm 17 \text{ (lumi)} \text{ pb}
\]
\[
R_{t\bar{t}/Z} = 1.144 \pm 0.006 \text{ (stat)} \pm 0.022 \text{ (syst)} \pm 0.003 \text{ (lumi)}
\]

*my rough addition*
inclusive & differential $t\bar{t}$

- Inclusive & single/double differential $\sigma_{t\bar{t}} (e\mu$ final state)

- Inclusive: Most precise inclusive $\sigma_{t\bar{t}}$ @ 13 TeV! $\rightarrow$ impressive systematics (0.8% lumi!)

- Differential: Kinematic dists. of 8 variables $\rightarrow$ good agreement with predictions except tails, improved MC needed (NNLO/EW corrections, threshold effects)

$$\sigma(pp \rightarrow t\bar{t}) = 829 \pm 1 \text{ (stat)} \pm 13 \text{ (syst)} \pm 8 \text{ (lumi)} \pm 2 \text{ (beam)} \text{ pb}$$
\( t\bar{t} \) measurements \( \text{NEW!} \)

search for violation of Lorentz invariance in \( t\bar{t} \) (CMS PAS TOP-22-007)
- dilepton \((e\mu)\) final state (2016+17)
- \( \text{diff} \sigma_{t\bar{t}} \) as function of sidereal time in EFT framework

CMS Preliminary \( 77.4 \text{ fb}^{-1} (13 \text{ TeV}) \)

\[ \text{diff} \sigma_{t\bar{t}} \text{ vs. sidereal time} \]

See talk by Nicolas Chanon!

boosted \( t\bar{t} \) differential jet substructure measurement (ATLAS-CONF-2023-027)
- lep+jets & all-had final states (Run II)
- single/double \( \text{diff} \sigma_{t\bar{t}} \) for 8 vars related to charged jet components

See talk by Mohammed Faraj!
single top production

1) pair production

2) single-top production

3) associated production

Highlights: single top production

• s-channel production

• t-channel production

• tWZ production
single top production

- t-channel → "golden channel" sensitive to FCNC
- tW observed at LHC, good probe of BSM couplings
- s-channel very challenging!

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$\sigma$ (pb)</td>
<td>$\sqrt{s} = 13$ TeV</td>
</tr>
<tr>
<td>t-channel (NNLO)</td>
<td>214.2$^{+4.1}_{-2.6}$</td>
</tr>
<tr>
<td>tW (NNLO)</td>
<td>79.3$^{+2.9}_{-2.8}$</td>
</tr>
<tr>
<td>s-channel (NLO)</td>
<td>10.32$^{+0.40}_{-0.36}$</td>
</tr>
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LHCHPhysics

ATLAS+CMS Preliminary
LHCTOPWG

Single top-quark production
November 2022

$\sqrt{s} [\text{TeV}]$

LHCTOPWGSummaryPlots

$\frac{\sigma}{\text{pb}}$
s-channel production

- **1-lep** final state
- CRs for major $t\bar{t}$ & $W + jets$ bkgs
- Data-driven QCD bg.
- Matrix-element method to derive signal probability per event $P(S|X)$
- First evidence of s-channel production @ 13 TeV!
- obs (exp) significance: 3.3 (3.9) s.d.

\[
\sigma_{s-channel} = 8.2 \pm 0.6 \text{ (stat)}^{+3.5}_{-2.9} \text{ (syst)} \text{ pb}
\]
t-channel production

- Production of single tops/antitops via t-channel exchange of virtual W
- 1-lep final state @13 TeV
- NN-based sig vs. bkg discrimination
- Include EFT interpretations, CKM result
- Good agreement with SM predictions

$$\sigma(tq + \bar{t}q) = 221 \pm 13 \text{ pb}$$

$$R_t = \frac{\sigma(tq)}{\sigma(\bar{t}q)} = 1.636^{+0.036}_{-0.034}$$

Also new 5 TeV result!!

See talk by Mohammed Faraj!
**tWZ production**

- Very rare ($\sigma_{tWZ}\sim 136$ fb)
- New physics potential via modified interactions, good probe of EFT
- First ever $tWZ$ search (multi lep final state)
- Use binary and multiclass NNs for sig. vs. bkg. ($tWZ$, $ttZ$, other)
- Reached evidence of $tWZ$ production
  - obs (exp) significance : $3.5$ ($1.4$) s.d.

\[
\sigma_{tWZ} = 0.37 \pm 0.05 \text{ (stat)} \pm 0.10 \text{ (syst) pb}
\]
associated production

1) pair production

2) single-top production

3) associated production

Highlights: associated production

- $t\bar{t}t\bar{t}$ production:
  - multi-channel (including all-hadronic)
  - $t\bar{t}t\bar{t}$ observation (CMS & ATLAS)  
    - NEW!

