New $t\bar{t}\gamma$ and tZq measurements in CMS

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EOS equinox meeting,
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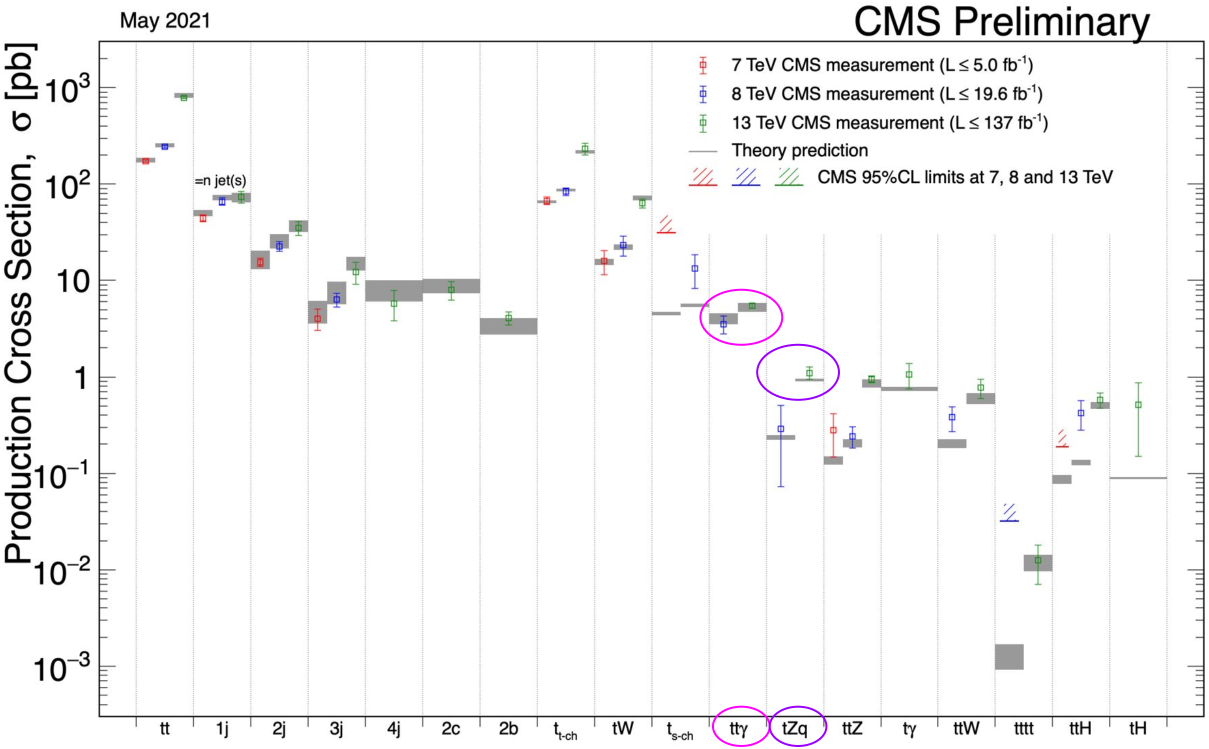
Introduction



All results at: http://cern.ch/go/pNj7

Interesting new results in top quark physics at CMS:

- ttγ: top quark pair + photon
- tZq: single top quark + Z boson

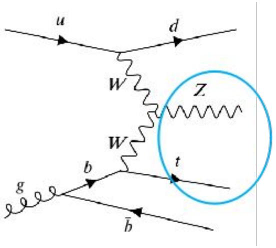
For both:

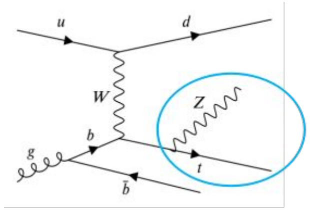
- Improved inclusive cross-section measurement!
- First/improved differential cross-section measurements!

tZq: introduction

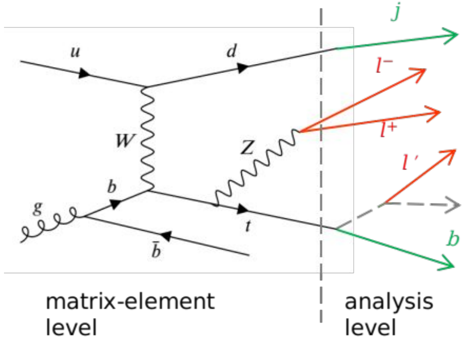
tZq is a probe for new physics:

- sensitive to: ttZ- and WWZ couplings,
  top quark polarization,
  proton PDFs via top quark-antiquark ratio.
- impacted by FCNC or more generally in the SMEFT phenomenology [1].





Earlier tZq measurements by CMS and ATLAS [2-4]: → precision: ±15%



- 3 leptons (electrons or muons)
  - selection based on new lepton MVA.
- ≥ 2 jets (pt > 25 GeV, eta < 5), ≥ 1 b-jet.

- Z boson candidate: OSSF lepton pair with … < 15 GeV.
- top quark candidate and accompanying b jet: reconstructed analytically.
- recoiling jet: leading non-b-tagged jet, tends to be forward.

background from nonprompt leptons estimated from data
and uncertainty constrained in dedicated nonprompt control region.

multiclass NN or BDT to distinguish tZq from backgrounds.

[1]: JHEP 10 (2018) 005, doi [2]: Phys. Lett. B 779 (2018) 358, doi [3]: Phys. Rev. Lett. 122 (2019) 132003, doi [4]: JHEP 07 (2020) 124, doi

tZq: inclusive results

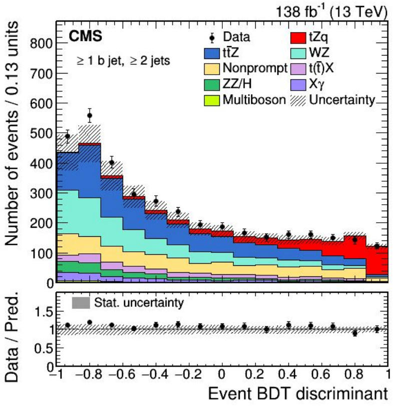
Inclusive tZq cross-section:

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

→ total uncertainty of ± 11%

Improvement of about 25%
w.r.t. earlier measurements, due to

- larger data set.
- larger measurement region.
- improved lepton MVA.
- constraining nonprompt background (dominant in earlier measurements).



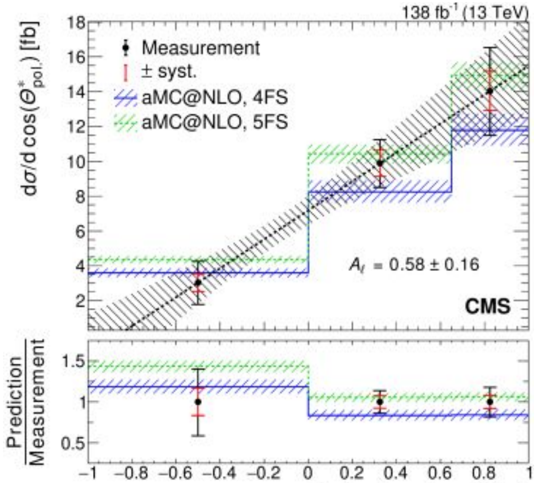
Spin asymmetry:

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

compared to prediction:

$$A_l^{4FS} = 0.437^{+0.004}_{-0.003}$$

$$A_l^{5FS} = 0.454^{+0.004}_{-0.005}$$



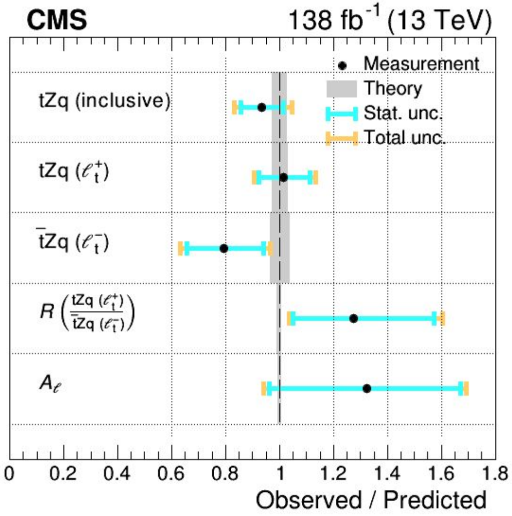
Plot by David Walter

Partial tZq cross-sections:

$$\sigma_{\mathrm{tZq}}(l_t^+) = 62.2^{+5.9}_{-5.7}(\mathrm{stat})^{+4.4}_{-3.7}(\mathrm{syst.})\ \mathrm{fb}$$

$$\sigma_{\mathrm{tZq}}(l_t^-) = 26.1^{+4.8}_{-4.6}(\mathrm{stat.})^{+3.0}_{-2.8}(\mathrm{syst.})\, fb$$

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



tZq: differential results

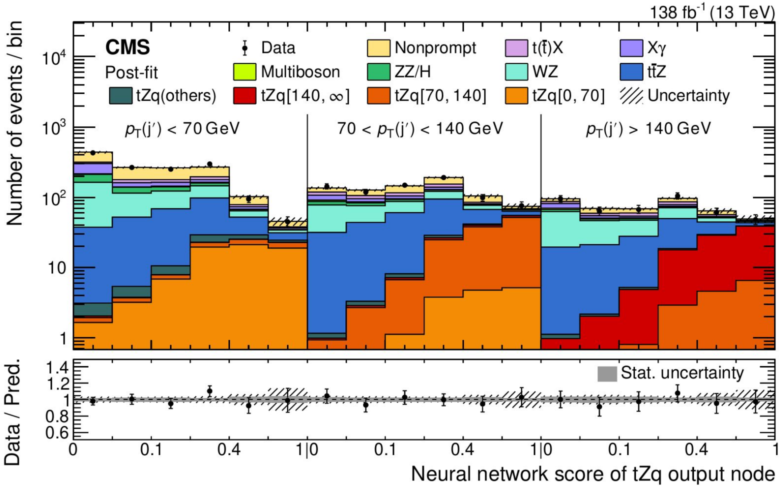
<u>Goal:</u> obtain distributions of jet, lepton, Z boson and top quark kinematics with detector effects removed.

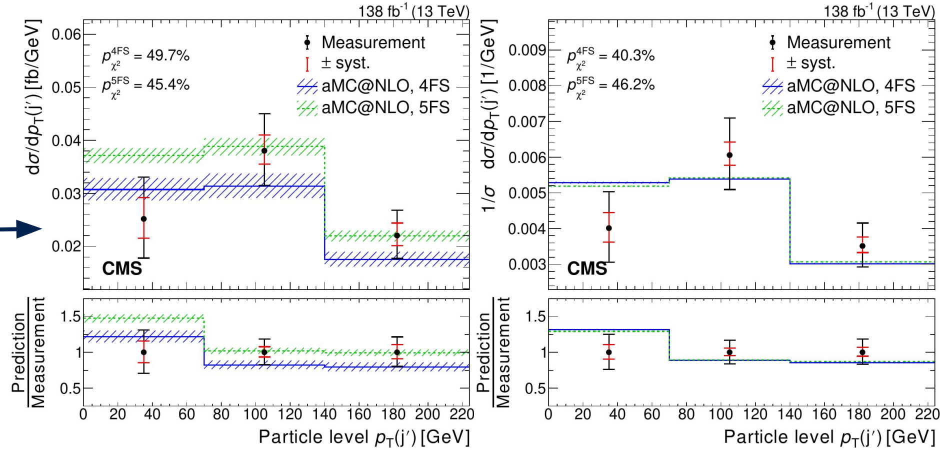
<u>Method:</u> maximum likelihood based unfolding.

