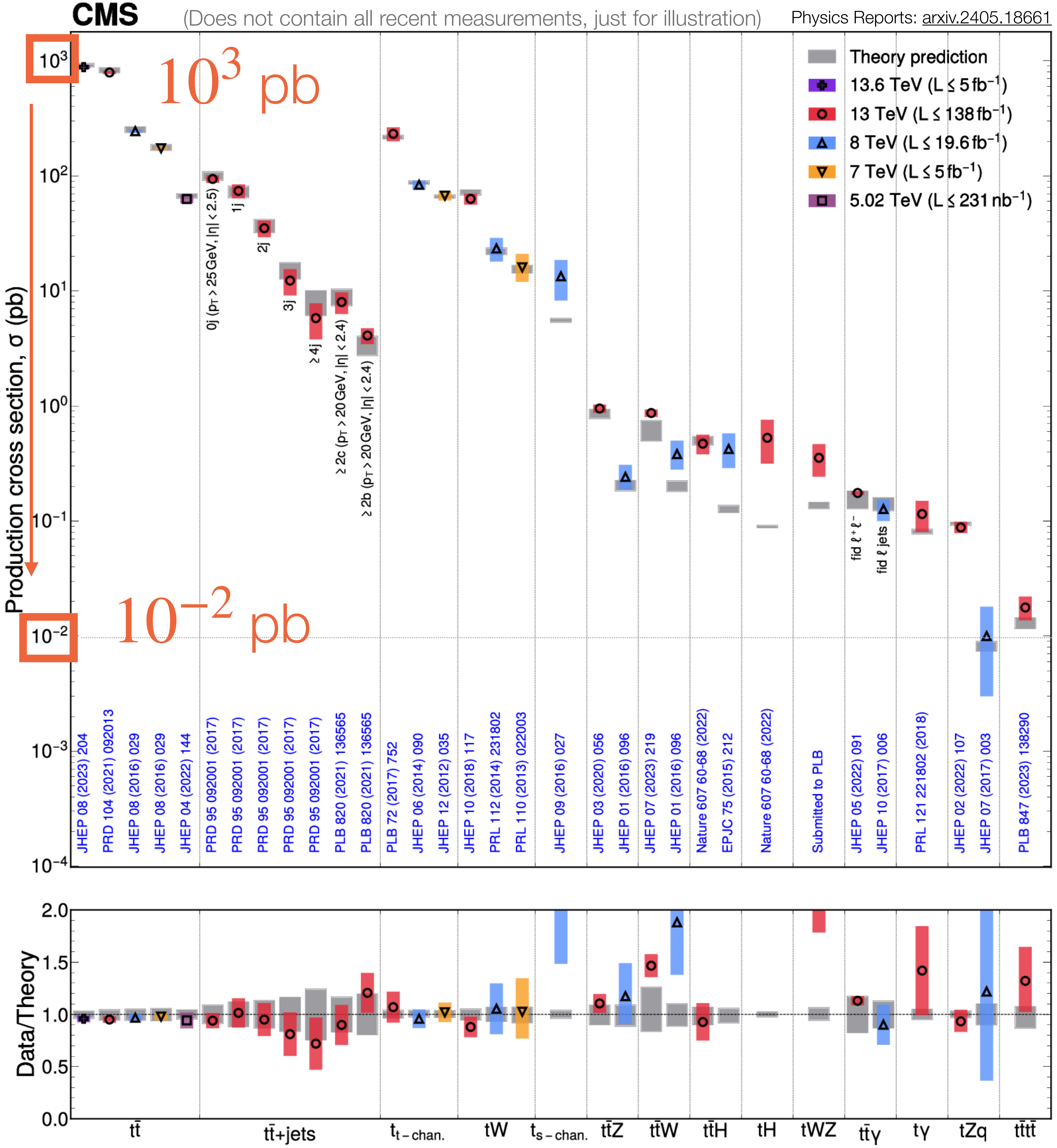
LA THUILE 2025 - Les Rencontres de Physique de la Vallée d'Aoste

Associated top-quark production at ATLAS and CMS

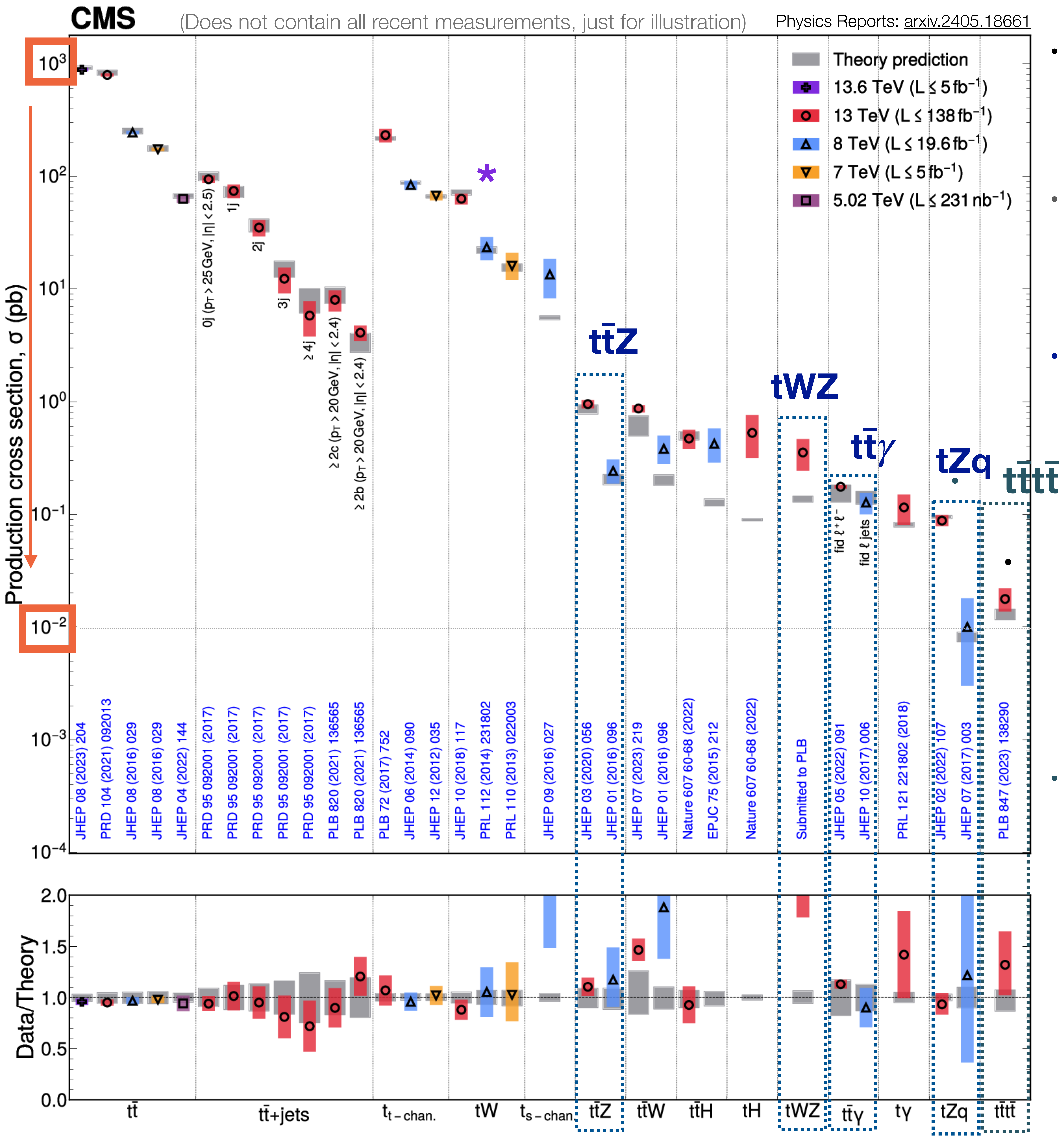
Beatriz Ribeiro Lopes, on behalf of the ATLAS and CMS collaborations

Electroweak and associated top quark production



- Top quark measurements are central to LHC program
- Span **many orders of magnitude**, from very abundant to extremely rare processes

Electroweak and associated top quark production



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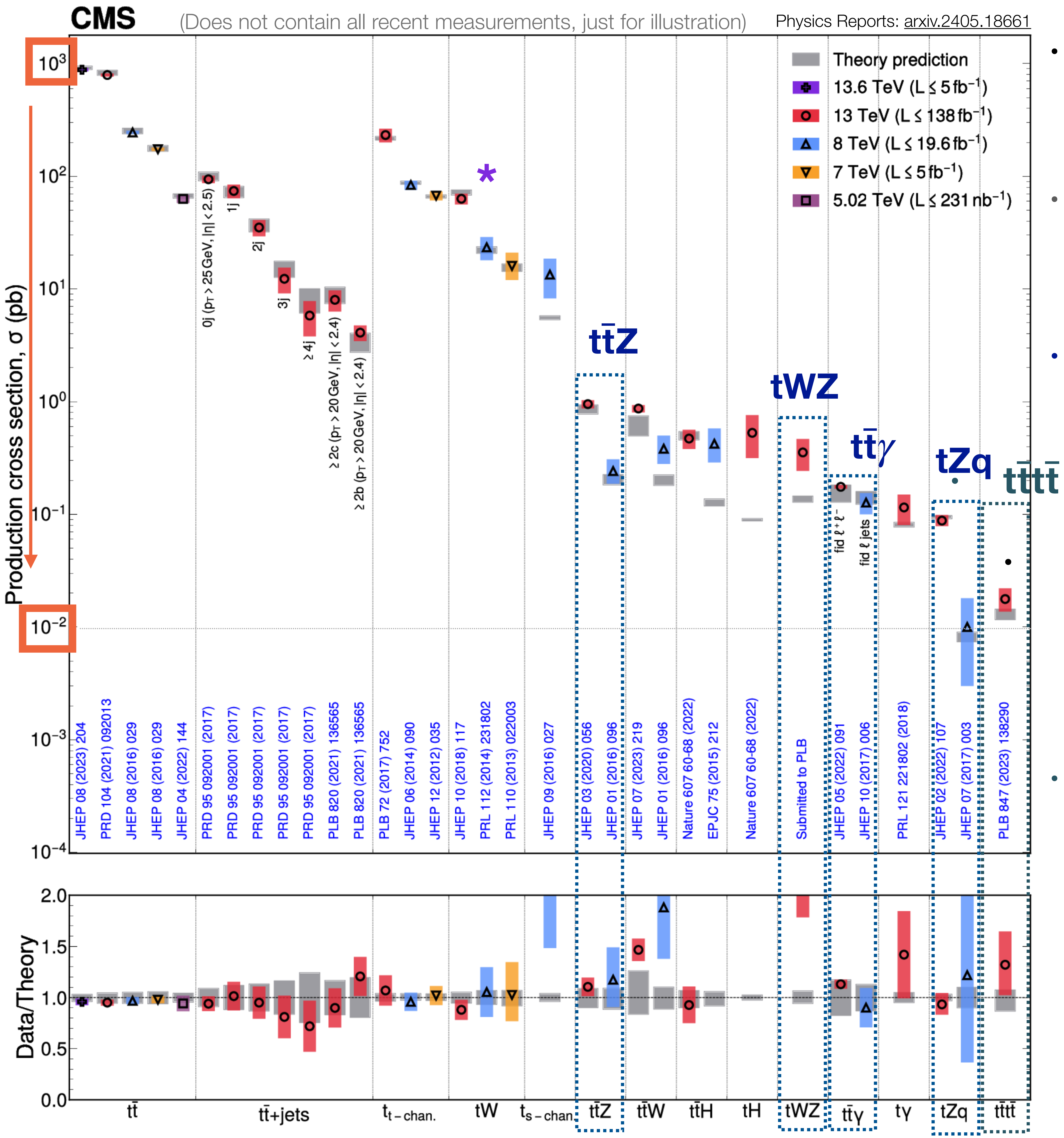
- Span **many orders of magnitude**, from very abundant to extremely rare processes
- **$t(\bar{t})$ + vector boson**
  - Powerful probes of both EW and QCD sectors
  - Rare processes, but with the data collected in Run 2, we **entered the precision era**
  - Differential distributions enhance sensitivity to BSM
- **$t\bar{t}t\bar{t}$**
  - Lowest cross section - very rare process!
  - **Recent observation - not discussed today**
  - Searches for new physics decaying to top quarks
  - Constraints on Higgs width and Top Yukawa

Electroweak and associated top quark production



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- **tt̄tt̄**
  - Lowest cross section - very rare process!
  - **Recent obse… day**
  - Searches for new physics decaying to top quarks
  - Constraints on Higgs width and Top Yukawa

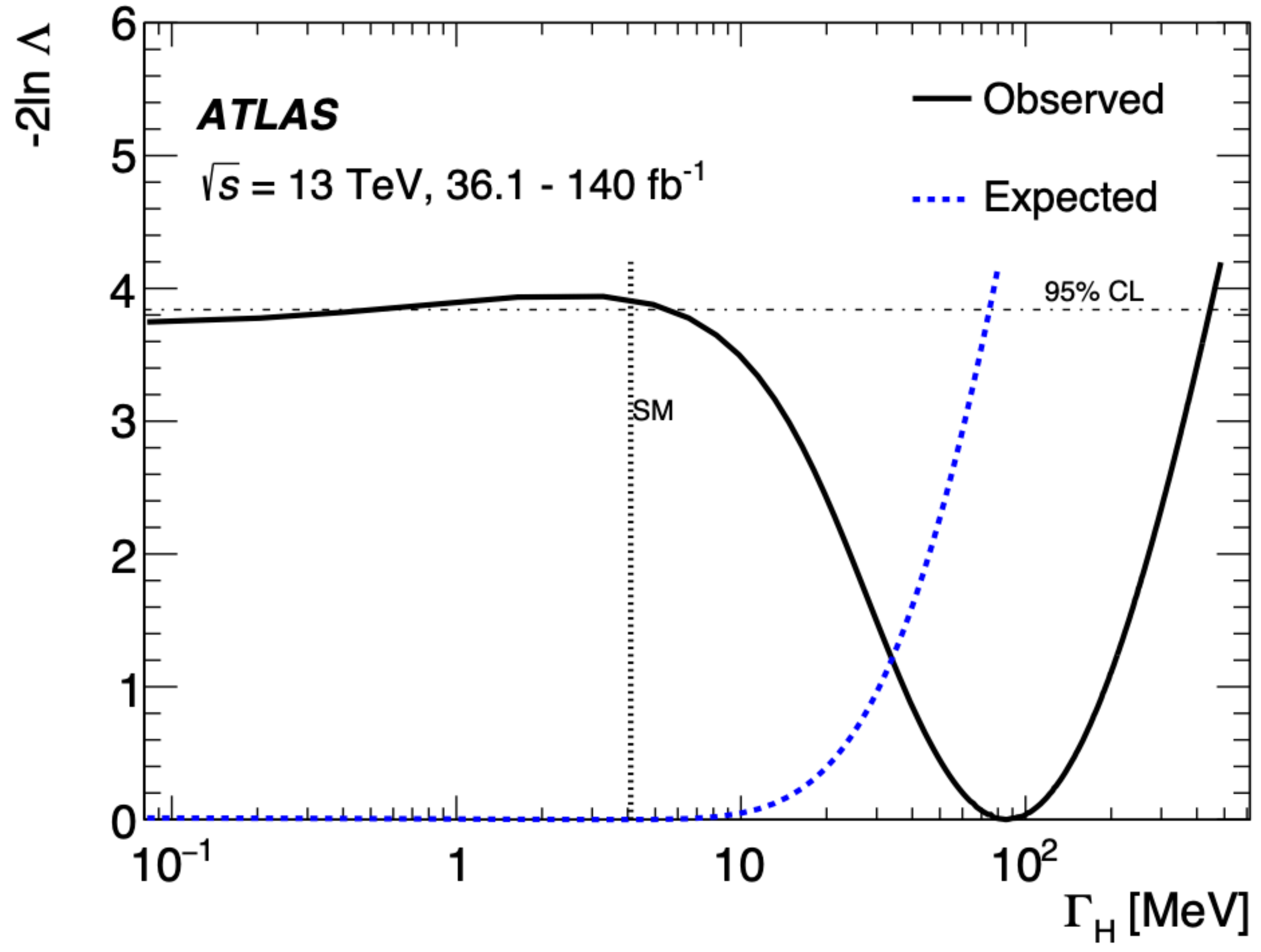
Talk by Regina Demina

Let’s start with $t\bar{t}t\bar{t}$ and $t\bar{t}H$

Constraint on the total Higgs width from H, $t\bar{t}H$ and $t\bar{t}t\bar{t}$

- Measure total Γ_H without needing to assume the production cross sections are the same for on- and off-shell Higgs (complementary to existing measurements)
- Combination of multiple previously published results based on profile likelihood ratio, with careful correlation scheme for systematic uncertainties and updated luminosity

Off-shell measurement	
$pp \to t\bar{t}t\bar{t}$	
On-shell measurement	
Production	Decay
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$
$t\bar{t}H + tH$	$H \to b\bar{b}$
WH, ZH	$H \to b\bar{b}$
VBF	$H \to b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$
ggF, VBF	$H \to WW$
WH, ZH	$H \to WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$
Inclusive	$H \to Z\gamma$



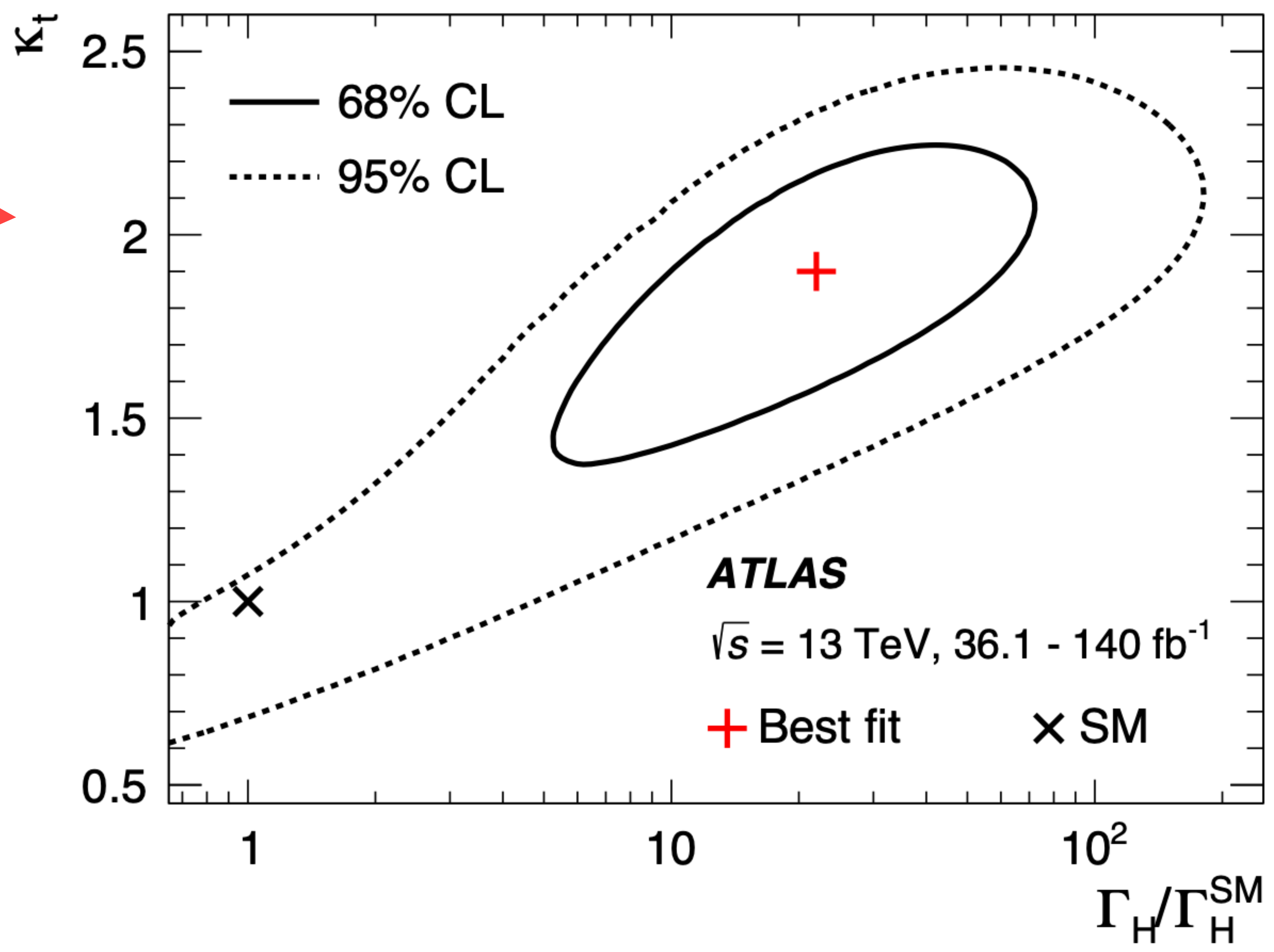
$\Gamma_H < 450$ MeV (75 MeV exp.)

- Some assumptions: tree-level κ_t same for on- and off-shell Higgs, no BSM contributions to $t\bar{t}t\bar{t}$

Constraint on the total Higgs width from H, $t\bar{t}H$ and $t\bar{t}t\bar{t}$

Phys. Lett. B 861 (2025) 139277)

- Measure total Γ_H without needing to assume the production cross sections are the same for on- and off-shell Higgs (complementary to existing measurements)
- Combination of multiple previously published results
- Simultaneous constraints on Higgs width and Top-Yukawa coupling strength also extracted based on a 2D fit



See also talk by Martina Manoni

Now on to $t(\bar{t})$ + vector bosons

Simultaneous measurement of $t\bar{t}Z$, tWZ, and tZq

Now published

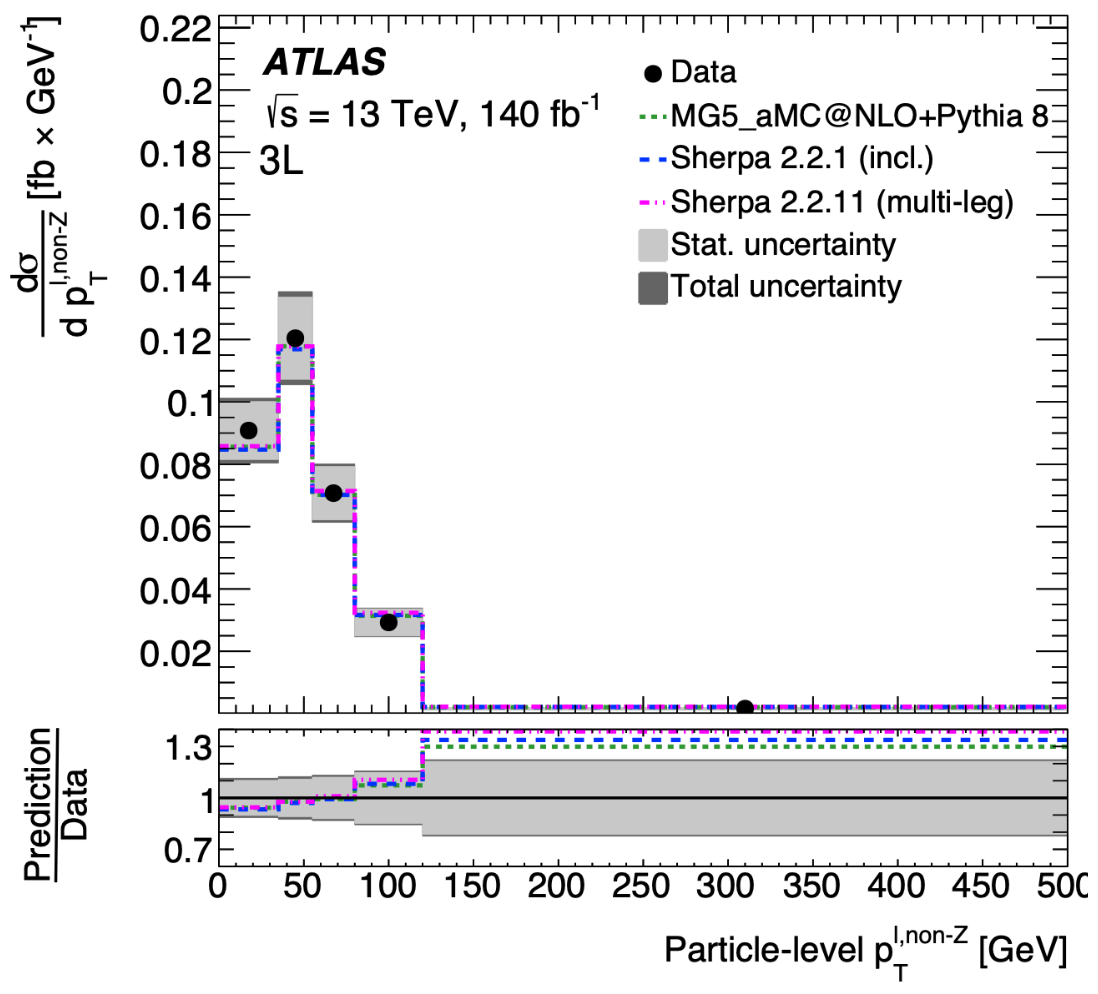
JHEP 02 (2025) 177
arXiv:2410.23475

- Inclusive and differential measurements of $\mathbf{t\bar{t}Z}$ and **tZq** with Run 2 by both ATLAS and CMS exist for a few years

- Evidence for **tWZ** reported by CMS

- Simultaneous measurement:
    - less dependent on signal modelling assumptions,
    - consistently treat correlations between systematic uncertainties
    - ✦ enhance sensitivity to deviations from SM that affect all processes (e.g. anomalous **tZ**, **tbW** couplings)

JHEP 07 (2024) 163



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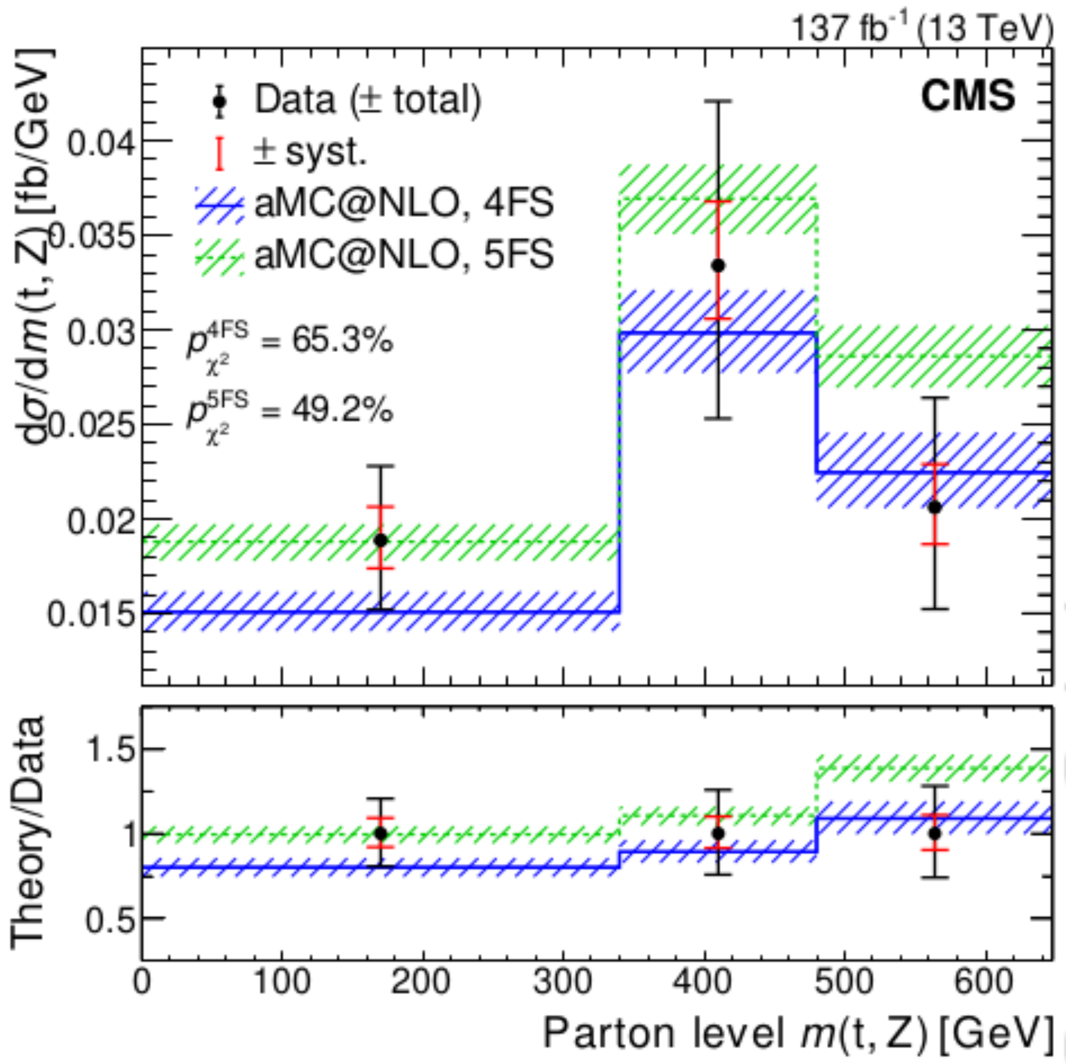

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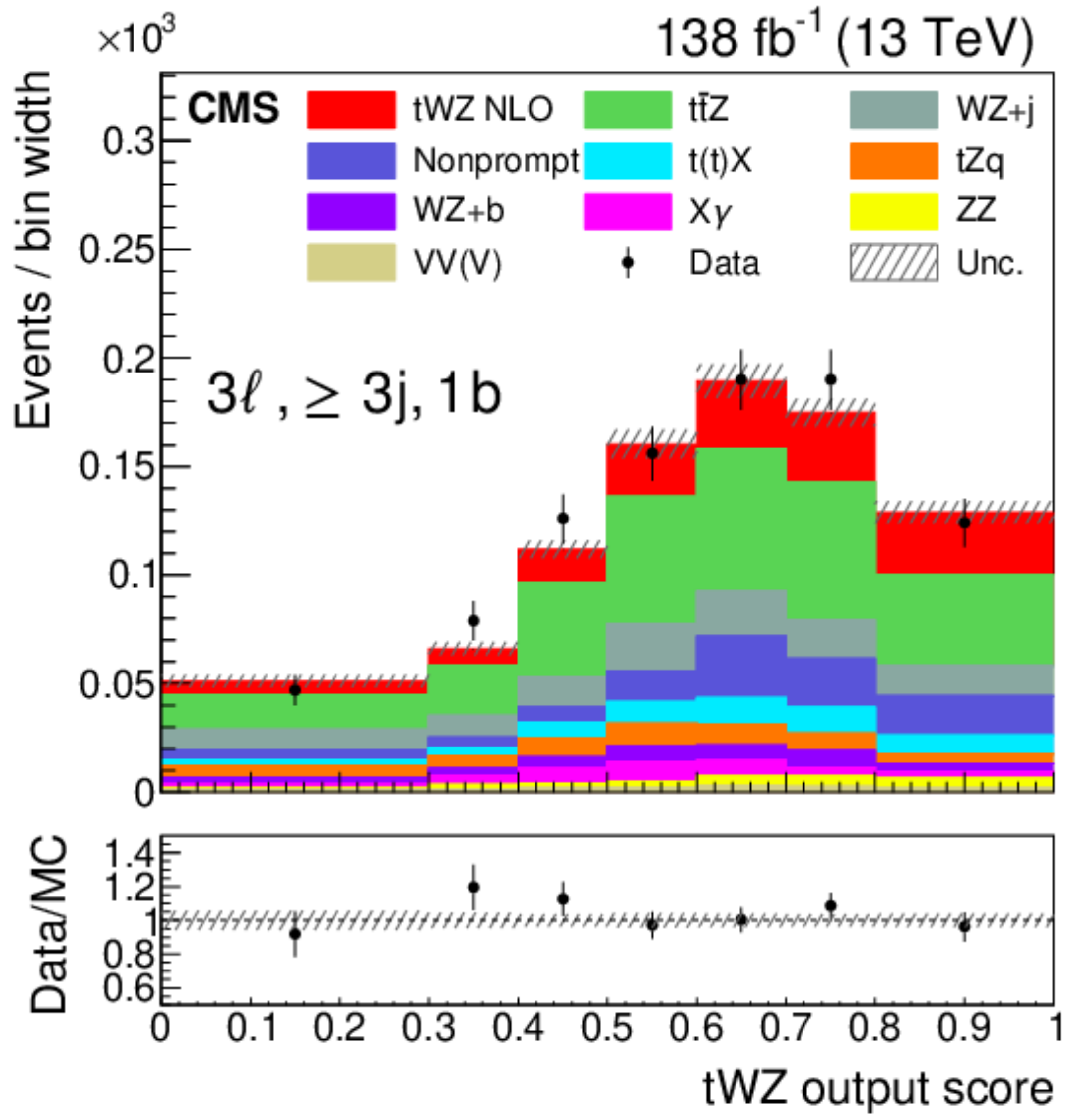
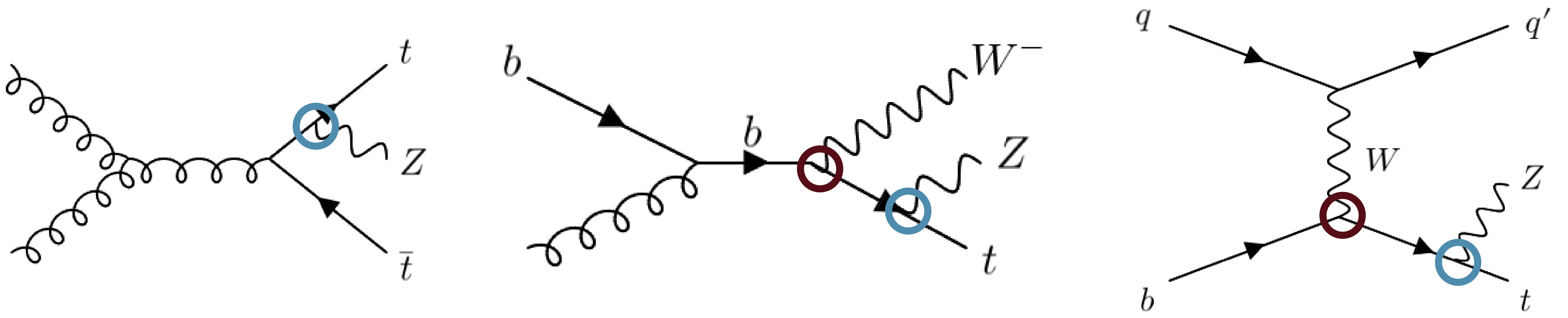


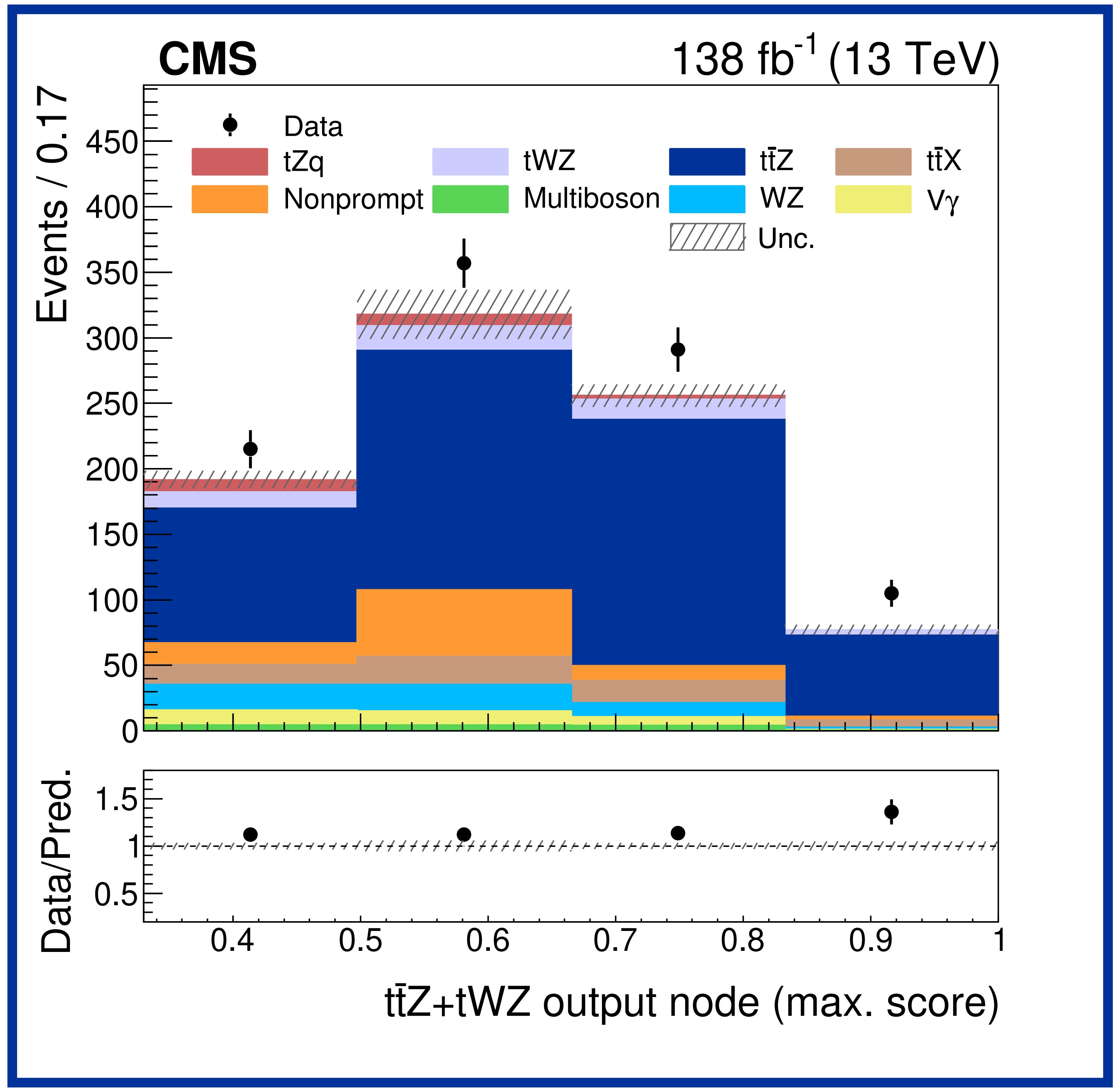


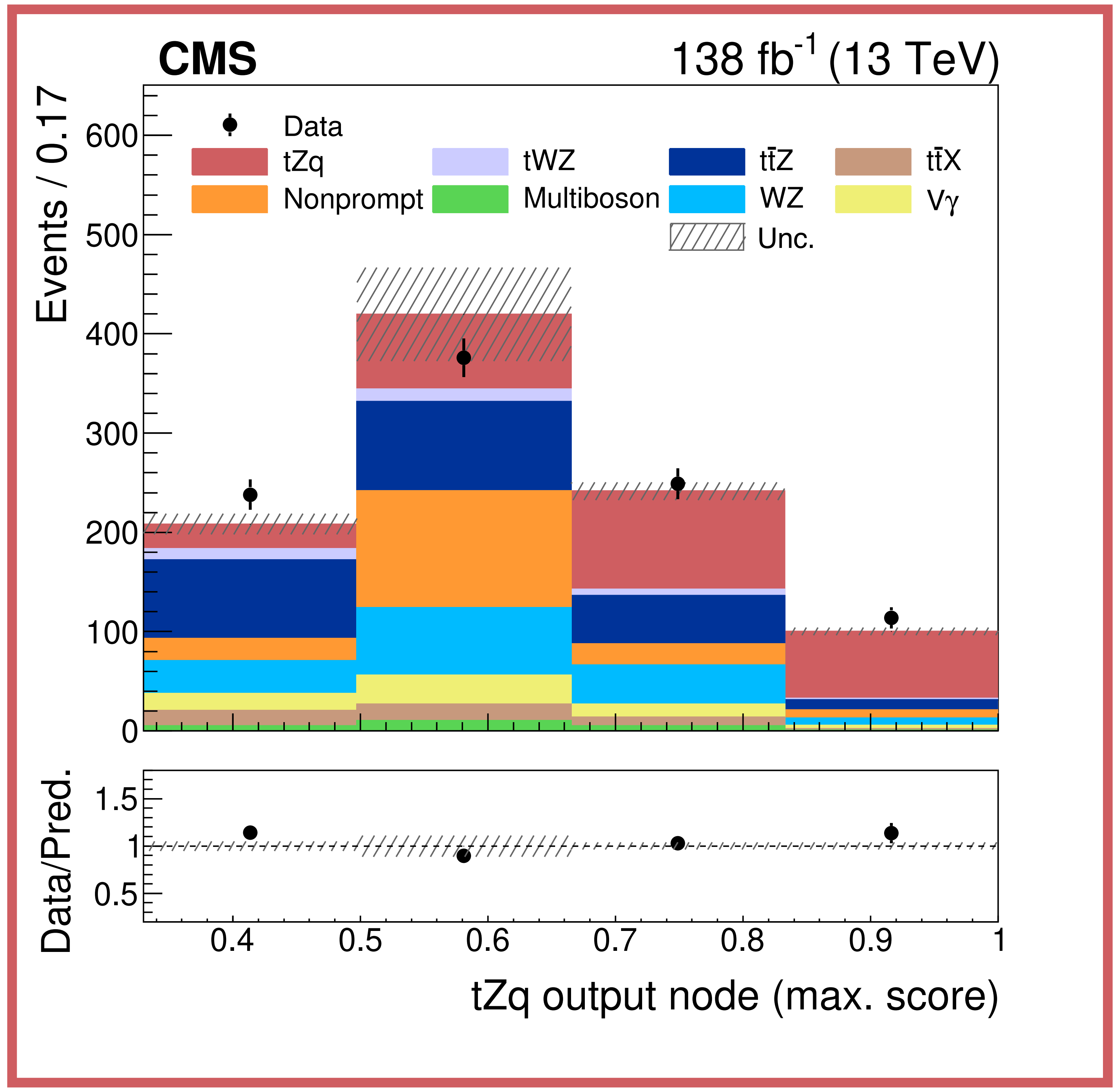
Interference between ttZ and tWZ - treated as one signal!

