Top quark measurements and Quantum entanglement

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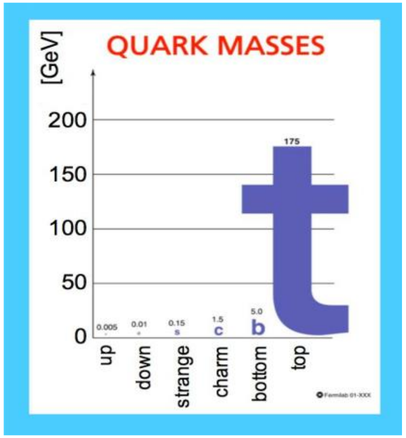
top-quark

- ➢ Top quark is the most massive known fundamental particle
- ➢ Top quark is extremely short lived



$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}s}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{decay}\\ 10^{-25}s}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}s}} < \underbrace{\frac{m_t}{\Lambda_{QCD}}}_{\substack{\text{spin-flip}\\ 10^{-21}s}}$$

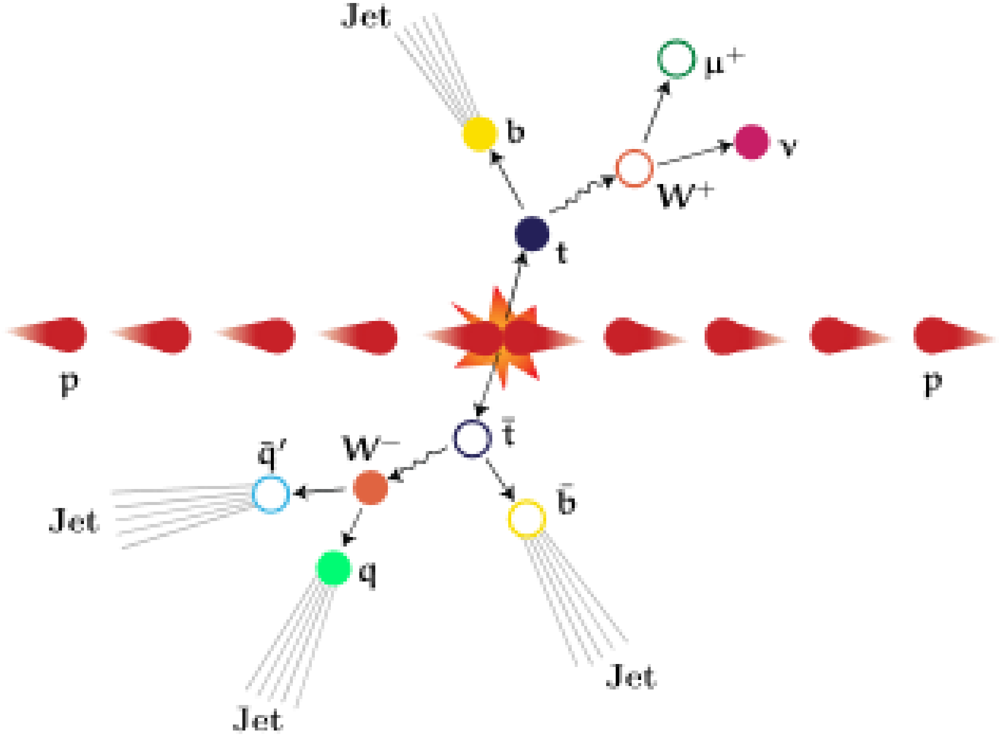
✓ Decays before hadronization & spin decorrelation
-- Give access to the physics of a "free" quark

✓ The decay preserves the spin information in the angular distribution of the decay products.

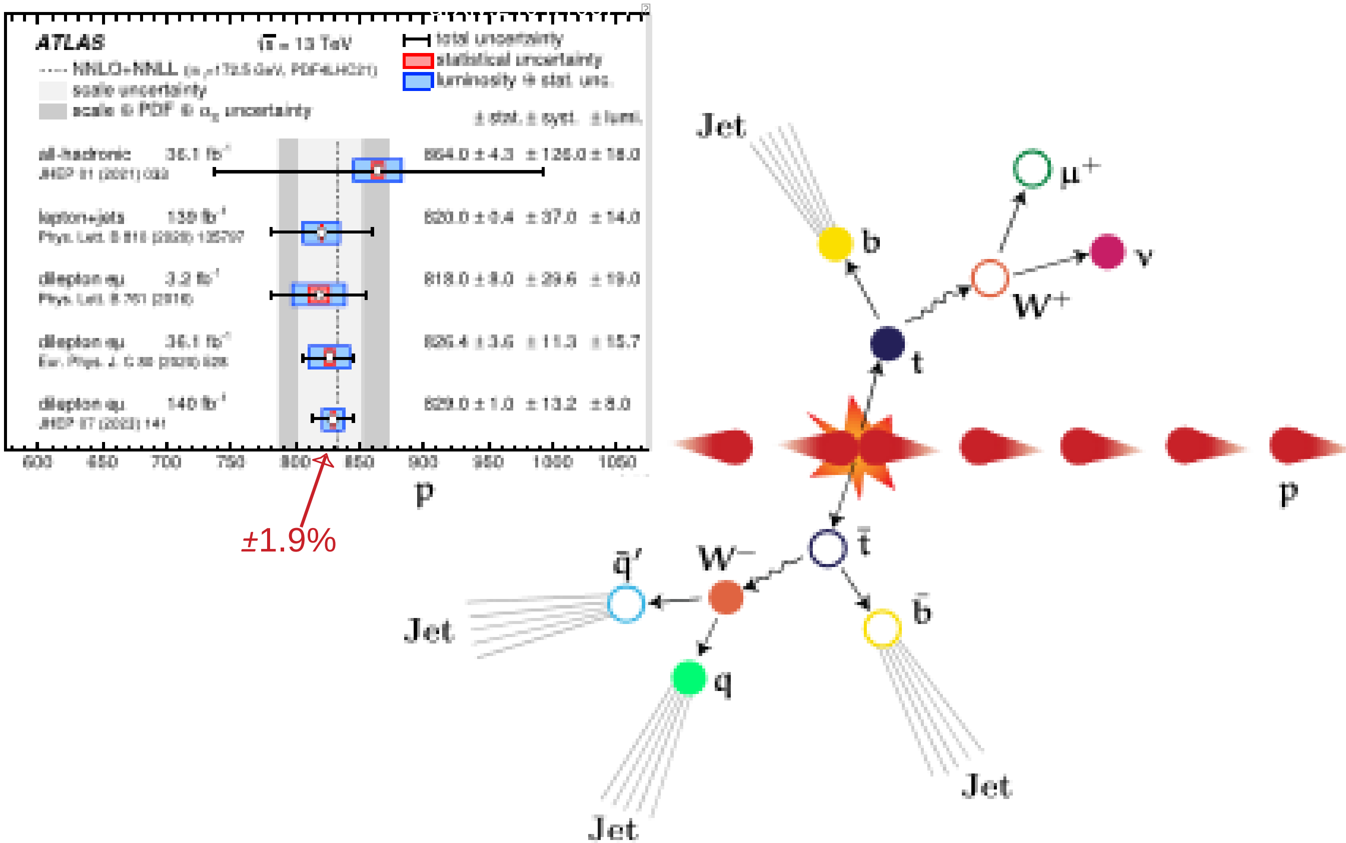
The LHC is a top factory and allows:

- ✓ Precise measurements of top pairs and single top production
- ✓ Observation of rare processes involving top
- ✓ To search for BSM physics
- ✓ Background to many rare SM and BSM processes
- ✓ Opportunity to test quantum information at colliders………

