

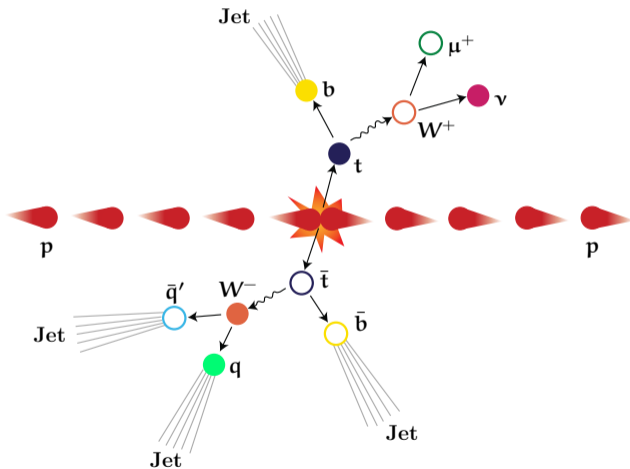
43rd International Symposium on Physics in Collision (PIC2024)  
October 22–25, 2024

# Measurements with top quarks at the LHC

**Joscha Knolle** on behalf of the ATLAS & CMS Collaborations

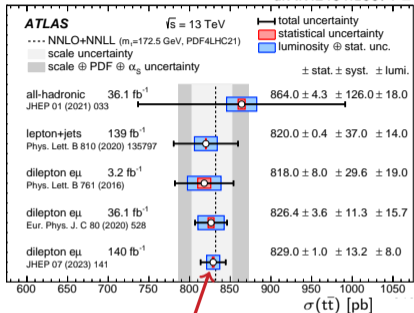


# Top quark pair production

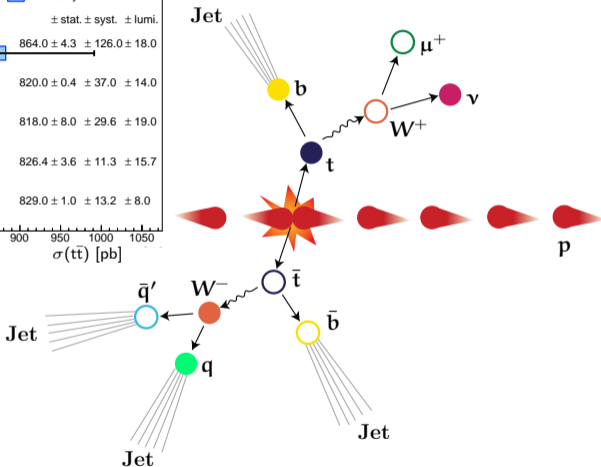


# Top quark pair production

arXiv:2404.10674

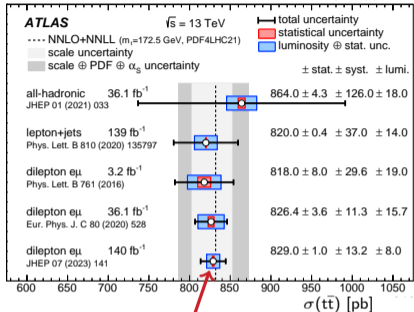


$\pm 1.9\%$

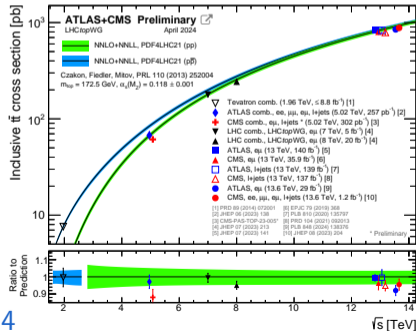
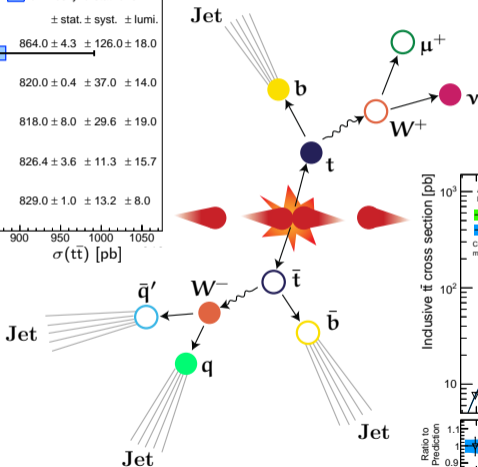