- $t\bar{t}b\bar{b}$ production  
  - NEW!

- $t\bar{t}W$ production  
  - NEW!

- $t\gamma$ observation

- top + additional leptons EFT search  
  - NEW!

Also see talks by Johnny Raine & Stergios Kazakos!
$t\bar{t}t\bar{t}$ production

- $\sigma_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8} \text{ fb (NLO (QCD + EW) + NLL @13TeV)}$ \cite{1}
- $\sigma_{t\bar{t}t\bar{t}} = 12 \text{ fb (NLO (QCD + EW) @13TeV)}$ \cite{2}
- Sensitive to Yukawa & EFT couplings
- Enhancement of $\sigma_{t\bar{t}t\bar{t}}$ predicted by BSM

\cite{1} arXiv:2212.03259
\cite{2} arXiv:1711.02116

Also see talks by Hesham El Faham & Laura Valero!
$t\bar{t}t\bar{t}$ evidence

- 1lep, OS 2-lep, all-hadronic combination
- First inclusion of all-hadronic channel!
  - difficult due to large QCD bkgs
  - normalizing flow NN used to predict QCD & $t\bar{t} + jets$ from data in CRs
- obs (exp) significance : 4.0 (3.2) s.d.
  $\rightarrow$ first evidence of $t\bar{t}t\bar{t}$

$\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 17 \pm 4 \text{ (stat)} \pm 3 \text{ (syst)} \text{ fb}$
**$\bar{t}t\bar{t}t$ observation - CMS**

- **New** 2+ lep SS result with **legacy reprocessing** of Run 2
- **Key improvements:**
  - BDT lep Id. $\rightarrow$ looser event sel.
  - Improved b-jet tags
  - Separate multi-class BDTs per SS 2lep, 3lep & 4lep channels ($\bar{t}t\bar{t}t$, $\bar{t}tV$ or $\bar{t}t$ like)
- obs (exp) significance: 5.5 (4.9) s.d.

\[ \sigma(pp \rightarrow \bar{t}t\bar{t}t) = 17.9^{+3.7}_{-3.5} \text{ (stat)} ^{+2.4}_{-2.1} \text{ (syst)} \text{ fb} \]
**Observation - ATLAS**

- **New 2+ lep SS result** with legacy reprocessing of Run 2
- **Key improvements:**
  - Looser event selection
  - Improved b-jet tags, improved systs.
  - Data-driven $t\bar{t}W + jets$, improved $t\bar{t}t$
  - GNN-based sig vs. bkg discrimination
- Also extract limits on $t\bar{t}t$, top-H Yukawa coupling, EFT interpretations
- Observed (expected) significance: 6.1 (4.3) s.d.

\[
\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 22.5^{+4.7}_{-4.3} \text{(stat)}^{+4.6}_{-3.4} \text{(syst)} \text{ fb}
\]
**tt̅tt̅ production - summary**

**NEW CMS 2LSS/ML 138 fb^{-1}**
17.9^{+6.1}_{−5.6} fb 
5.5 (4.9) σ

**NEW ATLAS 2LSS/ML 139 fb^{-1}**
22.5^{+9.3}_{−7.7} fb 
6.1 (4.3) σ

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**ATLAS+CMS Preliminary**
LHCTopWG

\[ \sigma_{ttt̅} = 12.0^{+2.2}_{−2.5} \text{ (scale) fb} \]
JHEP 02 (2018) 031
NLO QCD+EW

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**ATLAS, 2LSS/3L, 139 fb^{-1}**
EPJC 80 (2020) 1085

**ATLAS, 1L/2LOS, 139 fb^{-1}**
JHEP 11 (2021) 118

**ATLAS, comb., 139 fb^{-1}**
JHEP 11 (2021) 118

**CMS, 2LSS/3L, 137 fb^{-1}**
EPJC 80 (2020) 75

**CMS, 1L/2LOS, 35.8 fb^{-1}**
JHEP 11 (2019) 082

**CMS, 1L/2LOS/all-had, 138 fb^{-1}**
CMS-PAS-TOP-21-005 *

**CMS, comb., 138 fb^{-1}**
CMS-PAS-TOP-21-005 *

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Run 2, \( \sqrt{s} = 13 \) TeV, November 2022

**σ_{ttt̅} ± tot. (stat. + syst.)**
**Obs. (Exp.) Sig.**

- 24^{+7}_{−6} (5^{−5}_{−4}) fb 
4.3 (2.4) σ

- 26^{+8}_{−15} (8^{+15}_{−13}) fb 
1.9 (1.0) σ

- 24^{−7}_{−6} (4^{+5}_{−4}) fb 
4.7 (2.6) σ

- 12.6^{−5.8}_{−5.2} fb 
2.6 (2.7) σ

- 0^{+20}_{−20} fb 
0.0 (0.4) σ

- 38^{+13}_{−11} fb 
3.7 (1.5) σ

- 17^{−5}_{−5} fb 
3.9 (3.2) σ

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**my rough addition**
**$\bar{t}t\bar{b}b$ production (inclusive)**

