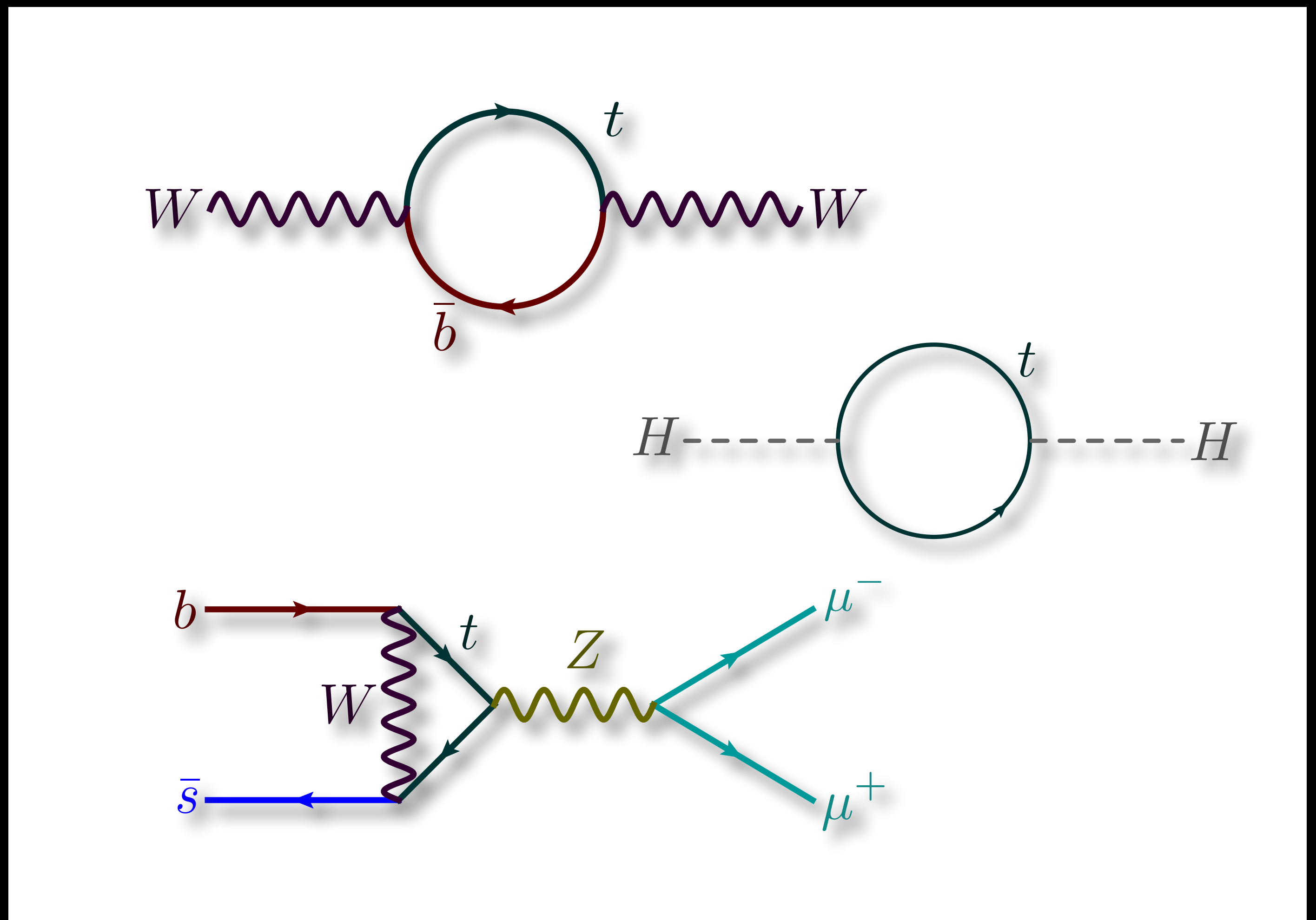
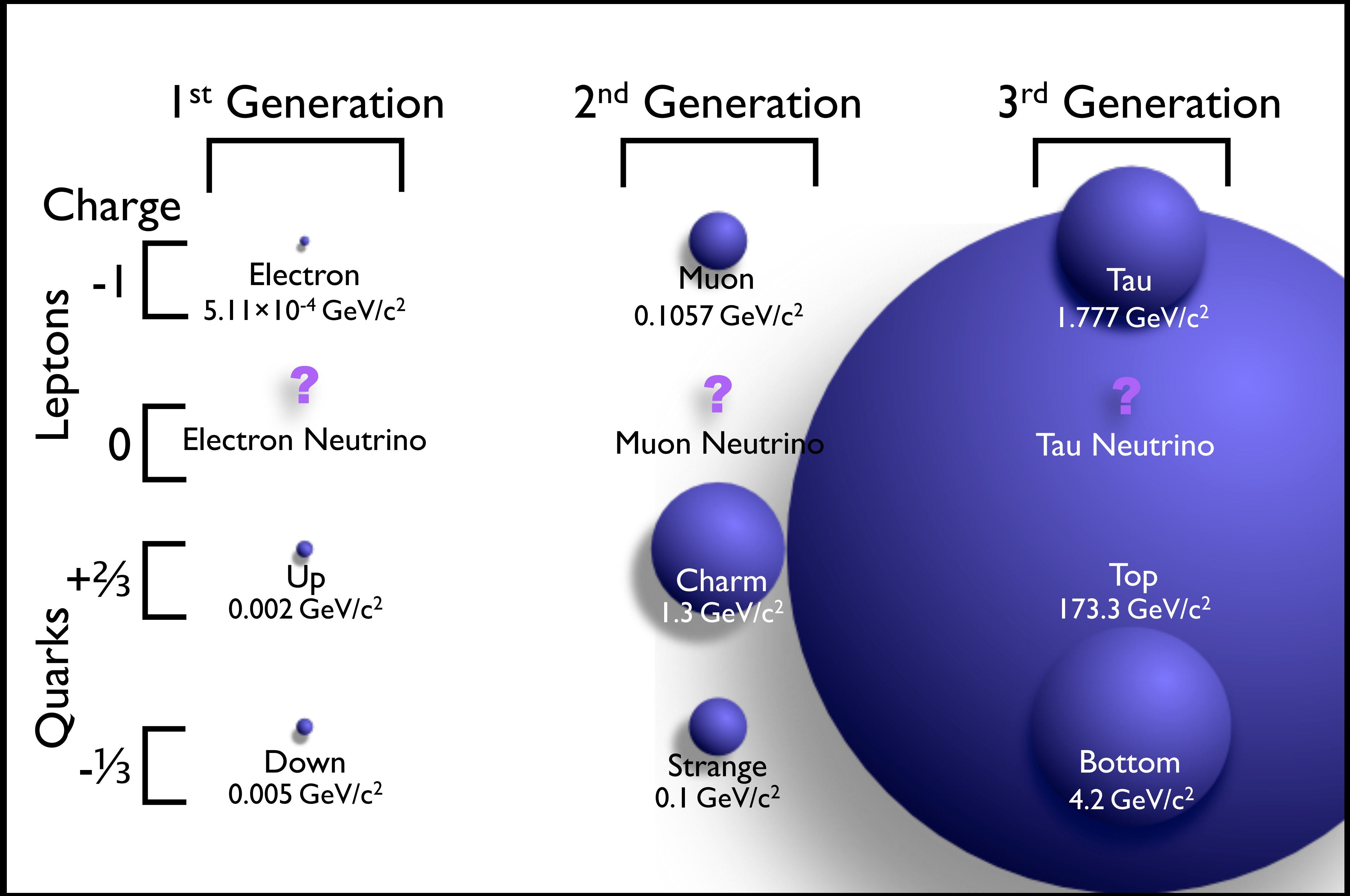
Recent Top Physics Results from CMS

Kevin Lannon
for the CMS Collaboration

Why Top Quark Physics?

- Top quarks stand out!
  - Most massive particle in the SM
- Fingerprints all over SM





Look for signs of new physics connected with top quarks!

CMS
35.9 fb⁻¹ (13 TeV)
BDT output
95% CL upper limits
Median expected
68% expected
95% expected
Observed
B(t → cH) [%]
B(t → uH) [%]
Inclusive tt̄ cross section (pb)
NNLO+NNLL
√s (TeV)
ATLAS+CMS √s = 8 TeV
ATLAS + CMS
Tevatron data from
19.7 fb⁻¹ (8 TeV)
e/μ+jets
Photon p_T (GeV)
Data/Sim.
2.3 fb⁻¹ (13 TeV)
Number of b-tagged jets
Obs/Exp
CMS Unpublished
Data/MC
JSF
2D fit
ρ = -0.94
M_t [GeV]
Leading-jet m_jet [GeV]
MADGRAPH+PYTHIA
MC@NLO+HERWIG
POWHEG+PYTHIA
t channel + bkg
total bkg
non-top
eμ
Ratio to MG+P
2.6 fb⁻¹ (13 TeV)
Single lepton: e
Single lepton: μ
Dilepton
bin id.
95 % CL limit on μ = σ_obs / σ_SM
SS Dilepton
OS Dilepton
Single Lepton
Combined
B (t → Zc) (%)
B (t → Zu) (%)
Observed
Expected
Expected 68% CL
2.2 fb⁻¹ (13 TeV)
Event category
4j,2t events
min Mass(lepton,b) [GeV]
Ratio
μ = σ/σ_th(m_t = 172.5 GeV)
CMS Preliminary
κ_Zu / Λ (GeV⁻¹)
35.8 fb⁻¹ (13 TeV)
1j1b BDT output bin
|y(tt̄)|
M(tt̄) [GeV]
m_t [GeV]
leading top quark p_T [GeV]
N_jets
Permutations / 5 GeV
World combination


Number of Top quark papers from CMS: 83

Number of Top quark papers from CMS: 83

Roughly 10/year over lifetime of CMS

Number of Top quark papers from CMS: 83

Roughly 10/year over lifetime of CMS

About 14/year in the last 3 years

Number of Top quark papers from CMS: 83

Roughly 10/year over lifetime of CMS

About 14/year in the last 3 years

Another 44 preliminary results (no associated paper)

Number of Top quark papers from CMS: 83

Roughly 10/year over lifetime of CMS

About 14/year in the last 3 years

Another 44 preliminary results (no associated paper)

New Results for 2017 (Paper + Preliminary): 23

Number of Top quark papers from CMS: 83

Roughly 10/year over lifetime of CMS

About 14/year in the last 3 years

Another 44 preliminary results (no associated paper)

New Results for 2017 (Paper + Preliminary): 23

Number of minutes for this talk: 15


Number of Top quark papers from CMS: 83
Roughly 10/year over lifetime of CMS
About 14/year in the last 3 years
Another 44 preliminary results (no associated paper)
New Results for 2017 (Paper + Preliminary): 23
Number of minutes for this talk: 15
Need to focus on a subset of results

Top Quark Physics Analysis

Top Quark Physics Analysis

Precision studies:

- ➡ Inclusive and differential cross sections
- ➡ W helicity
- ➡ spin correlations
- ➡ AFB/charge asymmetry

Top Quark Physics Analysis

Precision studies:
- ➡ Inclusive and differential cross sections
- ➡ W helicity
- ➡ spin correlations
- ➡ AFB/charge asymmetry

Explicit Searches for New Physics:
- ➡ Vector-like partners
- ➡ SUSY stop squarks
- ➡ X→ttbar

Top Quark Physics Analysis

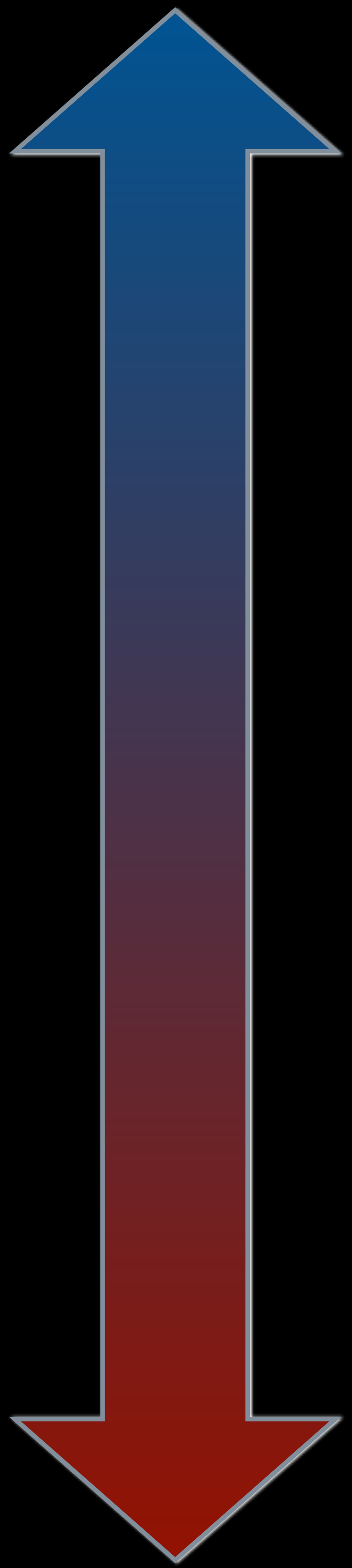
Precision studies:

- ➡ Inclusive and differential cross sections
- ➡ W helicity
- ➡ spin correlations
- ➡ AFB/charge asymmetry

Explicit Searches for New Physics:

- ➡ Vector-like partners
- ➡ SUSY stop squarks
- ➡ $X \rightarrow t\bar{t}$bar

Respect



What your colleagues feel towards you when you do an analysis of this type.

Envy

Top Quark Physics Analysis

Precision studies:

- ➡ Inclusive and differential cross sections
- ➡ W helicity
- ➡ spin correlations
- ➡ AFB/charge asymmetry

In between: Associated production! Search for rare (in SM) processes to check for deviations.