# Top quark pair production

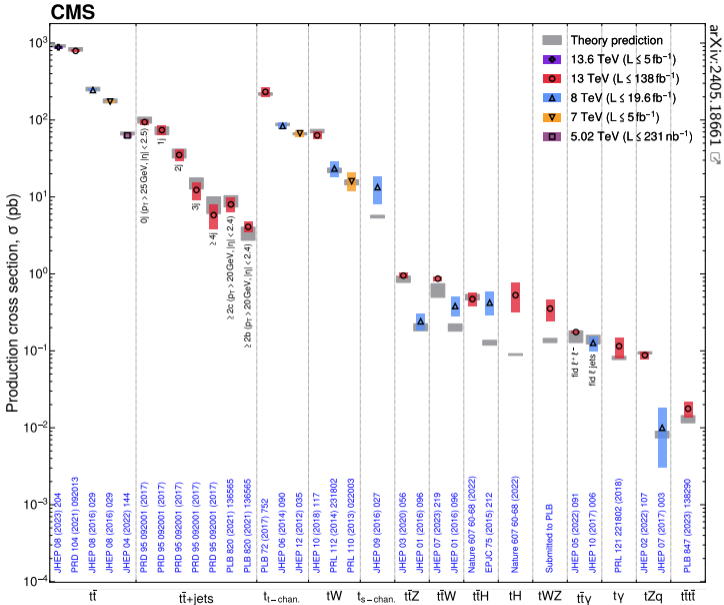
arXiv:2404.10674



±1.9%

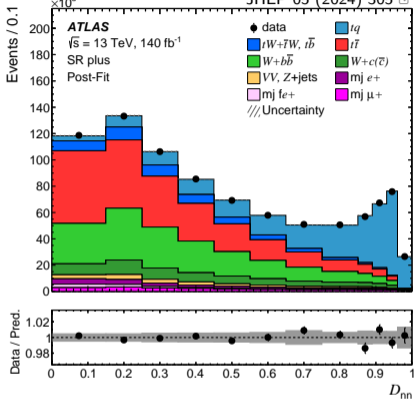


# From $t\bar{t}$ to $t\bar{t}\bar{t}\bar{t}$

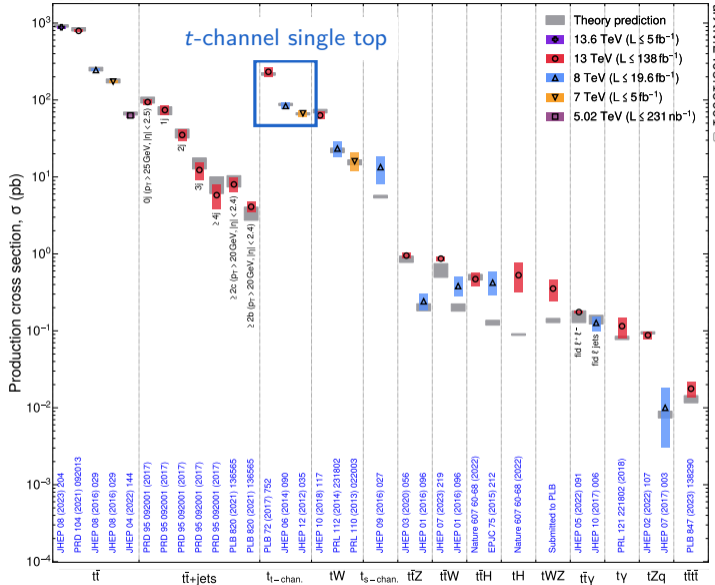


# From $t\bar{t}$ to $t\bar{t}\bar{t}$

JHEP 05 (2024) 305

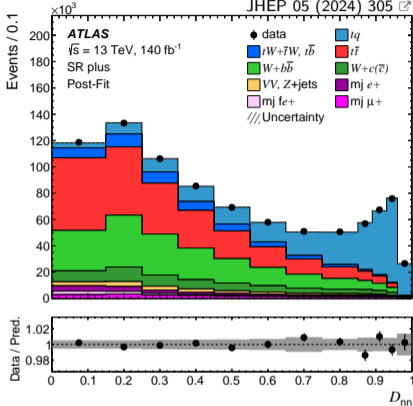


## CMS

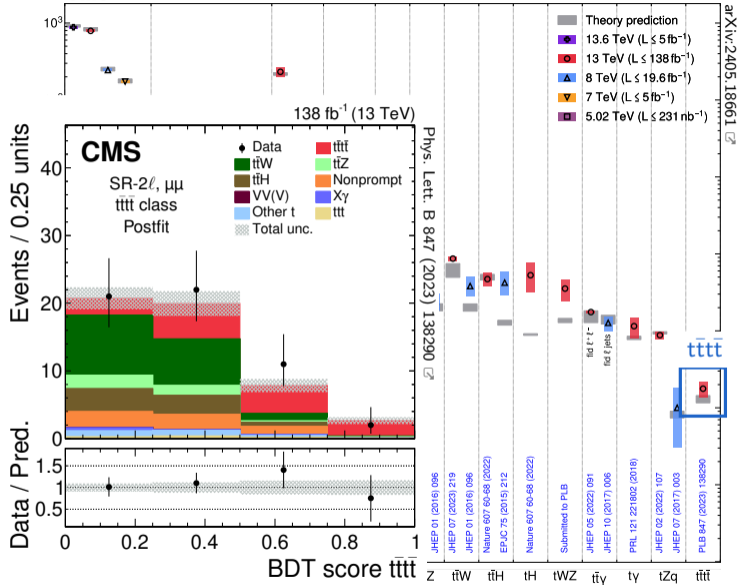


# From $t\bar{t}$ to $t\bar{t}t$

JHEP 05 (2024) 305

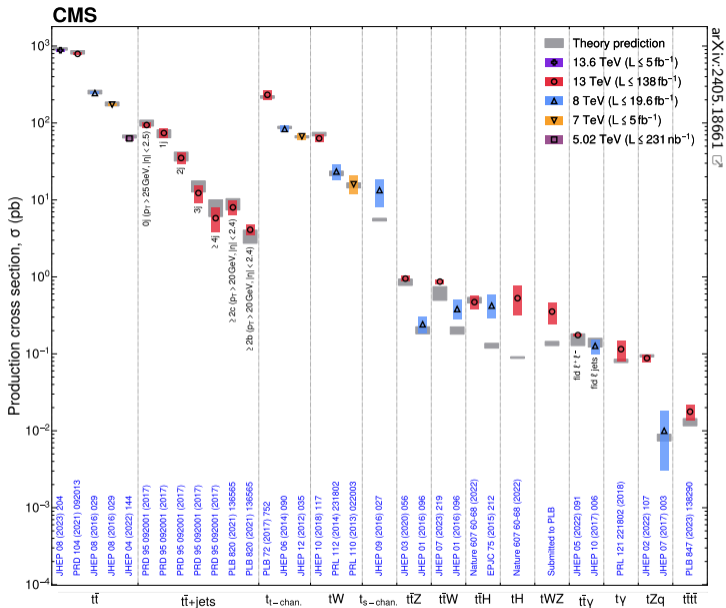


## CMS



# Highlights today

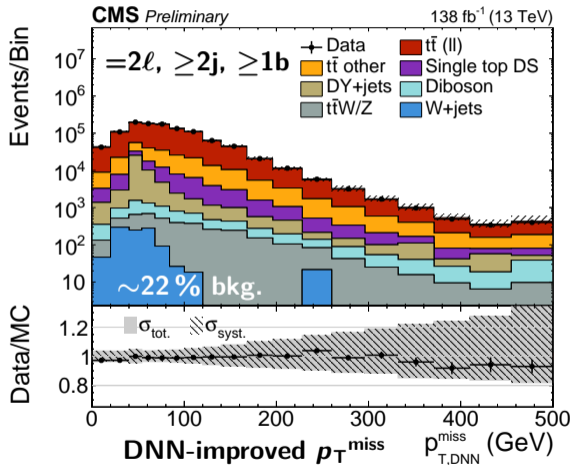
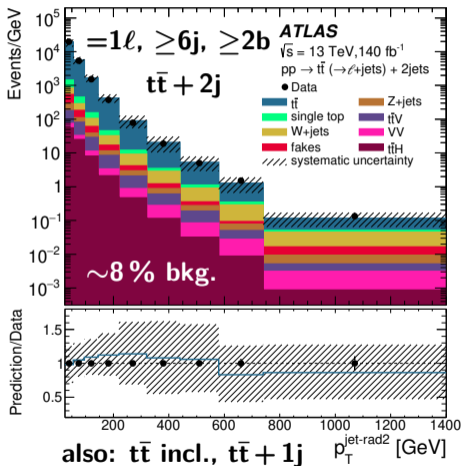
- differential  $t\bar{t}$
- $t\bar{t}$  in heavy-ion collisions
- entanglement in  $t\bar{t}$
- $t\bar{t}$  + heavy flavour
- single-top  $tW$
- top quark(s) + vector boson(s)





