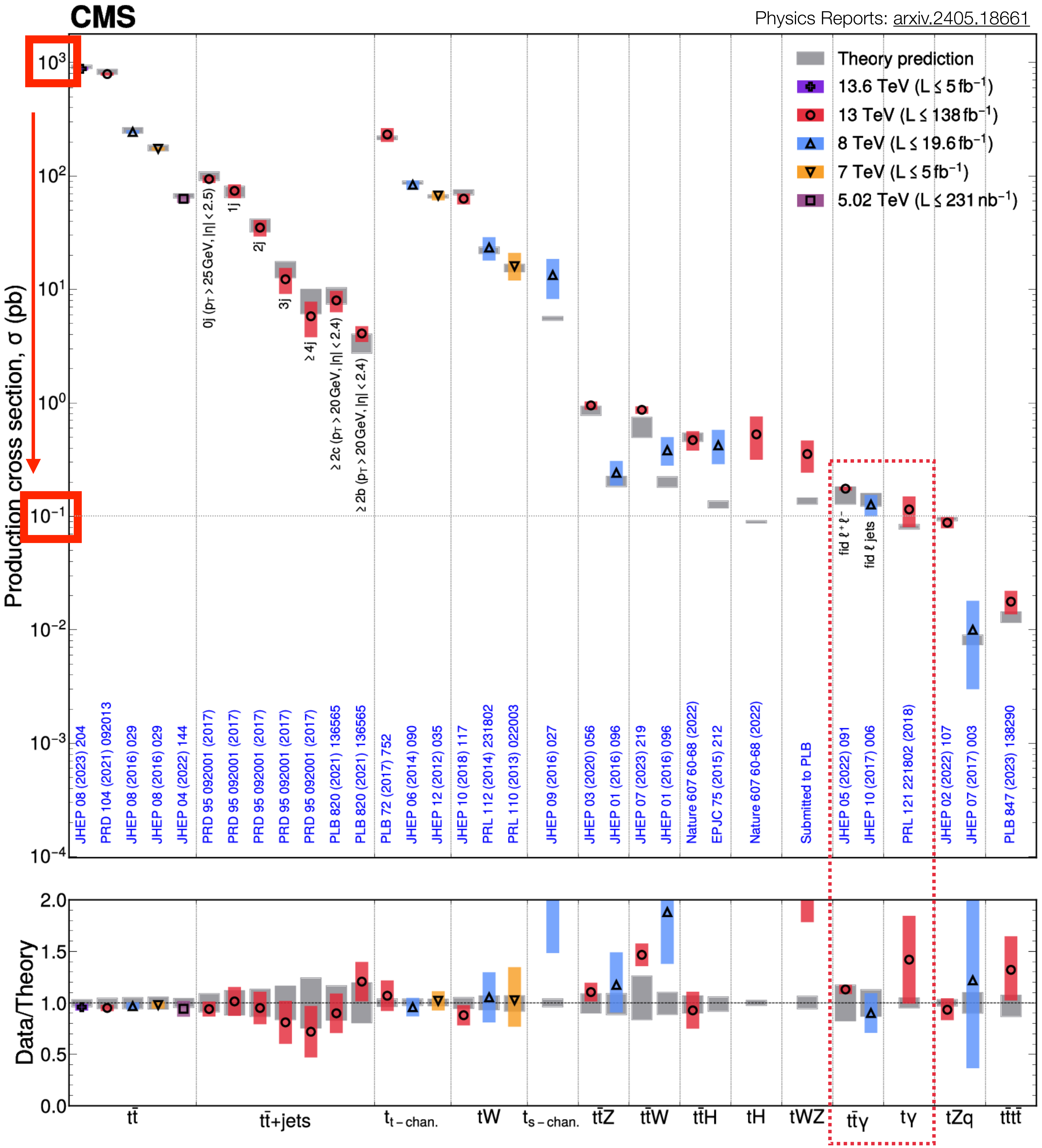
Photon production in top quark events at ATLAS and CMS

Beatriz Ribeiro Lopes, on behalf of the ATLAS and CMS collaborations

Photon production in top quark processes



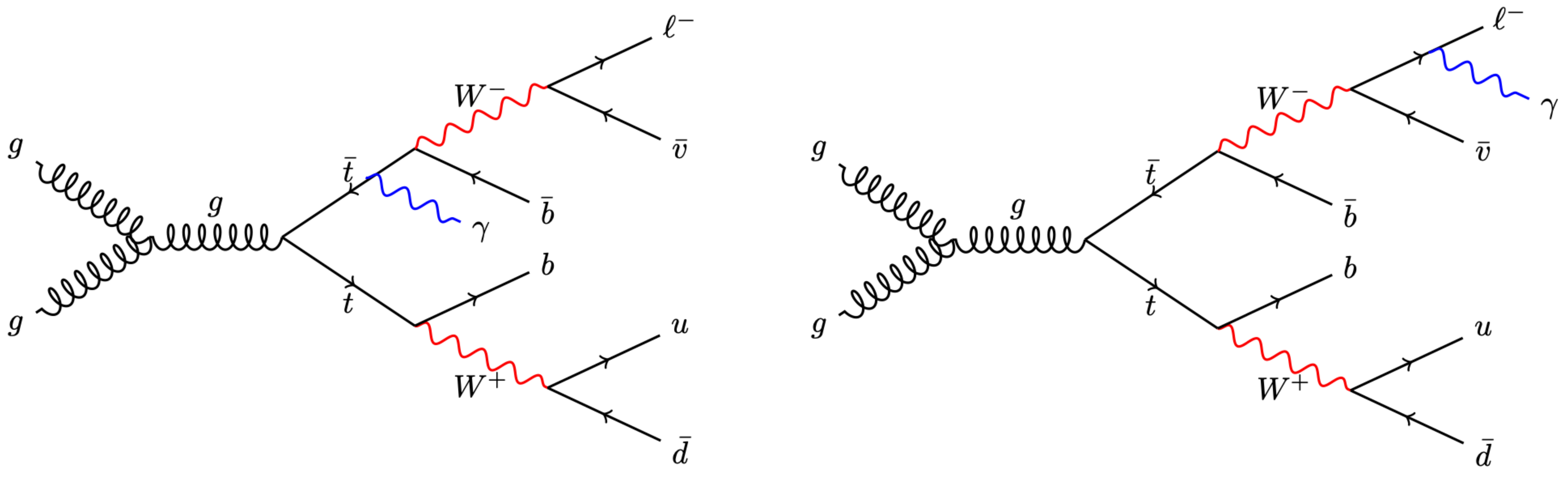
- Top quark measurements central to LHC program
- **t(t̄) + γ** processes offer insight into both EW and QCD sectors
  - Total cross section is the highest among tt̄+boson processes
  - Couplings may be sensitive to new physics→ EFT interpretations
  - Important backgrounds for BSM searches and SM measurements
- Very challenging from the modeling perspective (see previous talk by Daniel Stremmer)
- With Run 2 data we entered the precision era for tt̄γ:
  - Uncertainty in inclusive cross sections down to ~4%

    One of the most precise cross section measurements at CMS!

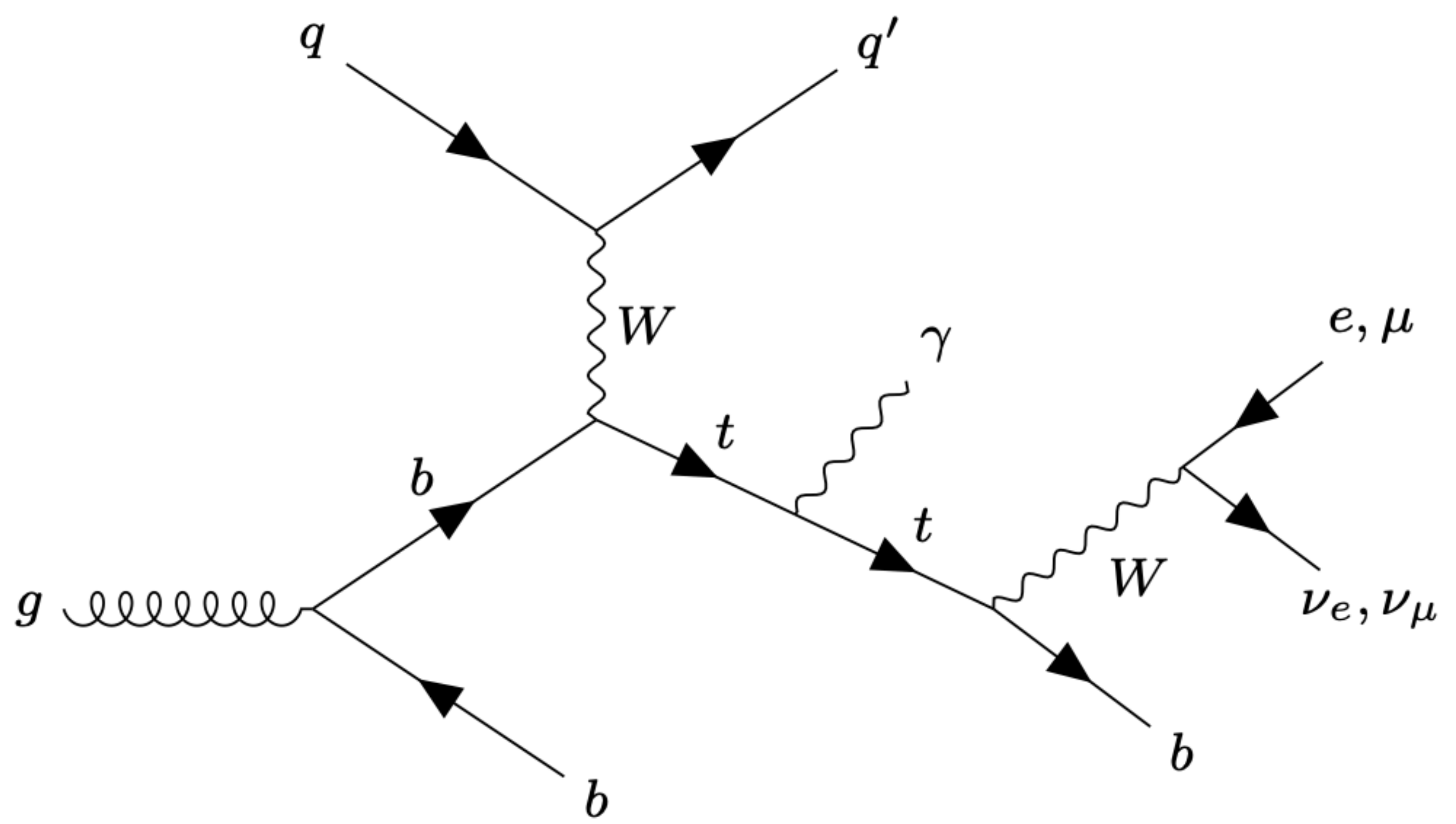
  - Differential measurements performed in several final states

Overview of processes involving top quarks and photons

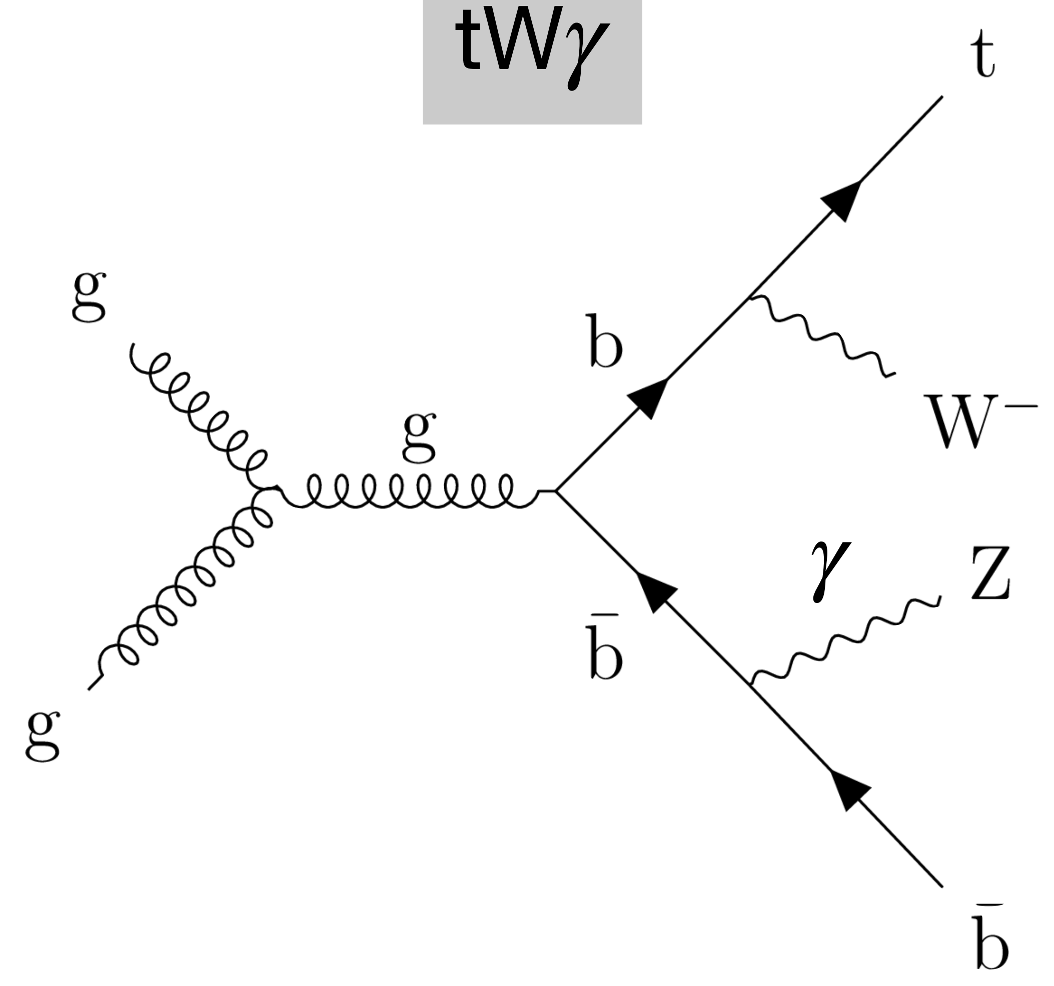
$t\bar{t}\gamma$



$tq\gamma$



$tW\gamma$

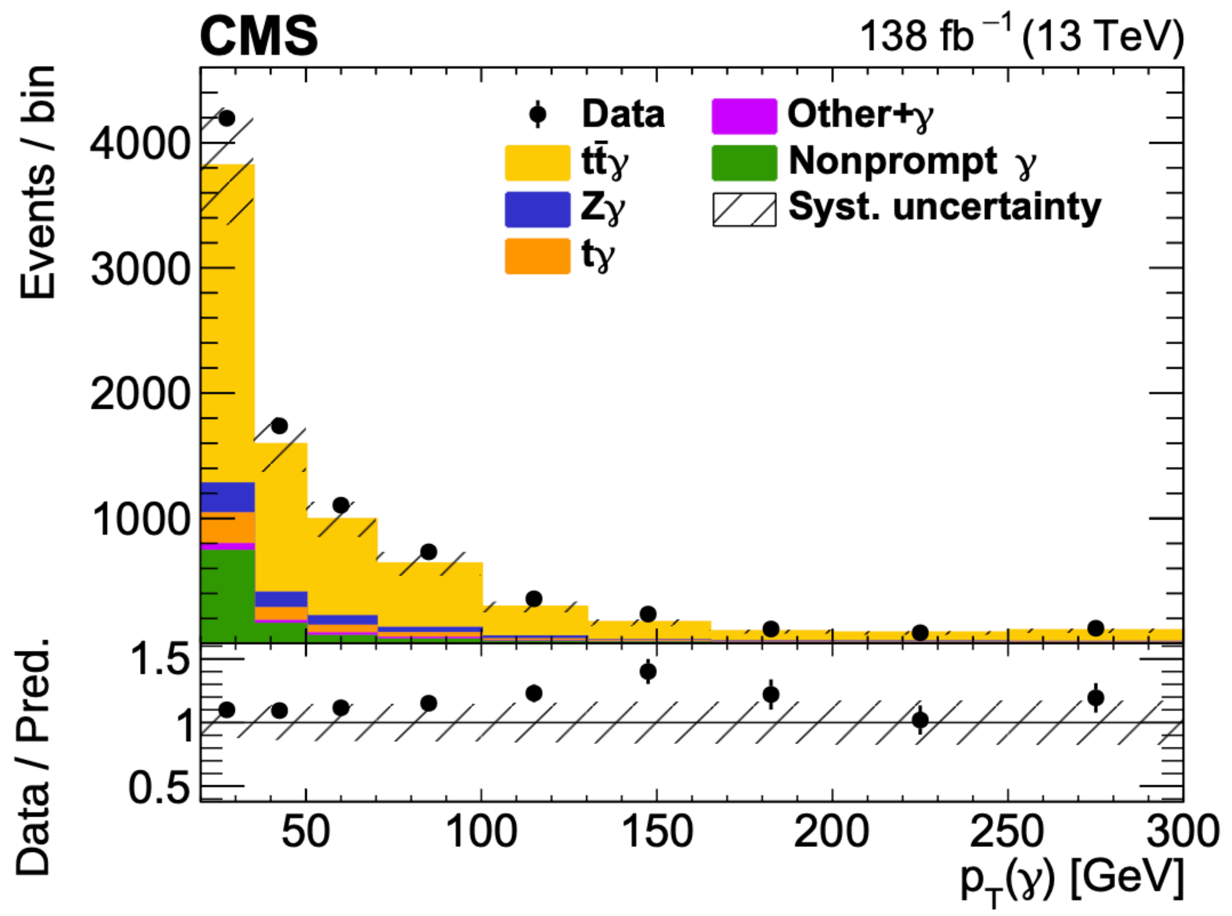


- **$t\bar{t}\gamma$** processes measured inclusively and differentially by both ATLAS and CMS (most of this talk!)
- **$tq\gamma$** observed (evidence) by ATLAS (CMS), inclusive cross section measurements only
- **$tW\gamma$** is an important background to $t\bar{t}\gamma$ and challenging to model ($t\bar{t}\gamma$+ $tW\gamma$ in $e\mu$ channel measured by ATLAS, dedicated measurement not yet performed)

