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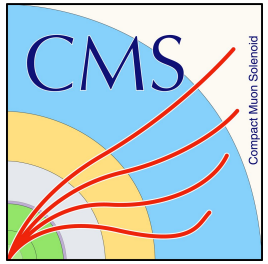
Universidad de Oviedo
ICTEA Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias



Rare top quark production and top quark properties in ATLAS and CMS

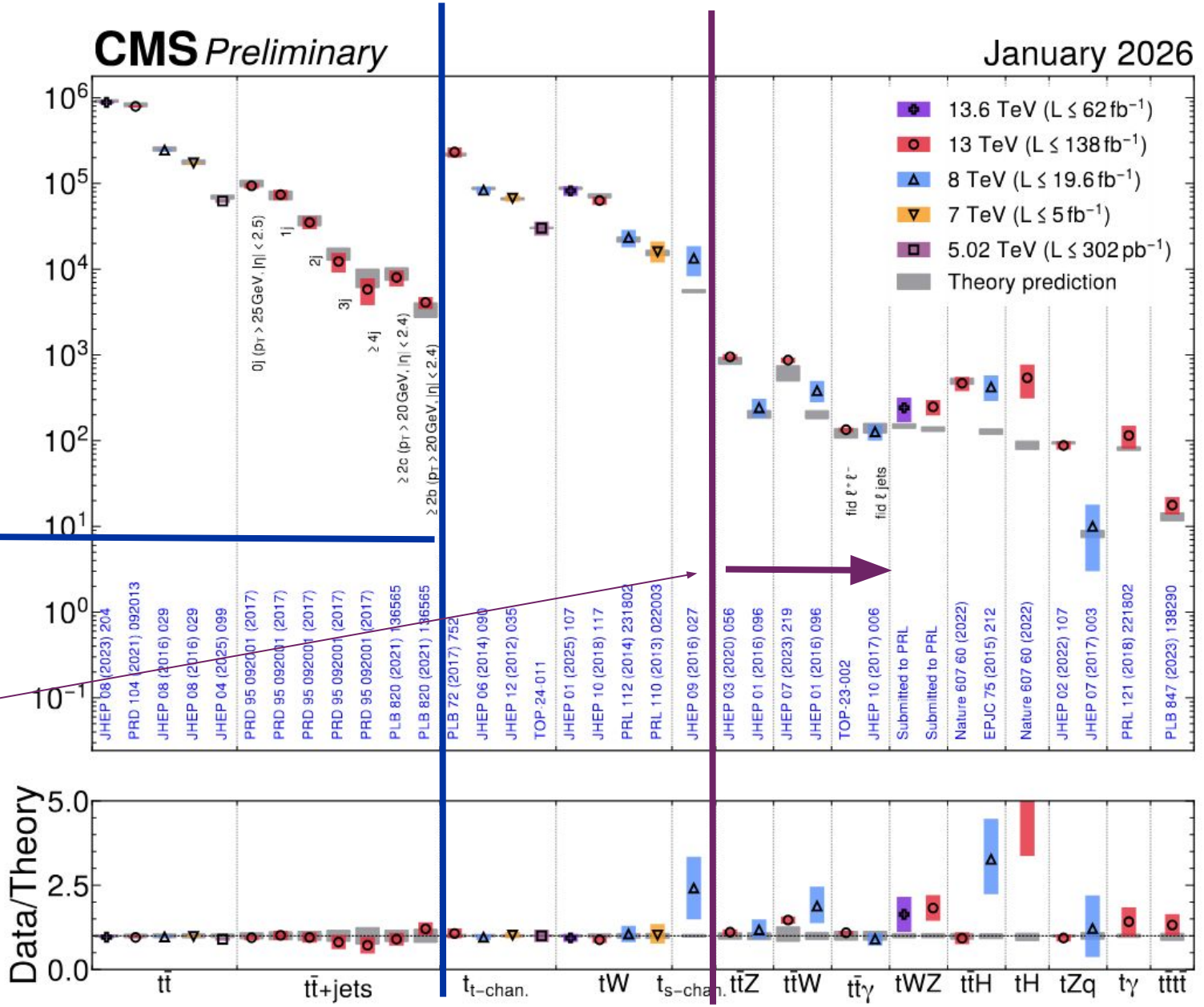
Sergio Sánchez Cruz (on behalf of the ATLAS and CMS Collaborations)

60th Rencontres de Moriond (electroweak sesion)
March 21st 2026 - sergio.sanchez.cruz@cern.ch

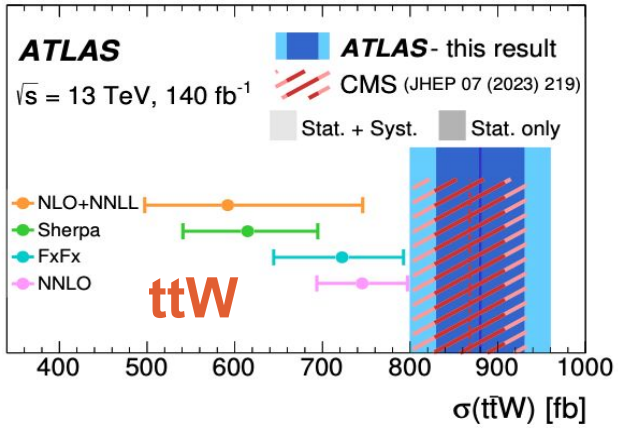
Rare top quark production

ttbar production - see [Baptiste's presentation]

This talk: rare (<1pb) production

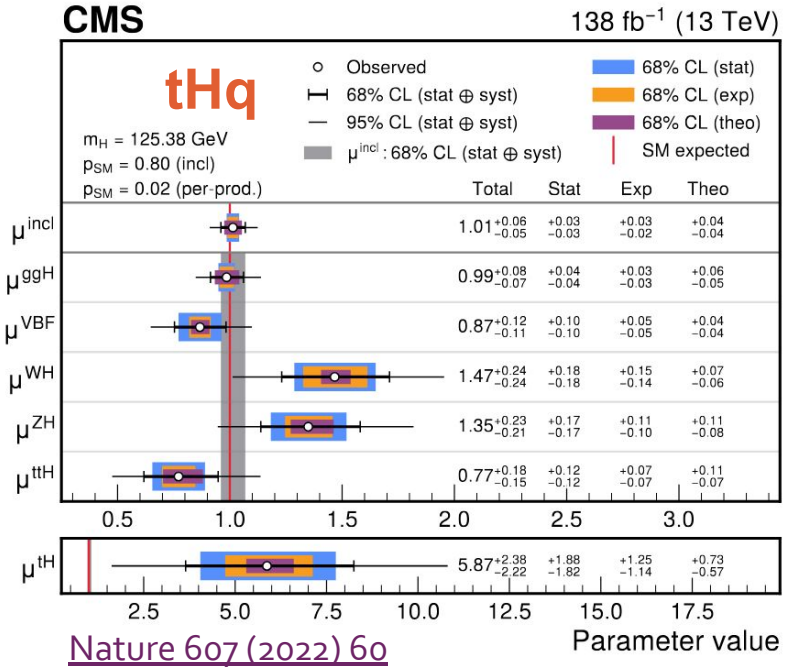


Rare top quark production (II)

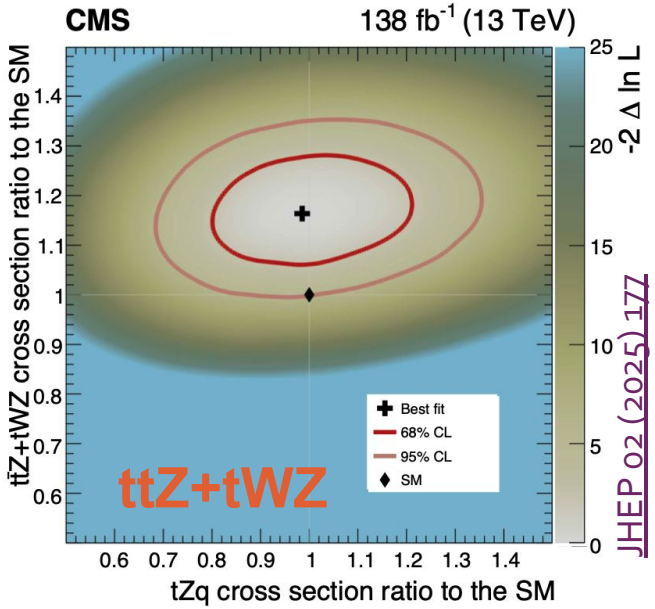


JHEP 05 (2024) 131

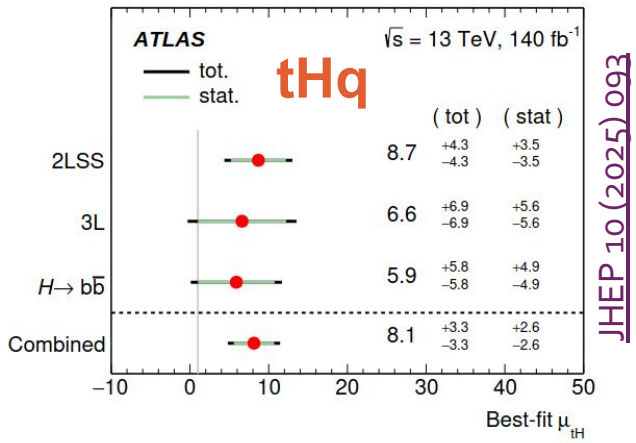
"No new physics in LHC run 2" but a few intriguing discrepancies in rare top production processes



Nature 607 (2022) 60



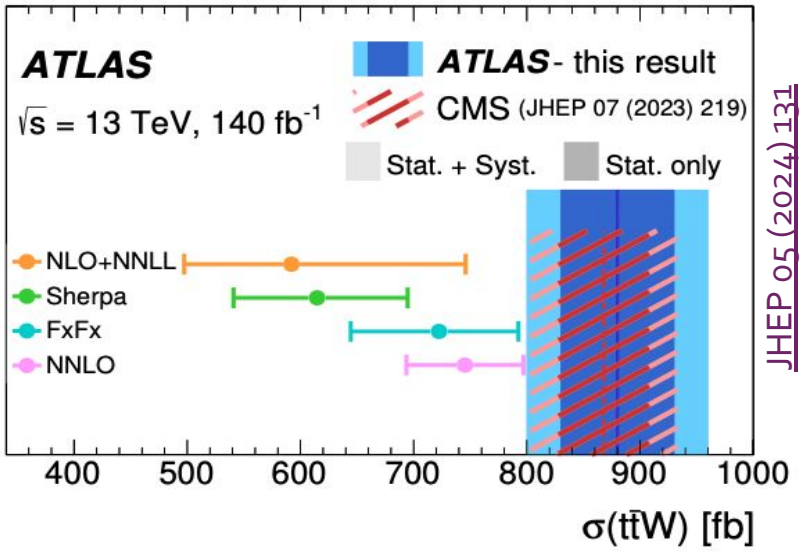
JHEP 02 (2025) 177



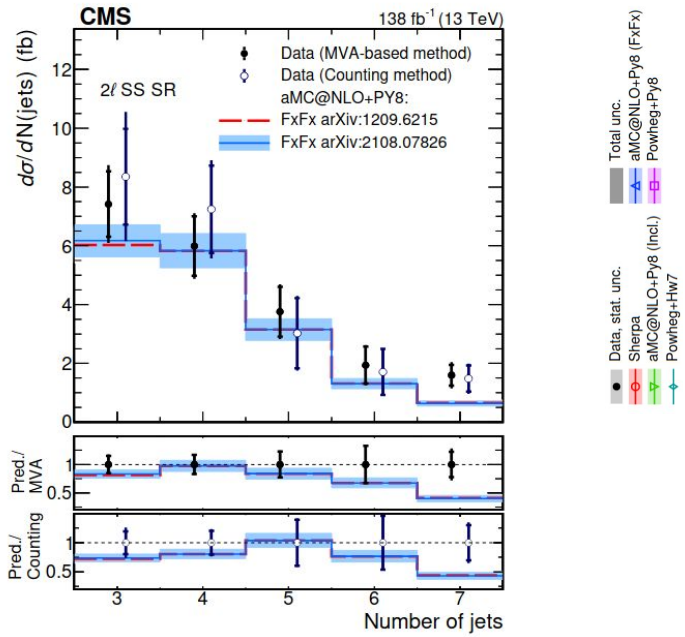
JHEP 10 (2025) 093

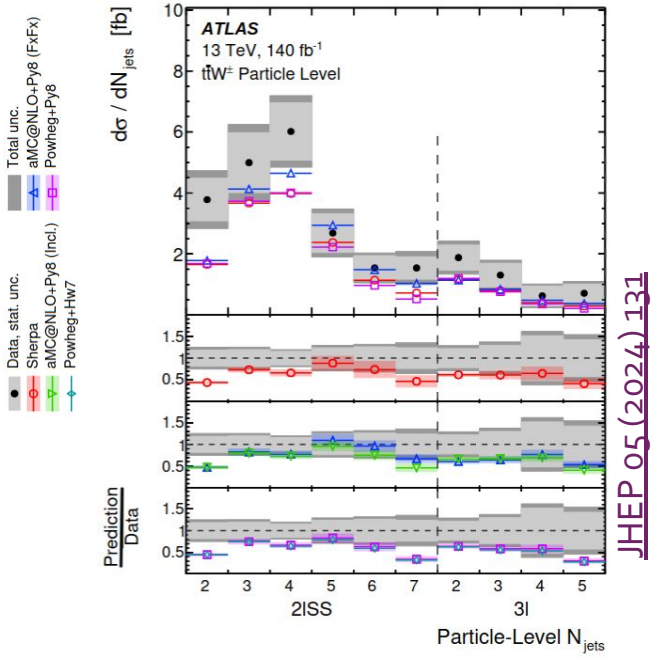
See Fabio's talk on New physics searches with top quarks!

ttW production

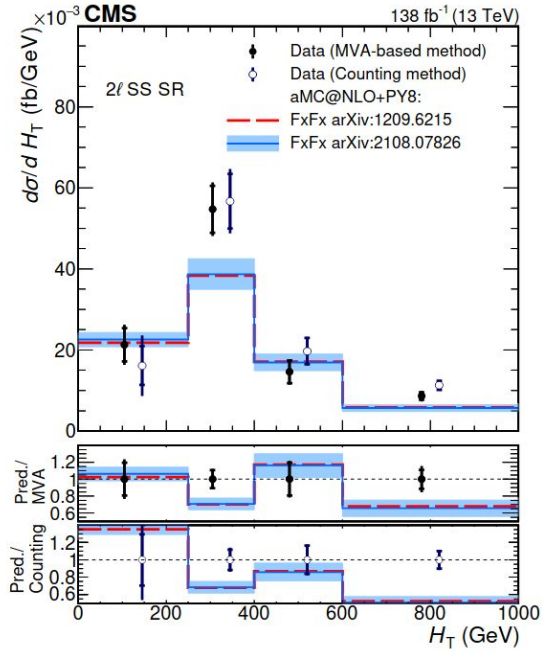


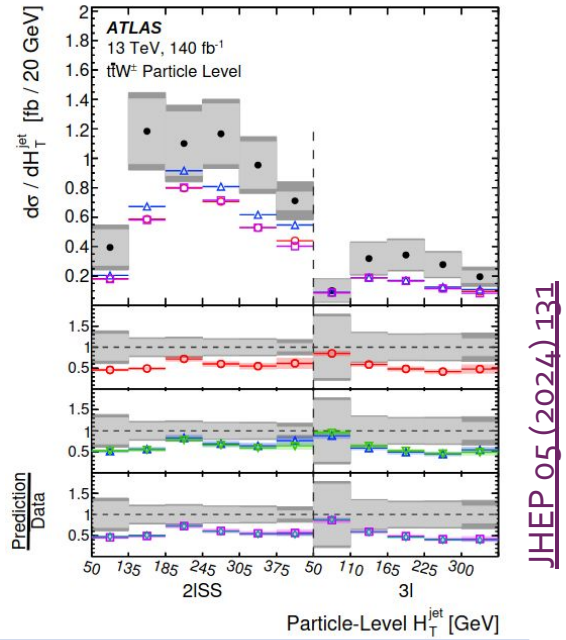
JHEP 05 (2024) 131





JHEP 05 (2024) 131





JHEP 05 (2024) 131

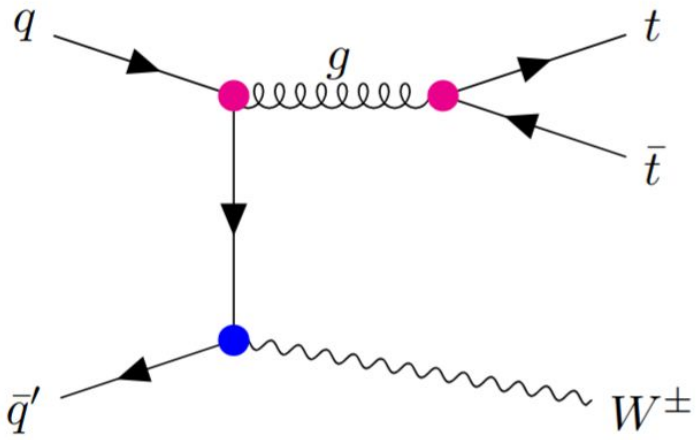
- Order of 2σ discrepancy wrt aNNLO predictions (PRL 131, 231901) in the inclusive cross section
- No sizeable trend in the differential measurements by neither ATLAS or CMS

ttW by orders

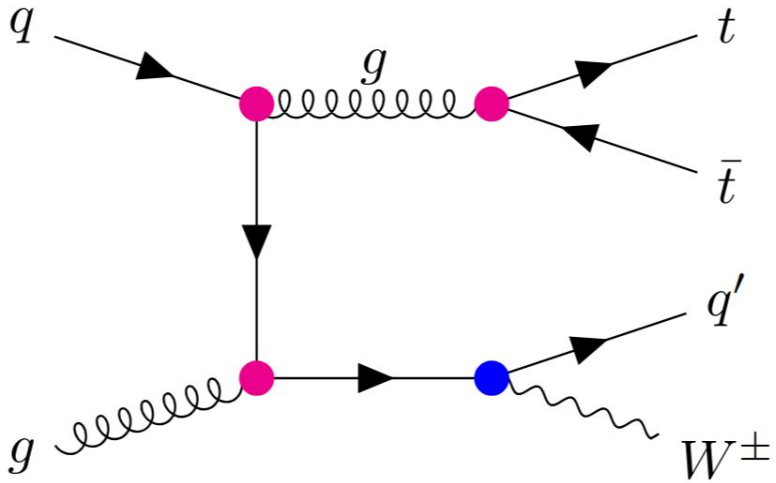
tW→tW scattering

JHEP 01 (2016) 071

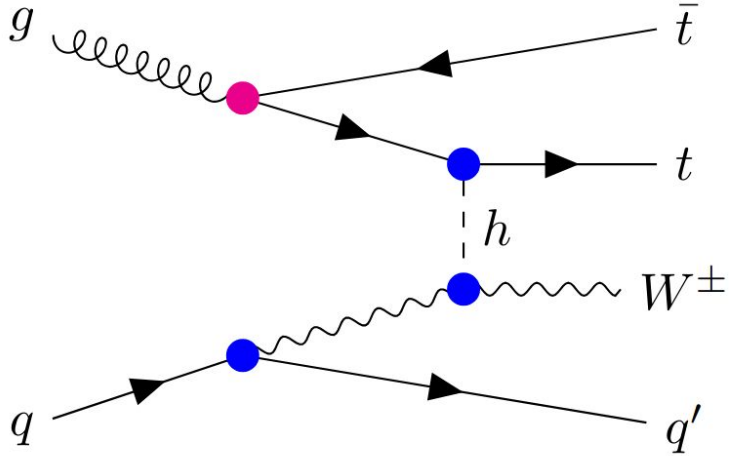
EPJC 80, 803 (2020)



