# Simultaneous t$\gamma$q+$t\bar{t}\gamma$ measurement

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**CMS TOP EFT meeting**

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# Overview

## Analysis Goal

- tγq+tt̄γ inclusive/differential cross sections
- tγq+tt̄γ EFT interpretation
- Analysing full Run2 data in the single lepton channel

## Effective Field Theory

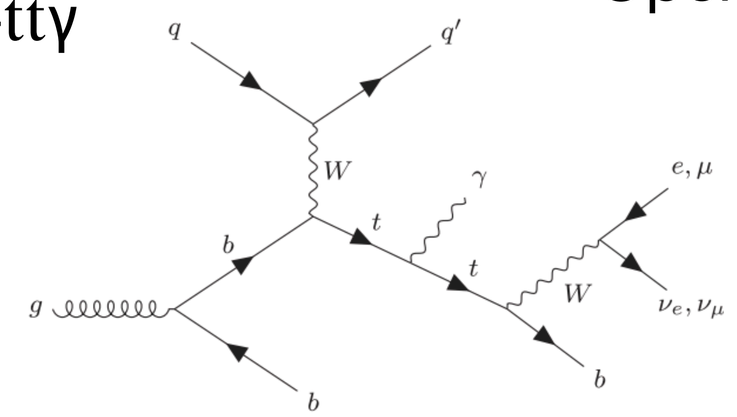
- Aim at do EFT fit for tγq+tt̄γ simultaneously

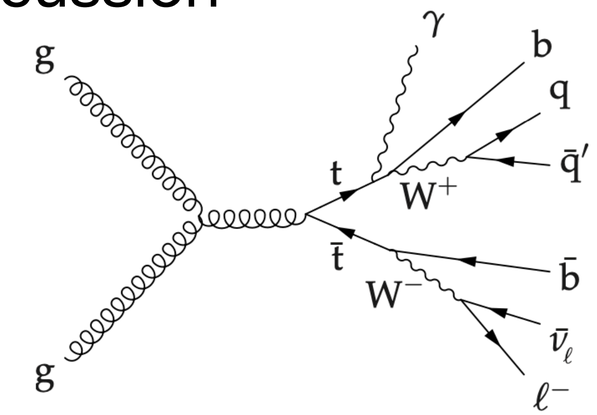
## More details:

- tX+ttX talk on April 23
- tX talk on May 29

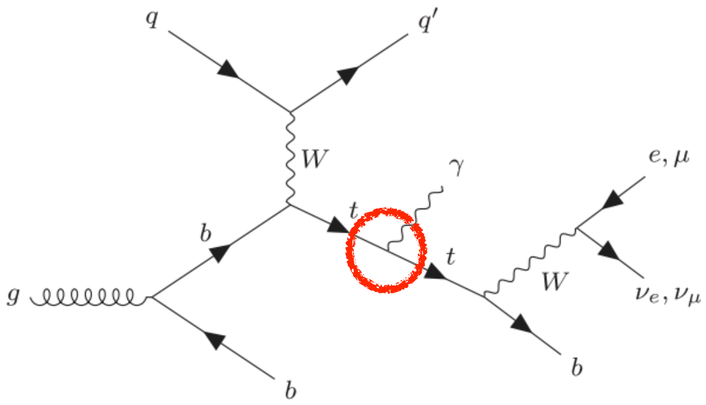
## Outline:

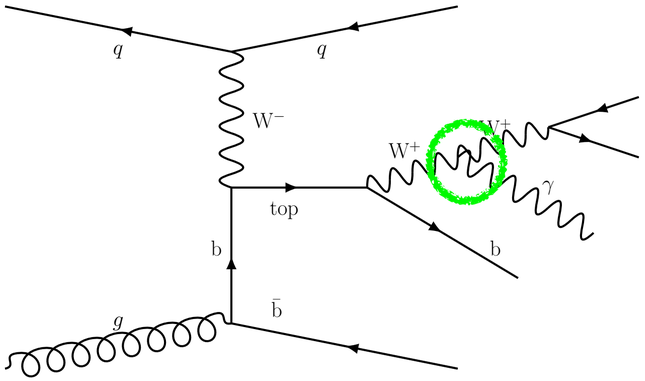
- Analysis overview
- EFT theory and framework
- Open discussion



# Motivation

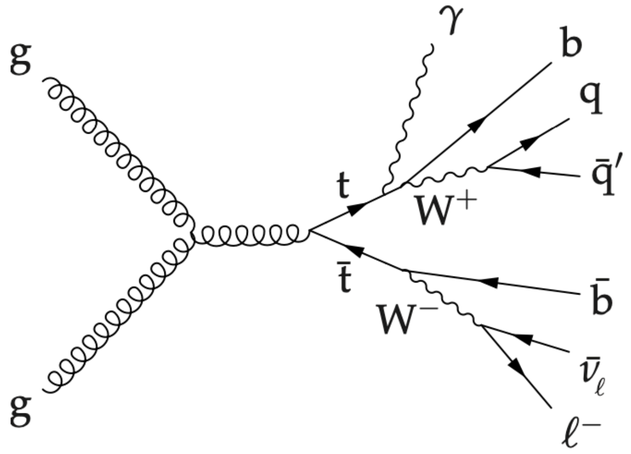



- The tγq process is observed by ATLAS. CMS has the evidence paper with partial data. No differential cross section results to date.
  - First-ever differential measurement
- This process represents a direct probe of the top-photon coupling
  - Anomalous top coupling (top-photon electroweak) by top EFT fit is interesting (tγq+ttγ EFT)
  - Could perform the EFT interpretation for tγq+ttγ

Advantage of the simultaneous fit for tγq+ttγ

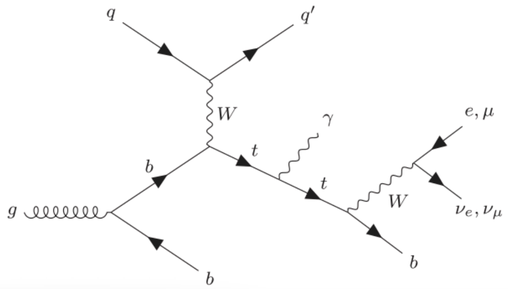
- Full set of correlations between the two processes
- Possible for a more straightforward EFT interpretation
- High precision ttγ results

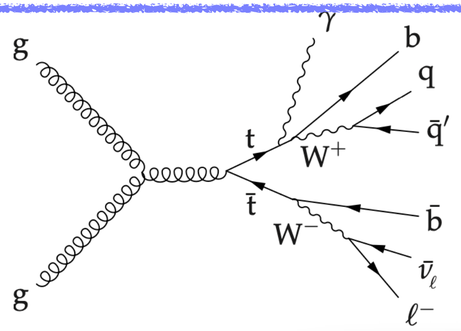


# Goal and strategy

## Separate signal and background

- Train **MVA** to separate tγq, $t\bar{t}\gamma$ and others



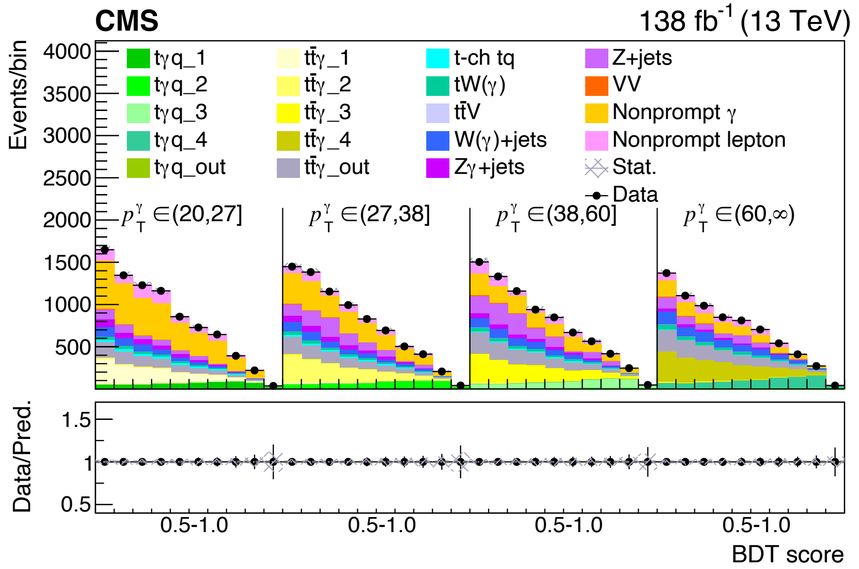



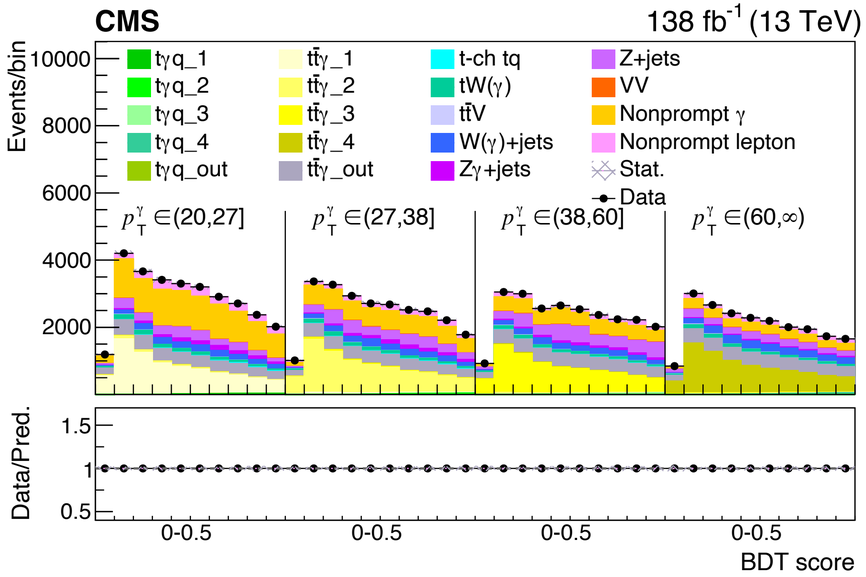

Events of interest: **$N_\ell$=1, $N_\gamma$ ≥1, $N_j$≥2, $N_b$≥1**

- tγq+$t\bar{t}\gamma$ inclusive/differential cross sections
- tγq+$t\bar{t}\gamma$ EFT interpretation