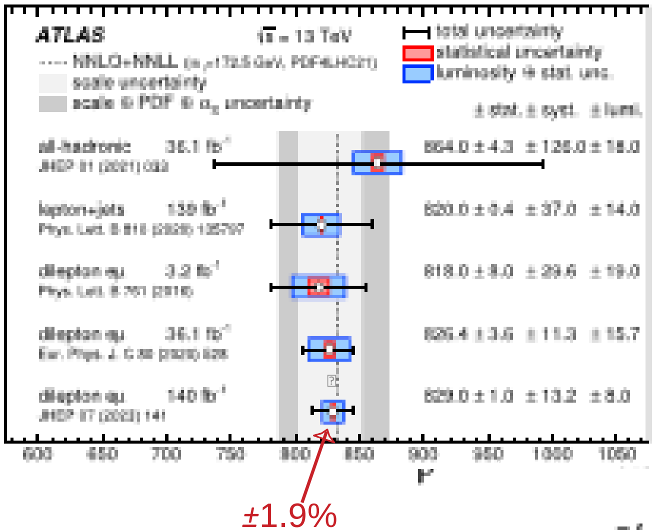
Top quark pair production

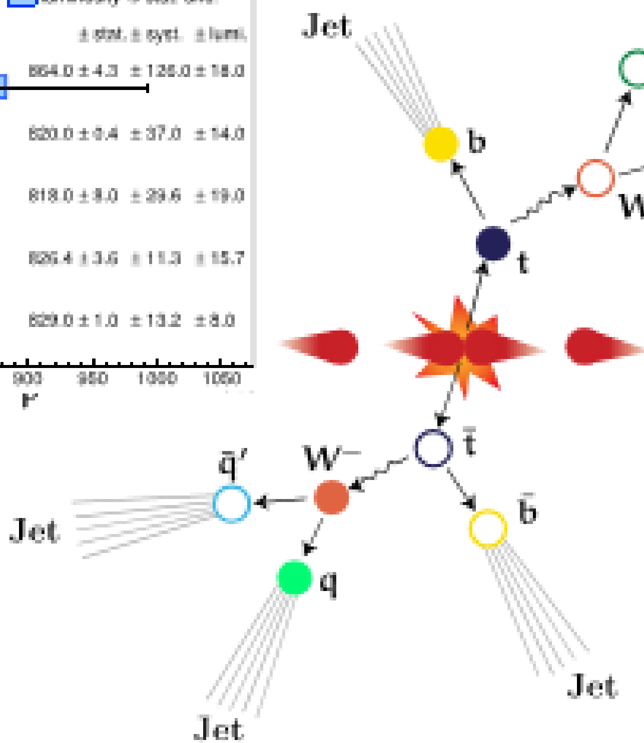


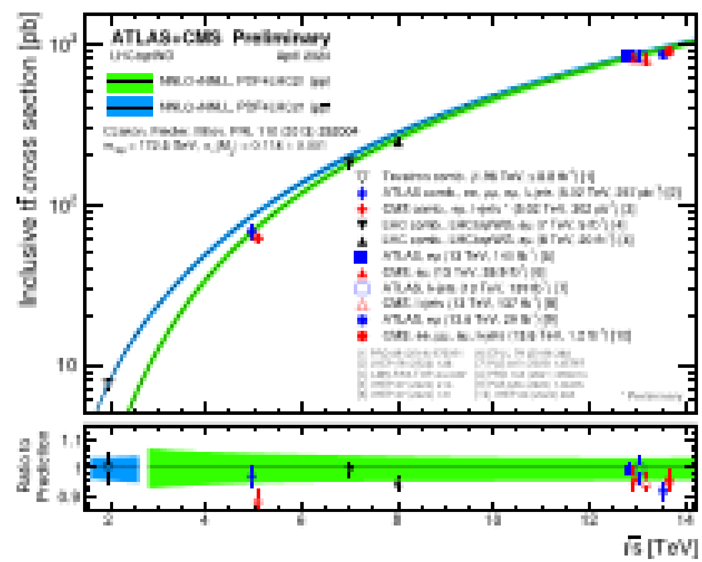
Top quark pair production



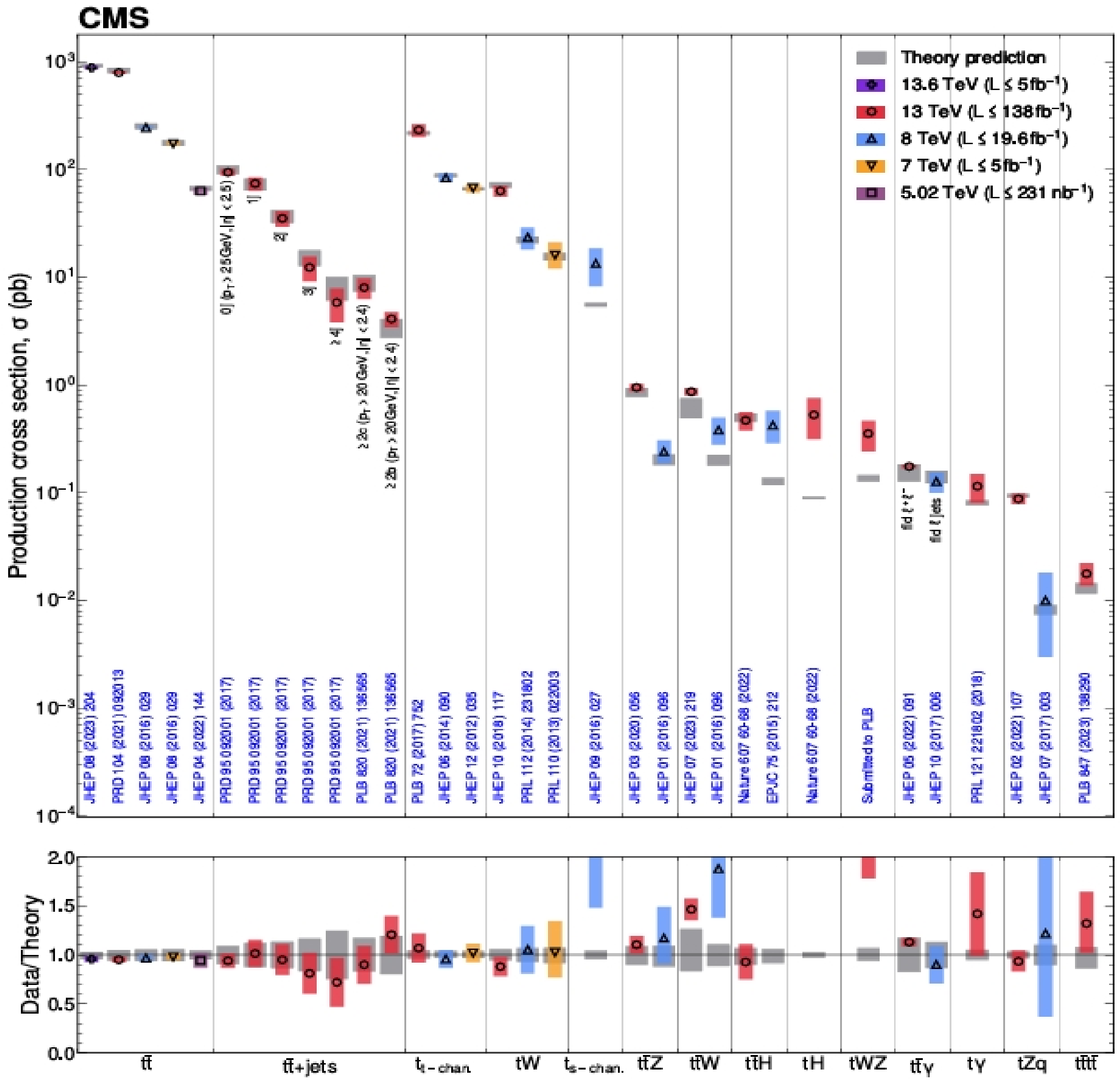
Top quark pair production



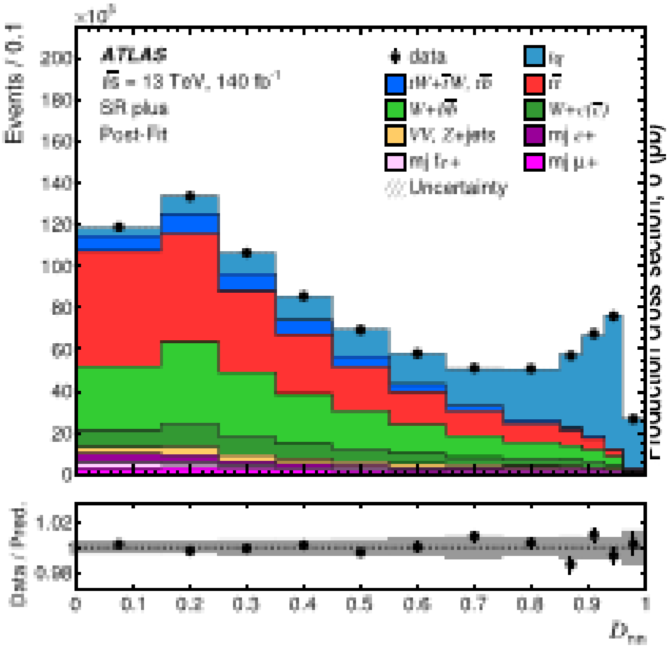


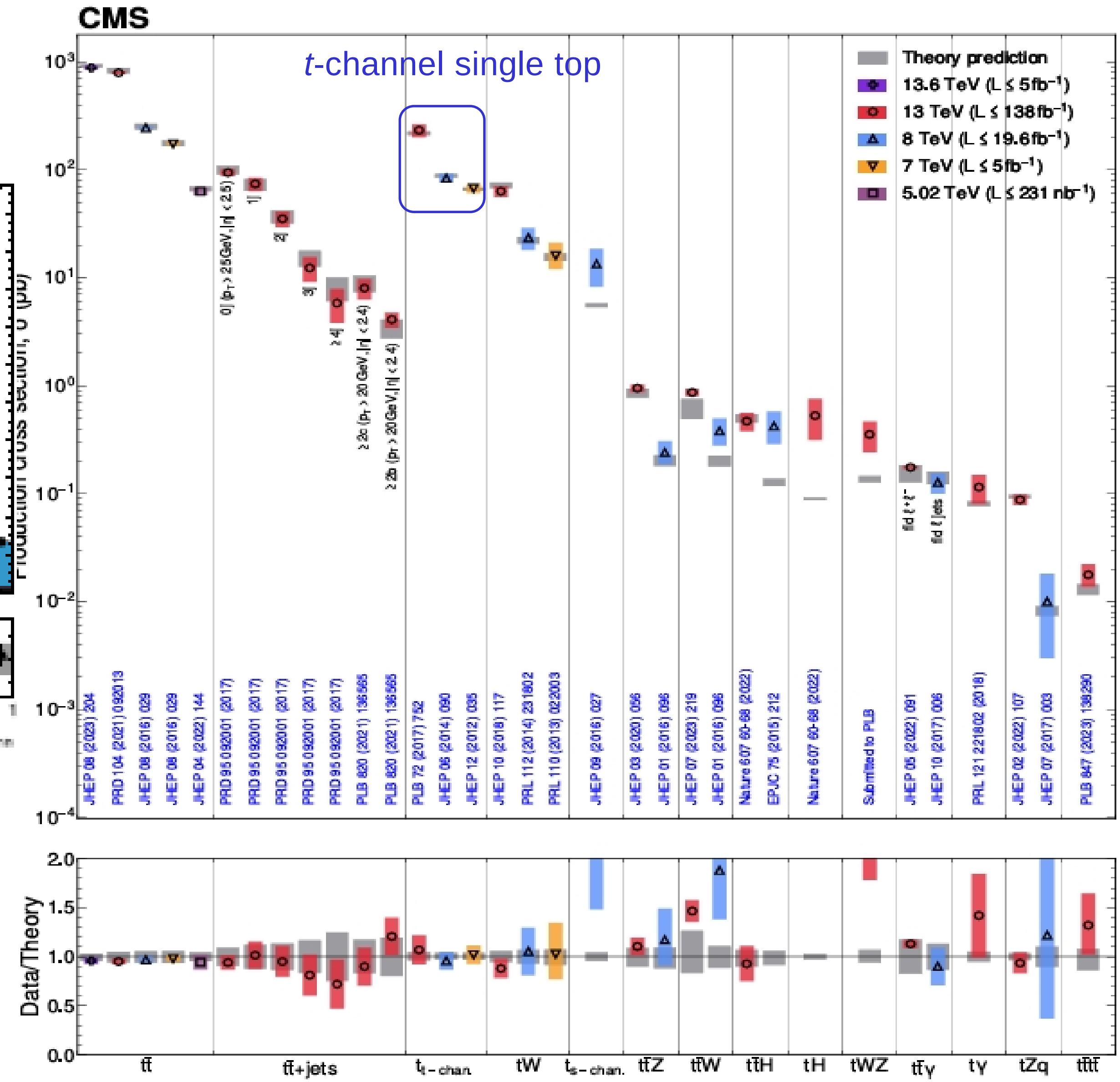


From tt to tttt

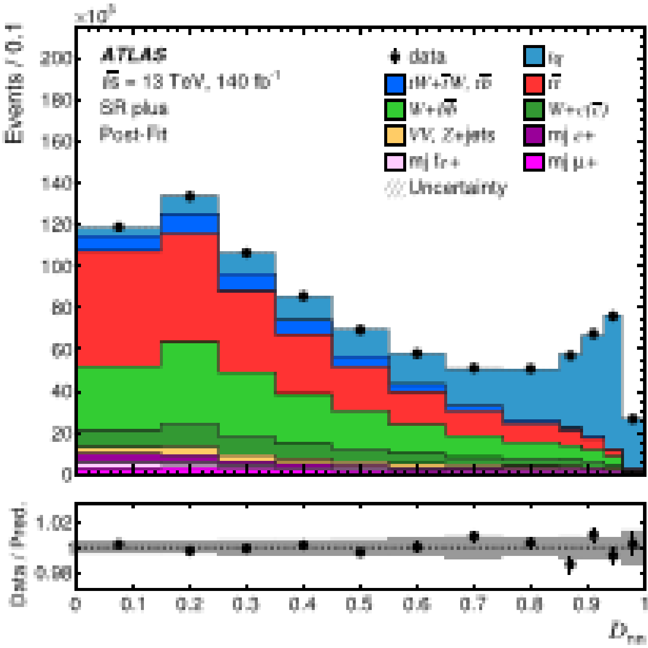


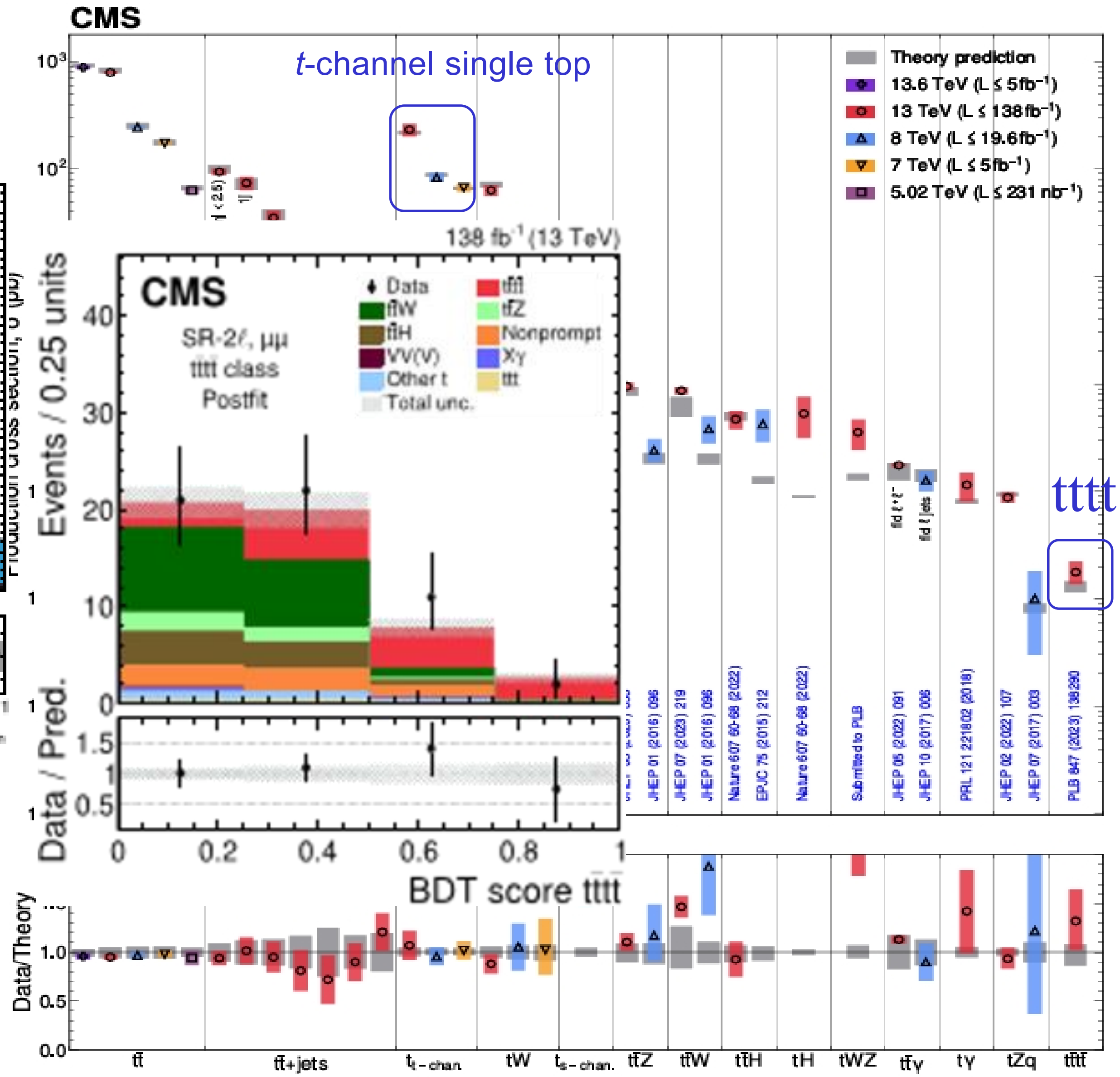
From tt to tttt





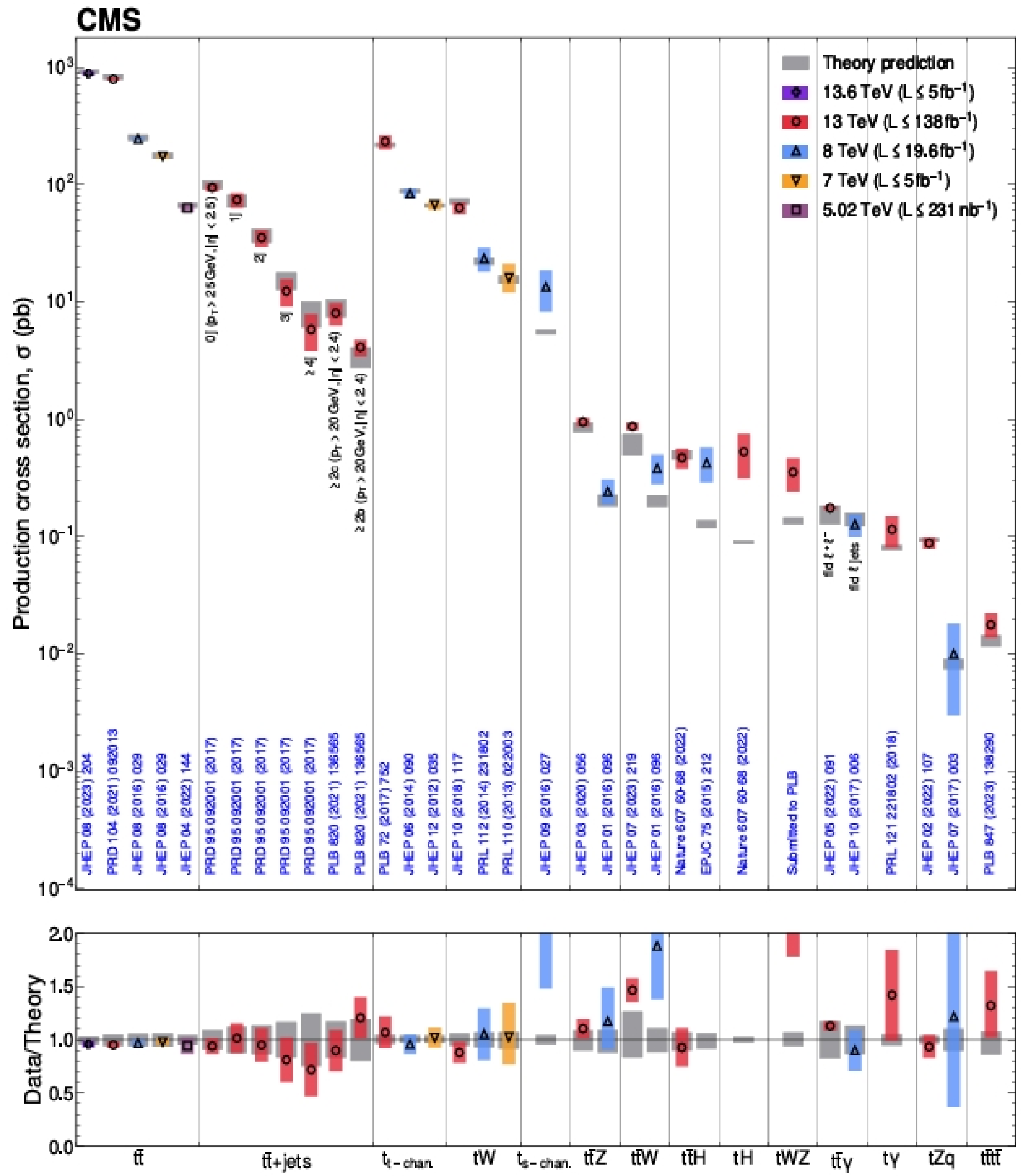
From tt to tttt





Highlights today

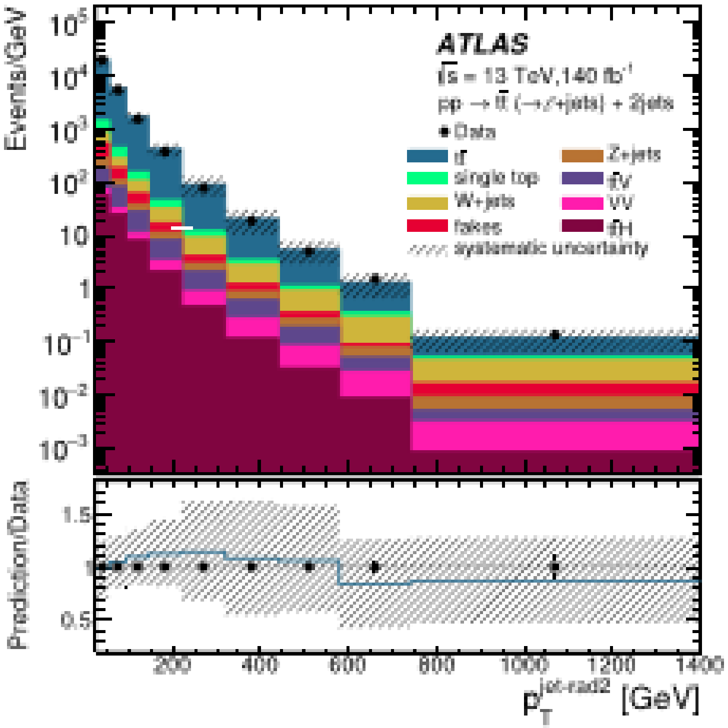
- ✓ differential tt
- ✓ tt in HI collisions
- ✓ tt + heavy flavour
- ✓ single-top tW
- ✓ top quark(s) + vector boson(s)
- ✓ entanglement in tt



Only a selection of recent LHC results with personal and potentially biased

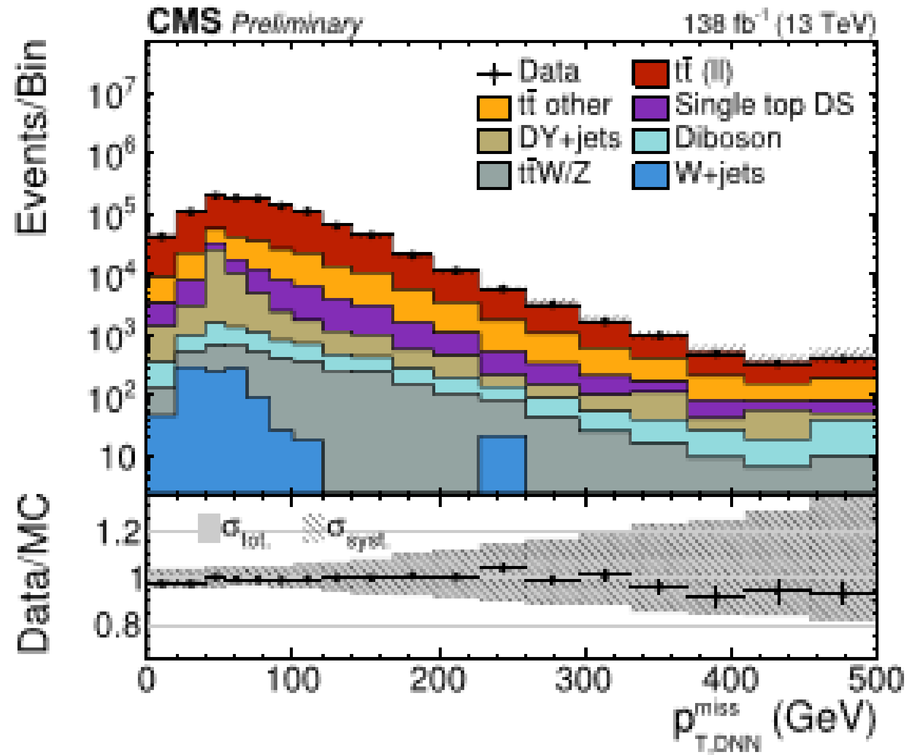
Differential tt

JHEP 08 (2024) 182



- tt + 2j: =1L, >=6j, >=2b
- Also tt + incl, tt + 1j
- ~8% bkg

CMS-PAS-TOP-24-001

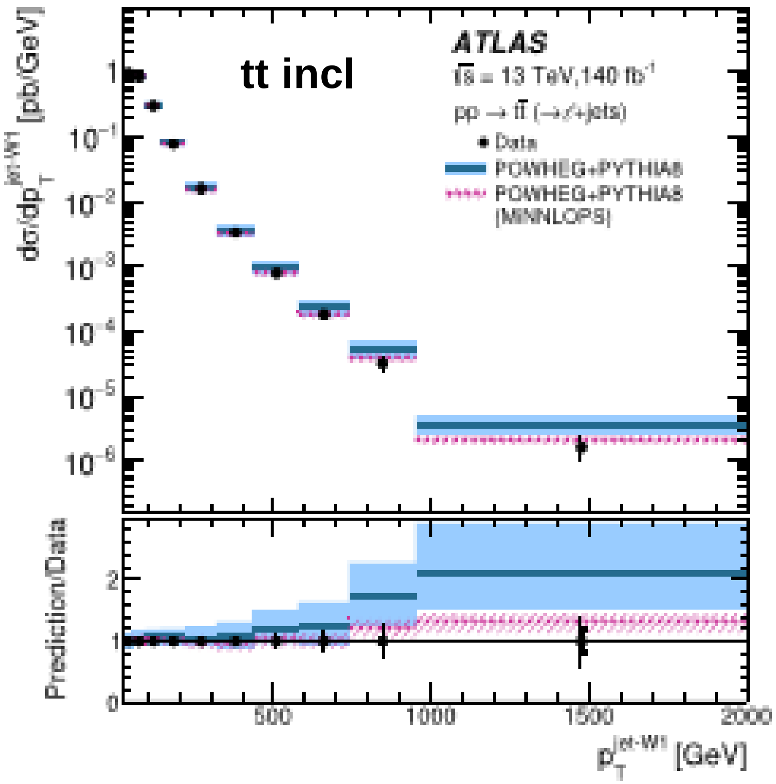


- =2L, >=2j, >=1b
- DNN improved miss Pt
- ~22% bkg

Differential : lepton+jets results

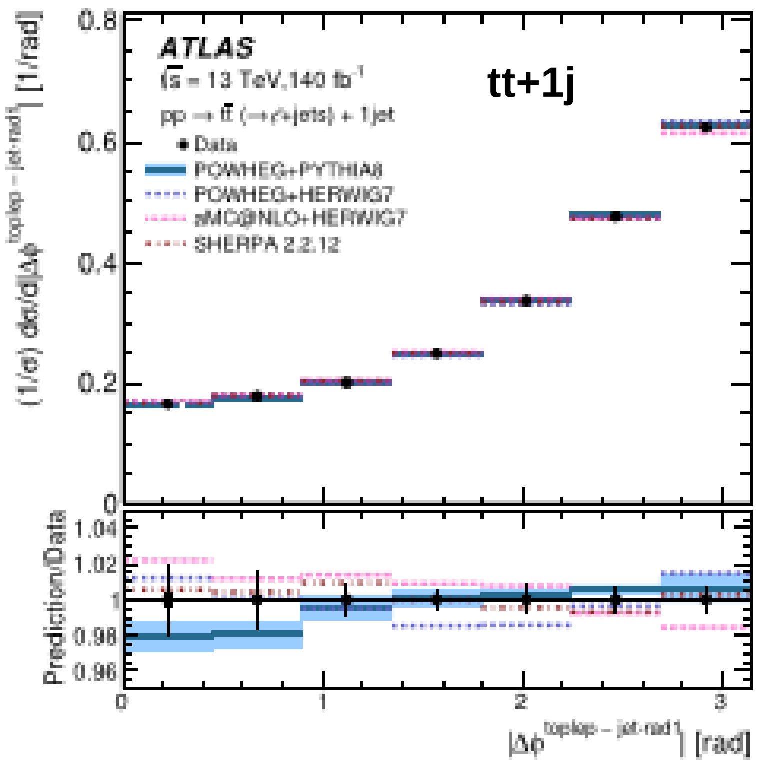
JHEP 08 (2024) 182

pT(lead. W jet)



well described by MiNNLOPS

Δφ(toplep, add. jet)