Explicit Searches for New Physics:

- ➡ Vector-like partners
- ➡ SUSY stop squarks
- ➡ X→ttbar

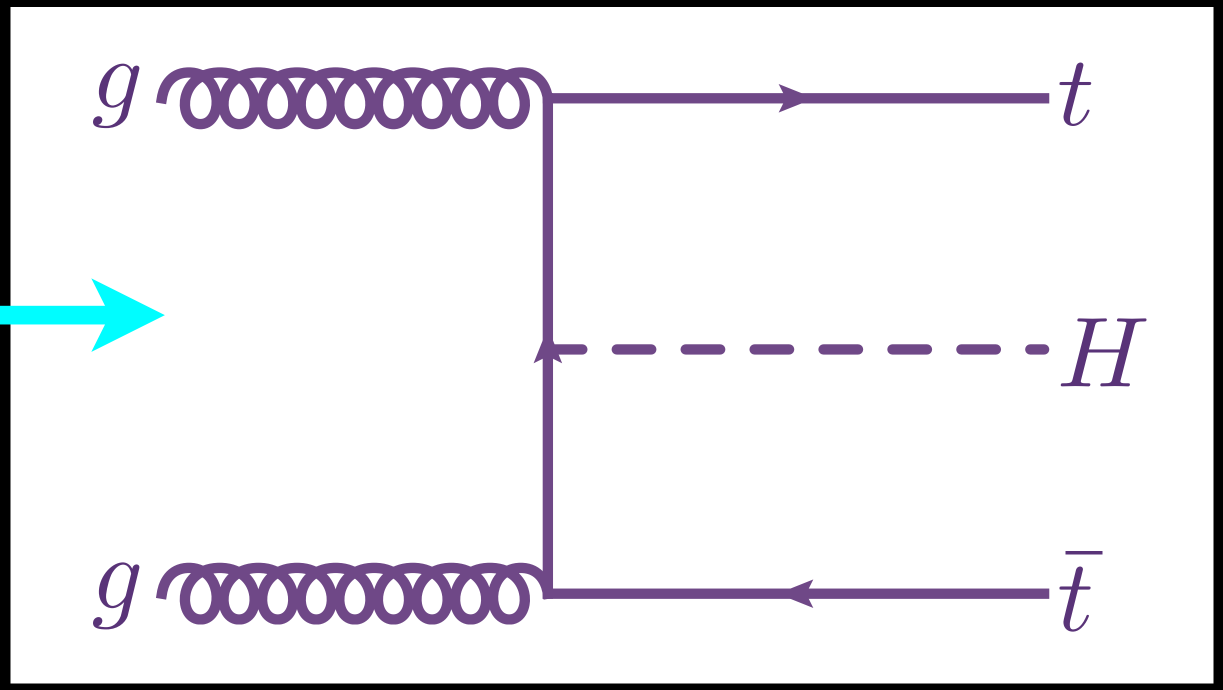
Respect

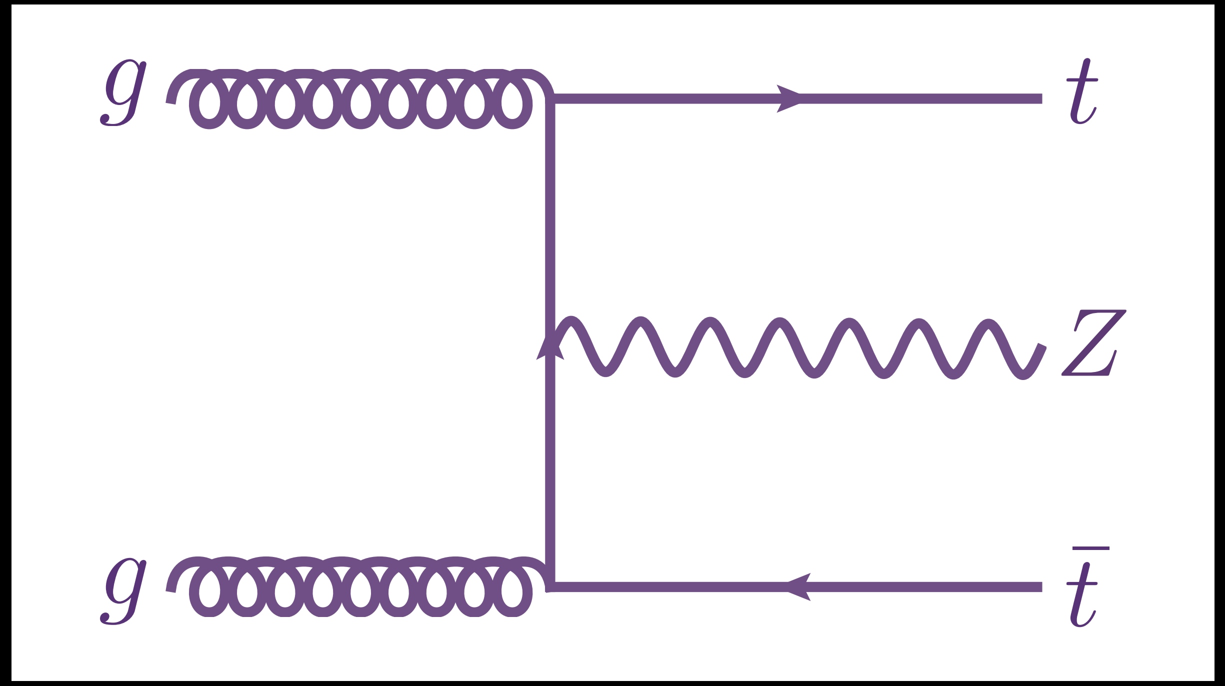
What your colleagues feel towards you when you do an analysis of this type.

Envy

Top Quarks + What?

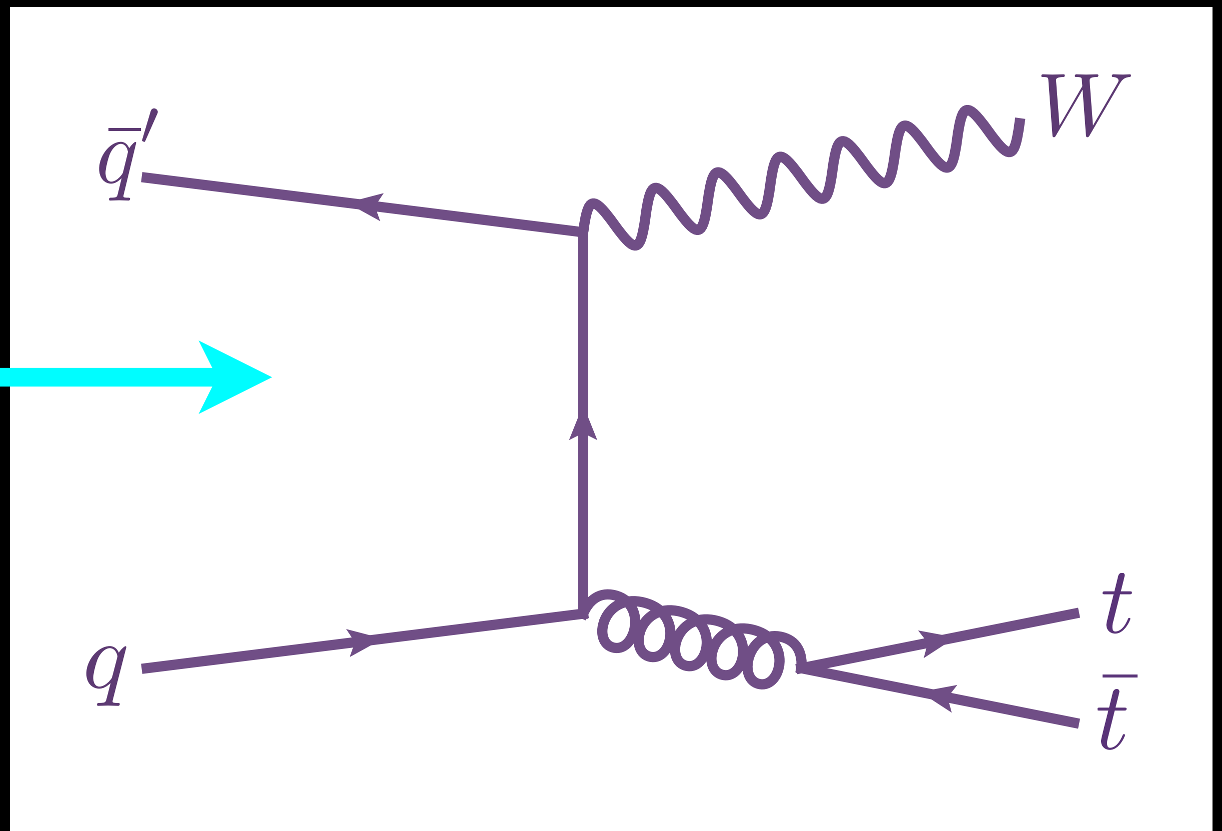
Top quarks + Higgs: Obviously! Source of mass and most massive particle. See earlier talk. Is a background for other signals here.





Top quarks + Z boson: Also very interesting! Hard to probe t-Z coupling directly any other way.

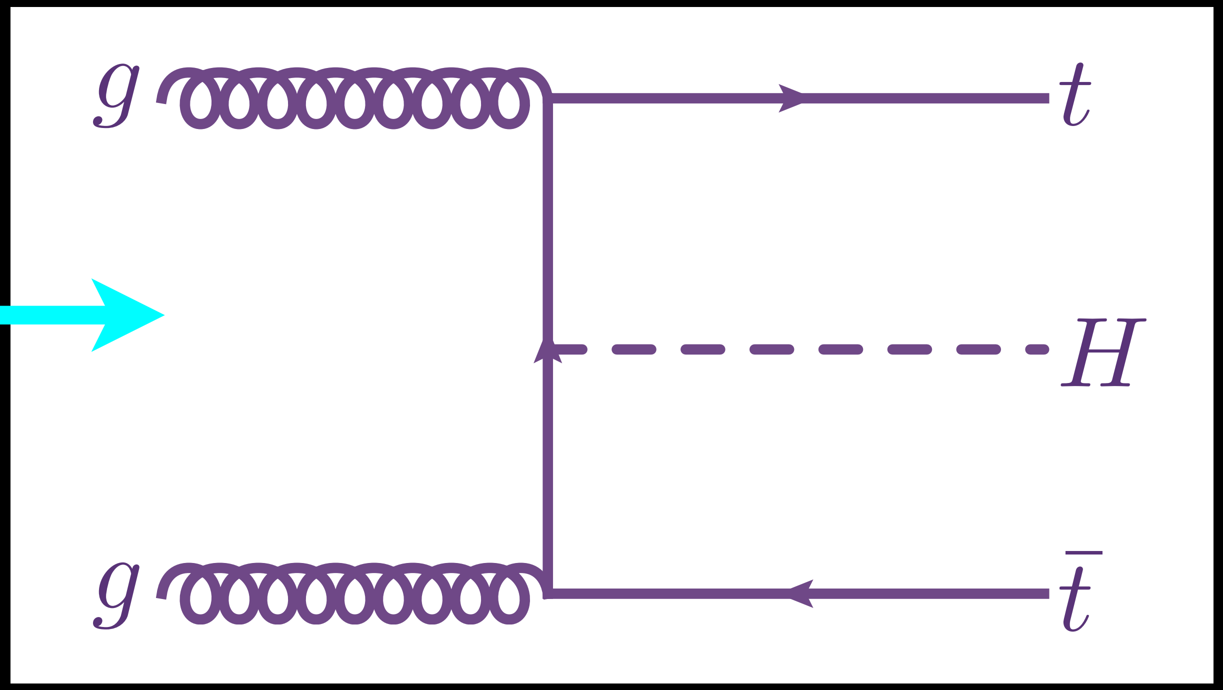
Top quarks + W boson: Not actually sensitive to t-W coupling at least in SM. But if you have top quarks + extra Ws, that could certainly be a sign of new physics (i.e. X->tW).

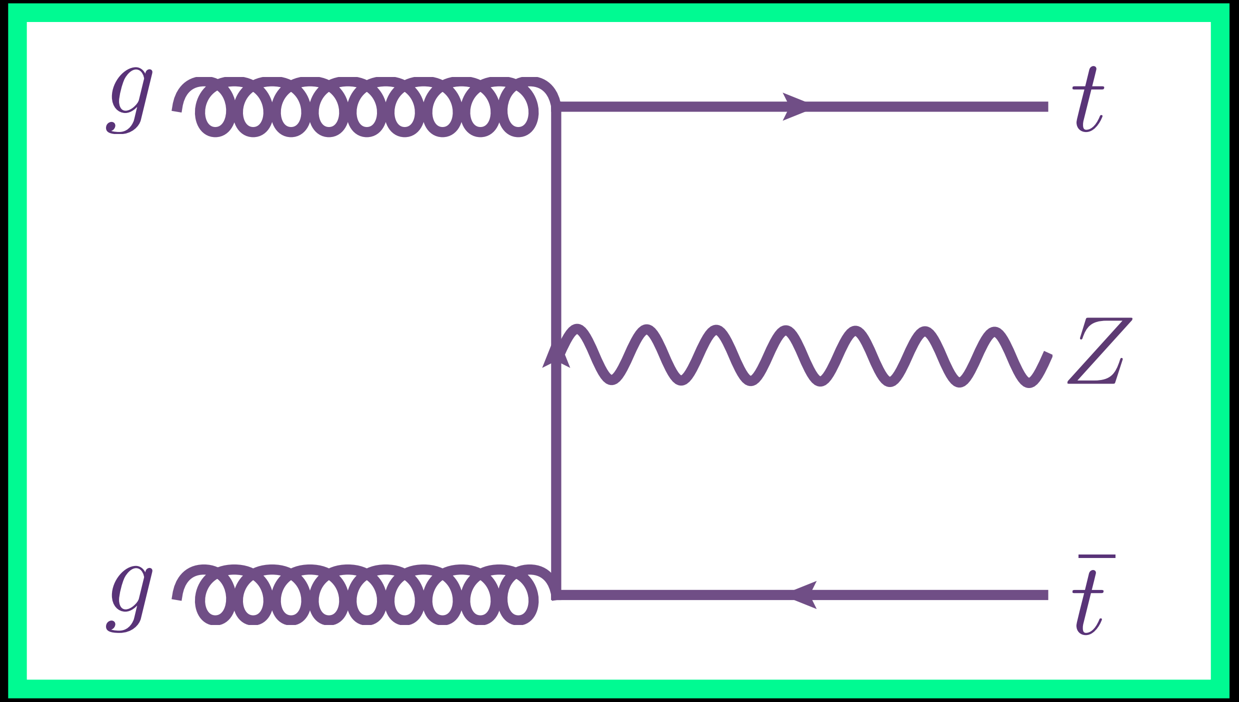


And More!
Top quarks + photons, bottom quarks, gluons/light quarks, top quarks (!): The list goes on and on.