“Fake” photons: an experimental challenge

JHEP 05 (2022) 091

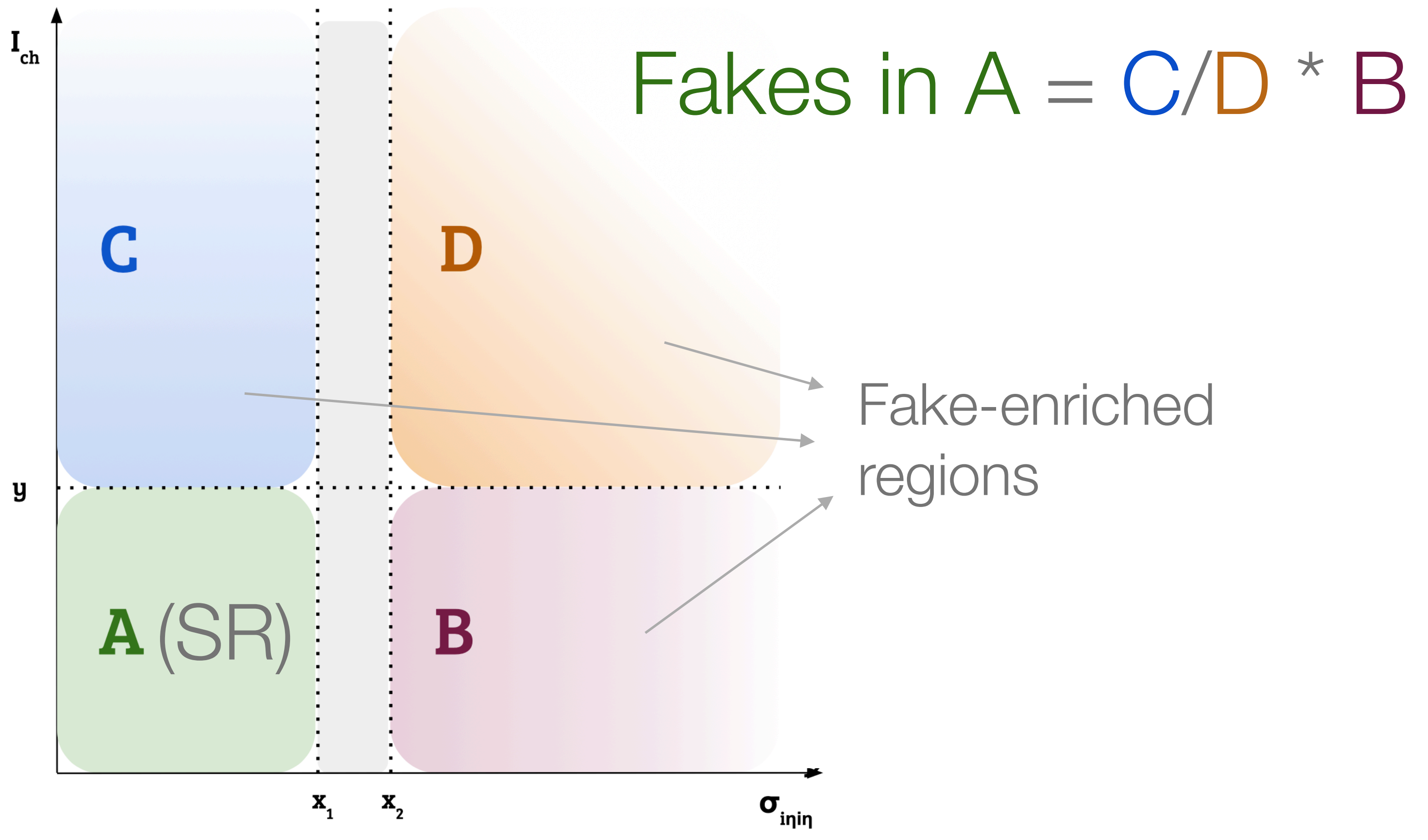
In $t\bar{t}\gamma$, very high signal purity can be achieved, however… the main background originates from **nonprompt / fake photons**

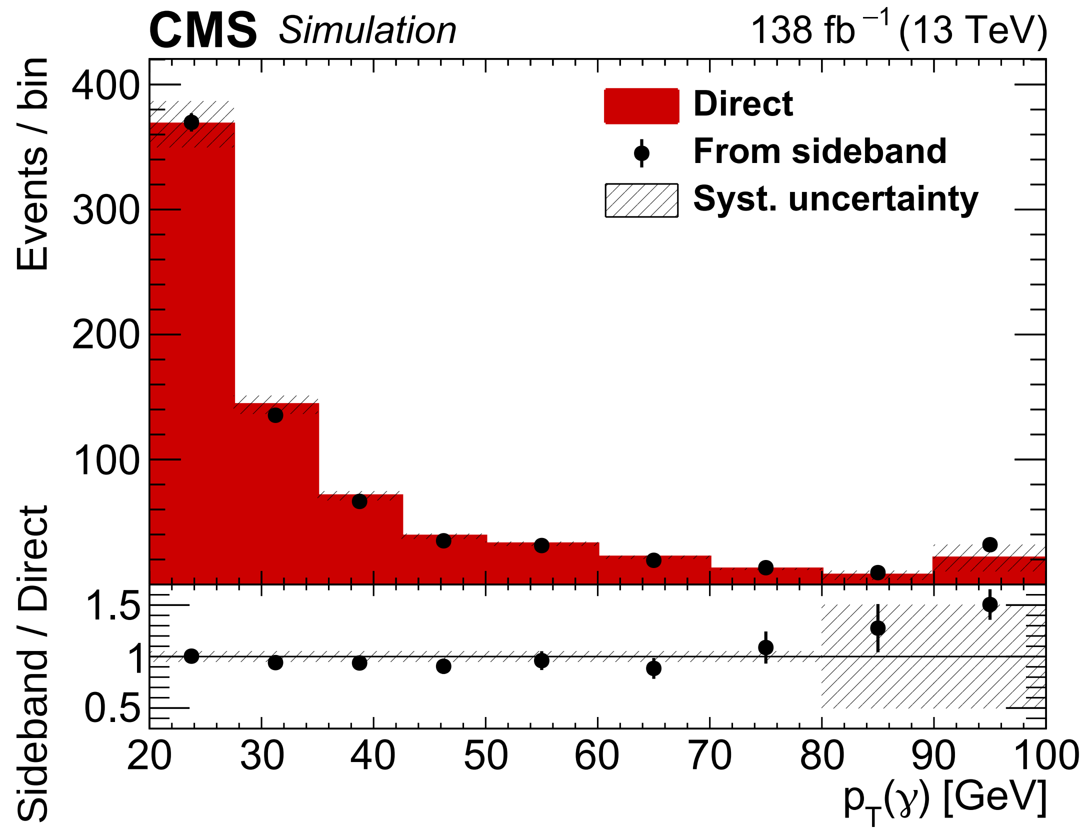


- Electrons or jets mis-reconstructed as photons
- Real photons that originate from the hadronisation process or from pileup events

Challenge: the simulation doesn’t always model these processes adequately, and even when it does, the associated statistical uncertainties are large → *data-driven methods*

- In CMS, ABCD methods are typically used, with the charged isolation (I_{ch}) and width of the electromagnetic shower ($\sigma_{i\eta i\eta}$) as variables





Closure test in simulation

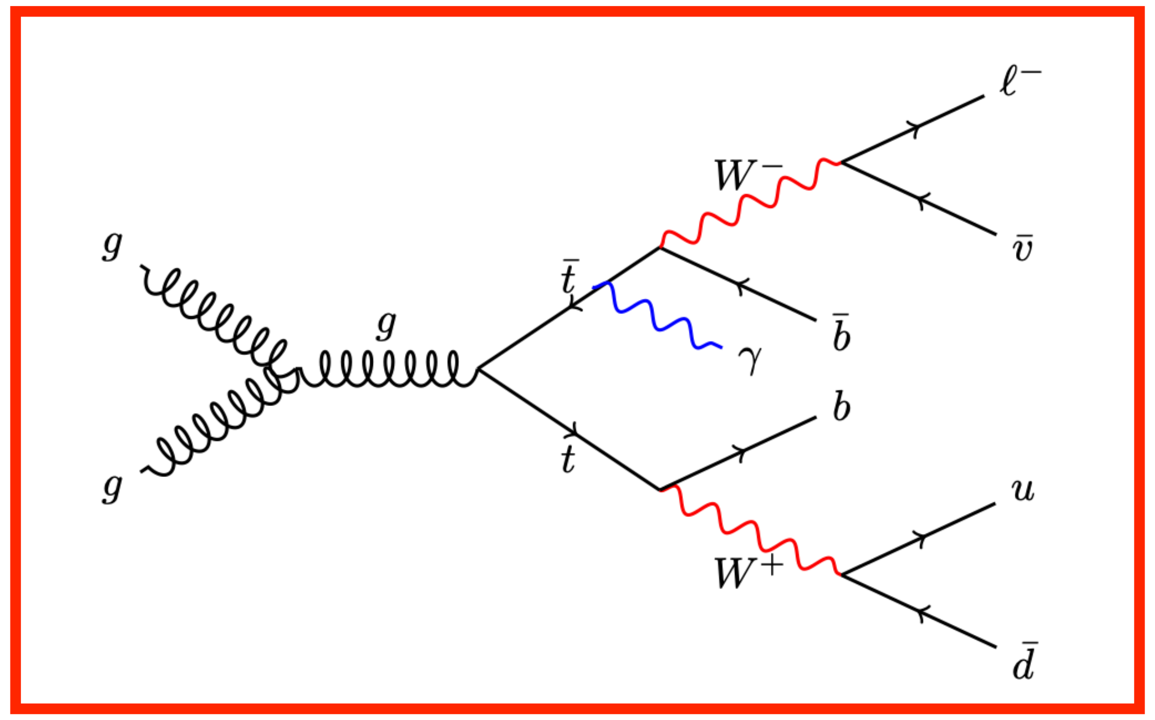
- In ATLAS analyses:
  - fakes from hadrons and pileup are estimated with a similar ABCD method
  - fakes from electrons are estimated from the fraction of electron–positron candidates from $Z \to ee$ decays that are reconstructed as $e\gamma$

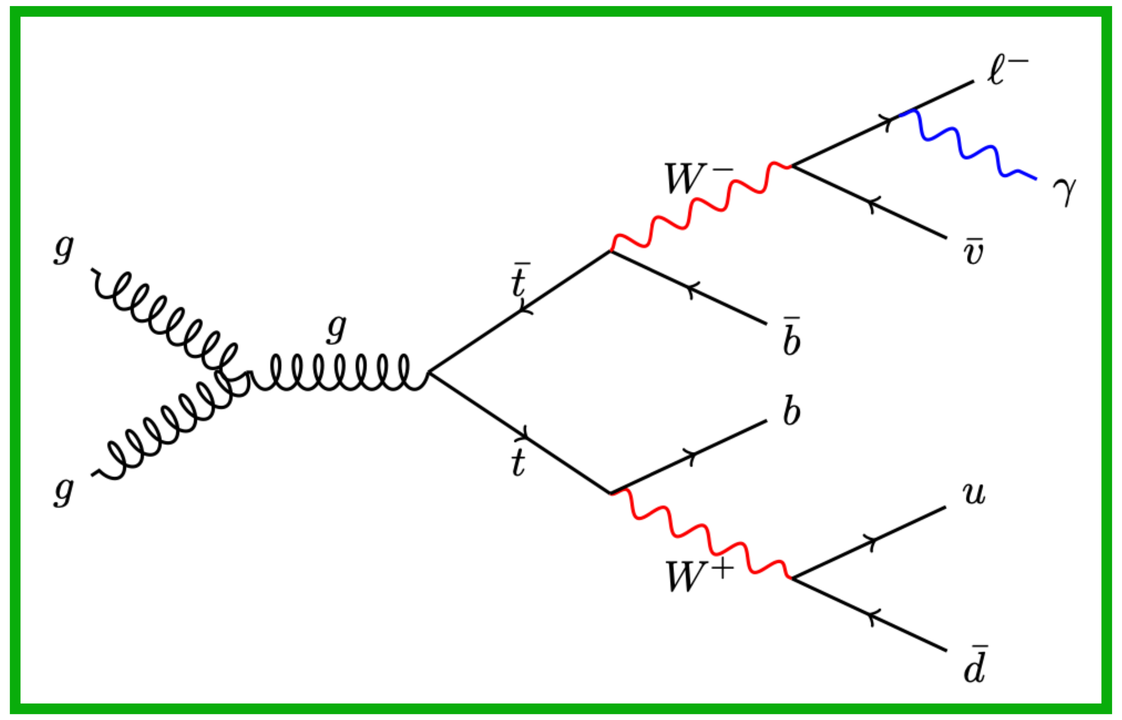
Inclusive cross section measurements of $t\bar{t}\gamma$

arXiv:2403.09452v1
Accepted by JHEP

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

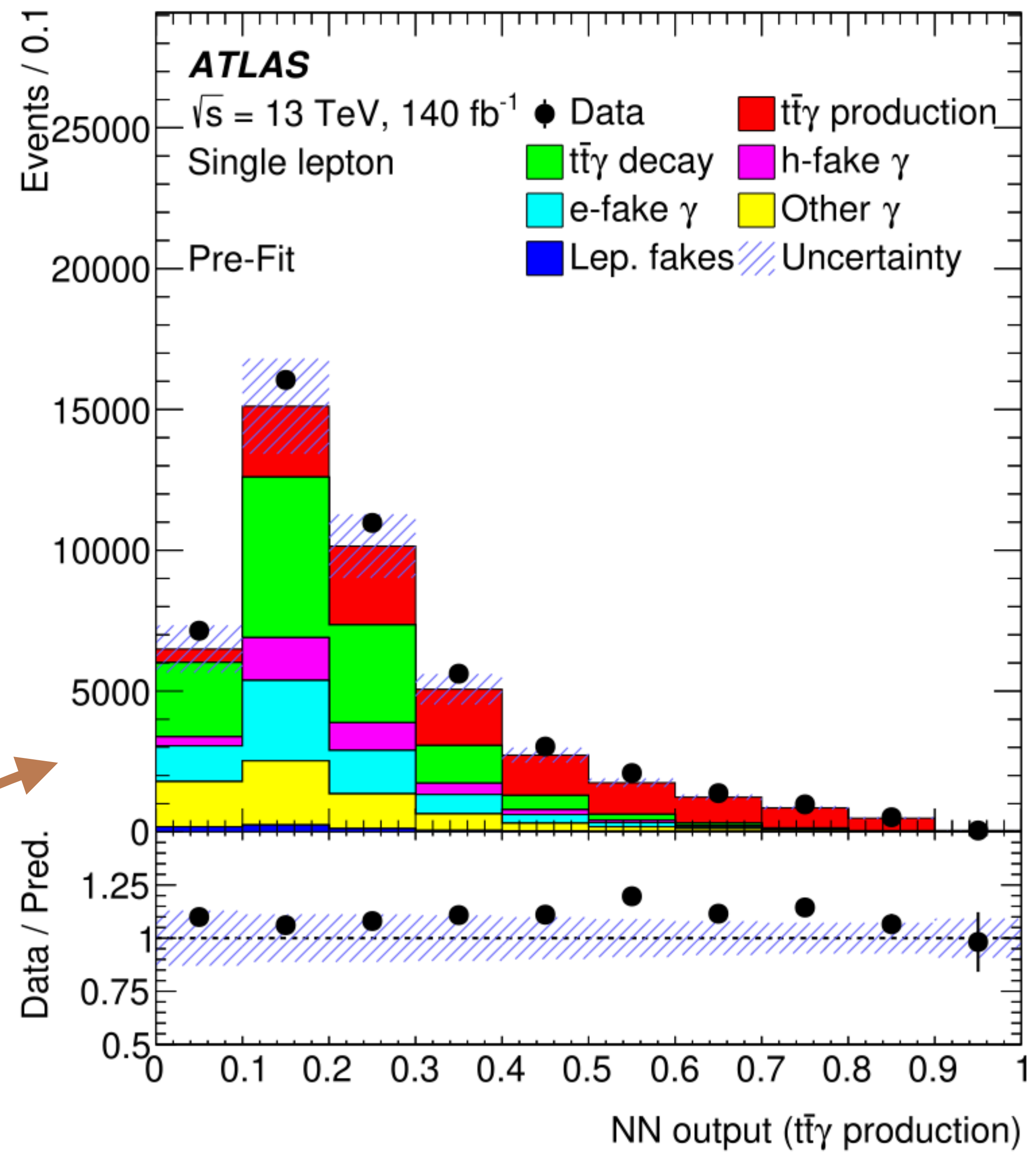
- $t\bar{t}\gamma$ production: photons from ISR or off-shell top quarks
- $t\bar{t}\gamma$ decay: photons emitted from decay products

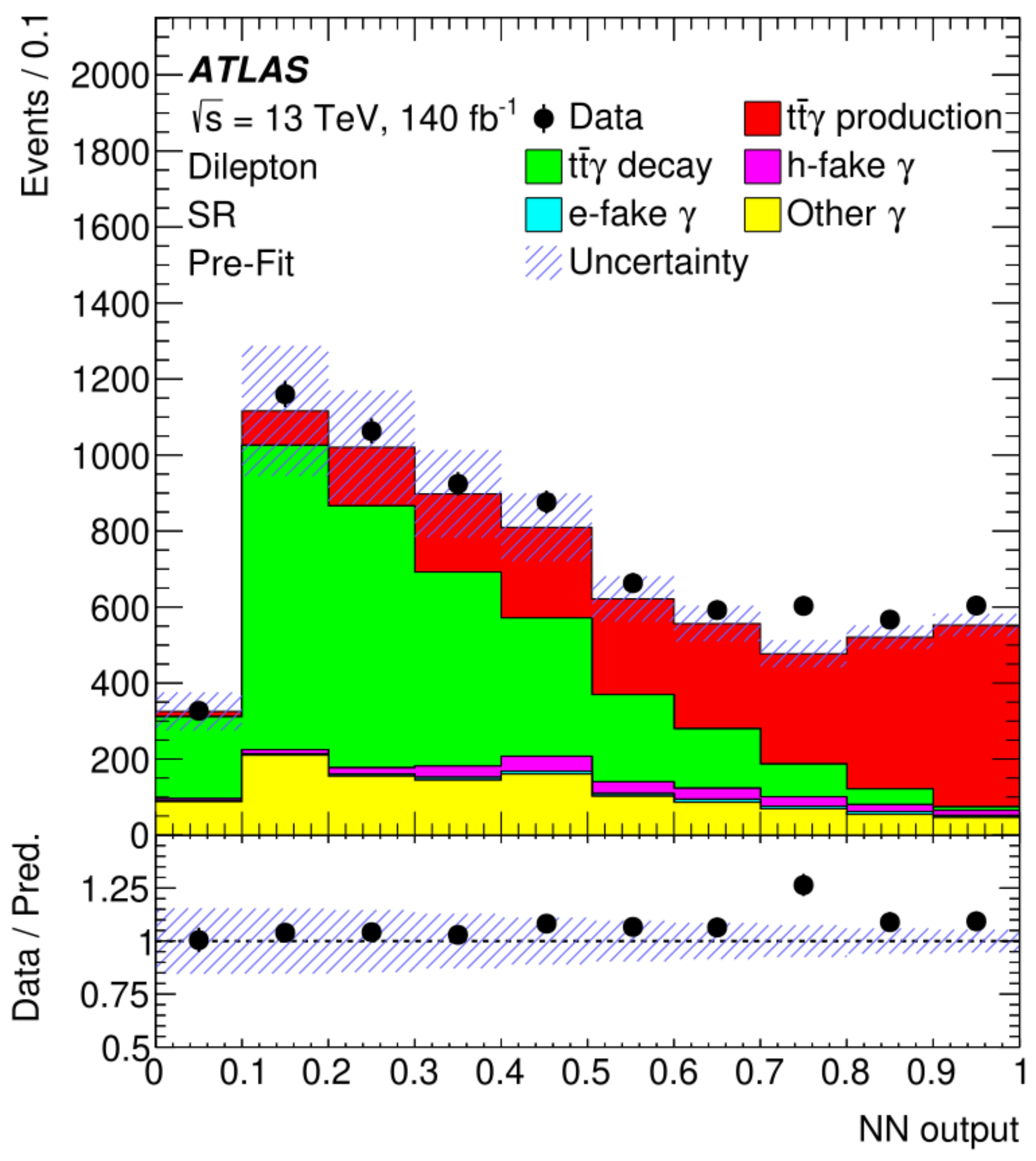




- Focus on single lepton and dilepton channels
- $t\bar{t}\gamma$ production modeled at NLO in QCD and $t\bar{t}\gamma$ decay at LO
- $t\bar{t}\gamma$ production measured separately for the first time
- Measuring also total fiducial $t\bar{t}\gamma$ cross section (production+decay)
- DNNs to separate $t\bar{t}\gamma$ production from other processes (multiclass in single lepton channel and binary in dilepton)
- Fake photon contribution estimated with data-driven methods