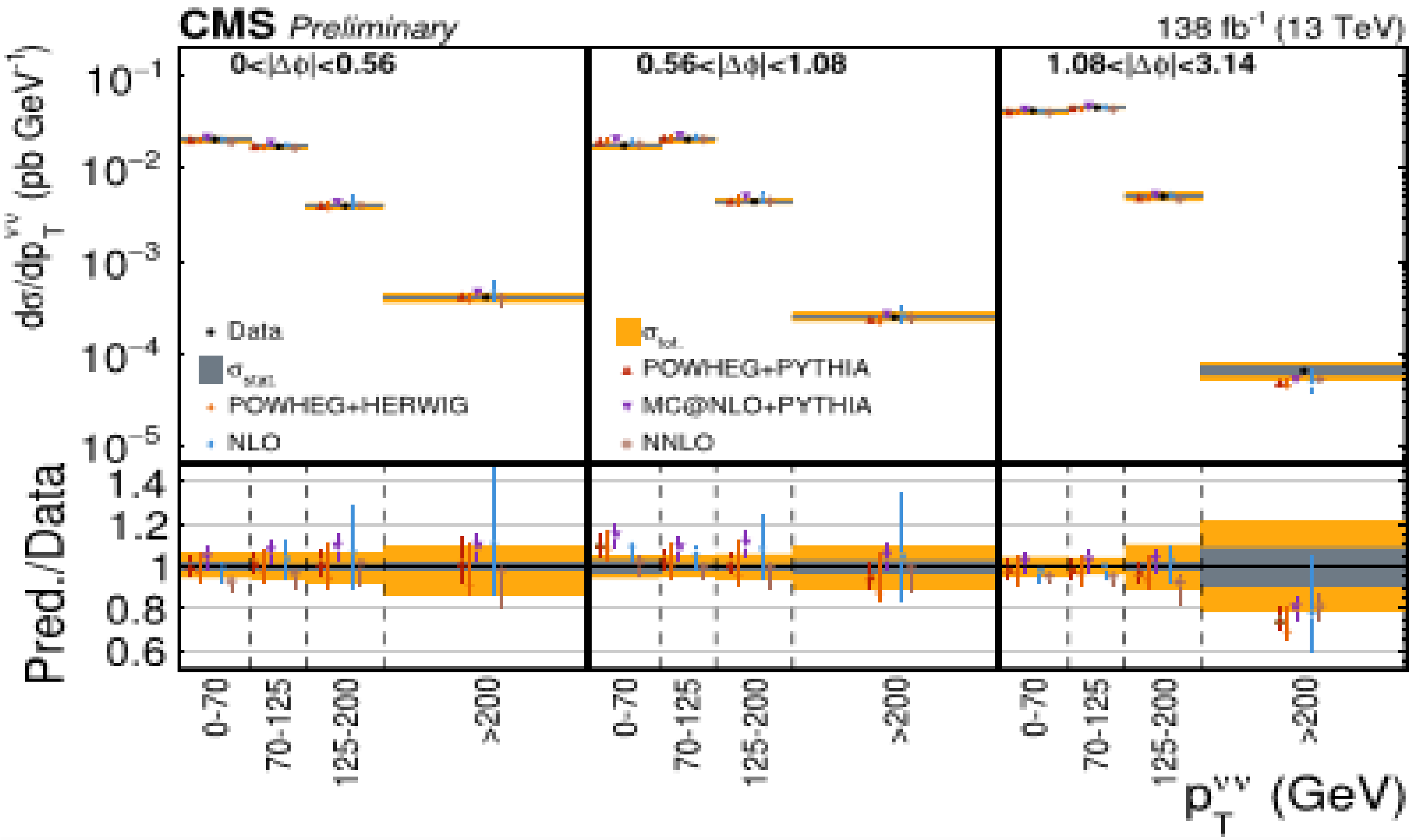


best described by SHERPA

Differential tt: dilepton results

CMS-PAS-TOP-24-001

$p_T(\nu\nu)$ X min $\Delta\varphi(\nu\nu, l)$



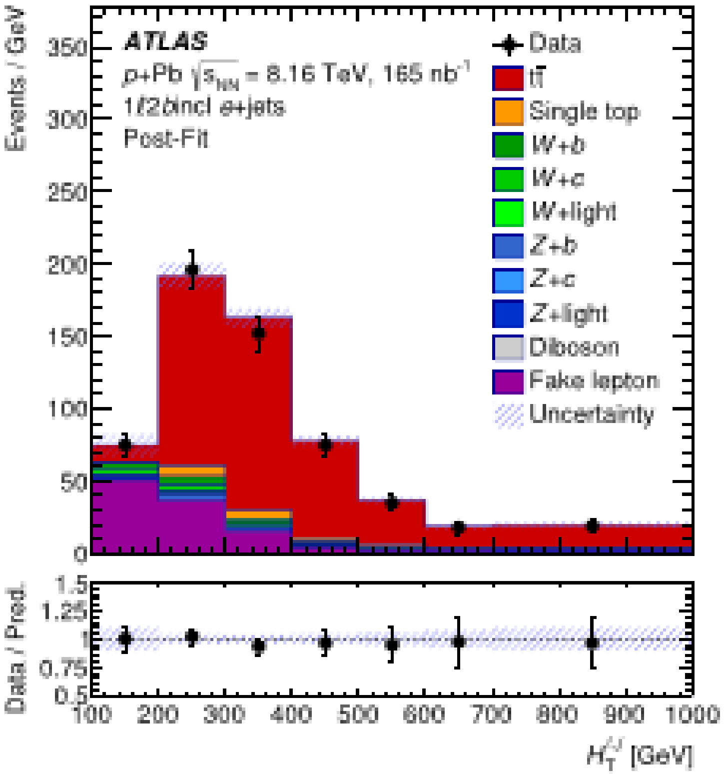
✓ **best described by NNLO pred.**

JHEP 05 (2021) 212

tt in heavy-ion collisions: pPb analysis

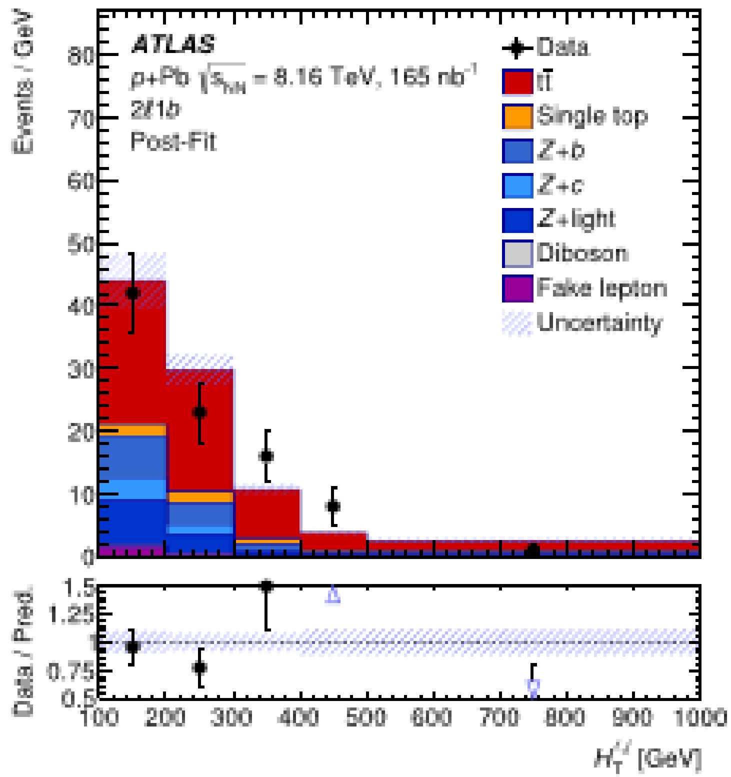
arXiv:2405.05078

1e, ≥4j, ≥2b



also:
=1e, =1b
=1μ, =1b
=1μ, ≥2b
=2L, ≥2b

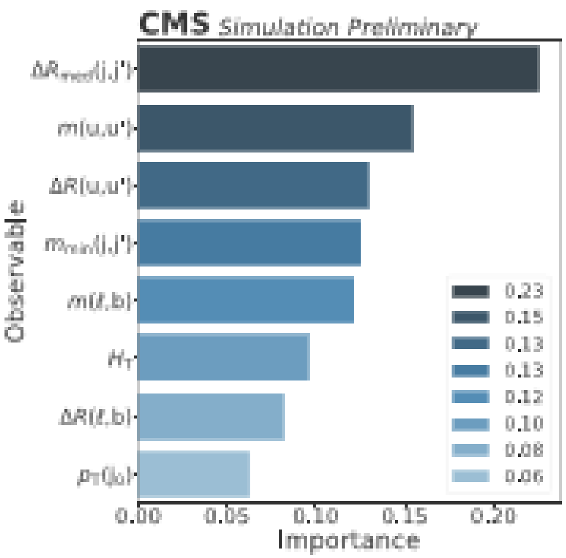
2*L*, ≥2j, =1b



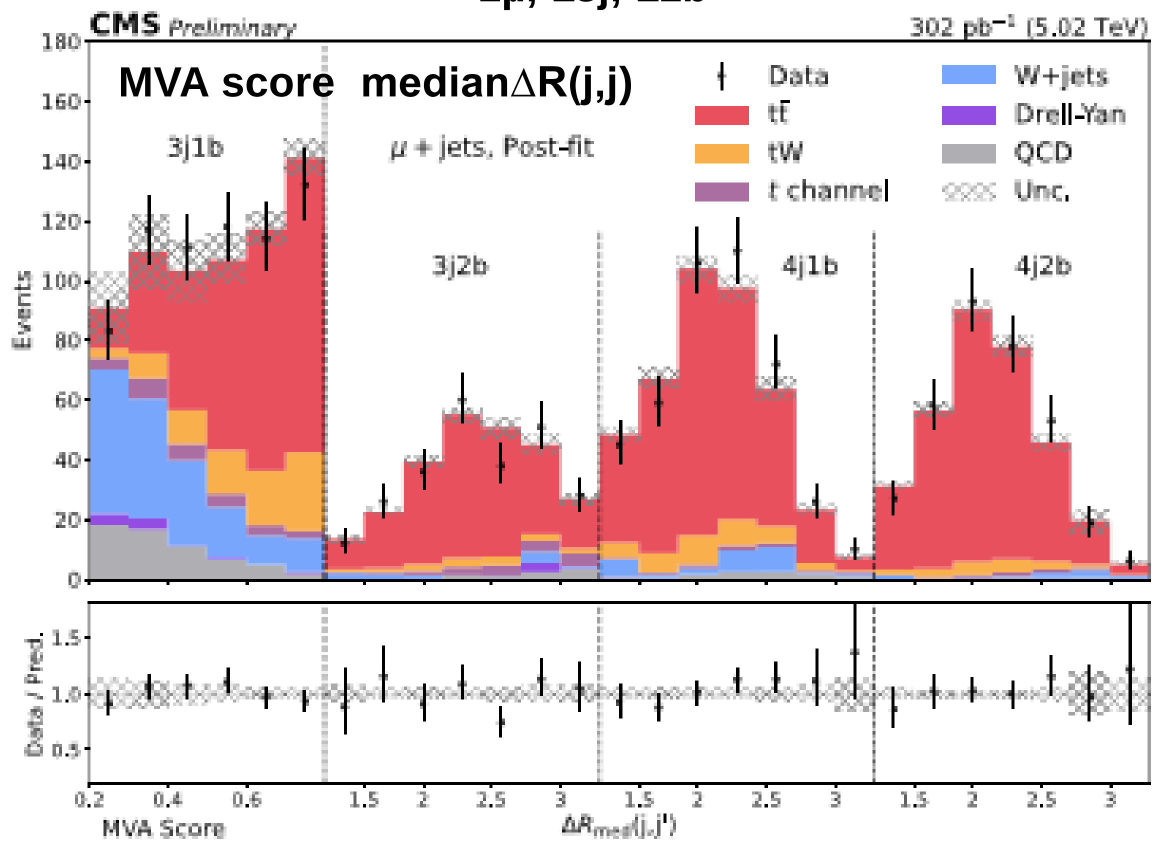
- ✓ **Combining the lepton + jets and dileptonic channel**
- ✓ **Binned in H_T of leptons & jets**

CMS-PAS-TOP-23-005

MVA in =3j, =1b trained with:



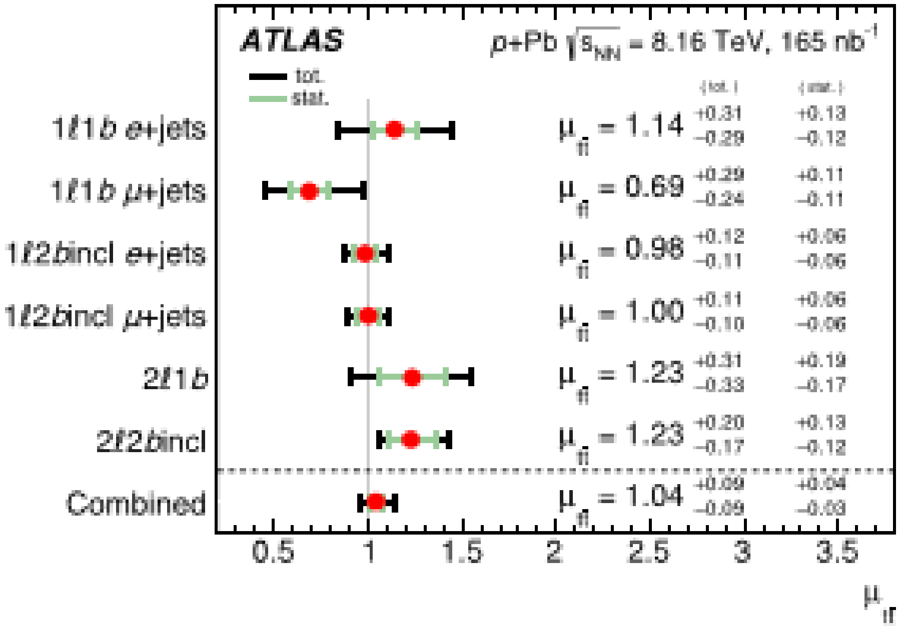
1μ, ≥3j, ≥1b

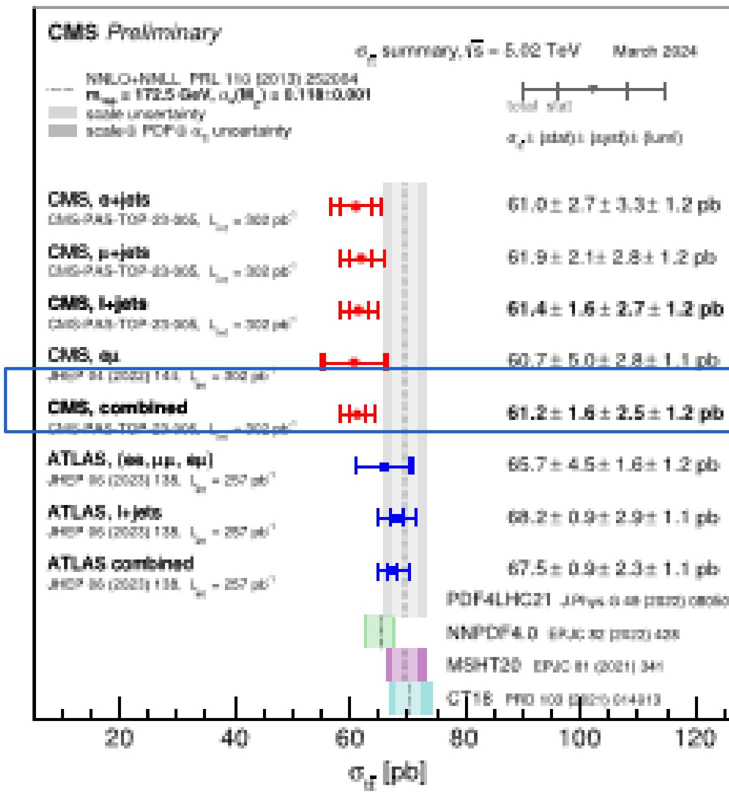


also e+jets

tt in heavy-ion collisions: results

first observation of dileptonic tt in pPb





Observed significance > 5 SD

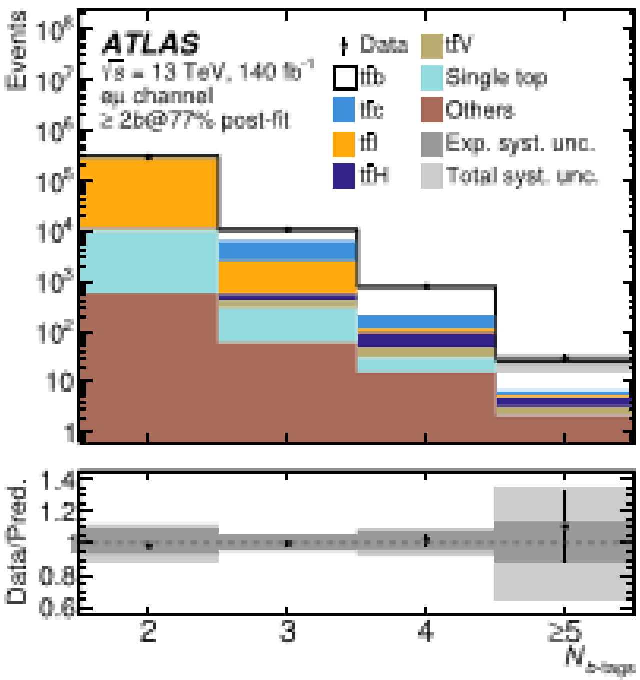
σ(tt)=58.1±5.1nb

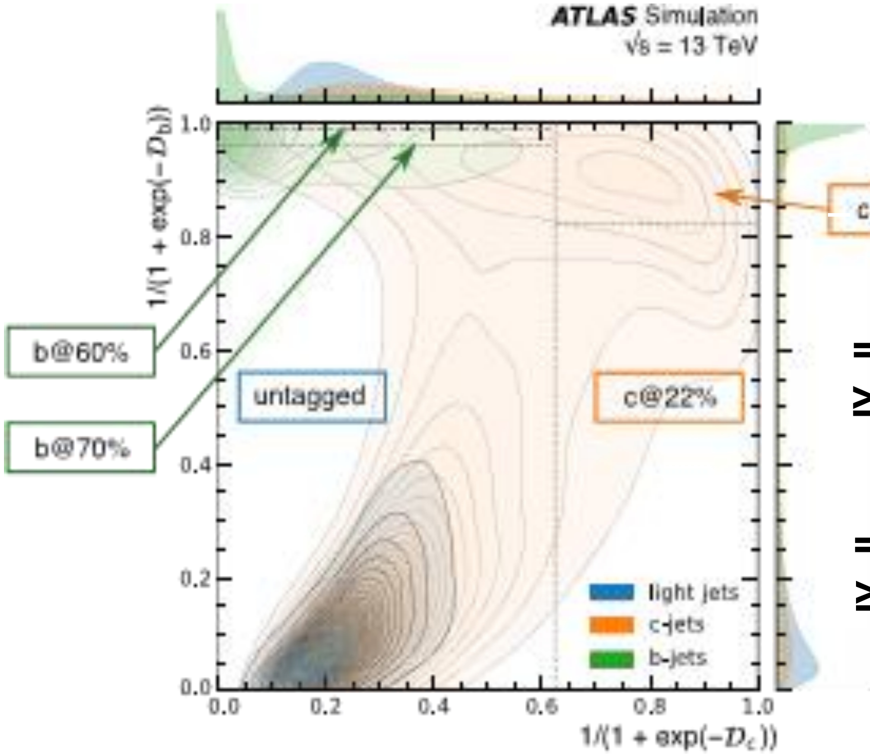
Agreement with prediction

tt + heavy flavour

- ✓ tt + heavy-flavor jets is a main background in
  - -- important SM process measurements (tt̄H and four-tops)
  - -- many BSM searches (vector-like quarks, SUSY…)
- ✓ Considered events with one or two charged lepton in the final states.