Top Quarks + What?

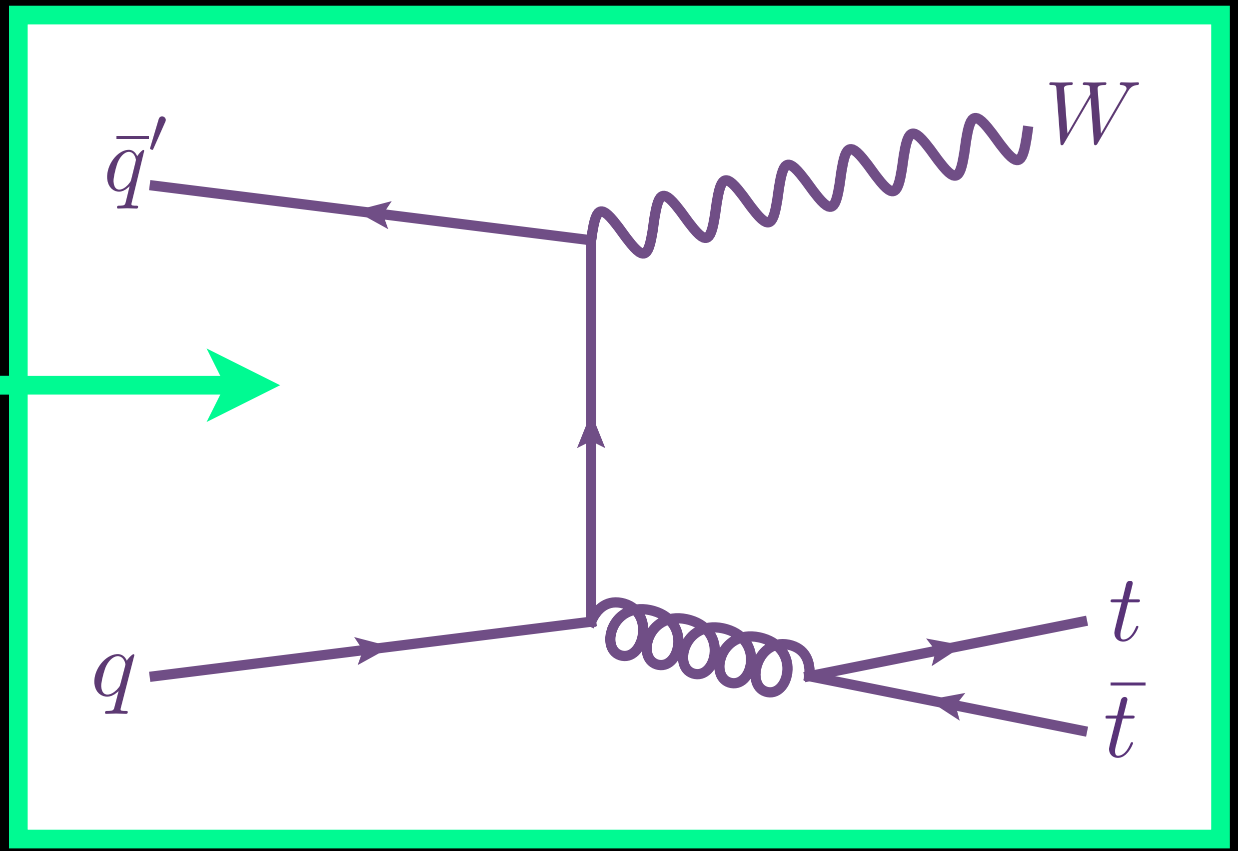
Top quarks + Higgs: Obviously! Source of mass and most massive particle. See earlier talk. Is a background for other signals here.





Top quarks + Z boson: Also very interesting! Hard to probe t-Z coupling directly any other way.

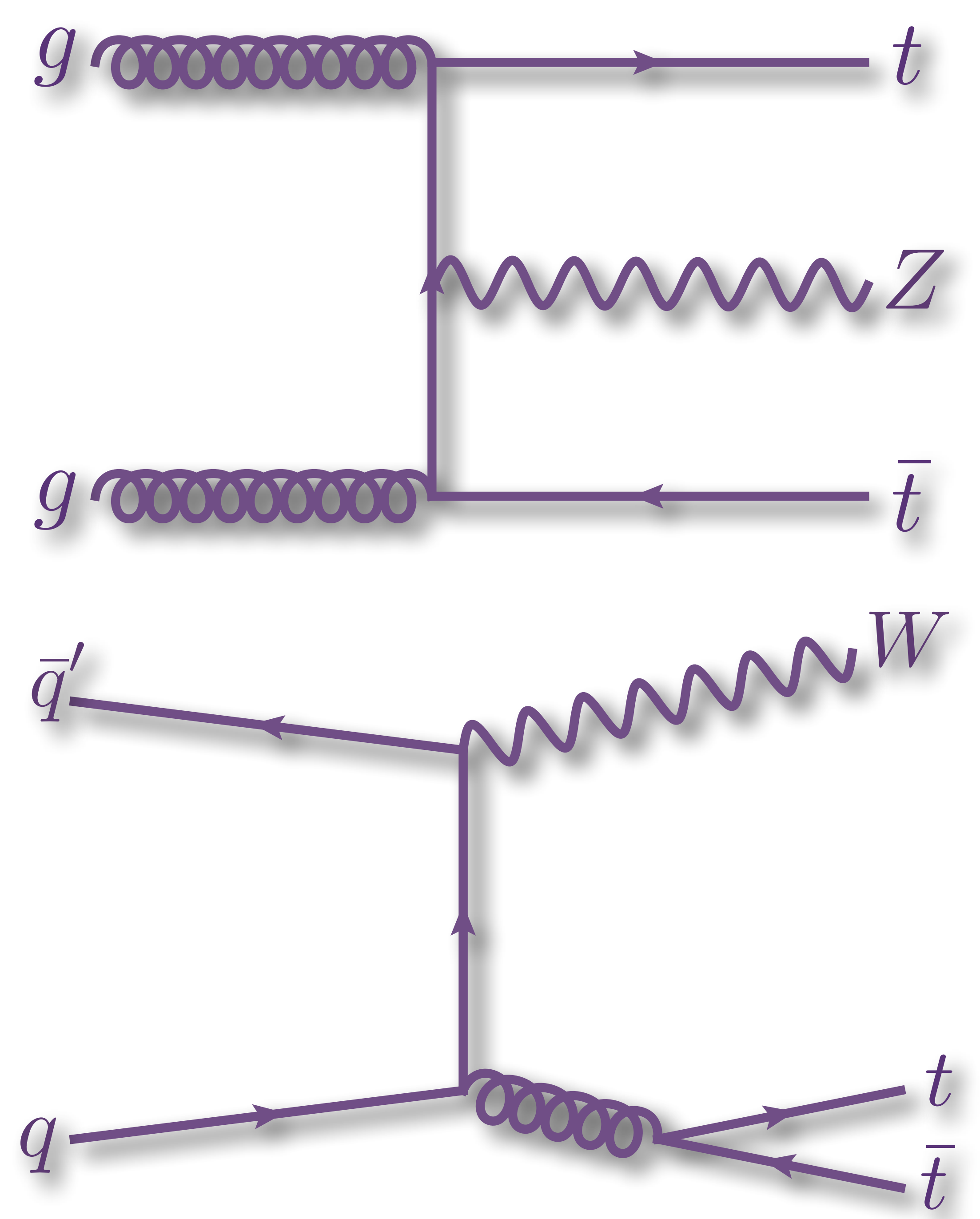
Top quarks + W boson: Not actually sensitive to t-W coupling at least in SM. But if you have top quarks + extra Ws, that could certainly be a sign of new physics (i.e. X→tW).



And More!
Top quarks + photons, bottom quarks, gluons/light quarks, top quarks (!): The list goes on and on.

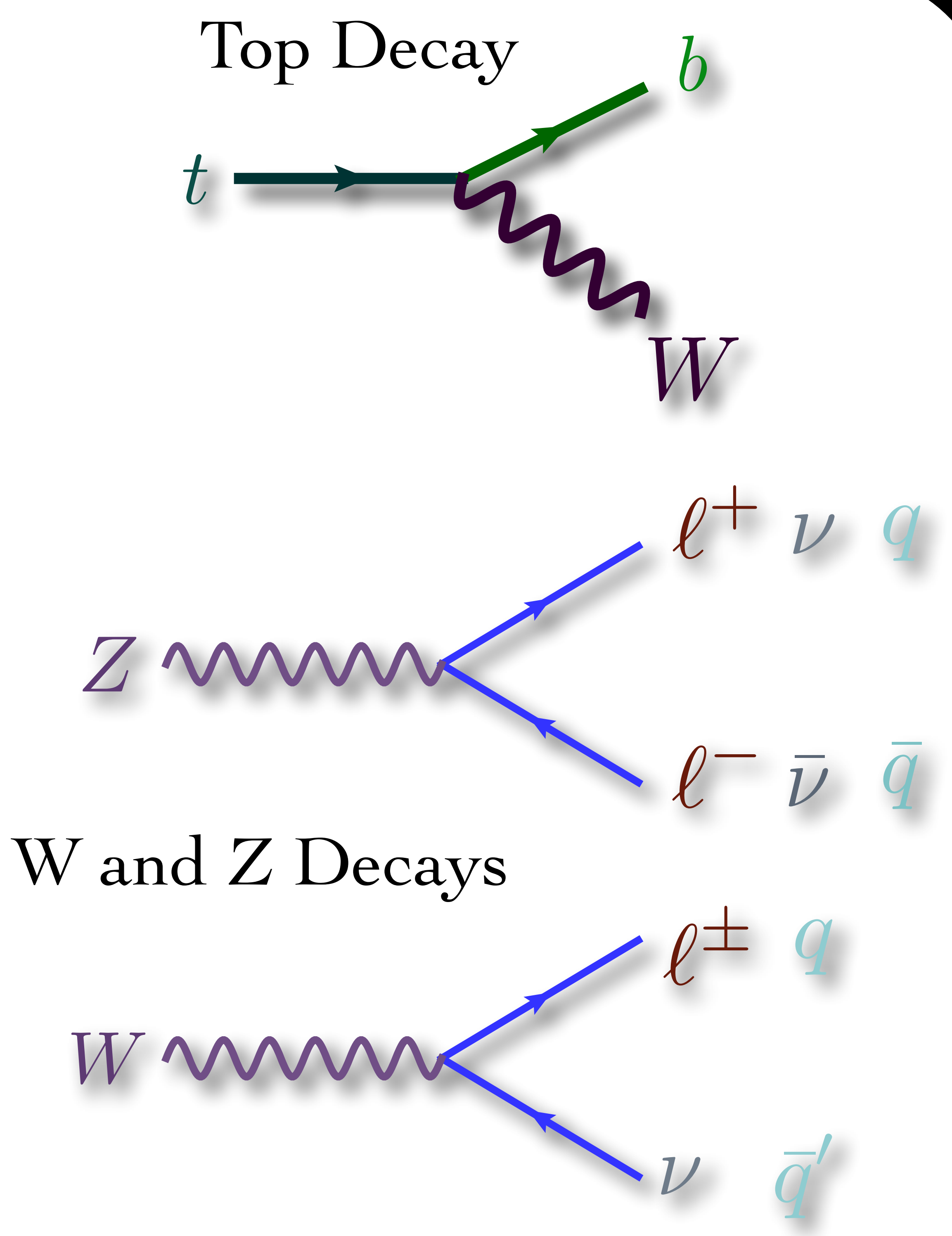
Experimental Signature

Focus on **multilepton signature**: at least one lepton from top quark and one from W or Z.