- Split signal sample into generator bins (colours),
- Split signal region in corresponding detector bins.
- Perform simultaneous fit on MVA output for all signals / signal regions.

<u>Results:</u>

- Observe good agreement between measurement and prediction.
- Compared to both 4FS and 5FS prediction.
  →no clear preference with current amount of data.
- Other variables: see public note (see conclusion) or backup!





By David Walter

$t\bar{t}\gamma$: introduction

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This analysis contains:

- full RunII data
- Inclusive and differential $t\bar{t}\gamma$ cross section measurement in the dilepton channel (all 3 channels: ee, eμ, μμ)
- EFT interpretation + combination with ℓ+jets EFT result

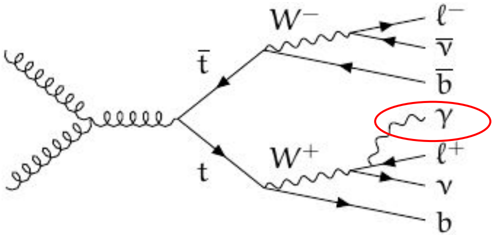
Motivation:

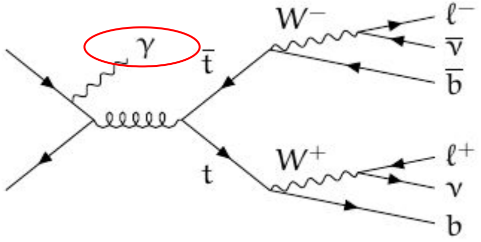
- Probe top-photon coupling ~ constrain EFT operators c_{tZ} and c_{tZI}
- stepping stone towards further measurements, e.g. $t\bar{t}\gamma\gamma$ and its ratio to $t\bar{t}\gamma$

Signal definition:

tt production in fully leptonic decay mode + photon radiated from

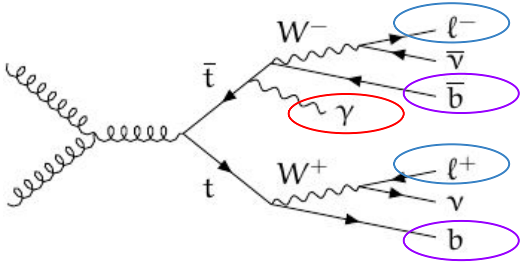
- initial-state particles,
- top quarks,
- their decay products.





Event selection:

Variable	Requirement
$p_T^{\text{leading}}(l)$	> 25 GeV
$p_T^{\text{trailing}}(l)$	> 15 GeV
N_{leptons}	$= 2$
Charge sum of the leptons	$= 0$
$p_T(\gamma)$	> 20 GeV
N_γ	$= 1$
N_γ looser ID	$= 1$
N_b	≥ 1
$m_{\ell\ell}$	> 20 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	> 15 GeV (SF channels)
$\lvert m_{\ell\ell\gamma} - m_Z \rvert$	> 15 GeV (SF channels)



ttγ: backgrounds

Backgrounds with prompt photon:

- Zγ
- Single-t+γ (single top samples)
- Other+γ (e.g. multi-boson, W+jets, tt̄H, tttt)

→ estimated using simulation.

prompt: match gen photon with leptonic/boson/quark origin.

Backgrounds with nonprompt photon:

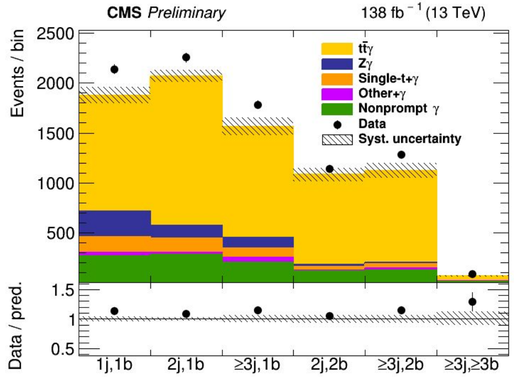
- basically all… (mostly DY and ttbar)

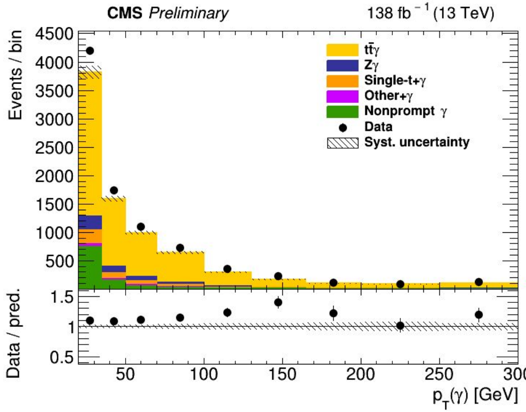
→ estimated from data, together ~9% of signal region.

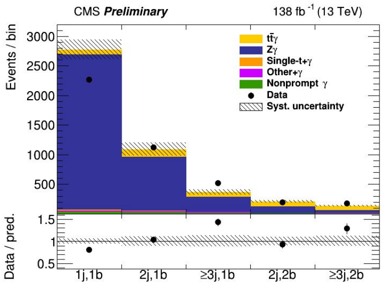
nonprompt: radiated by mesons, faked by jets or electrons, or from pileup.

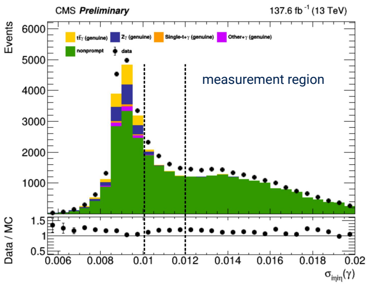
Zγ mismodeling observed, derived corrections in dedicated control region!

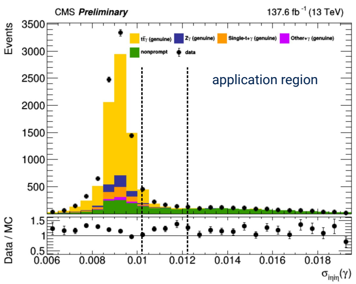
Nonprompt background estimated with ABCD method.







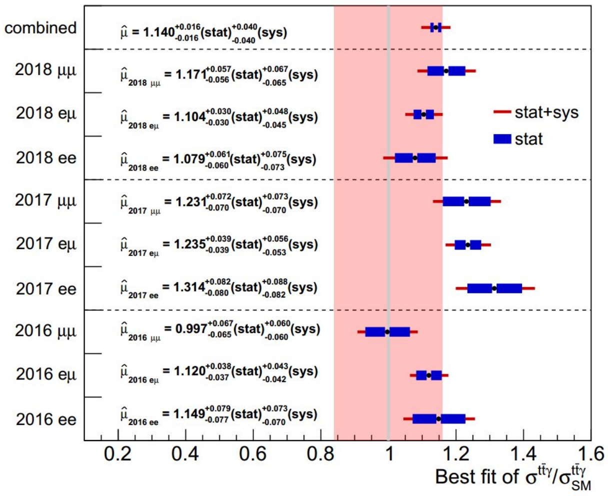


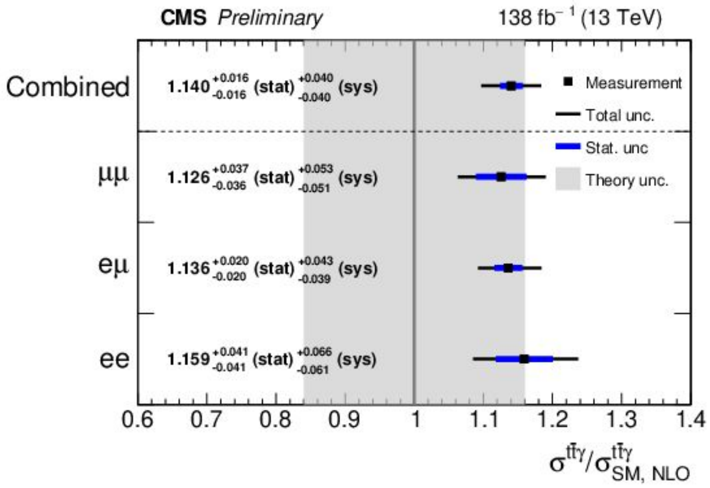


By Gianny Mestdach

$t\bar{t}\gamma$: inclusive results

- Binned maximum likelihood fit.
- Fit to photon p_T distribution, in 3 channels, histograms kept separate between years.
- Observed results:
  - Signal strength > 1, but within the current theoretical uncertainties.
  - Total experimental uncertainty < 4%, most precise measurement to date.
  - Experimental uncertainty << theoretical uncertainty.
  - Consistent between channels and years.



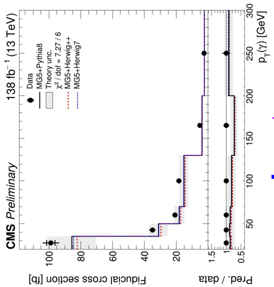


By Gianny Mestdach

$t\bar{t}\gamma$: differential results

Goal: obtain distributions of photon, lepton and jet kinematics with detector effects removed.

Method: explicit response matrix inversion.



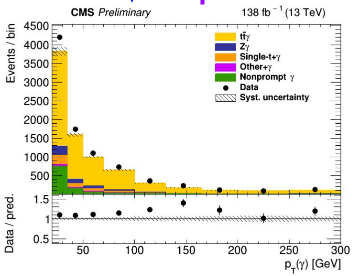
true distribution

Response matrix, containing
- detector inefficiencies,
- resolution effects, ...

