Measurements of associated top quark production with vector bosons at ATLAS and CMS

EPS-HEP2021 Conference

26-30 July 2021

David Walter,

on behalf of the ATLAS and CMS collaborations

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

EUROPEAN PHYSICAL SOCIETY HEP2021 VIRTUAL EDITION

ATLAS EXPERIMENT

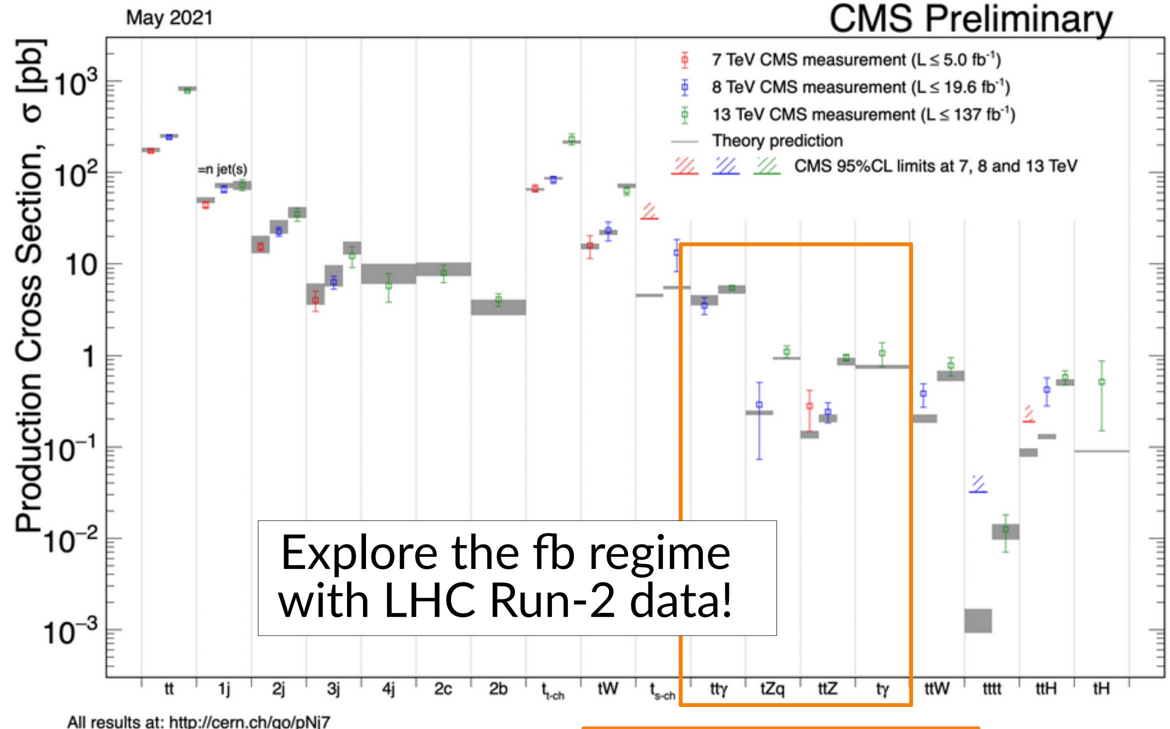
CMS

DESY.

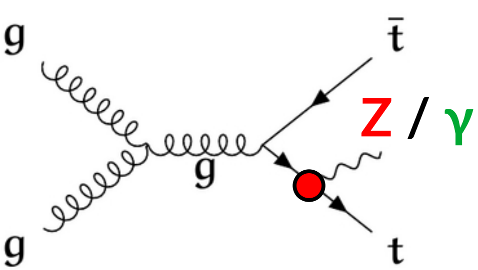
t(t) + Z/γ

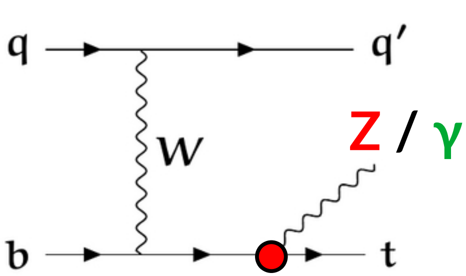
Electroweak couplings in top processes

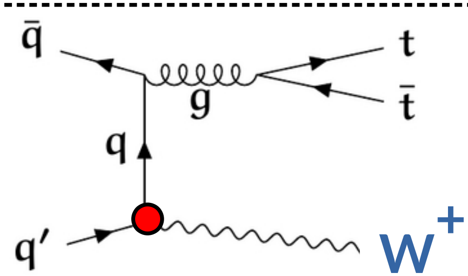
- Modified **t-W**, **t-Z** and **t-γ** couplings in many BSM models
  - FCNC, Z', VLQ, etc.
  - High sensitivity to Anomalous couplings
  - → **High discovery potential!**
- Improve t(t)X modeling as background
  - Higgs processes, tttt production, etc.



ttγ tZq ttZ tqγ



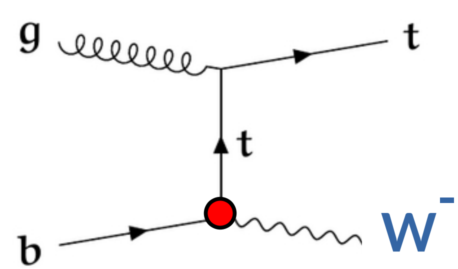




Not today

ATLAS: Phys.Rev.D 99 (2019) 082009

CMS: JHEP 08(2018)011



ATLAS: JHEP 01(2018)063

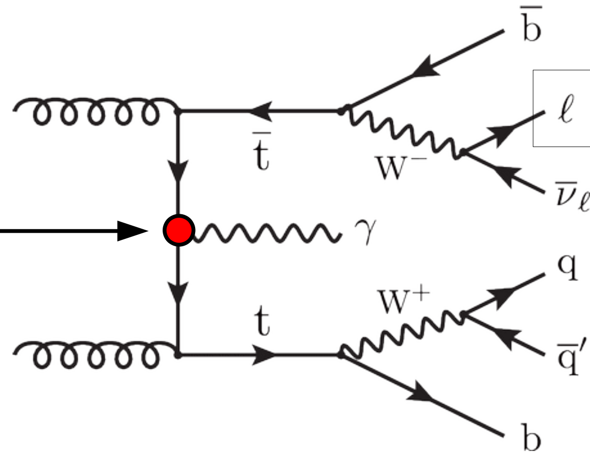
CMS: CMS-PAS-TOP-19-003

arXiv:210701508

$t\bar{t}\gamma$ inclusive and differential

tγ coupling at tree level

- Sensitive to BSM physics
  → EFT!



Single lepton final state

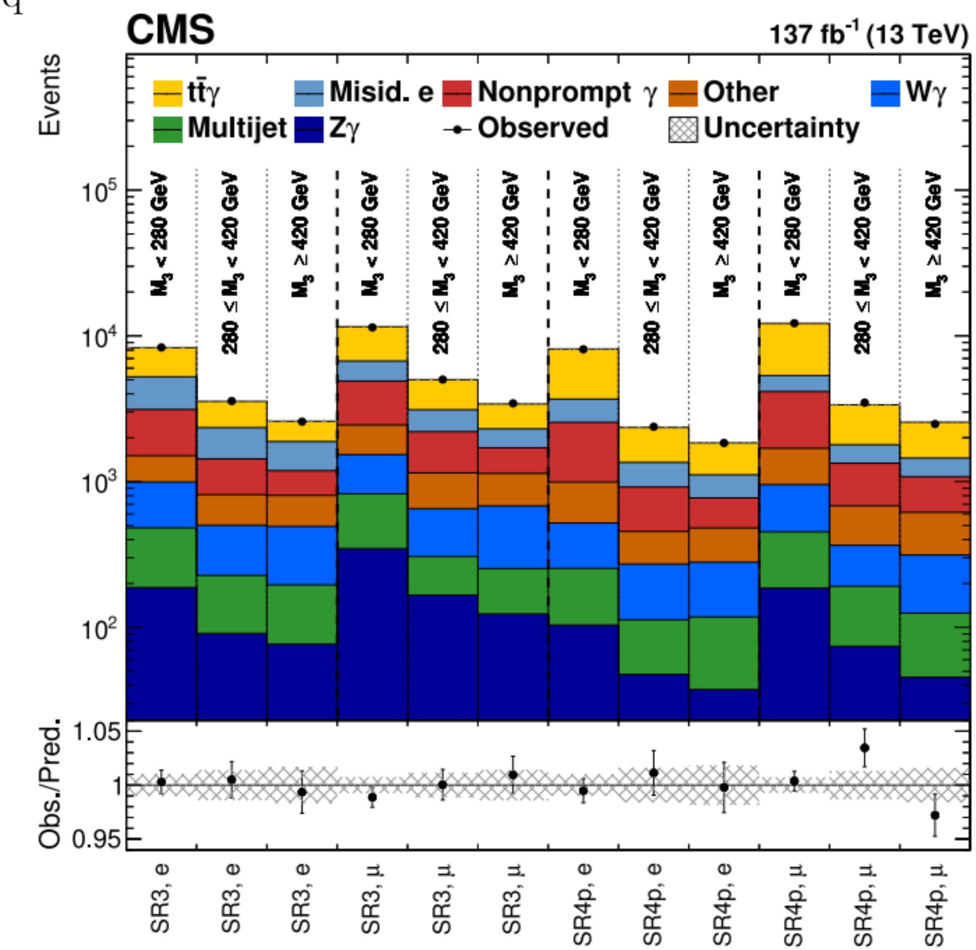
Full Run-2 data: 137fb^{-1}

Signal (genuine) photon:

- photon from ISR, top or top decay products

Challenge: background estimation

- **Electron misidentified as photon:**
  - Enriched control regions included in the fit
  - Also for Wγ and Zγ
- **Nonprompt photons from hadron decay:**
  - ABCD method (Shower shape and isolation)
- **Nonprompt leptons from QCD multijet:**
  - Template from data (loosened lepton isolation)
  - Normalization from measured transfer factor



arXiv:210701508

$t\bar{t}\gamma$ inclusive and differential

Extracted inclusive cross section:

$$\sigma_{tt\gamma} = 800 \pm 46(\mathrm{syst}) \pm 7(\mathrm{stat})\,\mathrm{fb}$$

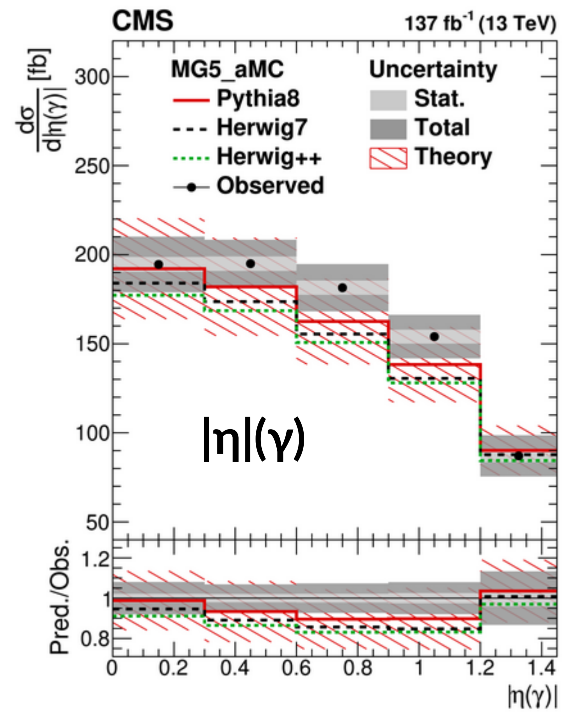
< 6% uncertainty → more precise than MadGraph5_aMC@NLO calculation!