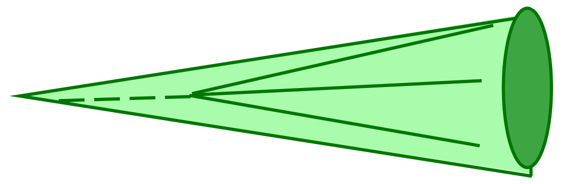
Signal

$\otimes$



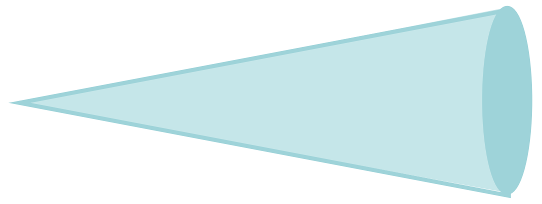
=

Bottom quark jet



(× 2)

Light quark



(× 0-2)

- Anti-k_T R = 0.4
- p_T > 30 GeV, |η| < 2.4
- Multivariate b-tagging

Electron or Muon

(× 2-4)

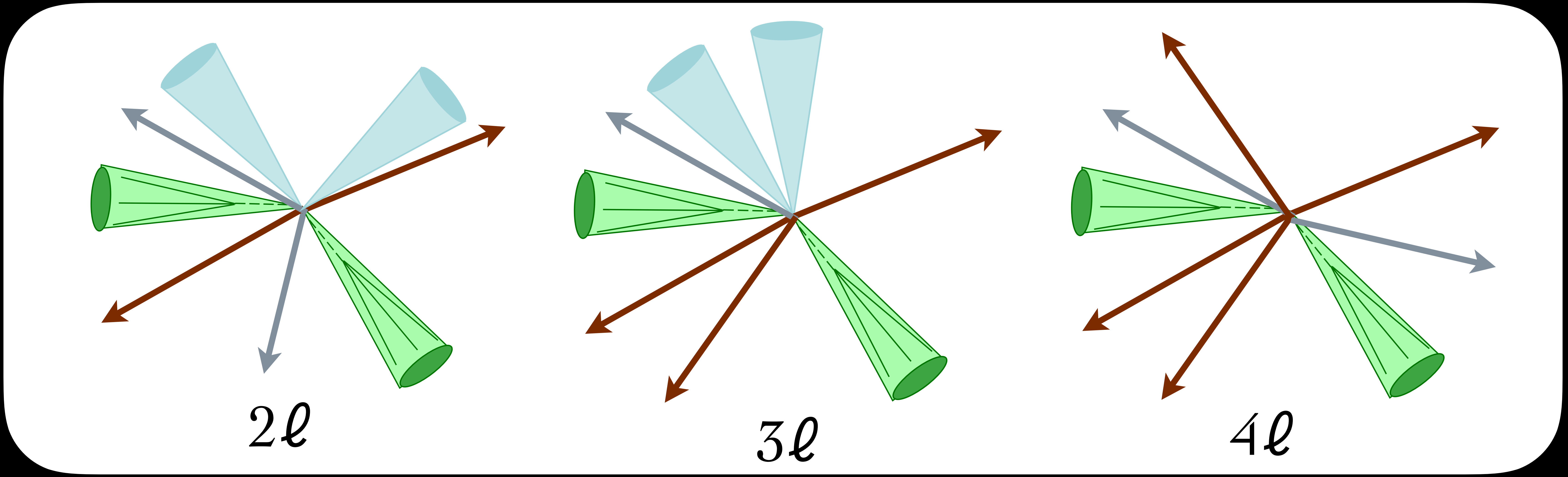
- p_T > 30 GeV, |η| < 2.5 (ele), 2.4 (muo)
- Higher p_T cuts on some depending on final state
- Isolated

Neutrino

(× 0-3)

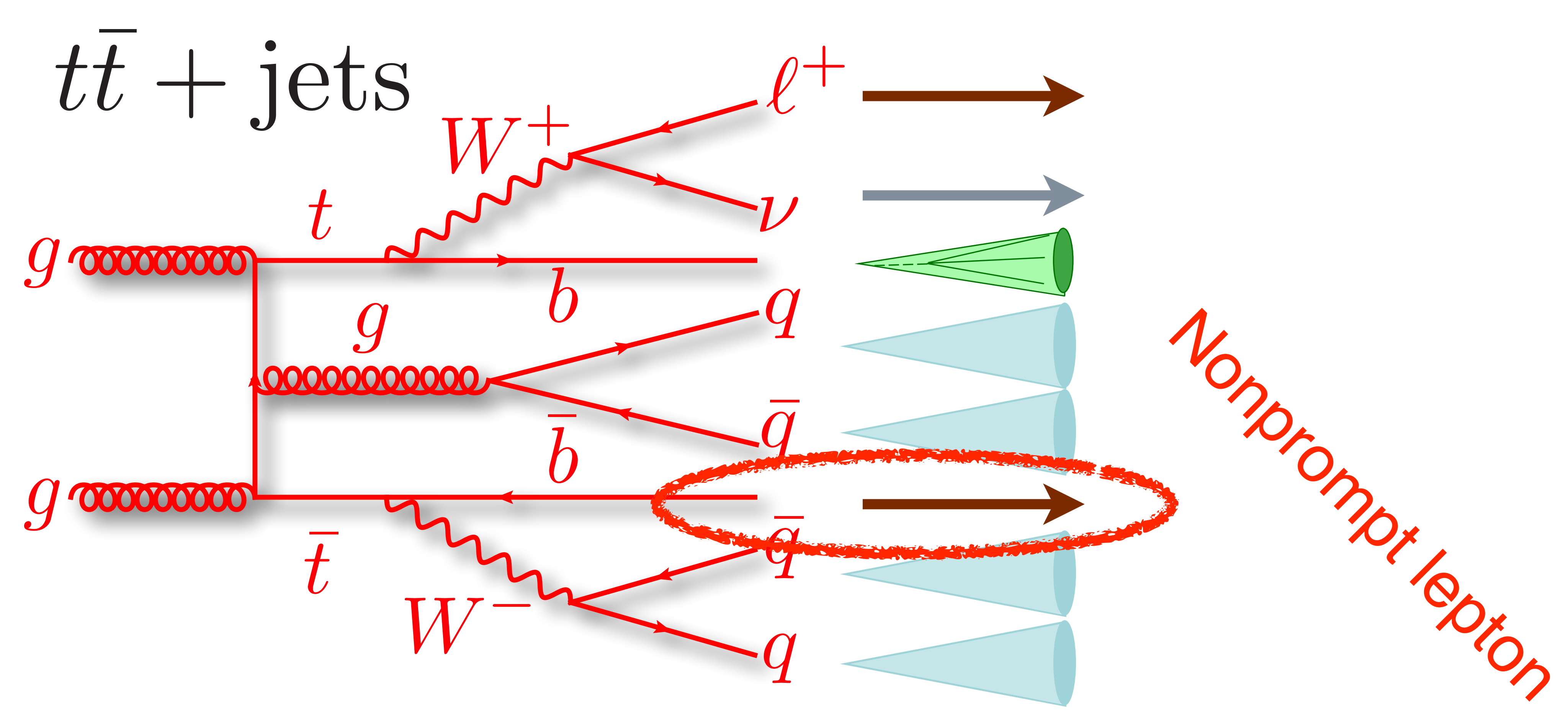
$p_{T,miss}$ > 30 GeV

Multilepton Event Categories



Lepton Requirements	p_T > 25 GeV p_T > 40 GeV for leading electron Require same-sign (SS)	p_T > 40, 20, 10 GeV $\lvert M(\ell\ell)-M(Z)\rvert < 10$ GeV	p_T > 40, 10, 10, 10 GeV $\lvert M(\ell\ell)-M(Z)\rvert < 20$ GeV Veto if 2nd Z found
Target	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}Z$

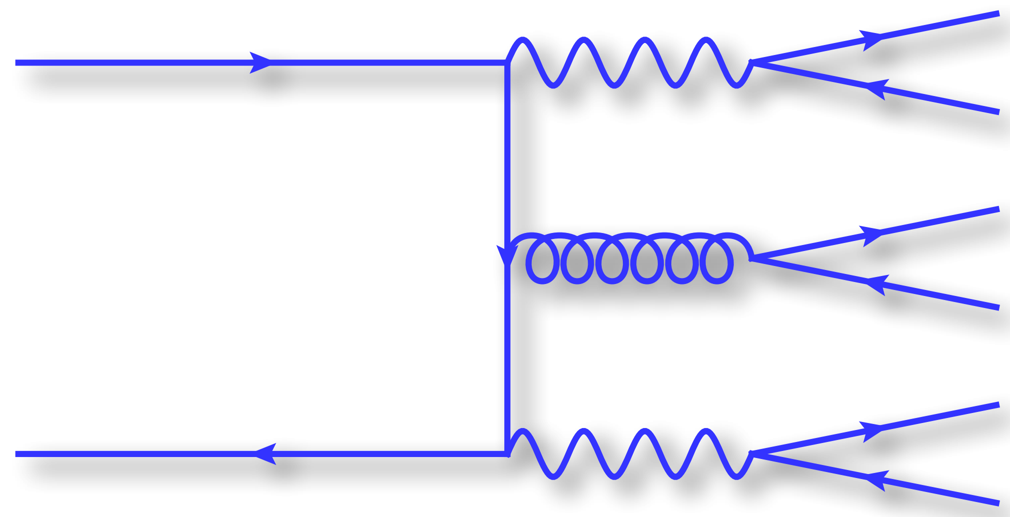
Backgrounds



- Nonprompt leptons from B decays, conversions, etc.
- Estimated using data via a fake rate method
- Background model obtained from leptons in isolation sideband

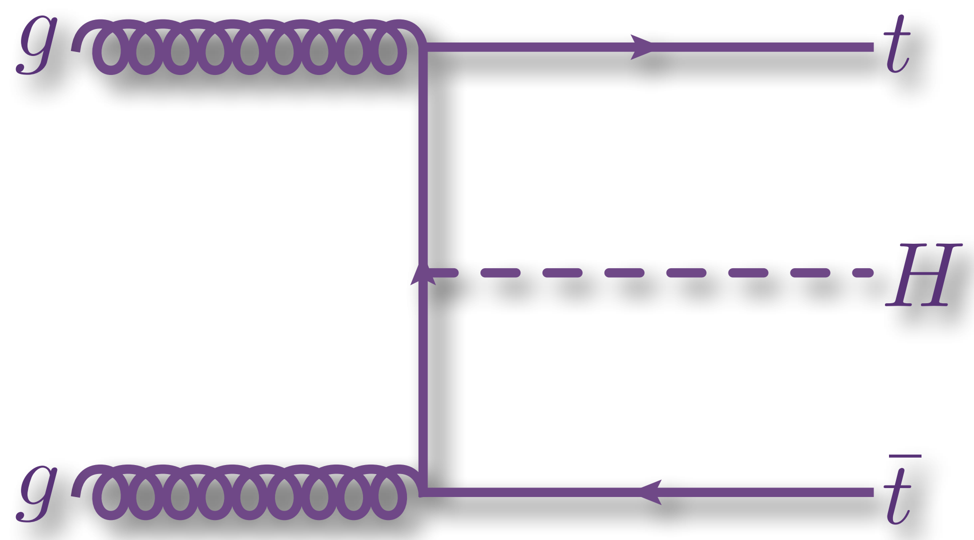
Diboson

- Prediction taken from MC
- Main contribution: WZ+jets, validated in control region



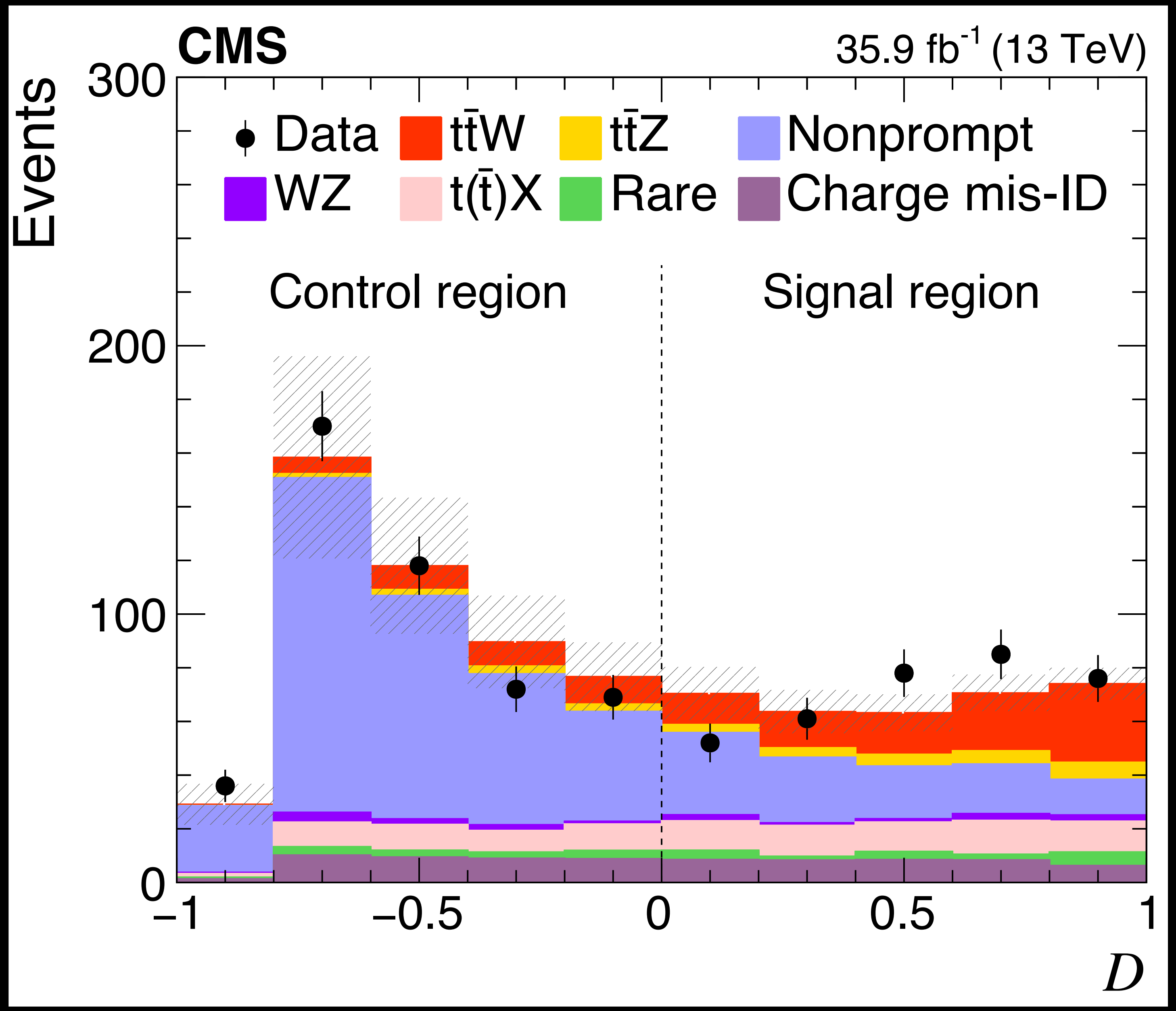
t(t)+X

- Challenging irreducible background, but generally small contribution
- Estimated by MC



