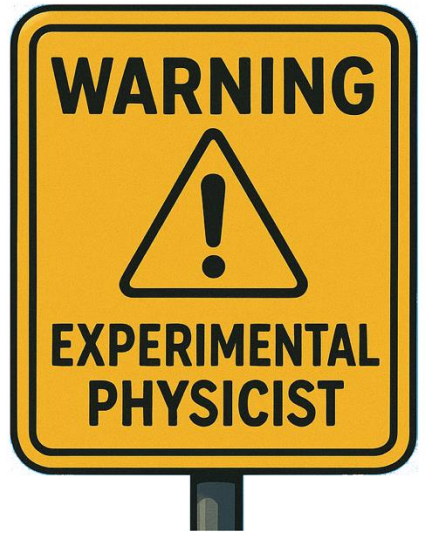
Overview of top physics

Sergio Sánchez Cruz
LHC BSM working group general meeting
10.10.2025

Top quark 30th anniversary celebration at TOP2025 in Seoul (Korea)

Disclaimer

- **I aim to give an overview of top physics studies that could be relevant for BSM searches**
- **I will focus on key measurements and/or outstanding discrepancies**
  - Rather than a compilation of new/recent results
- **I won't cover very important topics e.g. measurements of the top quark mass**
- **I won't be able to cover many on the ongoing efforts on the phenomenology/theory side**



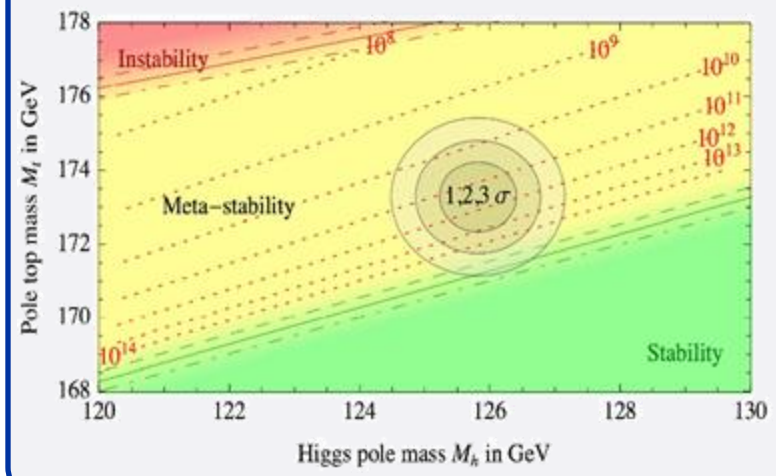
The top quark

Large mass
but strongly interacting!
→ precision modeling

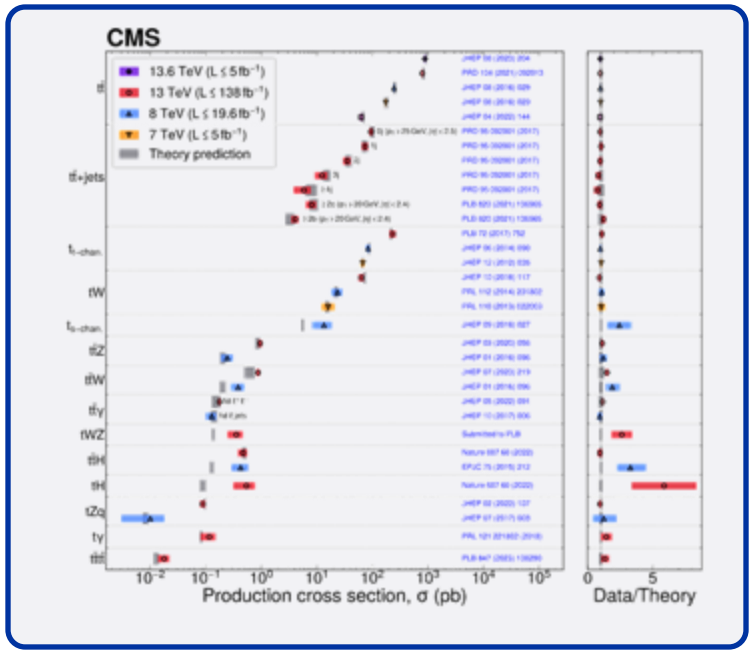
Yukawa
$g\bar{\psi}\phi\psi$

Natural coupling to the Higgs

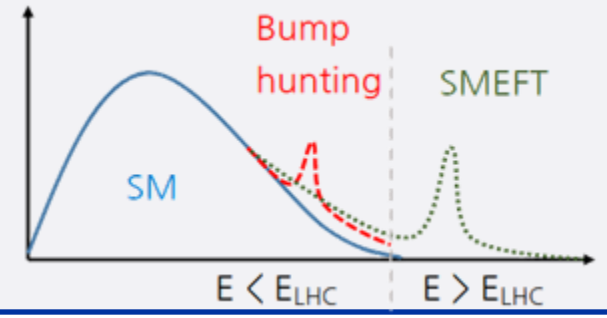
Vacuum stability



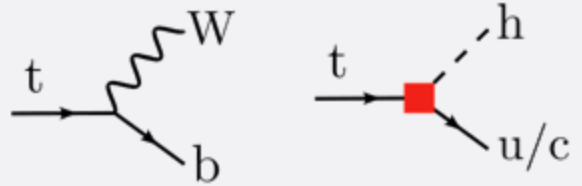
Abundant, rare, & very rare processes
(enhanced?)



Indirect searches



(Rare) decays and production modes



CKM
(measurements)

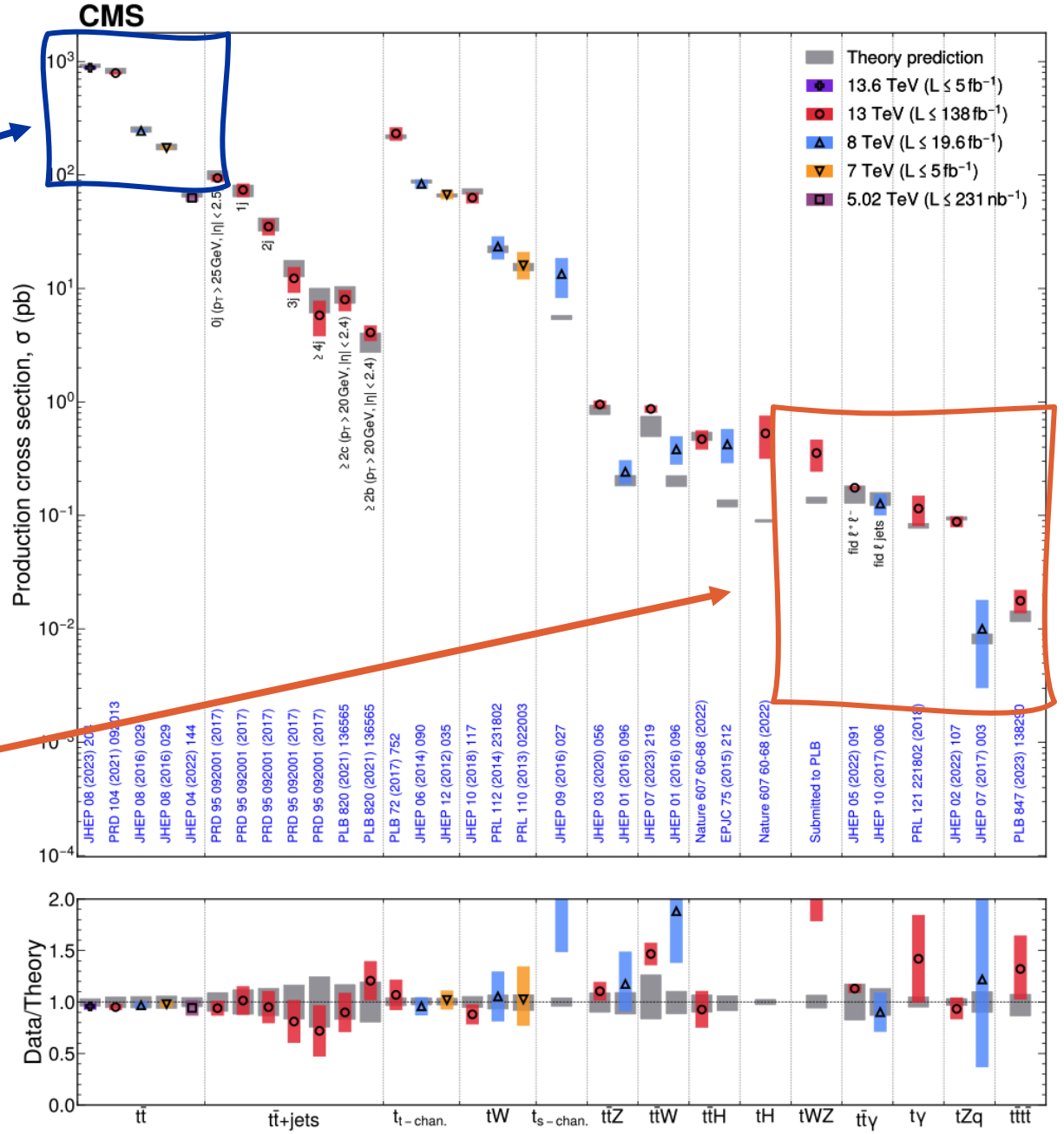
FCNC, LFU
(searches)

