



HAL
open science

Review of single top quark physics

J. Andrea, N. Chanon

► **To cite this version:**

J. Andrea, N. Chanon. Review of single top quark physics. Top LHC France 2023, May 2023, Strasbourg, France. in2p3-04930770

HAL Id: in2p3-04930770

<https://in2p3.hal.science/in2p3-04930770v1>

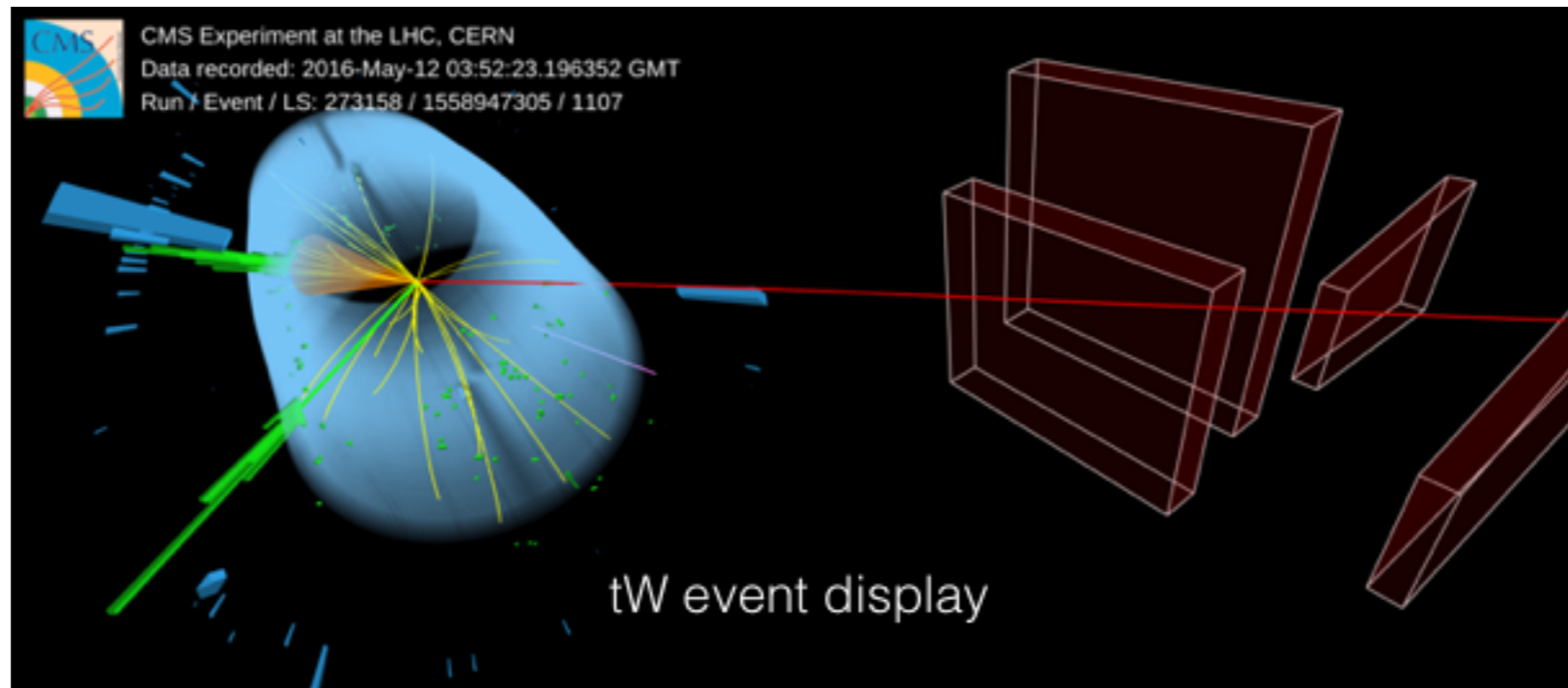
Submitted on 5 Feb 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Review of single top quark physics

Top LHC France 2023 - 16/05/2023



Jeremy Andrea – IPHC Strasbourg, CNRS/IN2P3

Nicolas Chanon – IP2I Lyon, CNRS/IN2P3

Introduction

- **Disclaimer:** this talk cannot cover all the topics
- In particular, it will not cover results obtained at Tevatron
- Focus on the LHC results

Outline:

- **Single top quark cross sections:** t-channel, tW, s-channel
- **Properties** related to Wtb vertex
- **Top quark production associated with Z/ γ bosons**
- **Top quark Yukawa coupling with tH process**

Processes considered in this seminar

Single top quark production

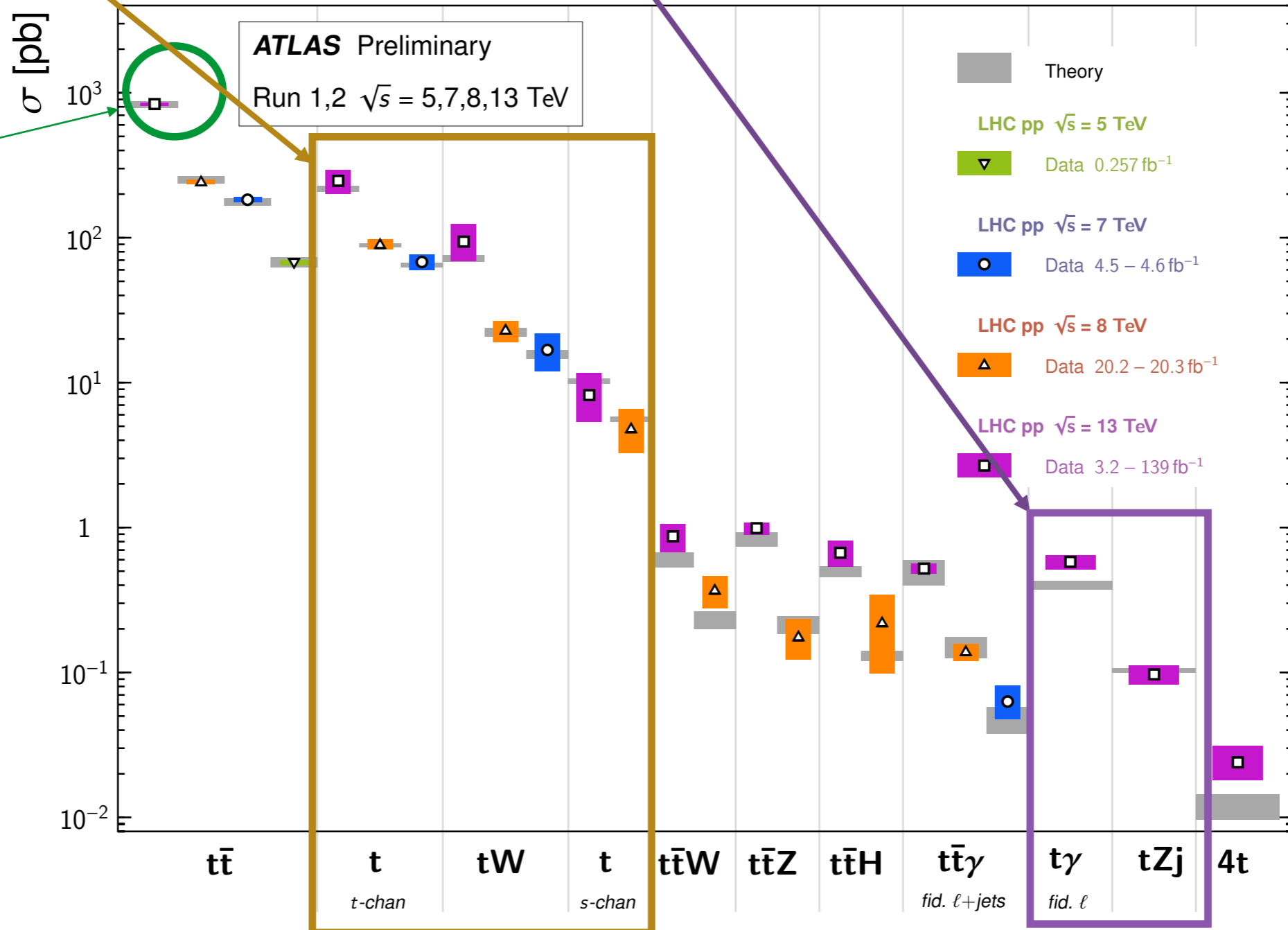
Processes involving **single top + gauge bosons**