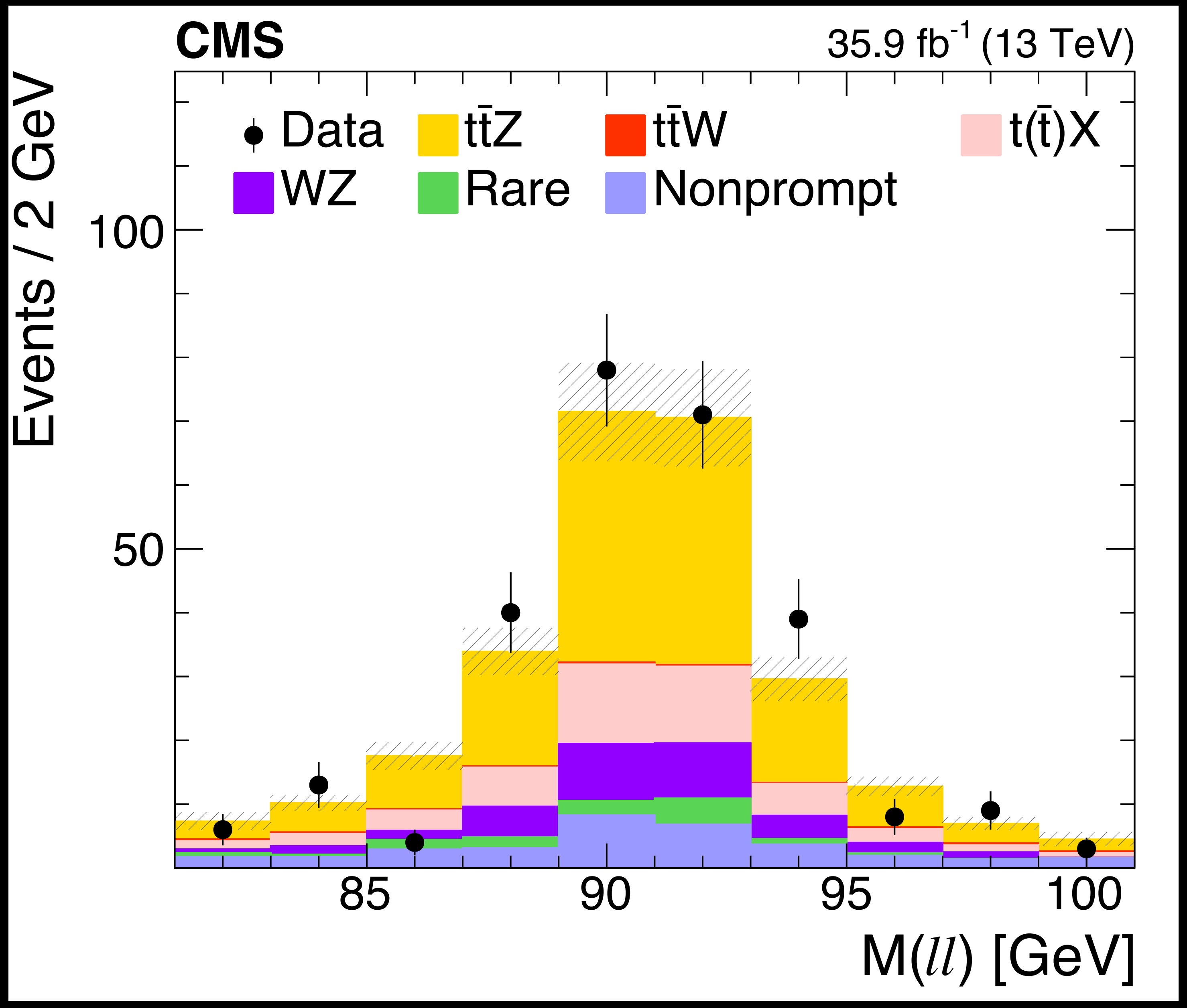
Signal Extraction

2ℓSS: Use BDT with kinematic variables to enhance signal sensitivity. Also divide by charge to take advantage of W charge asymmetry.

