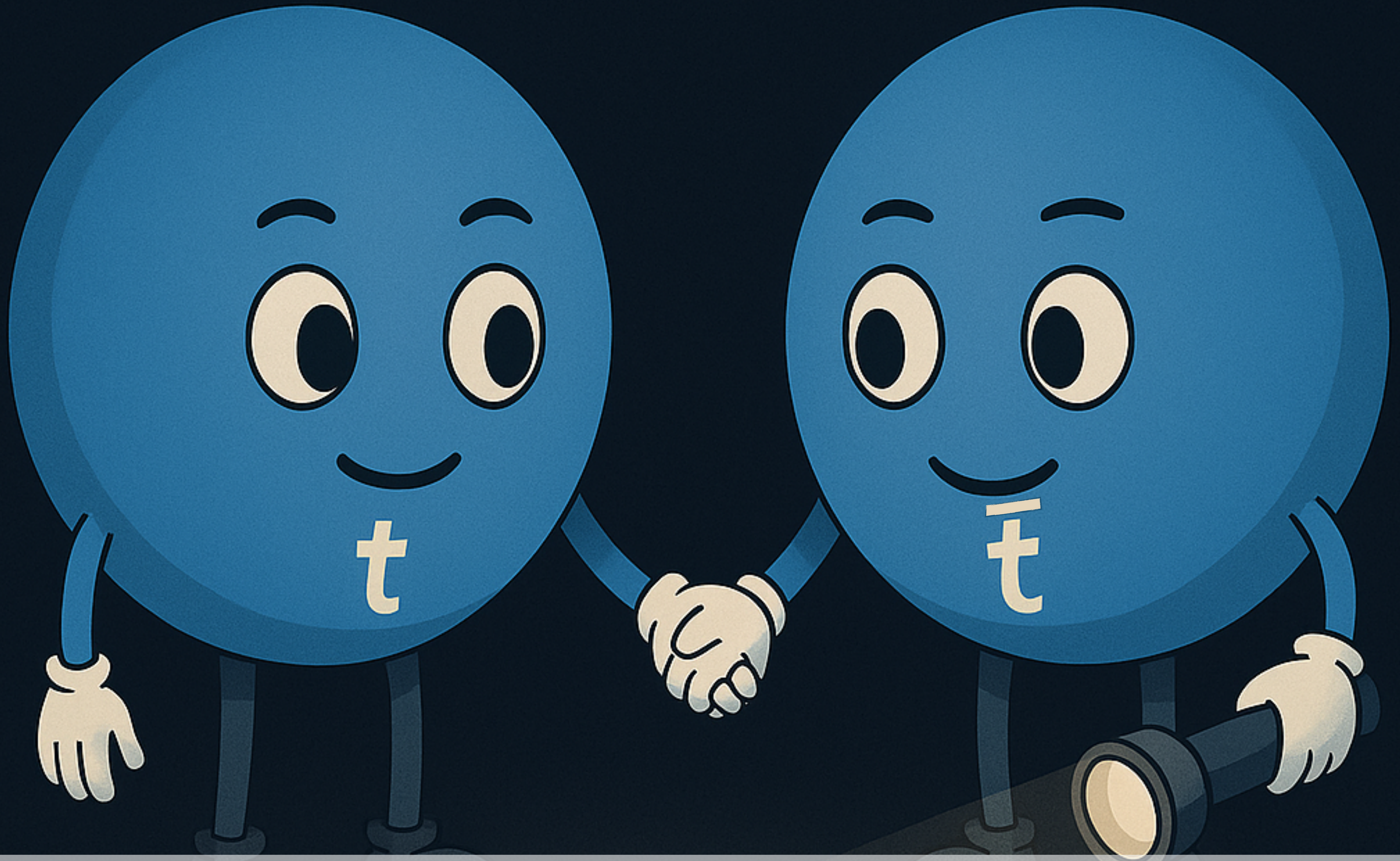
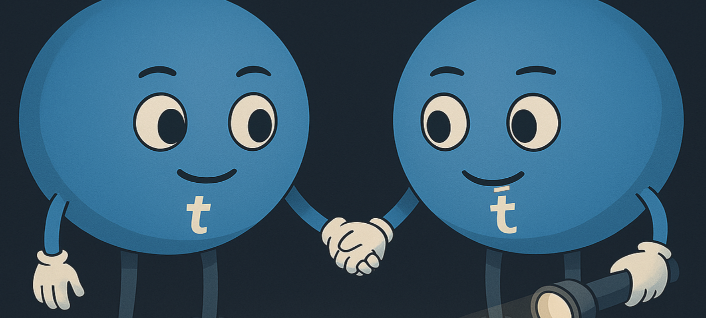
UGent seminar - 15th January 2026



Lighting up the top quark: New $t\bar{t}\gamma$ measurements at CMS

Beatriz Ribeiro Lopes, CERN

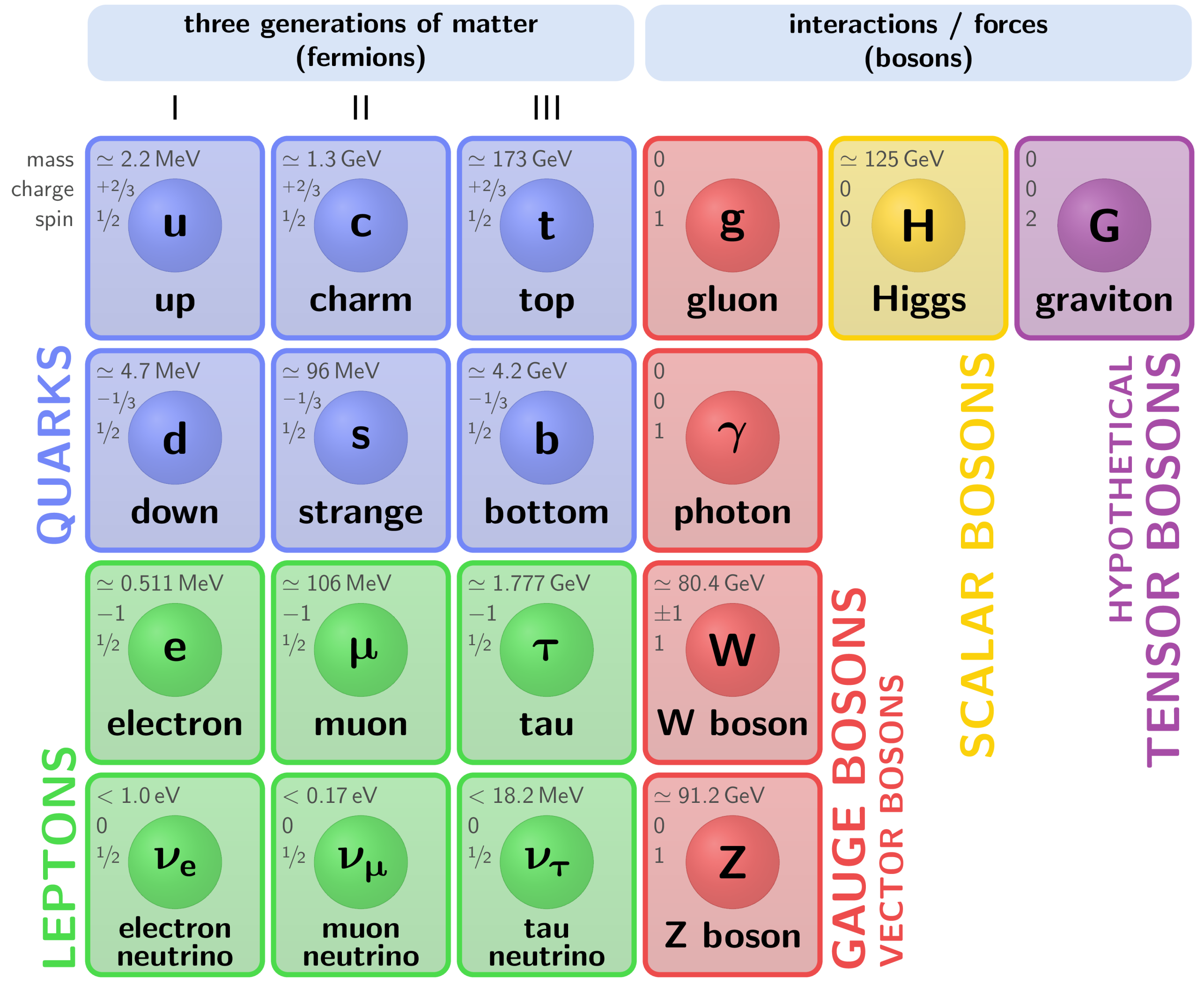
Introduction and motivation

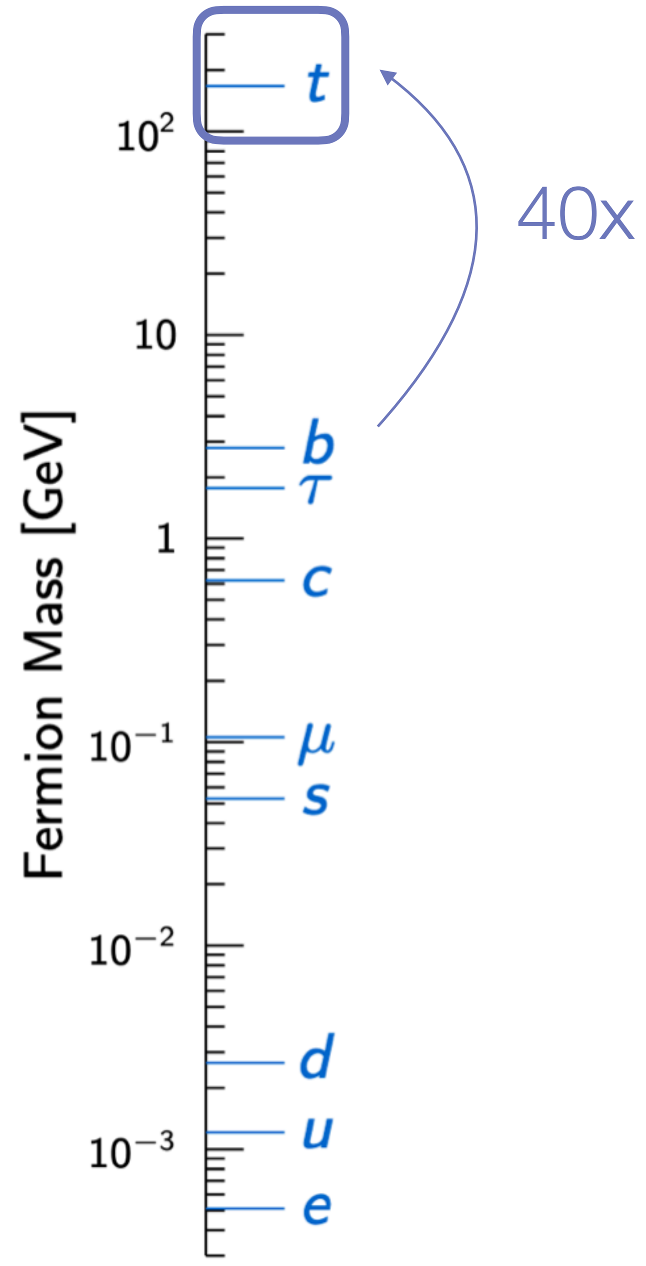


- 1995: Discovery of the **top quark**
- 2012: Discovery of the **Higgs boson** - completed the puzzle of the standard model (SM)
- Now, over a decade later:
    - Tremendous progress in understanding the Higgs boson and the top quark, with masses measured with per-mil precision
    - Cross sections for many standard model processes measured with precision down to a few percent
    - But not all is solved, some fundamental questions and issues remain (fermion masses added ad-hoc via Yukawa couplings, mass hierarchy of neutrinos, dark matter, …)
- What more can we do?

Look for new physics directly

- search for new particles predicted by theories (e.g. SUSY, ALPs, LQs, …)
- explore exotic signatures that may have escaped detection so far





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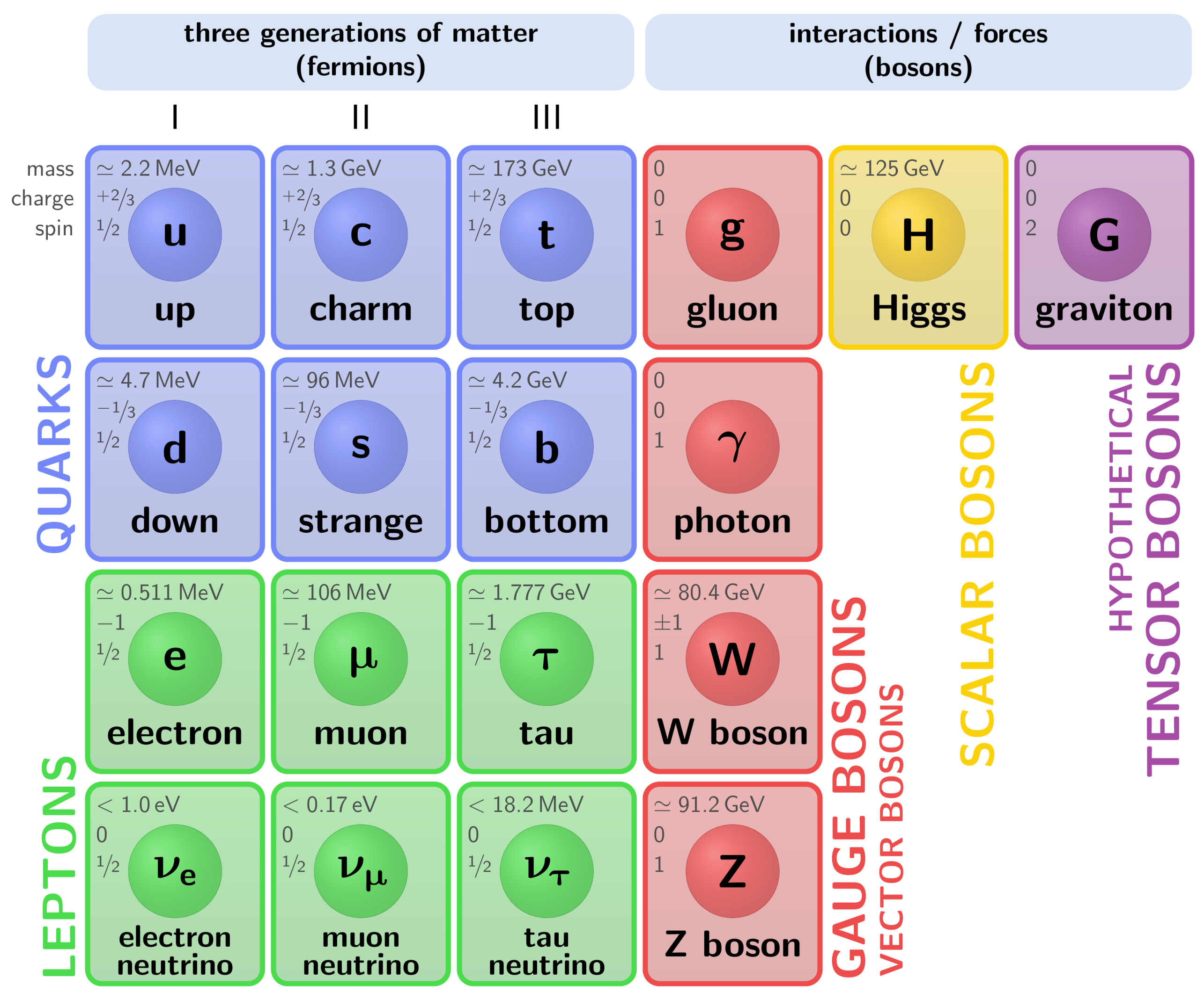

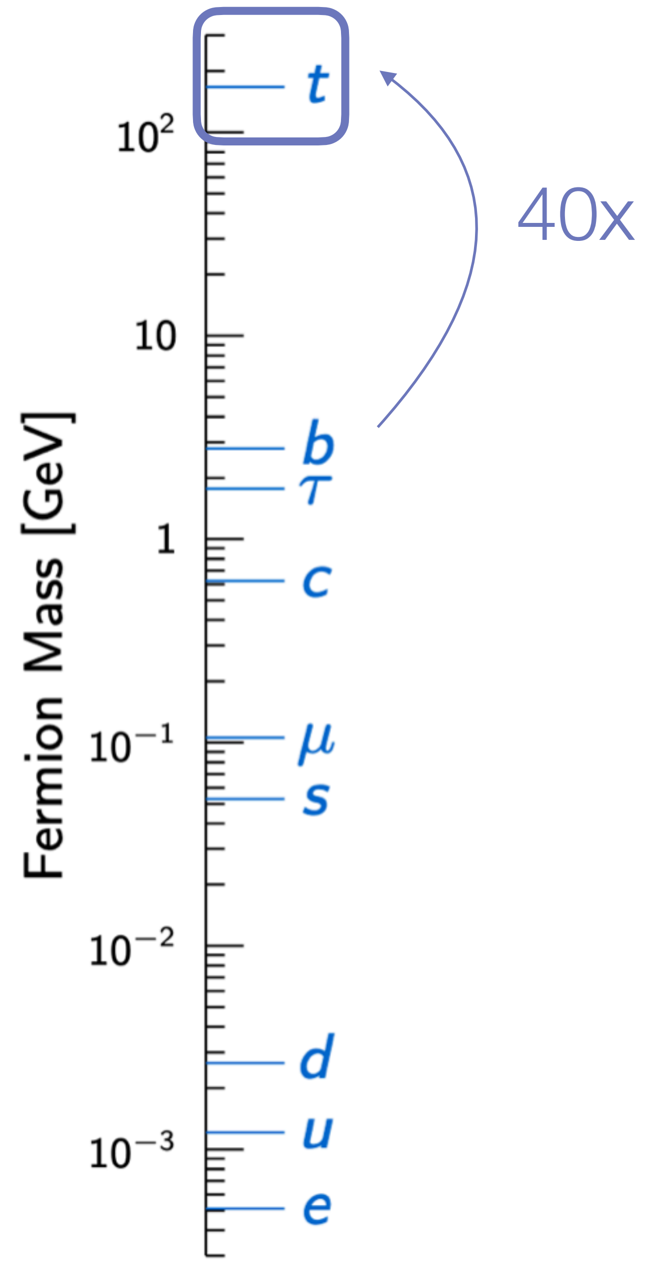

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Continue to stress test the SM:
- Measure cross sections and decay rates precisely
- Measure particle properties (mass, asymmetries, couplings, etc)
- Quantify deviations from the SM to constrain new physics scenarios

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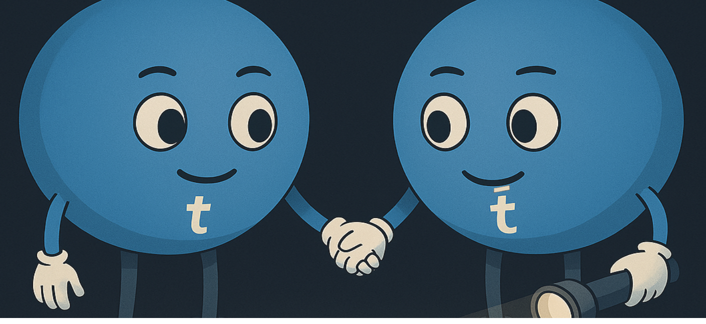

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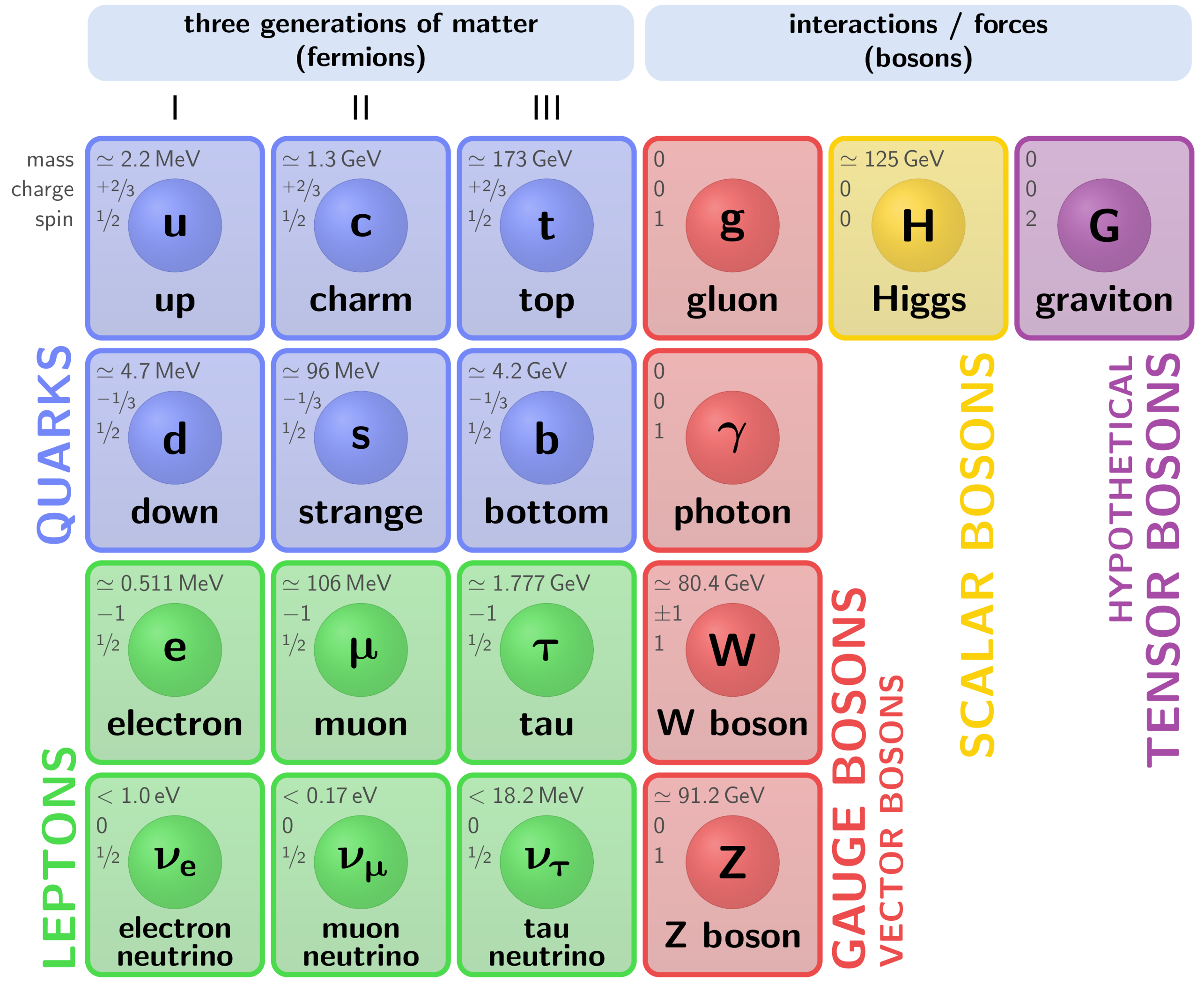

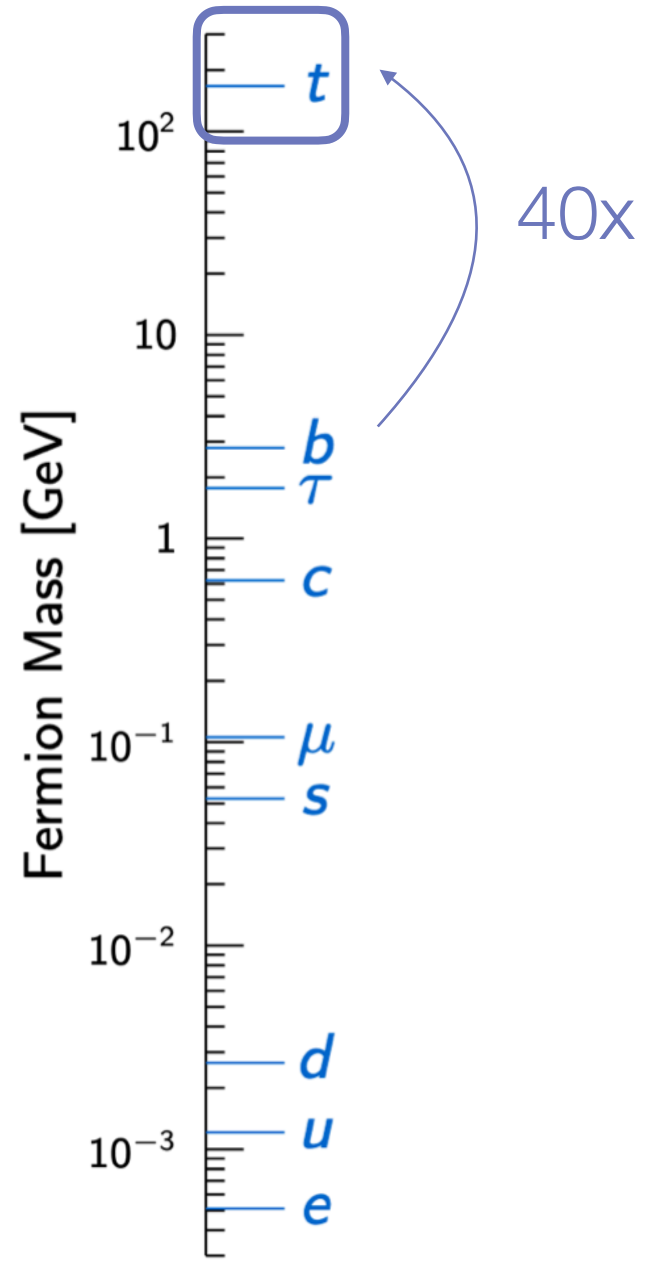

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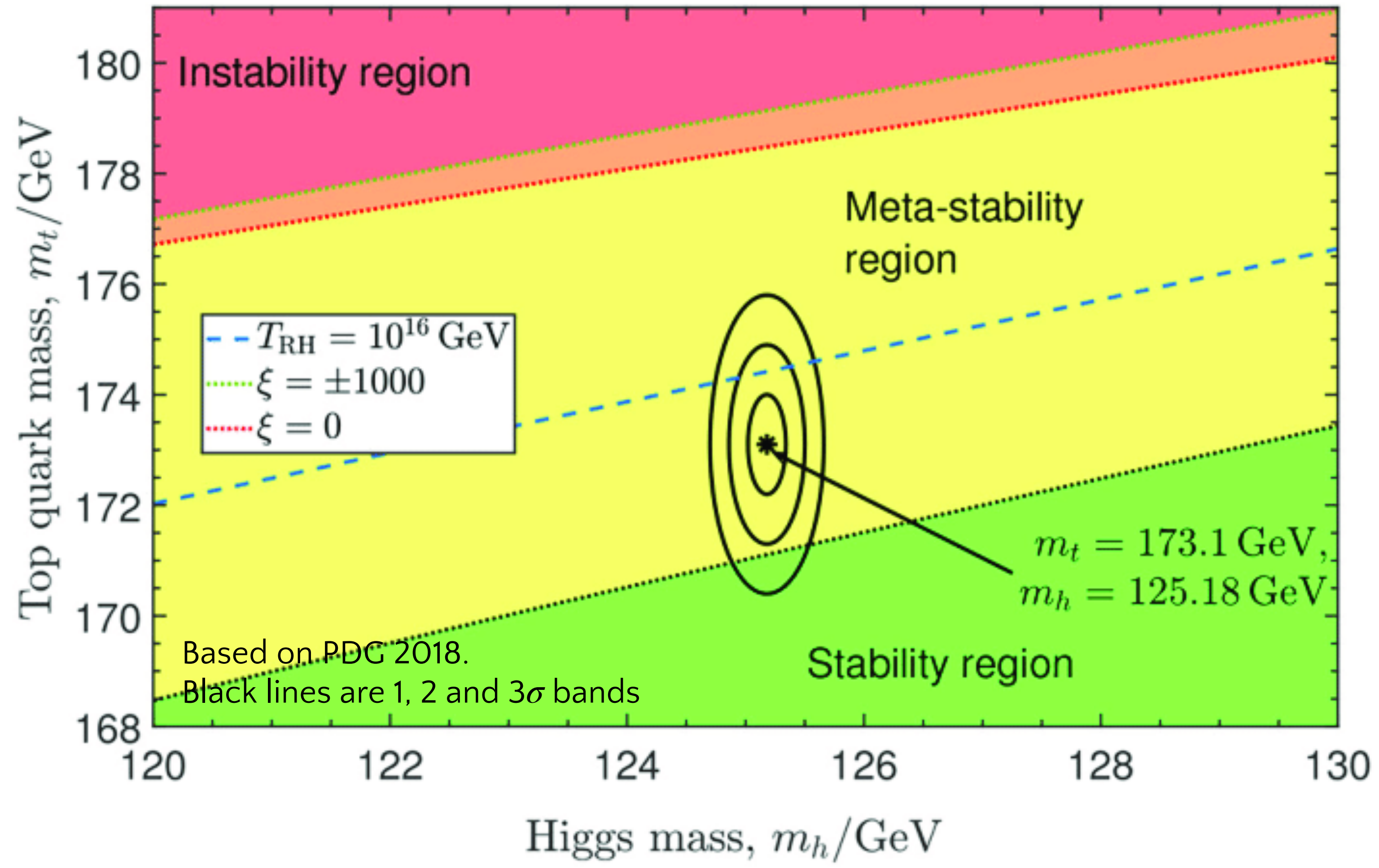
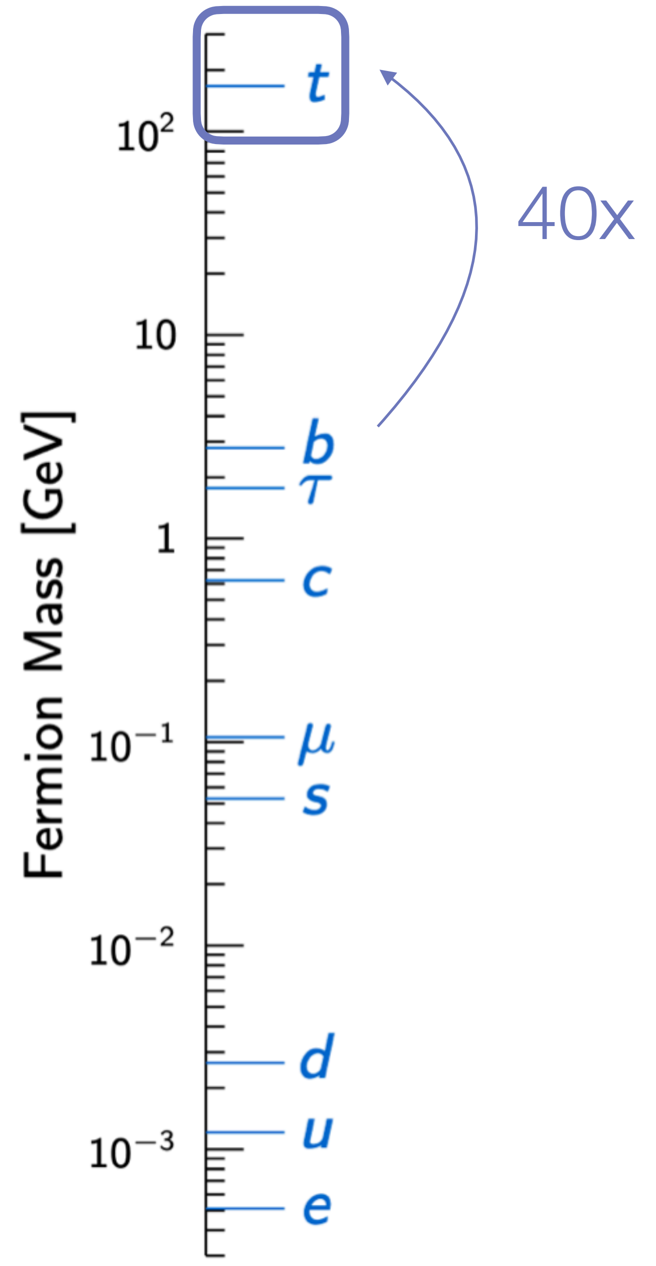
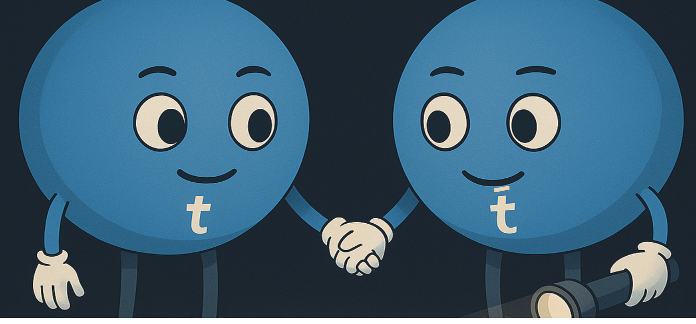
Top quark physics

- Top quark physics is a central part of the LHC programme. But why?
- The top quark:
  - is the **heaviest** particle in the SM (Yukawa coupling ~1)
  - is the only quark that **decays before hadronization** - prime opportunity to measure bare quark properties
  - mass is essential for electroweak vacuum stability