Consider “rare” top quark production

Top Quark Production Cross Section Measurements

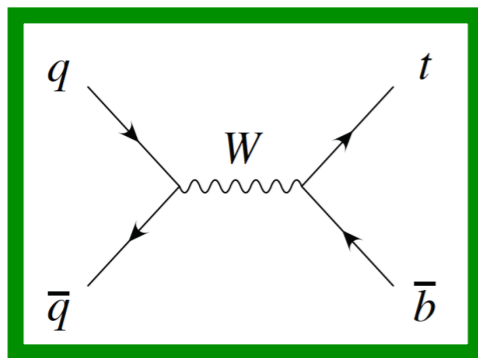
Status: November 2022

$t\bar{t}$ at 13 TeV:
~820 pb

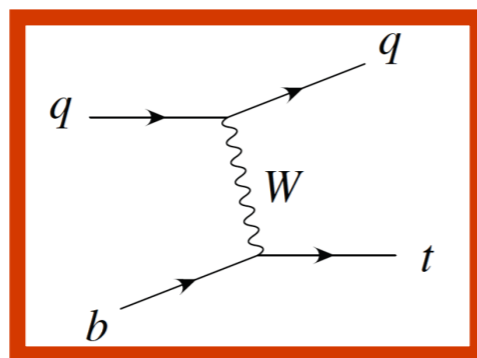


+tHj

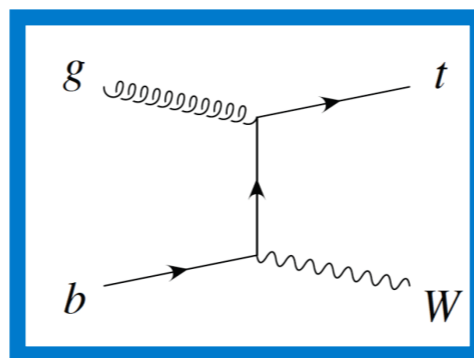
Single top quark cross sections



s-channel

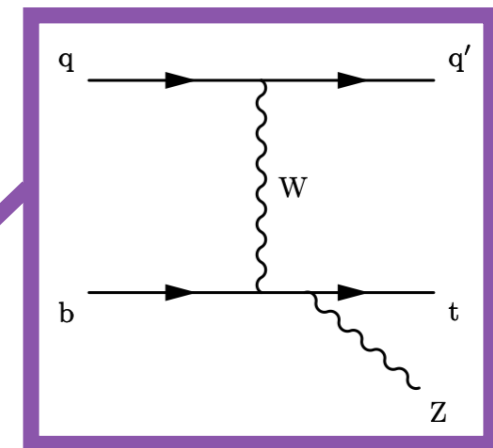
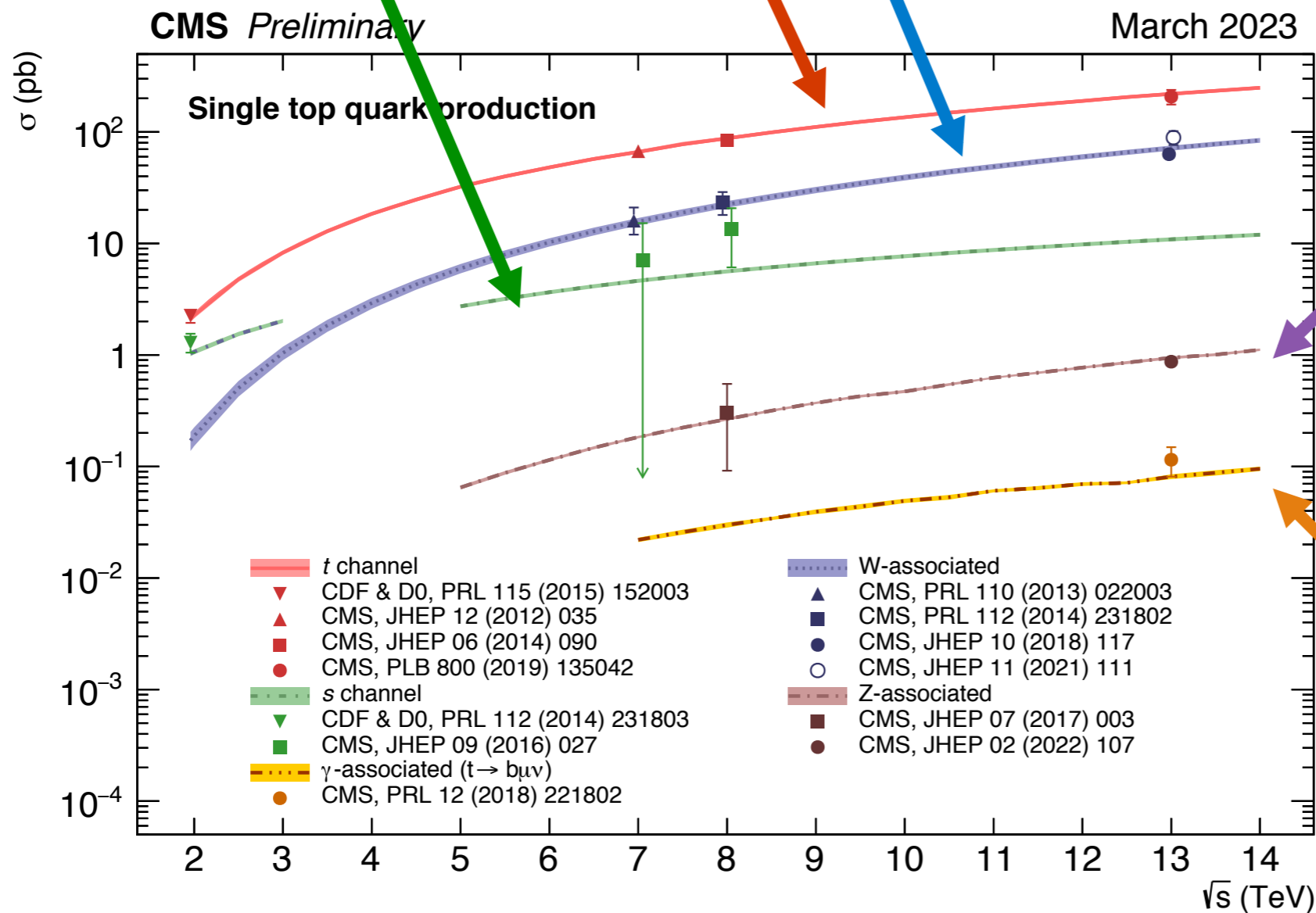