$$\sigma_{tt\gamma}^{\mathrm{MG5\_aMC@NLO}} = 770 \pm 140\,\mathrm{fb}$$

In agreement with SM prediction

Leading uncertainties

- Background normalization
- Parton shower modeling
- Jet energy scale



Differential cross section measurements

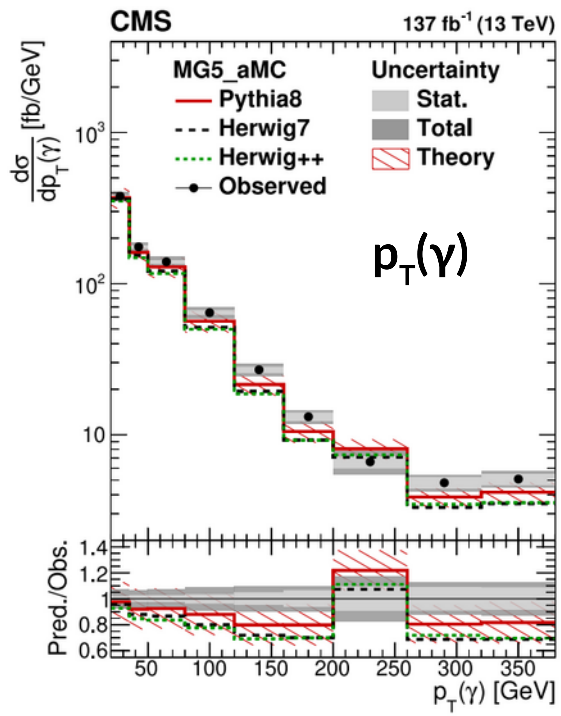
Fit repeated for each distribution Poster

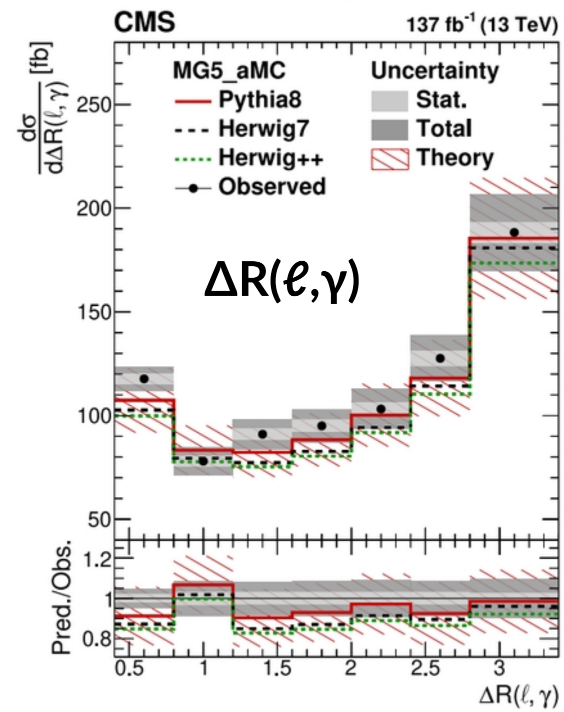
- $p_T(\gamma)$, $|\eta|(\gamma)$, $\Delta R(\ell,\gamma)$

Unfolded to particle level

Compared to different shower models

- Good agreement for Pythia8





EFT interpretation

- See talk from Robert Schoefbeck

$t\bar{t}\gamma$ + tWγ inclusive and differential

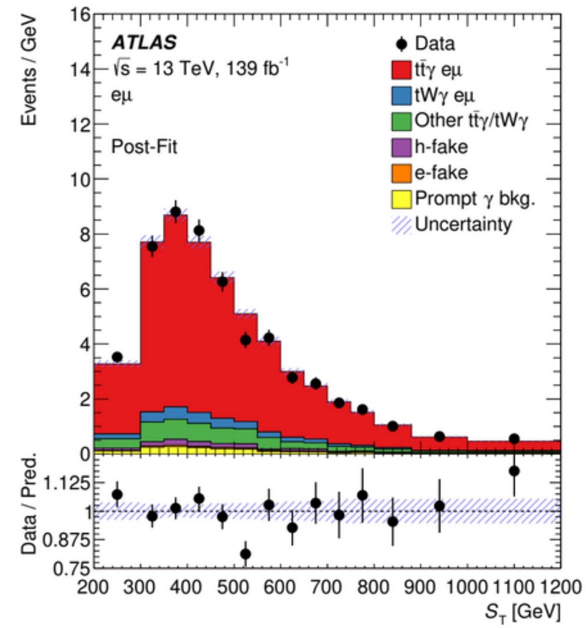
Dilepton final state: eμ final state

- Full Run-2 data: 139 fb^{-1}

Photon from various sources considered in simulation

- Doubly resonant production

$$pp \rightarrow b\ell\nu b\ell\nu\gamma$$
$$pp \rightarrow b\ell\nu\ell\nu\gamma$$
$$pp \rightarrow tW\gamma$$



S_T: Scalar sum of all transverse momenta in the event (leptons, photons, jets, MET)

Profile maximum likelihood fit, binned in S_T

- Measurement in fiducial phase space

$$\sigma_{\text{fid}} = 39.6^{+2.6}_{-2.2}(\text{syst}) \pm 0.8(\text{stat})\,\text{fb}$$

< 7% uncertainty

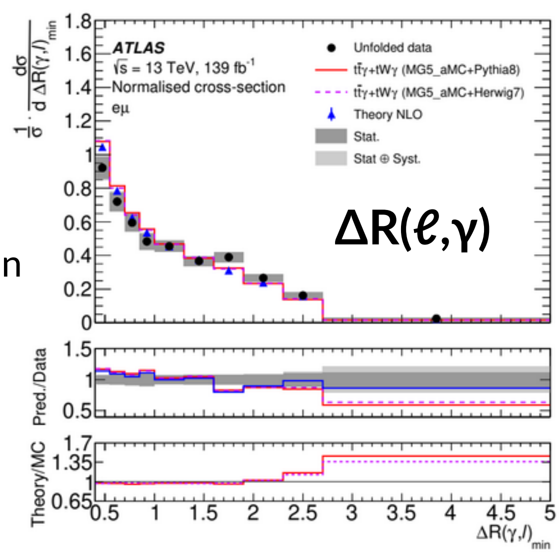
- Compared with theory prediction with off-shell top quarks (JHEP 10 (2018) 158)

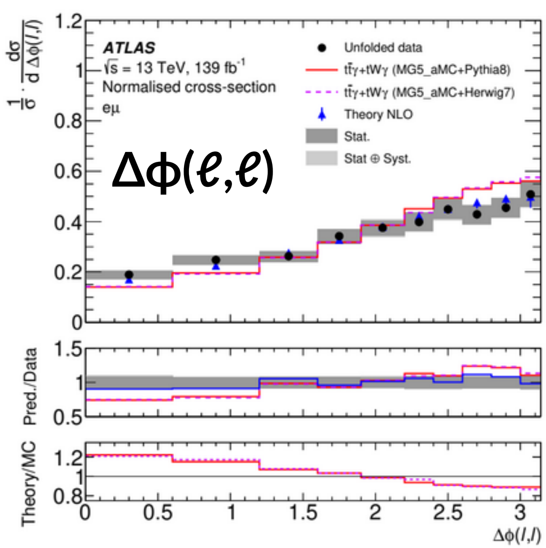
$$\sigma^{\text{Theory}}_{\text{fid}} = 38.5^{+1.2}_{-2.5}\,\text{fb}$$

Differential cross section measurements

Unfolded to parton level via iterative matrix inversion

- $p_T(\gamma)$, $|\eta|(\gamma)$
- $\Delta\phi(\ell,\ell)$, $\Delta\eta(\ell,\ell)$
- $\Delta R_{min}(\gamma,\ell)$ ← sensitive to tγ coupling

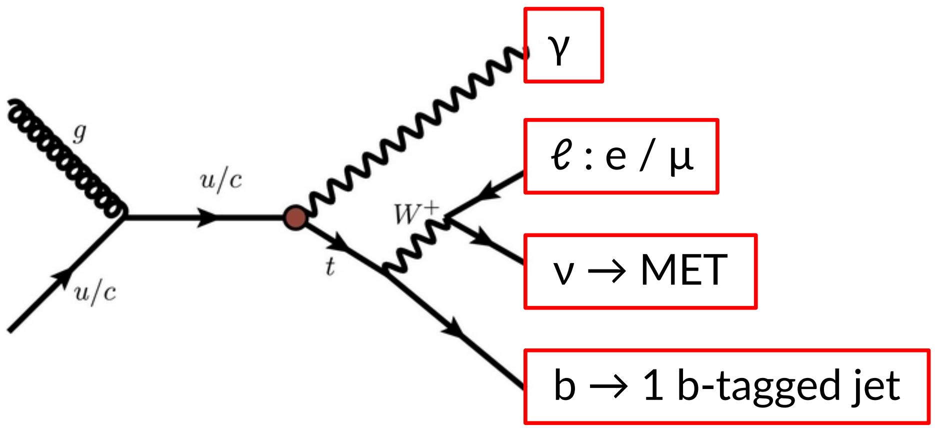




Phys. Lett. B 800 (2020) 135082

tγ – FCNC search

Focus on production channel:



- 2015-2017 data: 81 fb^{-1}

Data driven background estimations

- Electrons fake photons
  - → Fake rates measured
- Hadrons fake photons
  - → ABCD method

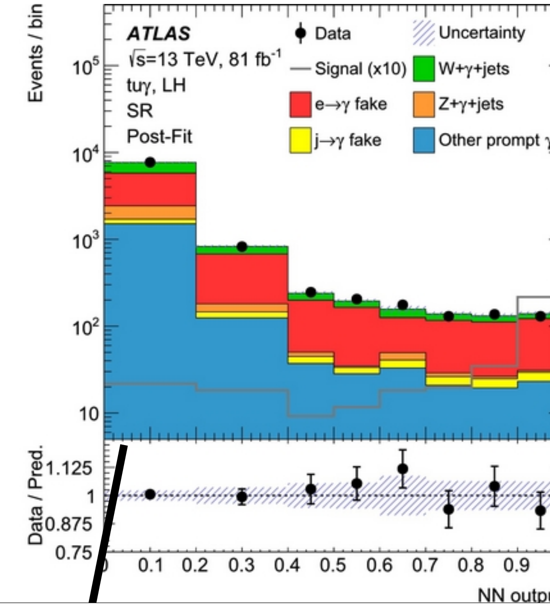
SM search by CMS:

- Phys. Rev. Lett. 121 (2019) 221802

Artificial intelligence!

Neural network!

- FCNC vs. background



Know your limits!