Connect to other sectors & "big BSM picture"

Top physics at the LHC

- **ttbar production:**
  - Large cross section O(100 M) events in Run 2+3
  - Precision in the bulk
  - Precision measurements e.g. top mass
  - Dedicated studies of the tails

- **Rare processes (top+boson, multiple tops)**
  - O(1000) events in Run 2+3 (or less)
  - Exotic signatures
  - Sensitivity to BSM physics



Phys. Rept. 1115 (2025) 3

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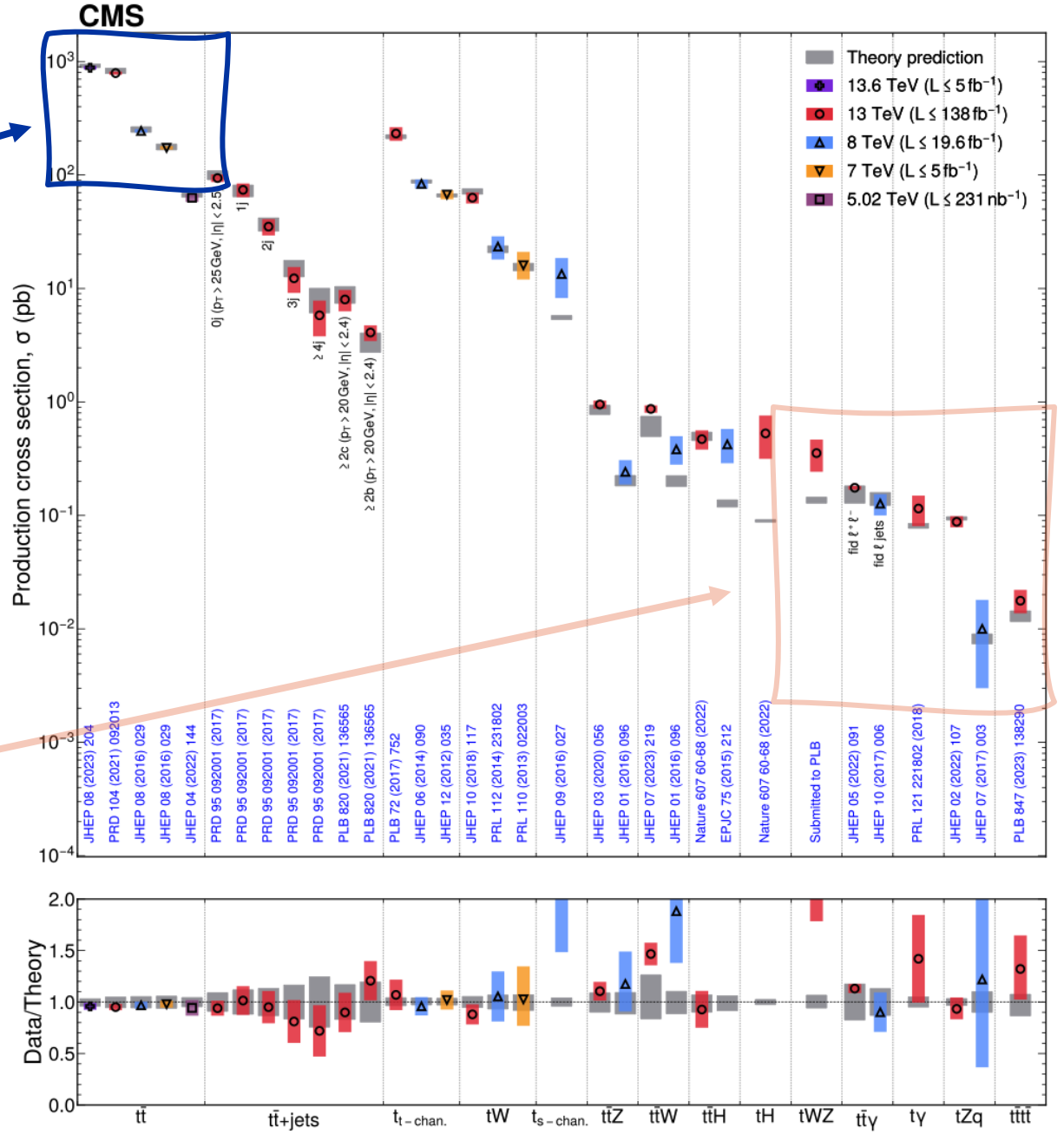
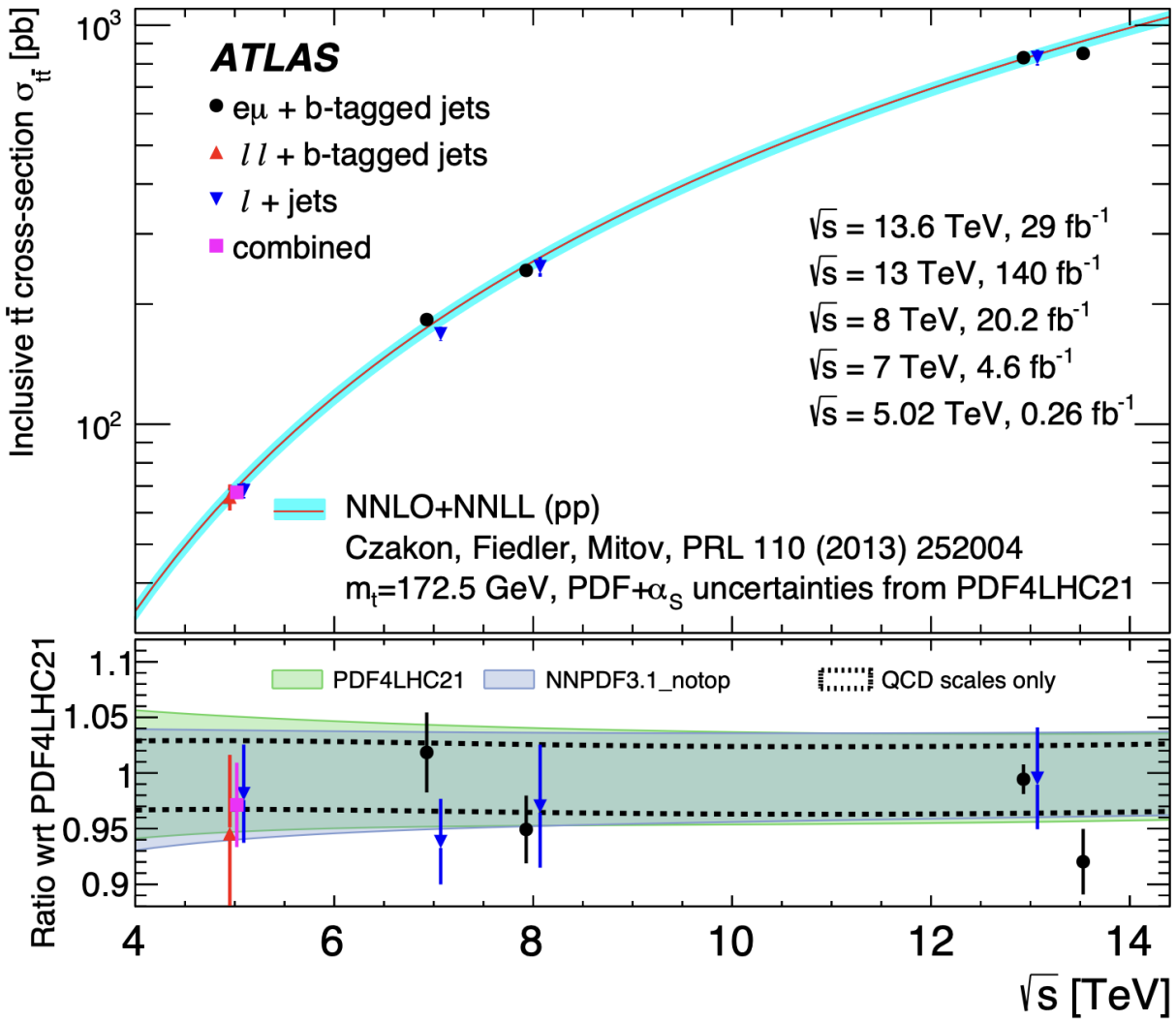