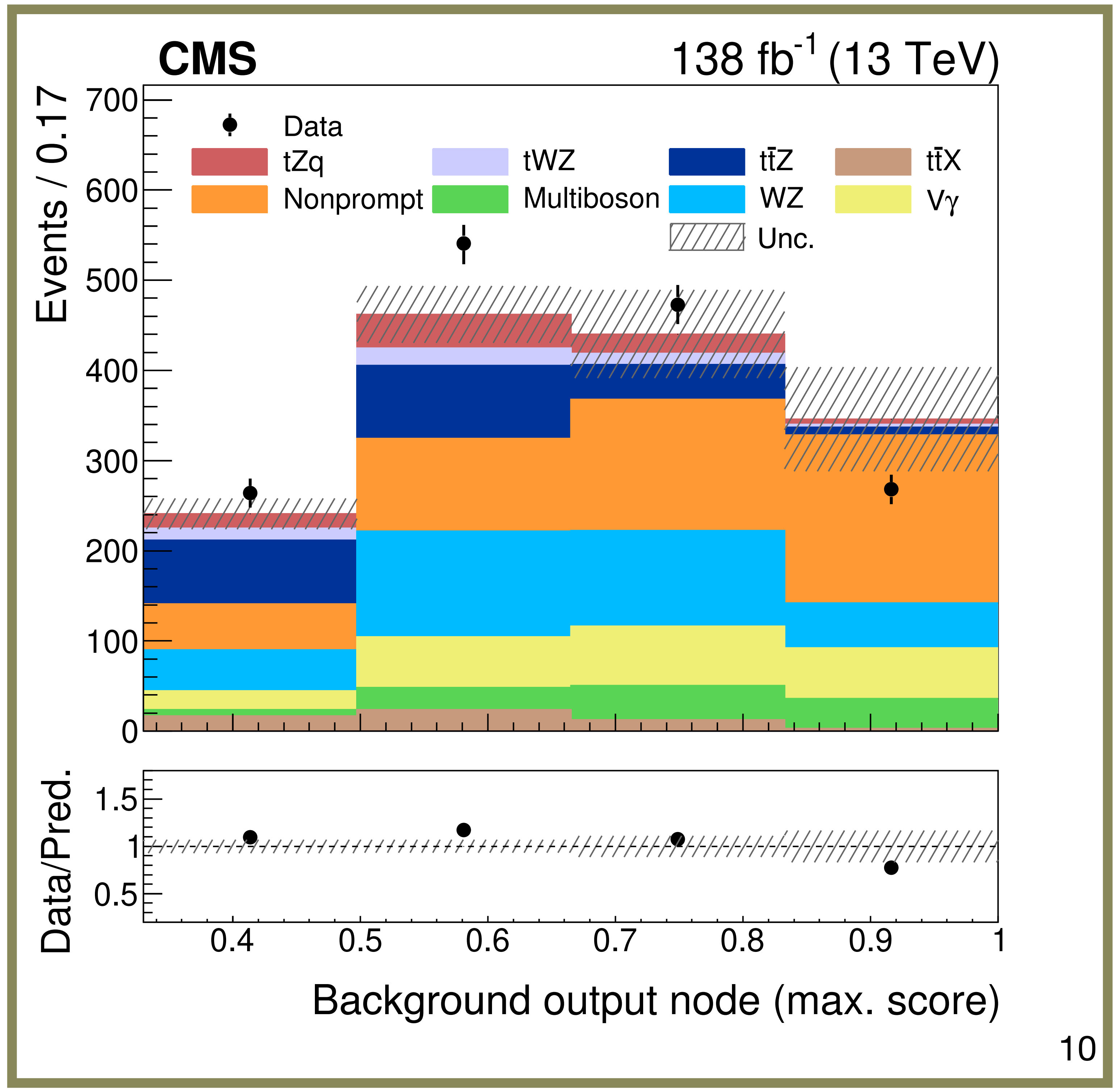
Selection strategy for $t\bar{t}Z$, tWZ, and tZq

JHEP 02 (2025) 177
arXiv:2410.23475

- Signal region with three leptons (e or μ), $\geq$2 jets, $\geq$1 b-tagged jet
- **Nonprompt lepton contribution** is estimated from data, **WZ** and other smaller backgrounds from simulation
- Neural network (multi-class classifier) to disentangle different signals and backgrounds
  - 3 output nodes for **$t\bar{t}Z$+tWZ**, **tZq**, and **background** (maximum-score splitting to build fit categories)







Inclusive measurement

- Simultaneous fit to 3 max-score output nodes in SR and number of jets / b jets in two extra regions - 4 leptons ($t\bar{t}Z$ enriched), and no b jets (WZ enriched)

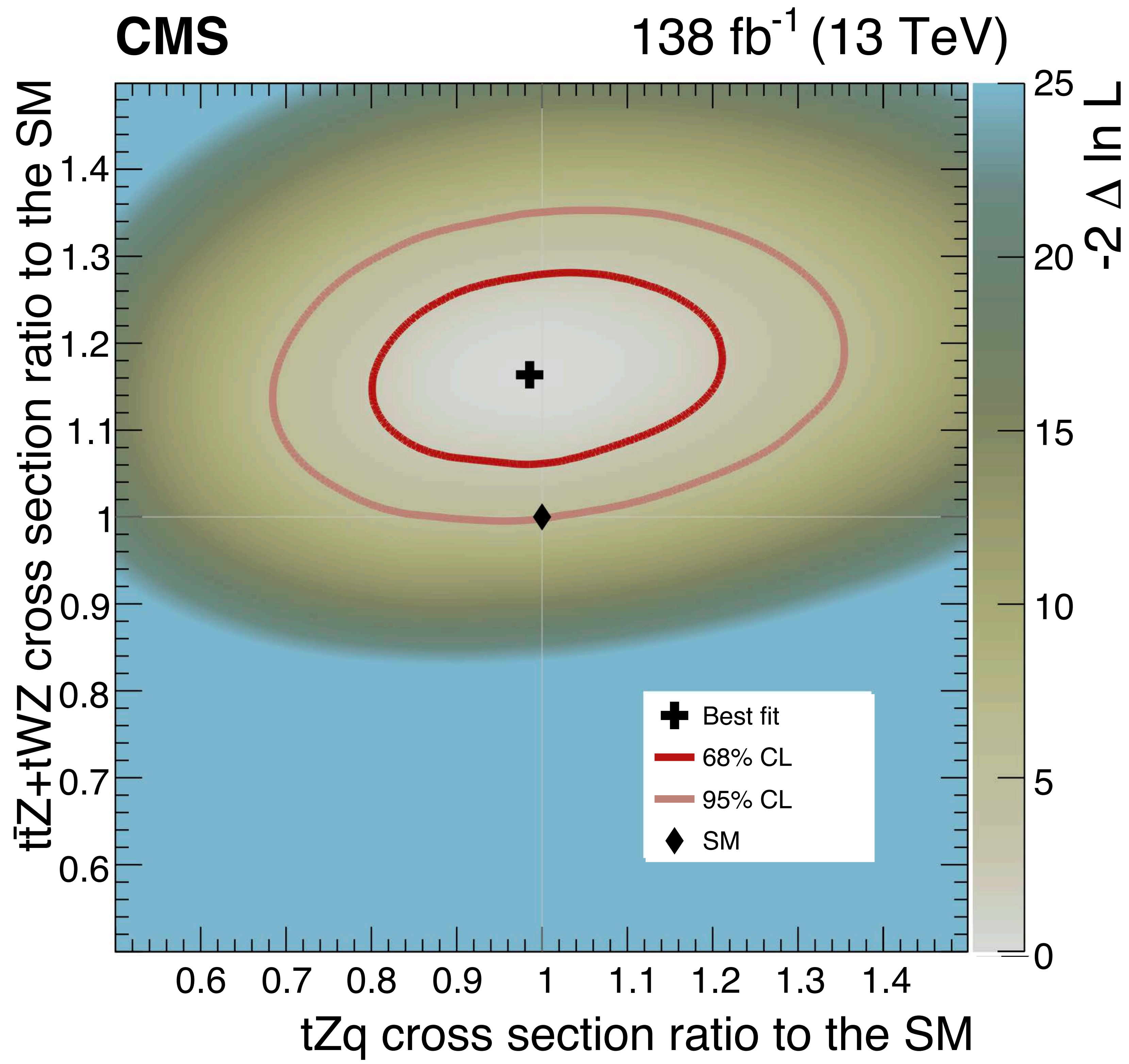
- Profiled likelihood-ratio scan for $\sigma_{t\bar{t}Z+tWZ}$ and σ_{tZq}

- Limited by statistics, main syst. uncertainties on background modelling and b tagging

- Inclusive cross sections measured to be:

$$\sigma_{t\bar{t}Z+tWZ} = 1.14 \pm 0.07 \text{ pb}$$

$$\sigma_{tZq} = 0.81 \pm 0.10 \text{ pb}$$



consistent with SM for tZq, slight excess for $t\bar{t}Z$+tWZ

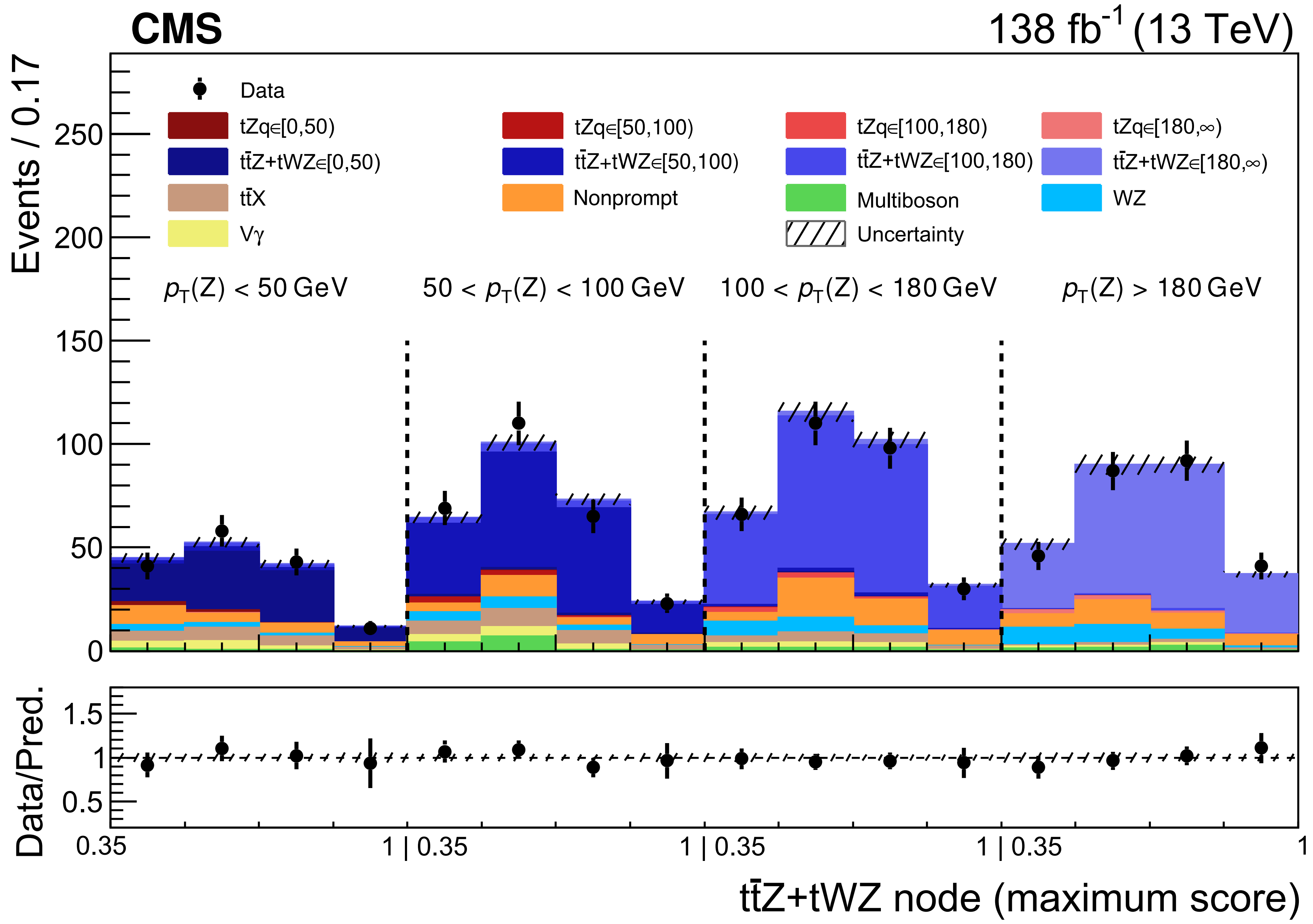
- Fixing the $t\bar{t}Z$ (tWZ) and tZq processes to the SM prediction yields a tWZ ($t\bar{t}Z$) cross section consistent with previous measurements

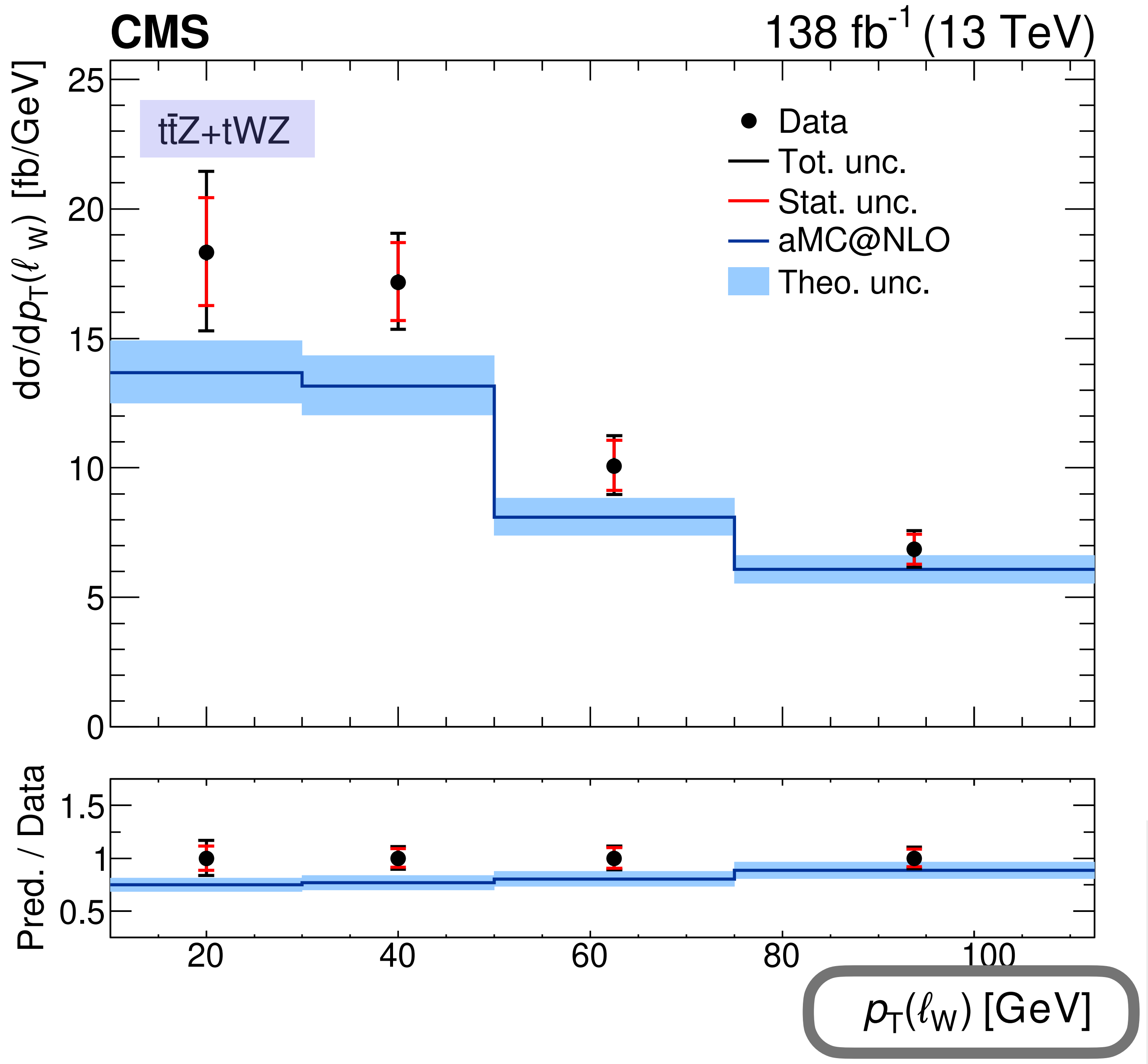
Compatible with the previous measurements

Differential measurements

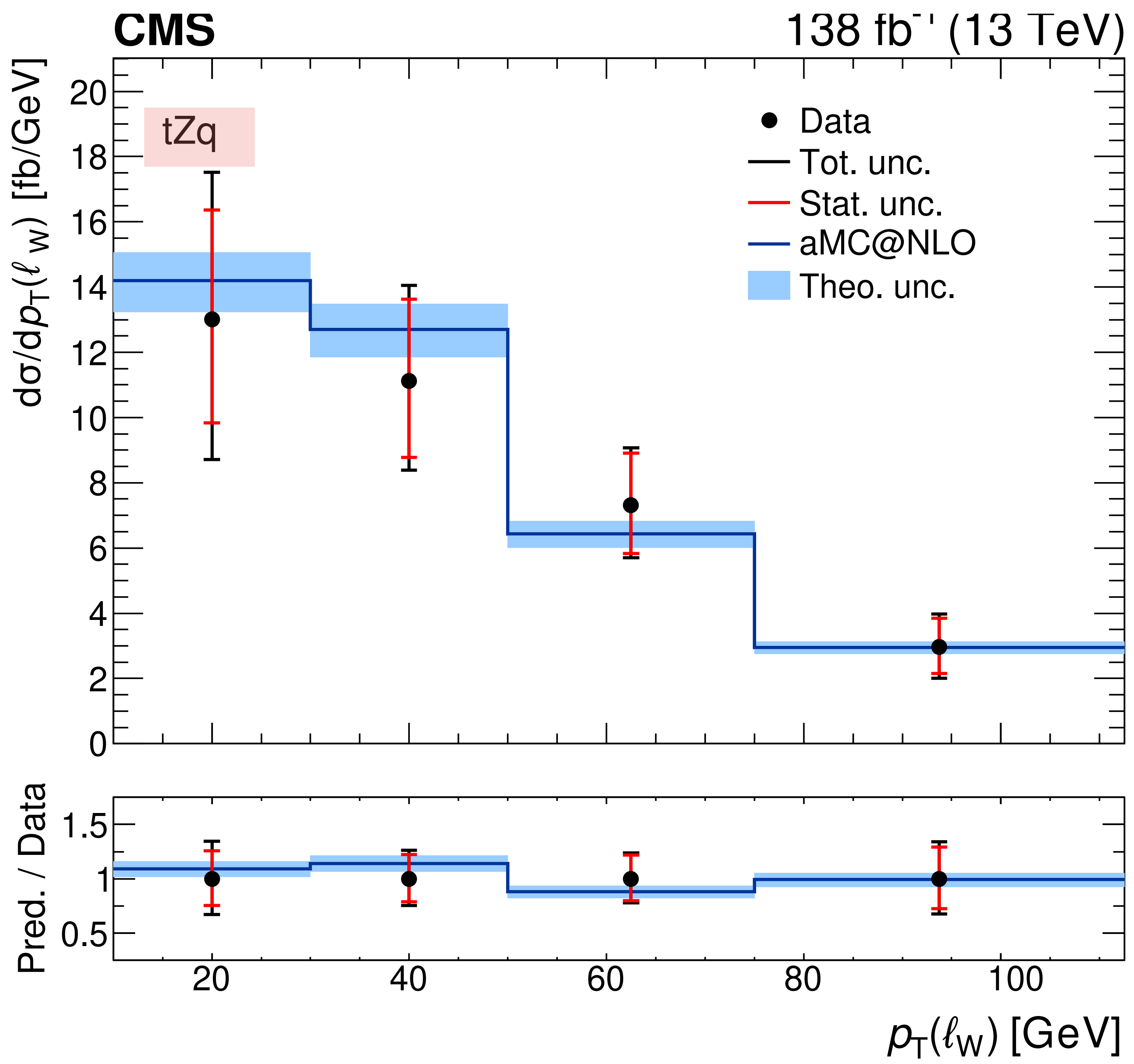
JHEP 02 (2025) 177
arXiv:2410.23475

- Cross sections measured as function of lepton and Z observables
- Maximum likelihood unfolding





p_T of the lepton from the W



- Measurements compared to predictions from aMC@NLO
- Good agreement overall for tZq, slight excess for tt̄Z+tWZ

First simultaneous measurement of these processes, useful for theory and EFT interpretations

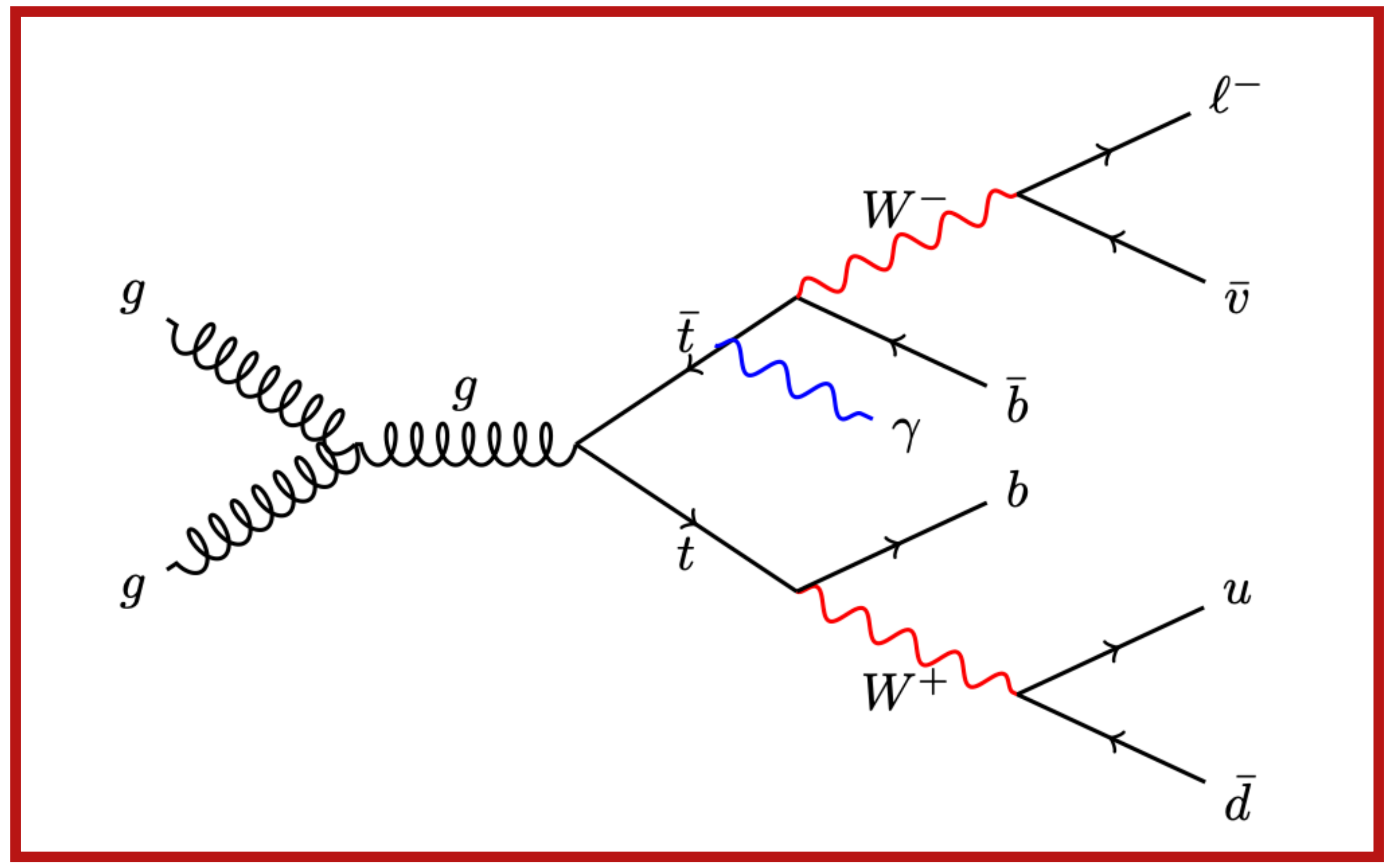
Inclusive cross section measurements of $t\bar{t}\gamma$

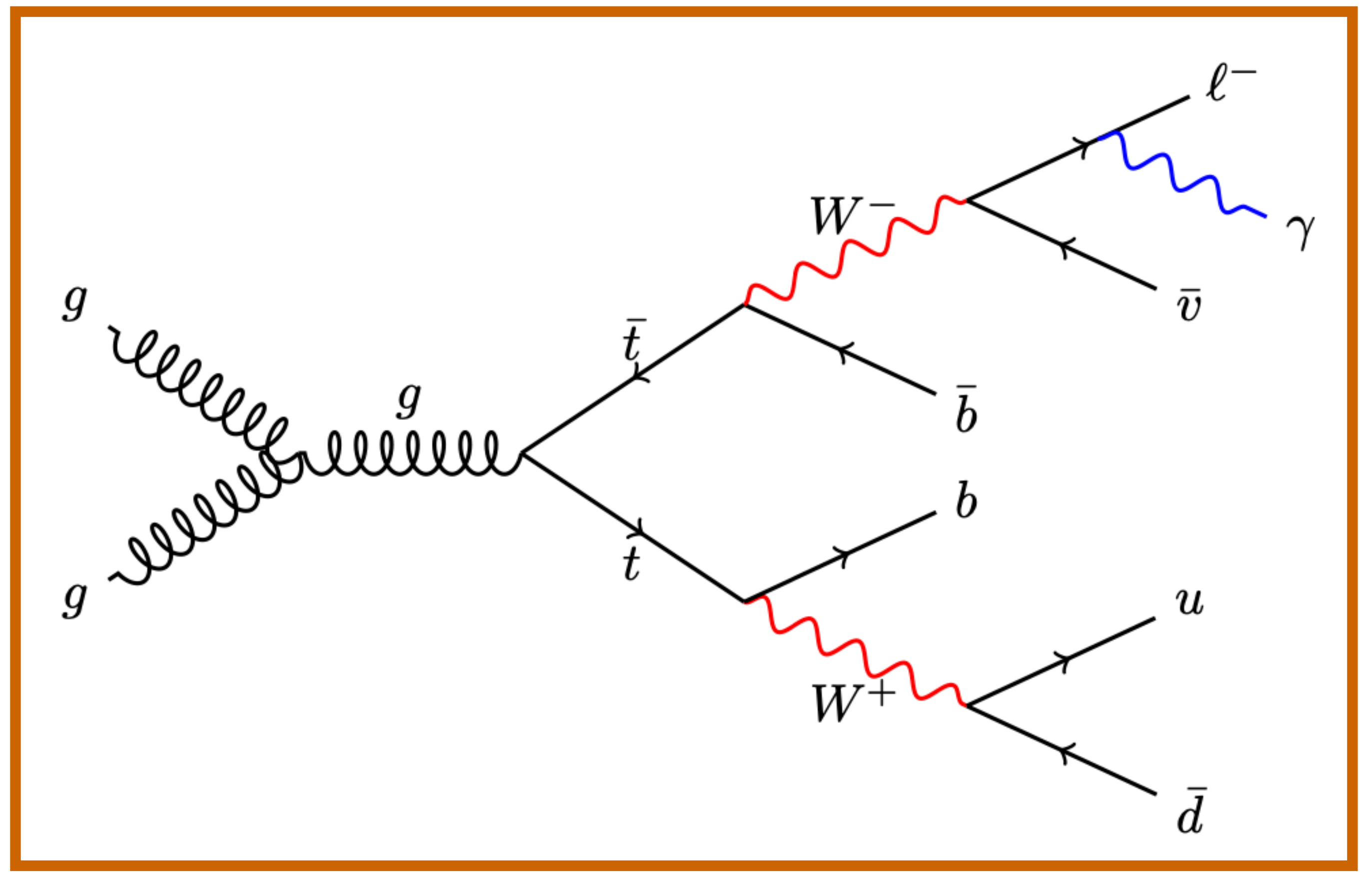
PAS-TOP-23-002

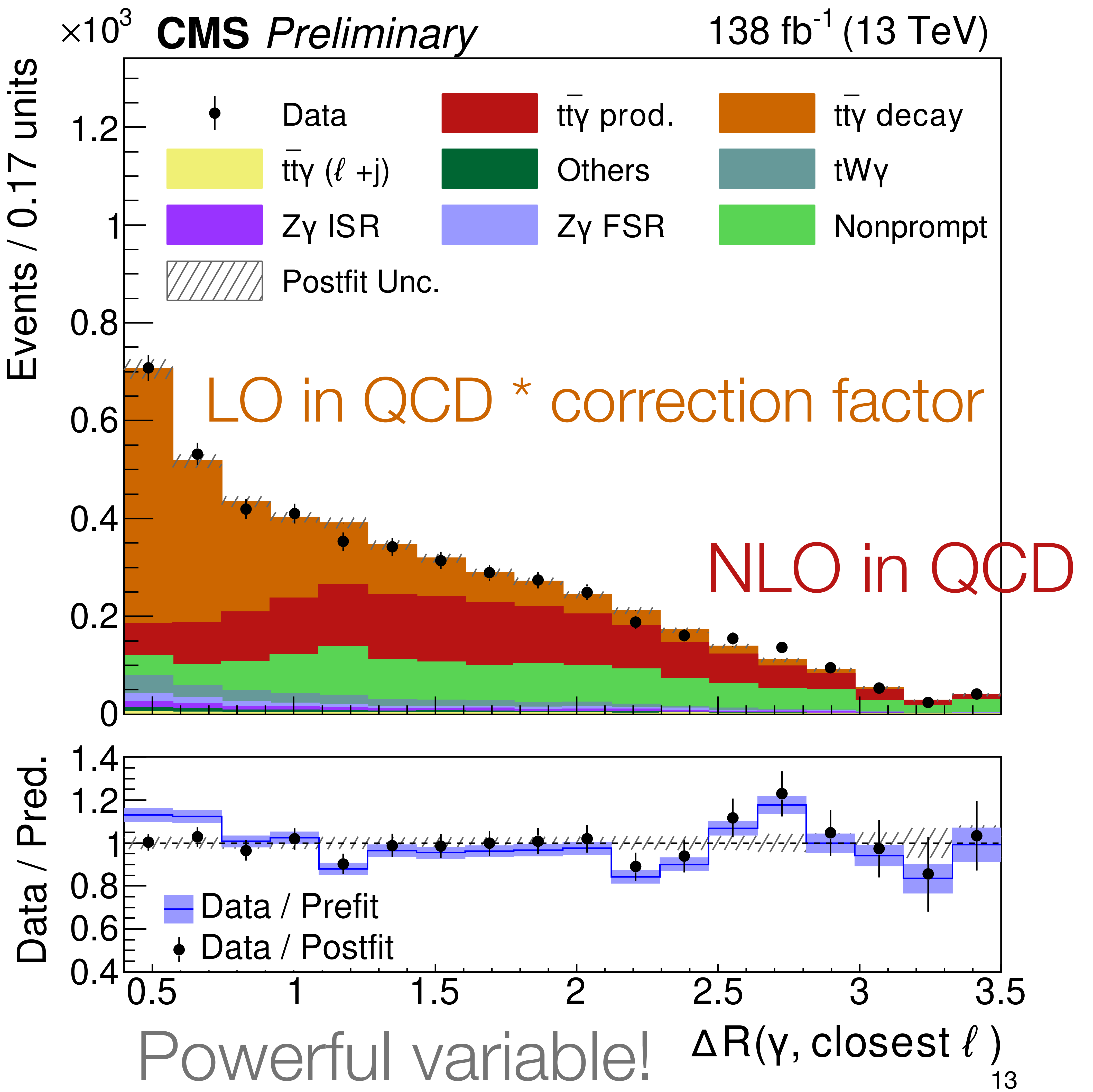
NEW!