- Limits on signal strength translated into constraints on effective couplings

Observable	Vertex	Coupling	Obs.	Exp.
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*} \rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)} \rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*} \rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)} \rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

EFT

Production

Decay

JHEP 03 (2020) 056

ttZ inclusive and differential

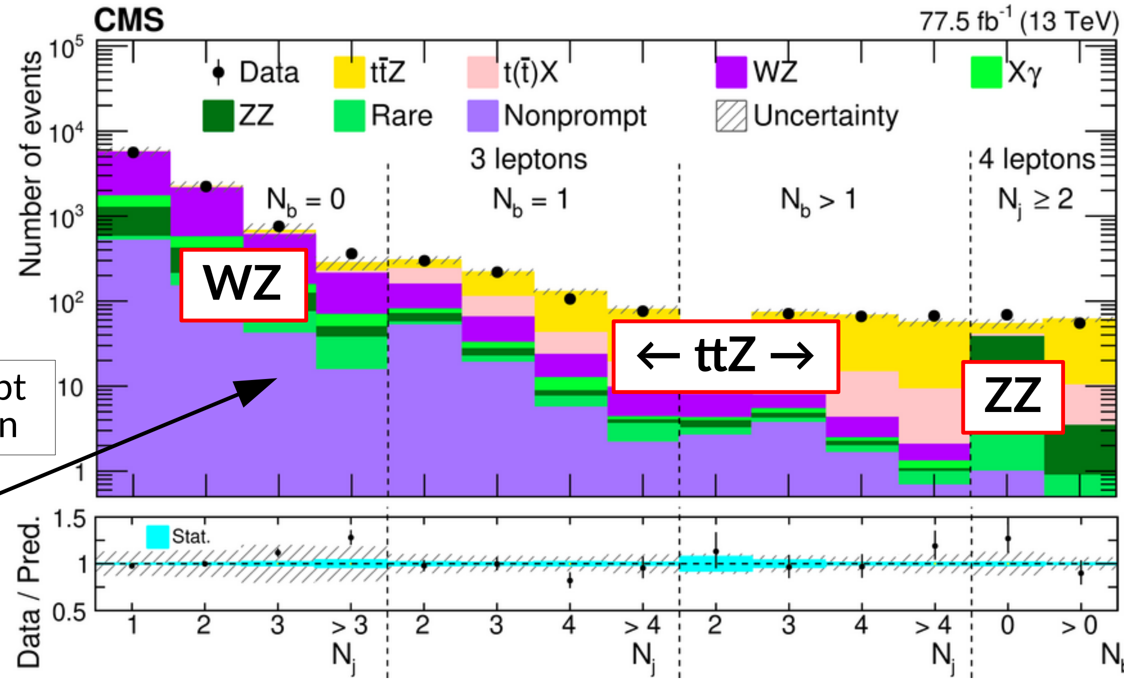
Final states 3 & 4 leptons (e/μ)

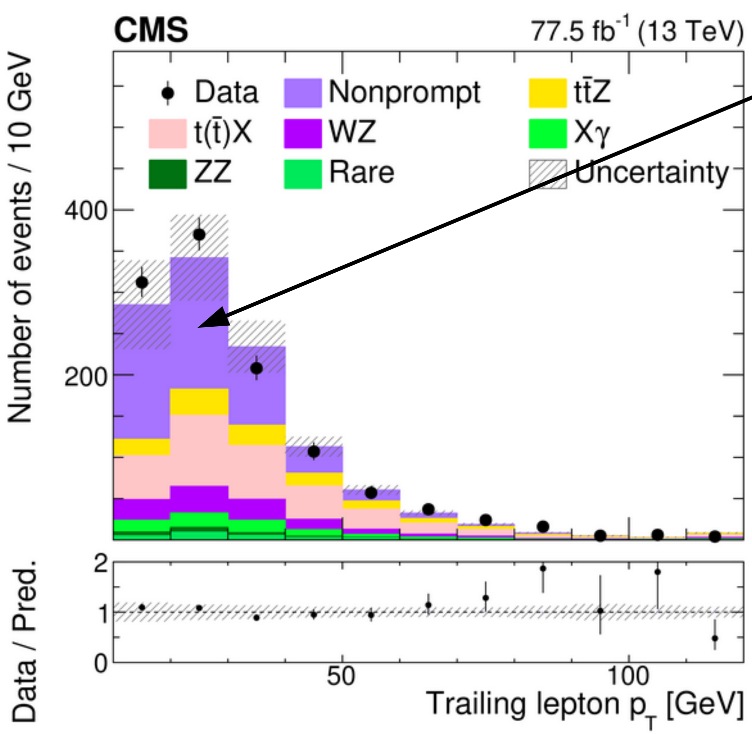
- Improved trigger strategy
- **Prompt lepton MVA!**

Categories of jet and b-jet multiplicities

→ Control backgrounds!

Data driven nonprompt background estimation





Simultaneous binned maximum likelihood fit

$$\sigma_{t\bar{t}Z} = 95 \pm 6(\mathrm{syst}) \pm 5(\mathrm{stat})\,\mathrm{fb}$$

~ 8% uncertainty

Leading systematic uncertainties

- Lepton identification
- t(t̄)X and WZ normalization
- Parton shower modeling

In agreement with SM predictions (Eur. Phys. J. C 80 (2020) 428)

$$\sigma_{t\bar{t}Z}^{\mathrm{Theory}} = 86^{+7}_{-8}(\mathrm{scale}) \pm 2(\mathrm{PDF} + \alpha_S)\,\mathrm{fb}$$

JHEP 03 (2020) 056

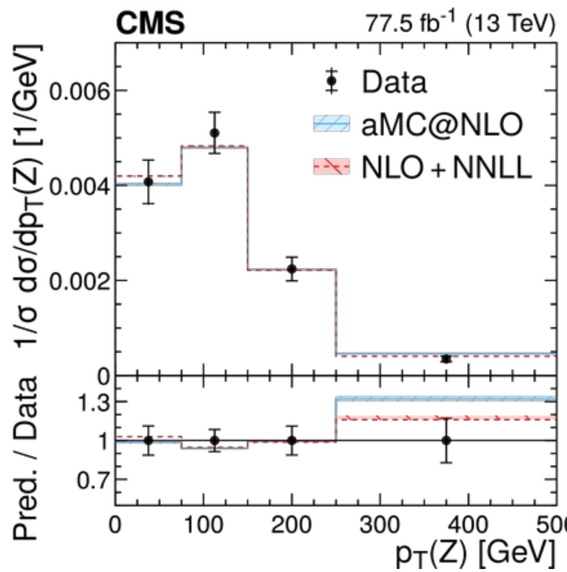
ttZ inclusive and differential

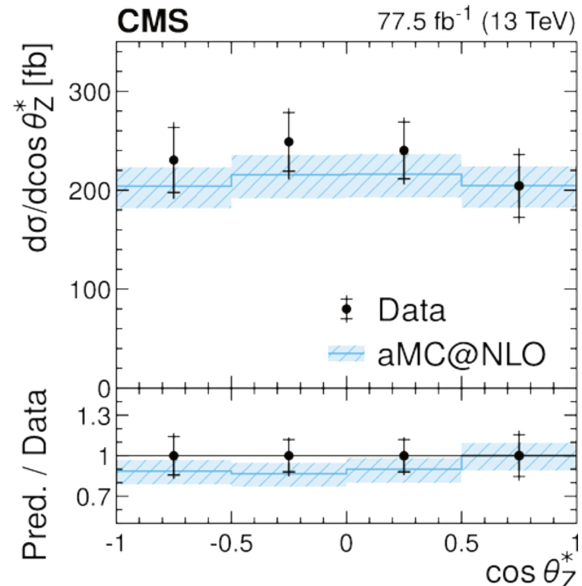
Differential cross section measurements

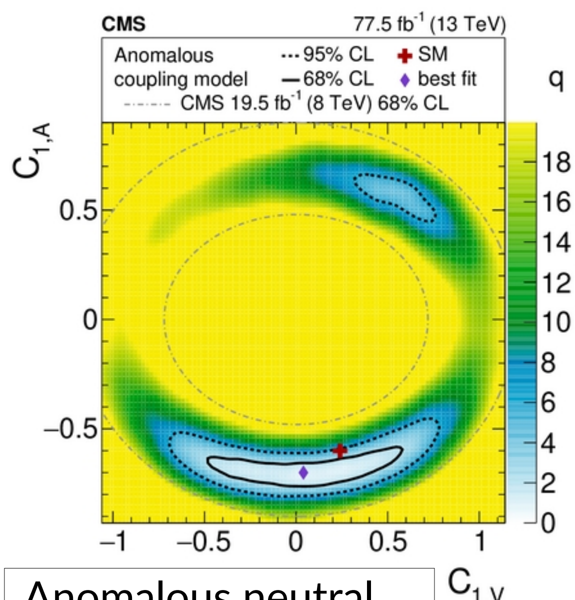
- Enriched signal region
  - 3ℓ, ≥3 jets, ≥1b

Poster

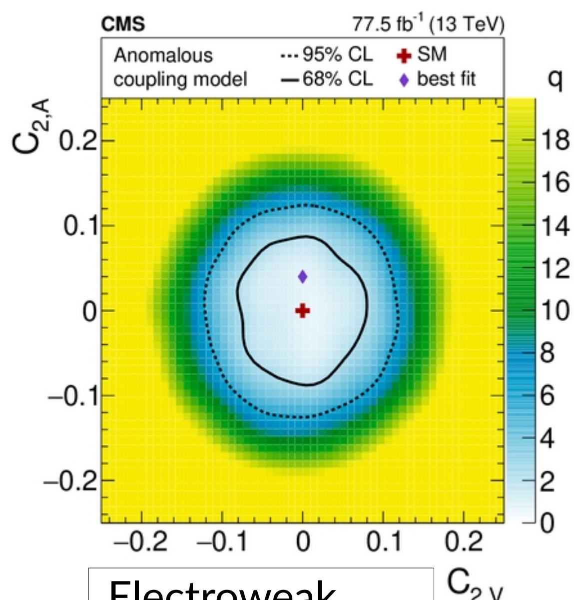
- Parton level
- Compared to NLO+NNLL
  - Eur. Phys. J. C 79 (2019) 249
  - Good agreement







Anomalous neutral current interactions



Electroweak dipole moments

Anomalous couplings

- Reweighting samples on detector level
- Fit event yields in bins of
  - N(ℓ), N(j), N(b), p_T(Z) and cos(θ^*_Z)
  - At detector level
- See EFT talk from Robert Schoefbeck

arXiv:2103.12603

ttZ inclusive and differential

Similar approach: 3ℓ and 4ℓ final states Poster

- Full Run-2 data: 139 fb^{-1}

$$\sigma_{t\bar{t}Z} = 105 \pm 9(\mathrm{syst}) \pm 5(\mathrm{stat})\ \mathrm{fb}$$

→ In agreement with CMS results and SM predictions

~ 10% uncertainty

Leading systematic uncertainties

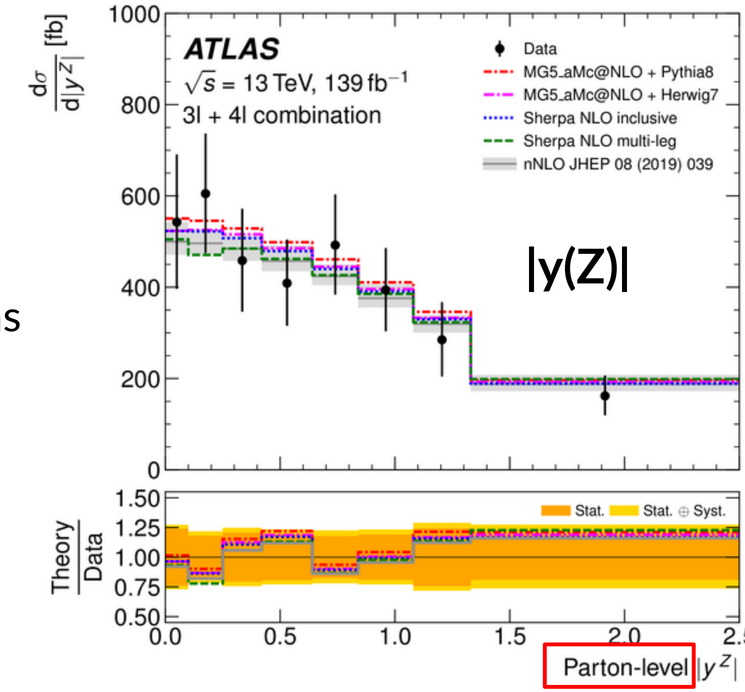
- Parton shower
- Modeling of tWZ, WZ and ZZ
- B tagging