Phys. Rept. 1115 (2025) 3

ttbar production – the bulk

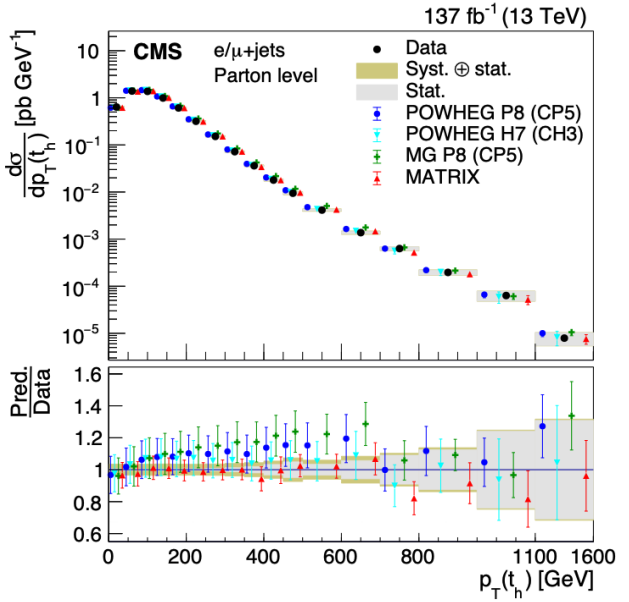


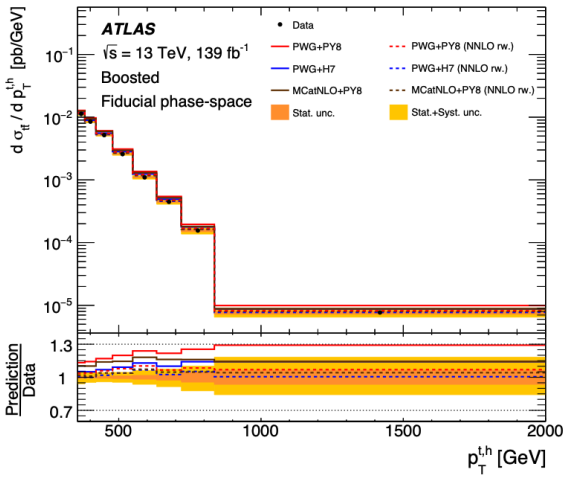
- ATLAS and CMS measuring ttbar at all available energy scales
- Remarkable agreement with NNLO+NNLL predictions across the board
- ATLAS already hitting the 1% accuracy in the measurement
  - 3-4 times more precise than predictions

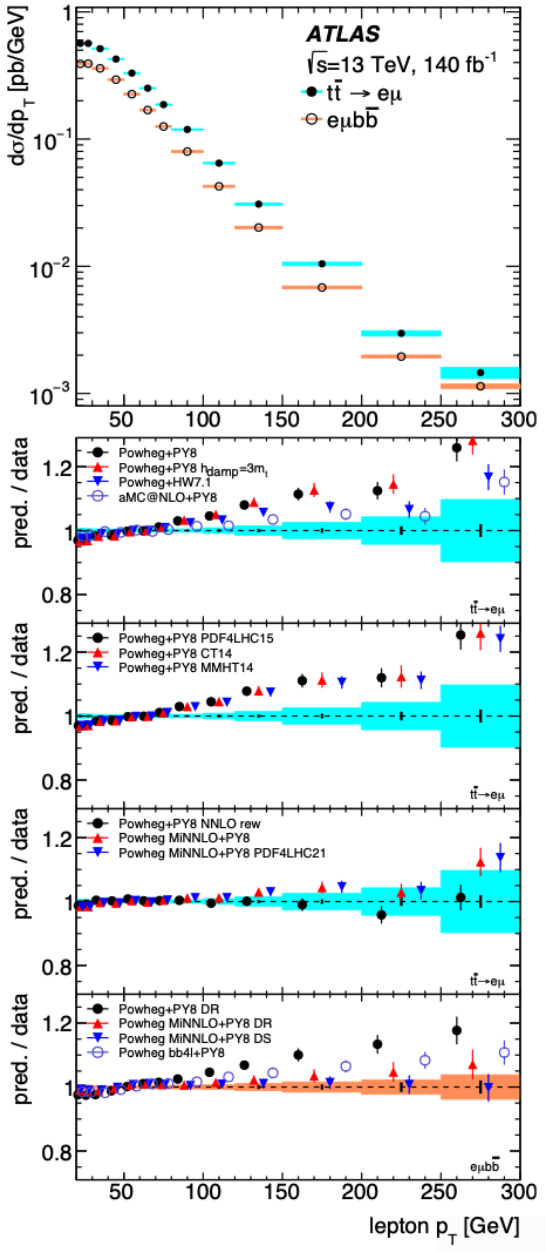
arXiv:2509.15066

tt production – differential measurements

- Plethora of 1D/2D/3D differential cross section measurements have been performed of tt production
- Relatively good agreement in most observables already by NLO predictions
- Improved description by NNLO(+PS) models in key observables e.g. top p_T, $\Delta\phi(\ell\ell)$, lepton p_T, …





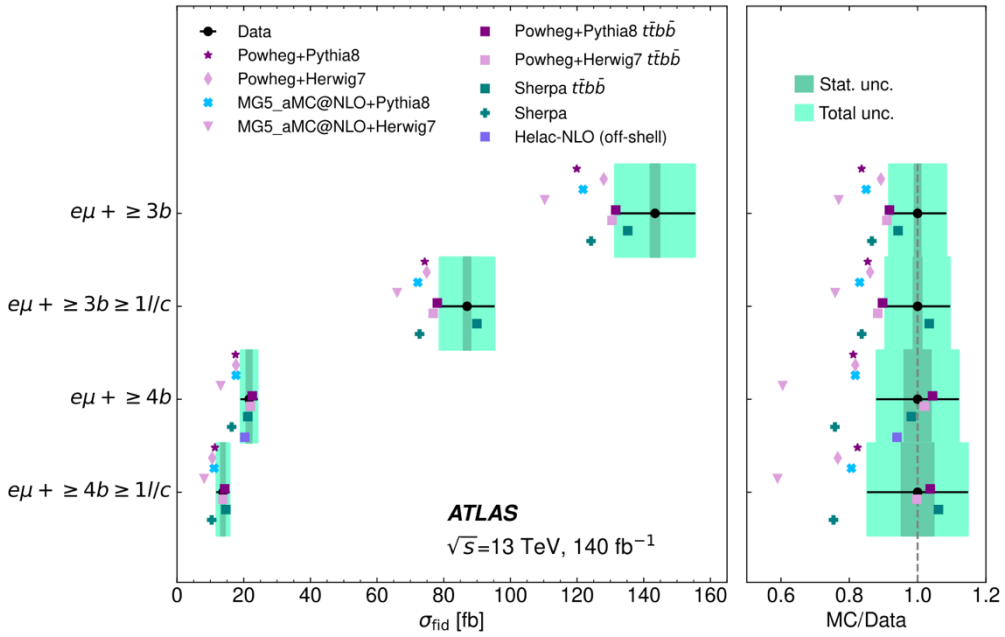


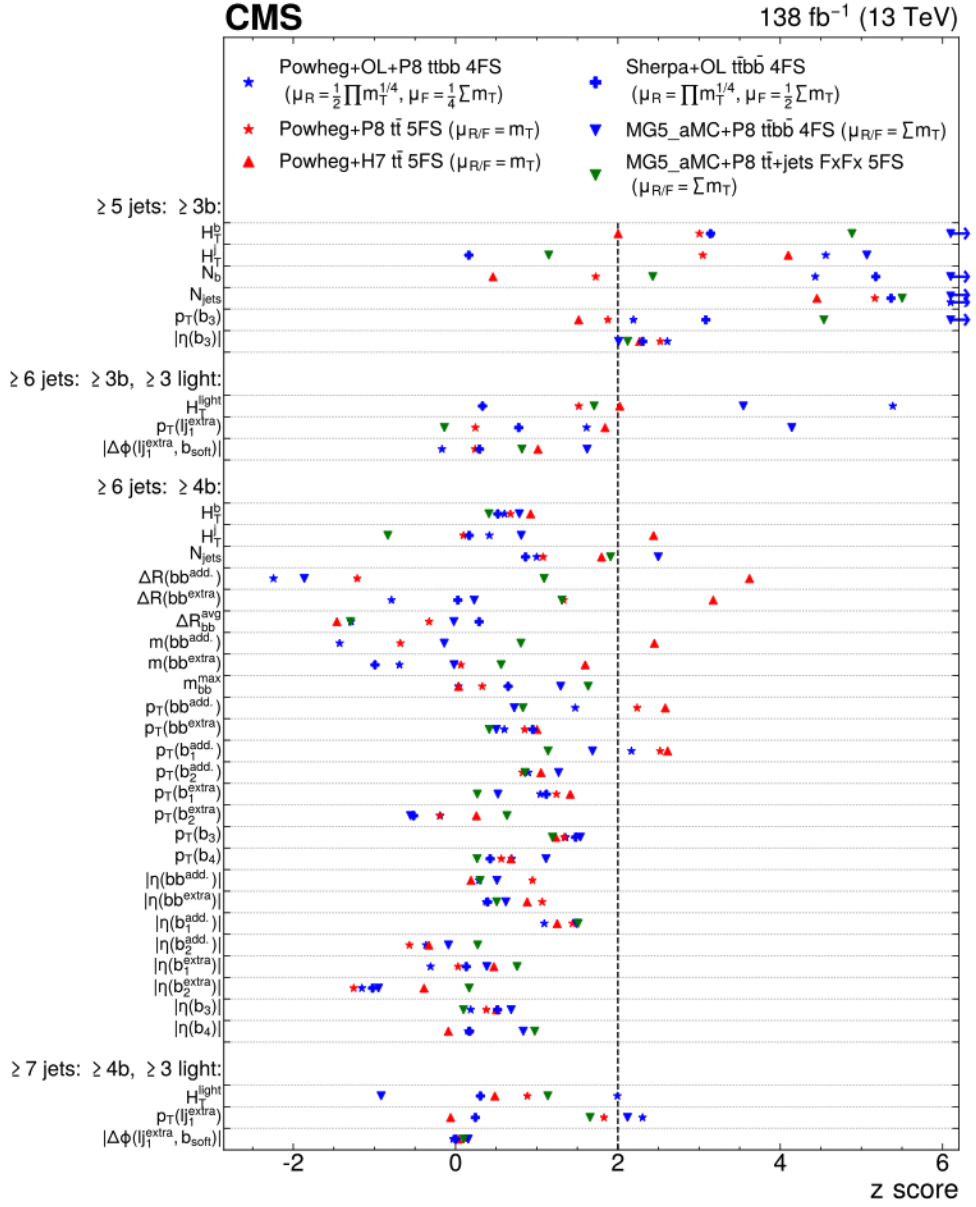
PRD 104 (2021) 092013
JHEP 06 (2022) 063