- Top pair production in association with a photon has the **highest cross section of all top+V processes**
- Direct probe of the top-photon coupling
- Challenging from the modelling perspective

$t\bar{t}\gamma$ 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





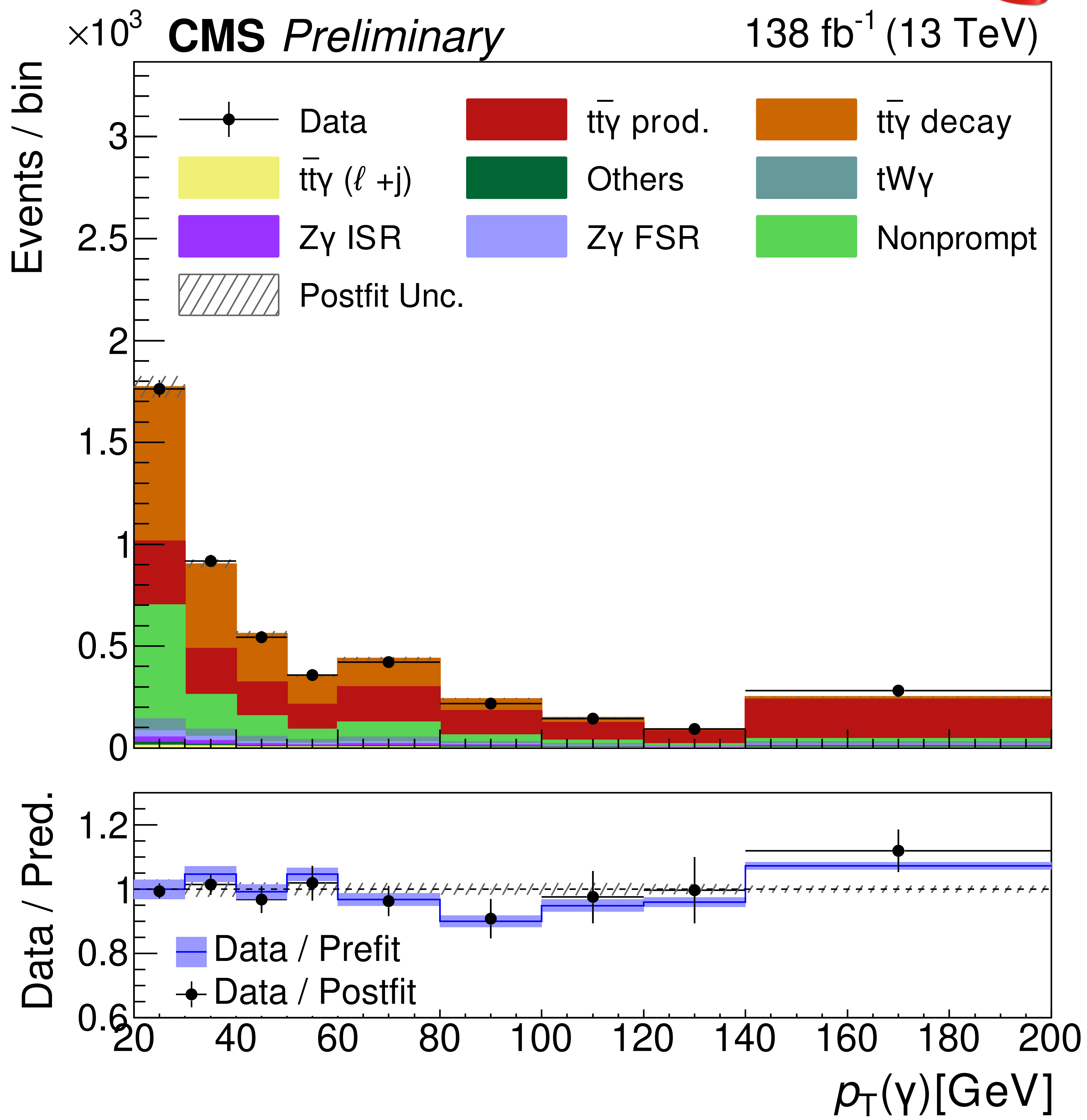


Powerful variable!

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

NEW!

- Focus on dilepton channel
- $t\bar{t}\gamma$ **production** modeled at NLO in QCD and $t\bar{t}\gamma$ **decay** at LO
- Measuring also total **fiducial** $t\bar{t}\gamma$ cross section (**production**+**decay**)
- **Fake photon** contribution estimated with data-driven methods
- Fit to min. $\Delta R(\gamma, \ell)$ including all systematic uncertainties
- Measure **σ($t\bar{t}\gamma$ production) = 134 ± 2 (stat) ± 4 (syst) fb (5.0%)**
  - In agreement with prediction of **123 ± 17 fb** (MadGraph5_aMC@NLO)
  - Limited by systematic uncertainties, mainly normalisation of the nonprompt background, γ identification, normalization of the $t\bar{t}\gamma$ decay, jet and b tagging



Fiducial phase space	Photon	Leptons	Jets
Number	==1	>=2	>=2, >=1 b
pT (GeV)	>20	>15	>30
$\lvert\eta\rvert$	<2.5	<2.5	<2.4
Others	Not from hadrons	Not from hadrons, isolated from photons	Isolated from photons and leptons

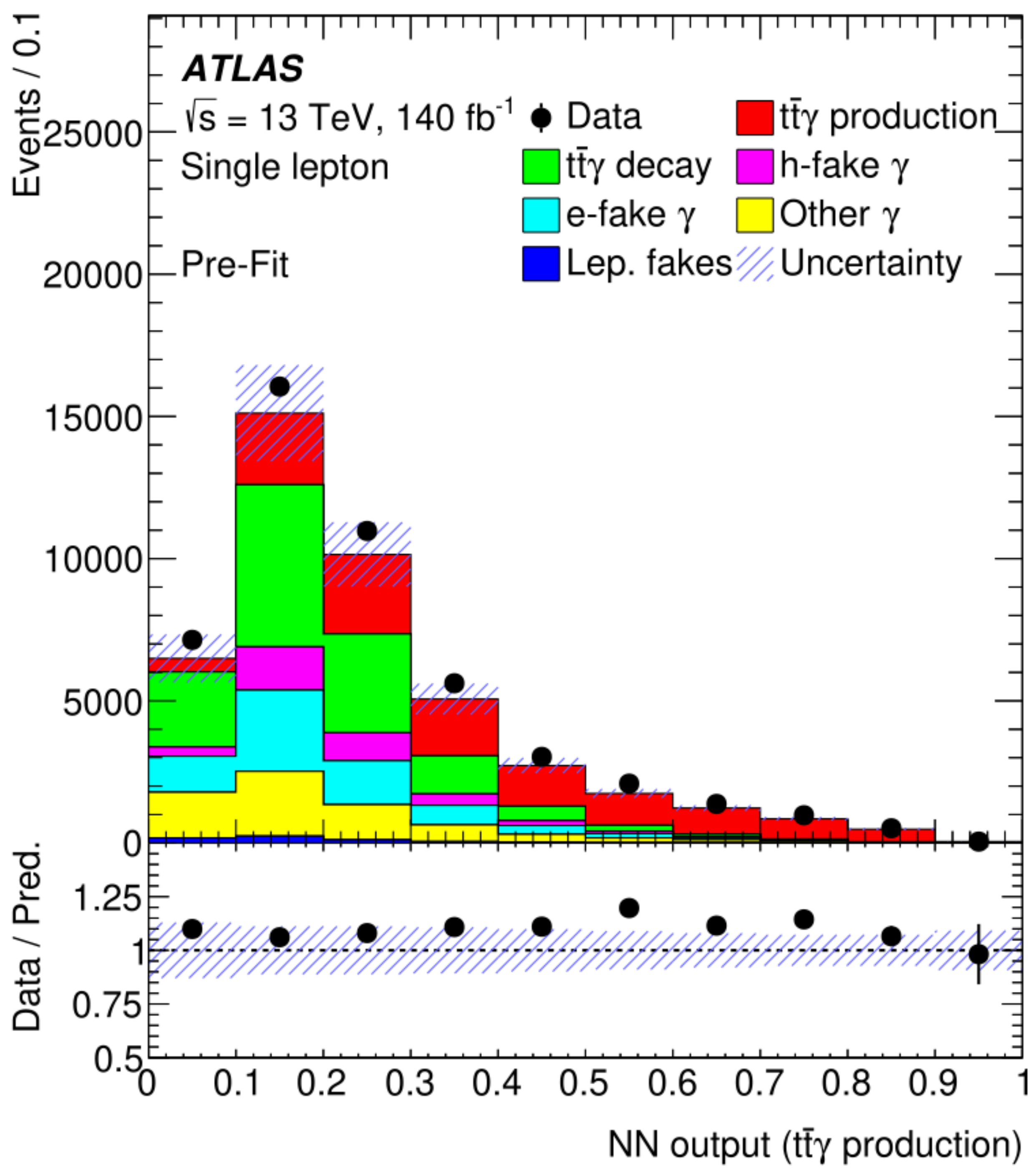
Inclusive cross section measurements of $t\bar{t}\gamma$

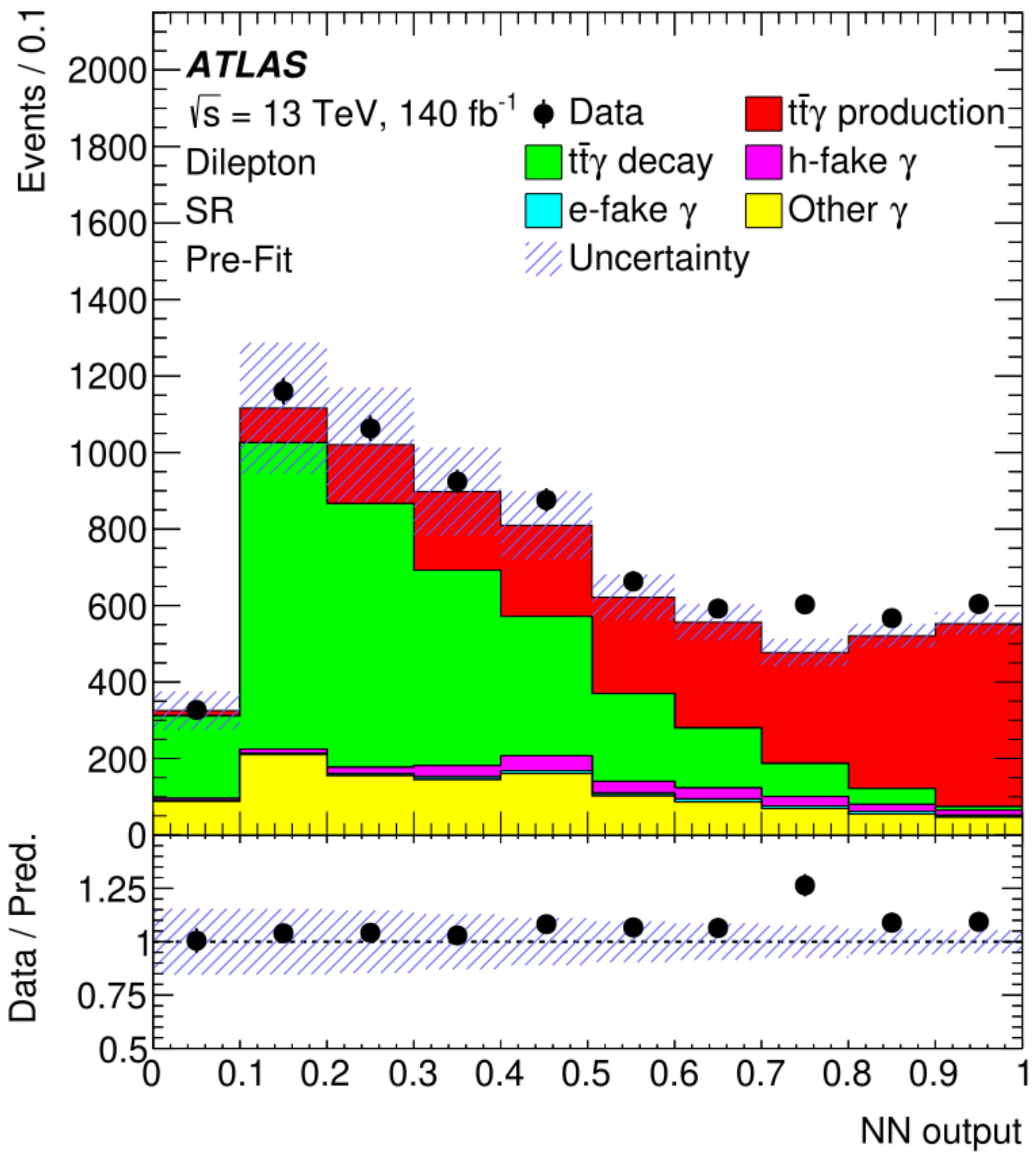
Now published
JHEP 10 (2024) 191
arXiv:2403.09452v2

- 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

Different phase space from CMS – dilepton & l+jets

- Measure **$\sigma(t\bar{t}\gamma$ 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





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

PAS-TOP-23-002

NEW!

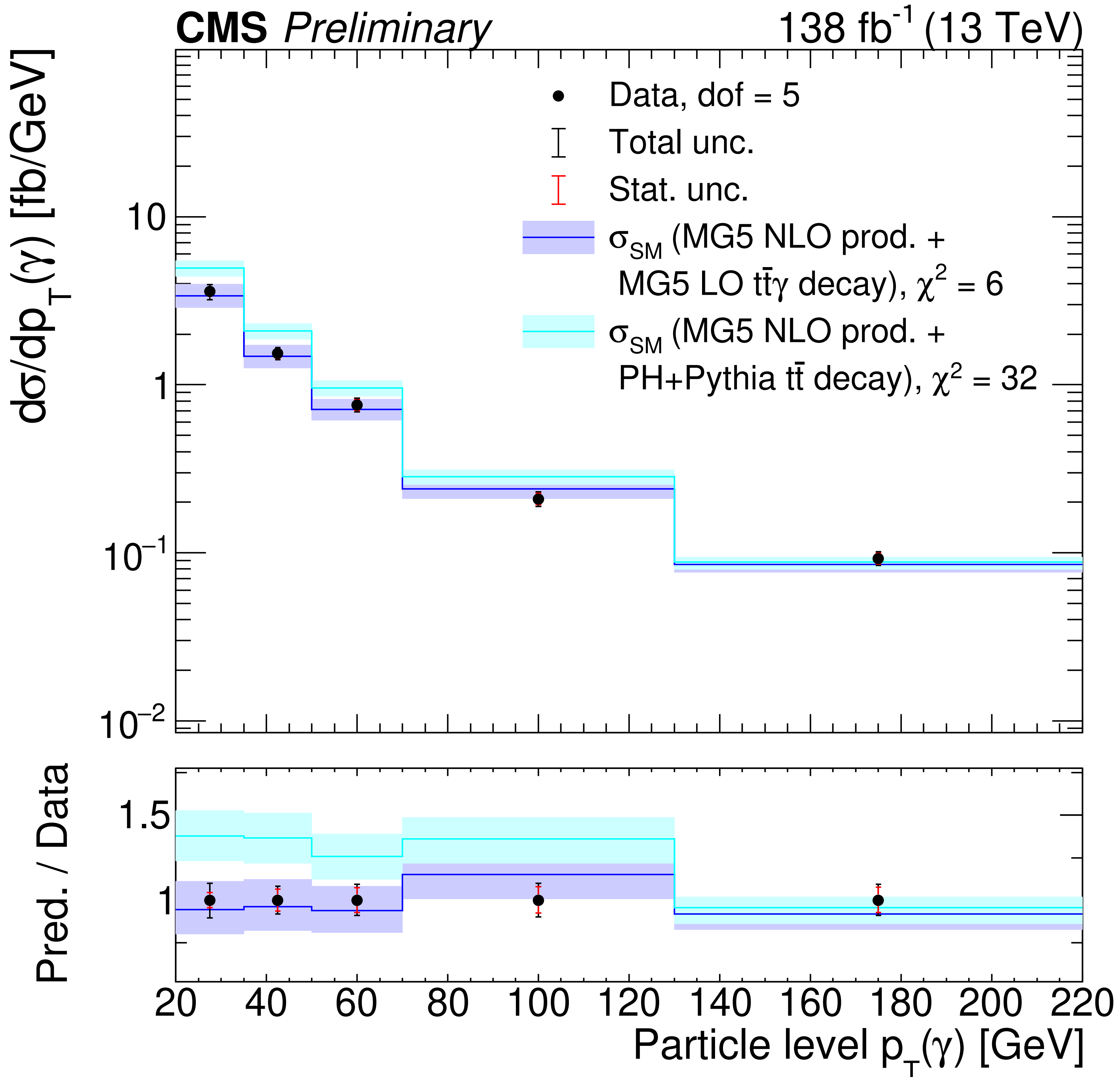
- Objects defined at
  - **Particle level** (final state objects, phase space mimics detector acceptance)
  - **Parton level** (intermediate particles before showering and hadronization, broad phase space)
- Observables: $p_T(\gamma)$, p_T(lepton), angular distance between leptons, **p_T(top), $m(t\bar{t})$, angular distances between photon and top/$t\bar{t}$**
- **Top/$t\bar{t}$ variables are being measured for the first time in this process**
- Normalised and absolute cross sections measured for production+decay

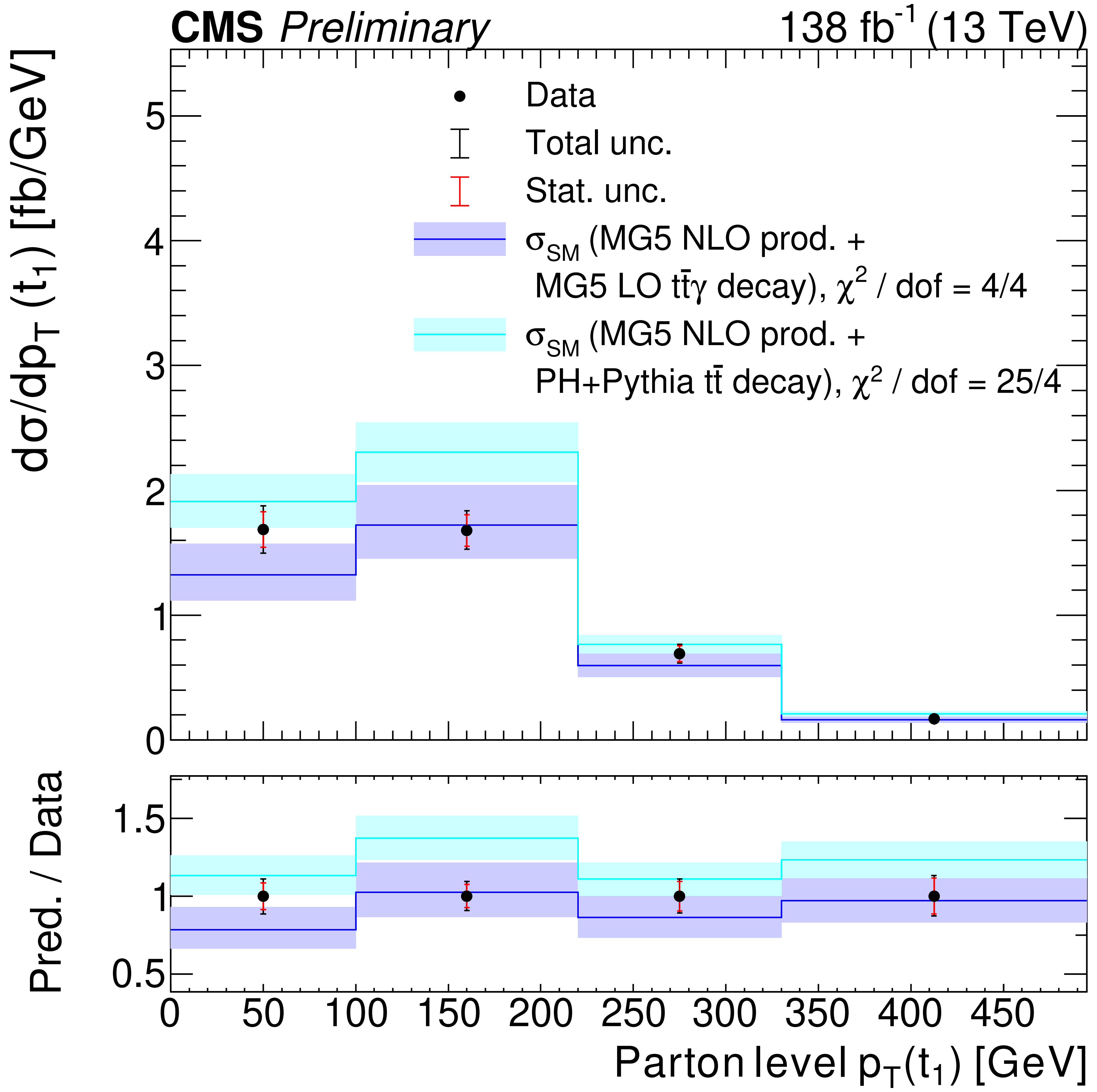
Differential cross section measurements of $t\bar{t}\gamma$

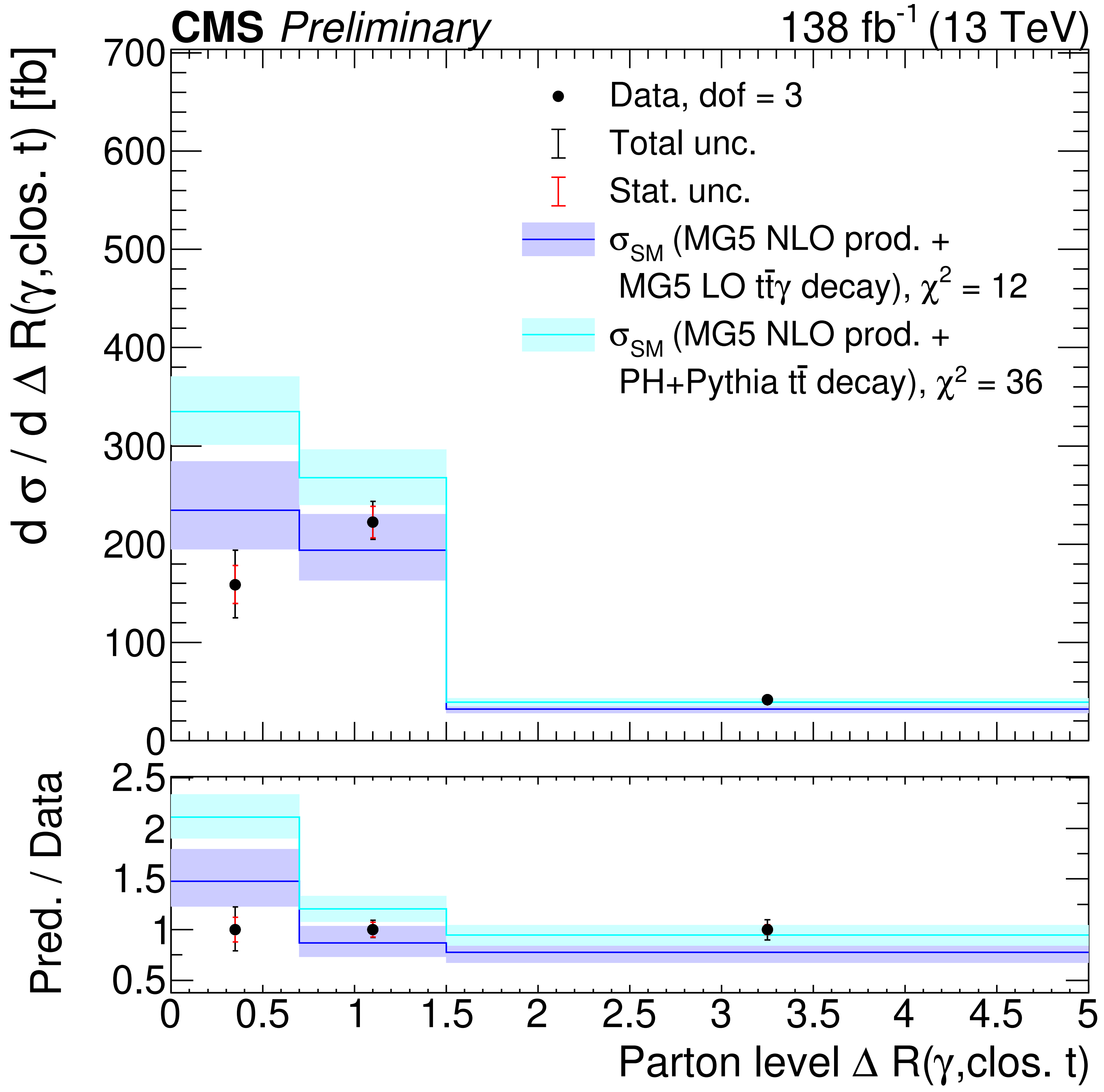
PAS-TOP-23-002

NEW!

- Compare to: **NLO $t\bar{t}\gamma^{prod}$ + LO ME $t\bar{t}\gamma^{decay}$** **NLO $t\bar{t}\gamma^{prod}$ + NLO $t\bar{t}$ PS ^{decay}**





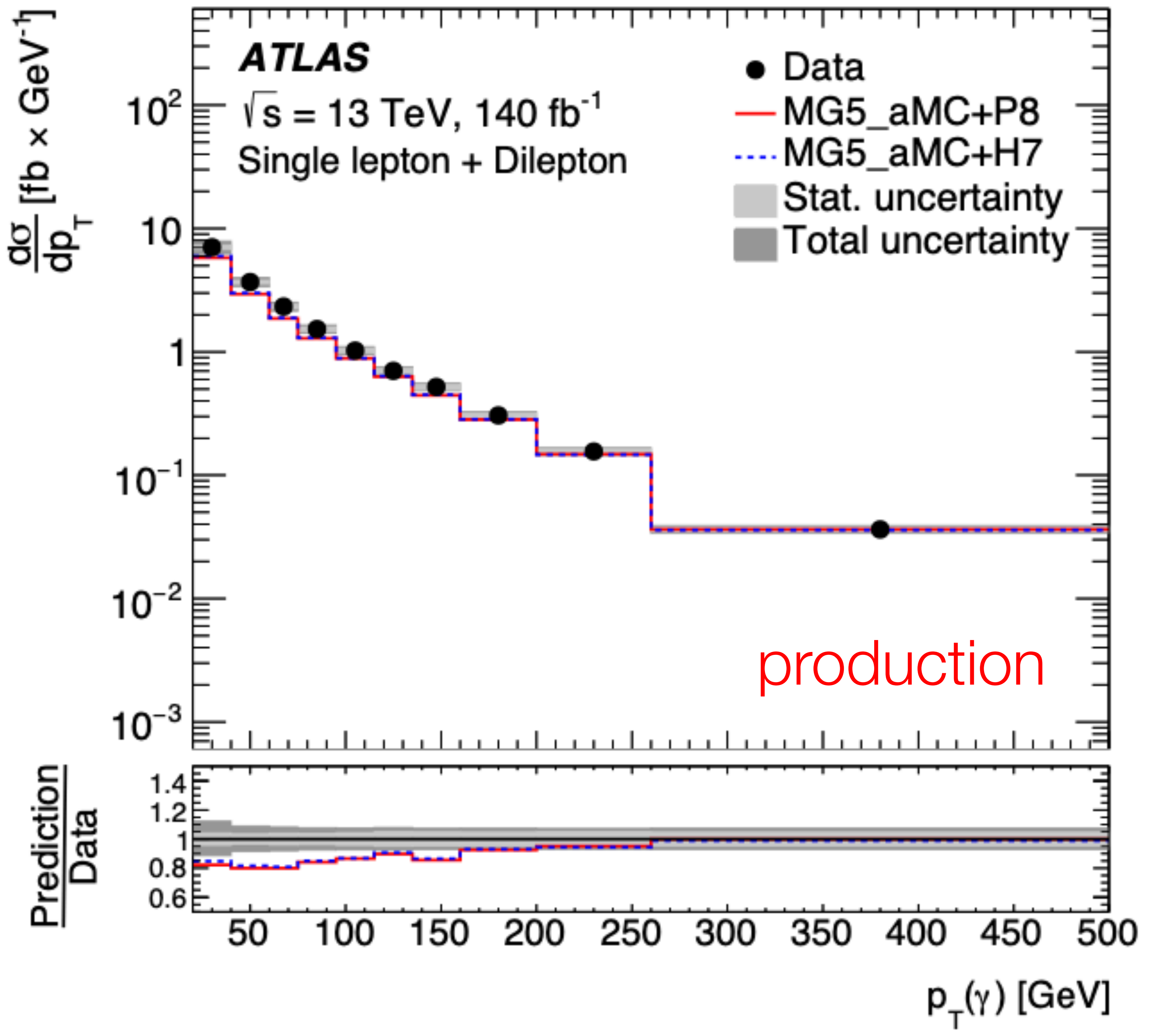


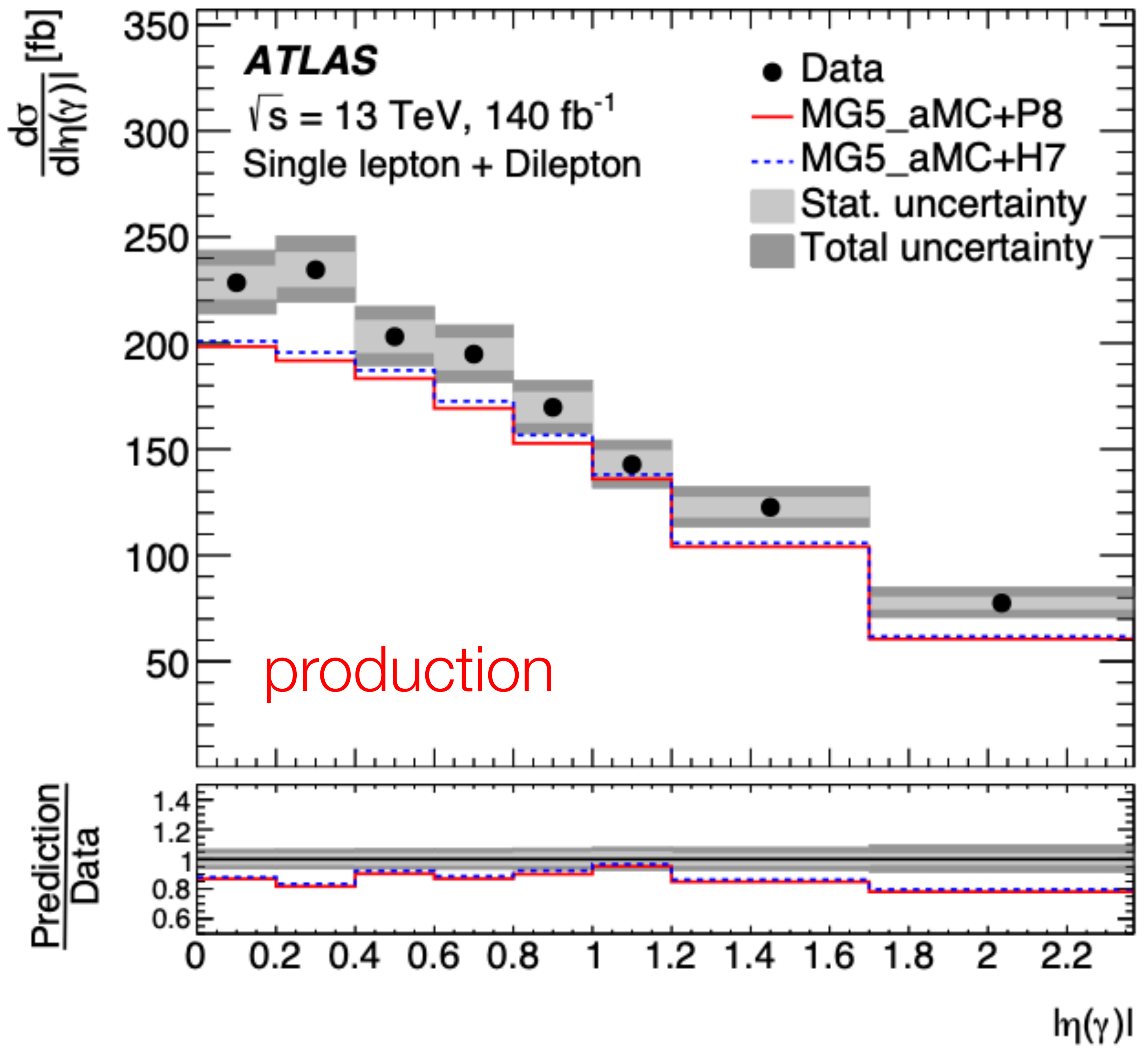
Momenta well described by simulation, angular variables show some trends

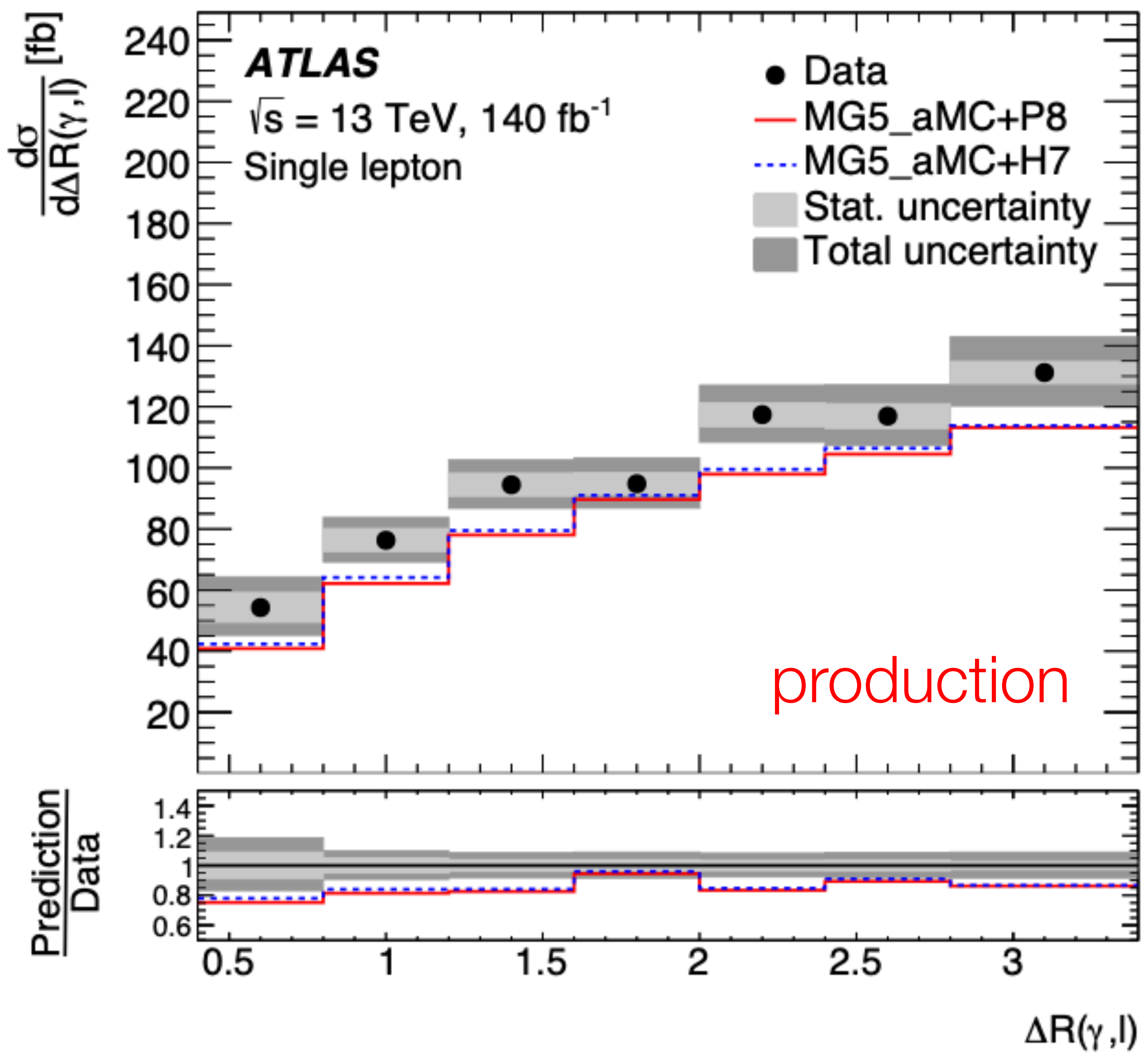
Differential cross section measurements of $t\bar{t}\gamma$