t-channel

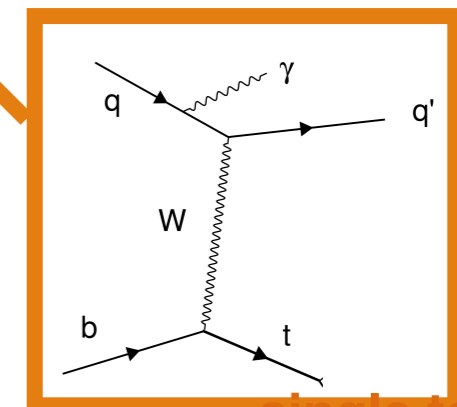


tW-channel

	13 TeV	Top	Antitop
t-channel		136 pb	81 pb
tW		36 pb	36 pb
s-channel		6 pb	4 pb



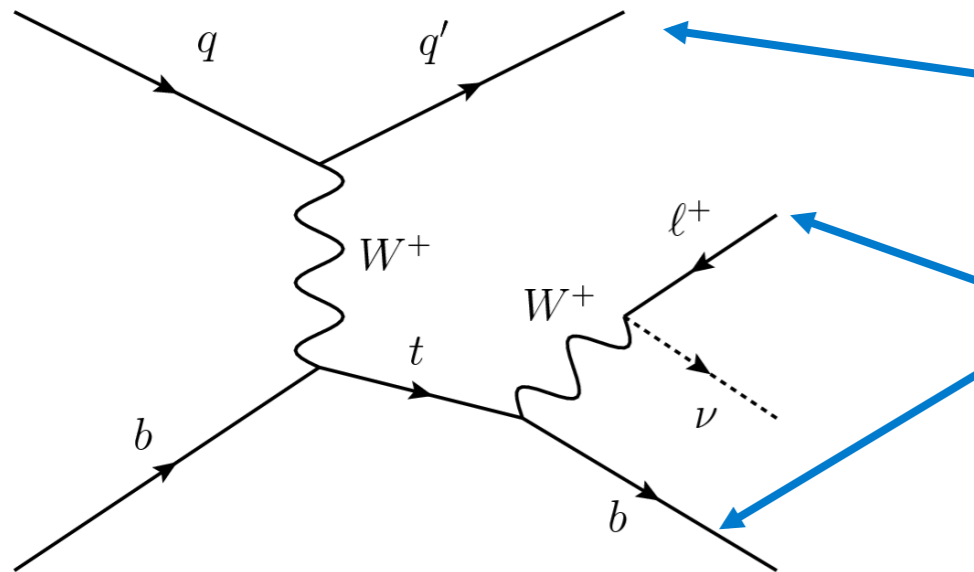
single top +Z



single top +photon

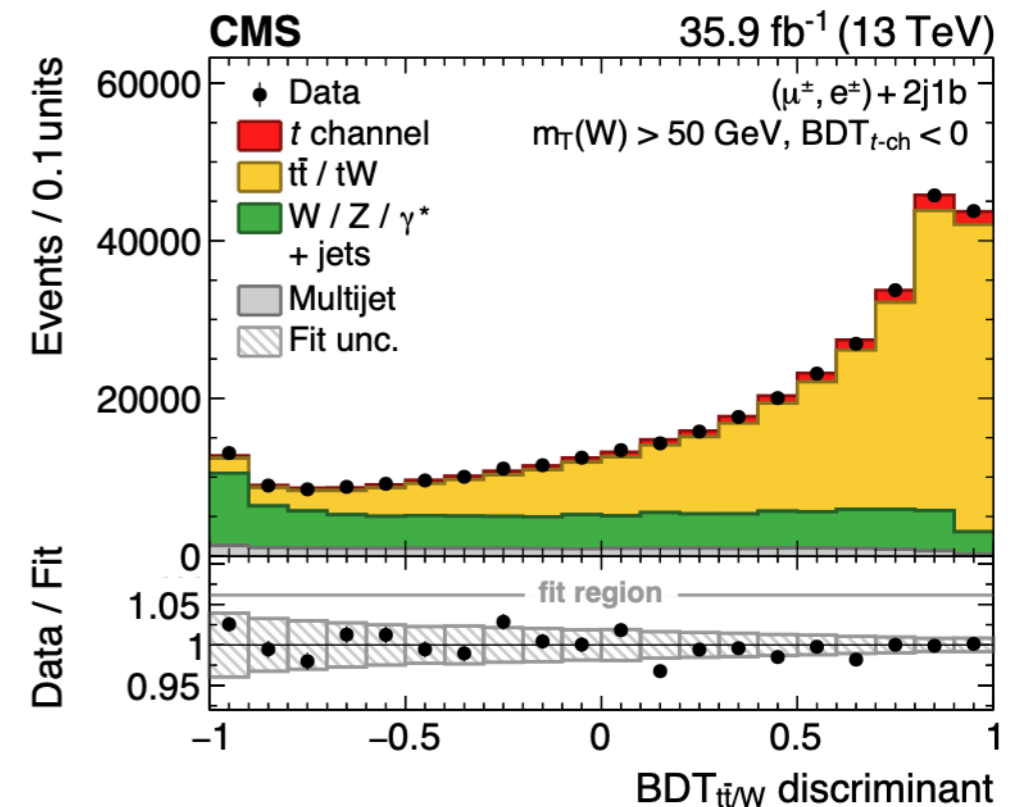
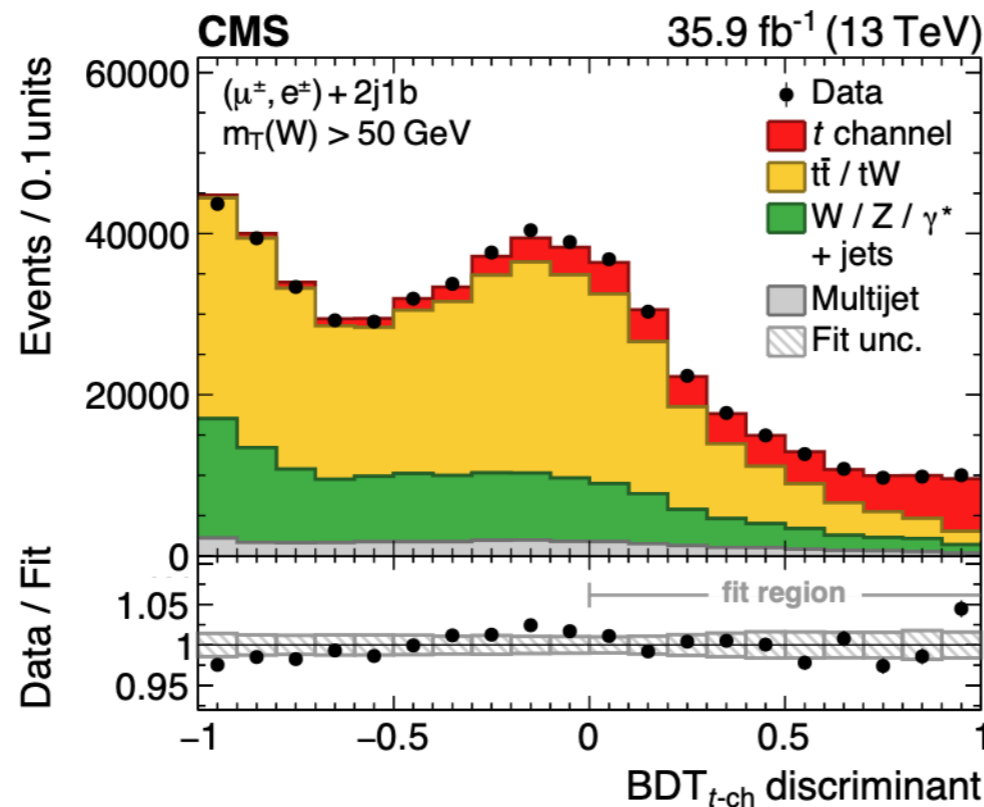
t-channel differential cross section

[CMS - Eur. Phys. J. C 80 \(2020\) 370](#)



- Jet $p_T > 40$ GeV in $|\eta| < 4.7$: **t-channel** is an **electroweak** production: features a **forward jet**
- 1 Muon (electron) $p_T > 26$ (35) GeV.
- One b-jet in $|\eta| < 2.4$ (tracker acceptance)
- **Define 3 categories**: signal region (2j1b), W+jet control region (2j0b) and ttbar control region (3j2b)
- QCD jet background estimated from data (revert lepton isolation)