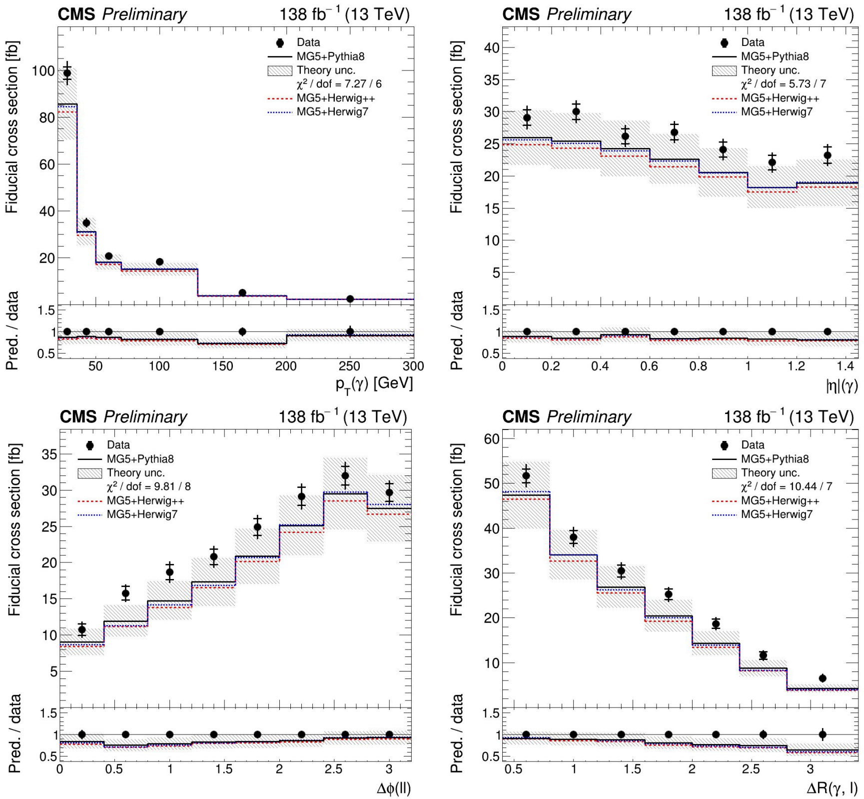
measurement

unfolding

measured distribution



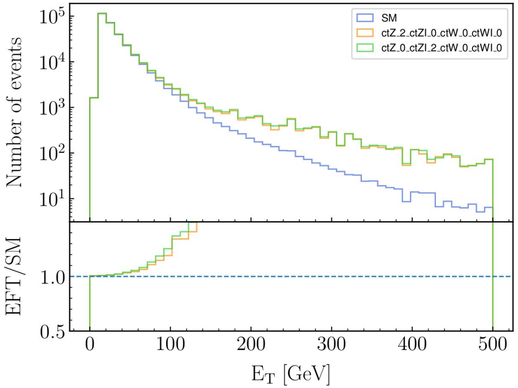
Results:

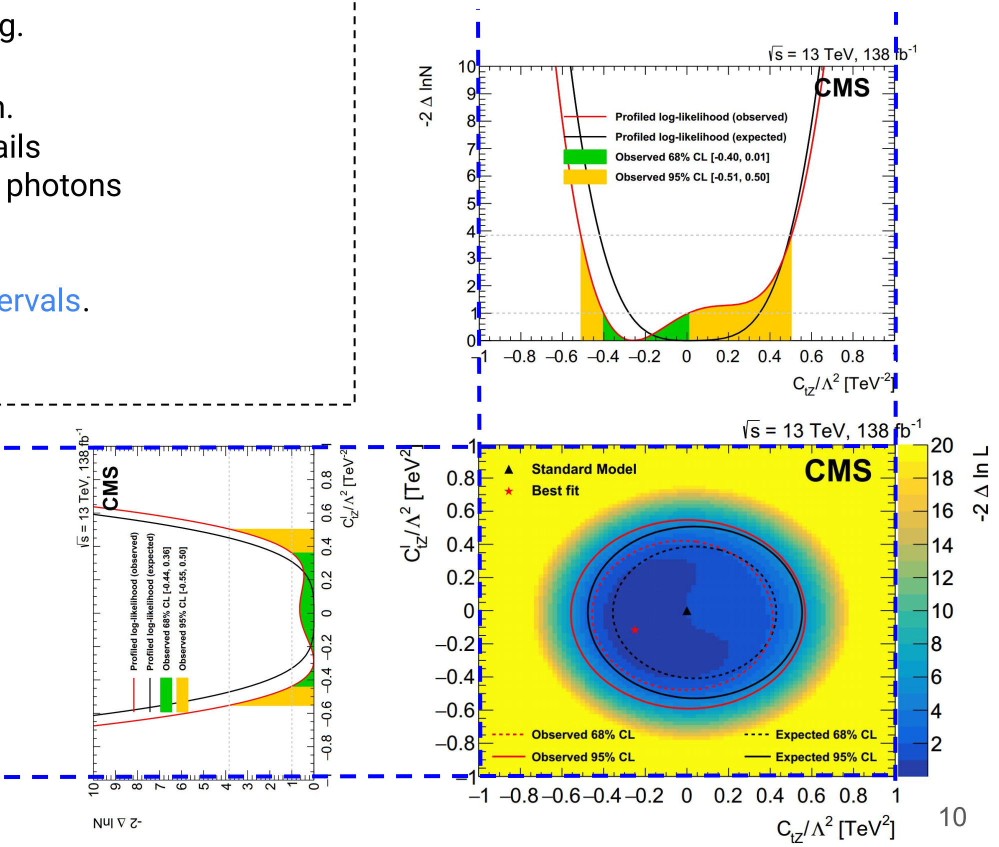


By Gianny Mestdach

ttγ: EFT results

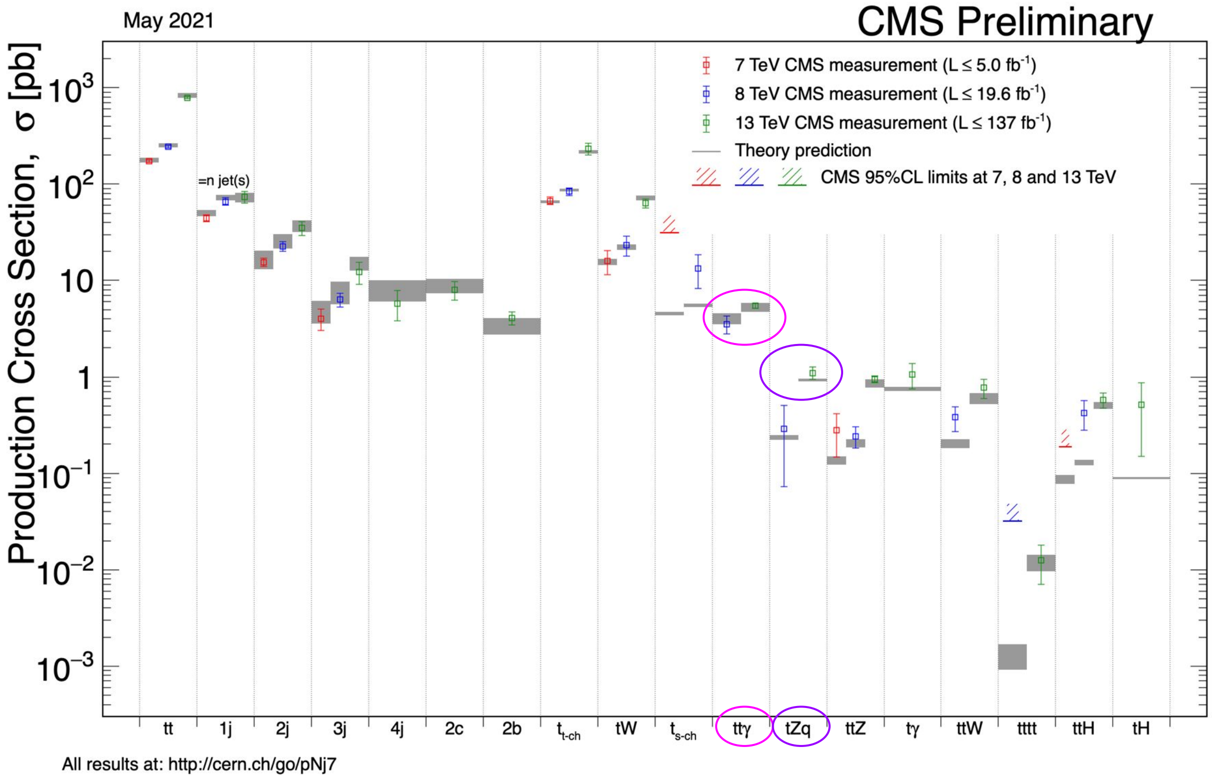
- Modeling operator effects using gen-sample reweighting.
- Constraints from profile likelihood scan based fit
- Limits obtained using differential photon p_T information.
  - great signal-to-background separation towards tails
  - EFT effects affect mostly the tails ~ top radiated photons
- Relevant operators: c_{tZ} & c_{tZI}
- Observed results:
  - SM result is contained within 68% confidence intervals.
  - Both in 2D fit as in 1D projections.
  - No clear indication of new physics yet…





By Gianny Mestdach

Conclusion



Most precise measurements of ttg and tZq up to now.

Both inclusive and differential.

Important pieces in testing the full experimentally accessible range of SM predictions.

All results consistent with SM expectations.

Both papers in review process…
Links to preliminary results:
tZq PAS CDS record (publicly available)
ttg CADI (CMS internal only)

Backup: tZq

Inclusive and differential tZq (TOP-20-010)

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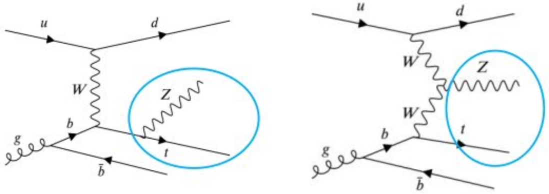
tZq is a probe for new physics:
- sensitive to ttZ- and WWZ couplings.
- sensitive to top quark polarization.
- sensitive to proton PDFs via top quark-antiquark ratio.
- impacted by FCNC or more generally in the SMEFT phenomenology [1].