## Background estimation/constraint ($t\bar{t}\gamma$ as signal):

- Simulation: $t\bar{t}$, V+Jets/Vγ+Jets, tW/tWγ, TTV, VV
- Data-Driven backgrounds:
  - j→γ, j→ℓ, e→γ (mainly in e channel)
- Define proper control regions
  - Constrain main and data-driven background normalisations



# SMEFT Parameter — Wilson Coefficients

Productions of tγq+tt̄γ are expected to be sensitive to several EFT operators coupling to the weak hypercharge and isospin gauge bosons, $C_{tB}$, $C_{tW}$.

$$C_{2,\mathrm{V}}^{Z} = \frac{v^2 m_t}{\sqrt{2} c_w s_w m_Z \Lambda^2} \Re\left[C_{tZ}\right], \quad C_{2,\mathrm{A}}^{Z} = \frac{v^2 m_t}{\sqrt{2} c_w s_w m_Z \Lambda^2} \Im\left[C_{tZ}\right],$$

$$C_{2,\mathrm{V}}^{\gamma} = \frac{\sqrt{2} v m_t}{e \Lambda^2} \Re\left[C_{t\gamma}\right], \quad C_{2,\mathrm{A}}^{\gamma} = \frac{\sqrt{2} v m_t}{e \Lambda^2} \Im\left[C_{t\gamma}\right],$$

$$C_{tZ} = c_w \cdot C_{tW} - s_w \cdot C_{tB},$$

$$C_{t\gamma} = s_w \cdot C_{tW} + c_w \cdot C_{tB}.$$

Two-heavy $(9 + 6$ CPV d.o.f.)

| | | |
|---|---|---|
| $c_{t\varphi}^{[I]}$ | $\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{u\varphi}^{(33)}\}$ | |
| $c_{\varphi q}^{-}$ | $\equiv C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$ | $c_{\varphi q}^{1}$ $[-3.1, 3.1]$ [45], $[-8.3, 8.6]$ [46] |
| $c_{\varphi Q}^{3}$ | $\equiv C_{\varphi q}^{3(33)}$ | $[-4.1, 2.0]$ [45], $[-8.6, 8.3]$ [46] |
| $c_{\varphi t}$ | $\equiv C_{\varphi u}^{(33)}$ | $[-9.7, 8.3]$ [45], $[-9.1, 9.1]$ [46] |
| $c_{\varphi tb}^{[I]}$ | $\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{\varphi ud}^{(33)}\}$ | |
| $c_{tW}^{[I]}$ | $\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{uW}^{(33)}\}$ | $c_{tW}$ $[-4.0, 3.5]$ [45], $[-4.1, 4.1]$ [46] |
| $c_{tZ}^{[I]}$ | $\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}$ | $c_{tB}$ $[-6.9, 4.6]$ [45], $[-7.6, 7.6]$ [46] |
| $c_{bW}^{[I]}$ | $\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{dW}^{(33)}\}$ | |
| $c_{tG}^{[I]}$ | $\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{uG}^{(33)}\}$ | $c_{tG}$ $[-1.32, 1.24]$ [45] |

Two-heavy-two-lepton $(8 + 3$ CPV d.o.f. $\times 3$ lepton flavours)

https://arxiv.org/pdf/1802.07237

where $s_w$ ($c_w$) is the sine (cosine) of the Weinberg angle, $m_Z$ is the $Z$ boson mass and $C_{t\gamma}$ and $C_{tZ}$ are the EFT operators, which are linear combinations of the dipole operators $C_{tB}$, $C_{tW}$

# SMEFT model

- SMEFTsim (2012.11343): only LO mode

  SMEFTsim_topU3l_MwScheme_UFO: A case with a $U(2)^3$ symmetry in the quark sector and a $U(3)^2$ symmetry in the lepton sector

  Wilson coefficients expressed in terms of their real and imaginary parts, rather than absolute values, correspond to CP conserving (violating)

  $\mathfrak{Re}c_{tG}$, $\mathfrak{Re}c_{tW}$, $\mathfrak{Re}c_{tB}$ are selected to do reweighting

[1] https://feynrules.irmp.ucl.ac.be/wiki/SMEFT#no1

# Workflow

Prepare MG cards (reweighting card)

Get reweighing model from MG5

Reweight NanoAOD events by branch LHEPart_*

An extra branch Reweights is added into NaNoAOD

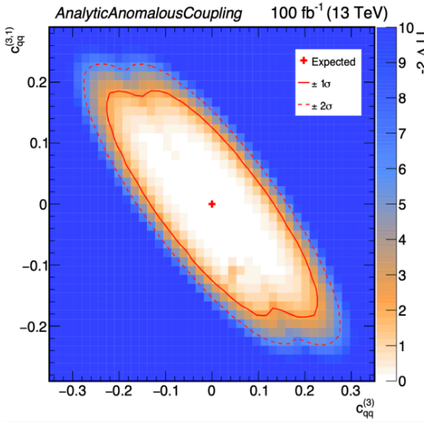
SM, Linear, Quad parts

AnomalousCouplingEFTNegative

```
## Shape input card
imax 1 number of channels
jmax * number of background
kmax * number of nuisance parameters
--------------------------------------------------------------------------------------------------------------
bin         inWW_cW
observation 0
shapes  *           * shapes/histos_inWW_cW.root     histo_$PROCESS histo_$PROCESS_$SYSTEMATIC
shapes  data_obs          * shapes/histos_inWW_cW.root     histo_Data
bin              inWW_cW                         inWW_cW                         inWW_cW
process          sm                              sm_lin_quad_cW                  quad_cW
process          1                               2                               3
rate             30611.7690                      34426.6029                      3957.9833
--------------------------------------------------------------------------------------------------------------
lumi  lnN        1.02                            1.02                            1.02
--------------------------------------------------------------------------------------------------------------
```

$$\begin{cases} \omega_{\text{Quad}} = 0.5 \cdot \left[\omega(k=1) + \omega(k=-1) - 2 \cdot \omega(k=0)\right] \\ \omega_{\text{SM}} = \omega(k=0) \\ \omega_{\text{Lin}} = 0.5 \cdot \left[\omega(k=1) - \omega(k=-1)\right] \end{cases}$$

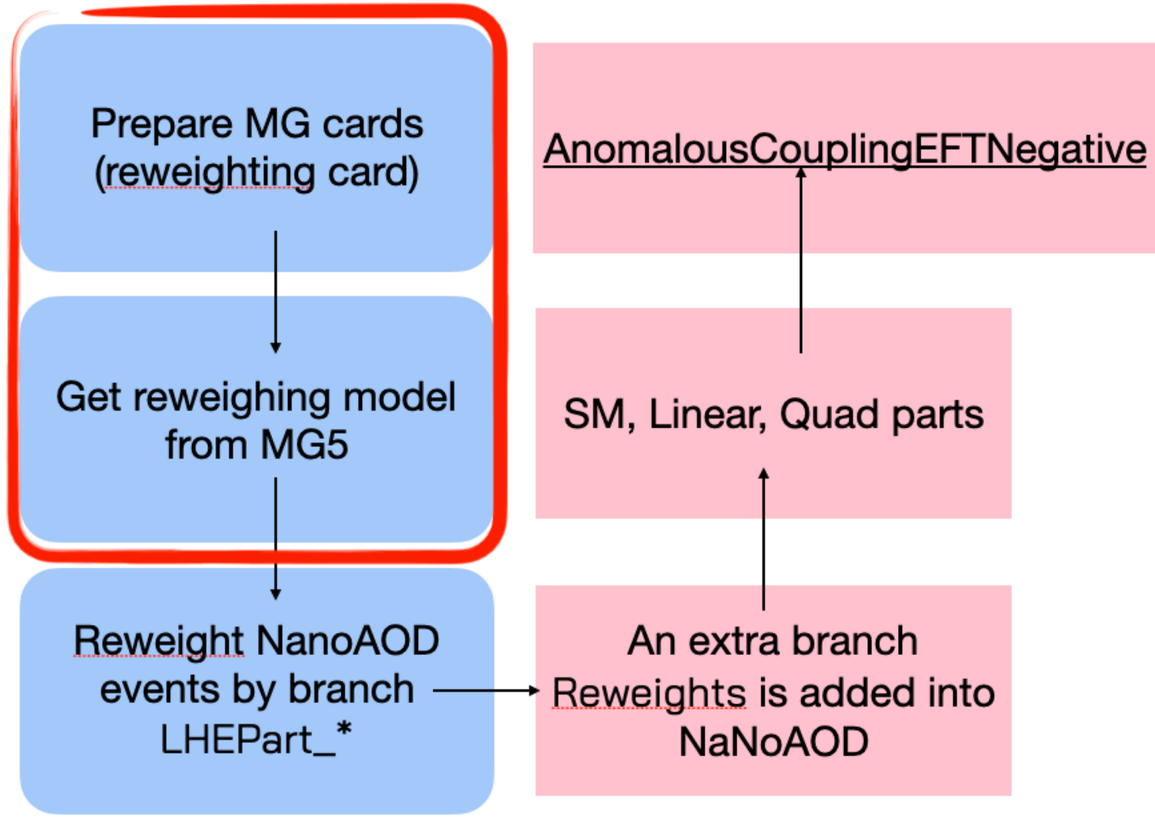
$$\omega_{\text{Mix}} = \omega(1,1) + \omega(0,0) - \omega(1,0) - \omega(0,1)$$