**Discriminant:
boosted decision
trees (BDT)**



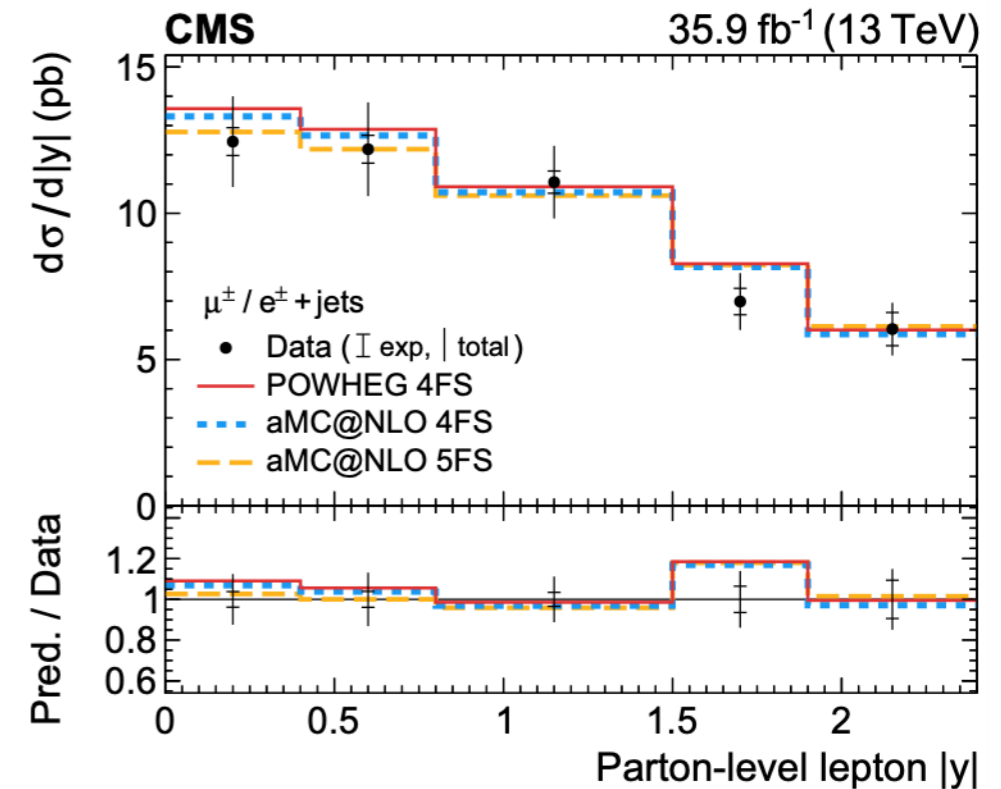
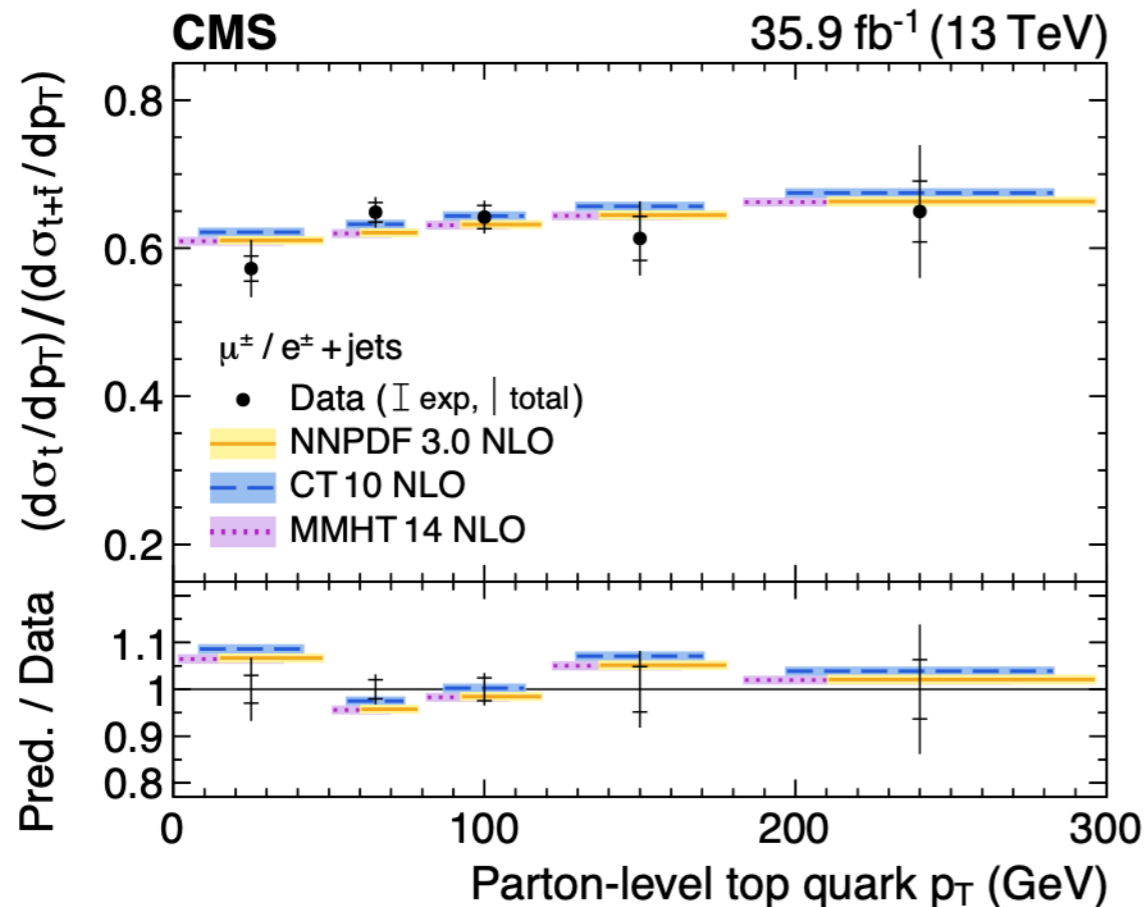
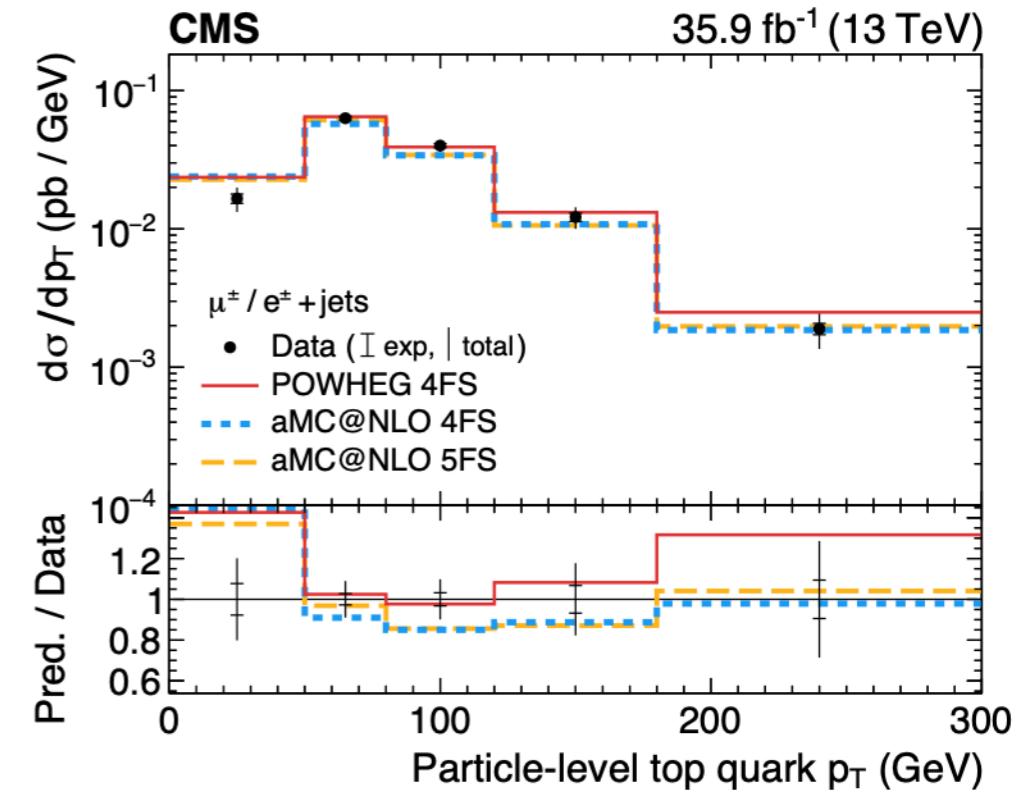
t-channel differential cross section

[CMS - Eur. Phys. J. C 80 \(2020\) 370](#)

Differential cross sections:

- Unfolding detector effects to parton-level (and particle level)
- **Reasonable agreement with NLO theory predictions**, within the uncertainties

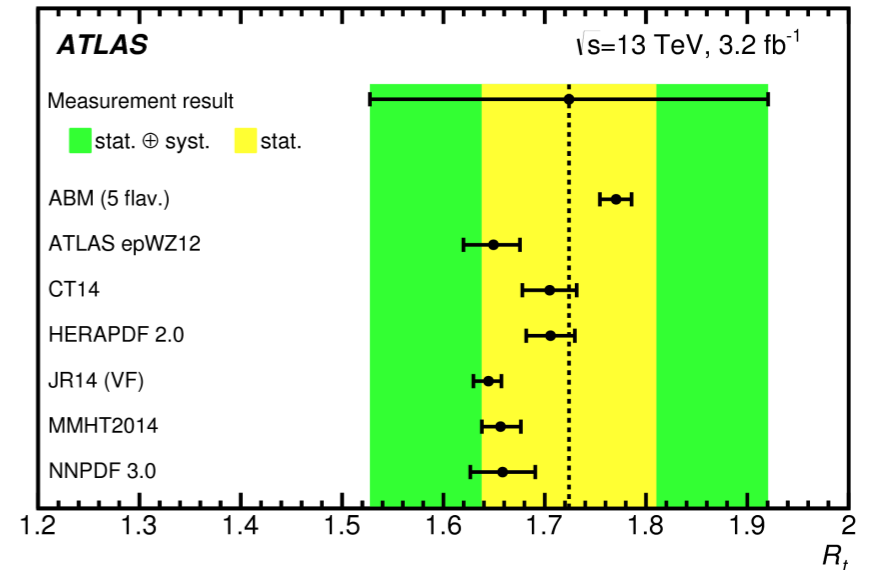
The **charge ratio** is sensitive to the parton content in the proton: >0.6 and increases with top p_T