- Rare SM process, irreducible $t\bar{t}H$ & $t\bar{t}t\bar{t}$ backgrounds
- lep+jets final state ($e$ or $\mu$, 5+ jets)
- Inclusive and differential (4 fiducial regions)
- Most precise inclusive $ttbb$ results so far
- Inclusive $\sigma$ higher than theor. preds (consistent with previous measurements)

**Inclusive $\sigma$s for phase spaces vs. sim preds.**

*NEW!*
$t\bar{t}b\bar{b}$ production (differential) **NEW!**

- **lep+jets** final state ($e$ or $\mu$, 5+ jets)
- Inclusive and differential (4 fiducial regions)
- Normalized differential $\sigma$: measured for 37 observables
- Varying compatibility with theoretical predictions

**Charts:**

**N_{Jets} for 5+ jets 3+ b-jets region**

**H_T of b-jets for 6+ jets 4+ b-jets region**
$t\bar{t}W$ production (inclusive) (NEW!)

- $\sigma_{t\bar{t}W} = 722^{+70}_{-78}$ (scale) ± 7 (PDF) fb (NLO (QCD + EW) @13TeV) $\leftrightarrow$ NNLO needed!
- SS and multi-lep final states
- Inclusive and differential
- Robust MC modeling + uncertainties
- Inclusive $\sigma$ higher than theor. preds (consistent with previous measurements)

$$\sigma(pp \rightarrow t\bar{t}W) = 890 \pm 50 \text{ (stat)} \pm 70 \text{ (syst)} \text{ fb}$$
**$t\bar{t}W$ production (differential)**

- SS and multi-lep final states
- Normalized differential $\sigma$: measured for 7 observables
- First differential measurement!
- Generally consistent with SM

![Graph showing lep charge combined normalized $H_T$ unfolding](image)
**$t\gamma$ observation**

- Final state: $1 \text{ lep}, 1 \gamma, +\text{jets}$
- $2 \text{ SRs w/ forward jets}$
- $\text{NNs to separate sig from bkg}$
- Previously 4.4 s.d. evidence (CMS 35.9 fb$^{-1}$ @ 13TeV)
- First observation!
- obs (exp) significance : $9.3 (6.8)$ s.d. 139 fb$^{-1}$ @ 13 TeV

<table>
<thead>
<tr>
<th>$\sigma_{t\gamma} \times \mathcal{B}(t \to b\ell\nu)$</th>
<th>Meas. fid. cross section (fb)</th>
<th>SM prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parton level</td>
<td>$688 \pm 23 \text{ (stat) }^{+75}_{-71} \text{ (syst)}$</td>
<td>$515^{+36}_{-42}$</td>
</tr>
<tr>
<td>Particle level</td>
<td>$303 \pm 9 \text{ (stat) }^{+33}_{-32} \text{ (syst)}$</td>
<td>$217^{+27}_{-15}$</td>
</tr>
</tbody>
</table>
top+leptons EFT search

- Potential new physics parametrized vs. 26 6-dim EFT operators
- Run II data categorized by lep/jet/b-jet multiplicities, total lep charge
- Fit to kinematic vars. (leading leps/jets transv. $p_T$, on-shell Z $p_T$)
- No significant deviation from SM predictions

Also see talks by Davide Valsecchi & Eleonora Rossi!
Conclusion

- Highlighted latest ATLAS & CMS top cross section and $t\bar{t}X$ measurements that showcase tops as key tool for probing limits of SM.

- Several new measurements and observations beyond expectations because of improved analysis strategies and techniques.
  - First Run 3 results!
  - First evidence of $tWZ$!
  - First $t\bar{t}t\bar{t}$ observation!
  - New $t\bar{t}b\bar{b}$, $t\bar{t}W$, top EFT, & single top t-channel measurements!