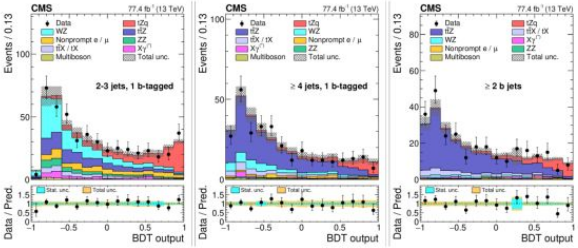
Earlier tZq measurements:

First evidence with 2016 data [2]

↓

First observation with 2016+2017 data [3]

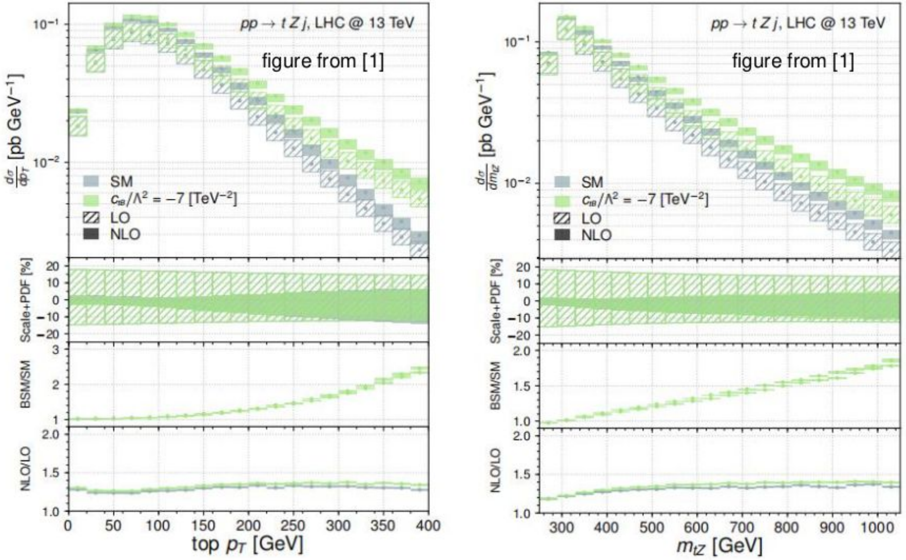
→ precision: ± 14-15%



↓

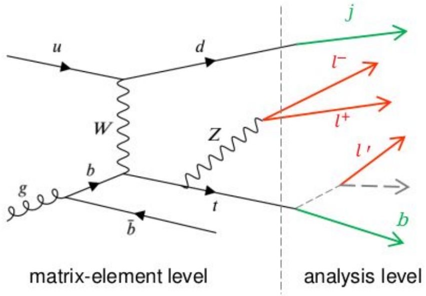
Observation at ATLAS with full Run II dataset [4]

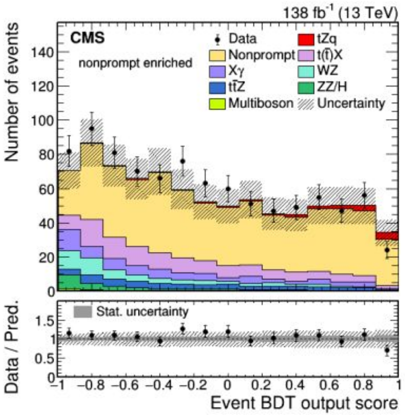
→ precision: ±15%



[1]: *JHEP* **10** (2018) 5, doi
[2]: *Phys. Lett. B* **779** (2018) 358, doi
[3]: *Phys. Rev. Lett.* **122** (2019) 132003, doi
[4]: *JHEP* **07** (2020) 124, doi

Inclusive and differential tZq (TOP-20-010)





- 3 leptons (electrons or muons)
  - selection based on new lepton MVA.
- 1 OSSF pair compatible with Z boson mass within 15 GeV.
- ≥ 2 jets ($p_T > 25$ GeV, $|\eta| < 5$).
- < 4 central jets ($|\eta| < 2.4$ (2016) / < 2.5 (2017/2018)) (only in differential).
- ≥ 1 b-jet (medium deepFlavor working point, central).

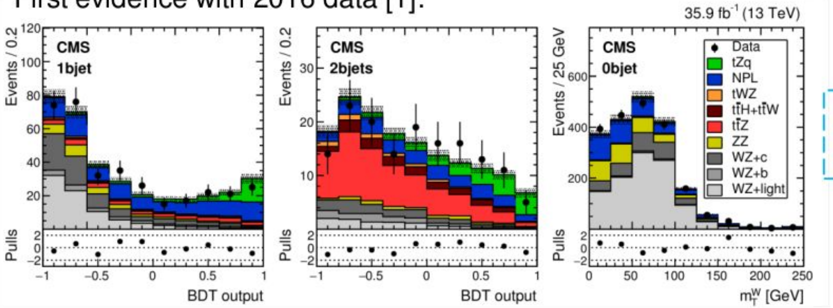
- Z boson candidate:
  - OSSF lepton pair with $|m_Z - m_{ll}| < 15$ GeV.
- top quark candidate and accompanying b jet
  - reconstructed analytically using W boson and top quark mass constraints.
- recoiling jet
  - non b-tagged jet with highest p_T.
  - tends to be emitted in forward region of the detector.

- background from nonprompt leptons estimated from data and uncertainty constrained in dedicated nonprompt control region.

- discriminating features based on presence of a hard forward jet, presence of at least one b-jet, charge asymmetry of the top quark etc.
- combined into MVA (multiclass NN or BDT) to distinguish tZq from WZ, ttZ and others.

Inclusive and differential tZq (TOP-20-010)

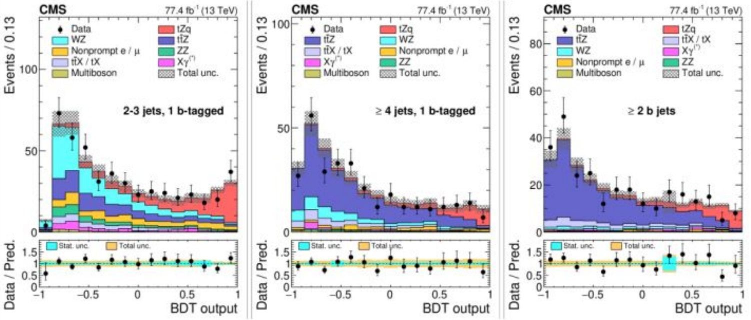
First evidence with 2016 data [1]:



Standard model prediction:
$\sigma_{\text{tZq}}^{\text{SM}} = 94.2^{+1.9}_{-1.8}$ (scale) ± 2.5 (PDF) fb [1]

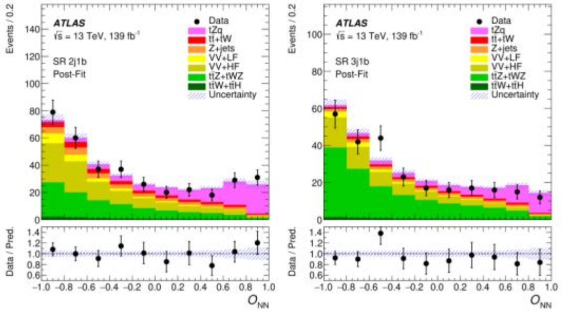
$\sigma_{\text{tZq}} = 123^{+33}_{-31}$ (stat.) $^{+29}_{-23}$ (syst.) fb
significance = 3.7 (obs.) / 3.1 (exp.)

First observation with 2016+2017 data [2]:



$\sigma_{\text{tZq}} = 111 \pm 13$ (stat.) $^{+11}_{-9}$ (syst.) fb (→ precision: ± 14-15%)
significance = 8.2 (obs.) / 7.7 (exp.)

Observation at ATLAS with full Run II dataset [3]:



$\sigma_{\text{tZq}} = 97 \pm 13$ (stat.) ± 7 (syst.) fb (→ precision: ±15%)

Significance >> 5σ → observation has been established.
Next challenges: improve precision on σ_{tZq}.
perform first differential measurement.

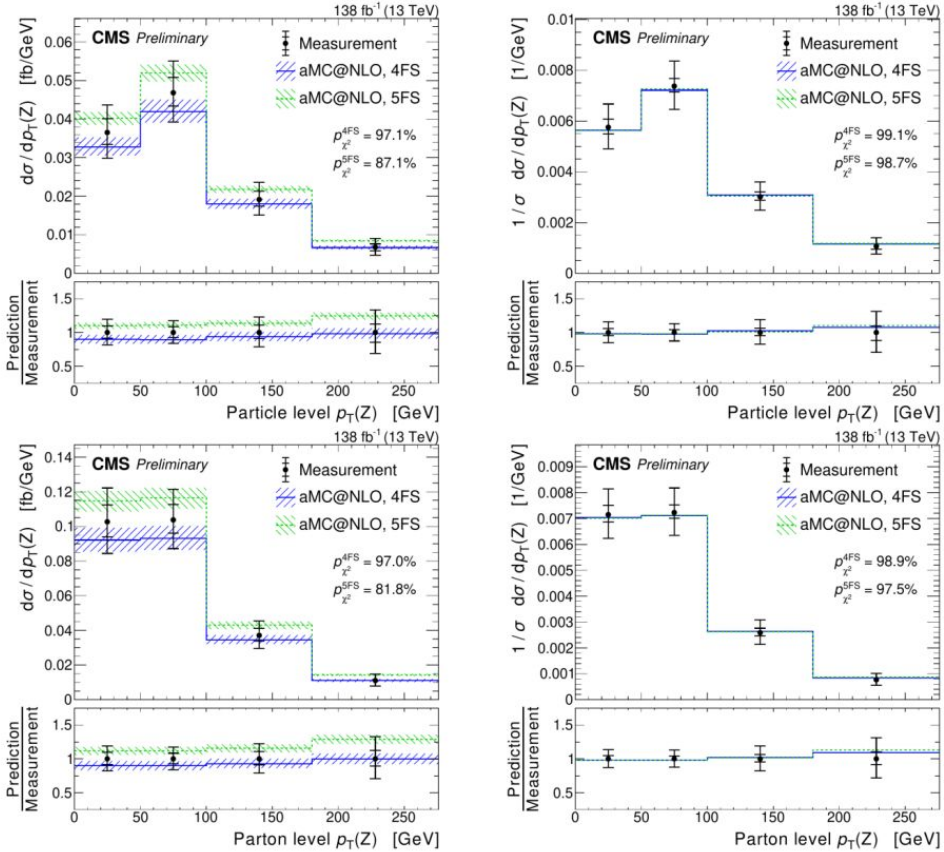
[1]: *Phys. Lett. B* **779** (2018) 358, doi
[2]: *Phys. Rev. Lett.* **122** (2019) 132003, doi
[3]: *JHEP* **07** (2020) 124, doi

Inclusive and differential tZq (TOP-20-010)

absolute normalized

particle level

parton level



- In general, observe good agreement between measurement and prediction.
- Compared to both 4FS and 5FS prediction.
- Uncertainties down to 15% for purely leptonic observables, down to 25% for observables including jets.

