What the LHC tells us about the …

*… the heaviest particle **in nature***

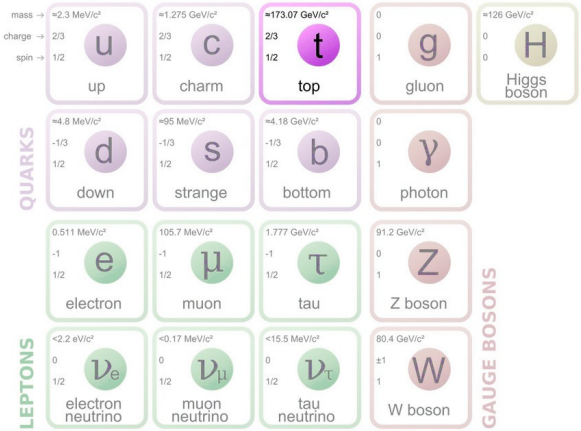
Matthias Komm
for the ATLAS & CMS Collaborations

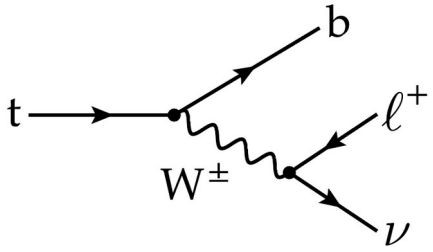
What is the top quark?

- Heaviest particle of the SM

$$m_{\mathrm{t}} > m_{\mathrm{W}} \gg m_{\mathrm{b}}$$

≈tungsten atom





- Short lifetime; no time for hadronization

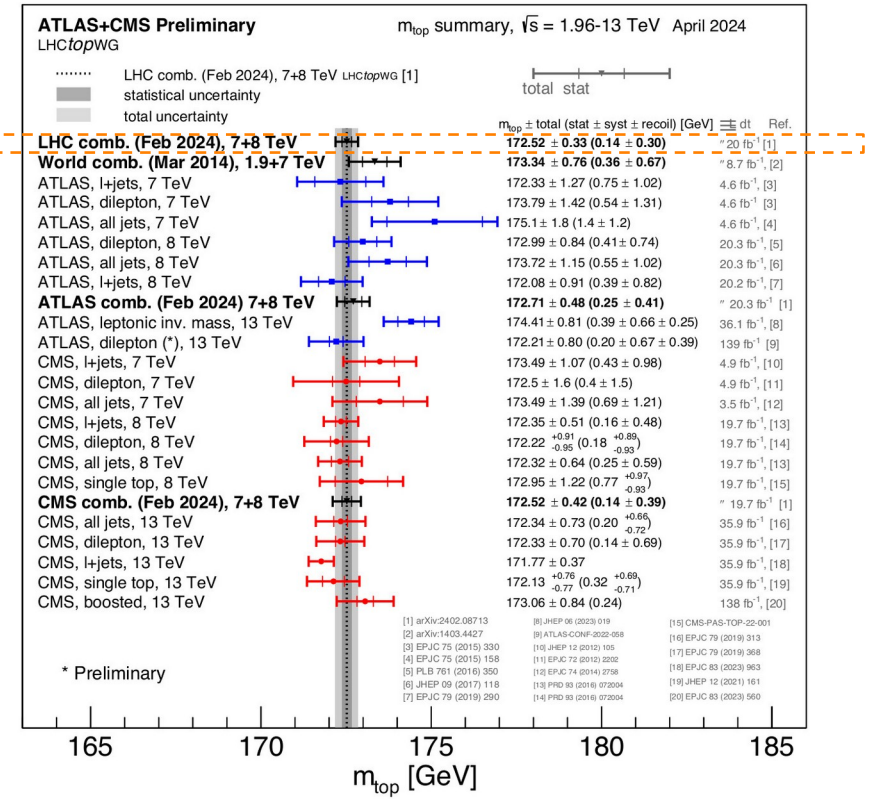
$$1/\Gamma_{\mathrm{t}} \approx 5 \cdot 10^{-25}\ \mathrm{s} \ll 1/\Lambda_{\mathrm{QCD}} = 10^{-23}\ \mathrm{s}$$

- Almost exclusively decays to b quark & W boson

Phys. Rev. Lett. 132 (2024) 261902

Measured mass: 172.52 ± 0.33 GeV

(ATLAS+CMS combination)

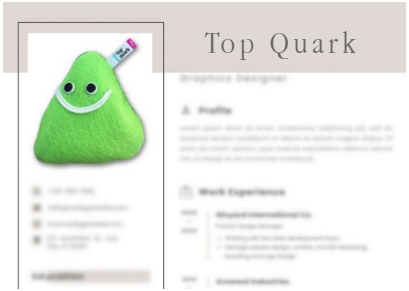


The top quark's CV

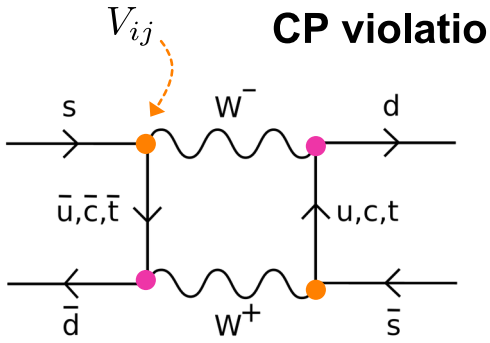
- First hints: CP violation
  → CKM matrix V_{ij} (1973)

- Graduation from Tevatron
  Top quark pairs (1995),
  Single top quarks (2009)

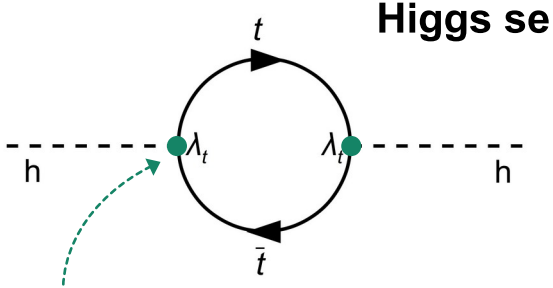
- It's **30 years** old!
  why do we (still) care?
  - electroweak interactions
  - $|\lambda_t| \approx 1$ coupling to Higgs
  - BSM with top quarks?



CP violation



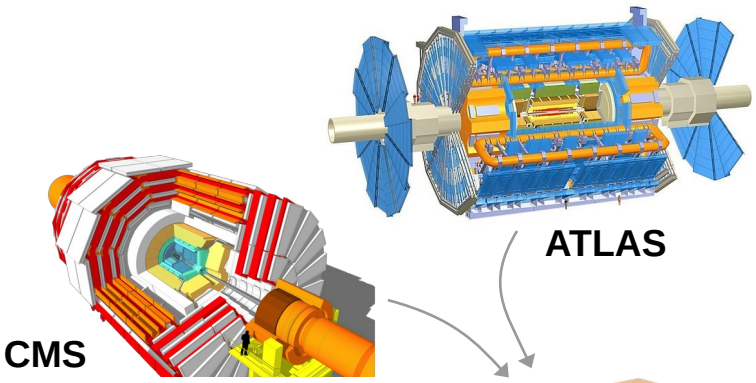
Higgs self energy



$$|\lambda_t| = \frac{\sqrt{2}m_t}{v} = \frac{\sqrt{2} \times 172.5\ \text{GeV}}{246\ \text{GeV}} = 0.992$$

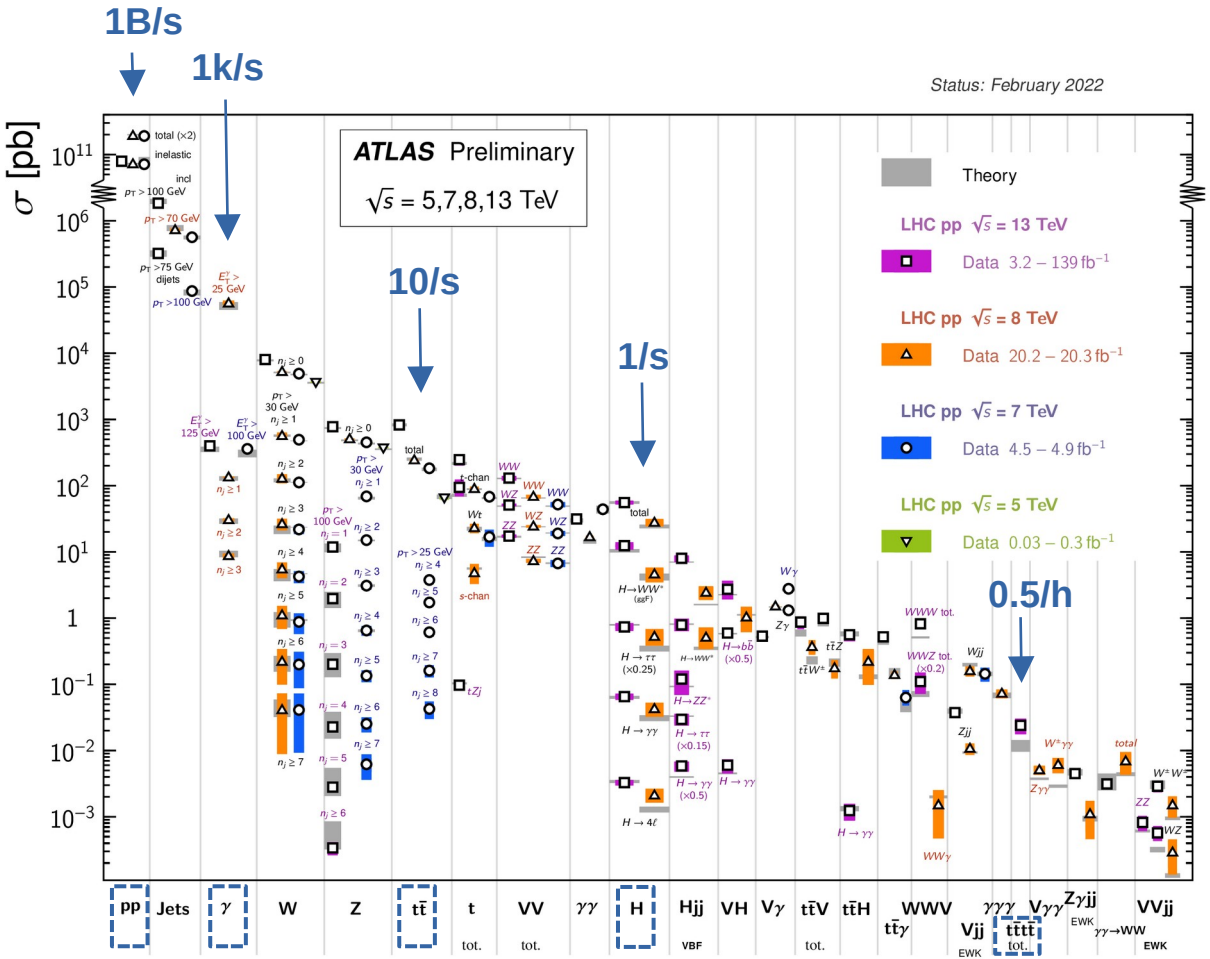
Making top quarks at the LHC

- LHC = top quark factory



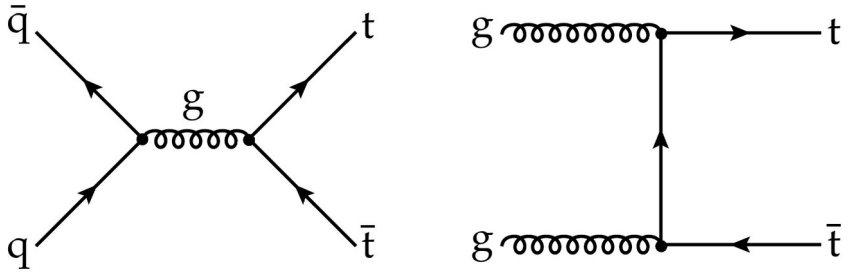
- We've ordered it!
  Let's unpack ...