- Measure **σ($t\bar{t}\gamma$ production) = 322 ± 5 (stat) ± 15 (syst) fb (5.2%)**
  - In agreement with prediction of **299 ± 31 fb** (MadGraph5_aMC@NLO)
  - Limited by systematic uncertainties, mainly $t\bar{t}\gamma$ modelling, normalisation of $t\bar{t}\gamma$ decay, jet and b-tagging uncertainties





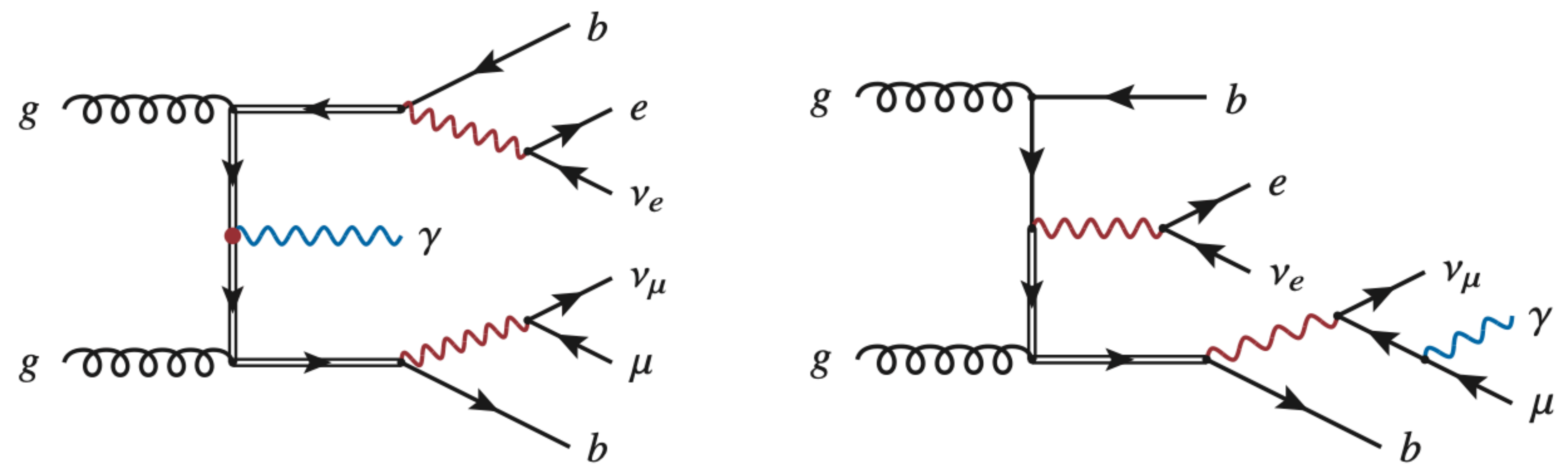
Single-lepton (dilepton) channels

Fiducial phase space	Photon	Leptons	Jets
Number	==1	==1(2)	==4(2), >=1 b
pT (GeV)	>20	25	25
$\lvert\eta\rvert$	<2.37	<2.5	<2.5
Others	Not from hadrons	Not from hadrons, isolated from photons	Isolated from photons and leptons

Cross section measurements of $t\bar{t}\gamma$+tWγ

JHEP 09 (2020) 049

- Interference between $t\bar{t}\gamma$ and tWγ



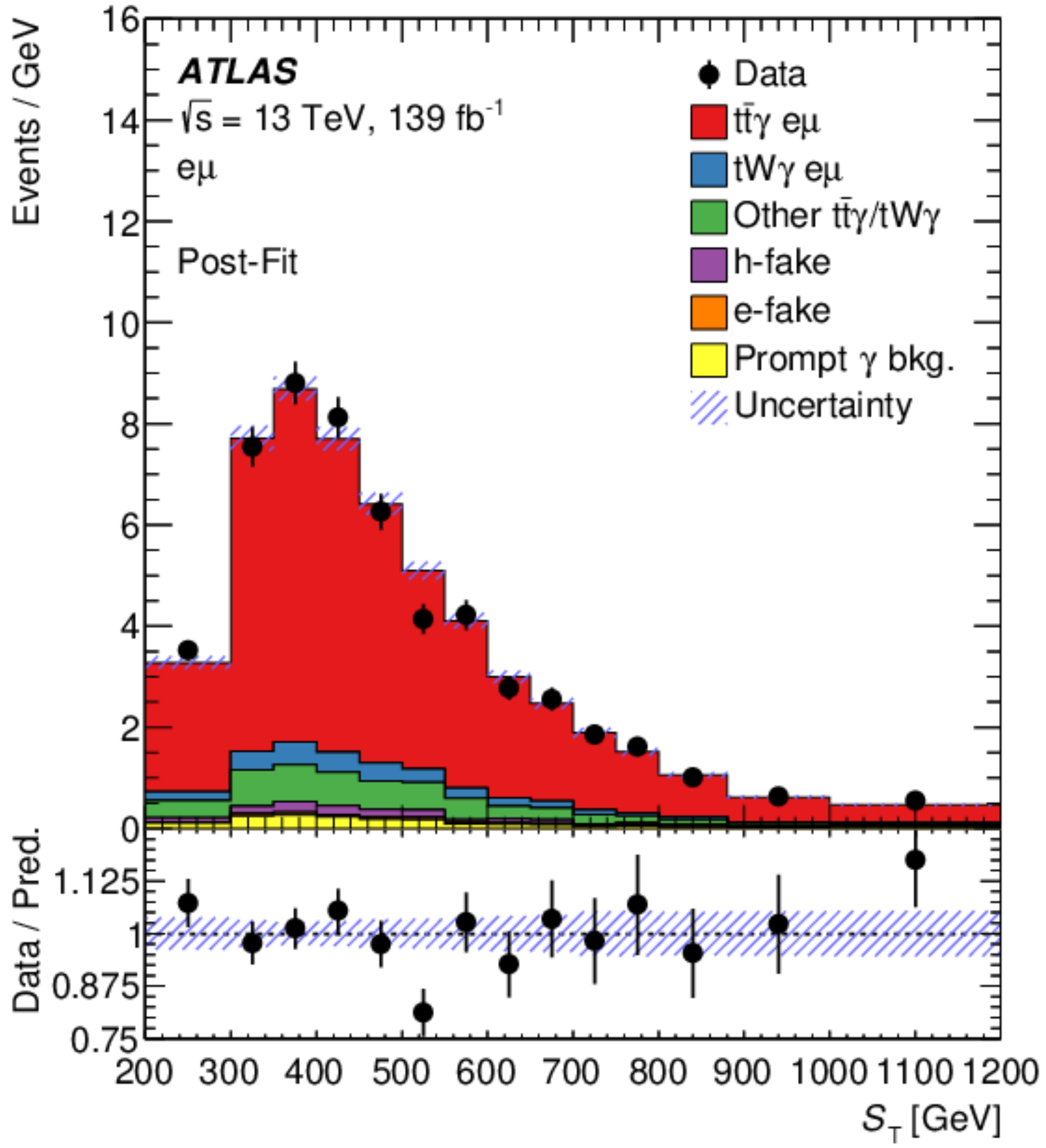
- Study of tWγ is challenging from the modelling point of view, but crucial for $t\bar{t}\gamma$ precision measurements

- In this analyses, both processes are modelled at LO in QCD, with the interference being removed

- Inclusive fiducial cross section: fit to the sum of both processes, using the ST distribution, in **good agreement** with dedicated fixed order calculation

$$\sigma^{\text{fid.}}_{\text{measured}} = 39.6\,^{+2.7}_{-2.3}\ \text{fb} \qquad \sigma^{\text{fid.}}_{\text{predicted}} = 38.50\,^{+0.56}_{-2.18}\,(\text{scale})\,^{+1.04}_{-1.18}\,(\text{PDF})\ \text{fb}$$

- Differential measurements also performed (not covered today, as more recent results exist)

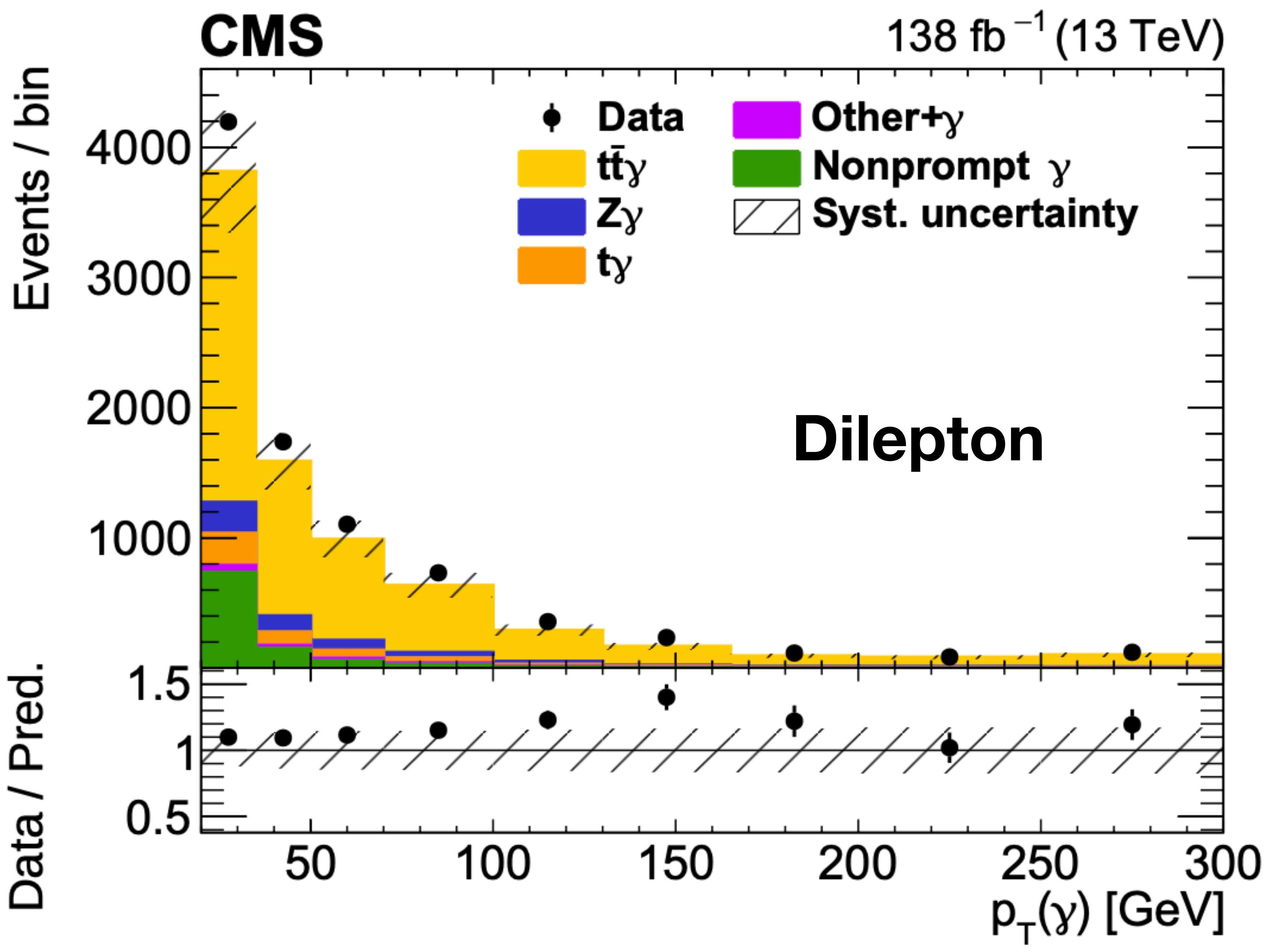


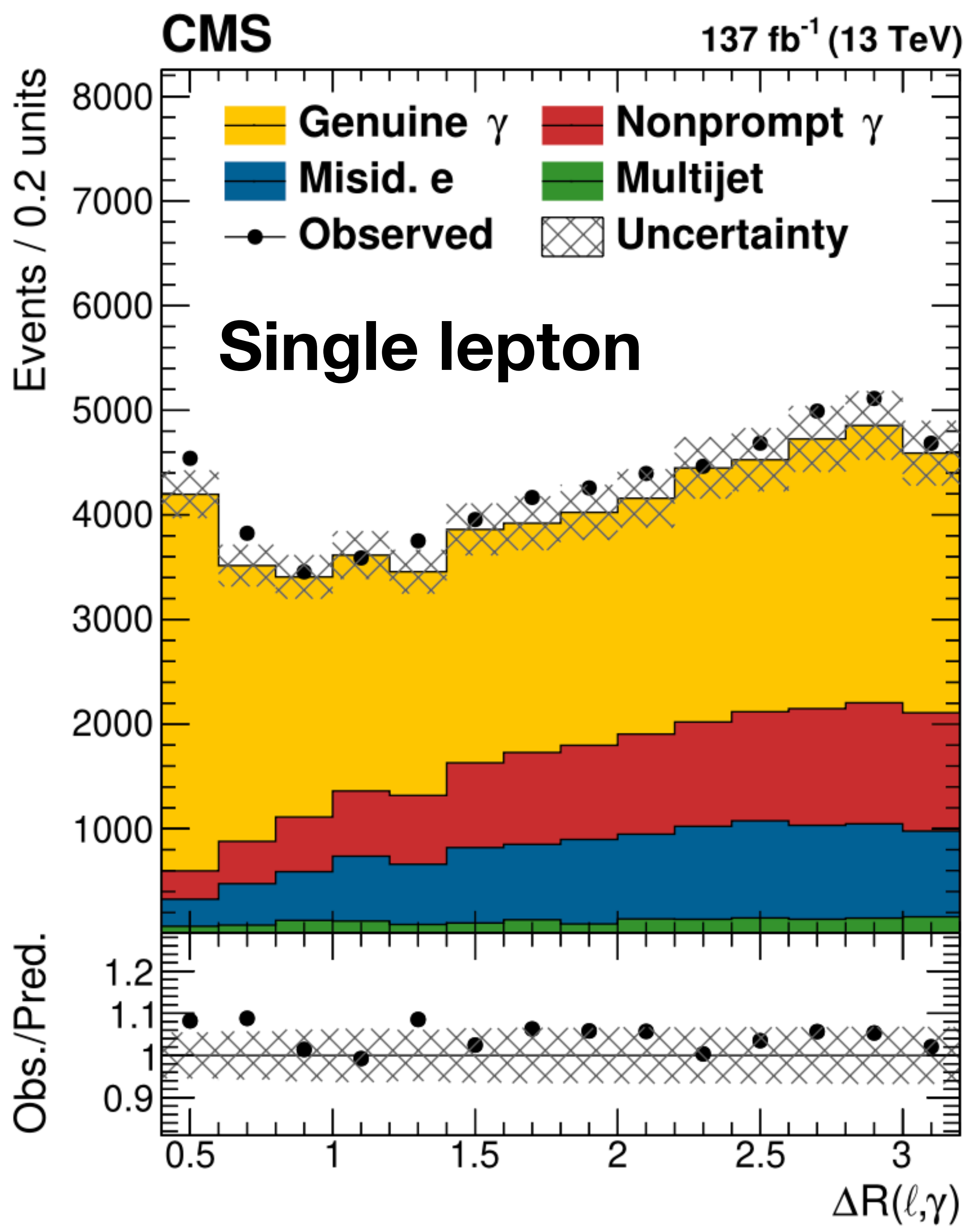
Dedicated tWγ measurements with improved modeling will be crucial for improving our understanding of top+photon processes

Inclusive cross section measurements of $t\bar{t}\gamma$

JHEP 05 (2022) 091
JHEP 12 (2021) 180

- Focus on single lepton and dilepton channels
- Measuring total $t\bar{t}\gamma$ cross section (production+decay)
- $t\bar{t}\gamma$ modeled at LO in QCD with MADGRAPH, scaled to NLO using k-factors
- Fake photon contribution estimated with data-driven methods