LO QCD



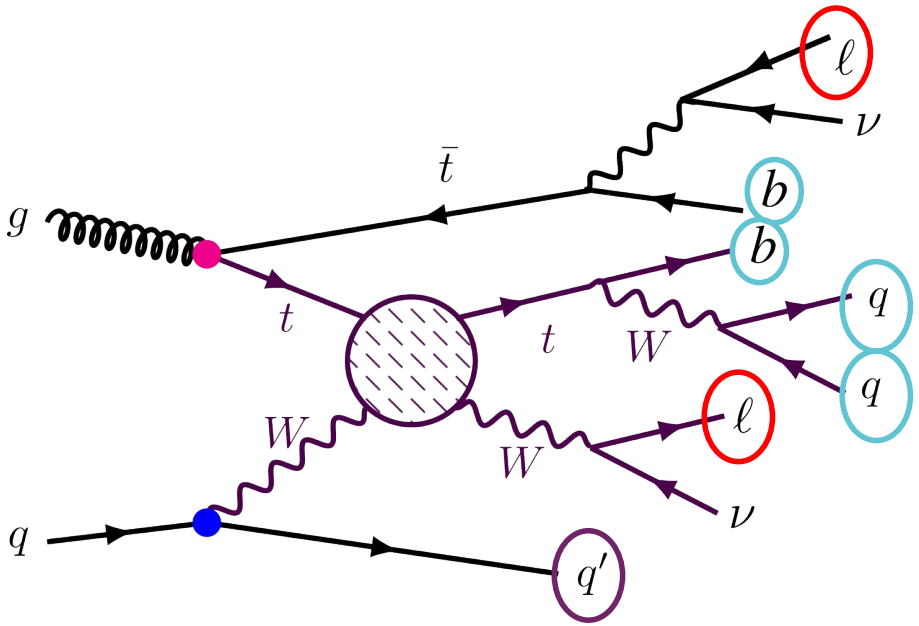
NLO QCD 30-60%



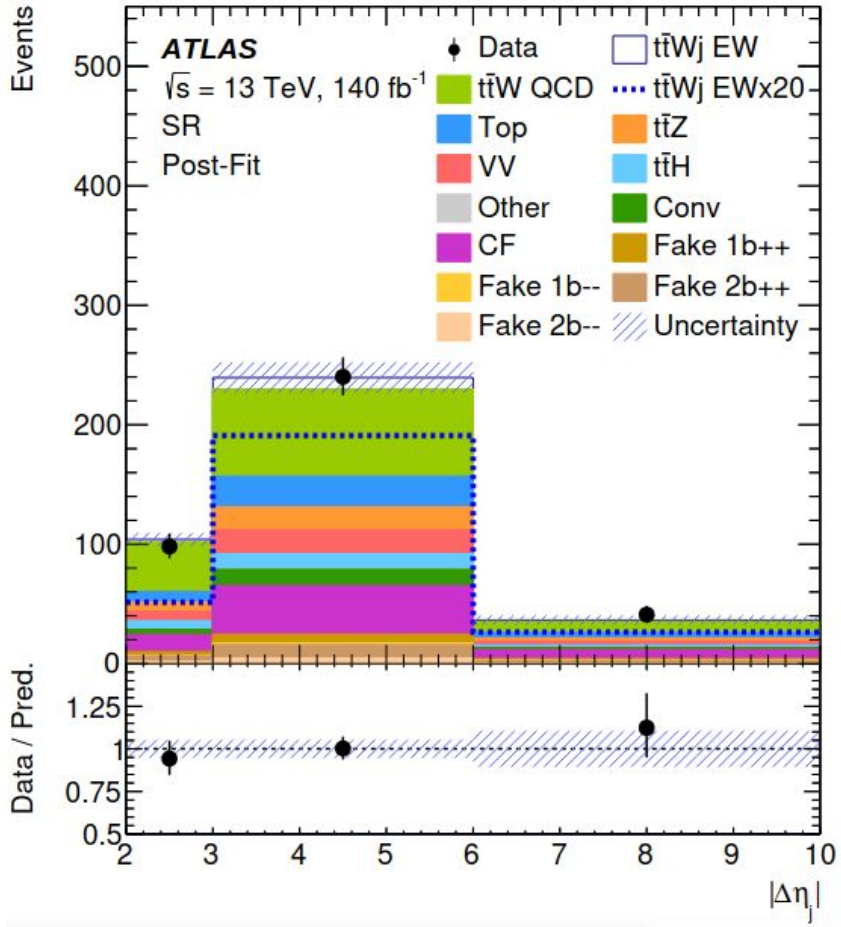
NLO QCD+EWK 12-13%

Probing tW→tW scattering in ttW production

Dedicated analysis targeting ttW electroweak production



- **Final state**:
  - 2 same-sign leptons
  - 1 spectator quark
  - Additional jet activity
- **Dedicated categories to constrain backgrounds**
- **Dominated by ttW QCD normalization and jet uncertainties**

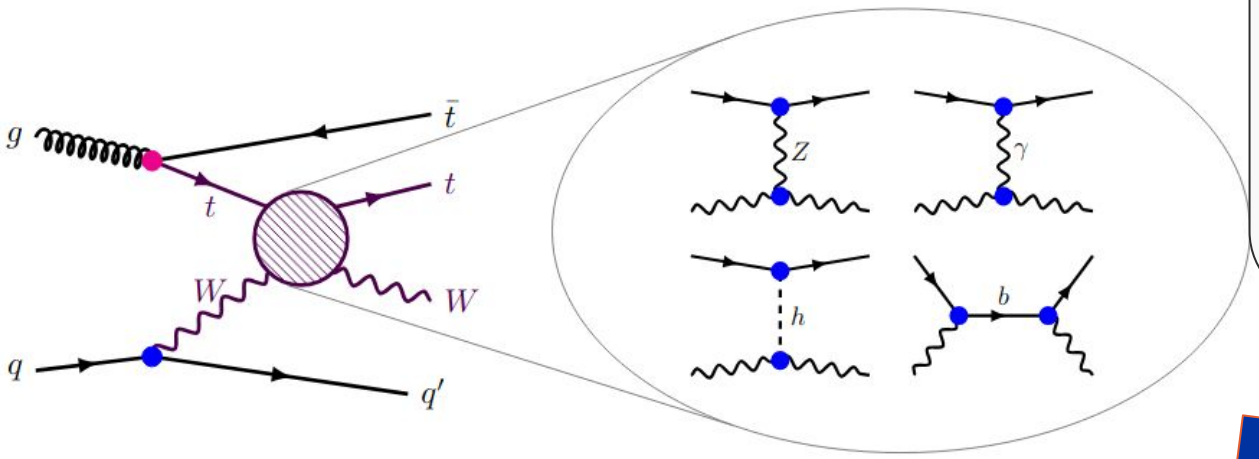


Upper limit on $\sigma_{ttW\text{-}EW}$ < 251 fb

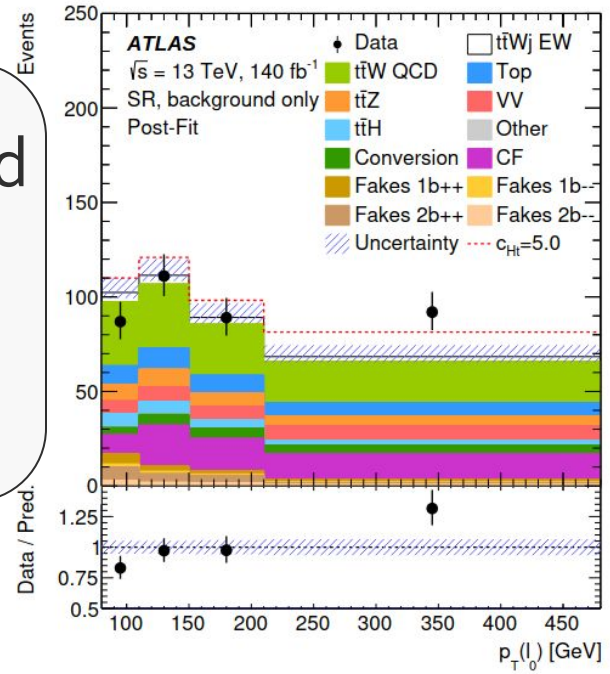
$\sigma_{ttW\text{-}EW}$ (SM) = 48 fb

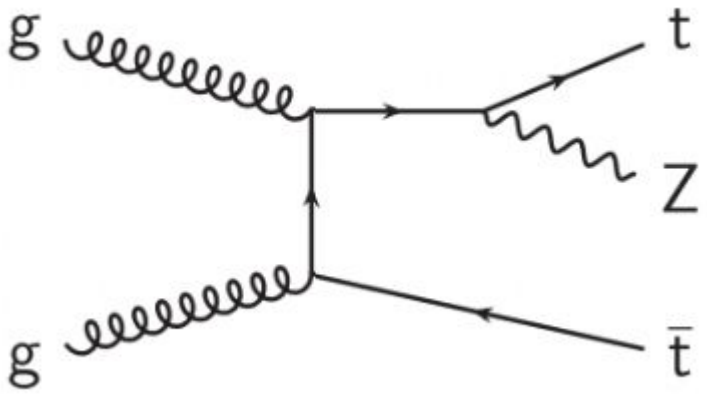
First time presented @ Moriond!

EFTs in tW→tW scattering



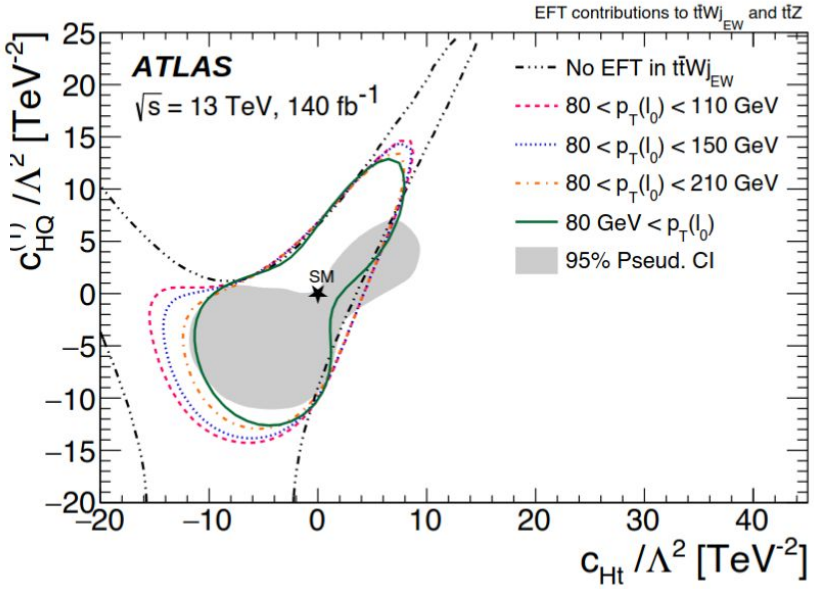
Electroweak ttW and ttZ allow to lift flat directions in EFT parameter space





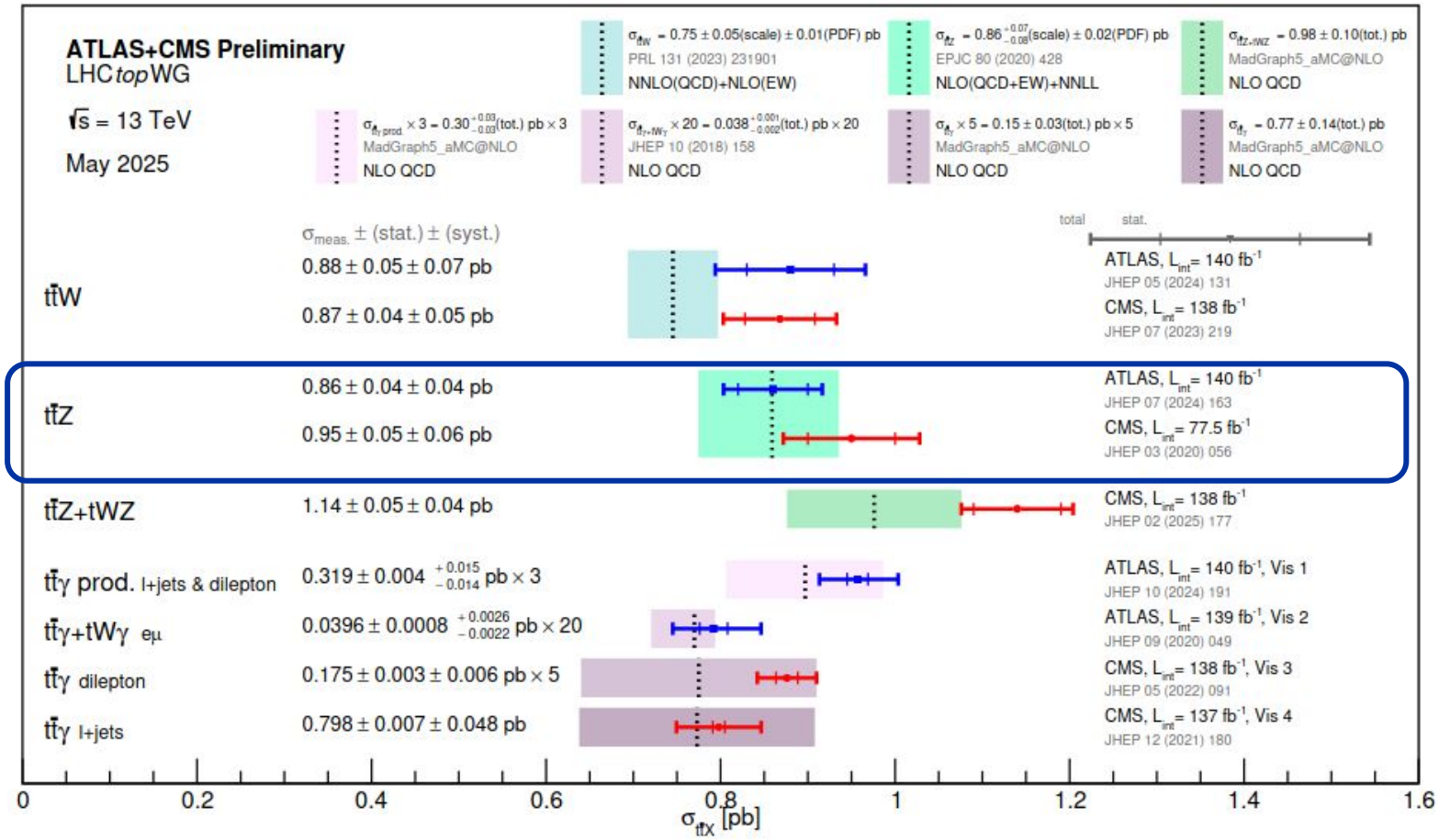
$$\frac{c_{Ht}}{\Lambda^2} O_{Ht} = \frac{c_{Ht}}{\Lambda^2} (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R)$$

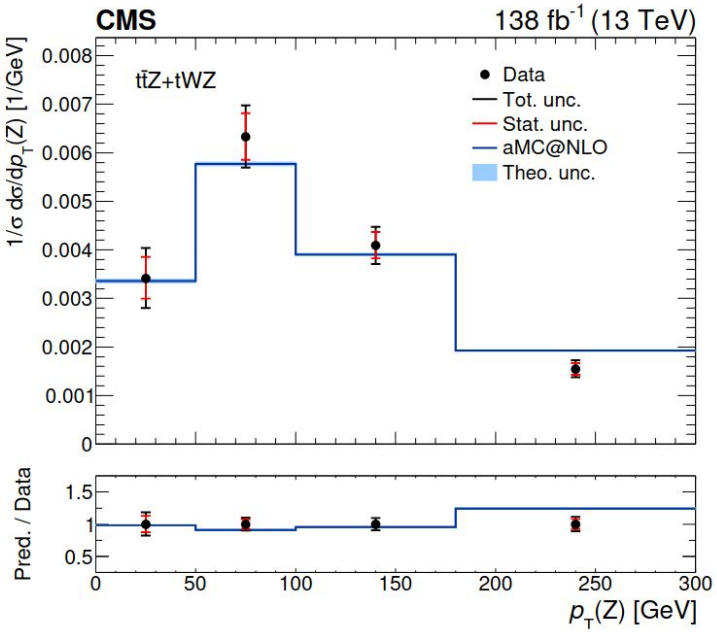
$$\frac{c_{HQ}^{(1)}}{\Lambda^2} O_{HQ}^{(1)} = \frac{c_{HQ}^{(1)}}{\Lambda^2} (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$$