- This talk
  - (Rare) production modes
  - Properties (spins, polarization, ...)
  - BSM searches



Overview:
Top quark production modes

Pair production

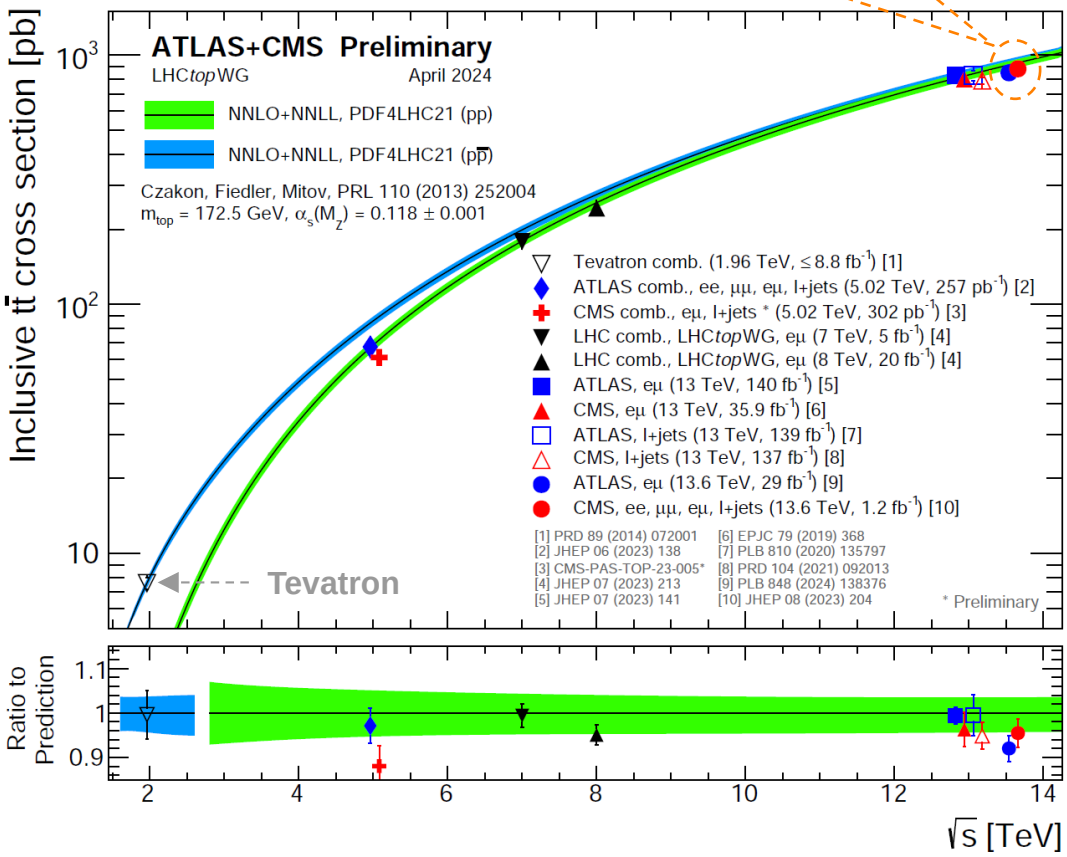


- Extensively measured at various CM energies: 5, 7, 8, 13 & 13.6 TeV

- Limited by systematic uncertainties
  - Especially precise knowledge of luminosity

$\sigma_{t\bar{t}}^{ATLAS} = 850 \pm 3\%$ pb

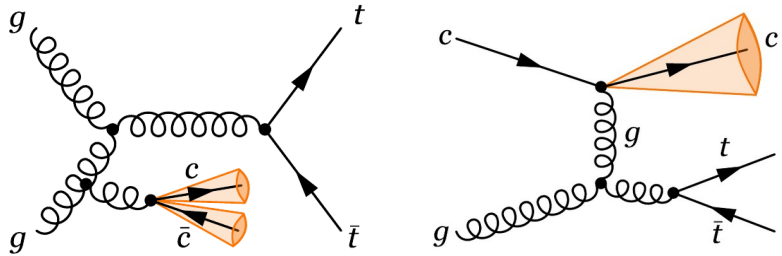
$\sigma_{t\bar{t}}^{CMS} = 881 \pm 3\%$ pb



Pair production (2)

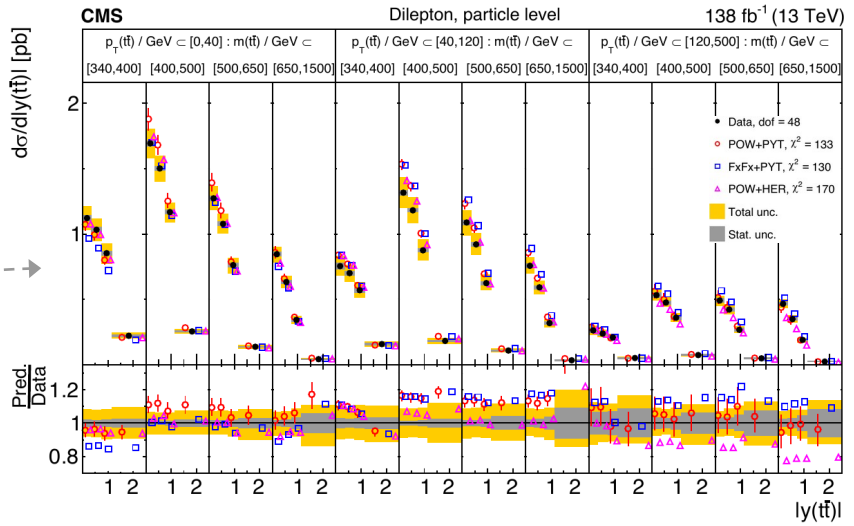
- High degree of understanding achieved
  → Made possible also through continuous exchange with theory community

- Recent examples
  - Multidifferential by CMS $p_{\mathrm{T}}(\mathrm{t\bar{t}}) \otimes m(\mathrm{t\bar{t}}) \otimes |y(\mathrm{t\bar{t}})|$
  - $\mathrm{t\bar{t}} + \mathrm{c}(\bar{\mathrm{c}})$ by ATLAS

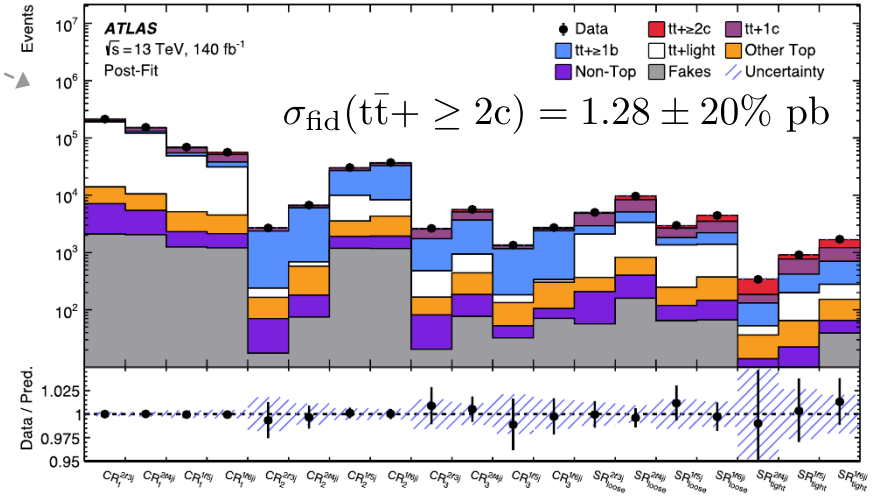


- Paradigm shift:
  - Run 1: tune simulation with data
  - Now: $\mathrm{t\bar{t}}$ = standard candle

JHEP02 (2025) 064



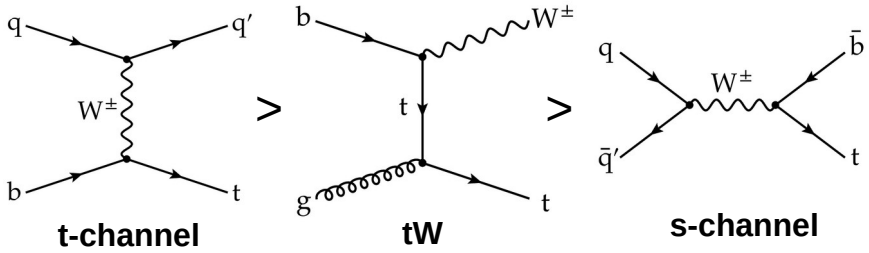
Phys. Lett. B 860 (2025) 139177



Most tops come in pairs …

… but some are “still” **single**

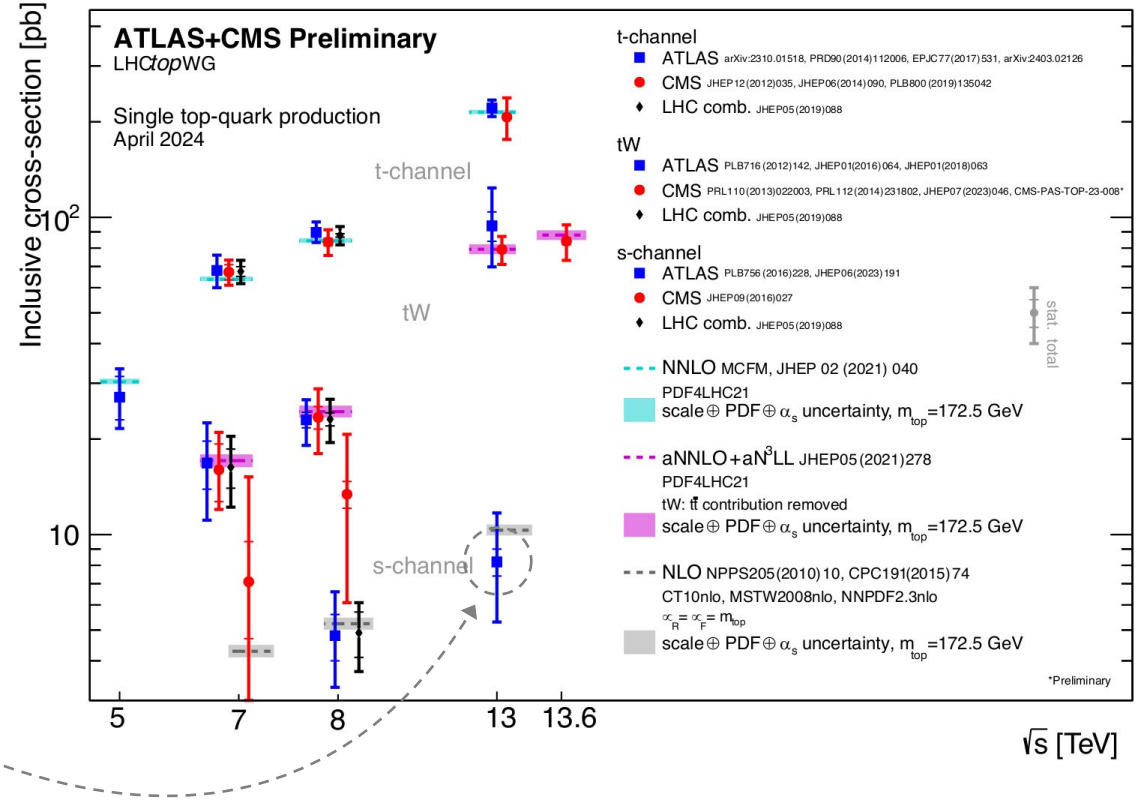
- 3 main electroweak channels



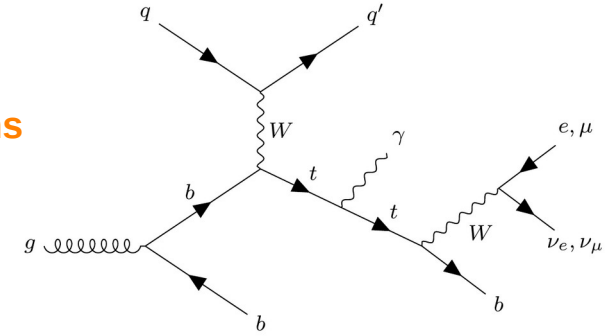
- t-channel & tW measured extensively
- s-channel elusive at LHC

$$\sigma^{\mathrm{ATLAS}}_{\mathrm{s-ch.}}(13\ \mathrm{TeV}) = 8.2^{+40\%}_{-34\%}\ \mathrm{pb}$$

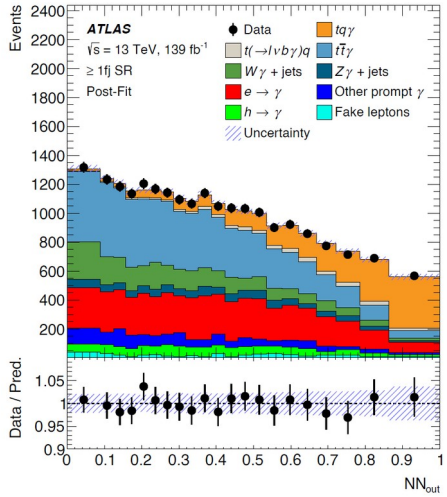
significance: 3.3 σ



Does it play with other bosons?



Phys. Rev. Lett. 131 (2023) 181901



- Observation: **tqγ** by ATLAS

  $\sigma_{\mathrm{fid}}(\mathrm{pp} \to \mathrm{tq}\gamma) \times \mathcal{B}(\mathrm{t} \to \ell\nu\mathrm{b}) = 688 \pm 11\%\ \mathrm{fb}$

- compatible with SM within 2.1 σ

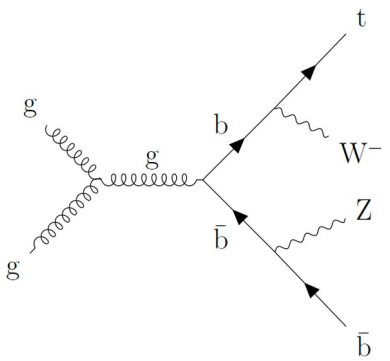
- Evidence: **tWZ** by CMS

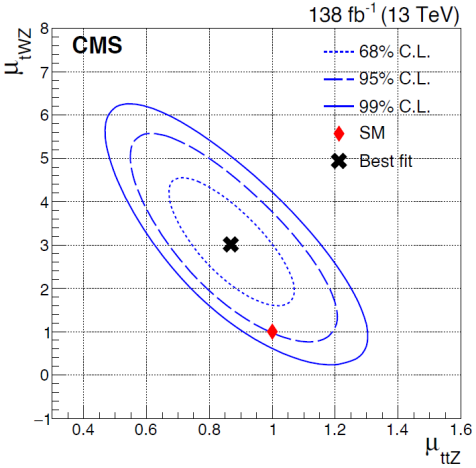
  $\sigma(\mathrm{tWZ}) = 354 \pm 31\%\ \mathrm{fb}$, significance: 3.4 σ (1.4 σ exp.)