tt+b: =1e, =1μ, ≥2j, ≥2b





tt+c:
=1L, ≥5j, ≥3b/c

or

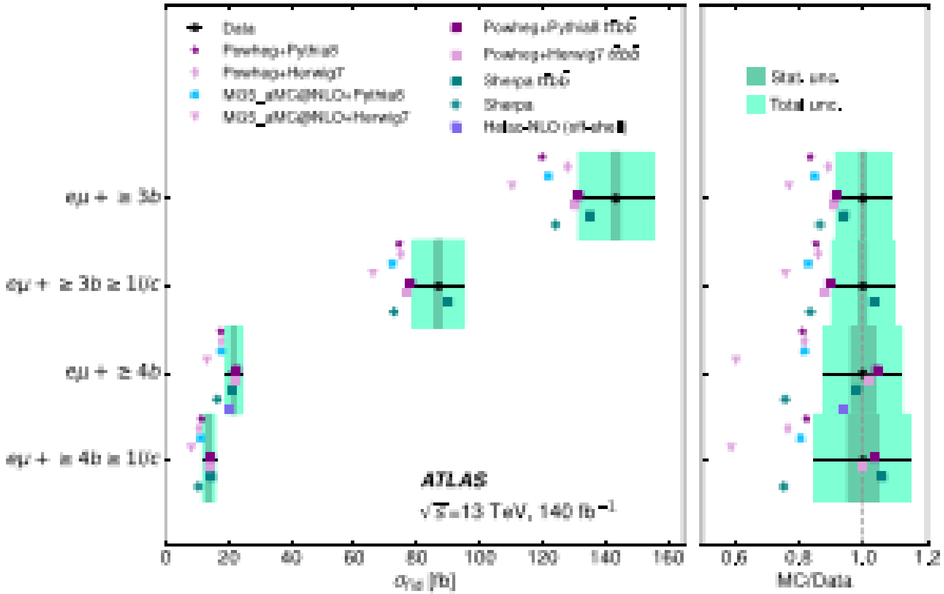
=2L, ≥3j, ≥2b/c

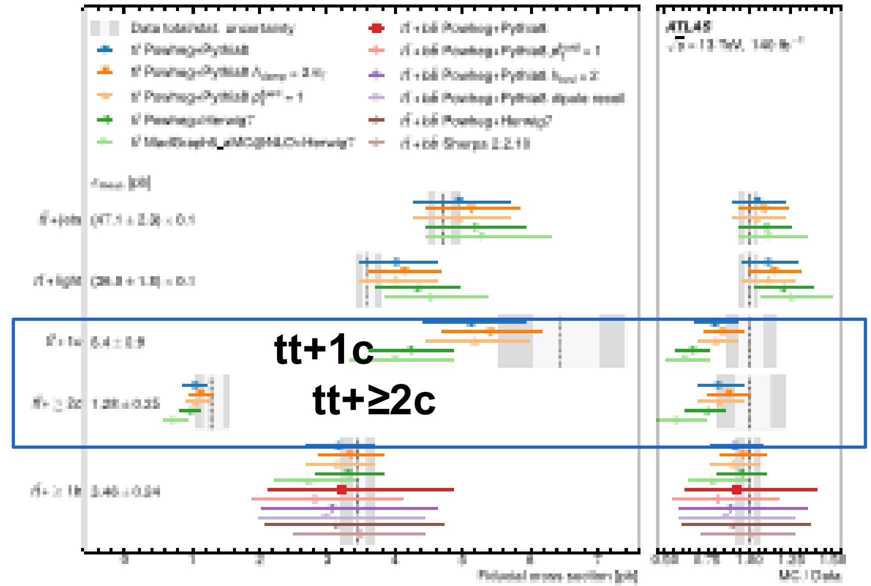
arXiv:2407.13473, arXiv:2409.11305

tt+heavy flavour: inclusive results

arXiv:2407.13473, arXiv:2409.11305

tt+b



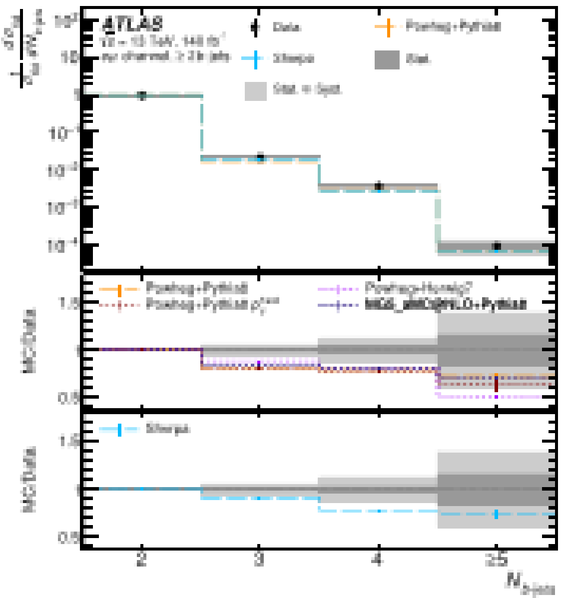


tt+b best described by SHERPA ttbb

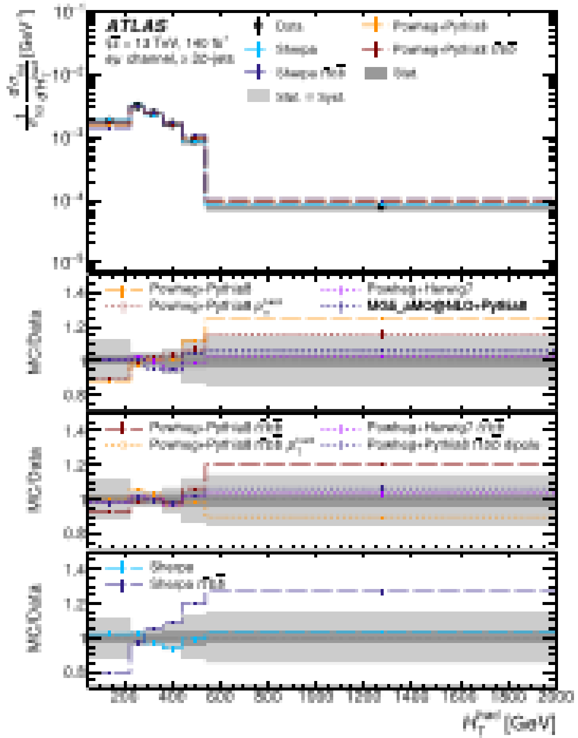
tt+c slightly underpredicted by NLO+PS

tt+heavy flavour: differential tt+b results

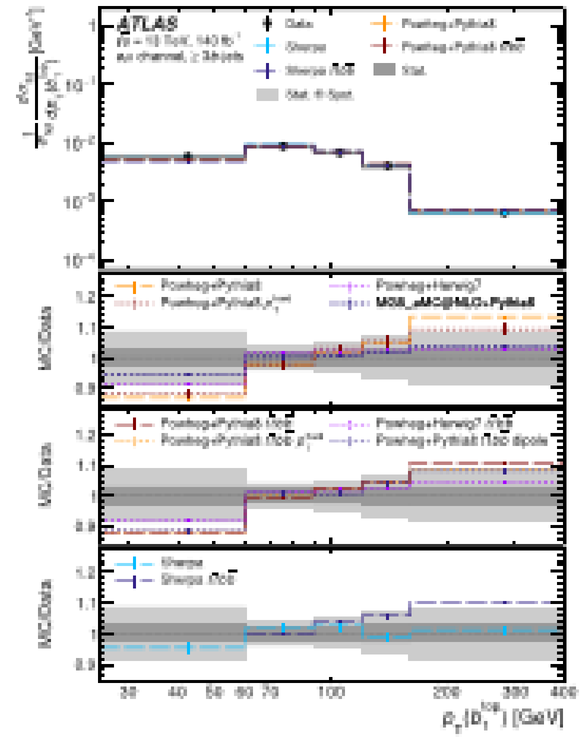
number of b jets



***H_T* of jets**



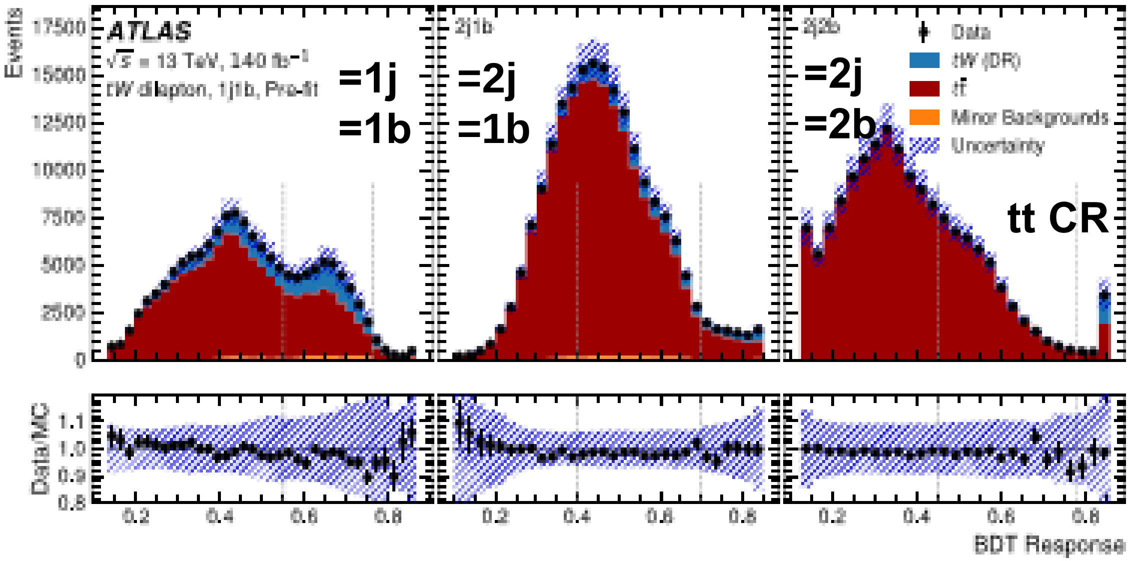
***p_T* of b jet from top**

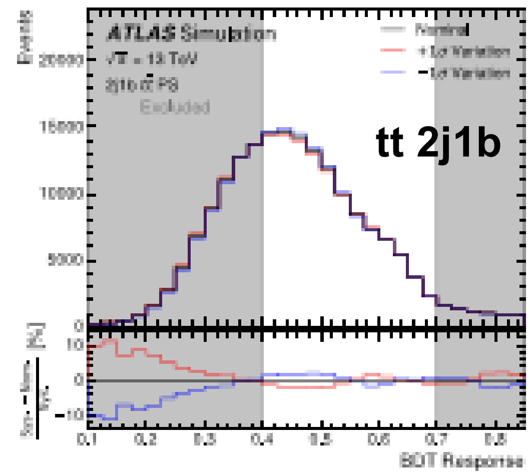


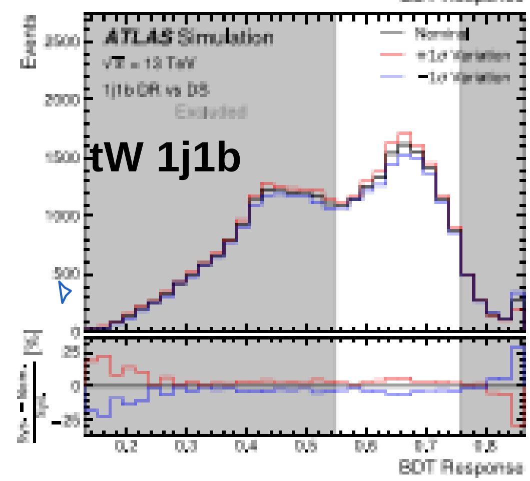
Single-top tW at 13TeV

arXiv:2407.15594

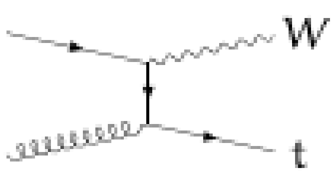
1e, =1μ, ≥1j, ≥1b

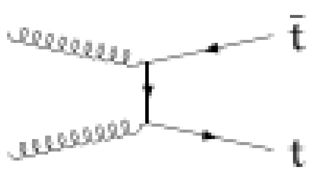






BDT tW vs. tt per region

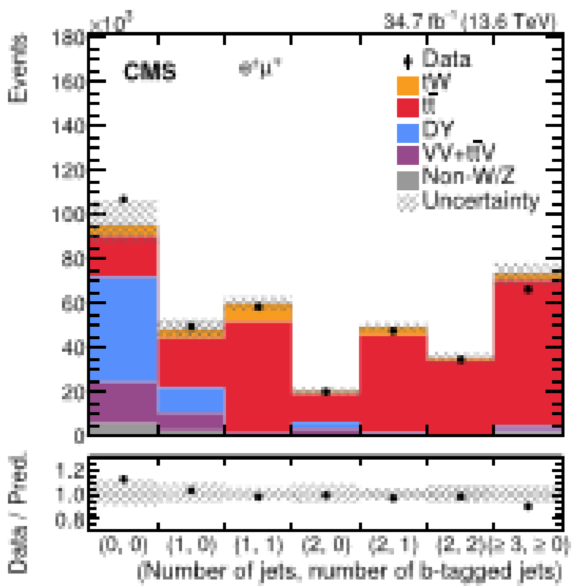




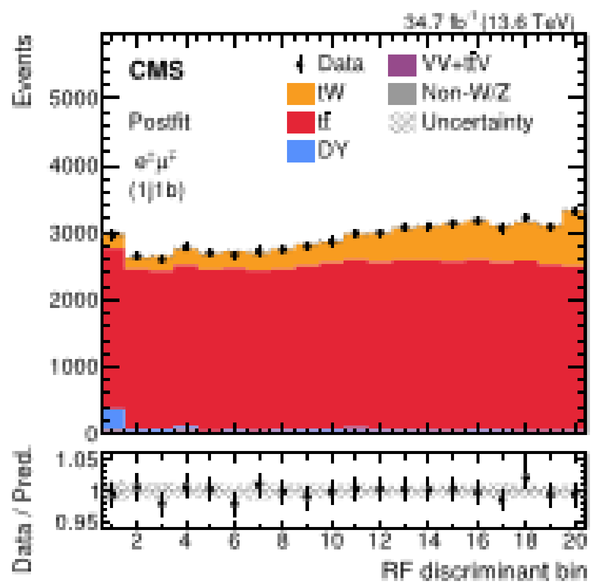
Single-top tW at 13.6TeV

arXiv:2409.06444

≥1e, ≥1μ

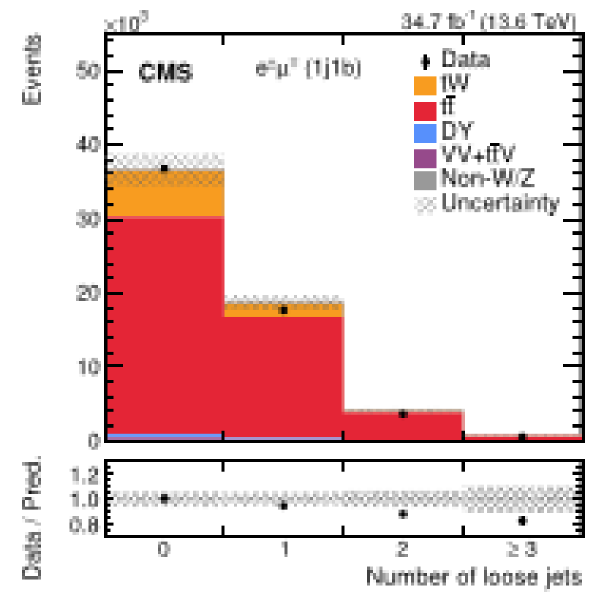


inclusive:
RFs in 1j1b, 2j1b



+ $p_T(j_2)$ in 2j2b

differential:
1j1b, veto add. low-pT jets



Single-top tW: results

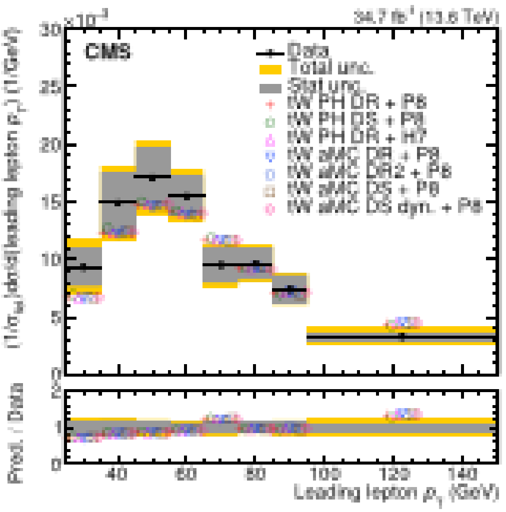
arXiv:2407.15594 ; arXiv:2409.06444

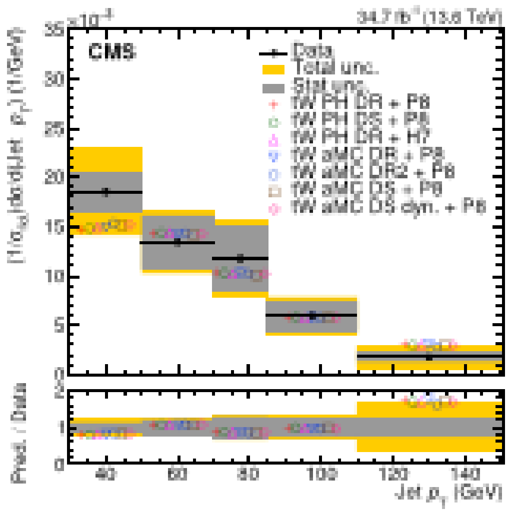
Inclusive: **13TeV** **13.6TeV**

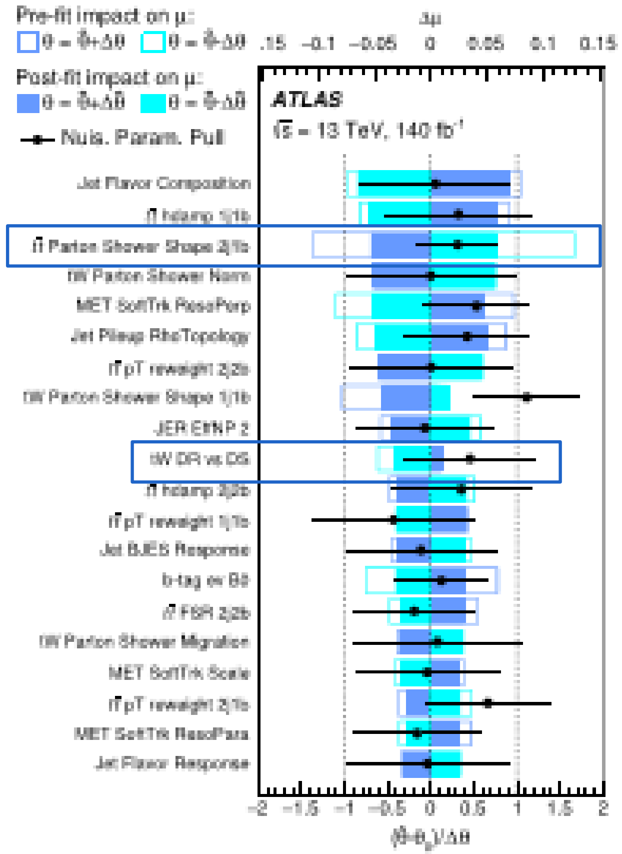
Measurement: 75±15 pb 82±11 pb

SM: 79± 3 pb 88± 3 pb

Differential:





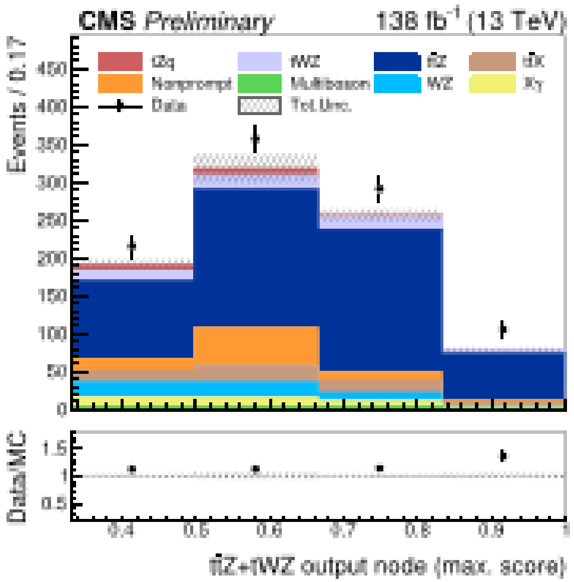


Top quark(s)+vector boson(s): ttZ+tWZ+tZq

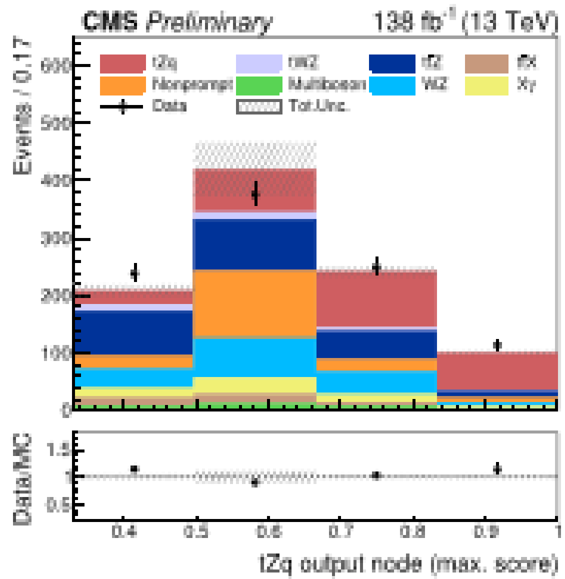
CMS-PAS-TOP-23-004

- ✓ **main event selection: =3*L*, 1 OSSF on-Z, ≥2j, ≥1b;**
- ✓ **split by multiclass DNN**

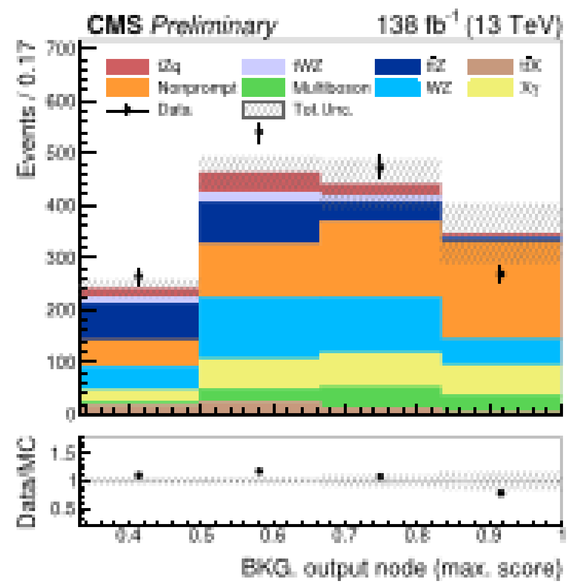
ttZ + tWZ

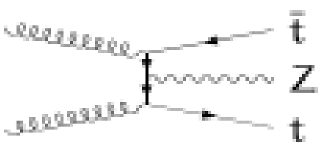


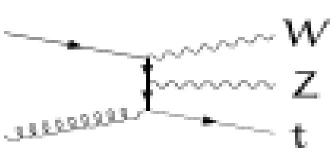
tZq

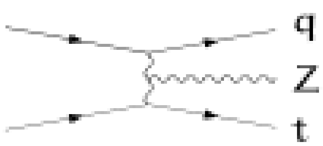


bkg.









also: =4*L* region for inclusive cross section

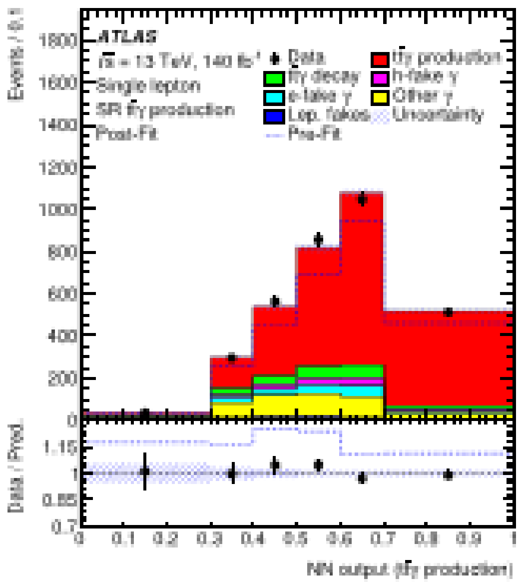
Top quark(s)+vector boson(s): $t\bar{t}\gamma$

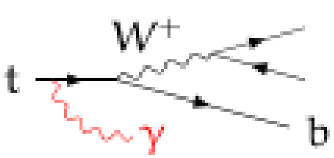
arXiv:2403.09452

- ✓ **=1γ, =1*L*, ≥4j,≥1b;**
- ✓ **split by multiclass NN**

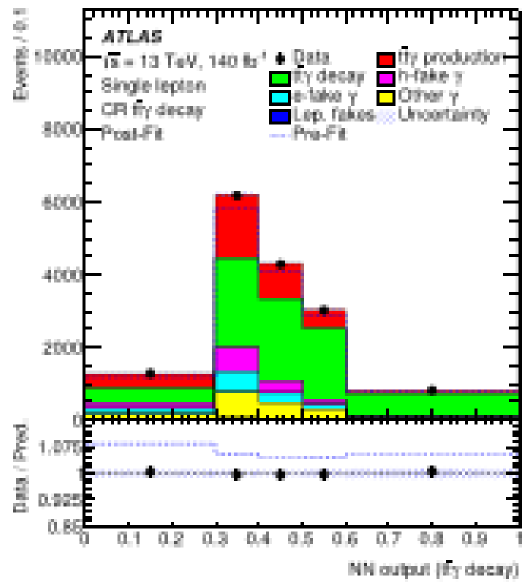
=1γ, =2*L*, ≥2j, ≥1b

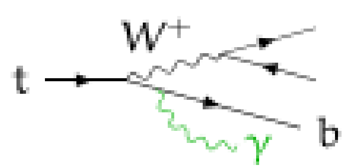
ttγ prod.

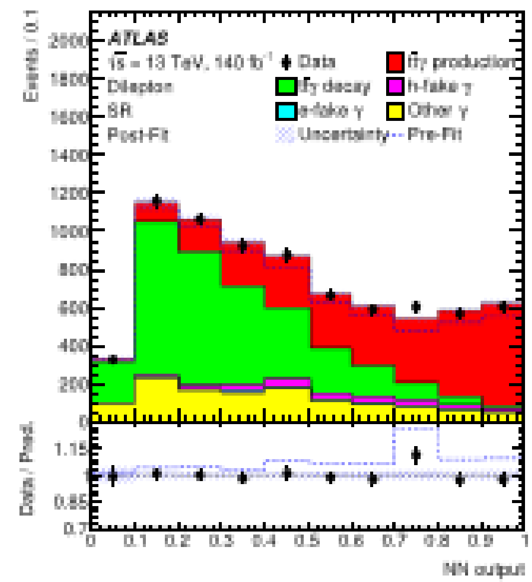




ttγ decay







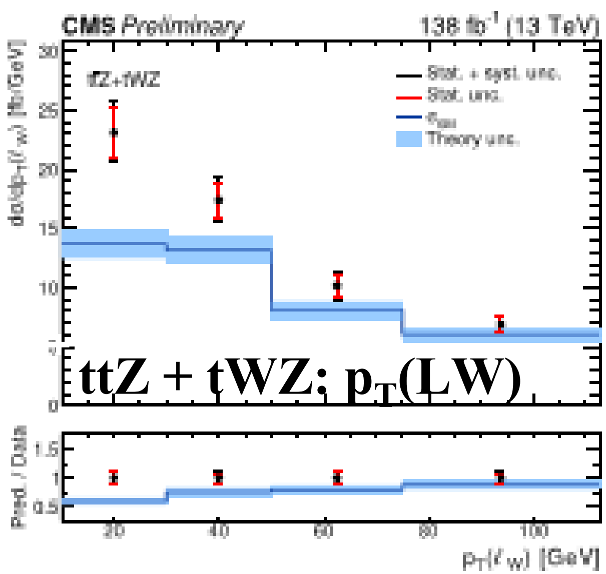
Top quark(s)+vector boson(s): Results

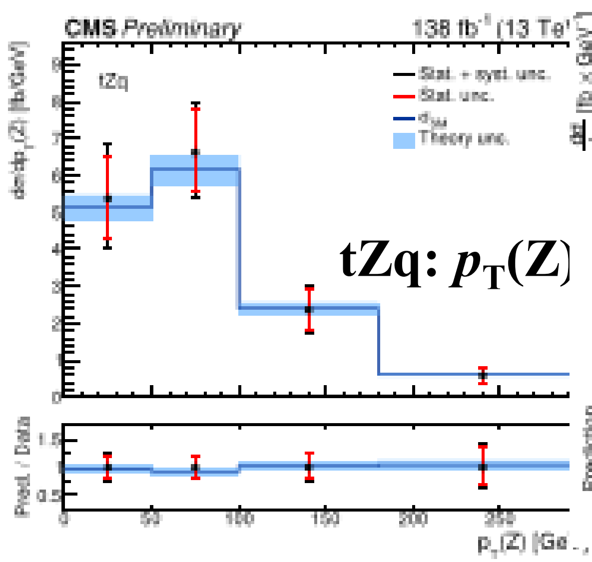
CMS-PAS-TOP-23-004; arXiv:2403.09452

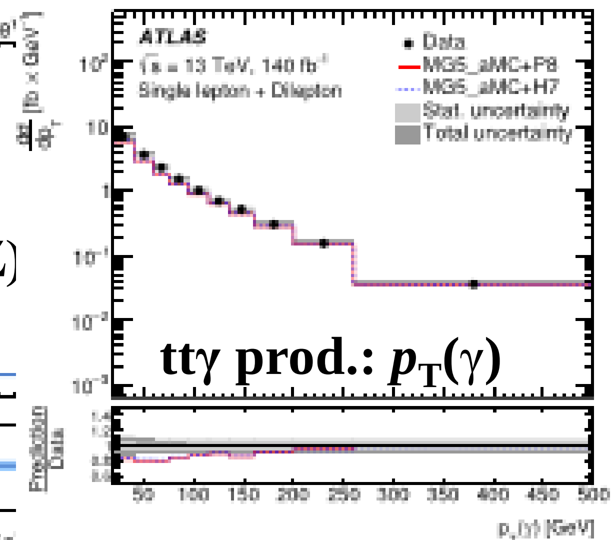
Inclusive: ttZ+tWZ: 1140 ± 64 fb tZq: 810 ± 92 fb ttγ prod.: 322 ± 16 fb

