# tt+γ Cross-Section @ 13TeV

CMS Data Analysis School @ LPC 2025

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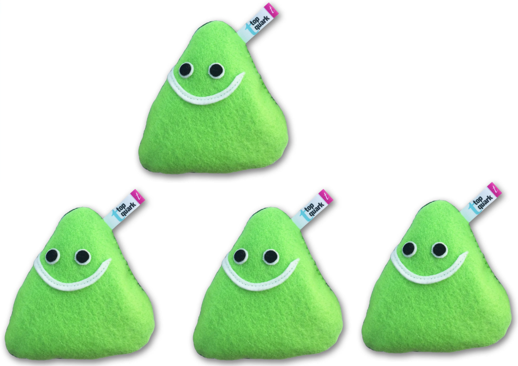
# Motivation - why tops?

- Top quark = Heaviest in Standard Model (since 1995)
- Key in searches for Beyond Standard Model Physics
- Large coupling to Higgs

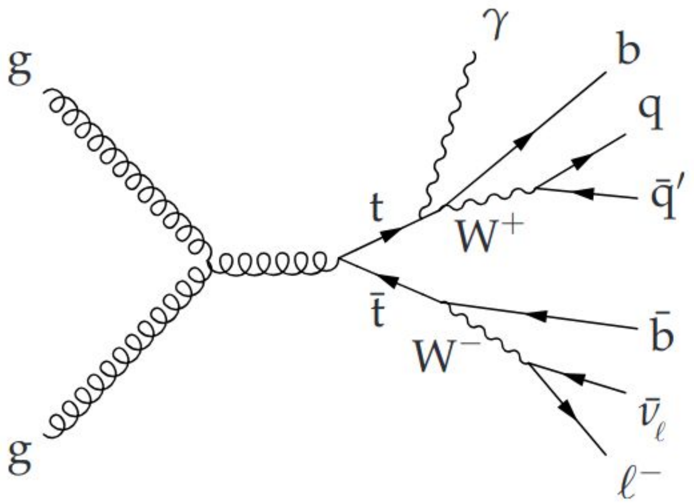
LHC is a top factory!



Alamy Stock Photos, Particle Zoo

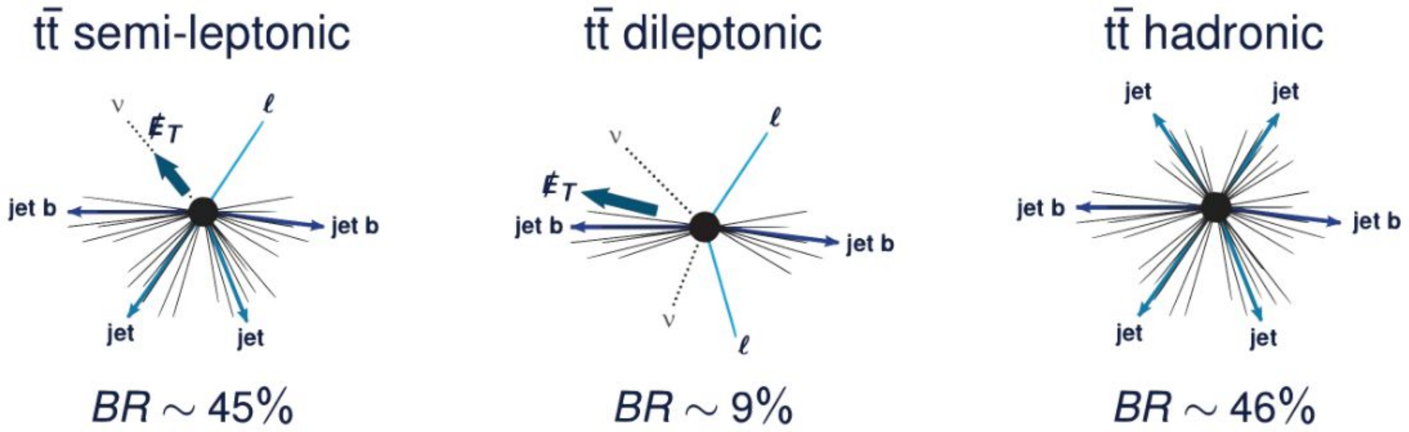
# Motivation - why $t\bar{t}\gamma$?