t-channel differential cross section 8 TeV

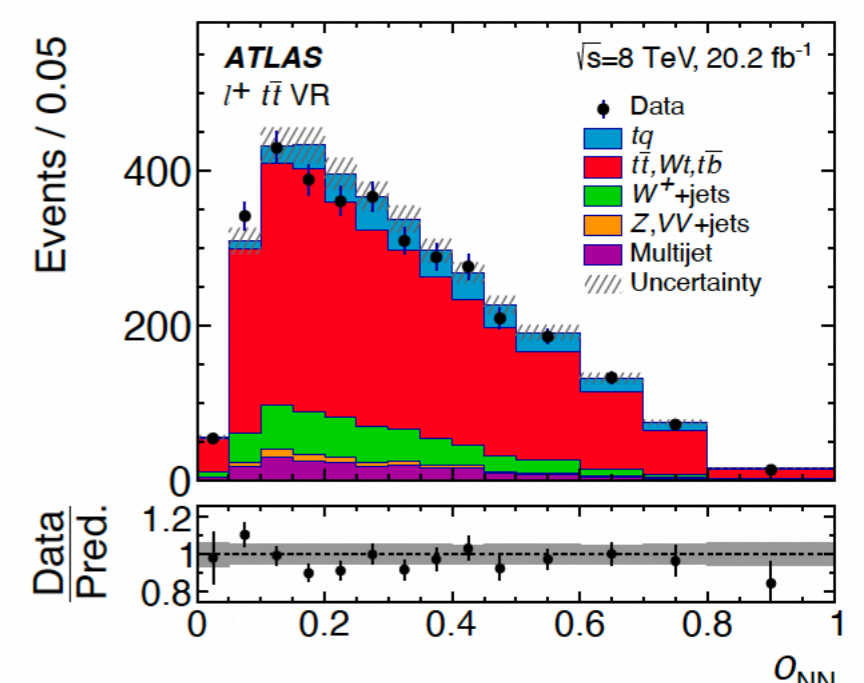
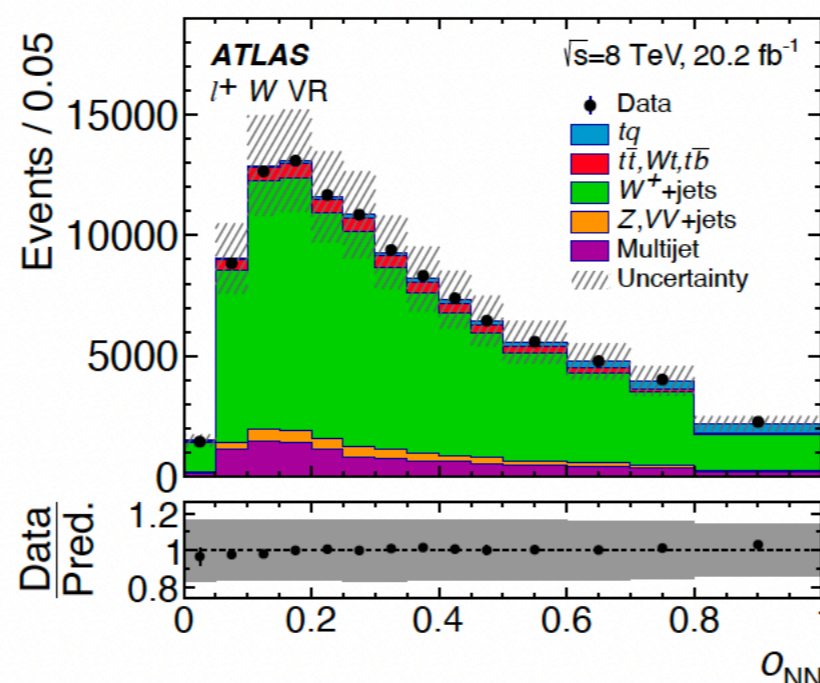
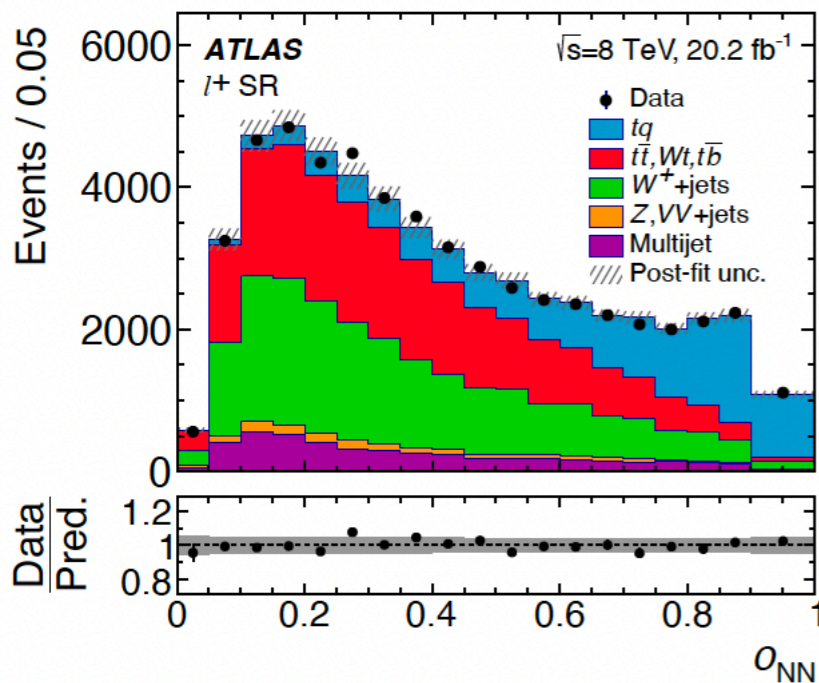
[ATLAS - JHEP 04 \(2017\) 086, Eur. Phys. J. C 77 \(2017\) 531](#)

ATLAS 13TeV: inclusive cross section



ATLAS 8 TeV, similar selection as CMS :

- looser pT selection for leptons (25 GeV) and jets (30 GeV)
- Similar SR definition (2j0b), W+jets VR (loose b-tagging) and ttbar VR (2j2b).
- VR are used to validate the background modeling, but are not part of the fit.
- QCD multijet => fit of missing ET distribution.
- Signal discrimination from Neural-Net.

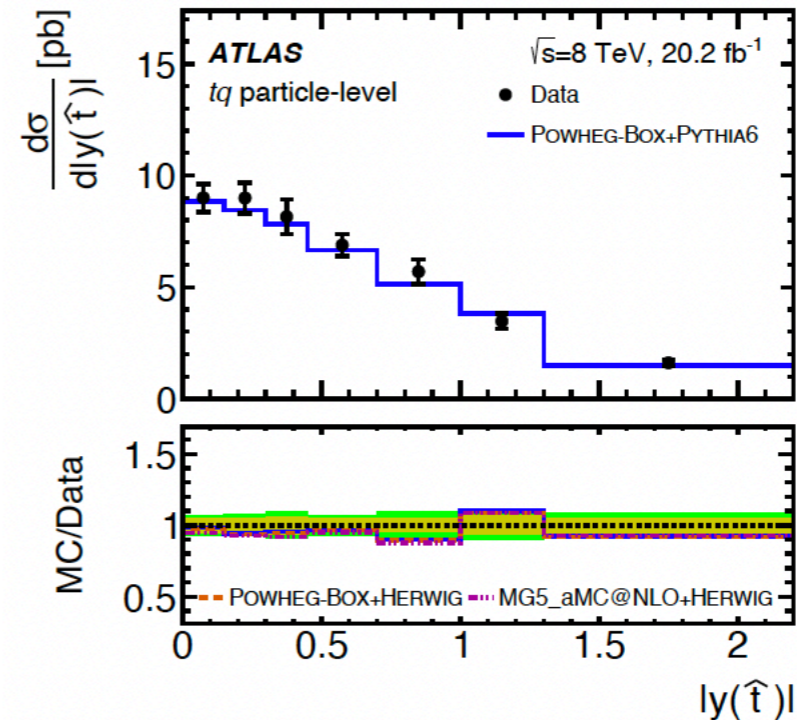
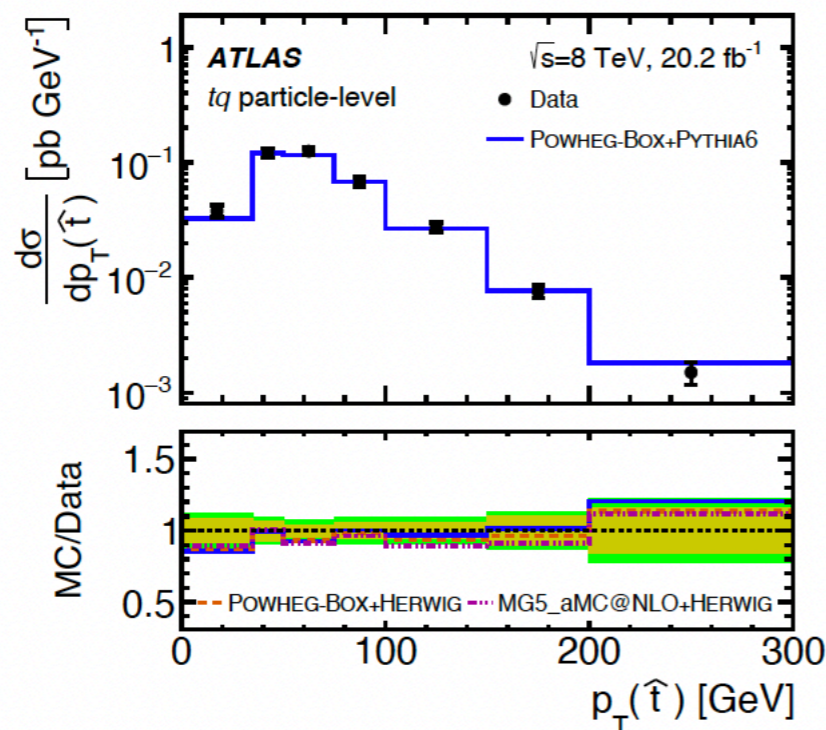
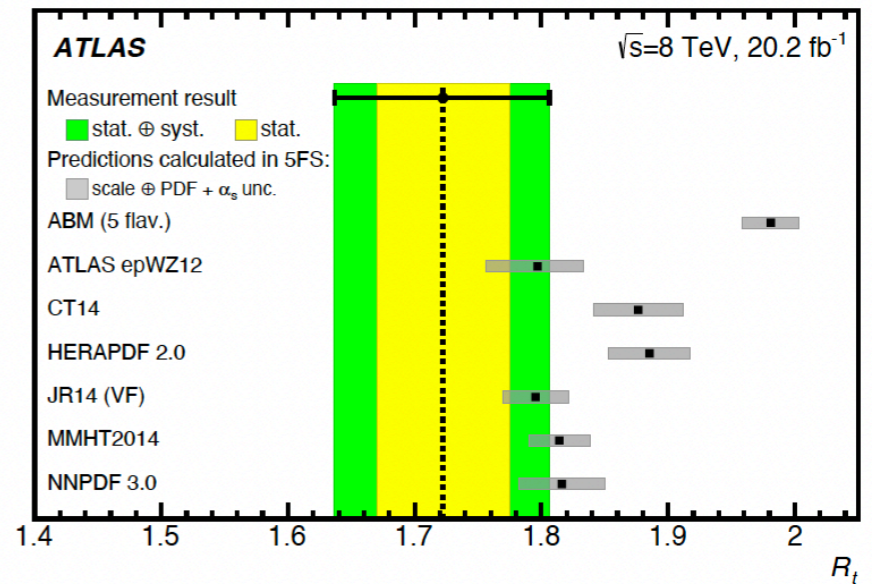
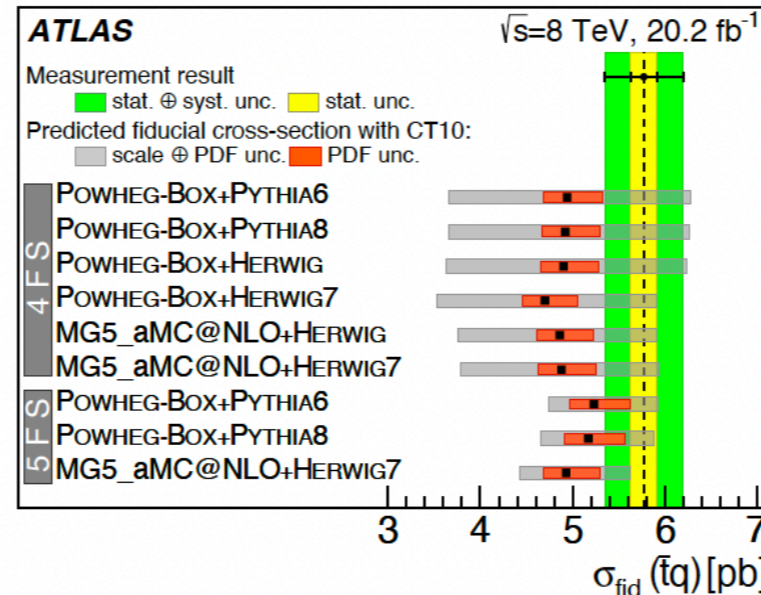
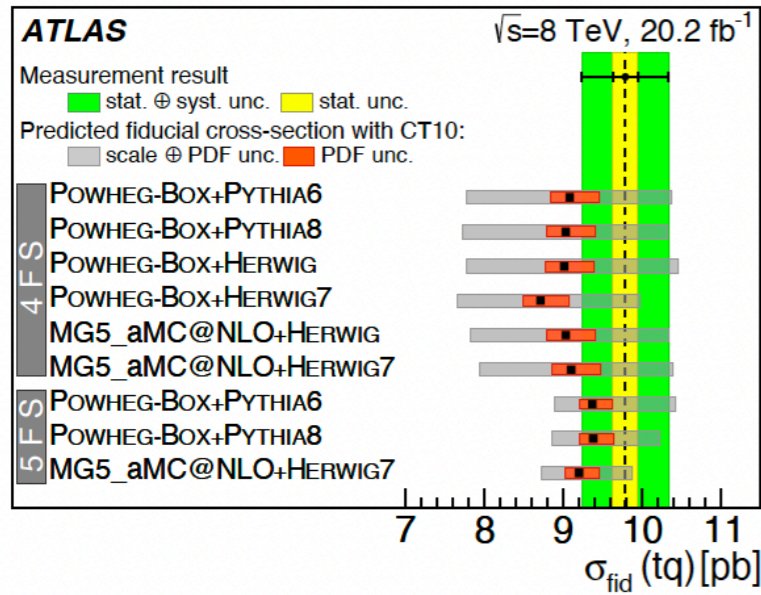