# Differential $t\bar{t}$ : event selection

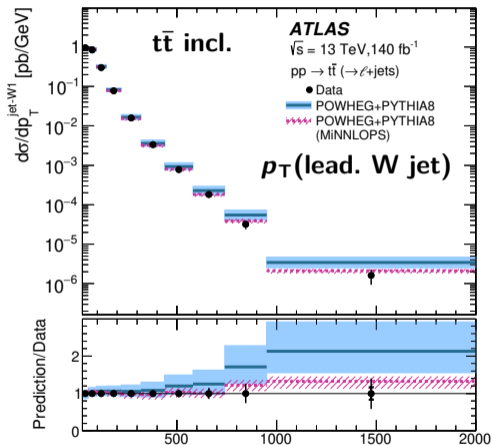
JHEP 08 (2024) 182 [↗](#), CMS-PAS-TOP-24-001 [↗](#)



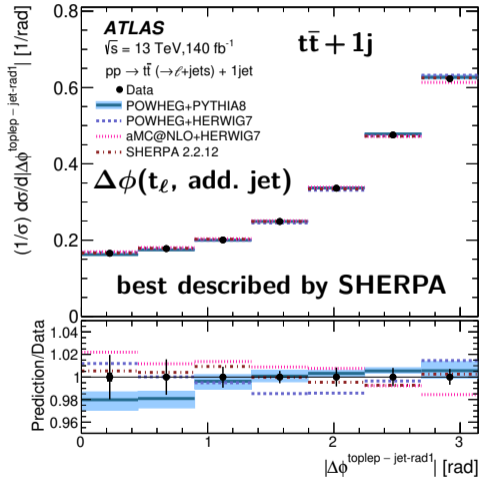
# Differential $t\bar{t}$ : lepton+jets results

JHEP 08 (2024) 182 [↗](#)

large unc.: b tagging, energy scale/resolution, backgrounds



well described by MiNNLOPS  $p_T^{\text{jet-W1}} [\text{GeV}]$





# Differential $t\bar{t}$ : dilepton results

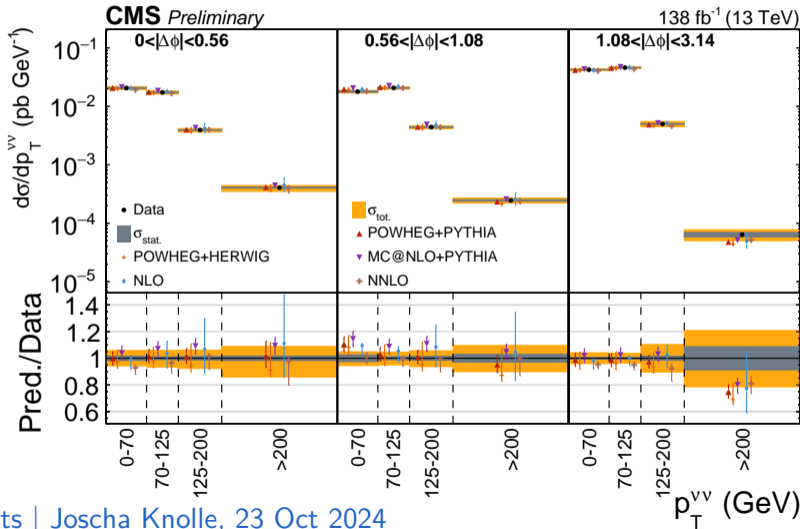
CMS-PAS-TOP-24-001 [↗](#)

large unc.: jet energy scale, lepton reconstruction,  $tW$  modeling

$$p_T(\nu\nu) \times \min \Delta\phi(\nu\nu, \ell)$$

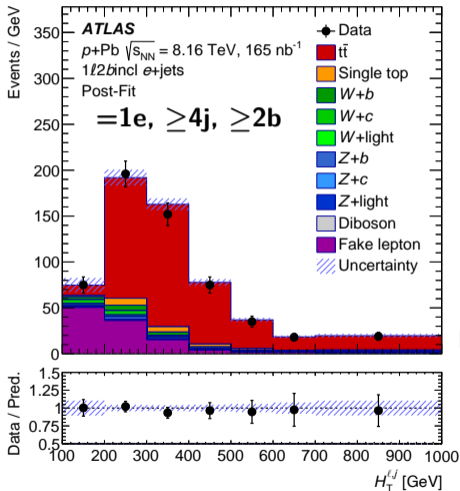
best described by NNLO pred.

JHEP 05 (2021) 212 [↗](#)



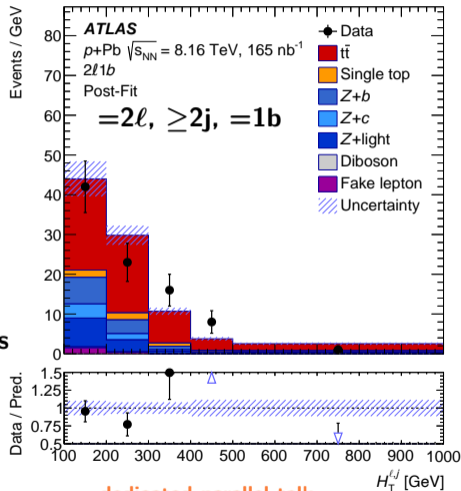
# $t\bar{t}$ in heavy-ion collisions: pPb analysis

arXiv:2405.05078 [↗](#)



also:  
 $=1e, =1b$   
 $=1\mu, =1b$   
 $=1\mu, \geq 2b$   
 $=2\ell, \geq 2b$

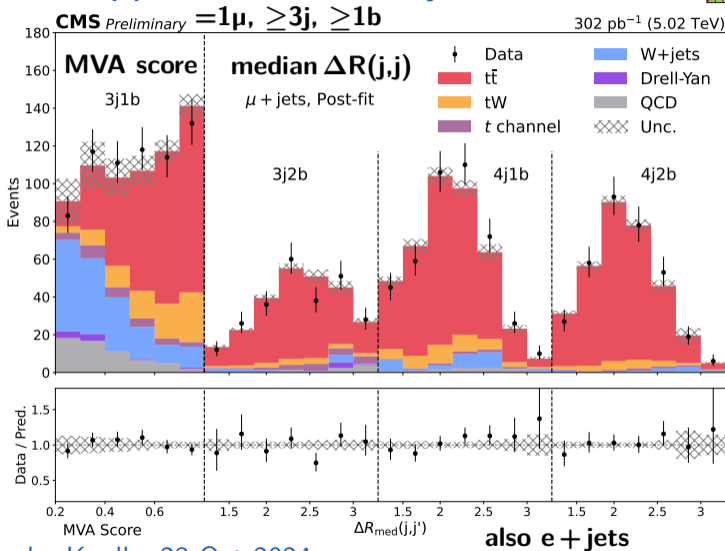
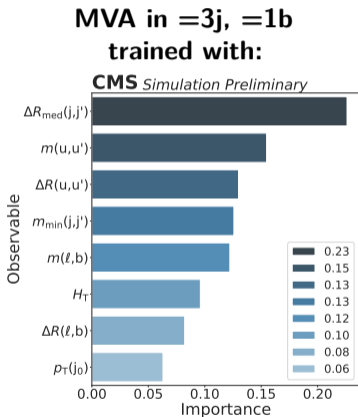
binned in  
 $\sum p_T$  of  
 leptons & jets



dedicated parallel talk  
 by Emily today!