- **We want to learn more about top quark pairings!**
- $t\bar{t}\gamma$ is sensitive to top EM properties
    - cross section proportional to top charge
- High multiplicity final state - experimentally interesting



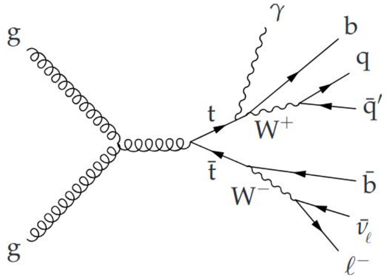
# Top quark decay channels

- Top quark decays into W, b
- Final states depend on how the 2 Ws decay
  - semi-leptonic, di-leptonic, hadronic channels
- Have to pick between signal/background purity and branching ratio

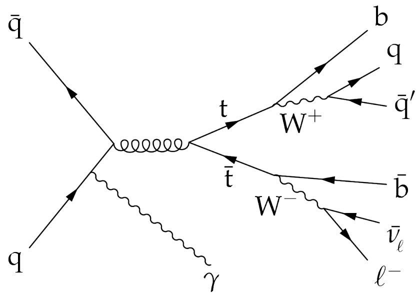


# Signal and background

- **Signal**
  - tt+$\gamma$
  - Event selection:
    - Exactly one e or μ
    - At least 4 jets (at least one is b-tagged)
    - Exactly one photon



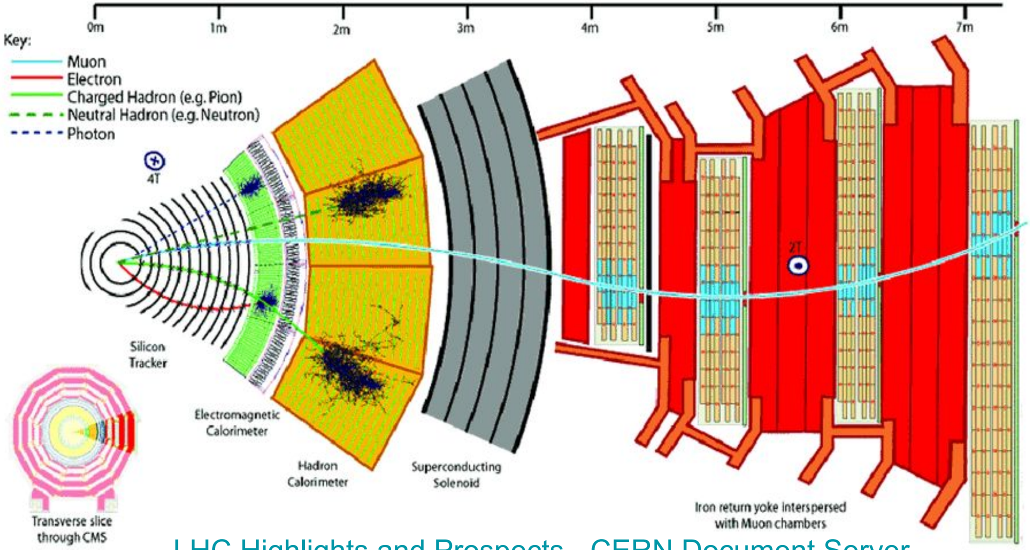

- **Background**
  - tt+$\gamma$ is not the only process that passes our selections
  - Categories:
    - Real photons without any top pair, e.g., W+$\gamma$ and Z+$\gamma$
    - Fake or non-prompt photons, e.g., tt, W+jets and Z+jets
    - Mis-identified electrons as photons, e.g. tt and Z+jets



# The CMS Detector

Important elements of the CMS detector for this analysis:

- Tracker - for precise vertexing
- ECAL - for identifying photons and electrons (and misidentifying electrons)
- HCAL - for identifying jets
- Muon Detector - for identifying muons




[LHC Highlights and Prospects - CERN Document Server]

# Analysis Strategy

## Control and Signal Regions

| No top + true γ | Other |
|---|---|
| W+γ<br>Z+γ<br>• ≥3 jets<br>• 0 b jets | (no top + fake γ) |
| **Top+ true γ** | **Fake γ** |
| • 4 Jets (≥1 b)<br>• Ch. Iso ≤1<br>• 1 tight γ<br>• 1 $e^-$ | **$e^-$**<br>• ≥3 jets<br>• 0 b jets<br>• 1 $e^-$<br><br>**Jets**<br>• Ch. Iso≥1 |

Unique feature of this analysis: 3 control regions to estimate MC backgrounds:

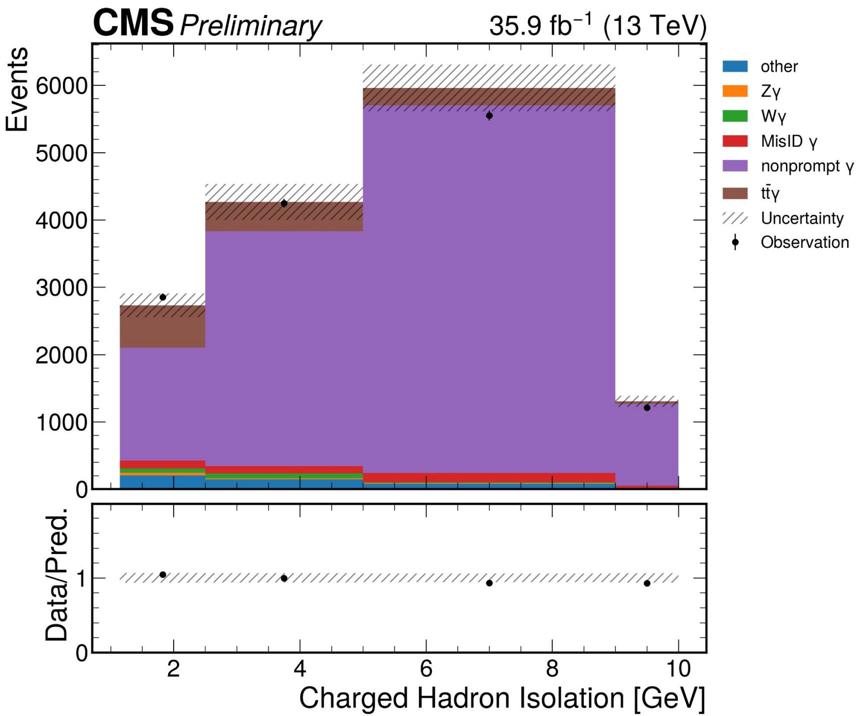
- V+γ (can Include a μ)
- MisID electrons (from Z→ee)
- Non-prompt γ (Jets)

Distinguished by inverting cuts on the signal region.

We then perform a maximum likelihood fit to obtain scale on the MC samples.

# Charge Hadron Isolation Control Region Prefit

- Focused on jets faking photons to study background contributions.
- Dominated by tt processes with misidentified photons.