t-channel differential cross section

[ATLAS - Eur. Phys. J. C 77 \(2017\) 531](#)

Fiducial and **differential** cross sections for **top** and **antitop**

Ratio of top to antitop:
Tensions with data?

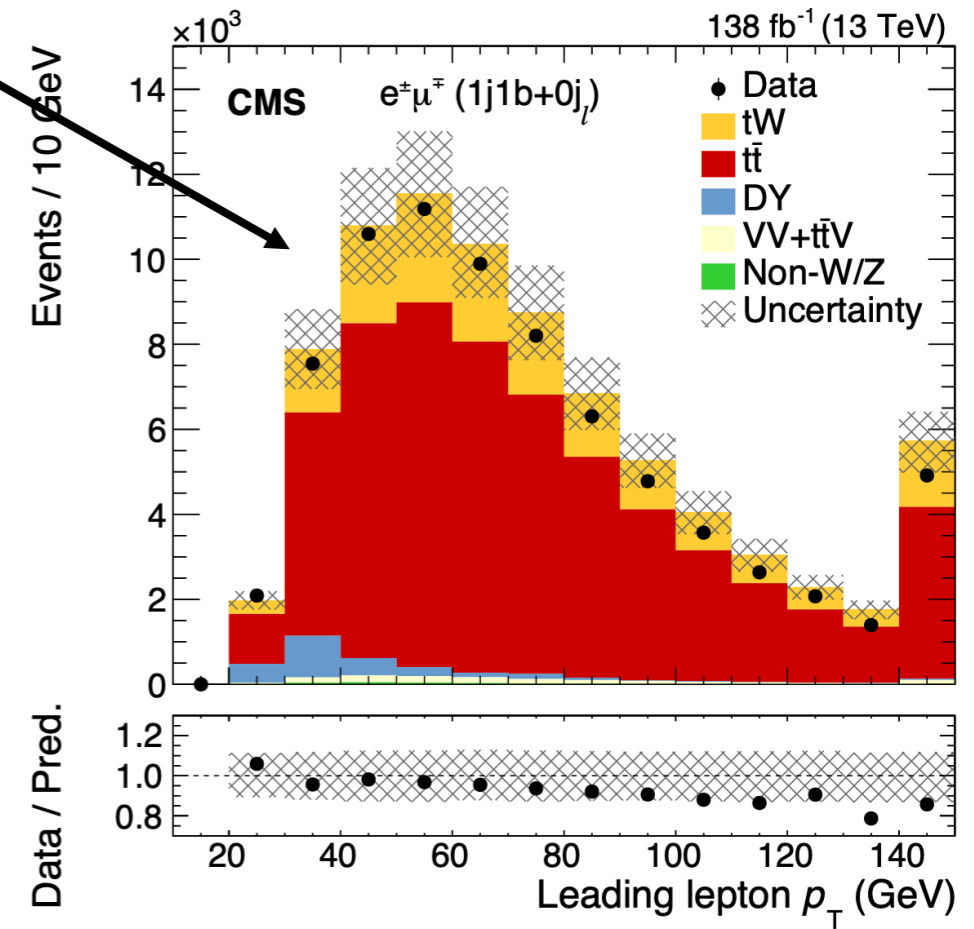
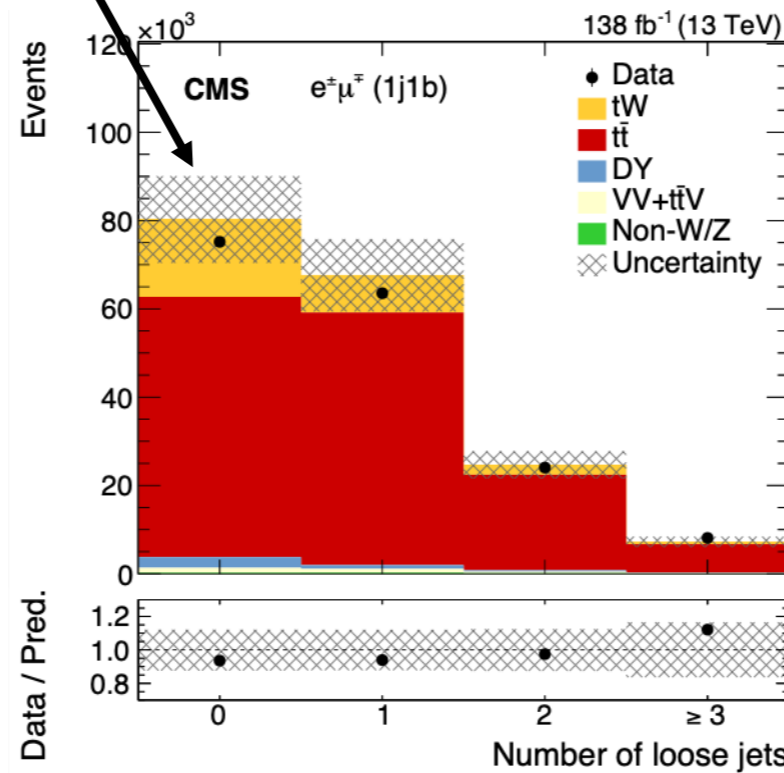
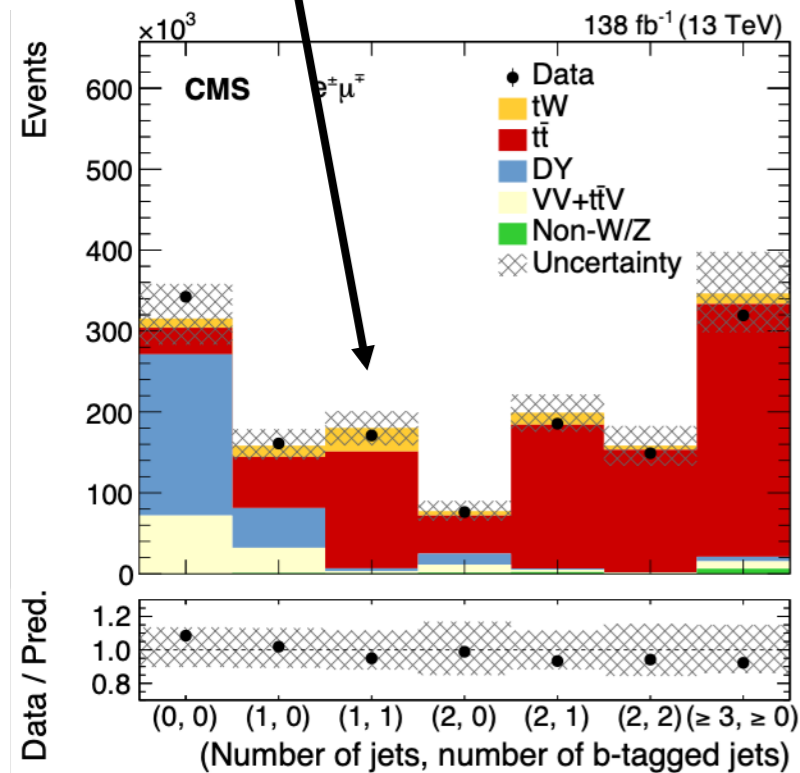
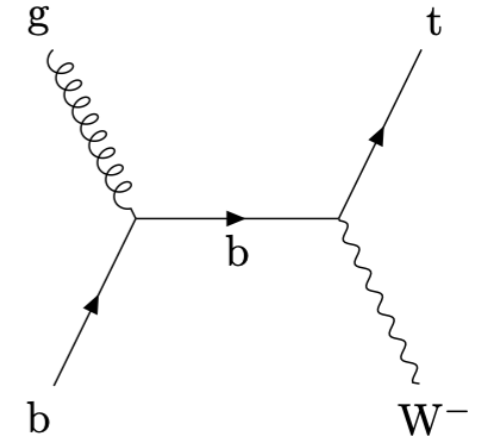