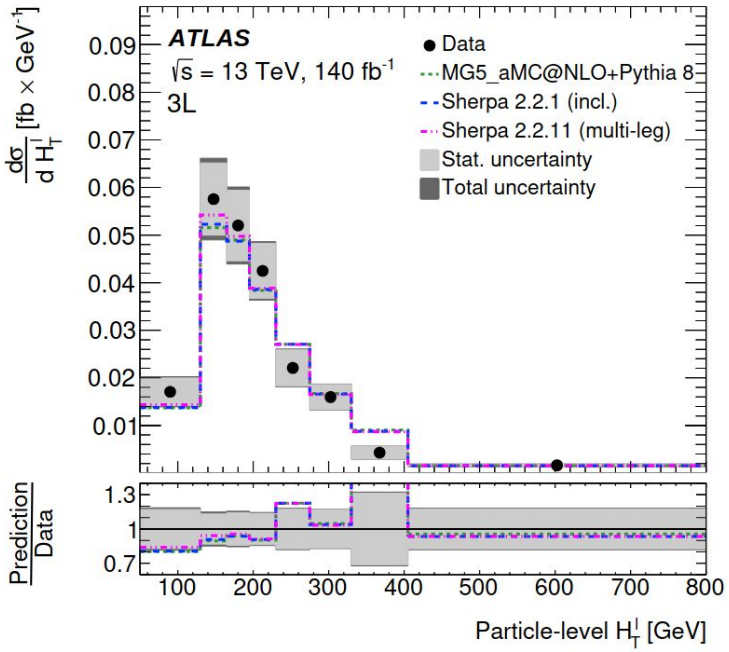
arXiv:2509.19038

ttZ production in ATLAS and CMS





JHEP 02 (2025) 177

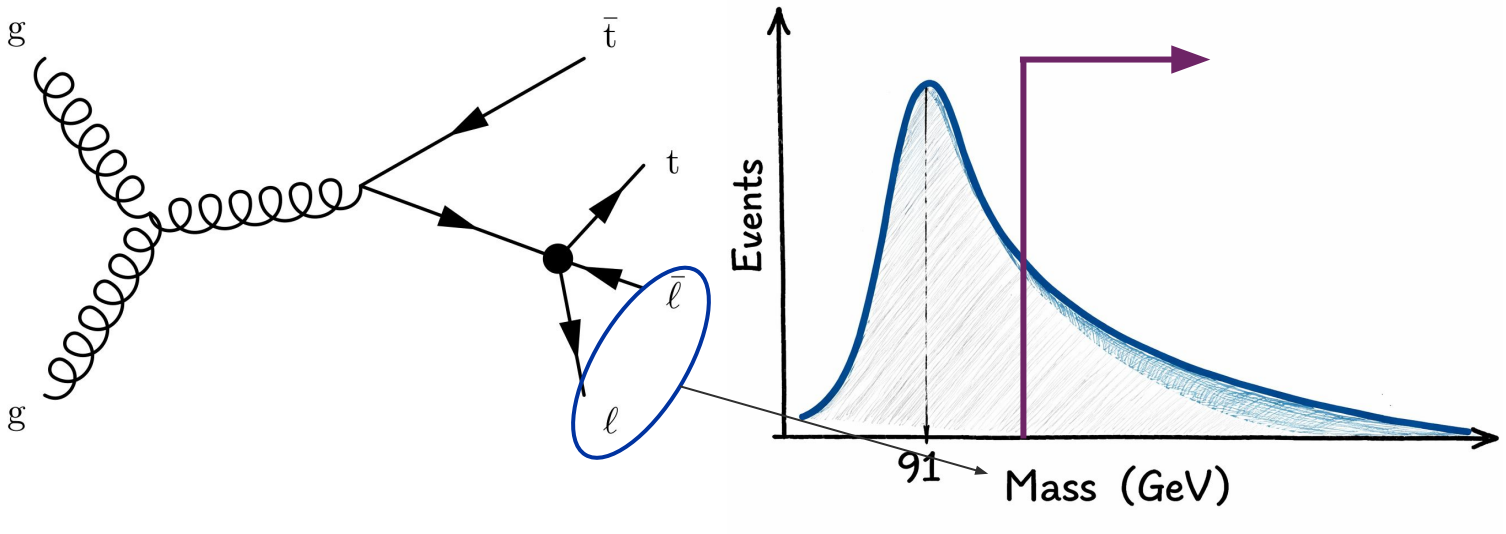


JHEP 07 (2024) 163

ttZ high mass measurement

First time presented @ Moriond!

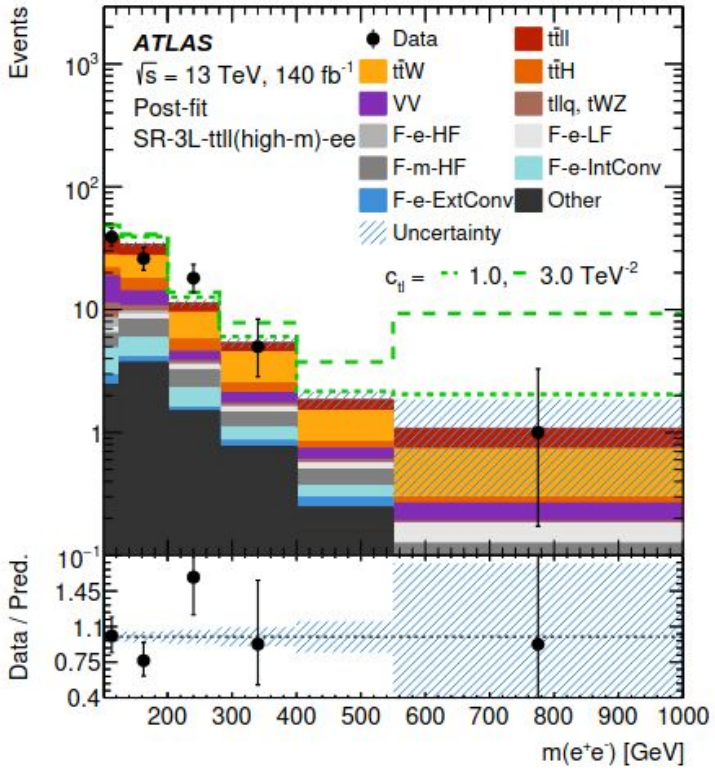
- ttll high mass by ATLAS (EPJC 85, 1434 (2025))
- Sensitivity to new physics coupling to leptons and top quarks
- Also probed in a global analysis by CMS (JHEP 12 (2023) 068)

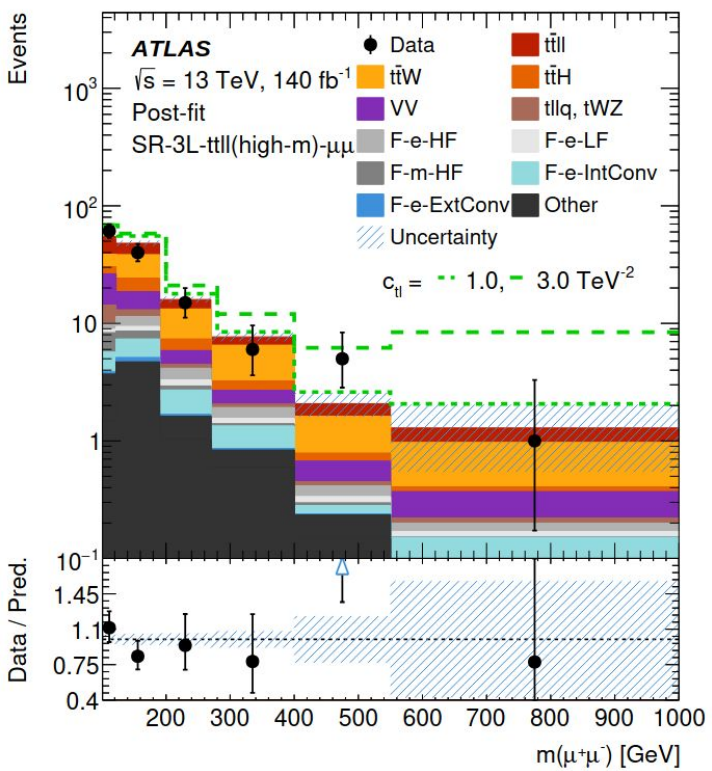


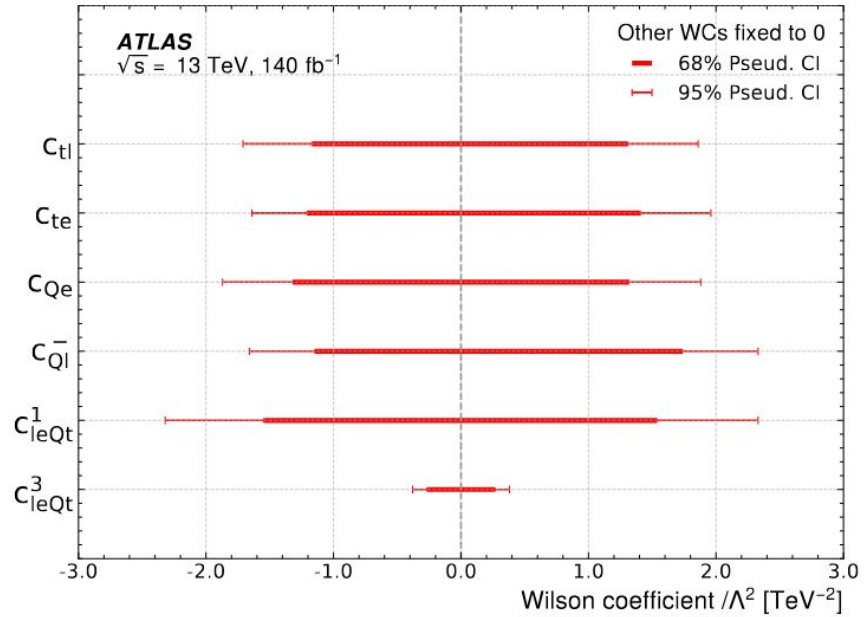
- Searching for events with 3 leptons:
  - 1 from the top
  - 2 not compatible with a Z boson
- With additional (b)-jets
- ttZ and ttW are the dominant backgrounds

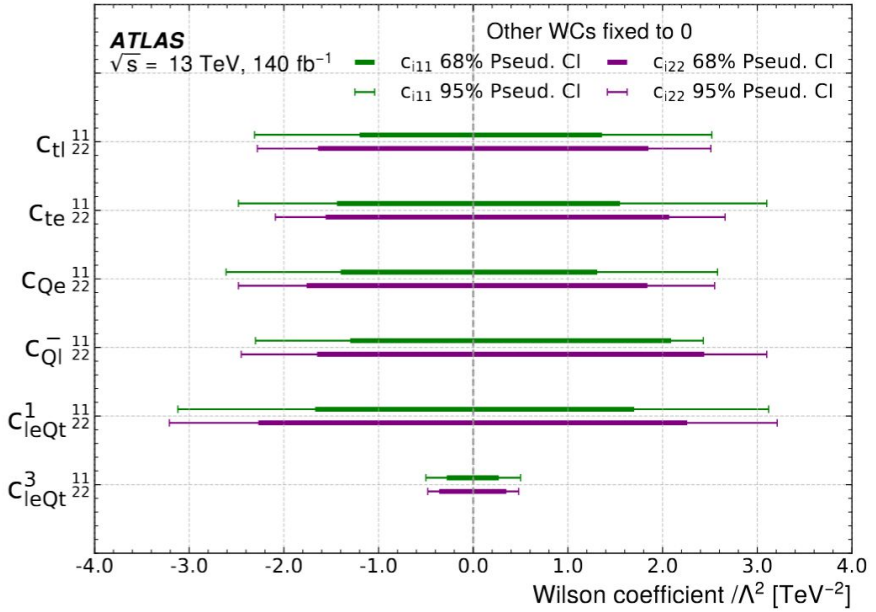
ttZ high mass measurement

- Analysis used to probe different top+lepton contact interactions
- Sensitivity separately for electrons and muons









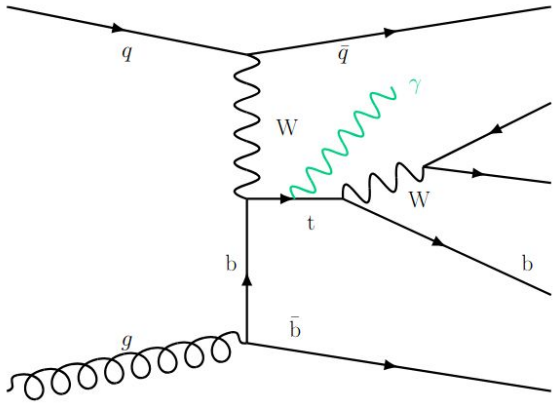
EPJC 85, 1434 (2025)

Simultaneous measurement of tty and tqγ

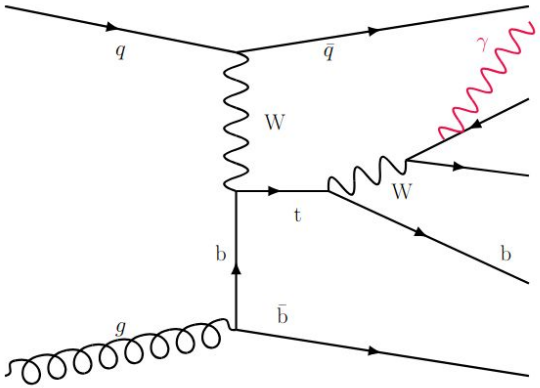
NEW result
CMS-PAS-TOP-25-003

- Complementary to the dedicated analysis on tqγ by ATLAS (PRL 131, (2023) 181901)
- First observation of tqγ by CMS and first differential measurement ever!