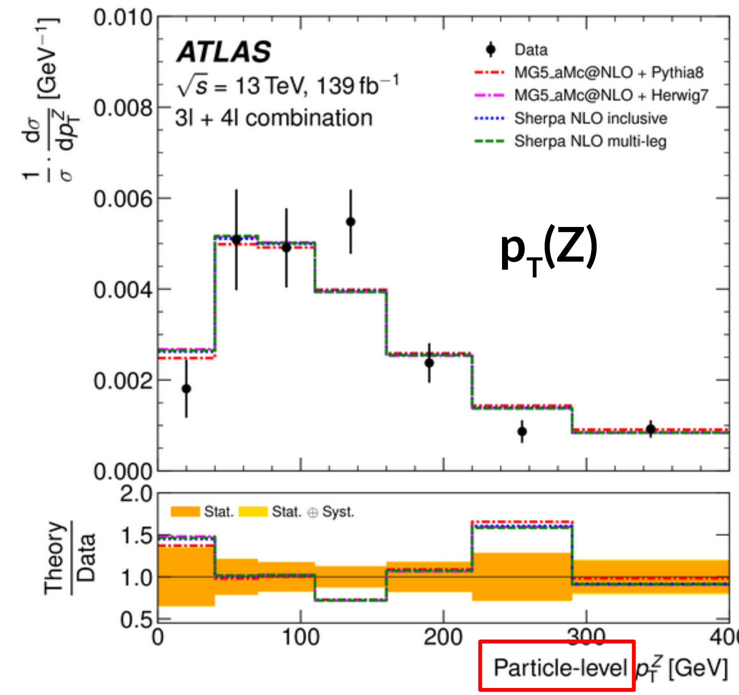
	Variable
$3\ell + 4\ell$	p_T^Z
	$\lvert y^Z \rvert$
3ℓ	N_{jets}
	$p_T^{\ell,\text{non}-Z}$
	$\lvert\Delta\phi(Z, t_{lep})\rvert$
	$\lvert\Delta y(Z, t_{lep})\rvert$
4ℓ	N_{jets}
	$\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert$
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$
	$p_T^{t\bar{t}}$

Differential cross section measurements

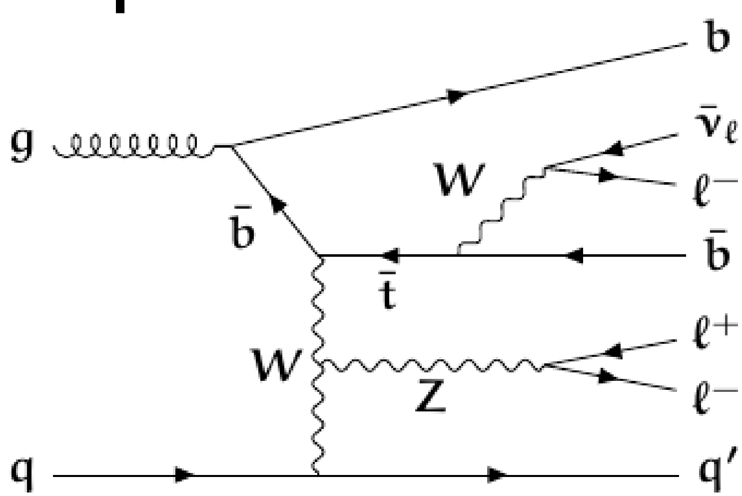
- Iterative bayesian unfolding
- Absolute / normalized

- Sensitive to generator modeling, BSM effects
- Probe QCD effects
- Top p_T modeling
- Probe t-Z vertex
- Spin correlation





tZq



ATLAS inclusive cross section measurement

- Simultaneous fit of 2 SR and 6 CR

$$\sigma_{\mathrm{tZq}} = 97 \pm 7(\mathrm{syst}) \pm 13(\mathrm{stat})\ \mathrm{fb}$$

~ 15% uncertainty!

- Observation confirmed by both experiments
- In agreement with SM prediction

$$\sigma_{\mathrm{tZq}}^{\mathrm{MG5\_aMC@NLO}} = 94.2 \pm 3.1\ \mathrm{fb}$$

Final state with 3 isolated prompt leptons (e/μ)

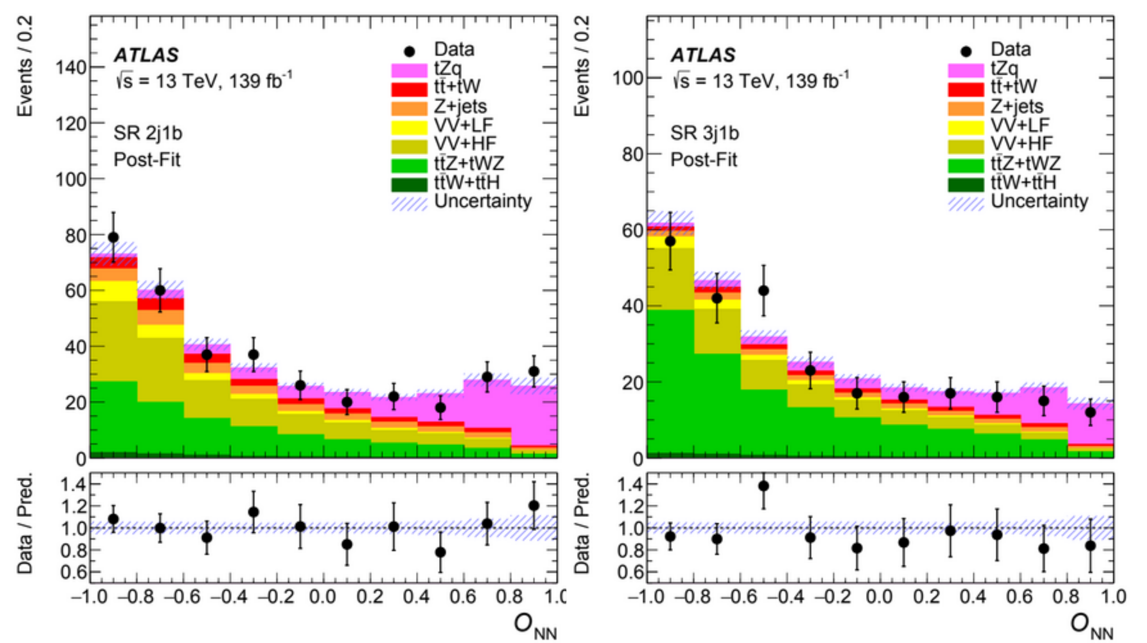
- Full Run-2 data: 139fb^{-1}

Challenges:

- Backgrounds with nonprompt leptons
  - b-jet replacement
- Separation signal vs. background
  - Full event reconstruction
  - Neural network classifier

Distinctive features

- Charge asymmetry
- Light flavor jet with high p_T in forward region



tZq

CMS measurements

Poster 1 Poster 2

Inclusive cross section measurement

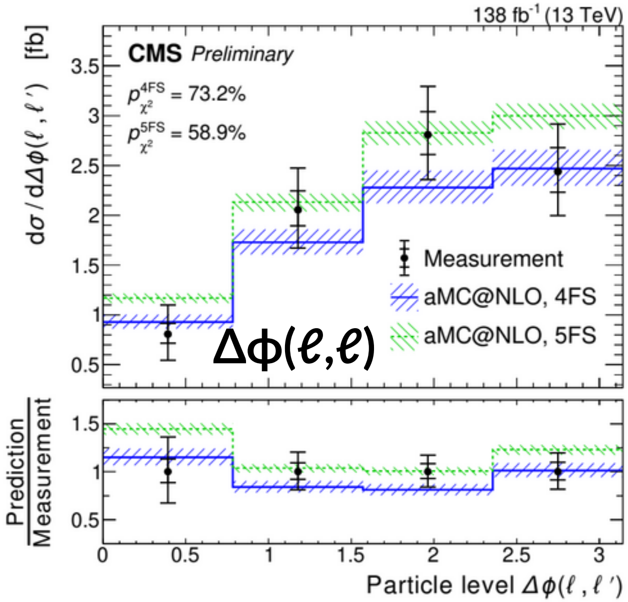
$$\sigma_{\mathrm{tZq}} = 87.9^{+7.3}_{-6.0}(\mathrm{syst})^{+7.5}_{-7.3}(\mathrm{stat})\ \mathrm{fb}$$

< 12% uncertainty!

- Including charge ratio!

First differential cross section measurements!

- Maximum likelihood based unfolding
- 9 observables:
  - Parton/particle level – Absolute/normalized
  - Good agreement with SM predictions



First measurement of the top quark spin asymmetry in tZq!

- Sensitive to anomalous couplings

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

→ In agreement with SM predictions!

$$A_\ell^{\mathrm{MG5\_aMC@NLO}} = 0.437^{+0.004}_{-0.003}$$

More content:

- See talk from Luka Lambrecht
  - More on Electroweak top production in CMS
- See talk from Robert Schoefbeck
  - arXiv:2107.13896: EFT search, including tZq, ttZ and tWZarX
  - JHEP 03 (2021) 095: EFT search considering 16 WCs!