Top quark physics



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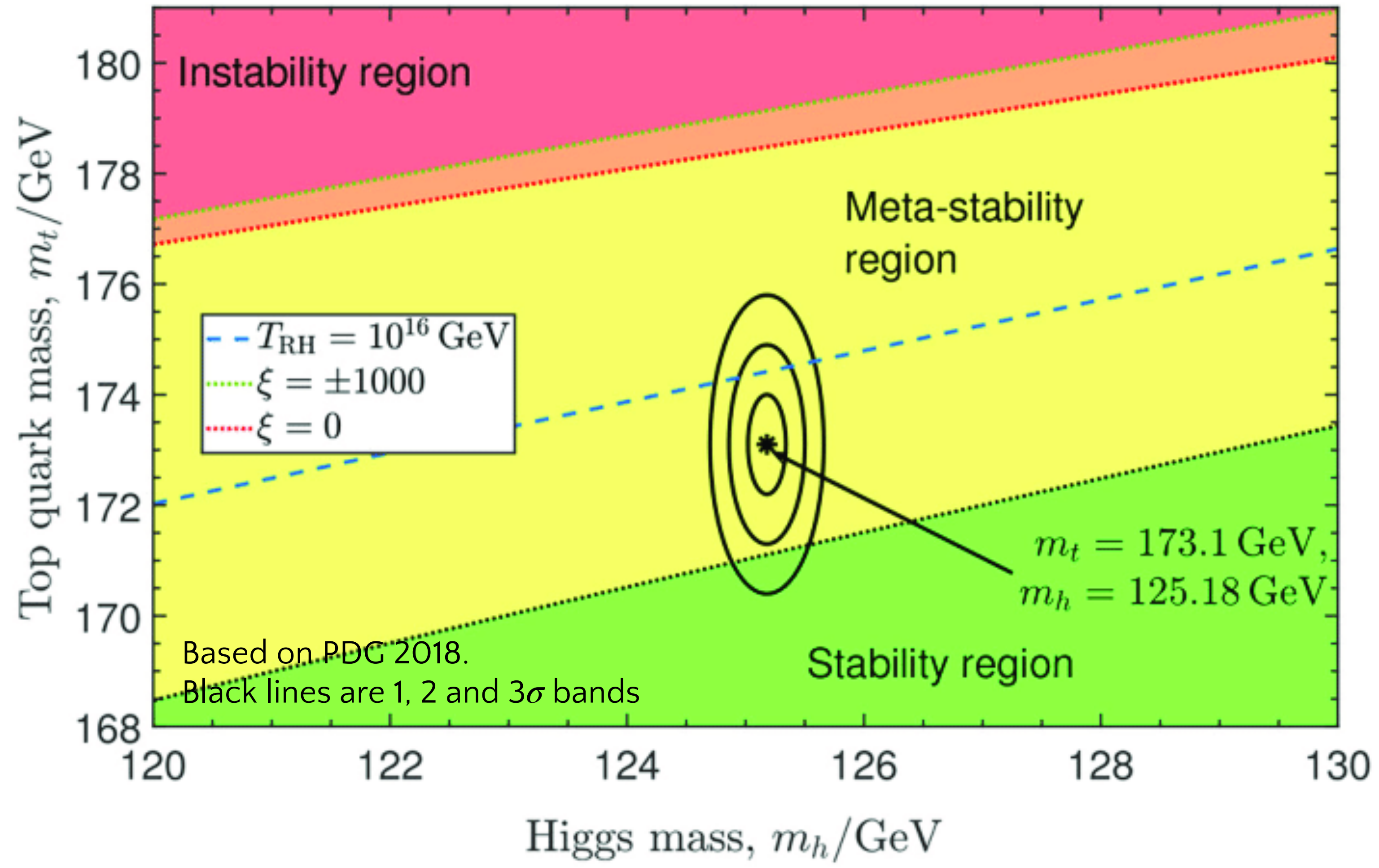
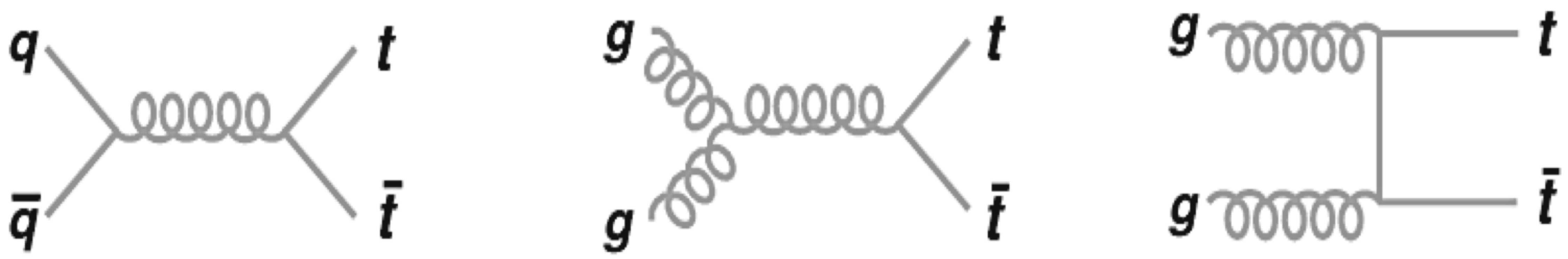
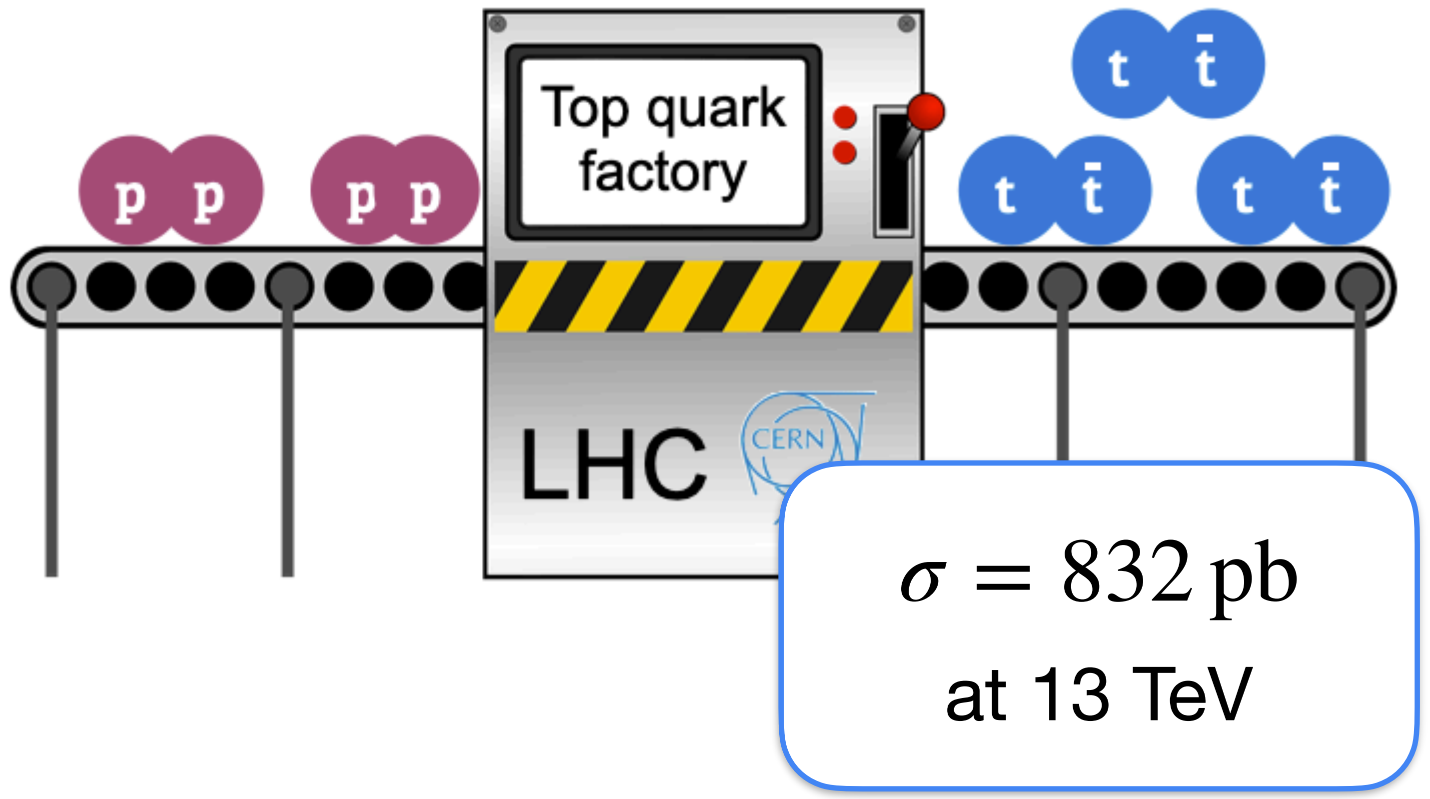
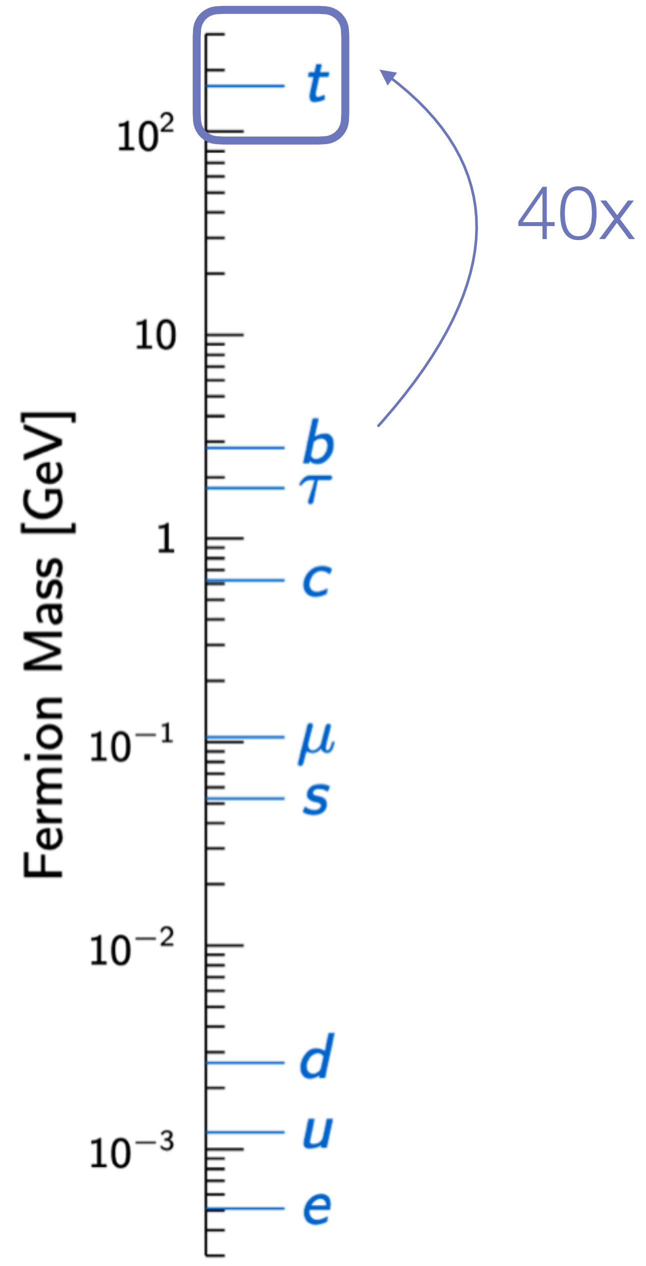


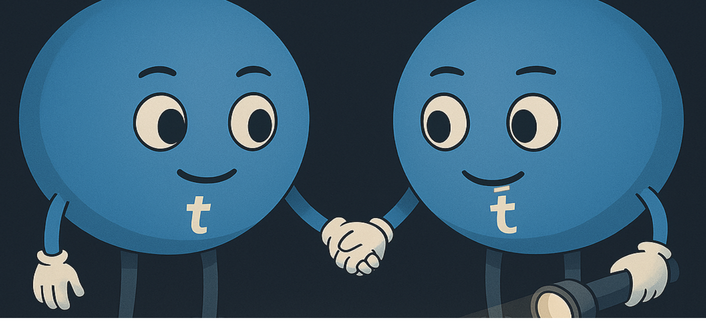
- Tops are abundantly produced at the LHC, mainly in the form of top quark-antiquark pairs
- With >100 million top quark pairs produced at the LHC, we can do a lot, from precision physics to spotting **rare processes**







Top quark physics - still making the news after 30 years



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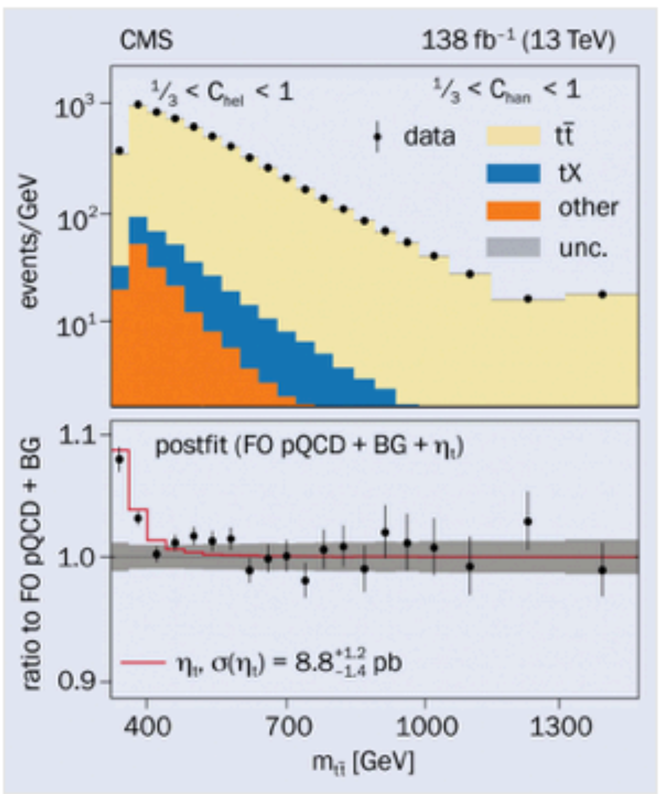
STRONG INTERACTIONS | NEWS

CMS observes top–antitop excess

2 April 2025



Threshold excess The invariant mass spectrum of top quark–antiquark pairs observed by the CMS experiment in certain domains of the reconstructed spin-correlation observables c_{hel} and c_{han} (top panel) and the signal-to-background ratio (bottom panel). Excess events at threshold can be modelled by including a new top–antitop bound state in the background model (red line). Credit: CMS Collab. 2025 arXiv:2503.22382.

CERN's Large Hadron Collider continues to deliver surprises. While searching for additional Higgs bosons, the CMS collaboration may have instead uncovered evidence for the smallest composite particle yet observed in nature – a "quasi-bound" hadron made up of the most massive and shortest-lived fundamental particle known to science and its antimatter counterpart. The findings, which do not yet constitute a discovery claim and could also be susceptible to other explanations, were reported this week at the Rencontres de Moriond conference in the Italian Alps.

Almost all of the Standard Model's shortcomings motivate the search for additional Higgs bosons. Their properties are usually assumed to be simple. Much as the 125 GeV Higgs boson discovered in 2012 appears to interact with each fundamental fermion with a strength proportional to the fermion's mass, theories postulating additional Higgs bosons generally expect them to couple more strongly to heavier quarks. This puts the singularly massive top quark at centre stage. If an additional Higgs boson has a mass greater than about 345 GeV and can therefore decay to a top quark–antiquark pair, this should dominate the way it decays inside detectors. Hunting

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Article | Open access | Published: 18 September 2024

Observation of quantum entanglement with top quarks at the ATLAS detector

The ATLAS Collaboration

Nature **633**, 542–547 (2024) | Cite this article

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Abstract

Entanglement is a key feature of quantum mechanics[1,2,3], with applications in fields metrology, cryptography, quantum information and quantum computation[4,5,6,7,8] been observed in a wide variety of systems and length scales, ranging from the microscopic[9,10,11,12,13] to the macroscopic[14,15,16]. However, entanglement remains l unexplored at the highest accessible energy scales. Here we report the highest-ene observation of entanglement, in top–antitop quark events produced at the Large H Collider, using a proton–proton collision dataset with a centre-of-mass energy of √ and an integrated luminosity of 140 inverse femtobarns (fb)$^{-1}$ recorded with the AT experiment. Spin entanglement is detected from the measurement of a single obse inferred from the angle between the charged leptons in their parent top- and antito rest frames. The observable is measured in a narrow interval around the top–antito

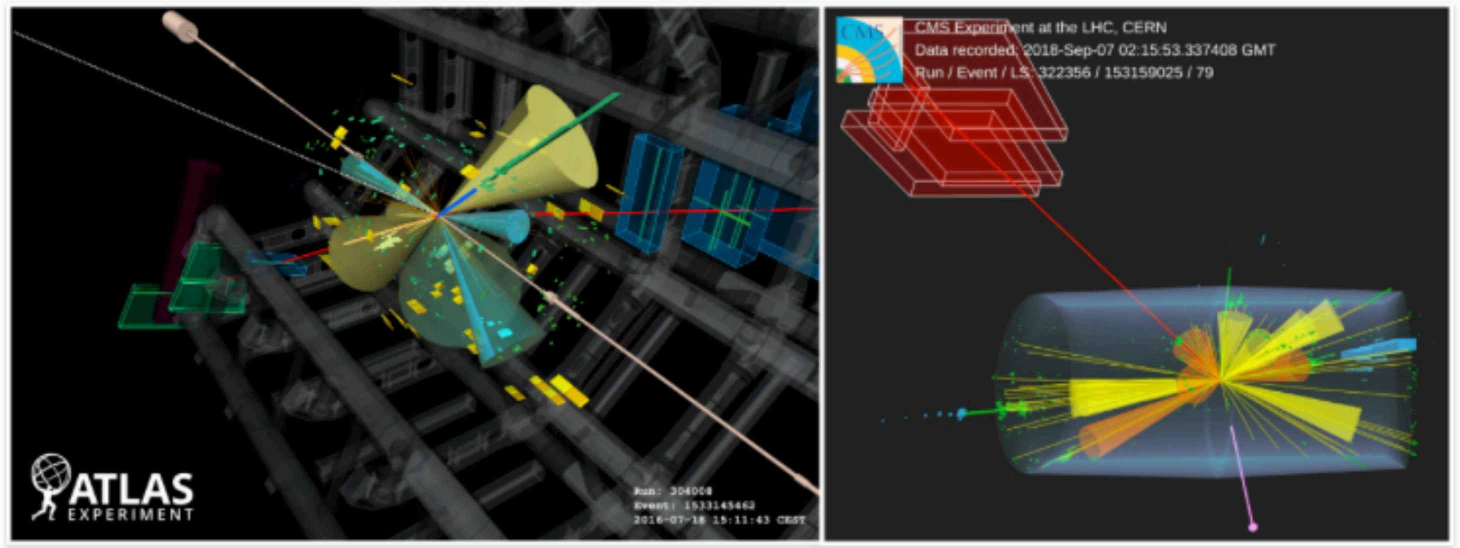
News › News › Topic: Physics

Voir en français

ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore

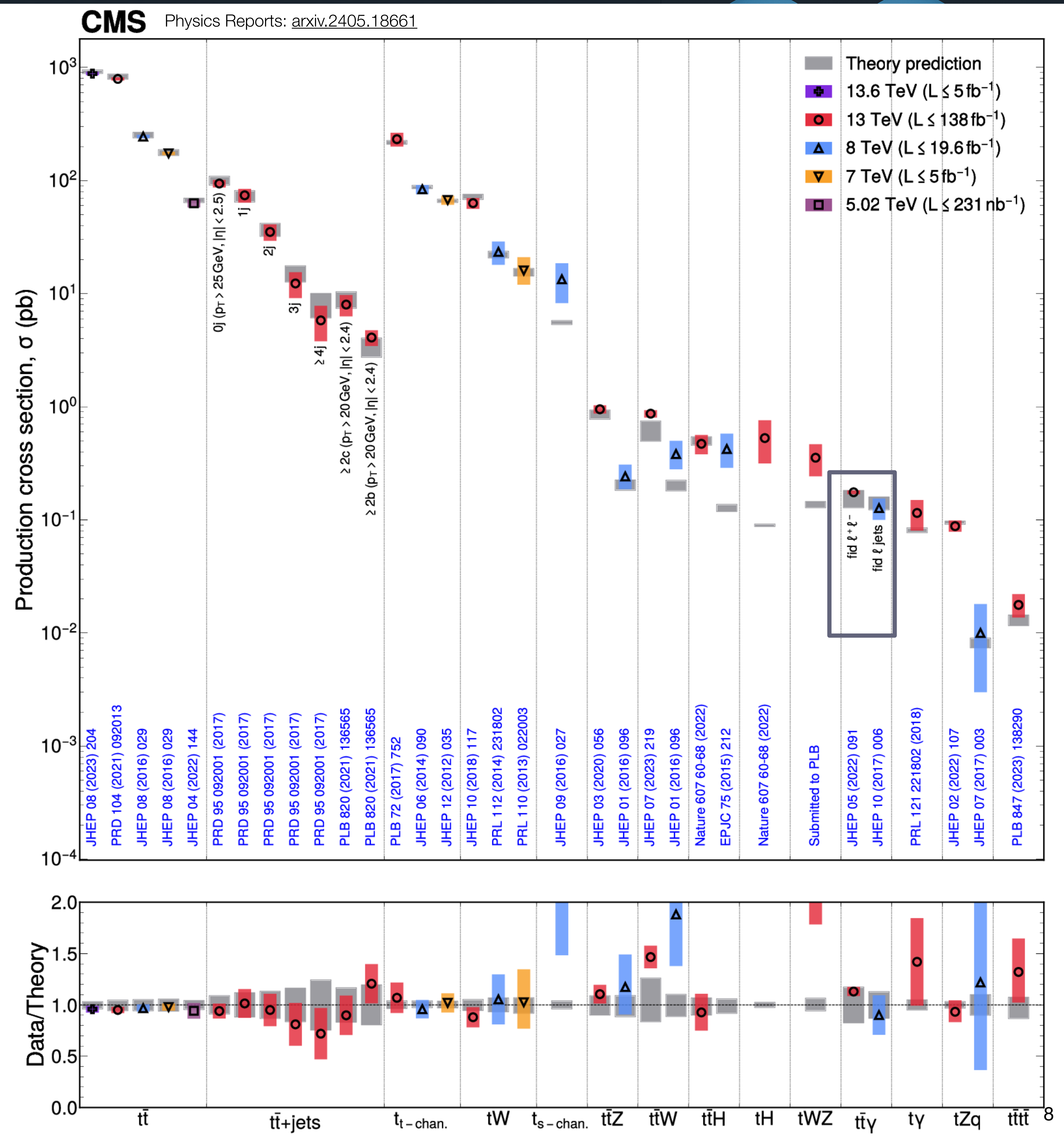


Event displays of four-top-quark production from ATLAS (left) and CMS (right).

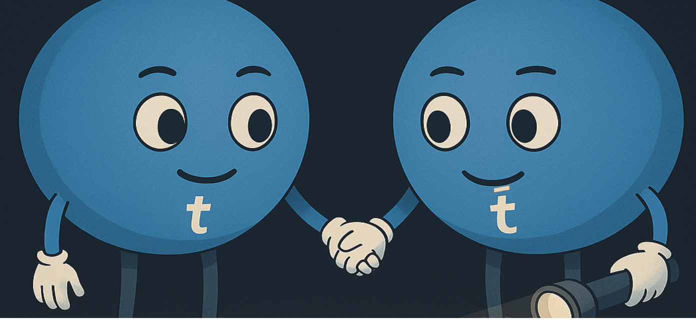
Today, at the Moriond conference, the ATLAS and CMS collaborations have both presented the observation of a very rare process: the simultaneous production of four top quarks. They were observed using data from collisions during Run 2 of the Large Hadron Collider (LHC). Both experiments' results pass the required five-sigma statistical significance to count as an observation – ATLAS's observation with 6.1 sigma, higher than the expected significance of 4.3 sigma, and CMS's observation with 5.5 sigma, higher than the expected 4.9 sigma – making them the first observations of this process.

Associated top quark production

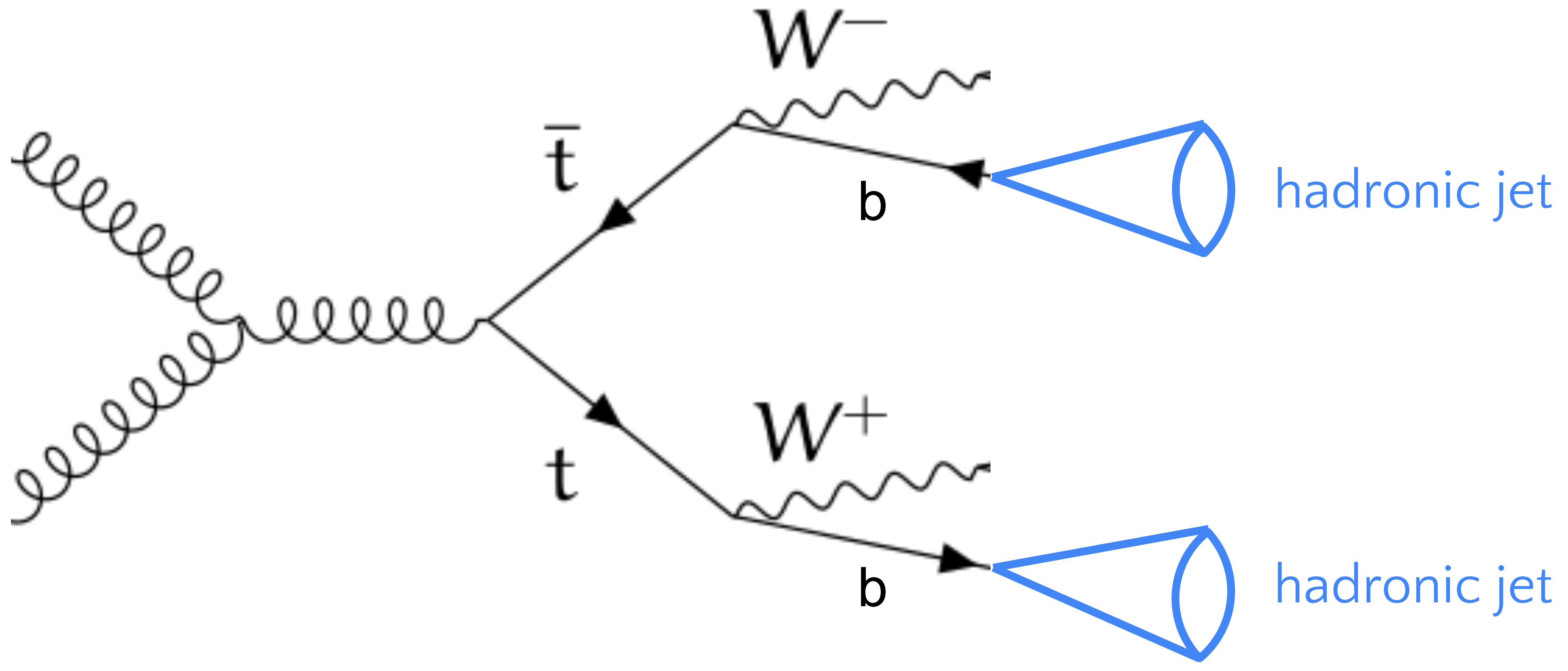
- $t\bar{t}$ cross section ~10^3 pb
- $t\bar{t}$ associated with other particles (bosons but not only) is much rarer, ~0.01-1 pb
  - Interesting to study because of sensitivity to top EW and Yukawa couplings
  - With the very large datasets of LHC, we entered the precision era for these processes
- $t\bar{t}\gamma$ is a special example
  - *"All things emit light all the time"*
  - When we talk about $t\bar{t}\gamma$, we have to impose a minimum photon momentum and isolation - **"fiducial"** cross sections
  - Relatively large cross section - can do precision measurements and even go differential



Reminder - top quark decays

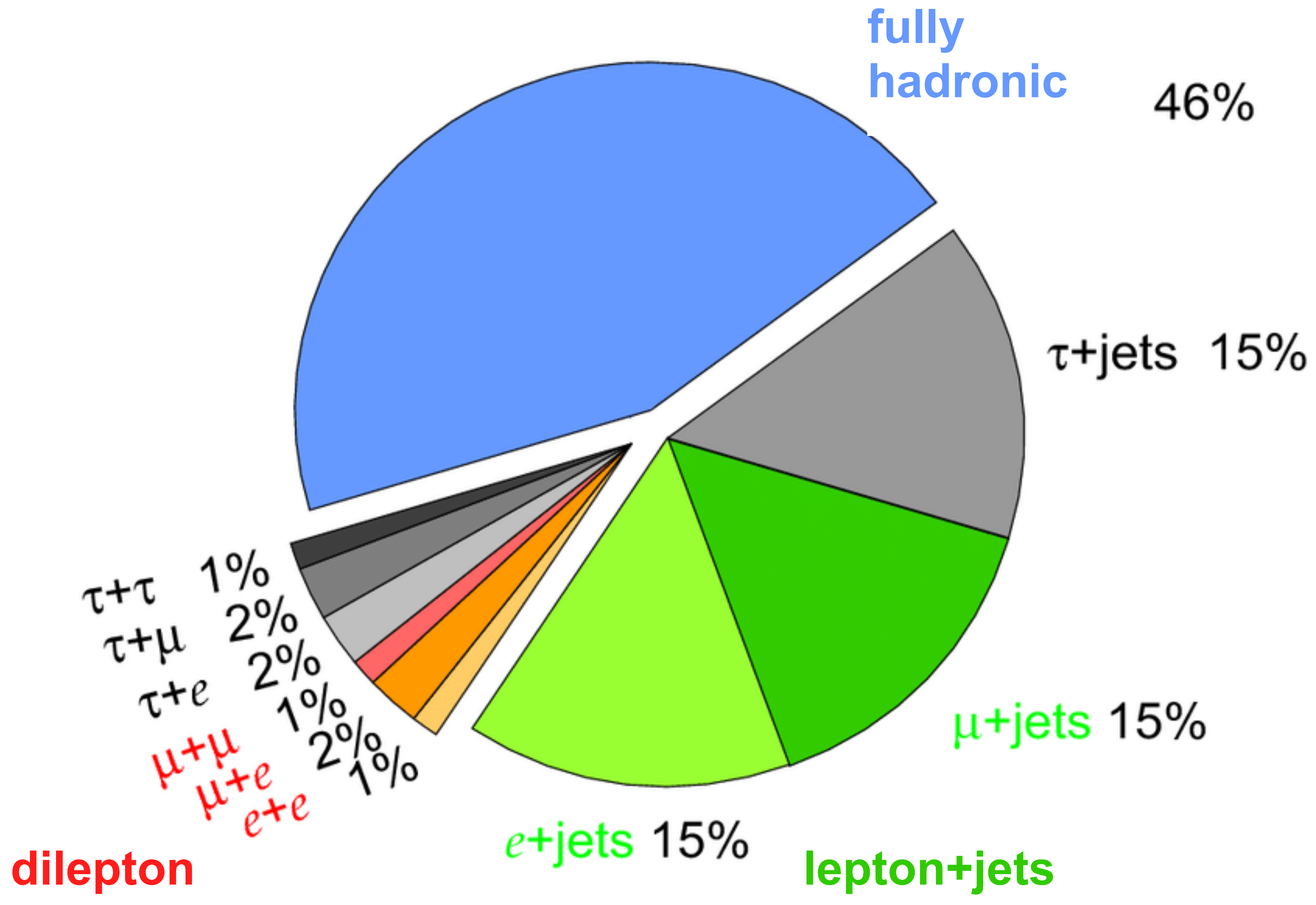


- Top decays almost exclusively to a W boson and a b quark
- b quarks hadronise forming jets, which can be identified as b jets
- $t\bar{t}$ events are characterised by W decay possibilities

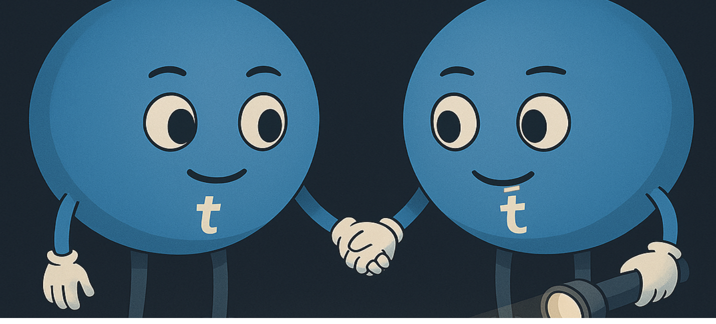


dilepton decay channel is the rarest, but

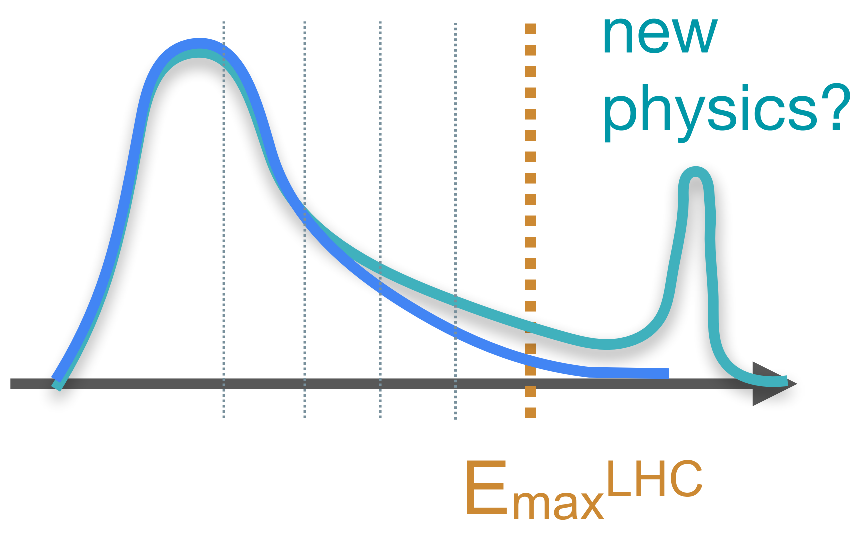
- lowest contribution from backgrounds
- Great resolution for lepton reconstruction in CMS



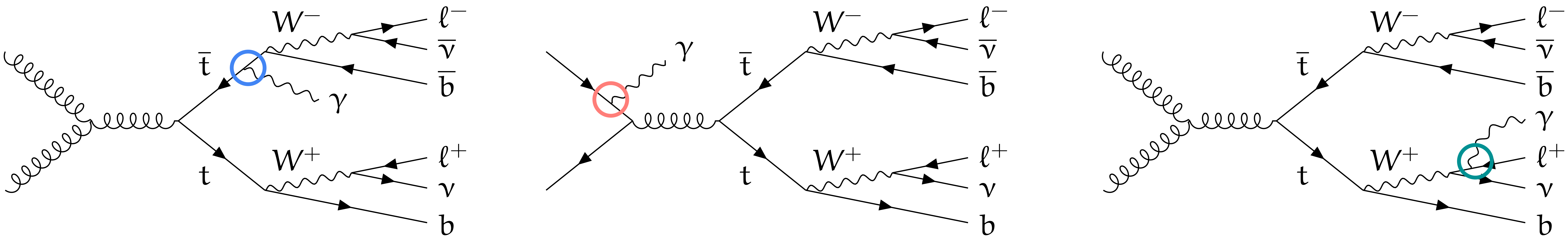
The $t\bar{t}\gamma$ process



- $t\bar{t}\gamma$: production of $t\bar{t}$ in association with a hard (here >20 GeV) and isolated photon
- Gives direct access to the $t\gamma$ coupling → *precision test of the SM*
- Differential measurements are sensitive to potential new physics effects at the tails of the distributions



- Experimentally, we cannot distinguish the photon origin, so we must consider all possible origins - the top quarks, initial state quarks, and the top decay products



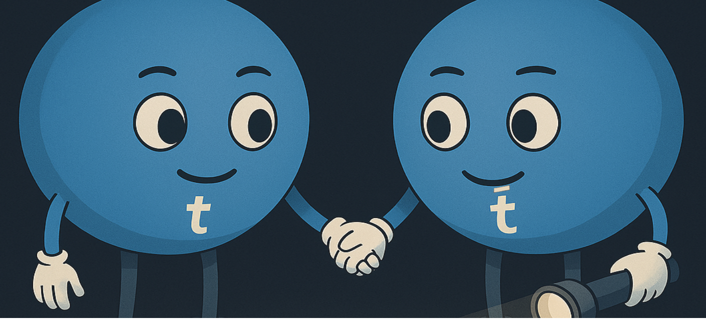
- Events with photons from hadron decays are not considered as $t\bar{t}\gamma$