arXiv:2509.15066

tt production with additional jets

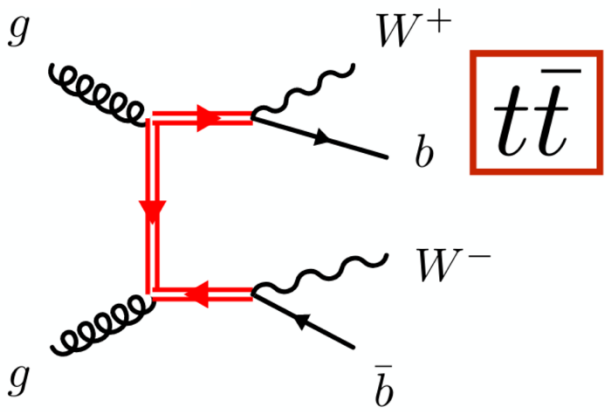
- Modeling of tt in association with additional (heavy) jets is quite challenging
- Different Monte Carlo models, simulating the additional jets emission as part of the matrix element or parton shower
  - No generator describes all variables perfectly



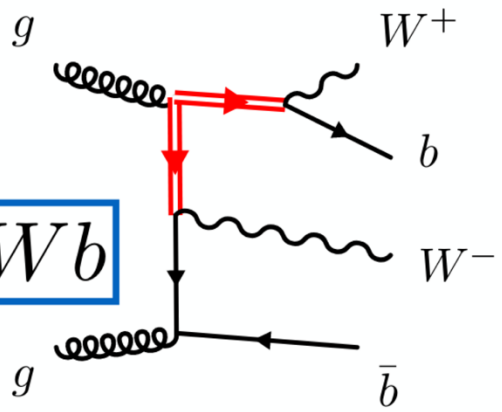


JHEP 01 (2025) 068
JHEP 05 (2024) 042

tt production in the tail – bb4l

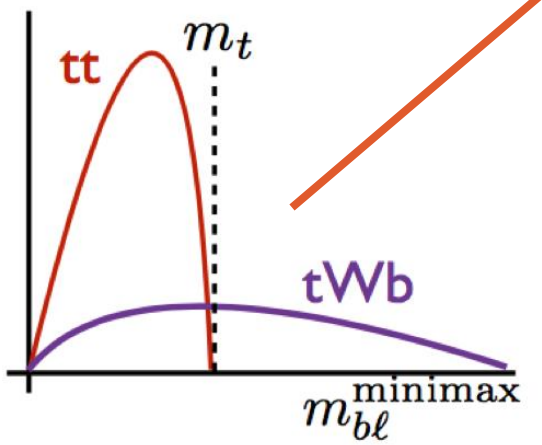


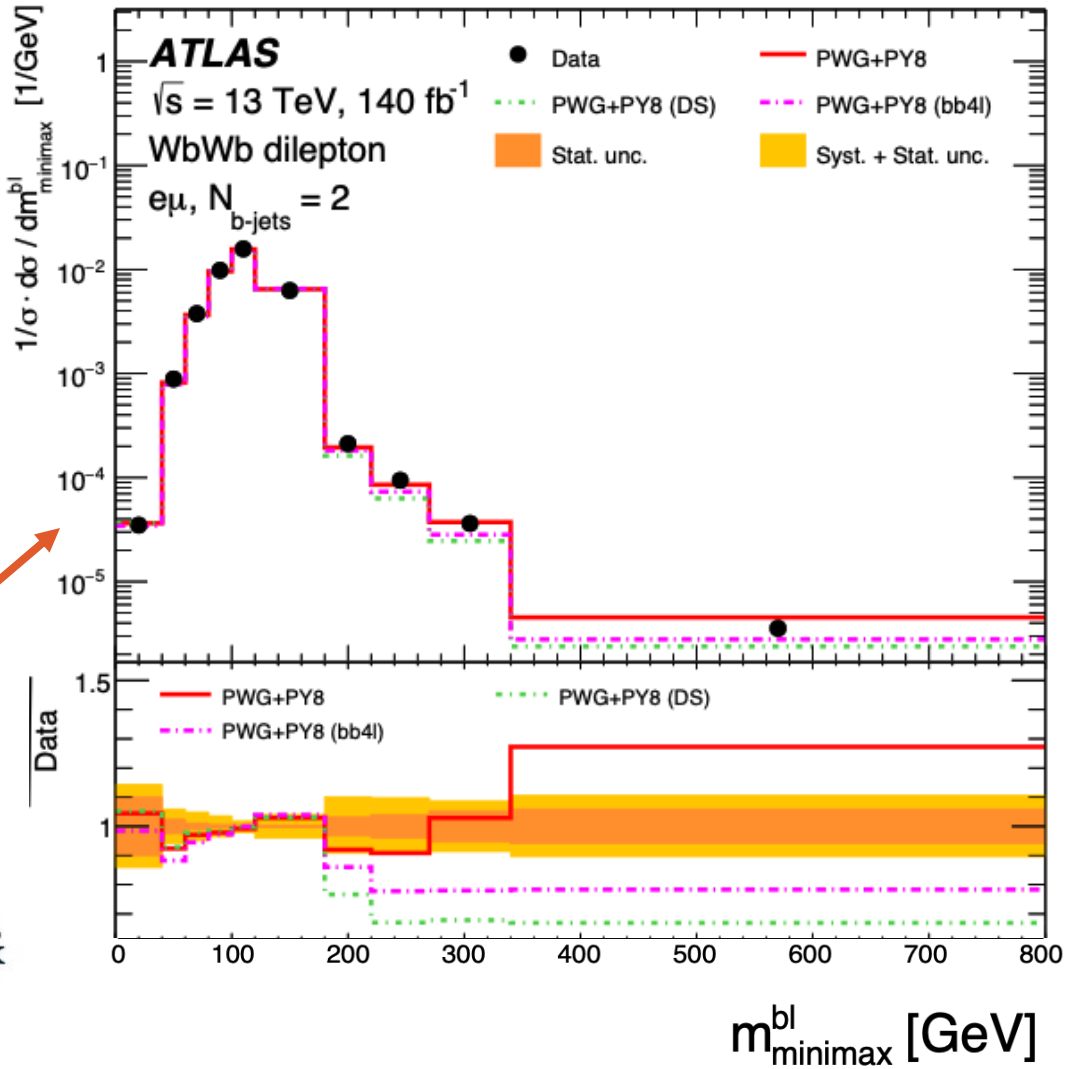
$t\bar{t}$



tWb

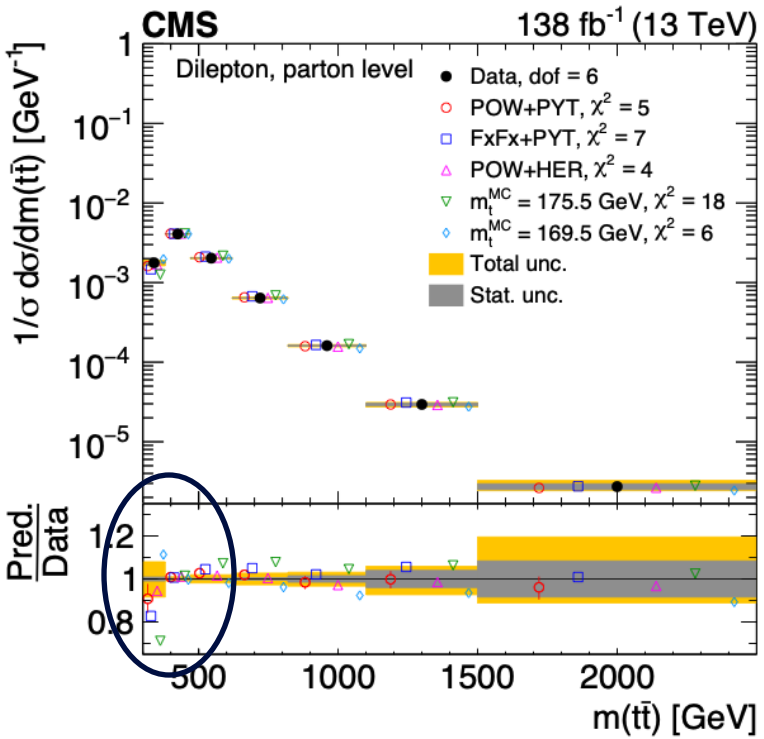
- Interference effects between tt and tW relevant in the tails of the phase space (high pt, offshell)
- bb4l (tt+tW at NLO+PS) underestimates the tail of the distribution