# EFT sample

- ✳ Official SM NLO tγq production with 4f scheme (no FSR)
- ✳ Private SM LO tγq production with 4f scheme (no FSR)
- ✳ Private SMEFTsim LO tγq production with 4f scheme (no FSR)

- ✦ Official SM NLO $t\bar{t}\gamma$ production with 5f scheme (no FSR)
- ✦ Official SM LO $t\bar{t}\gamma$ production with 4f scheme
- ✦ Private SM LO $t\bar{t}\gamma$ production with 4f scheme (no FSR)
- ✦ Private SMEFTsim LO $t\bar{t}\gamma$ production with 4f scheme (no FSR)

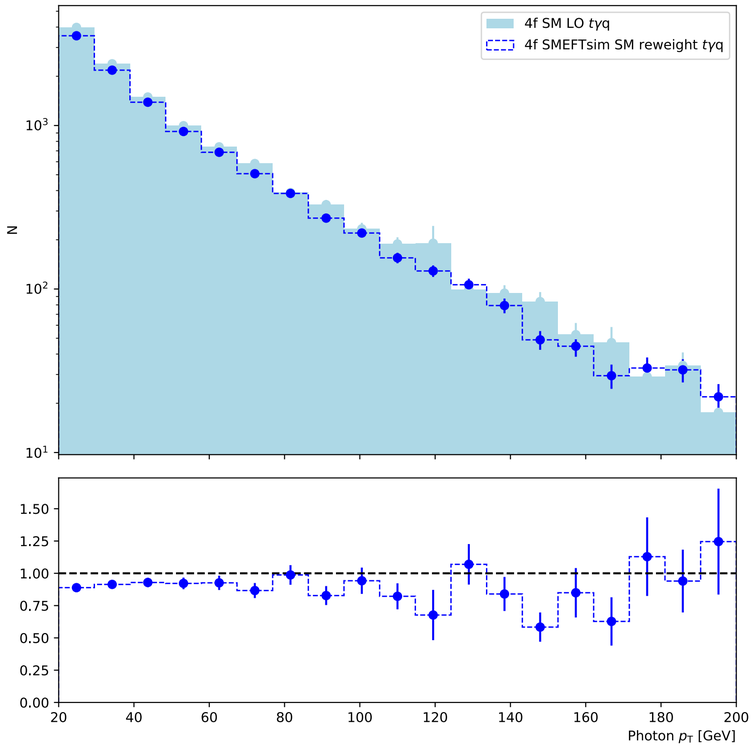


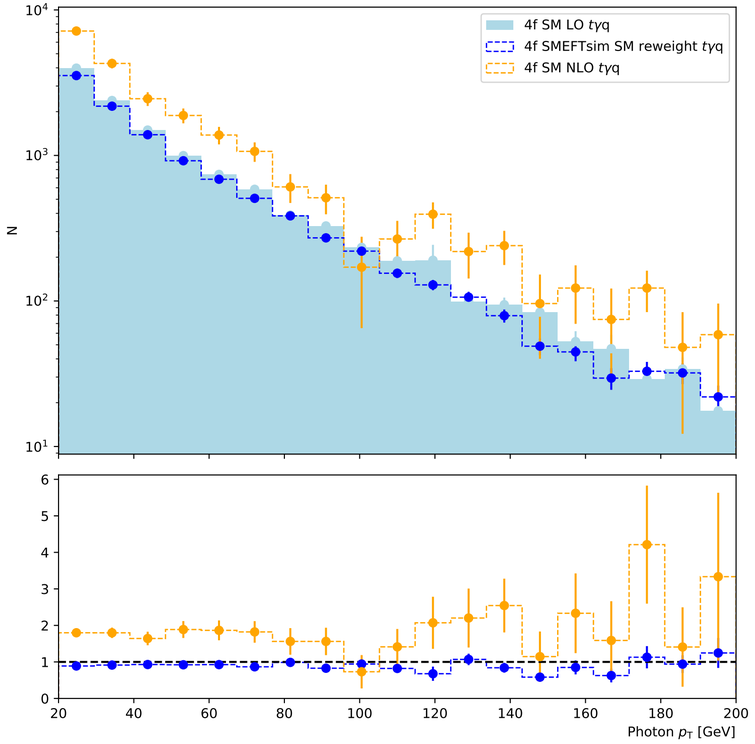

The signal samples used in our SM measurement are both NLO sample for tγq+ $t\bar{t}\gamma$, so a private LO SM gridpacks are produced to validate our EFT sample

# EFT sample validation — tγq

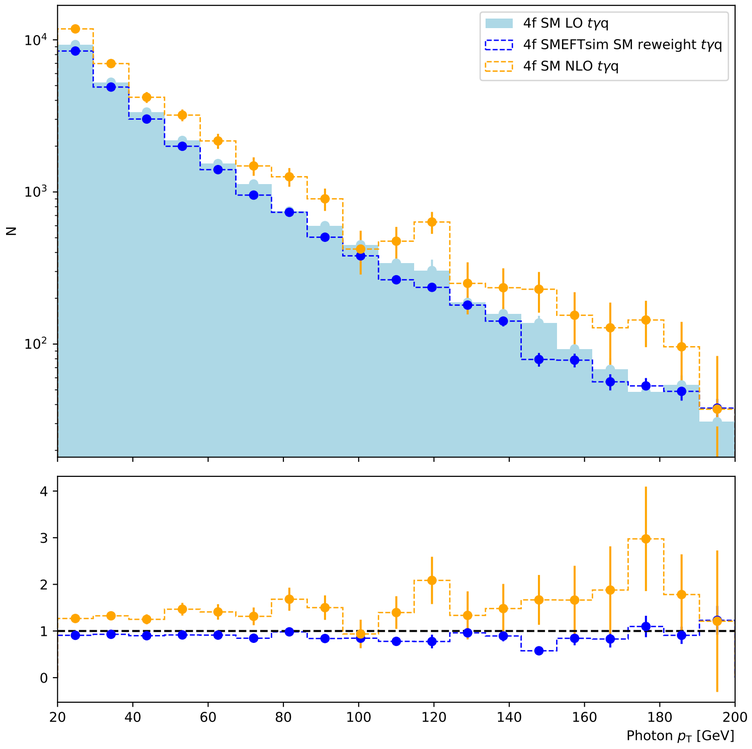
LHE level

Selection: **$N_\ell$=1, $N_\gamma \geq 1$, $N_j \geq 1$, $N_b \geq 1$** with $p_T$ > 20, 20, and 30 GeV