tW differential measurement in dilepton channel

[CMS - arXiv:2208.00924](https://arxiv.org/abs/2208.00924)

eμ channel analyzed:

- Two isolated leptons with $p_T > 25, 20$ GeV
- $m_{ll} > 20$ GeV, jets $p_T > 30$ GeV
- **Signal region** defined as:
 - exactly 1 jet tagged as b-jet,
 - and 0 additional loose jets



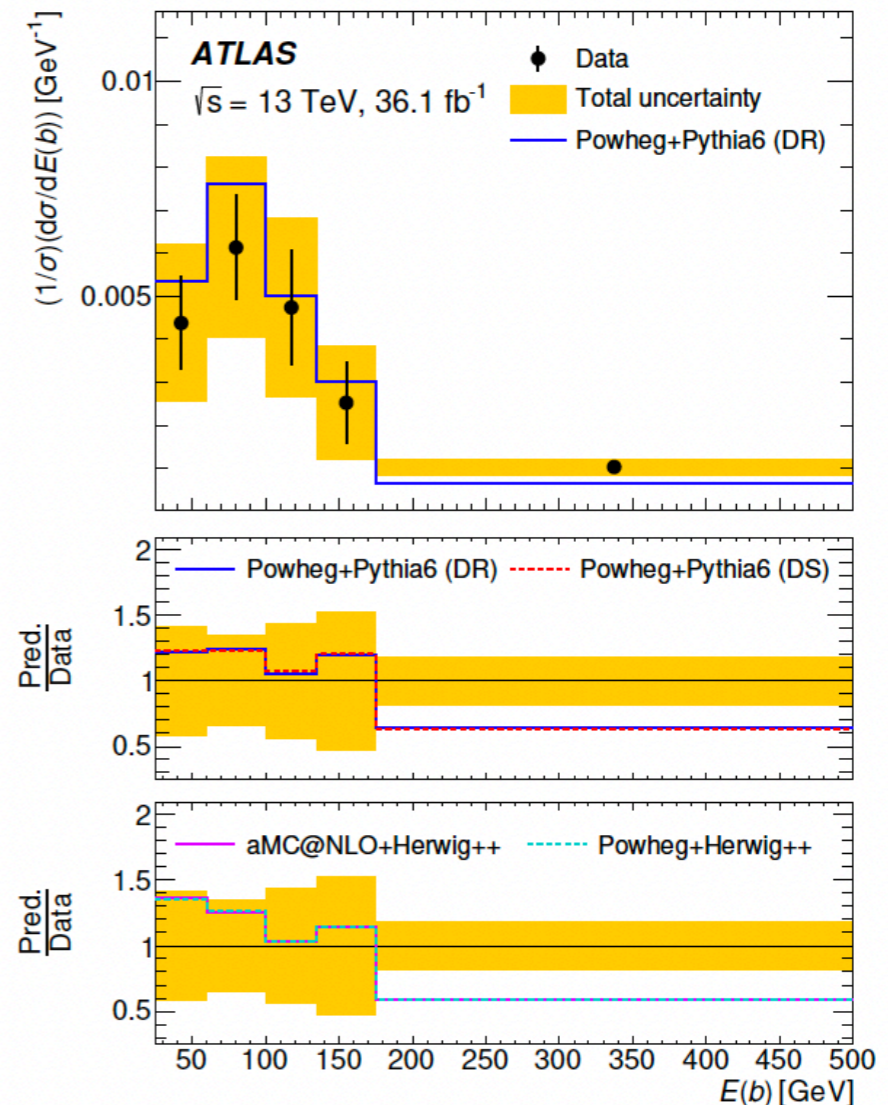
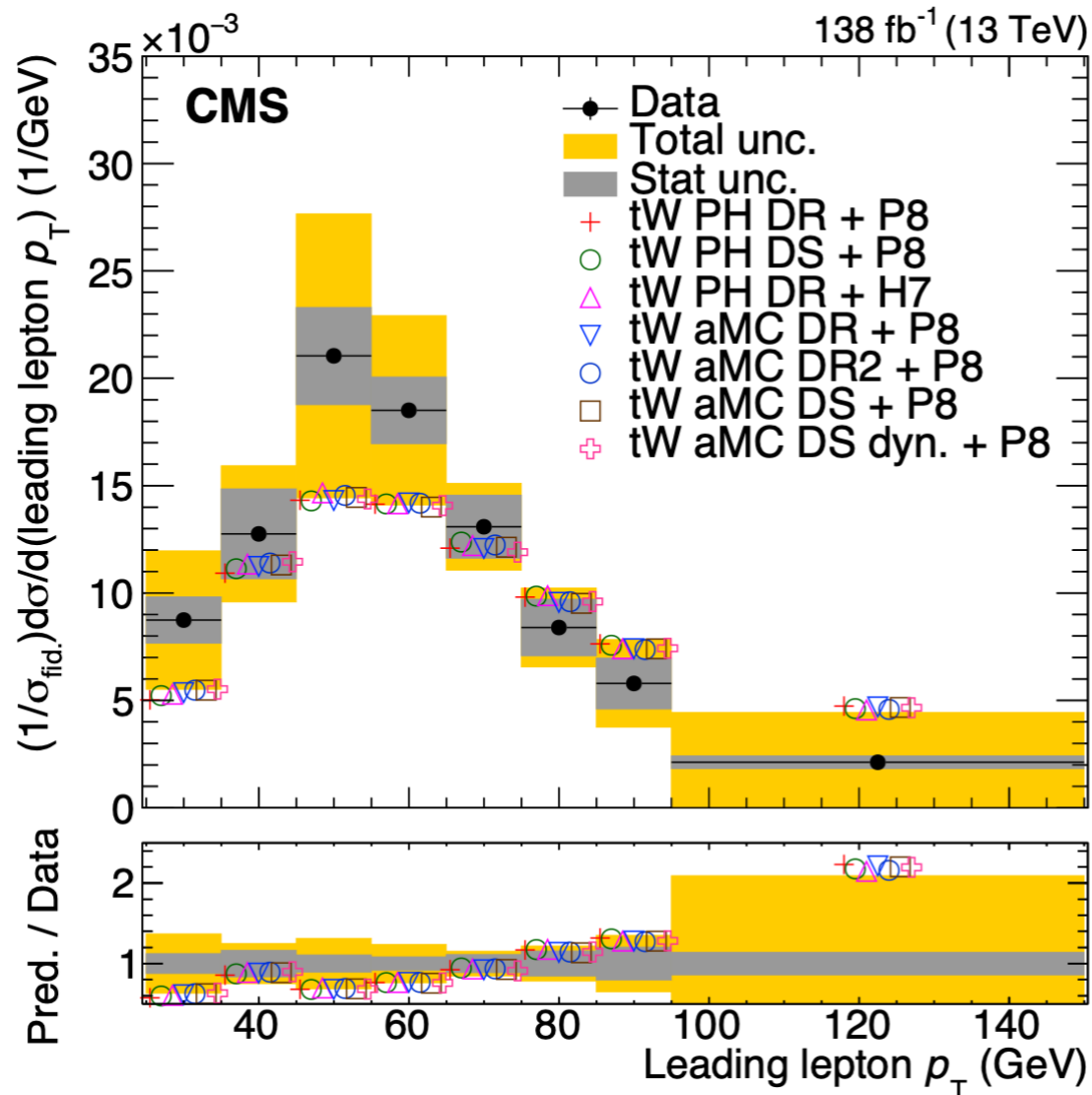
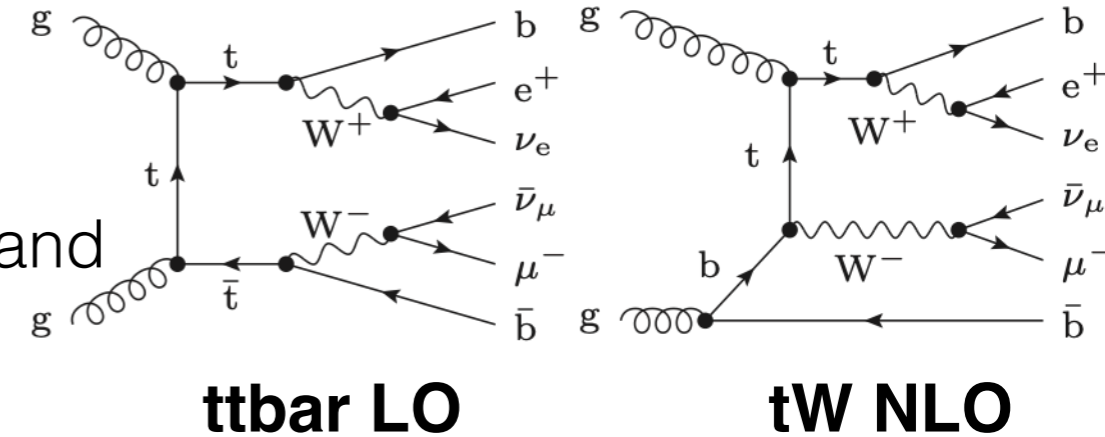
- **ttbar** and other background **estimated from simulation**, normalised by a fit to data