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Inclusive and differential tZq (TOP-20-010)

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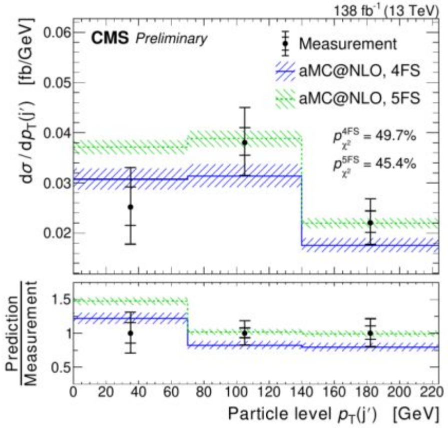

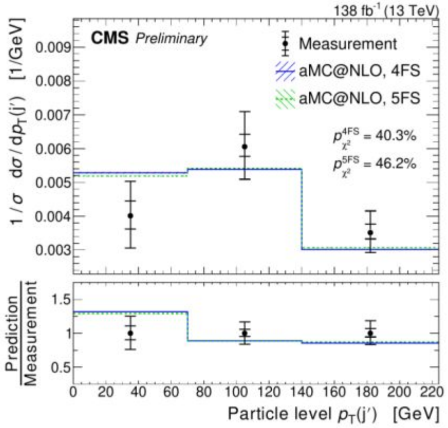

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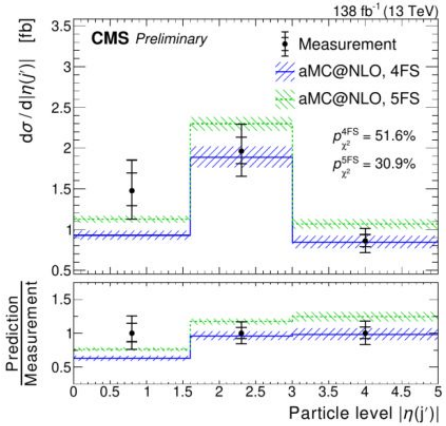

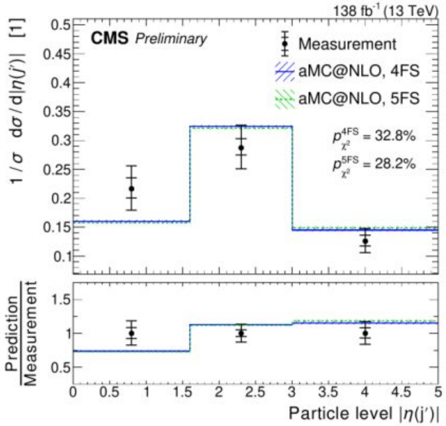

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absolute | normalized

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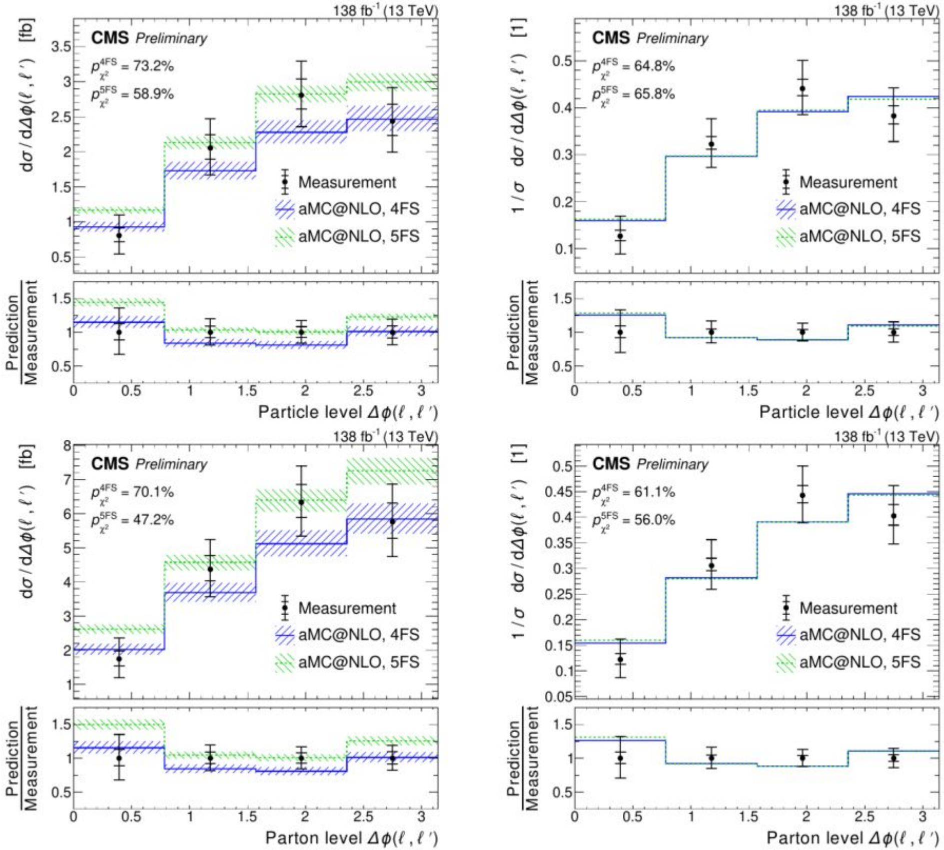

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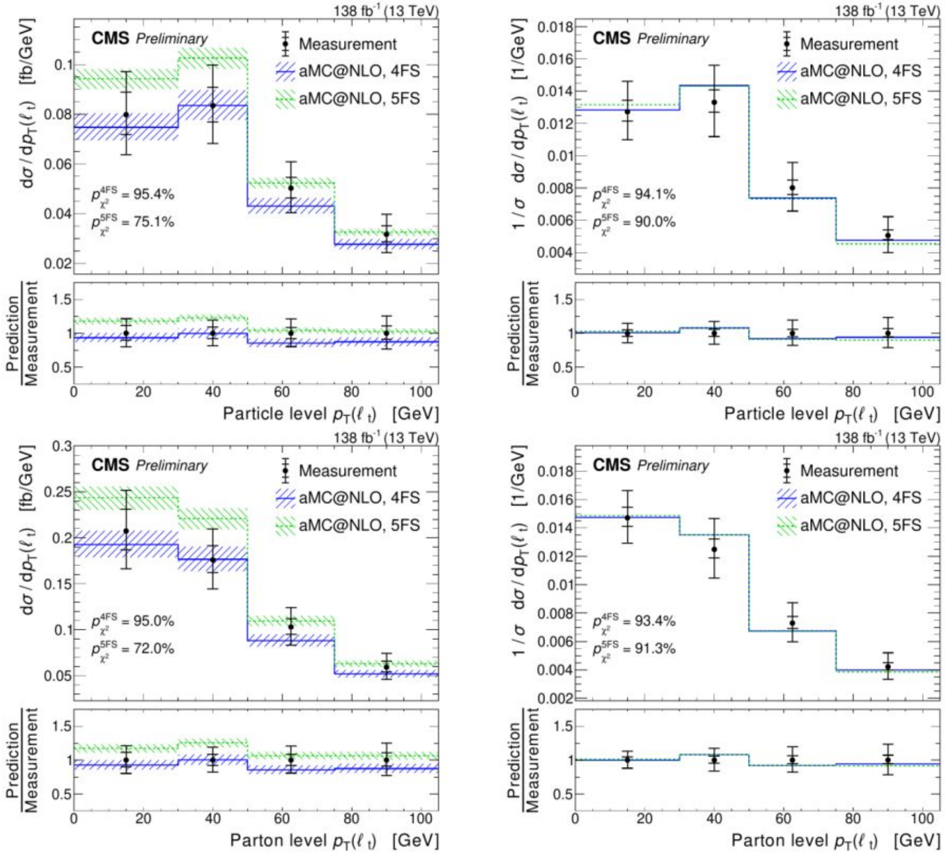

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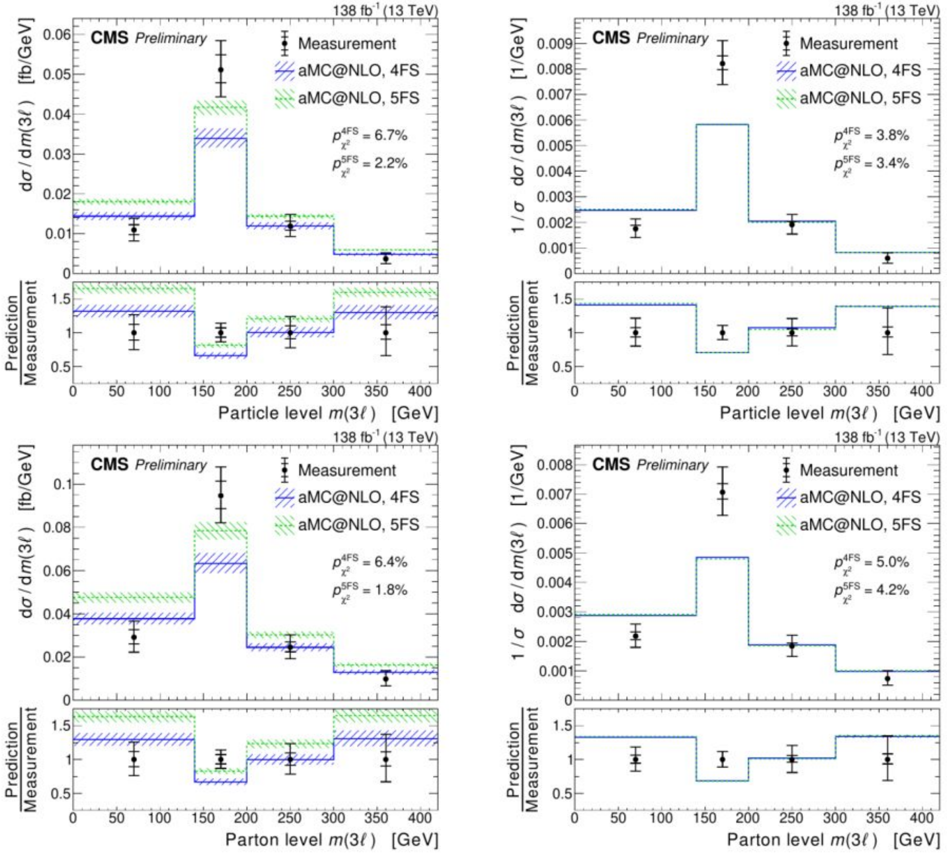

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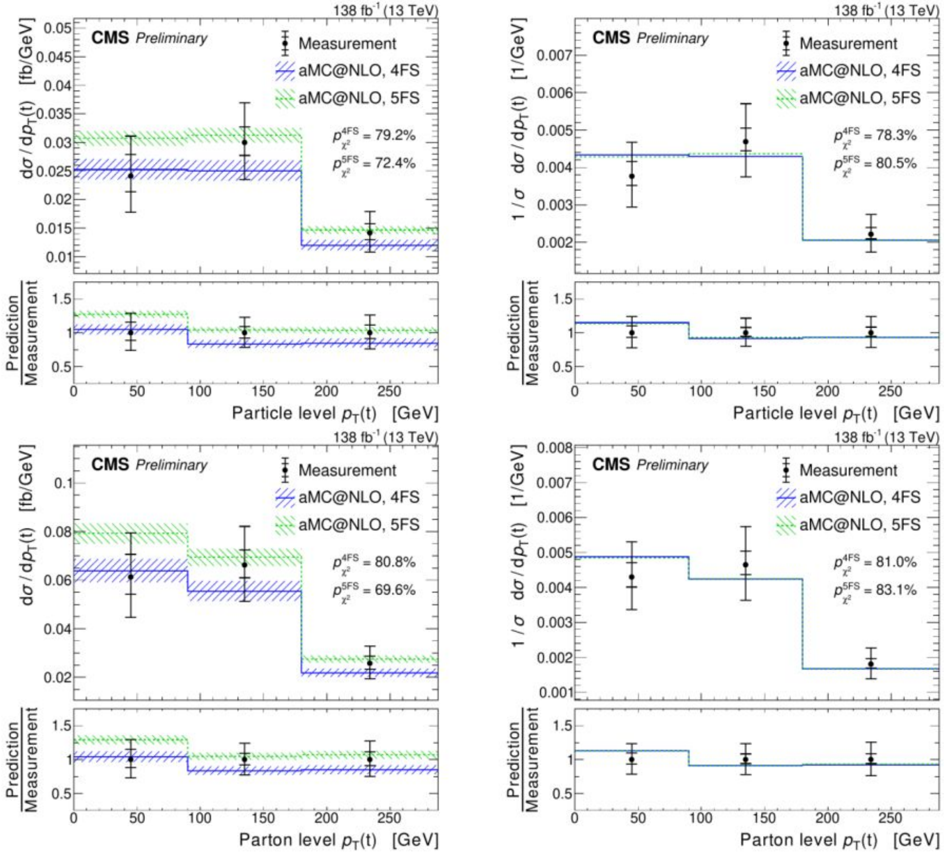