- Relax the selection on the photon by inverting the charged hadron Isolation cut for the photon to perform the fit.
- Large tail of non-prompt photons.
- Exclude the first bin in the fit to avoid overlap with the signal region to prevent double counting,..




$$\sum_i P_{T,charge\ Hadron}$$

# Charge Hadron Isolation Control Region Postfit

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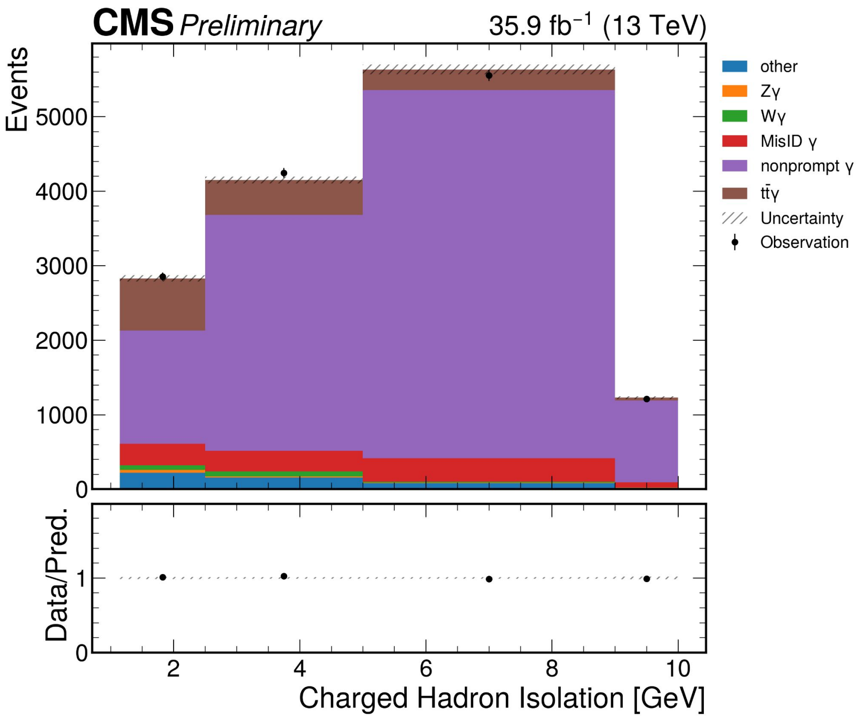
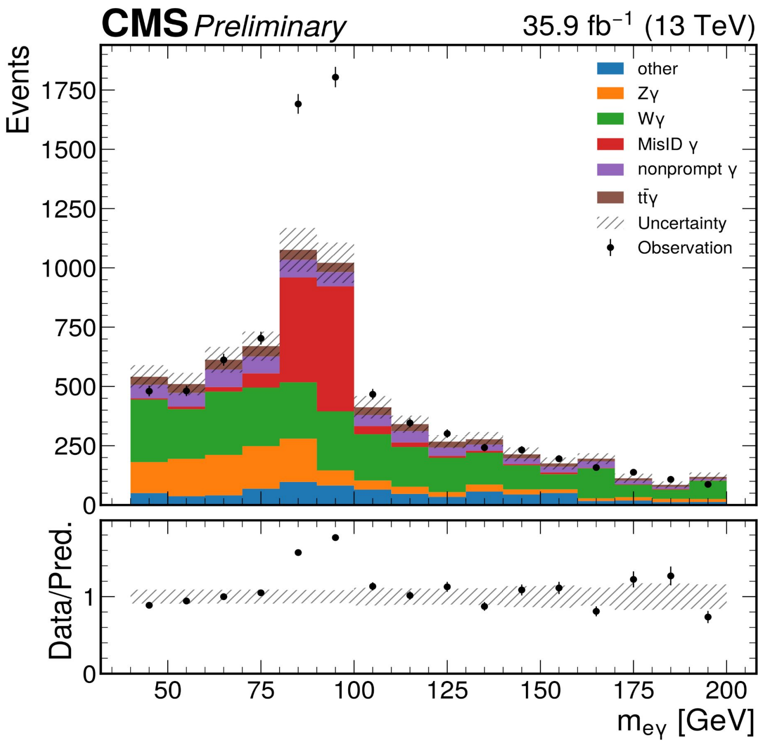
**Scale Factor: 0.91 +/- 0.04**