- compatible with SM within 2.0 σ

- More t(t)+X results in talk by J. van der Linden

Phys. Lett. B 855 (2024) 138815



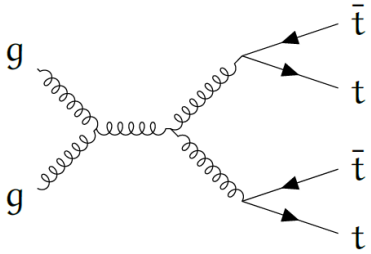


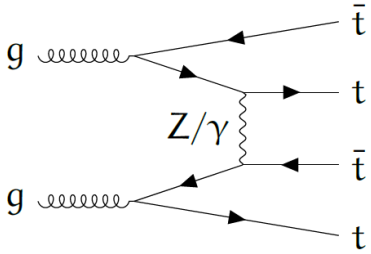
Let's have a **top quark party**

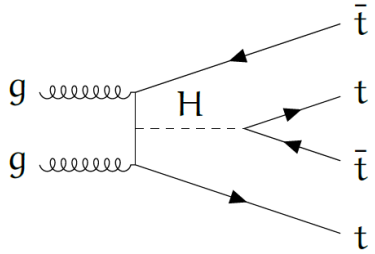
- **4 top quarks** in one pp collision (= up to 12 jets & 4 b jets)
- Enhanced in BSM theories (eg. new mediators)
- Tiny SM cross section

  $12.0 \pm 20\%$ fb

  R. Frederix, et al
  JHEP 02 (2018) 031





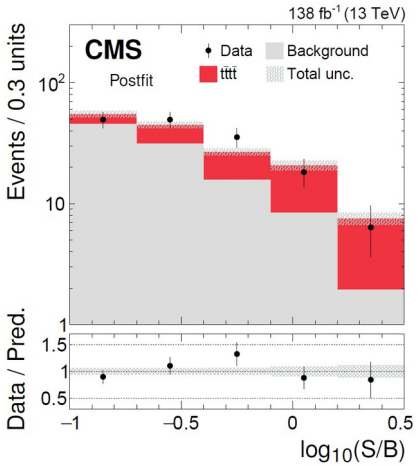


- ATLAS

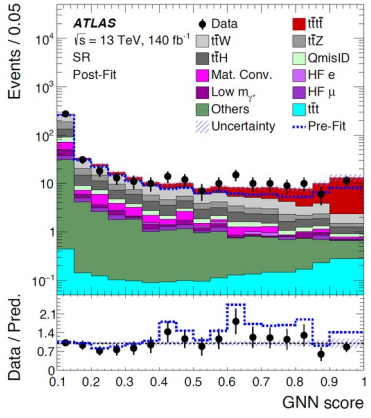
  $22.5^{+30\%}_{-24\%}$ fb (6.1σ obs.)
- CMS

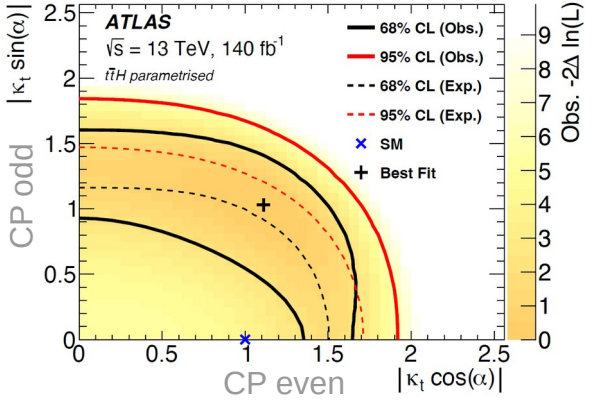
  $17.7^{+25\%}_{-22\%}$ fb (5.6σ obs.)

Phys. Lett. B 847 (2023) 138290



Eur. Phys. J. C 83 (2023) 496





Top quark properties

CKM matrix element: V_{tb}

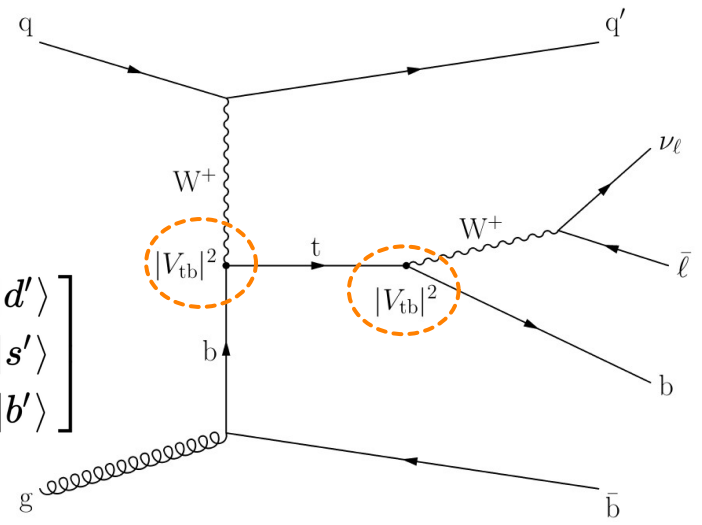
- Single top quark processes scale as

$$\sigma(\mathrm{pp} \to \mathrm{t} + X) \propto |V_{\mathrm{tb}}|^2, \ \mathcal{B}(\mathrm{t} \to \mathrm{bW}) \approx 1$$

- Unique access to V_{tb} <u>without</u> assuming CKM unitarity

CKM matrix

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix}$$

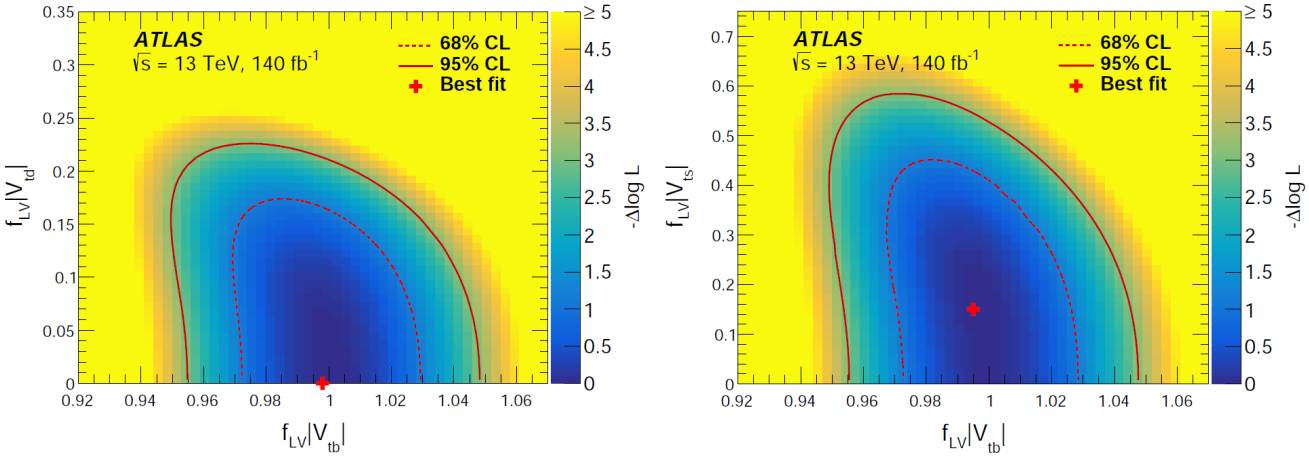


- Simultaneous measurement of $|V_{tb}|$, $|V_{td}|$, $|V_{ts}|$ by ATLAS

- CMS Phys. Lett. B 808 (2020) 135609

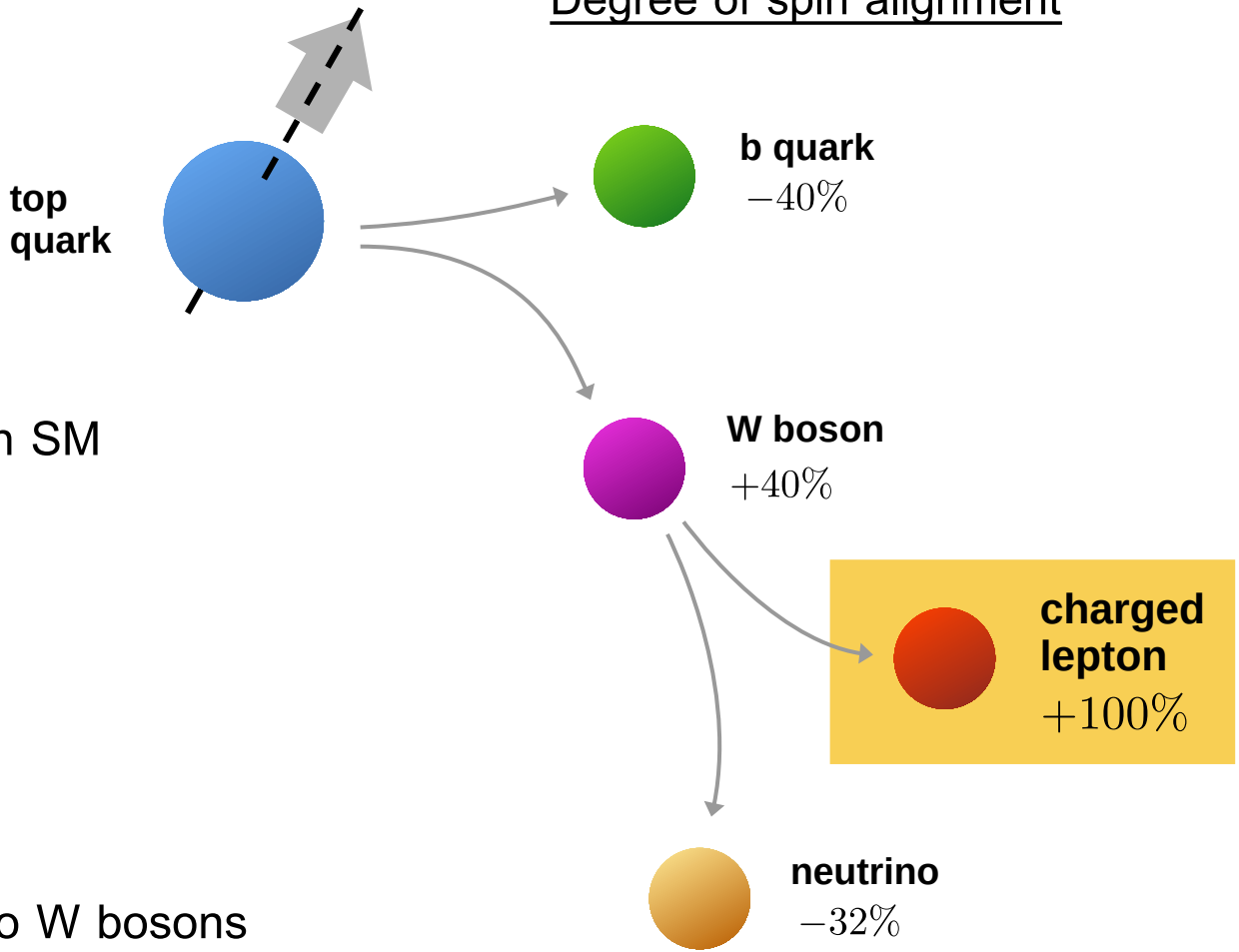
$$|\mathrm{V_{tb}}| > 0.970, \ |\mathrm{V_{td}}|^2 + |\mathrm{V_{ts}}|^2 < 0.057$$