SM: 840 ± 100fb SM: 820 ± 50 fb SM: 299 ± 30 fb

Differential:







also: prod. + decay

tt spin correlation and entanglement

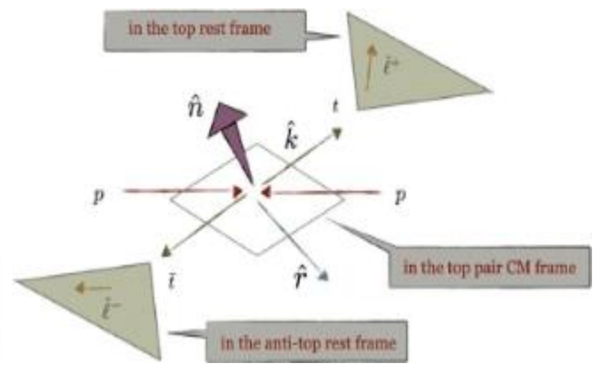
- *tt* pairs predicted (and verified) to have **correlated spins**:
  - *t* and *t* spins accessed via decay product angular *distributions*
  - can also study **quantum mechanics effects**:
    - quantum **entanglement**: "spin correlations beyond classical"
- All *tt* spin information encoded in "**spin density matrix**":
  - for dilepton *tt* (*ℓ spin-analysing power = 1*):

polarization vectors

spin-correlation matrix

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+\cdot\hat{\ell}^+ + \mathbf{B}^-\cdot\hat{\ell}^- - \hat{\ell}^+\cdot\mathbb{C}\cdot\hat{\ell}^-\right)$$

$$\begin{bmatrix} C_{nn} & C_{nr} & C_{nk} \\ C_{rn} & C_{rr} & C_{rk} \\ C_{kn} & C_{kr} & C_{kk} \end{bmatrix}$$



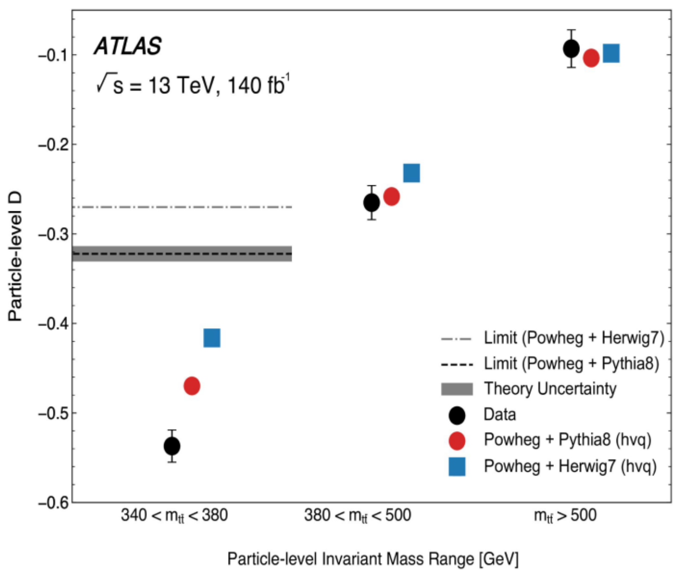
- **Entanglement markers** defined as combinations of these coefficients

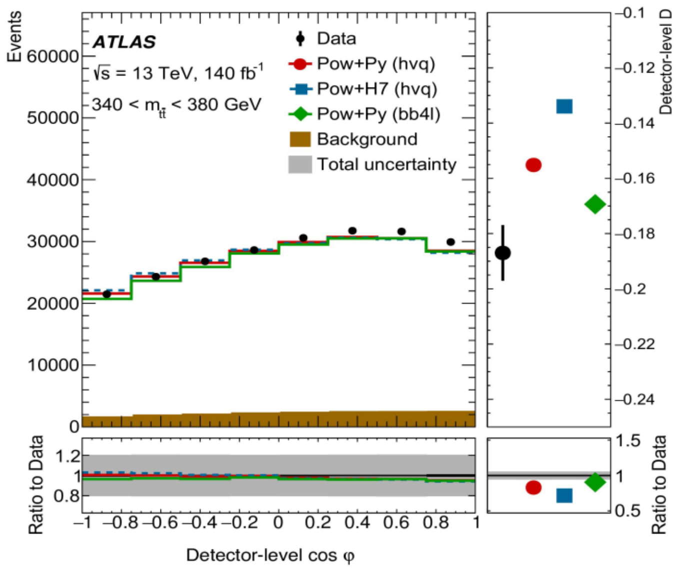
(e.g. see *EPJP(2021)136:907 (Afik et al.), PRL127(2021)16,161801 (Fabbrichesi et al.)*)

Observation of Entanglement -ATLAS

Nature 633 (2024) 542

- ***eμ*** channel
- Entanglement marker $D = -tr[C]/3 = -(C_{nn}+C_{rr}+C_{kk})/3$
  - obtained from angle btw. leptons in top rest frames
  - $D < 1/3 \Rightarrow$ entangled system
- Measurement in narrow **low-m_{tt} region**:
  - to enhance entanglement effect





✓ **> 5σ over no-entanglement hypothesis**

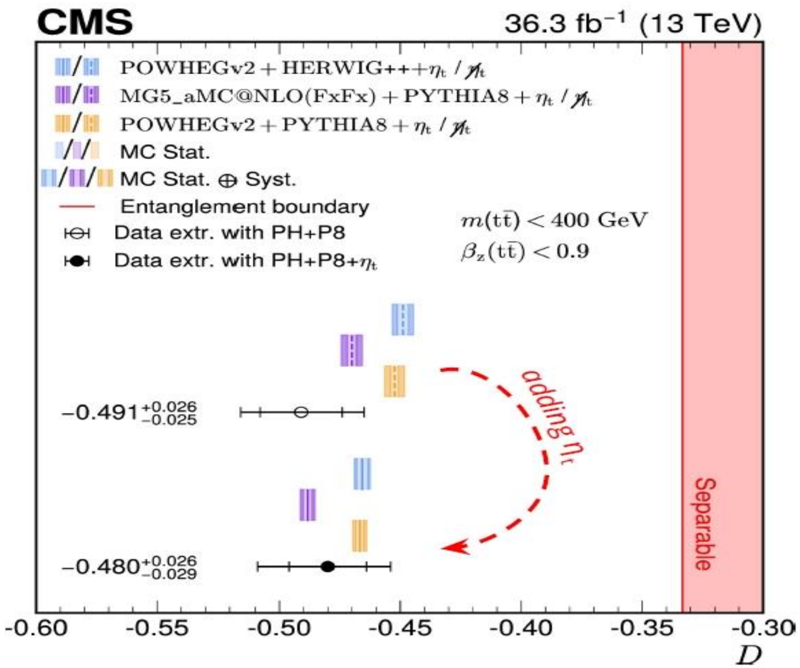
✓ **Discrepancy** observed btw. data and predictions from NLO+PS simulation:

- data "more entangled" than MC (!!)

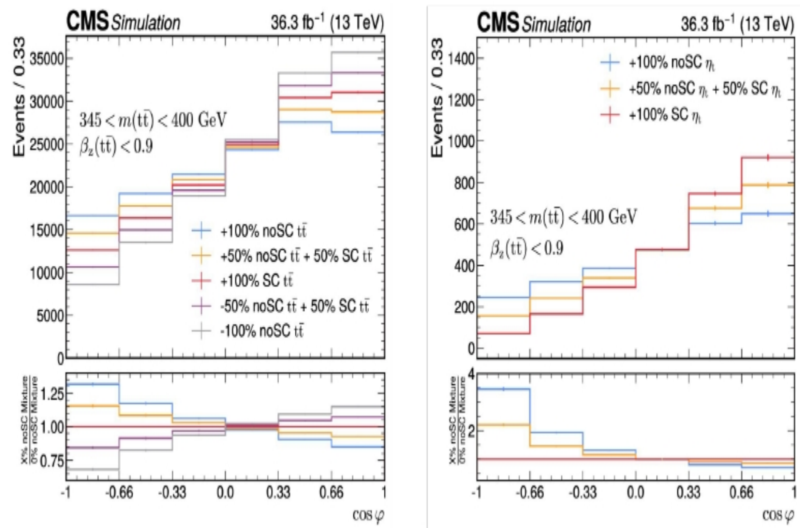
Observation of Entanglement - CMS

▸ arXiv:2406.03976

- *eμ/ee/μμ* channels, **kinematic reconstruction** of *tt* system
- Same observable ***D*** extracted from *cosφ*:



- low-m_{tt} selection
- *D* measured with **binned likelihood fit**

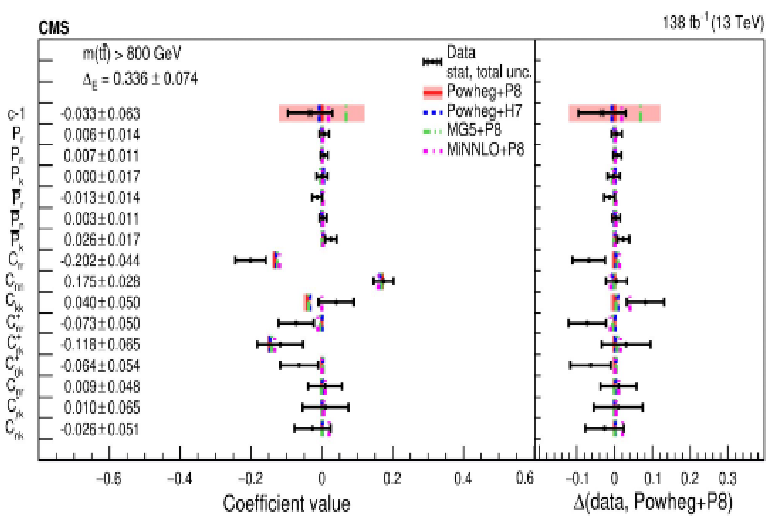


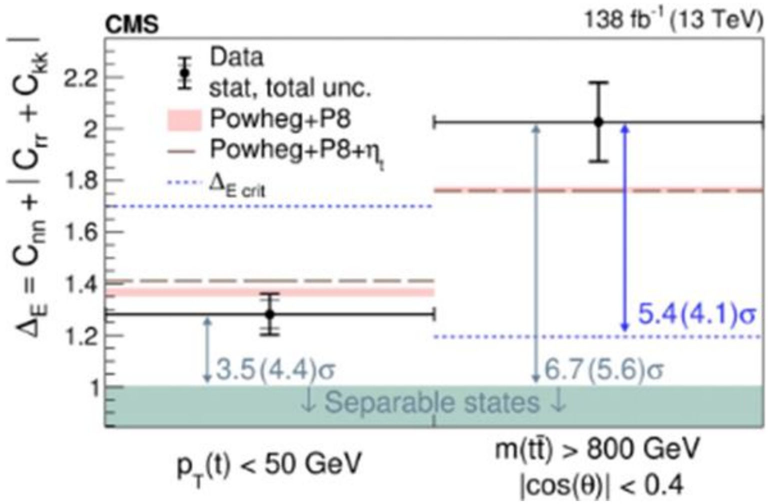
- Inclusion of **"toponium" effect (η_t)** at LO
  (σ(η_t) = 6.43 ± 0.90 pb - arXiv:2102.11281 [hep-ph])
- **Entanglement observed** with > 5σ significance
  - **both** with and without η_t inclusion in the model

Spin Density & Entanglement - CMS

- ✓ **ℓ+jets *tt*** → allow to access spin correlation and entanglement at **higher m_{tt}**
- ✓ **tt system reconstruction with DNN**
- ✓ **Binned likelihood fit** to extract: arXiv:2409.11067
  - ✓ full **spin-density matrix** (polarization & spin correlation)
  - ✓ **entanglement** markers *D* and *D* (modified version for high-mass region)

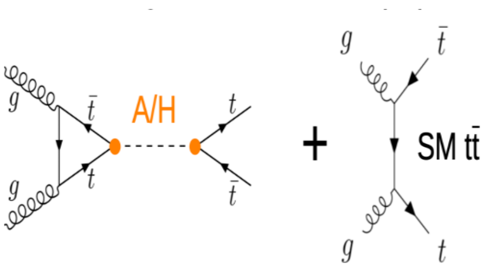
- ✓ Events **categorized** vs. number of *b*-tagged jets and vs. DNN output
- ✓ Measurements **in bins** of m_{tt} **vs. |*cos(θ)*|** and p_T^t **vs. |*cos(θ)*|**





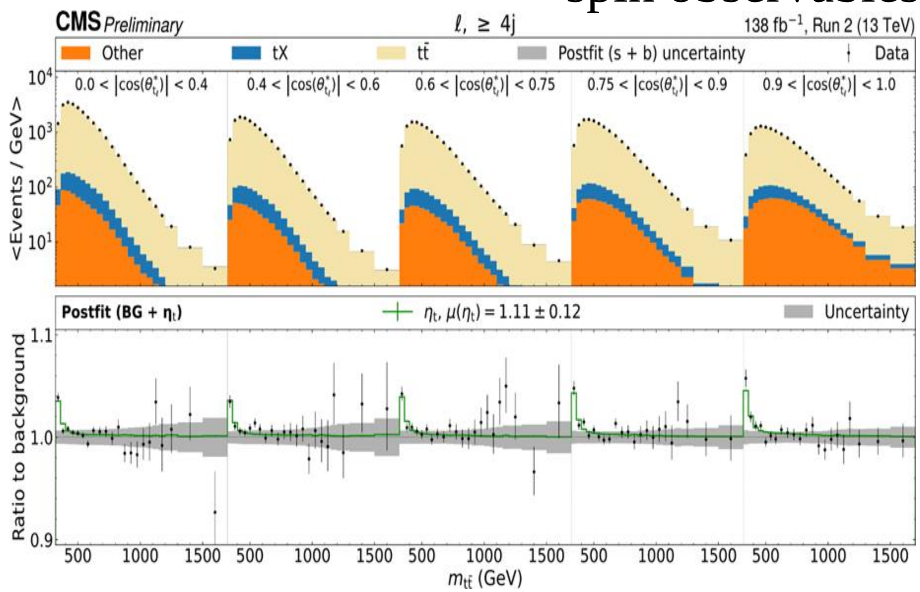
- <u>**Entanglement results**</u>:
  - **at threshold 3.5σ**
  - **m_{tt} > 800 GeV & |cosθ| < 0.4 → 6.7 σ**

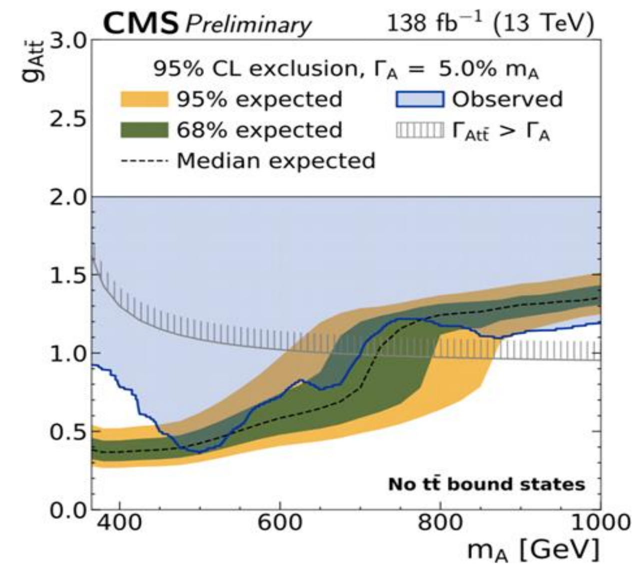
Pseudoscalar resonance at tt threshold?



- ✓ SM predicts tt bound states below the tt threshold
- ✓ Not observed yet (but there are hints: entanglement…)

- Final states with 1 or 2 charged leptons used
- Dilepton and l+jets channels, using mtt, angular and spin observables

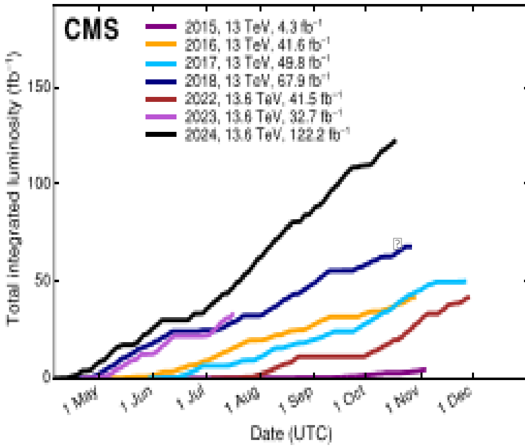




- ✓ Differences between data and prediction observed in low m_{tt} bins!
- ✓ Excess >5 SD, consistent with pseudosclar A or η_t
- ✓ Measured η_t cross section, 7.1 pb +/- 11%

CMS-PAS-HIG-22-013

Summary



✓ **Exciting top quark physics results**

-- using all energies and collision systems
-- covering wide range of top quark production processes

✓ **Several recent ATLAS & CMS highlights shown**

✓ **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 Run-3 data in preparation**

✧ LHCTopWG https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG
✧ ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
✧ CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Backup

OPERATORS AND PHYSICS IMPLICATIONS

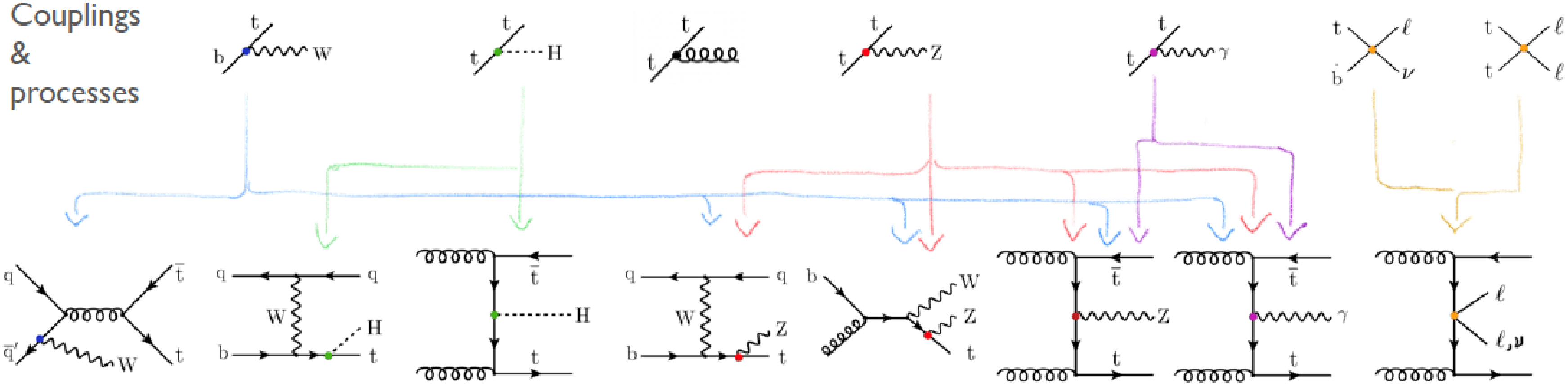
SMEFT Lagrangian

$$\mathcal{L} = \mathcal{L}_{4,\mathrm{SM}} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \boxed{\frac{1}{\Lambda^2}\mathcal{L}_6} + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Operators

$\mathcal{O}_{\phi\mathrm{tb}}$	$i(\tilde{\phi}\, D_\mu\, \phi)\,(\bar{t}_R\,\gamma^\mu\, b_R) + \mathrm{h.c.}$	$\mathcal{O}_{\mathrm{tB}}$	$i(\bar{q}_L\sigma^{\mu\nu}\, t_R)\,\tilde{\phi}\, B_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(3)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I \phi)\,(\bar{q}_L\,\gamma^\mu\,\tau^I q_L)$	$\mathcal{O}^1_{qq}$	$(\bar{q}_L\,\gamma_\mu\, q_L)\,(\bar{q}_L\,\gamma^\mu q_L)$
$\mathcal{O}_{\mathrm{t}\phi}$	$(\phi^\dagger\phi)\,\bar{q}_L\, t_R\,\tilde{\phi} + \mathrm{h.c.}$	$\mathcal{O}_{\mathrm{tG}}$	$i(\bar{q}_L\sigma^{\mu\nu}\lambda^a\, t_R)\,\tilde{\phi}\, G^a_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(1)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)\,(\bar{q}_L\,\gamma^\mu\, q_L)$	$\mathcal{O}^8_{qq}$	$(\bar{q}_L\,\gamma_\mu T^A\, q_L)\,(\bar{q}_L\,\gamma^\mu T^A\, q_L)$