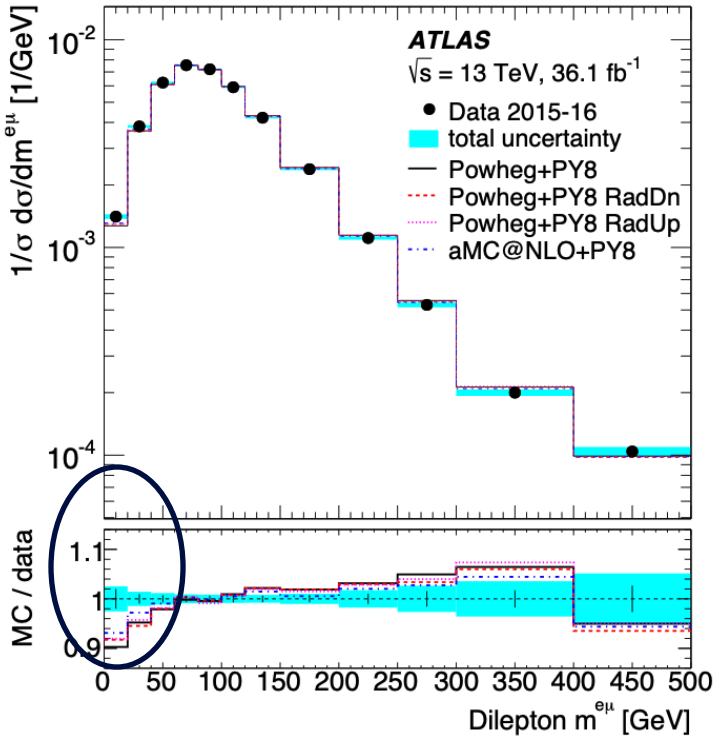




Studies at the tt threshold

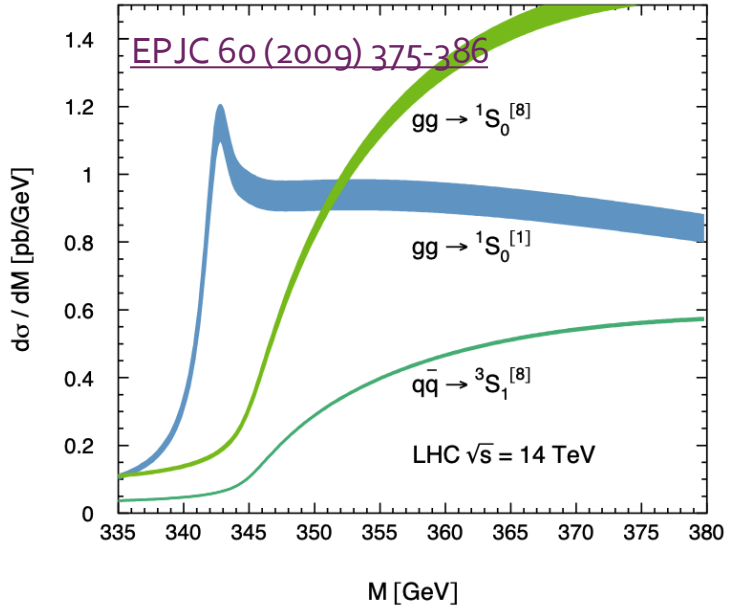
- Persistent discrepancy in ttbar production at $m_{tt} \sim 2m_t$
- Sizeable experimental resolution *O*(20%)
- Tricky phase space from the modeling point of view
  - Soft-gluon emission, etc
- Or, could be a new physics!

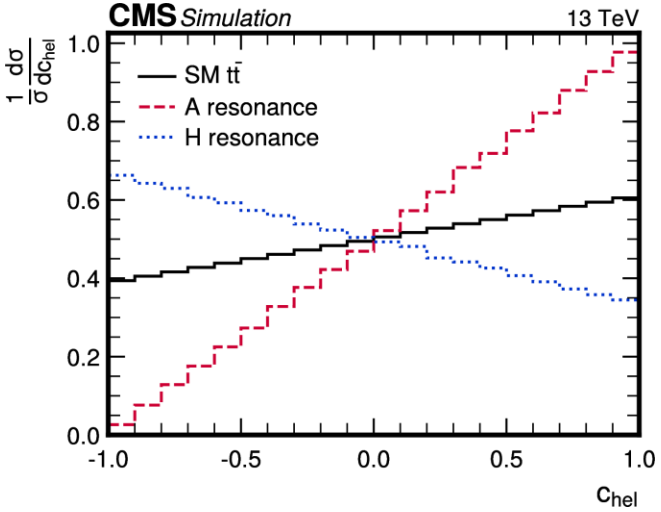


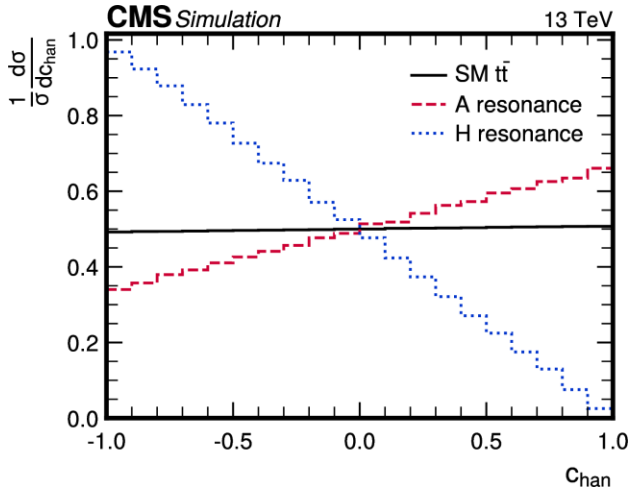


Studies at the tt threshold

- 2HDM models predict additional (pseudo)scalars
- Quasi-bound state η_t at $m_{tt} \sim 2m_t$ are predicted by non-relativistic QCD (JETP Lett. 46 (1987), 525-529, Z.Phys.C 48 (1990) 613-622, EPJC 60 (2009) 375-386, JHEP06(2020)158, EPJC 85 (2025) 157, arXiv:2407.20330, …)
  - Dominant pseudoscalar component
- Spin correlations can help!