$$\sum_i P_{T,charge\ Hadron}$$

# Misidentified Electrons Control Region Prefit

- Electrons misidentified as photons. Events will be from Z -> ee.
- If one electron is misidentified as photon, we can see a peak near Z mass.
- Fit the invariant mass of e+γ
  - Require exactly 1 electron.
  - Require 0-b tagged jets.
- Before the prefit, the data and MC have poor agreement, hence we expect a very huge scale factor.



# Misidentified Electrons Control Region Postfit

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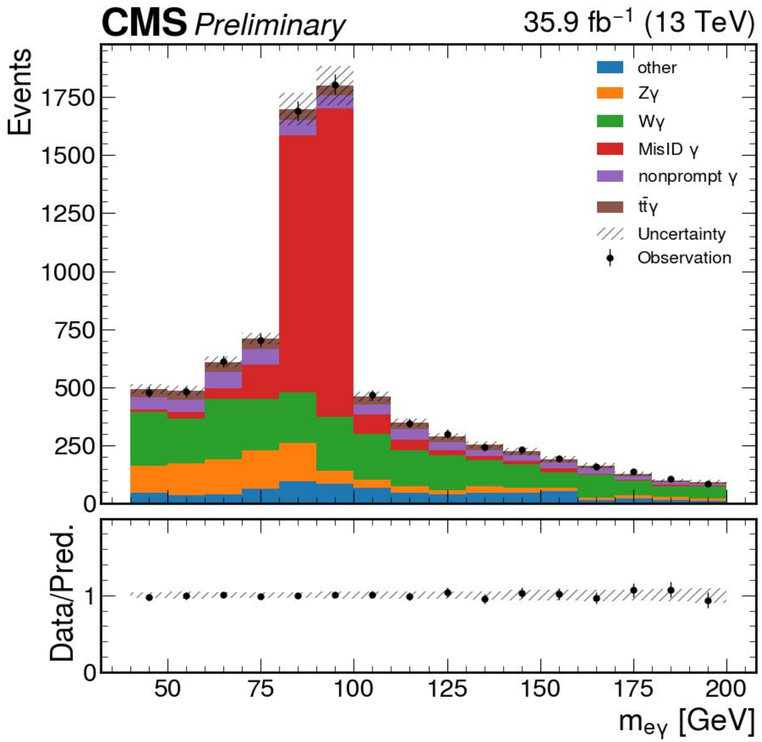
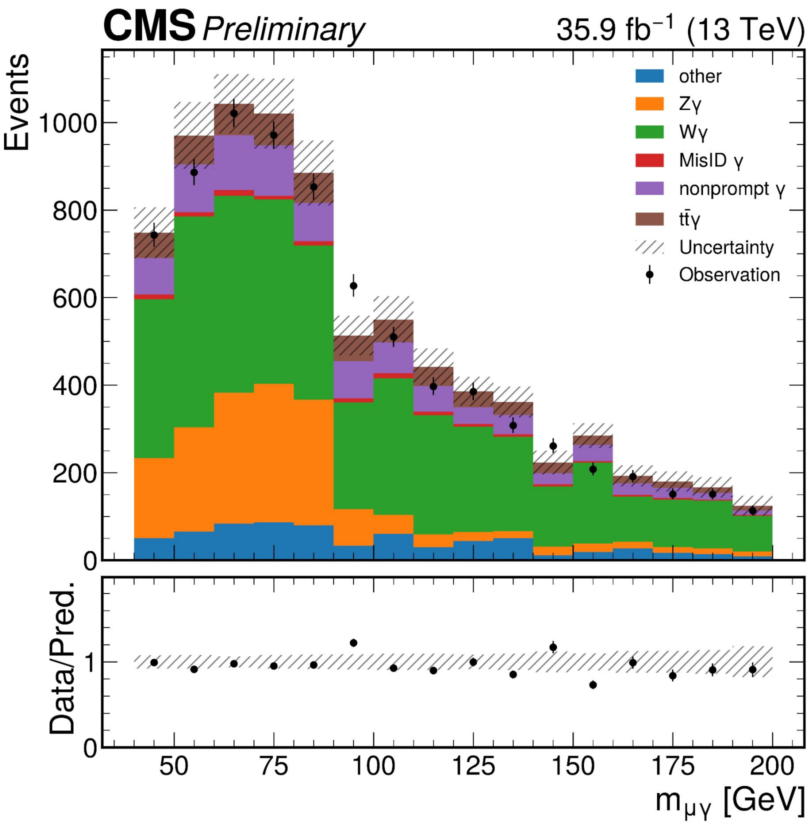
- If one electron is misidentified as photon, we can see a peak near Z mass.
- Fit the invariant mass of e+γ
    - Require exactly 1 electron.
    - Require 0-b tagged jets.
- After the postfit, the data and MC have a very good agreement.