Couplings & processes



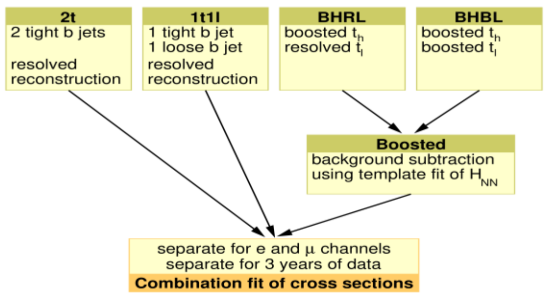
Parametrized predictions

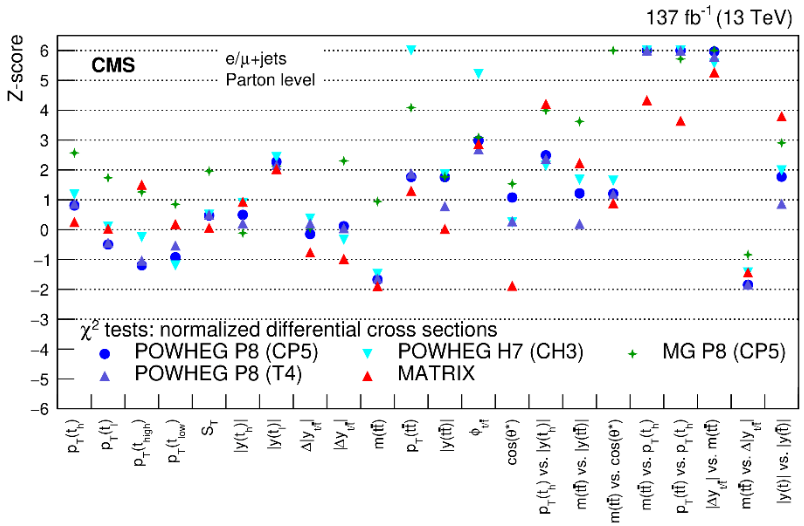
$$N\left(\frac{\vec{c}}{\Lambda^2}\right) = S_0 + \sum_j S_{1j}\frac{c_j}{\Lambda^2} + \sum_j S_{2j}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} S_{3jk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

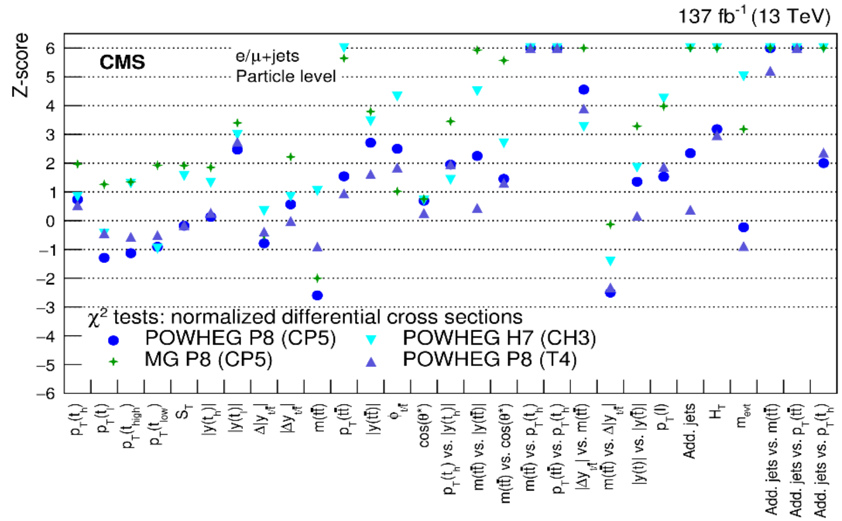
Differential and double-differential σ($t\bar{t}$) in lepton+jets   arXiv:2108.02803

- ✓ High precision measurement of differential and double-differential cross sections
- ✓ For the first time the full spectra of differential cross sections are determined

-- combine of resolved and boosted $t\bar{t}$ topologies







Most of the predictions are in good agreement with the measurement, except:

- ➢ M($t\bar{t}$) vs. pT(th) and pT($t\bar{t}$) vs. pT(th) shows largest disagreements.
- ➢ At particle level add. jets vs. kinematic observable are difficult to describe by NLO.

Inclusive cross section: **791 ± 1 (stat.) ± 21 (syst.) ± 14 (lumi.) pb**

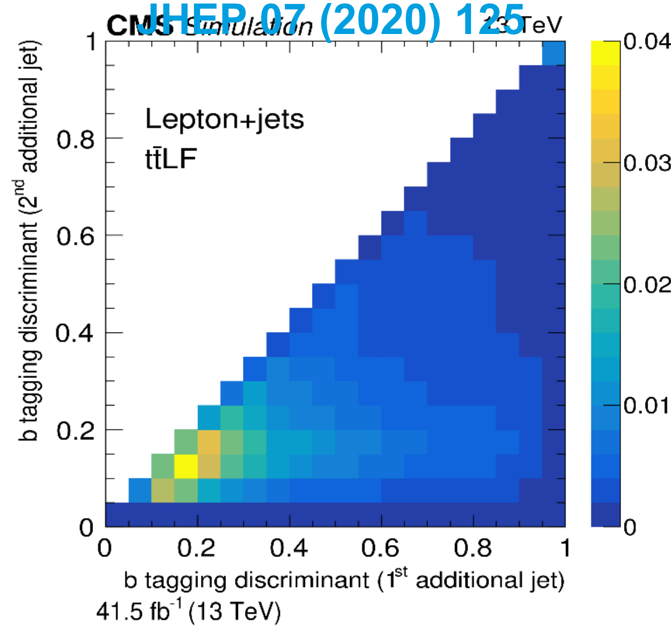
- ✓ most precise measurement in lepton + jets channel
- ✓ Dominanted by: JES and b-tagging

$t\bar{t}c\bar{c}/b\bar{b}$ and $t\bar{t}jj$ production

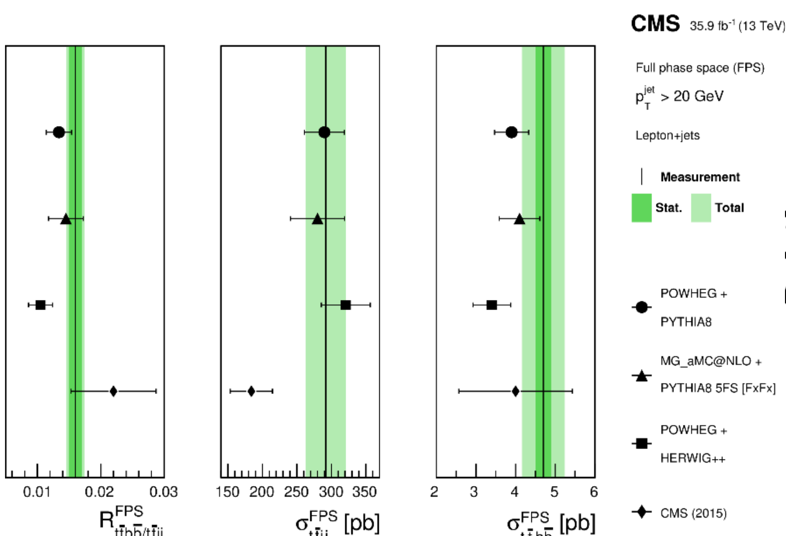
PLB 820 (2021) 136565

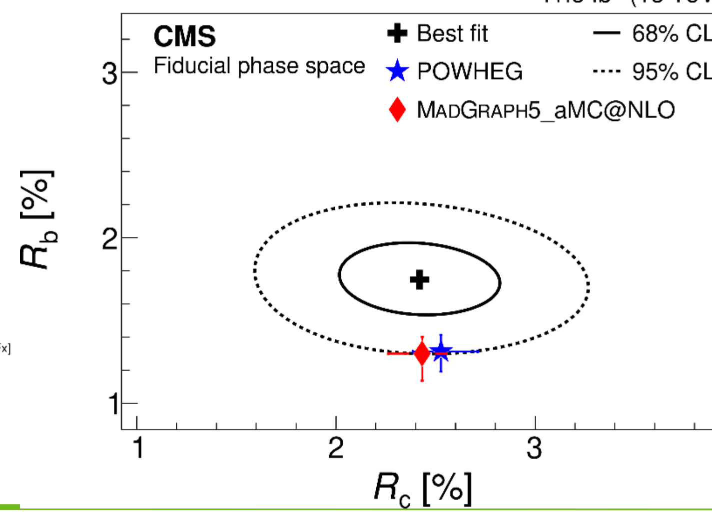
JHEP 07 (2020) 125

- Test the state-of-art predictions at NLO
- Irreducible background to ttH, $H \rightarrow bb$
- $\boldsymbol{ttb\bar{b}}$ and $\boldsymbol{ttj\bar{j}}$ measurement
  - $\sigma_{t\bar{t}bb}$ and $\sigma_{t\bar{t}bb}/\sigma_{t\bar{t}jj}$ extracted simultaneously from a 2D discriminant
  - PowhegPythia8 and MG_aMC@NLO+Pythia8 provide the best description



- **First** measurement of $\boldsymbol{t\bar{t}c\bar{c}}$ production
  - Simultaneous extraction of $\sigma_{t\bar{t}bb}$, $\sigma_{t\bar{t}c\bar{c}}$ and $\sigma_{t\bar{t}LL}$ using a template fit procedure





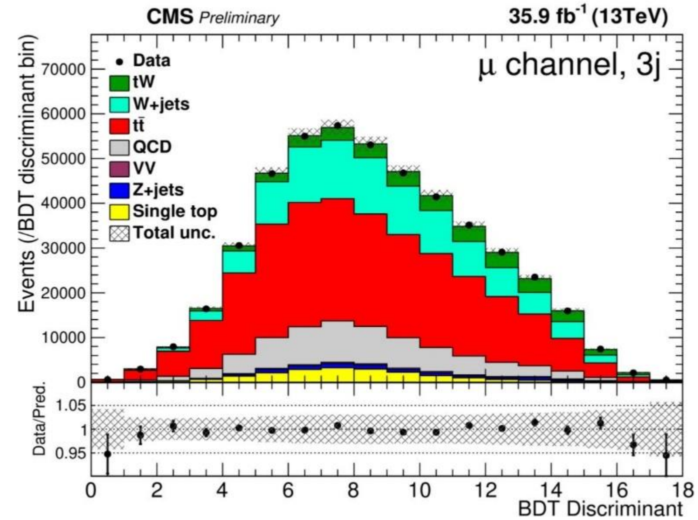
Precision dominated by : MC modelling, JES, c-tagging

tW production in ℓ+jets

CMS-PAS-TOP-20-002

- ➢ Categories based on jet multiplicity and 1 b-tagged jet: 2J1T (W+Jets). **3J1T** (tw Signal region) and 4J1T (ttbar)
- ➢ Data-driven background
- ✓ One BDT is trained per lepton flavor in signal (3J1T) region and evaluation in all regions
- ✓ Simultaneous ML fit performed in all categories using BDT discriminants
- ✓ Dominant uncertainty:

Background estimation, JES and modeling



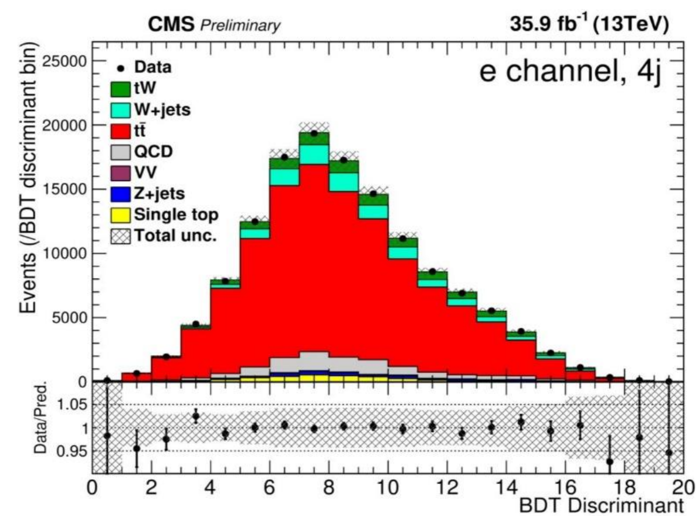
Measured (expected) signal strength:

μ = 1.24 ± 0.18 (1.00 ± 0.17)

Cross section:

σ_{tW} = 89 ± 4 (stat.) ± 12 (syst.) pb

σ_{SM} = 72 ± 4 pb



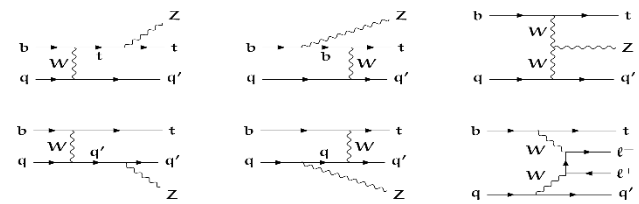
✓ Observed (expected) significance is 7.4 (6.8) standard deviations

First observation of tW production in ℓ+jets

Inclusive and differential tZq

CMS-PAS-TOP-20-010

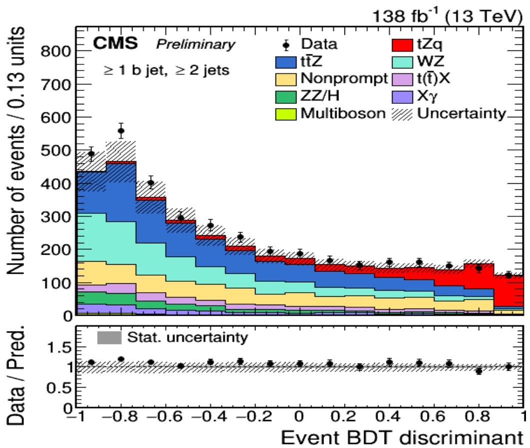
- ✓ Full run2 dataset
- ✓ 3 leptons with improved lepton MVA
- ✓ constraining nonprompt background
- ✓ multiclass NN or BDT



Inclusive tZq cross-section:

$$\sigma_{tZq} = 87.9\ ^{+7.5}_{-7.3}\ \text{(stat)}\ ^{+7.3}_{-6.0}\ \text{(syst) fb}\ .$$

Improvement 30%
w.r.t.earlier measurements



Partial tZq cross-sections:

$$\sigma_{tZq(\ell_t^+)} = 62.2\ ^{+5.9}_{-5.7}\ \text{(stat)}\ ^{+4.4}_{-3.7}\ \text{(syst) fb}\ ,$$

$$\sigma_{\bar{t}Zq(\ell_t^-)} = 26.1\ ^{+4.8}_{-4.6}\ \text{(stat)}\ ^{+3.0}_{-2.8}\ \text{(syst) fb}\ ,$$

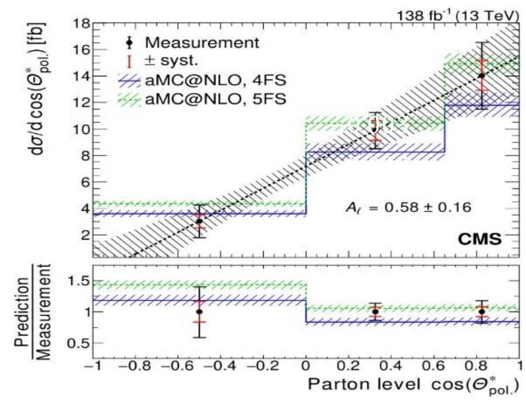
$$R = 2.37\ ^{+0.56}_{-0.42}\ \text{(stat)}\ ^{+0.27}_{-0.13}\ \text{(syst)}\ .$$

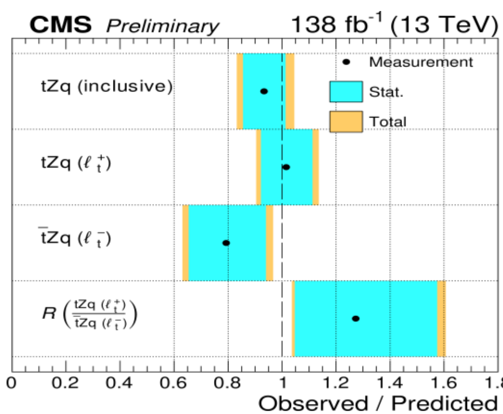
First time!

Spin asymmetry:

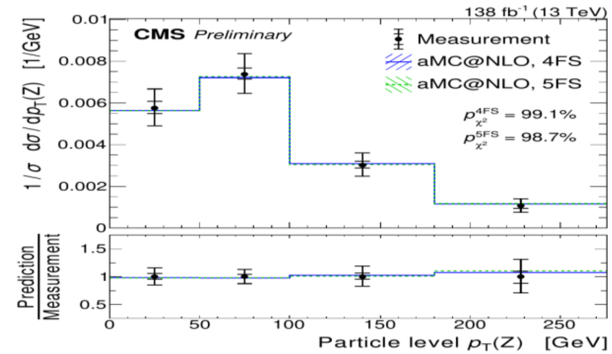
$$A_\ell = 0.58\ ^{+0.15}_{-0.16}\ \text{(stat)}\ \pm 0.06\ \text{(syst)}\ .$$

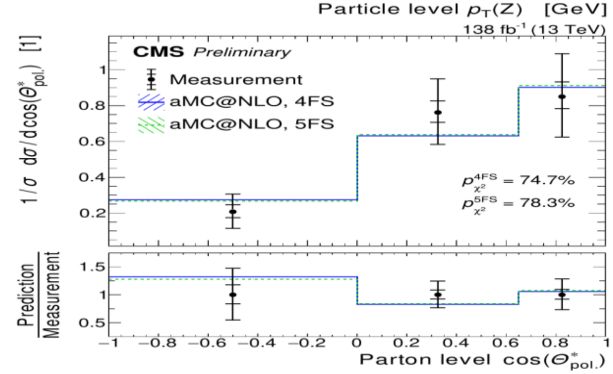
Agreement with SM prediction:





Differential tZq cross-section:





In general, observe good agreement between measurement and prediction.

Rare top production: $t\bar{t}V$

arXiv: 2107.01508

$t\bar{t}Z$ production JHEP 03 (2020) 056

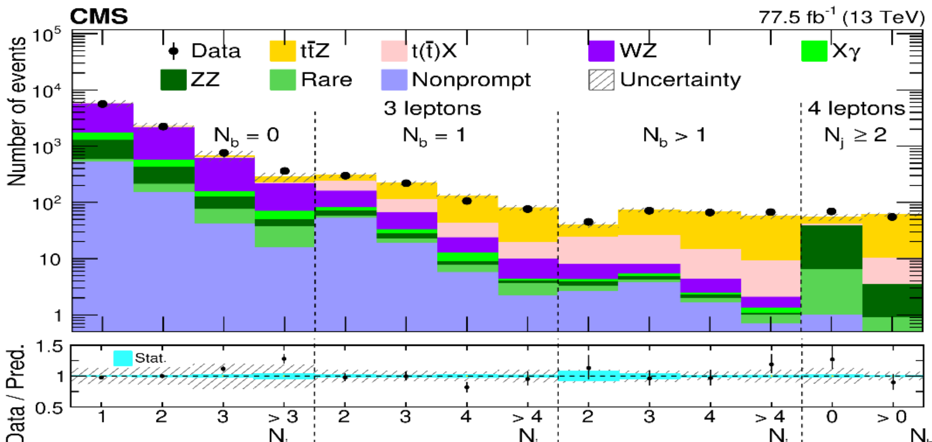
- Targets 3 or 4 isolated lepton channel with Z to l^+l^-
- Inclusive cross section already systematic limited

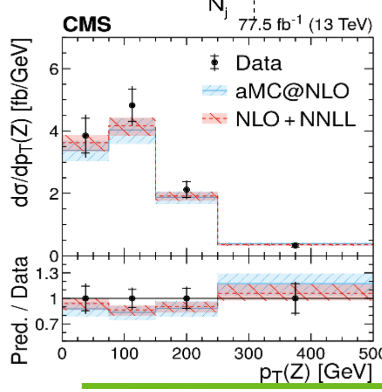
$$\sigma(t\bar{t}Z) = 0.95 \pm 0.05\ (\text{stat}) \pm 0.06\ (\text{syst})\ \text{pb}$$

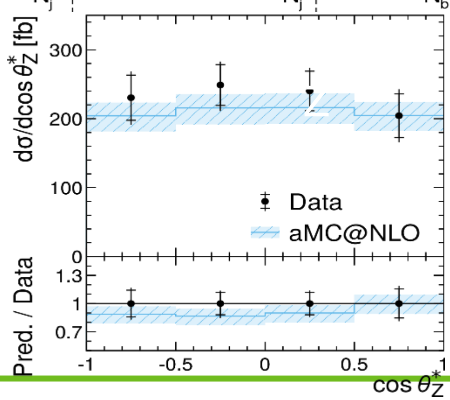
- Dominated by signal/background MC modelling
- Differential cross sections are measured fist time

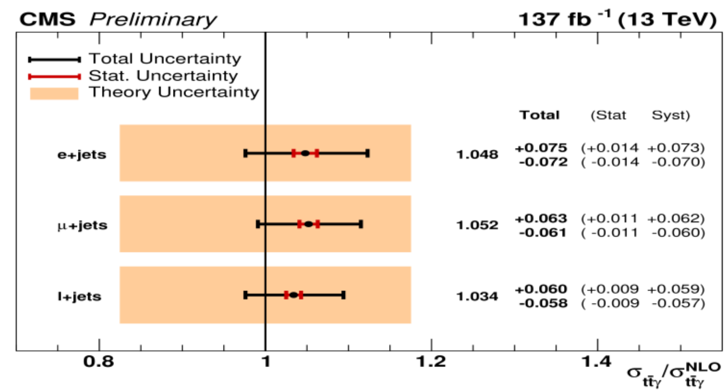
$t\bar{t}\gamma$ production

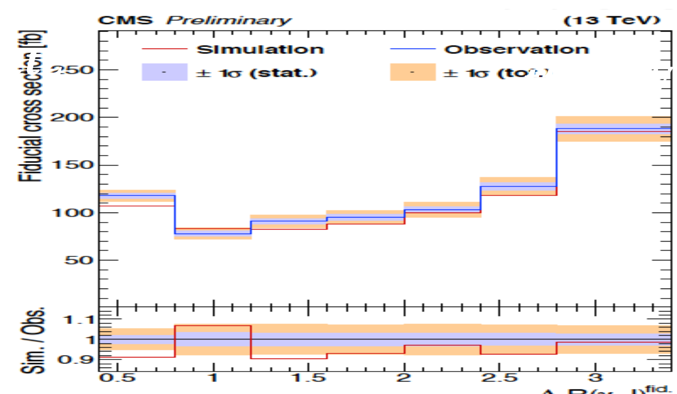
- ✓ Measured in lepton+jets channel
  $800 \pm 46\ (\text{syst}) \pm 7\ (\text{stat})$ fb,
- ✓ Precision limited by MC modelling
- ✓ Differential cross sections measured in several kinematic observables
- ✓ Good agreement with SM prediction