JHEP 10 (2024) 191
arXiv:2403.09452v2

- 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





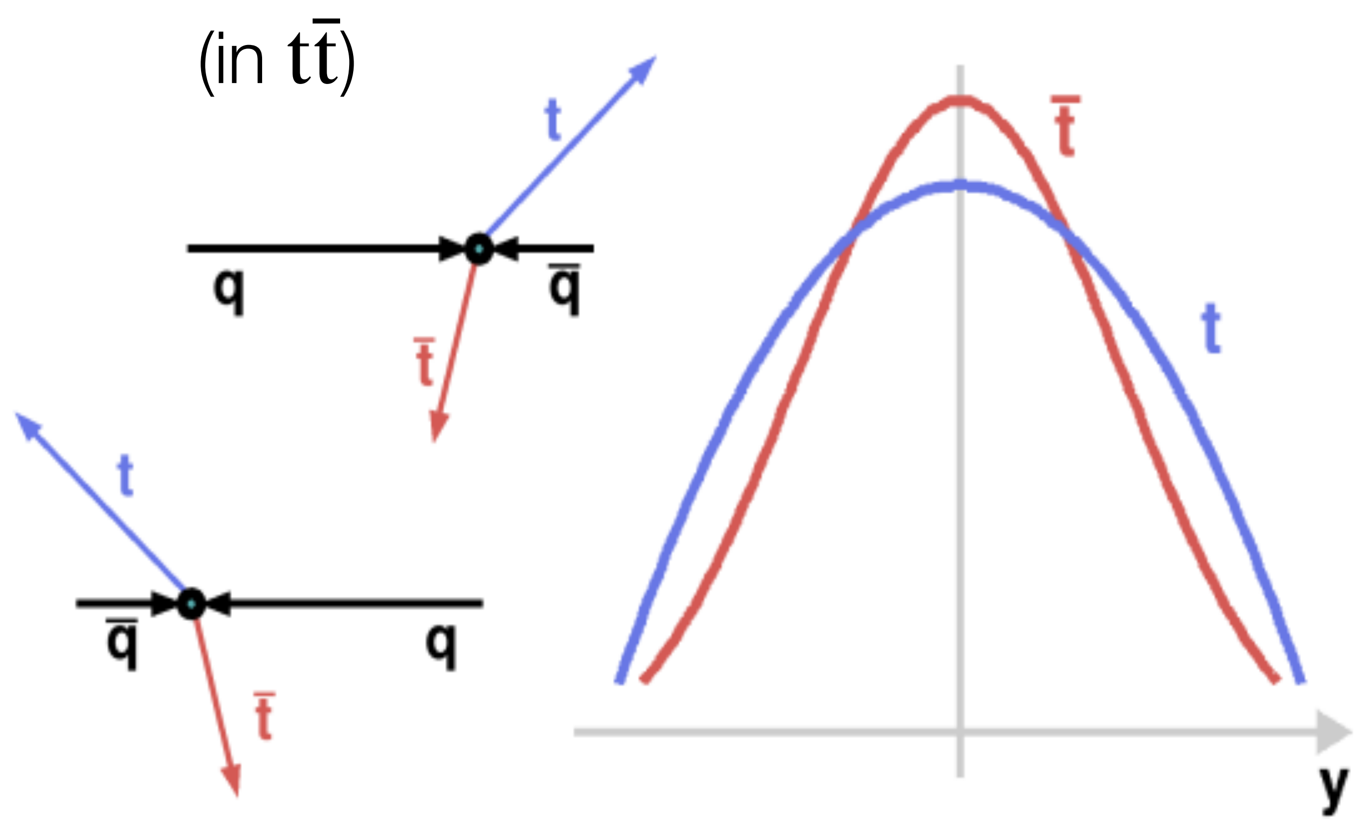


Top quark charge asymmetry using $t\bar{t}\gamma$ events

CMS PAS-TOP-23-002

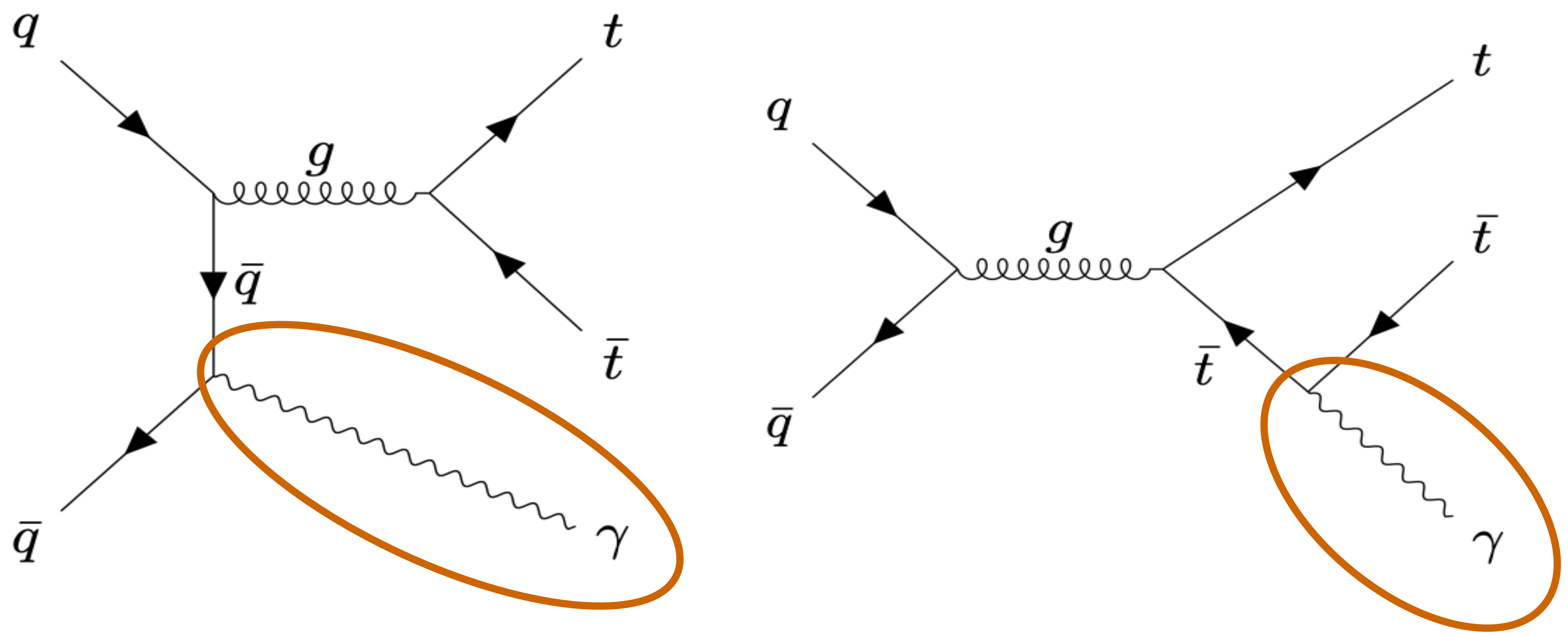
ATLAS Phys. Lett. B 843 (2023) 137848

- 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

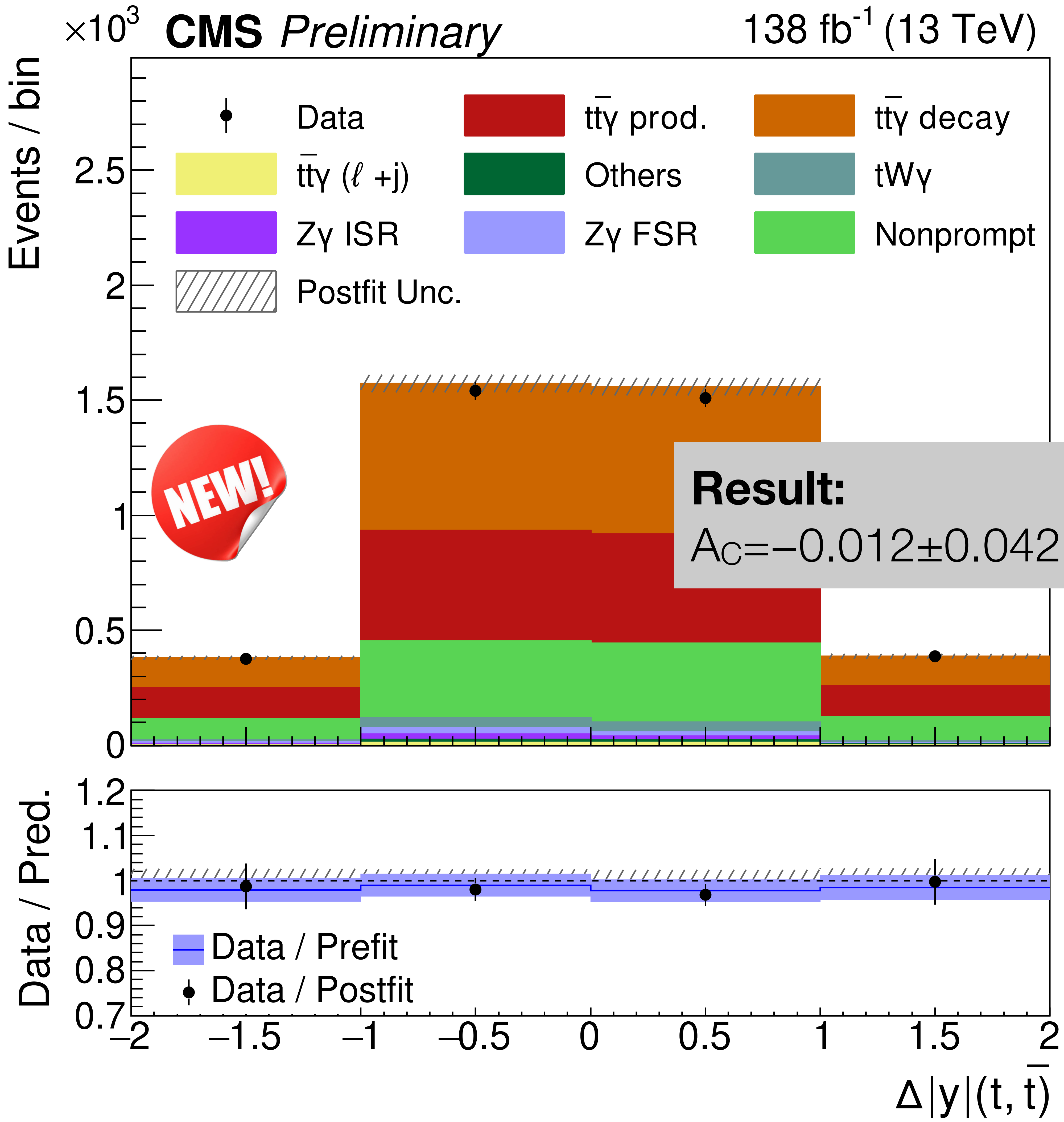


- Analysis strategy:
  - Similar modeling strategy as cross section measurements just reported
  - A_C extracted from fit to $|y(t)|-|y(\bar{t})|$

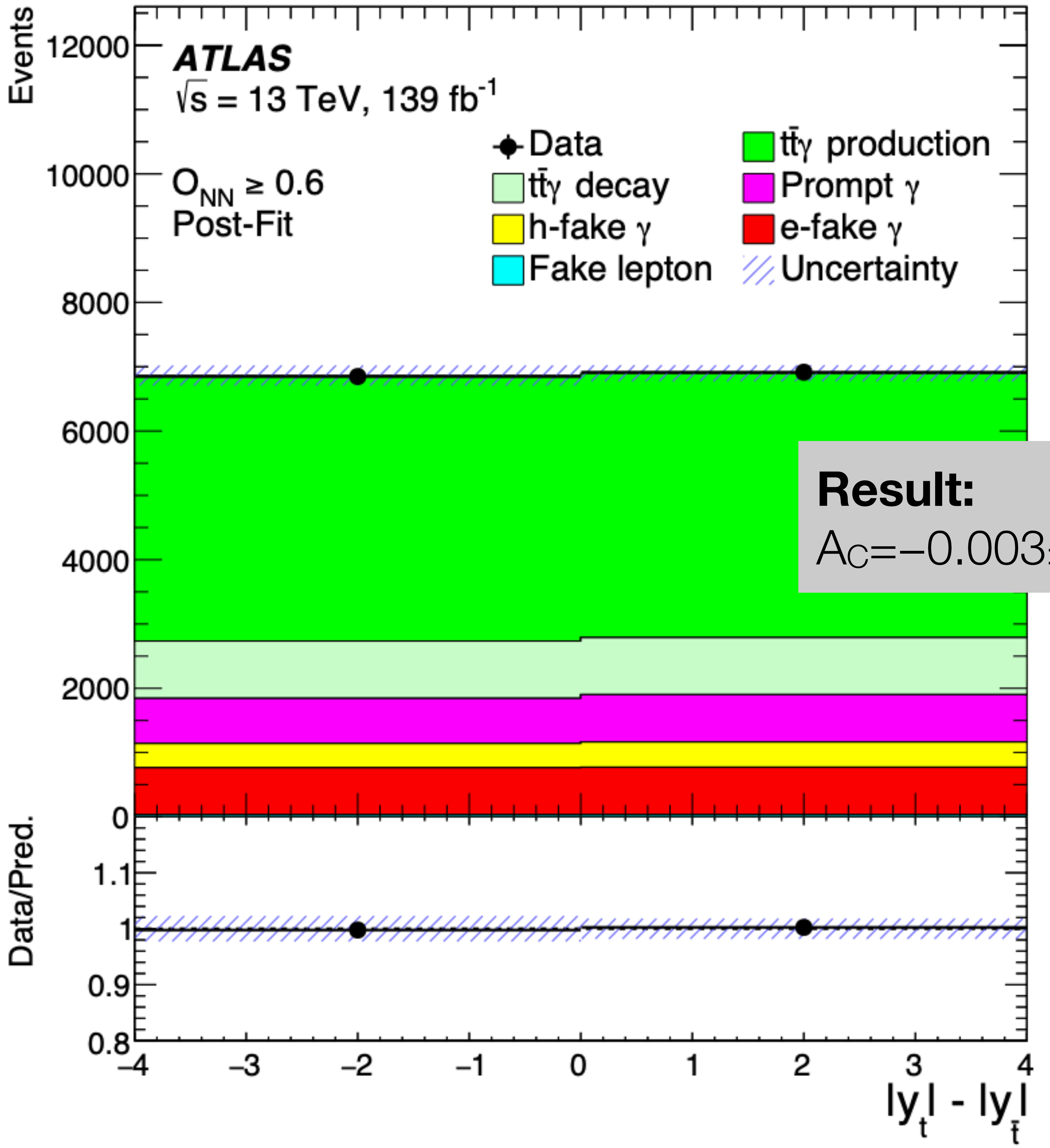
Top quark charge asymmetry using $t\bar{t}\gamma$ events

PAS-TOP-23-002

Phys. Lett. B 843 (2023) 137848



Result:
$A_C = -0.012 \pm 0.042$



Result:
$A_C = -0.003 \pm 0.029$

Both compatible with the SM and with no-asymmetry

(limited by statistical uncertainty)

First ever measurement of the $t\bar{t}\gamma/t\bar{t}$ ratio at the LHC

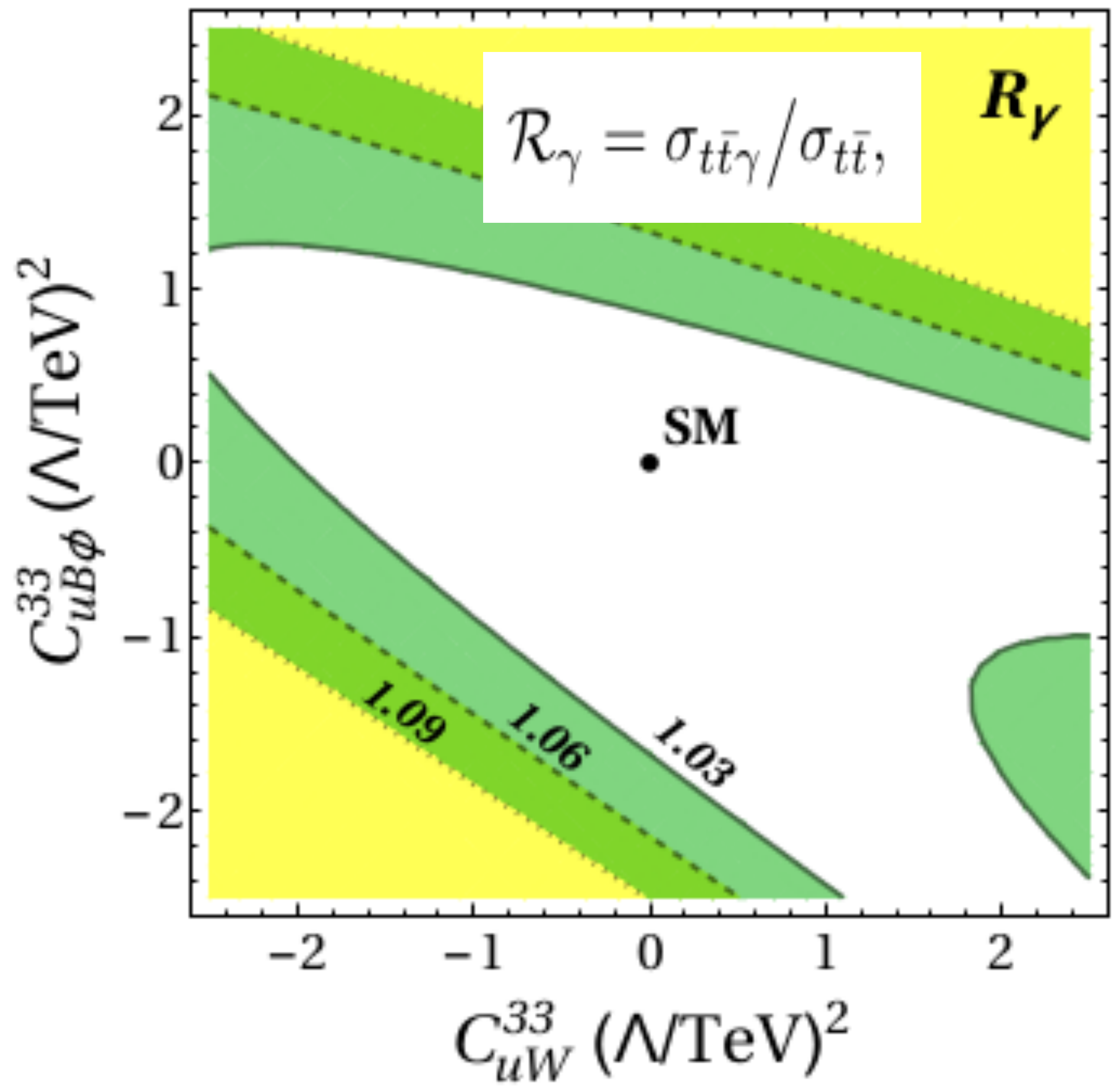
CMS PAS-TOP-23-002

- Measuring ratios between cross sections allows achieving higher precision
  - $t\bar{t}$ and $t\bar{t}\gamma$ are both QCD production - many systematics cancel out
  - Can be used to set limits on Effective Field Theory operators

inclusive

$$\mathcal{R} = \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}$$

arxiv:1603.08911v2

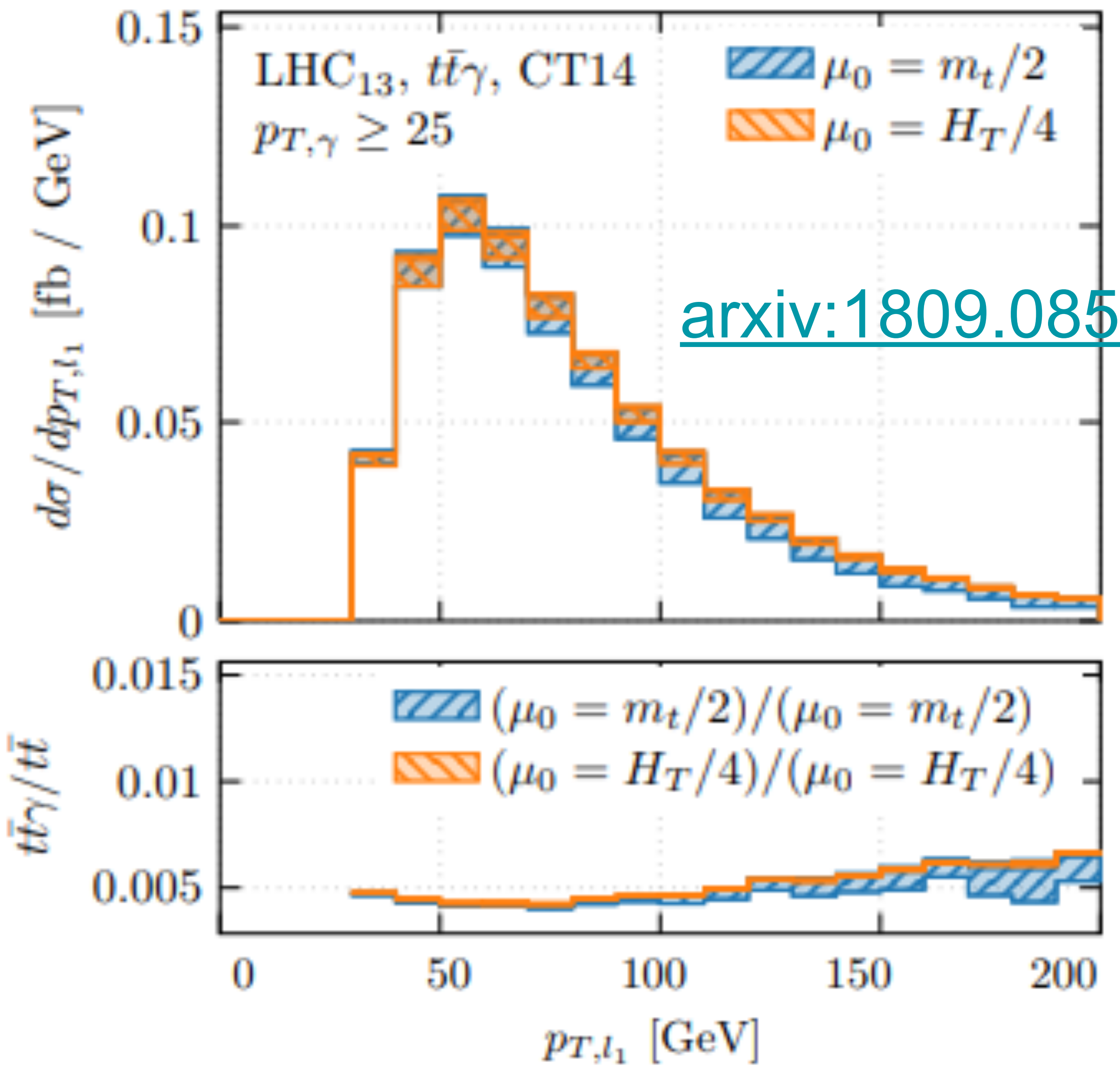


- Correlations between $t\bar{t}$ and $t\bar{t}\gamma$ depend on the phase space
  - Differential ratio measurements give additional sensitivity to potential deviations from SM
  - Theory papers suggest variables with larger variation of the ratio
  - Sensitive to modelling aspects

differential

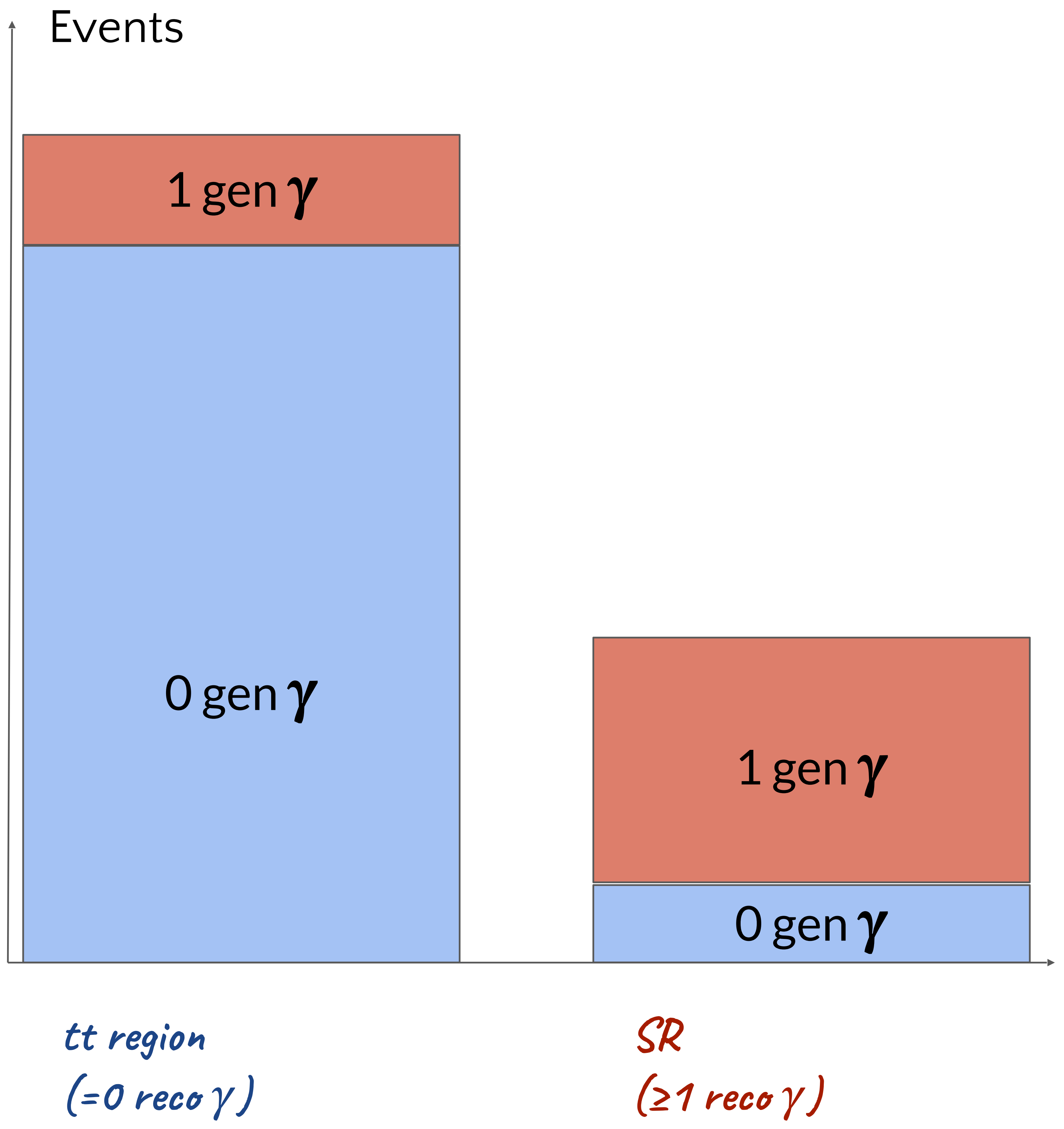
$$\mathcal{R}_X = \left(\frac{d\sigma_{t\bar{t}\gamma}}{dX}\right)\left(\frac{d\sigma_{t\bar{t}}}{dX}\right)^{-1}$$

arxiv:1809.08562



First ever measurement of the $t\bar{t}\gamma/t\bar{t}$ ratio at the LHC

- A $t\bar{t}$ (0-photon) region is built, in addition to the SR, by inverting cut on =1 reconstructed photon



- The ratio is computed as: $$R_\gamma = \frac{\sigma_{t\bar{t},=1\gamma}}{\sigma_{t\bar{t},=0\gamma} + \sigma_{t\bar{t},=1\gamma}}$$

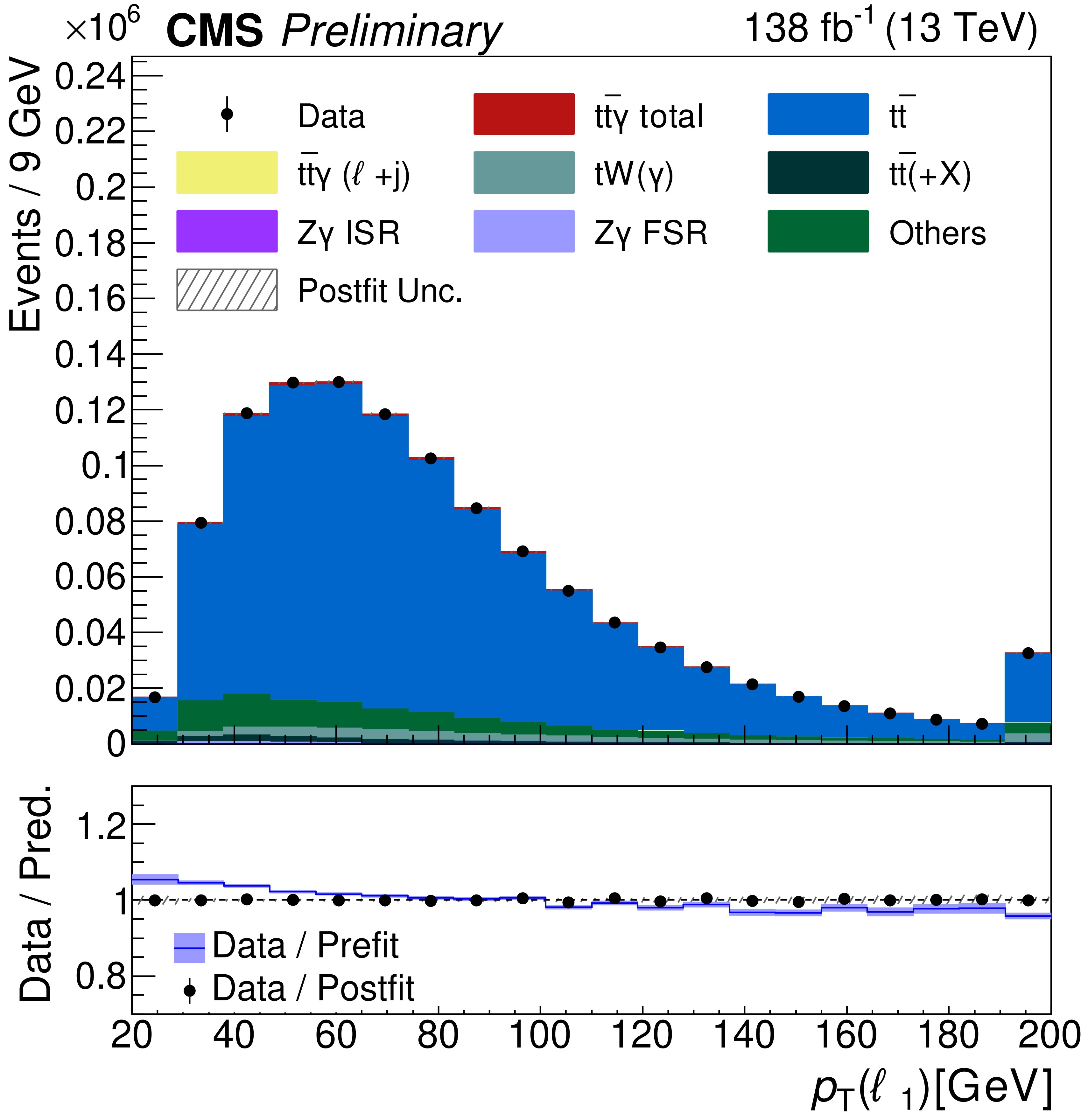
- 0-photon region has many events - allows for measuring $t\bar{t}$ precisely
- It is possible to write the $t\bar{t}$ and $t\bar{t}\gamma$ signal strengths as a function of R
- Extract R directly from the fit - direct handling of all correlations between systematic uncertainties

First ever measurement of the $t\bar{t}\gamma/t\bar{t}$ ratio at the LHC

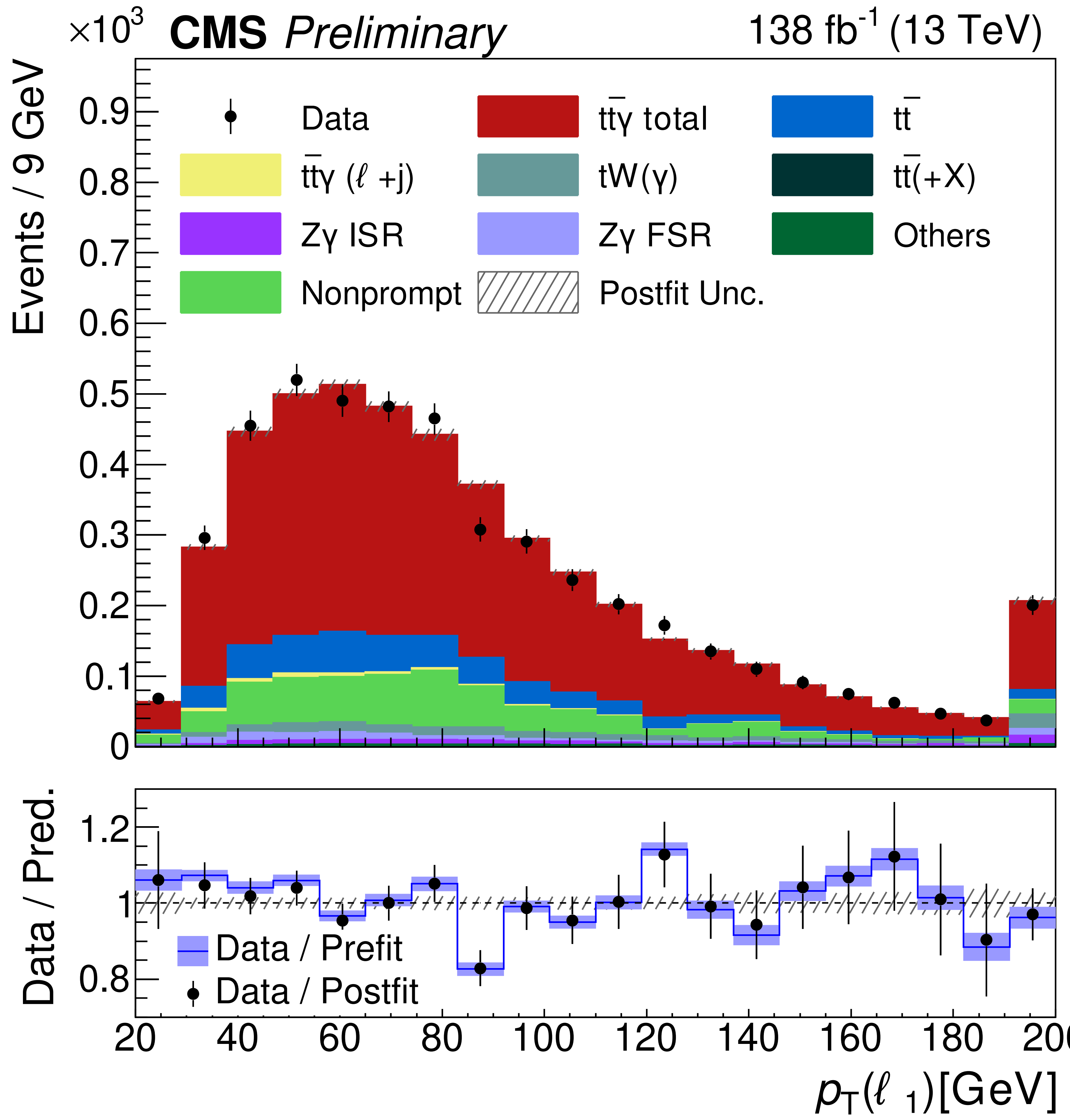
PAS-TOP-23-002

NEW!