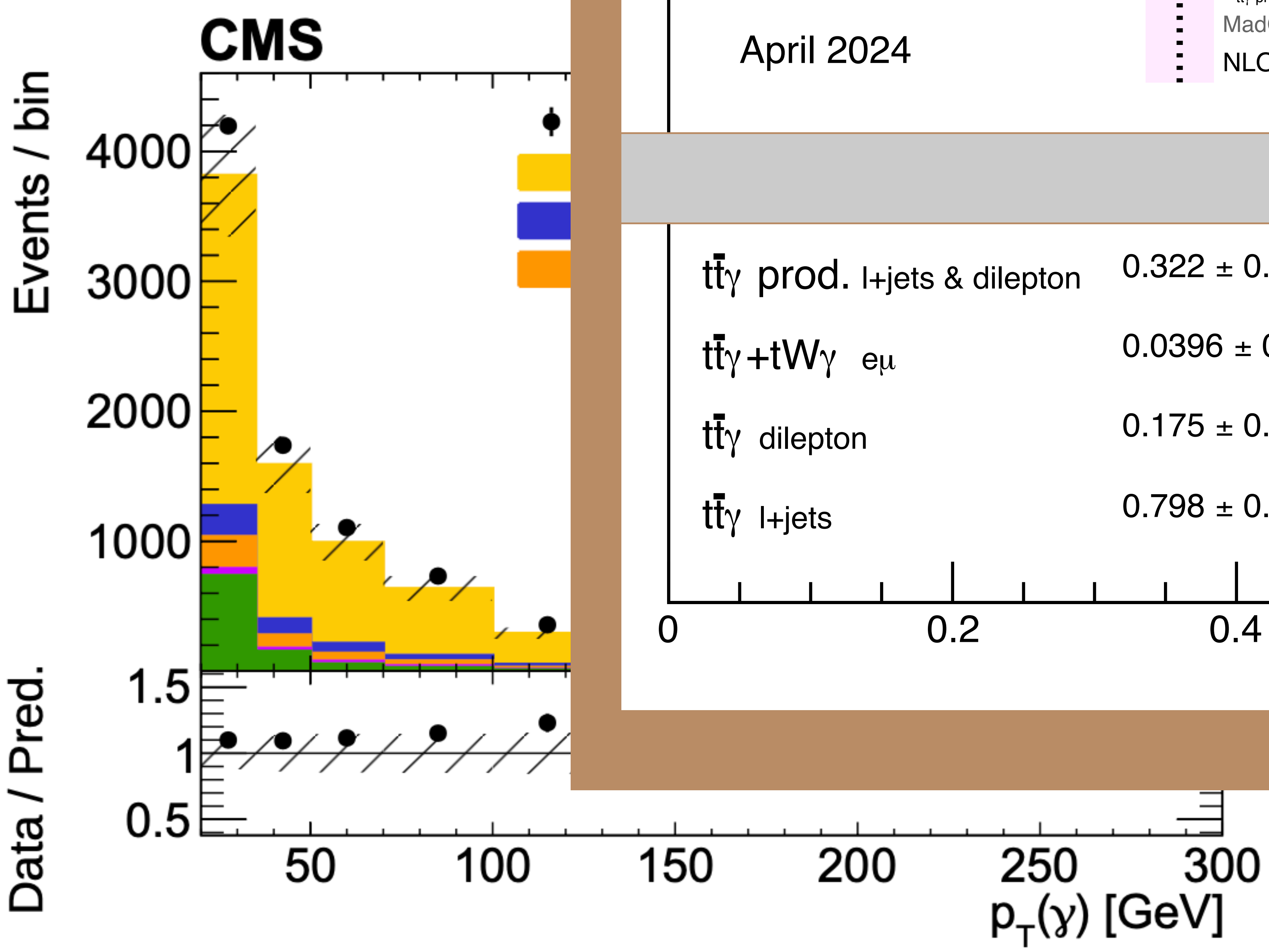
- Single lepton channel:
  - Simultaneous fit to 2SRs and 6CRs
  - Main systematic uncertainties: normalization of $W\gamma$ background, estimation of nonprompt photons, luminosity
- Dilepton channel:
  - Fit to photon pT distribution in SR
  - Main systematic uncertainties: luminosity, the signal modelling, and b tagging

Interesting to note different systematic contributions in the ATLAS and CMS analyses

Inclusive cross section measurements of $t\bar{t}\gamma$

JHEP 05 (2022) 091
JHEP 12 (2021) 180

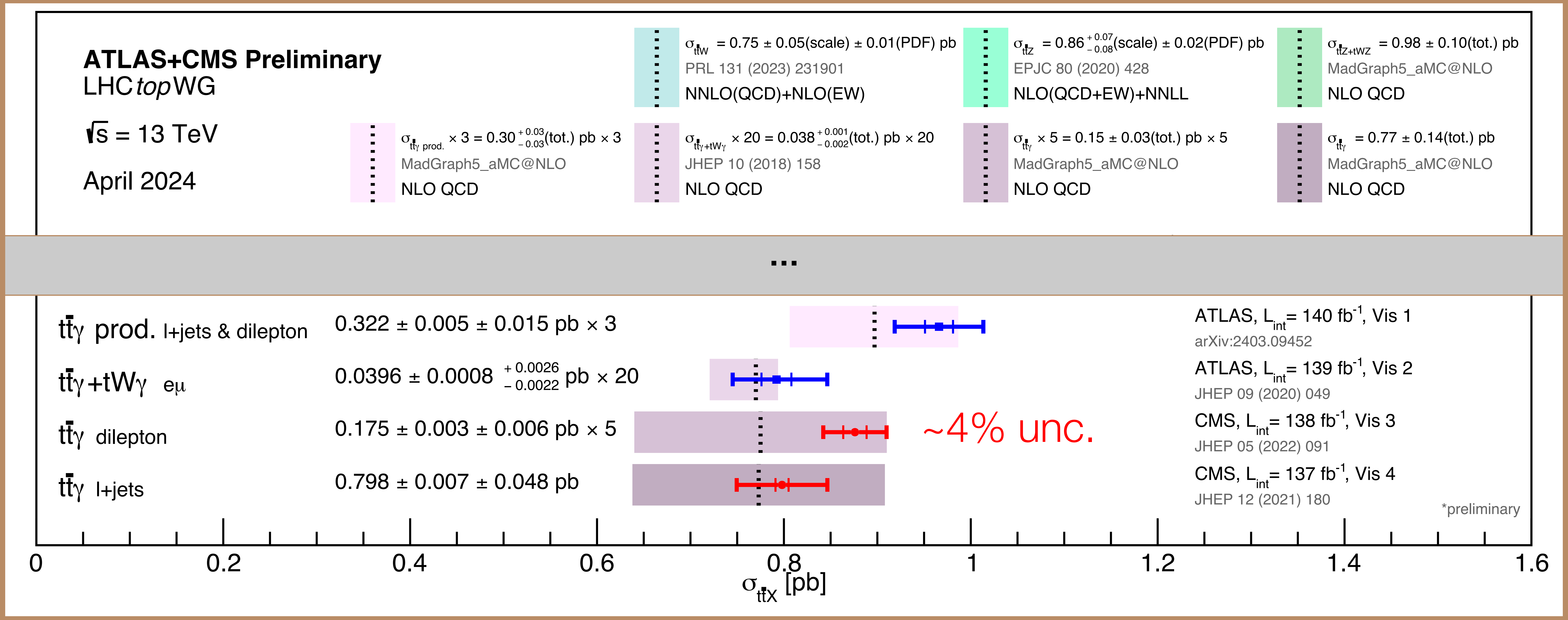
- Focus on single lepton and dilepton channels
- Measuring total $t\bar{t}\gamma$
- $t\bar{t}\gamma$ modeled at LO
- Fake photon cont

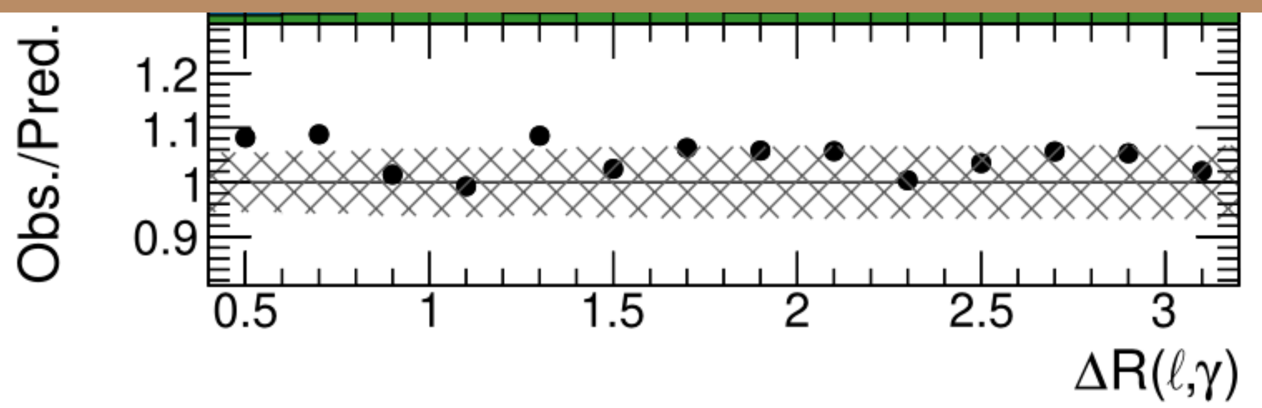


- Single lepton channel:

2SRs and 6CRs
certainties:
background,
ompt photons,
ribution in SR
certainties:
l modelling, and

Results compatible with SM predictions:

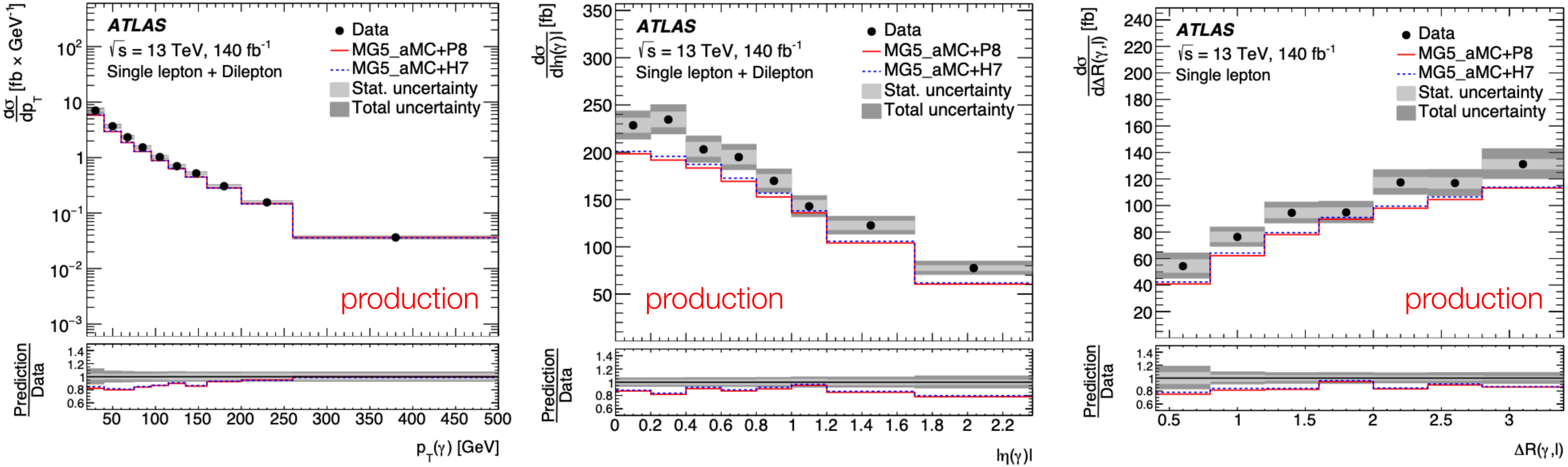




Differential cross section measurements of $t\bar{t}\gamma$

arXiv:2403.09452v1
Accepted by JHEP

- Objects defined at particle level
- Observables: $p_T(\gamma)$, $\eta(\gamma)$, angular variables involving photons and jets/leptons
- Normalised and absolute cross sections measured both for production and production+decay

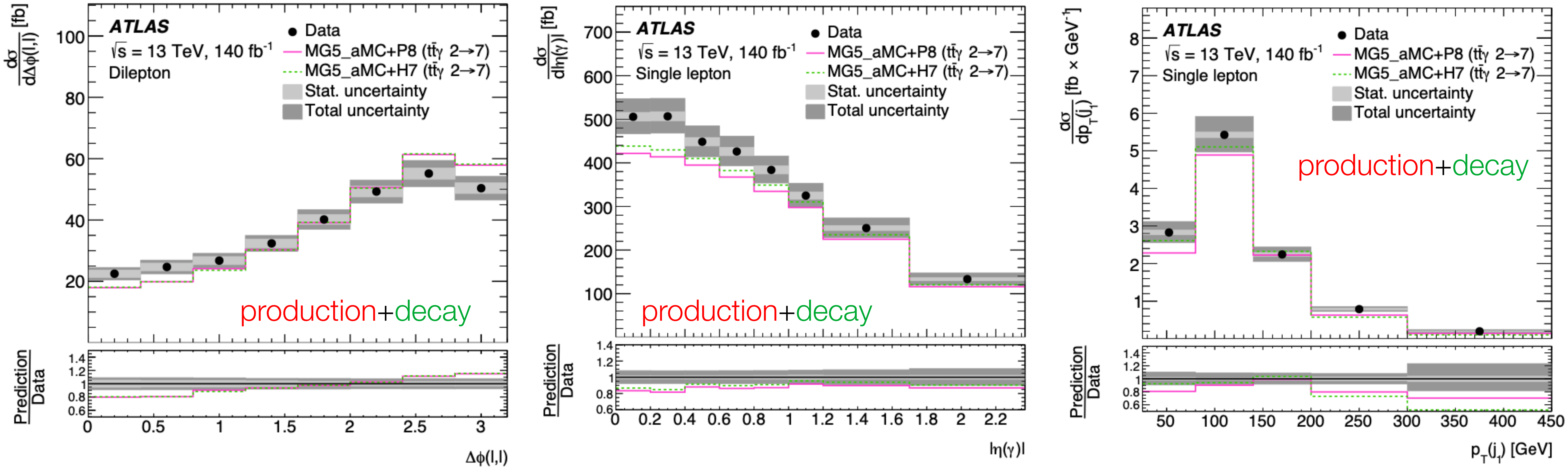


- More sensitive to $t\gamma$ coupling

Differential cross section measurements of $t\bar{t}\gamma$

arXiv:2403.09452v1
Accepted by JHEP

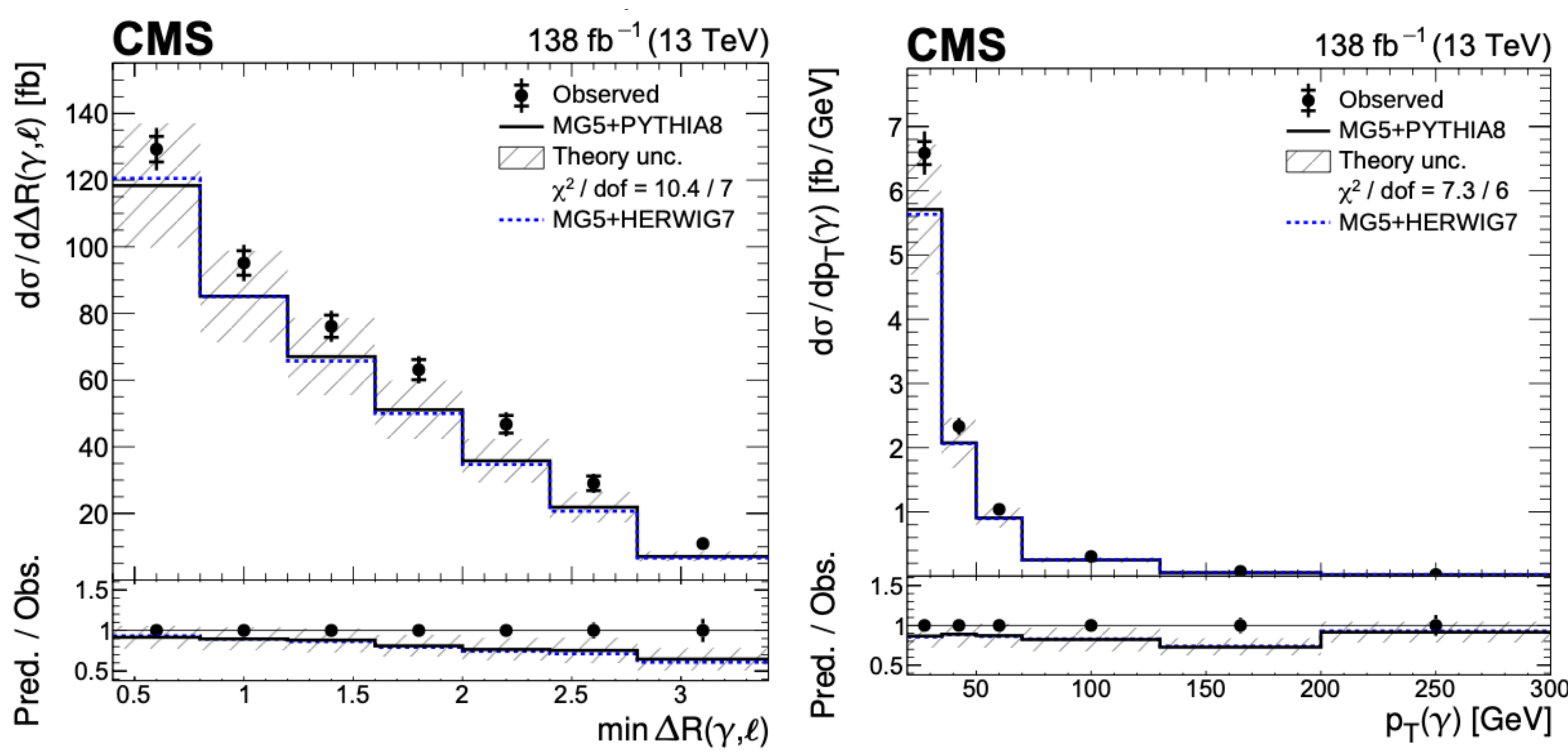
- Objects defined at particle level
- Observables: $p_T(\gamma)$, $\eta(\gamma)$, angular variables involving photons and jets/leptons
- Normalised and absolute cross sections measured both for production and production+decay