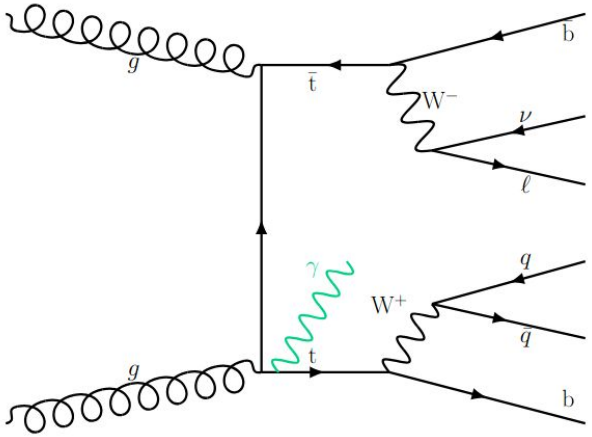
tqγ production



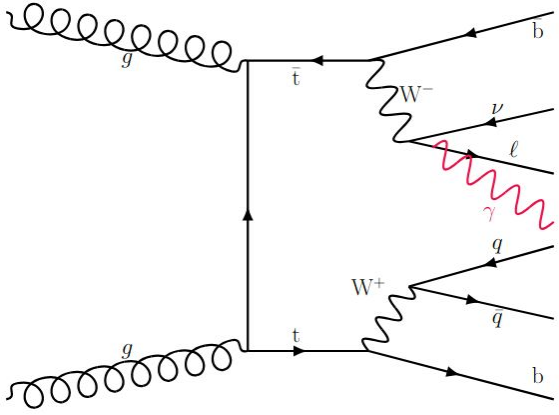
tqγ decay



ttγ production

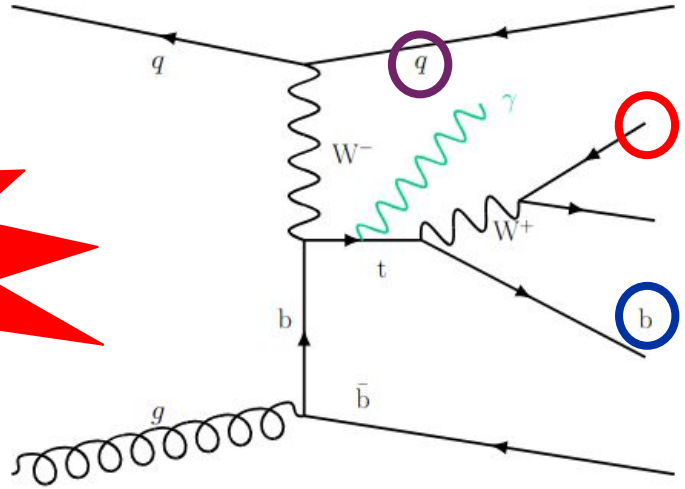


ttγ decay

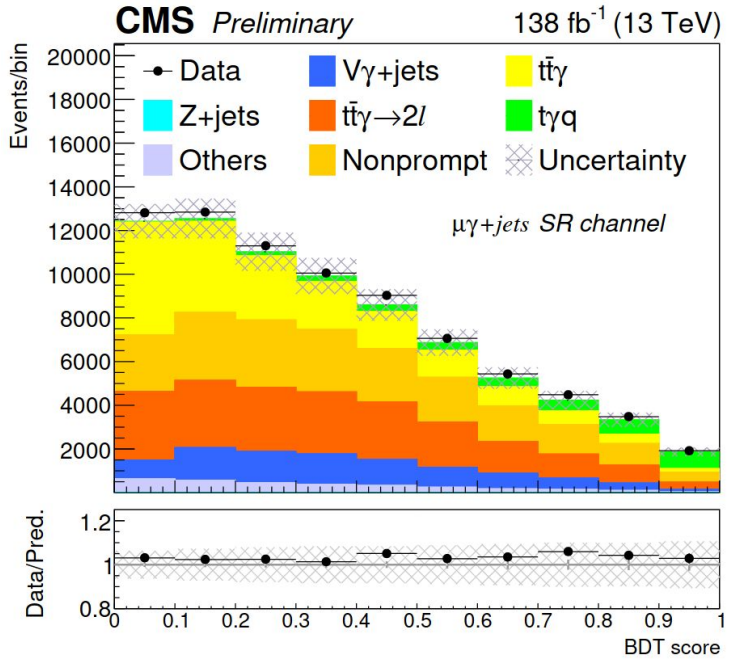


Simultaneous tty and tqy measurement

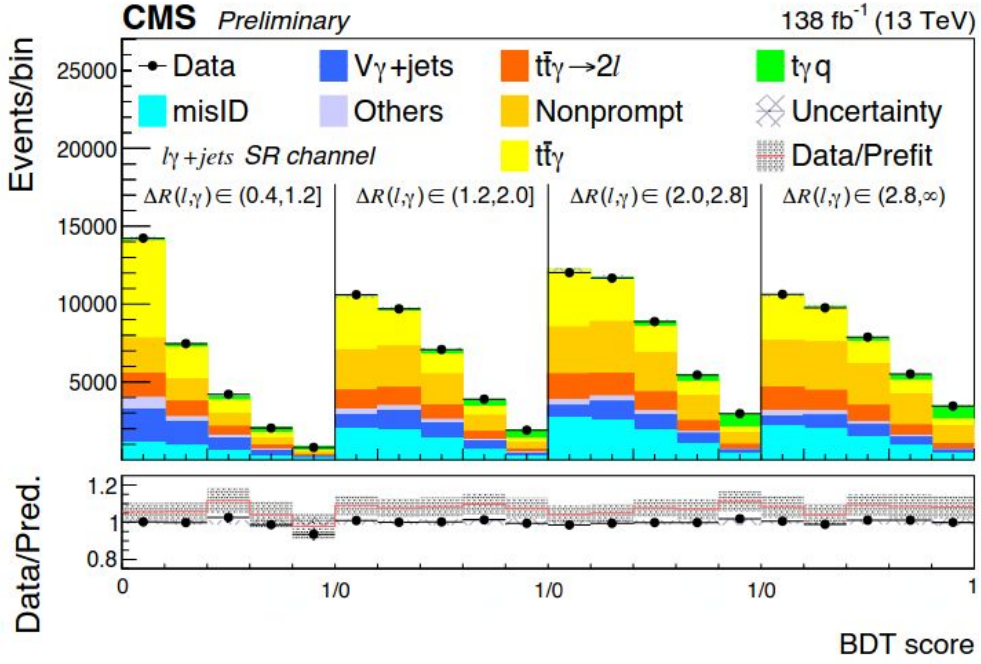
NEW result
CMS-PAS-TOP-25-003



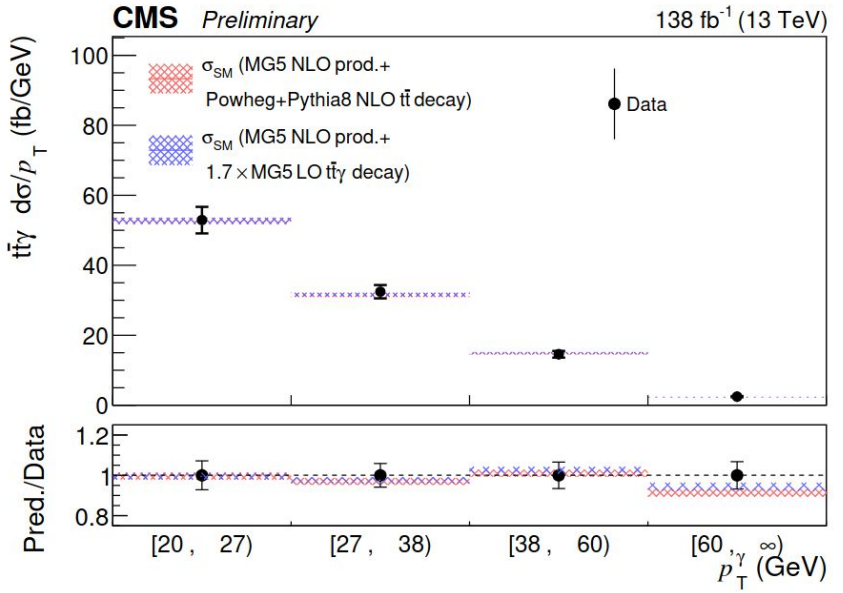
- Topology characterized by 1 lepton, 1 b-tagged jet and one spectator jet
- Leading backgrounds due different processes, constrained in dedicated control regions:
  - Nonprompt leptons and photons
  - Electrons misidentified as photons
  - Wγ production
  - Dileptonic tty
- Dedicated BDT trained to separate tty and tqy

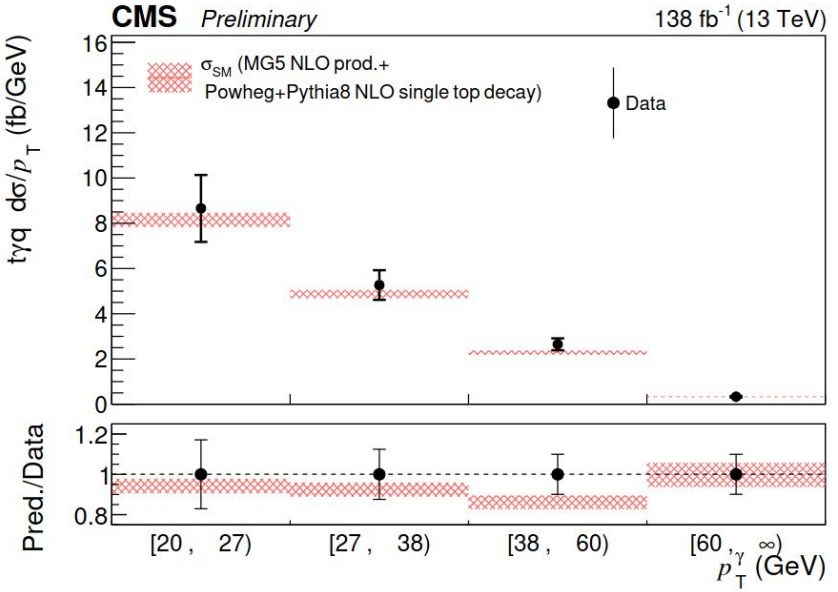


Simultaneous tty and tqy measurement



NEW result
CMS-PAS-TOP-25-003





- Simultaneous measurement of tty and tqy inclusively and differentially

  $\sigma_{tγq}$ = 236 +/- 17 fb $\sigma_{tγq}$(SM)= 207 +/- 9 fb

  $\sigma_{ttγ}$ = 1445 +/- 80 fb $\sigma_{ttγ}$(SM)= 1369 +/- 23 fb

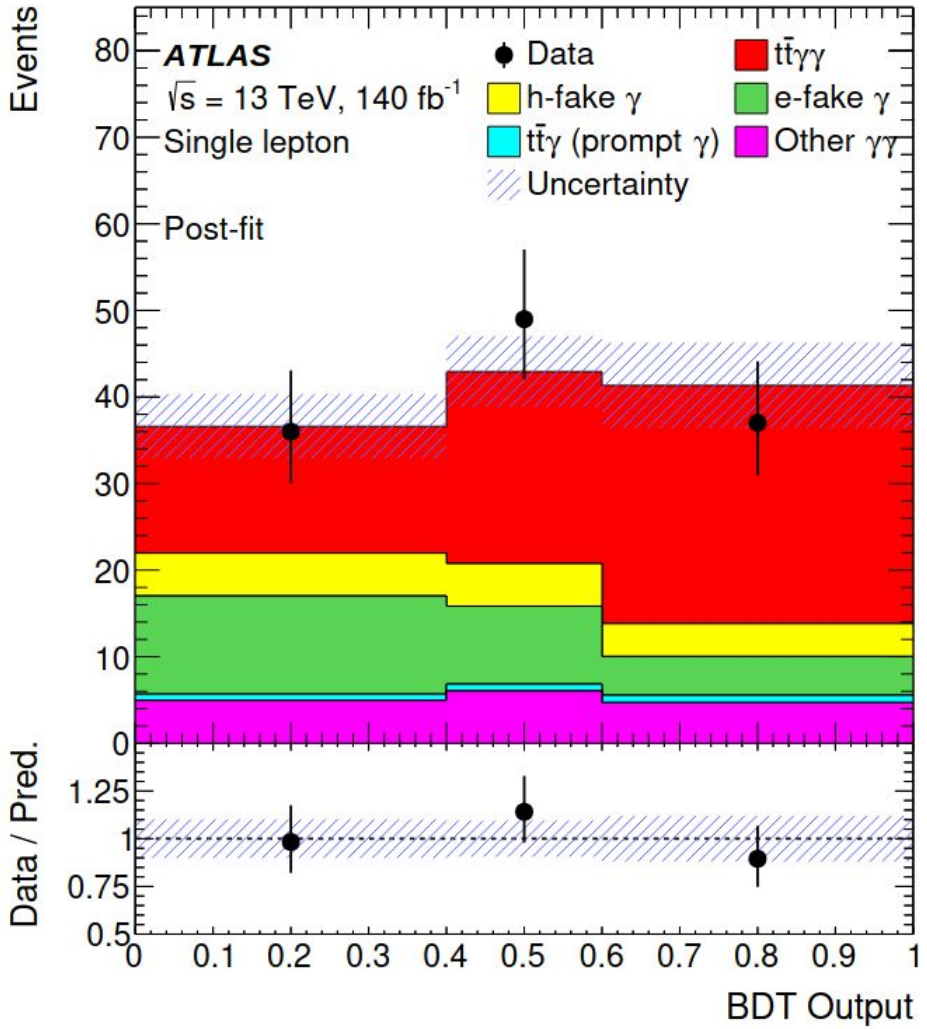
- Results consistent with the predictions

Even rarer… top+dibosons

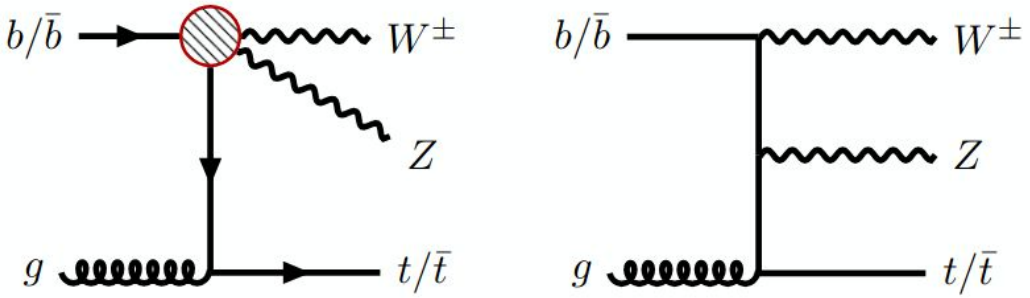
First time presented @ Moriond!

- **First observation** of ttγγ by ATLAS (Phys. Lett. B 874 (2026) 140195)
- Minuscule fiducial cross section *O*(2fb)
- Enhanced sensitivity to EFT, irreducible background to ttH production
- Very clean and pure selection: 1 lepton, 2 photons, 4 jets
- BDT used to enhance the sensitivity

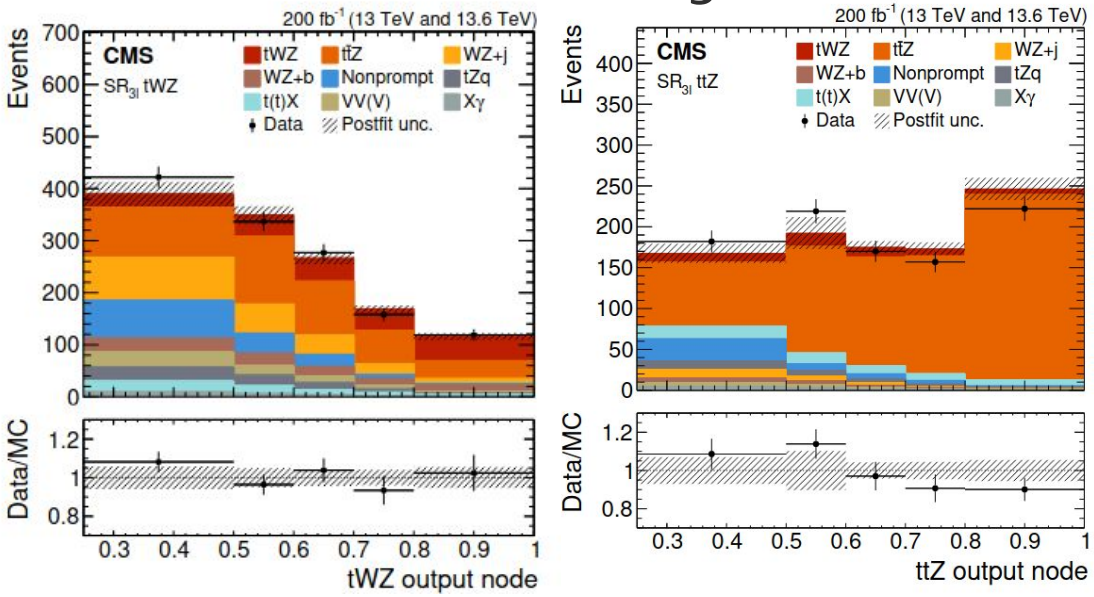
- **Observed significance** for ttγγ: 5.2 σ
- $\sigma_{tt\gamma\gamma}$ = 2.42 + 0.58 - 0.53 fb
- $\sigma_{tt\gamma\gamma}$(SM, LO) = 1.5 + 0.5 - 0.4 fb (K-factor ~ 1.7)
  - **Ratio ttγγ/ttγ** also measured consistent with the SM



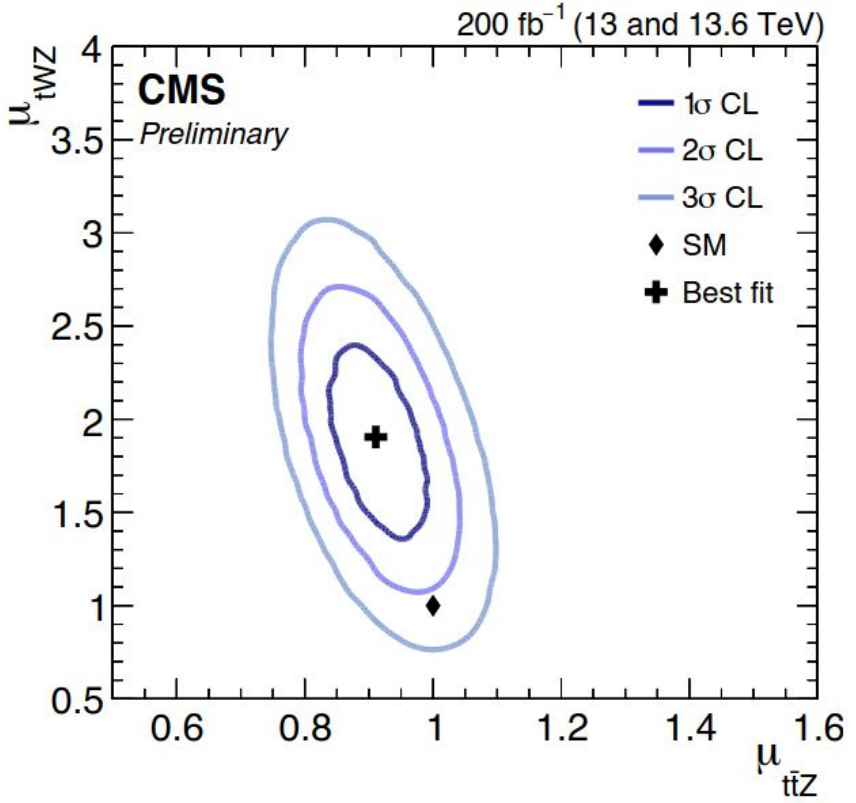
Top+dibosons… tWZ production



- tWZ production introduces additional sensitivity to BSM effects
- Interference with the ttZ background



- Enhanced ttZ/tWZ separation wrt Run 2 analysis thanks to the usage of transformers



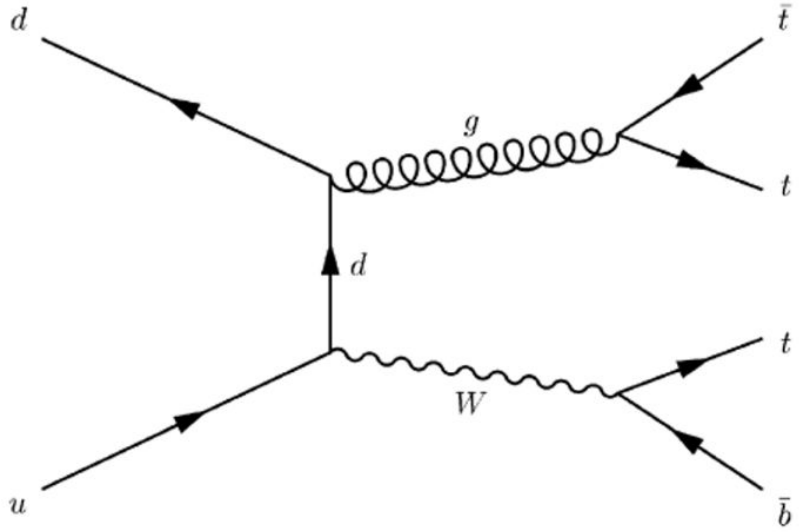
- **Observed significance for tWZ**: 5.8 σ (3.5 σ exp)

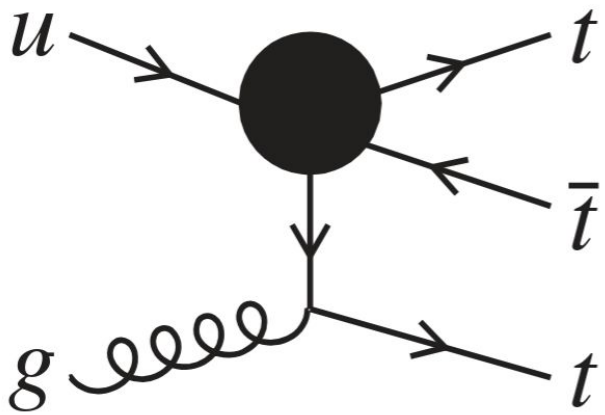
PRL 136 (2026) 081802

First time presented @ Moriond!