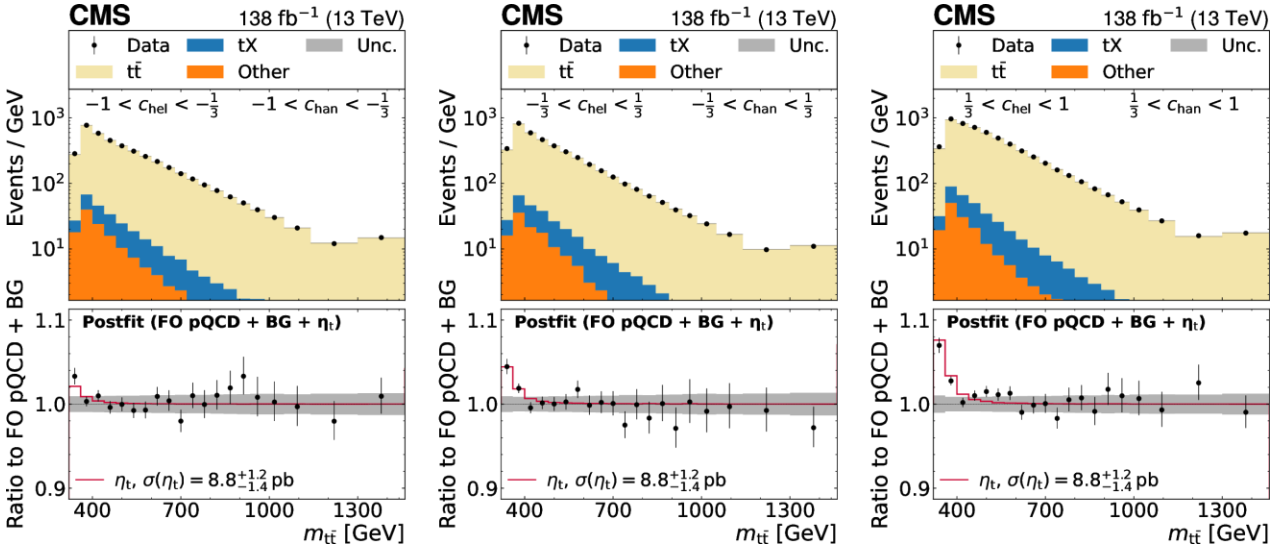


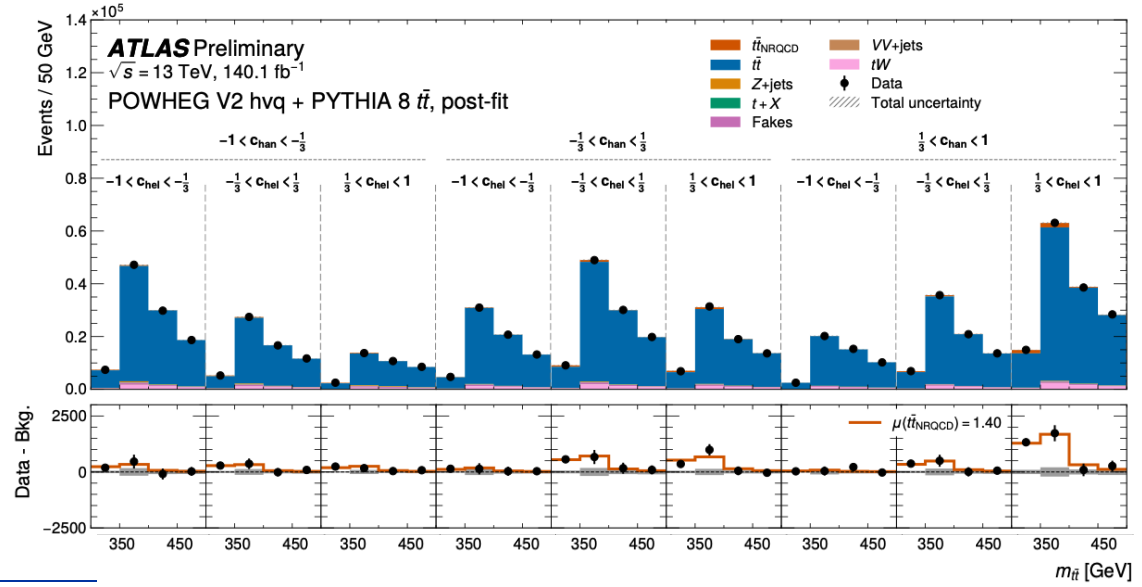


arXiv:2507.05119

Observation of a pseudoscalar excess at ttbar threshold

- Similar analyses in ATLAS and CMS using m_{tt} x c_{han} x c_{hen}
- Both experiments report **>> 5 sigma** excesses
- Data favors the pseudoscalar excess hypothesis against the scalar one
- Data well described by continuum ttbar + η_t from NRQCD-inspired models
- Continuum ttbar at threshold (and η_t) remain challenging to model! Many new results coming soon!





Rep. Prog. Phys, 88 (2025) 087801
ATLAS-CONF-2025-008

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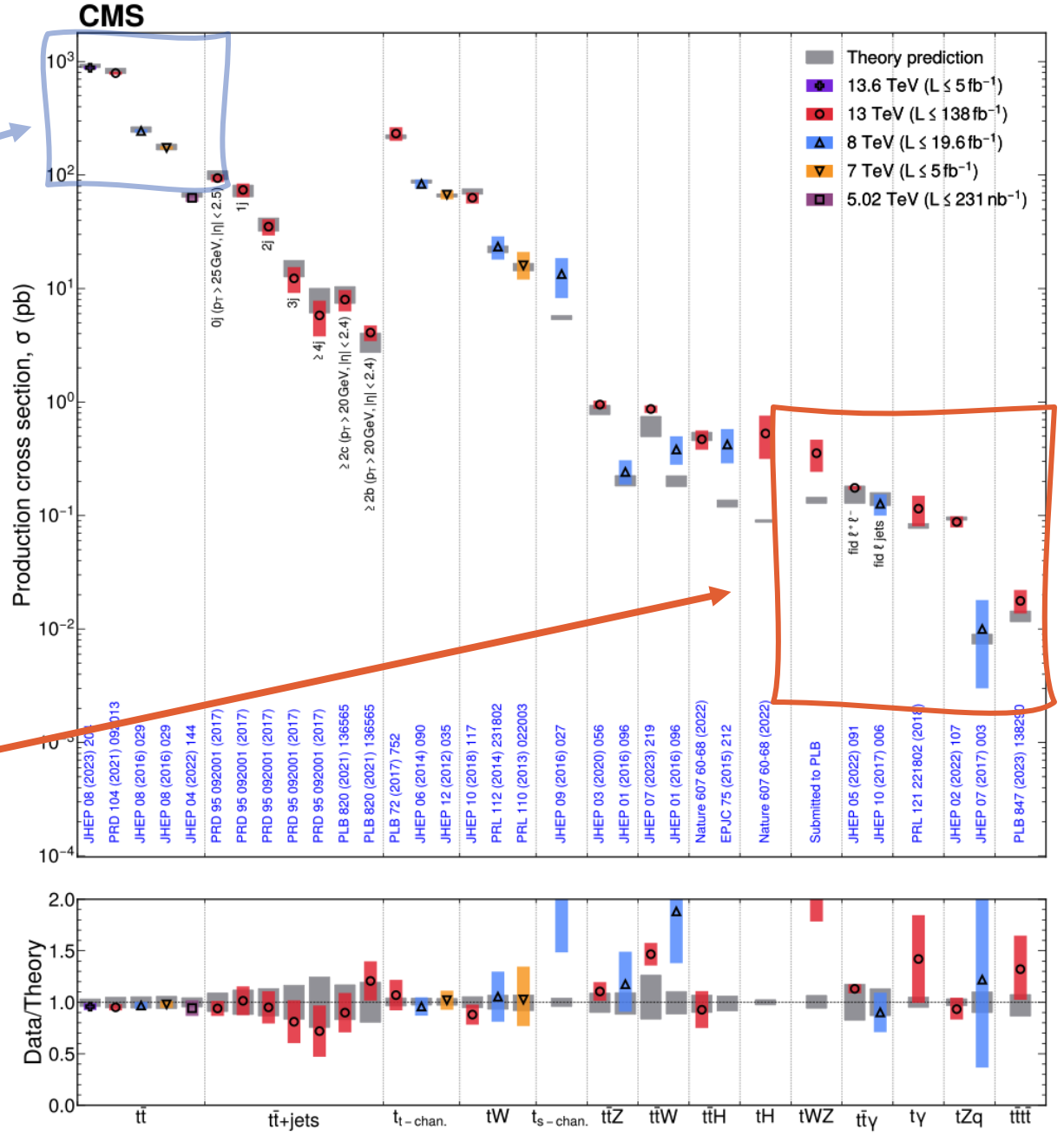
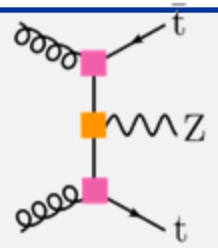
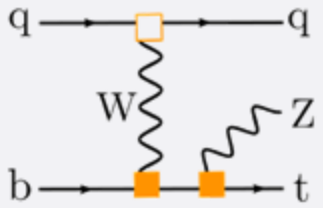


Rare processes

Top + Z

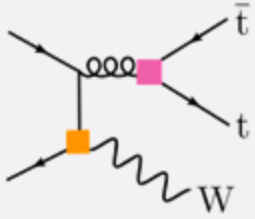


σ~0.8 pb (ttZ)



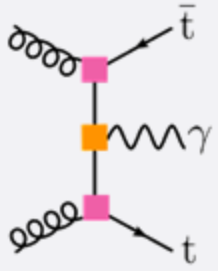
σ~ 0.1 pb (tZq)

Top + W

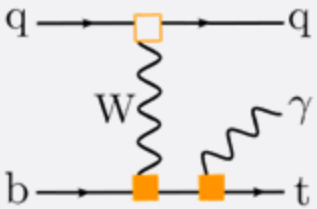


σ~ 0.9 pb

Top + photon

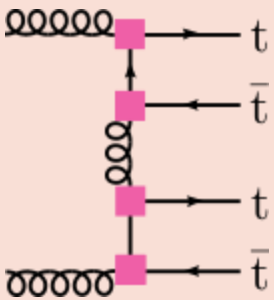


σ~ 0.8 pb (vis.)