JHEP 05 (2024) 305

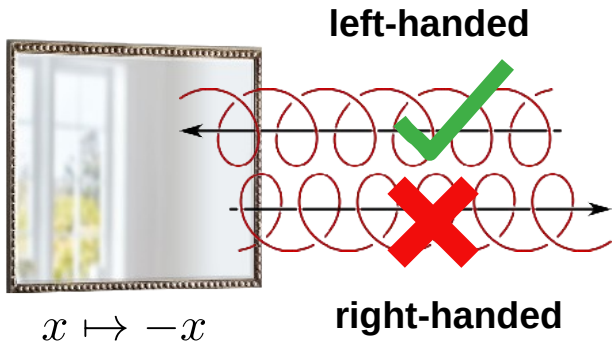


Top quark **spins** around

- Spin information transferred to decay products



- Consequence of **parity violation** in SM



Only left-handed fermions couple to W bosons

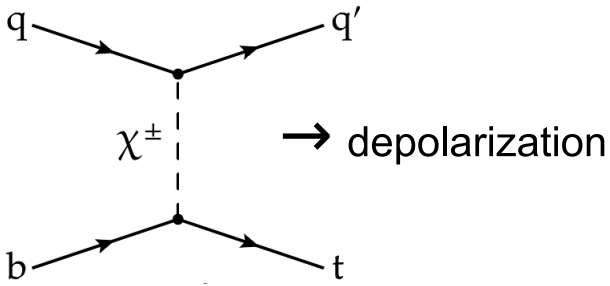
→ process **forbidden** when mirrored

Single top quark **polarization**

- Top quark maximally polarized at leading order

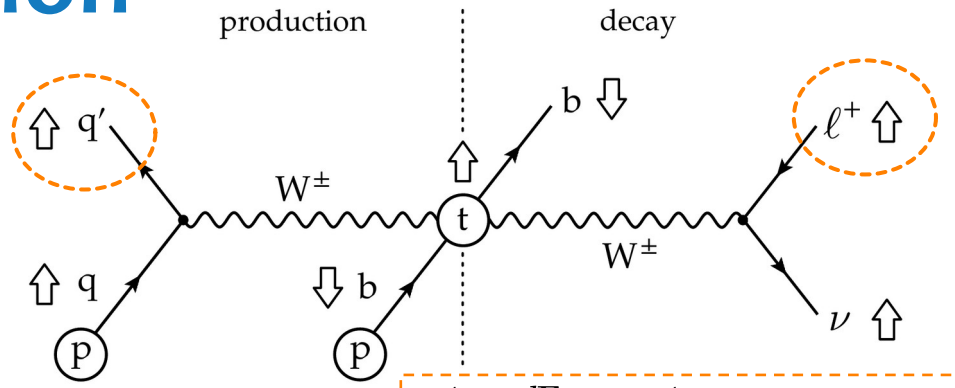
$$P \approx 100\%$$

- Indirect BSM test; eg.



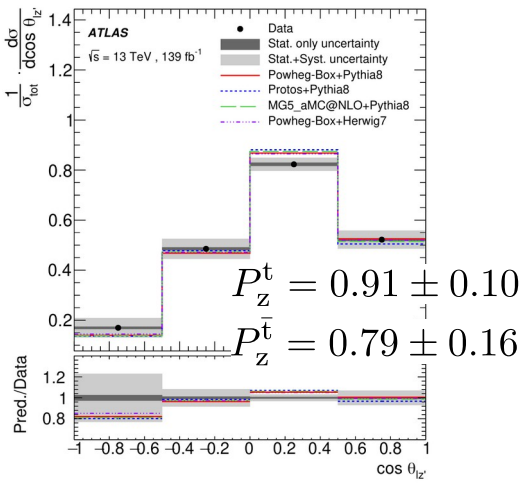
→ depolarization

- ATLAS & CMS results compatible with SM predictions



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^\star} = \frac{1}{2}(1 + P\alpha\cos\theta^\star)$$

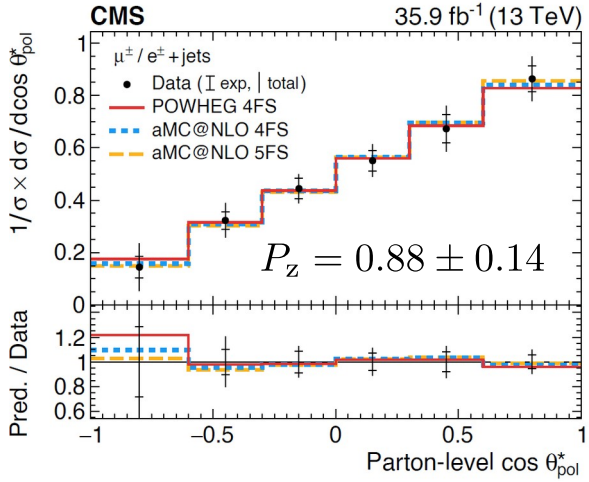
JHEP 11 (2022) 040



$P_z^t = 0.91 \pm 0.10$

$P_z^{\bar{t}} = 0.79 \pm 0.16$

Eur. Phys. J. C 80 (2020) 370



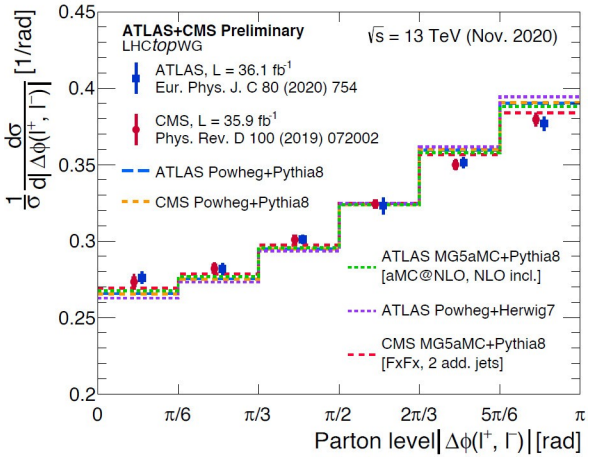
$P_z = 0.88 \pm 0.14$

Spin correlations & entanglement

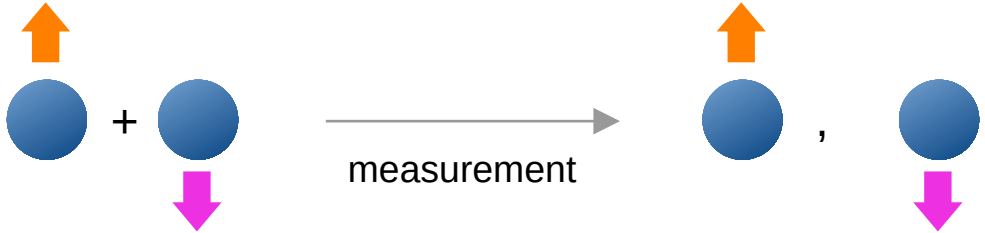
- Decompose differential $t\bar{t}$ cross section

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_a\, d\cos\theta_b} = \frac{1}{4}(1 + P_t\cos\theta_a + P_{\bar{t}}\cos\theta_b - C\cos\theta_a\cos\theta_b)$$

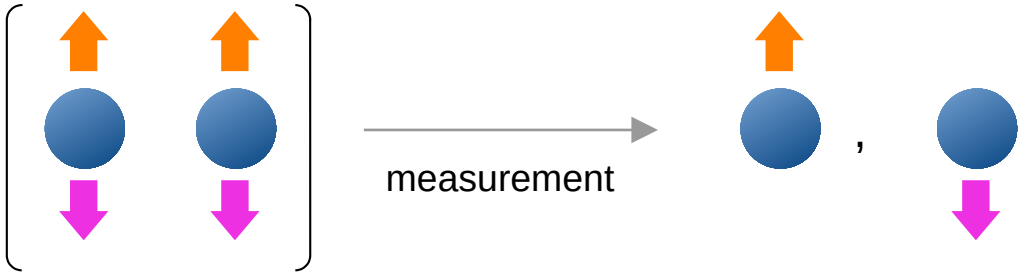
polarization ≈ 0 3x3 spin correlation

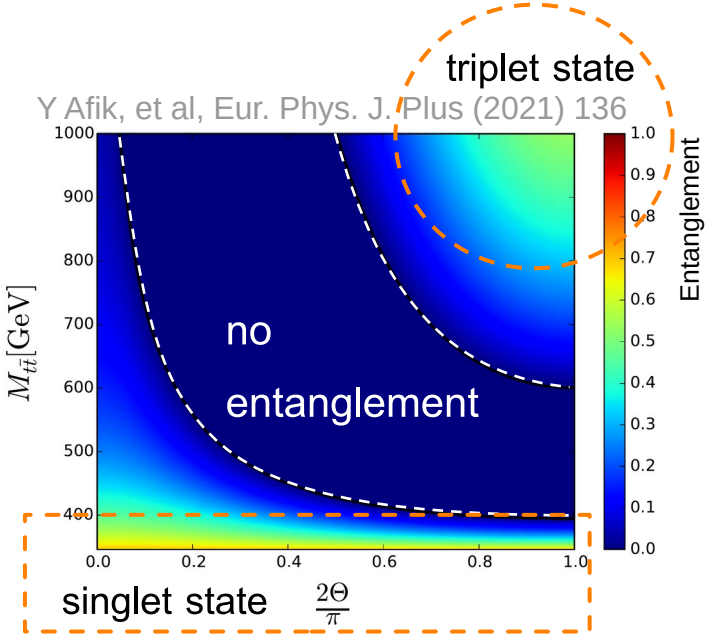


- Spins are correlated = superposition of individual states



- Spins are entangled = one wave function

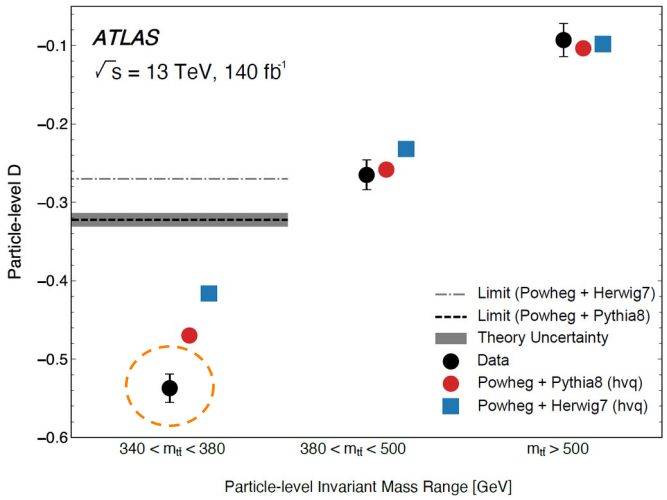




$t\bar{t}$ entanglement

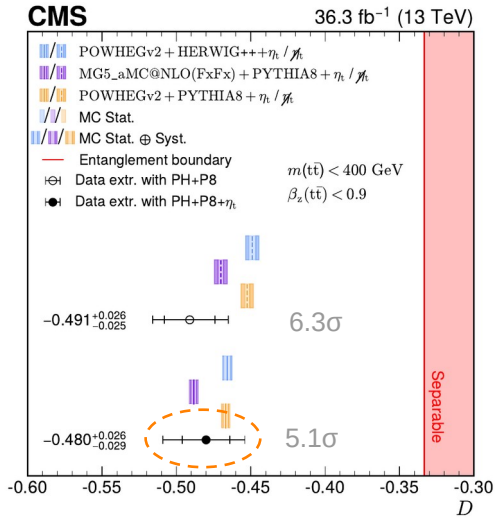
low $m_{t\bar{t}}$ region; criterion: $D = \mathrm{Tr}(C)/3 < -\frac{1}{3}$

Nature 633 (2024) 542



$D = -0.537 \pm 0.019$

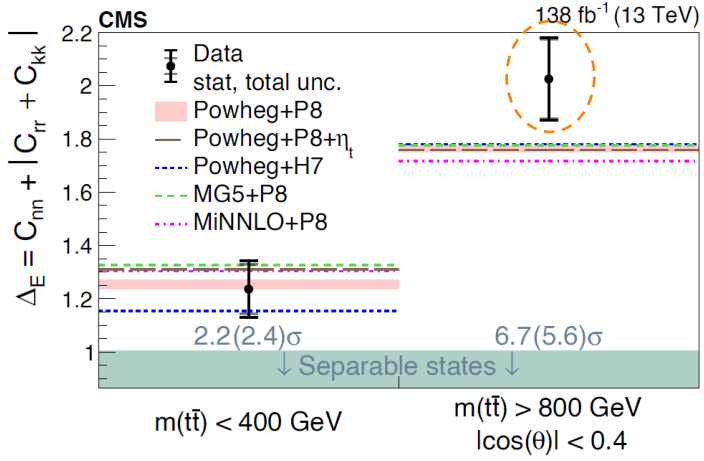
Rep. Prog. Phys. 87 (2024) 117801



$D = -0.480^{+0.026}_{-0.029}$

high $m_{t\bar{t}}$ region; criterion: $\Delta_E > 1$

Phys. Rev. D 110 (2024) 112016

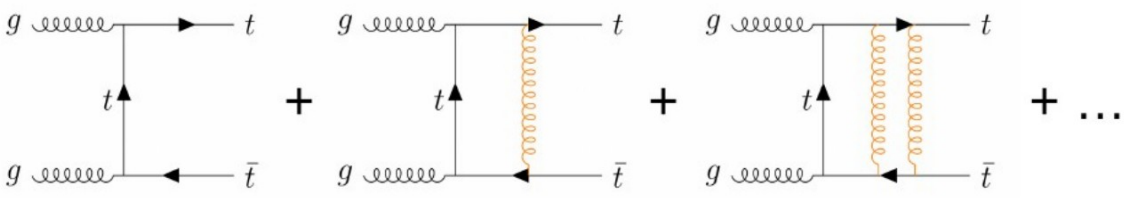


$\Delta_E = 2.03 \pm 0.15$

- Results proof fundamental **quantum nature** of top quarks
  = cannot be described as a classical particle

Are top quarks secretly **holding hands**?