Summary

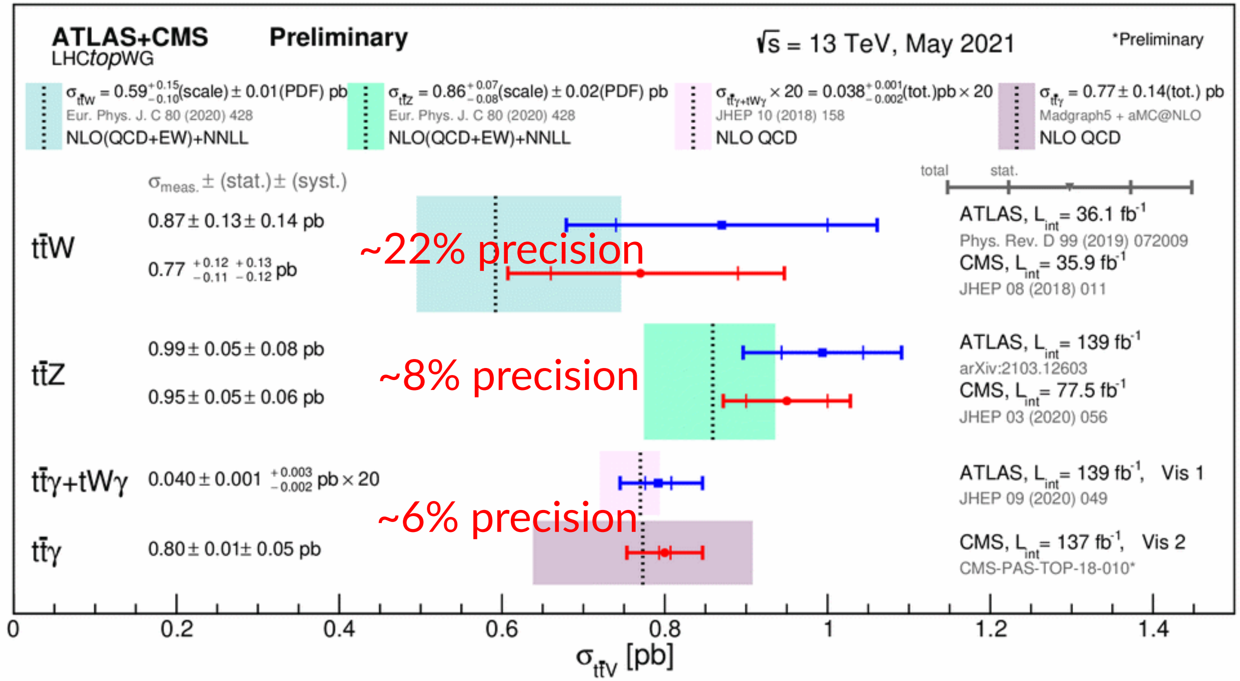
Measurements on $t(\bar{t})$+X in precision era

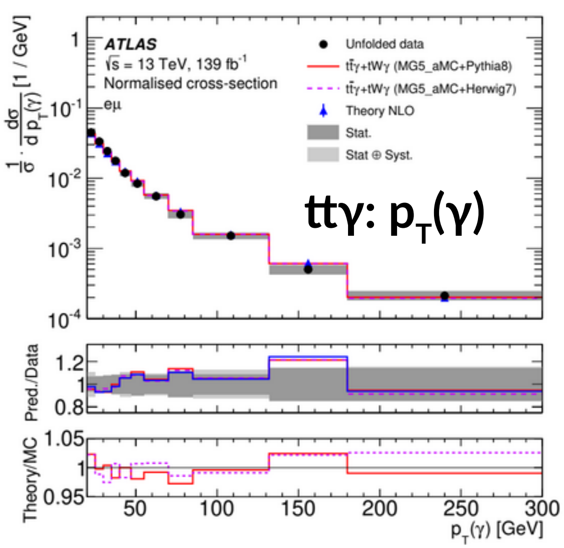
- Going differential
- Limits on anomalous couplings
- Limits on FCNC
- Good agreement with SM

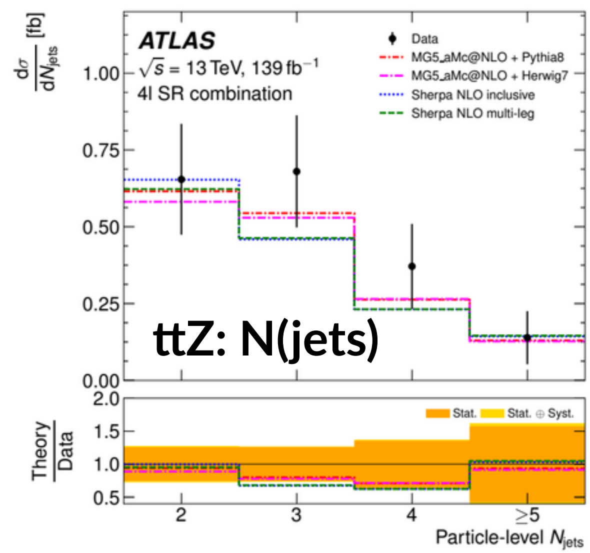
Todo: exploit fully the Run-2 datasets

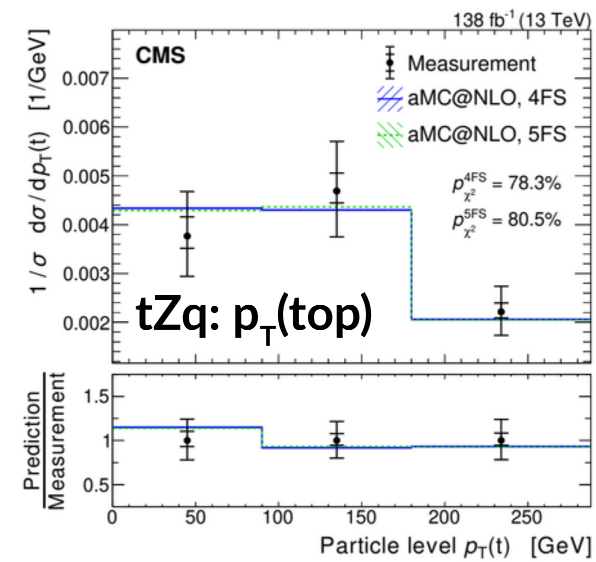
- Improved precision
- Unexplored processes
- Combined measurements
  - Also LHC combinations

→ stay tuned!









Thanks !

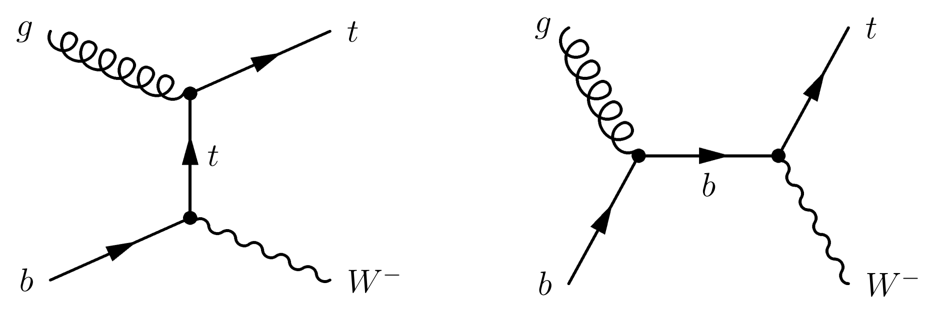
BACKUP

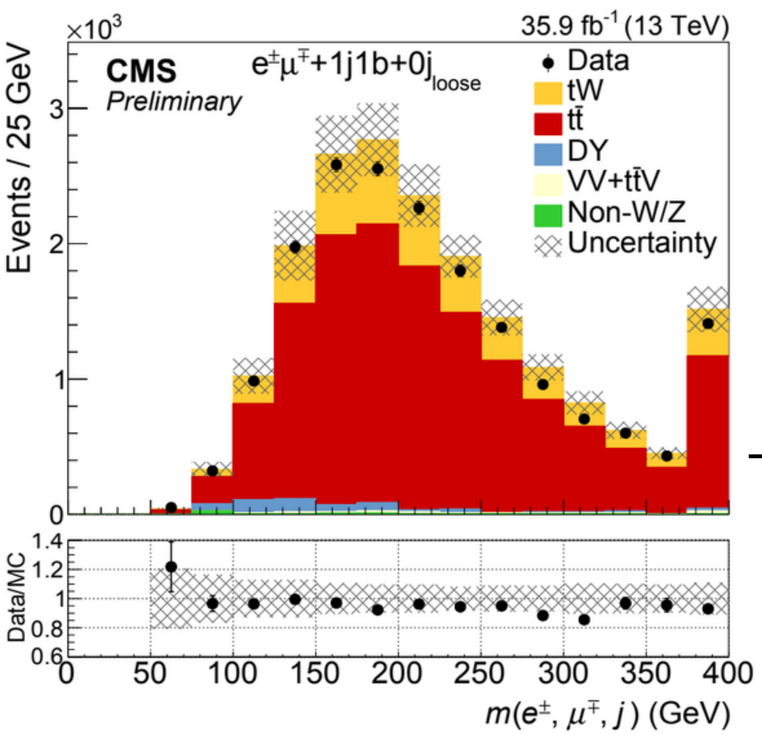
tW

Differential cross section measurements

Poster

- 2016 data: 35.9 fb^{-1}
- 1e, 1μ, 1jet (1b)
- In diagram removal (DR) scheme
- Overall good agreement with SM predictions!

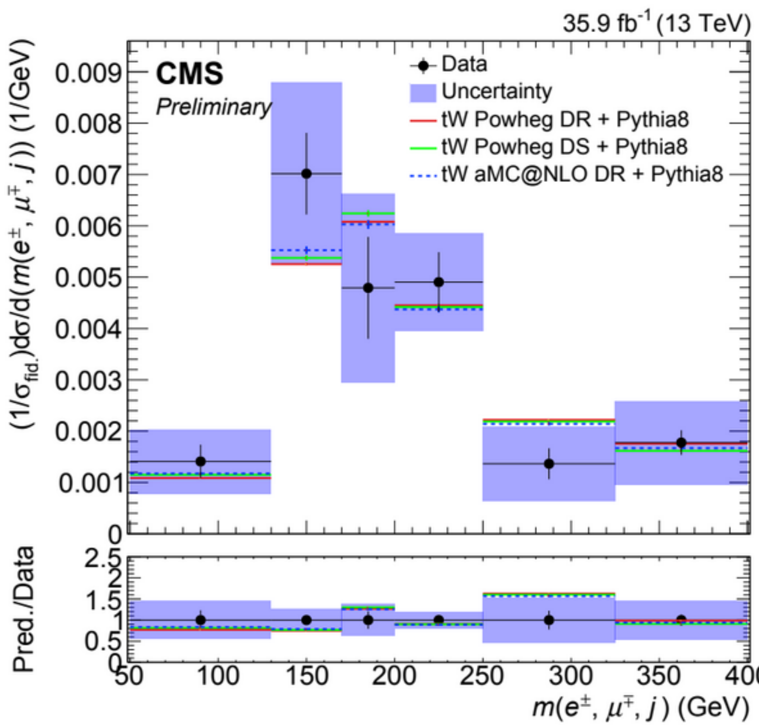




χ² minimization

$$N_{\mathrm{i}}^{\mathrm{sig}} = \sum_{\mathrm{j}=1} R_{\mathrm{ij}} N_{\mathrm{j}}^{\mathrm{sig,unf}}$$