**Scale Factor: 2.41 +/- 0.15**



# Vγ Control Region - Prefit

- We obtain scale factors for W+γ and Z+γ rates using the invariant mass of $\mu+\gamma$, where these are the dominant processes.
- Event selections:
  - Require one muon to suppress contributions from misID electrons
  - Require 0 b-tagged jets (separation from signal)
- Fit performed using a statistical shape analysis, yielding the scale factors:
  - W+γ: +0.91 ± 0.07
  - Z+γ: +0.85 ± 0.13



# Vγ Control Region - Postfit

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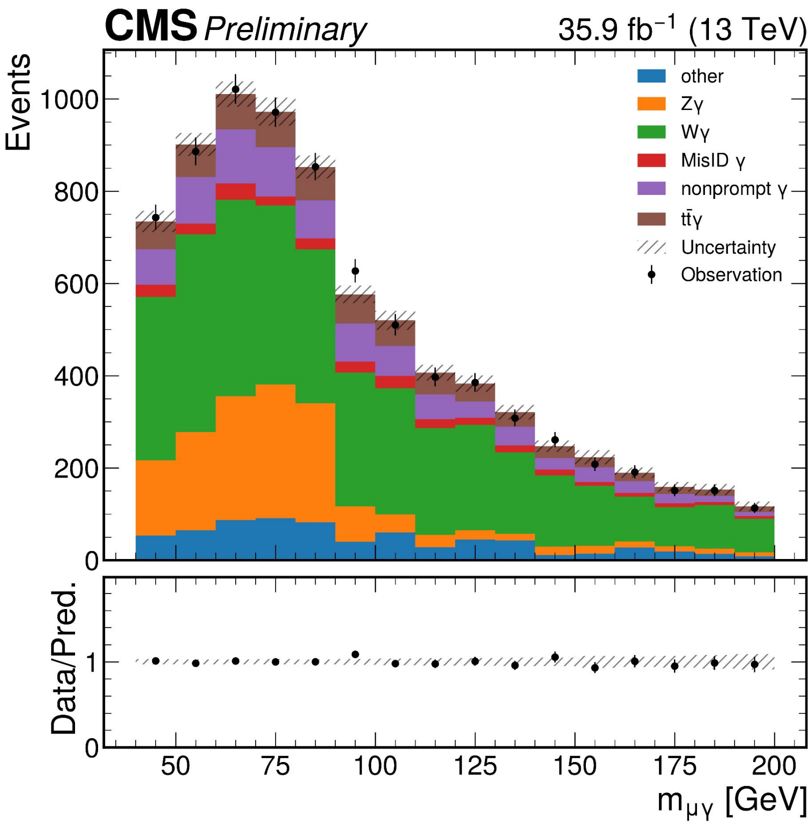
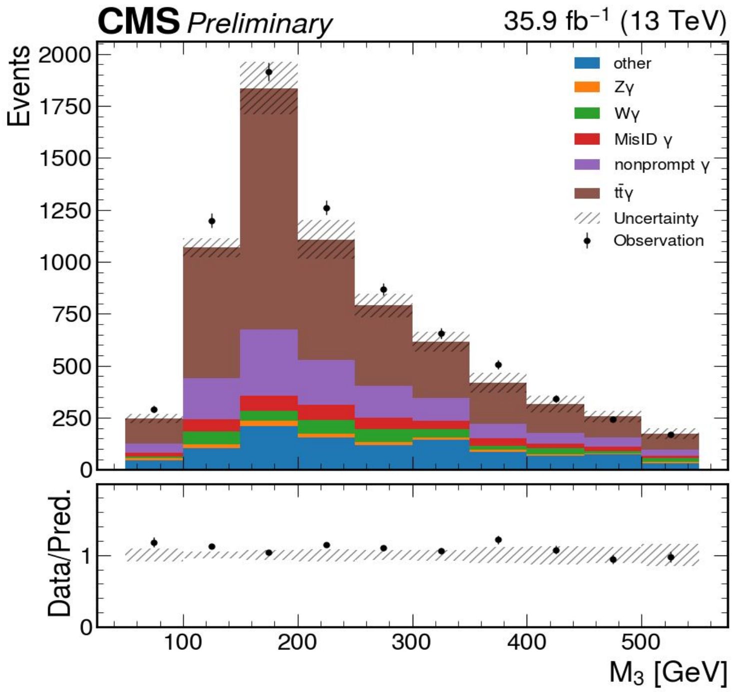
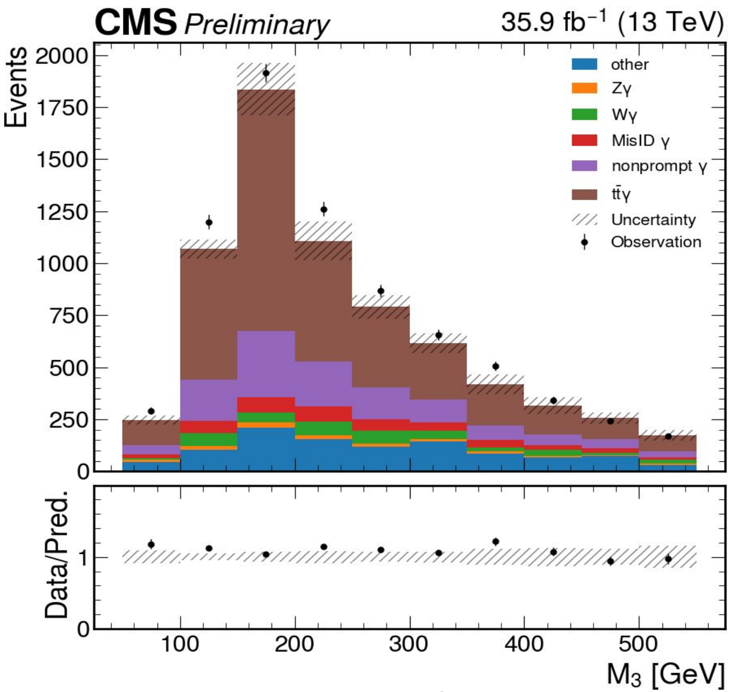