Search for 3top production

- Very rare production mode O(2fb), sensitive to FCNCs
- Employing two channels: single lepton and **multilepton:**
  - 2 same-sign or 3 leptons
  - additional jets and b-tagged jets
  - largest backgrounds: ttW and nonprompt leptons



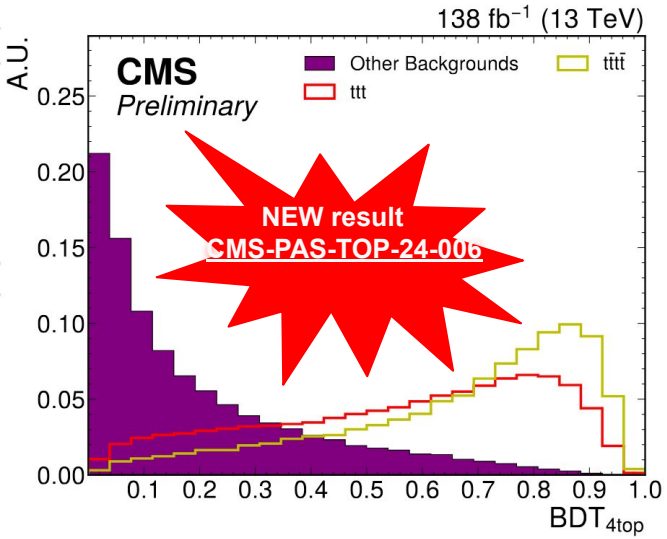


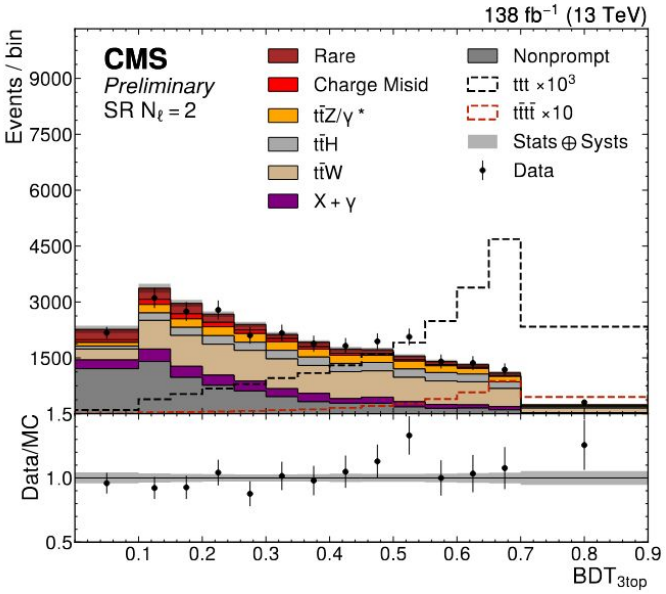
NEW result
CMS-PAS-TOP-24-006

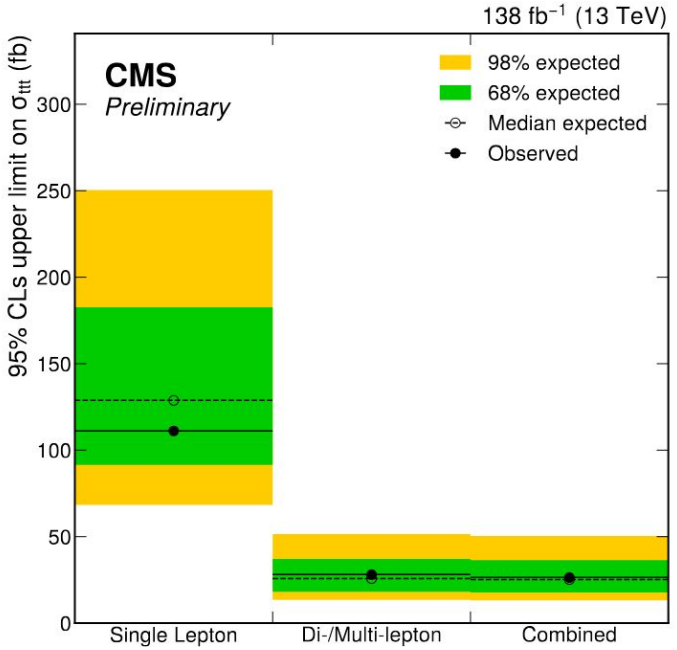
Search for 3top production

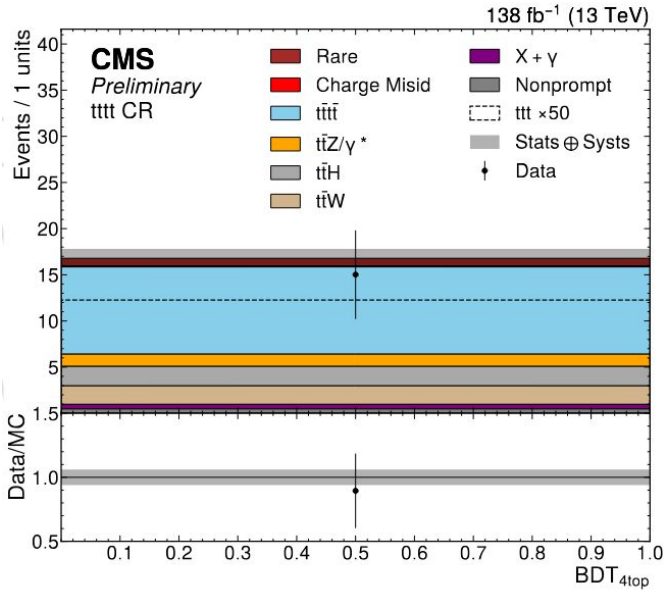
- BDT to discriminate 4tops from background+3top
- BDT to discriminate 3tops from background

- Upper limit on signal strength σ_{ttt} < 25 fb (26 fb exp)
- σ_{ttt} (SM) = 2 fb
- Measurement **limited by statistical** uncertainty



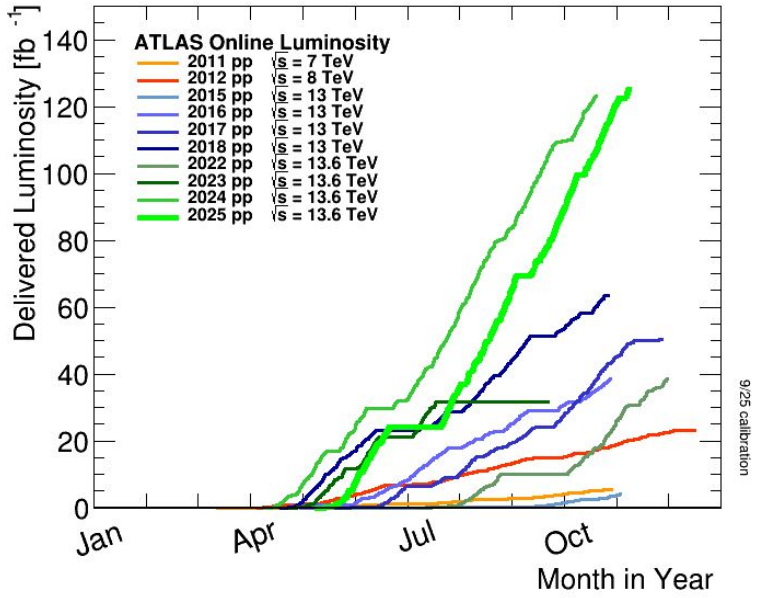


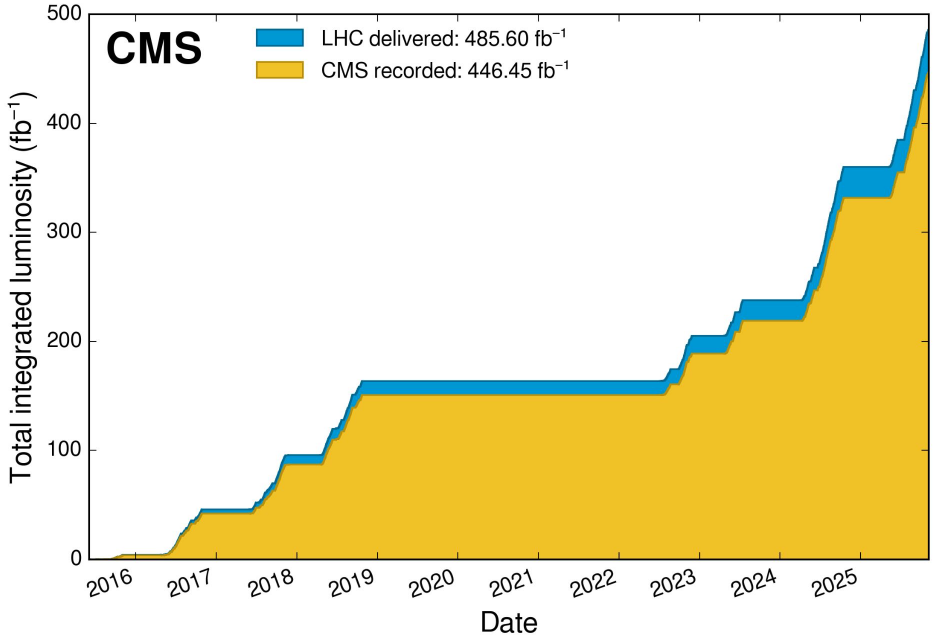




Conclusions

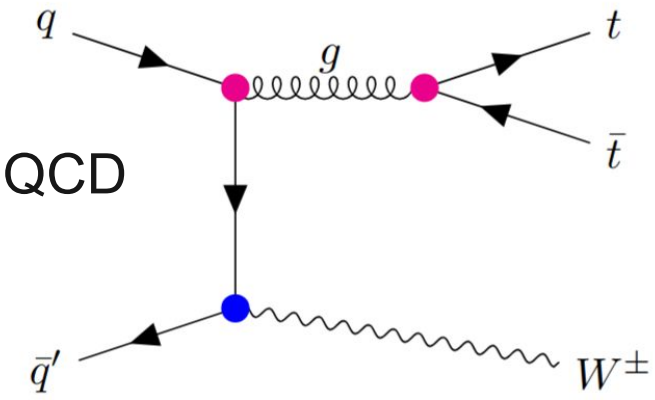
- Presented the most recent set of results on rare top quark production
- Excellent tests of the SM and probes for new physics
- Mild tensions observed in some channels, but no clear picture (yet?)
- High luminosity allows us to explore even rarer processes!
- Upcoming results with Run 3 data:
  - twice the luminosity, new sqrt(s)



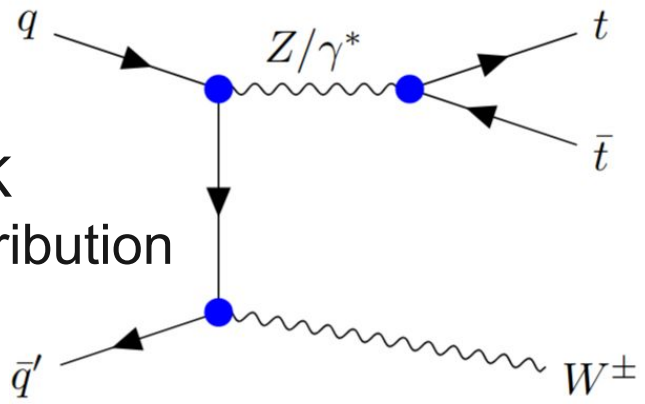


Back-up

ttW structure

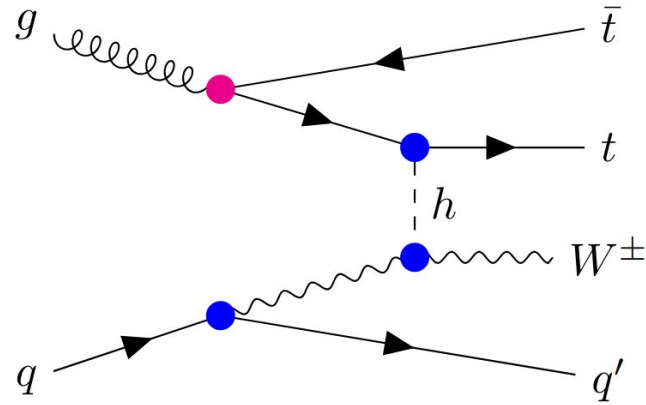


LO QCD



EWK contribution

	Naive estimation*	Actual correction
LO_1 α_s	O(10%)	30-60%
LO_1 α	O(1%)	-4 %
LO_2 α_s	**O(0.1%)**	**12-13 %**
LO_2 α	O(0.01%)	0.02-0.05 %



tW→tW scattering

JHEP 01 (2016) 071

EPJC 80, 803 (2020)

*See talk by R. Frederix in LHCtopWG meeting

tW → tW scattering - signal regions

	Preselection	Signal Region
Leptons	2 same-charge leptons	2 same-charge leptons
$p_T(l_0)$	> 28 GeV	> 80 GeV
$p_T(l_1)$	> 20 GeV	> 40 GeV
$\|\eta(e)\|$	< 2.0	< 2.0
$\|\eta(\mu)\|$	< 2.5	< 2.5
N (jets)	≥ 3	≥ 4
N (b-jets)	≥ 1	≥ 1
$p_T(j_0)$	—	> 60 GeV
m_{ll}	> 30 GeV	> 125 GeV
m_{ee}	—	∉ [81.1, 101.1] GeV
$\|\Delta\eta_j\|$	—	> 2.0
$\sum p_T(j)$	—	> 250 GeV
Conversion radius (e)	—	≥ 50 mm

tW → tW scattering - background control regions

Control Regions	3J-CR	4J-lo$\Delta\eta$-CR	4J-hi$\Delta\eta$-CR	Conv-CR	CF-CR	3L-CR ($t\bar{t}Z$)	3L-CR
Leptons	2 same-charge	2 same-charge	2 same-charge	2 same-charge (ee or $e\mu$)	2 same-charge ee	3 leptons	3 leptons
$p_T(l_0)$	> 28 GeV	> 28 GeV	> 80 GeV	> 28 GeV	> 50 GeV	> 28 GeV	> 28 GeV
$p_T(l_1)$	> 20 GeV	> 20 GeV	> 20 GeV	> 20 GeV	> 30 GeV	> 20 GeV	> 20 GeV
$p_T(l_2)$	—	—	—	—	—	> 20 GeV	> 20 GeV
N(jets)	= 3	≥ 4	≥ 4	≥ 4	≥ 3	≥ 4	= 3
N(b-jets)	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	≥ 2	= 1
$p_T(j_0)$	—	> 60 GeV	> 60 GeV	> 60 GeV	> 60 GeV	> 60 GeV	—
m_{ll}	> 160 GeV	> 30 GeV	> 30 GeV	> 30 GeV	—	SFOC, ∈ [81.1, 101.1] GeV	—
m_{ee}	∉ [81.1, 101.1] GeV	∉ [81.1, 101.1] GeV	∉ [81.1, 101.1] GeV	∉ [81.1, 101.1] GeV	∈ [81.1, 101.1] GeV	—	—
$\lvert\Delta\eta_j\rvert$	—	< 2.0	> 2.0	(< 2.0 OR	—	—	—
$\sum p_T(j)$	—	—	—	< 250 GeV)	—	—	—
Conversion radius (e)	—	≥ 50 mm	≥ 50 mm	< 50 mm	≥ 50 mm	—	—
E_T^{miss}	—	—	—	—	< 100 GeV	—	—
Veto condition	—	—	SR Veto	—	—	—	—