- TUnfold
- Particle level



Phys.Rev.D 99 (2019) 082009

Simultaneous measurement of ttZ and ttW

High sensitivity to top-Z coupling

Important background e.g. ttH

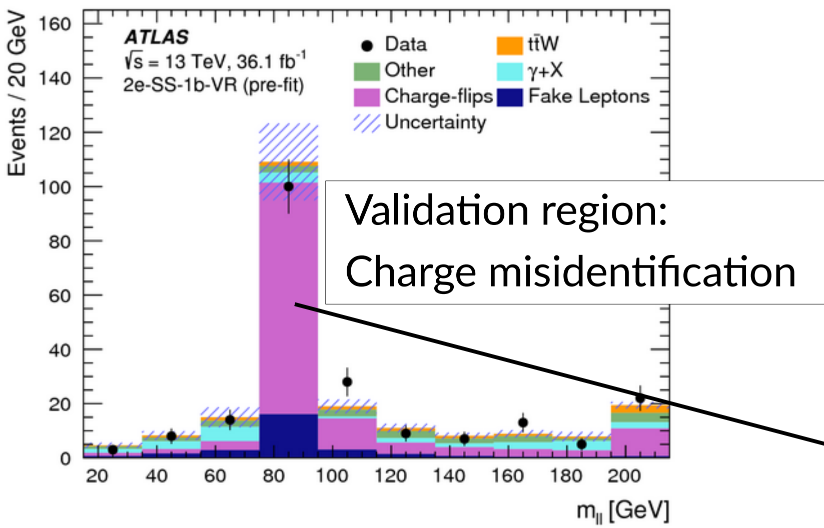
Partial dataset: 36.1 fb^{-1}

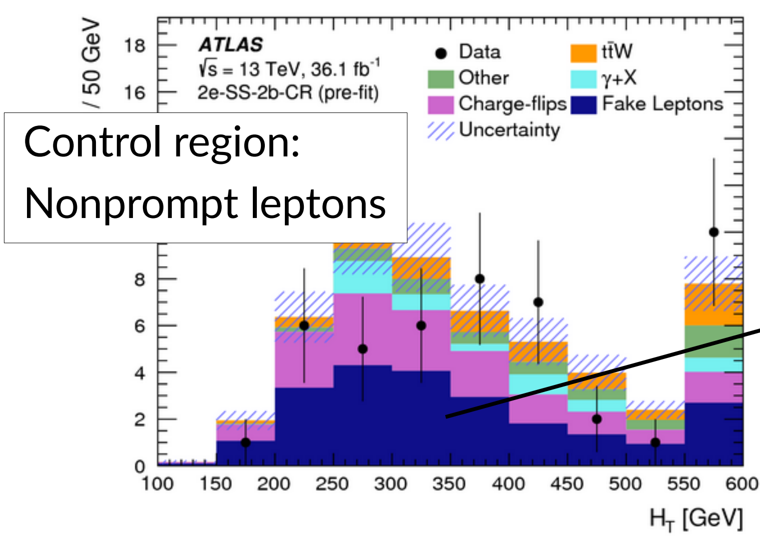
Regions: ***2ℓ, 3ℓ, 4ℓ***

- Prompt lepton MVA
- MVA for electron charge

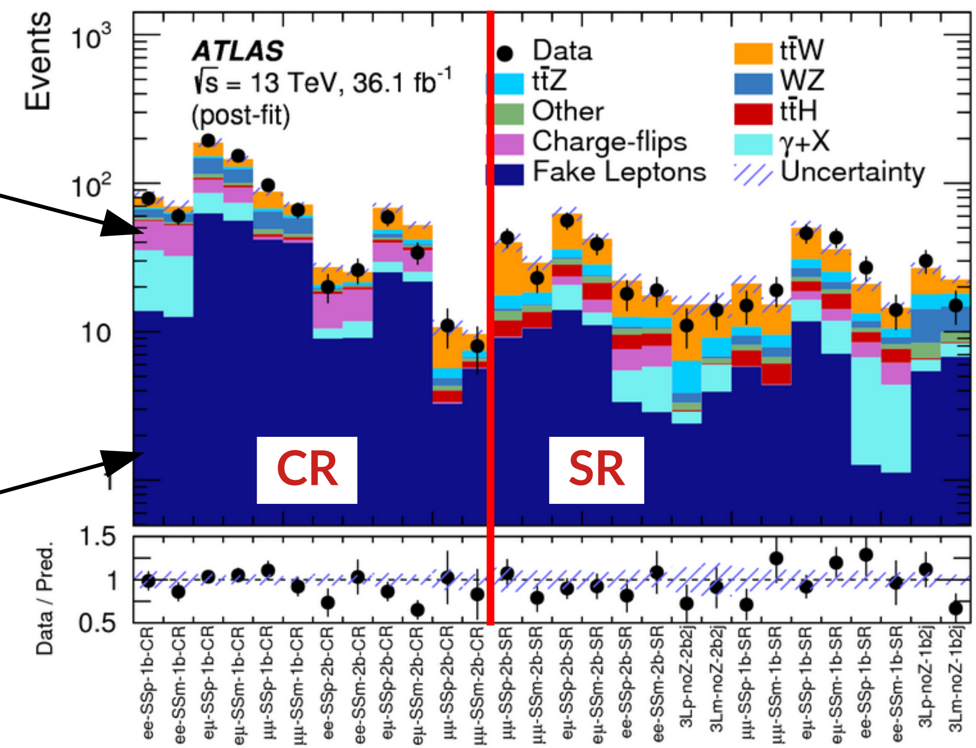
Data driven background estimation

- Nonprompt leptons → tight to loose ratio
- Charge misidentification





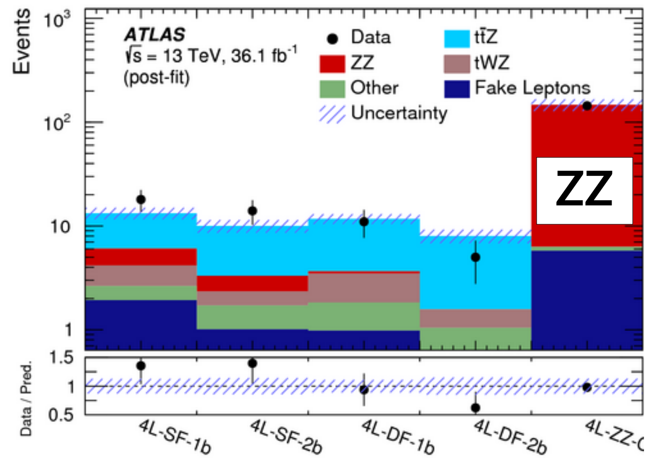
ttW regions

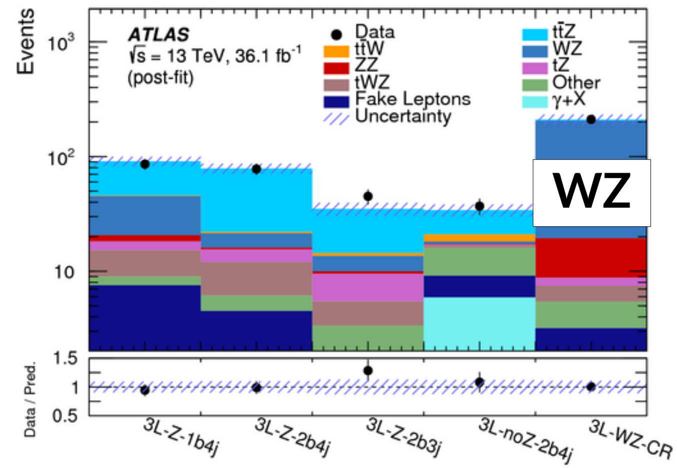


Phys.Rev.D 99 (2019) 082009

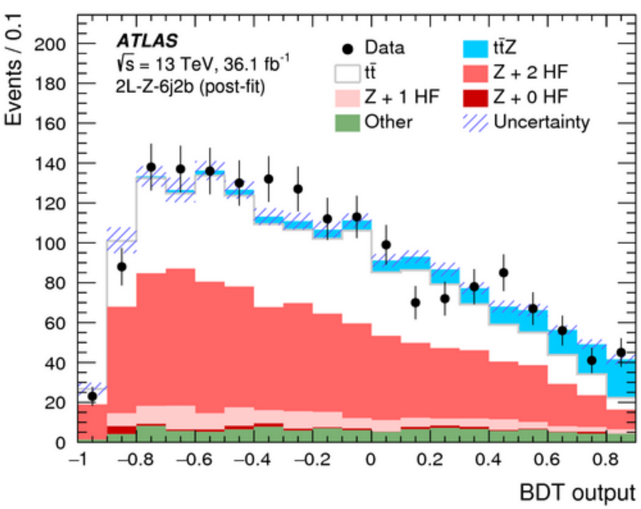
Simultaneous measurement of ttZ and ttW

Control regions for
- 3ℓ WZ: 0 b-jets
- 4ℓ ZZ: 2 Z candidates



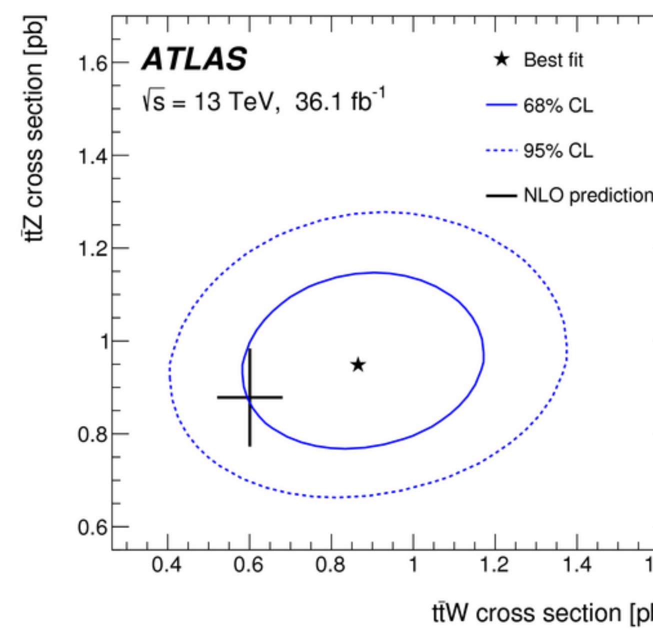


BDTs for ttZ in 2ℓ OS region
- tt control region
- DY split in hadron flavor categories



Combine and conquer!

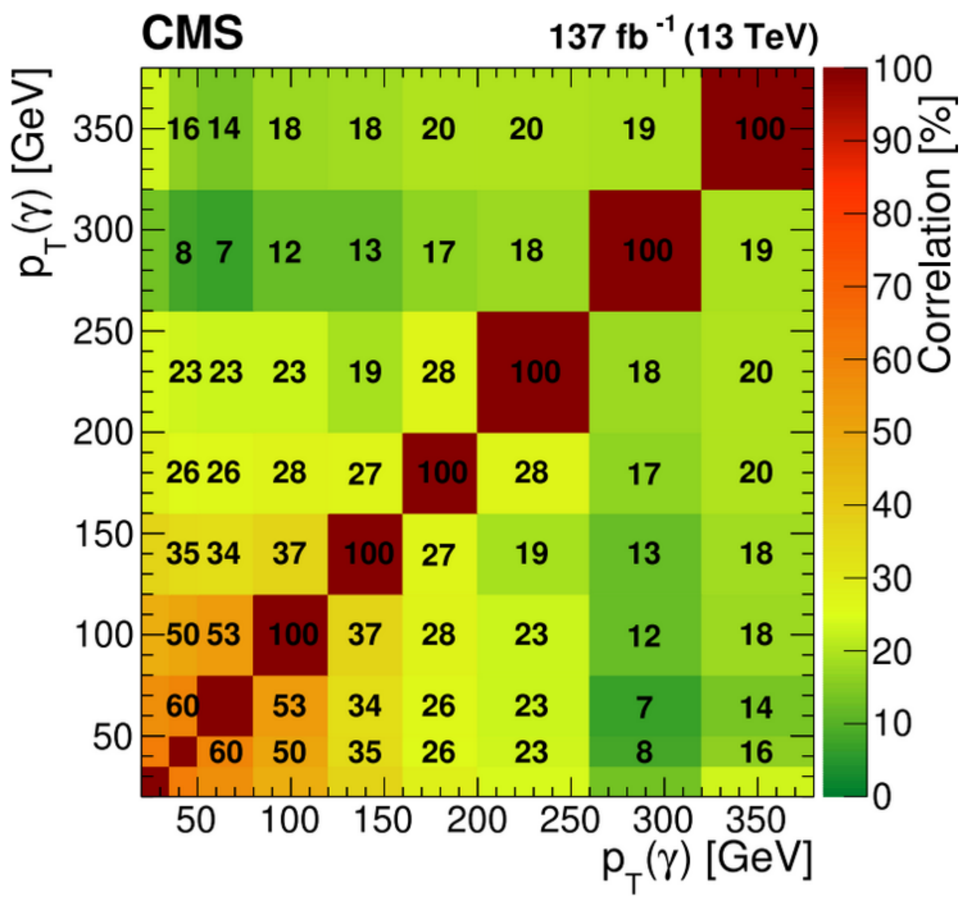
Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
3ℓ $t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and 3ℓ $t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–