$\sigma \sim 2\,\mathrm{pb}$

at 13 TeV in $\ell\ell$ channel

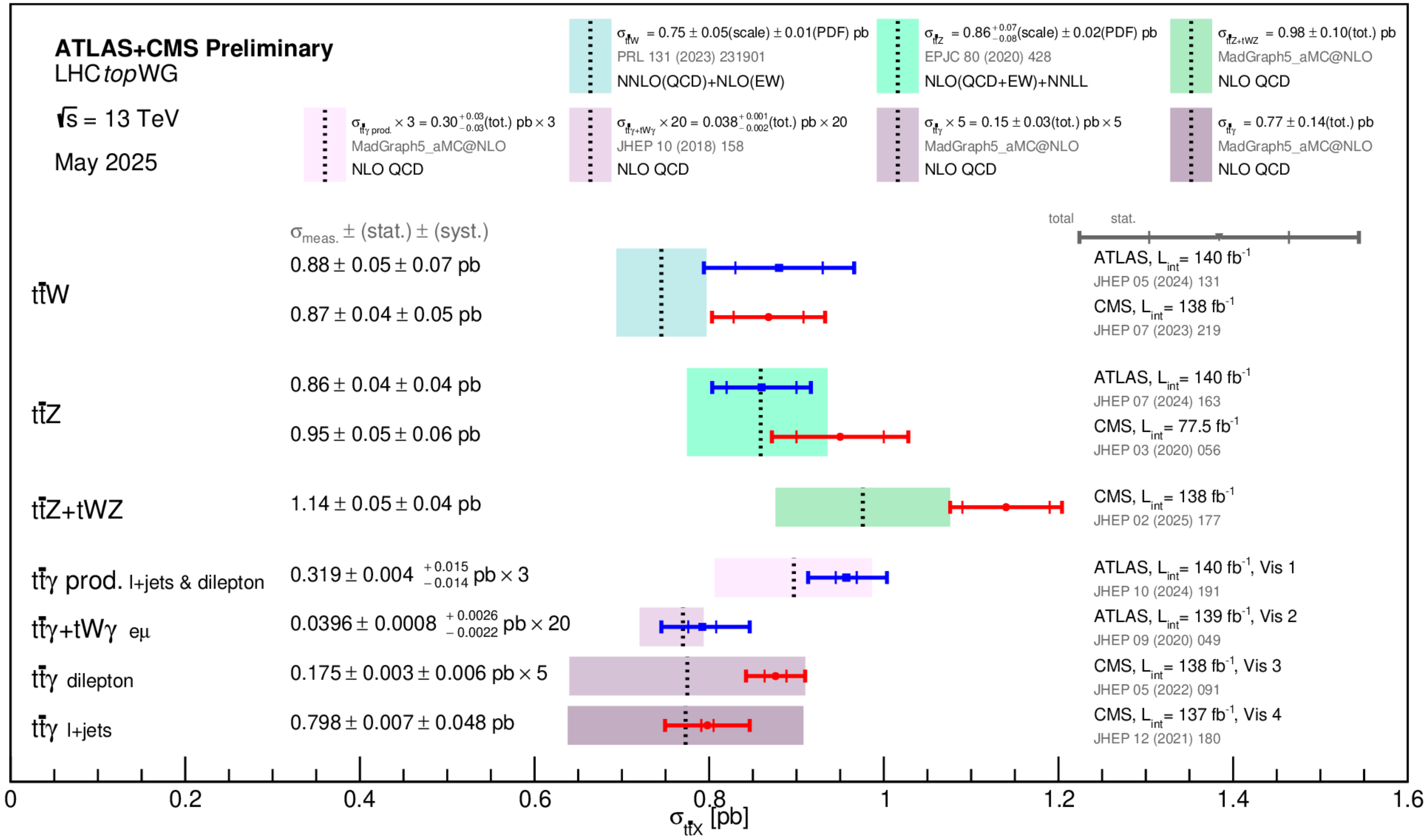
>200k events in Run 2

Existing measurements and why do we still care



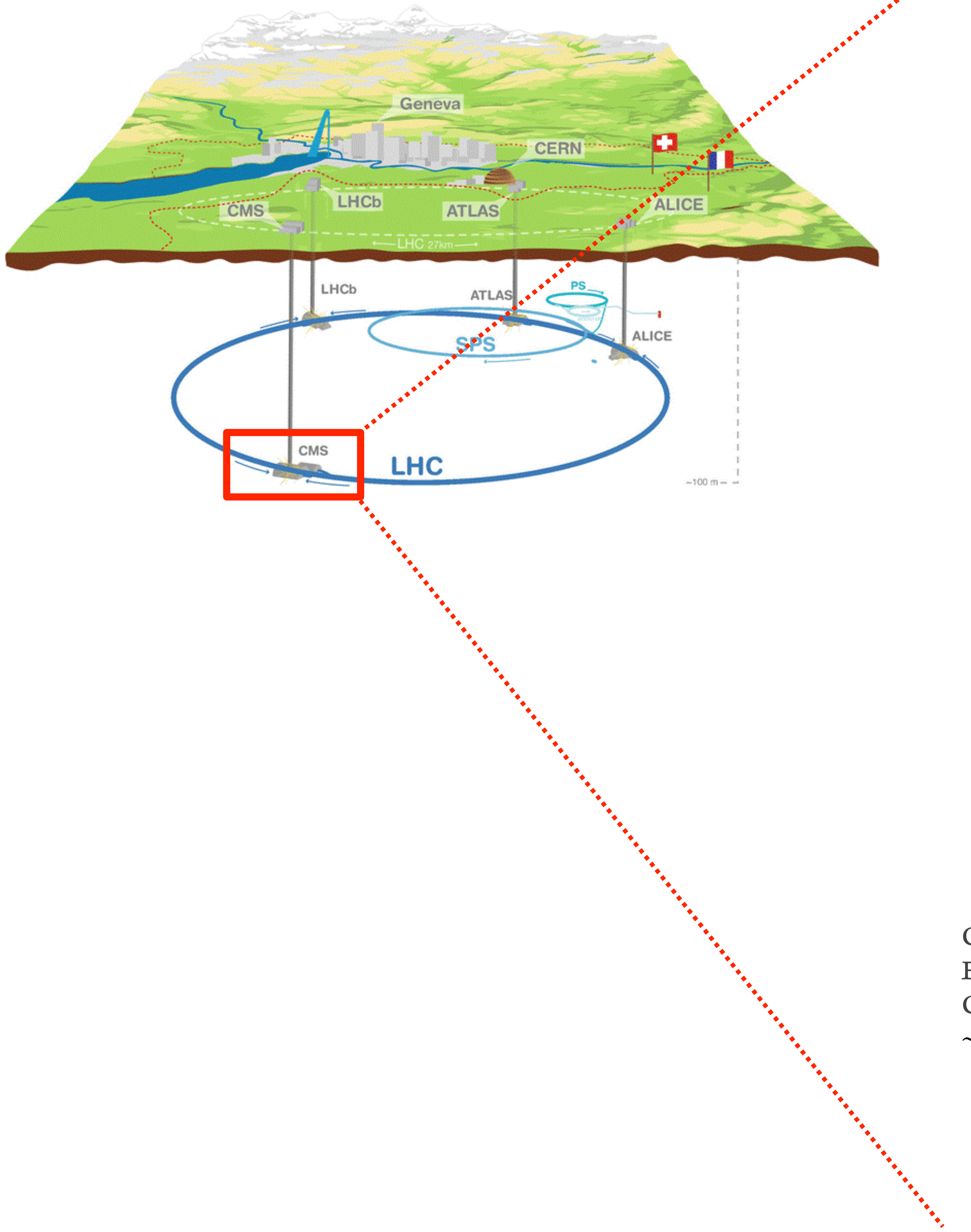
Inclusive and differential measurements by ATLAS and CMS exist

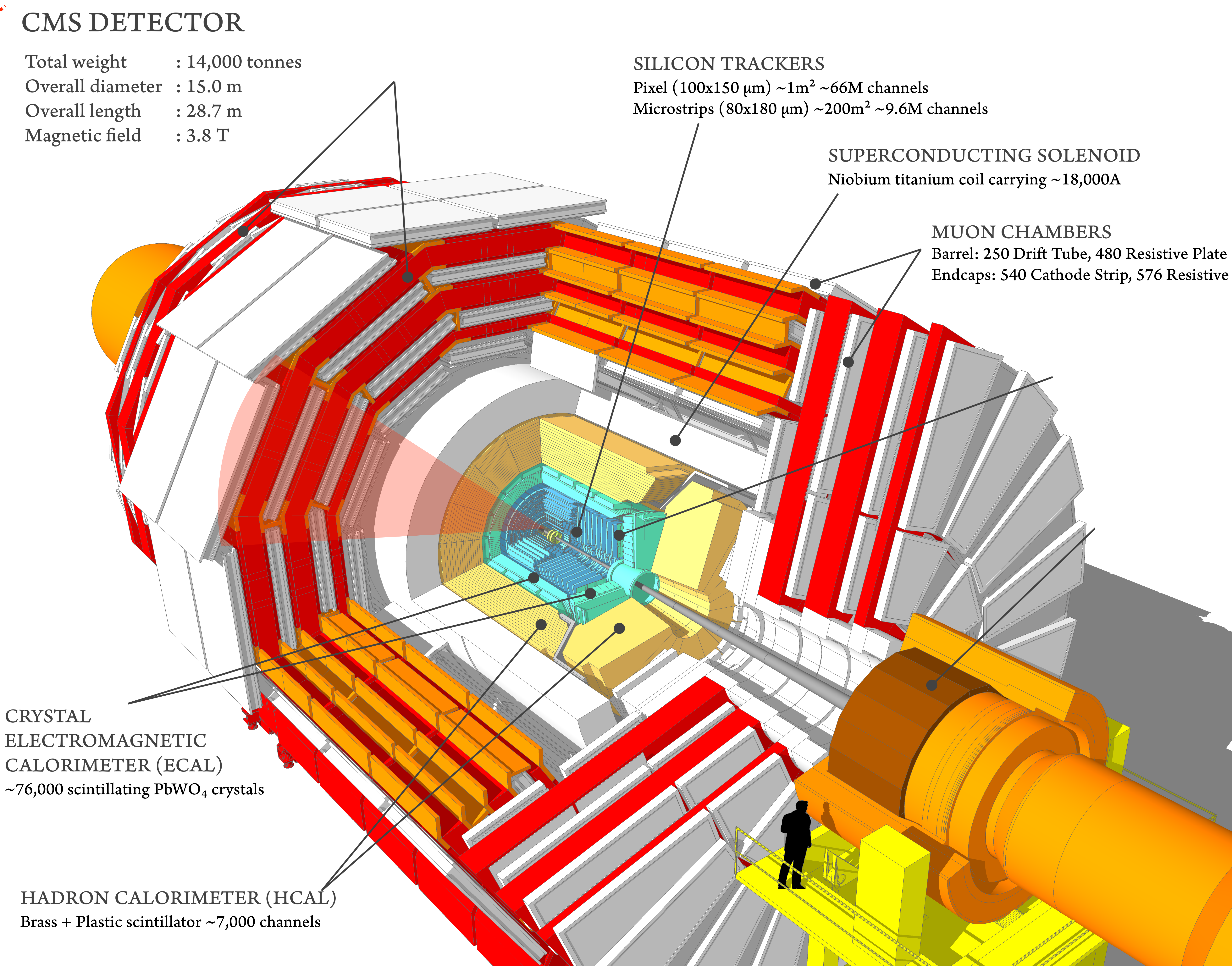
(including EFT interpretations)



- Differential measurements published with lepton and photon variables
- Available differential measurements did not contain top quark properties, which are sensitive to modelling and $t\gamma$ coupling
- Ratio $t\bar{t}\gamma/t\bar{t}$ (inclusive and differential) opens the way to extra precision, due to cancellation of systematic uncertainties, but had never been measured

Seeing $t\bar{t}\gamma$ in CMS





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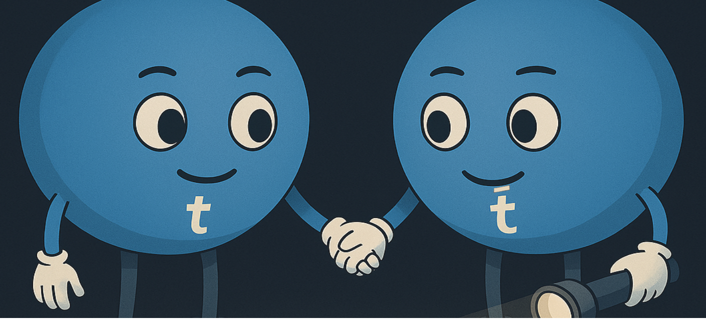
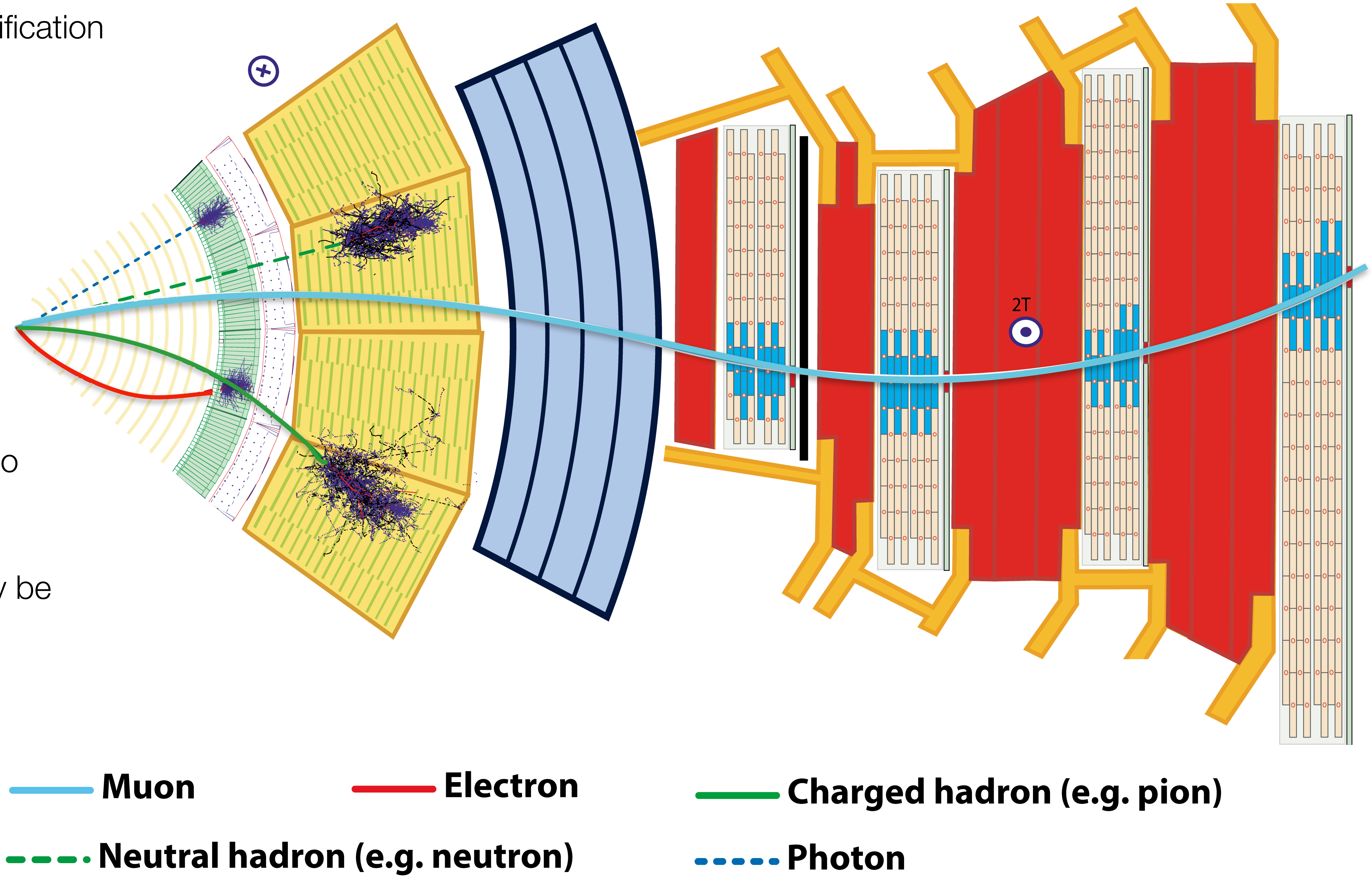
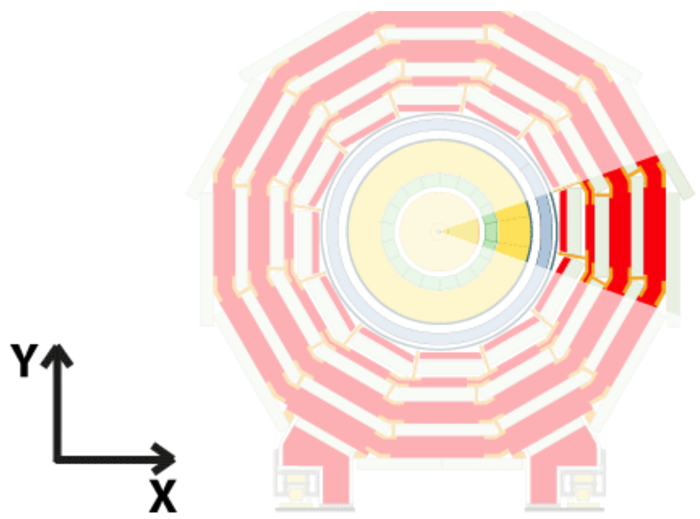


- Layered structure for particle identification

> ✓ Information from all sub detectors combined to reconstruct particle candidates



- Good photon resolution essential to reconstruct $t\bar{t}\gamma$ events
- Electrons and neutral hadrons may be misidentified as photons



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- Layered stru

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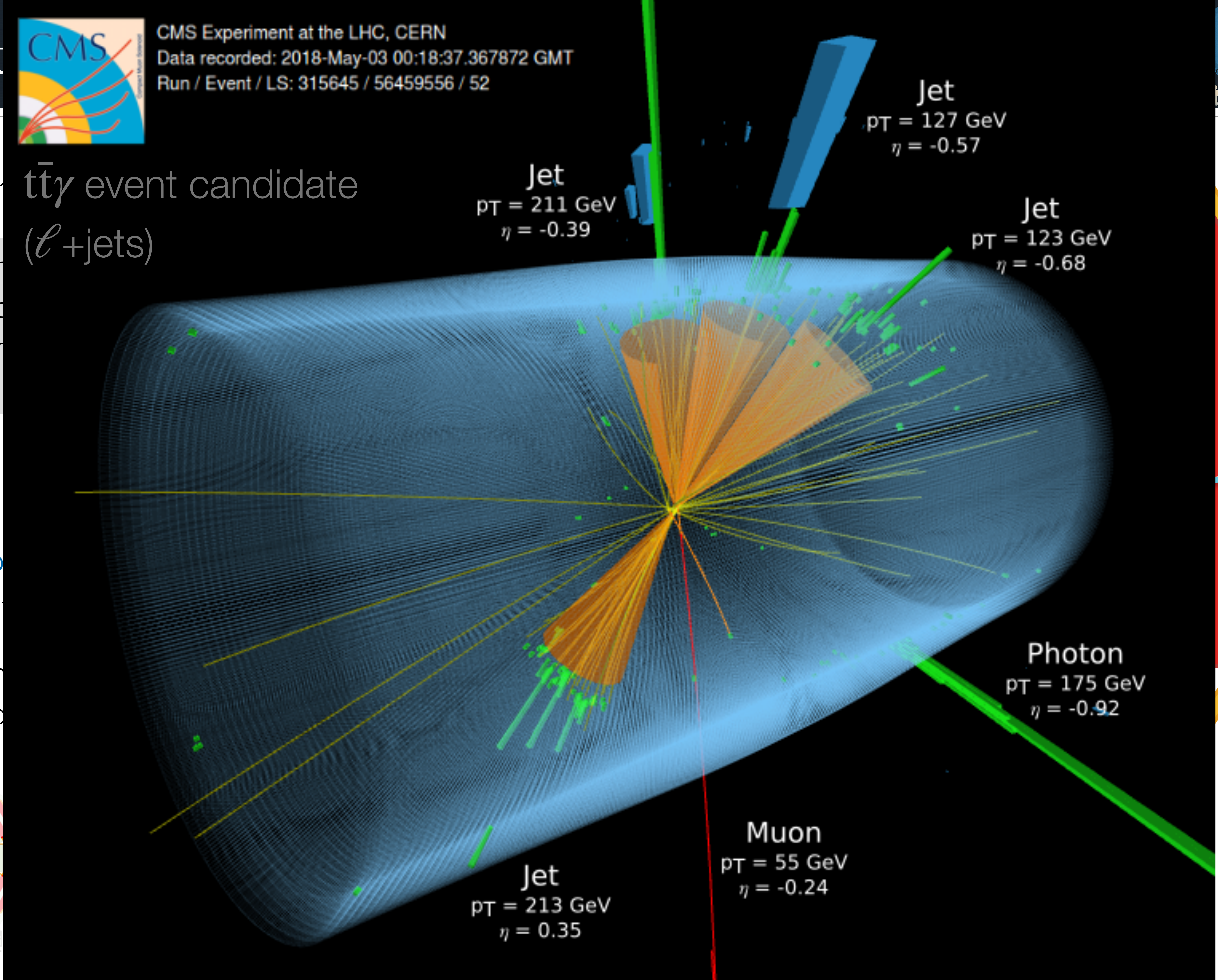
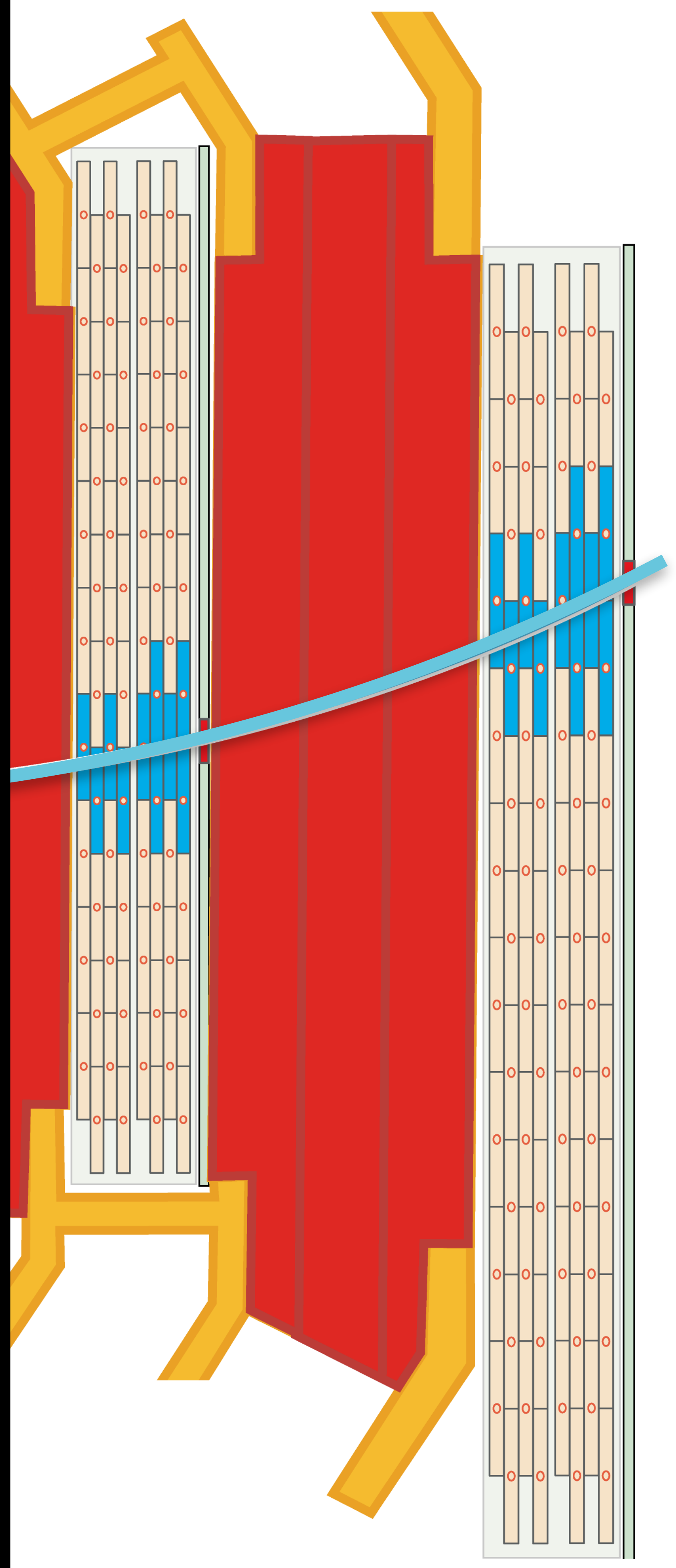
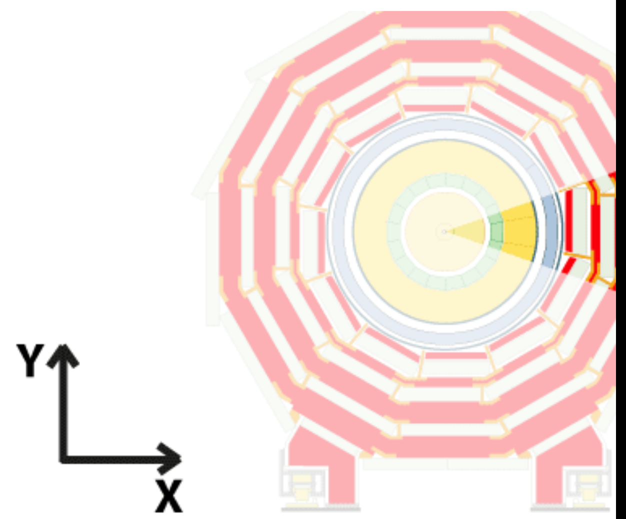




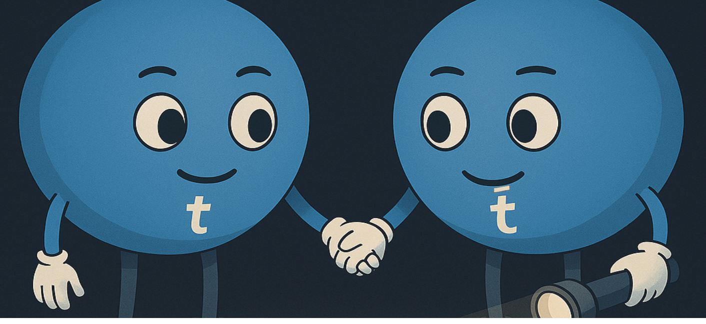
(e.g. pion)

- Good photo
reconstruct

- Electrons ar
misidentified

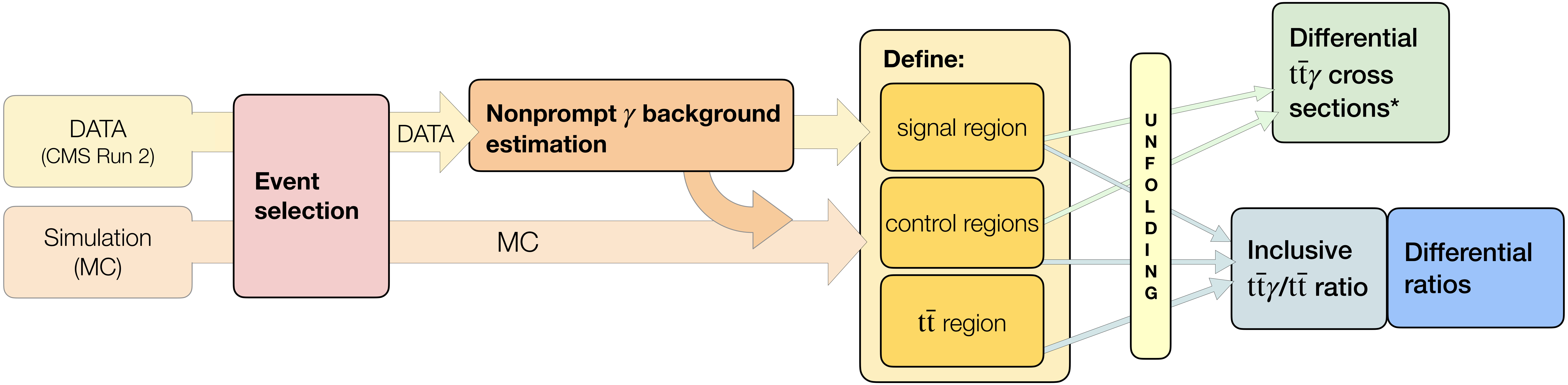


The new CMS analysis in a nutshell



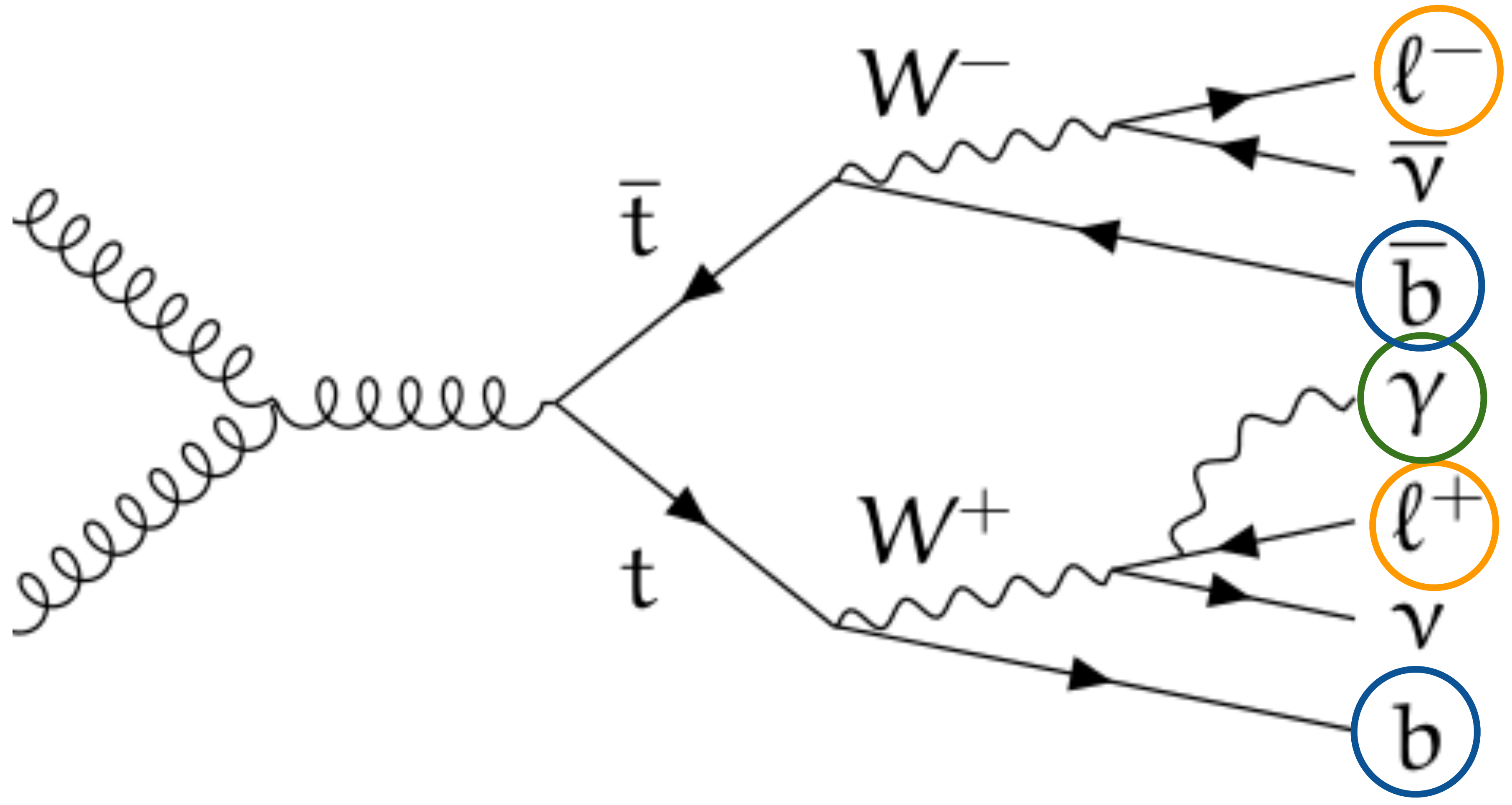
- Use data collected in CMS during the full Run 2 (2016-2018), corresponding to 138 fb^{-1}
- Look at the dilepton decay channel

arXiv:2511.01995
Submitted to JHEP



*and a **top quark charge asymmetry** study

Selecting $t\bar{t}\gamma$ events



≥2 opposite charge leptons

off Z peak
(for same flavour leptons)

=1 photon

well separated from leptons

M($\ell\ell\gamma$) off Z peak
(for same flavour leptons)

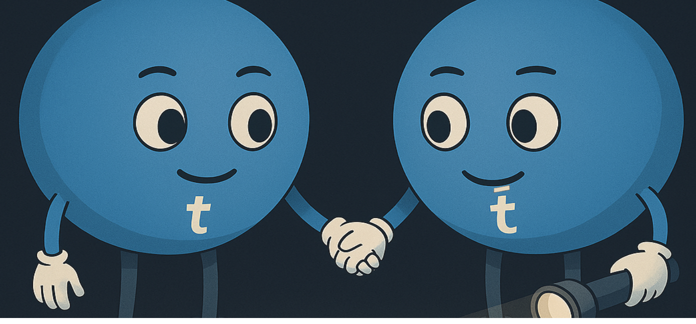
≥2 jets, ≥1 b tag

well separated from photons and leptons
b tagging using deep neural network algorithm

Reconstruction of $t\bar{t}$
(for top-related variables)