0 photon region



1 photon region



- Result:

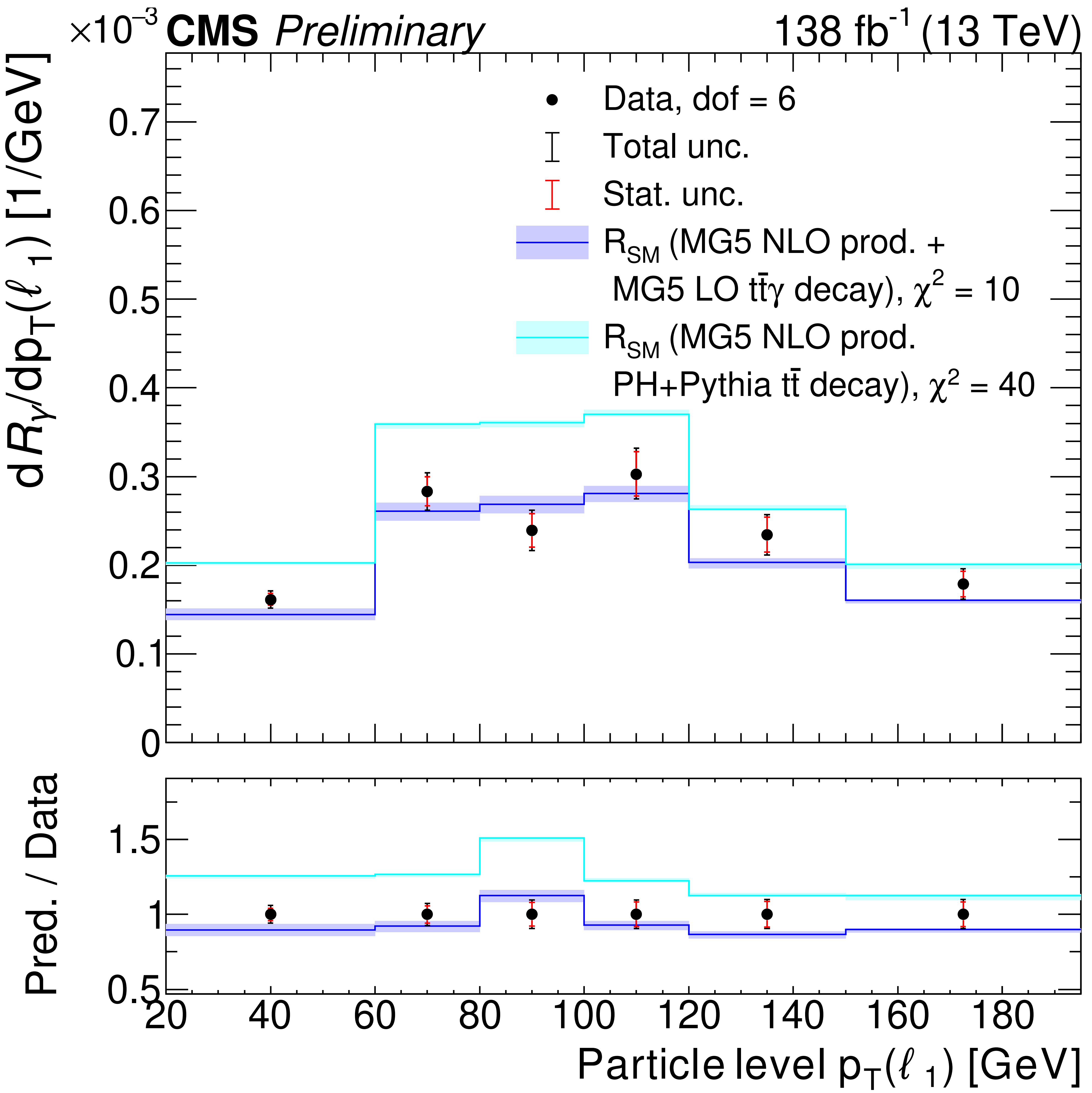
Ratio = (1.25 ± 0.05) %

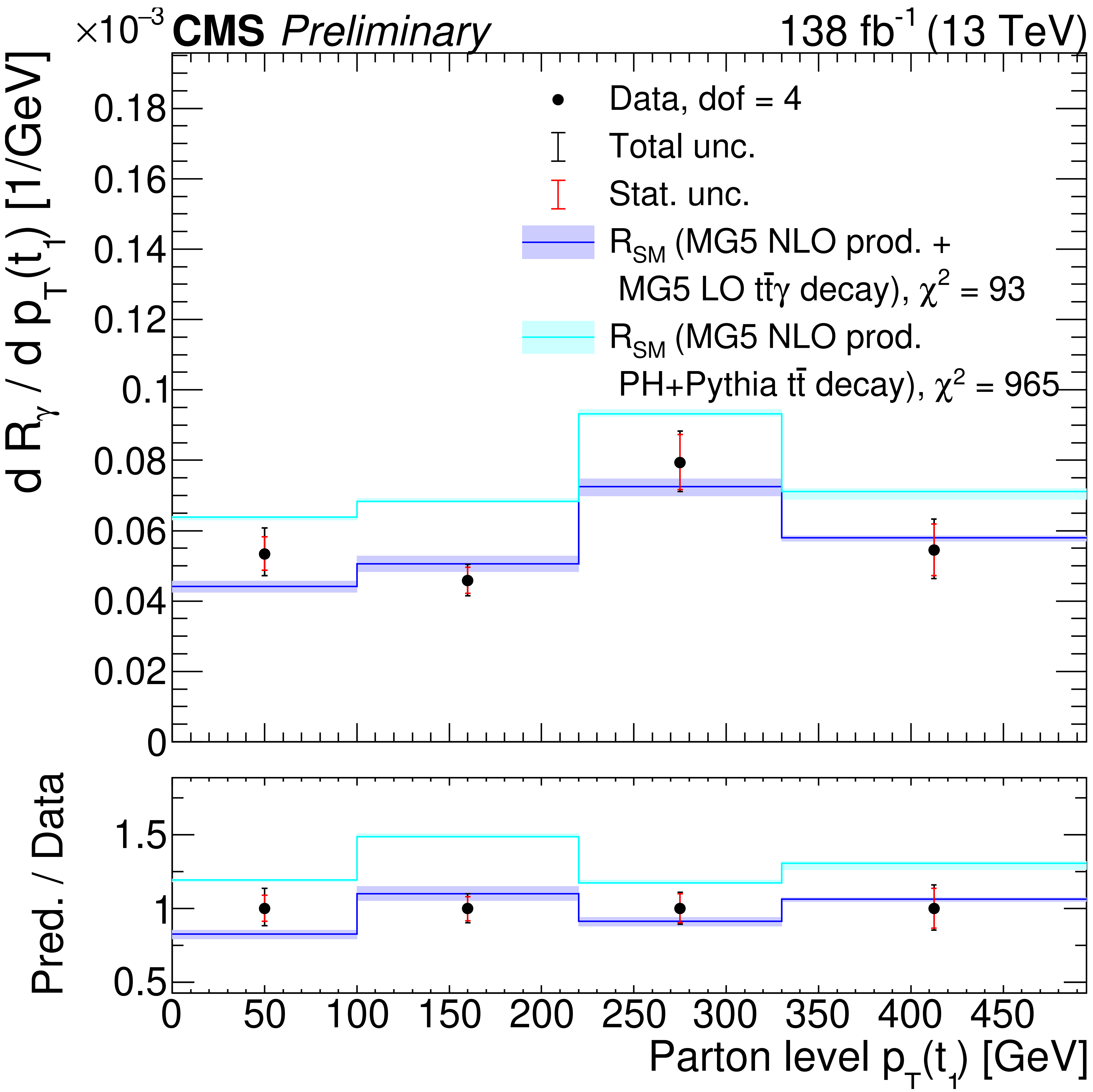
Limited by systematic uncertainties, mainly photon identification, nonprompt photon, DY and $Z+\gamma$ backgrounds, and modelling

$t\bar{t}$ normalization measured to be compatible with NNLO QCD prediction with 2% uncertainty

The $t\bar{t}\gamma/t\bar{t}$ ratio - also differential!

PAS-TOP-23-002





Compatible with SM predictions!

Summary

- Putting the SM to the test with top quark rare processes, especially those involving top quark EW couplings

- Simultaneous measurements enhance sensitivity to BSM effects

- Run 2 and Run 3 data give access to **very rare top** processes

- **New!:** Inclusive and differential $t\bar{t}\gamma$ results, and for the first time at the LHC, ratio between $t\bar{t}\gamma$ and $t\bar{t}$

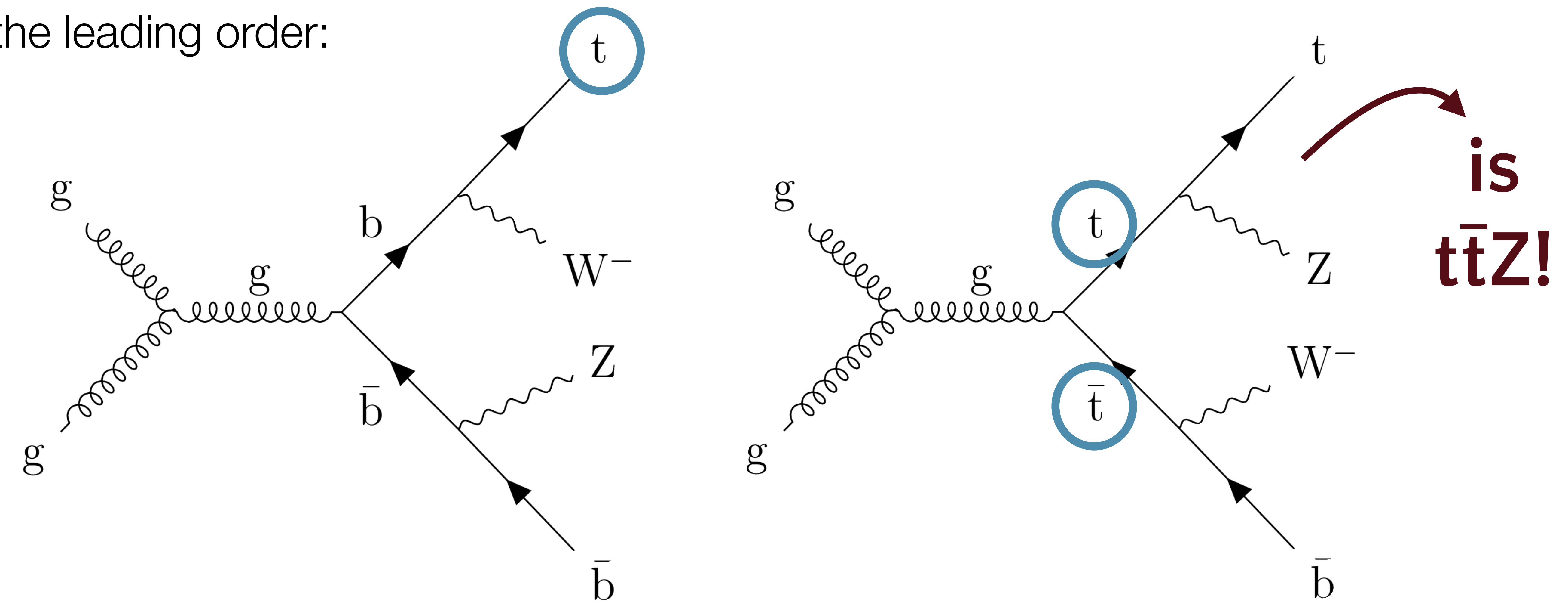
More results on their way: stay tuned!

Thank you!

BACKUP

Modelling tWZ and treating the interference

- Overlaps with $t\bar{t}Z$ and $t\bar{t}$ within the SM beyond the leading order:



- Amplitude split into resonant and non-resonant part $\mathscr{A}_{pp\to tWZ} = \mathscr{A}^{\text{non-resonant}}_{pp\to tWZ} + \mathscr{A}^{\text{resonant}}_{pp\to tWZ}$

$$|\mathscr{A}_{pp\to tWZ}|^2 = |\mathscr{A}^{\text{non-resonant}}_{pp\to tWZ}|^2 + |\mathscr{A}^{\text{resonant}}_{pp\to tWZ}|^2 + 2\mathscr{R}(\mathscr{A}^{\text{non-resonant}}_{pp\to tWZ}\mathscr{A}^{\text{resonant}\,\dagger}_{pp\to tWZ})$$

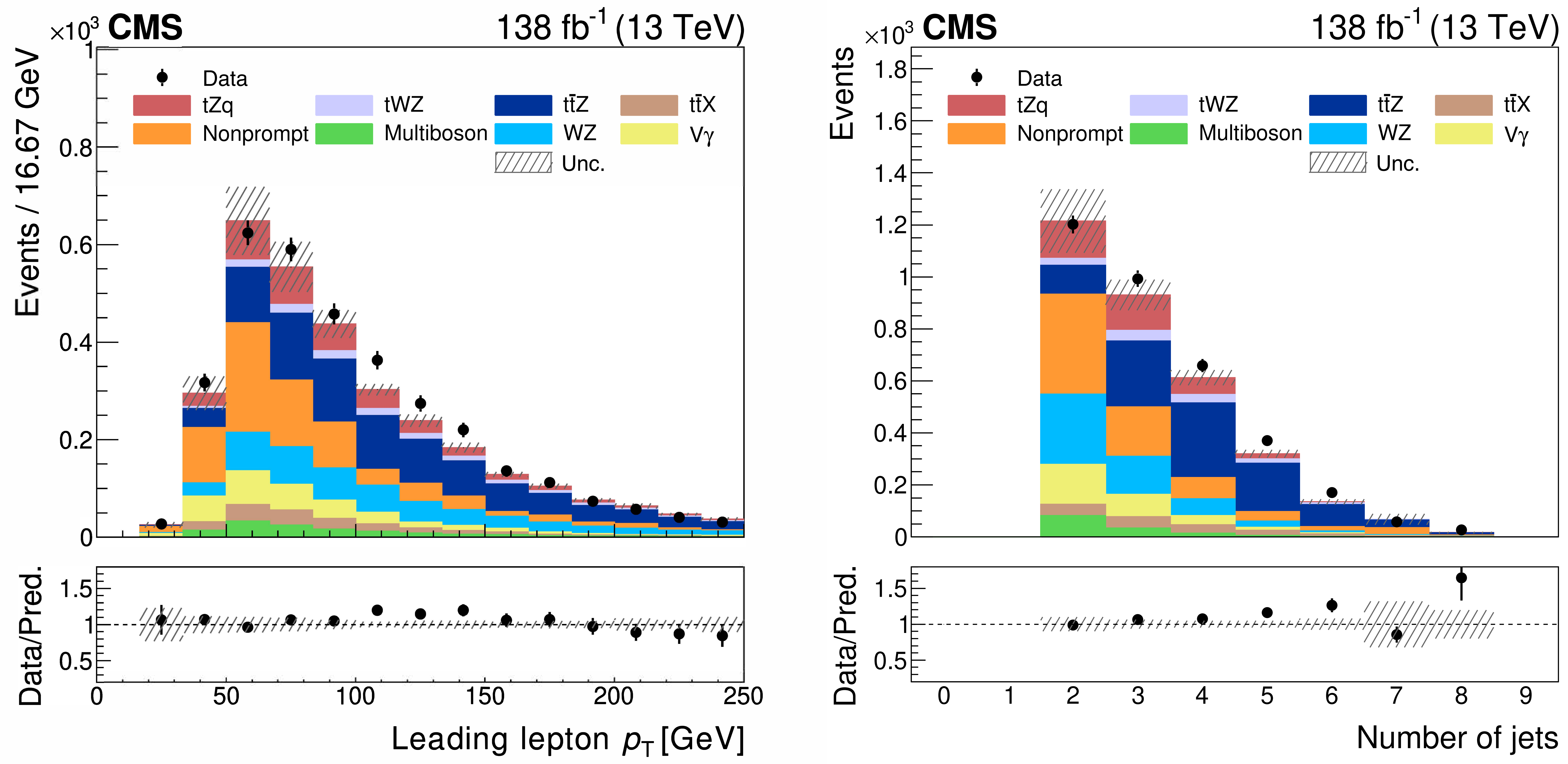
$t\bar{t}Z$ and tWZ are treated as one signal

- **DR1** removes $\mathscr{A}^{\text{resonant}}_{pp\to tWZ}$ in $\mathscr{A}$, **DR2** removes $|\mathscr{A}^{\text{resonant}}_{pp\to tWZ}|^2$ in $\mathscr{A}^2$, leaving interference term, DS adds a subtraction term

- **DR1 used as nominal**, DR2 for uncertainty (DS lies in between the two)

Selection strategy for $t\bar{t}Z$, tWZ, and tZq

- Signal region with three leptons (e or μ), $\geq$2 jets, $\geq$1 b-tagged jet
- **Nonprompt lepton contribution** is estimated from data, **WZ** and other smaller backgrounds from simulation



Nonprompt lepton estimation

Measurement region (MR)

- QCD multijet samples
- Exactly 1 “fakeable”* lepton
- >= 1 jet well-separated from

Application region (AR)

- Same selection as SR, but with “fakeable” leptons

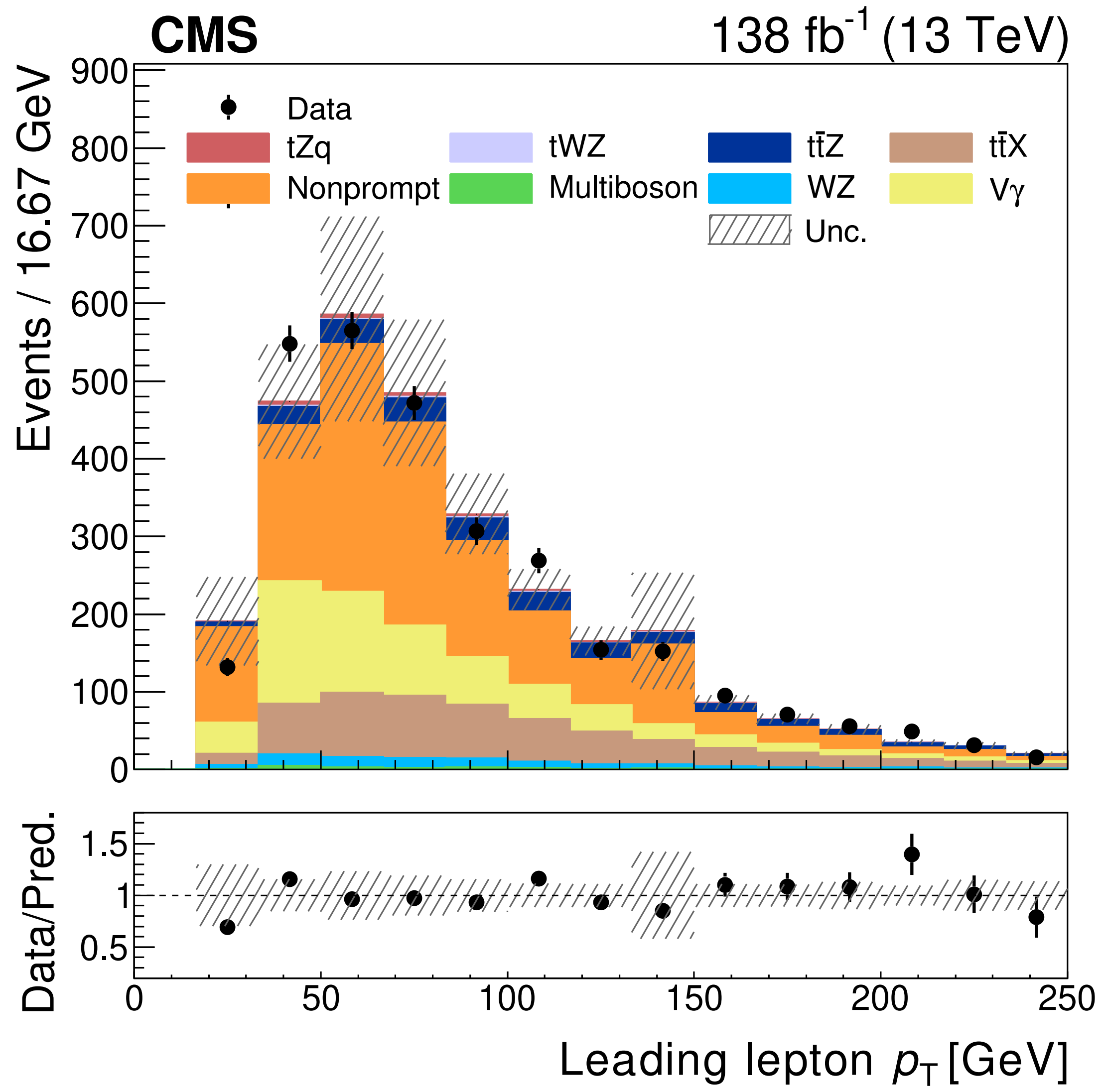
Compute per lepton:

$$\text{"fake" factor } f_i = \frac{N_{\text{tight}}}{N_{\text{tight}} + N_{\text{fakeable}}}$$

per event:

$$\text{weight} = (-1)^{n^{**}-1} \prod_{i=1}^{3} \frac{f_i}{1-f_i}$$

Apply to



- Contribution in SR = (Reweighted data in AR - prompt contribution from simulation)
- Estimation validated in off Z-peak region
- Statistical uncertainties on f_i propagated from MR & additional per-bin uncertainty for residual nonclosure

*fakeable: leptons with loose quality criteria

**n: # of fakeable leptons not passing the tight ID

Uncertainties on the nonprompt estimation

- Per bin nuisance: $\sigma_{nonprompt,i} = \sqrt{\sigma^2_{FR,i} + \sigma^2_{AR,i} + (30\% \text{ of bin content})^2}.$

  Statistical unc. in MR **Statistical unc. in AR** **Systematic unc. to cover from residual mismodellings**

- No difference in the behavior was observed as a function of lepton flavor
- Limited statistics in AR → some terms in FF application are = 0.
  - However, the uncertainties are not 0, but a one-sided uncertainty is set as the upper confidence interval of the Poisson statistics for 0 observed events, $1.8 \cdot \frac{f_i}{1 - f_i}$
  - This is more relevant at low lepton pT, where the fake rates are close to 1

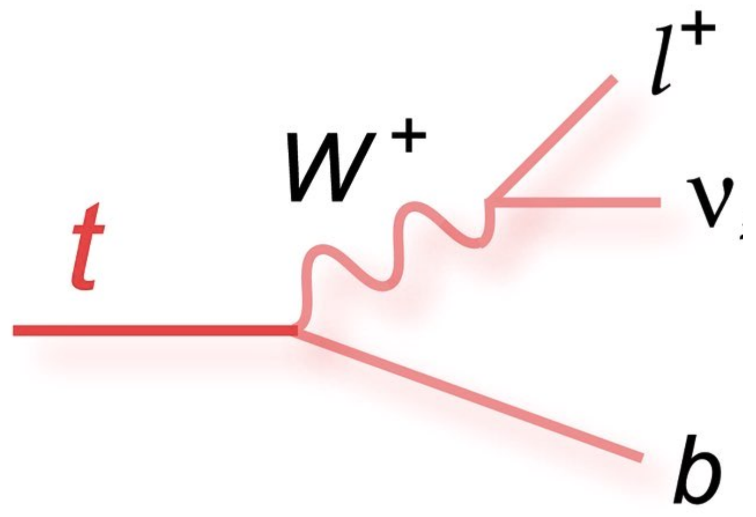
Top quark reconstruction

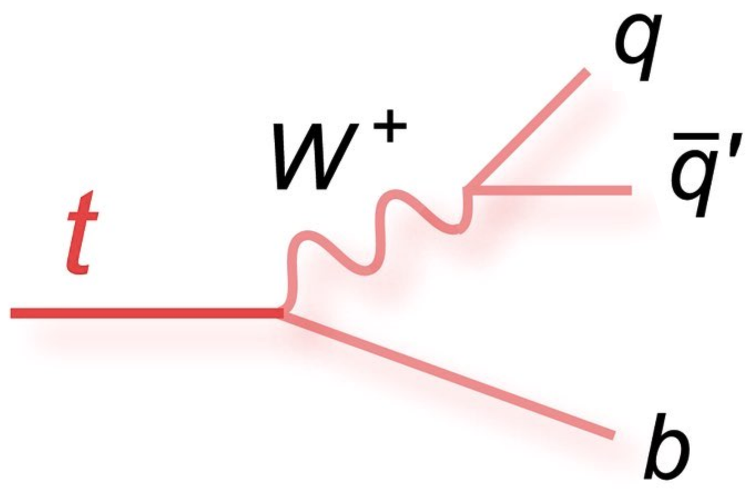
- Top quark reconstruction algorithm considers three cases:
  - **2 jets, 1 b tag:** leptonic top is reconstructed from $\ell + \nu + b$
  - **3 jets, ≥1 b tag:** leptonic and hadronic top candidates are reconstructed separately, lowest χ^2 kept

$$\chi^2_{t,lep} = \left(\frac{m_{l\nu b} - m_t}{\sigma_{t,lep}}\right)^2 \qquad \chi^2_{t,had} = \left(\frac{m_{jjb} - m_t}{\sigma_{t,had}}\right)^2$$

  - **≥4 jets, ≥1 b tag:** both hadronic and leptonic top are reconstructed

$$\chi^2_t = \left(\frac{m_{l\nu b} - m_t}{\sigma_{t,lep}}\right)^2 + \left(\frac{m_{jjb} - m_t}{\sigma_{t,had}}\right)^2$$

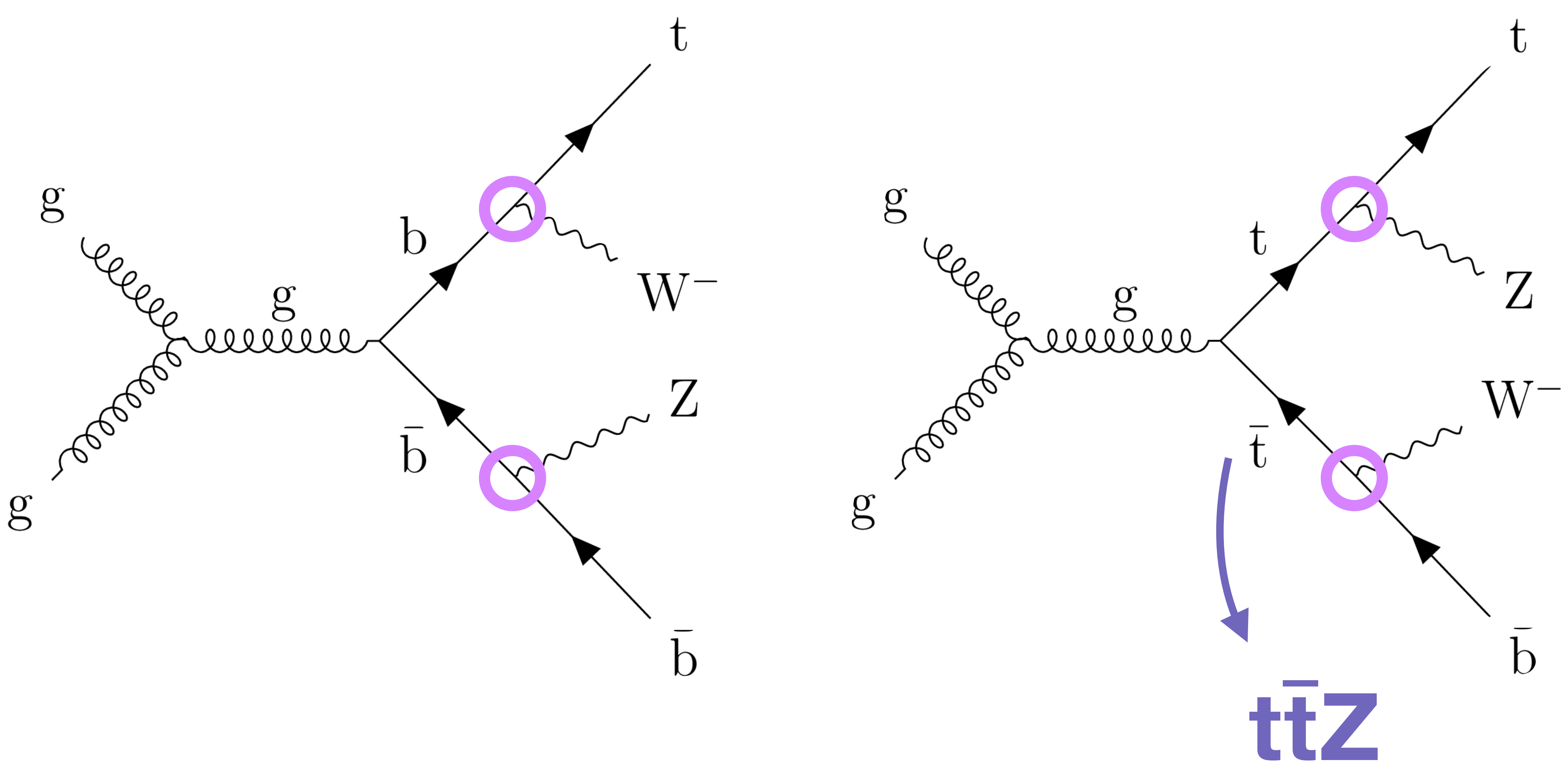




tWZ production

- Explore two top quark electroweak couplings in one process

tWZ:

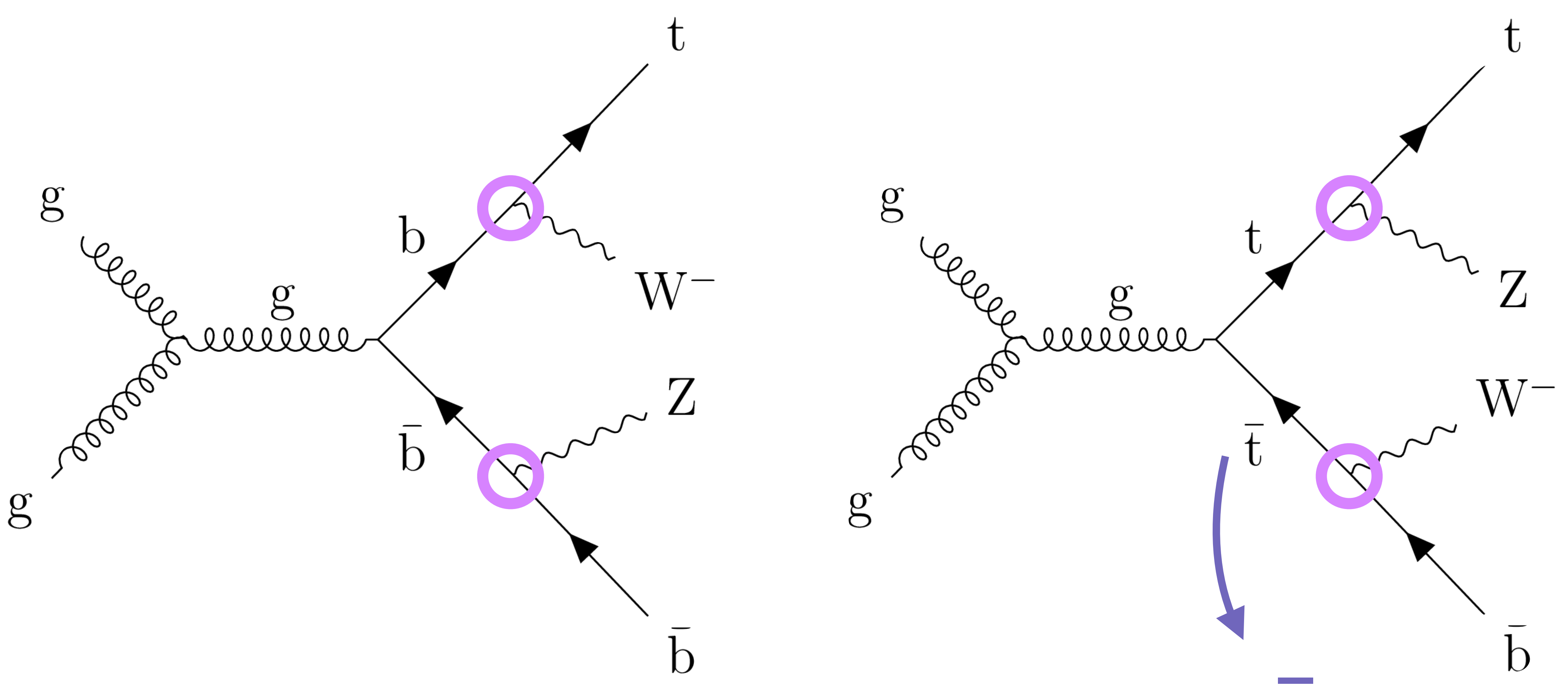


- Challenges:
  - Very rare process: exp. cross section ~136 fb (NLO in QCD)
  - Overwhelming and irreducible tt̄Z background
  - Interference with the tt̄Z process within the SM beyond the leading order

tWZ production

- Explore two top quark electroweak couplings in one process

tWZ:



$t\bar{t}Z$

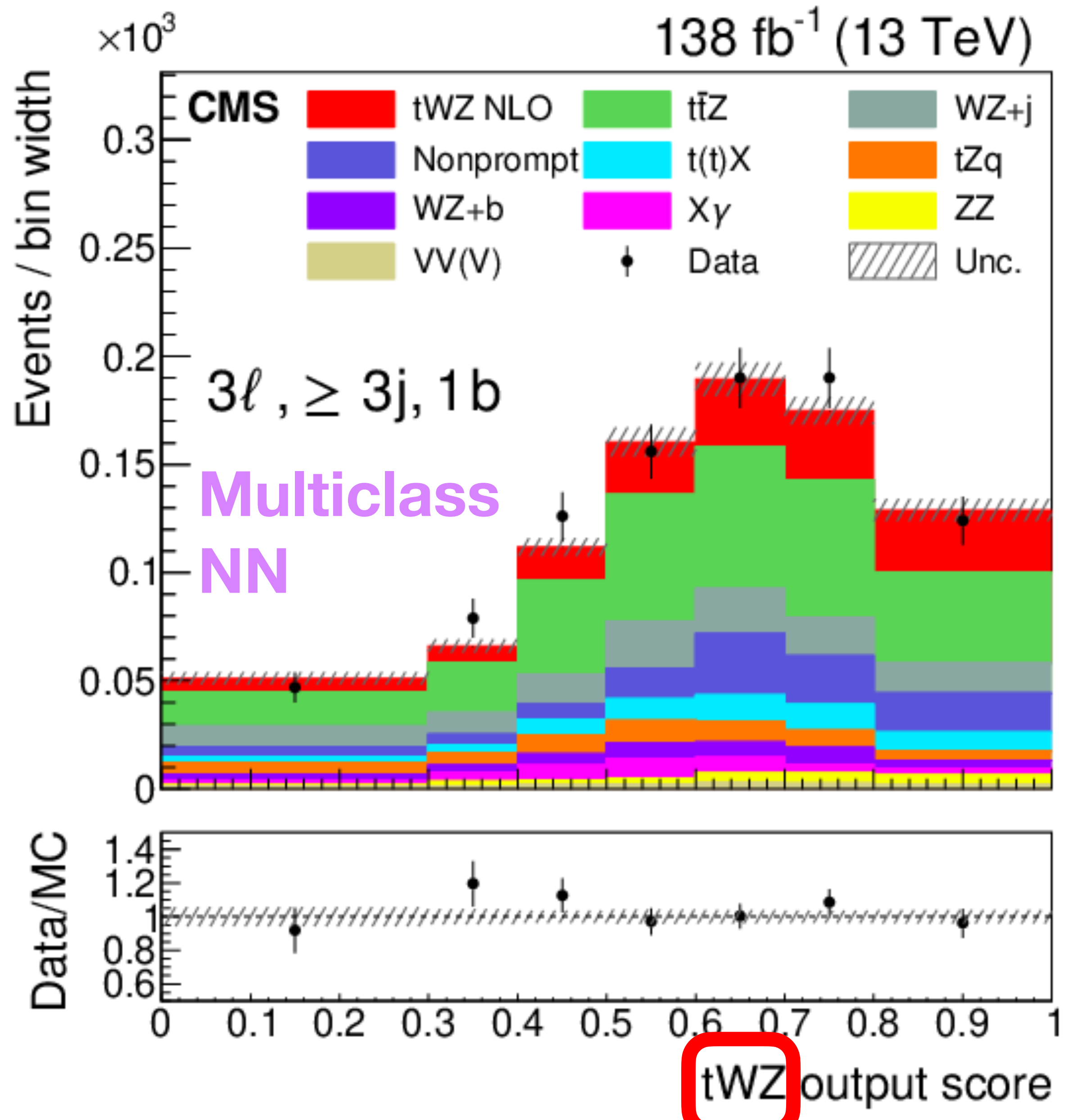
- Challenges:
  - Very rare process: exp. cross section ~136 fb (NLO in QCD)
  - Overwhelming and irreducible $t\bar{t}Z$ background
  - Interference with the $t\bar{t}Z$ process within the SM beyond the leading order

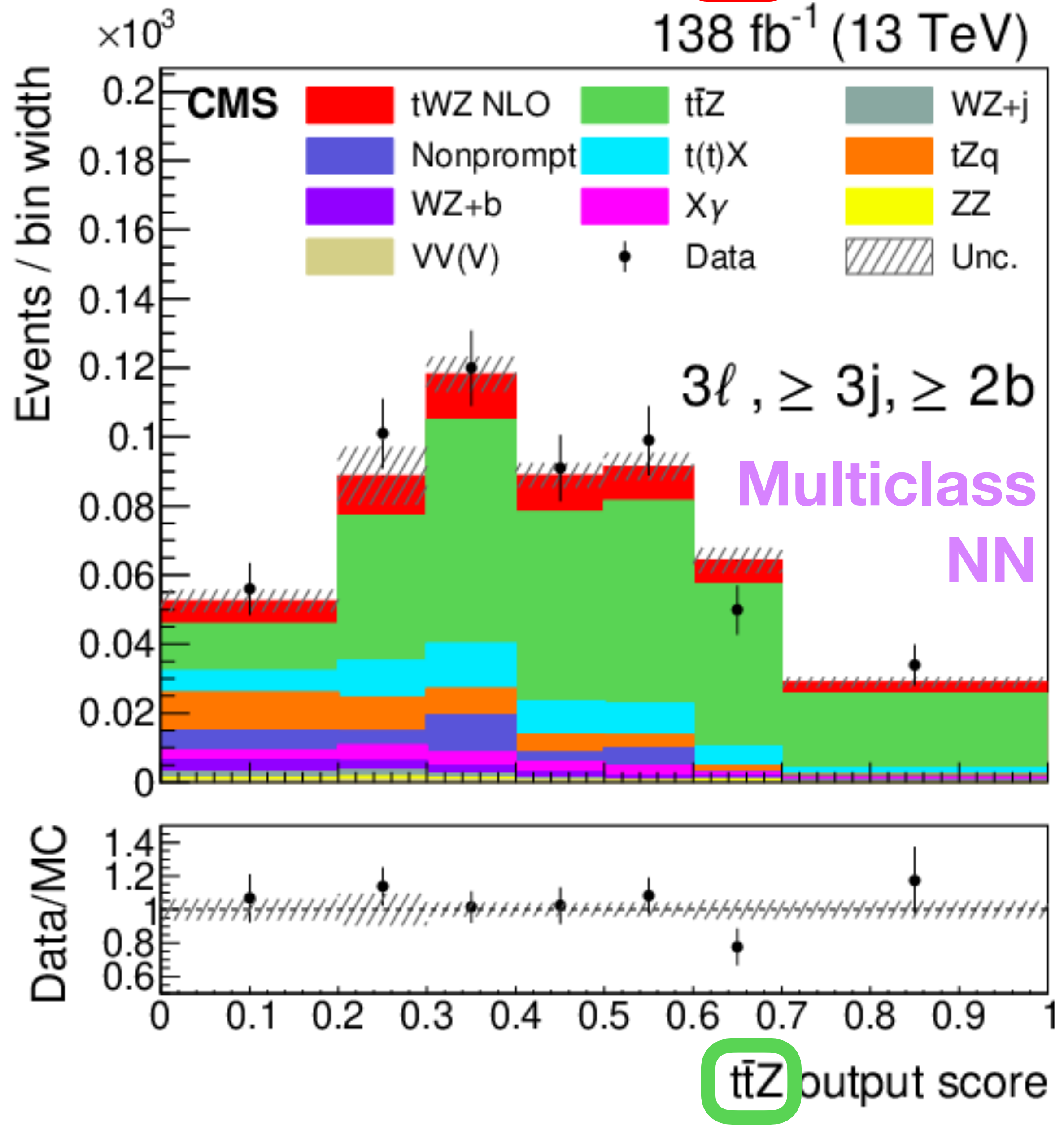
First analysis using state-of-the-art tWZ signal modeling at NLO, consistently treating the interference