Without any selection

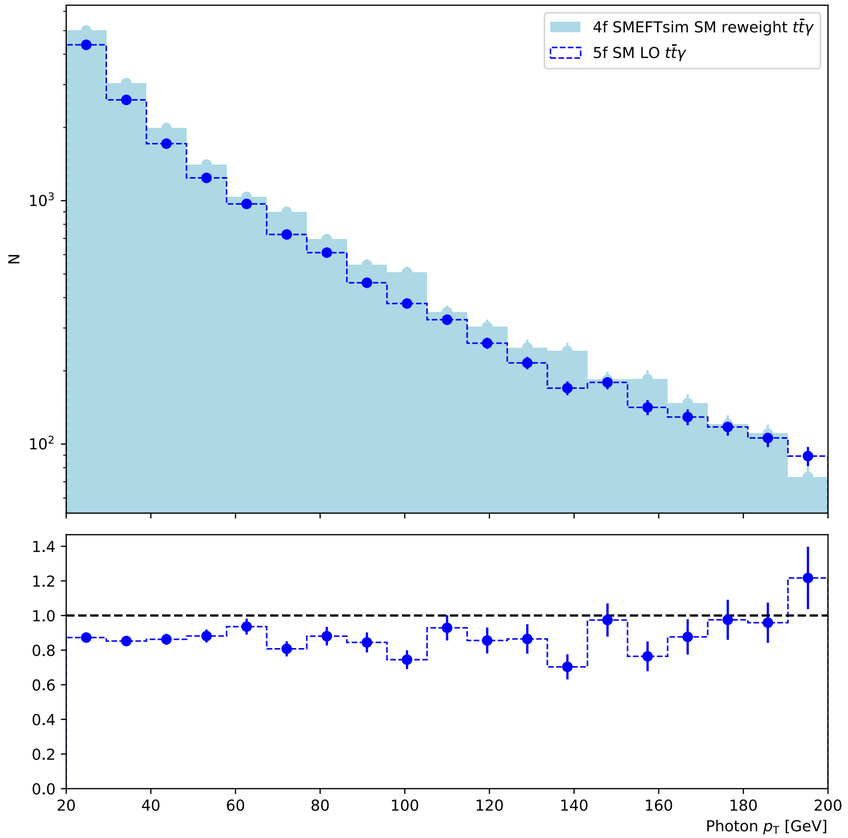


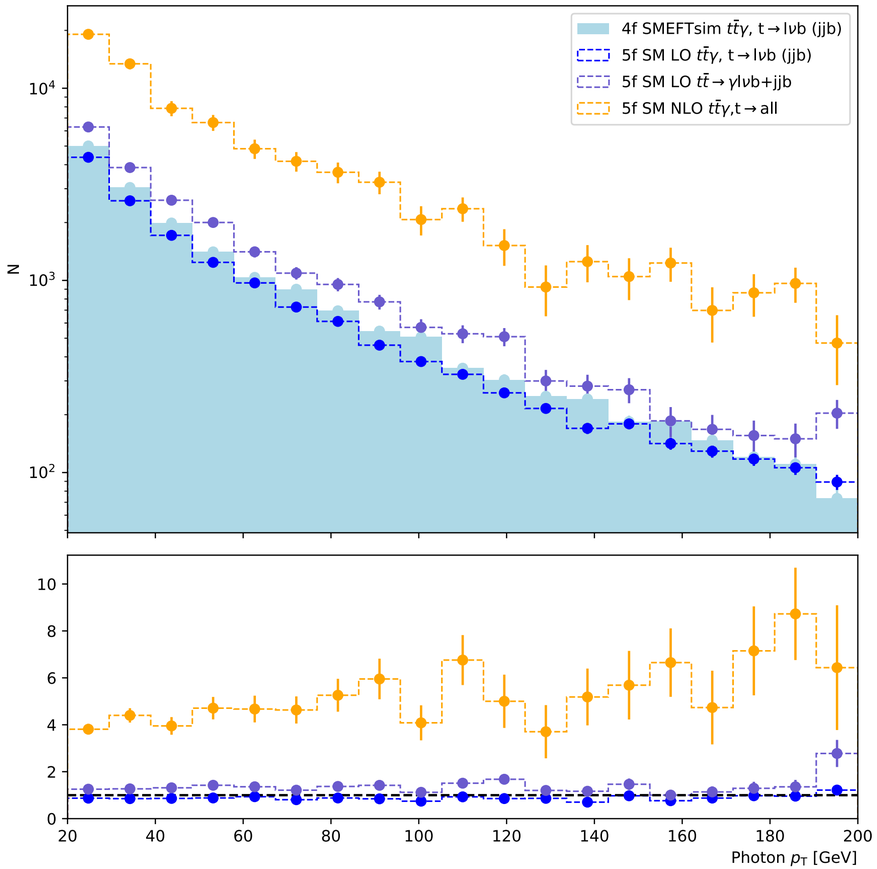

The agreement between EFT sample with SM reweight and SM LO sample looks reasonable in shape.
The difference in normalisation should come from the cross section values.

| XS/process | NLO tγq | LO tγq | EFT tγq with SM |
|---|---|---|---|
| Cross section/pb | 0.992 +- 0.004 | 0.72 +- 0.003 | 0.82 +- 0.1 |

# EFT sample validation — ttγ

LHE level  Selection: **$N_\ell \geq 1$, $N_\gamma \geq 1$, $N_j \geq 1$** with $p_T$ > 20, 20, and 30 GeV



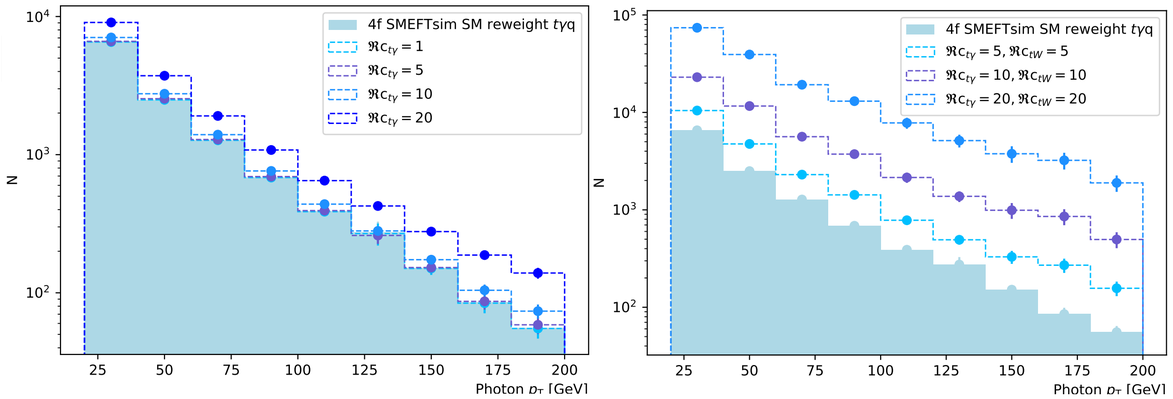




Similar case that no shape effect. But the normalisation difference between LO and NLO is really large.

| XS/process | NLO ttγ | LO ttγ (with FSR) | LO ttγ | EFT ttγ with SM weight |
|---|---|---|---|---|
| Cross section/pb | 2.58 +- 0.005 | 5.121 +- 0.004 | 0.6145 +- 0.002 | 0.73 +- 0.08 |

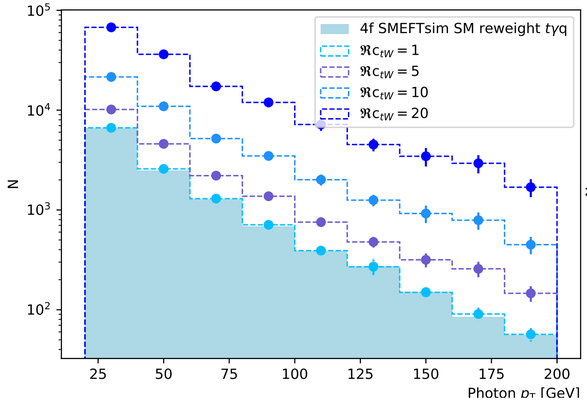
# Photon $p_T$ distributions — LHE-level