Event must pass kinematic reconstruction of $t\bar{t}$

Background estimation

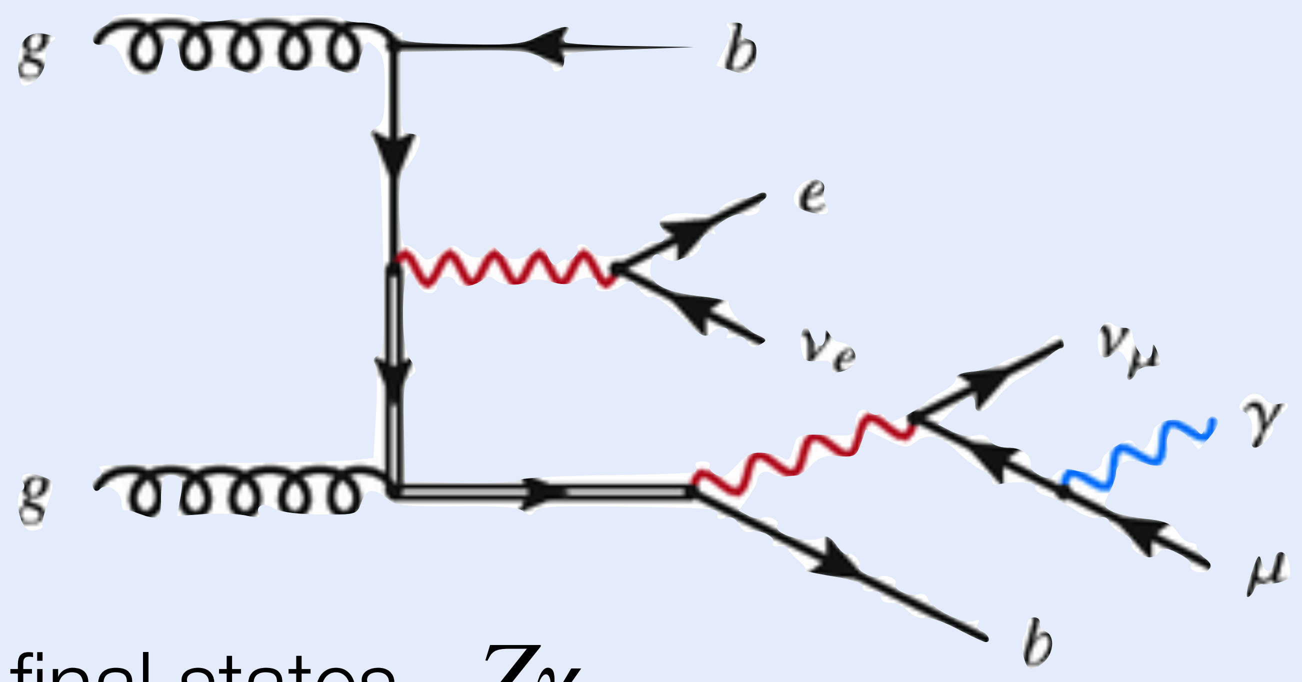


Two main types of background contributions:

Real photon backgrounds

- Estimated using MC simulations
- Largest source is single top quark in association with a photon - $\mathrm{t}W\gamma$
  - ✓ Treated with dedicated simulation at NLO – *first time!*

example diagram:



- Important background in ee and $\mu\mu$ final states - $Z\gamma$
  - ✓ Handled with control region
  - ✓ M($\ell\ell\gamma$) cut inverted

"Fake" photon backgrounds

- Real photons from pileup or hadron decays
- Misreconstructed electrons or jets

✓ Simulation has large uncertainties

✓ Estimated from data - next slides

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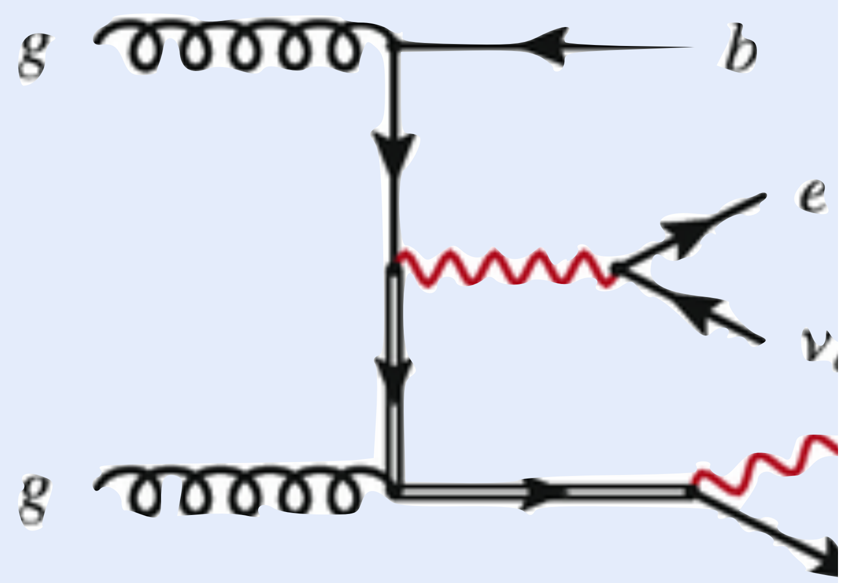

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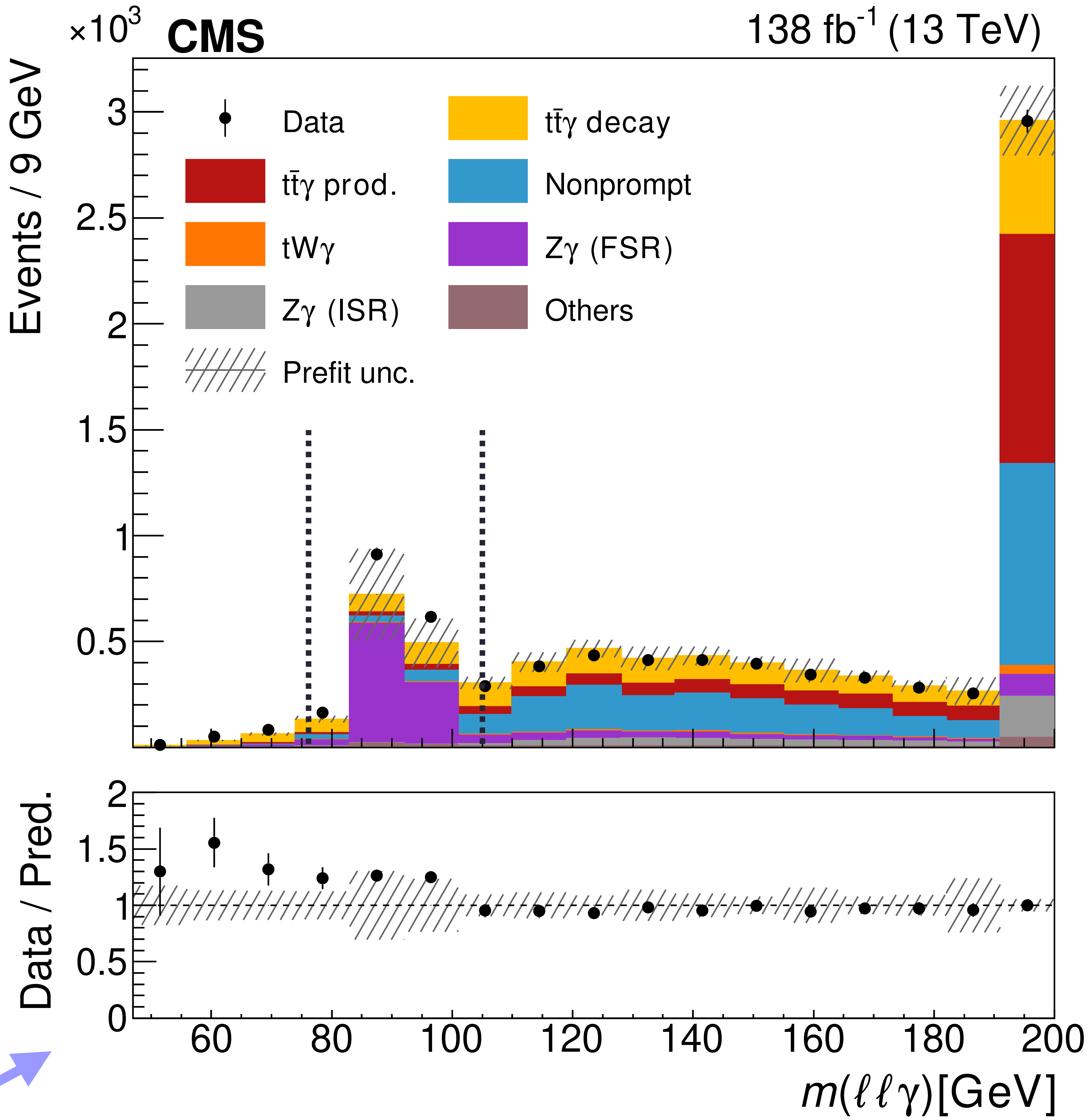

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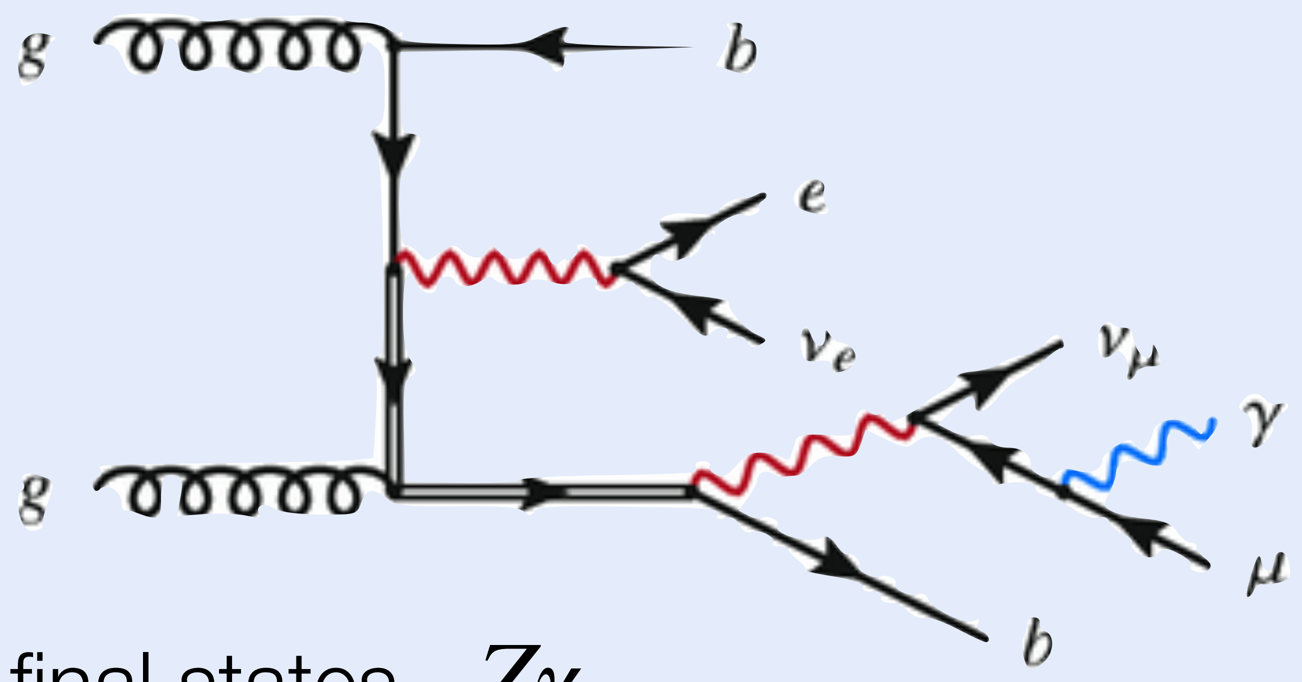

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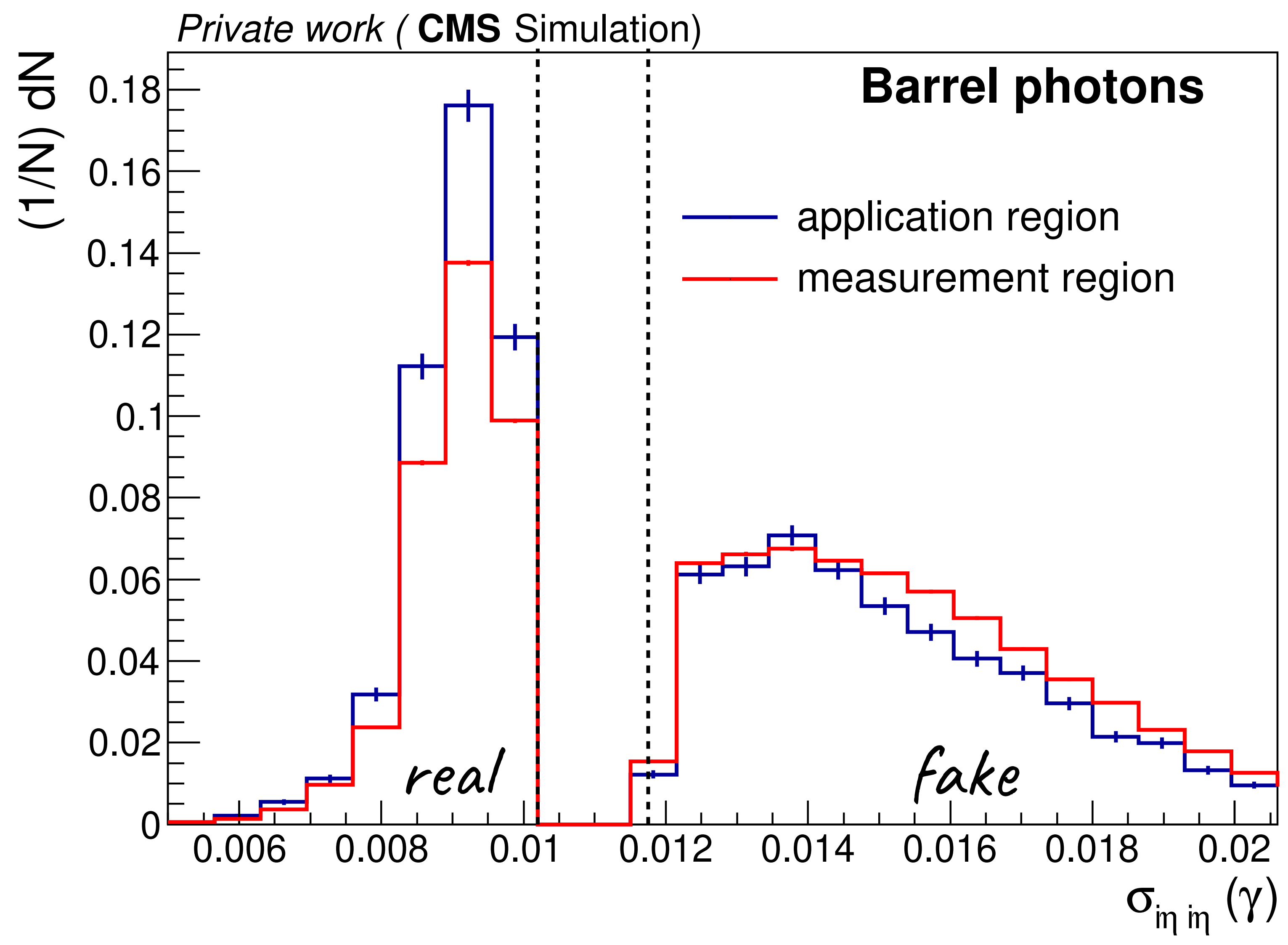
Nonprompt photon estimation

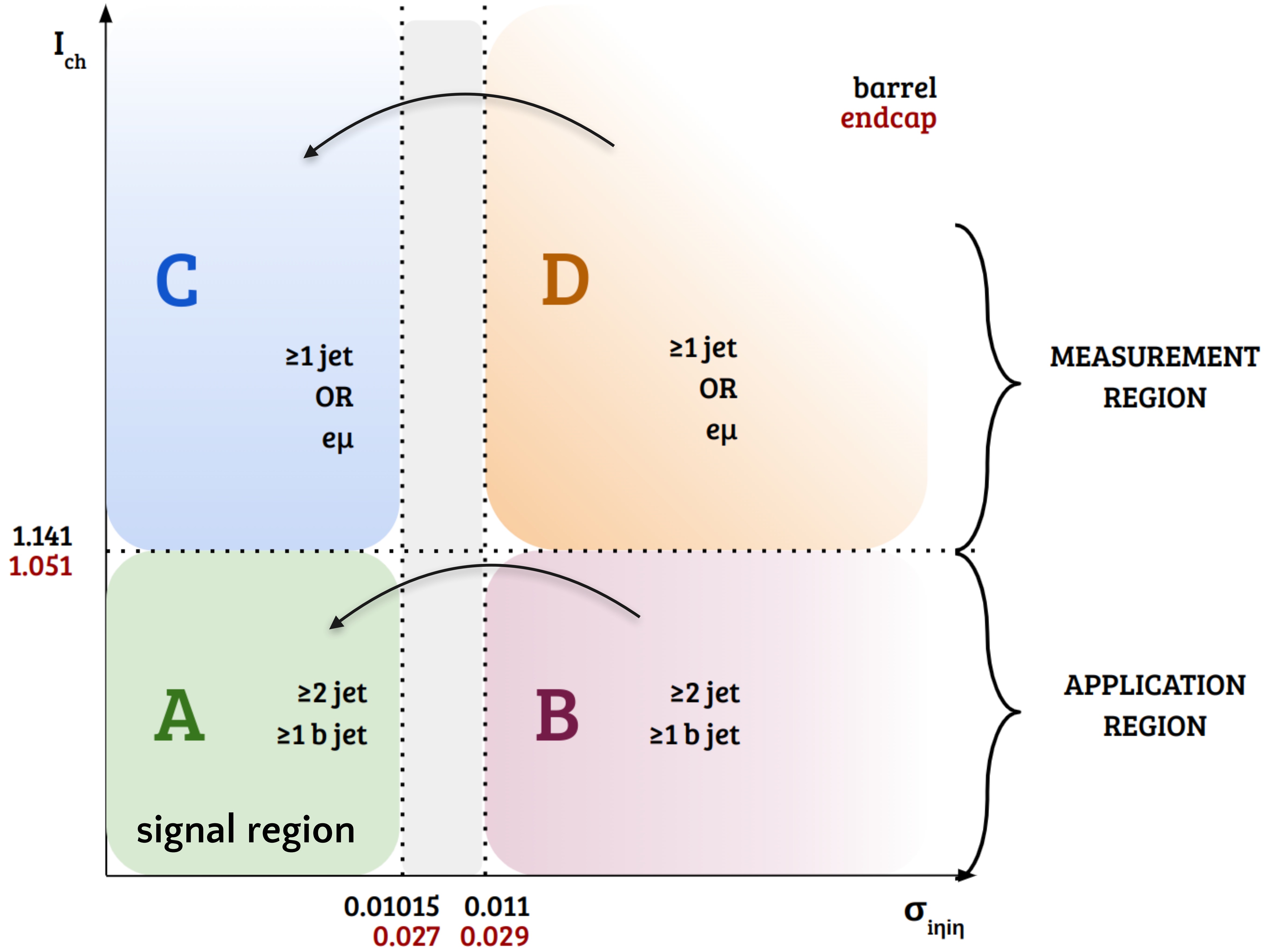
- How to identify nonprompt/fake photons?
  - ✓ Poor isolation from charged particles around I_{ch}
  - ✓ Wide electromagnetic showers in ECAL $\sigma_{i\eta i\eta}$

almost uncorrelated



- Define A, B, C, D regions
- Compute C/D ratio from data = fake rate

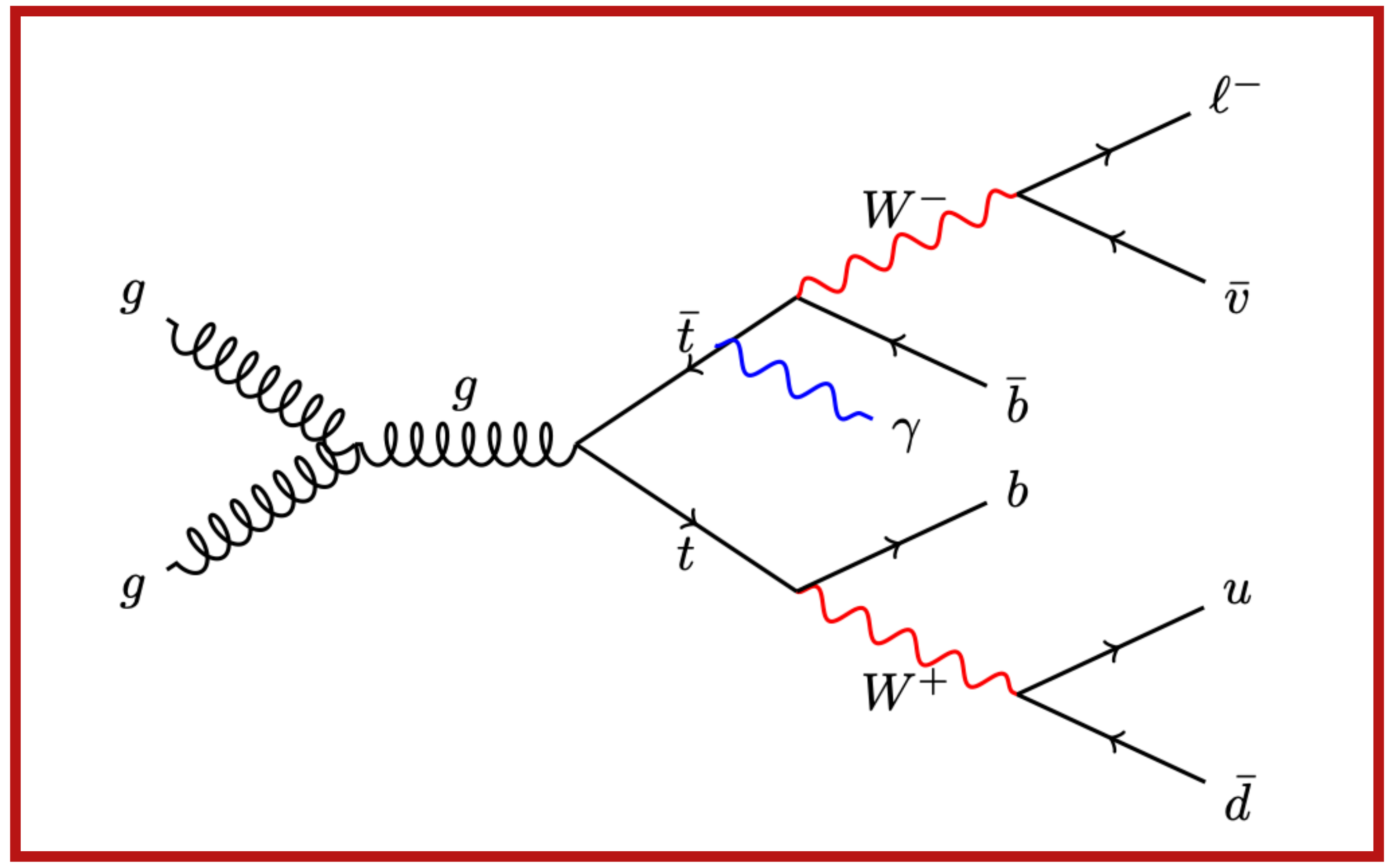
$$\text{nonprompt in signal region} = \text{nonprompt in B} \times \frac{\text{nonprompt in C}}{\text{nonprompt in D}}$$

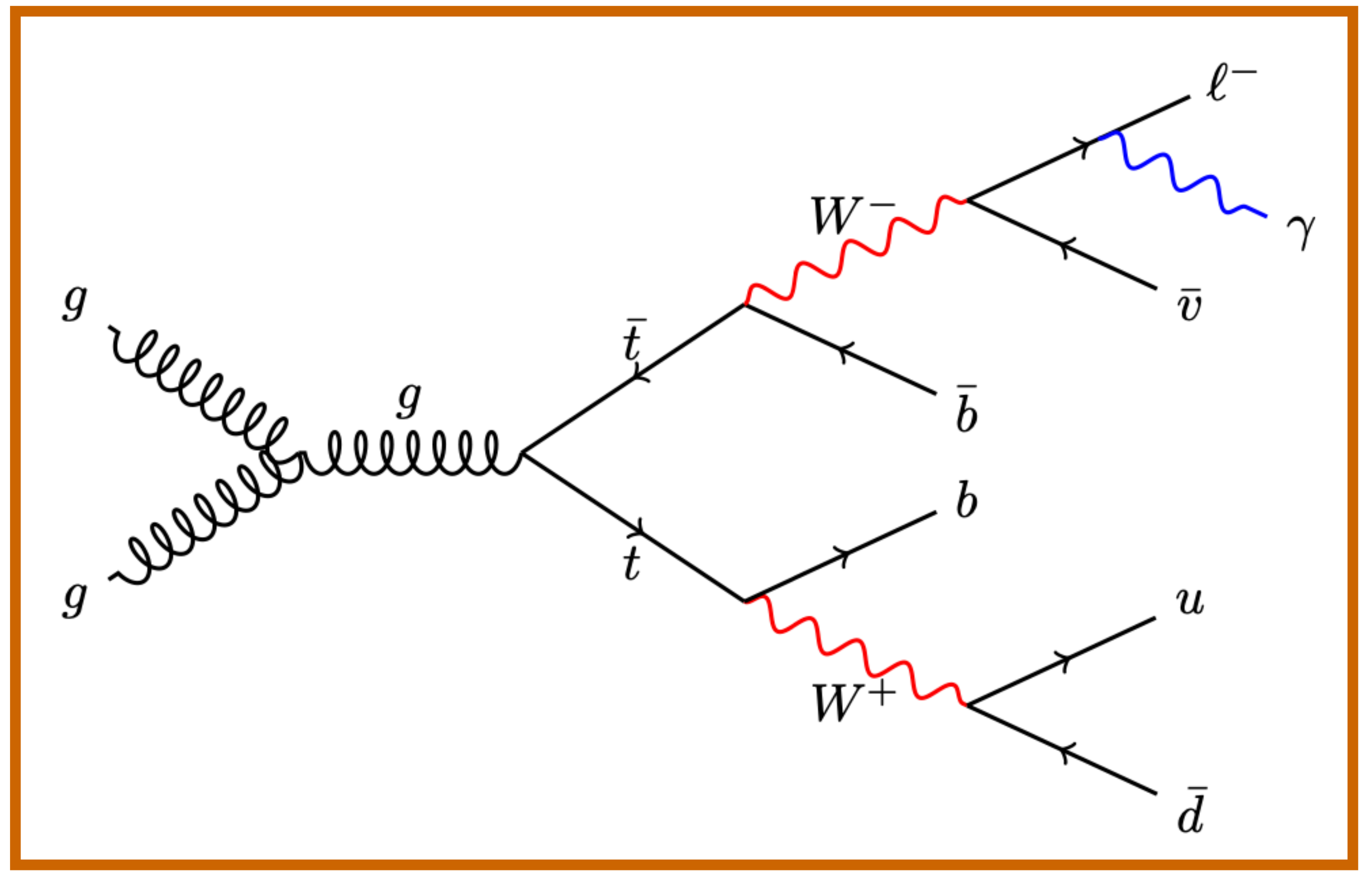


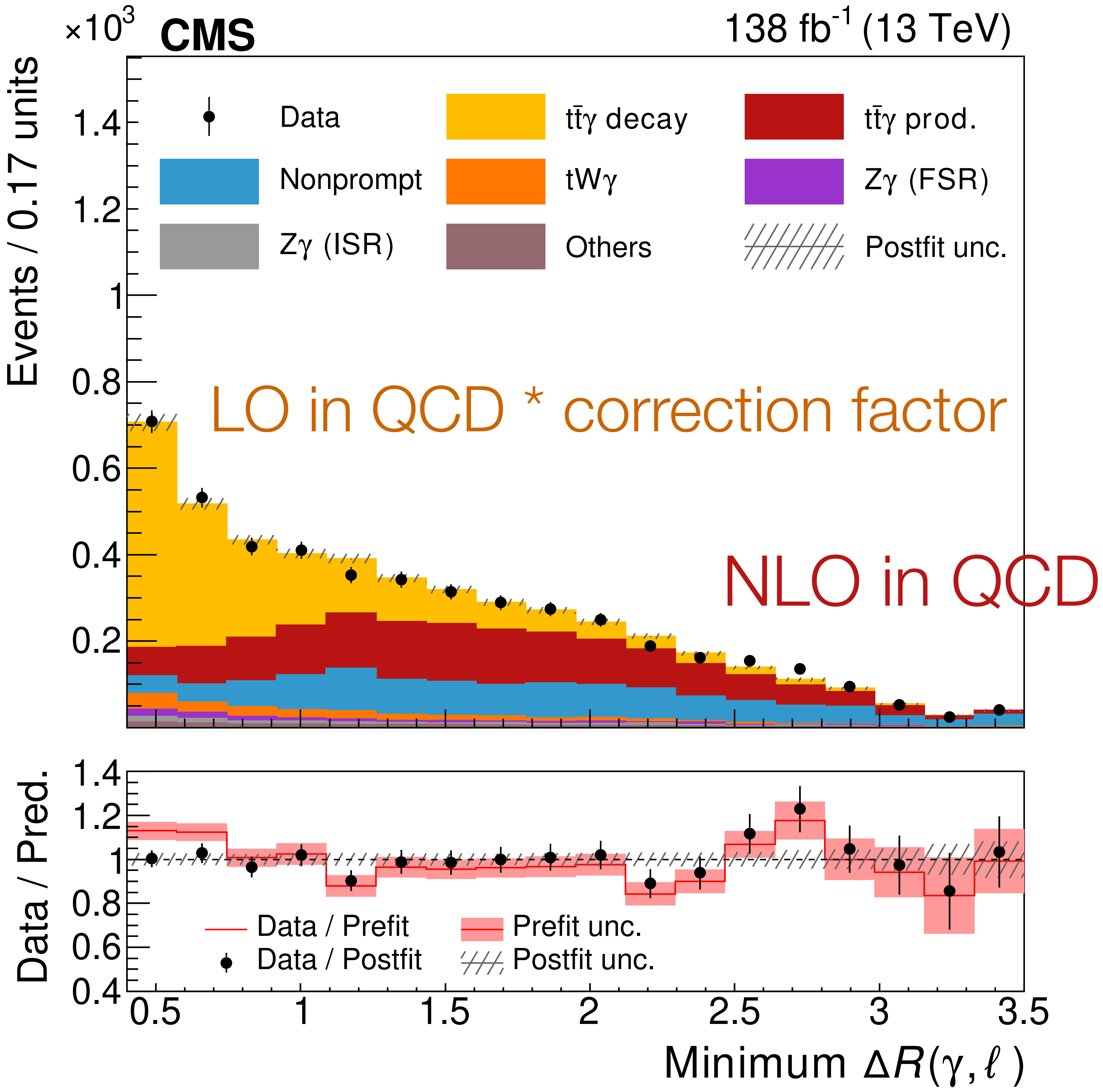
Some words about signal modelling…

$t\bar{t}\gamma$ 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





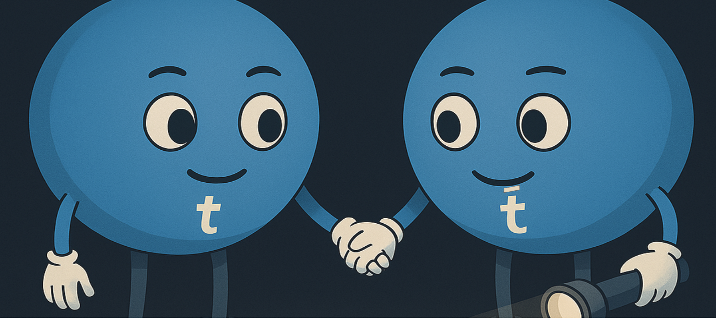


- It is impossible with current generators to simulate the whole process at once at NLO in QCD
- We need to “stitch” two samples:
  - Production at NLO
  - Decay at LO, multiplied by a correction factor

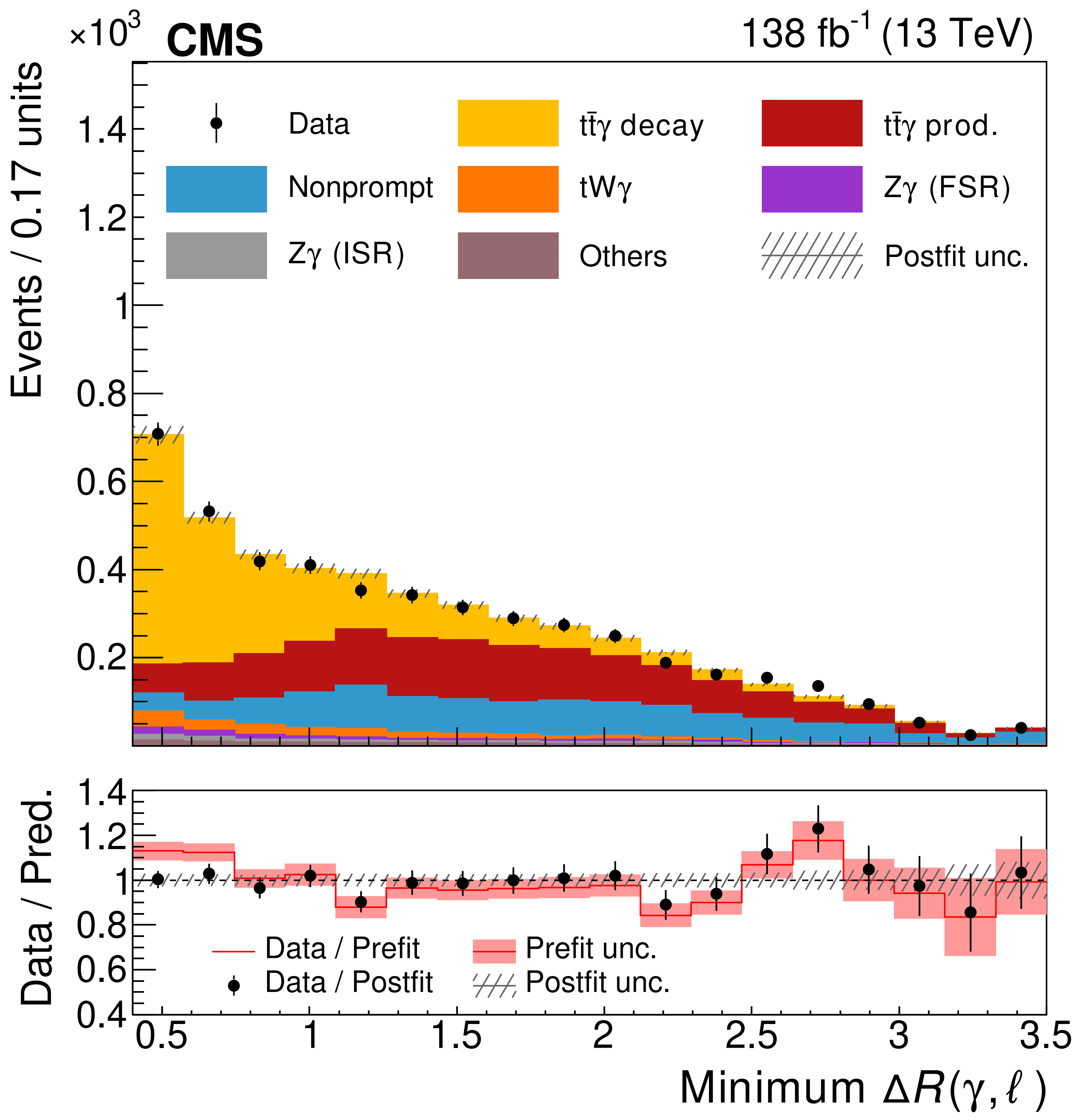
Comparison data/predictions

- Generally good description for all variables
- $t\bar{t}\gamma$ production ~ 40% of signal contribution