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Inclusive and differential tZq (TOP-20-010)

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absolute | normalized

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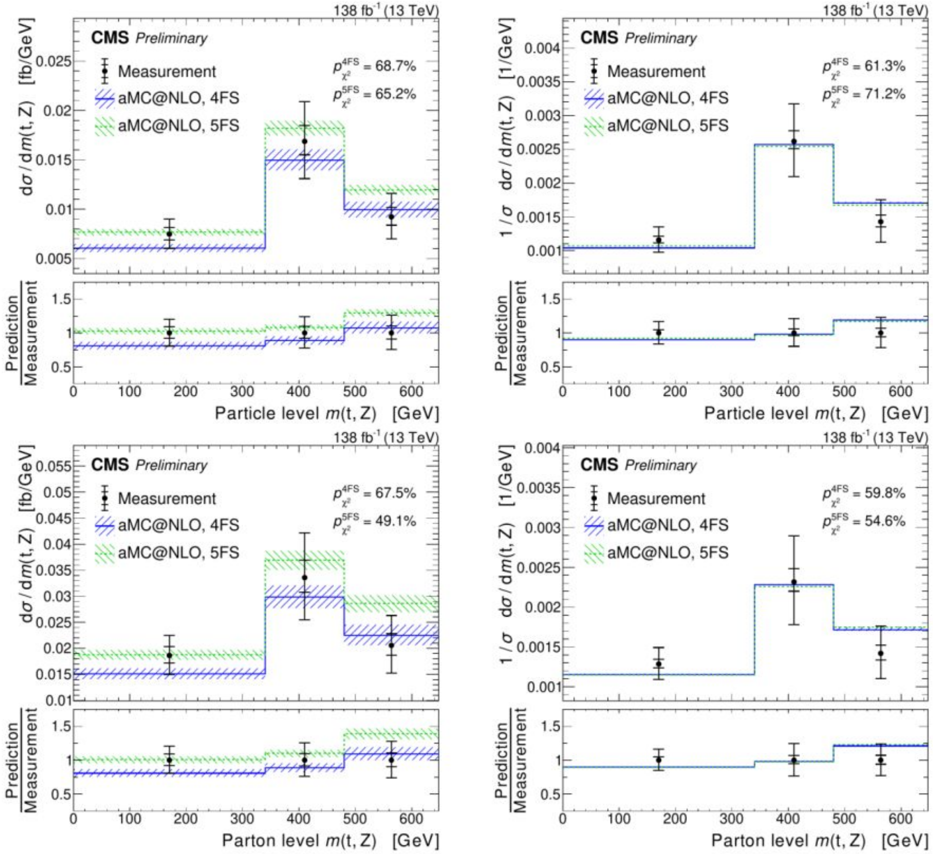

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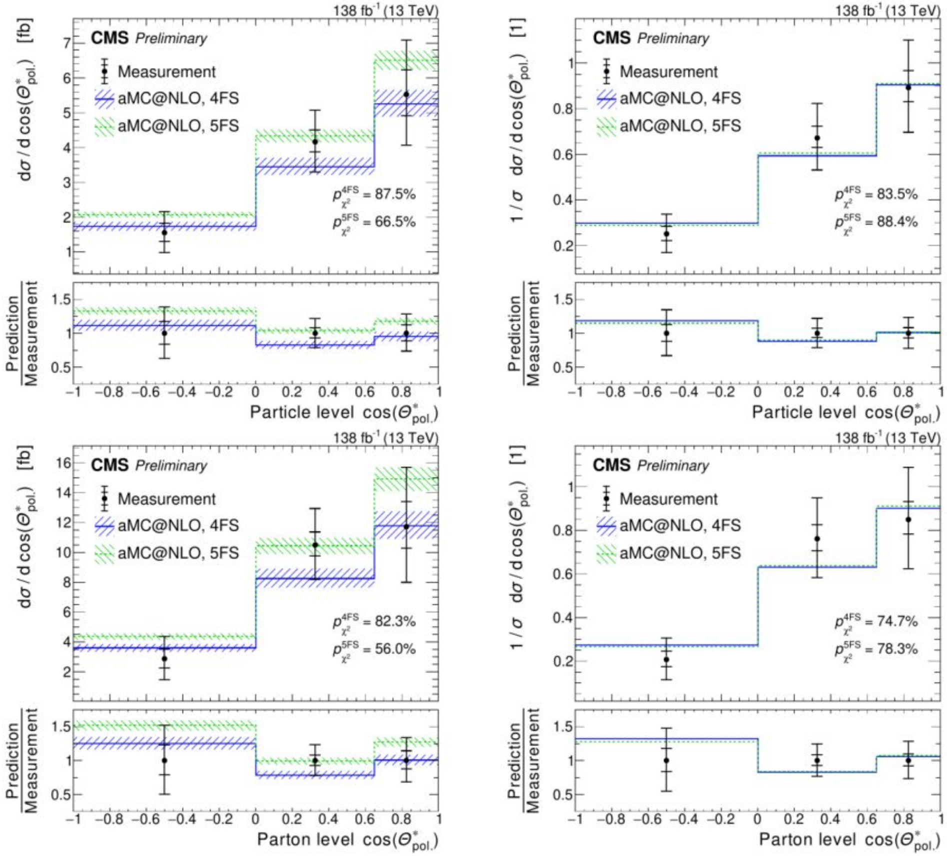
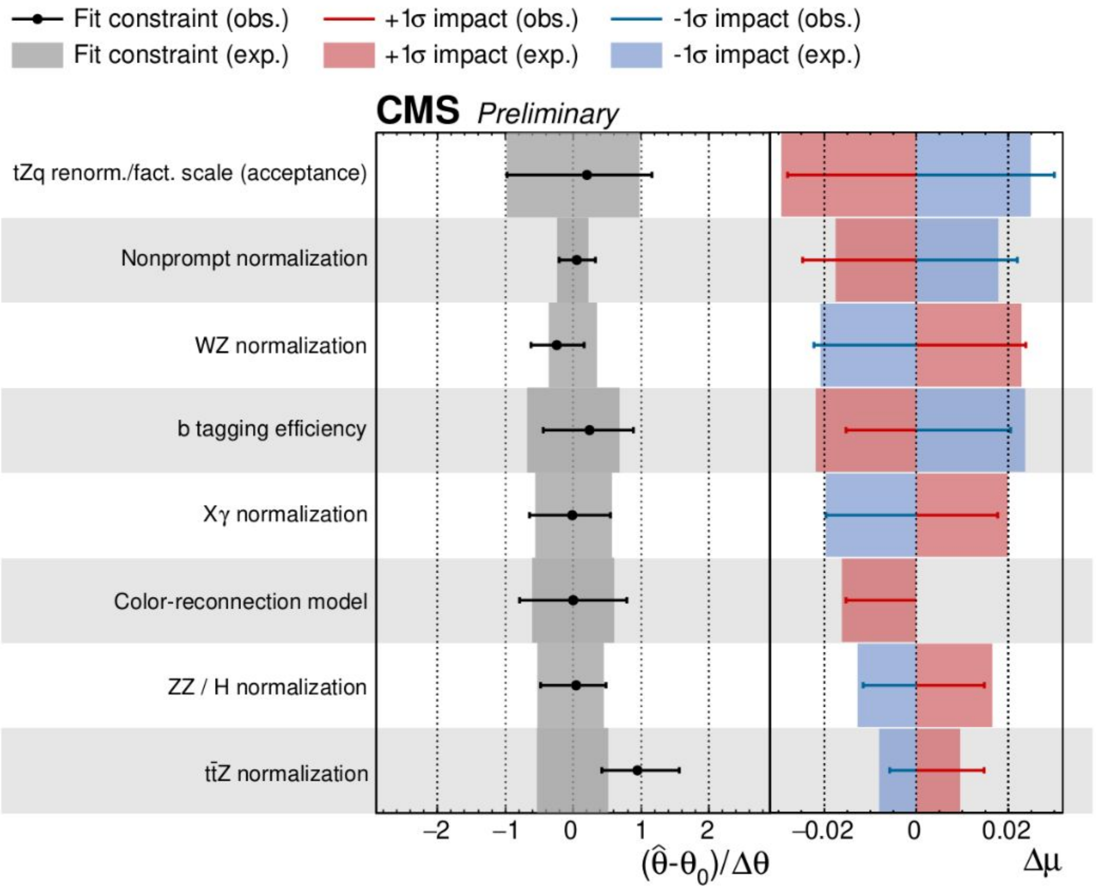
parton level



- In general, observe good agreement between measurement and prediction.
- Compared to both 4FS and 5FS prediction.
- Uncertainties down to 15% for purely leptonic observables, down to 25% for observables including jets.

Inclusive and differential tZq (TOP-20-010)



"Summary of the dominant systematic uncertainties affecting the inclusive tZq cross section measurement. The left column lists the sources of systematic uncertainty, treated as nuisance parameters in the fit, in order of importance. In the middle column, the black points with the horizontal bars show for each source the difference between the observed best-fit value (θ) and the nominal value (θ_i), divided by the expected standard deviation ($\Delta\theta$). The right column plots the change in the tZq signal strength μ if a nuisance parameter is varied one standard deviation up (red), or down (blue). The gray, red and blue bands display the same quantity as their corresponding markers, but using a simulated data set where all nuisance parameters are set to their expected values."