ttW QCD + nonprompt

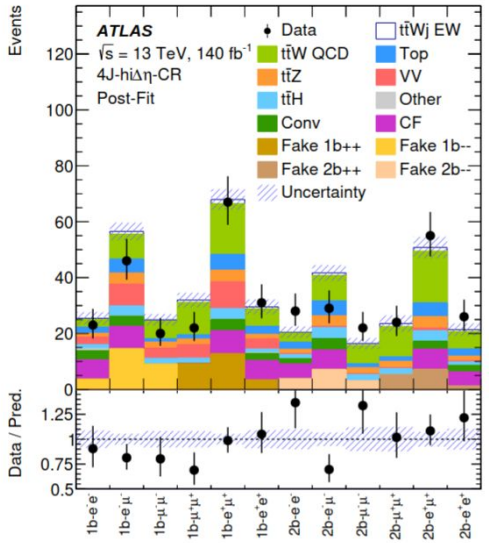
flavor, nb, lep charge-binned

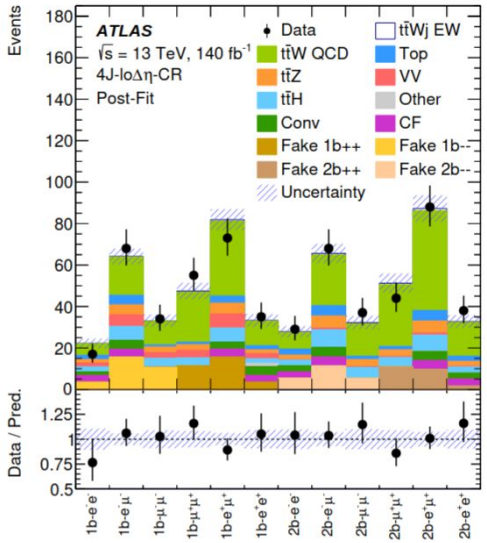
Charge flips

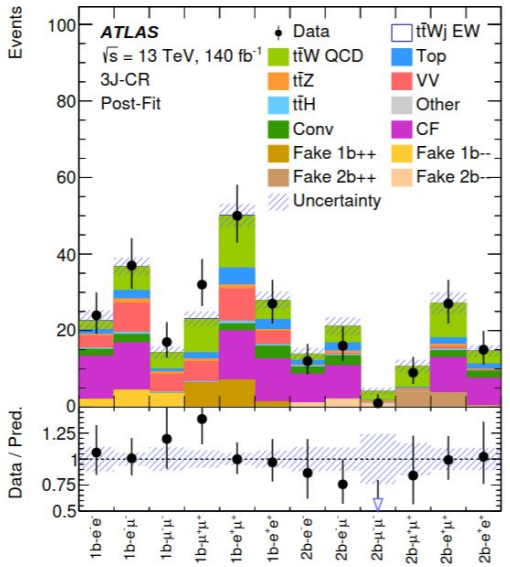
ttZ **Diboson**

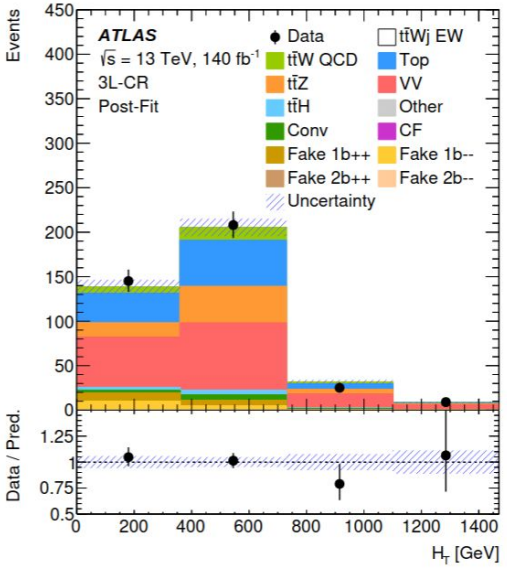
HT binned

tW → tW scattering - background control regions





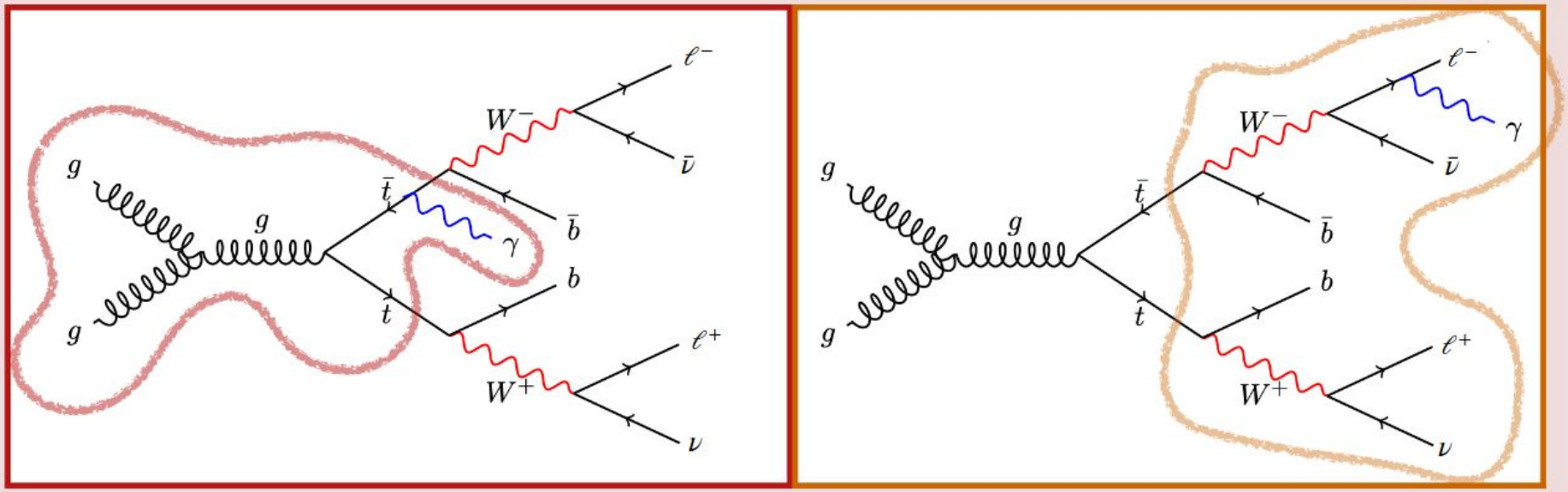




ttγ, tqγ - production and decay

The $t\bar{t}\gamma$ process contains:

- $t\bar{t}\gamma$ production: photons from initial state quarks or off-shell top quarks
- $t\bar{t}\gamma$ decay: photons emitted in the top quark decay chain



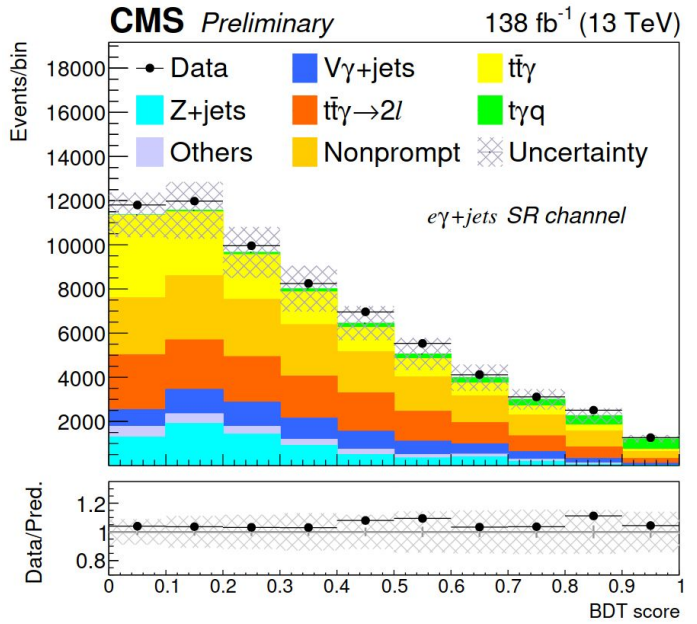
Sketches by Beatriz Ribeiro

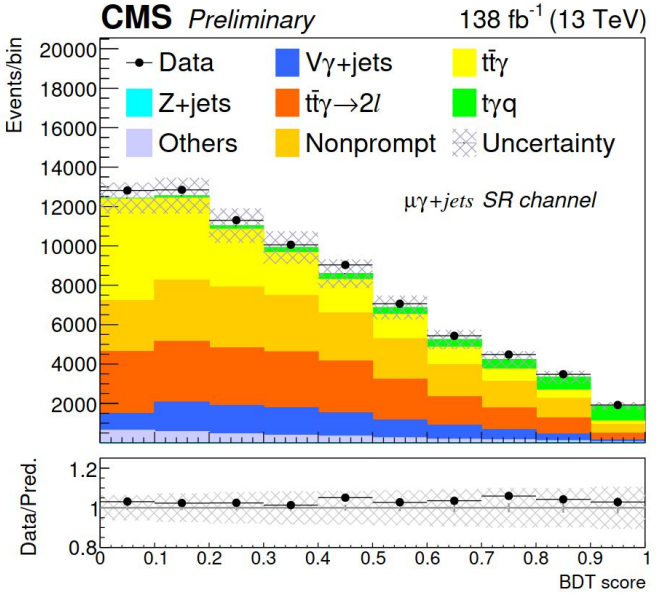
ttγ, tqγ - BDT

Input variables:

Observable	Objects
p_T (GeV)	ℓ, γ, b jet, light-flavor jet, $\text{top}_{\text{had.}}$
η	ℓ, γ, b jet, light-flavor jet
ΔR	(ℓ, j), (ℓ, γ), (j, γ)
$\Delta\eta$	$(\text{top}_\ell, \gamma)$, $(\text{top}_{\text{had.}}, \gamma)$
Mass	top_ℓ, $\text{top}_{\text{had.}}$, $m_{\ell\gamma}$, m_T^W
Energy	reco W, E_T^{miss}
N	$N_{\text{central jet}}$

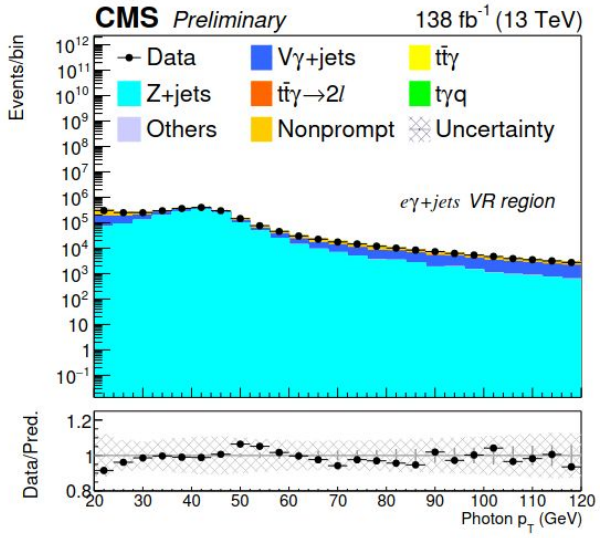
Trained to separate ttγ from tqγ
Most relevant variables: kinematics of the light flavor jet, mass of the reconstructed top