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

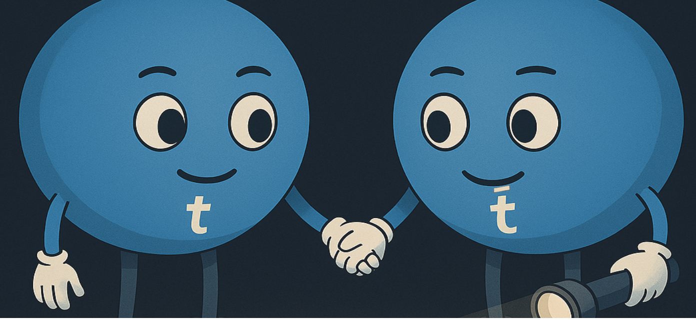


- Measuring **fiducial** $t\bar{t}\gamma$ cross section (**production**+**decay**) and also the **production** component separately
- Fit to min. $\Delta R(\gamma, \ell)$ including all systematic uncertainties
  - Powerful variable to separate production and decay
- Measure **$\sigma(t\bar{t}\gamma)$ = 137 ± 3 (stat) ± 7 (syst) fb (6%)**
  - In agreement with prediction of **126 ± 19 fb** (MadGraph5_aMC@NLO)
  - Limited by systematic uncertainties, mainly normalisation of the nonprompt background, γ identification, fraction of the $t\bar{t}\gamma$ decay component, jet and b tagging



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

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

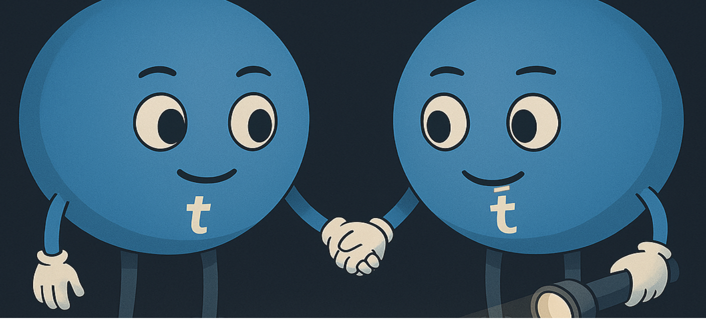


- Choose observables to measure:
    - p_{T} of top quark; $\Delta R(\gamma, \mathrm{t\bar{t}})$, min. $\Delta R(\gamma, \mathrm{t})$, $m(\mathrm{t\bar{t}})$ - new, sensitive to photon origin and new physics
    - p_{T} of leading lepton and photon, $\Delta\phi(\ell, \ell')$ - cross-check with previous CMS analyses

- Objects defined at
    - **Parton level** (intermediate particles before showering and hadronization, broad phase space)
    - **Particle level** (final state objects, phase space mimics detector acceptance)

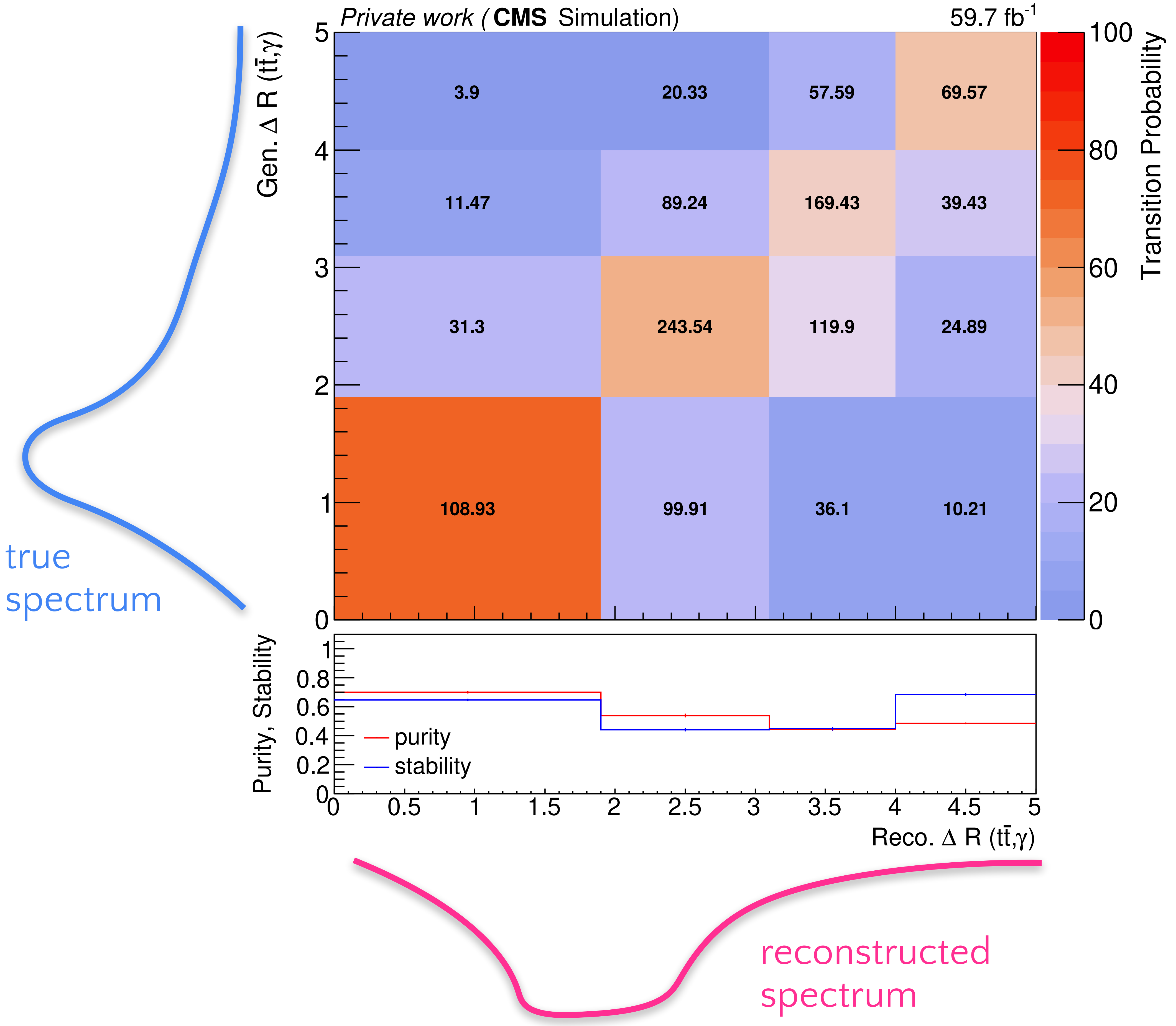
- **Top/$\mathrm{t\bar{t}}$ variables are being measured for the first time in this process**
- Normalised and absolute cross sections measured for production+decay

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

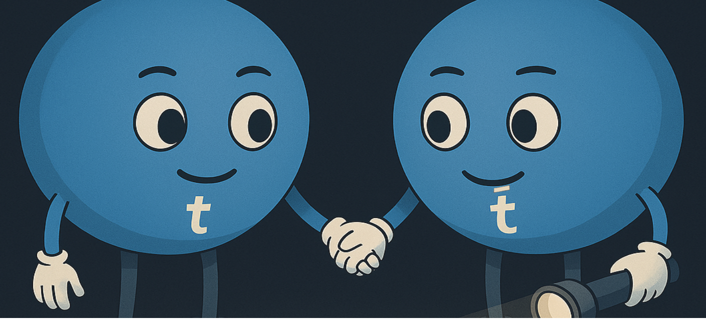


- How do we make differential measurements?
  - Build response matrices with reconstructed vs. generated quantities
  - Decide on binning based on purity and stability (how diagonal is the matrix?)
  - Build signal templates for each bin at generator-level
  - Perform maximum likelihood fit to distributions in the signal region and control region simultaneously
  - All systematic uncertainties and respective correlations handled directly in the fit
  - Extract signal strength modifiers for each gen.-level bin $\mu_i = \frac{\sigma_i}{\sigma_i^{\text{exp}}}$

example:



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

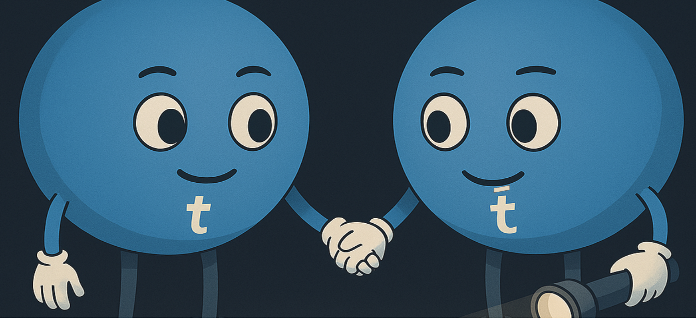


- Compare to: **NLO $t\bar{t}\gamma^{prod}$ + LO ME $t\bar{t}\gamma^{decay}$** | **NLO $t\bar{t}\gamma^{prod}$ + NLO $t\bar{t}$ PS ^{decay}** | **Fixed-order prediction**

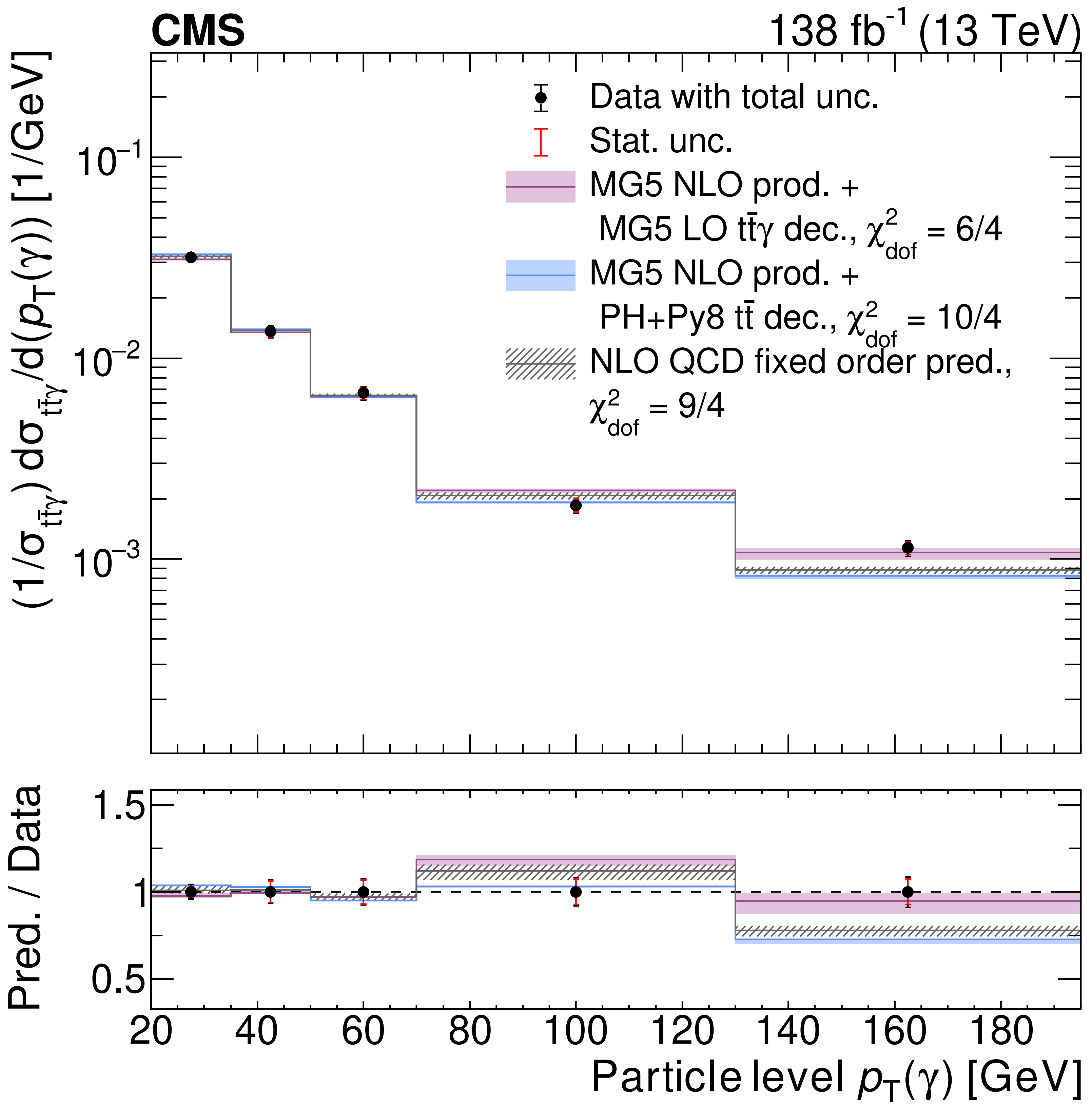
Momenta well described by simulation, angular variables show some trends.

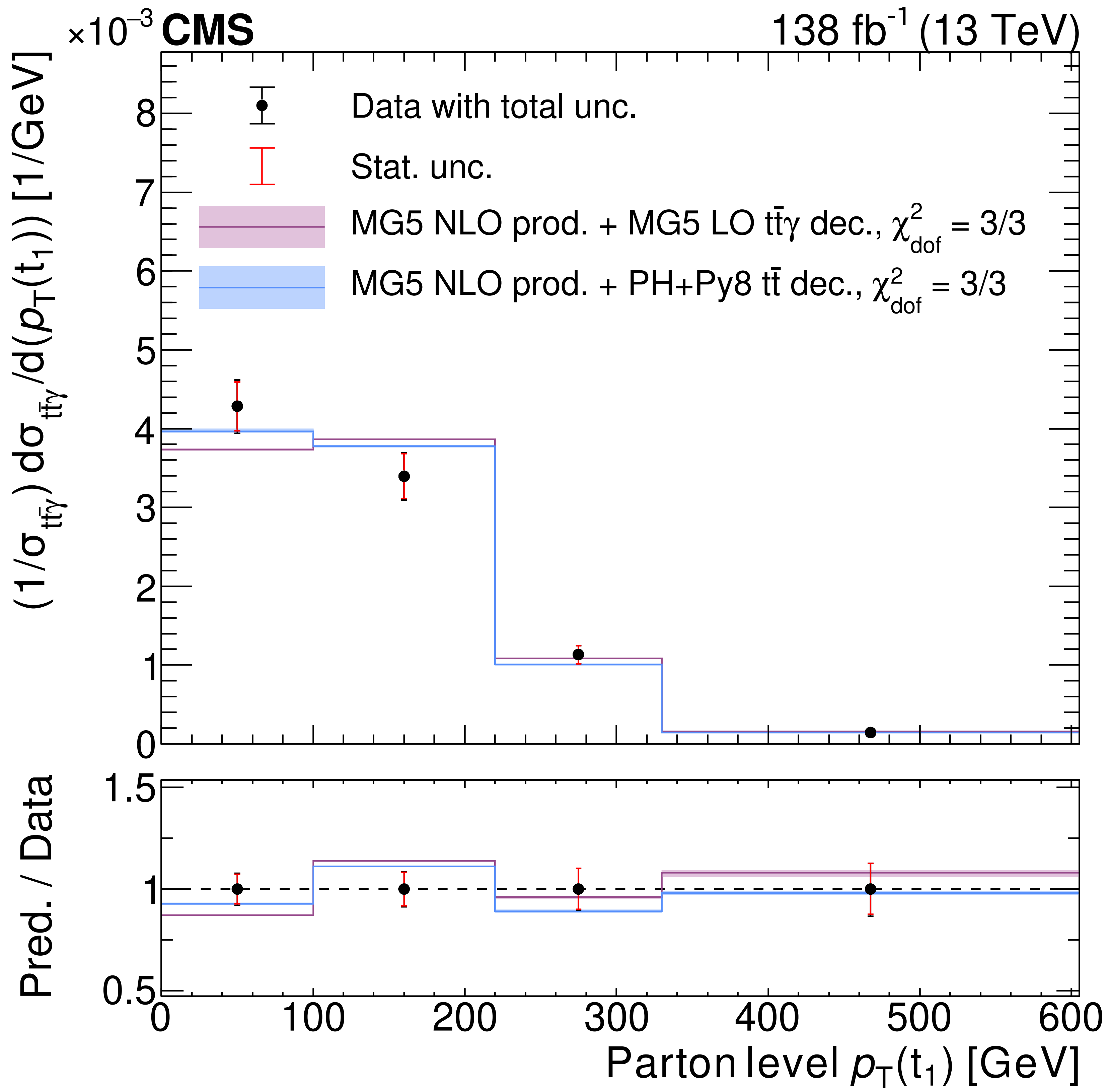
Very precise results, down to 4% unc. in some bins

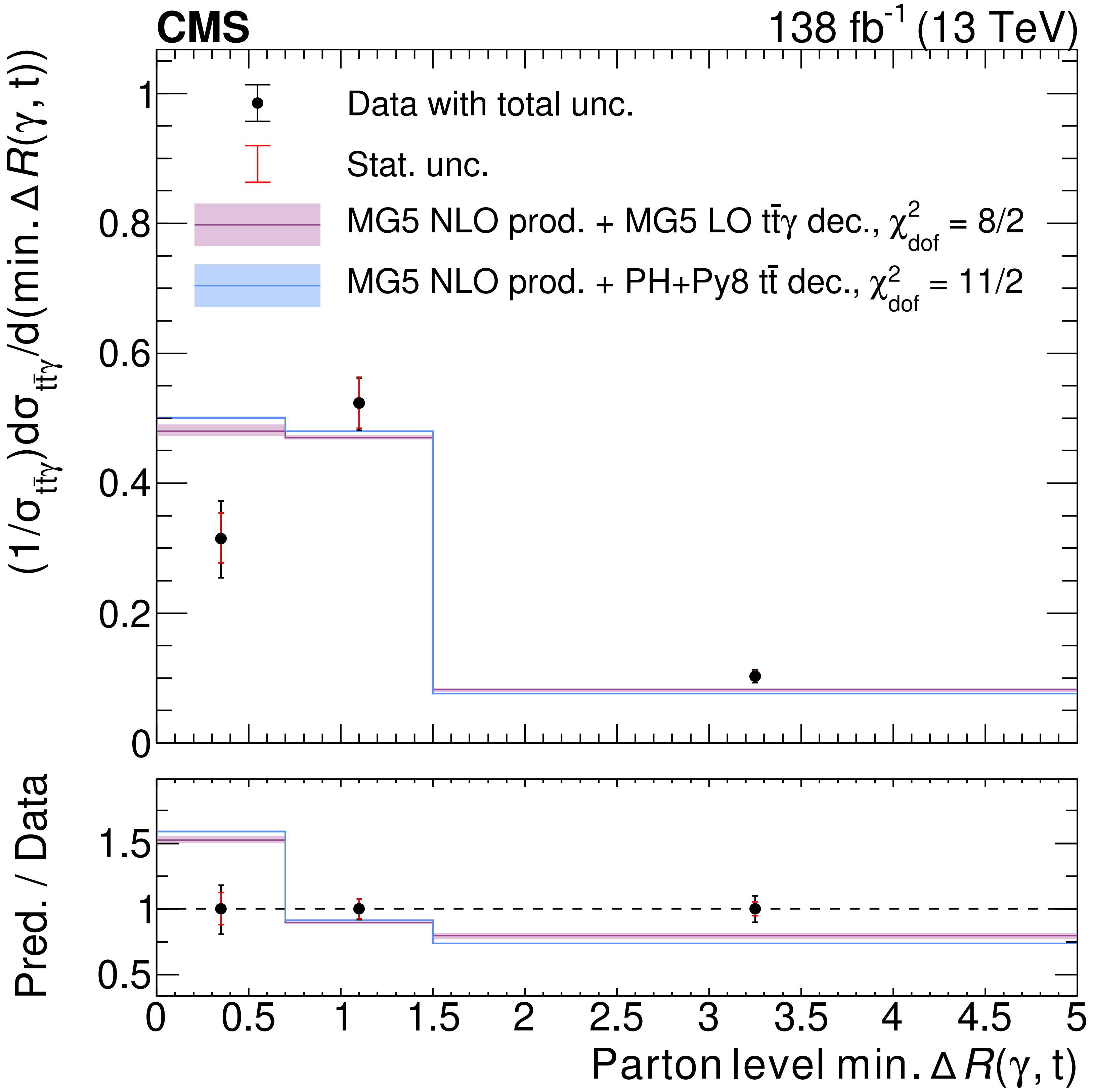
Differential cross section measurements of $t\bar{t}\gamma$ - normalized



- 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}** | **Fixed-order prediction**



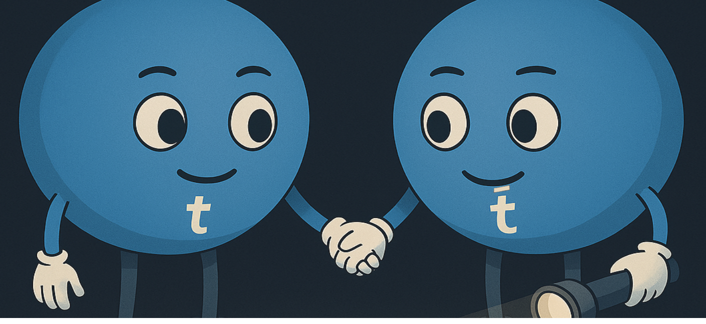




Normalized distributions show very good agreement for both predictions, except for angular variables

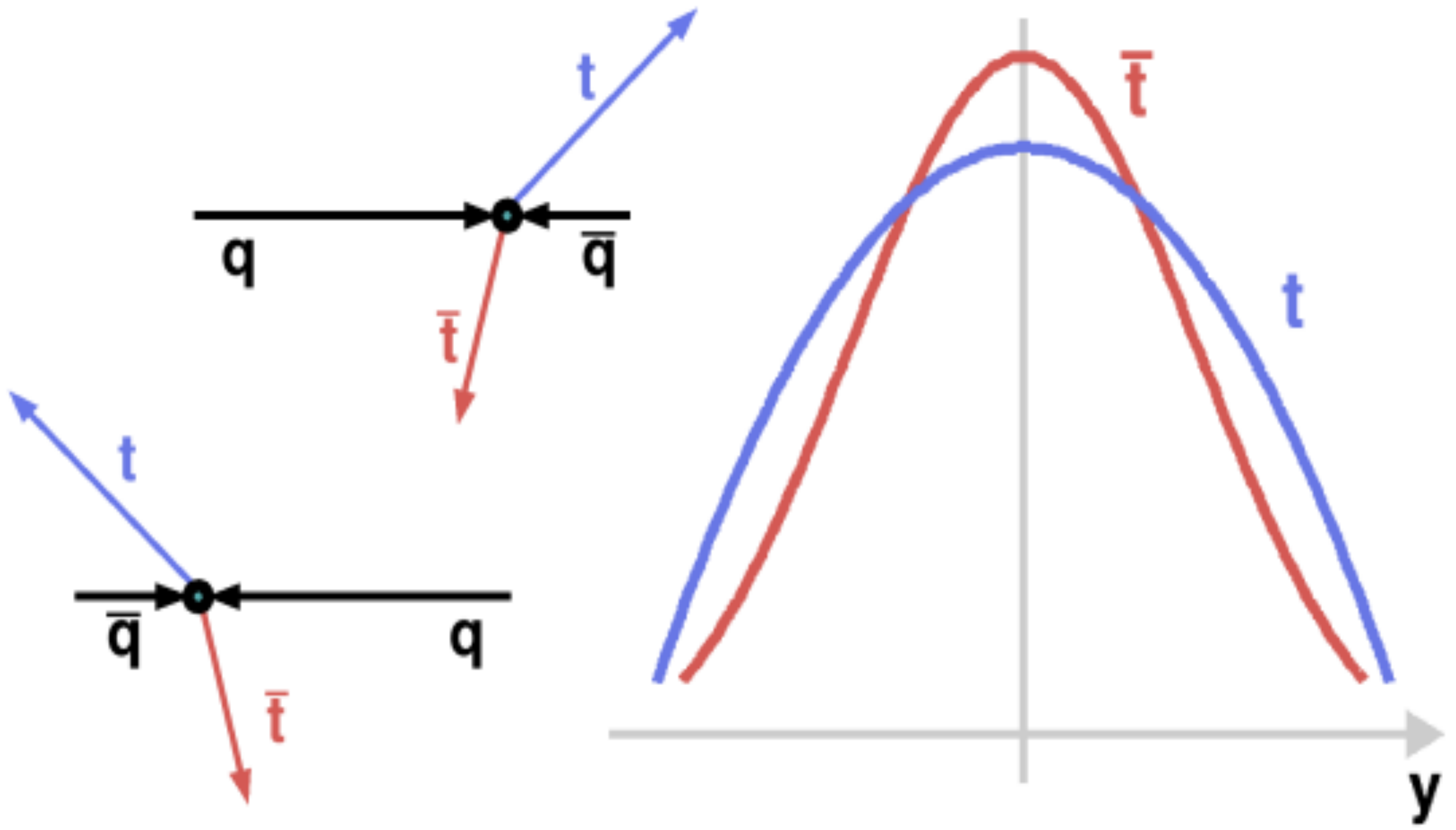
Most likely reflects difficulties in modelling, a complete NLO model would allow for more consistent interpretation

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

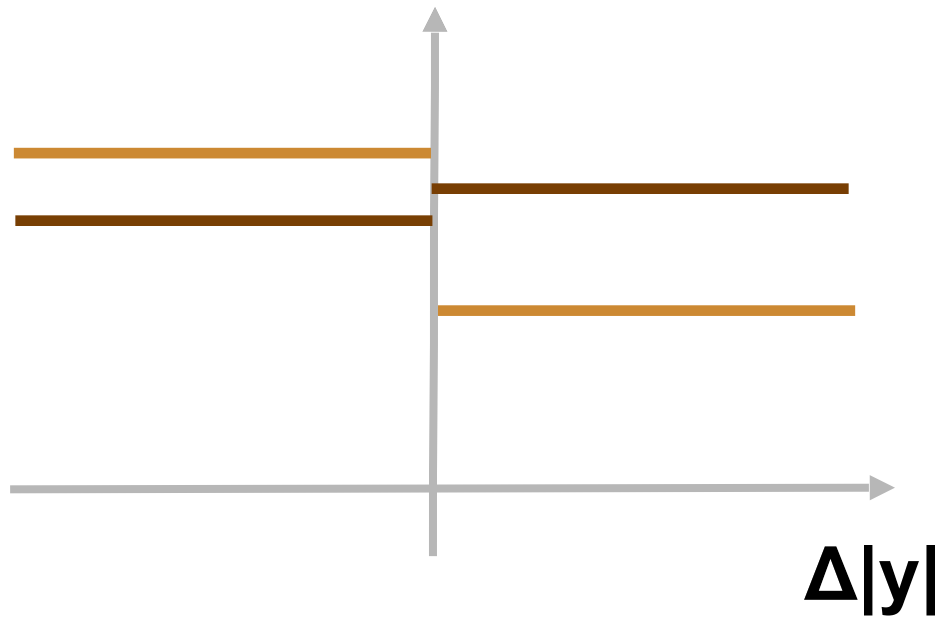


- Top quark charge asymmetry (A_C) in $t\bar{t}$ production: anisotropy in the angular distributions of the final-state top quark and antiquark
  - Top quark preferentially produced in the direction of incoming quark
  - Anti-top quarks scatter more centrally (lower rapidity) than top quarks

SM prediction at NLO in QCD for $t\bar{t}$: 0.6%



$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



- Effect in $t\bar{t}\gamma$ is enhanced
  - $q\bar{q}$ production mode is a larger fraction
  - Asymmetry already at LO in $t\bar{t}\gamma$, as opposed to NLO in $t\bar{t}$

$$A_C = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}$$

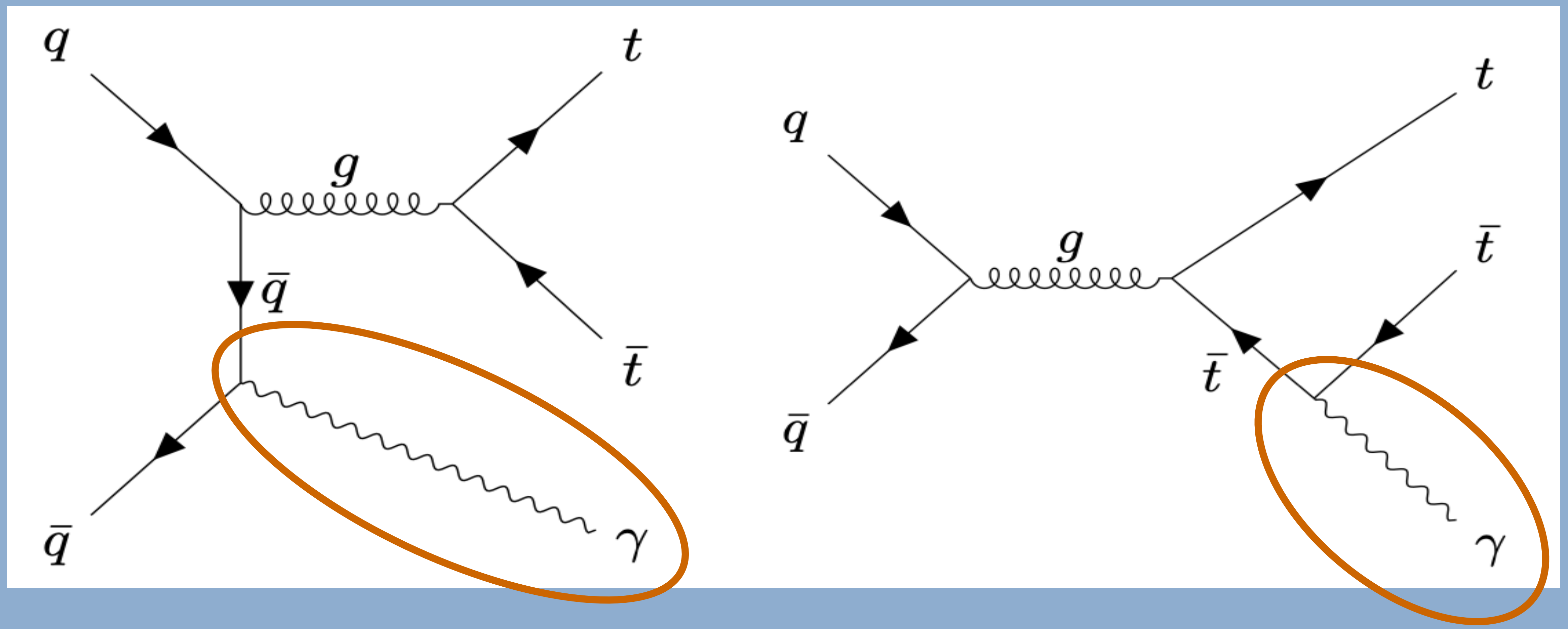
Total asymmetry for $t\bar{t}\gamma$: [-0.5%,-2%] depending on kinematics

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

- Top quark charge asymmetry (A_c) in $t\bar{t}$ production: anisotropy in the angular distributions of the final-state top quark a
  - Top quark preferentially produced in the directi quark
  - Anti-top quarks scatter more centrally (lower ra quarks

SM prediction at NLO in QCD fo

Caused by the interference of diagrams like:

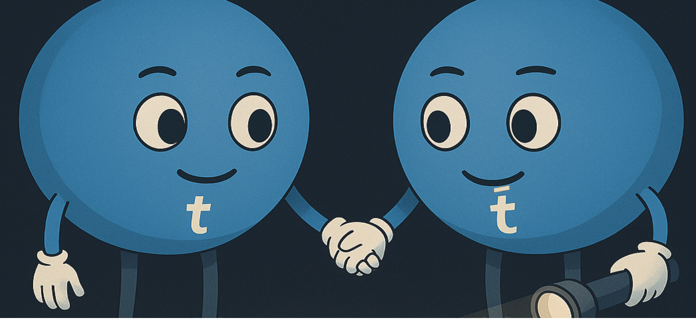


- Effect in $t\bar{t}\gamma$ is enhanced
  - $q\bar{q}$ production mode is a larger fraction
  - Asymmetry already at LO in $t\bar{t}\gamma$, as oppos

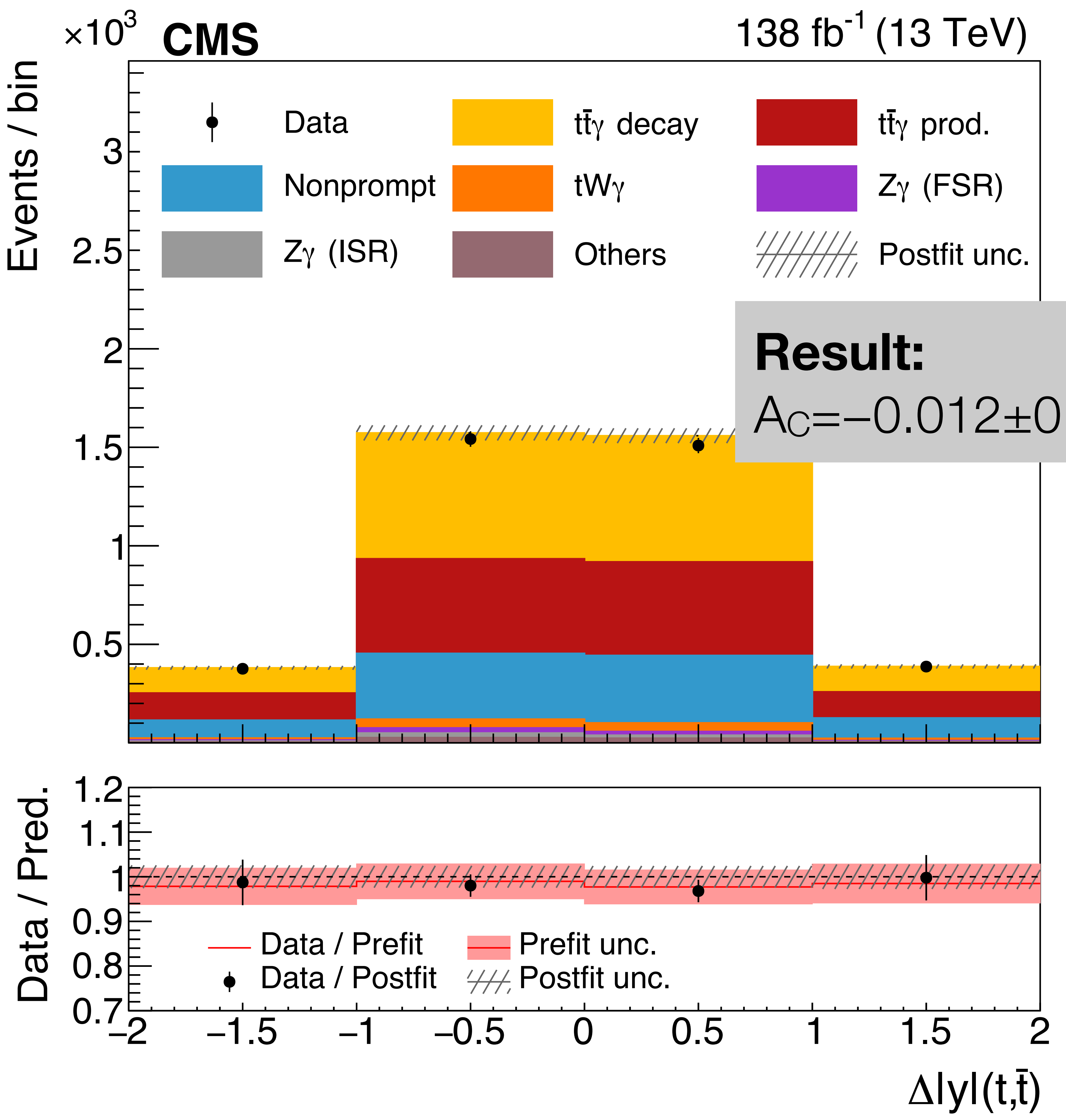
$$A_C = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}$$