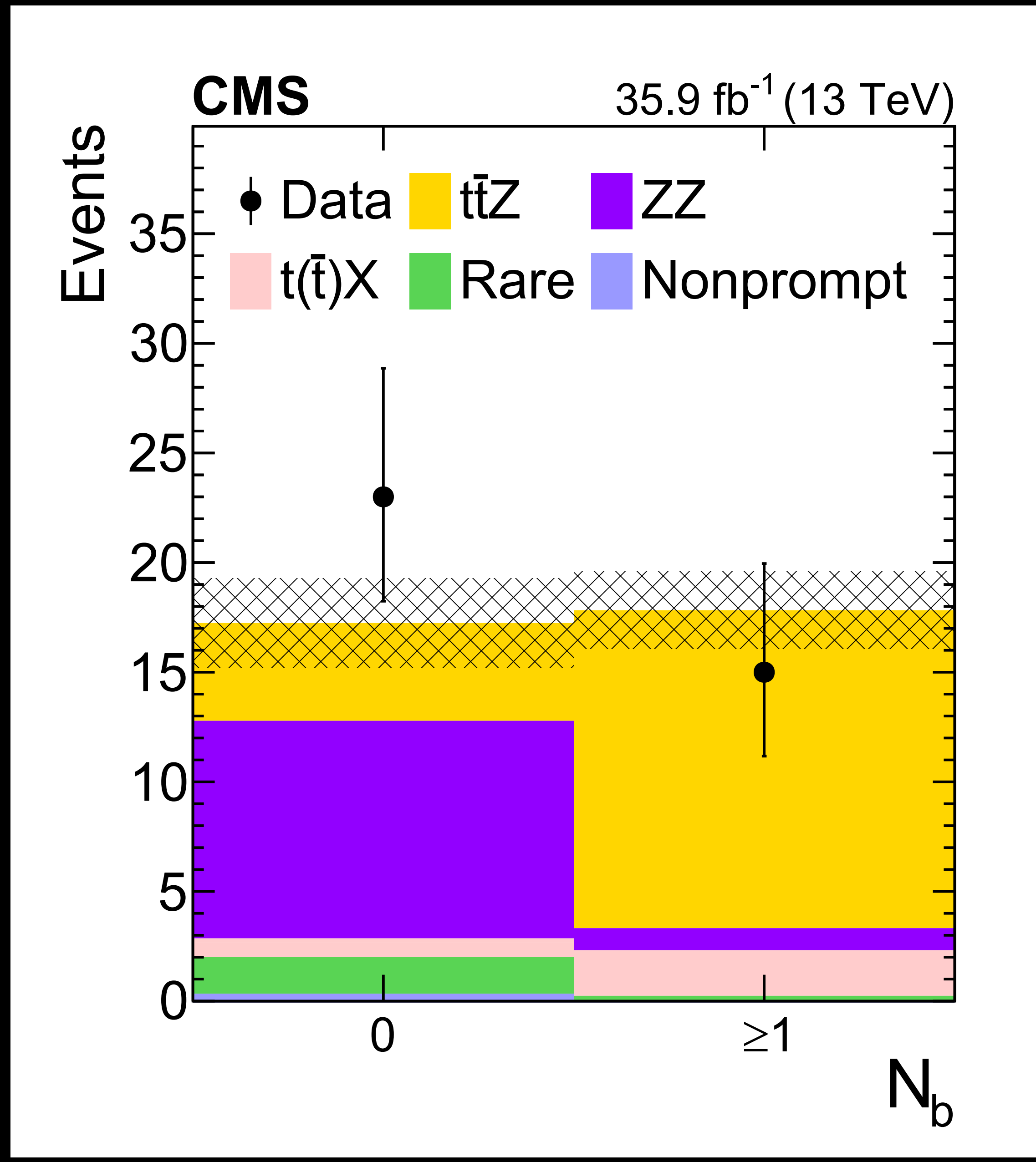


3ℓ and 4ℓ: Rely on Z mass window and presence of b quarks to reduce background

3ℓ

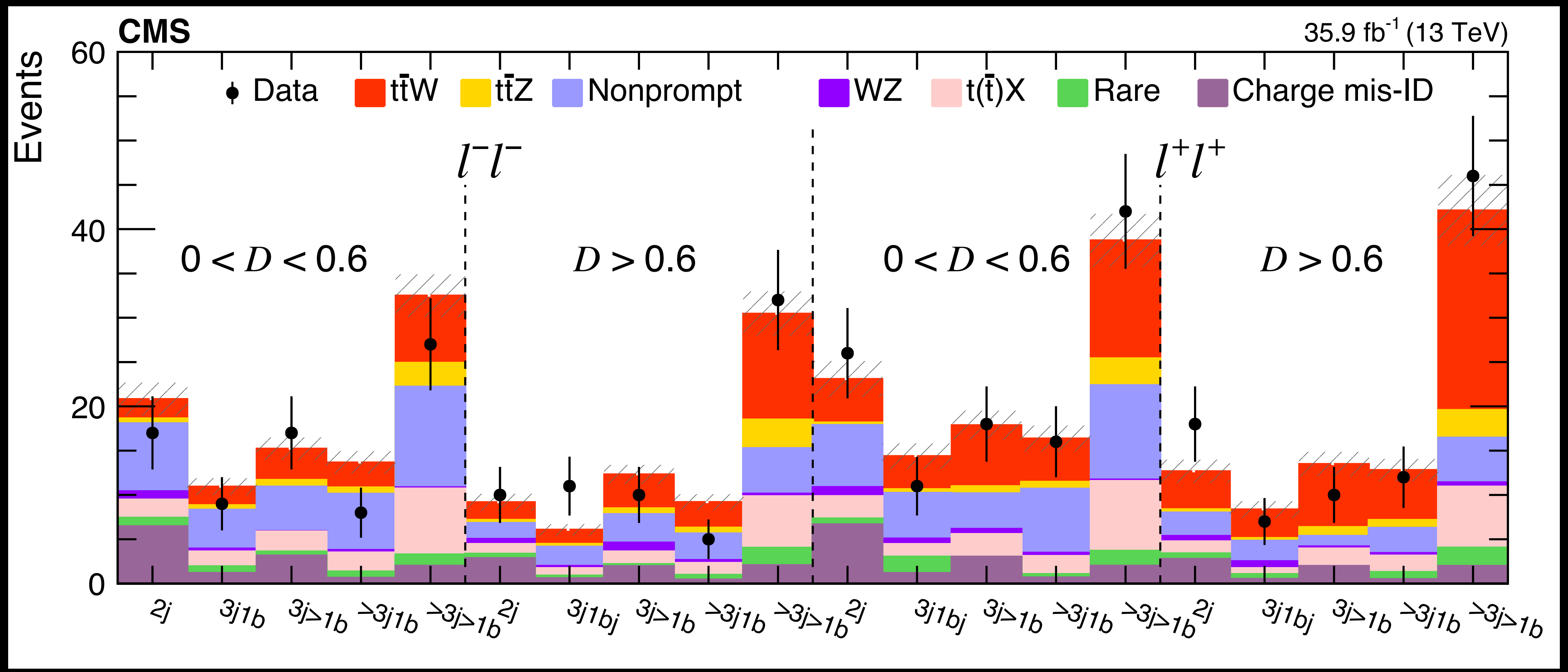


4ℓ



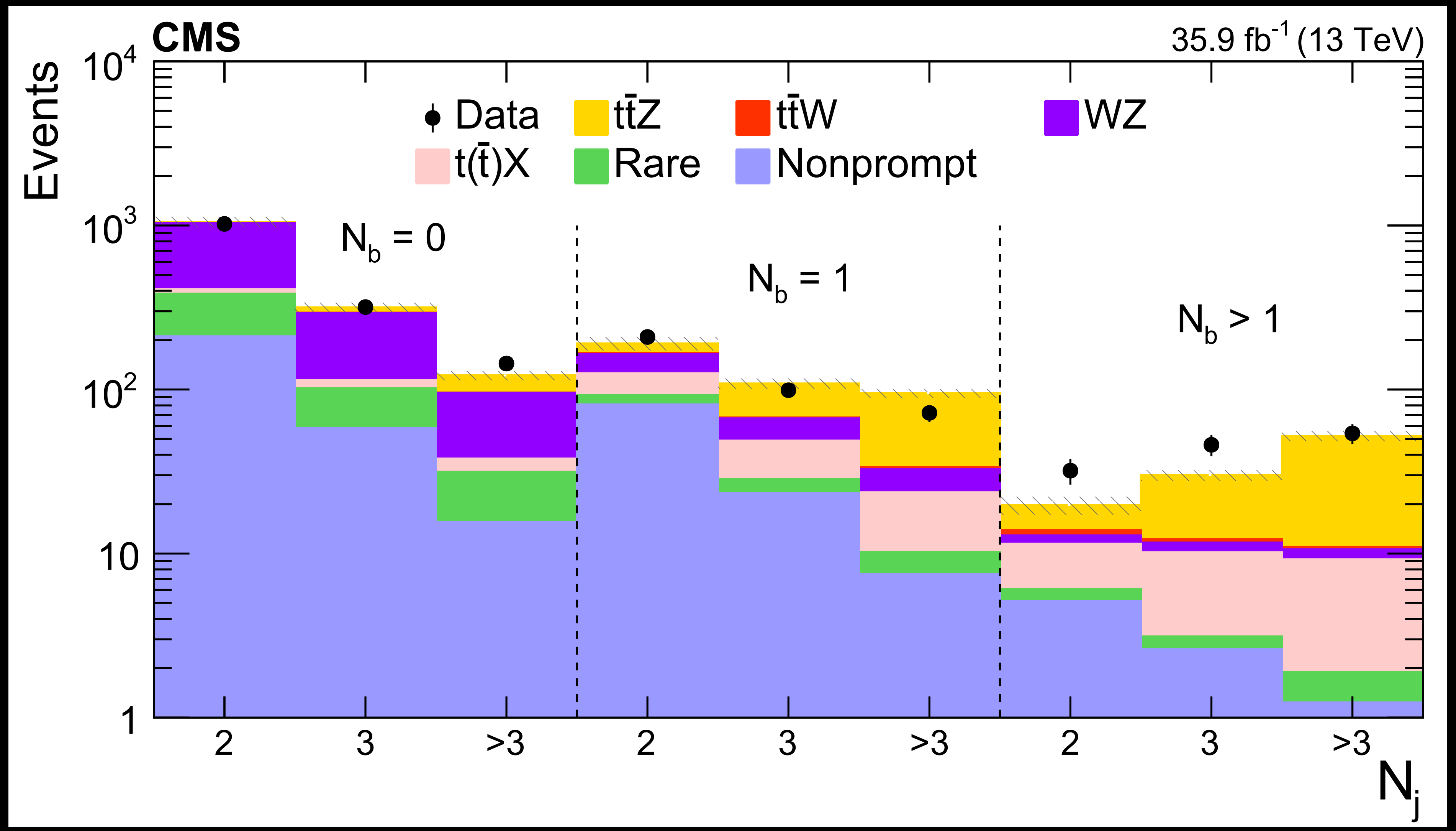
arXiv:1711.02547

Fitting Signal Regions

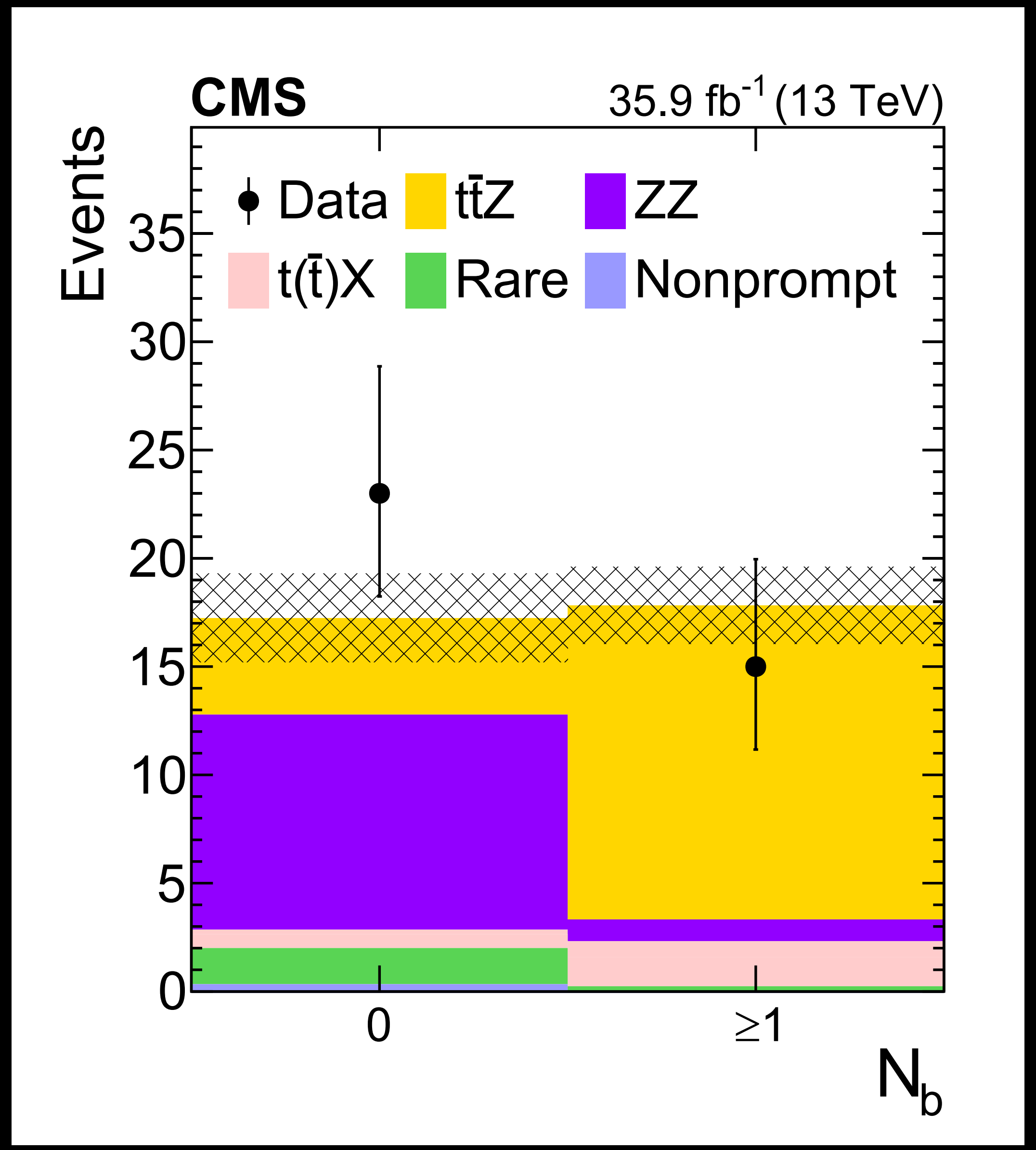


2ℓSS

- Fit regions for ttW and ttZ individually and also simultaneously.
- When fit individually, treat other process as background



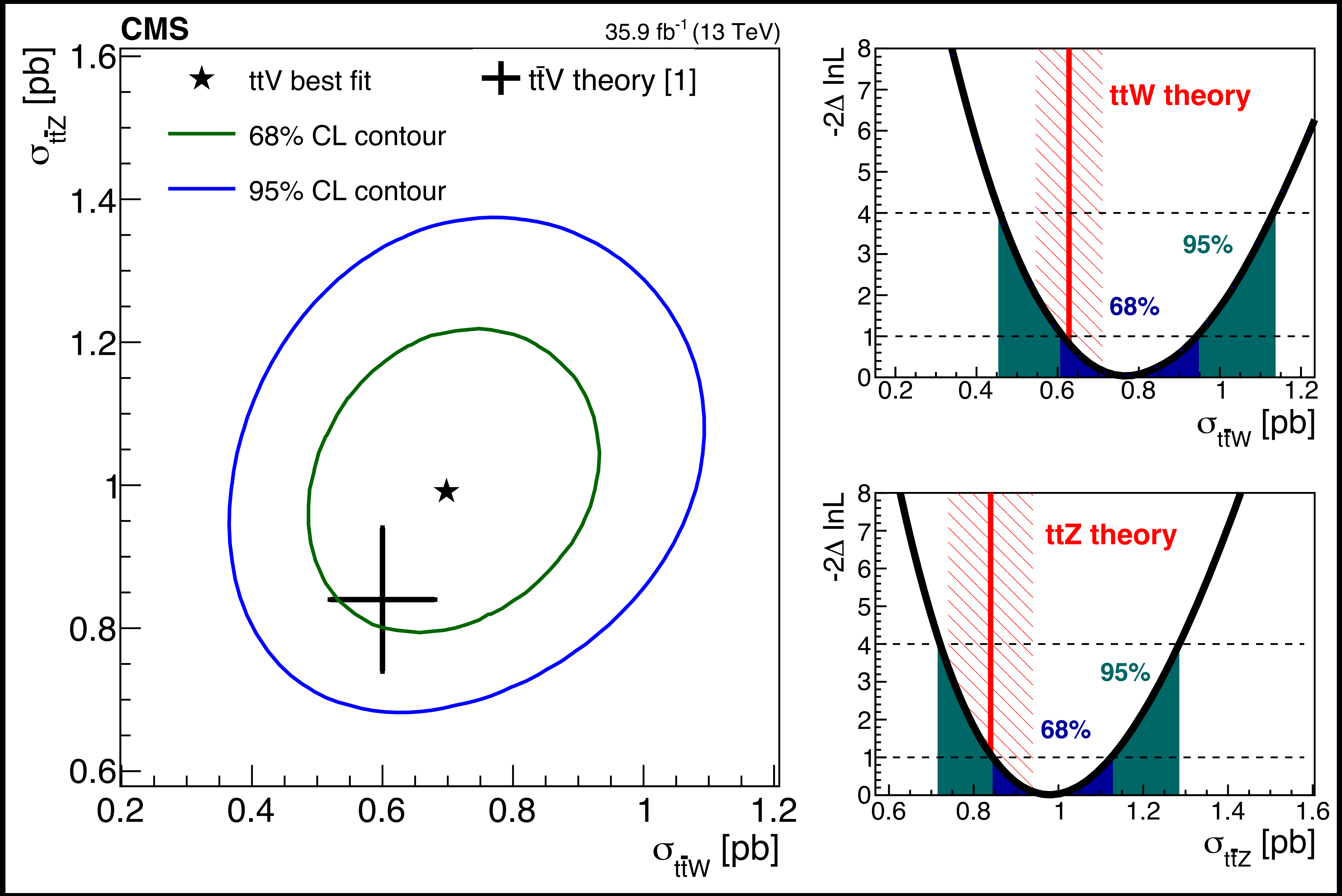
3ℓ



4ℓ

arXiv:1711.02547

Results



$$\sigma(pp \to t\bar{t}W) = 0.77^{+0.12}_{-0.11}(\mathrm{stat})^{+0.13}_{-0.12}(\mathrm{syst})\ \mathrm{pb}$$

$$\sigma(pp \to t\bar{t}W^+) = 0.58 \pm 0.09(\mathrm{stat})^{+0.09}_{-0.08}(\mathrm{syst})\ \mathrm{pb}$$

$$\sigma(pp \to t\bar{t}W^-) = 0.19 \pm 0.07(\mathrm{stat}) \pm 0.06(\mathrm{syst})\ \mathrm{pb}$$

$$\sigma(pp \to t\bar{t}Z) = 0.99^{+0.09}_{-0.08}(\mathrm{stat})^{+0.12}_{-0.10}(\mathrm{syst})\ \mathrm{pb}$$

arXiv:1711.02547

EFT Introduction

- Cross section measurements are great way to assess compatibility with SM
- What about interpreting in terms of new physics?
- One option: Effective Field Theory
  - Extend SM by adding higher dimensional operators representing new physics associated with particles too heavy to produce at LHC

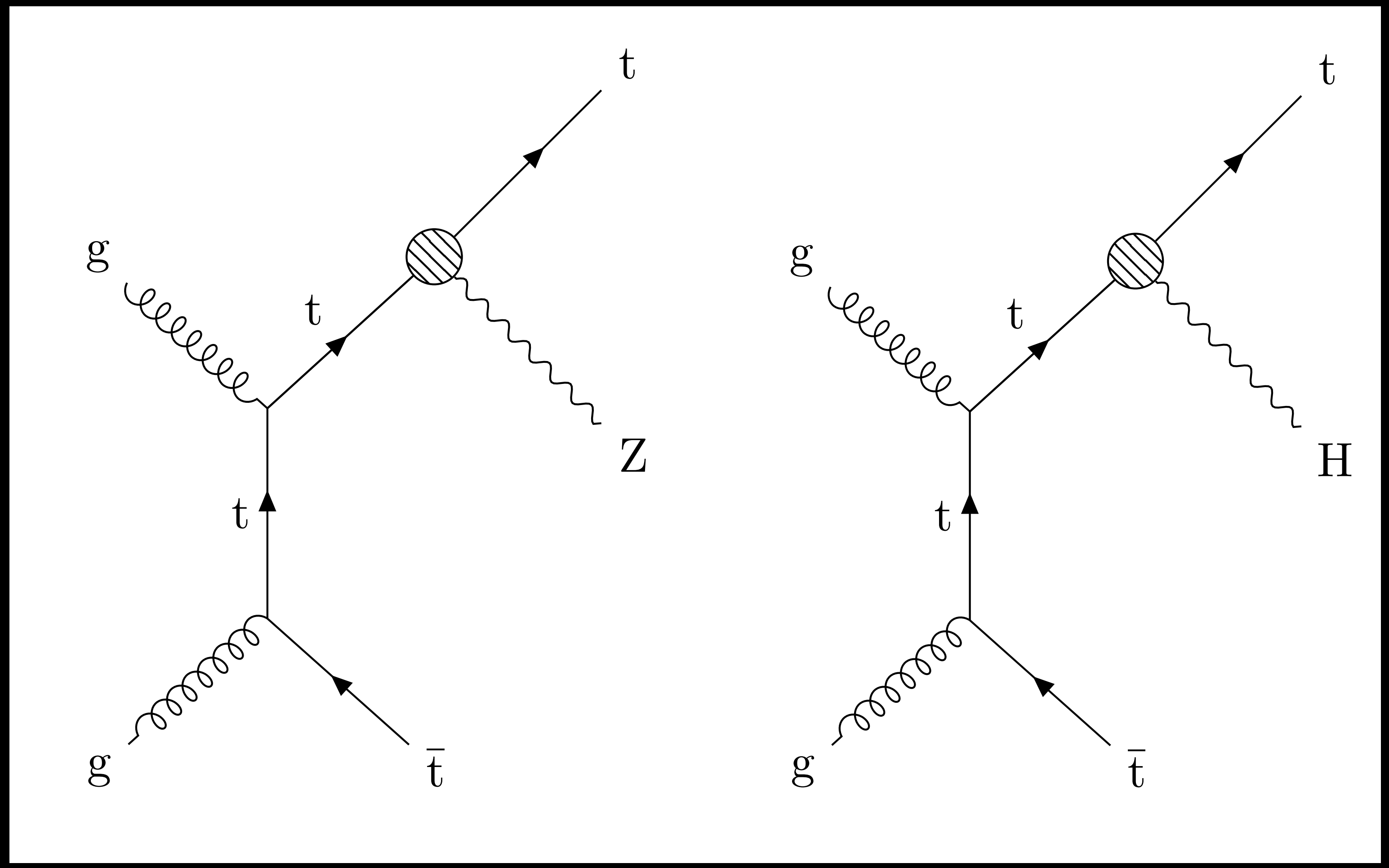
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda}\sum_i c_i \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_j c_j \mathcal{O}_j^{(6)} + \cdots$$