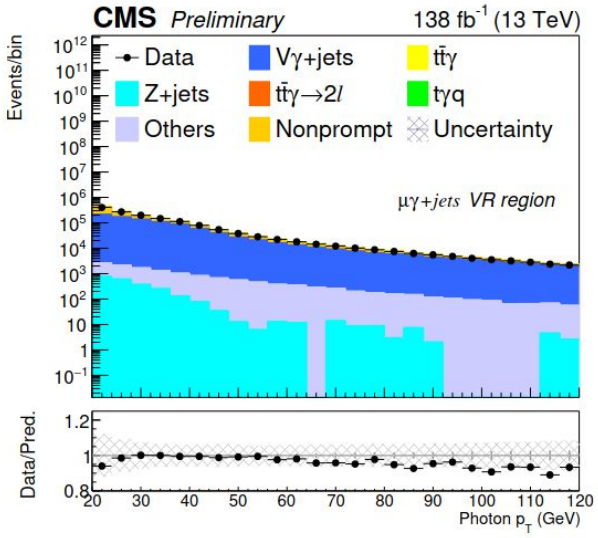


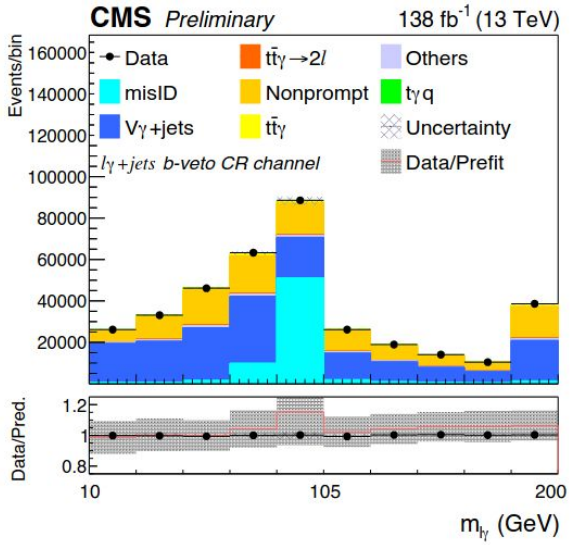


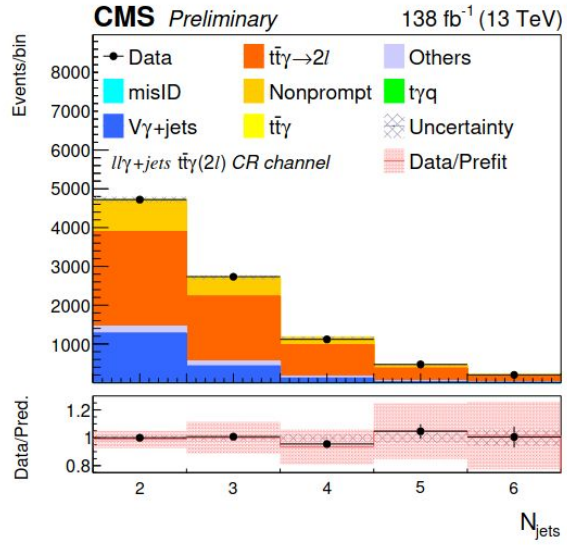
tty, tqy - background control regions

Vγ validation region: nb=0

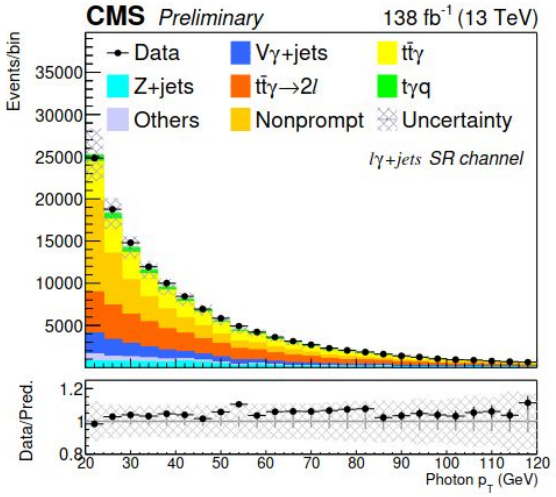


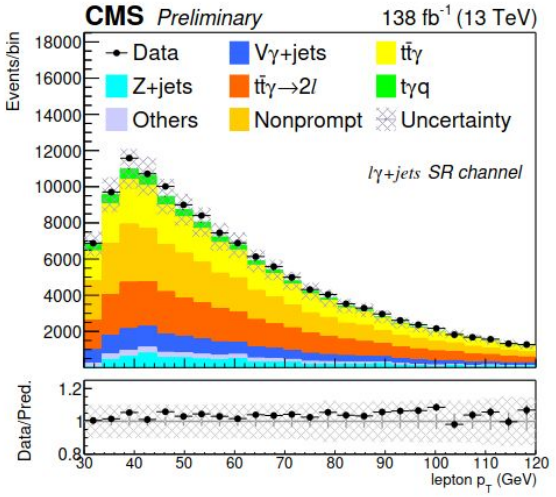


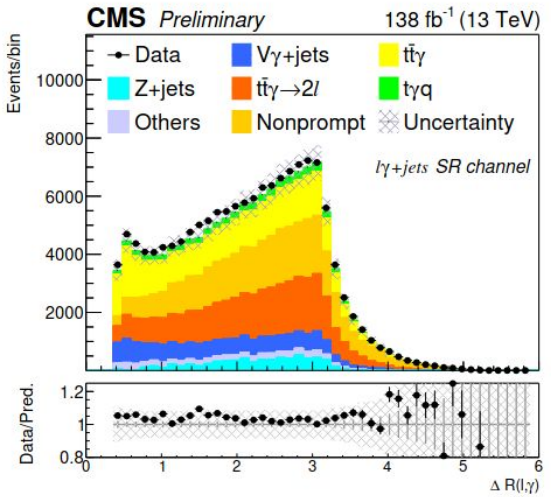


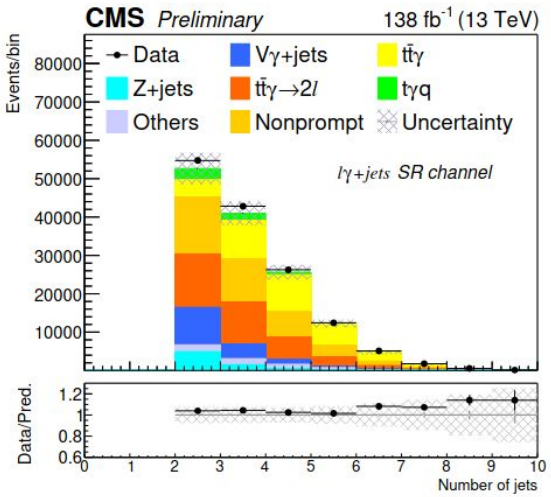


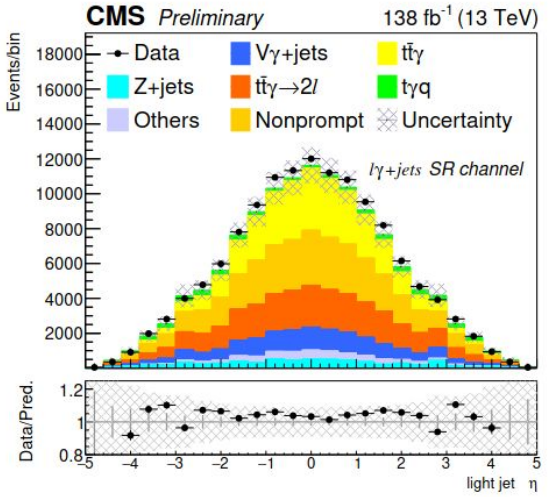
ttγ, tqγ - signal regions

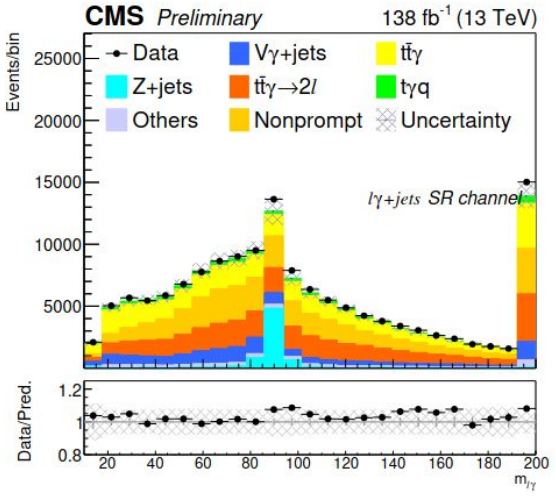


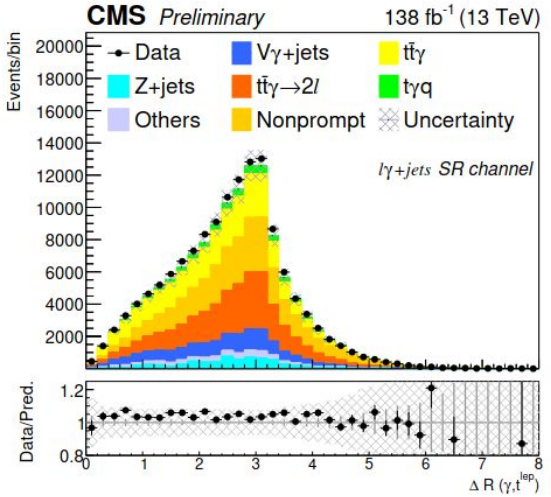


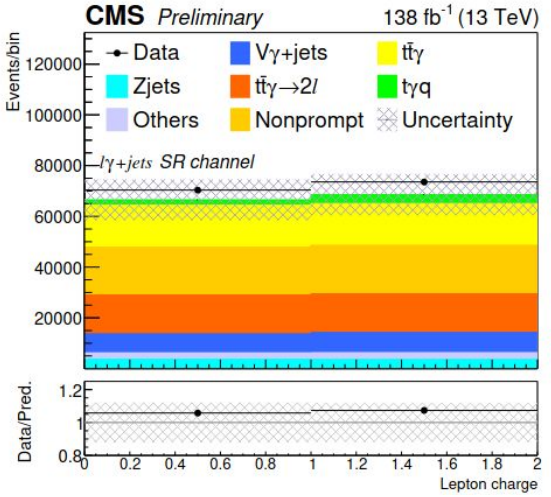




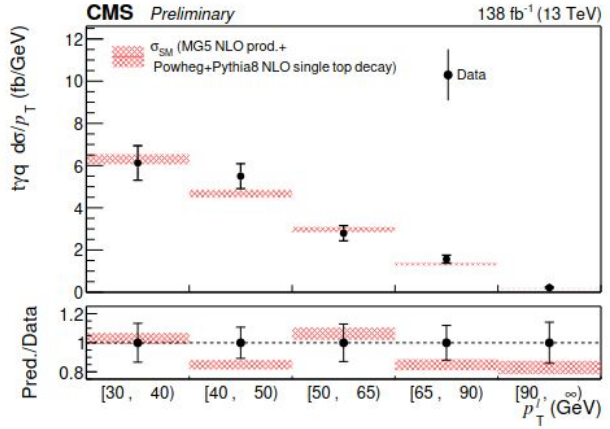


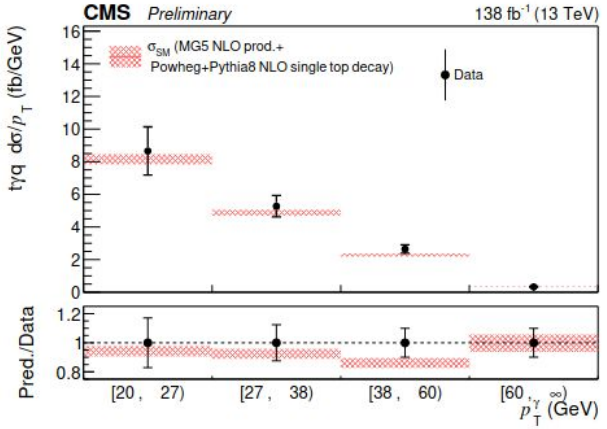


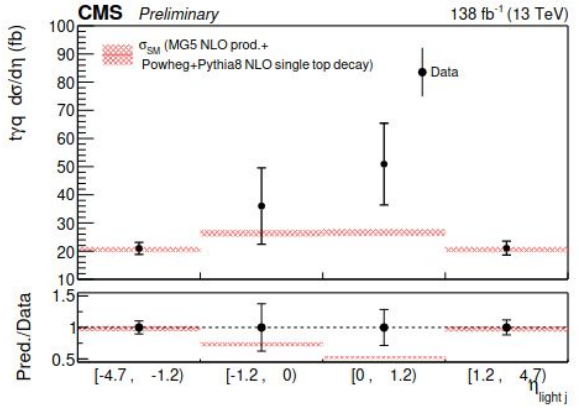


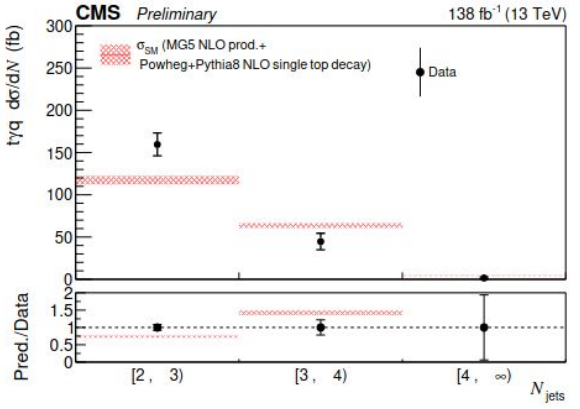


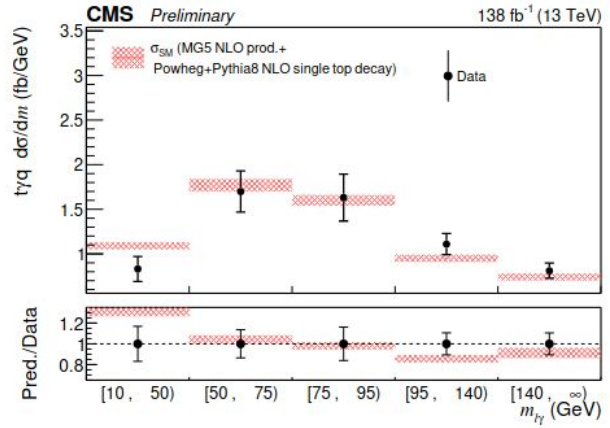
ttγ, tqγ - unfolded distributions

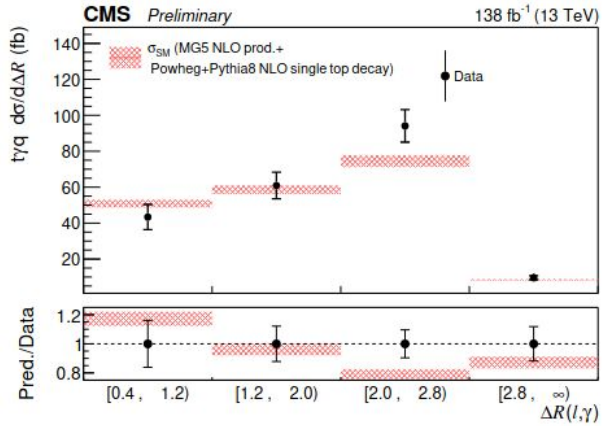


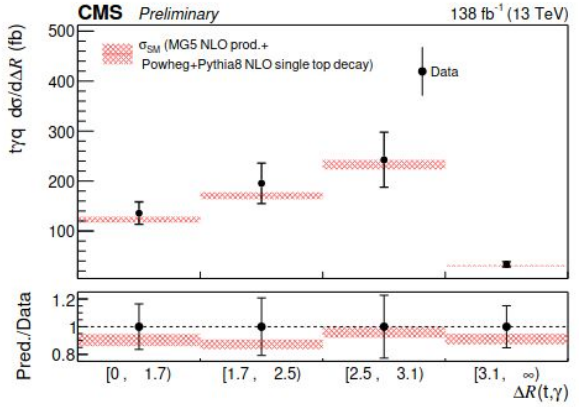


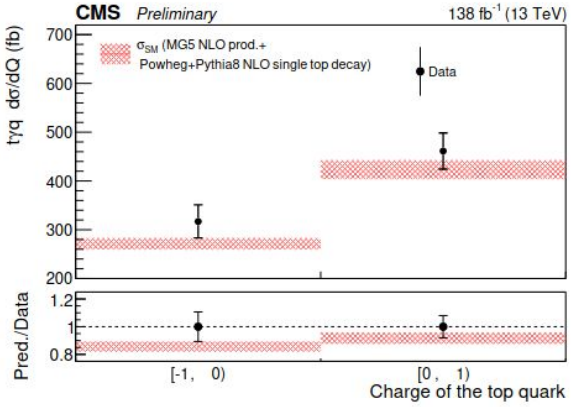








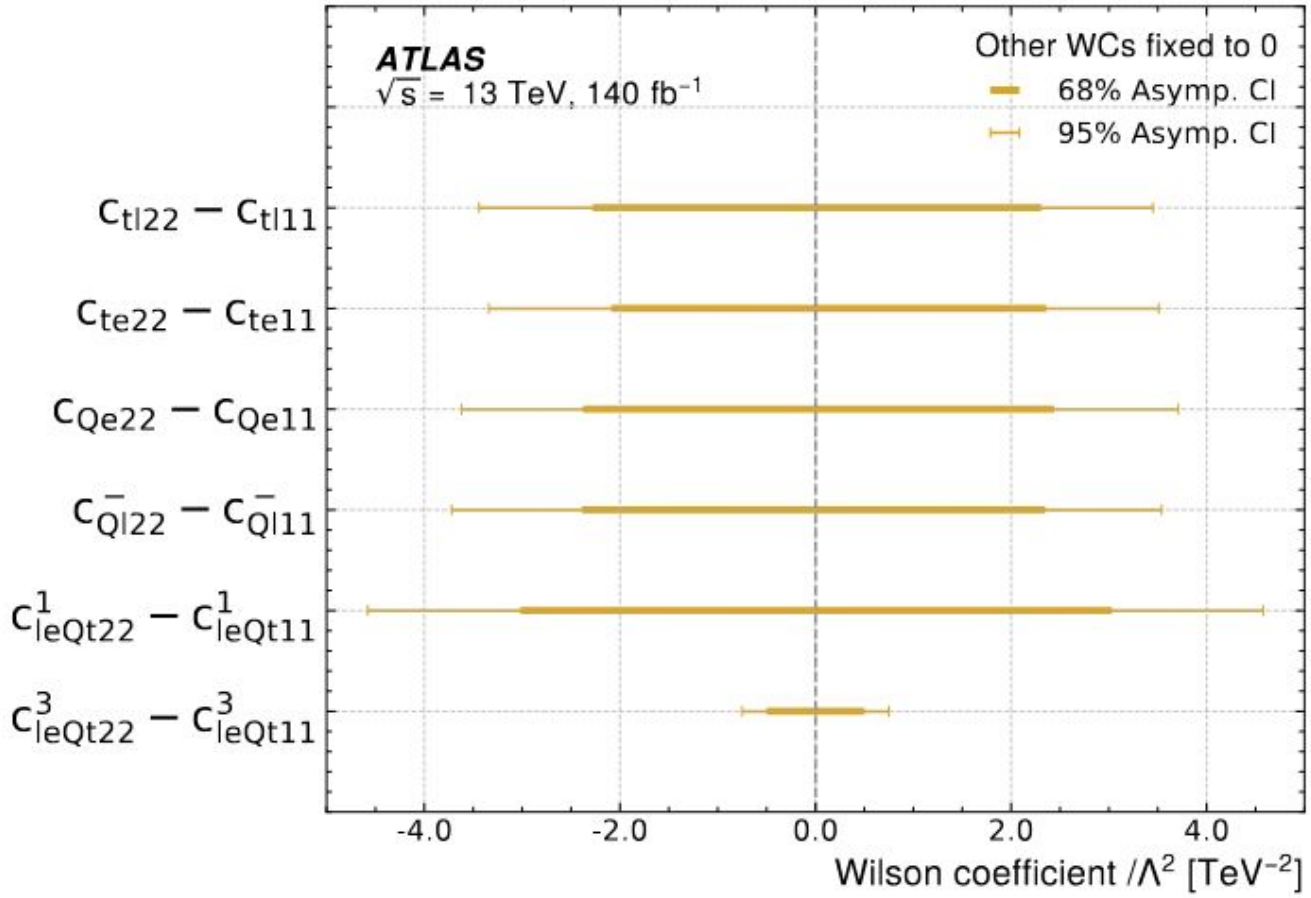




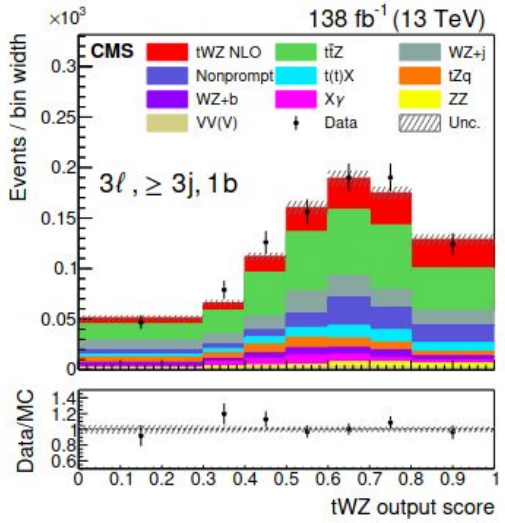
ttγ, tqγ - systematic uncertainties

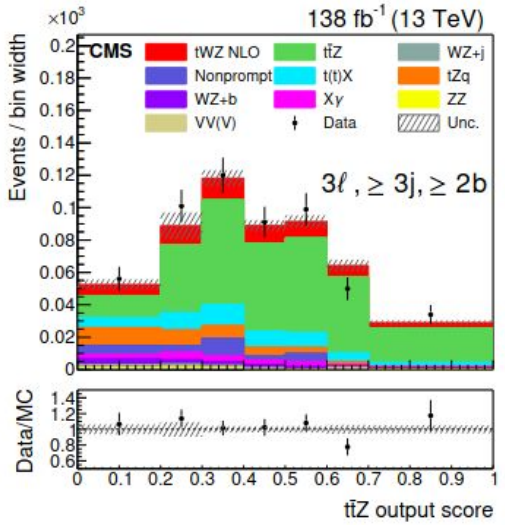
Systematic uncertainty	Impact from inclusive fit [%]		Impact from differential fit [%]	
	$\mu_{t\gamma q}$	$\mu_{t\bar{t}\gamma}$	$\sum_i \mu^i_{t\gamma q}$	$\sum_i \mu^i_{t\bar{t}\gamma}$
MC statistical uncertainties	+4.2, −4.2	+2.5, −2.8	+4.8, −4.8	+2.6, −2.6
Theoretical uncertainties	+4.0, −3.9	+3.1, −2.9	+2.9, −2.8	+3.0, −2.8
Jet energy correction	+1.7, −1.9	+2.1, −2.1	+3.3, −3.2	+1.0, −1.2
N_{jet} modeling	+1.5, −2.0	+3.7, −3.9	+0.7, −0.5	+2.1, −1.9
b tagged and PU jet ID	+1.3, −1.3	+1.0, −1.0	+0.7, −0.7	+0.6, −0.7
misID normalization	+2.1, −2.1	+1.4, −1.6	+1.9, −2.1	+1.9, −1.9
Related to lepton and γ	+1.1, −1.2	+1.6, −1.4	+0.9, −0.8	+1.5, −1.4
Nonprompt bkg. estimate	+1.2, −1.4	+0.4, −0.6	+2.4, −2.5	+1.4, −1.4
Others	+2.0, −2.0	+0.1, −0.3	+1.3, −1.2	+0.2, −0.4
Integrated luminosity	+0.6, −0.9	+1.3, −1.1	+0.6, −0.5	+0.9, −0.8
Total systematic uncertainty	+6.7, −6.6	+5.5, −5.5	+6.3, −6.3	+4.8, −4.8

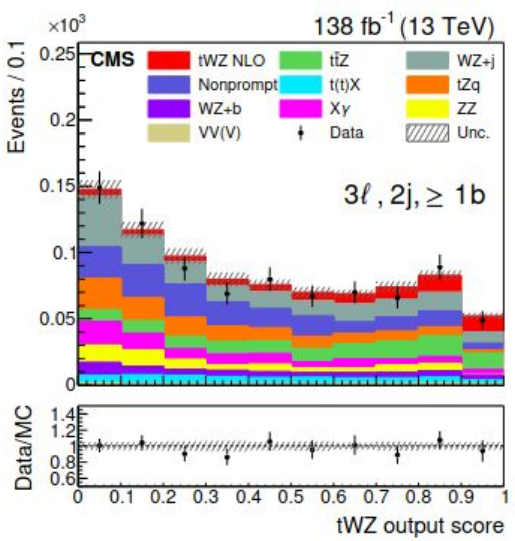
ttZ high mass - lepton flavor universality