Total asymmetry for $t\bar{t}\gamma$: [-0.5%,-2%] depending on kinematics

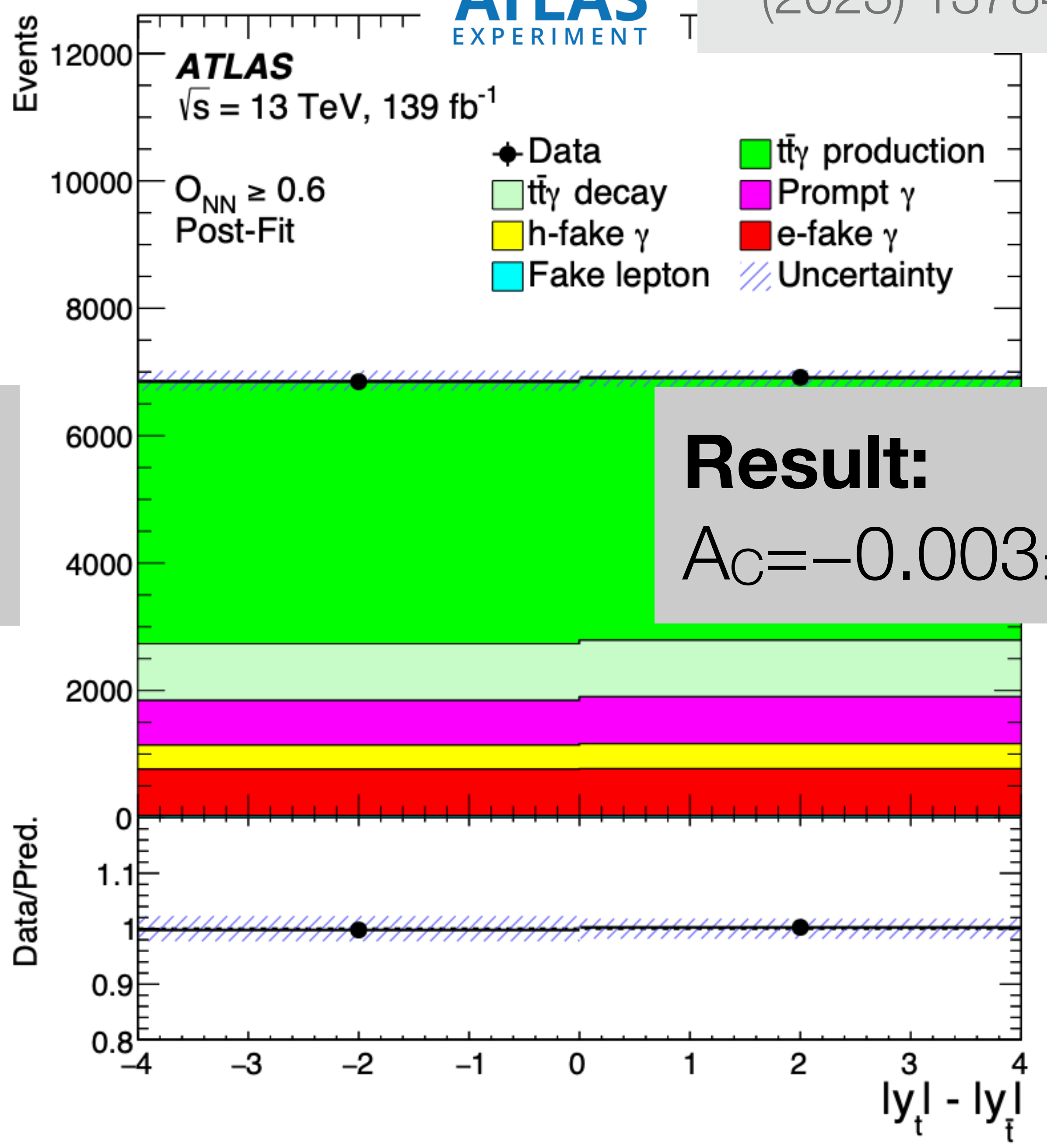
Top quark charge asymmetry using $t\bar{t}\gamma$ events



- Fit to $\Delta|y|$ between top quarks
- Extract charge asymmetry directly
- Heavily limited by statistical uncertainty (we are trying to measure a very small effect)



Result:
$A_C = -0.012 \pm 0.042$



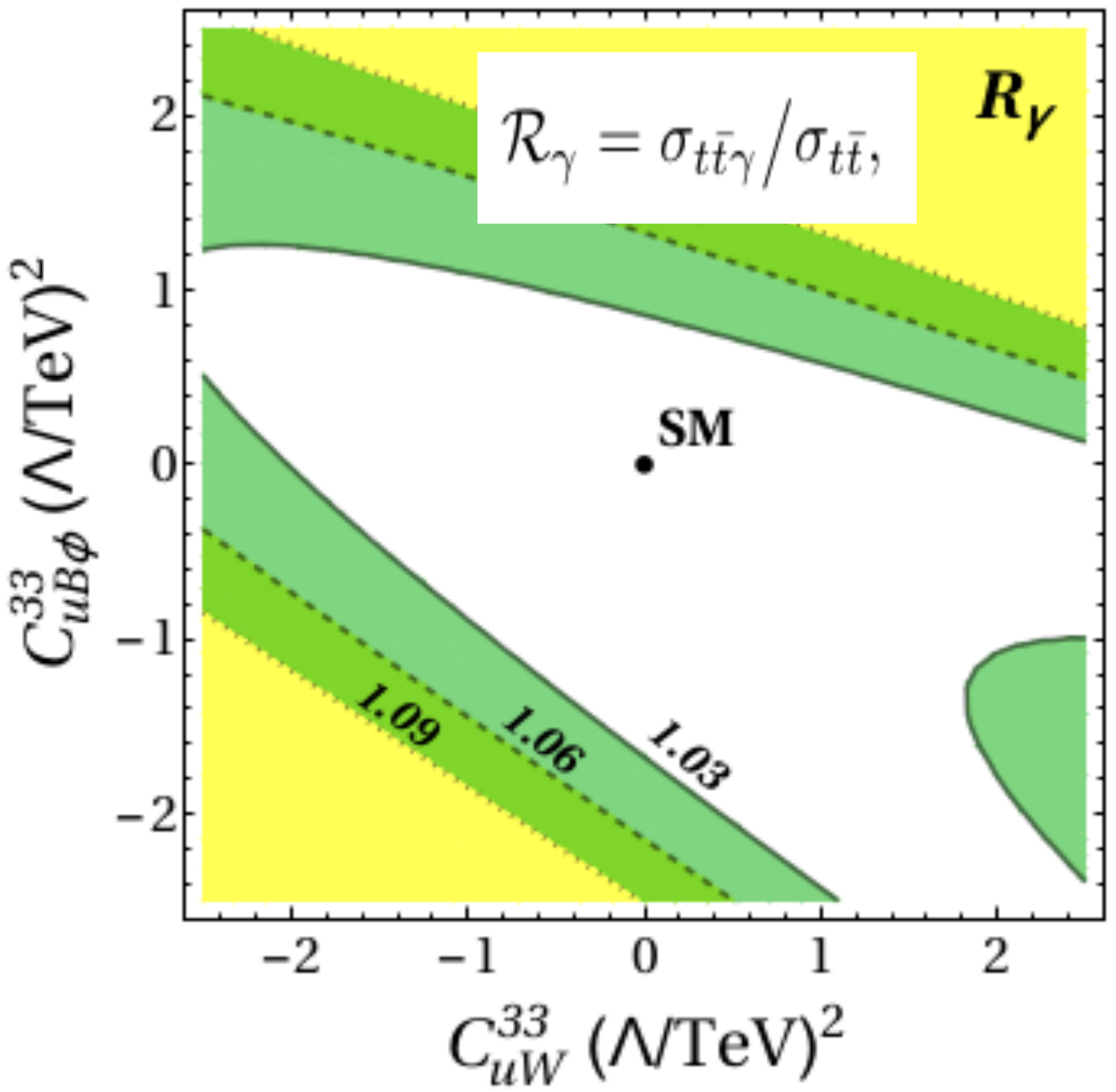
Phys. Lett. B 843 (2023) 137848

Result:
$A_C = -0.003 \pm 0.029$

Compatible with the SM and with no-asymmetry scenarios

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

arxiv:1603.08911v2



- 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

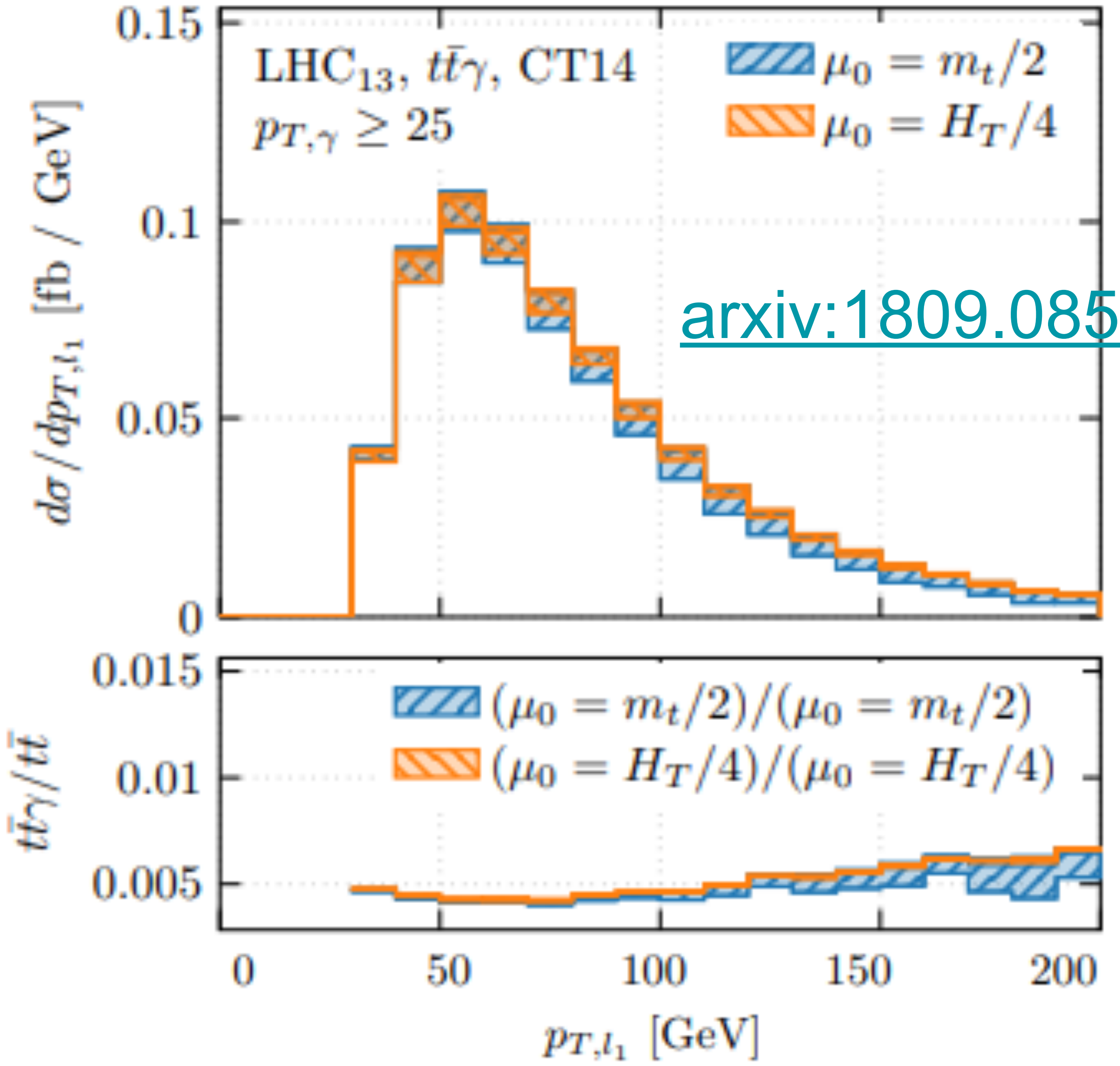
$$\mathcal{R} = \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}$$

- 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

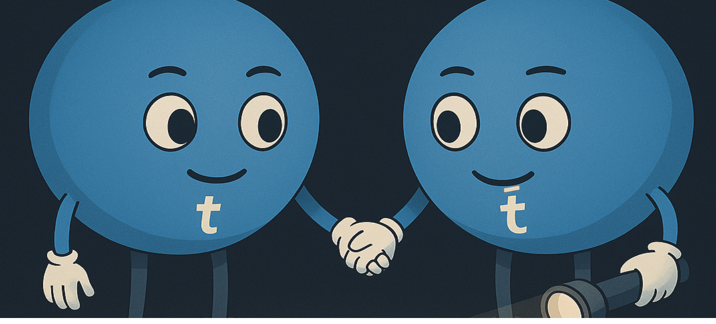
differential

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

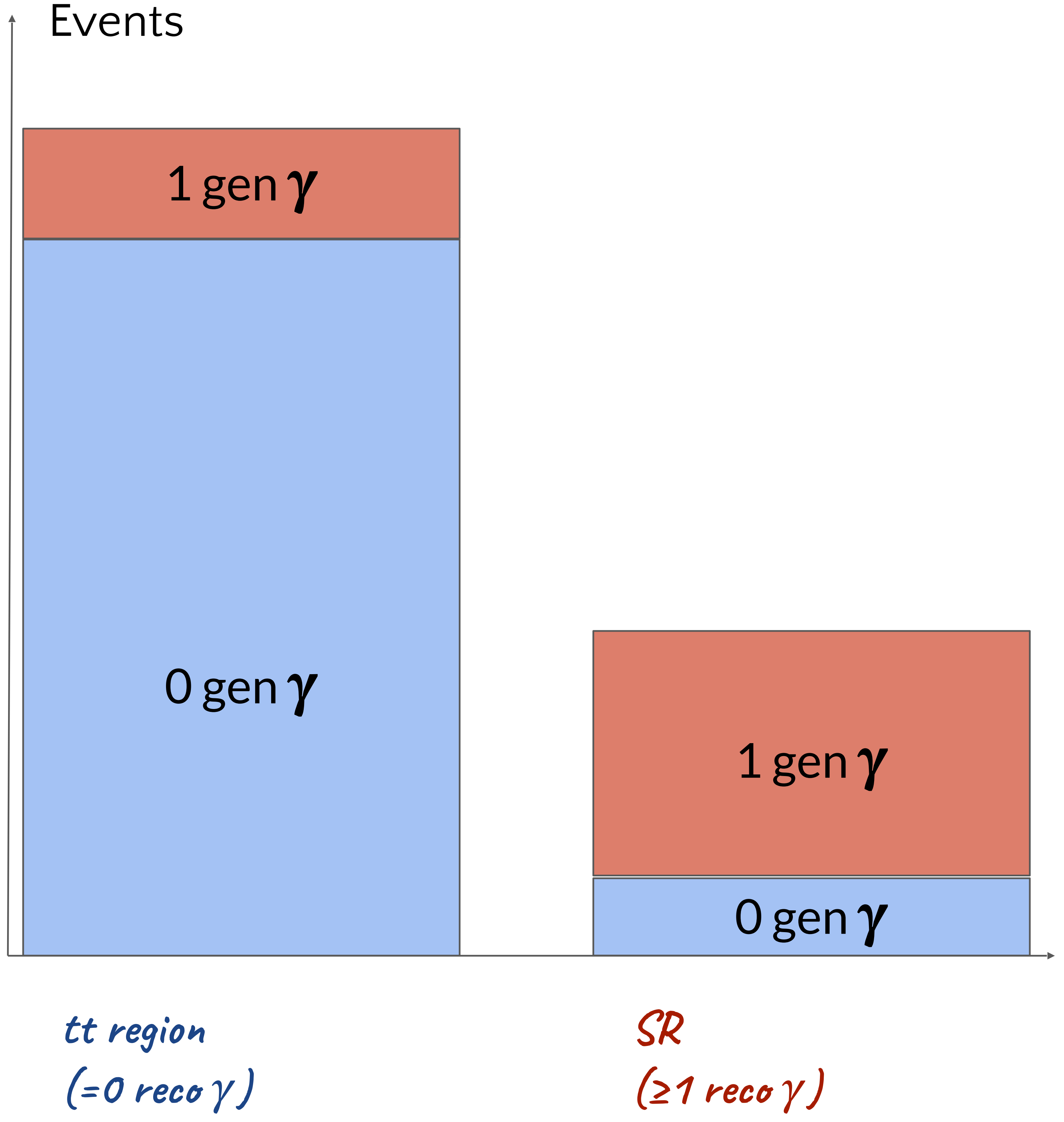
arxiv:1809.08562



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

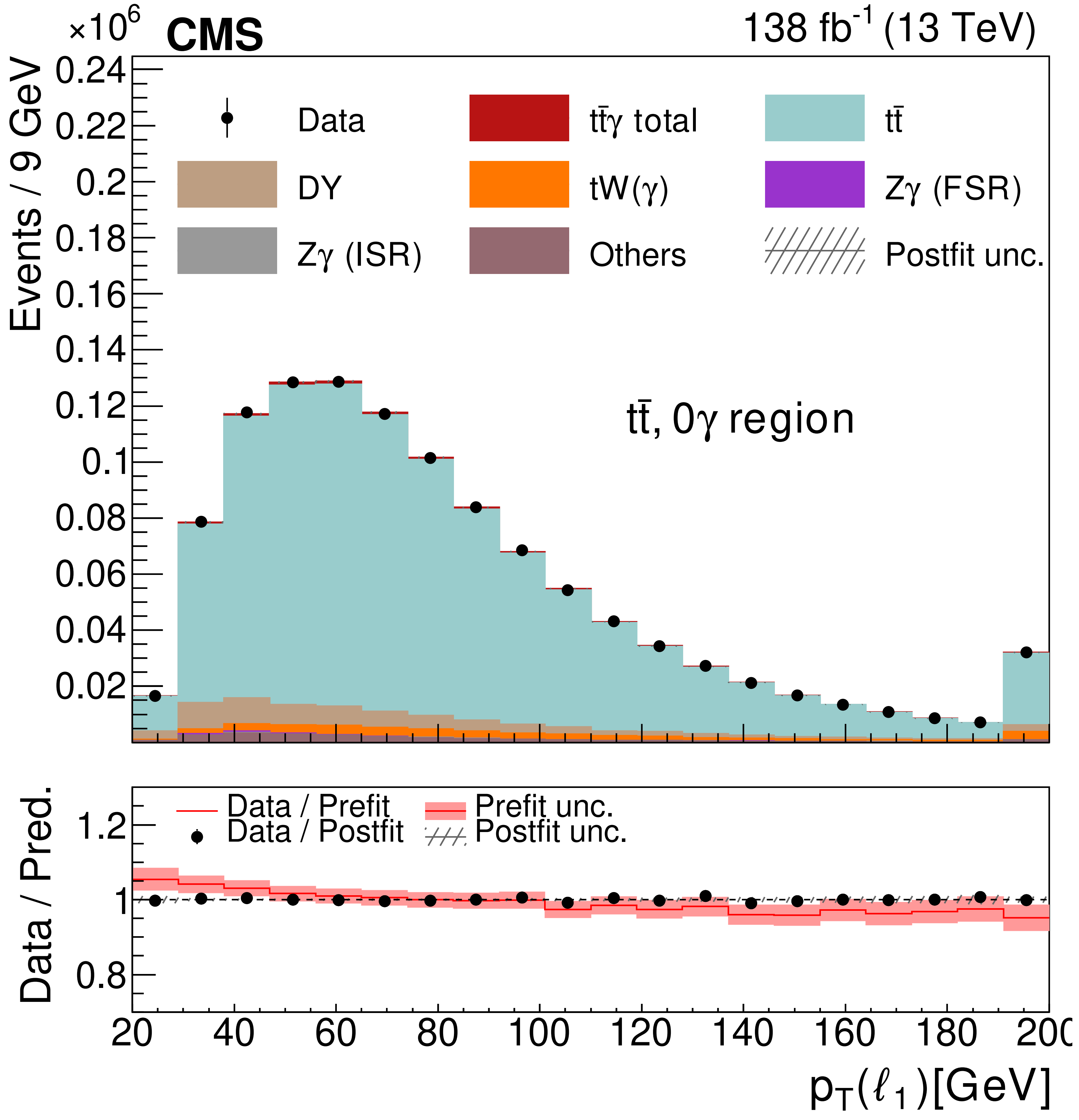


- The ratio is computed as: $$R_\gamma = \frac{\sigma_{t\bar{t},=1\gamma}}{\sigma_{t\bar{t},=0\gamma} + \sigma_{t\bar{t},=1\gamma}}$$

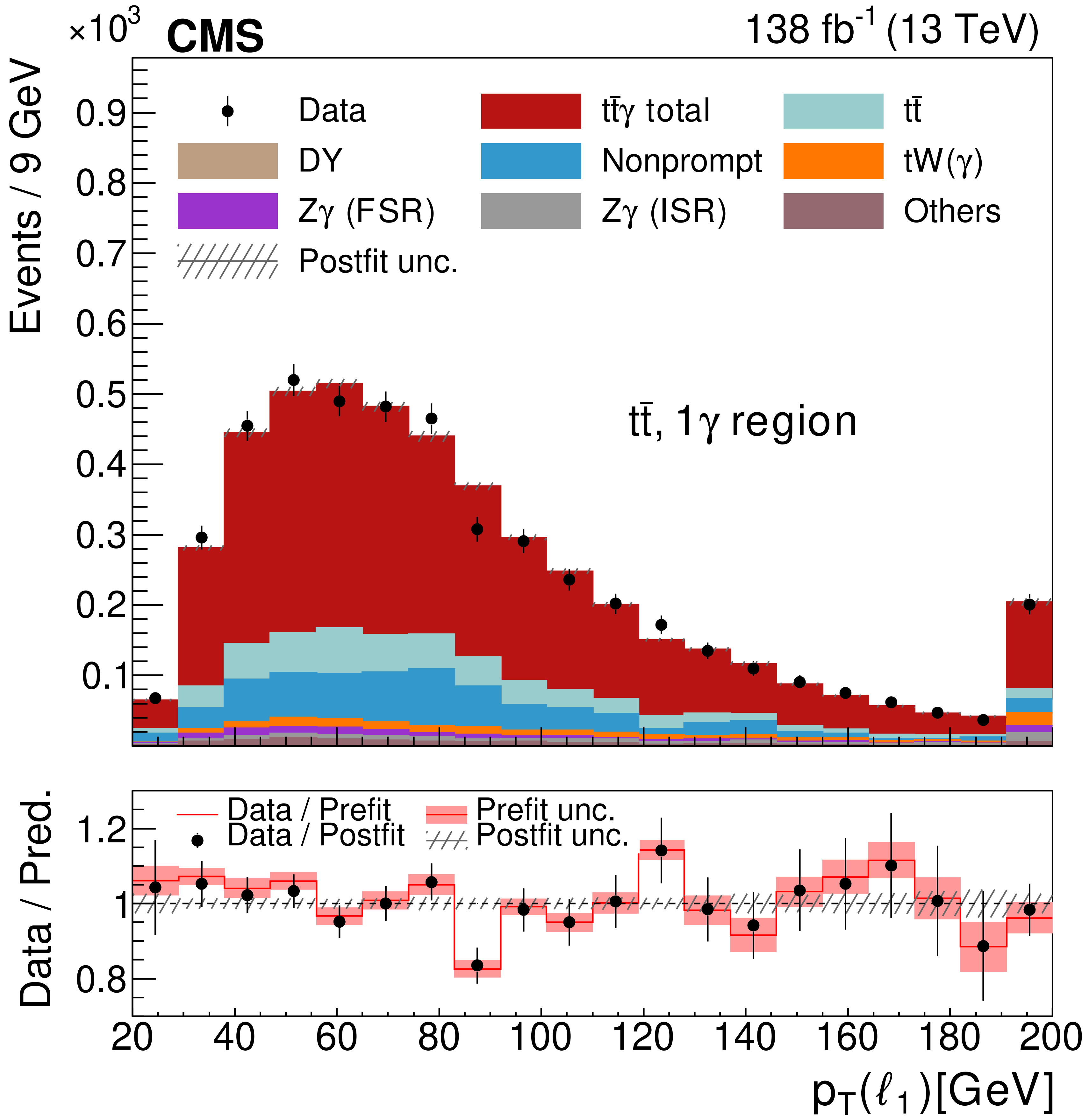
- 0-photon region has many events - allows for measuring $t\bar{t}$ precisely
- It is possible to write the $t\bar{t}$ and $t\bar{t}\gamma$ signal strengths as a function of R
- Extract R directly from the fit - direct handling of all correlations between systematic uncertainties

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

0 photon region



1 photon region

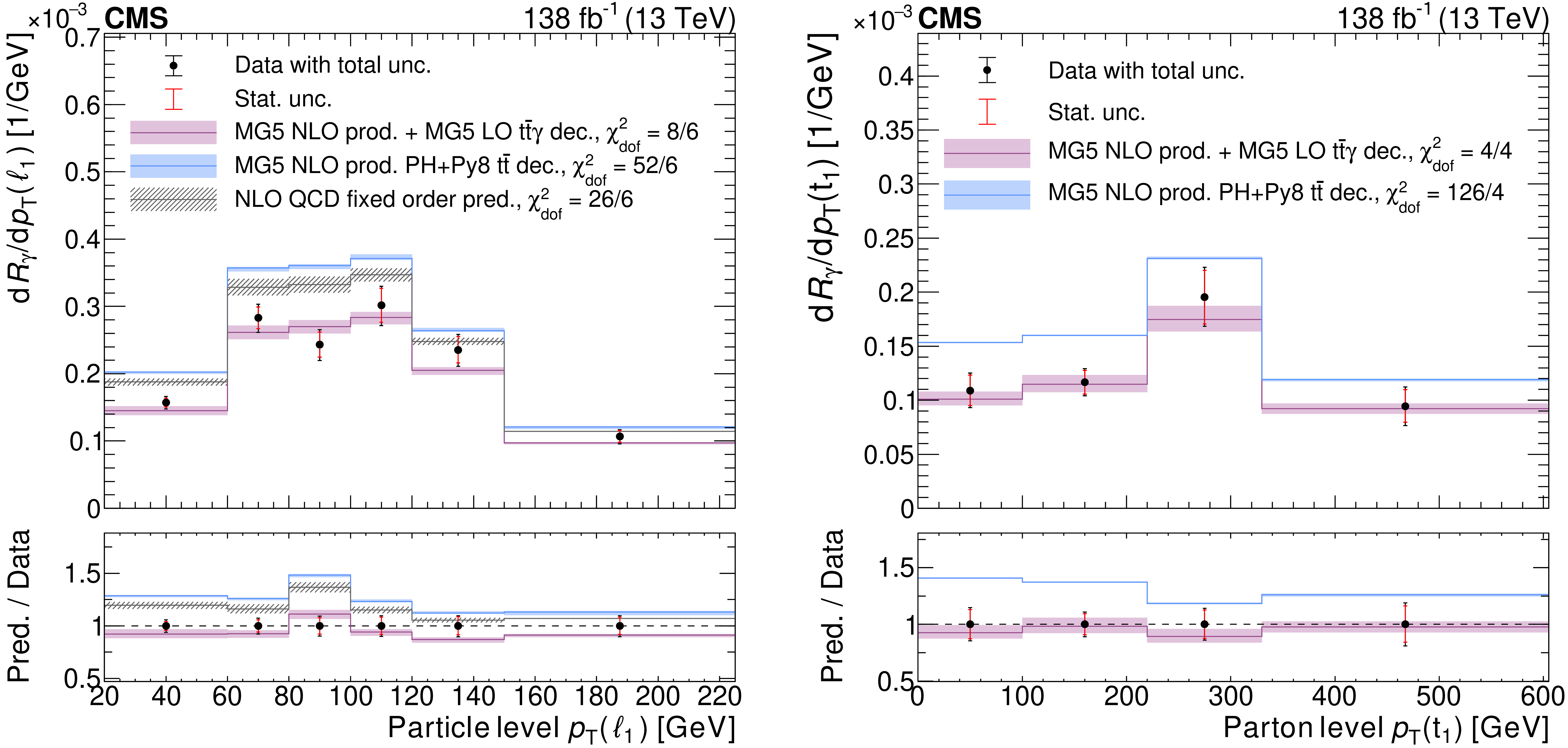


- Result:

  Ratio = (1.33 ± 0.05) %

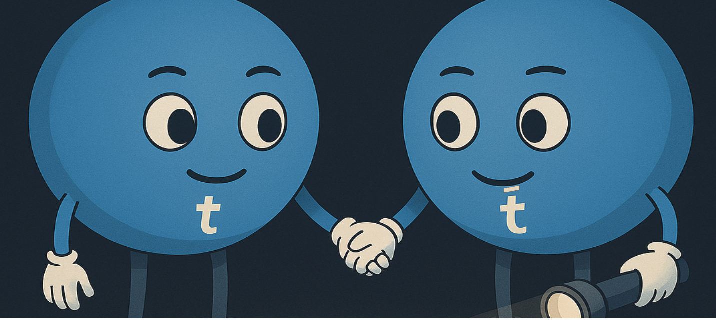
- Limited by systematic uncertainties, mainly photon identification, nonprompt photon, DY and Z+γ backgrounds, and modelling
- $t\bar{t}$ normalization measured to be compatible with NNLO QCD prediction with 2% uncertainty

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



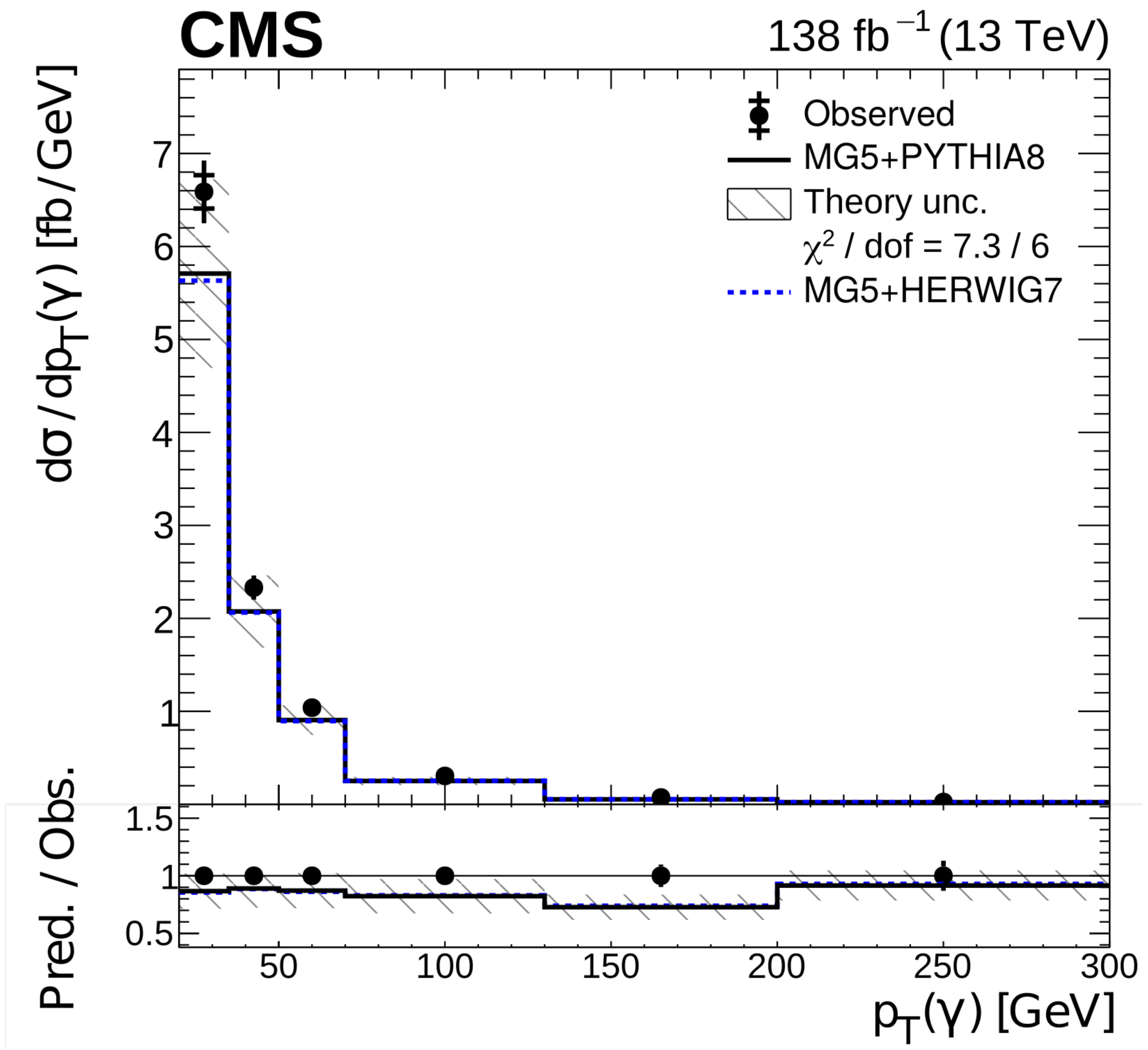
Compatible with SM predictions!