# $t\bar{t}$ in heavy-ion collisions: pp@5.02 TeV analysis

CMS-PAS-TOP-23-005 [↗](#)

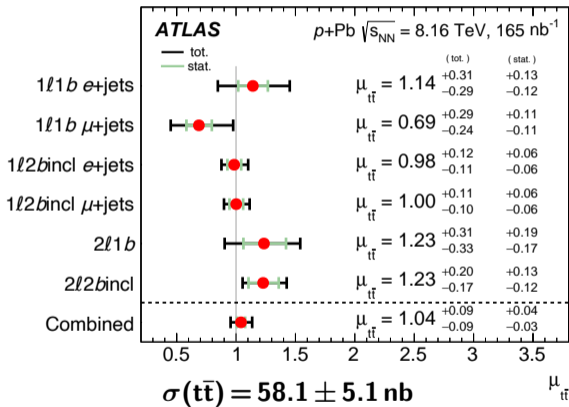


# $t\bar{t}$ in heavy-ion collisions: results

arXiv:2405.05078 , CMS-PAS-TOP-23-005 

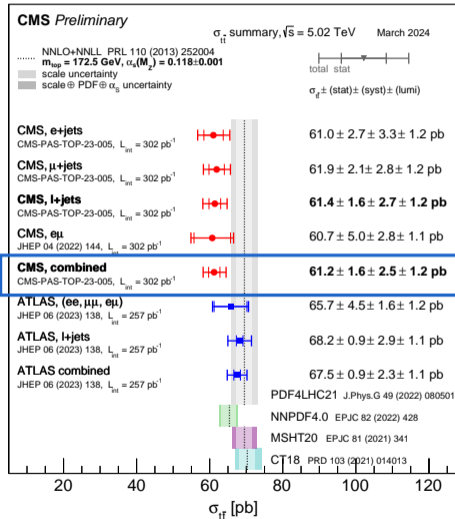


## first observation of dileptonic $t\bar{t}$ in pPb



large unc.: jet energy scale,  $t\bar{t}$  modeling

Top quark measurements | Joscha Knolle, 23 Oct 2024

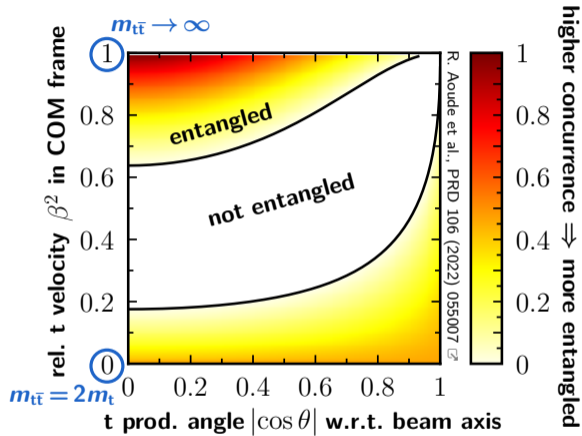


large unc.: b tagging,  $t\bar{t}$  modeling, trigger eff.

# Entanglement in $t\bar{t}$ : introduction



entangled state e.g.:  $|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow, \downarrow\rangle - |\downarrow, \uparrow\rangle)$



# Entanglement in $t\bar{t}$ : introduction



entangled state e.g.:  $|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow, \downarrow\rangle - |\downarrow, \uparrow\rangle)$

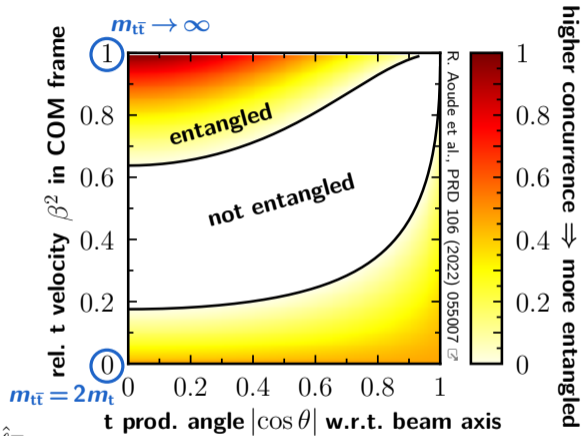
probe **polarization** and **spin correlations** in angular distribution of decay products:

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega_+ d\Omega_-} \sim (1 + B^+ \cdot \hat{\ell}^+ + B^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot C \cdot \hat{\ell}^-)$$

sufficient condition for **entanglement**:  $\text{tr}[C] < -1$

can be probed in single distribution:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\varphi} = \frac{1}{2} \left( 1 + \frac{\text{tr}[C]}{3} \cos\varphi \right), \text{ with } \cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$$



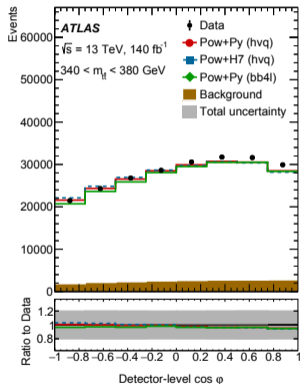


# Entanglement in $t\bar{t}$ : analysis strategy

Nature 633 (2024) 542 [↗](#), arXiv:2406.03976 [↗](#), arXiv:2409.11067 [↗](#)

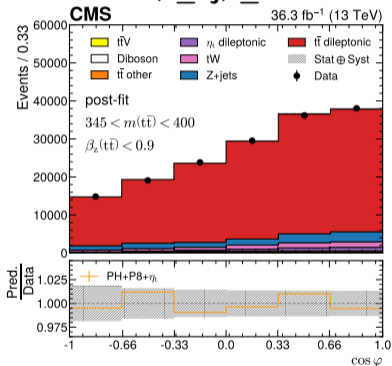


**=1e, =1μ, ≥2j, ≥1b**



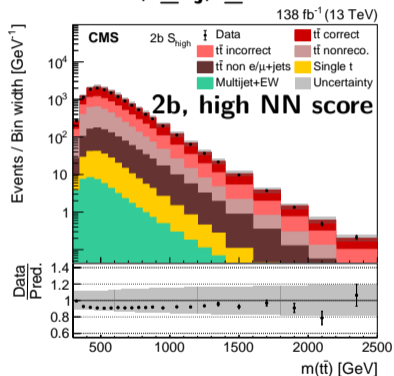
**$340 < m_{t\bar{t}} < 380 \text{ GeV}$**