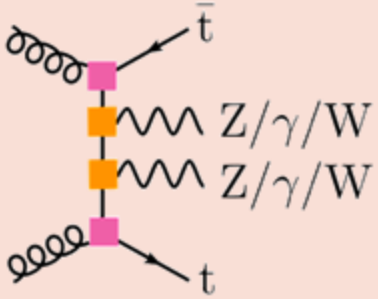


4tops

σ~ 12 fb



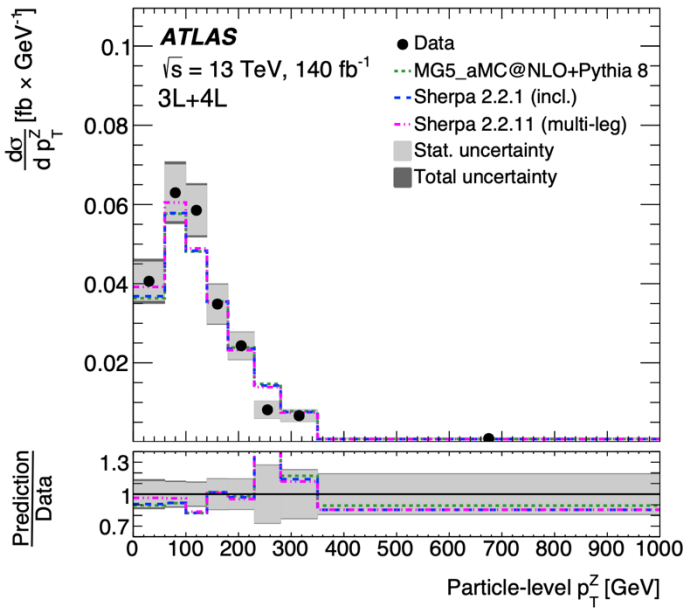
top+diboson

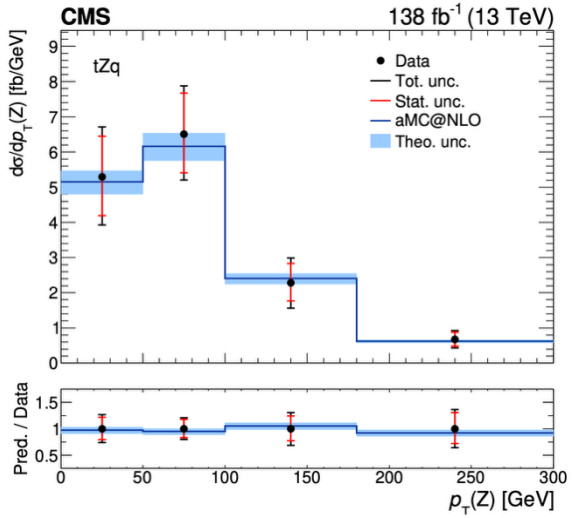


σ~ 0.2 pb (tWZ)
σ~ 2 fb (ttγγ, vis.)

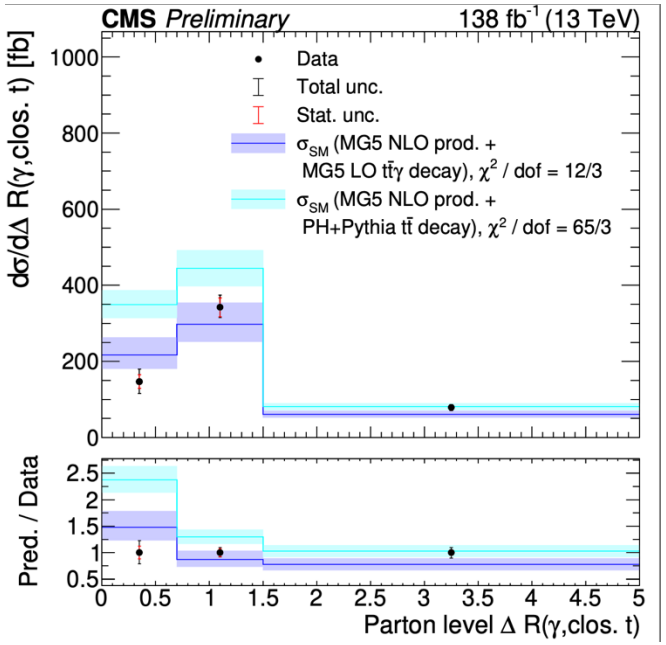
- In orange, observed with full Run 2 dataset for the first time

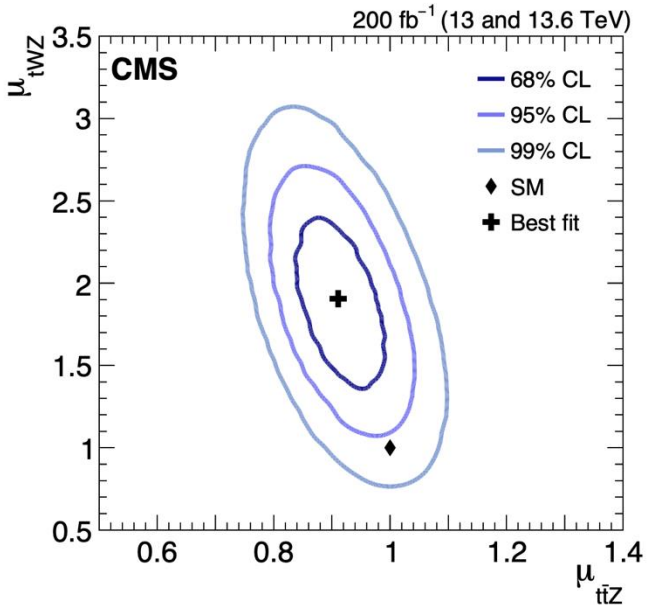
Rare processes – top+bosons (I)





- Measurements of top+Z/photon by ATLAS and CMS
- Sensitive to the top-Z/top-photon coupling (aka top g-2)
- ttZ and tZq remarkably consistent with NLO predictions!
- Overall good description of ttγ – description of photon from decay challenging
- First observation of tWZ production by CMS – small excess over data