# Signal Strength Prefit

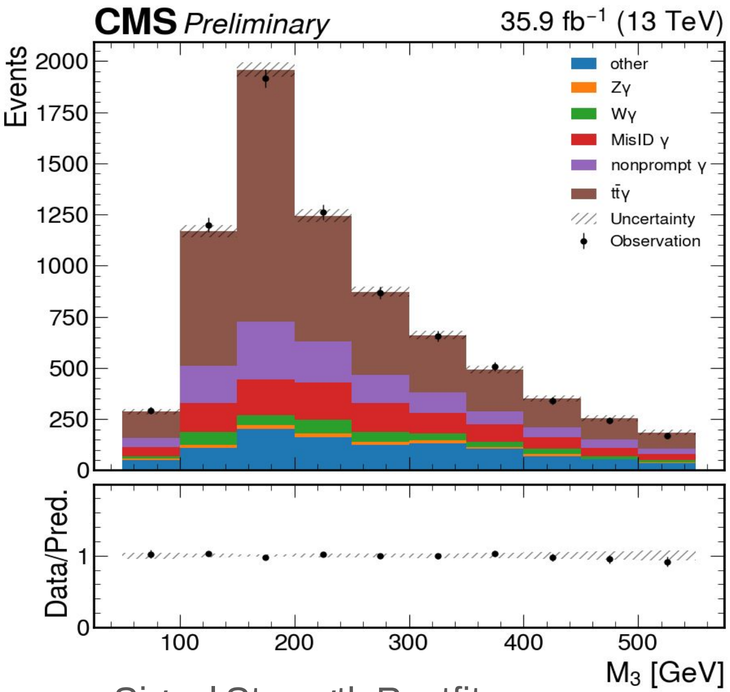
- TTGamma invariant mass (signal)
- Obtain scale factors from control regions
- Apply maximum likelihood fit
- Measured Value/ SM Value



# Signal Strength Pre/Postfit



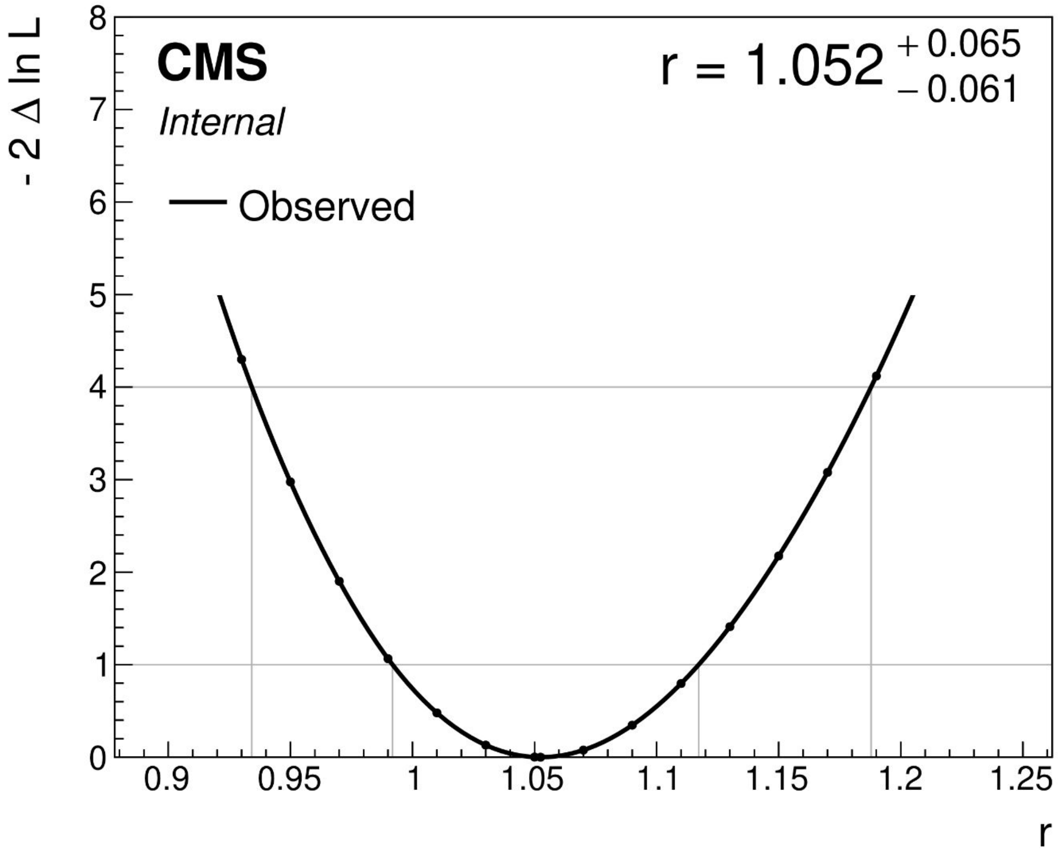

Signal Strength Prefit




Signal Strength Postfit

# Likelihood Scan

- Shape of $-2\Delta\ln L$ in the minimization region
  - $-2\Delta\ln L = 1$ sets 68% CL
  - $-2\Delta\ln L = 4$ sets 95% CL