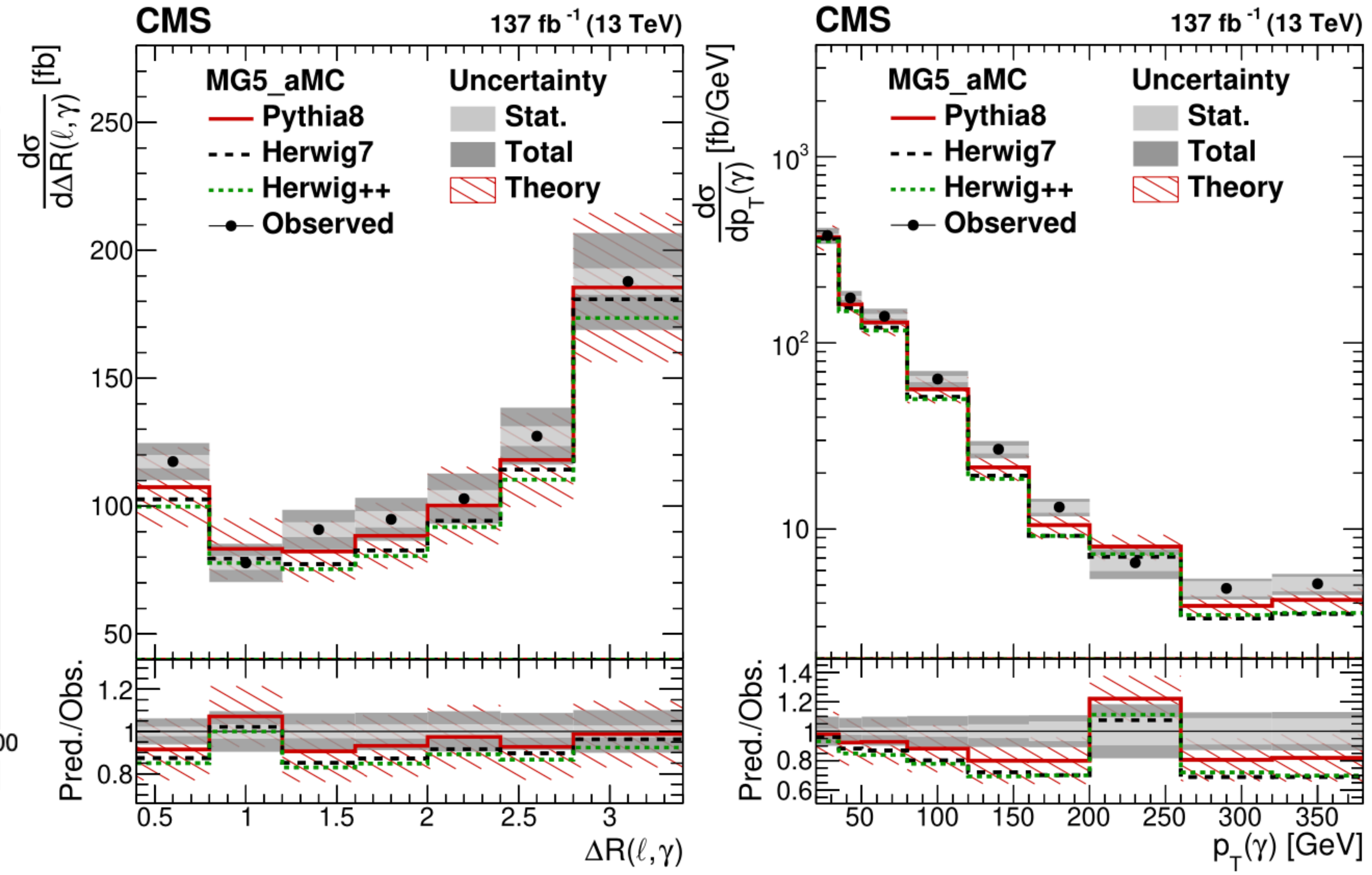
Differential cross section measurements of $t\bar{t}\gamma$

JHEP 05 (2022) 091
JHEP 12 (2021) 180

- Objects defined at particle level
- Observables: $p_T(\gamma)$, $\eta(\gamma)$, lepton and jet kinematics, and angular variables involving photons and jets/leptons
- Normalised and absolute cross sections measured



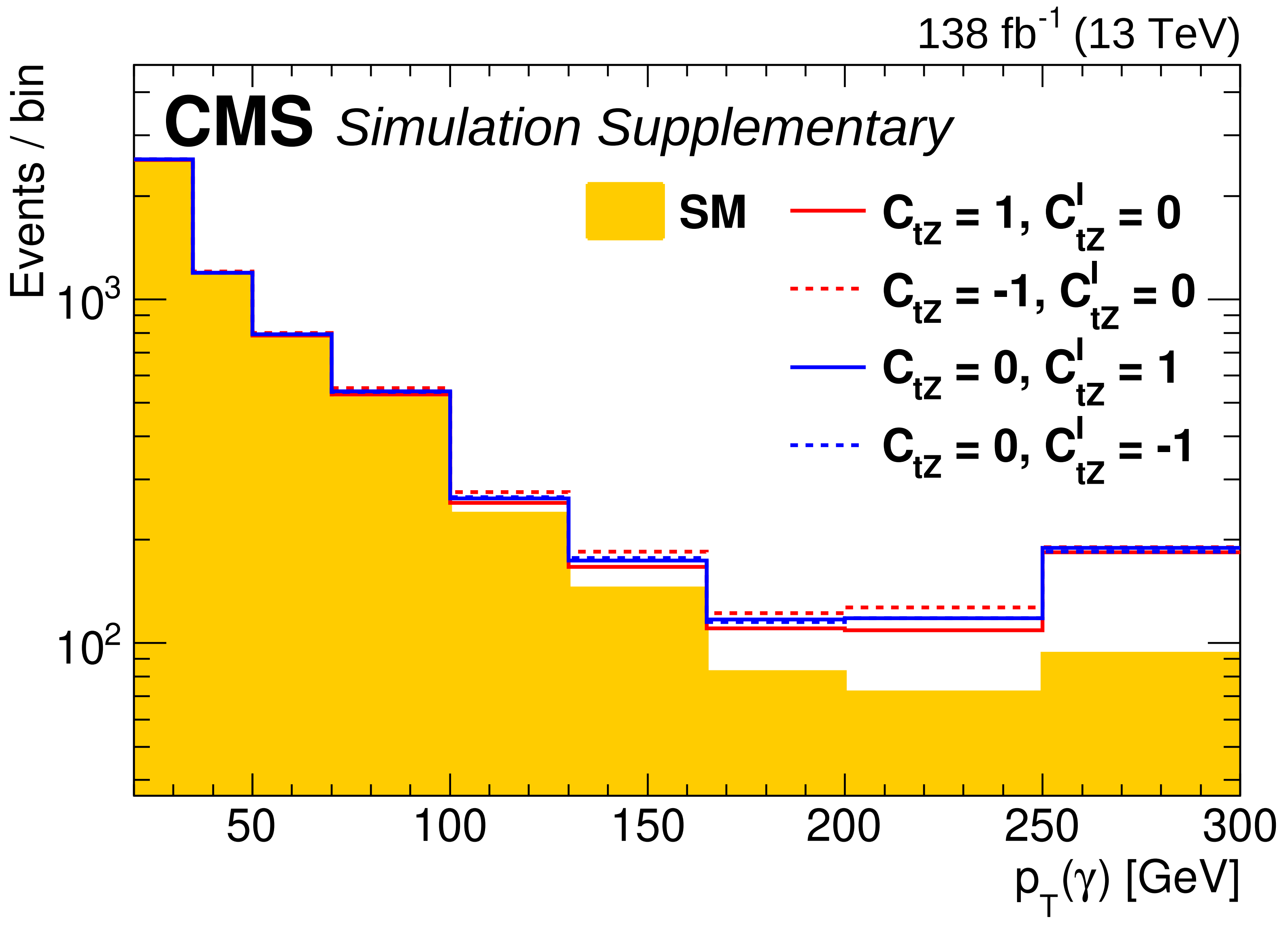
Dilepton

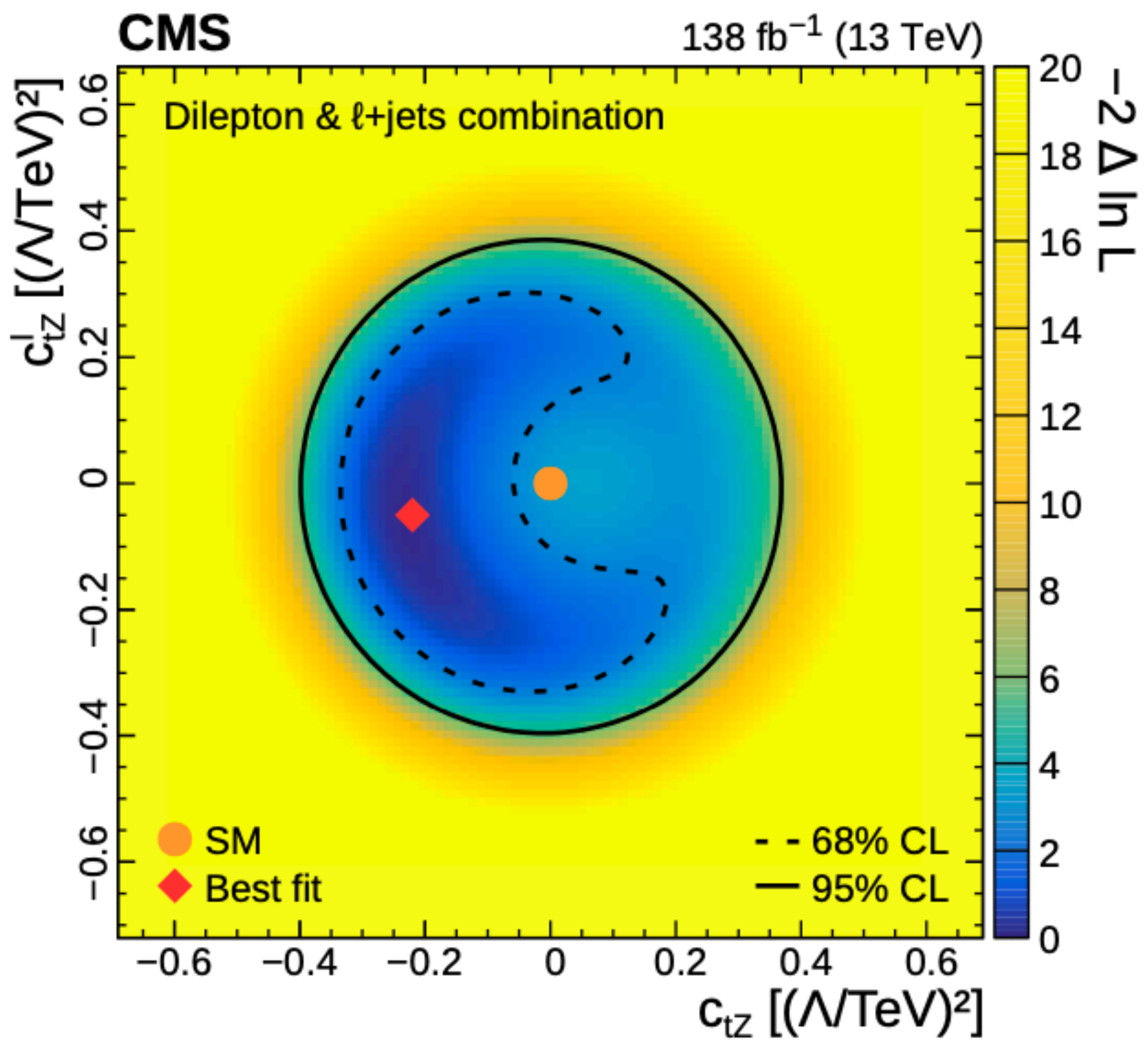


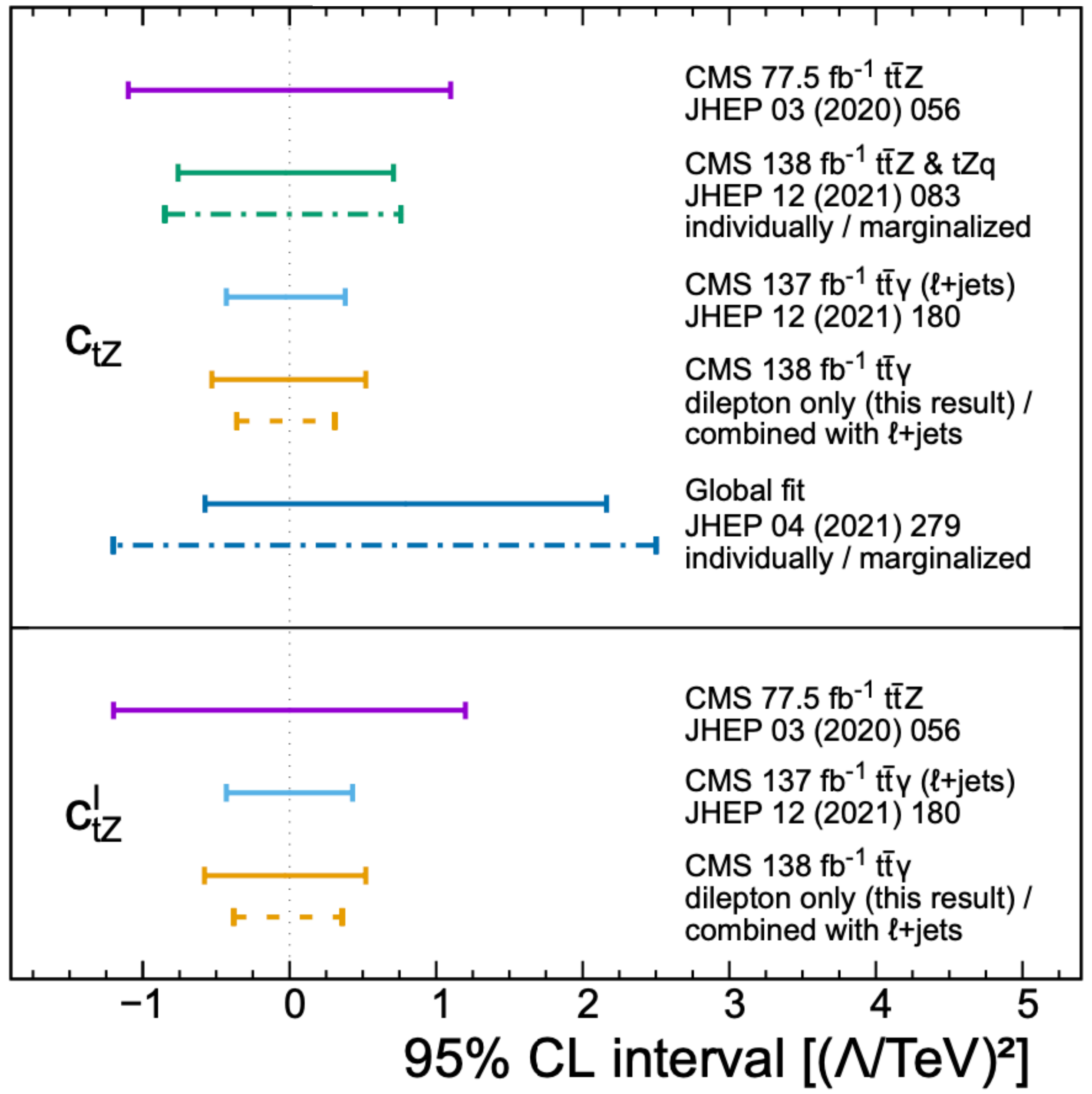
Single lepton

EFT interpretation using $t\bar{t}\gamma$

- Photon pT distribution sensitive to several EFT operators:







Operators modifying $t\gamma$ coupling also modify tZ coupling

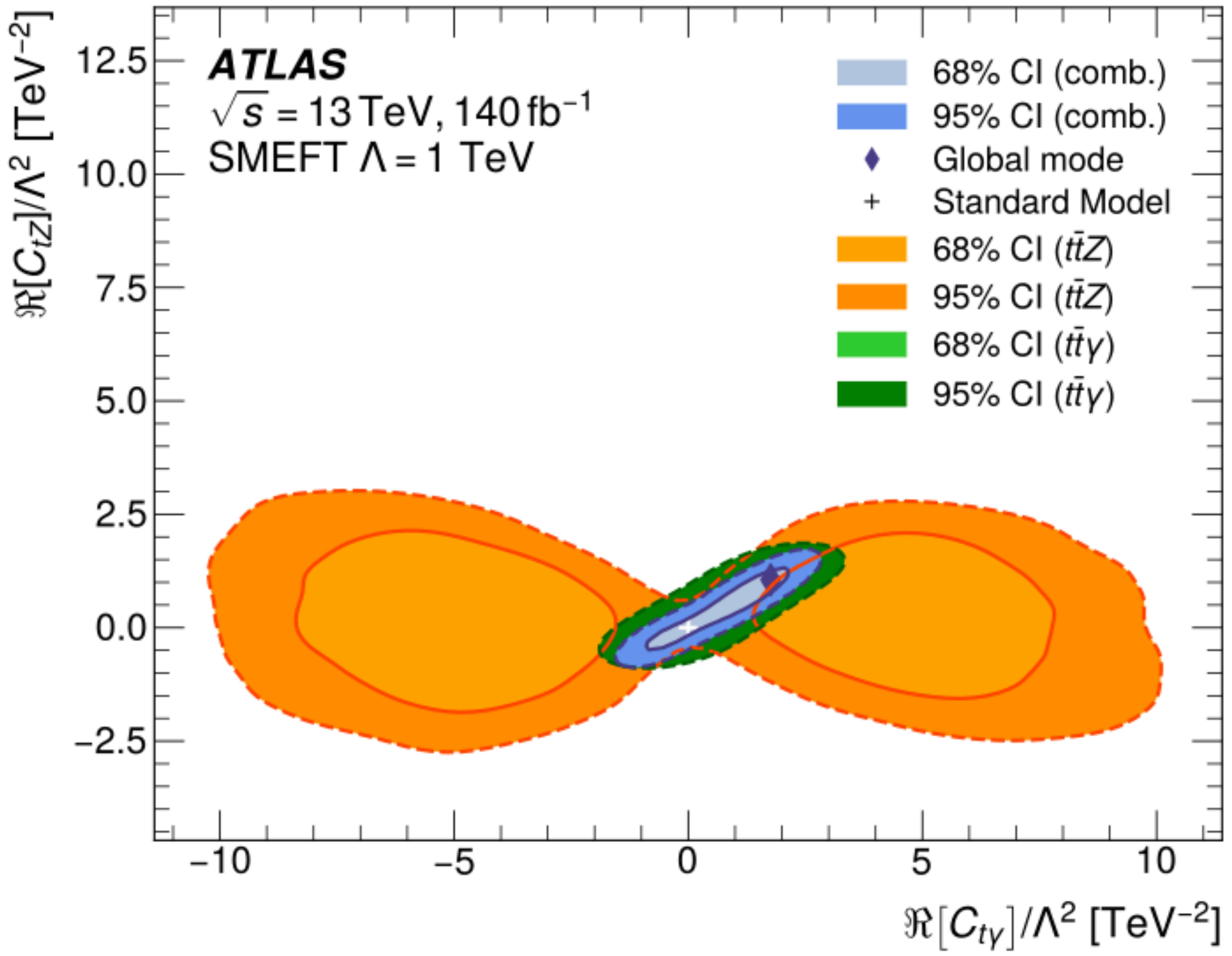
- Dilepton and single lepton channels combined for EFT interpretation
- Dilepton channel benefits from high signal purity while the single lepton channel has larger amount of events populating the photon pT tails
- Simultaneous fit to photon pT distributions in both final states