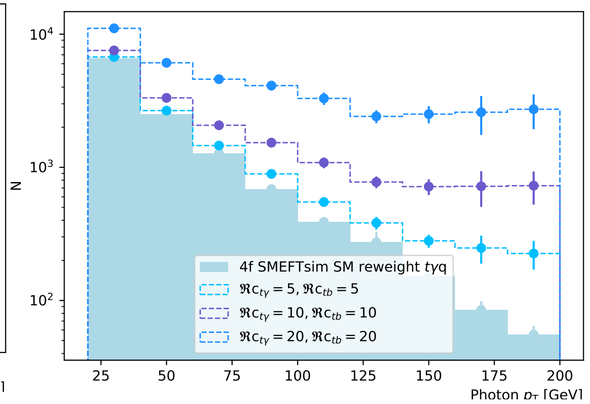
tγq

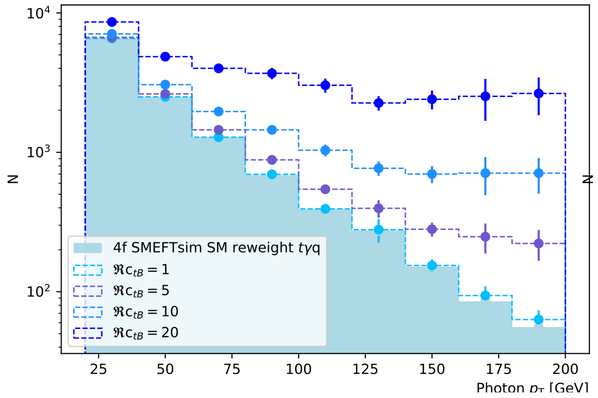


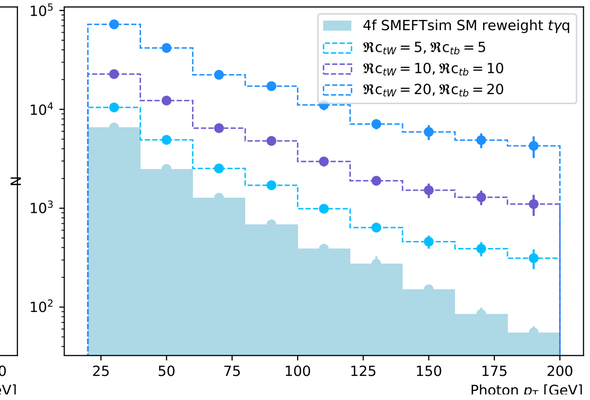




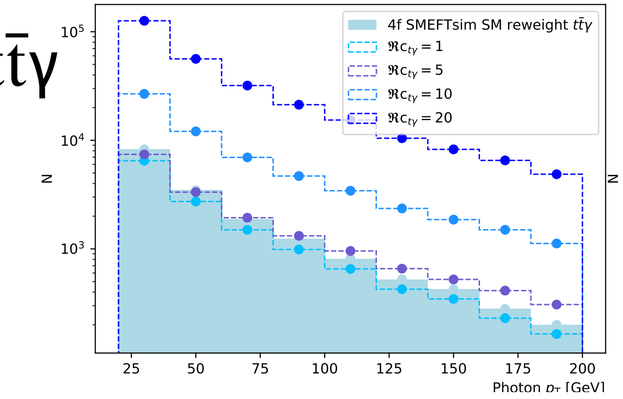


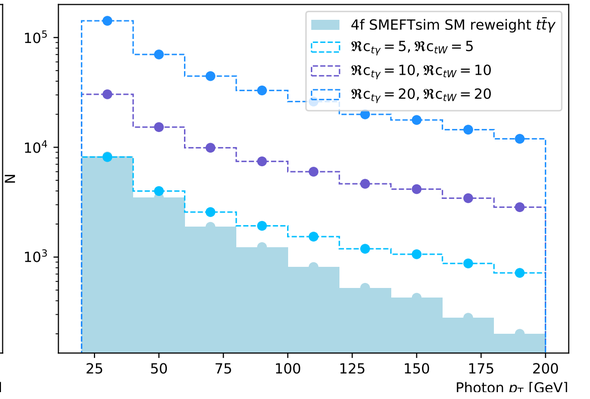



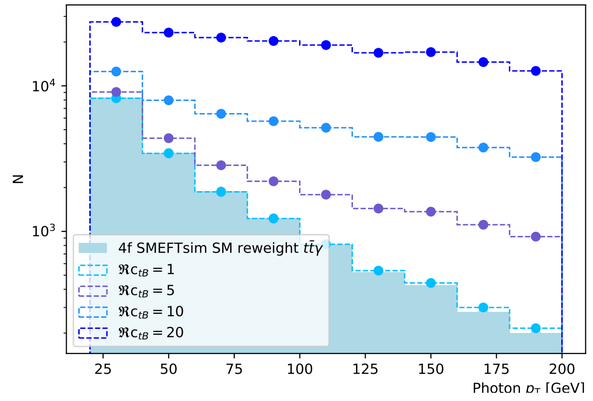



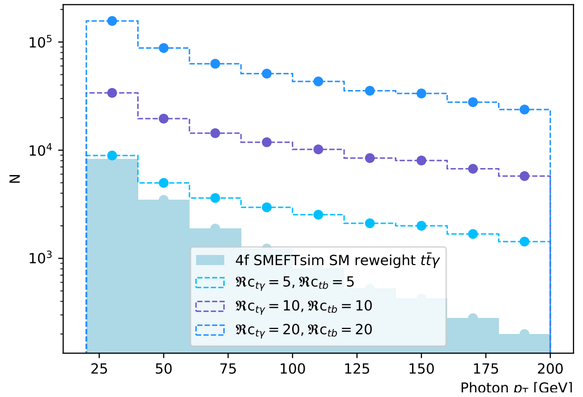



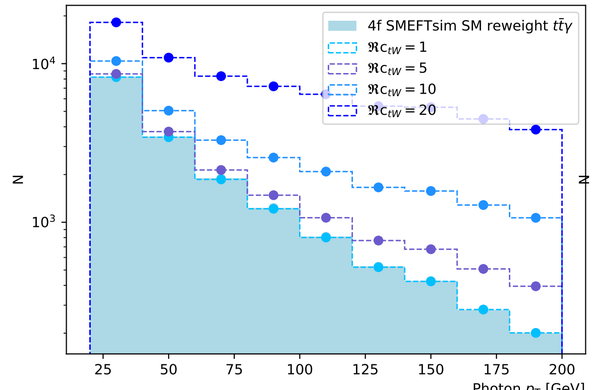

tt̄γ

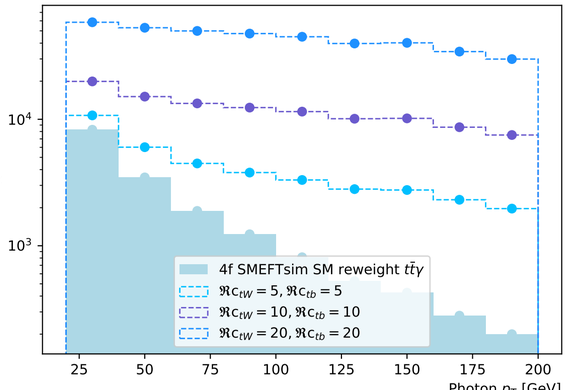


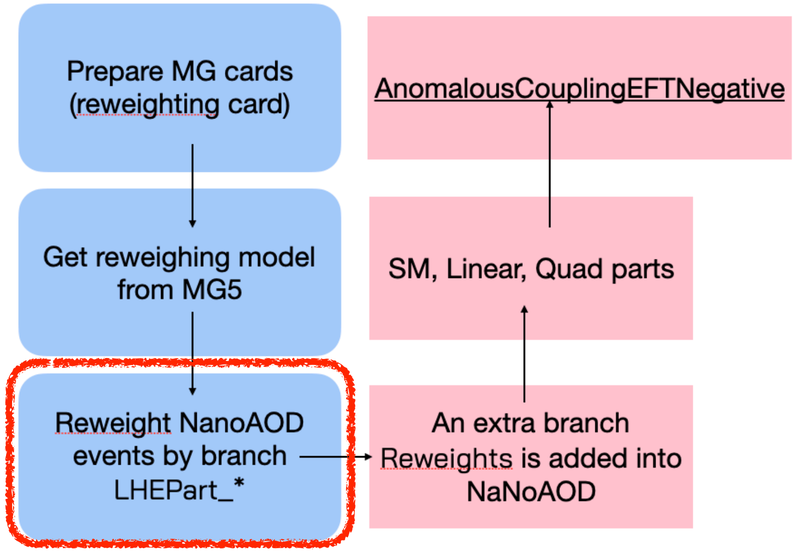



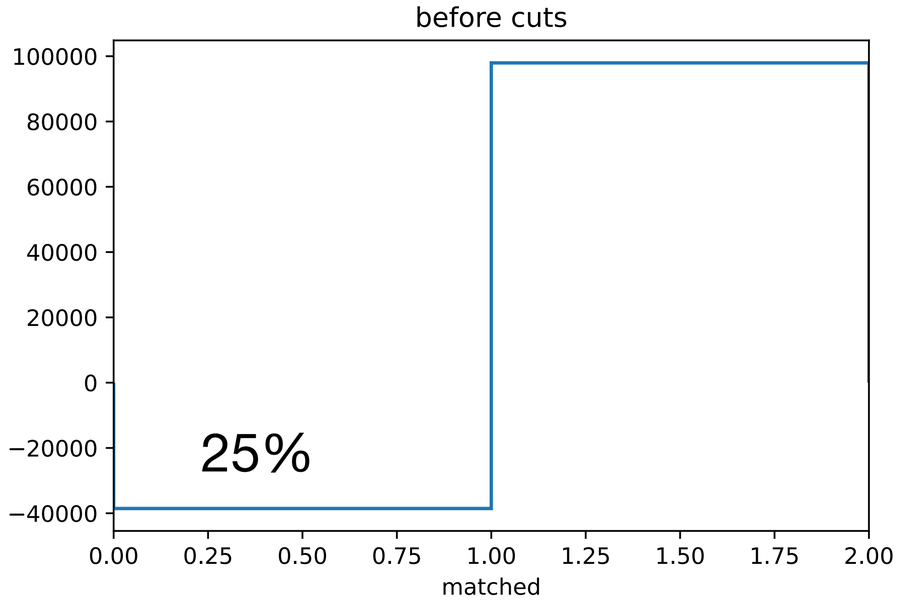



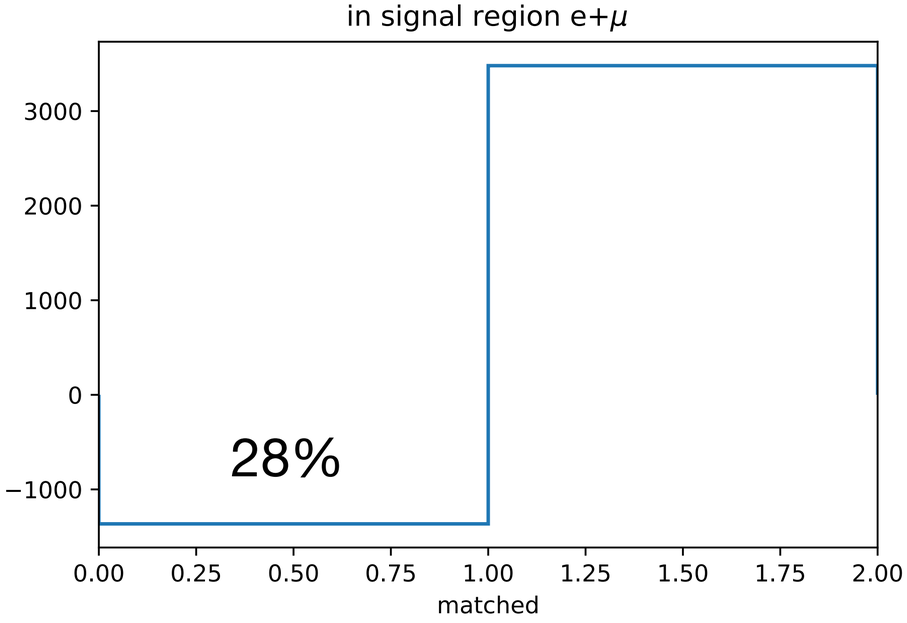
# Reweight to NanoAOD




It's doing a mapping from a PDG list got from MG5 production to NanoAOD LHEPart:

1. If the NanoAOD LHE event can be matched to the PDG list, we get the $\text{reweight} = w_{\text{ori}}^{\text{NLO}} \times \frac{w_i^{\text{LO}}}{w_{sm}^{\text{LO}}}$
2. If the NanoAOD LHE events can't be matched to the PDG list, the Reweights are just same as the generator weight