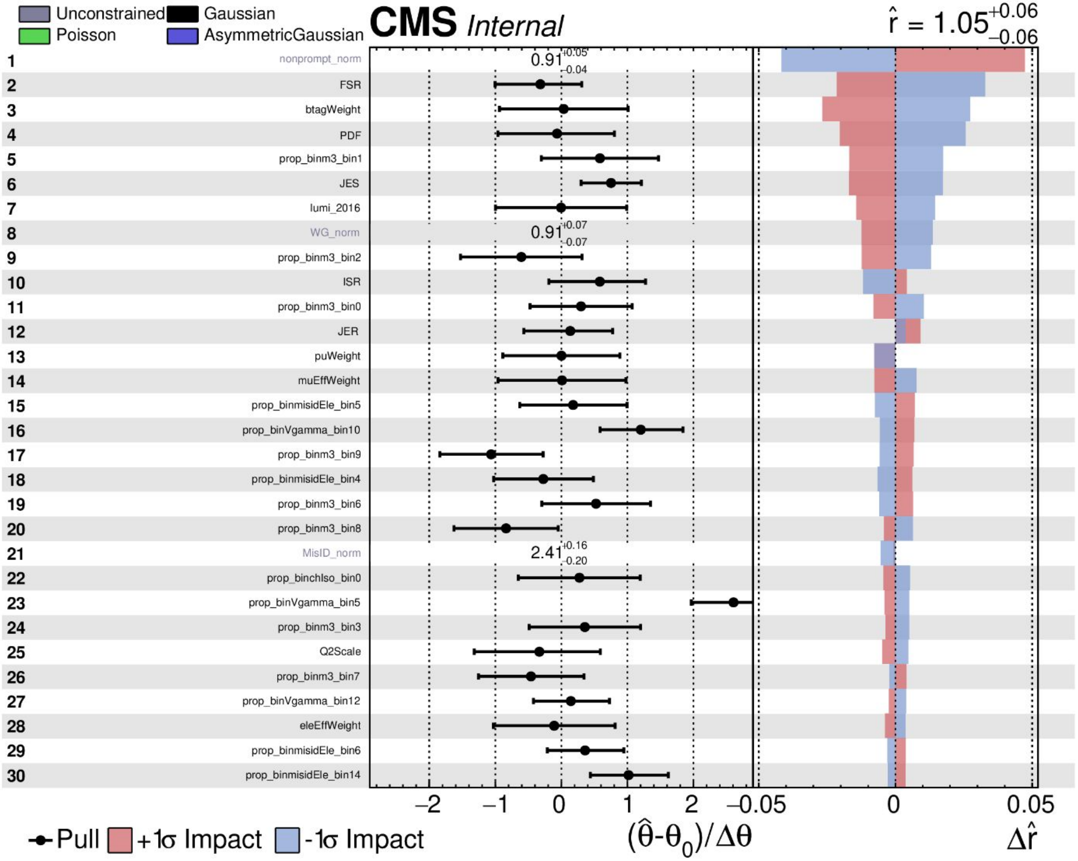


# Systematics

- **ISR**: Initial state radiation scale weighting
- **FSR**: Final state radiation scale weighting
- **PDF**: Parton distribution function parameter uncertainty
- **JES**: Jet energy scale scale corrections to jet momentum
- **JER**: Jet energy resolution scale corrections to jet momentum
- **b-tagging**: b-tag scale factor uncertainty (light and heavy jets)
- **lumi**: Integrated luminosity uncertainty
- **Pileup**: Reweighting uncertainty based on 1$\sigma$ variations
- **Muon Efficiency**: Muon trigger, identification, and reconstruction scale factor
- **Electron Efficiency**: Electron trigger, identification, and reconstruction scale factor

# Uncertainties

- Largest from theory uncertainty, b-tagging, jet related systematics
- Non-prompt is largest background in the SR
- b-tagging used to distinguish SR from CR
- M3 bins contain most of the signal
- M3, a jet mass sum, is highly dependant on JES and JER



# Conclusion

- Precision measurement of the tt+γ cross-section
  - Event selection: 4 jets (at least 1 b-tagged jet), 1 photon, 1 lepton
- Main backgrounds: jets/electrons faking photons, W/Z+γ
- Three control regions defined to estimate background
  - Charged Hadron Isolation
  - Misidentified Electrons
  - V+γ

Measured signal strength: $r = 1.05^{+0.06}_{-0.06}$

$$\sigma_{t\bar{t}+\gamma} = 15.98^{+0.99}_{-0.93}\,\mathrm{pb} \qquad \sigma_{SM} = 15.19\,\mathrm{pb}$$

**Consistent with Standard Model with 6% precision!**

# Acknowledgement

Thank you to our very very cool facilitators!!

Raghav Kansal, Ali Simsek, Honor Hare, Eddie McGrady, Leonardo Giannini, Aashwin Basnet, Georgios Krintiras.