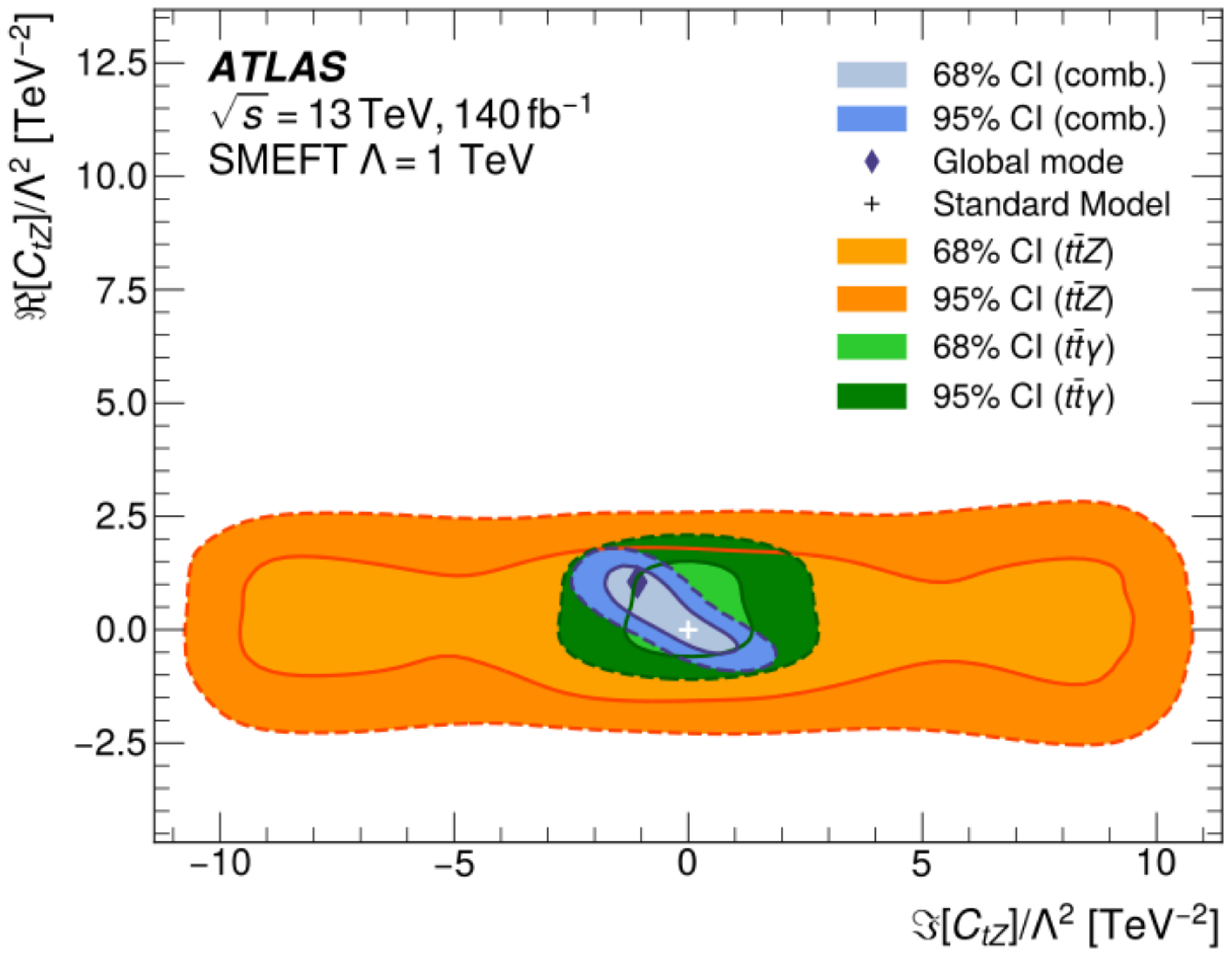
EFT interpretation using $t\bar{t}\gamma$ and $t\bar{t}Z$

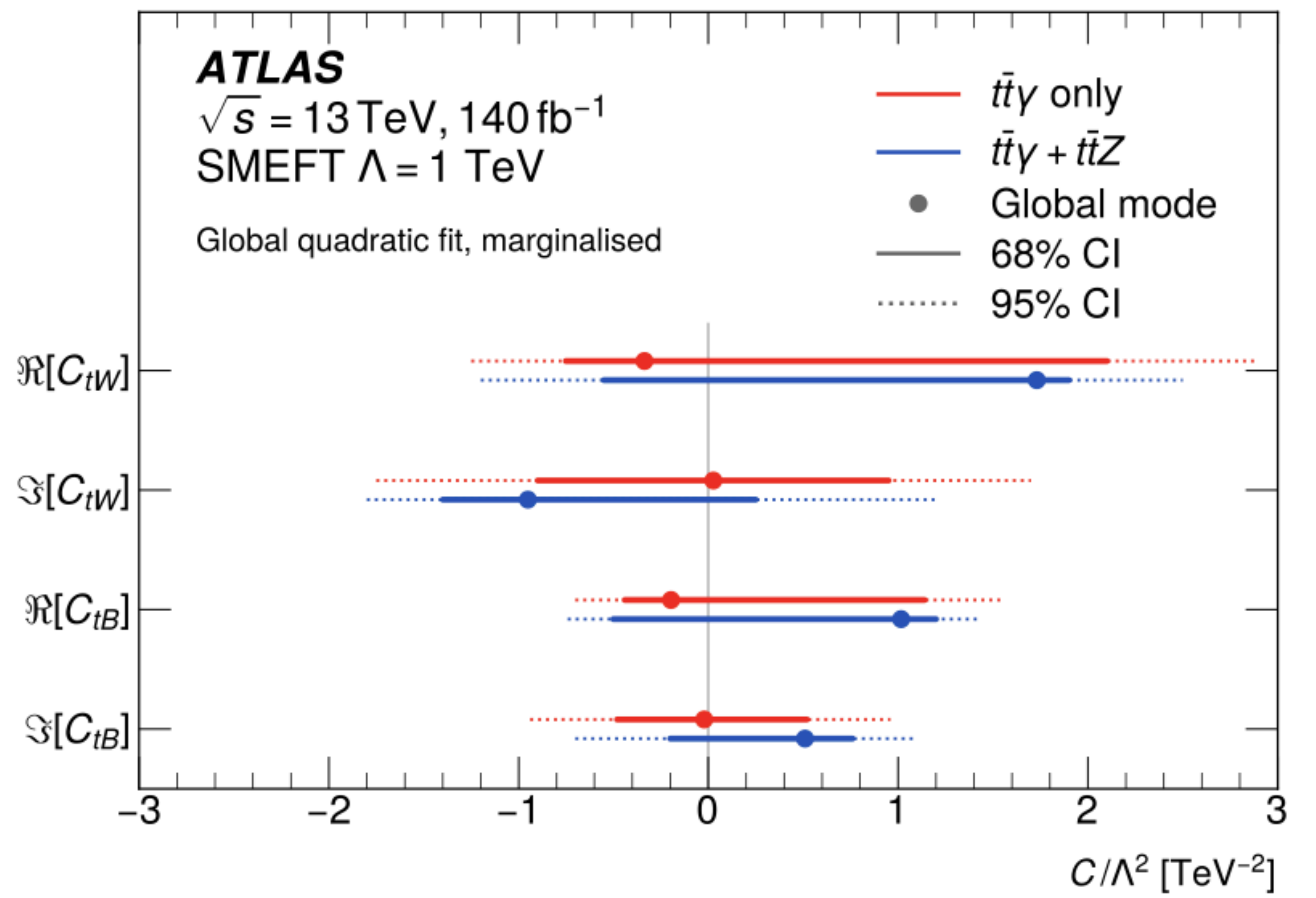
arXiv:2403.09452v1
Accepted by JHEP
JHEP 07 (2024) 163P

- Operators modifying $t\gamma$ coupling also modify tZ coupling → benefit from combination with $t\bar{t}Z$
- Transverse momentum of Z and γ unfolded simultaneously

See next talk on top+V processes by Jan van der Linden







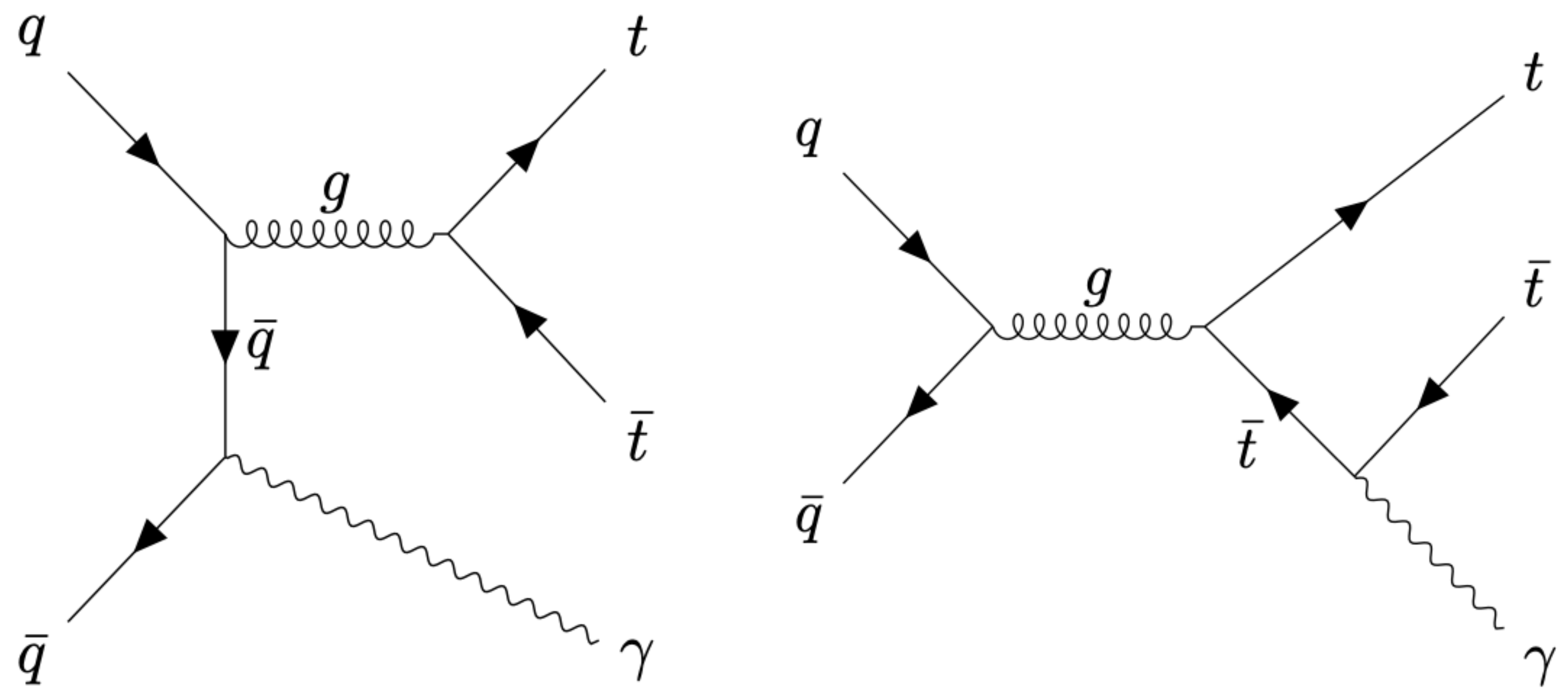
Again, the sensitivity is driven by $t\bar{t}\gamma$, but the combination brings additional constraints

- Results provided in C_{tB} C_{tW} and C_{tZ} $C_{t\gamma}$ basis

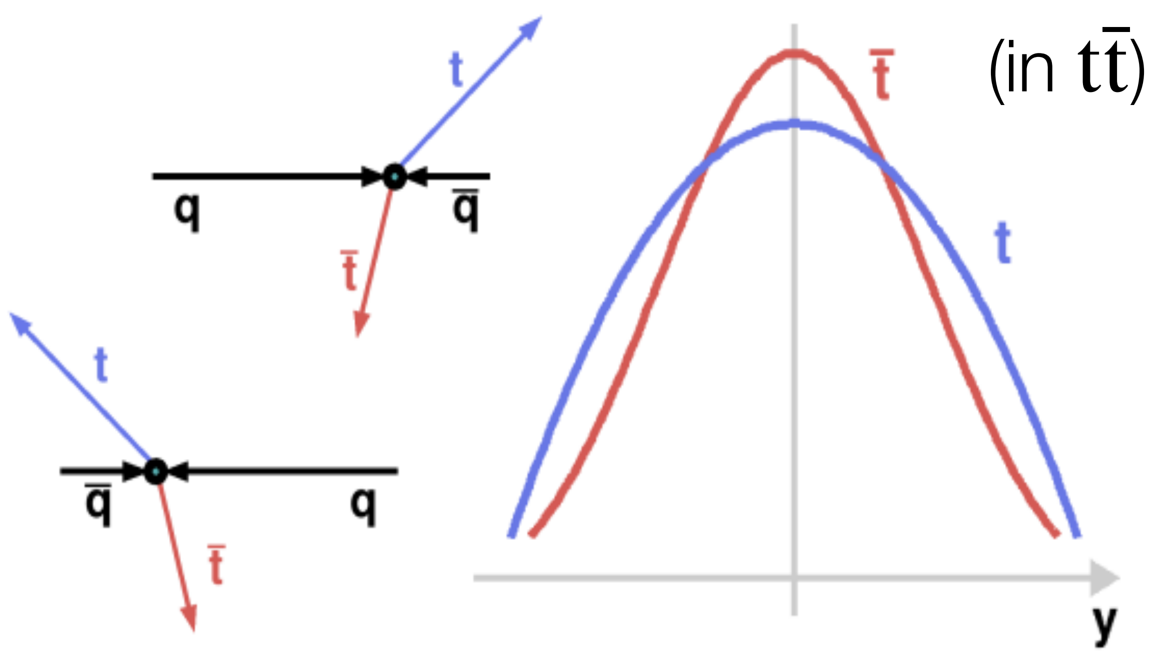
Top quark charge asymmetry using $t\bar{t}\gamma$ events

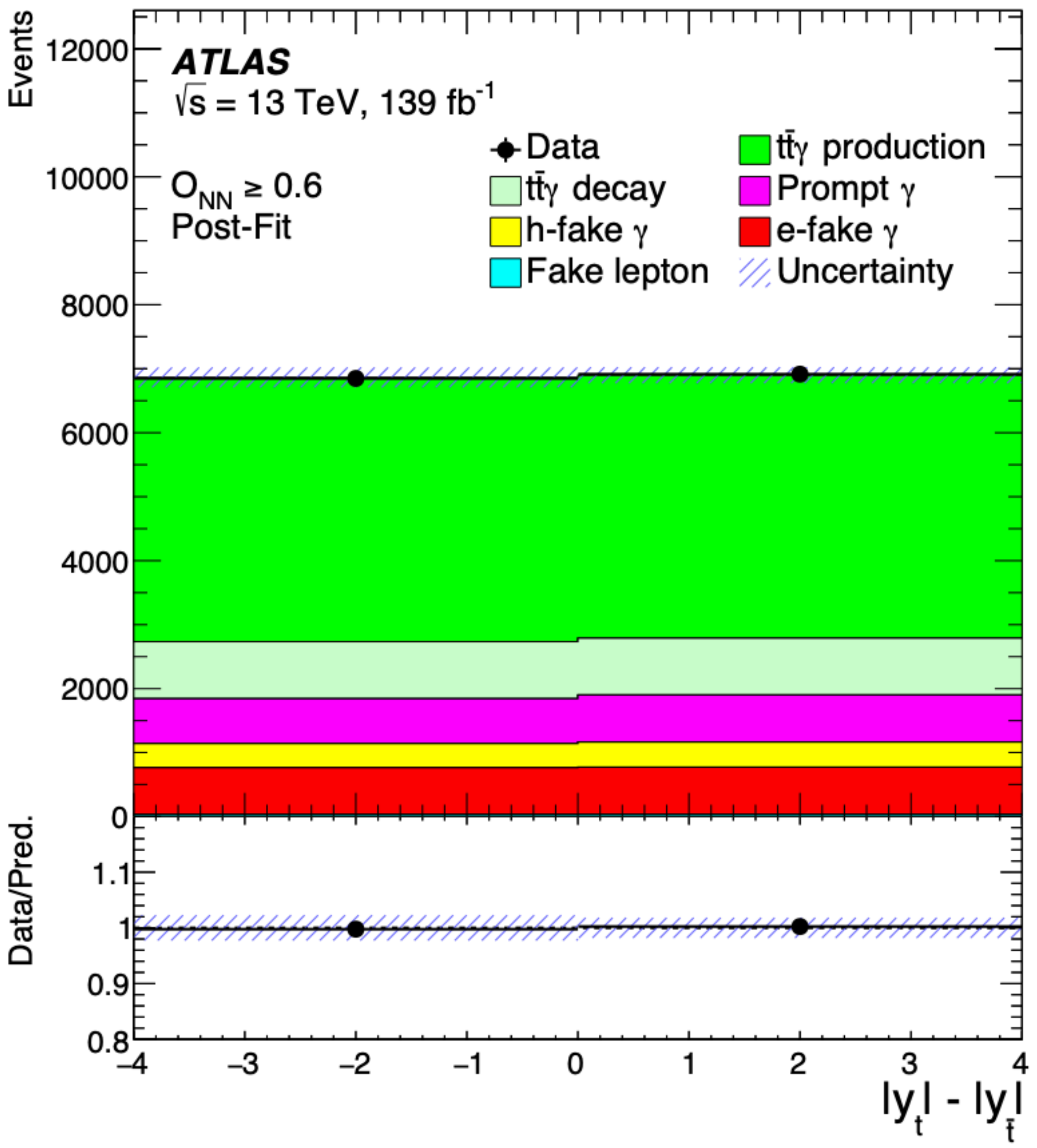
Phys. Lett. B 843 (2023) 137848

- Top quark charge asymmetry (A_c) in $t\bar{t}$ production: anisotropy in the angular distributions of the final-state top quark and antiquark **- SM prediction at NLO in QCD for $t\bar{t}$: 0.6%**
- Charge asymmetry in $t\bar{t}\gamma$ potentially enhanced (and opposite sign) compared to $t\bar{t}$, and present already at LO **- SM prediction at NLO: [-0.5%,-2%] depending on kinematics**
- Caused by interference between diagrams such as



- Analysis strategy:
  - Similar modeling strategy as cross section measurements just reported
  - NN to separate $t\bar{t}\gamma$ production (signal) and backgrounds
  - A_c extracted from fit to $|y(t)|-|y(\bar{t})|$