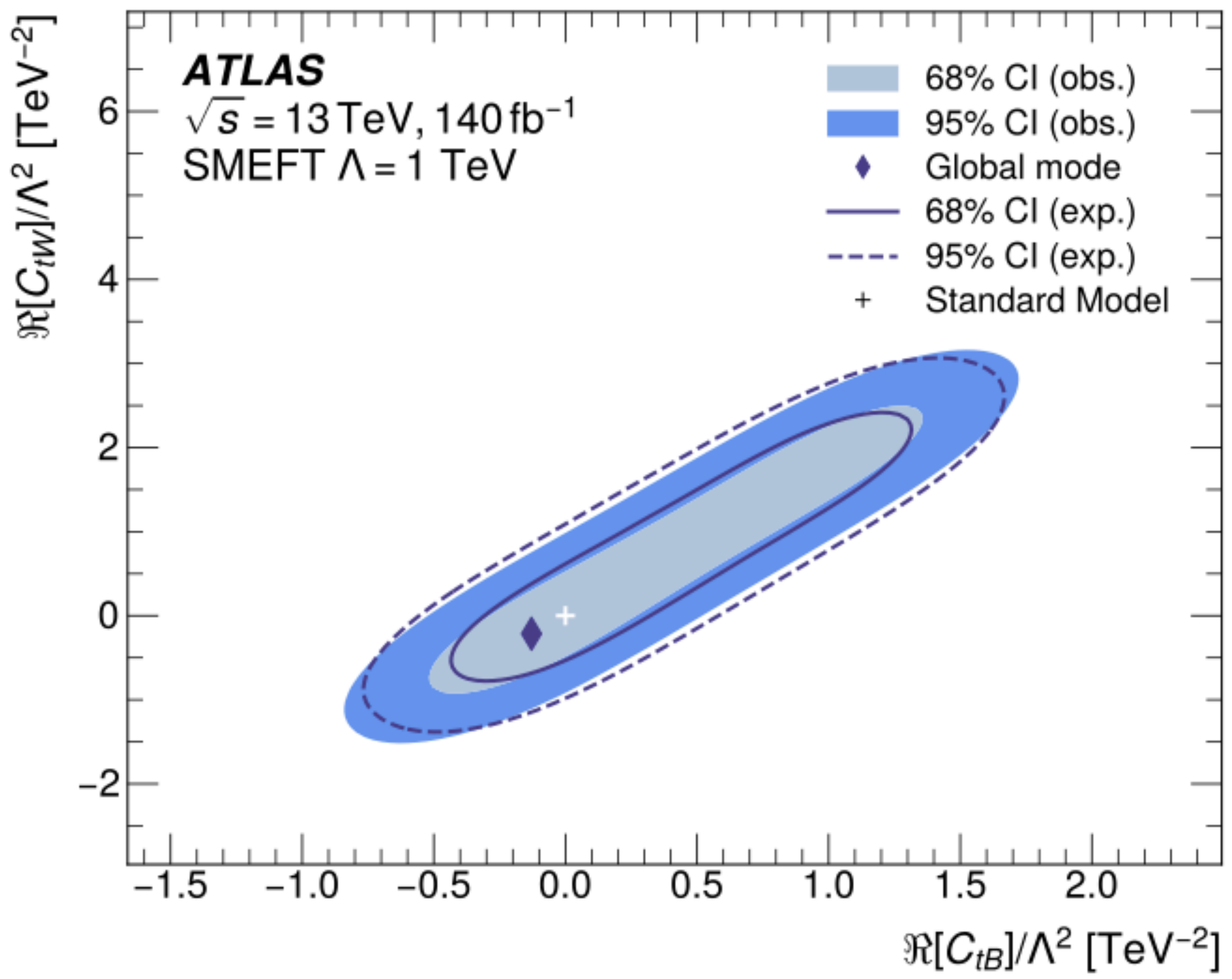
What have we learned?

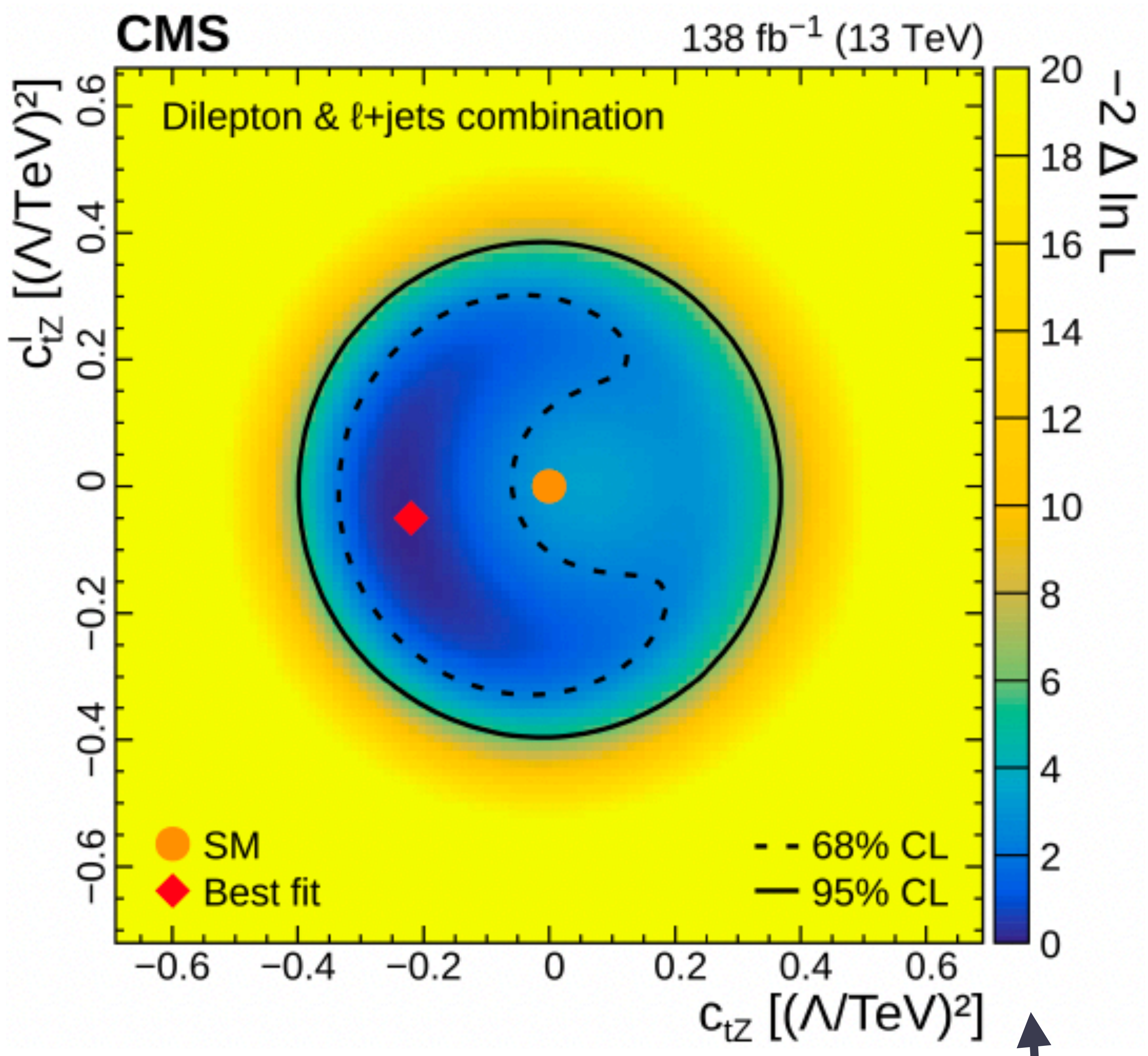


- Precision in inclusive and different cross sections between 4-10% depending on exact phase space - **very precise measurements, all in good agreement with the SM**

- **New modelling strategy improves agreement** with respect to previous measurements that relied on LO simulations

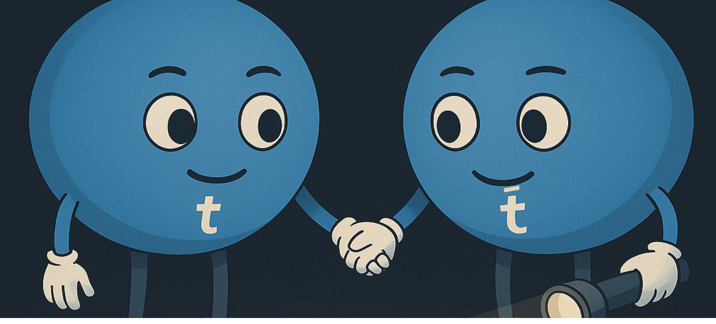






- ALTAS and CMS have performed Effective Field Theory interpretations which allow to **constrain new physics scenarios** modifying the $t\bar{t}\gamma$ coupling

Summary



- Presented the recent CMS results on $\mathrm{t\bar{t}}\gamma$ production using Run 2 data
  - Inclusive and differential cross sections
  - Top quark charge asymmetry
  - Inclusive and differential ratio to $\mathrm{t\bar{t}}$ cross sections
- Very precise measurements, in good agreement with the SM predictions

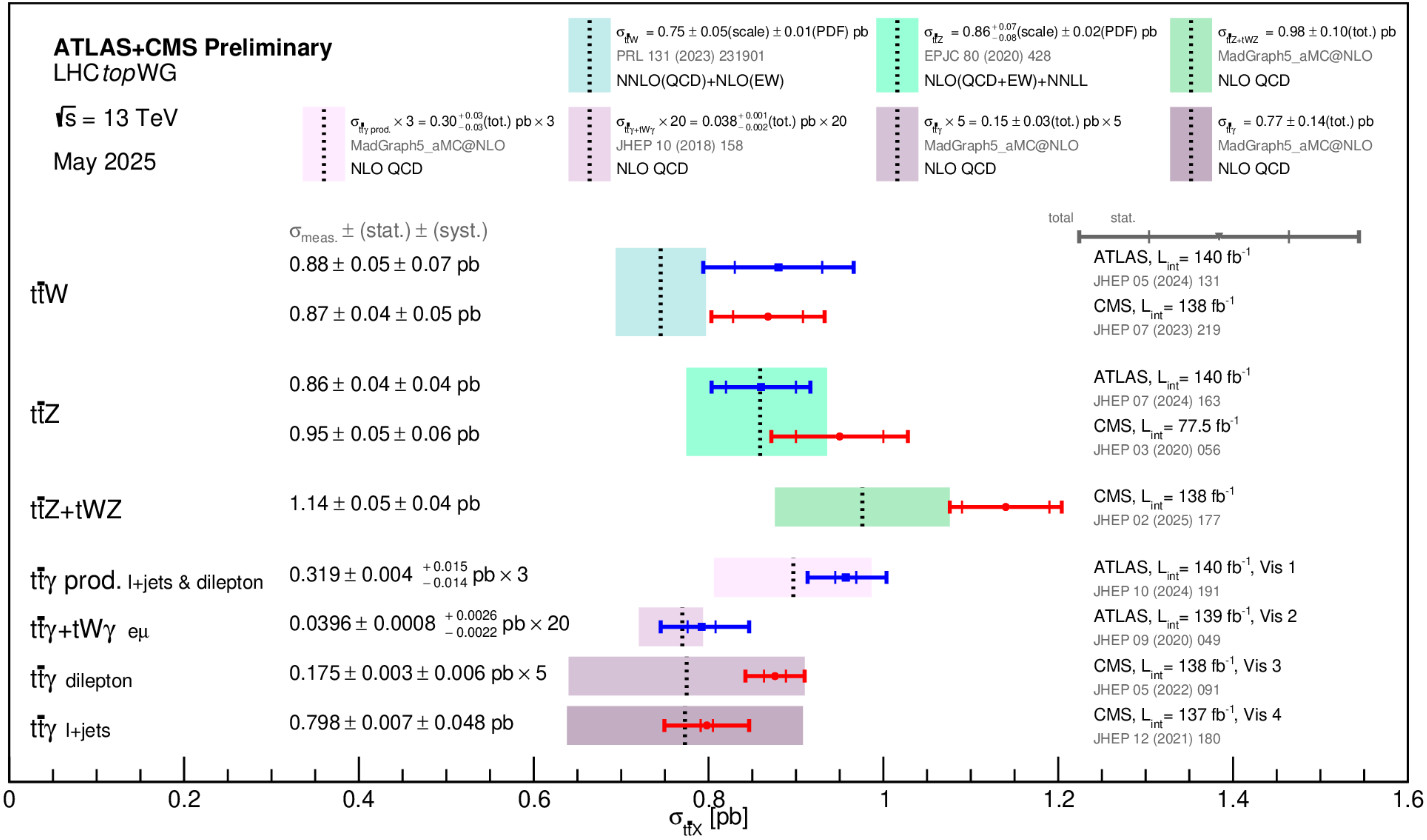
Outlook:

- Useful for EFT interpretations (some already exist, more can be done in the future, especially combining several processes)
- Differential measurements (of cross sections and ratios) still mostly limited by statistical uncertainties.
  → Very large dataset of Run 3 can bring improved precision!
- Improvements in the modelling, in particular full NLO samples, would allow for much clearer interpretation

Thank you!

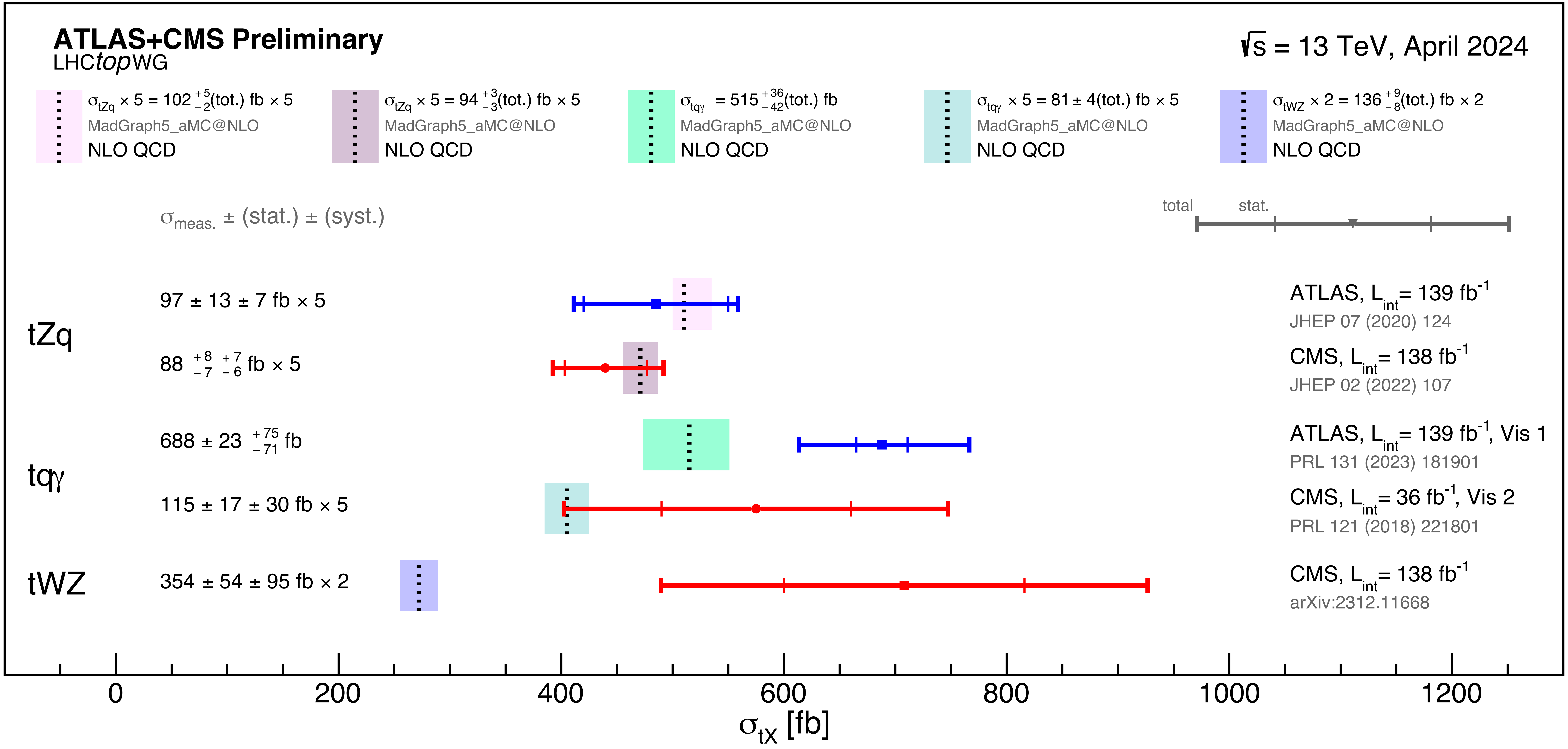
BACKUP

Summary



ATLAS+CMS Preliminary
LHC topWG
√s = 13 TeV
May 2025
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
JHEP 05 (2024) 131
0.87 ± 0.04 ± 0.05 pb
CMS, L_int = 138 fb^-1
JHEP 07 (2023) 219
ttZ
0.86 ± 0.04 ± 0.04 pb
ATLAS, L_int = 140 fb^-1
JHEP 07 (2024) 163
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
JHEP 02 (2025) 177
ttγ prod. l+jets & dilepton
0.319 ± 0.004 +0.015 −0.014 pb × 3
ATLAS, L_int = 140 fb^-1, Vis 1
JHEP 10 (2024) 191
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
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
σ_ttX [pb]

Summary

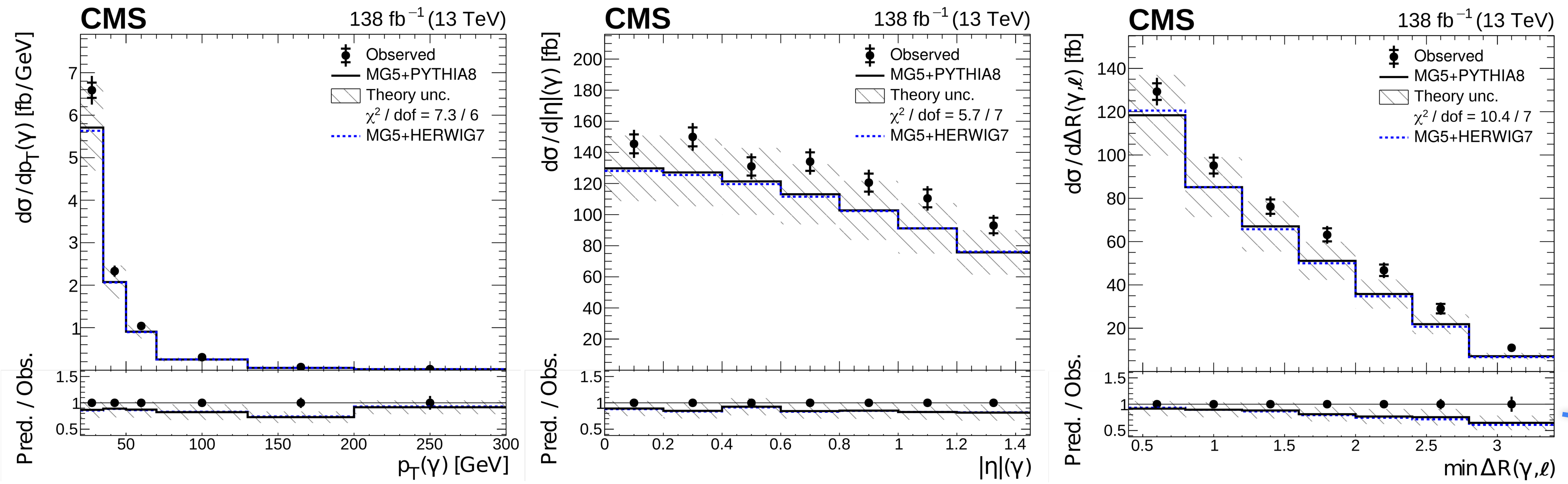


ATLAS+CMS Preliminary
LHC*top*WG
$\sqrt{s}$ = 13 TeV, April 2024
$\sigma_{tZq} \times 5 = 102\,^{+5}_{-2}$(tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
$\sigma_{tZq} \times 5 = 94\,^{+3}_{-3}$(tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
$\sigma_{tq\gamma} = 515\,^{+36}_{-42}$(tot.) fb
MadGraph5_aMC@NLO
NLO QCD
$\sigma_{tq\gamma} \times 5 = 81 \pm 4$(tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
$\sigma_{tWZ} \times 2 = 136\,^{+9}_{-8}$(tot.) fb × 2
MadGraph5_aMC@NLO
NLO QCD
$\sigma_{meas.}$ ± (stat.) ± (syst.)
total
stat.
tZq
97 ± 13 ± 7 fb × 5
88 $^{+8}_{-7}$ $^{+7}_{-6}$ fb × 5
tqγ
688 ± 23 $^{+75}_{-71}$ fb
115 ± 17 ± 30 fb × 5
tWZ
354 ± 54 ± 95 fb × 2
ATLAS, L_{int} = 139 fb^{-1}
JHEP 07 (2020) 124
CMS, L_{int} = 138 fb^{-1}
JHEP 02 (2022) 107
ATLAS, L_{int} = 139 fb^{-1}, Vis 1
PRL 131 (2023) 181901
CMS, L_{int} = 36 fb^{-1}, Vis 2
PRL 121 (2018) 221801
CMS, L_{int} = 138 fb^{-1}
arXiv:2312.11668
0
200
400
600
800
1000
1200
σ_{tX} [fb]

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

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.

How about non-resonant tops?

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

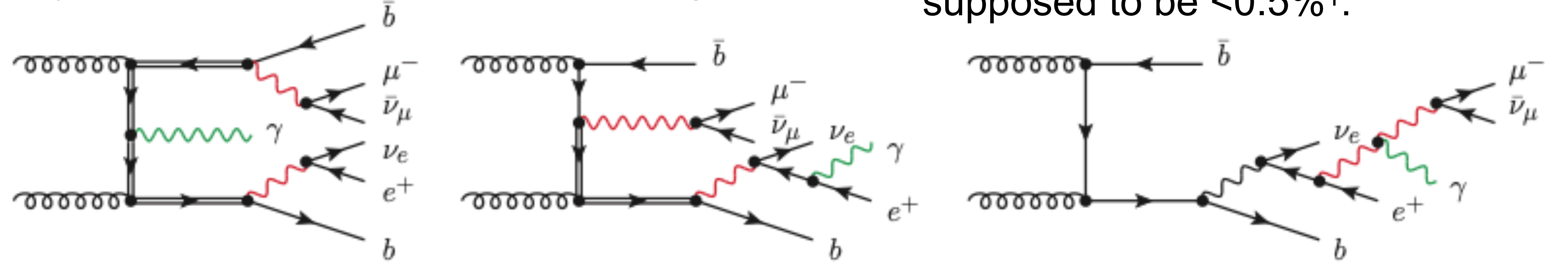
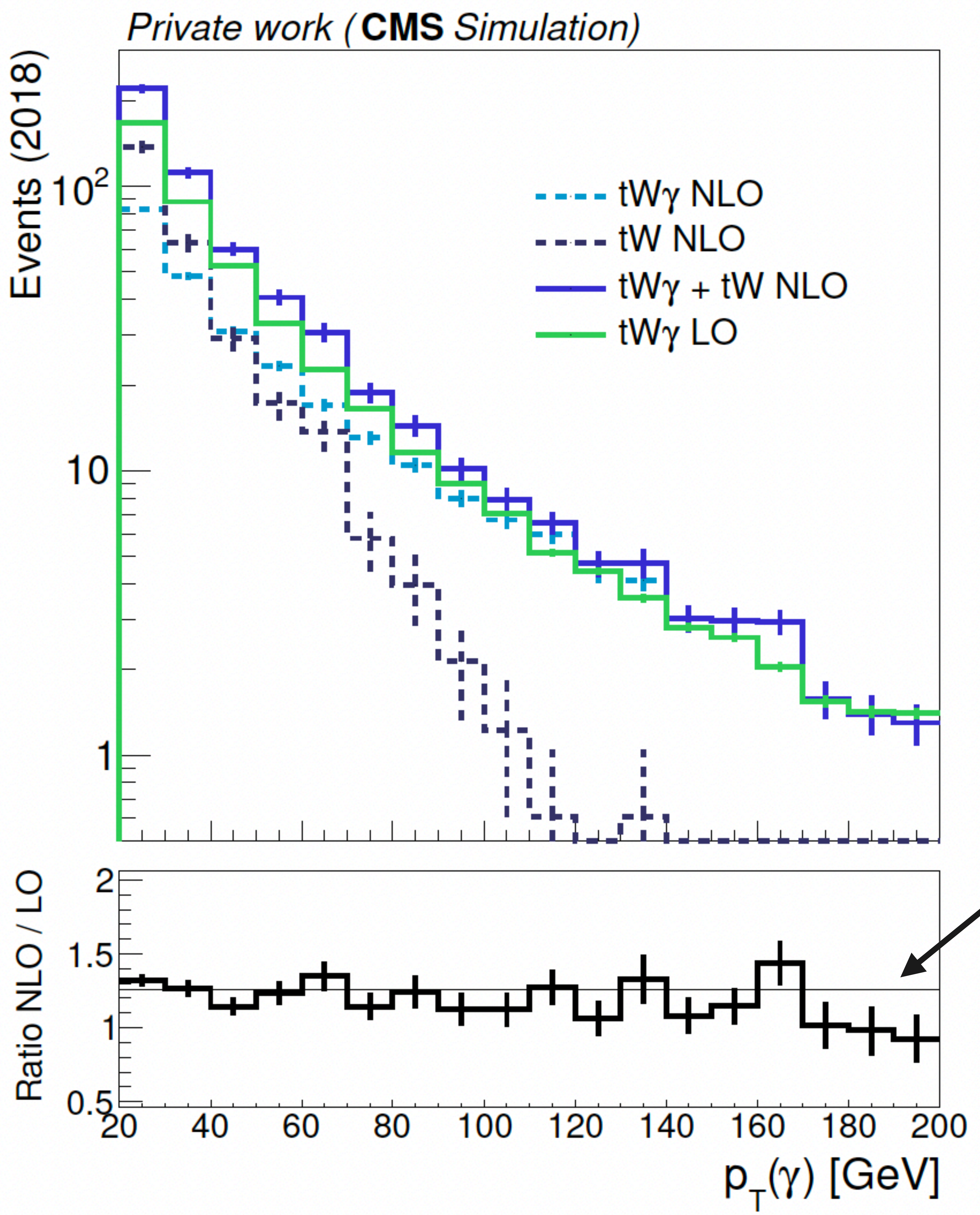


Figure 1. *Representative Feynman diagrams, involving two (first diagram), one (second diagram) and no top quark resonances (third diagram), contributing to pp $\rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ production at leading order.*

[1]: computed in arXiv 1912.09999v2

Simulating tWγ at LO



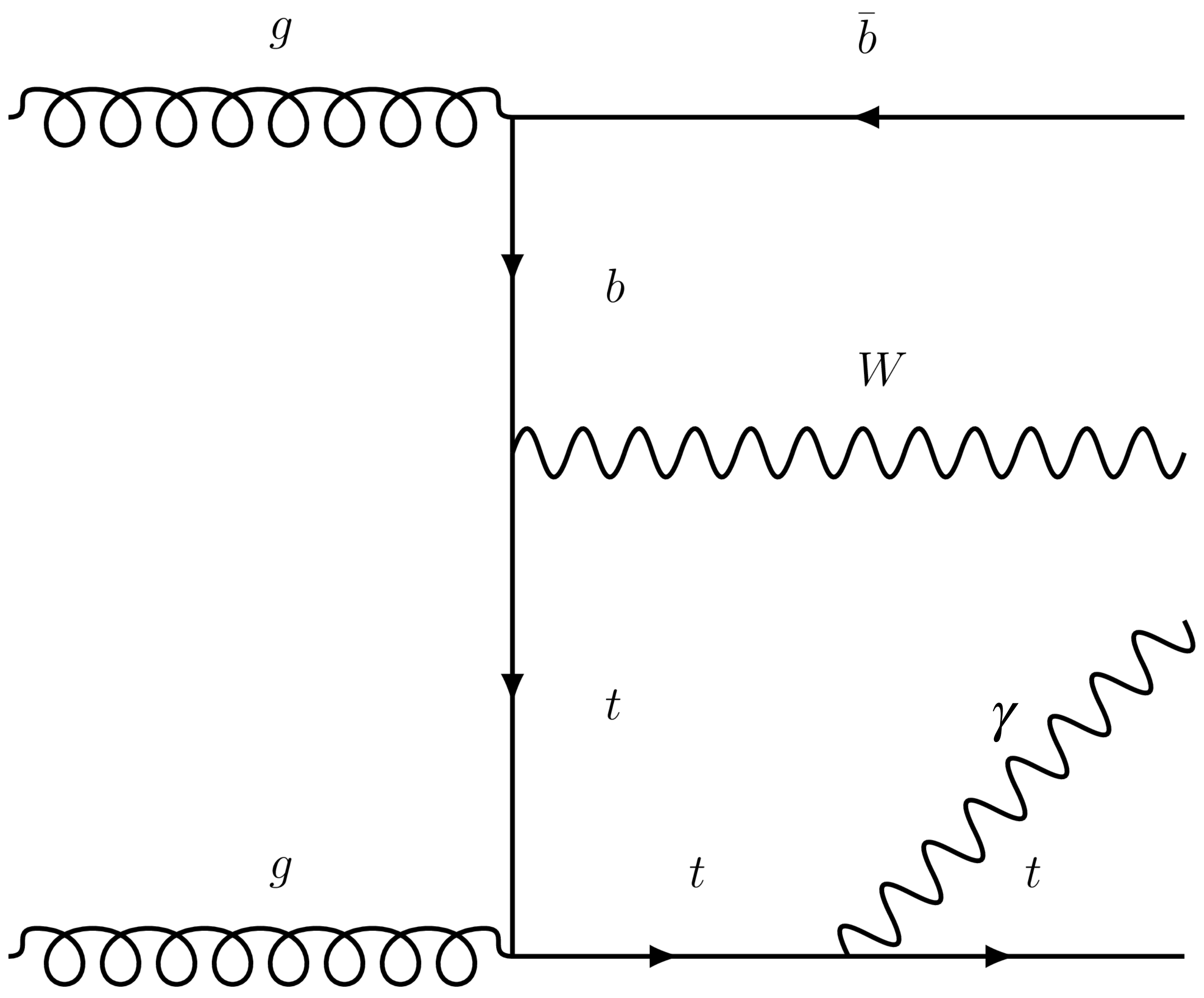
- Small sample simulated at NLO with aMC@NLO containing photons from production, but not from top decay
- Photons from decay present in tW NLO sample

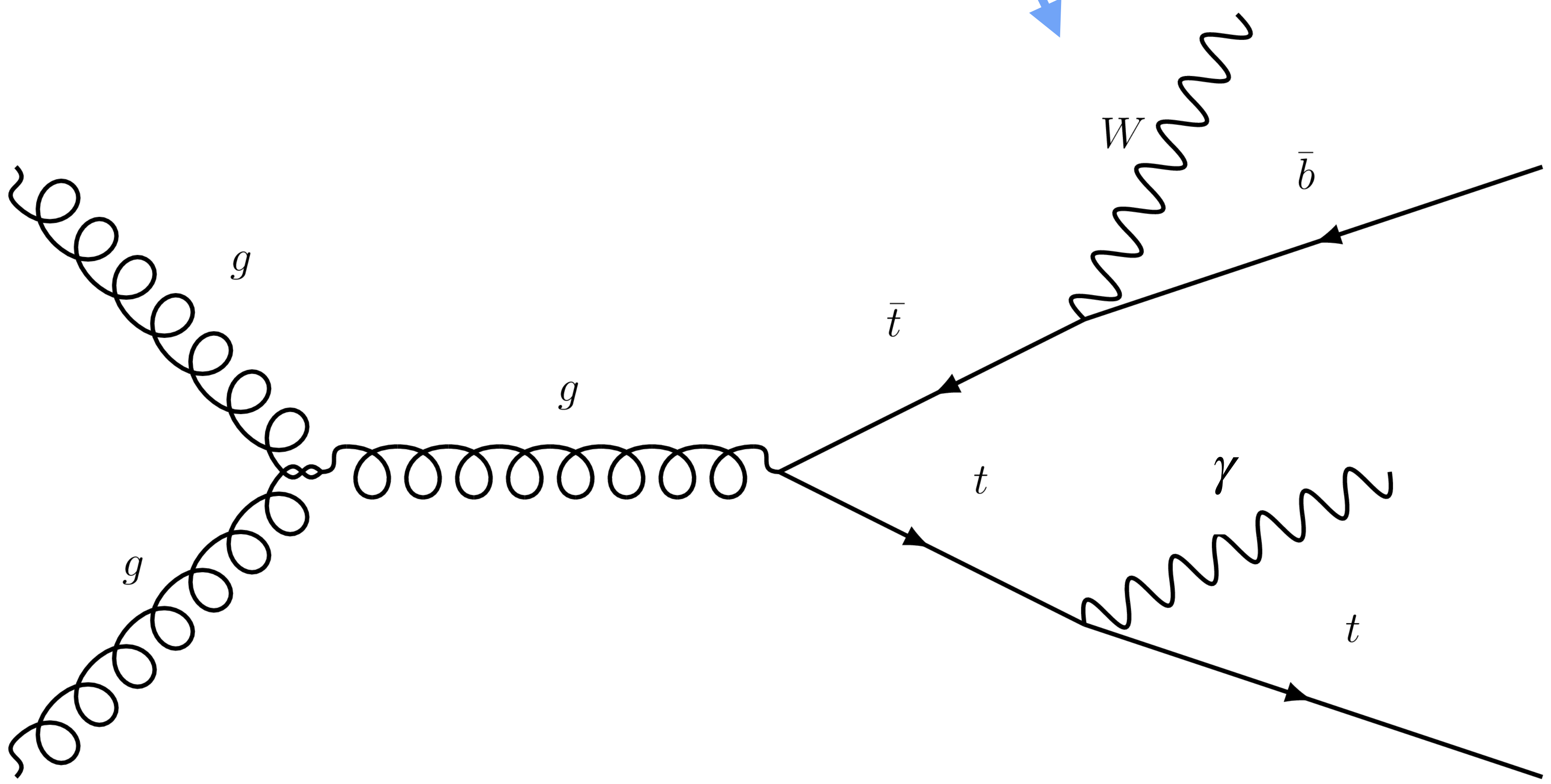
- Sum between two NLO samples compared with LO sample which contains all photon origins
- Distributions match
- Inclusive k-factor is derived

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 $tW\gamma$ at NLO

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

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

- Matrix element:

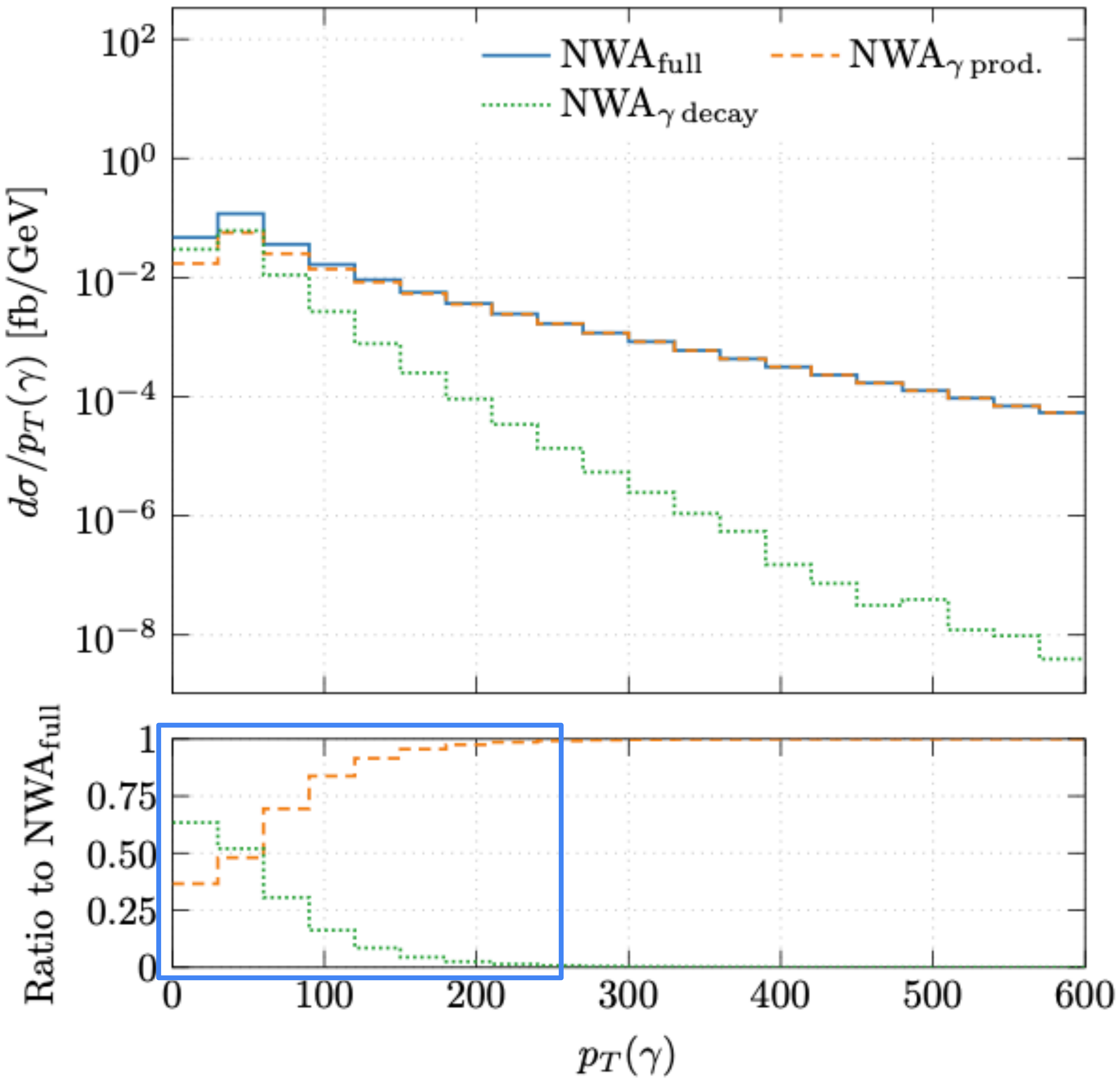
$$|\mathscr{A}_{pp\rightarrow tW^-\gamma}|^2 = |\mathscr{A}^{\text{non-resonant}}_{pp\rightarrow tW^-\gamma}|^2 + \cancel{|\mathscr{A}^{\text{resonant}}_{pp\rightarrow tW^-\gamma}|^2} + 2\mathscr{R}(\mathscr{A}^{\text{non-resonant}}_{pp\rightarrow tW^-\gamma}\mathscr{A}^{\text{resonant}\,\dagger}_{pp\rightarrow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

DR2

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.