**=2ℓ, ≥2j, ≥1b**



**$345 < m_{t\bar{t}} < 400 \text{ GeV}$**   
 **$\beta_z(t\bar{t}) < 0.9$**

**=1ℓ, ≥4j, ≥1b**

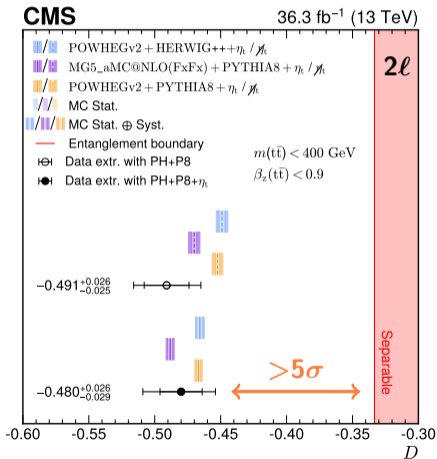


**$t\bar{t}$  reconstruction with NN**  
**both low and high  $m_{t\bar{t}}$**

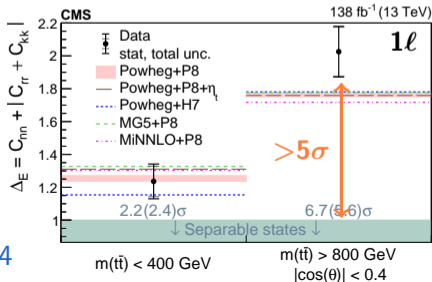
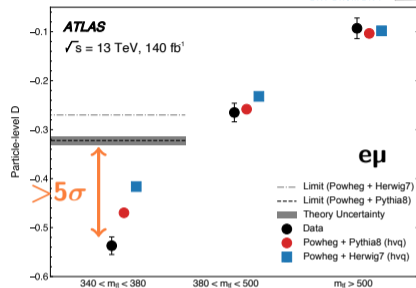
# Entanglement in $t\bar{t}$ : results

Nature 633 (2024) 542 [↗](#), arXiv:2406.03976 [↗](#),  
arXiv:2409.11067 [↗](#)

dedicated parallel talks by  
Didar and Matthew today!



quantum  
entanglement  
in  $t\bar{t}$   
observed  
at low and  
high  $m_{t\bar{t}}$

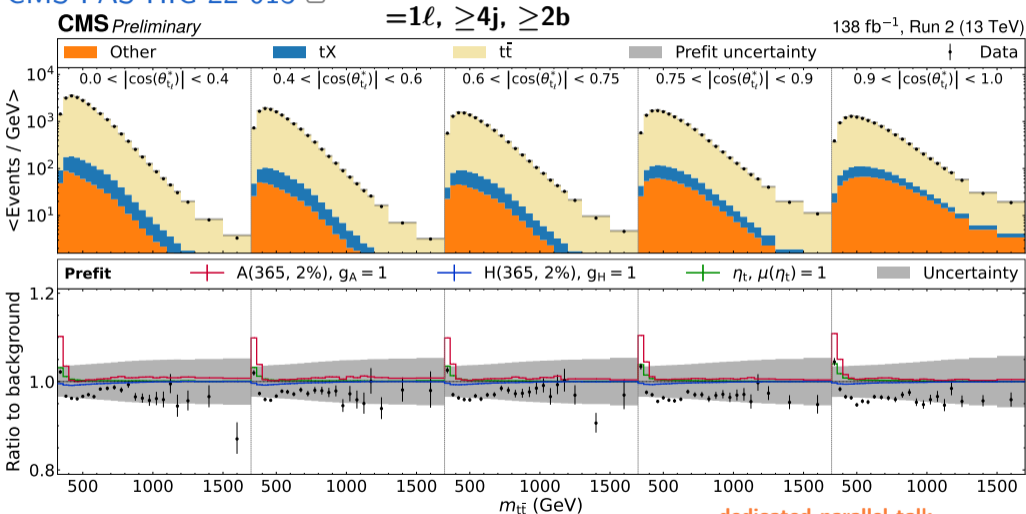


Top quark measurements | Joscha Knolle, 23 Oct 2024



# Bonus slide: Pseudoscalar resonance at $t\bar{t}$ threshold?

CMS-PAS-HIG-22-013 [↗](#)



also:  
1l3j  
2l

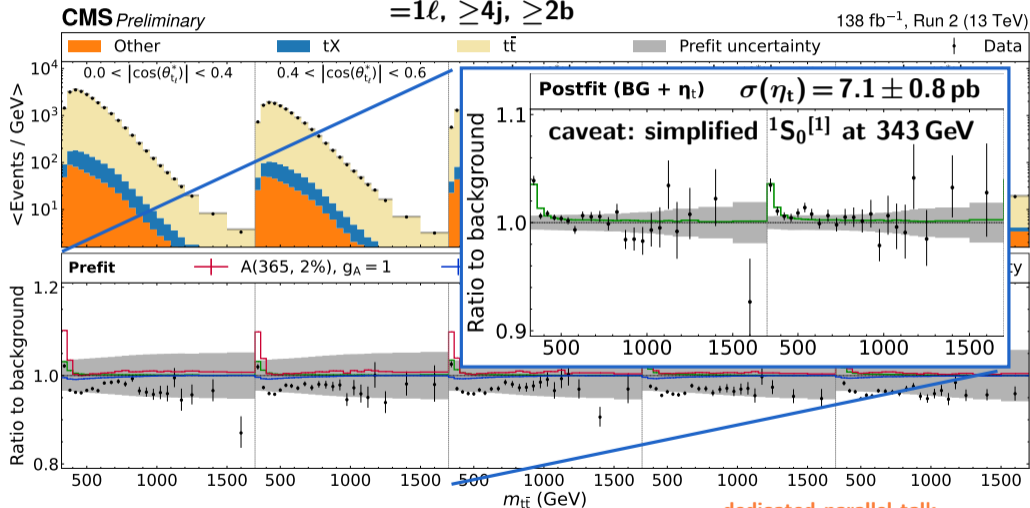


# Bonus slide: Pseudoscalar resonance at $t\bar{t}$ threshold?

CMS-PAS-HIG-22-013 [↗](#)

$=1\ell, \geq 4j, \geq 2b$

138 fb<sup>-1</sup>, Run 2 (13 TeV)