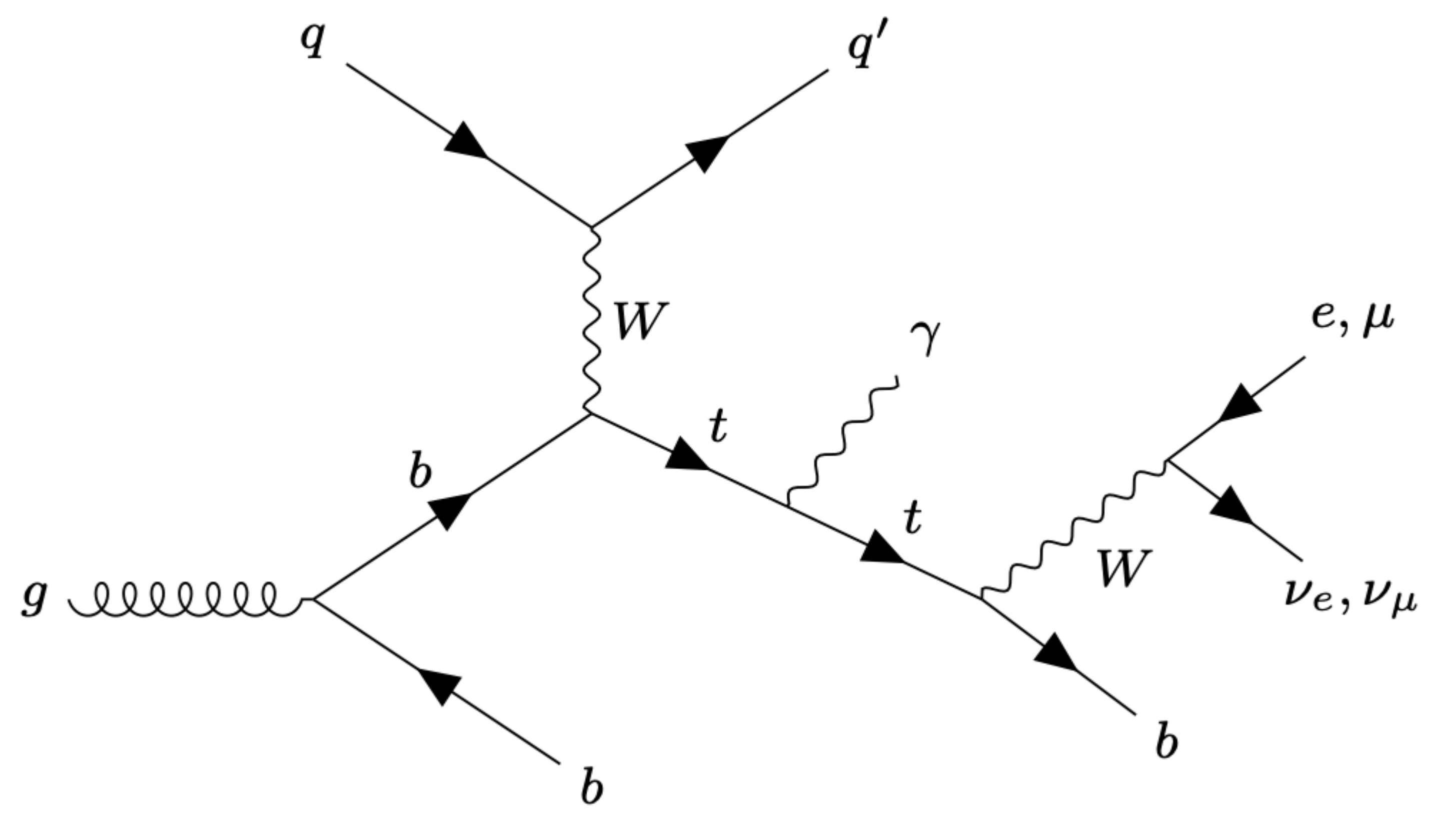


Result: A_C=−0.003±0.029 in agreement with the Standard Model expectation

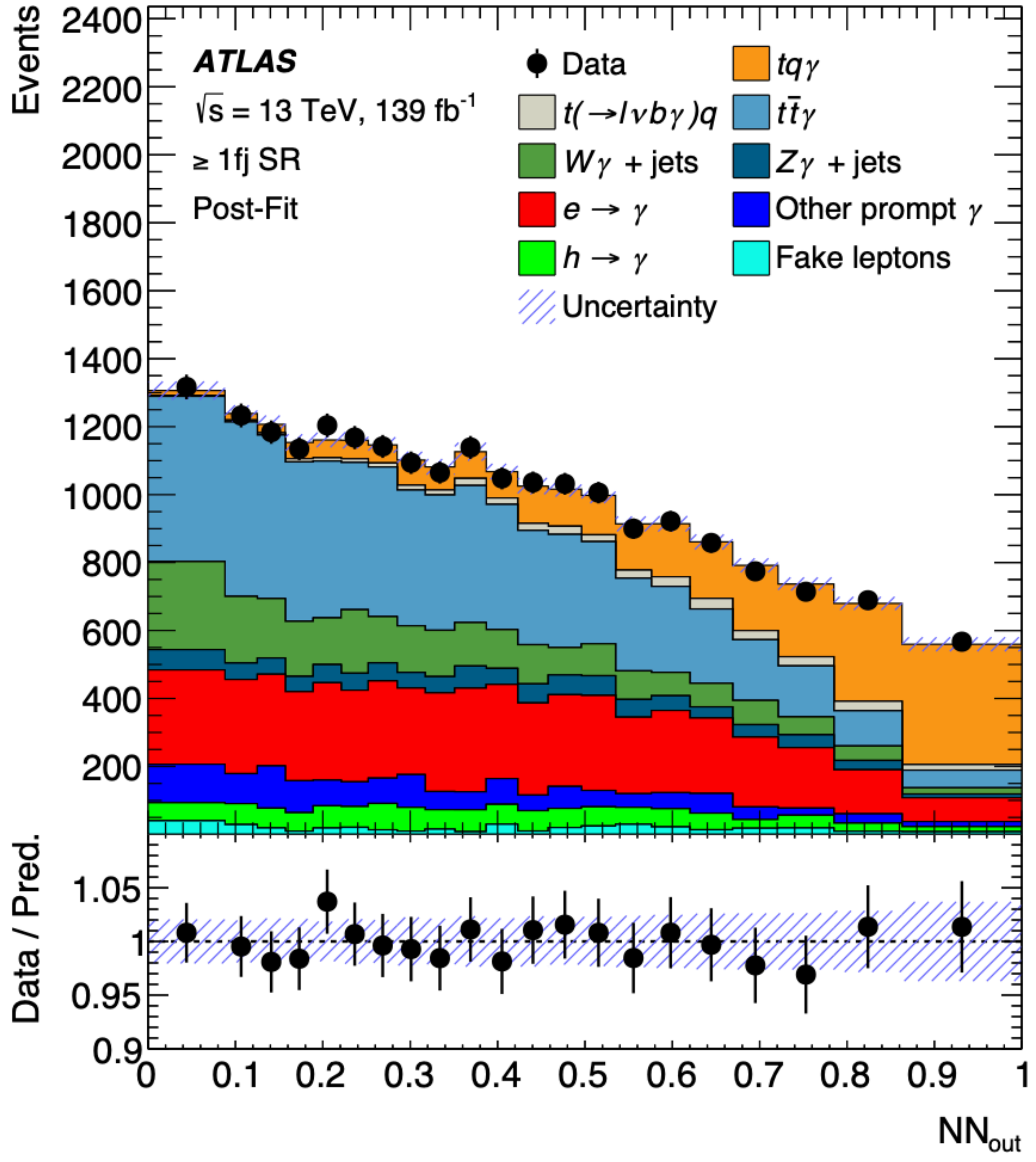
(limited by statistical uncertainty)

Quick note on single top with photon - tqγ

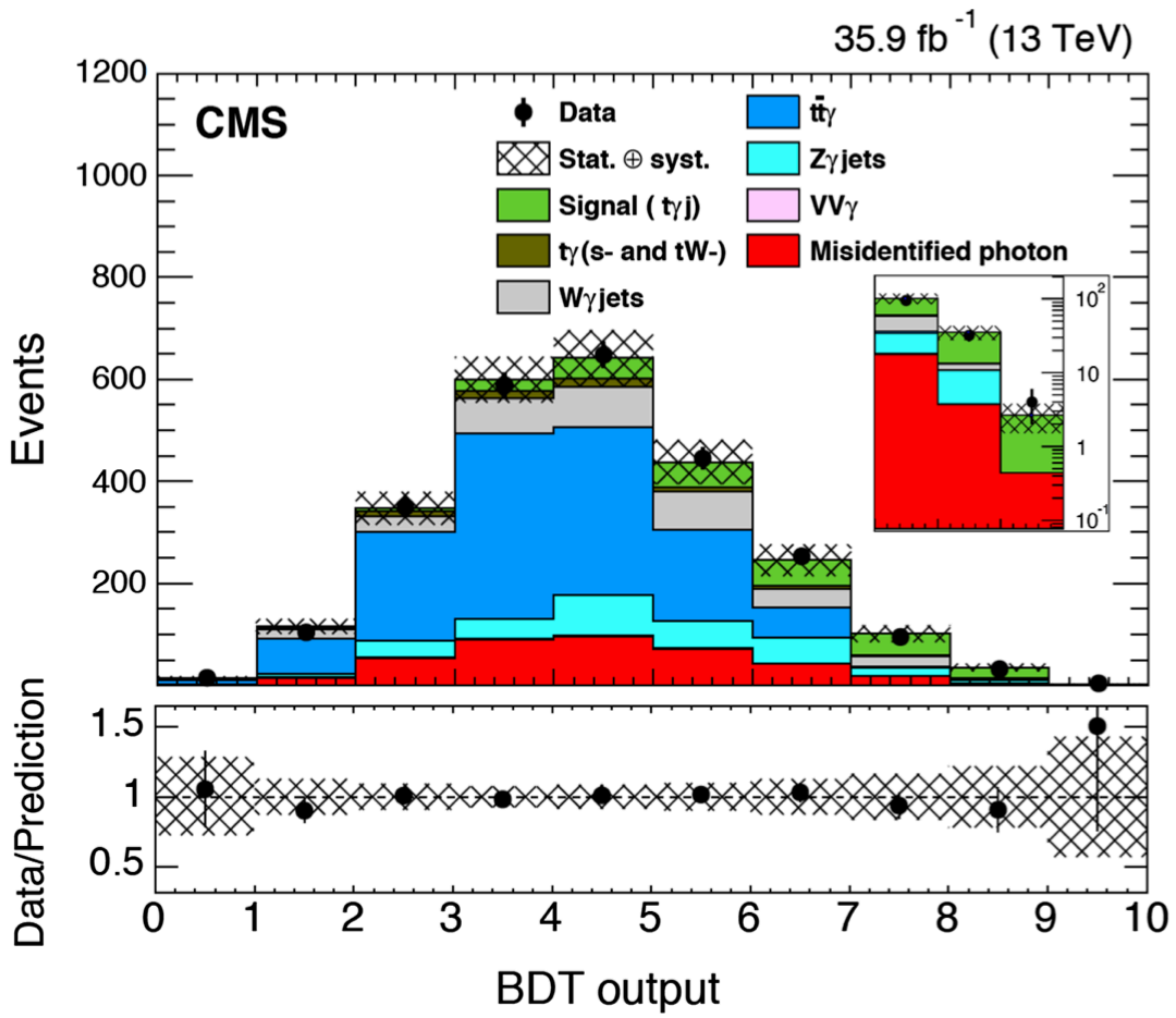
- Measuring single top in association with a photon:
  - Important input for EFT
  - Background to BSM searches
- First evidence from CMS in 2018, using 35.9 fb^{-1} of data and only muons
- First observation from ATLAS in 2023, with 140fb^{-1}



Phys. Rev. Lett. 131 (2023) 181901



Phys. Rev. Lett. 121 (2018) 221802



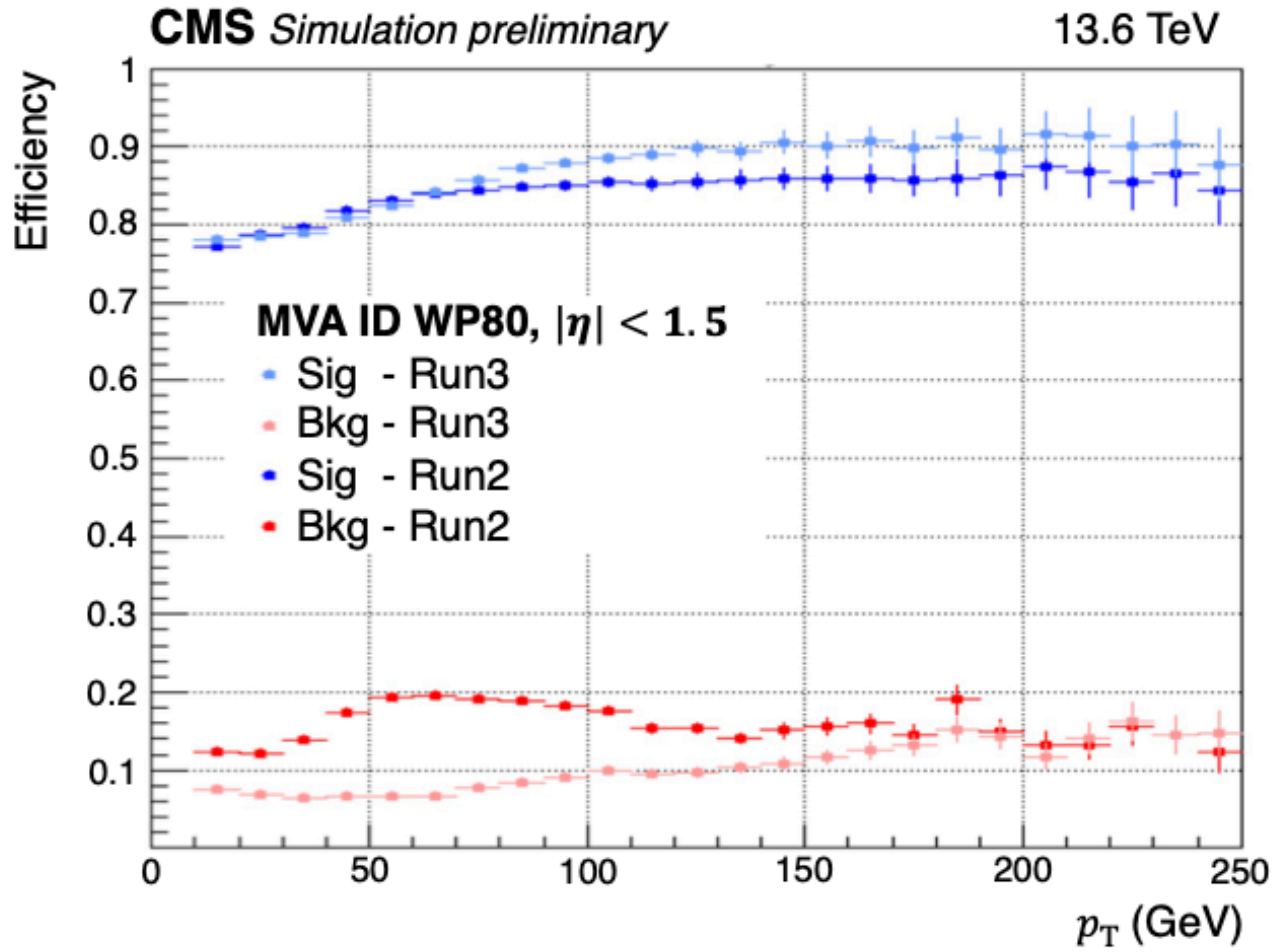
Cross sections 30-40% higher than SM prediction in both analyses, will be interesting to further measure this process, especially differentially

The future is bright!