Backup: ttγ

Comparison with ATLAS

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CMS result:

Fiducial cross section:

$$174.4 \pm 6.1\,(syst.) \pm 2.5\,(stat.)$$

Signal strength:

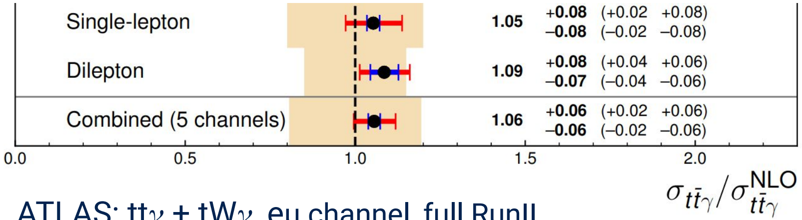
$$1.140 \pm 0.040\,(syst.) \pm 0.016\,(stat.)$$

ATLAS results:

ATLAS: ttγ, leptonic final states, 2015 + 2016 data

$$\sigma^{SL}_{fid} = 521 \pm 9(\text{stat.}) \pm 41(\text{sys.})\ \text{fb and}$$
$$\sigma^{DL}_{fid} = 69 \pm 3(\text{stat.}) \pm 4(\text{sys.})\ \text{fb},$$

particle level



ATLAS: ttγ + tWγ, eμ channel, full RunII

$\sigma_{fid}(tt\gamma)$ = $39.6^{+2.7}_{-2.3}$ fb (= 6.3% total rel unc.) parton level

comparison to of systematic uncertainties:

Source	ATLAS	CMS
signal modeling	3.8%	1.7%
bkg. modeling	2.1%	1.5%
photons	1.9%	0.9%
luminosity	1.8%	1.7%
jets	1.6%	1.3%
pilup	1.3%	0.6%
leptons	1.1%	1.1%
MC statistics	0.4%	0.9%
MET	0.2%	-
prefiring	-	0.3%
Total	6.3%	3.6%

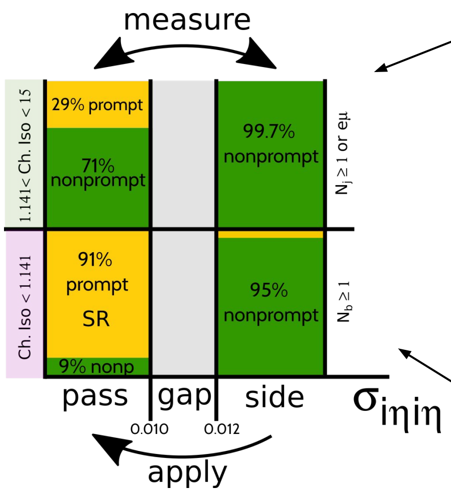
ATLAS paper: arxiv:2007.06946

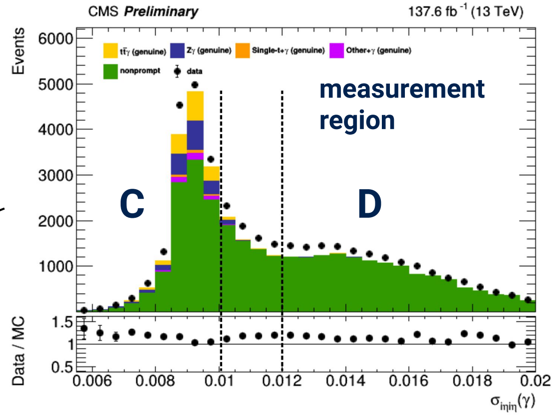
ttγ + tWγ measurement in eμ only, full RunII

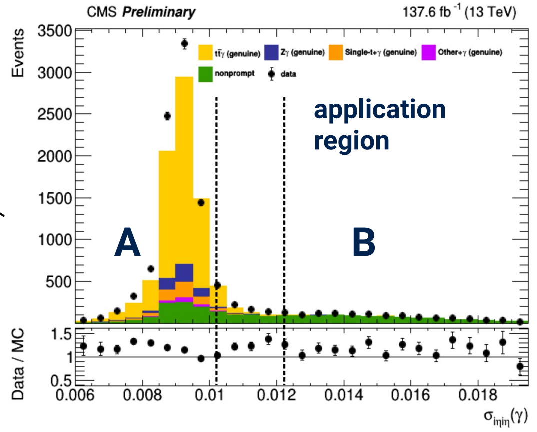
Nonprompt background estimation

- Parametrized ABCD method: relaxing $\sigma_{i\eta i\eta}$ and Charged Iso. cuts from photon ID
- Ratio used: # passing $\sigma_{i\eta i\eta}$ cut / # falling in sideband (leaving a gap)
    - coarse binning in photon p_T and η
- Measurement region:
    - $N_j \geq 1$ in SF channels, no jet cut in eμ
    - $1.141 < \text{Ch. Iso} < 15$

→ nonprompt photon dominated, from ttbar & DY

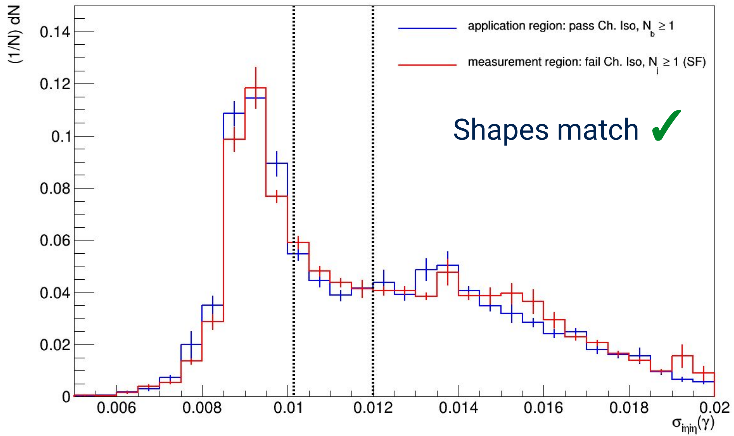




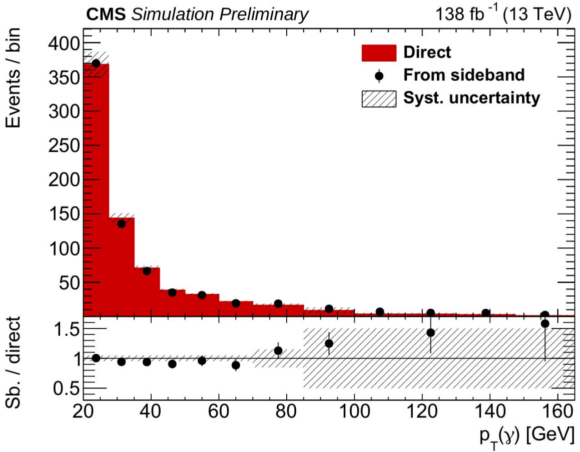


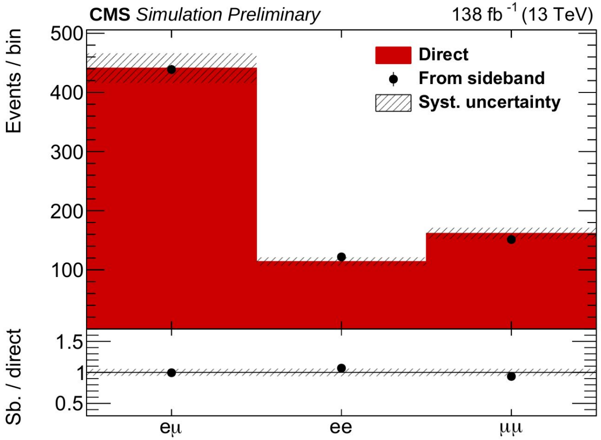
Nonprompt background estimation: closure test

- MC based closure test: measure in ttbar & DY (dominate C & D regions)
- Apply + check closure in ttbar (dominates application region)
- check performed in 3 years combined
- checked channels, N_j/N_b distributions + all kinematic distributions used in unfolding
- overall great closure, except overprediction towards high photon p_T
- systematics assigned: 5% flat + 50% for p_T > 80 GeV (separately)
- in analysis/fits: statistical uncertainty ~ data stats sideband



Shapes match ✓





Systematic uncertainties

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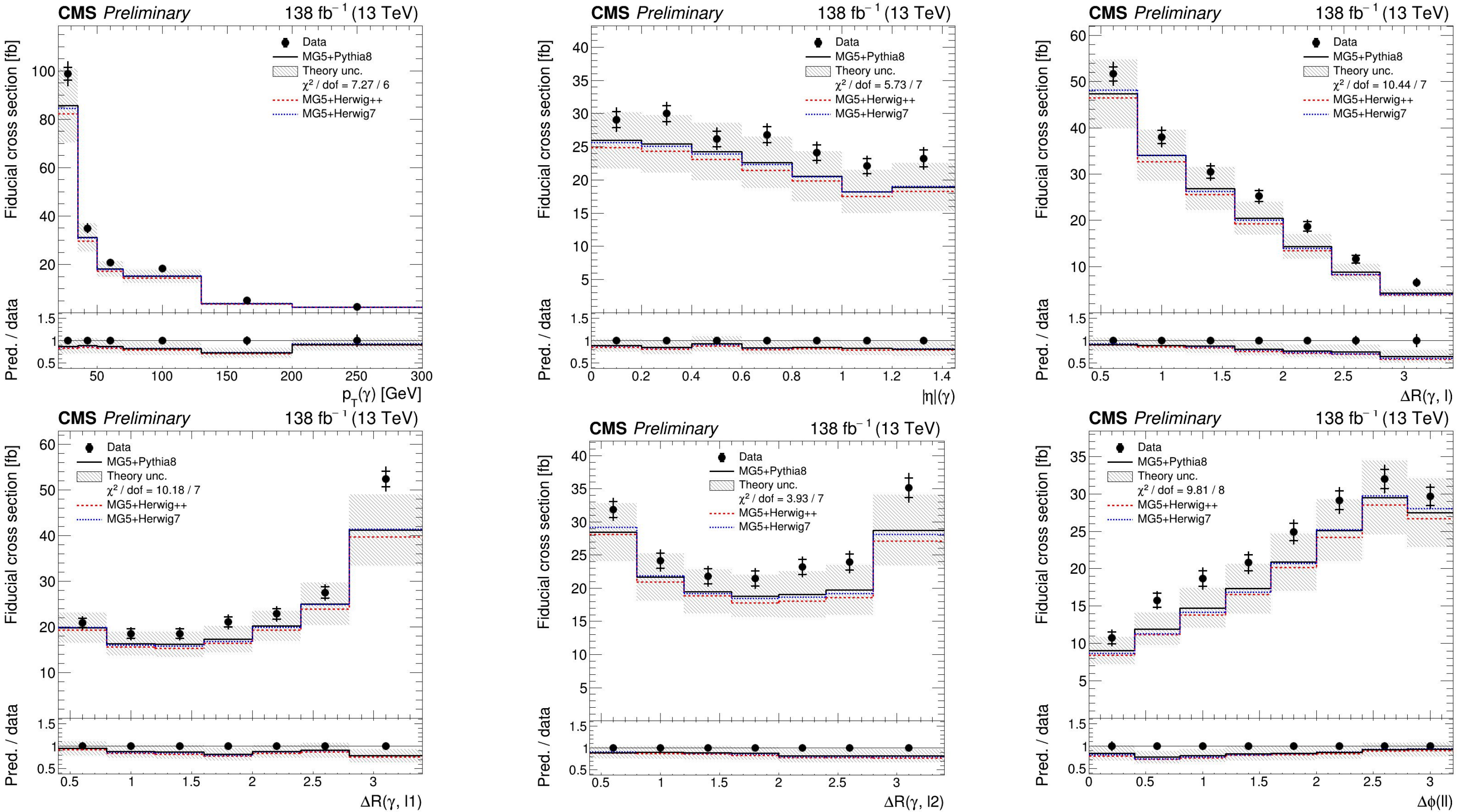
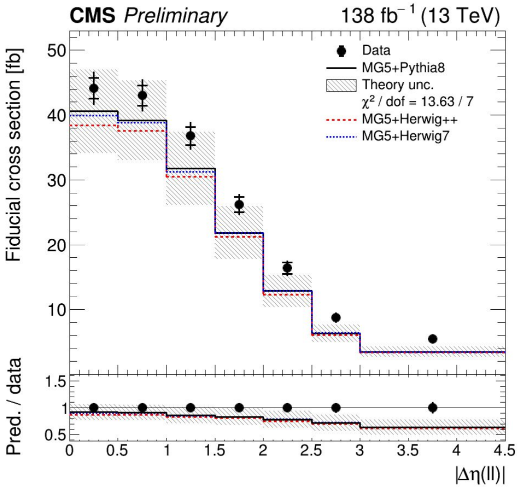
- Normalization uncertainties:
  $Z\gamma$: 1.5%
  Single-t+γ: 10%
  Other+γ: 30%
- JEC: simplified/grouped splitting
- lumi: recent update implements, full correlation pattern
  (table shows simplified summary)
- renormalization and factorization scale: envelope evaluated pre-fit