- Generally good agreement with SM with some excesses ($t\bar{t}t\bar{t}$, $t\bar{t}W$, $tWZ$...)
  - NNLO calculations & improved MC needed
  - Look forward to further exploration in Run 3/HL-LHC!
BACKUP
inclusive & differential $t\bar{t}$

- $p_T^\ell$, the single-lepton transverse momentum ($\ell = e$ or $\mu$);
- $|\eta^\ell|$, the single-lepton pseudorapidity;
- $m^{e\mu}$, the $e\mu$ system invariant mass;
- $p_T^{e\mu}$, the $e\mu$ system transverse momentum;
- $|y^{e\mu}|$, the $e\mu$ system rapidity;
- $E^e + E^\mu$, the sum of lepton energies;
- $p_T^e + p_T^\mu$, the scalar sum of lepton transverse momenta;
- $|\Delta\phi^{e\mu}|$, the azimuthal angular separation of the leptons.
s-channel production

- the right-hand plot is data minus all background
- different error bars in the left and the right plot come from the background subtraction and correlations of uncertainties
Templates used in the maximum likelihood fit

- **tWZ NLO phase space**
  - Low-energy region
    - 3 leptons
      - $2j, \geq 1b$
      - $\geq 3j, \geq 1b$
  - Boosted region
    - 4 leptons
      - $1b$
      - $\geq 2b$
      - $\geq 1b$

- **Control regions**
  - ZZ CR
  - WZ+jets CR

- **Binary DNN**
  - 3 leptons
- **Multiclass DNN**
  - N(b-jets)

#events

- #events
- #events
Table 1: List of WCs included in this analysis. The definitions of the WCs and the definitions of the corresponding operators can be found in Table 1 of Ref. [18]. Note that in order to allow MADGRAPH5_aMC@NLO to properly handle the emission of gluons from the vertices involving the $c_{tG}$ WC, an extra factor of the strong coupling is applied to the $c_{tG}$ coefficients.

<table>
<thead>
<tr>
<th>Operator category</th>
<th>WCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two heavy quarks</td>
<td>$c_{tQ}$, $c_{Q^-}$, $c_{Q^+}$, $c_{Q^0}$, $c_{Q^T}$, $c_{Q^B}$, $c_{tW}$, $c_{tZ}$, $c_{bW}$, $c_{tG}$</td>
</tr>
<tr>
<td>Two heavy quarks two leptons</td>
<td>$c_{Q^T}^{3(\ell)}$, $c_{Q^T}^{-3(\ell)}$, $c_{Q^T}^{3(\ell)}$, $c_{Q^T}^{3(\ell)}$, $c_{tQ}^{5(\ell)}$, $c_{T(\ell)}$</td>
</tr>
<tr>
<td>Two light quarks two heavy quarks</td>
<td>$c_{Q^Q}^{31}$, $c_{Q^Q}^{38}$, $c_{Q^Q}^{11}$, $c_{Q^Q}^{18}$, $c_{tQ}^{18}$, $c_{tQ}^{8}$, $c_{tQ}^{1}$</td>
</tr>
<tr>
<td>Four heavy quarks</td>
<td>$c_{Q^Q}^{1}$, $c_{Q^Q}^{1}$, $c_{Q^Q}^{8}$, $c_{Q^Q}^{1}$, $c_{tQ}^{1}$</td>
</tr>
</tbody>
</table>

Event distribution in CMS preliminary postfit with 138 fb$^{-1}$ at 13 TeV.
top+leptons EFT search

Figure 1: Summary of the event selection categorization. The details for the selection requirements are described in Sections 5.1, 5.2, and 5.3.
Additional Analyses
FCNC in $t\gamma$

- Search for FCNC top interactions in assoc. with $\gamma + \text{jets}$
- Final states with 1 lep 1 $\gamma$, +jets
- BDTs to separate sig vs. bkg
- Obs (exp) upper limits set on FCNC coupling strengths ($\kappa_{tq\gamma}$) & branching fractions of top quark decays

<table>
<thead>
<tr>
<th>Combined</th>
<th>Obs. limit</th>
<th>Exp. limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{tu\gamma}$</td>
<td>$6.2 \times 10^{-3}$</td>
<td>$6.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\kappa_{tc\gamma}$</td>
<td>$7.7 \times 10^{-3}$</td>
<td>$7.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>$B(t \to u + \gamma)$</td>
<td>$0.95 \times 10^{-5}$</td>
<td>$1.20 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B(t \to c + \gamma)$</td>
<td>$1.51 \times 10^{-5}$</td>
<td>$1.54 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
FCNC in $tZ$

- Search for FCNC top interactions in assoc. with $Z$
- Final states with 1 or 2 tops, 3 leps, 1 b-jet, MET
- BDTs to separate sig from bkg
- Obs (exp) upper limits set on FCNC coupling strengths & branching fractions of top quark decays
single top $tW$ production

- 1-lepton final state ($e$ or $\mu$)
- inclusive and differential
- max likelihood fit to BDTs & subleading jet $p_T$ in 1 & 2 jet/b-jet regions.

- Study differential distributions of 6 kinematic variables
- Consistent with SM predictions

$$\sigma_{tW} = 79.2 \pm 0.8 \text{ (stat)}^{+7.0}_{-7.2} \text{ (syst)} \pm 1.1 \text{ (lumi)} \text{ pb}$$