Analysis strategy for tWZ

- Two regions of the phase space considered:
  - ✓ Low top quark p_T (**resolved**): higher stat., sensitive to the SM tWZ production
  - ✓ Top quark with $p_T > 270$ GeV (**boosted**): enhanced sensitivity for new phenomena
- Signal and control regions built based on number of leptons and b jets
  - Resolved: 3 leptons, 2j, ≥ 1b → **Binary NN**
    3 leptons, ≥ 3j, ≥ 1(2)b → **Multiclass NN**
    4 leptons, ≥ 1b
  - Boosted: hadronic top decay (fat jet)
    leptonic top decay (lep. top tagger)
  - Diboson CRs: 4 leptons (ZZ)
    3 leptons, 0b (WZ)

Simultaneous fit of 7 distributions





Inclusive tWZ cross section

- Observed (expected) significance of 3.4σ (1.4σ) → **evidence!**

σ_{tWZ} = 354 ± 54 (stat) ± 95 (syst) fb

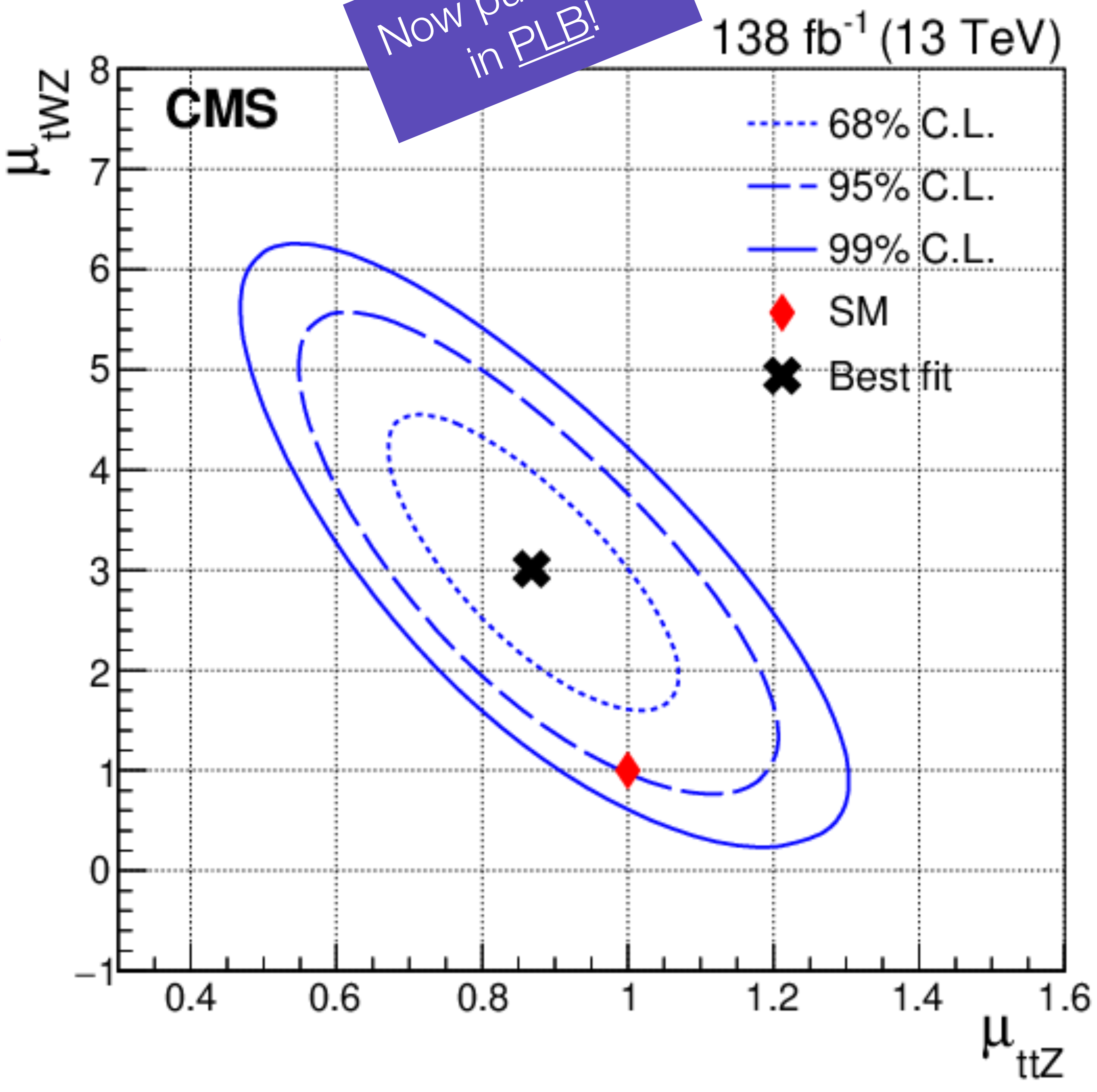
(two s.d. above the SM)

- Dominant systematic uncertainties:
    - **tt̄Z** normalization: 18% - strongly anti-correlated with the signal

      Additional studies showed that when fixing the tt̄Z cross section to the previously measured value, the significance stays above 3σ

    - Other background normalization
- Sensitivity driven by resolved SRs, especially the SR with **3 leptons, ≥ 3j, ≥ 1b**

Now published in PLB!



Treating the interference between tWZ and ttZ

MadSTR plugin used for removal through diagram removal schemes

Amplitude A divided into A(res) and A(non-res)

- **DR1**: removes A(res) in A, used for **nominal**
- DR2: removes $|A(res)|^2$ in $|A|^2$ (leaves interference term) for uncertainty
- DS: subtraction term, lies between DR1 and DR2

Overview of diagram removal/subtraction schemes

Frixione et al., JHEP12(2019)008

NLO process: $a + b \longrightarrow \delta + \gamma + X$

with a possible resonance: $\beta \longrightarrow \delta + \gamma$

$$\mathcal{A}_{ab\to\delta\gamma X} = \underbrace{\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}}_{\text{non-resonant}} + \underbrace{\mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}}_{\text{resonant}}$$

$$|\mathcal{A}_{ab\to\delta\gamma X}|^2 = \left|\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\right|^2 + 2\Re\left(\cancel{\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\mathcal{A}^{(\beta)\dagger}_{ab\to\delta\gamma X}}\right) + \left|\cancel{\mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}}\right|^2$$

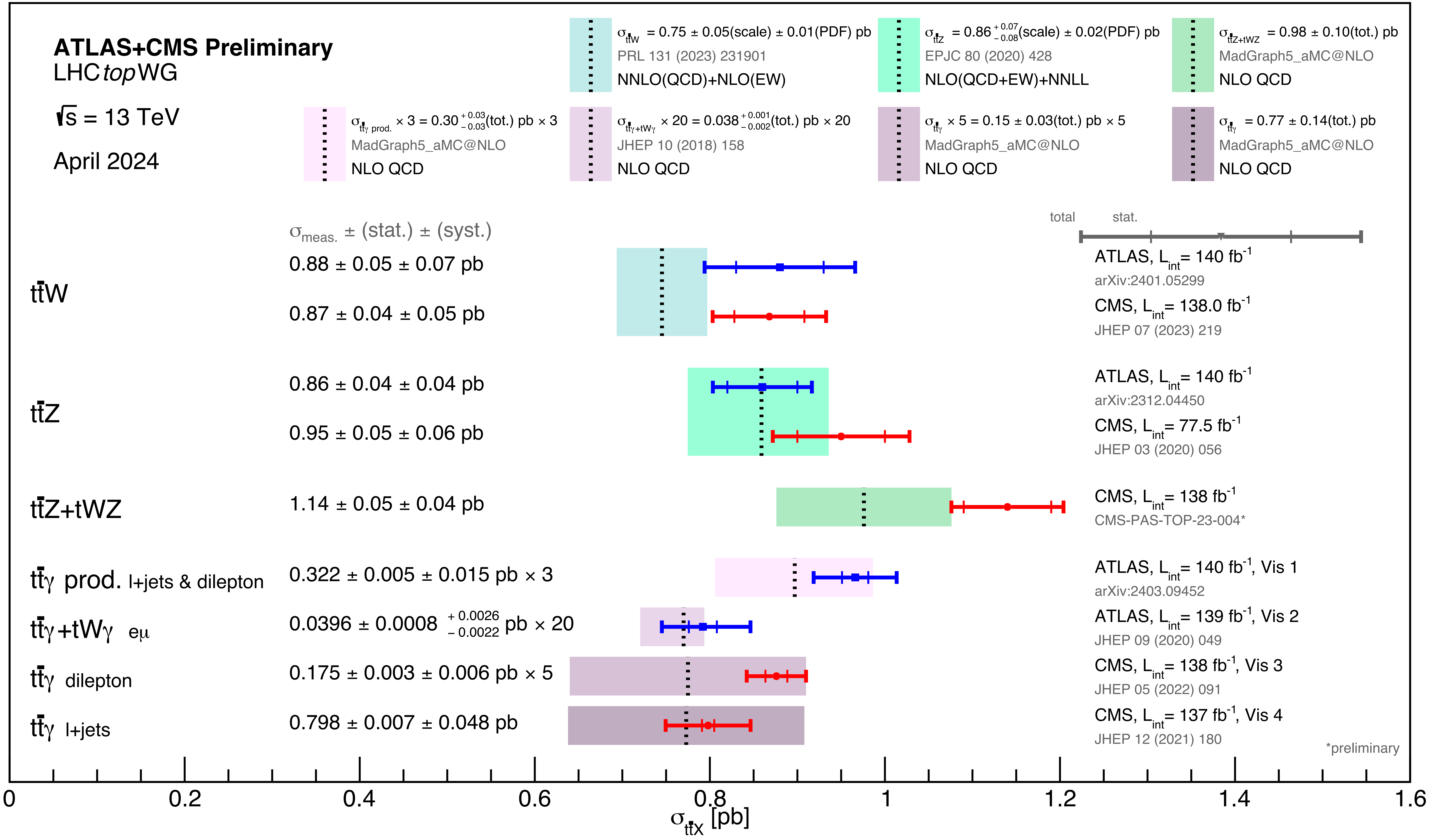
- DR+I (DR1): removes both resonance and interference term
- DR2: removes only the resonant term
- The diagram subtraction (DS) scheme implements removal at the cross section level

A. Saggio
LHCTopWG meeting
07/06/2023

ttZ, tWZ and tZq - systematic uncertainties

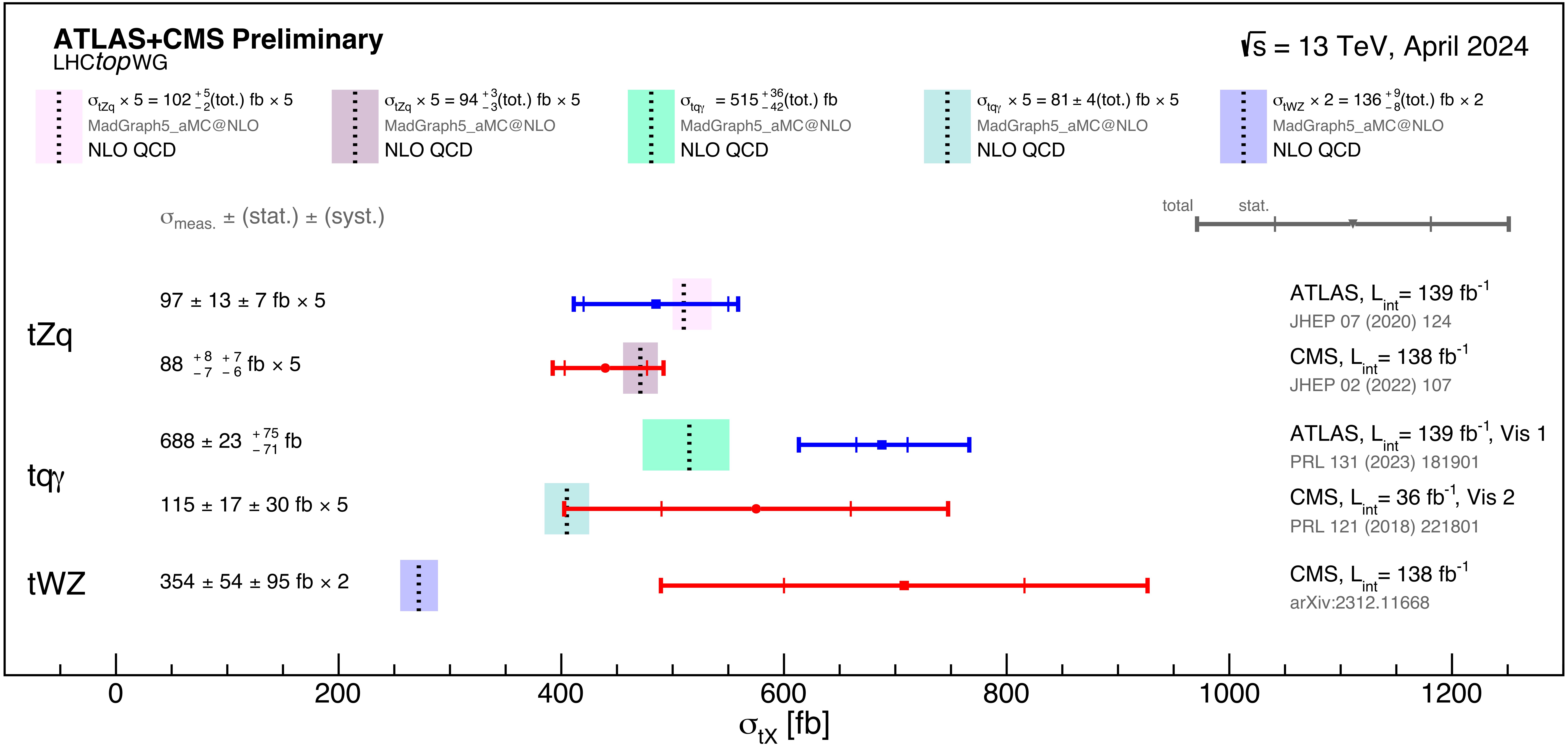
Source	$\sigma(t\bar{t}Z + tWZ)$	$\sigma(tZq)$
Trigger	2%	2%
Trigger prefiring	<1%	2%
Lepton identification efficiencies	1%	2%
b tagging	1%	2%
Jet energy scale	1%	3%
Jet energy resolution	<1%	1%
Missing transverse momentum	<1%	3%
Nonprompt background	2%	3%
Pileup	<1%	1%
Luminosity	2%	2%
Statistical	3.7%	10%
Background modeling	2%	4%
Factorization scale	1%	1%
Renormalization scale	1%	2%
Parton shower	<1%	2%
PDF and α_S	<1%	<1%
Underlying event and color reconnection	1%	2%
tWZ modeling	<1%	<1%
MC statistical	<1%	1%
Total	6%	13%

Summary



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

Summary


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

Measurement of $t\bar{t}c(\bar{c})$

ATLAS EXPERIMENT

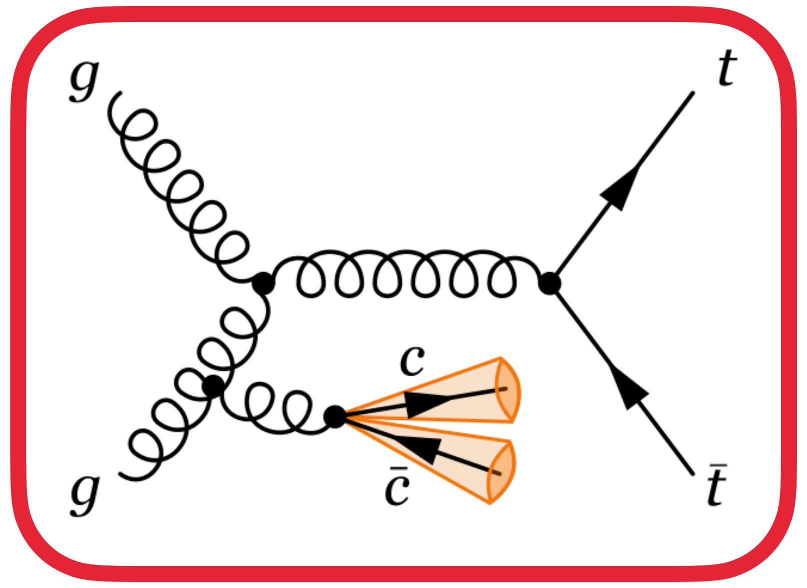
Phys. Lett. B 860 (2025) 139177
arXiv:2409.11305

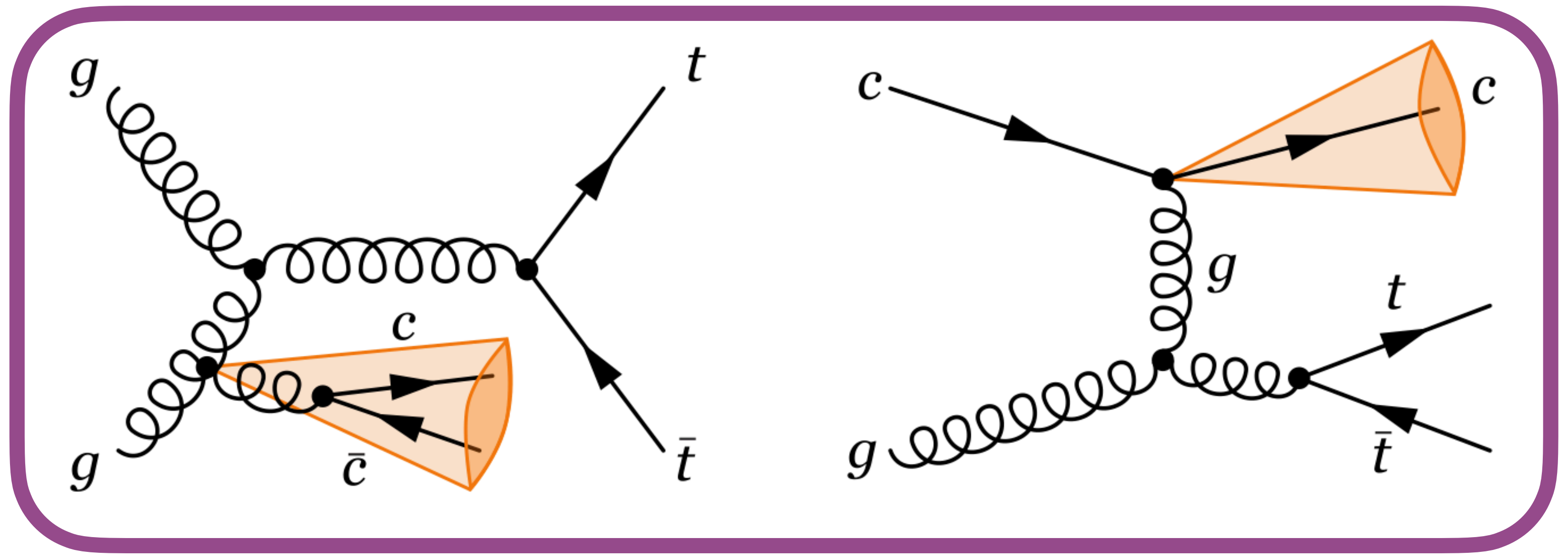
Now published

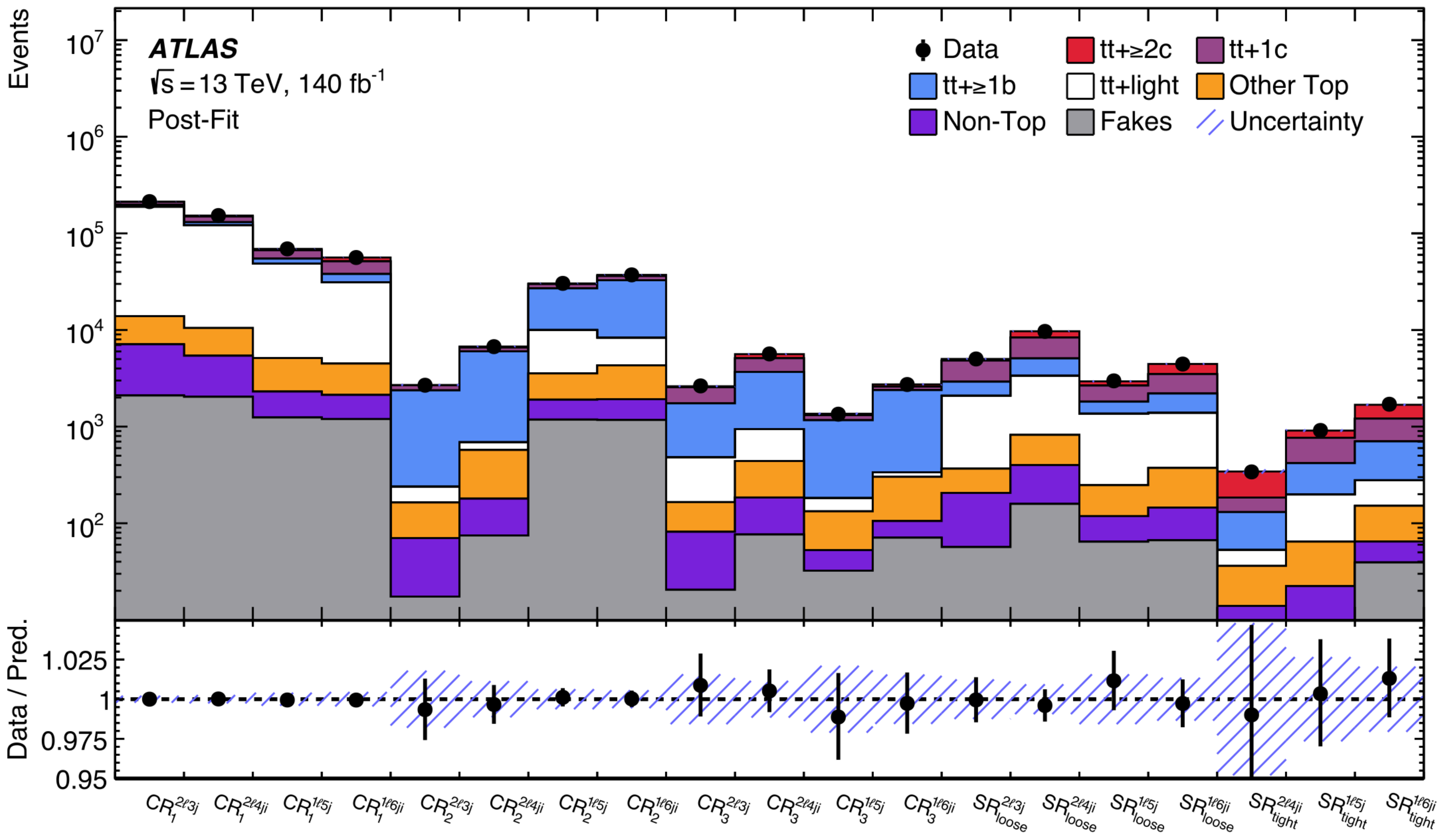
- Important background for ttH->bb and ttH->cc processes
- Challenging from the modelling perspective: blah blah blah
- tt+c and tt+cc measured separately, in the single lepton and dileptonic final states
- Custom flavour tagging algorithm used to tag b and c jets simultaneously
- Main uncertainties are background modelling (tt and ttbb), the tagger calibration, and data statistics
- Results largely compatible with predictions, with slight excesses of 0.5-2 sigma

$$\sigma_{\mathrm{tt+1c}} = 1.28^{+0.16}_{-0.10}(\mathrm{stat})^{+0.21}_{-0.22}(\mathrm{syst})\ \mathrm{pb}$$

$$\sigma_{\mathrm{tt+\geq 2c}} = 6.4^{+0.5}_{-0.4}(\mathrm{stat}) \pm 0.8(\mathrm{syst})\ \mathrm{pb}$$







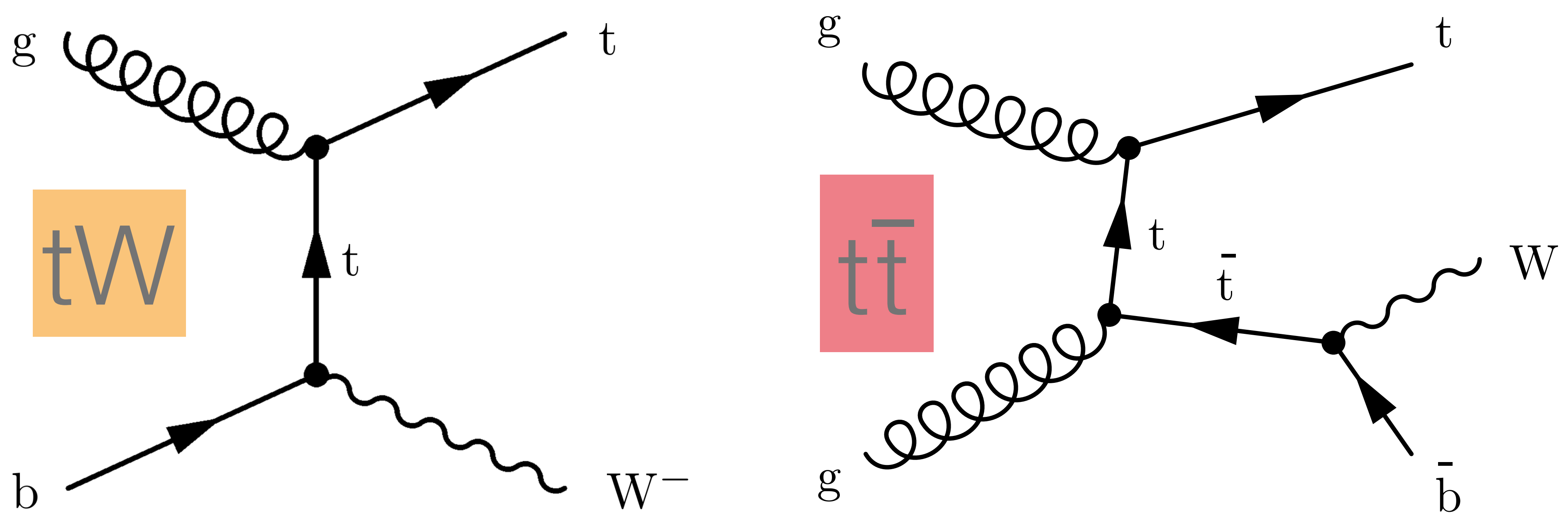
Ttgamma

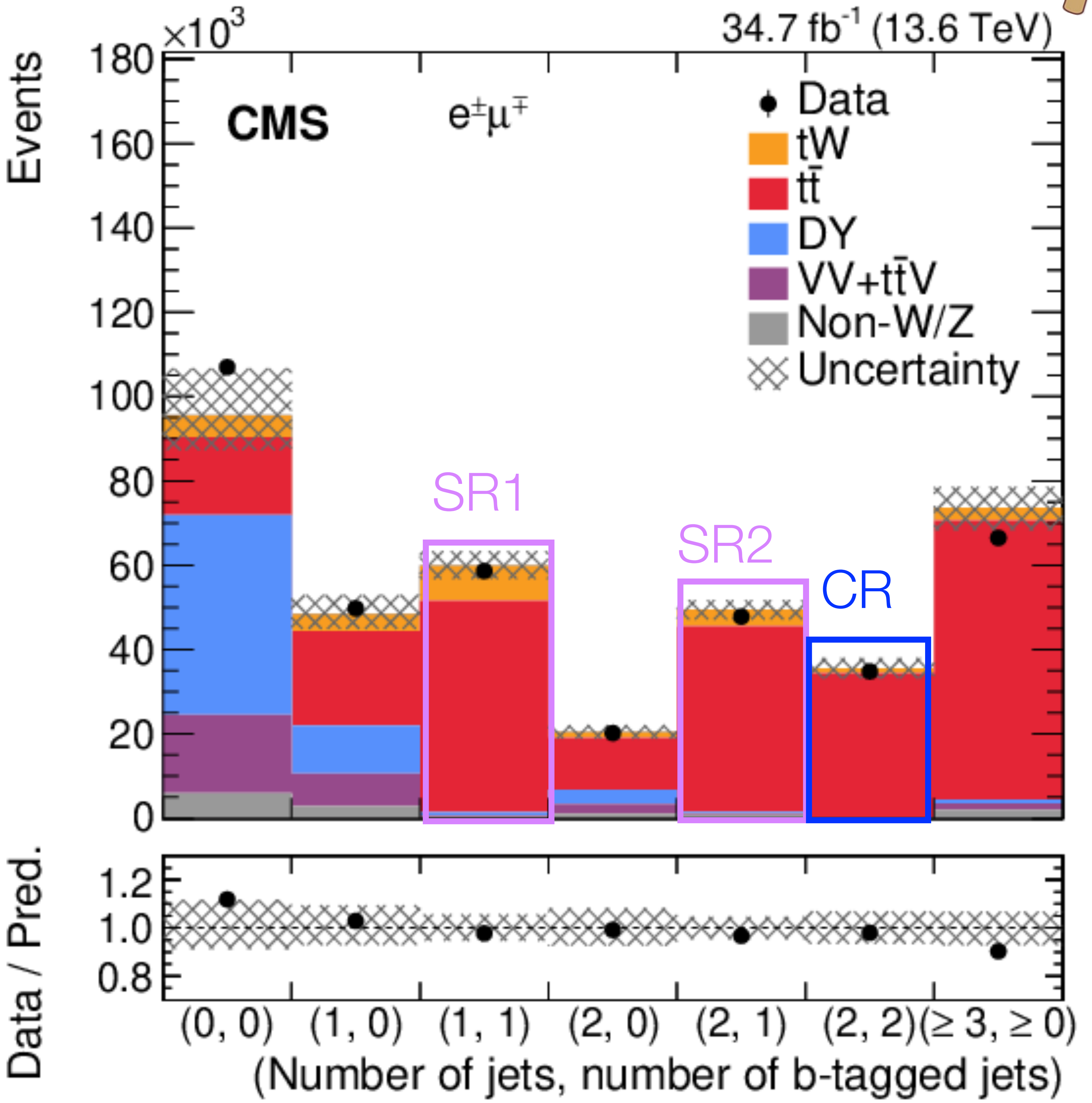
The tW process at the LHC Run 3

JHEP 01 (2025) 107
arXiv:2409.06444

Now published

- First tW measurement at 13.6 TeV, using full 2022 dataset (34.7 fb^{-1})
- Focusing on $e\mu$ final states





- Two SRs and CR defined based on number of jets and b jets

The tW process at the LHC Run 3

JHEP 01 (2025) 107
arXiv:2409.06444

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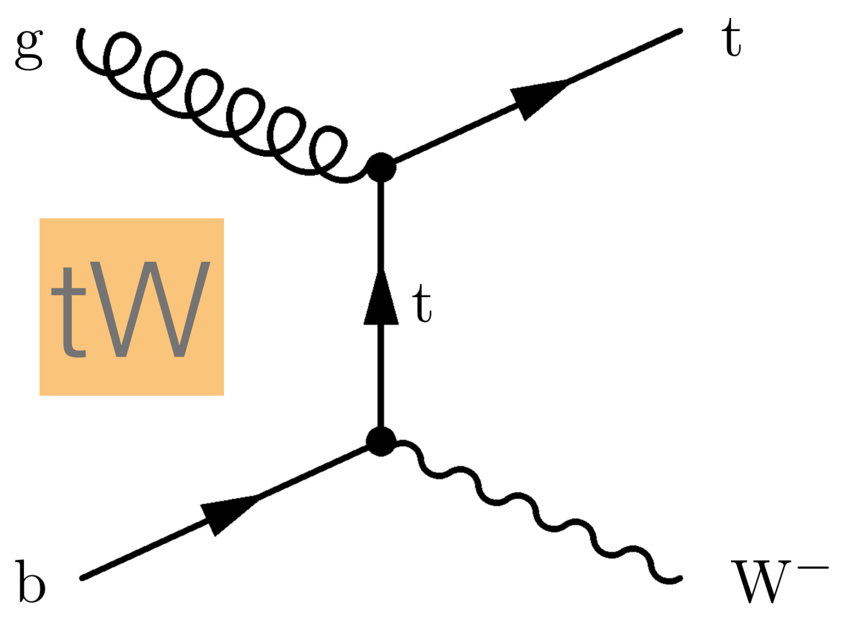
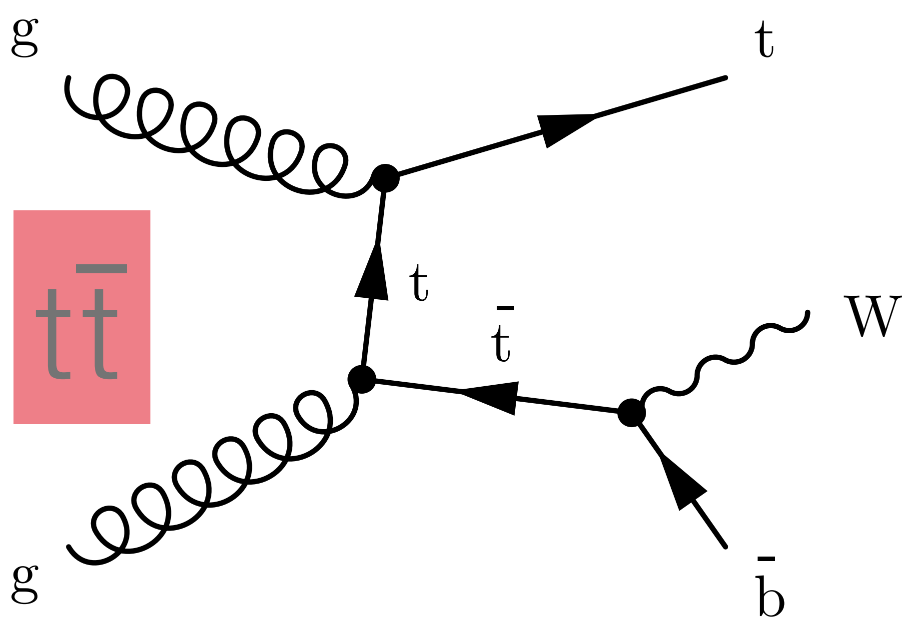
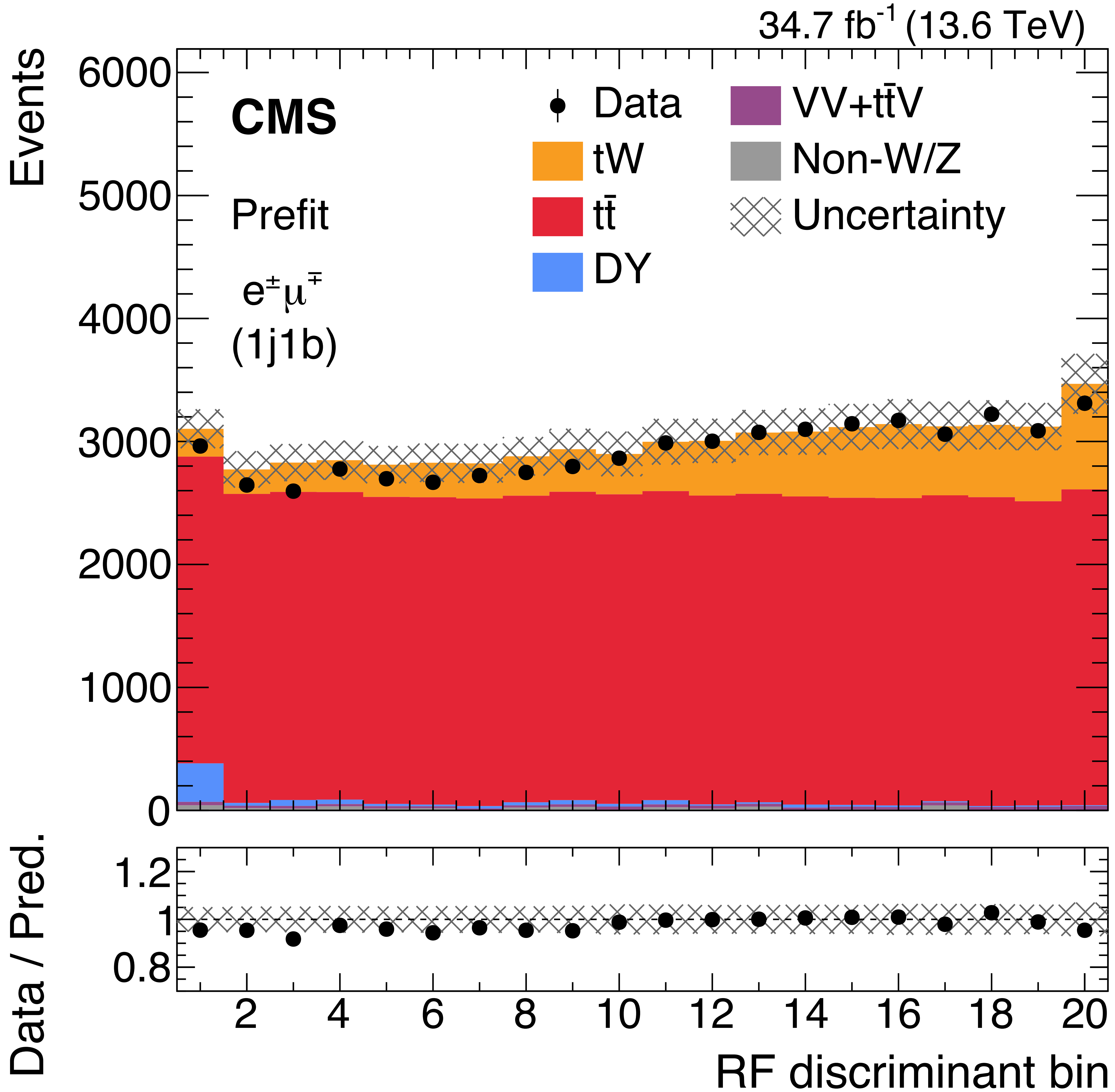