- SM pseudoscalars



→ color singlet attractive; peak below $m_{t\bar{t}}$ threshold

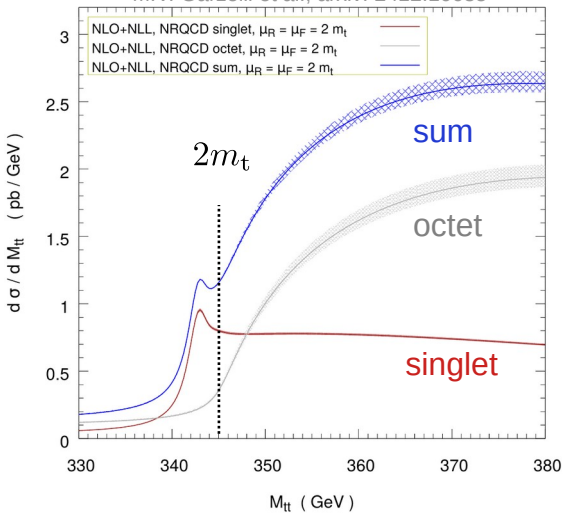
- Simplified Monte-Carlo model from fit to non-relativistic QCD prediction

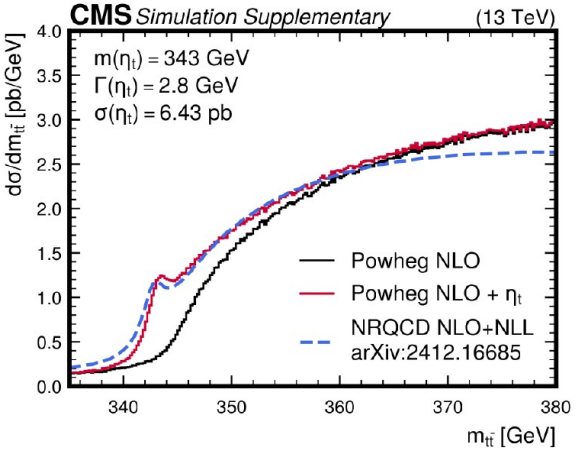
$$m(\eta_t) = 2m_t - 2\ \text{GeV},\ \Gamma(\eta_t) = 2\Gamma(t) = 2.8\ \text{GeV}$$

F. Maltoni et al., JHEP 03 (2024) 099

- NOT a “classical” bound state (eg. J/Ψ)
  → top quark decays “instantly”

M.V. Garzelli et al., arxiv: 2412.16685





Observation of excess near threshold

arXiv:2503.22382,
submitted to ROPP

- Analysis exploits 3 observables:

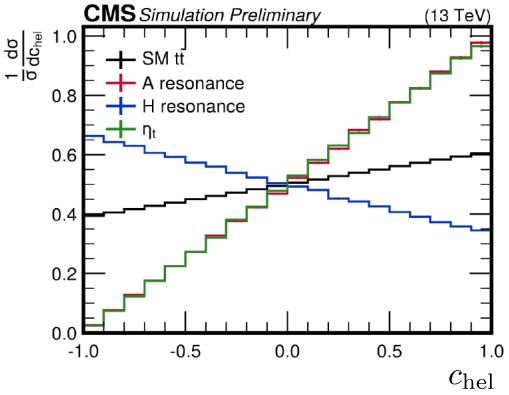
$$m_{\mathrm{t\bar{t}}} \otimes c_{\mathrm{hel}} \otimes c_{\mathrm{han}}$$

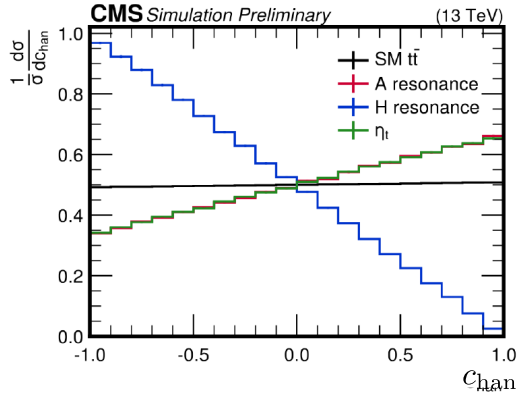
- Excess found! fits to **toponium** model
- Measured cross section

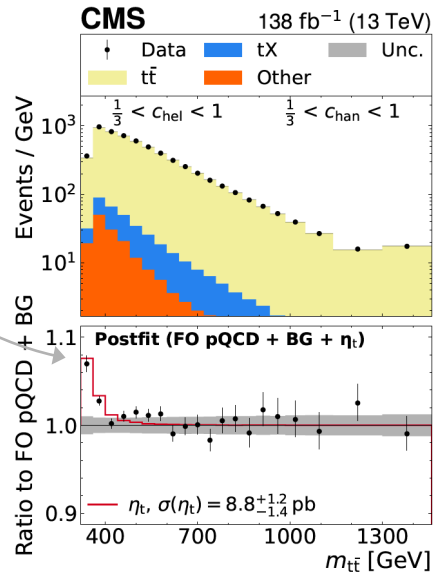
$$\sigma(\eta_{\mathrm{t}}) = 8.8^{+14\%}_{-16\%}\ \mathrm{pb}$$

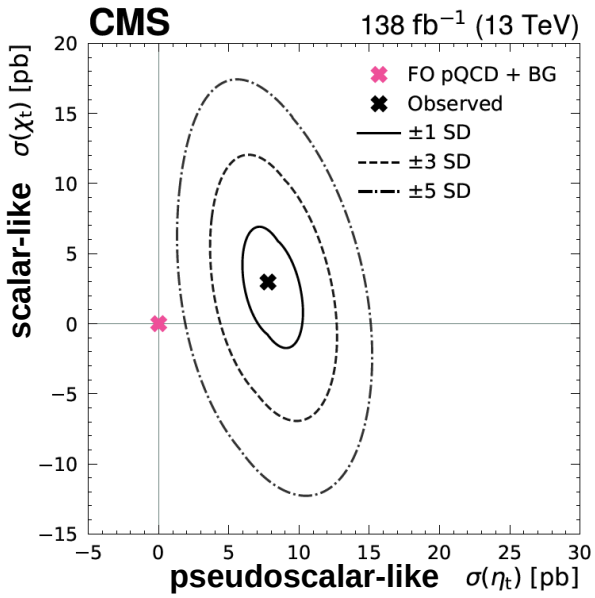
(pseudo-scalar like)

- Excess cannot be explained by
  - alternative background models
  - systematic uncertainties
- Exciting times ahead!





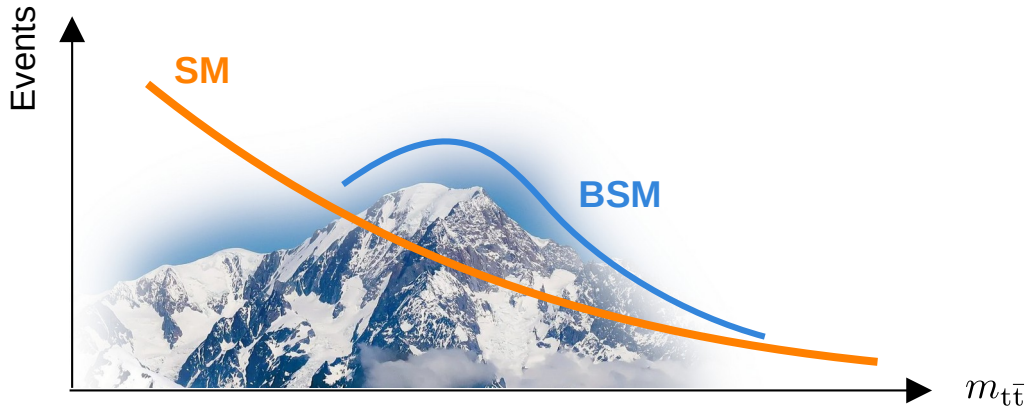




Searches for new physics with top quarks

Top of the **peak**

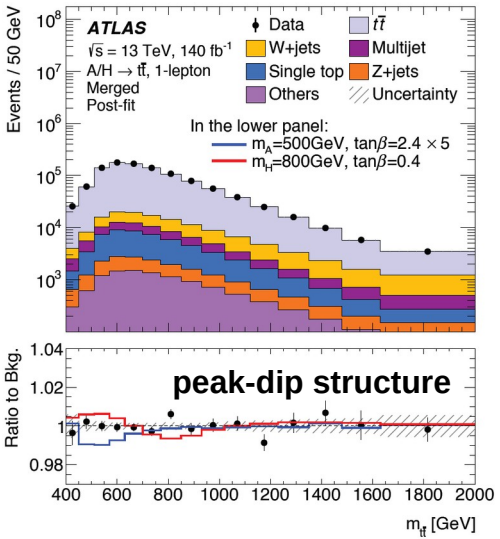
- Searching for structures in falling SM $m_{t\bar{t}}$ spectrum



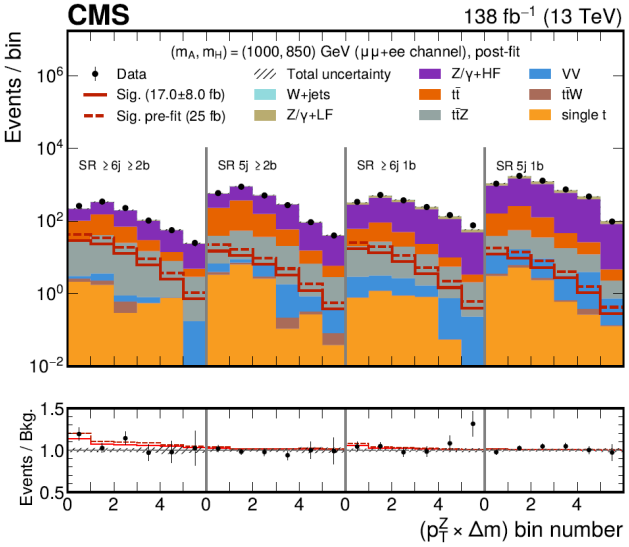
- ATLAS: heavy $A/H \to t\bar{t}$ production
- Interference with $t\bar{t}$ SM exploited
  → see K. Behr talk

- CMS: $A \to ZH,\ H \to t\bar{t}$ (2HDM)
- Dominant process for $m_A > m_Z + m_H$

JHEP 08 (2024) 013

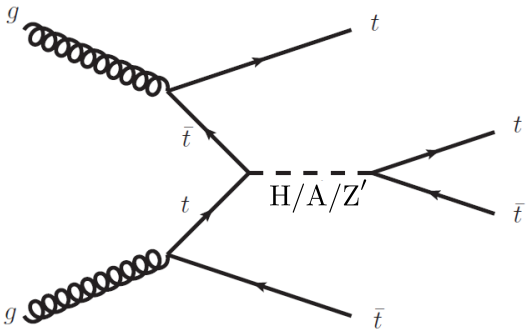


arXiv:2412.00570, *submitted to PLB*

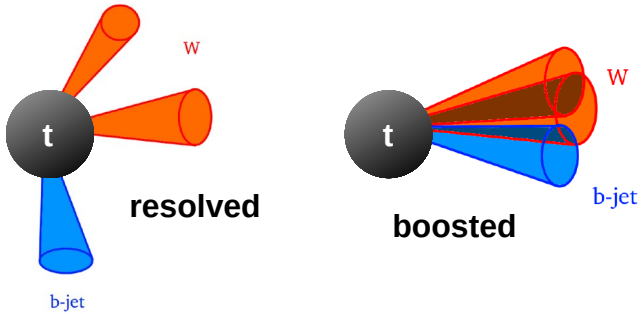


Top of the **peak** (2)

- Top-philic resonances
  = couple only to top quarks

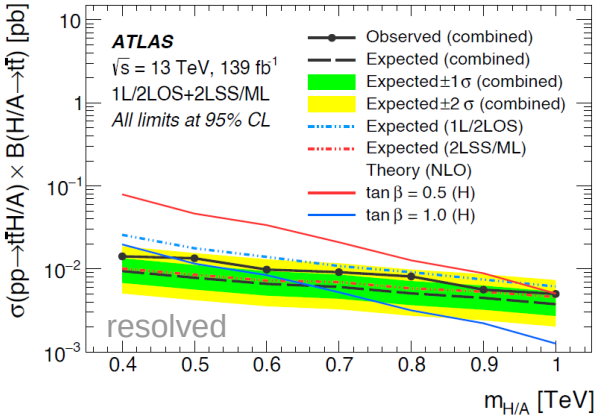


→ 3 & 4 top quark events

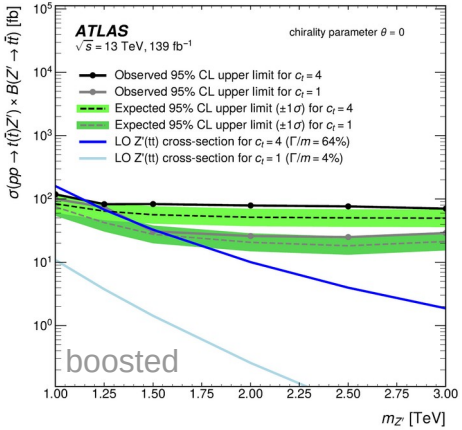


- Boosted top quarks for Z' (> 1 TeV)