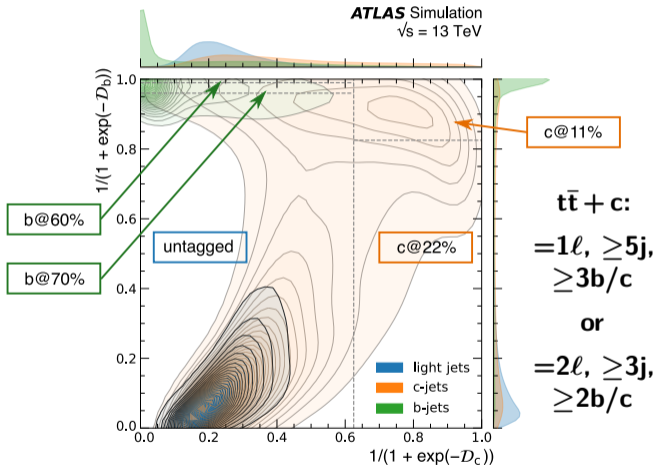
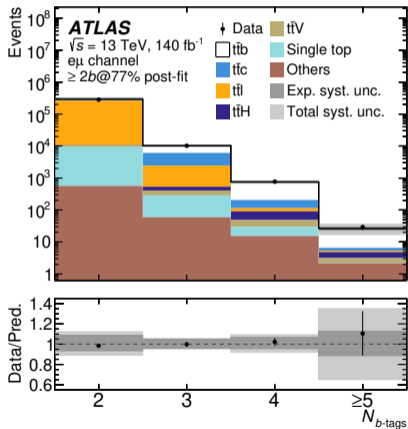


also:  
1l3j  
2l

# $t\bar{t}$ + heavy flavour: analysis strategy

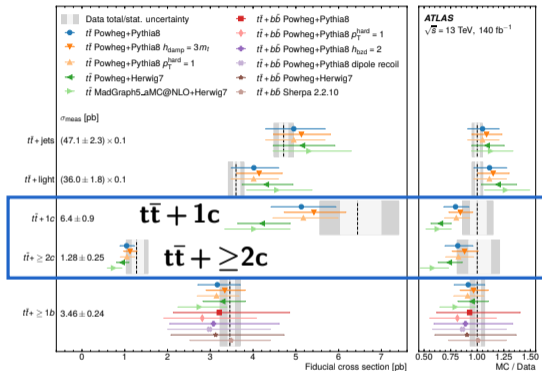
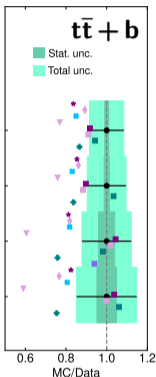
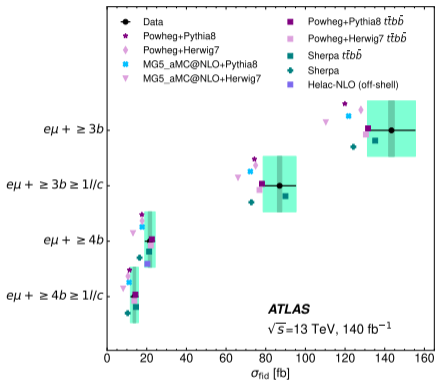
arXiv:2407.13473 [↗](#), arXiv:2409.11305 [↗](#)

$t\bar{t} + b$ :  $=1e, =1\mu, \geq 2j, \geq 2b$



# $t\bar{t}$ + heavy flavour: inclusive results

arXiv:2407.13473 [↗](#), arXiv:2409.11305 [↗](#)



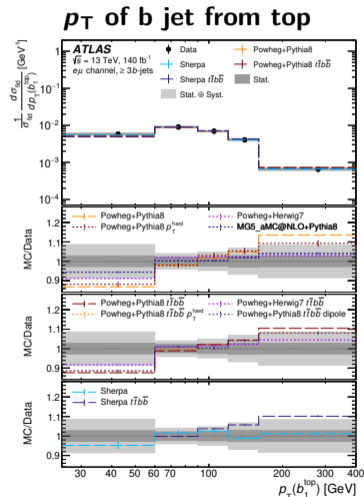
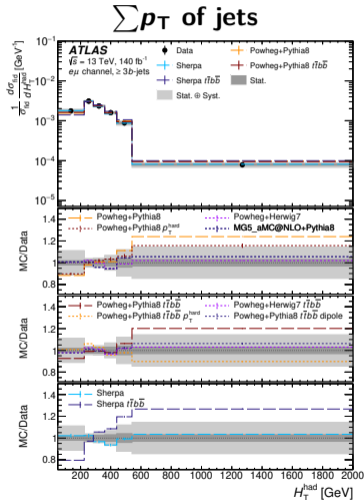
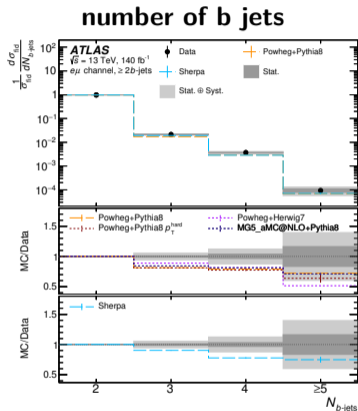
$t\bar{t} + b$  best described by SHERPA  $t\bar{t}b\bar{b}$

$t\bar{t} + c$  slightly underpredicted by NLO+PS

large unc.: b/c tagging,  $t\bar{t}$  modeling, jet energy scale, data statistics (for  $t\bar{t} + c$ )

# $t\bar{t} + \text{heavy flavour}$ : differential $t\bar{t} + b$ results

arXiv:2407.13473 



# Single-top tW at 13 TeV

arXiv:2407.15594 

$=1e, =1\mu, \geq 1j, \geq 1b$

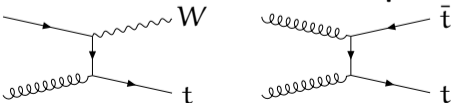
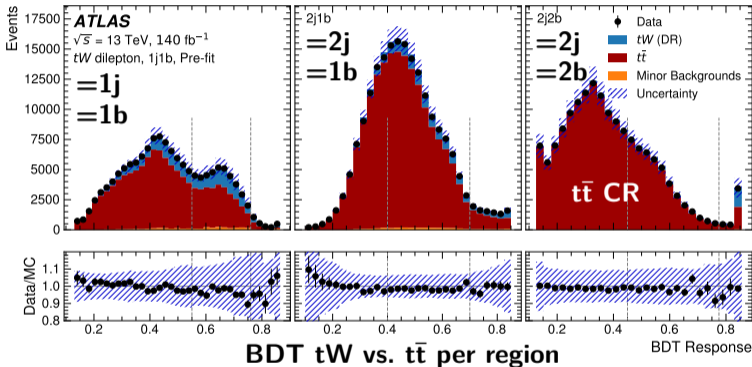
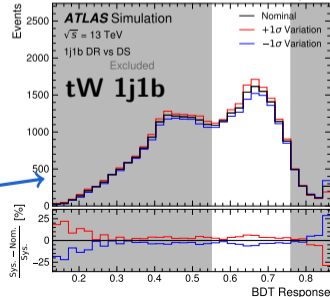
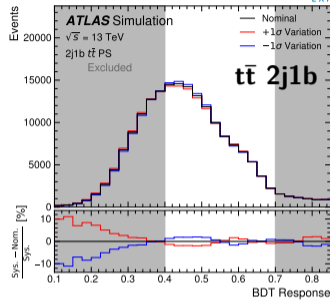


diagram removal (DR) vs. diagram subtraction (DS)