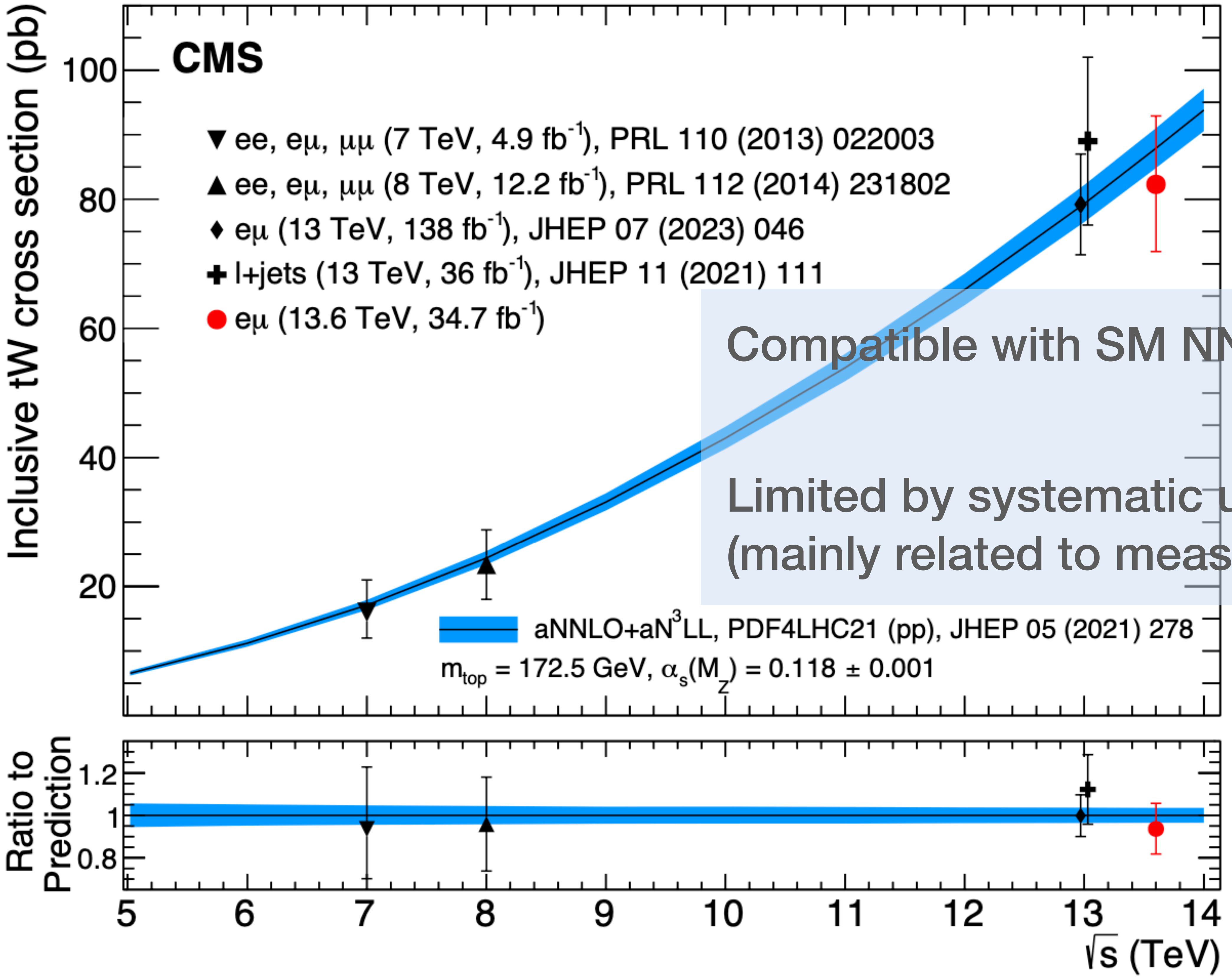
- Two SRs and CR defined based on number of jets and b jets
- MVA classifiers (Random Forests) to separate tW from irreducible $t\bar{t}$ background in SRs

Inclusive and differential tW cross sections at 13.6 TeV

JHEP 01 (2025) 107
arXiv:2409.06444

- Inclusive result:

$$\sigma_{tW} = 84.1 \pm 2.1(\text{stat.})^{+9.8}_{-10.2}(\text{syst.}) \pm 3.3(\text{lum})\ \text{pb}$$



Compatible with SM NNLO prediction

Limited by systematic uncertainties (mainly related to measurement of jets)

Inclusive and differential tW cross sections at 13.6 TeV

JHEP 01 (2025) 107
arXiv:2409.06444

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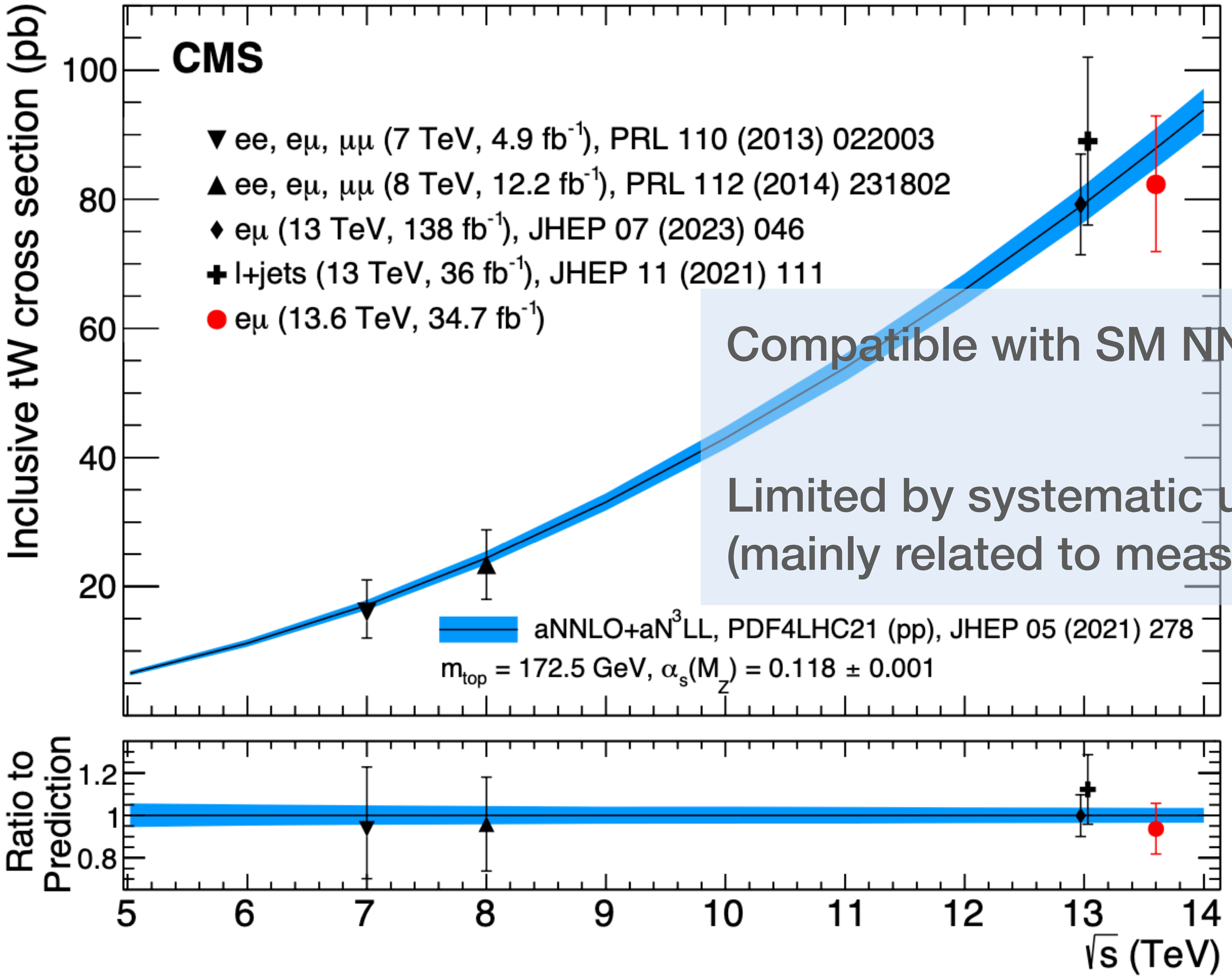
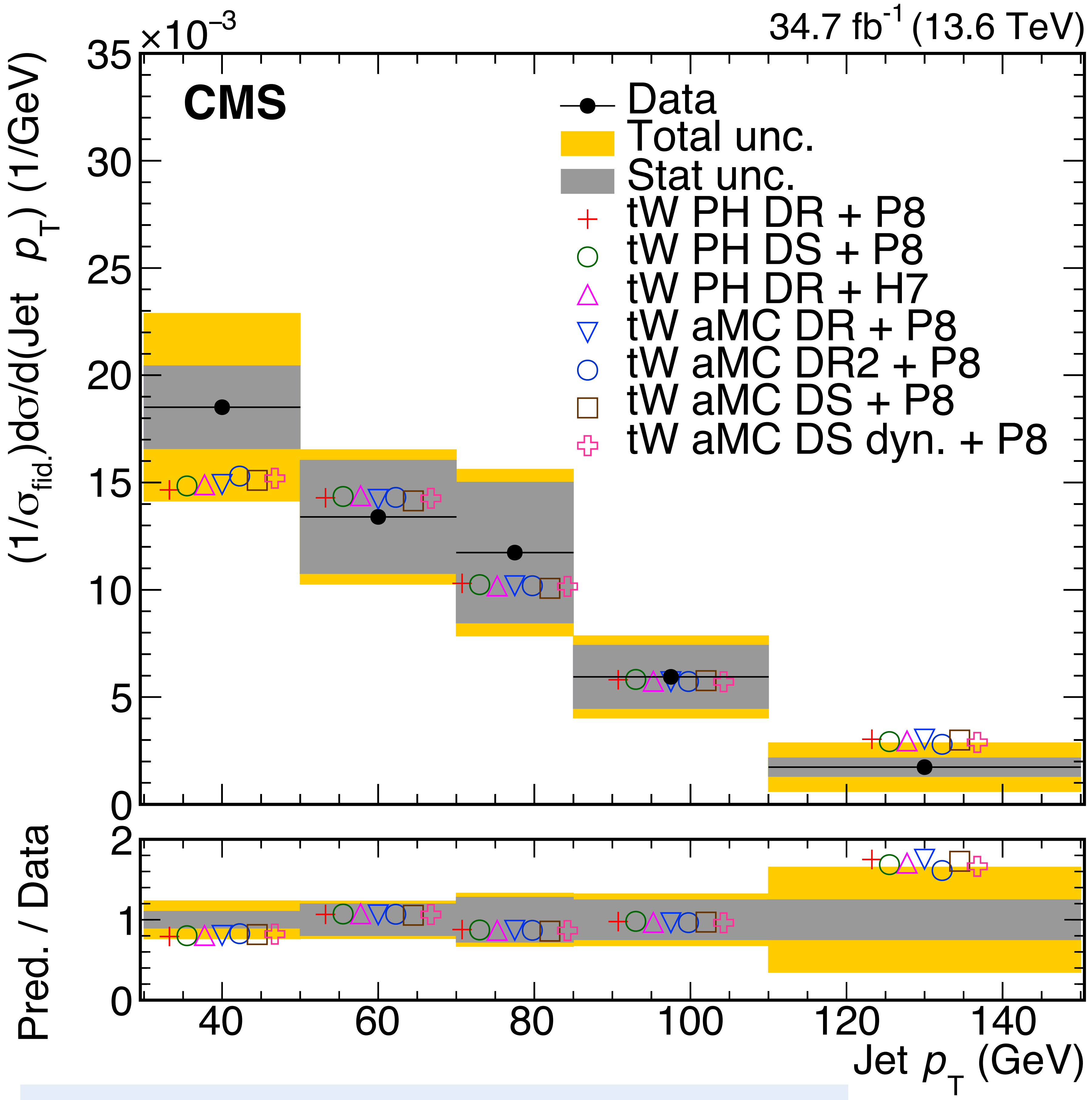


Compatible with SM NNLO prediction

Limited by systematic uncertainties (mainly related to measurement of jets)

- Differential results (example):

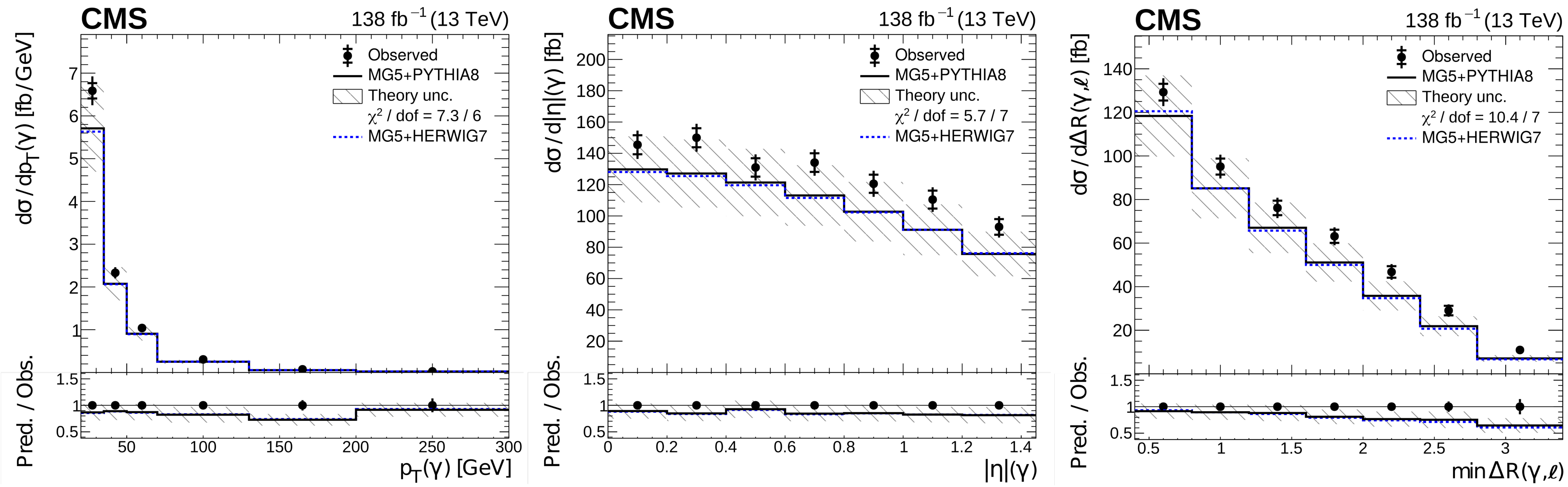


Compatible with predictions from different generators and modeling choices

Previous $t\bar{t}\gamma$ measurements

- Already measured by CMS and ATLAS
- Inclusive and differential measurements as a function of lepton and photon kinematic observables exist

example from [1]:



Note:

- Inclusive cross section slightly higher than prediction
- Imperfect description of photon origin

- **Not measured before at the LHC: cross section vs. top quark and $t\bar{t}$ variables, ratio between $t\bar{t}\gamma$ and $t\bar{t}$**

- focus of this paper (+ improved modelling strategy)

$t\bar{t}$ and $t\bar{t}\gamma$ cross section calculations

- $t\bar{t}$ cross section computed using the TOP++ framework by Czakon, Mitov et al.
- Computed at NLO in QCD with NLL resummation

- $t\bar{t}\gamma$ total cross section computed using Madgraph aMC@NLO to simulate two samples:
  - 2->3 pp $\rightarrow t\bar{t}\gamma$, removing hard isolated photons from FSR. Remain photons from ISR, off-shell tops
  - 2->2 pp $\rightarrow t\bar{t}$, removing hard isolated photons from ISR. Remain photons from FSR, on-shell tops

  - Distribution of photon pT compared to LO sample, and since it was compatible, k-factor derived

How about non-resonant tops?

only this is simulated: this is tWgamma: this is not simulated, but supposed to be <0.5%[1]:

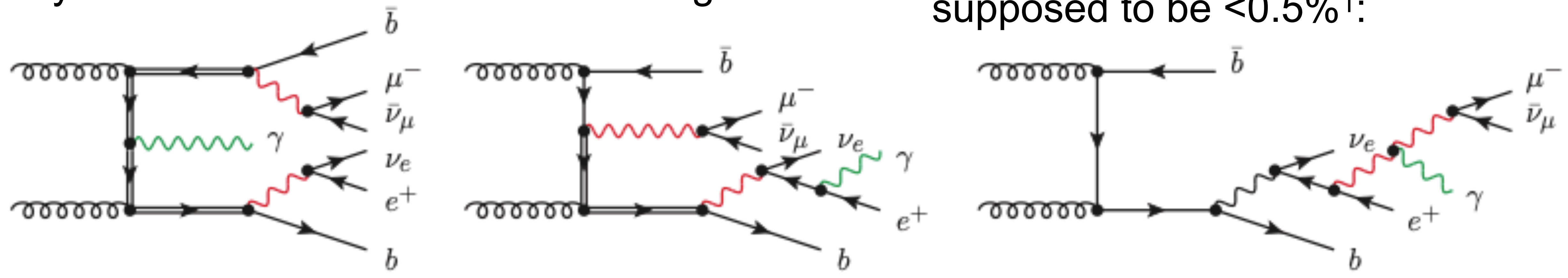


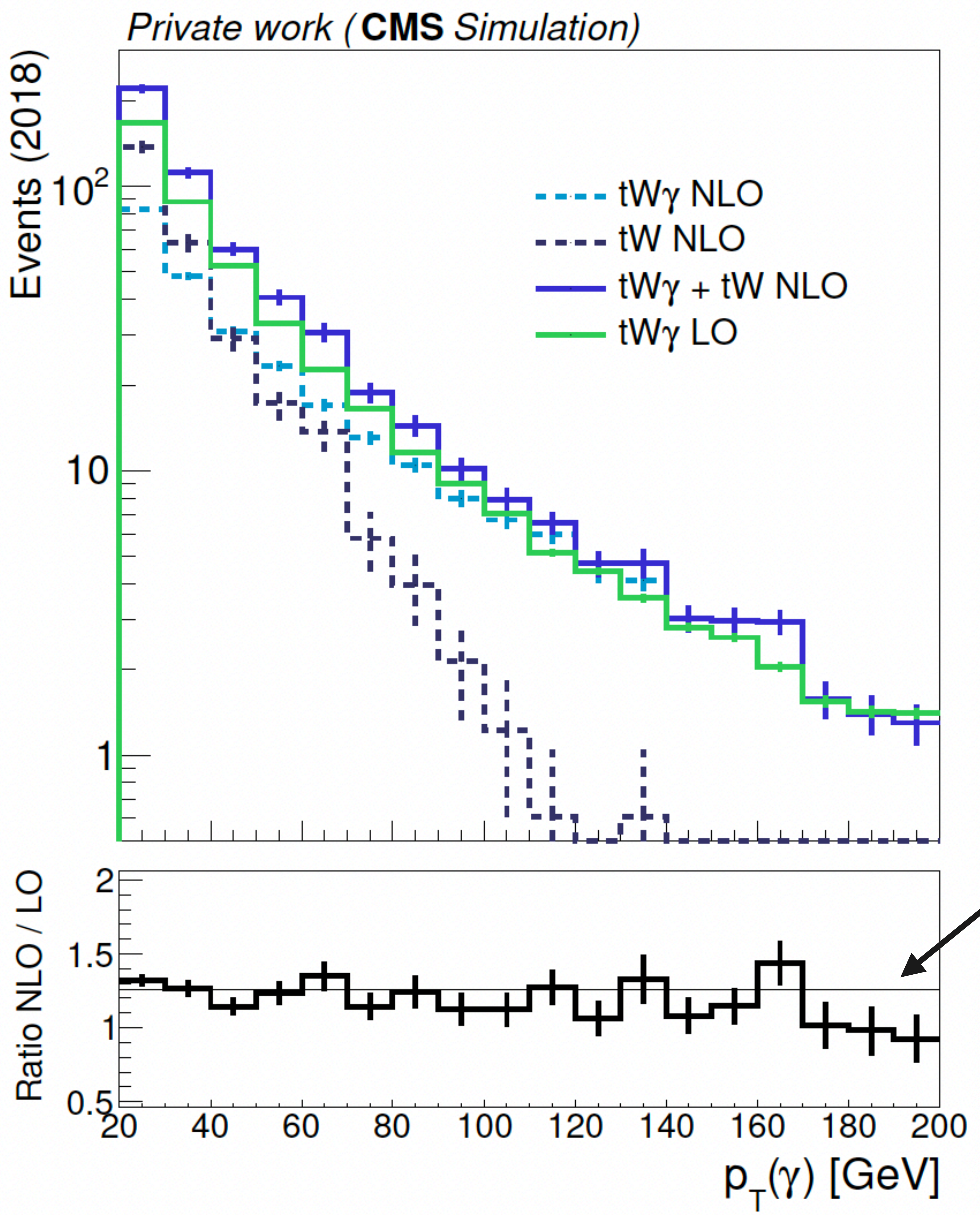
Figure 1. *Representative Feynman diagrams, involving two (first diagram), one (second diagram) and no top quark resonances (third diagram), contributing to pp $\rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ production at leading order.*

min. p_T (γ) [GeV]	max. $\lvert\eta(\gamma)\rvert$	max. $\lvert\eta(\ell)\rvert$	min. $\Delta R(\gamma, j)$	min. $\Delta R(\gamma, \ell)$
10	5	5	0.1	0.1

Table 3.1: Fiducial phase space where the $t\bar{t}\gamma$ cross section is measured, based on the sample production requirements in MadGraph.

[1]: computed in arXiv 1912.09999v2

Simulating tWγ at LO



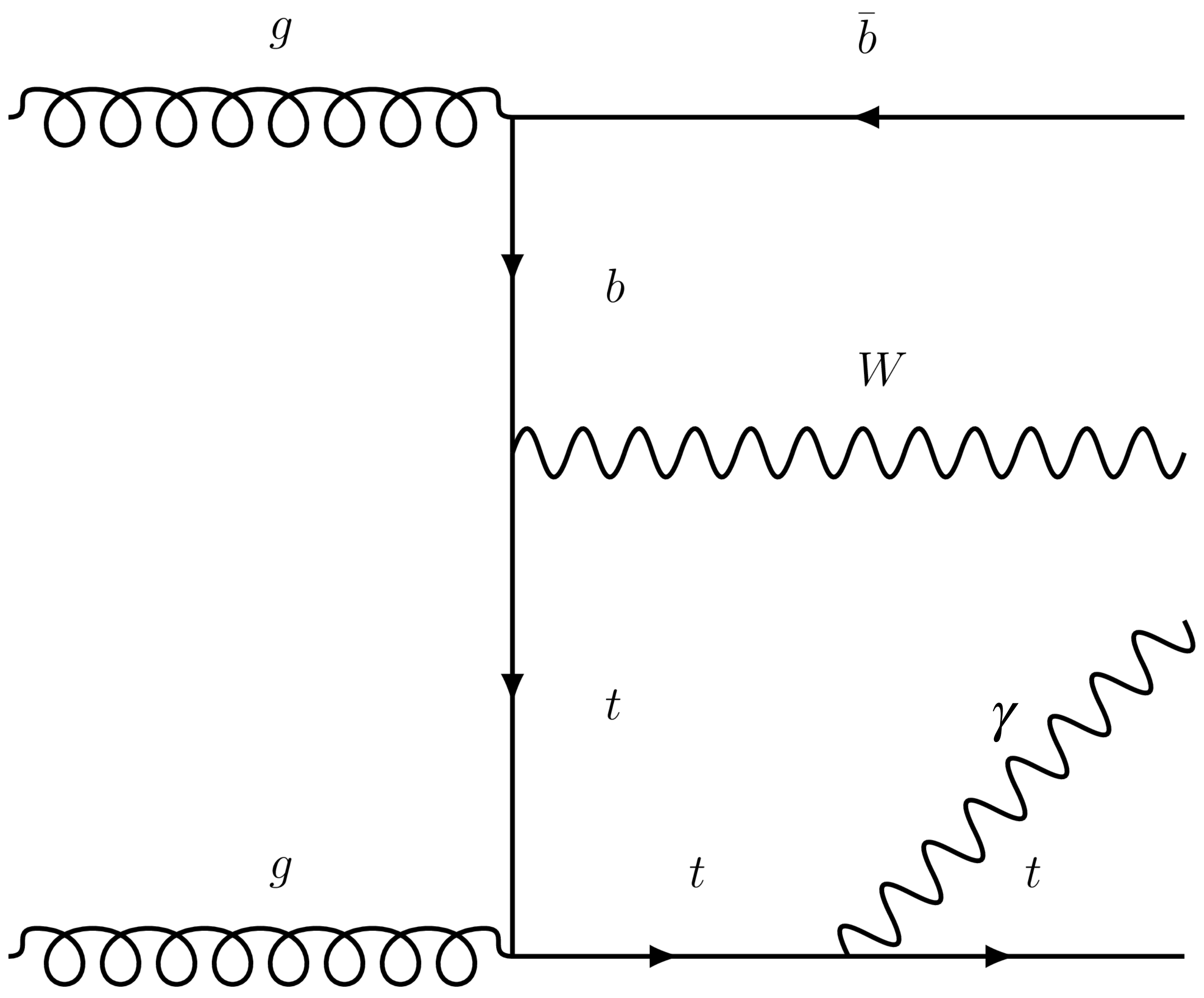
- Small sample simulated at NLO with aMC@NLO containing photons from production, but not from top decay
- Photons from decay present in tW NLO sample

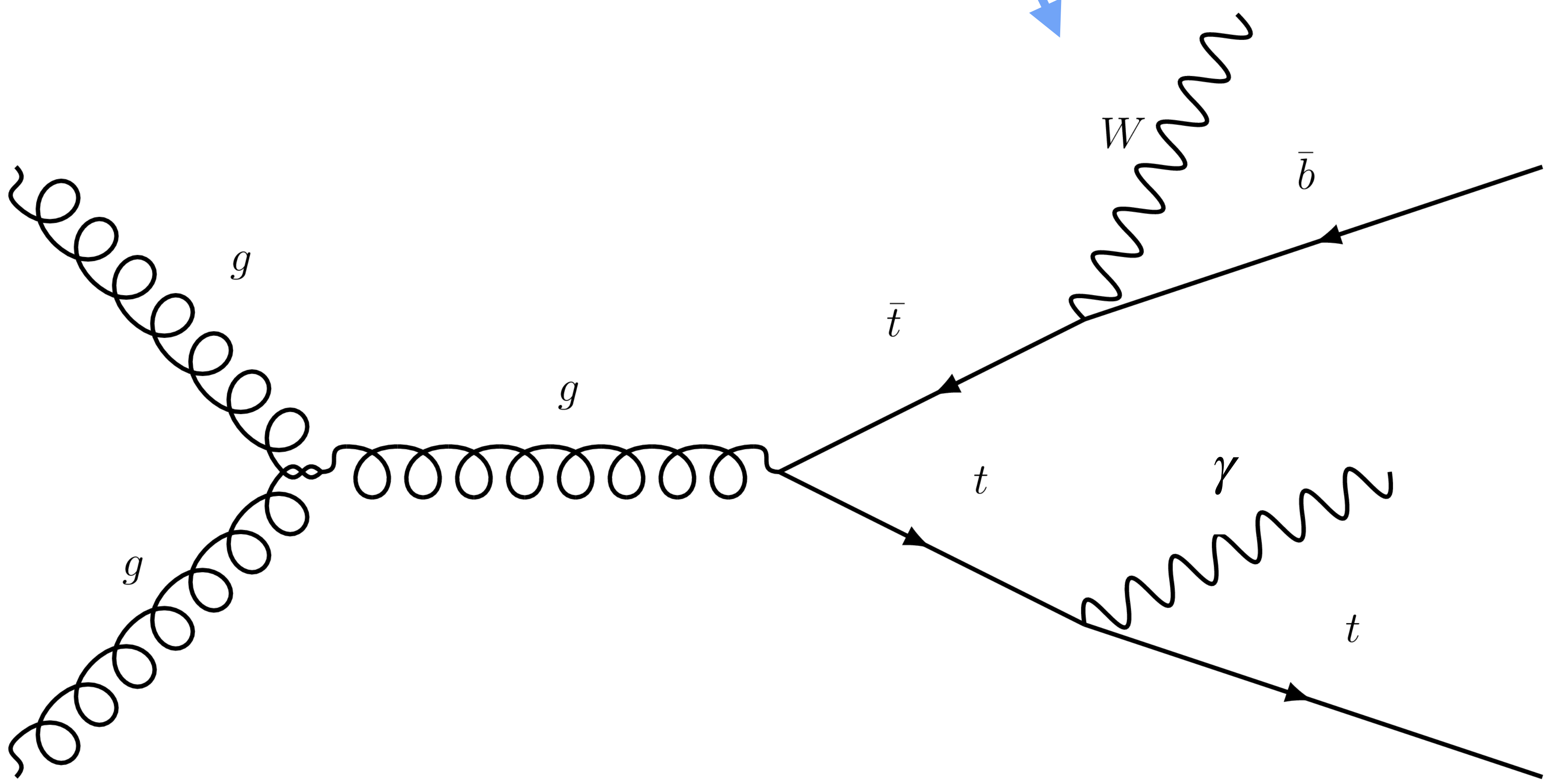
- Sum between two NLO samples compared with LO sample which contains all photon origins
- Distributions match
- Inclusive k-factor is derived

Figure 3.5: Comparison of the p_T (γ) distribution of the tWγ NLO sample (blue) with the tWγ LO sample used in the analysis (green). Photons from top and W decays are not present in the NLO sample and are added from the tW sample (dark blue dashed line).

Simulating $tW\gamma$ at NLO

- Small $tW\gamma$ sample simulated at next-to-leading order (NLO) with aMC@NLO
- Final state with $tWb\gamma$ appears at NLO
- The same final state can be the result of a resonant **LO** $t\bar{t}\gamma$ production





- The latter do not belong to $tW\gamma$ production but to $t\bar{t}\gamma$ and thus need to be removed
- Diagram removal is implemented using the DR2 scheme (same as in tWZ evidence paper from our group)

Simulating $\mathrm{tW}\gamma$ at NLO

- NLO with real emission: $\mathrm{p} + \mathrm{p} \rightarrow \underbrace{\mathrm{t} + \mathrm{W}^-}_{\text{can be resonant } \bar{\mathrm{t}}} + \bar{\mathrm{b}} + \gamma$

- Amplitude: $\mathscr{A}_{pp\rightarrow tW^-\gamma} = \mathscr{A}^{\mathrm{non-resonant}}_{pp\rightarrow tW^-\gamma} + \mathscr{A}^{\mathrm{resonant}}_{pp\rightarrow tW^-\gamma}$

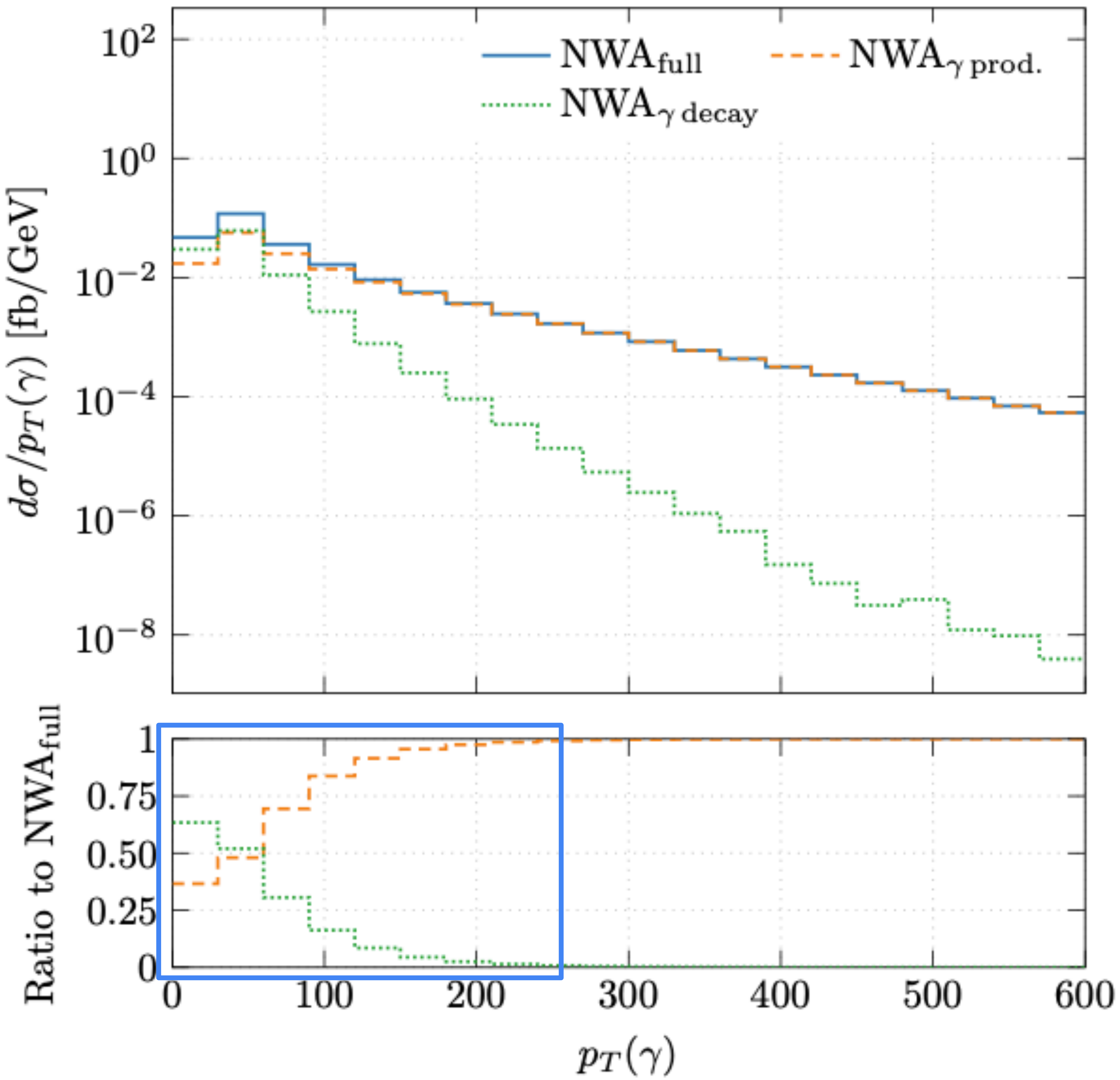
- Matrix element:

$$|\mathscr{A}_{pp\rightarrow tW^-\gamma}|^2 = |\mathscr{A}^{\mathrm{non-resonant}}_{pp\rightarrow tW^-\gamma}|^2 + \underbrace{\cancel{|\mathscr{A}^{\mathrm{resonant}}_{pp\rightarrow tW^-\gamma}|^2}}_{\text{DR2}} + 2\mathscr{R}(\mathscr{A}^{\mathrm{non-resonant}}_{pp\rightarrow tW^-\gamma}\mathscr{A}^{\mathrm{resonant}\,\dagger}_{pp\rightarrow tW^-\gamma})$$

interference terms are kept

Photon origins in $t\bar{t}\gamma$

[arXiV:1912.09999v2]



Nonprompt photon contribution

- Photon from hadron decay: the reconstructed photon is matched to a generator-level photon originating from a hadron decay (most commonly a π^0 meson). This type of photons are often called fragmentation or hadronic photons.