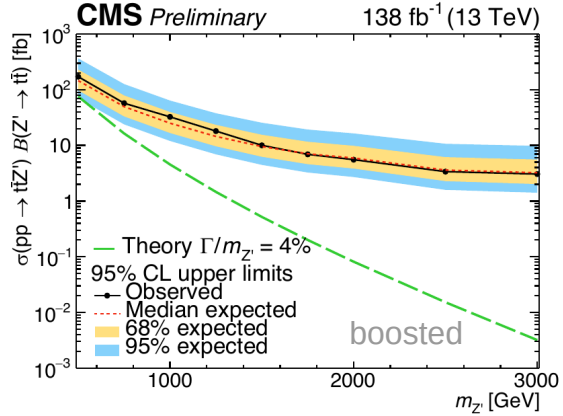
arXiv:2408.17164, submitted to EPJC



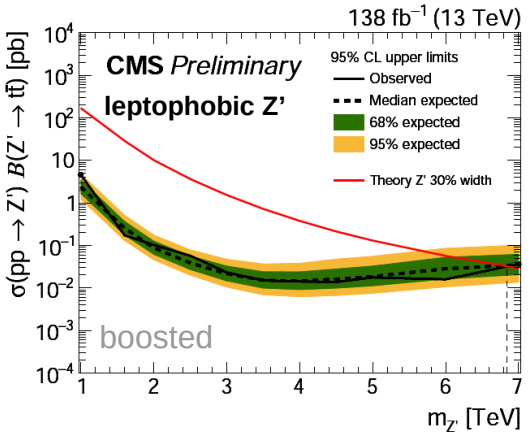
Eur. Phys. J. C 84 (2024) 157



CMS PAS B2G-24-009

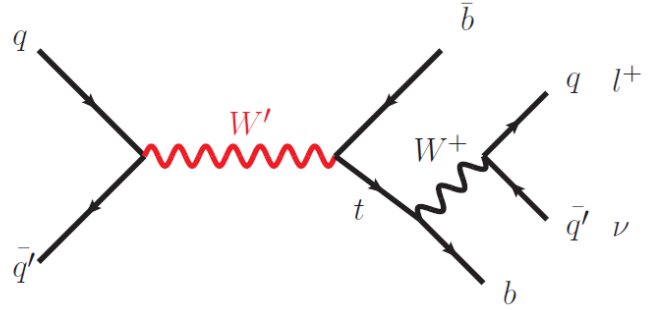


CMS PAS B2G-24-003



t+X resonances

- Heavy W boson partner

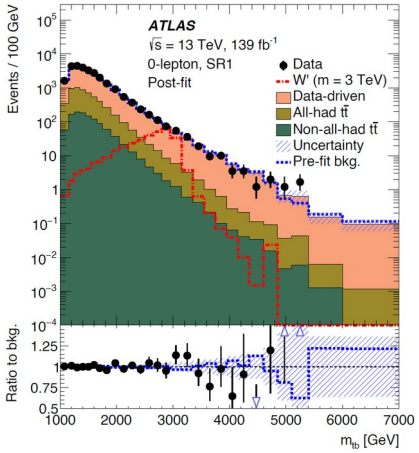


- Excluded up to 4.6 TeV
- Excess not seen by ATLAS

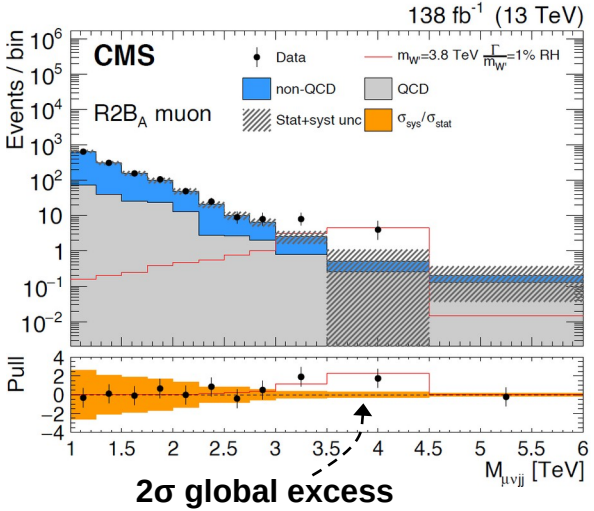
- Vector-like quarks
  (non-chiral, Dirac mass)

$$T \to bW^+, \quad T \to tZ, \quad T \to tH$$
$$B \to tW^-, \quad B \to bZ, \quad B \to bH$$
$$X_{5/3} \to tW^+$$
$$Y_{4/3} \to bW^-$$

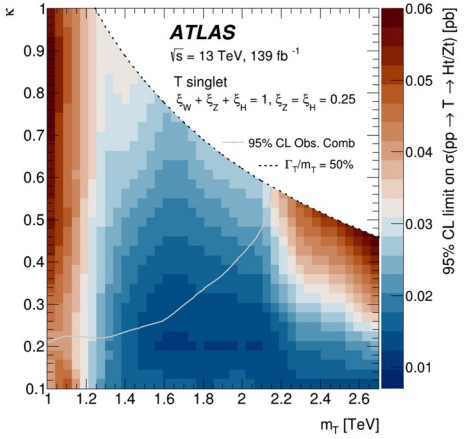
JHEP 12 (2023) 073



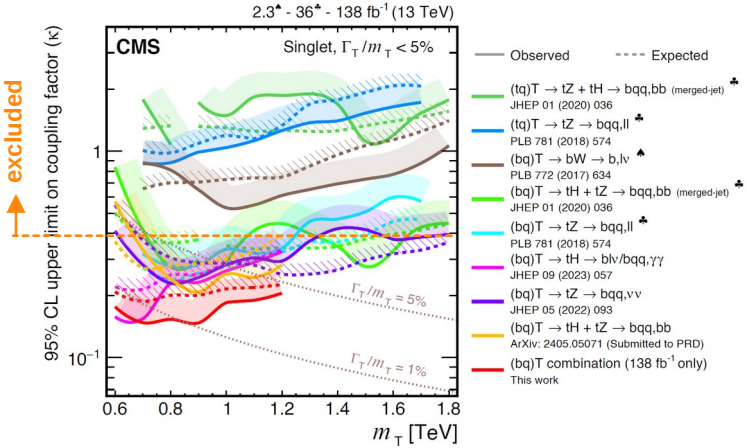
JHEP 05 (2024) 046



Phys. Rev. D 111 (2025) 012012



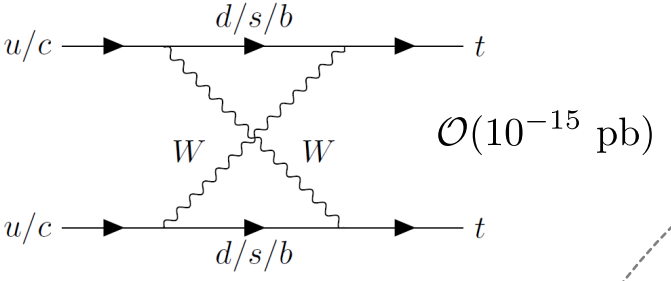
arXiv:2405.17605



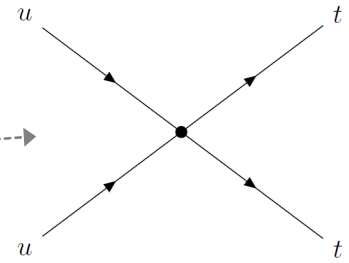
Same-charge top quark pairs

JHEP 02 (2025) 084

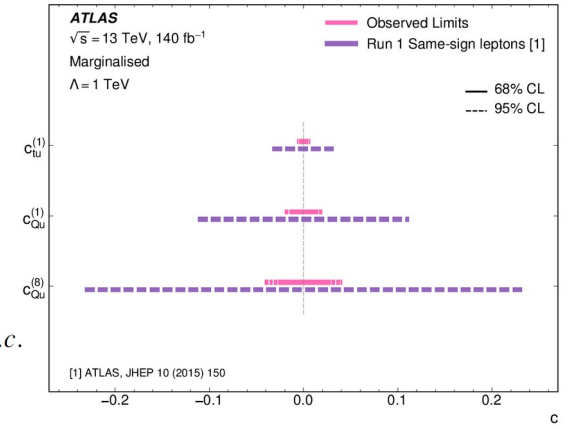
- Heavily suppressed in SM



$\mathcal{O}(10^{-15}\ \text{pb})$

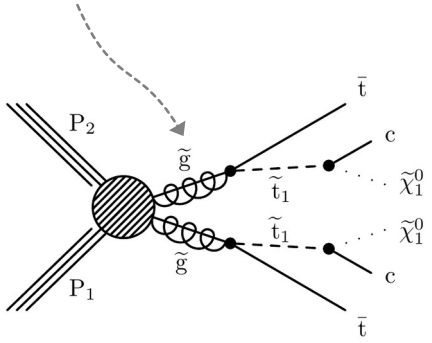


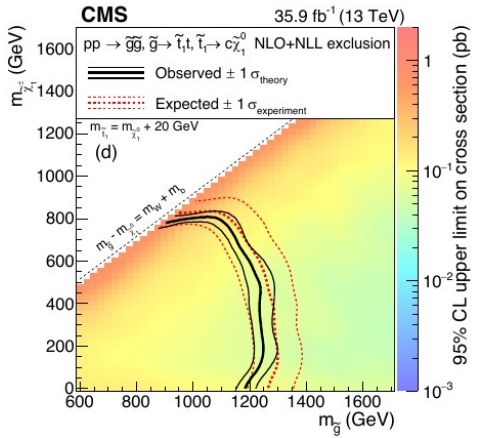
$$\mathcal{L}_{\text{D=6}}^{qq\to tt} = \frac{1}{\Lambda^2}\left(c_{tu}^{(1)}O_{tu}^{(1)} + c_{Qu}^{(1)}O_{Qu}^{(1)} + c_{Qu}^{(8)}O_{Qu}^{(8)}\right) + h.c.$$