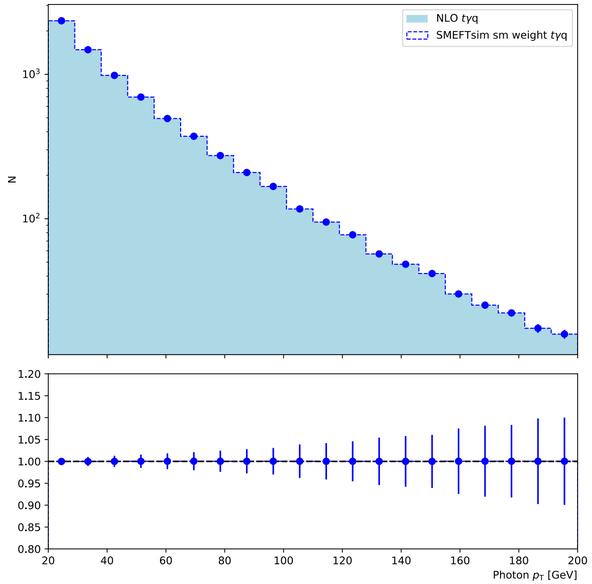



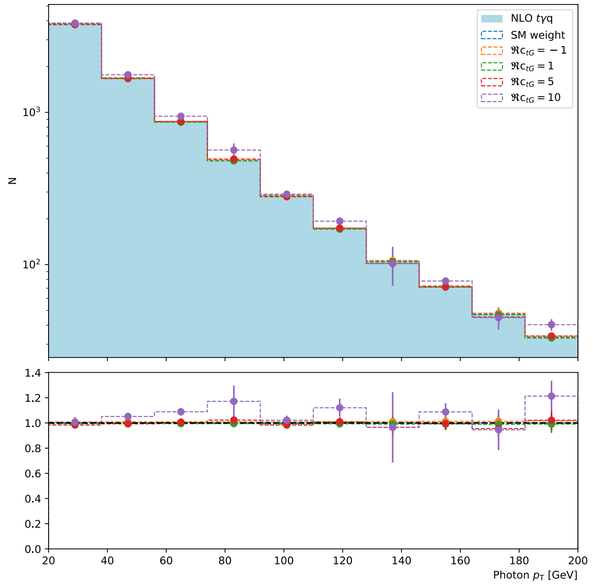

This is a bool variable distribution:

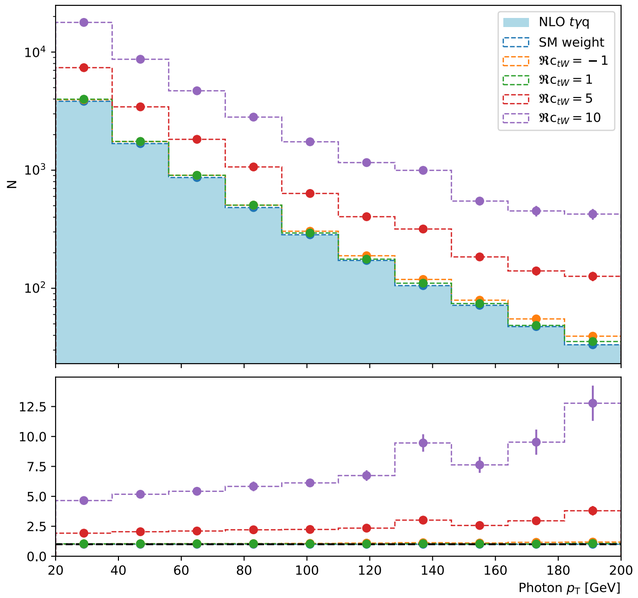
- Almost unmatched events are with negative genweight
- The percent of unmatched to total is 28% less or more before or after selection

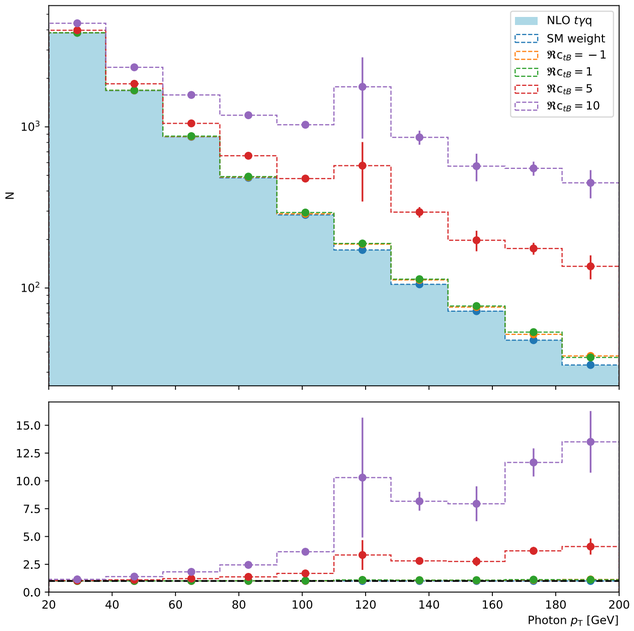
# Gen-level distributions

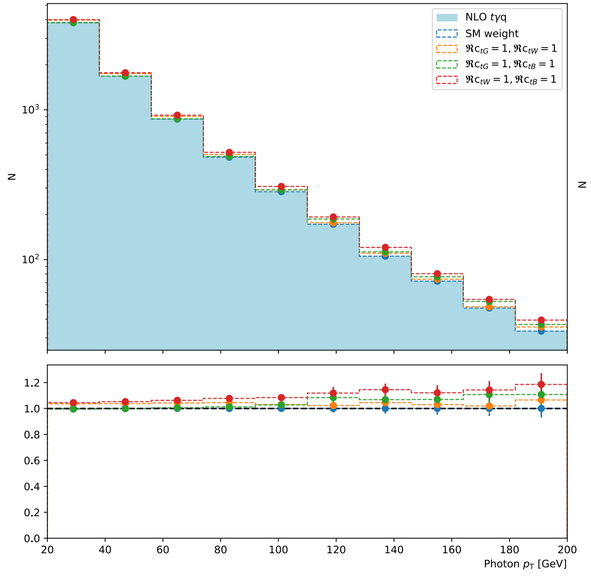
## e+μ channels

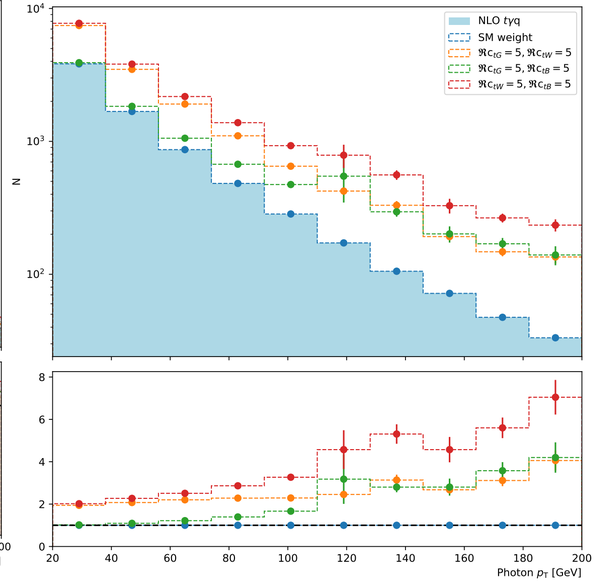


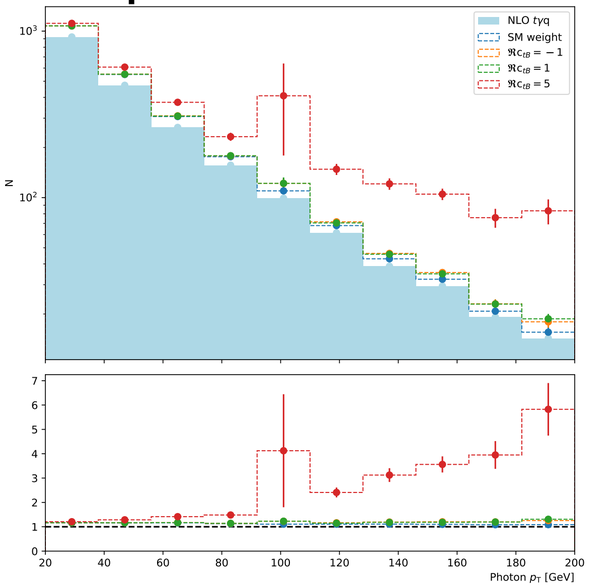



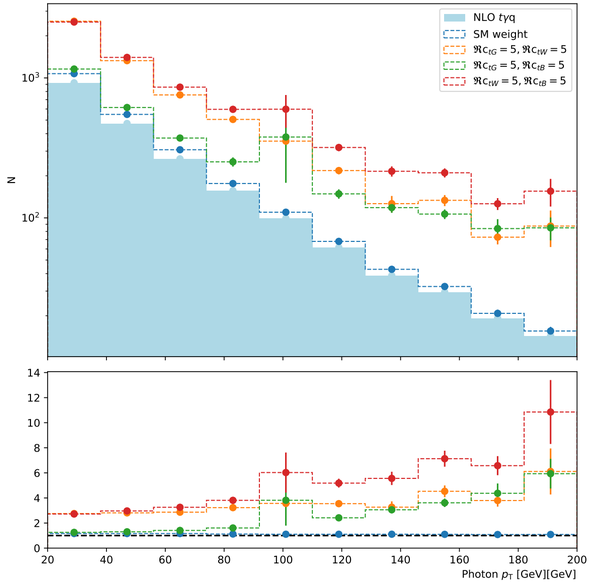



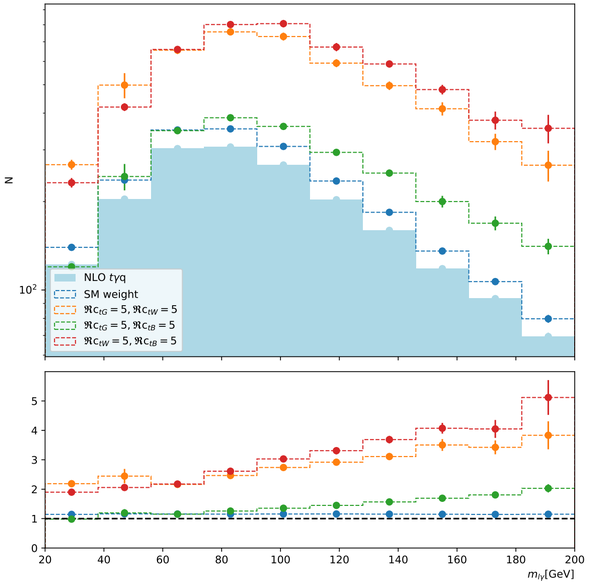

| Selection | gen-ℓ | gen-γ | gen-j | gen-b |
|---|---|---|---|---|
| $p_T$/GeV | > 30 | > 15 | > 30 | > 30 |
| \|η\| | < 2.5 | < 2.5 | < 4.7 | < 2.5 |
| status | 1 | 1 | — | — |
| \|pdgID\| | 13/11 | 22 | — | — |
| Others | No meson mother | • No meson mother<br>• Isolated<br>• ΔR(ℓ,γ) > 0.1 | • ΔR(ℓ,j) > 0.4<br>• ΔR(ℓ,γ) > 0.1 | • \|partonFlavour\| = 5<br>• ΔR(ℓ,j) > 0.4<br>• ΔR(ℓ,γ) > 0.1 |