Dim-5 operators violates lepton number conservation

59 Dim-6 operators consistent with all symmetries and conservation laws
https://arxiv.org/abs/1008.4884

EFT for ttW/Z

- Focus on 39 operators that include at least one gauge or Higgs field
- Discard 15 operators that don't affect rates of ttW, ttZ, or ttH
    - Can't ignore ttH because similar event signature and many operators affect both ttH and ttZ
- Exclude from consideration 16 operators that affect other processes than ttW, ttZ, or ttH too much (e.g. would be constrained better in other measurements)
- 8 operators remaining that affect ttW, ttZ, or ttH but not significantly impacting other processes

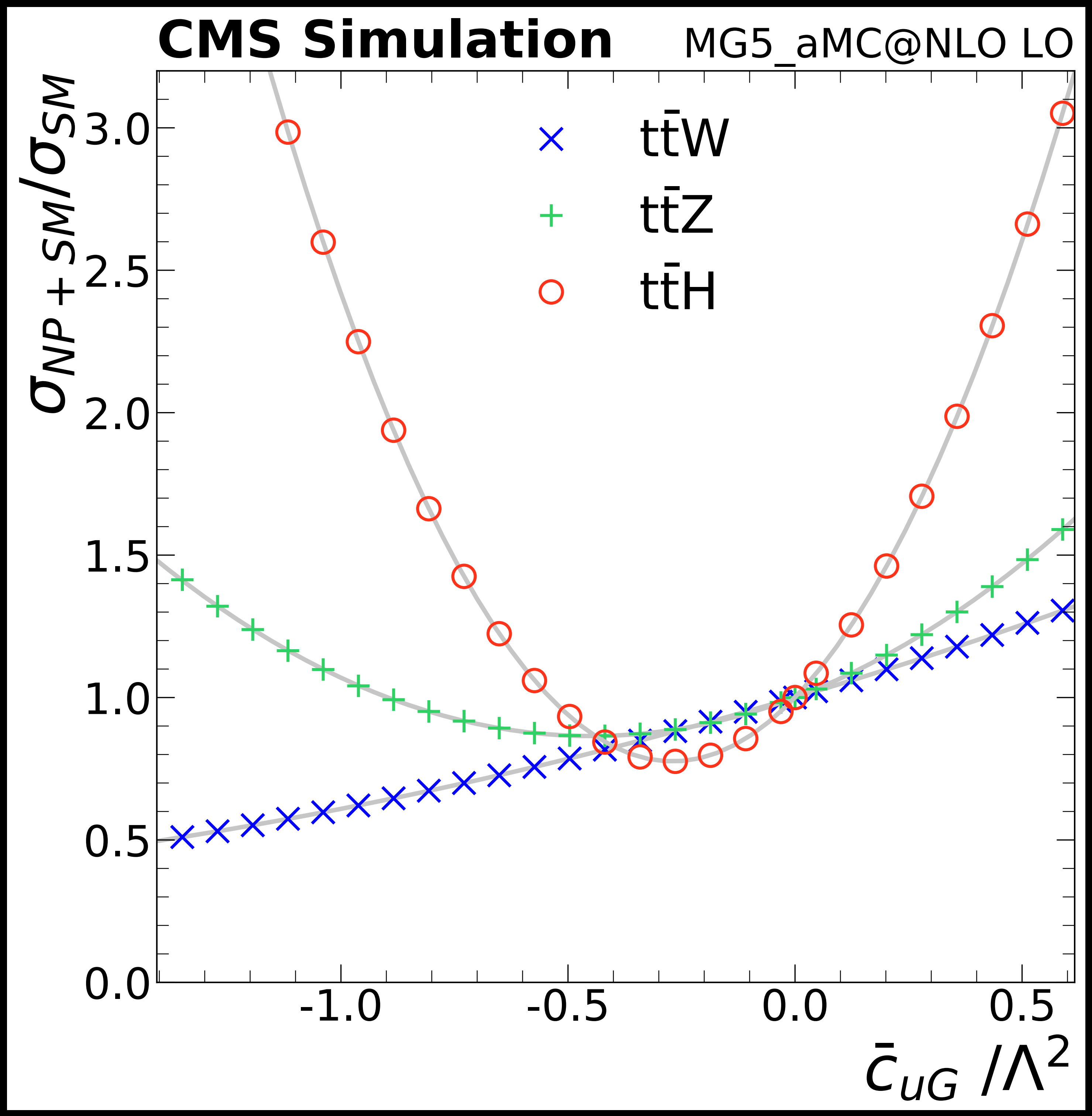


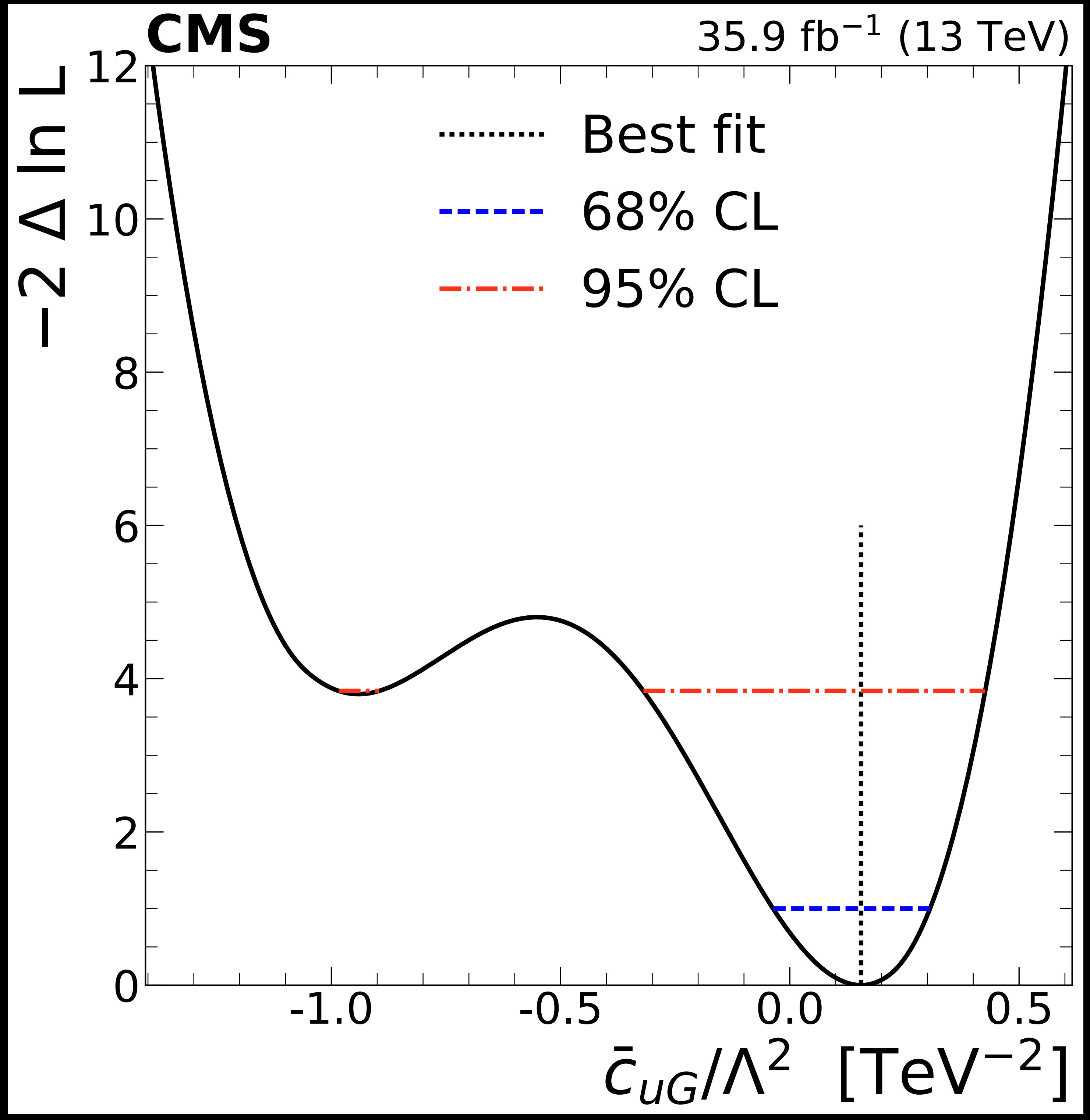
Characterize how each operator impacts ttW, ttZ, and/or ttH rates.

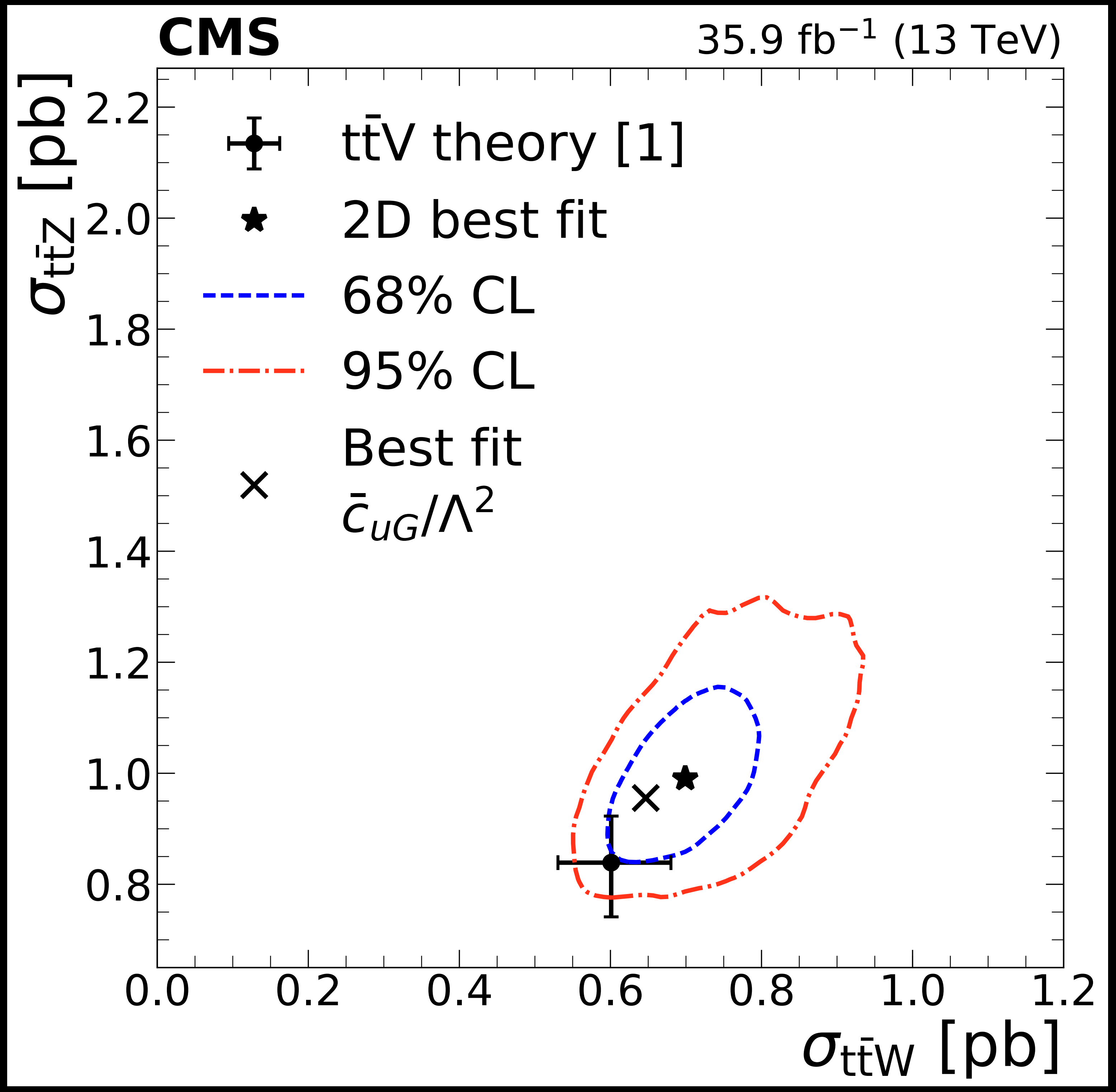
Use observed rates to constrain Wilson coefficient values