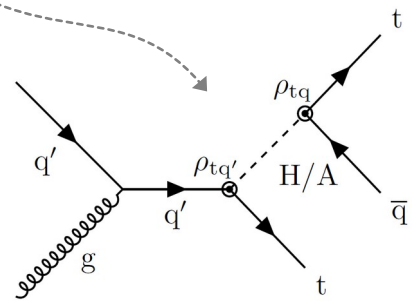


- BSM scenarios: contact-interactions, FCNC, SUSY

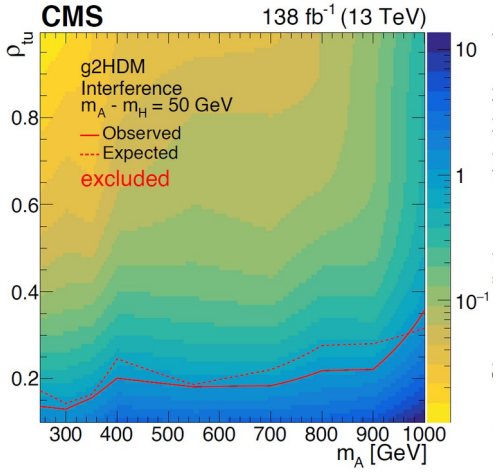
Eur. Phys. J. C 77 (2017) 578



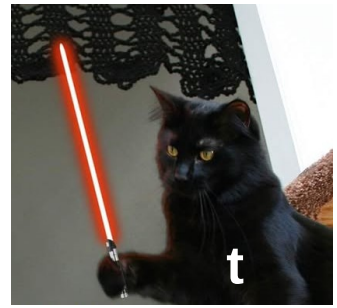




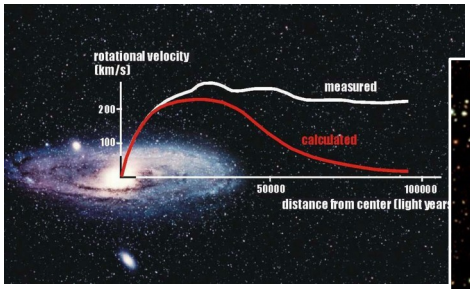
Phys. Lett. B 850 (2024) 138478



Top quark joins the **dark side?**

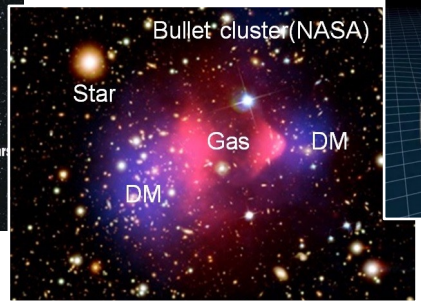


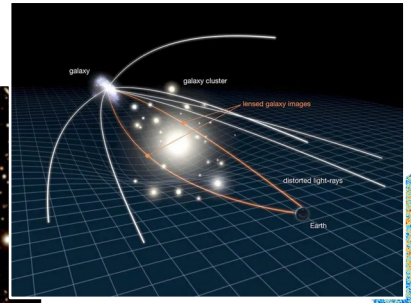
- Motivations for **dark matter**



galaxy rotation

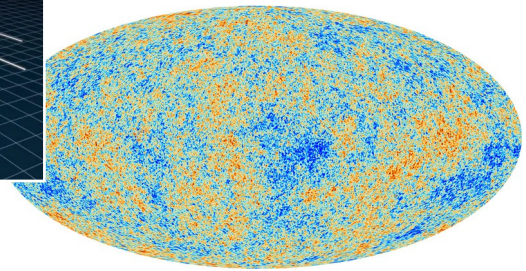
mass distribution



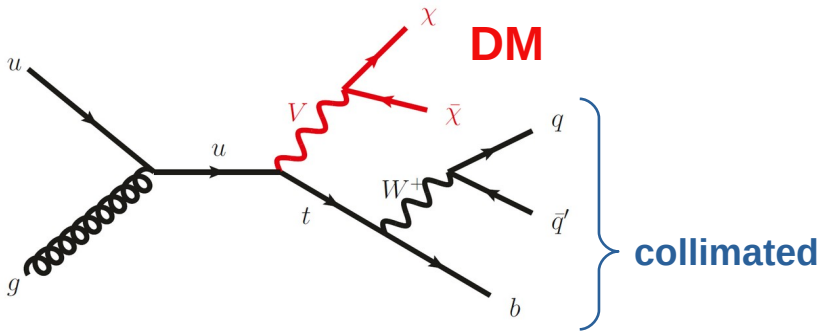


gravitational lensing

acoustic oscillations

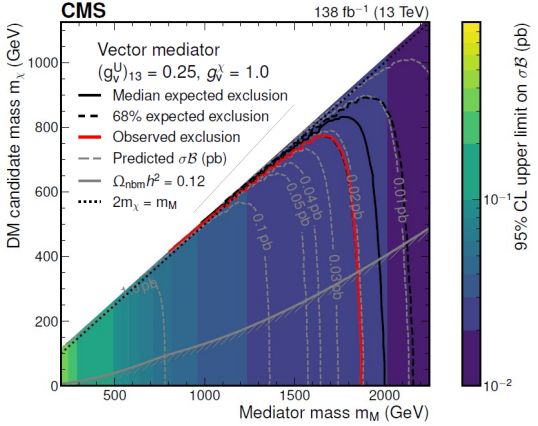


- Top + missing energy → “mono tops”

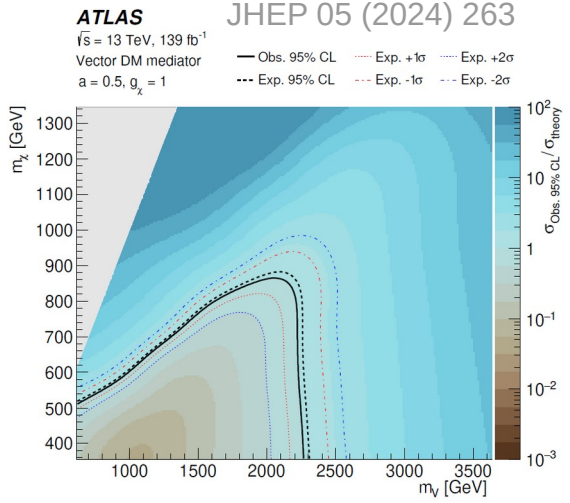


- Various mediator types investigated

arXiv:2503.20033, *submitted to JHEP*

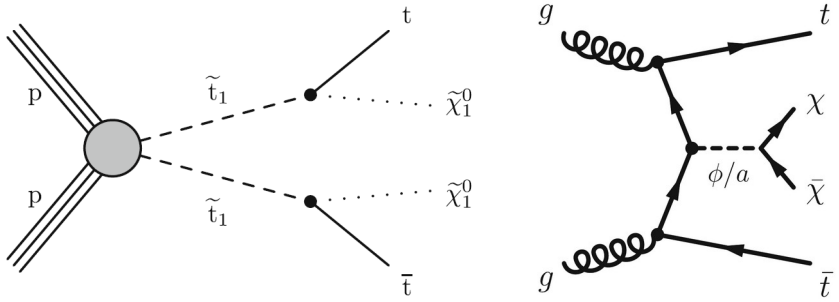


JHEP 05 (2024) 263



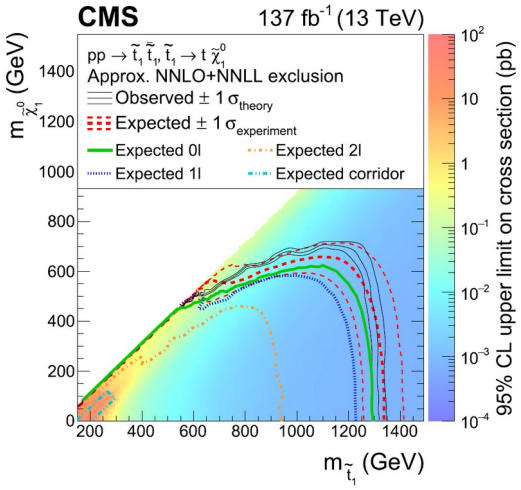
Dark matter & top quarks

- DM with top quark pairs
- Models: SUSY, scalar mediator

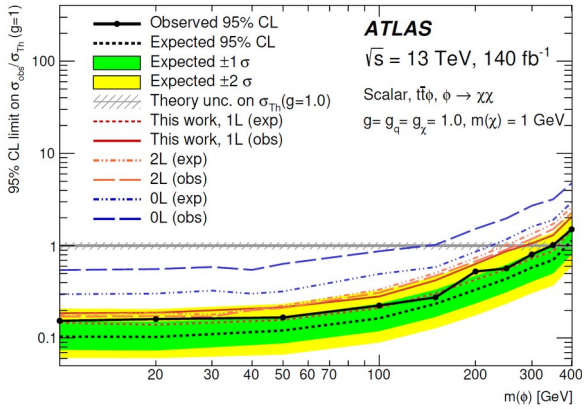


- Indirect in neutrino spectrum or through interference

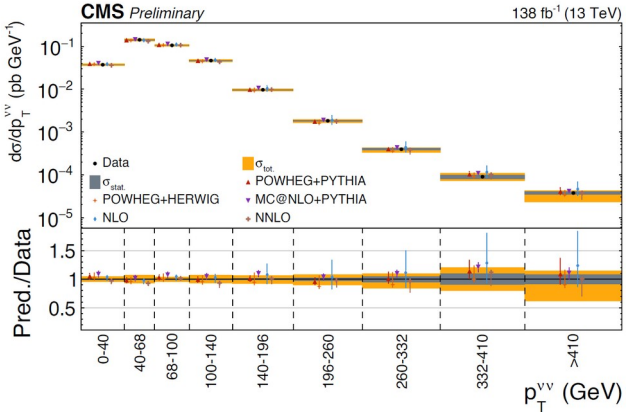
Eur. Phys. J. C 81 (2021) 970



JHEP 03 (2024) 139



CMS PAS TOP-24-001



Summary

LHC = top-quark-measurement-machine©

top quark + friends (W,Z,H,g,γ,..)

entangled tops

- Precisely measured production modes
- V_{tb}, polarization, spin correlation & entanglement
- **Observation** near $t\bar{t}$ threshold! Toponium?
- Top quarks & new physics

Continuous stream of **new observations & searches** even after 30 years of top quark's discovery!

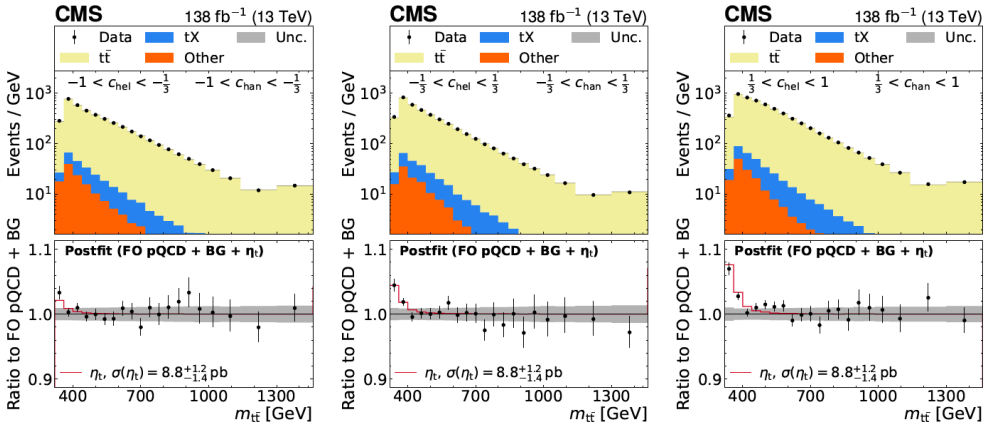
resonances

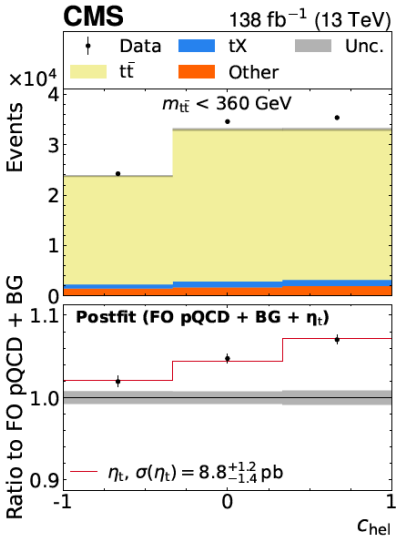
Matthias Komm
Fellow at DESY, mkomm@cern.ch, matt-komm.github.io

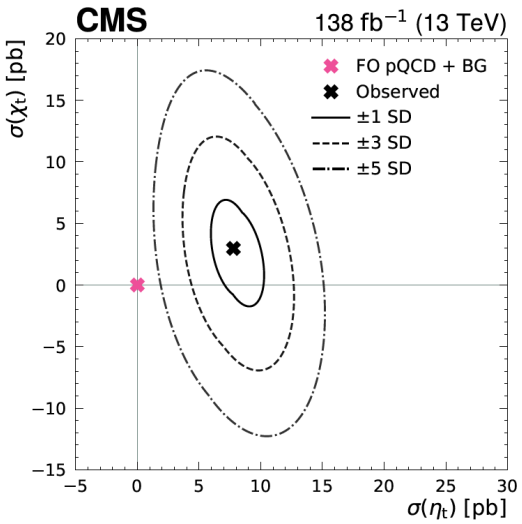
Backup

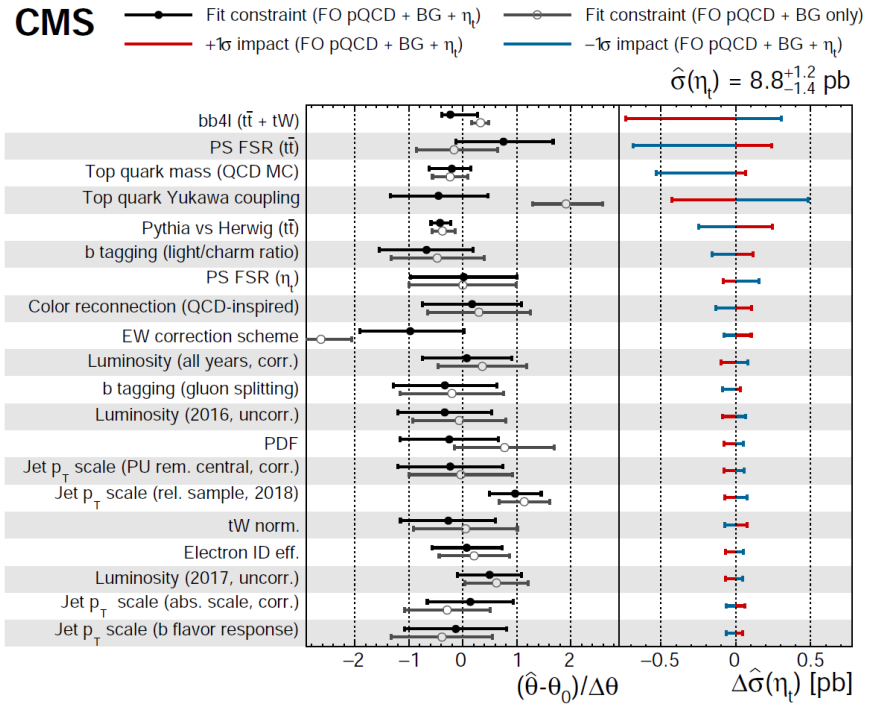
Toponium

arXiv:2503.22382,
submitted to ROPP









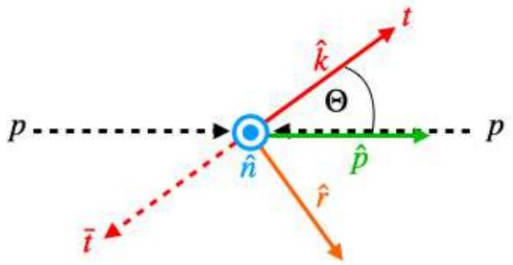
FO pQCD generator setup	$\sigma(\eta_t)$ [pb]
POWHEG v2 `hvq` + PYTHIA	8.7 ± 1.1
POWHEG v2 `hvq` + HERWIG	8.6 ± 1.1
MADGRAPH5_aMC@NLO FxFx + PYTHIA	9.8 ± 1.3
POWHEG vRES `bb4l` + PYTHIA	6.6 ± 1.4
Nominal result	$8.8^{+1.2}_{-1.4}$