Top quark measurements | Joscha Knolle, 23 Oct 2024



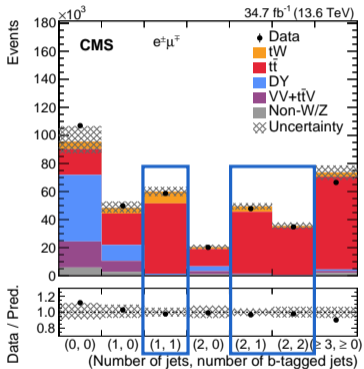




# Single-top $tW$ at 13.6 TeV

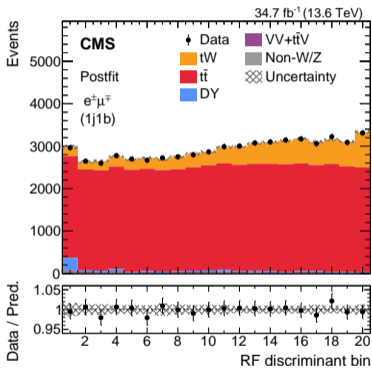
arXiv:2409.06444

$\geq 1e, \geq 1\mu$



inclusive:

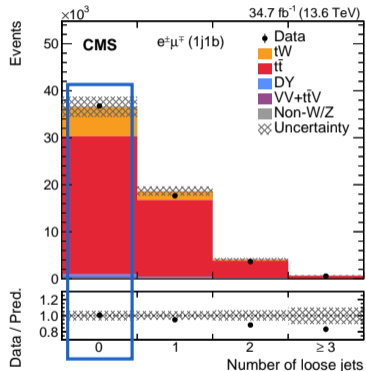
RFs in 1j1b, 2j1b



+  $p_T(j_2)$  in 2j2b

differential:

1j1b, veto add. low- $p_T$  jets



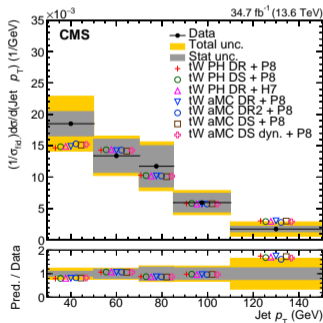
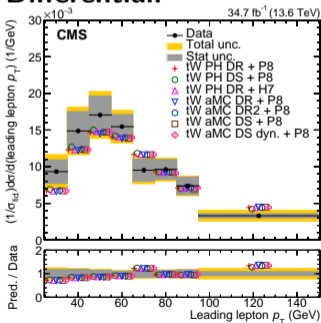
# Single-top tW: results

arXiv:2407.15594 [↗](#); arXiv:2409.06444 [↗](#)



**Inclusive:**      13 TeV      13.6 TeV  
 measured:  $75 \pm 15$  pb     $82 \pm 11$  pb  
 SM:  $79 \pm 3$  pb       $88 \pm 3$  pb

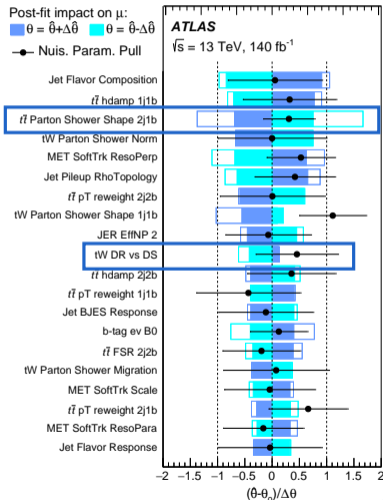
## Differential:



Pre-fit impact on  $\mu$ :  
 $\theta = \hat{\theta} + \Delta\theta$      $\theta = \hat{\theta} - \Delta\theta$      $\Delta\mu$     .15   -.1   -.05   0   .05   .1   .15

Post-fit impact on  $\mu$ :  
 $\theta = \hat{\theta} + \Delta\hat{\theta}$      $\theta = \hat{\theta} - \Delta\hat{\theta}$

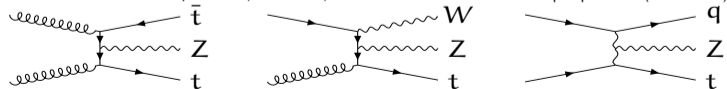
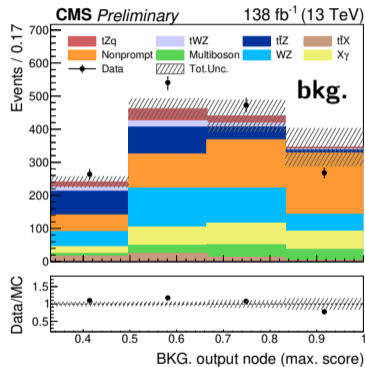
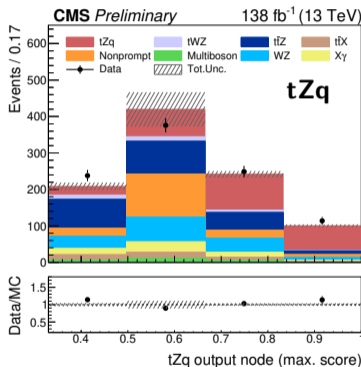
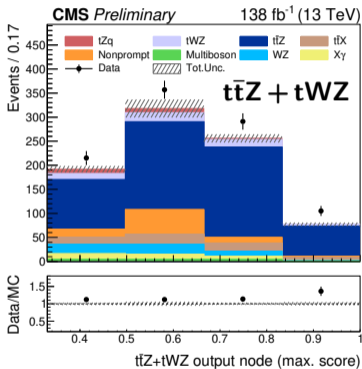
● Nuis. Param. Pull



# Top quark(s) + vector boson(s): $t\bar{t}Z + tWZ + tZq$

CMS-PAS-TOP-23-004

main event selection:  $=3\ell, 1 \text{ OSSF on-Z}, \geq 2j, \geq 1b$ ; split by multiclass DNN