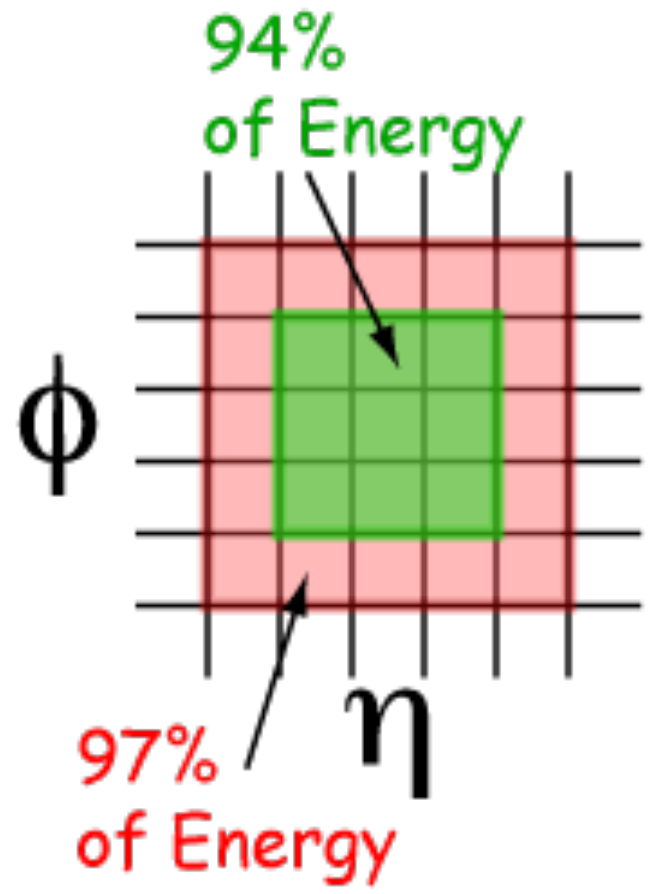
- Misidentified ("fake") jet: the matching procedure fails as there is no generated particle close to the reconstructed photon to carry at least 50% of its p_T. There are however multiple generated particles inside the ΔR cone around the reconstructed photon. These objects are not real photons, rather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

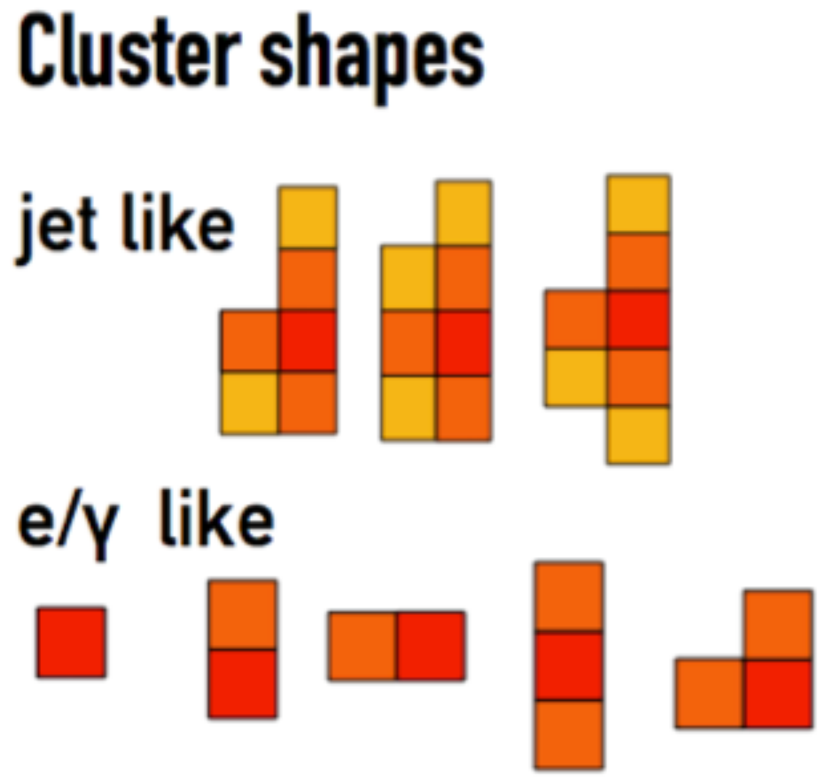
- Photon from pileup: the matching procedure fails, as no particle is found within the ΔR cone. These photons are often attributed to pileup and represent a relatively large contribution to the nonprompt category. This is because photons are not reconstructed from tracks, and therefore it is not trivial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

Nonprompt photon estimation (1)

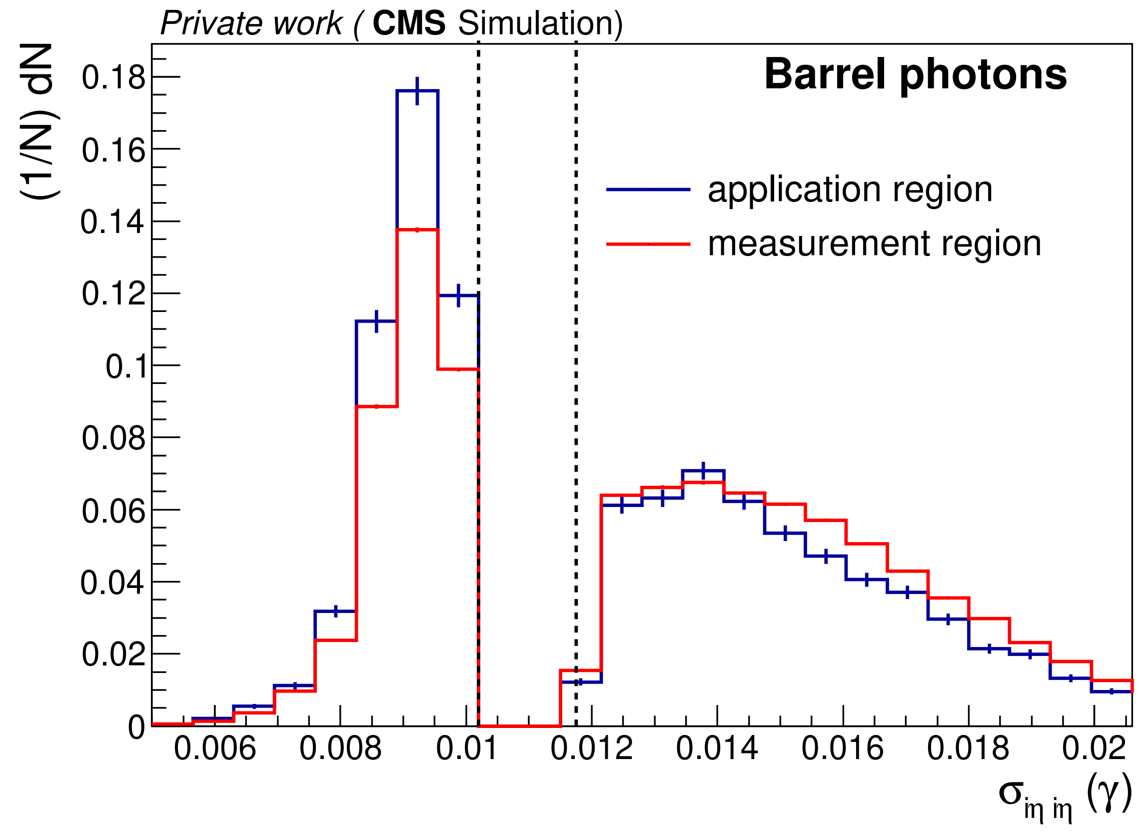
- Width of the EM shower ($\sigma_{i\eta i\eta}$): The $\sigma_{i\eta i\eta}$ is defined as the second moment of the log-weighted distribution of crystal energies in η, calculated in the 5×5 matrix around the most energetic crystal in the SC and re-scaled to units of crystal size. This distribution is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

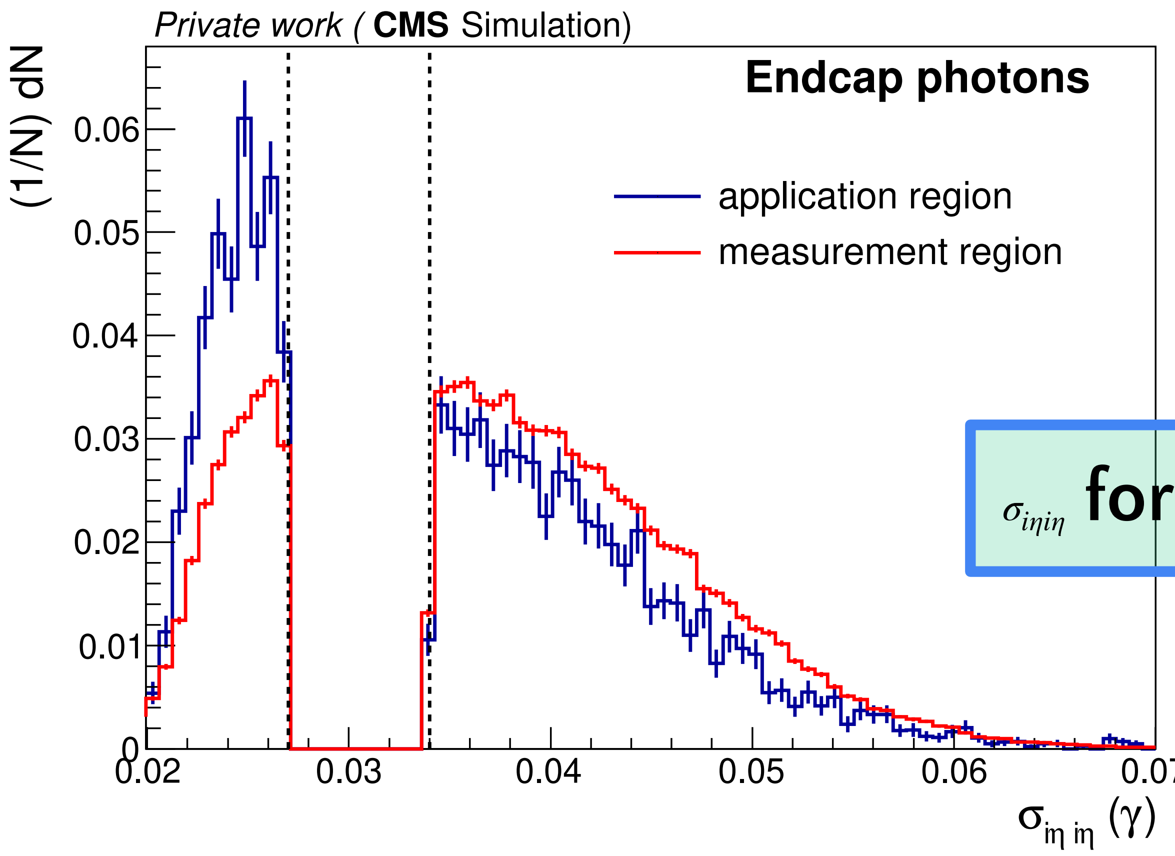
- Charged and neutral hadron and photon isolation: The isolation variables are obtained by summing the transverse momenta of charged hadrons (I_{ch}), neutral hadrons (I_{n}) or photons (I_{γ}) inside an isolation cone of $\Delta R = 0.3$ with respect to the photon direction. The neutral hadron and photon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



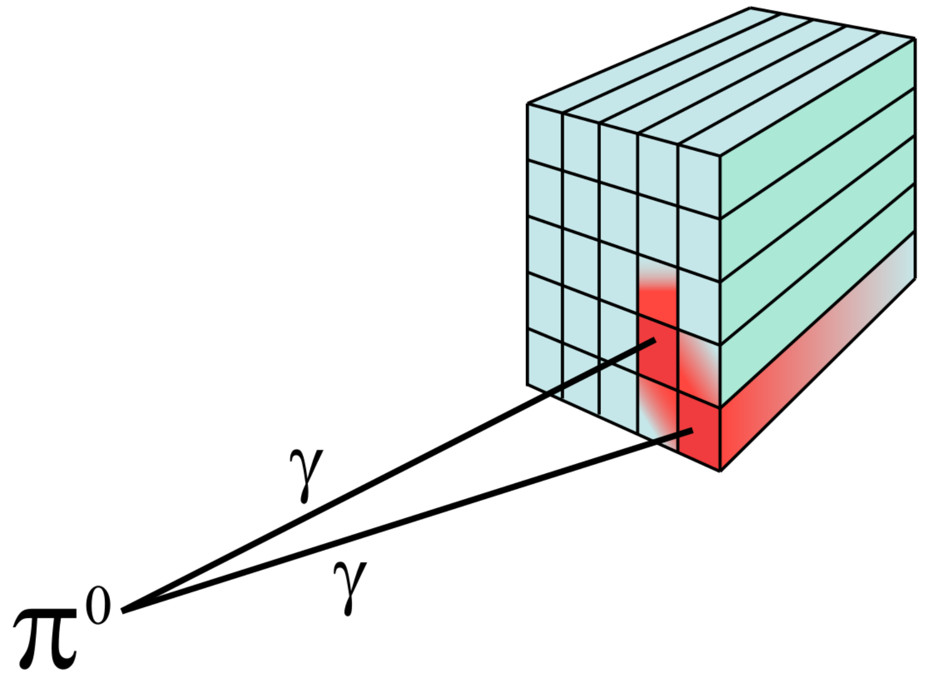


for ABCD method, must be mostly uncorrelated
– they are, but residual correlations exist, especially in endcap





$\sigma_{i\eta i\eta}$ 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

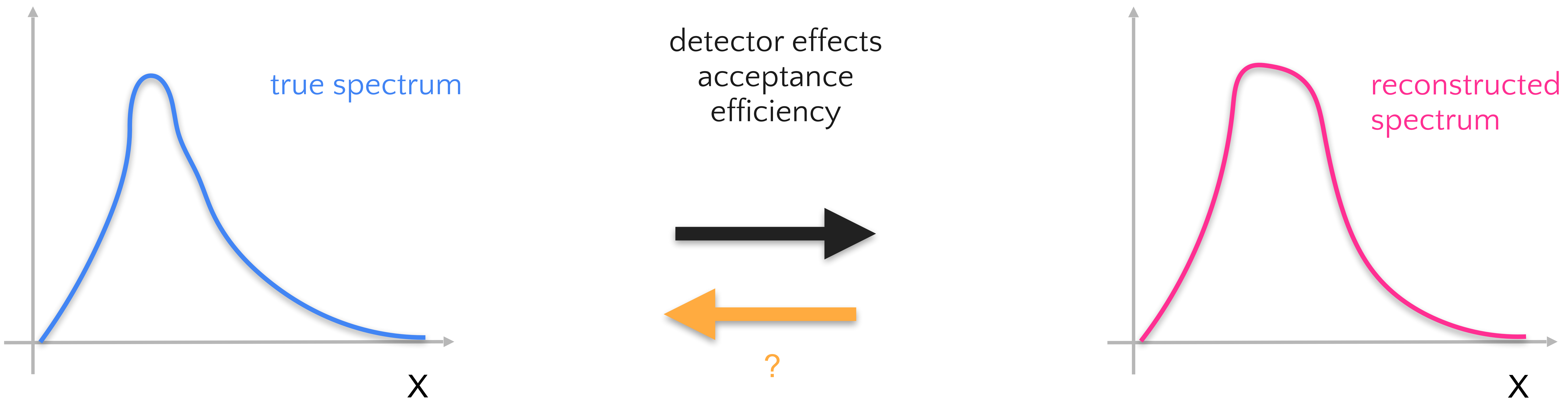
$$\not{E}_{\mathrm{x}} = p_{\mathrm{x},\nu} + p_{\mathrm{x},\bar{\nu}}$$
$$\not{E}_{\mathrm{y}} = p_{\mathrm{y},\nu} + p_{\mathrm{y},\bar{\nu}}$$

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

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

- 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 $\lambda_i(\mu) = \mu \cdot s_i + \sum_j^{N_{\rm bkg}} b_{i,j}$ events in bin i, where $\mu = \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}\gamma}^{SM}}$ 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): $\mathscr{L}(\mathbf{n}|\mu) = \prod_{i=1}^{N} \frac{\lambda_i(\mu) e^{-\lambda_i(\mu)}}{n_i!}$

With M systematic uncertainties included as nuisance parameters Θ: $\mathscr{L}(\mathbf{n}|\mu) = \prod_{i=1}^{N} \frac{\lambda_i(\mu, \mathbf{\Theta}) e^{-\lambda_i(\mu, \mathbf{\Theta})}}{n_i!} \cdot \prod_{m=1}^{M} f(\Theta_m)$

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

maximised, by minimising −2 log($\mathscr{L}$)

Profiled likelihood ratio:

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

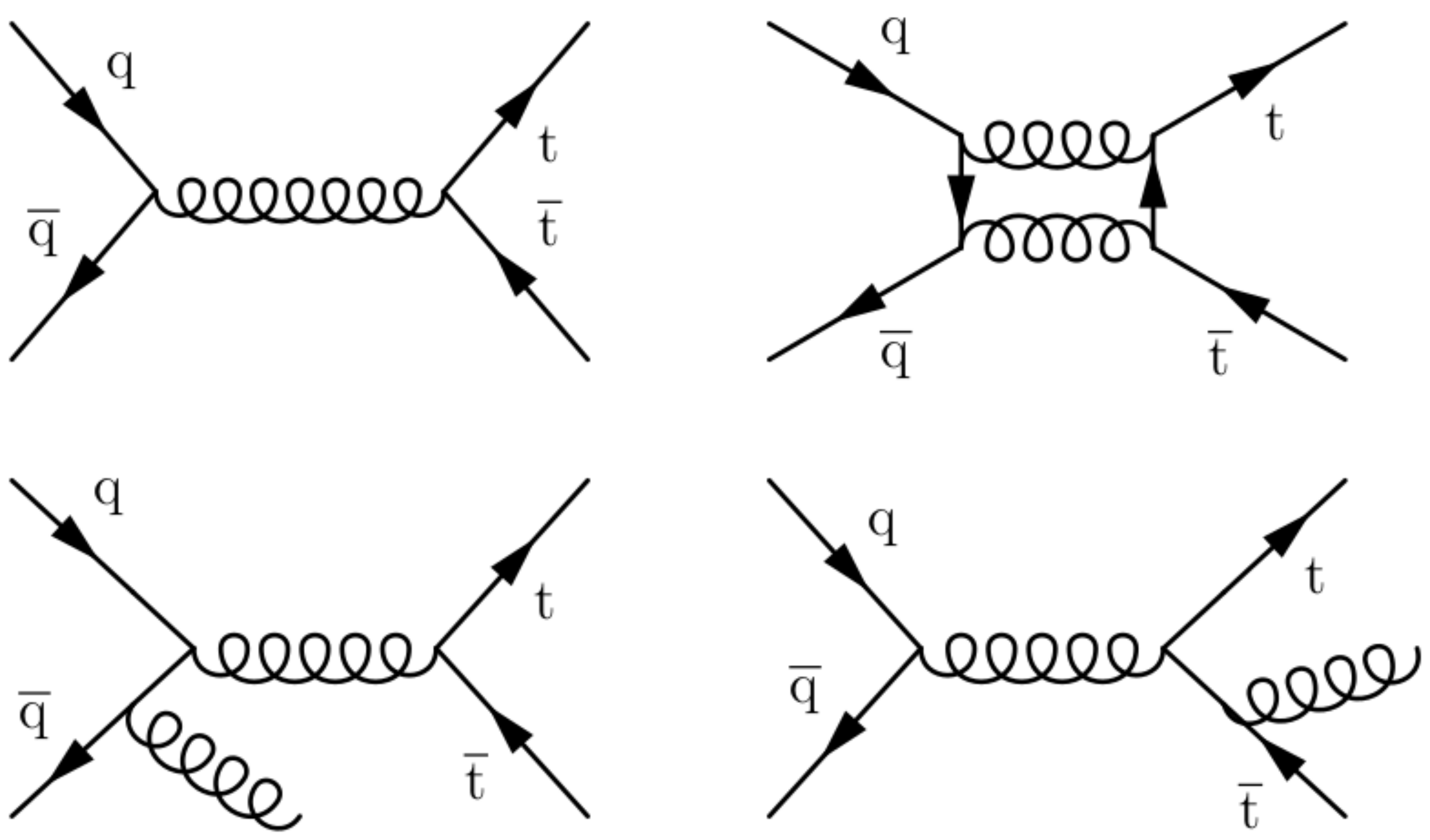
maximum for each μ

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

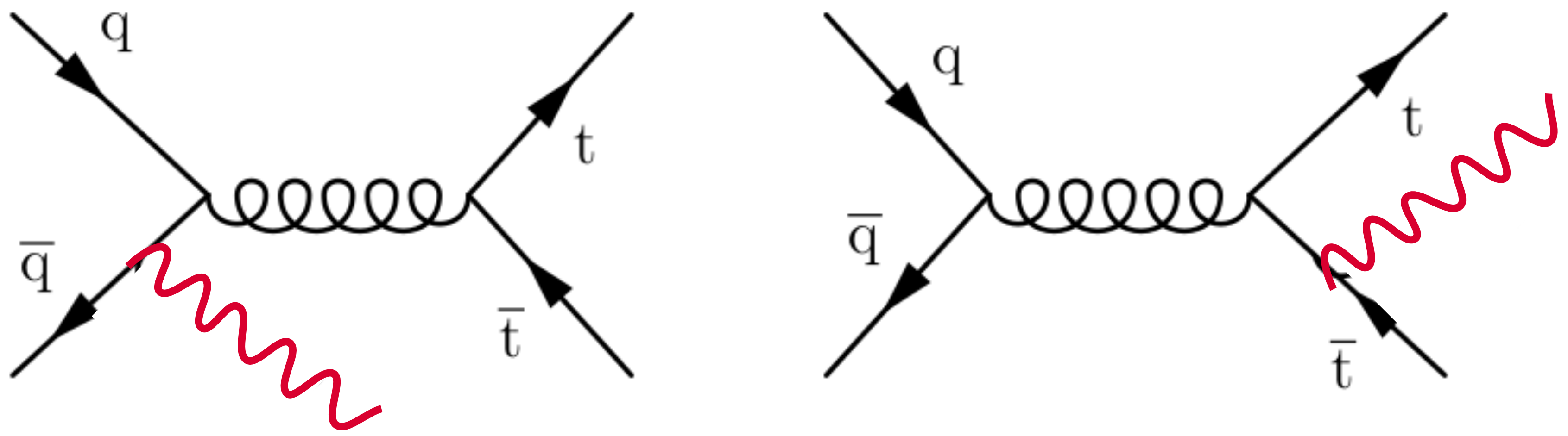


Why measure it in $t\bar{t}\gamma$?

- 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

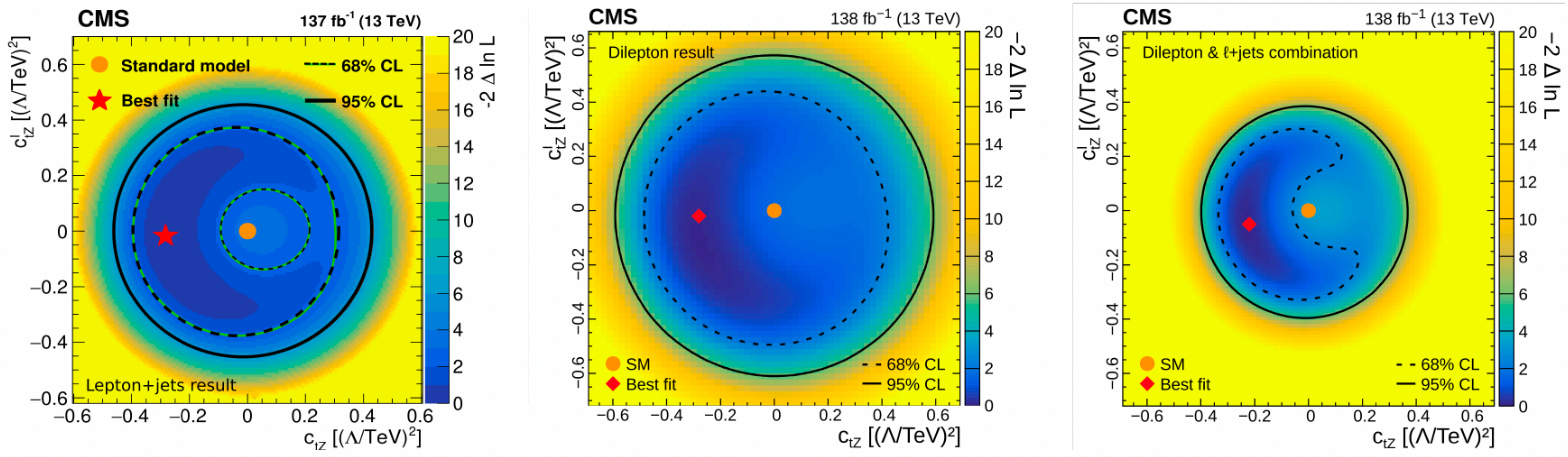


Figure 3.1: Result from the two-dimensional scan of the Wilson coefficients c_{tZ} and c^{I}_{tZ} using the photon p_T distribution from the lepton+jets analysis (left), the dilepton (centre) or the combination of the two (right). The shading quantified by the colour scale on the right reflects the negative 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 $t\bar{t}\gamma/t\bar{t}$

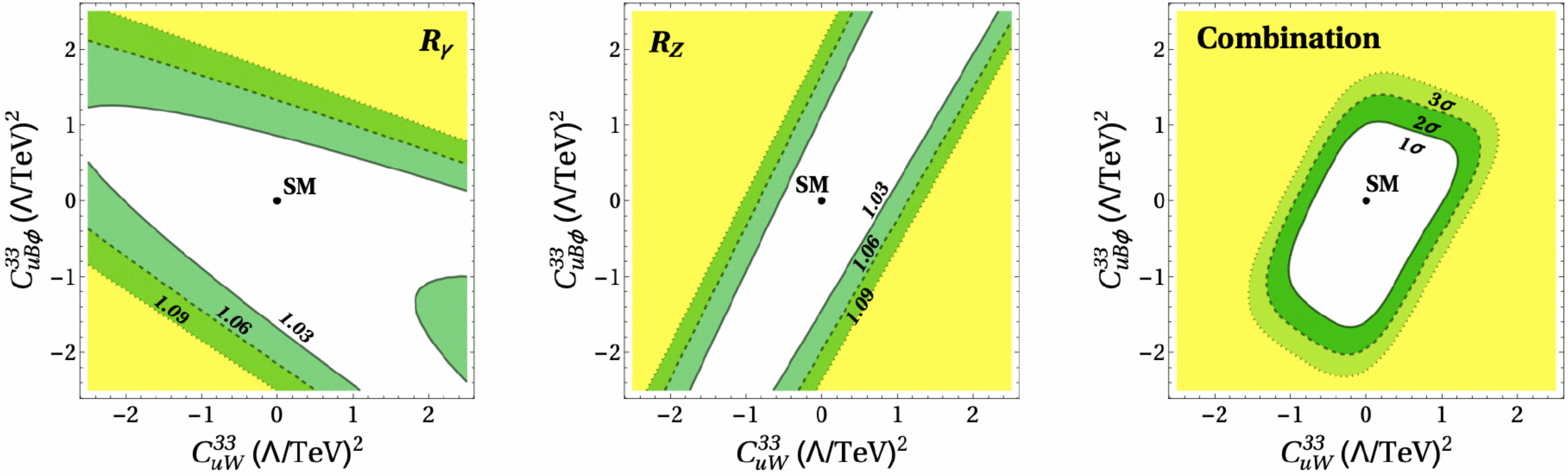


Figure 1.15: Cross section ratios R_γ (left) and R_Z (middle) normalized to their SM values (R_{SM}) as a function of the γ/Z anomalous dipole operator couplings. The contours show the deviation from the SM value in steps of 3, 6, and 9 per cent. On the right, we show the 1, 2, 3σ contours from combining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

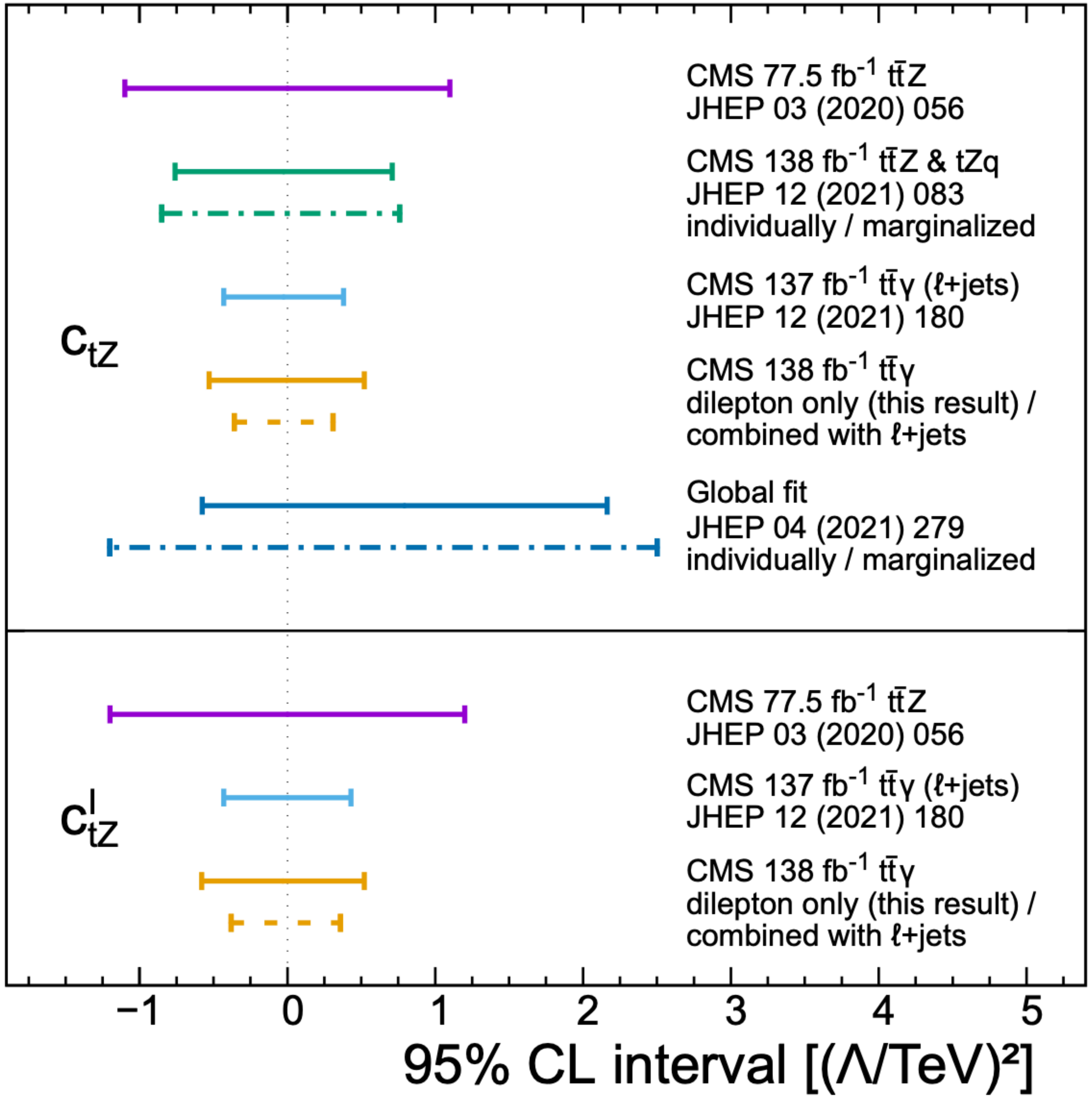
SMEFT with $t\bar{t}\gamma$ and $t\bar{t}Z$

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

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

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

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



SMEFT with top quarks