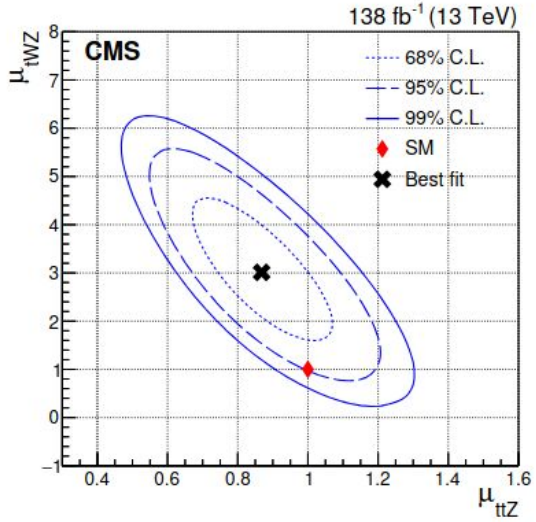


tWZ production - from evidence to observation









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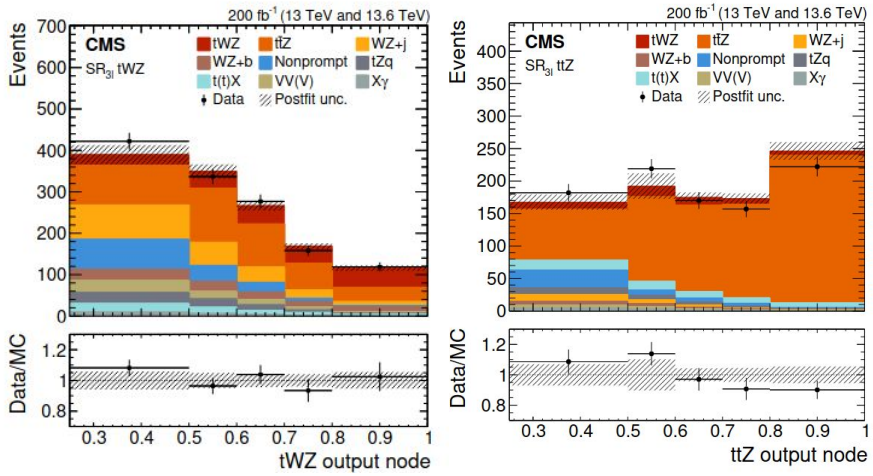

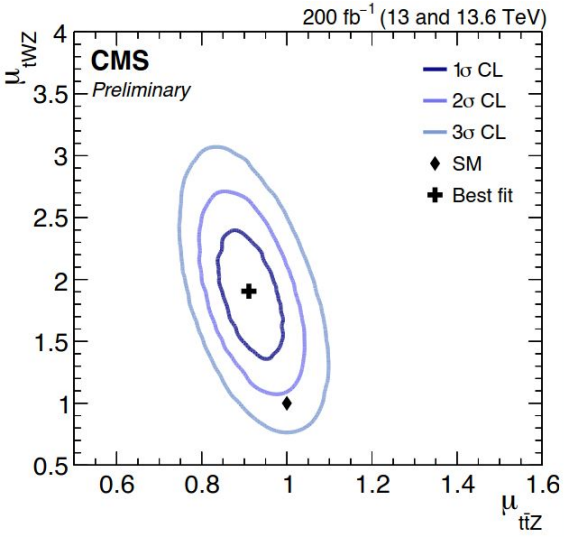

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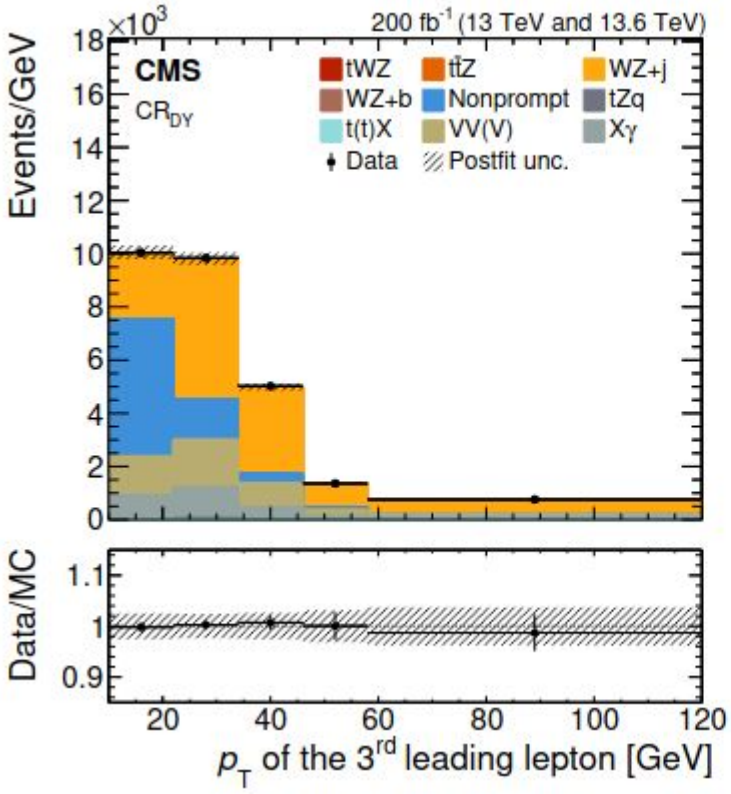
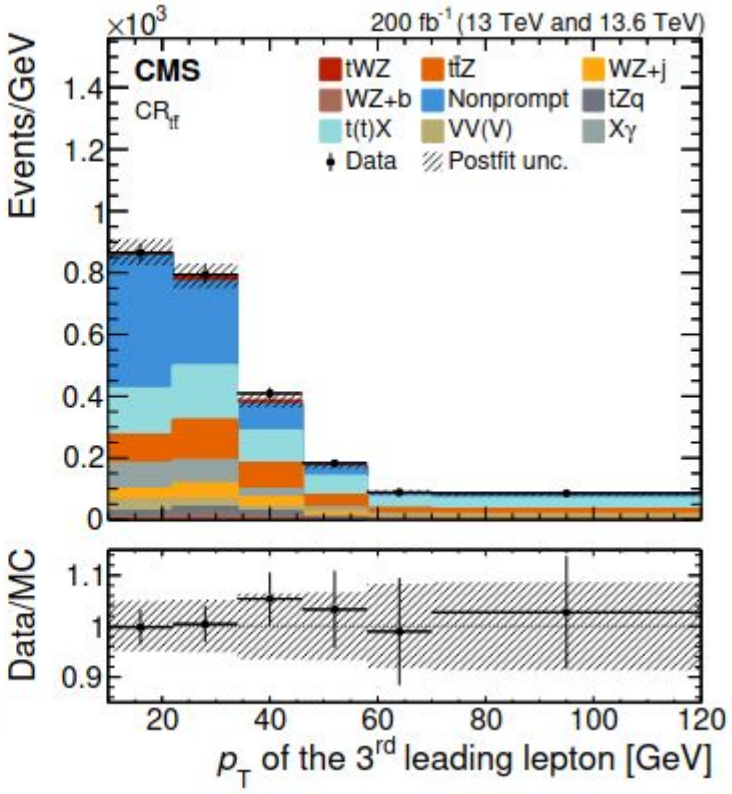
tWZ production - background estimation

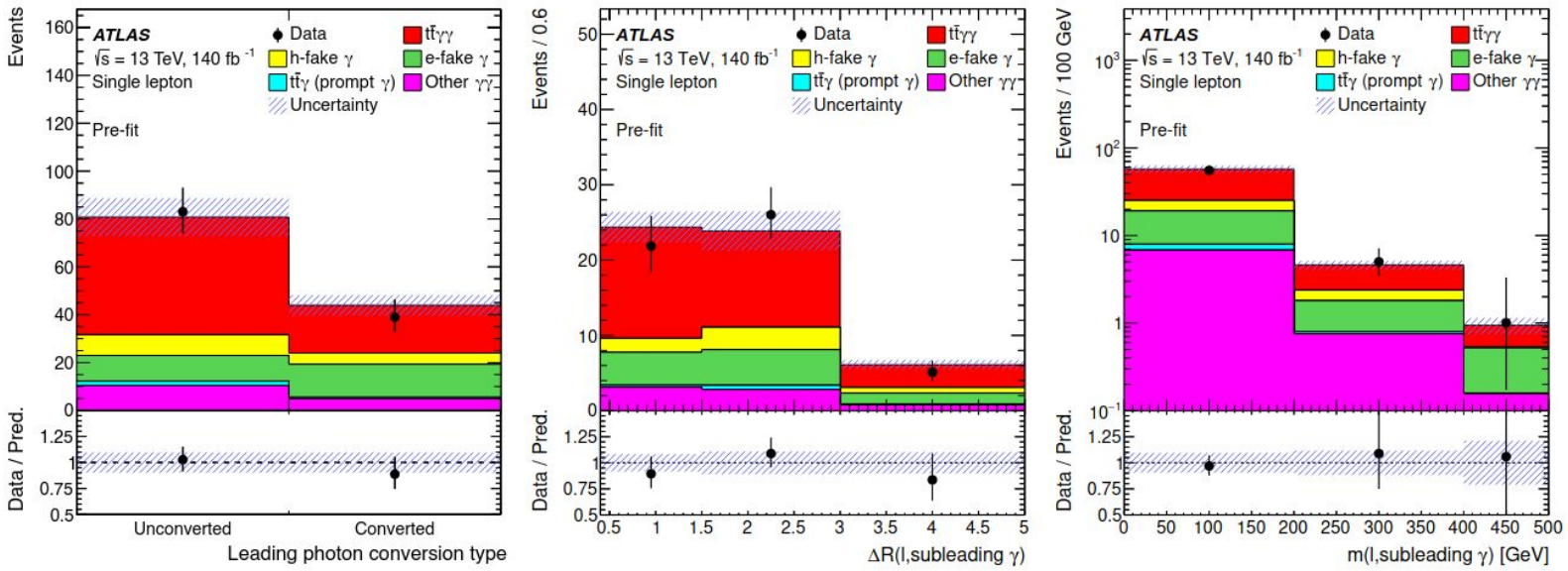




ttγγ signal modeling

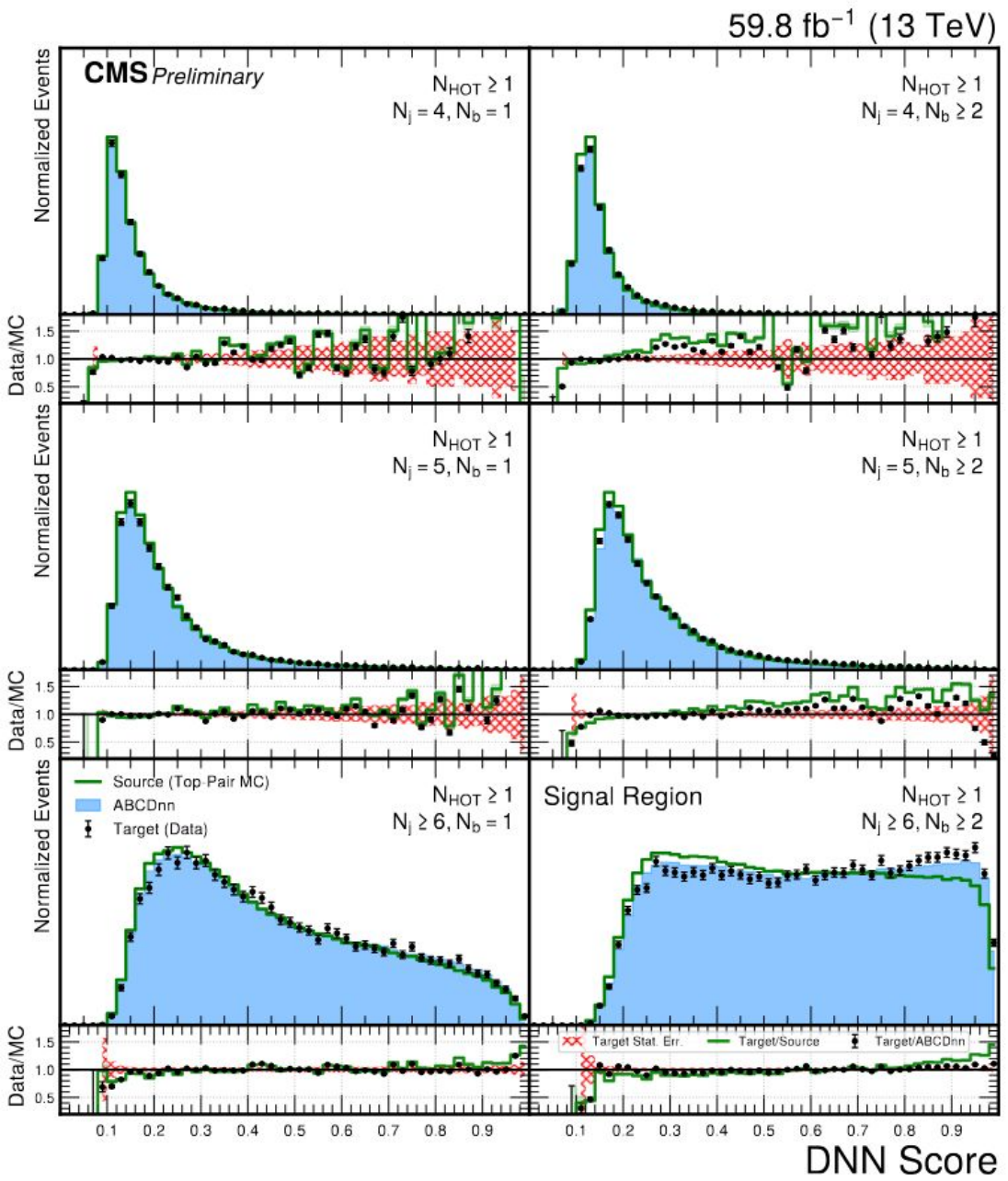
- Signal simulated as a 2⟶8 process at LO with Madgraph aMC@NLO
  - LO cross section: 1.5 + 0.5 - 0.4 fb
- k-factor determined using 2⟶4 ttγγ samples at LO and NLO (production only)
  - Resulting k-factor 1.7

ttγγ BDT


ATLAS
√s = 13 TeV, 140 fb-1
Single lepton
Pre-fit
Data
h-fake γ
tt̄γ (prompt γ)
Uncertainty
tt̄γγ
e-fake γ
Other γγ
Events
Data / Pred.
Unconverted
Converted
Leading photon conversion type
Events / 0.6
ΔR(l,subleading γ)
Events / 100 GeV
m(l,subleading γ) [GeV]

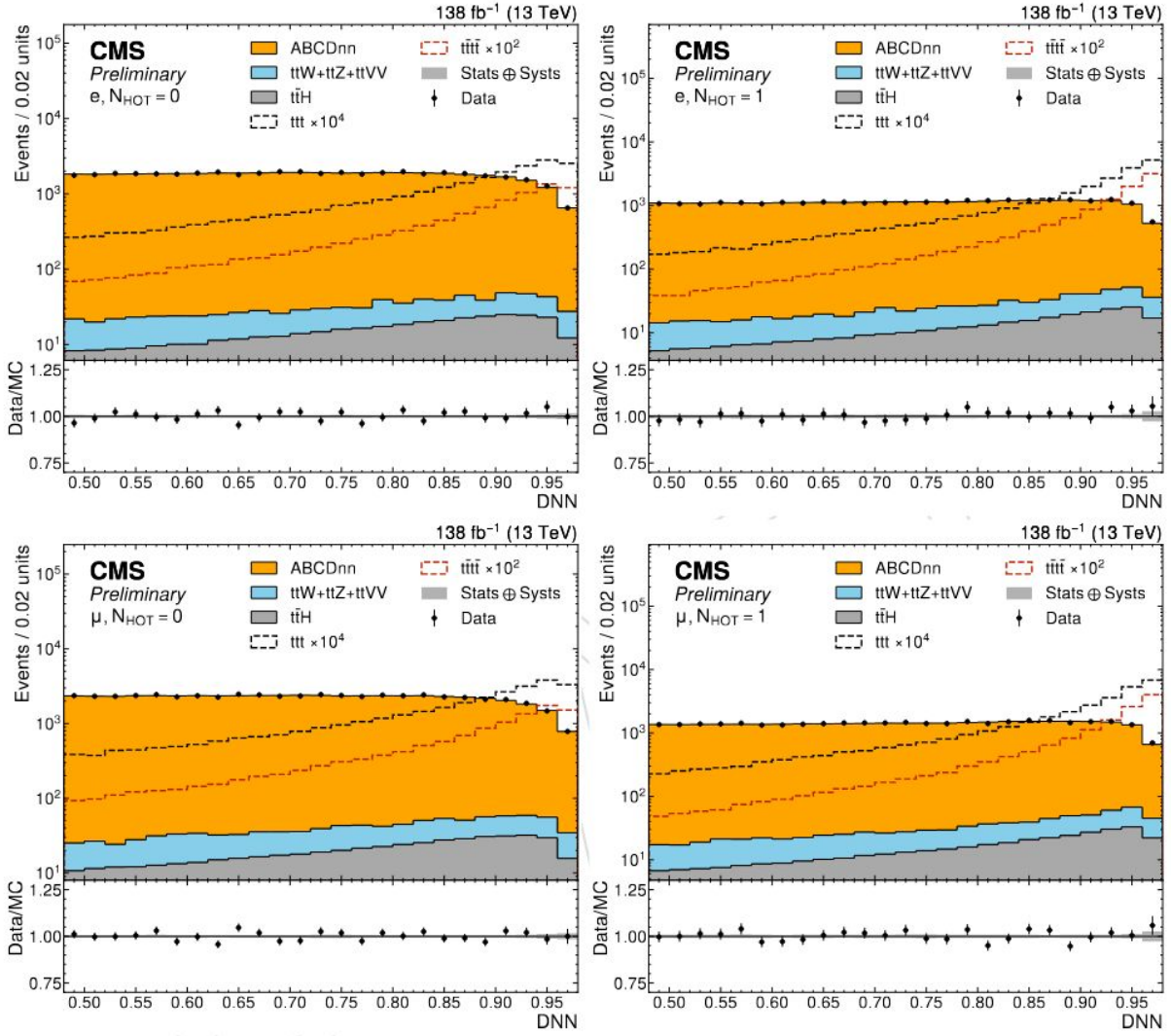
3tops - single lepton channel

- Requiring HT > 450 (500) GeV, 4+ jets, 1+ b-jets, ptmiss > 20 GeV
- Events classified according to jet, and b-tagged jet multiplicity, and number of resolved top candidates
- Neural network using 30 variables to classify ttbar vs 4tops
- ABCDnn+extended ABCD to predict the background



3tops - single lepton channel

- Fit performed separately for electrons and muons, and for the resolved top categories



3tops - SS/ML category

- Two SS or three leptons, HT > 250 GeV, 1+ jets, 1+ b-tagged jets, ptmiss > 50 GeV, Z veto