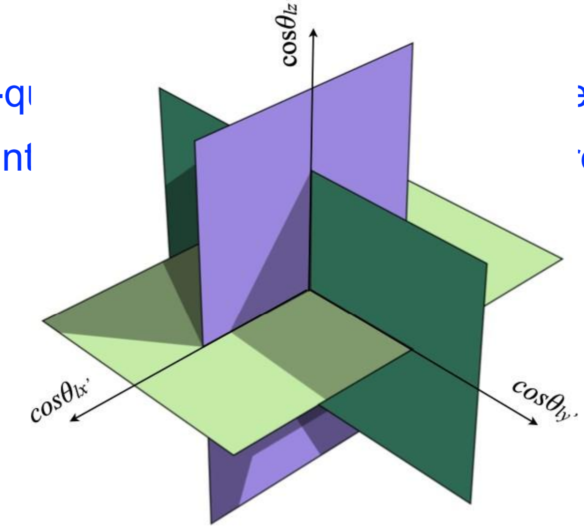


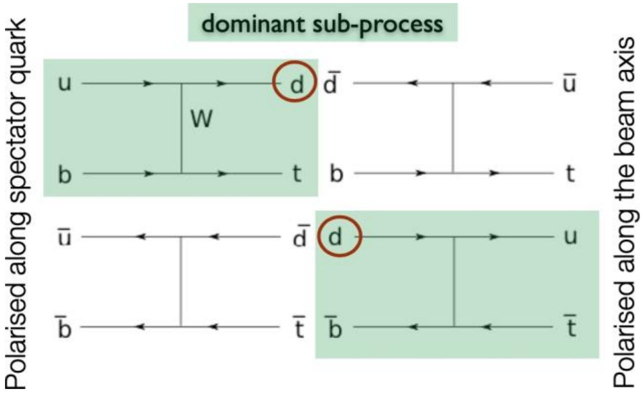
Top polarisation

Top quarks in t-channel are strongly polarised

t-q… …ection

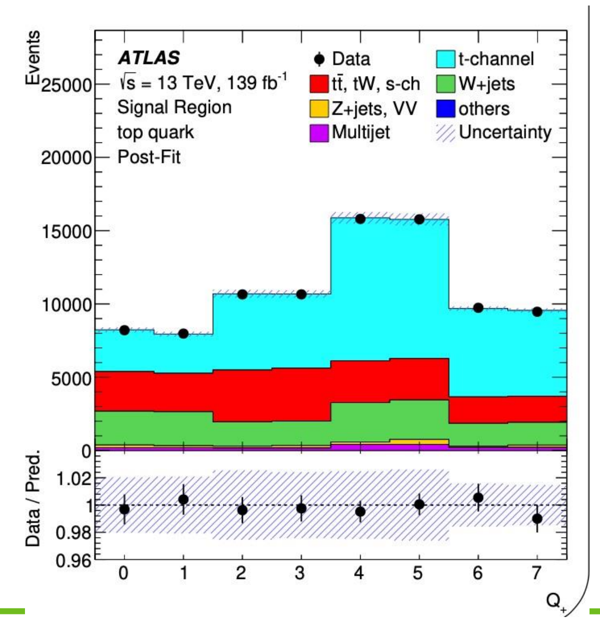
ant… …ection





Signal regions defined by sign of $\cos\theta_{li}$ and lepton charge

$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

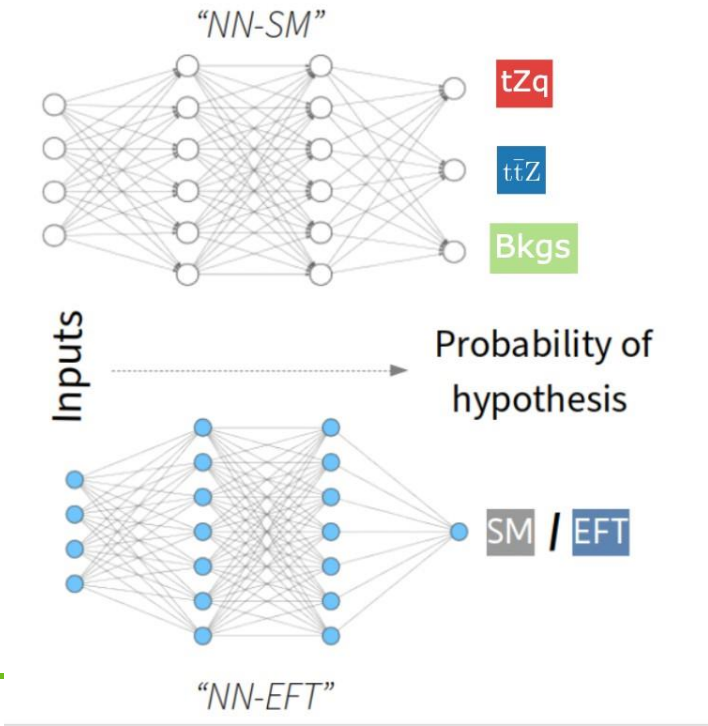


Template fit result: strong polarisation along z-axis

Machine learning in Top

Conclusions

- ML has **significant role** in top physics!
- Wide array of strategies and applications, very **active field of research**
  - CMS example [CMS-TOP-21-001]
  - ATLAS example [ATLAS-CONF-2022-049]
- Many **new developments** on-going
  - **DCTR** [PhysRevD.101.091901]
  - But also **much more**! E.g. [TOP22, M. Fenton]



Search for CP Violation

- CP violation in SM is insufficient to describe the matter-antimatter asymmetry of the universe
- In the SM, CPV in the production and decay of top quark pairs is predicted to be very small
- Simple CP odd observables

$$A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}.$$

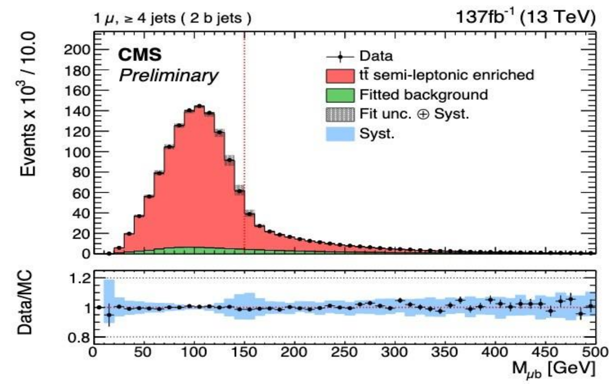
- chromo-electric dipole moment (CEDM) of top quark in top pair production induces CPV

✓ Lepton + jets final states [137 fb^{-1}]

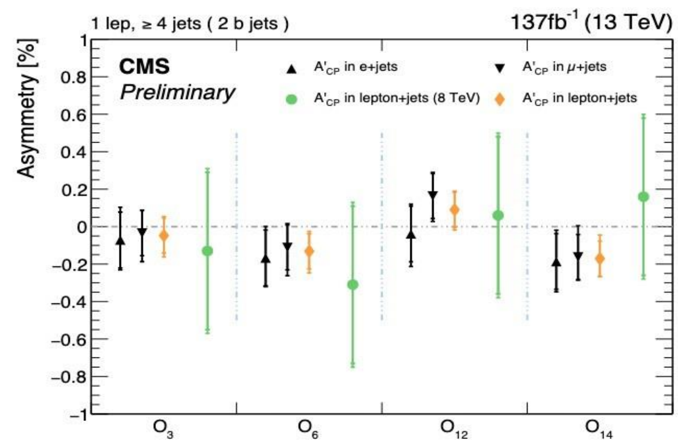
✓ Observables; O_3, O_6, O_{12} and O_{14}

✓ Top quark and antiquark candidates are reconstructed using a χ^2 sorting algorithm

✓ The background contribution in the signal region is estimate from a fit to the mass distribution



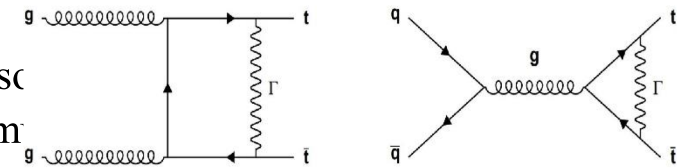
- There is no significant evidence of CPV in each observable
  - Consistent with the SM prediction



	$A'_{CP}(\%)$		
	$e+jets$	$\mu+jets$	Combined
O_3	$-0.071 \pm 0.149(\text{stat.})^{+0.092}_{-0.058}(\text{syst.})$	$-0.035 \pm 0.120(\text{stat.})^{+0.022}_{-0.094}(\text{syst.})$	$-0.048 \pm 0.094(\text{stat.})^{+0.041}_{-0.065}(\text{syst.})$
O_6	$-0.167 \pm 0.149(\text{stat.})^{+0.077}_{-0.038}(\text{syst.})$	$-0.111 \pm 0.120(\text{stat.})^{+0.042}_{-0.093}(\text{syst.})$	$-0.131 \pm 0.094(\text{stat.})^{+0.049}_{-0.068}(\text{syst.})$
O_{12}	$-0.039 \pm 0.149(\text{stat.})^{+0.056}_{-0.090}(\text{syst.})$	$+0.163 \pm 0.120(\text{stat.})^{+0.038}_{-0.065}(\text{syst.})$	$+0.090 \pm 0.094(\text{stat.})^{+0.034}_{-0.053}(\text{syst.})$
O_{14}	$-0.186 \pm 0.149(\text{stat.})^{+0.075}_{-0.065}(\text{syst.})$	$-0.162 \pm 0.120(\text{stat.})^{+0.117}_{-0.032}(\text{syst.})$	$-0.171 \pm 0.094(\text{stat.})^{+0.085}_{-0.023}(\text{syst.})$

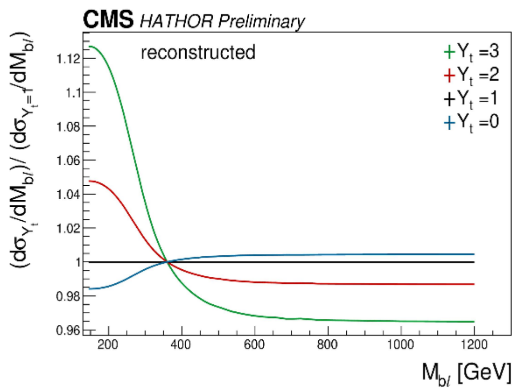
Measurement of the y^t

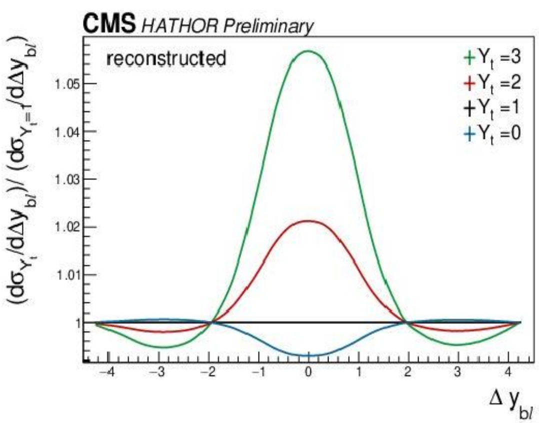
- ✓ Measure the Yukawa (y^t) coupling in $t\bar{t}$ production.
  - ✓ Exploit the large effect that the radiation of a virtual H bosc
- ✓ $t\bar{t}$ predictions for different values of y^t obtained as event-based m HATHOR:
  - ✓ Applied on POWHEG predictions



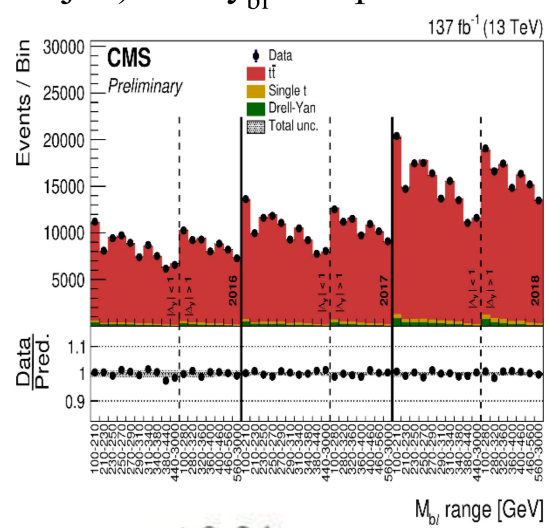
$$R_{\mathrm{EW}}(M_{t\bar{t}}, \Delta y_{t\bar{t}}) = \frac{d^2\sigma_{\mathrm{HATHOR}}}{dM_{t\bar{t}}\, d\Delta y_{t\bar{t}}} \Bigg/ \frac{d^2\sigma_{\mathrm{LO\ QCD}}}{dM_{t\bar{t}}\, d\Delta y_{t\bar{t}}}$$

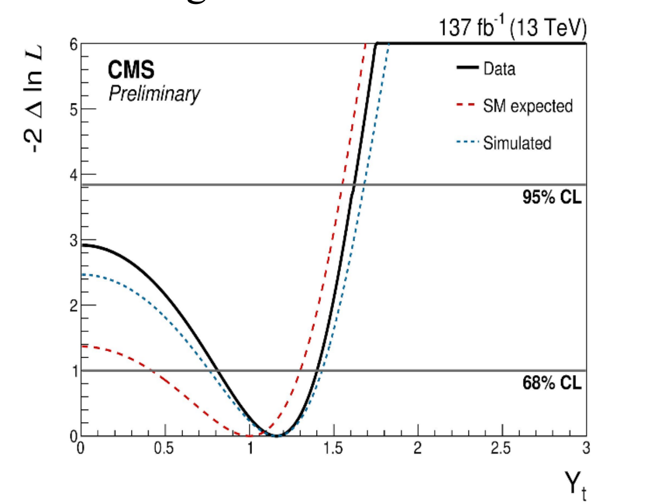
- ✓ The comparison with an additive approach is taken as uncertainty





- ✓ Event collected in the diletopn channel, >=2bjets
- ✓ Variables used based on partial system reconstruction: $M(l^+ + l^- + 2$ b-jets) and Δy_{bl} : requires the correct matching of b and l





$$Y_t = 1.16^{+0.24}_{-0.36}$$

Compatible with the result in l+jets

$$Y_t = 1.07^{+0.34}_{-0.43}$$

PRD 102 (2020) 092013

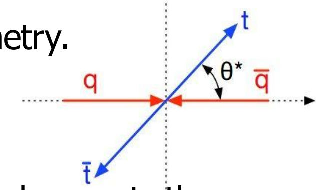
PRD 100 (2019) 072002

$t\bar{t}$ forward-backward asymmetry

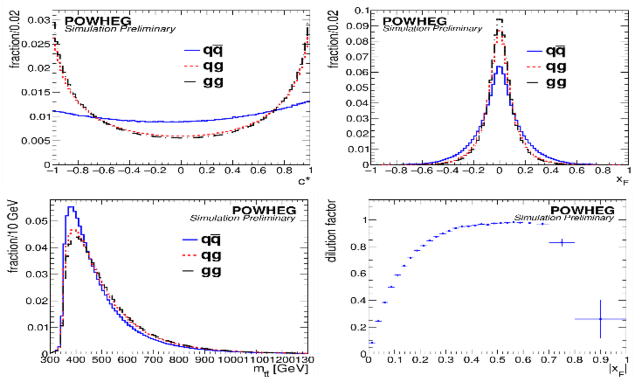
JHEP 06 (2020) 146

- ✓ NLO interference terms in $t\bar{t}$ production from qq initial state creates a forward-backward asymmetry.

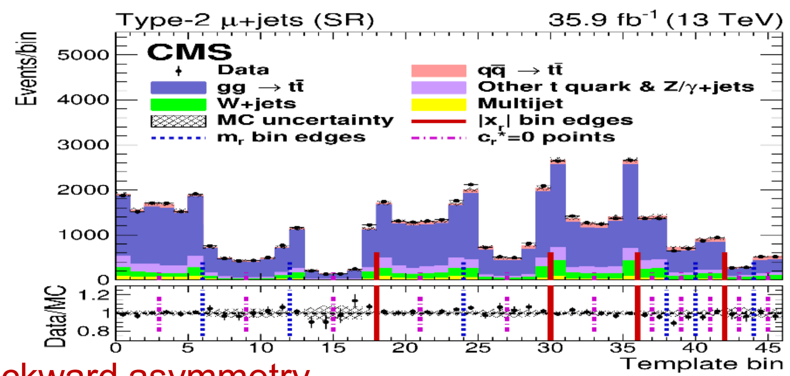
$$A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$

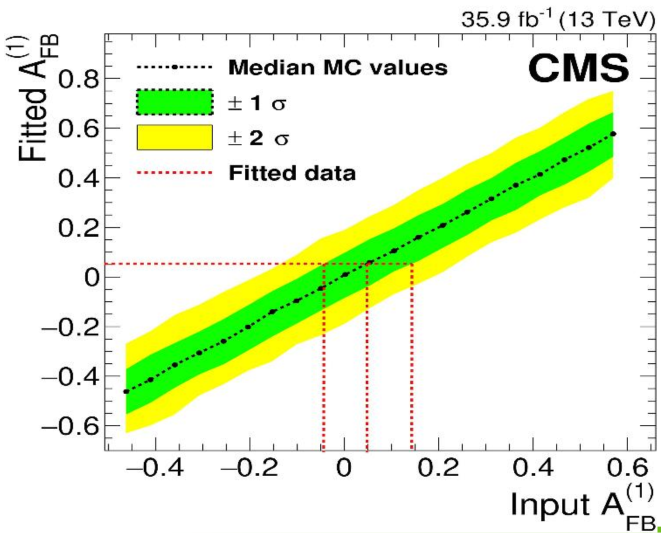


- ✓ Quantity never measured before @LHC, where the charge asymmetry is measured as a proxy
- ✓ Use variables sensitive to the difference between qq, qg and gg initial state to build templates and separate the qq
- ✓ Extract A_{FB} and anomalous chromoelectric and chromomagnetic dipole moments



- ✓ Events collected in the l+jets channel
- ✓ Both resolved and boosted topologies.
- ✓ Profile likelihood-fit to the 3D template to extract AFB and the anomalous moments separately





forward-backward asymmetry

$$A_{FB}^{(1)} = 0.048\,^{+0.095}_{-0.087}\,(\text{stat})\,^{+0.020}_{-0.029}\,(\text{syst}),$$

chromomagnetic moments

$$\hat{\mu}_t = -0.024\,^{+0.013}_{-0.009}\,(\text{stat})\,^{+0.016}_{-0.011}\,(\text{syst}),$$

anomalous chromoelectric

$$|\hat{d}_t| < 0.03 \text{ at 95\% confidence level.}$$

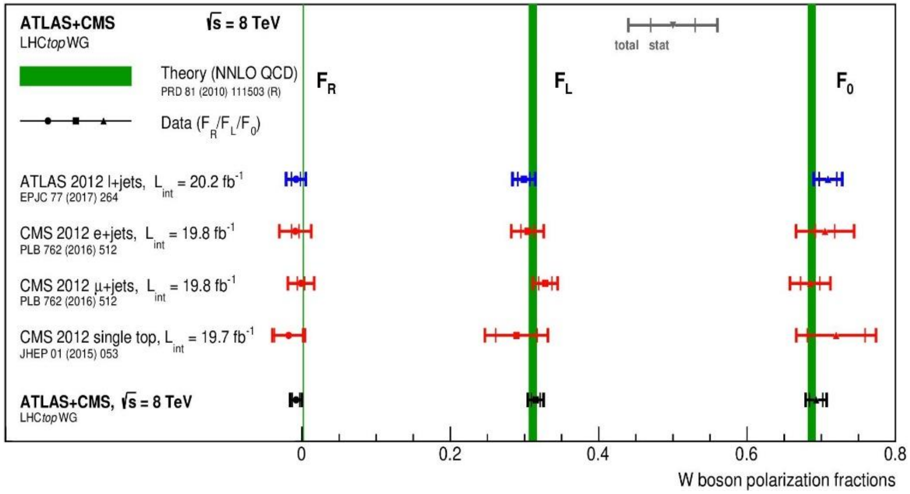
Consistent with the SM and previous CMS results

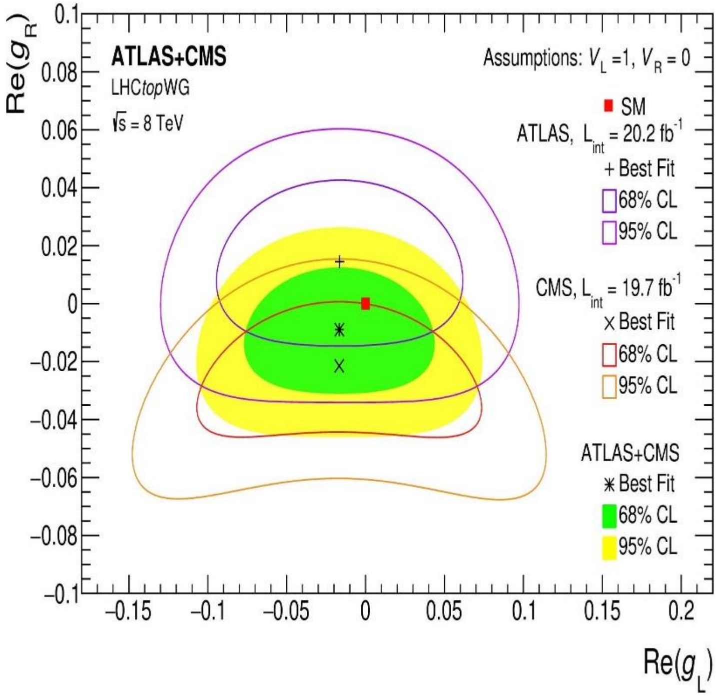
W polarization in ATLAS and CMS

JHEP 08 (2020) 051

- ✓ Combination of the W boson polarization in top quark decays, on Run1(8 TeV, 20fb[-1]) data.
  - ✓ W boson polarization determined by the V-A structure of the tWb vertex