- Misidentified ("fake") electron: the reconstructed photon is matched to a generator-level electron. The contribution of this category to nonprompt photons is very small, especially after applying the pixel seed veto, described in section 3.3.1.

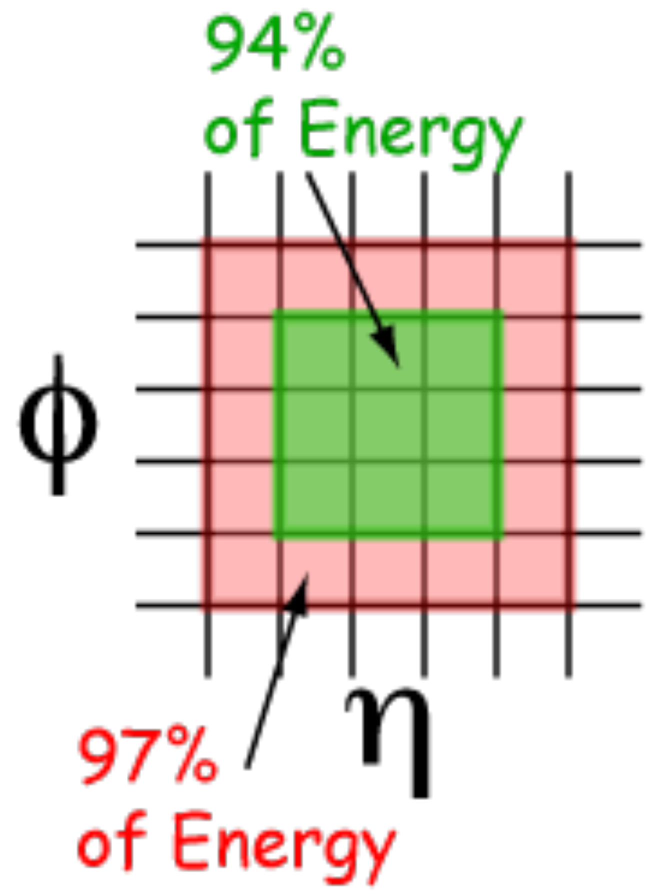
- Misidentified ("fake") jet: the matching procedure fails as there is no generated particle close to the reconstructed photon to carry at least 50% of its p_{T}. There are however multiple generated particles inside the ΔR cone around the reconstructed photon. These objects are not real photons, rather they correspond to hadronic jets.

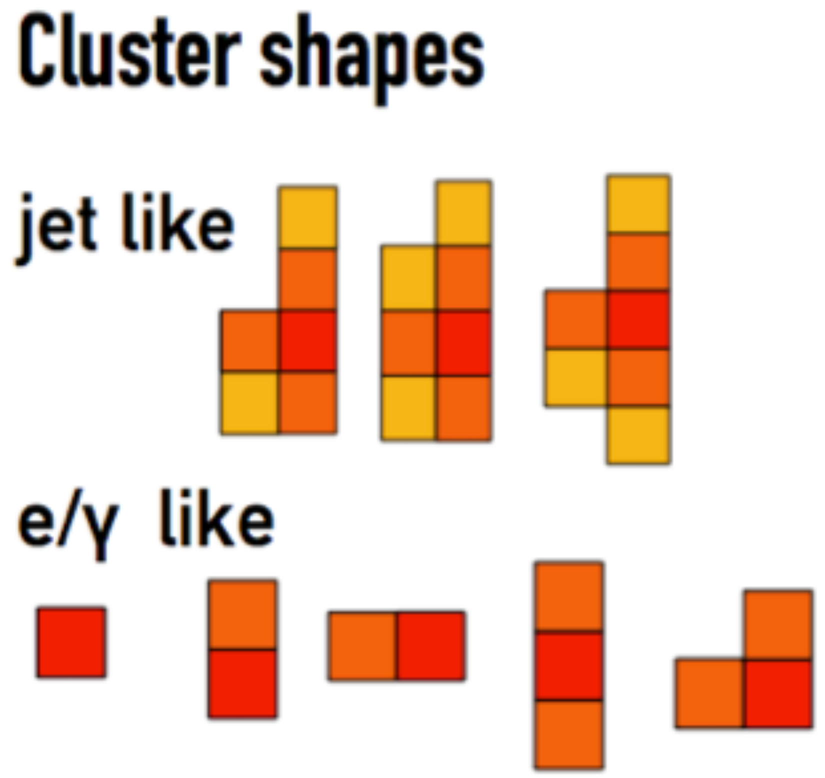
- Photon from pileup: the matching procedure fails, as no particle is found within the ΔR cone. These photons are often attributed to pileup and represent a relatively large contribution to the nonprompt category. This is because photons are not reconstructed from tracks, and therefore it is not trivial to match them to the PV.

Nonprompt photon estimation (1)

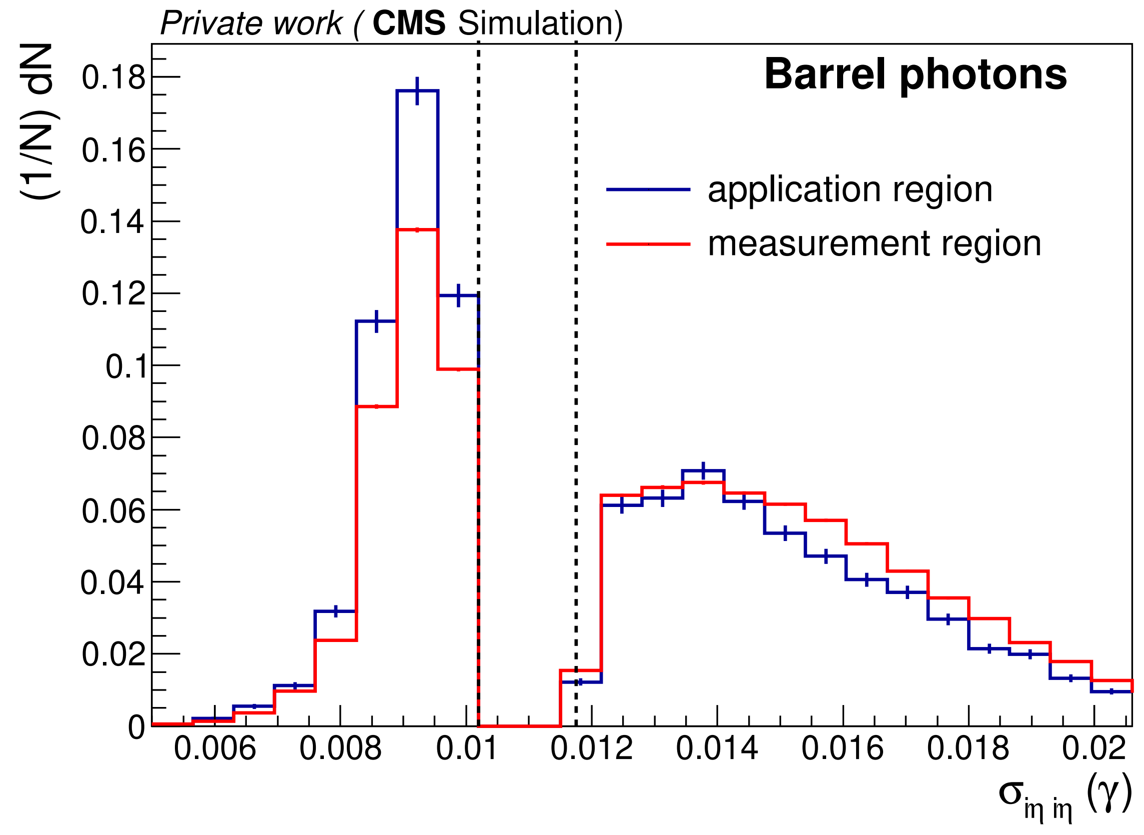
- Width of the EM shower ($\sigma_{i\eta i\eta}$): The $\sigma_{i\eta i\eta}$ is defined as the second moment of the log-weighted distribution of crystal energies in η, calculated in the 5×5 matrix around the most energetic crystal in the SC and re-scaled to units of crystal size. This distribution is expected to be narrow for electrons and single photons, and wider for double-photon signals originating from the decays of π^0 mesons.

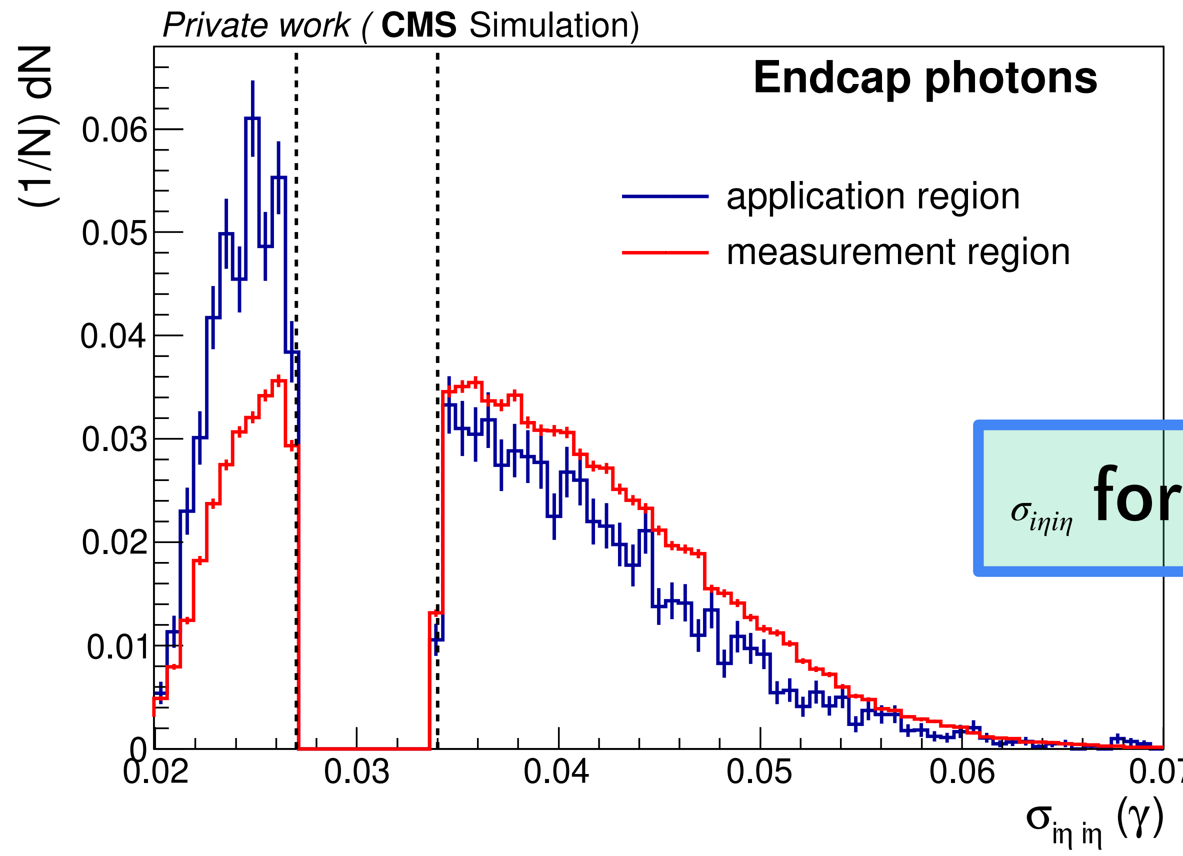
- Charged and neutral hadron and photon isolation: The isolation variables are obtained by summing the transverse momenta of charged hadrons (I_{ch}), neutral hadrons (I_{n}) or photons (I_γ) inside an isolation cone of $\Delta R = 0.3$ with respect to the photon direction. The neutral hadron and photon isolation are computed as a function of the photon p_{T}.



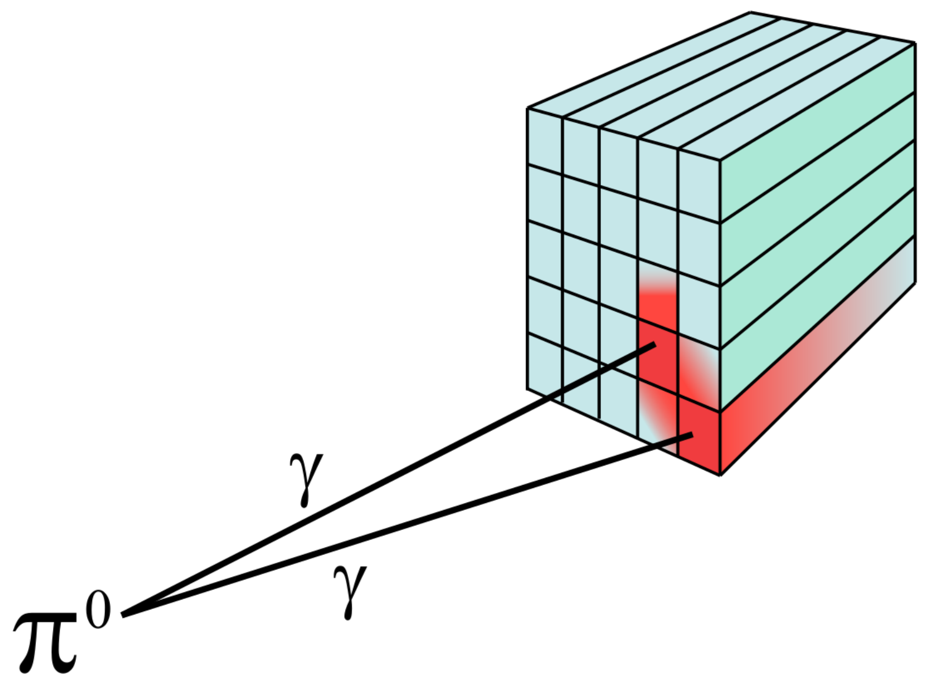


for ABCD method, must be mostly uncorrelated
– they are, but residual correlations exist, especially in endcap





$\sigma_{i\eta i\eta}$ for two ranges of I_{ch}



Algorithm for $t\bar{t}$ reconstruction

- Algebraic method is used: six kinematics constraints applied to determine the 4-momentum of the 2 neutrinos
- Equations solved analytically with a maximum of 4 solutions
- To improve reconstruction efficiency, energies and directions of jets and leptons are smeared according to detector resolution

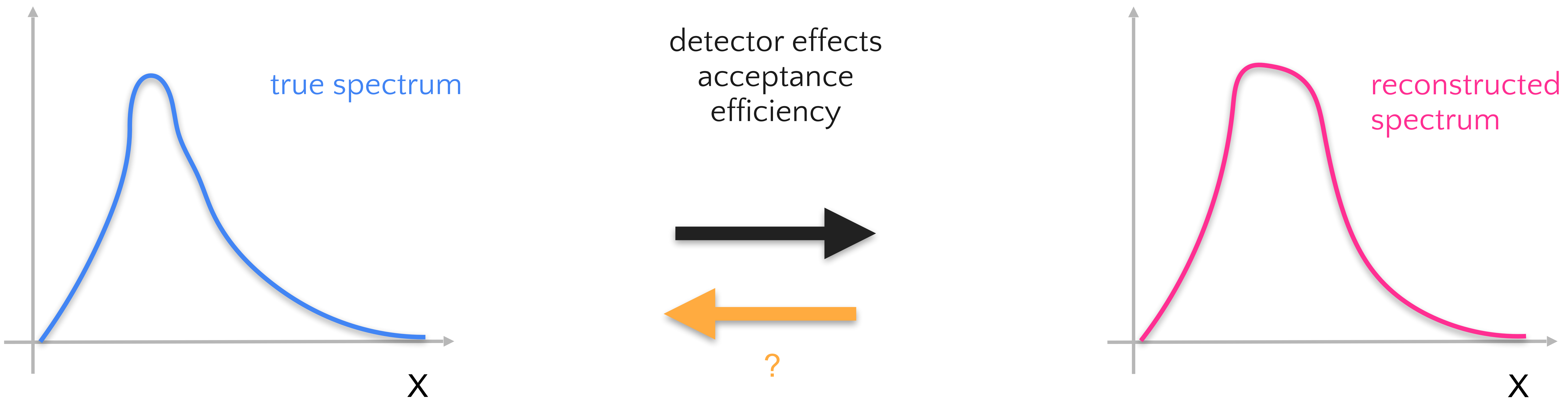
$$\not{E}_{\mathrm{x}} = p_{\mathrm{x},\nu} + p_{\mathrm{x},\bar{\nu}}$$
$$\not{E}_{\mathrm{y}} = p_{\mathrm{y},\nu} + p_{\mathrm{y},\bar{\nu}}$$

$$\begin{aligned}
m_{W^+}^2 &= (E_{\ell^+} + E_\nu)^2 - (p_{\mathrm{x},\ell^+} + p_{\mathrm{x}.\nu})^2 \\
&- (p_{\mathrm{y},\ell^+} + p_{\mathrm{y},\nu})^2 - (p_{\mathrm{z},\ell^+} + p_{\mathrm{z},\nu})^2 \\
m_{W^-}^2 &= (E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\mathrm{x},\ell^-} + p_{\mathrm{x},\bar{\nu}})^2 \\
&- (p_{\mathrm{y},\ell^-} + p_{\mathrm{y},\bar{\nu}})^2 - (p_{\mathrm{z},\ell^-} + p_{\mathrm{z},\bar{\nu}})^2
\end{aligned}$$

$$\begin{aligned}
m_t^2 &= (E_{\ell^+} + E_\nu + E_b)^2 - (p_{\mathrm{x},\ell^+} + p_{\mathrm{x},\nu} + p_{\mathrm{x},b})^2 \\
&- (p_{\mathrm{y},\ell^+} + p_{\mathrm{y},\nu} + p_{\mathrm{y},b})^2 - (p_{\mathrm{z},\ell^+} + p_{\mathrm{z},\nu} + p_{\mathrm{z},b})^2 \\
m_{\bar{t}}^2 &= (E_{\ell^-} + E_{\bar{\nu}} + E_{\bar{b}})^2 - (p_{\mathrm{x},\ell^-} + p_{\mathrm{x},\bar{\nu}} + p_{\mathrm{x},\bar{b}})^2 \\
&- (p_{\mathrm{y},\ell^-} + p_{\mathrm{y},\bar{\nu}} + p_{\mathrm{y},\bar{b}})^2 - (p_{\mathrm{z},\ell^-} + p_{\mathrm{z},\bar{\nu}} + p_{\mathrm{z},\bar{b}})^2
\end{aligned}$$

- Based on method by Sonnenschein [Phys.Rev.D73:054015,2006]

Unfolding



- Need to recover true spectrum (unfolding)
- Corresponds to inverting the response matrix (entries are reco. vs gen. quantities in bins 1,…,i,…N)
- Can be done by subtracting the backgrounds and inverting the matrix – classical method, usually implemented in TUnfold [arXiv:1205.6201]
- Can also be done by doing a **simultaneous maximum-likelihood fit** to N signal templates, each defined by requiring that the event is in the i^{th} generator-level bin.
  - ✓ Background template normalisations are included as nuisance parameters, as well as all relevant sources of experimental and systematic uncertainties

Maximum likelihood fit

We expect $\lambda_i(\mu) = \mu \cdot s_i + \sum_j^{N_{\text{bkg}}} b_{i,j}$ events in bin i, where $\mu = \frac{\sigma_{t\bar{t}\gamma}}{\sigma^{\text{SM}}_{t\bar{t}\gamma}}$ is the parameter of interest (POI).

Probability of observing n_i events when $\lambda_i(\mu)$ are expected is $P(n_i | \mu) = \frac{\lambda_i(\mu) e^{-\lambda_i(\mu)}}{n_i!}$ without systematic uncs.

Likelihood (probability of seeing the observed data for a given μ): $\mathcal{L}(\mathbf{n} | \mu) = \prod_{i=1}^{N} \frac{\lambda_i(\mu) e^{-\lambda_i(\mu)}}{n_i!}$

With M systematic uncertainties included as nuisance parameters Θ:

$$\underbrace{\mathcal{L}(\mathbf{n} | \mu) = \prod_{i=1}^{N} \frac{\lambda_i(\mu, \boldsymbol{\Theta}) e^{-\lambda_i(\mu, \boldsymbol{\Theta})}}{n_i!} \cdot \prod_{m=1}^{M} f(\Theta_m)}_{\text{maximised, by minimising } -2 \log(\mathcal{L})}$$

p.d.f. constraining each NP, typically Gaussian

Profiled likelihood ratio:

maximum for each μ

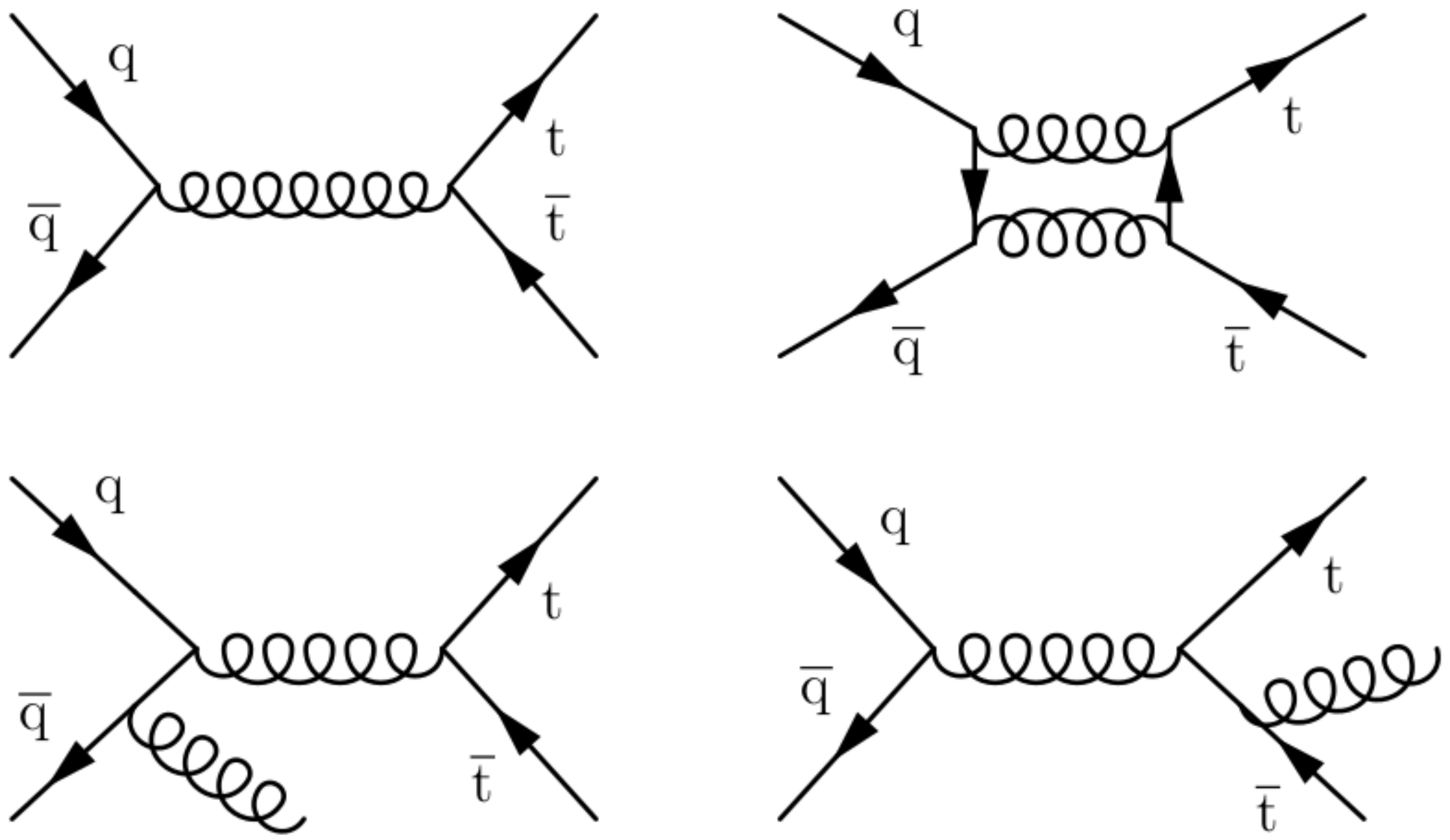
$$q_\mu = \frac{\mathcal{L}(\mathbf{n} | \mu, \hat{\hat{\Theta}}_\mu)}{\mathcal{L}(\mathbf{n} | \hat{\mu}, \hat{\Theta})}$$

global maximum

used to quantify how compatible the observed data is with a given hypothesis

Charge asymmetry

- In $t\bar{t}$: caused by interference between NLO $q\bar{q}$ diagrams

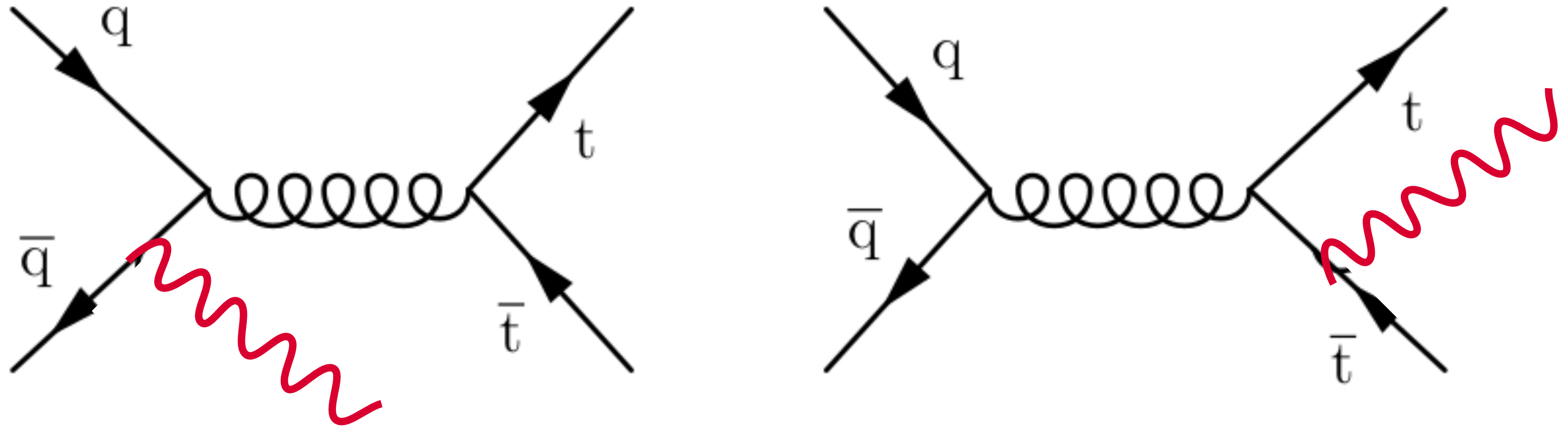


Why measure it in $t\bar{t}\gamma$?

- gg fusion diagrams represent 79% (88%) of $t\bar{t}\gamma$ ($t\bar{t}$)
- Interference with photon diagrams bring additional (negative) contribution

- In $t\bar{t}\gamma$: caused by interference between NLO in QCD $q\bar{q}$ diagrams and **additionally** LO diagrams with photons from initial state quarks or tops

$t\bar{t}\gamma$ (LO):



$t\bar{t}\gamma$ limits on EFT by CMS

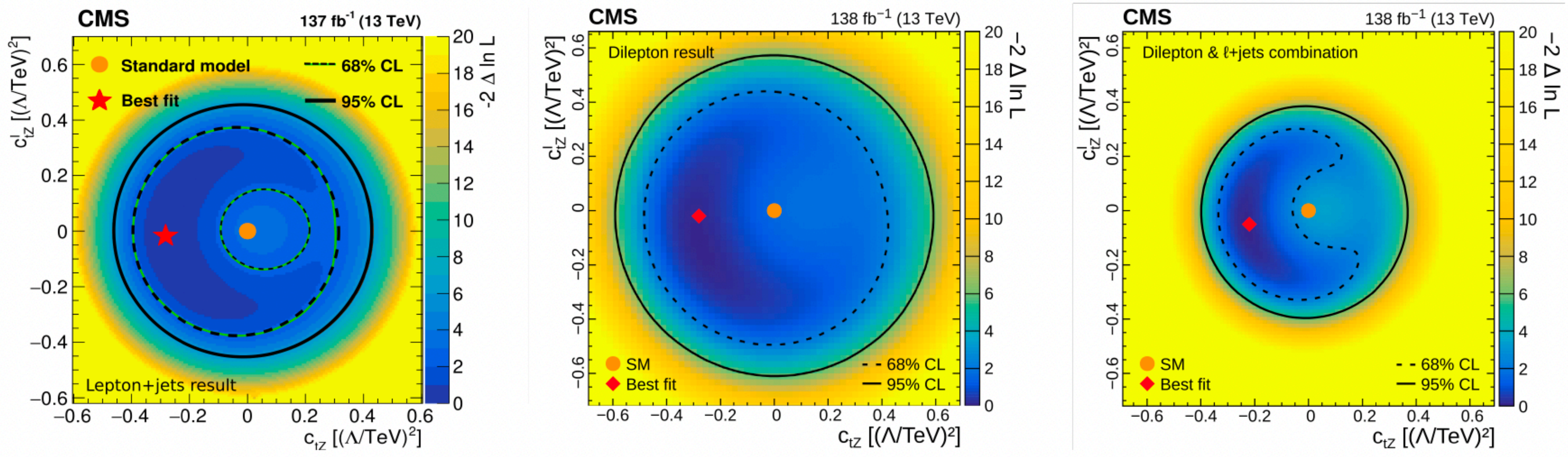


Figure 3.1: Result from the two-dimensional scan of the Wilson coefficients c_{tZ} and c^{I}_{tZ} using the photon p_T distribution from the lepton+jets analysis (left), the dilepton (centre) or the combination of the two (right). The shading quantified by the colour scale on the right reflects the negative log-likelihood difference with respect to the best fit value that is indicated by the red diamond. The 68% (dashed curve) and 95% (solid curve) CL contours are shown for the observed result. The orange circle indicates the SM prediction. Images adapted from Refs. [138, 139].

SMEFT with $t\bar{t}\gamma/t\bar{t}$

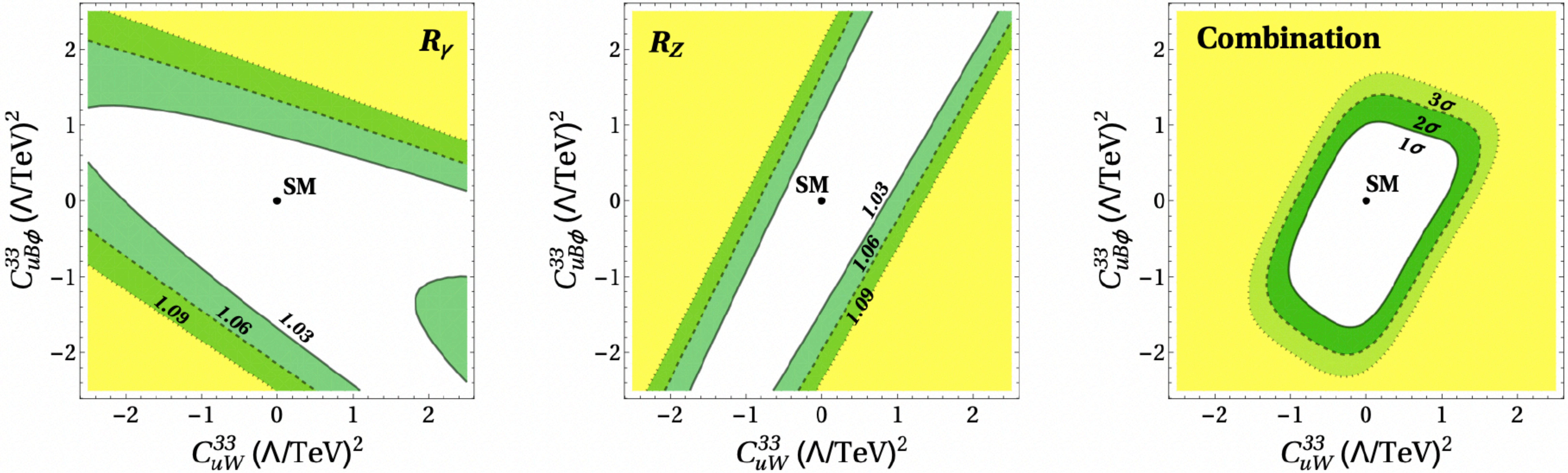


Figure 1.15: Cross section ratios R_γ (left) and R_Z (middle) normalized to their SM values (R_{SM}) as a function of the γ/Z anomalous dipole operator couplings. The contours show the deviation from the SM value in steps of 3, 6, and 9 per cent. On the right, we show the 1, 2, 3σ contours from combining R_γ and R_Z with an assumed uncertainty of 3%. From Ref. [79].

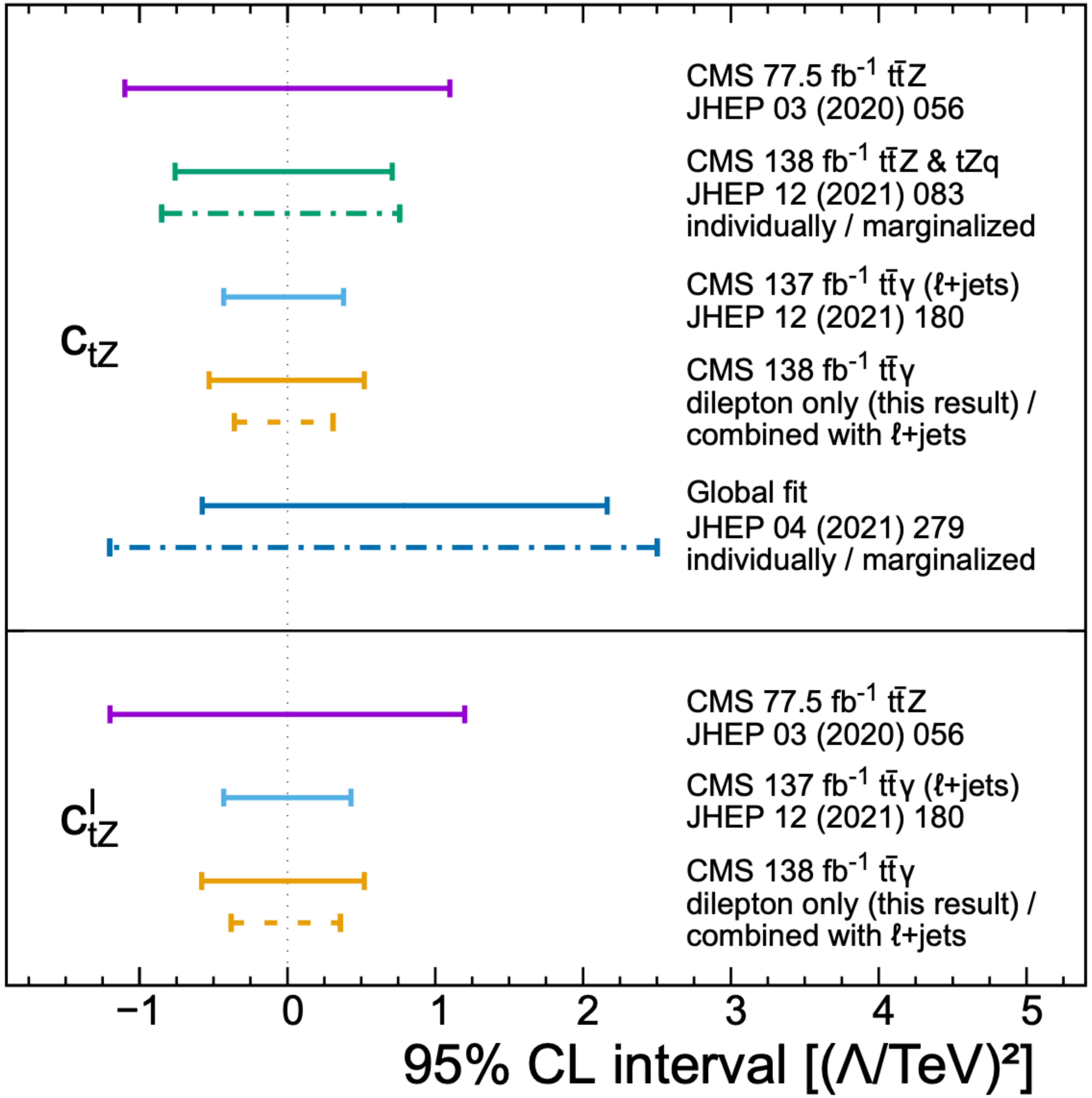
SMEFT with $t\bar{t}\gamma$ and $t\bar{t}Z$

$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_W c_{uB}^{(33)} + \cos\theta_W c_{uW}^{(33)}\right),$$

$$c_{tZ}^{I} = \mathrm{Im}\left(-\sin\theta_W c_{uB}^{(33)} + \cos\theta_W c_{uW}^{(33)}\right),$$

$$c_{t\gamma} = \mathrm{Re}\left(\cos\theta_W c_{uB}^{(33)} - \sin\theta_W c_{uW}^{(33)}\right),$$

$$c_{t\gamma}^{I} = \mathrm{Im}\left(\cos\theta_W c_{uB}^{(33)} - \sin\theta_W c_{uW}^{(33)}\right).$$



SMEFT with top quarks