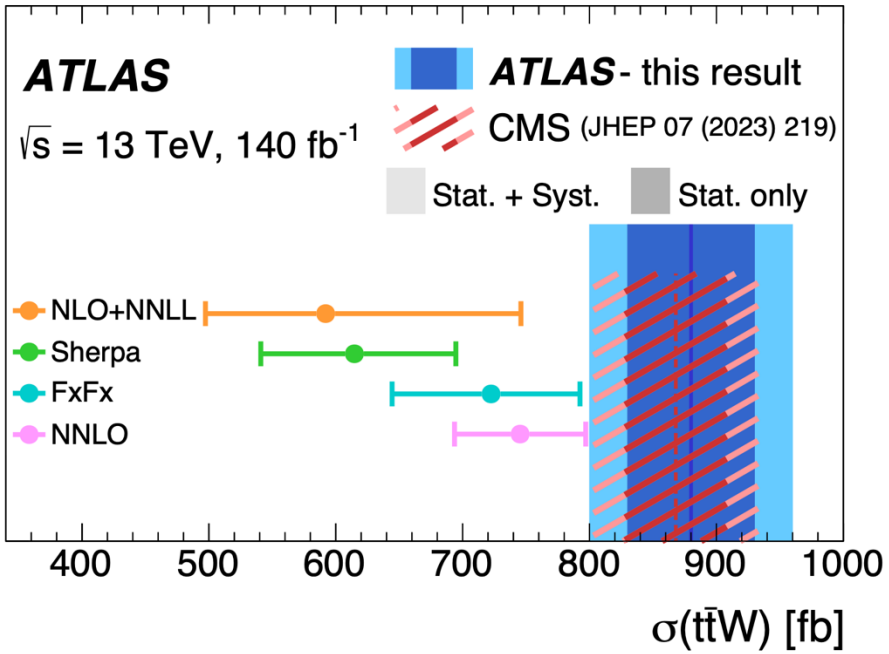


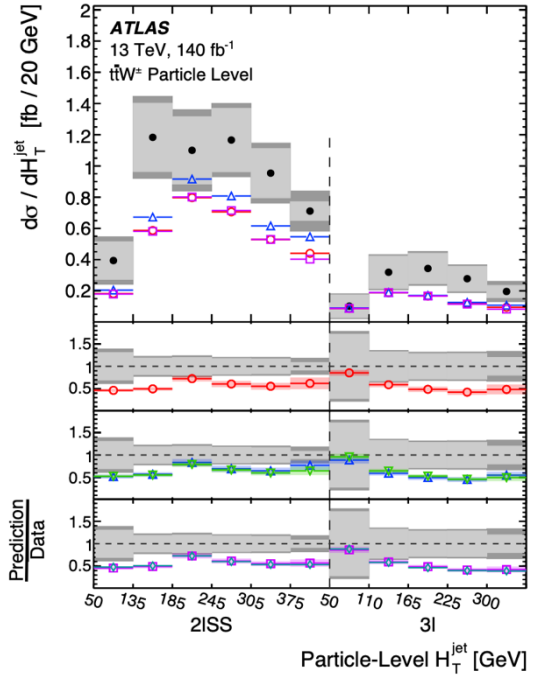


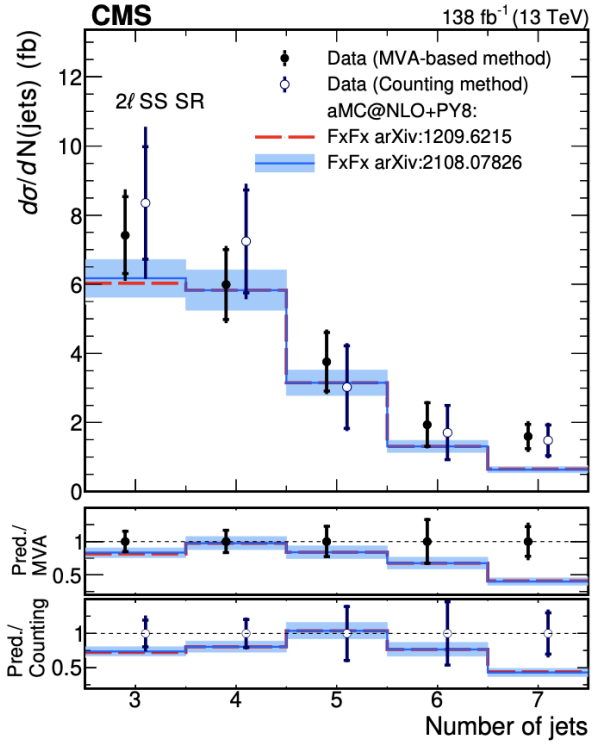
JHEP 07 (2024) 163 JHEP 02 (2025) 177 CMS-PAS-TOP-23-004

ttW production

- Challenging modeling of this process: sizeable NNLO QCD corrections[Ref], large EWK corrections [Ref], off-shell effects [Ref], …
- 20% (2 sigma) excess observed, consistently between ATLAS and CMS
- No significant trends in differential cross section measurements

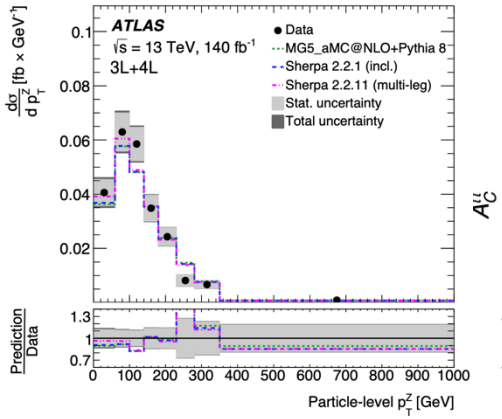


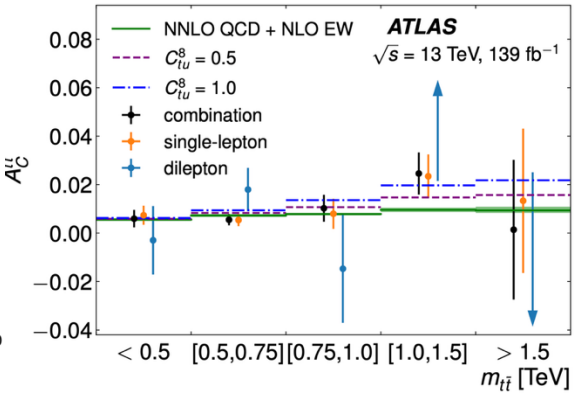


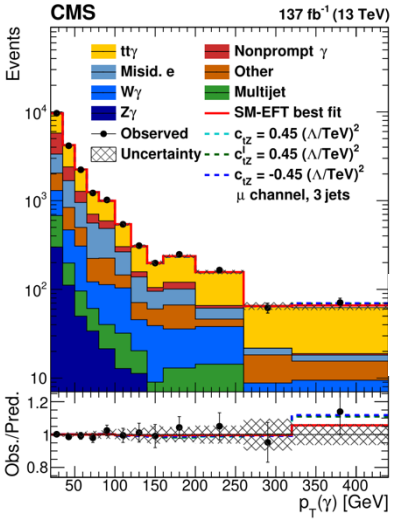


JHEP 05 (2024) 131 JHEP 07 (2023) 219 arXiv:2509.13512

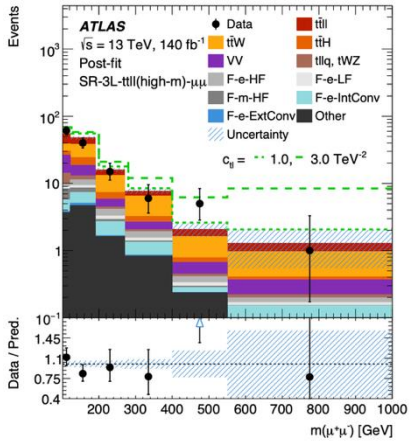
BSM interpretations of top measurements

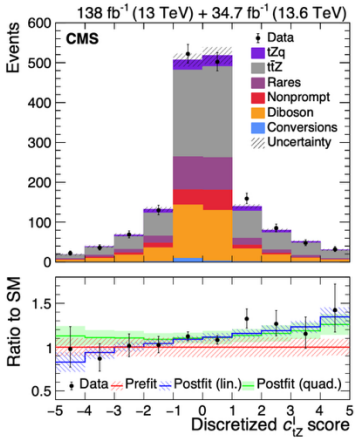


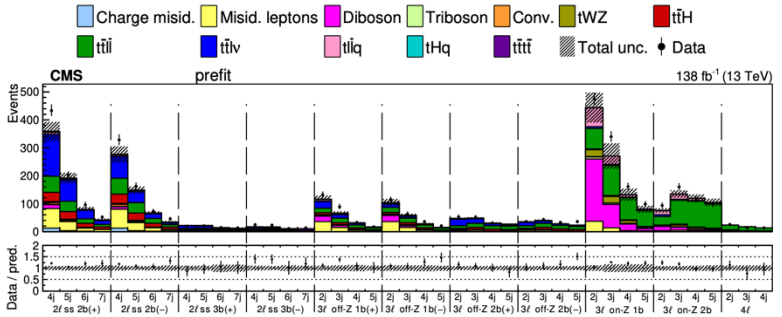


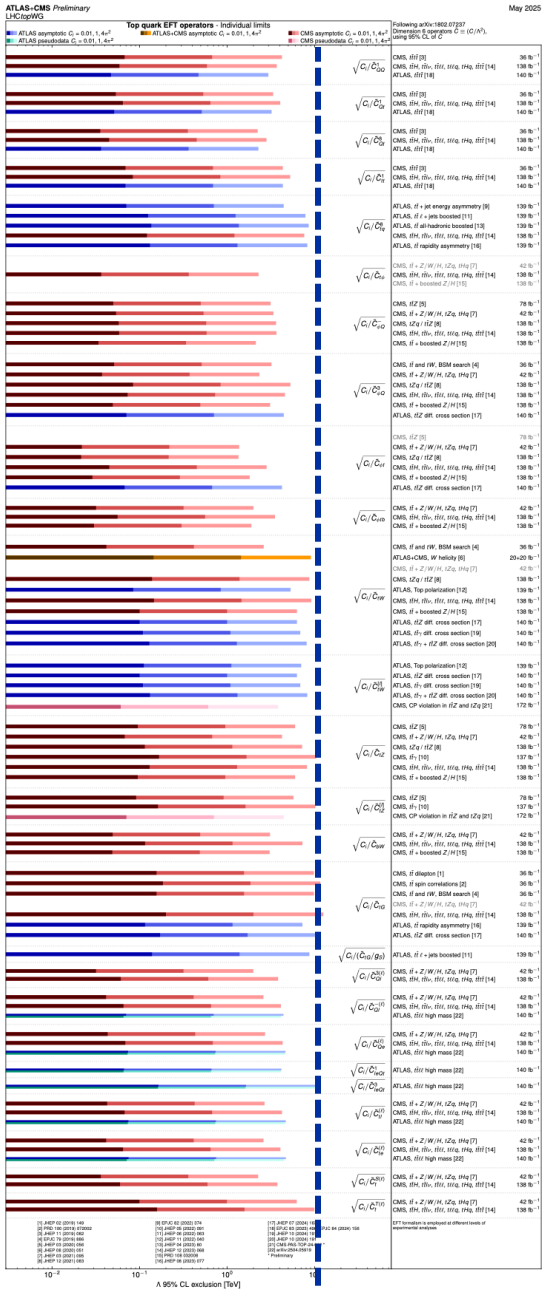


$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i$$









10 TeV
Limits on new physics scale

More in Gauthier's talk!!

Summary

- **The top quark is celebrating its 30th anniversary alive and kicking!**
- High precision program is being put together by ATLAS+CMS
  - **Enabled by superb predictions by the theory community**
  - Profiting from best calibrations of the detectors and algorithms after > 10 years of running
  - Very granular / tails precision studies are possible
- Study of rare processes is ongoing, with more promising results coming as we take more data