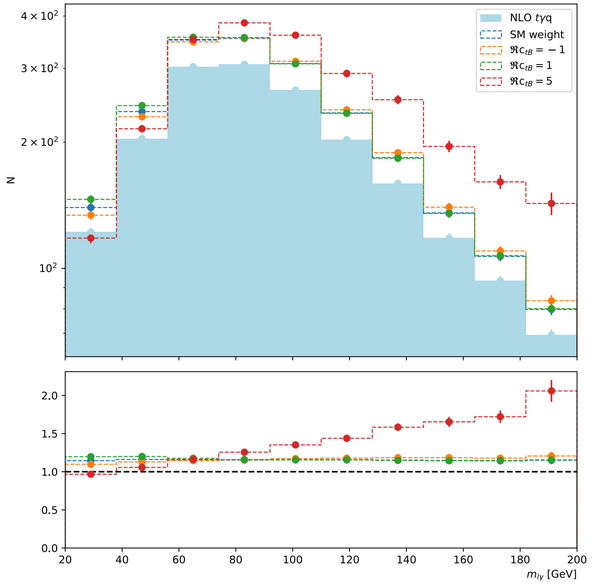
# Reco-level distributions

## e+μ channels



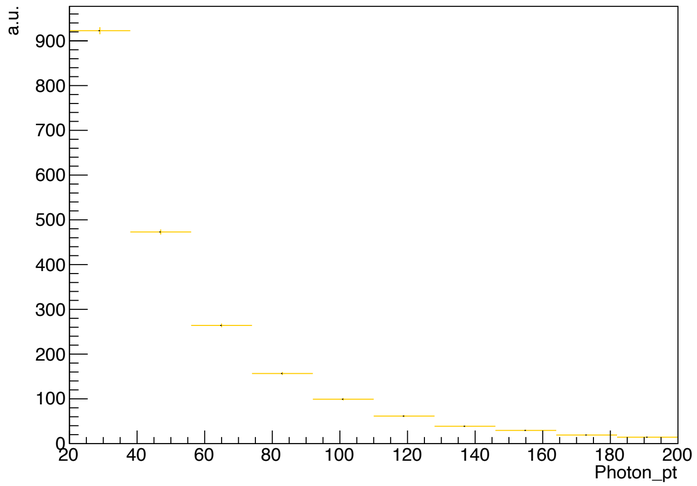

Selection: **$N_\ell$=1, $N_\gamma \geq 1$, $N_j \geq 1$, $N_b \geq 1$**

- Event ≥ 1 good PV and pass MET Filters and pass high-level trigger
- Exactly one lepton
  - Reject events containing extra ℓ with veto lepton requirement
- At least one photon
- At least two jet with one at least one being b-jet
- $\Delta R(\ell,\gamma) > 0.4, \Delta R(\ell,j) > 0.4, \Delta R(\gamma,j) > 0.4$
- MET $p_T > 20$ GeV

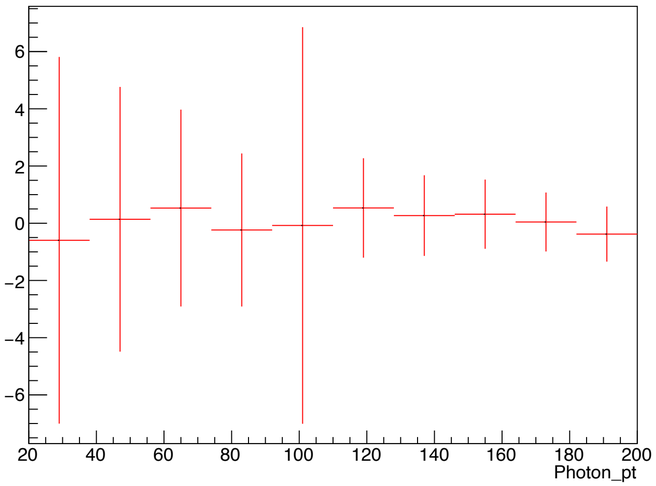
Here, the SM reweight values (blue hist) without reweigting and scale factors for all objects. If they are included, the agreement should be fine.

# EFT decomposition

SM parts



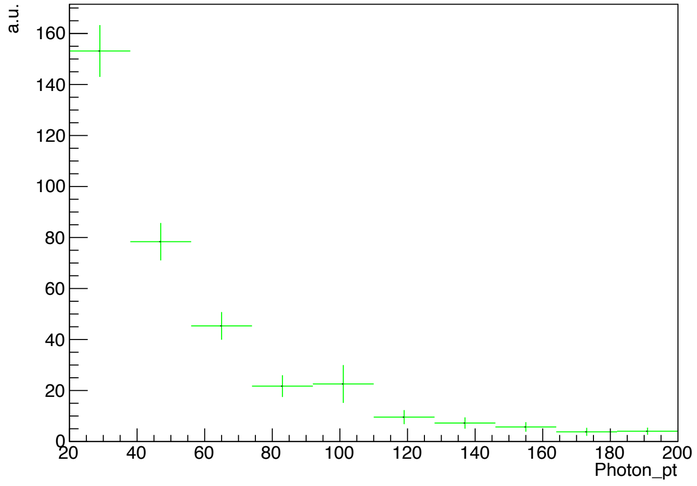

Linear parts $c_{tB}$



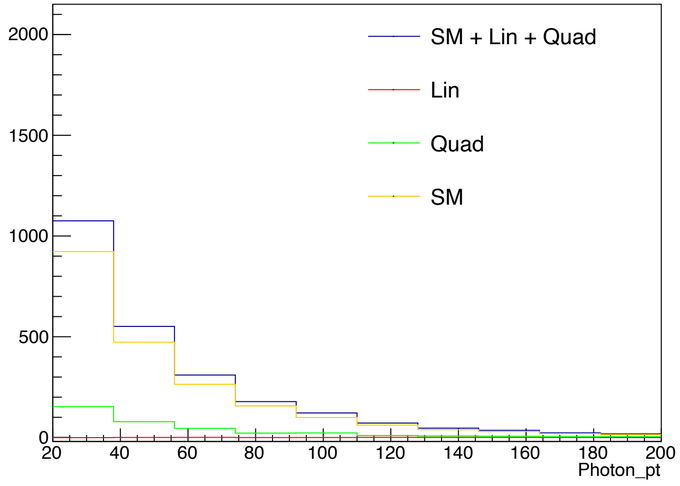

$$\begin{cases} \omega_{\text{Quad}} = 0.5 \cdot \left[\omega(k=1) + \omega(k=-1) - 2 \cdot \omega(k=0)\right] \\ \omega_{\text{SM}} = \omega(k=0) \\ \omega_{\text{Lin}} = 0.5 \cdot \left[\omega(k=1) - \omega(k=-1)\right] \end{cases}$$

