CMS Management Visit to Ghent University, 23 Apr 2025

Four top quark production: observation and beyond

Niels Van den Bossche









Re-analysis of Run 2 data

- Improved lepton identification
- Improved b-tagging
- Better analysis strategy $\sigma(H)/\sigma(tttt) \approx 3,700$ $\sigma(tt)/\sigma(tttt) \approx 70,000$



Niels Van Den Bossche needs two hands to hold all the tops he has (4 to be precise). It's the heaviest final state ever measured at the LHC and @ATLASexperiment and @CMSExperiment see more of it than they expected (and they just can't get enough of it!) #TOPQ2023 #4tops

TOP2023

Ø ...

CERN Seminar

9 000.

9 .901

 $(\sigma_{i7} \times 10^{-5})$

Production cross section ≈ 12 fb

Expecting ≈ 2000 events in Run 2
 Multiple final states

· Very rare but distinctive!

ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore







Four top, three top or new physics?



PLB 847 (2023) 138290

0

20

40

60

 σ_{tftf} [fb]

80

100

Two ongoing analyses in our group:

- Interpretations of the four top observation
- Four top in run 3
 - Improved b-tagging Ο
 - 20% higher production rate Ο

120

Four top, three top or new physics?



0.5 1.0 1.5

-1

-2

b-tagged
 light jet
 muon
 electron

2.5 3.0 R distance (1/3 metrics Observed

-1

0

- Four top in run 3
 - Improved b-tagging
 - 20% higher production rate

NEW

2

Kt

Expected

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Associated top quark production: ttW

David Marckx





ttW: an important piece of the puzzle

- Ghent started with the 2016 ttZ/ttW measurement
 - Both processes seemed to have larger cross sections than SM predictions!







ttW: an important piece of the puzzle

- Ghent started with the 2016 ttZ/ttW measurement
 - Both processes seemed to have larger cross sections than SM preds!
- With Tu Thong we worked out a completely new analysis strategy and performed the full Run 2 inclusive cross section measurement.
 - Great work together with Oviedo
 - With 7.5% uncert. most precise measurement to date!









ttW: an important piece of the puzzle

- Exploit the high quality UL dataset to perform new measurements
 - Continue the great work together with Oviedo
 - First CMS differential cross section results and first CMS charge asymmetry measurement!
 - a process that really catches the attention of theorists
 - rich future ahead with Run 3!









70 year CERN celebration in Brussels



Jan van der Linden



Higgs-charm coupling – the next highlight of Higgs physics



- Analysis of ttH(H \rightarrow cc) with Run 2 data
 - \rightarrow Only 2000 signal events expected
 - \rightarrow Large contributions from UGent team
 - \rightarrow Physics briefing and PAS released for Moriond

Successful collaboration with CERN, Brown, NKU Athens



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• Best limits on Higgs-charm coupling yet!



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Successful collaboration with CERN, Brown, NKU Athens

Beating the High-Lumi projections from 3 years ago!



Key ingredients from UGent:

- Jet flavor tagging
 - \rightarrow First time ParticleNet in Run 2
 - \rightarrow Custom calibration



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- Difficult tt+heavy flavor jets backgrounds
 - \rightarrow Detailed uncertainty model
 - \rightarrow Thorough stress tests and validations



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- Fully hadronic channel
 - → Excellent QCD background rejection
 - \rightarrow Thorough validation by Maarten!



The future of Higgs-charm coupling at UGent

Future projects:

- Extending ttH(cc) to Run 3
 - \rightarrow Even better flavor tagging at CMS in Run 3!
 - \rightarrow Improved background models for Run 3?
- ttH(cc̄) with boosted Higgs boson decays?
 → Great potential to contribute more





Measuring the important backgrounds – tt+charm jets

Current UGent project: Run 2 differential tt+charm measurement (by Dati + Jan)

• Goals:

- \rightarrow Improve understanding of tt+charm
- \rightarrow Is modeling sufficient?

- Key ingredients:
 - \rightarrow Jet flavor tagging
 - → Separation from overwhelming tt+jets processes

• **Publication goal:** End of the year :)



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Precision measurement of single top quark production

Maarten De Coen



Precision top physics

LHC is a precision machine! And Ghent is on top of it!

- high precision luminosity
 - measuring / calibrating beam positions
 - leading uncertainty in tt cross-section
- high performance lepton identification
- many forefront cross-section measurements (see other presentation)

New in town: t-channel single top





CMS@LHC: a precision story

LHC is a precision machine!

- detailed studies of the proton
- quantum tests (e.g. entanglement)

t-channel single top offers both:

• **o** polarized top quark 🔆 b-quark pdf





t-channel single top: a precision story

- Previous CMS measurement 2016 only
- Aim for higher precision
 - full run 2 UL dataset (higher stats)
 - advanced techniques from multi-lepton analysis (TOP lepton MVA)
 - innovative machine learning (ttHcc experience)





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Associated top quark production: ttz, ttγ, tZq

Joscha Knolle



Precision ttZ cross section measurements



First observation of tZq production

Phys. Rev. Lett. 122 (2019) 132003 JHEP 02 (2025) 177



Most precise tty cross section measurement



Summary

numerous top physics results from UGent

6/9 PhD students graduated, one CMS thesis award

currently ttX and TMG conveners

continue to reach for more precision and higher energies



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Heavy neutral lepton searches with prompt & displaced signatures

Adina Tomaru



Beyond the Neutrino: Searching for the Heavy Siblings

Heavy Neutral Leptons (HNL) are capable of explaining phenomena that SM leaves still open:

- Neutrino masses
- Baryon Asymmetry in the Universe
- Dark Matter



Ghent has made significant contributions to the field with **4 PhD students** graduating on this topic!



Production of HNL at the LHC

HNL mix with the SM neutrinos

 \Rightarrow HNL can be produced in processes that generate high amounts of ν

- → production from heavy meson decays: $B \rightarrow \ell N X$
- → production via weak boson decays: $Z \rightarrow v N \text{ or } W \rightarrow \ell N$



- ✓ High $\sigma(p p \rightarrow b b)$
- X Challenging due to lack of trigger
- Recent CMS result using

B-parking data <u>JHEP 06 (2024) 183</u>



- X Low $\sigma(p \ p \rightarrow W \rightarrow \ell \ v)$
- Clear experimental signature for both prompt
 & displaced searches
- Most explored N production channels

Ghent searches for HNLs in a nutshell



• First paper that whipped out a large phase space previously unexplored.



- EXO-20-009 (1l prompt 2l displaced)
 - First CMS search for displaced HNL sig.
- EXO-21-011 (1l prompt 1l in j displaced)

- EXO-22-011 (3^l prompt)
 - First constraints on tau neutrino couplings for $m_N > m_W$. Most stringent to date.





Ongoing work: displaced HNL signature in the LRSM



New HNL signature from **LRSM** in a parameter space never explored before:

1 prompt l (e /µ) +
 1 displaced jet
 encompassing a l



First presentation of the analysis in the EXO LLP group last month.