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$





- ➢ Combination of the polarization fractions from 4 measurements

- ✓ Combination Improvement > 20% wrt the most precise measurement
- ✓ Measurement used to set limits on the anomalous coupling in the tWb vertex

	95% CL interval		
Coupling	ATLAS	CMS	ATLAS+CMS combination
$\mathrm{Re}(V_R)$	$[-0.17, 0.25]$	$[-0.12, 0.16]$	$[-0.11, 0.16]$
$\mathrm{Re}(g_L)$	$[-0.11, 0.08]$	$[-0.09, 0.06]$	$[-0.08, 0.05]$
$\mathrm{Re}(g_R)$	$[-0.03, 0.06]$	$[-0.06, 0.01]$	$[-0.04, 0.02]$

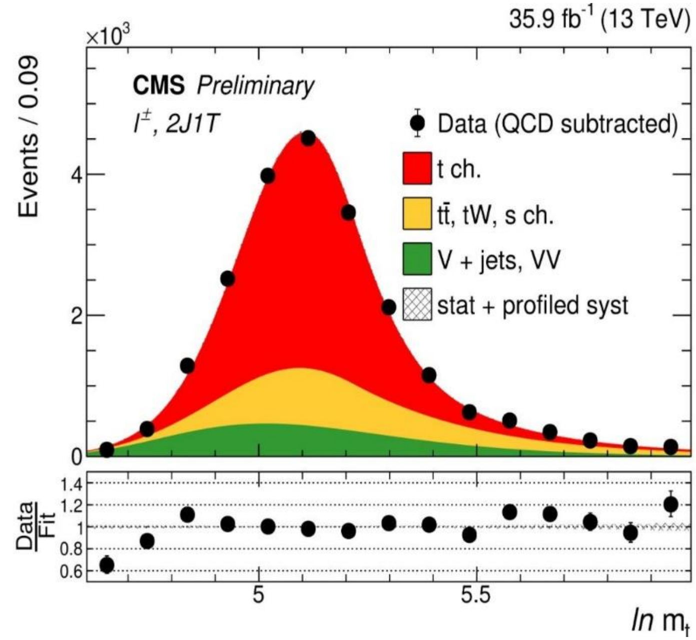
Mass measurement in single top events

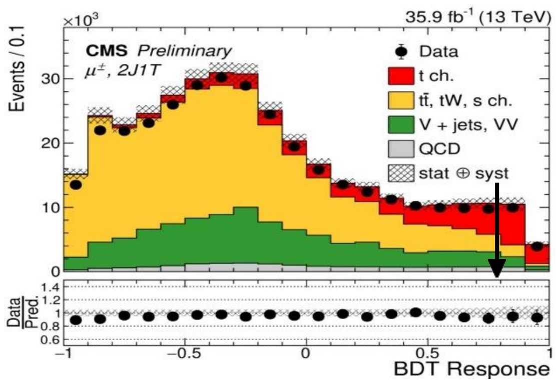
CMS-PAS-TOP-19-009

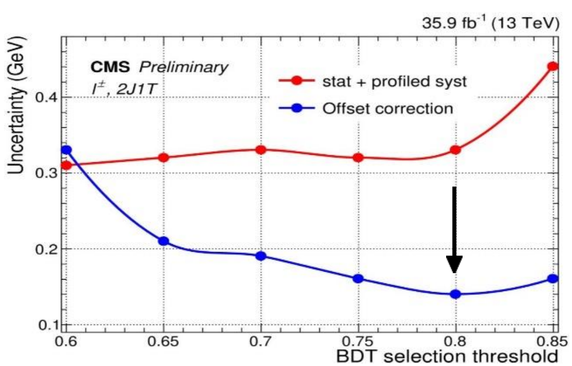
- ✓ BDT discriminator and cut optimization
- ✓ Data-driven QCD is subtracted from the data
- ✓ Simultaneous ML fit using $y = \ln(m_t)$ distributions in μ and e final states, validated in control region

$$F(y) = f_{t-ch}\,F_{t-ch}(y\,;\,y_0) + f_{Top}\,F_{Top}(y\,;\,y_0) + f_{EWK}F_{EWK}(y)$$

- ✓ y_0, f_{t-ch}, f_{Top} and f_{EWK} are allowed to float during the fit







mass results:

Sub GeV precision

$$m_t = 172.13 \pm 0.32\,(\mathrm{stat+prof})\,^{+0.69}_{-0.70}\,(\mathrm{syst})\ \mathrm{GeV} = 172.13^{+0.76}_{-0.77}\ \mathrm{GeV}$$

$$m_t = 172.62 \pm 0.37\,(\mathrm{stat+prof})\,^{+0.97}_{-0.65}\,(\mathrm{syst})\ \mathrm{GeV} = 172.62^{+1.04}_{-0.75}\ \mathrm{GeV},$$

$$m_{\bar{t}} = 171.79 \pm 0.58\,(\mathrm{stat+prof})\,^{+1.32}_{-1.39}\,(\mathrm{syst})\ \mathrm{GeV} = 171.79^{+1.44}_{-1.51}\ \mathrm{GeV}.$$

Masses ratio and difference (a check for CPT Invariance)

$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.995 \pm 0.004\,(\mathrm{stat+prof})\,^{+0.002}_{-0.004}\,(\mathrm{syst}) = 0.995^{+0.005}_{-0.006}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69\,(\mathrm{stat+prof})\,^{+0.35}_{-0.74}\,(\mathrm{syst})\ \mathrm{GeV} = 0.83^{+0.77}_{-1.01}\ \mathrm{GeV}$$

Precision limited by : JES and modelling

Search for FCNC in the top sector

- Flavor changing neutral currents (FCNC) allow for transitions between quarks of different flavor but same electric charge
- FCNC processes are highly suppressed in the SM due to the GIM mechanism
  - Small contributions appear at one loop level
- Many extensions of the SM predict the presence of FCNC and give rise to detectable FCNC amplitude

Any evidence of FCNC will indicate the existence of new physics

	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

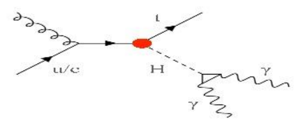
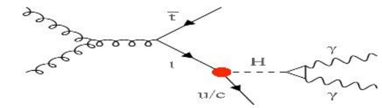
Branching ratios for top FCN decays in the SM, models with $Q = 2/3$ quark singlets (QS), a general 2HDM, a flavour-conserving (FC) 2HDM, in the MSSM and with R parity violating SUSY.

Search for FCNC tHq interaction by H→γγ

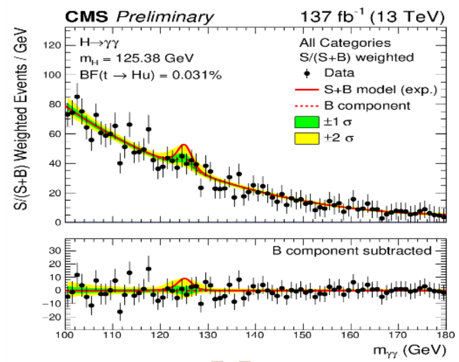
CMS-PAS-TOP-20-007

- Signal modeling: effective Lagrangian

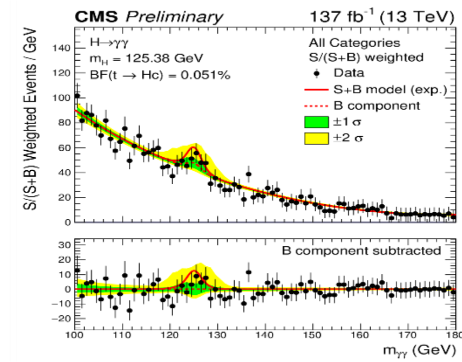
$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t}\kappa_{Hqt}\left(F^{L}_{Hq}P_L + F^{R}_{Hq}P_R\right)qH + h.c.,$$

- Production & decay
- Signal regions: 2 photons, 100 < $m_{\gamma\gamma}$ < 180 GeV
  - leptonic: ≥1 jet, ≥1ℓ
  - hadronic: ≥3 jet, ≥1 b-jet

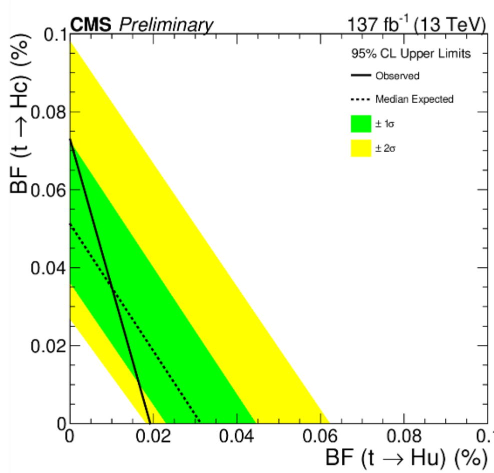


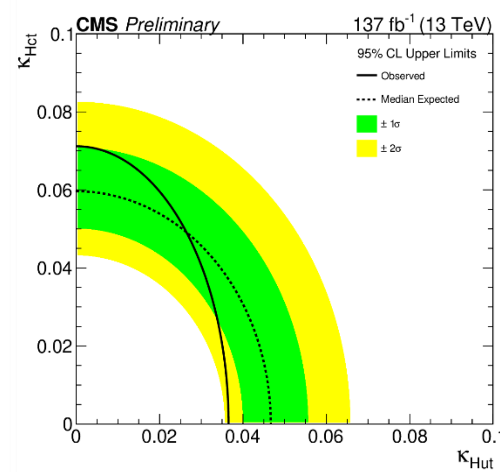
tHu



tHc

- Strategy
  - 8 BDTs: (u, c) ×(lep, had) ×(res, non-res bkg)
  - 7 categories defined by BDT score
  - 14 $m_{\gamma\gamma}$ distributions to fit





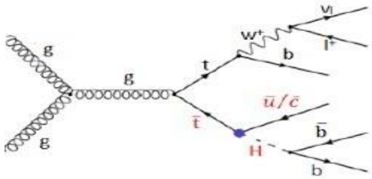
- Dominant uncertainties:

  b-tagging and γ identification
- Data compatible with absence of signal
- Upper limits on the signal cross sections are translated to the strength of the tqH anomalous couplings and related branching fractions

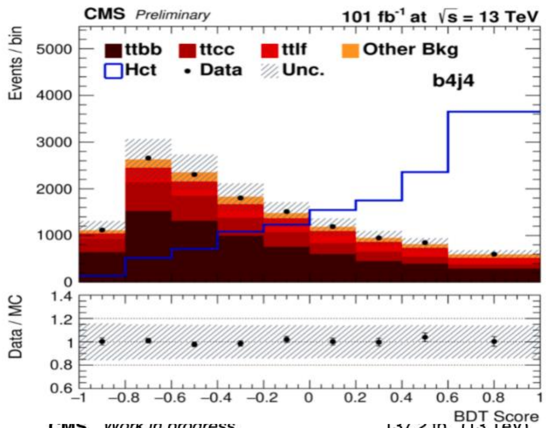
- **Upper limits**
  - $B(t\to Hu) < 1.9\times10^{-4}$ (exp. 3.1×10^{-4})
  - $B(t\to Hc) < 7.3\times10^{-4}$ (exp. 5.1×10^{-4})

Search for FCNC tHq interaction by H→bb CMS-PAS-TOP-19-002

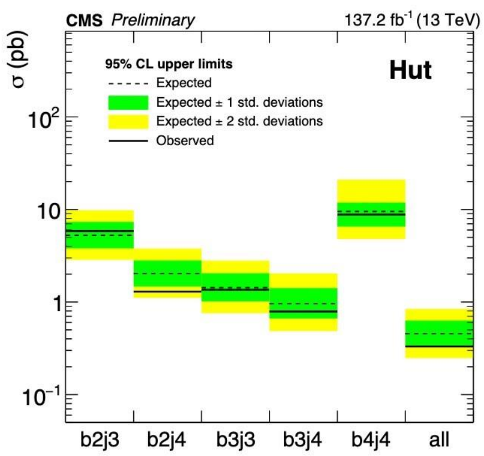
- Production & decay

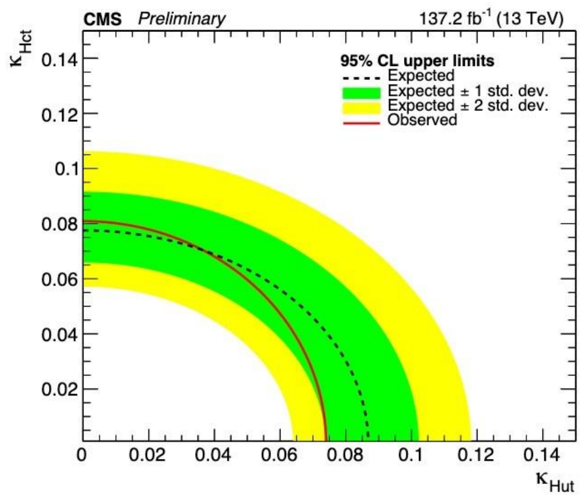


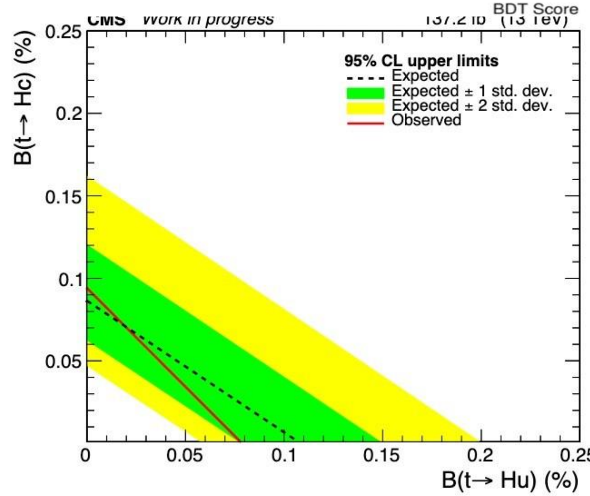
- Signal region: 1ℓ , ≥3 jet, ≥2 b-jet
- A deep neural network is used to associate the reconstructed objects to the matrix-element partonic final state
- BDTs are used to distinguish the signal from the background event
- All bjet-jet categories are combined
- No significant excess with respect to the SM background expectations: 95% CL limits are set on the xs, couplings and BRs



- Significant improve with respect to the early run-2 search







➢Upper limits:

- B(t→Hu) < 7.9 ×10^{-4}(exp: 11×10^{-4})
- B(t→Hc) < 9 .4×10^{-4}(exp: 8.6×10^{-4})

Search for CLFV interactions

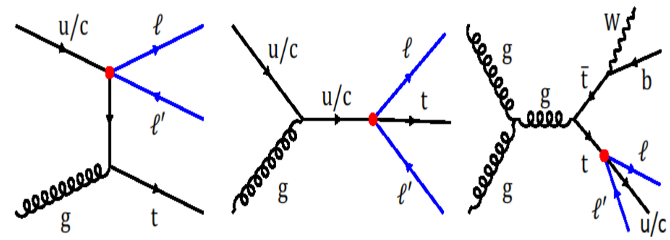
CMS-PAS-TOP-19-006

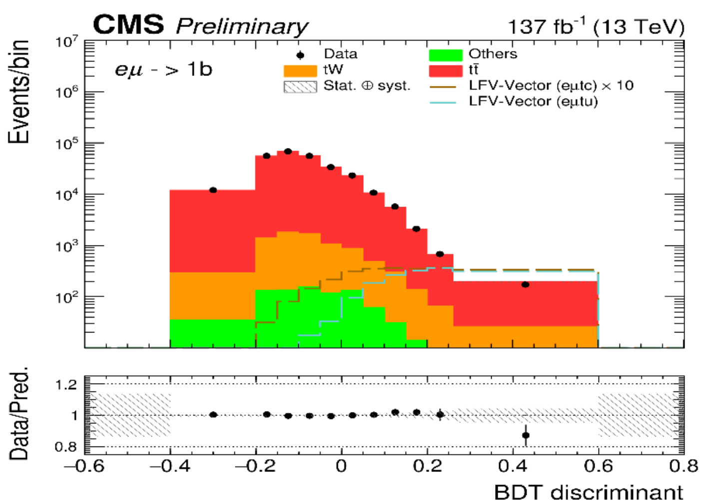
- In the SM, lepton flavor is conserved in all interactions
- Many new physics models predict sizable CLFV (neutrino mass, multi-Higgs doublet models,…)
- If the new physics responsible for the CLFV is at scales beyond what the LHC can directly probe, the SM Lagrangian can be extended by dimension-6 operators

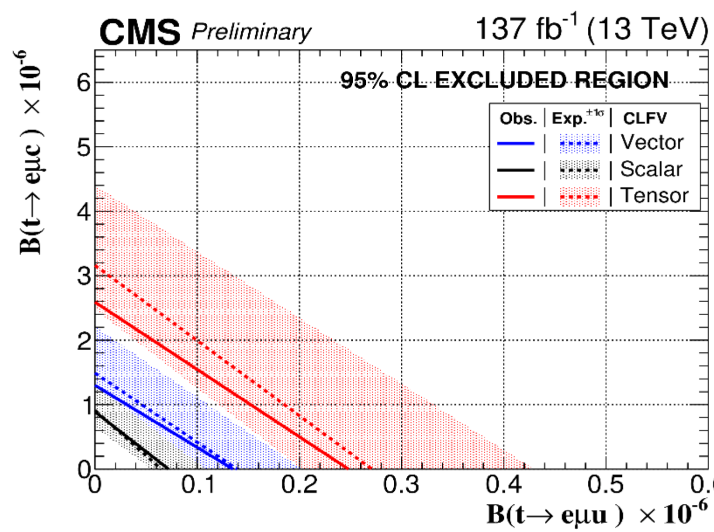
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \ldots ,$$

- ✓ Search for CLFV in $e\mu$ final state [137 fb^{-1}]
- ✓ Production & decay
- ✓ Signal: CLFV vector, scalar and tensor
- ✓ BDT is used to discriminate signal from BG events
- ✓ Data consistent with SM expectation
  - ✓ Upper limits are set at 95% CL

Production Decay



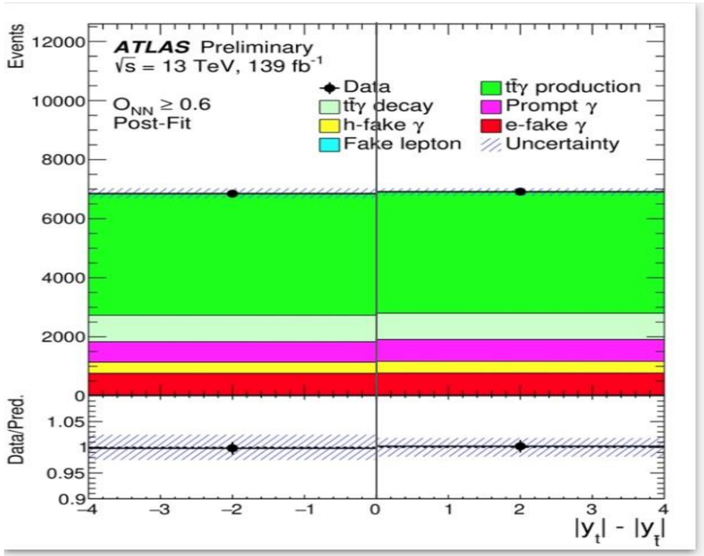




Asymmetry in ttγ and ttW

ttγ

Asymmetry from ISR/FSR interference
Similar definition as in tt
Much lower statistics, 2 bins



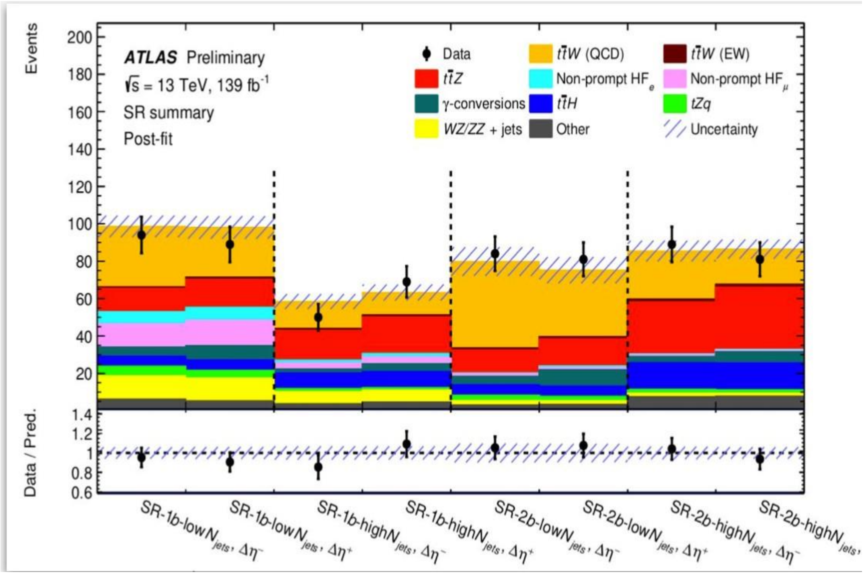
$A_C = -0.006 \pm 0.024(\text{stat}) \pm 0.018(\text{syst})$

in agreement with prediction from MG5aMC

$A_C = -0.014 \pm 0.001(\text{scale})$

ttW

Expected to be larger than in tt due qq initial stat
3-lepton channel, lepton as proxy for top



Fiducial result unfolded to particle-level:

$A_C = -0.112 \pm 0.170\ (\text{stat}) \pm 0.055\ (\text{syst})$

in agreement with Sherpa NLO+EW simulation

Statistically dominated analyses, Run 3 data will help