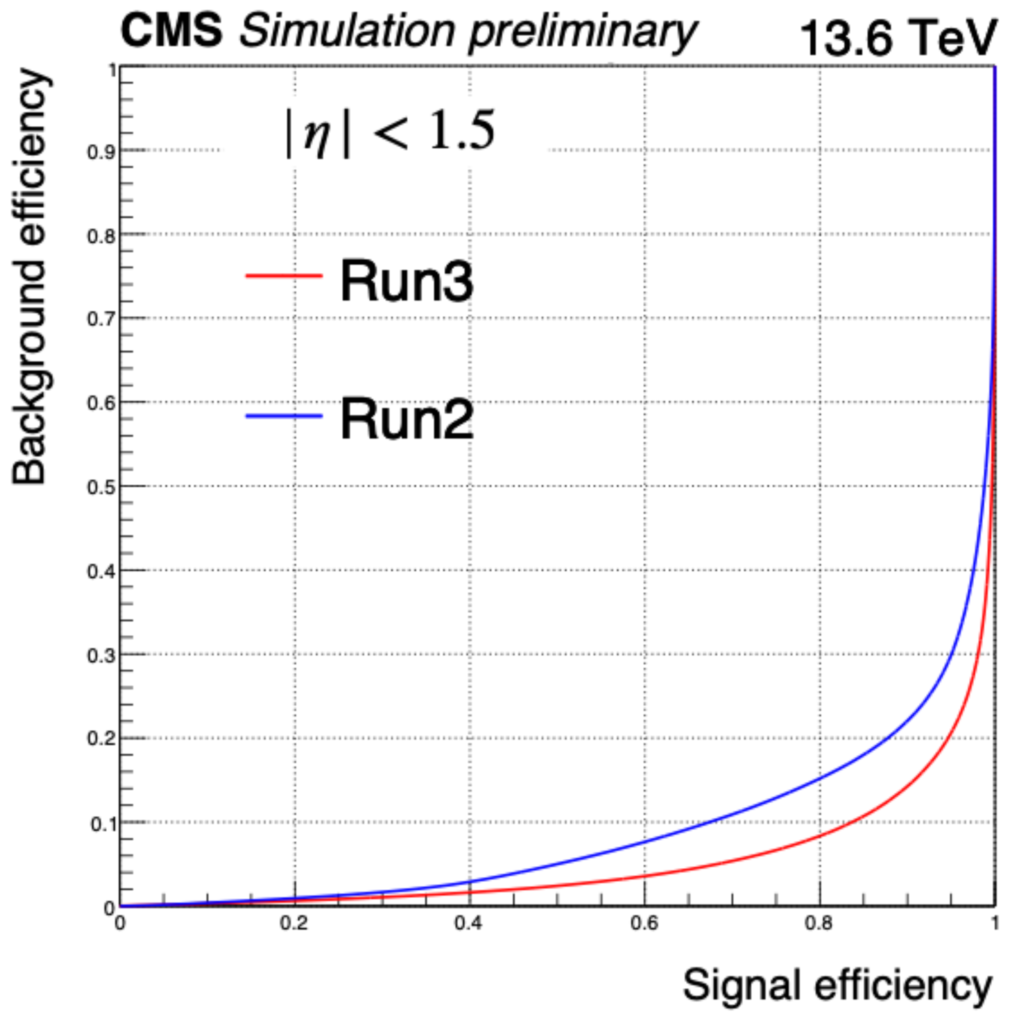
CMS DP -2024/052

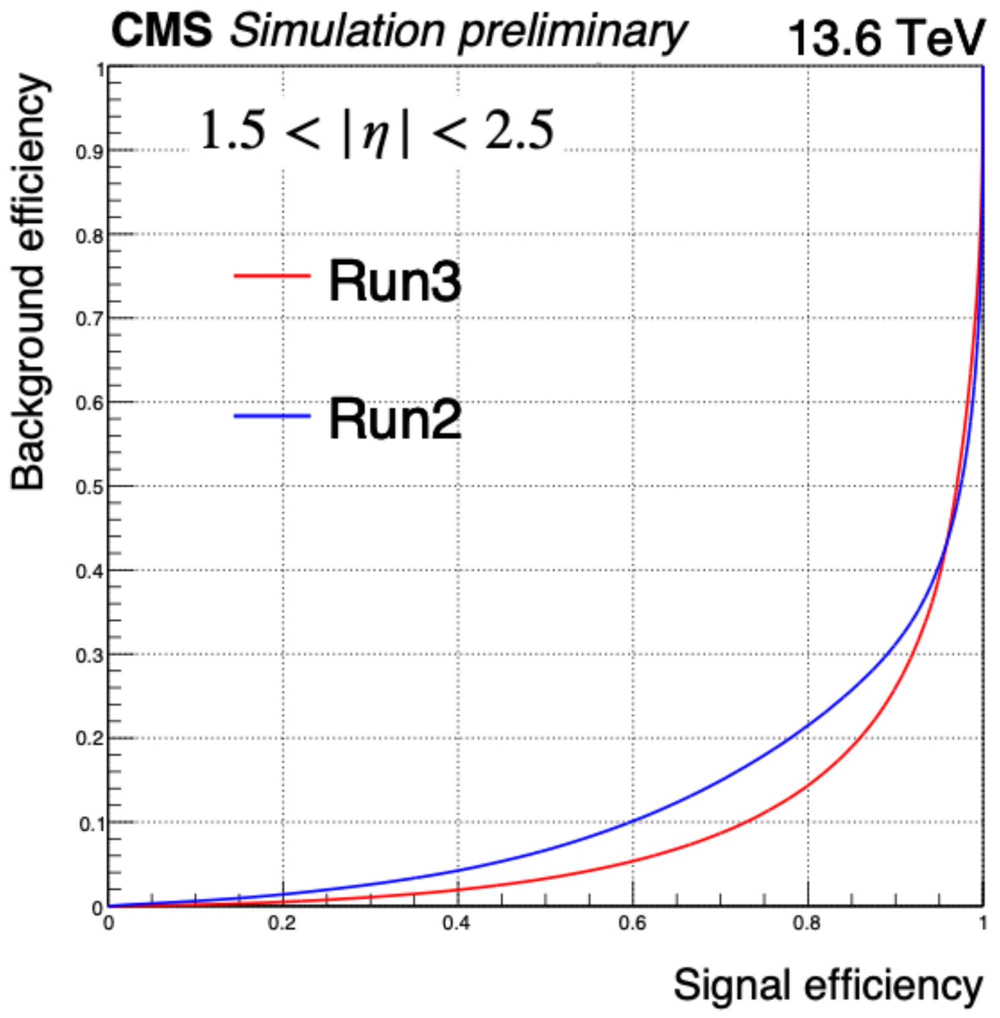
- Photon reconstruction and identification performances evaluated in CMS for the data-taking periods of 2022 and 2023

- MVA-based photon identification algorithms show improved signal efficiency when compared to Run 2



Photons are ready for Run 3 analyses, new results with improved precision can be expected!





Summary

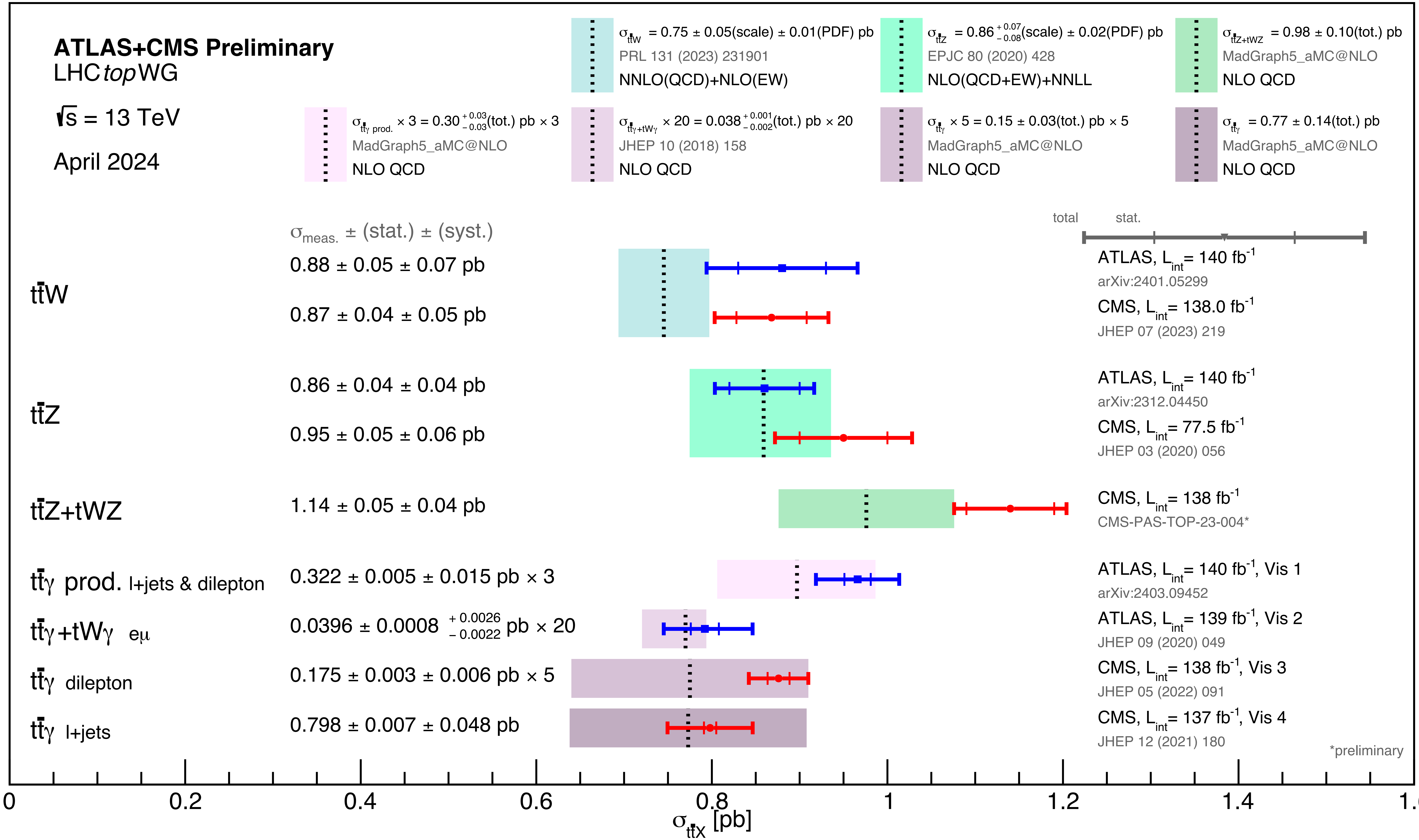
- Putting the SM to the test with top processes involving photon production
- **Shown today:**
  - Inclusive and differential $t\bar{t}\gamma$ measurements by ATLAS and CMS
    - Recent improvements in modeling strategy
  - EFT interpretation using $t\bar{t}\gamma$ events by ATLAS and CMS
  - Charge asymmetry study with $t\bar{t}\gamma$ events
  - Observation of the $tq\gamma$ processes

More exciting results on their way: stay tuned!

top 2024
17th International Workshop on Top Quark Physics
September 22 to 27
Saint-Malo, France

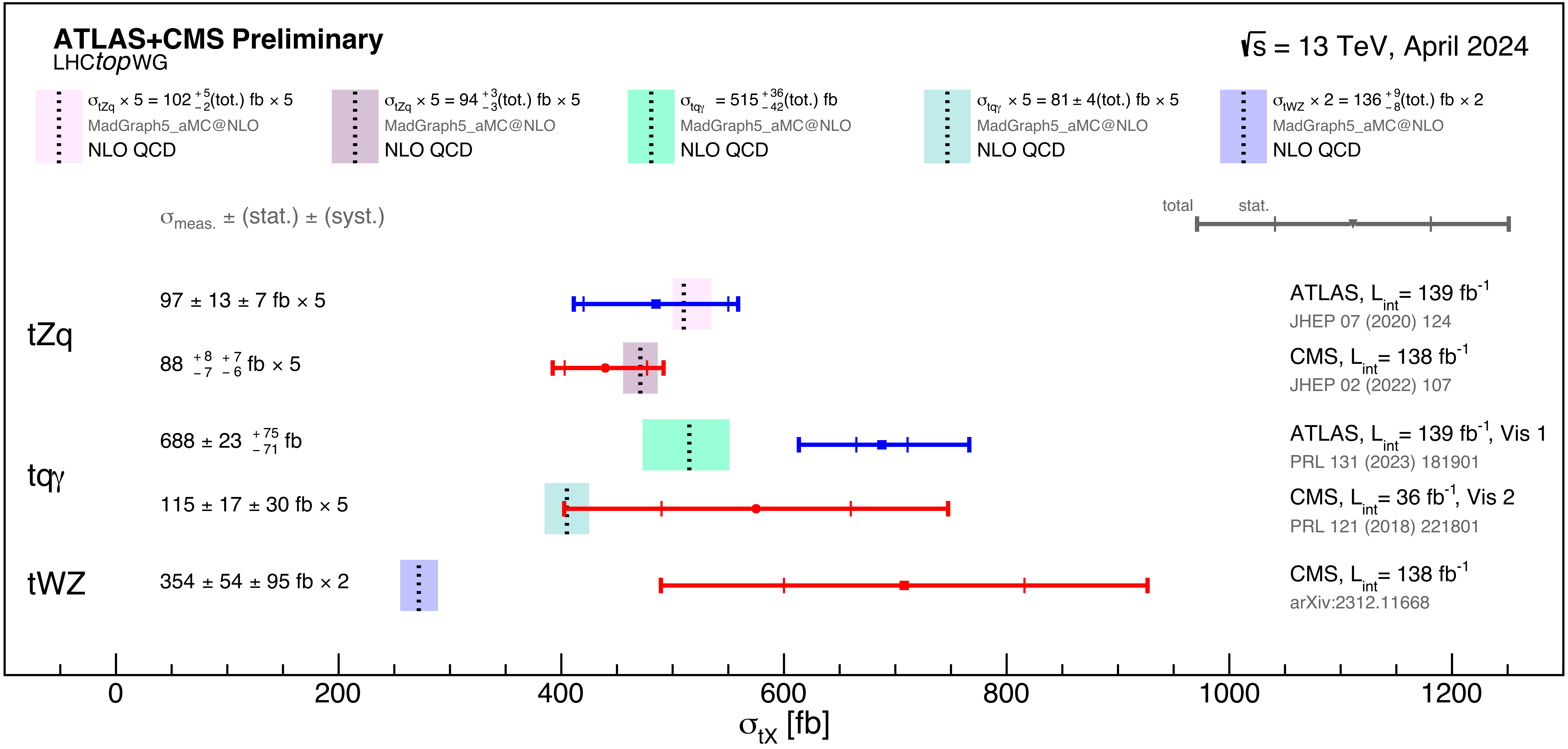
BACKUP

Summary



ATLAS+CMS Preliminary
LHC*top*WG
√s = 13 TeV
April 2024
σ_ttW = 0.75 ± 0.05(scale) ± 0.01(PDF) pb
PRL 131 (2023) 231901
NNLO(QCD)+NLO(EW)
σ_ttZ = 0.86 +0.07 −0.08 (scale) ± 0.02(PDF) pb
EPJC 80 (2020) 428
NLO(QCD+EW)+NNLL
σ_ttZ+tWZ = 0.98 ± 0.10(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ prod. × 3 = 0.30 +0.03 −0.03 (tot.) pb × 3
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ+tWγ × 20 = 0.038 +0.001 −0.002 (tot.) pb × 20
JHEP 10 (2018) 158
NLO QCD
σ_ttγ × 5 = 0.15 ± 0.03(tot.) pb × 5
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ = 0.77 ± 0.14(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σ_meas. ± (stat.) ± (syst.)
total
stat.
ttW
0.88 ± 0.05 ± 0.07 pb
ATLAS, L_int = 140 fb⁻¹
arXiv:2401.05299
0.87 ± 0.04 ± 0.05 pb
CMS, L_int = 138.0 fb⁻¹
JHEP 07 (2023) 219
ttZ
0.86 ± 0.04 ± 0.04 pb
ATLAS, L_int = 140 fb⁻¹
arXiv:2312.04450
0.95 ± 0.05 ± 0.06 pb
CMS, L_int = 77.5 fb⁻¹
JHEP 03 (2020) 056
ttZ+tWZ
1.14 ± 0.05 ± 0.04 pb
CMS, L_int = 138 fb⁻¹
CMS-PAS-TOP-23-004*
ttγ prod. l+jets & dilepton
0.322 ± 0.005 ± 0.015 pb × 3
ATLAS, L_int = 140 fb⁻¹, Vis 1
arXiv:2403.09452
ttγ+tWγ eμ
0.0396 ± 0.0008 +0.0026 −0.0022 pb × 20
ATLAS, L_int = 139 fb⁻¹, Vis 2
JHEP 09 (2020) 049
ttγ dilepton
0.175 ± 0.003 ± 0.006 pb × 5
CMS, L_int = 138 fb⁻¹, Vis 3
JHEP 05 (2022) 091
ttγ l+jets
0.798 ± 0.007 ± 0.048 pb
CMS, L_int = 137 fb⁻¹, Vis 4
JHEP 12 (2021) 180
*preliminary
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
σ_ttX [pb]

Summary



ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, April 2024
σtZq × 5 = 102 +5 −2 (tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtZq × 5 = 94 +3 −3 (tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtqγ = 515 +36 −42 (tot.) fb
MadGraph5_aMC@NLO
NLO QCD
σtqγ × 5 = 81 ± 4(tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtWZ × 2 = 136 +9 −8 (tot.) fb × 2
MadGraph5_aMC@NLO
NLO QCD
σmeas. ± (stat.) ± (syst.)
total
stat.
tZq
97 ± 13 ± 7 fb × 5
ATLAS, Lint = 139 fb-1
JHEP 07 (2020) 124
88 +8 −7 +7 −6 fb × 5
CMS, Lint = 138 fb-1
JHEP 02 (2022) 107
tqγ
688 ± 23 +75 −71 fb
ATLAS, Lint = 139 fb-1, Vis 1
PRL 131 (2023) 181901
115 ± 17 ± 30 fb × 5
CMS, Lint = 36 fb-1, Vis 2
PRL 121 (2018) 221801
tWZ
354 ± 54 ± 95 fb × 2
CMS, Lint = 138 fb-1
arXiv:2312.11668
0
200
400
600
800
1000
1200
σtX [fb]

Inclusive cross section measurements of $t\bar{t}\gamma$ production - fiducial phase space

arXiv:2403.09452v1

Accepted by JHEP

Photons are required to not originate from a hadron decay, satisfy $E_T > 20$ GeV and $|\eta| < 2.37$, and that the sum of transverse momenta of all charged particles surrounding the photon within $\Delta R = 0.2$ is less than 5% of its own p_T. Muons and electrons are required to have $p_T > 25$ GeV and $|\eta| < 2.5$, and must not originate from hadron decays. The momenta of nearby photons, within a $\Delta R = 0.1$ cone, are added to the lepton before applying the selection. Particle-level jets are clustered with the anti-k_t algorithm with a radius parameter of $R = 0.4$. All stable particles are considered in the clustering, except for the selected electrons, muons and photons, and the neutrinos originating from the top quarks. Jets are required to satisfy $p_T > 25$ GeV and $|\eta| < 2.5$. A jet is identified as a b-jet if a hadron with $p_T > 5$ GeV containing a b-quark is matched to the jet through a ghost-matching method [81]. Muons and electrons with separation $\Delta R < 0.4$ from a jet are excluded. Jets are removed if they are within $\Delta R = 0.4$ of an isolated photon candidate. Events are additionally required to satisfy $\Delta R(\gamma, \ell) > 0.4$, where ℓ is the electron or muon.

The fiducial phase space in the single-lepton channel is defined by requiring exactly one photon, exactly one electron or muon, and at least four jets, and in the dilepton channel by requiring exactly one photon and two leptons, and at least two jets. In both cases, at least one jet must be a b-tagged jet. For the combination of the channels, a union of the single-lepton and dilepton fiducial phase spaces is used.

Inclusive cross section measurements of $t\bar{t}\gamma$ production - syst. uncertainties

arXiv:2403.09452v1
Accepted by JHEP

Source	$\Delta\sigma_{t\bar{t}\gamma\text{ production}}/\sigma_{t\bar{t}\gamma\text{ production}}$ (%) Single lepton	Dilepton	Combination
Statistical uncertainty	1.8	3.3	1.5
MC statistical uncertainties	1.5	1.5	1.0
Modelling uncertainties			
$t\bar{t}\gamma$ production PS uncertainty	2.4	3.7	0.9
Other $t\bar{t}\gamma$ production modelling	5.1	1.6	3.0
$t\bar{t}\gamma$ decay modelling	0.3	1.3	0.8
$t\bar{t}\gamma$ decay normalisation	2.4	3.1	2.1
Prompt photon background normalisation	1.5	2.0	2.0
Fake photon background estimate	0.8	1.5	1.6
Fake lepton background estimate	0.4	–	0.1
Other Background modelling	0.7	0.2	0.5
Experimental uncertainties			
Jet uncertainties	3.5	3.0	1.7
B-tagging uncertainties	2.6	2.1	1.0
Photon	0.5	1.5	0.8
Lepton	1.3	1.4	1.3
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.3	0.4	0.4
Pile-up	0.3	0.7	0.5
Luminosity	0.8	1.0	0.8
Total systematic uncertainty	7.6	7.1	5.0
Total uncertainty	7.8	7.7	5.2