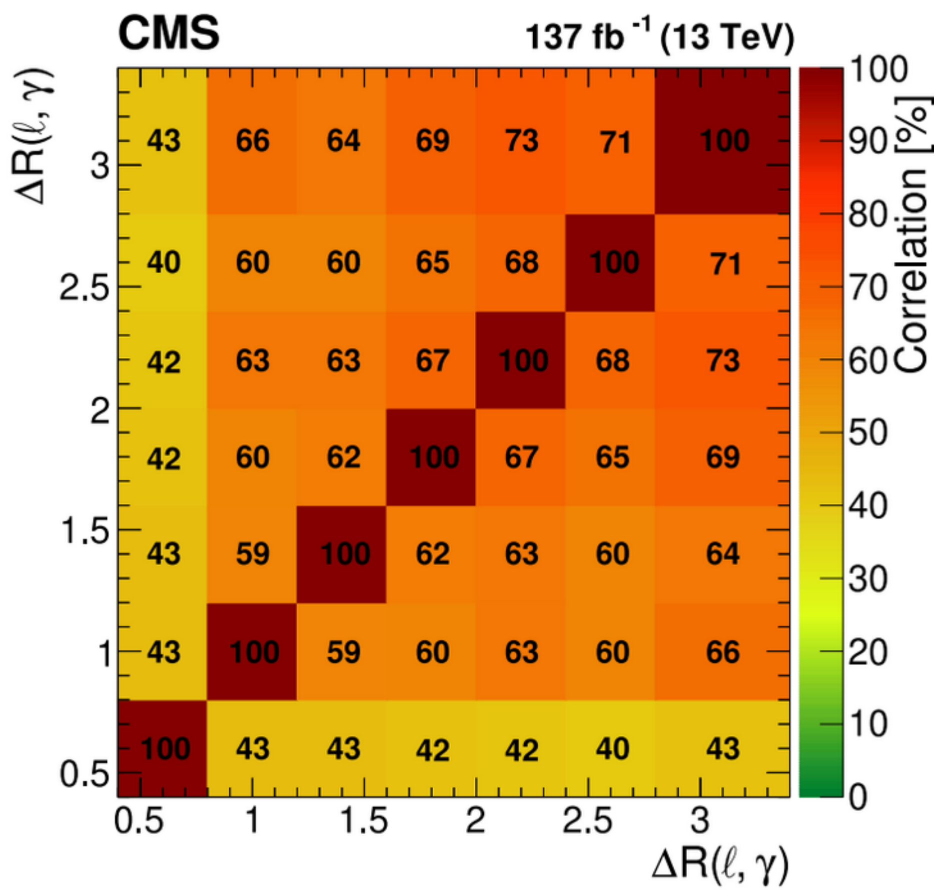


ttZ ~ 13% uncertainty
ttW ~ 22% uncertainty

arXiv:210701508

$t\bar{t}\gamma$ – response matrices



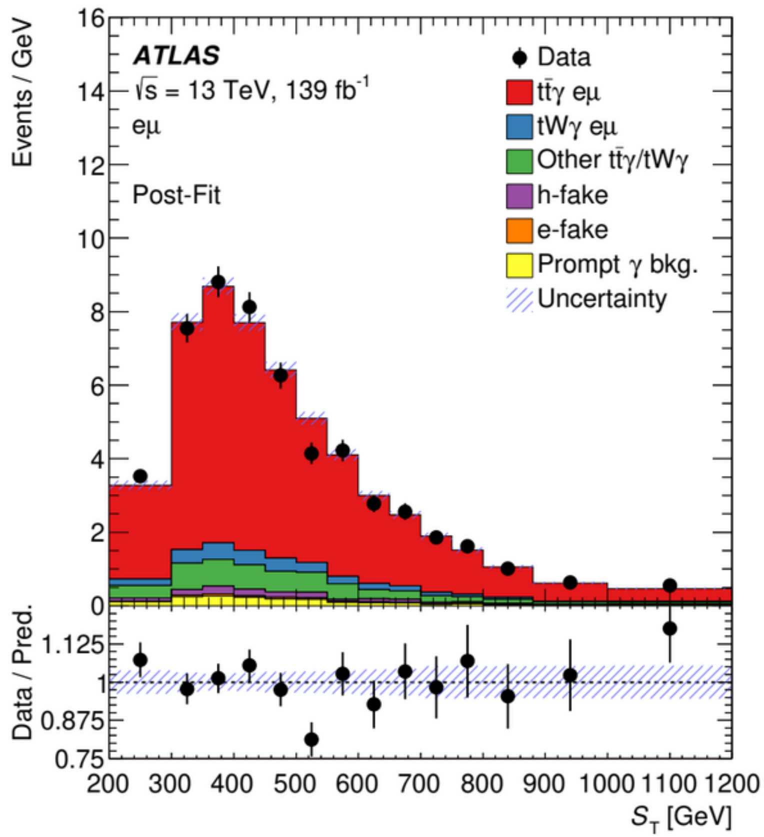


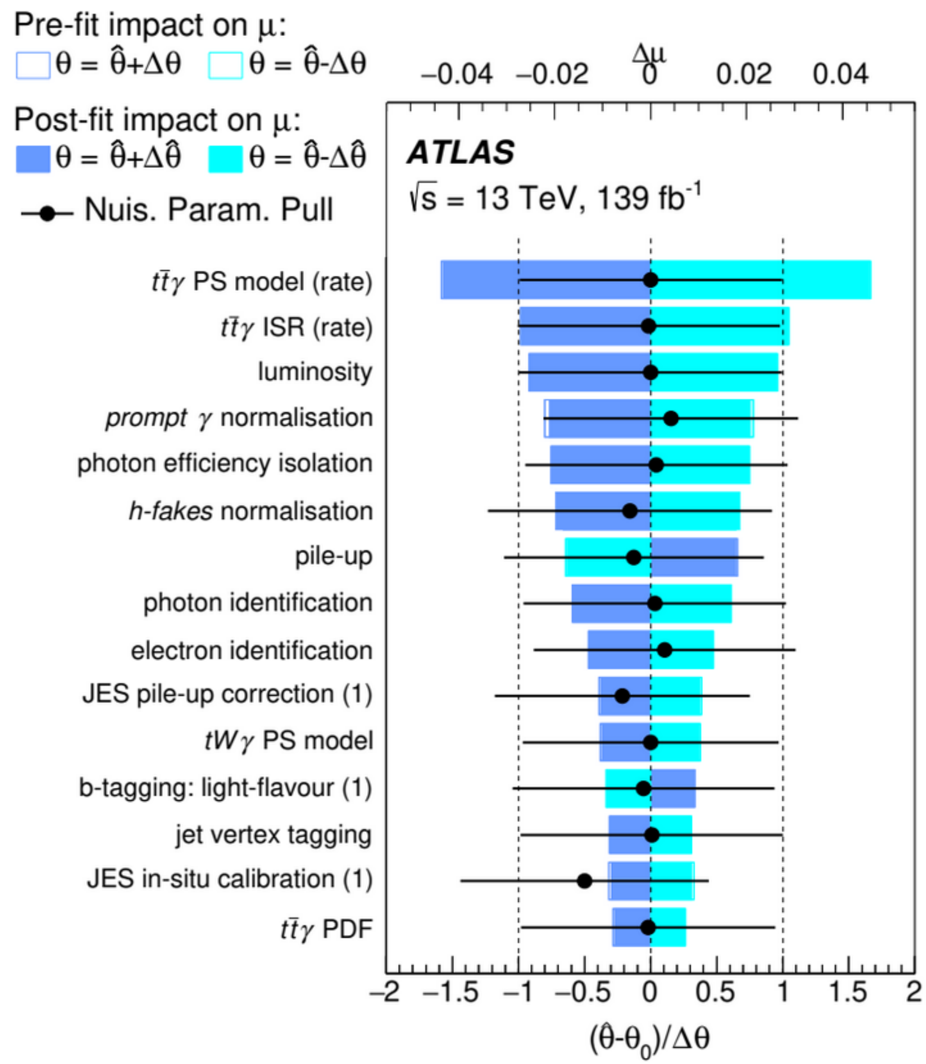
JHEP 09 (2020) 049

$t\bar{t}\gamma$ + tWγ

Fit performed on S_T:

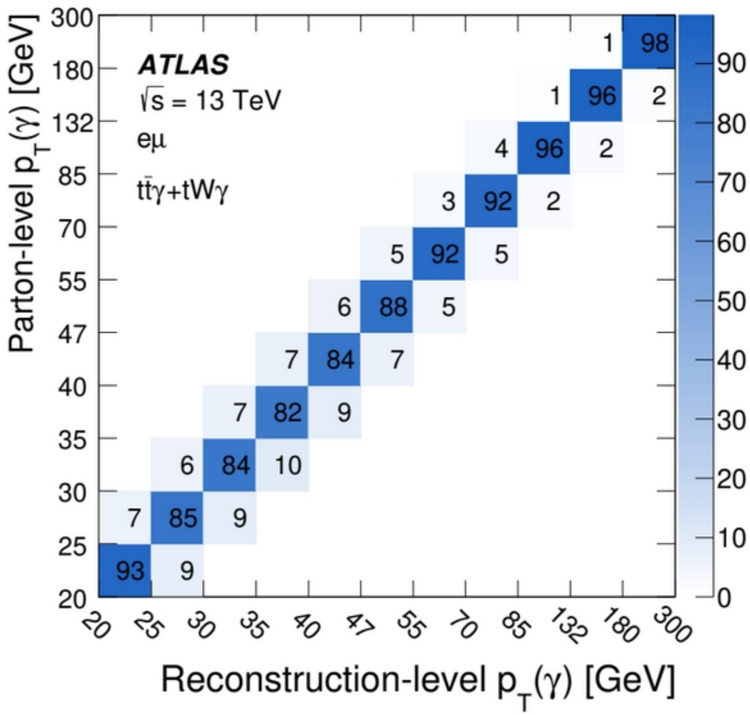
Scalar sum of all transverse momenta in the event (leptons, photons, jets, MET)





$t\bar{t}\gamma$ + tWγ

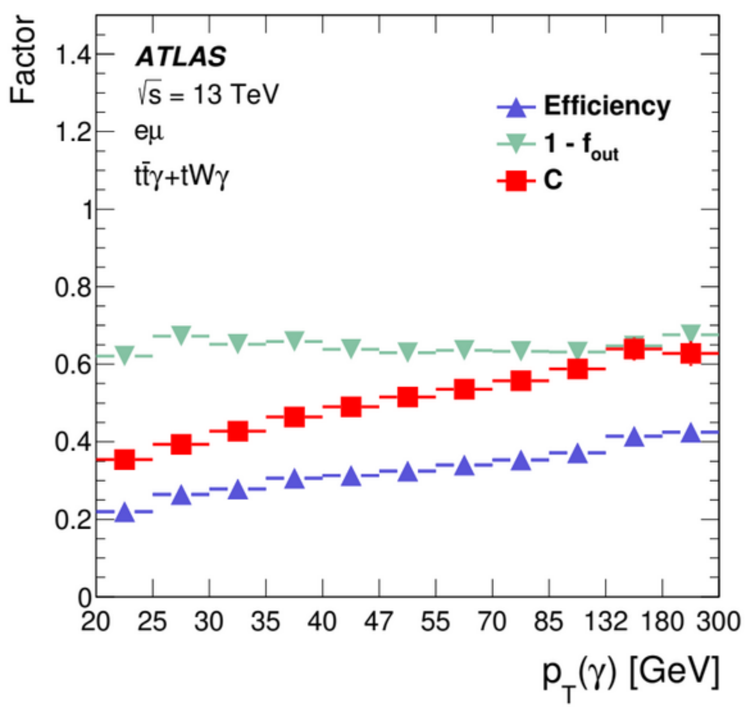
Migration matrix



Correction factor C:

Take into account events outside of fiducial phase space that pass event reconstruction

$$f_{\mathrm{out}} = \frac{N_{\mathrm{reco}}^{\mathrm{non\text{-}fid}}}{N_{\mathrm{reco}}}, \qquad \epsilon = \frac{N_{\mathrm{reco}}^{\mathrm{fid}}}{N_{\mathrm{MC}}^{\mathrm{fid}}} \qquad \Rightarrow C = \frac{\epsilon}{1 - f_{\mathrm{out}}} = \frac{N_{\mathrm{reco}}}{N_{\mathrm{MC}}^{\mathrm{fid}}}$$



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tqγ

Standard model search

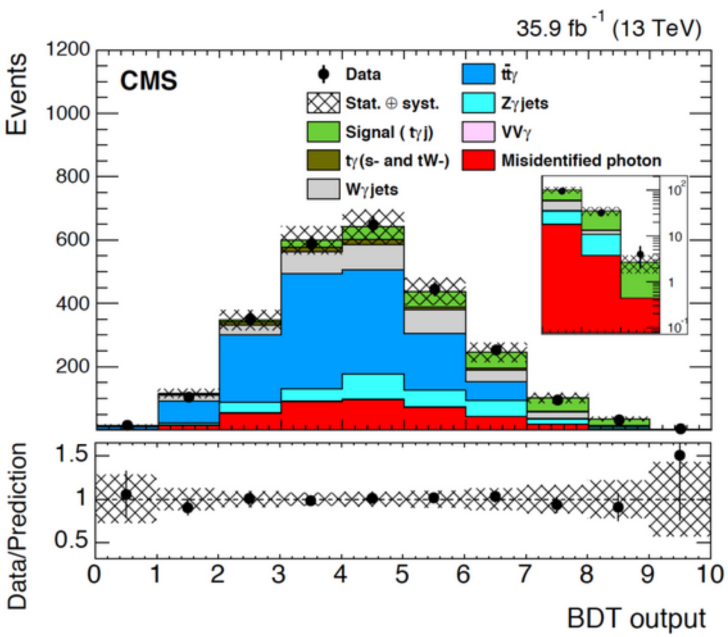
- 2016 data: 35.9 fb^{-1}
- 1 μ, 1 γ, ≥2 jets (1 b), $p_T^{Miss.}$

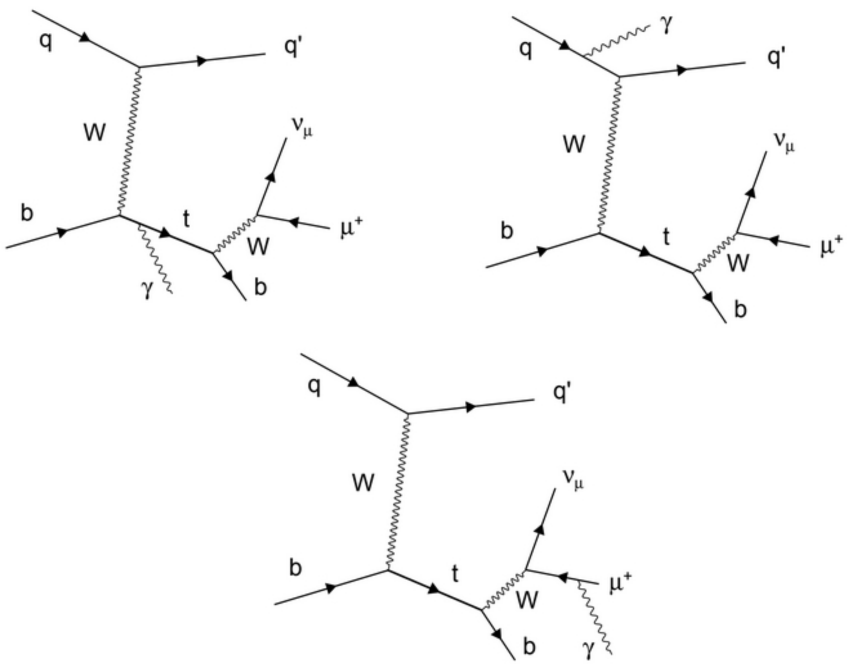
BDT to separate signal from background

- High p_T light flavor forward jet
- Top quark polarization, …

$$\sigma_{\mathrm{tq}\gamma,\ \mathrm{t}\rightarrow\mu\nu\mathrm{b}} = 115 \pm 30(\mathrm{syst}) \pm 17(\mathrm{stat})\ \mathrm{fb}$$

4.4 standard deviation → evidence!





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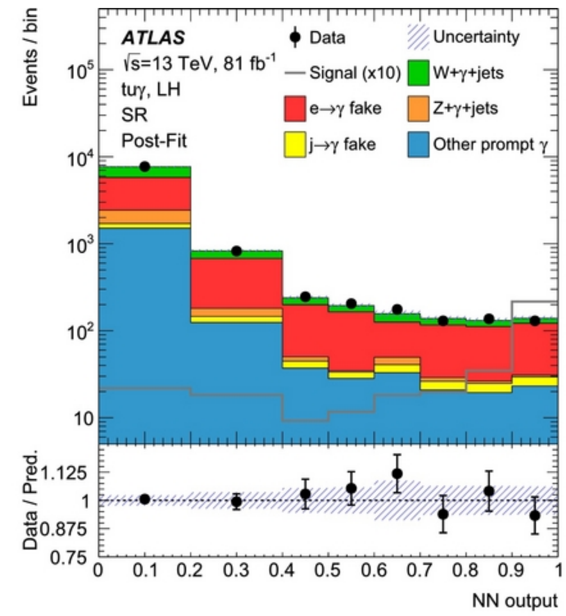
tqγ – search for FCNC



Search region:

- 1 Muon/Electron
- 1 Photon
- = 1 b jet and not further jet
- $p_T^{Miss.}$ > 30 GeV

Electron fakes photon – data driven

- Measurement of fake rate
  - Z→ ee vs. Z→ eγ

Hadron fakes photon – data driven

- Normalization with ABCD method
  - shower shape vs. isolation

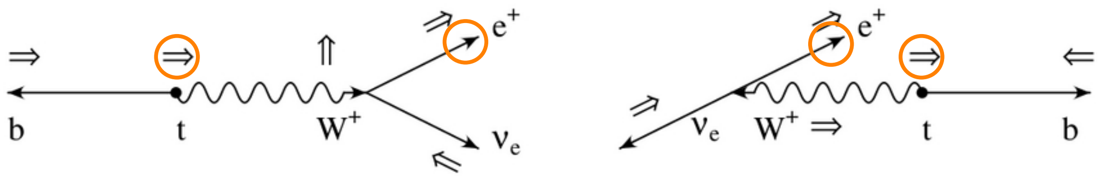
Neural network

- Signal (FCNC) vs. background

	Observable	Vertex	Coupling	Obs.	Exp.
EFT	$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*}\rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
	$\lvert C_{uW}^{(31)} + C_{uB}^{(31)}\rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
	$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*}\rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
	$\lvert C_{uW}^{(32)} + C_{uB}^{(32)}\rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
Production	$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
	$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
	$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
	$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
Decay	$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
	$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
	$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
	$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

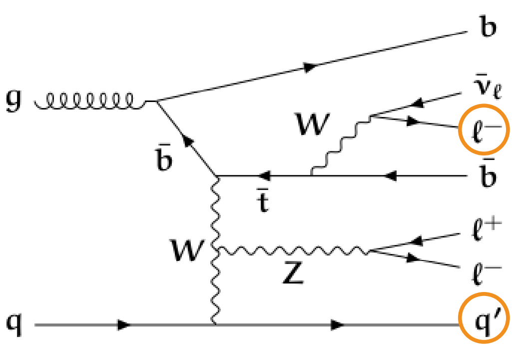
tZq – top quark spin asymmetry

Lepton from top quark (antiquark) decay prefers to travel alongside (against) the top quark (antiquark) spin

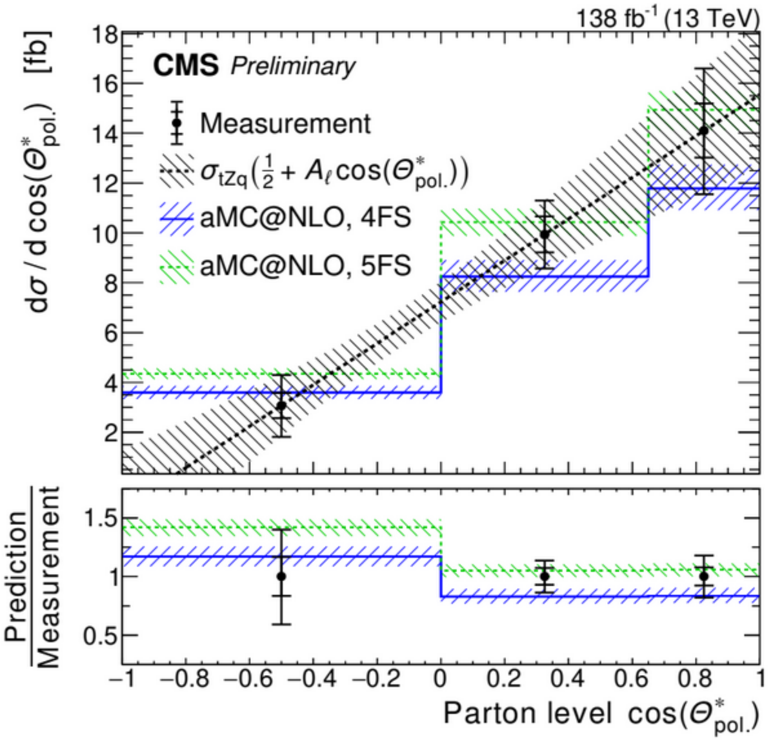


Polarization angle defined in "optimized basis"

- Spectator quark serves as reference



$$\cos(\theta^\star_{\mathrm{pol}}) = \frac{\vec{p}(\mathrm{q}'^\star)\cdot\vec{p}(\ell^\star_\mathrm{t})}{|\vec{p}(\mathrm{q}'^\star)|\,|\vec{p}(\ell^\star_\mathrm{t})|}$$



Spin asymmetry $A_\ell = 1/2 * P * a_\ell$ related as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta^\star_{\mathrm{pol}})} = \sigma_{\mathrm{tZq}}\left(\frac{1}{2} + A_\ell \cos(\theta^\star_{\mathrm{pol}})\right)$$

Fit re parameterized and spin asymmetry measured as

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

$$A_\ell^{\mathrm{MG5\_aMC@NLO}} = 0.437^{+0.004}_{-0.003}$$