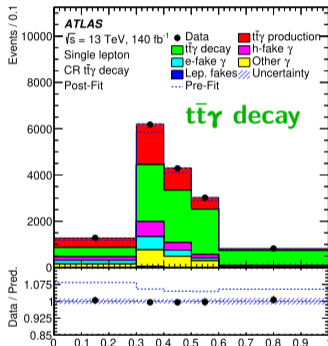
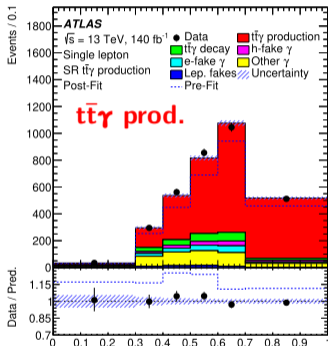


also:  $=4\ell$  region for inclusive cross section

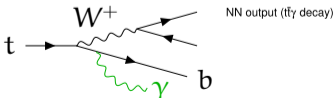
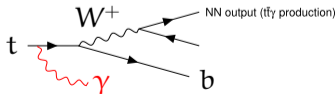
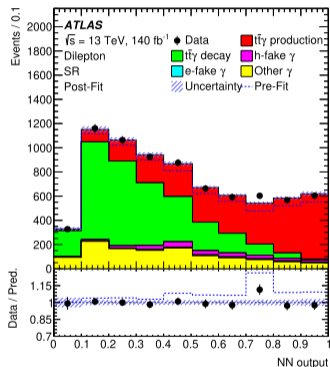
# Top quark(s) + vector boson(s): $t\bar{t}\gamma$

arXiv:2403.09452

$=1\gamma, =1\ell, \geq 4j, \geq 1b$ ; split by multiclass NN



$=1\gamma, =2\ell, \geq 2j, \geq 1b$



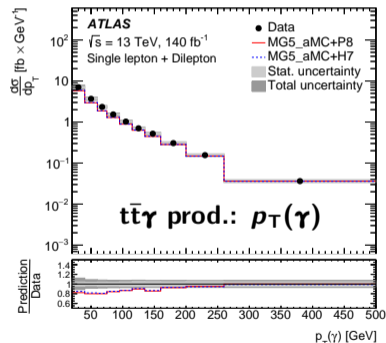
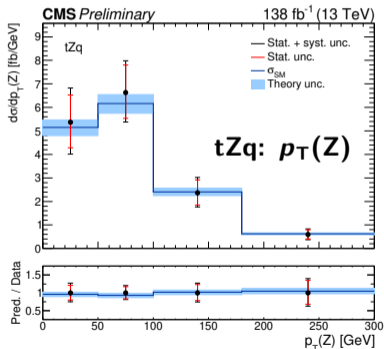
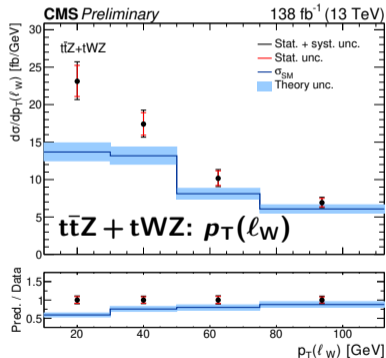
# Top quark(s) + vector boson(s): Results

CMS-PAS-TOP-23-004 [↗](#); arXiv:2403.09452 [↗](#)



**Inclusive:**  $t\bar{t}Z + tWZ$ :  $1140 \pm 64$  fb     $tZq$ :  $810 \pm 92$  fb     $t\bar{t}\gamma$  prod.:  $322 \pm 16$  fb  
 SM:  $840 \pm 100$  fb    SM:  $820 \pm 50$  fb    SM:  $299 \pm 30$  fb

## Differential:

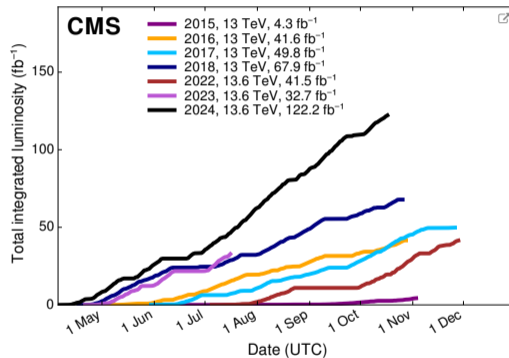


large statistical uncertainties








also: prod. + decay;  
per channel

# Summary








- exciting top quark physics programme at the LHC
  - using all energies and collision systems
  - covering wide range of top quark production processes
- several recent ATLAS & CMS highlights shown today
- many more topics omitted, e.g.:
  - precision measurements of mass and other properties
  - EFT interpretations
  - new-physics signatures with top quarks
- many more results with new Run-3 data in preparation



# ATLAS references

-  Observation of quantum entanglement in top-quark pairs using the ATLAS detector, Nature 633 (2024) 542 [↗](#)
-  Measurement of differential cross-sections in  $t\bar{t}$  and  $t\bar{t}$ +jets production in the lepton+jets final state in pp collisions at  $\sqrt{s} = 13$  TeV using  $140 \text{ fb}^{-1}$  of ATLAS data, JHEP 08 (2024) 182 [↗](#)
-  Measurements of inclusive and differential cross-sections of  $t\bar{t}\gamma$  production in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, arXiv:2403.09452 [↗](#), submitted to JHEP
-  Observation of  $t\bar{t}$  production in the lepton+jets and dilepton channels in p+Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV with the ATLAS detector, arXiv:2405.05078 [↗](#), submitted to JHEP
-  Measurement of  $t\bar{t}$  production in association with additional b-jets in the  $e\mu$  final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, arXiv:2407.13473 [↗](#), submitted to JHEP
-  Measurement of single top-quark production in association with a W boson in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, arXiv:2407.15594 [↗](#), submitted to Phys. Rev. D
-  Measurement of top-quark pair production in association with charm quarks in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, arXiv:2409.11305 [↗](#), submitted to Phys. Lett. B

# CMS references

-  Observation of quantum entanglement in top quark pair production in proton-proton collisions at  $\sqrt{s} = 13$  TeV, arXiv:2406.03976 [↗](#), accepted by Rep. Prog. Phys.
-  Measurement of inclusive and differential cross sections of single top quark production in association with a W boson in proton-proton collisions at  $\sqrt{s} = 13.6$  TeV, arXiv:2409.06444 [↗](#), submitted to JHEP
-  Measurements of polarization and spin correlation and observation of entanglement in top quark pairs using lepton+jets events from proton-proton collisions at  $\sqrt{s} = 13$  TeV, arXiv:2409.11067 [↗](#), submitted to Phys. Rev. D
-  Inclusive and differential measurement of top quark cross sections in association with a Z boson, CMS-PAS-TOP-23-004 [↗](#)
-  Measurement of the inclusive  $t\bar{t}$  cross section in final states with one lepton and additional jets at 5.02 TeV with 2017 data, CMS-PAS-TOP-23-005 [↗](#)
-  Measurement of the dineutrino system kinematics in dileptonic top quark pair events in pp collisions at  $\sqrt{s} = 13$  TeV, CMS-PAS-TOP-24-001 [↗](#)
-  Search for heavy pseudoscalar and scalar bosons decaying to top quark pairs in proton-proton collisions at  $\sqrt{s} = 13$  TeV, CMS-PAS-HIG-22-013 [↗](#)