EFT Analysis Interpretation

- Example of one operator that affects all three processes







arXiv:1711.02547

EFT Results

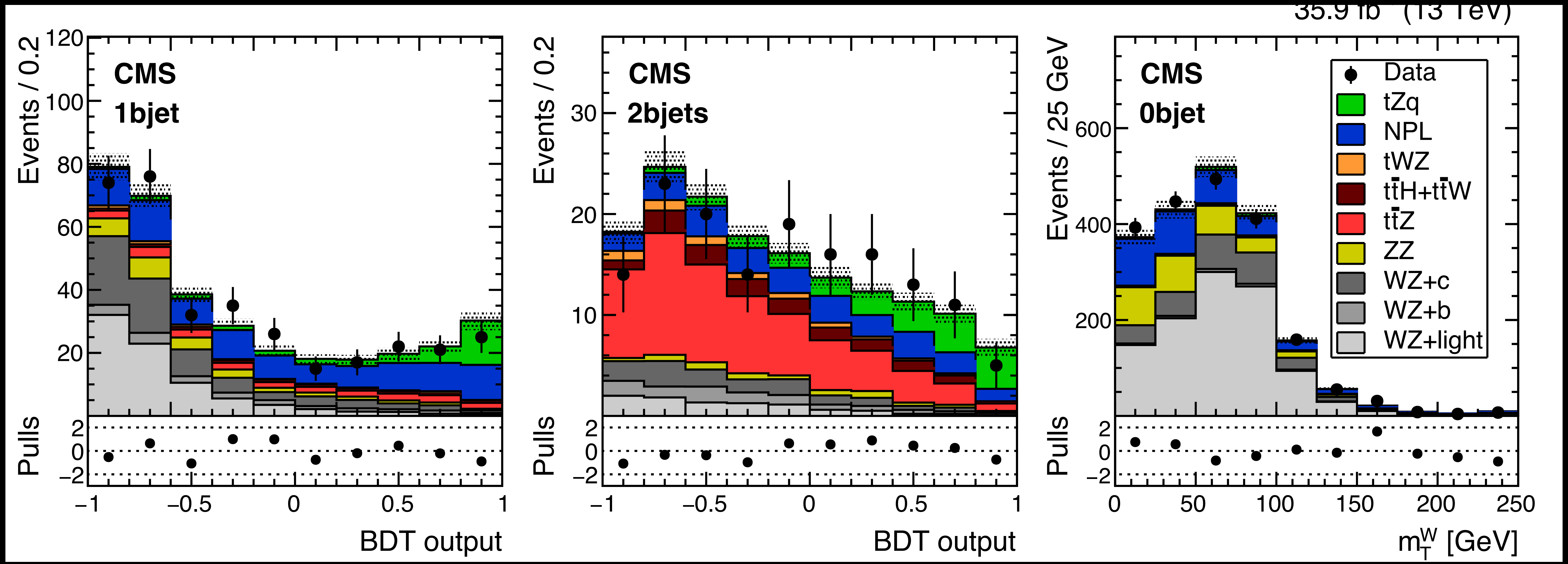
- At 95% CL, all operators consistent with SM (c_i = 0).

Wilson coefficient	Best fit $[\mathrm{TeV}^{-2}]$	68% CL $[\mathrm{TeV}^{-2}]$	95% CL $[\mathrm{TeV}^{-2}]$
$\bar{c}_{\mathrm{uW}}/\Lambda^2$	1.7	$[-2.4, -0.5]$ and $[0.4, 2.4]$	$[-2.9, 2.9]$
$\lvert\bar{c}_{\mathrm{H}}/\Lambda^2 - 16.8\ \mathrm{TeV}^{-2}\rvert$	15.6	$[0, 23.0]$	$[0, 28.5]$
$\lvert\widetilde{c}_{3\mathrm{G}}/\Lambda^2\rvert$	0.5	$[0, 0.7]$	$[0, 0.9]$
$\bar{c}_{3\mathrm{G}}/\Lambda^2$	-0.4	$[-0.6, 0.1]$ and $[0.4, 0.7]$	$[-0.7, 1.0]$
$\bar{c}_{\mathrm{uG}}/\Lambda^2$	0.2	$[0, 0.3]$	$[-1.0, -0.9]$ and $[-0.3, 0.4]$
$\lvert\bar{c}_{\mathrm{uB}}/\Lambda^2\rvert$	1.6	$[0, 2.2]$	$[0, 2.7]$
$\bar{c}_{\mathrm{Hu}}/\Lambda^2$	-9.3	$[-10.3, -8.0]$ and $[0, 2.1]$	$[-11.1, -6.5]$ and $[-1.6, 3.0]$
$\bar{c}_{2\mathrm{G}}/\Lambda^2$	0.4	$[-0.9, -0.3]$ and $[-0.1, 0.6]$	$[-1.1, 0.8]$

arXiv:1711.02547

Single tZq

- Event signature: 3 leptons, 2 jets (1 b-jet)
    - 2 b-jet provides ttZ control region
    - 0 b-jet provides WZ control region
- BDT with Matrix Element variables provides additional discrimination against backgrounds
- Provides another probe of t-Z coupling



Significance:
- Expected: 3.1
- Observed: 3.7

arXiv:1712.02825

SM Prediction:

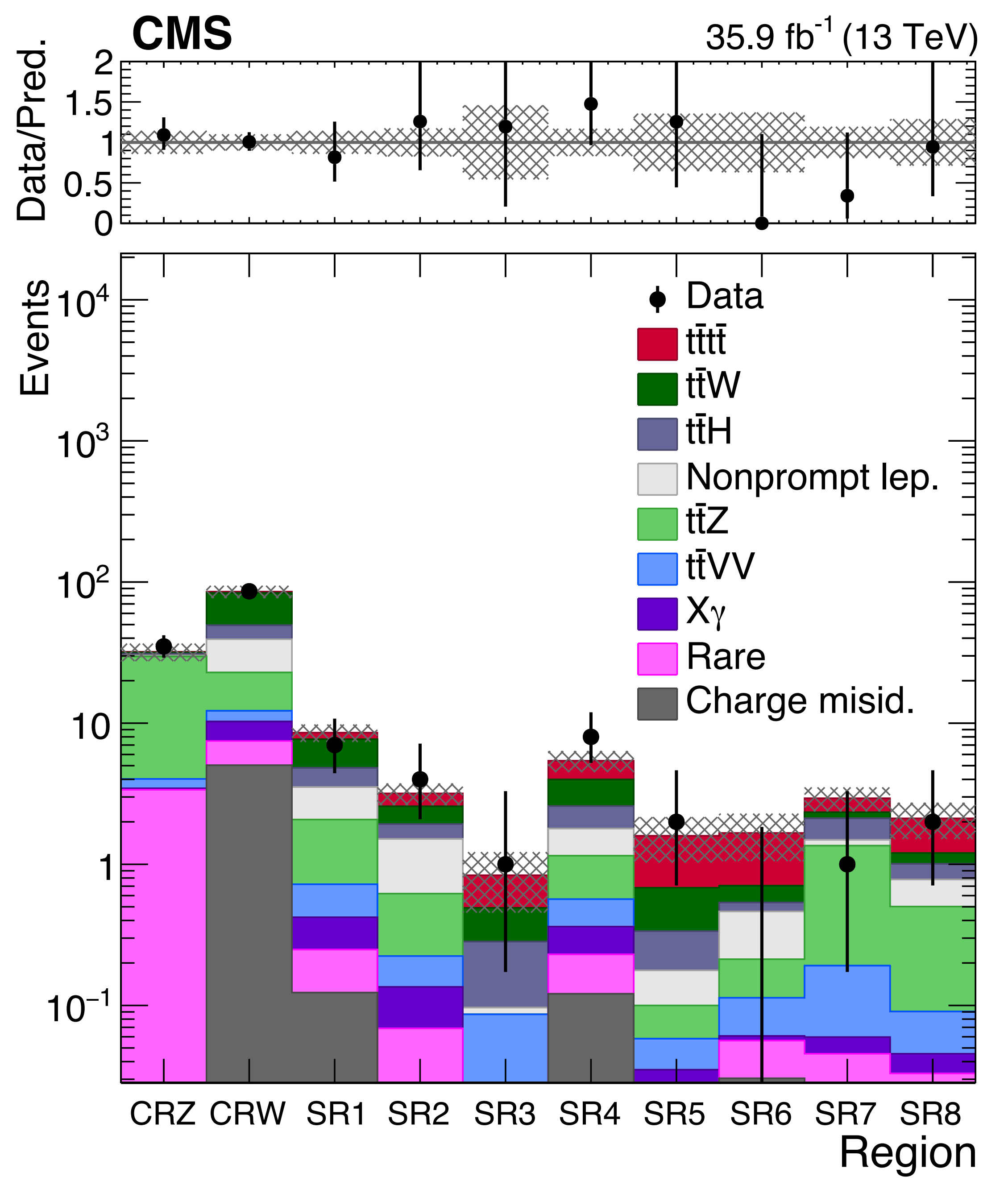
$$\sigma = 94.2 \pm 3.1 \text{ fb}$$

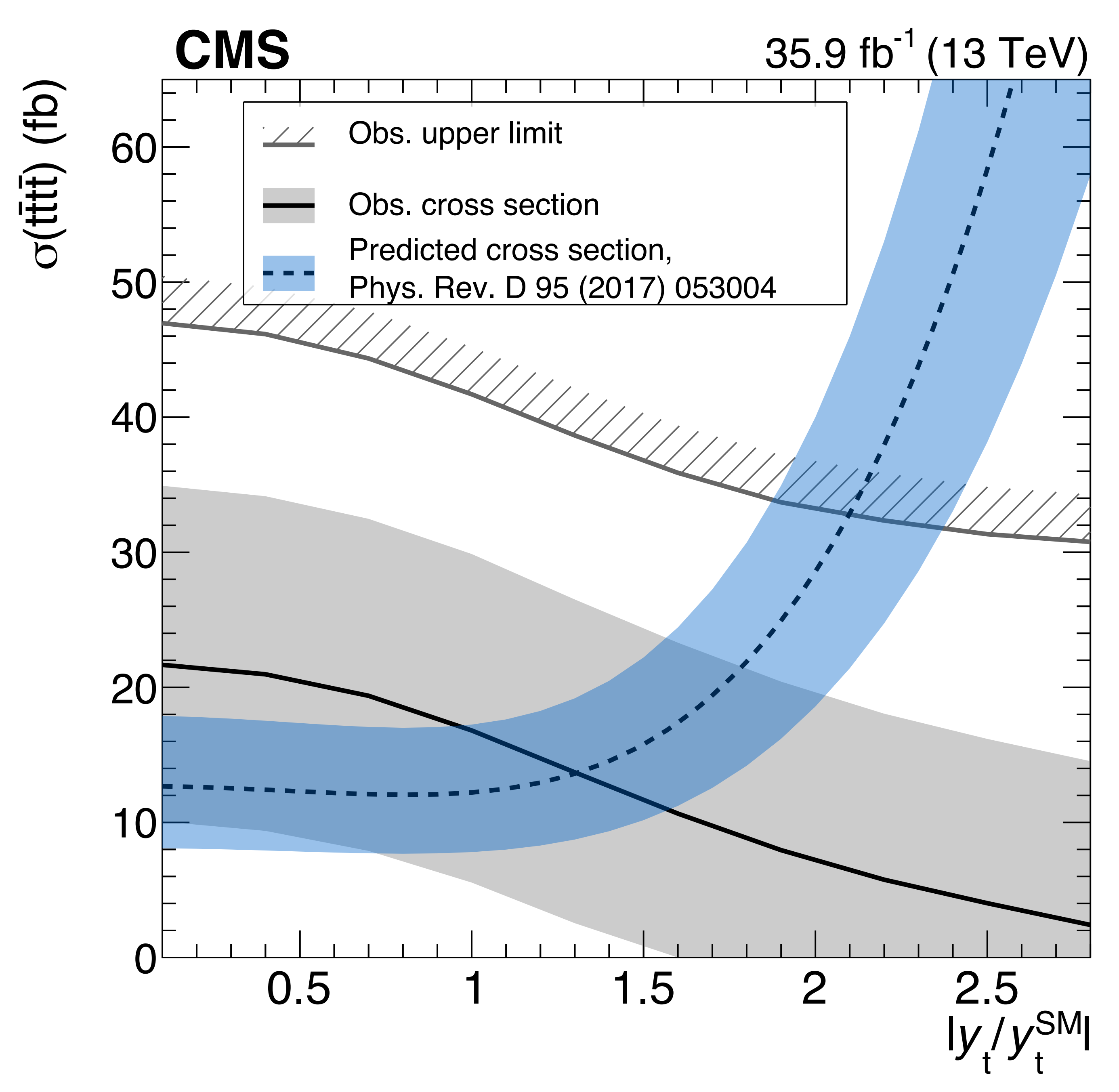
$$\sigma(t\ell^+\ell^- q) = 123^{+33}_{-31}(\text{stat})^{+29}_{-23}(\text{syst}) \text{ fb}$$

Four Top Production

- Experimental signature: ≥ 2ℓ (SS for 2ℓ), ≥ 4 jets (≥ 2 b-jets)
- Break into different signal regions (SR) based on number of leptons, jets, and b-jets plus two control regions (CR)

N_ℓ	N_b	N_{jets}	Region
2	2	≤5	CRW
		6	SR1
		7	SR2
		≥8	SR3
	3	5, 6	SR4
		≥7	SR5
	≥4	≥5	SR6
≥3	2	≥5	SR7
	≥3	≥4	SR8
Inverted Z veto			CRZ





Measured:

$$\sigma = 16.9^{+13.8}_{-11.4}\ \text{fb}$$

Predicted:

$$\sigma = 9.2^{+2.9}_{-2.4}\ \text{fb}$$

$$|y_t/y_t^{\text{SM}}| < 2.1$$

arXiv:1710.10614

Summary

- Top quark associated production provides an interesting laboratory to investigate the top sector for signs of new physics
  - ttW, ttZ, and ttγ (not shown) signals wells established
  - Evidence for ttH, tZq
  - Even very rare signals like tttt starting to yield results!
- Multilepton signature is useful for probing many of these processes.
- Increasing LHC integrated luminosity will allow exploration of differential distributions
- EFT provides interesting framework for characterizing possible new physics contributions to top quark associated production
- Only a small fraction of CMS Top results included. Visit the Top group results page for more results.