$$\omega_{\text{Mix}} = \omega(1,1) + \omega(0,0) - \omega(1,0) - \omega(0,1)$$

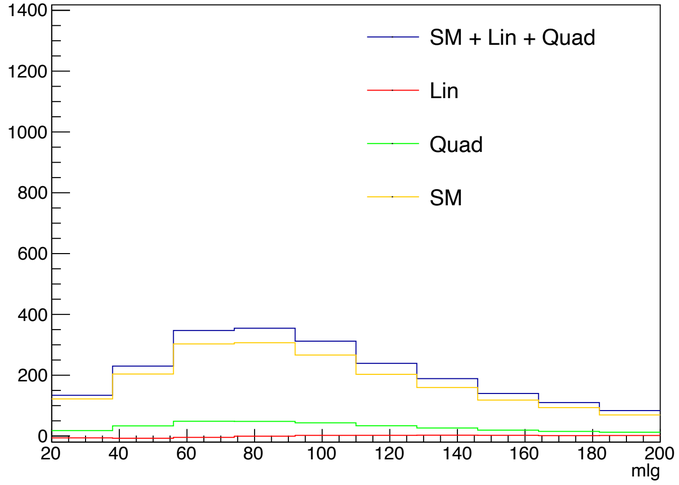
Quad parts $c_{tB}$




SM + Lin + Quad $c_{tB}$

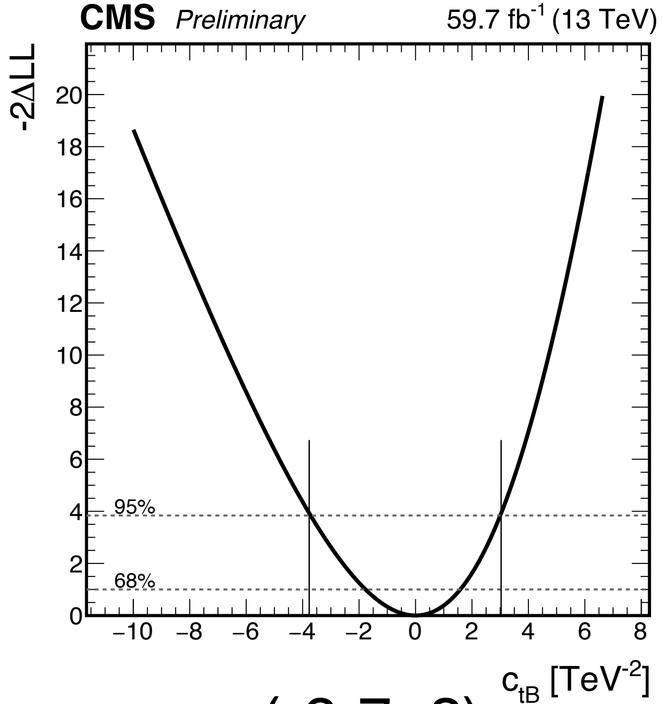



SM + Lin + Quad $c_{tB}$

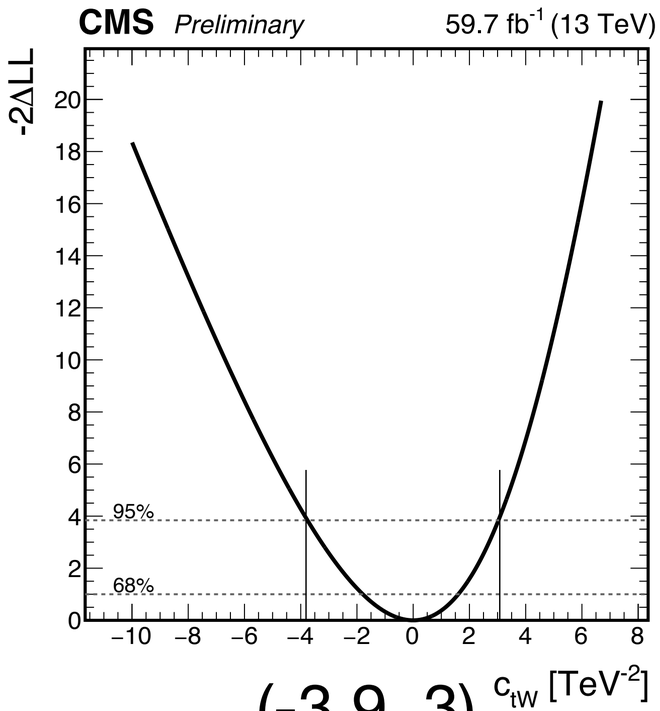


# EFT fit result

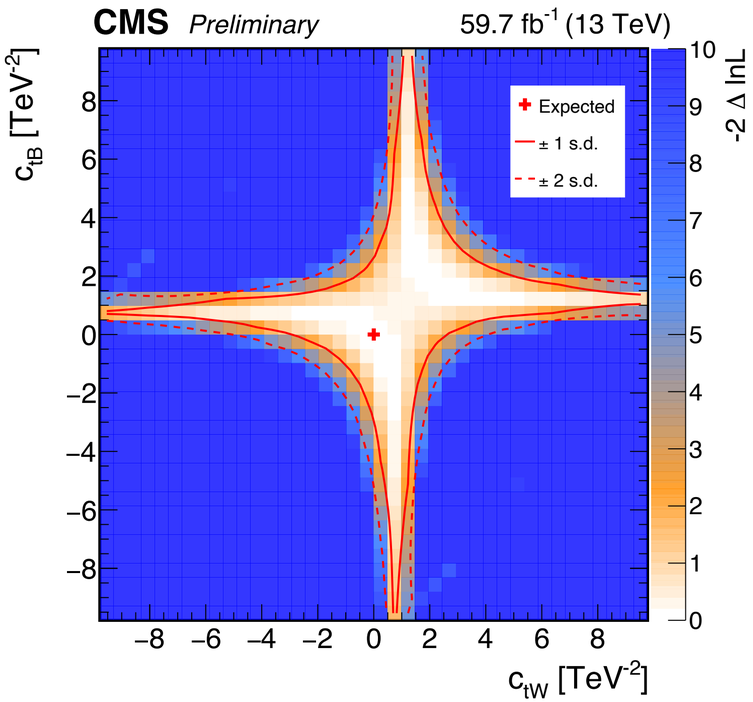
- POIs: the value of the coefficients
- Fit signal region ($N_j \geq 2$, $N_b \geq 1$) in photon $p_T$ distributions
- All uncertainties considered but in lnN style uncertainties → will update to shape
- Currently the fit is for tγq in 2018 data and MC muon channel




(-3.7, 3)




(-3.9, 3)



# Summary

- Present the EFT framework for doing the EFT interpretation
  - Produce private gridpacks by SM and SMEFTsim models
  - Using reweighting approach to add EFT weights into NanoAOD
  - Preliminary EFT limits for operators $\mathfrak{R}c_{tG}$, $\mathfrak{R}c_{tW}$, $\mathfrak{R}c_{tB}$ (2018 muon channel)

- Open question:
  - EFT model: The current model SMEFTsim_topU3l_MwScheme_UFO somehow is not allowed to modify the cpv coefficient aka. the imaginary part
  - Unmatched event: How handle these events? Is that fine to just leave them there?
  - More operators?

# Backup

# tγq SM process

## Official NLO tγq production

**In 4-flavour scheme:**

**Process card**

import model loop_sm-ckm
generate p p > t b~ j a $$ w+ w- [QCD] @0
add process p p > t~ b j a $$ w+ w- [QCD] @1

**Madspind card**

decay t > w+ b, w+ > ell+ vl
decay t~ > w- b~, w- > ell- vl~

Cross section: 2.909 +- 0.013e pb (without decay)
0.992 pb (considering ℓ branching ratio)

## Private LO tγq production

**In 4-flavour scheme:**

**Process card**

import model sm-ckm
generate p p > t b~ j a $$ w+ w- , (t > w+ b, w+ > l+ vl) @0
add process p p > t~ b j a $$ w+ w- , (t~ > w- b~, w- > l- vl~) @1

Cross section: 0.7209 +- 0.002831 pb

# tγq EFT process with reweight

tγq **LO production with 4-flavour scheme:**

**Process card**

import model SMEFTsim_topU3l_MwScheme_UFO-massless
generate p p > t b~ j a $$ w+ w- NP=1, (t > w+ b NP=0, w+ > l+ vl NP=0) @0 SMHLOOP=0
add process p p > t~ b j a $$ w+ w- NP=1, (t~ > w- b~ NP=0, w- > l- vl~ NP=0) @1 SMHLOOP=0

Cross section with SM weight: 0.82 +- 0.096 pb (1.26 pb with $c_{t\gamma} = 25$)

# ttγ SM process

## Official $t\bar{t}\gamma$ (NLO or LO) production

**NLO production with 5-flavour scheme:**

**Process card**

```
import model loop_sm-ckm_no_b_mass
generate p p > t t~ a [QCD] @0
add process p p > t t~ a j [QCD] @1
```

Cross section: 6.052 +- 0.014 pb (All decays)

~2.58 pb for semi-leptonic decay

**LO production with 5-flavour scheme:**

**Process card**

```
import model sm-ckm_no_b_mass
generate p p > t t~ > l+ vl b ds uc~ b~ a
add process p p > t t~ > uc ds~ b l- vl~ b~ a
```

Cross section: 5.121 +- 0.003712 pb

## Private LO $t\bar{t}\gamma$ production

**LO production with 5-flavour scheme:**

**Process card**

```
import model sm-ckm_no_b_mass
generate p p > t t~ a, (t > w+ b, w+ > l+ vl), (t~ > w- b~, w- > uc~ ds) @0
add process p p > t t~ a, (t > w+ b, w+ > uc ds~), (t~ > w- b~, w- > l- vl~) @1
```

Cross section: 0.6145 +- 0.00173 pb

# ttγ EFT process with reweight

**$t\bar{t}\gamma$ LO production with 4-flavour scheme:**

**Process card**

```
import model SMEFTsim_topU3l_MwScheme_UFO-massless
generate p p > t t~ a NP=1, (t > w+ b NP=0, w+ > l+ vl NP=0), (t~ > w- b~ NP=0, w- > uc~ ds NP=0) @0 SMHLOOP=0
add process p p > t t~ a NP=1, (t > w+ b NP=0, w+ > uc ds~ NP=0), (t~ > w- b~ NP=0, w- > l- vl~ NP=0) @1 SMHLOOP=0
```

Cross section with SM weight: 0.73 +- 0.078 pb (16.8 pb with $c_{t\gamma} = 25$)

**$t\bar{t}\gamma$ LO production with 5-flavour scheme:**

**Process card**

```
import model SMEFTatNLO-LO
generate p p > t t~ a NP=2, (t > w+ b NP=0, w+ > l+ vl NP=0), (t~ > w- b~ NP=0, w- > uc~ ds NP=0) @0
add process p p > t t~ a NP=2, (t > w+ b NP=0, w+ > uc ds~ NP=0), (t~ > w- b~ NP=0, w- > l- vl~ NP=0) @1
```

Cross section with SM weight: 0.66 +- 0.029 pb (4.34 pb with $c_{tZ} = c_{tW} = c_{t\gamma} = 7.5$)