$t\bar{t}$ entanglement

- Decompose differential cross section

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_a\, d\cos\theta_b} = \frac{1}{4}(1 + P_t \cos\theta_a + P_{\bar{t}} \cos\theta_b - C \cos\theta_a \cos\theta_b)$$

$$\mathrm{P} = \begin{pmatrix} c_x \\ c_y \\ c_z \end{pmatrix} \qquad \mathrm{C} = \begin{pmatrix} c_{xx} & c_{xy} & c_{xz} \\ c_{yx} & c_{yy} & c_{yz} \\ c_{zx} & c_{zy} & c_{zz} \end{pmatrix}$$



- Measure coefficients in kin. regions

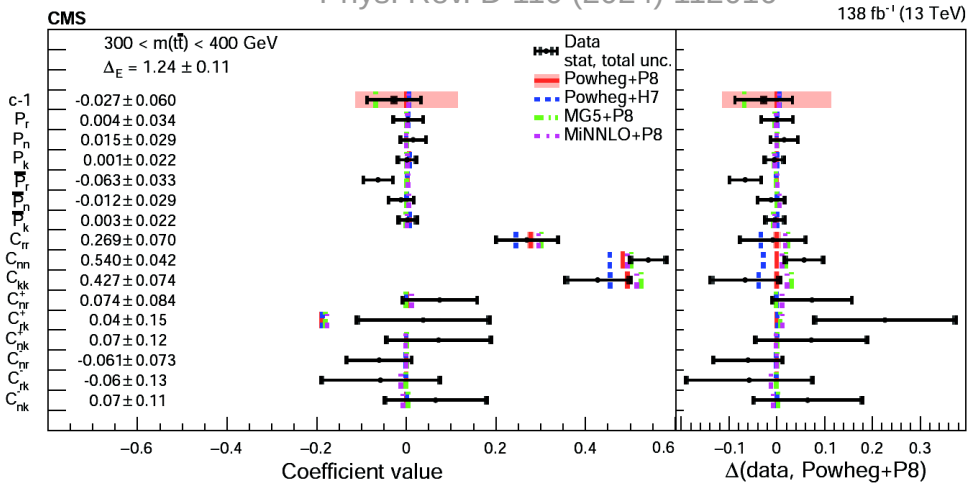
$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 + \text{coeff.}\, x) f(x)$$

- Peres-Horodecki criterion

→ tests separability of joint density matrix

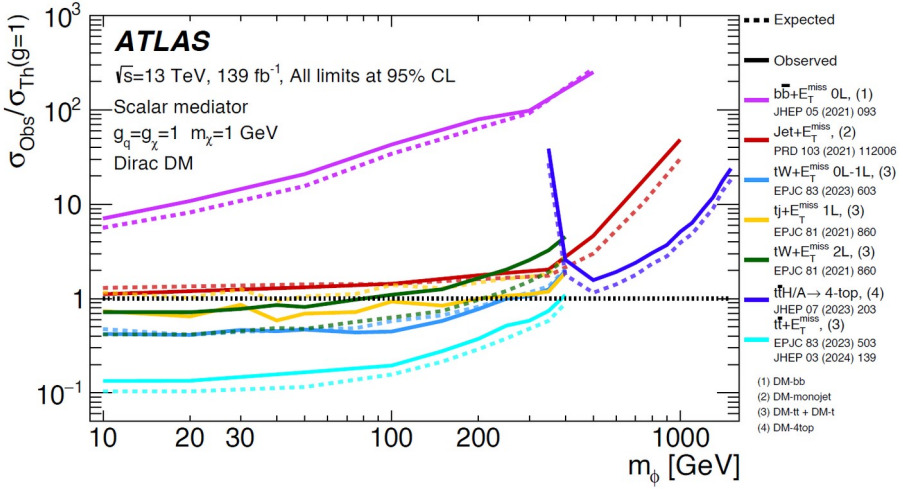
$$\rho = \sum q_n \rho_n^A \otimes \rho_n^B$$

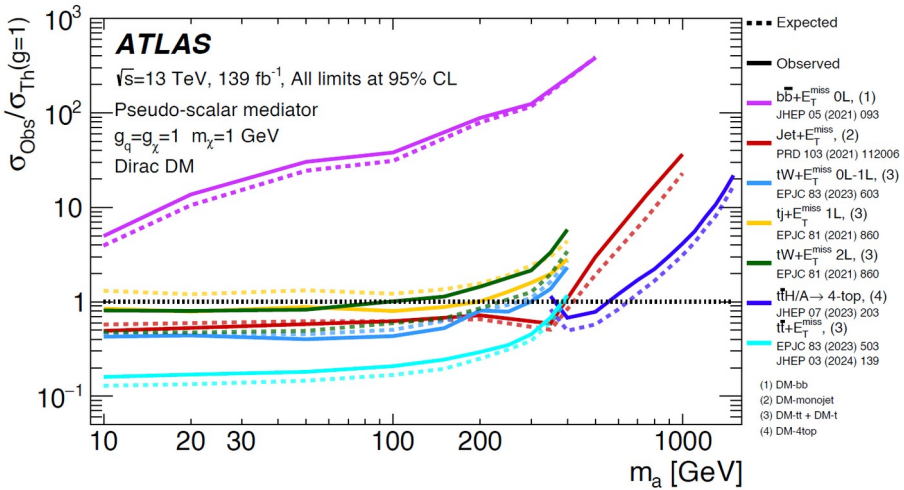
Phys. Rev. D 110 (2024) 112016

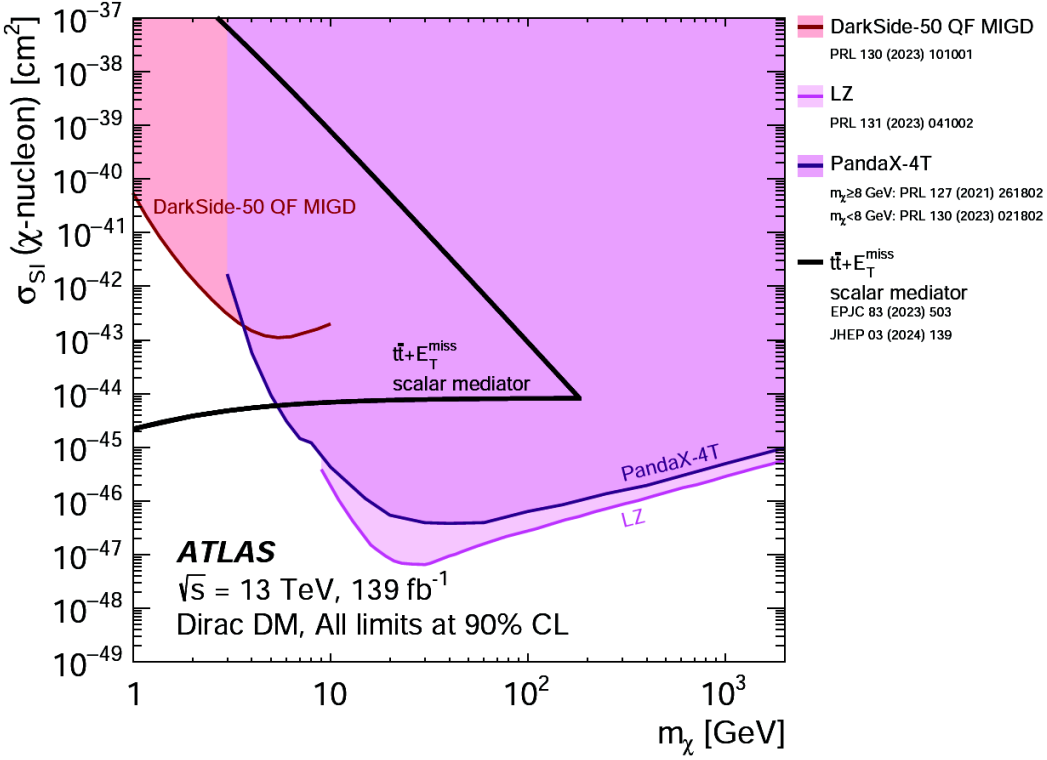


DM + top quarks

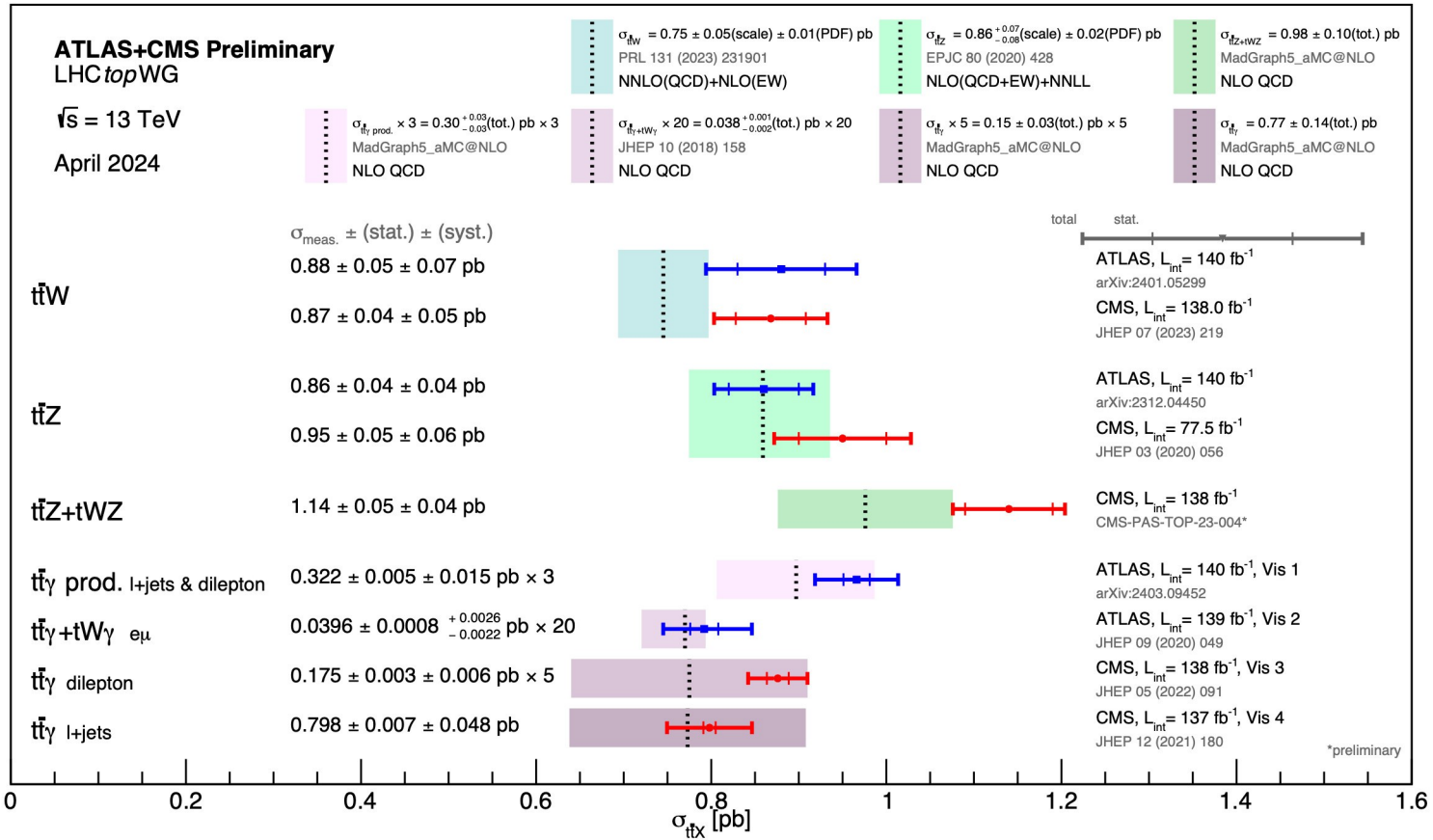
Eur. Phys. J. C 84 (2024) 1102







$t\bar{t}$ + X cross section measurements



t + X cross section measurements