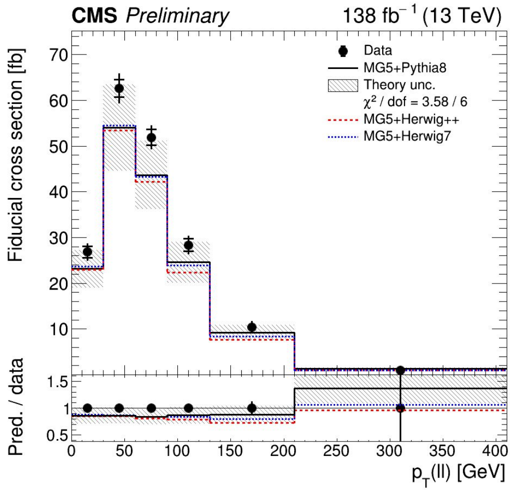
	Source	Correlation	Uncertainty [%] Prefit range	Postfit
Experimental	Integrated luminosity	~	1.3–3.2	1.7
	Pileup	✓	0.1–1.4	0.6
	Trigger efficiency	×	0.6–1.7	0.6
	Electron selection efficiency	~	1.0–1.3	1.1
	Muon selection efficiency	~	0.3–0.5	0.5
	Photon selection efficiency	~	0.4–3.7	0.9
	Jet energy scale	~	0.1–1.3	0.5
	Jet energy resolution	✓	0.0–0.6	<0.1
	b tagging efficiency	~	0.9–1.4	1.1
	L1 prefiring	✓	0.0–0.8	0.3
Theoretical	Choice in μ_R and μ_F	✓	0.3–3.5	1.5
	PDF choice	✓	0.3–4.5	0.2
	PS modelling: ISR & FSR scale	✓	0.3–3.5	1.2
	PS modelling: colour reconnection	✓	0.0–8.4	0.2
	PS modelling: b fragmentation	✓	0.0–2.2	0.6
	Underlying event tune	✓	0.5	0.5
Background	$Z\gamma$ correction & normalization	✓	0.0–0.2	<0.1
	$t\gamma$ normalization	✓	0.0–0.9	0.8
	other+γ normalization	✓	0.3–1.0	0.8
	Nonprompt γ normalization	✓	0.0–1.8	0.9
	MC statistics	×	1.5–7.6	0.9
	Total systematic uncertainty			3.6
	Statistical uncertainty			1.4
	Total uncertainty			3.9

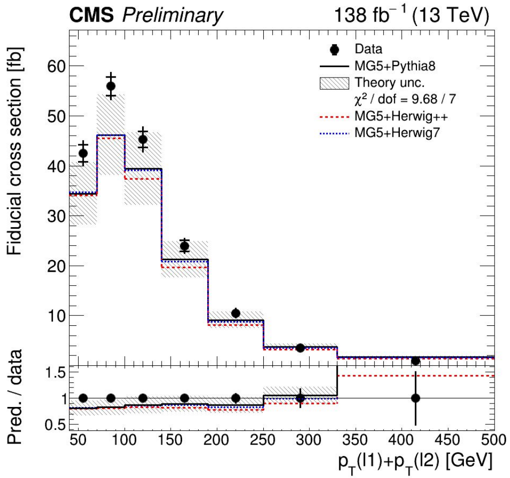
differential results (1)

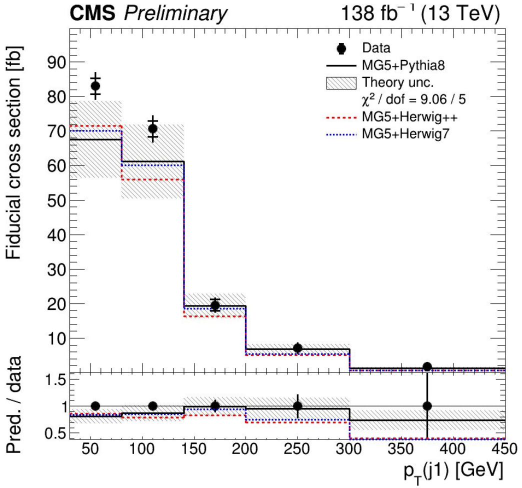


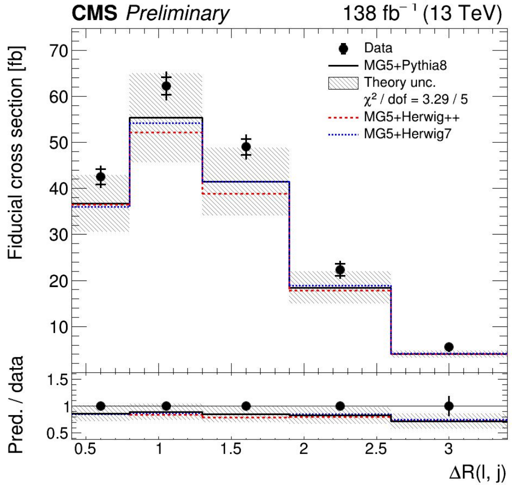
differential results (2)

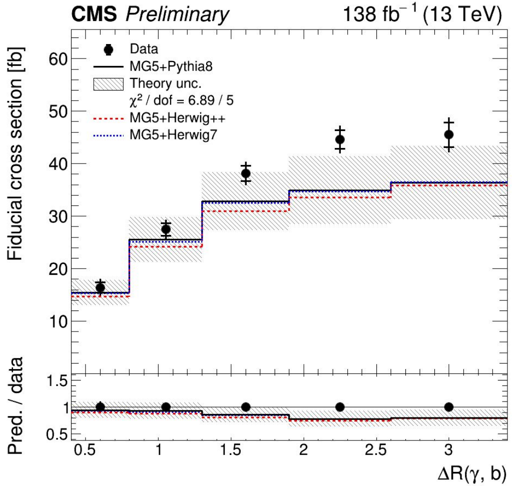




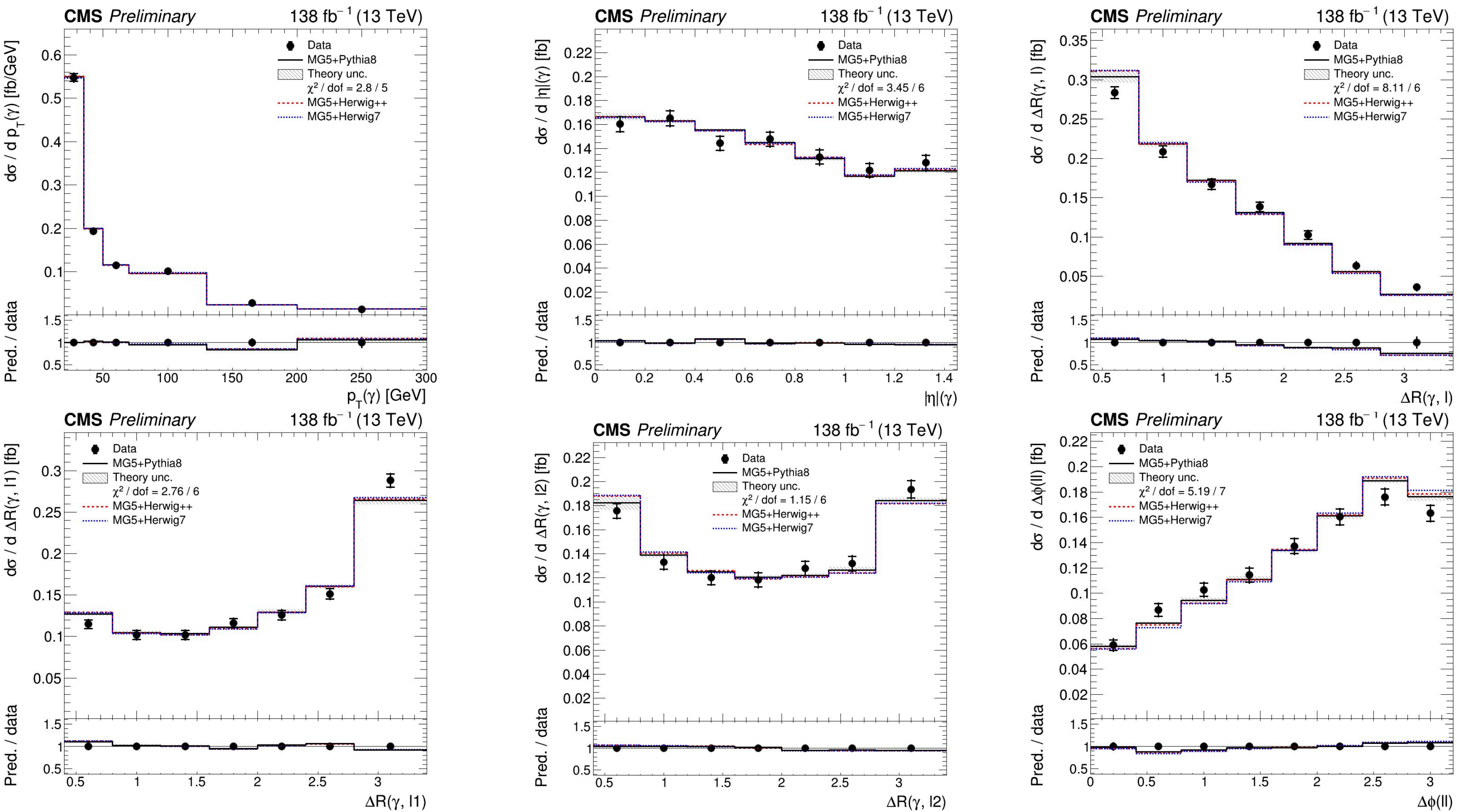








normalized differential results (1)



normalized differential results (2)