tW differential measurement in dilepton channel

[CMS - arXiv:2208.00924](#), [ATLAS - EPJC78\(2018\)186](#)

Interference between tW NLO and ttbar LO:

- comparisons of tW NLO predictions with ttbar resonance removed using DR (diagram removal) and DS (diagram subtraction) schemes.
- need more data to conclude.



Probing the interference between $t\bar{t}b$ and tW

[ATLAS - PRL121\(2018\)152002](#)

Dedicated measurement in $WbWb$ phase-space to probe the interference:

- Events selected with 2 b-jets
- Good agreement with dedicated so-called “bb4l” predictions, which includes the resonances and the interferences
- Various comparisons of generators and resonance removal schemes.

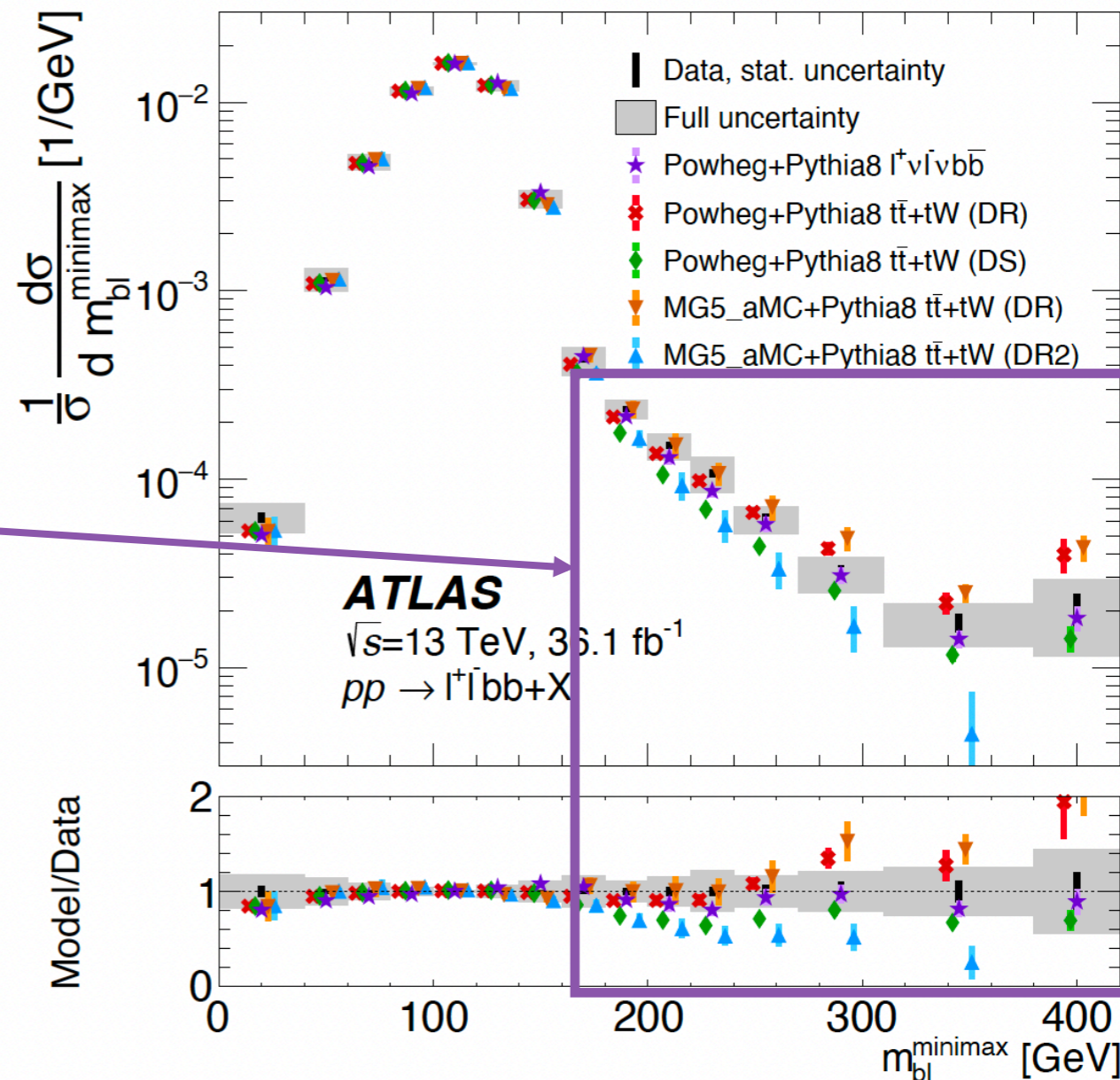
$$m_{bl}^{minimax} = \min\left(\max(m_{b_1l_1}, m_{b_2l_2}), \max(m_{b_1l_2}, m_{b_2l_1})\right)$$

at LO, $m_{bl}^{minimax} < \sqrt{m_t^2 - m_W^2}$.

Sensitive to the interference

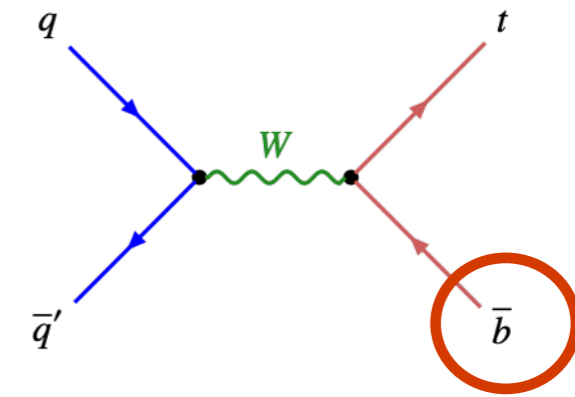
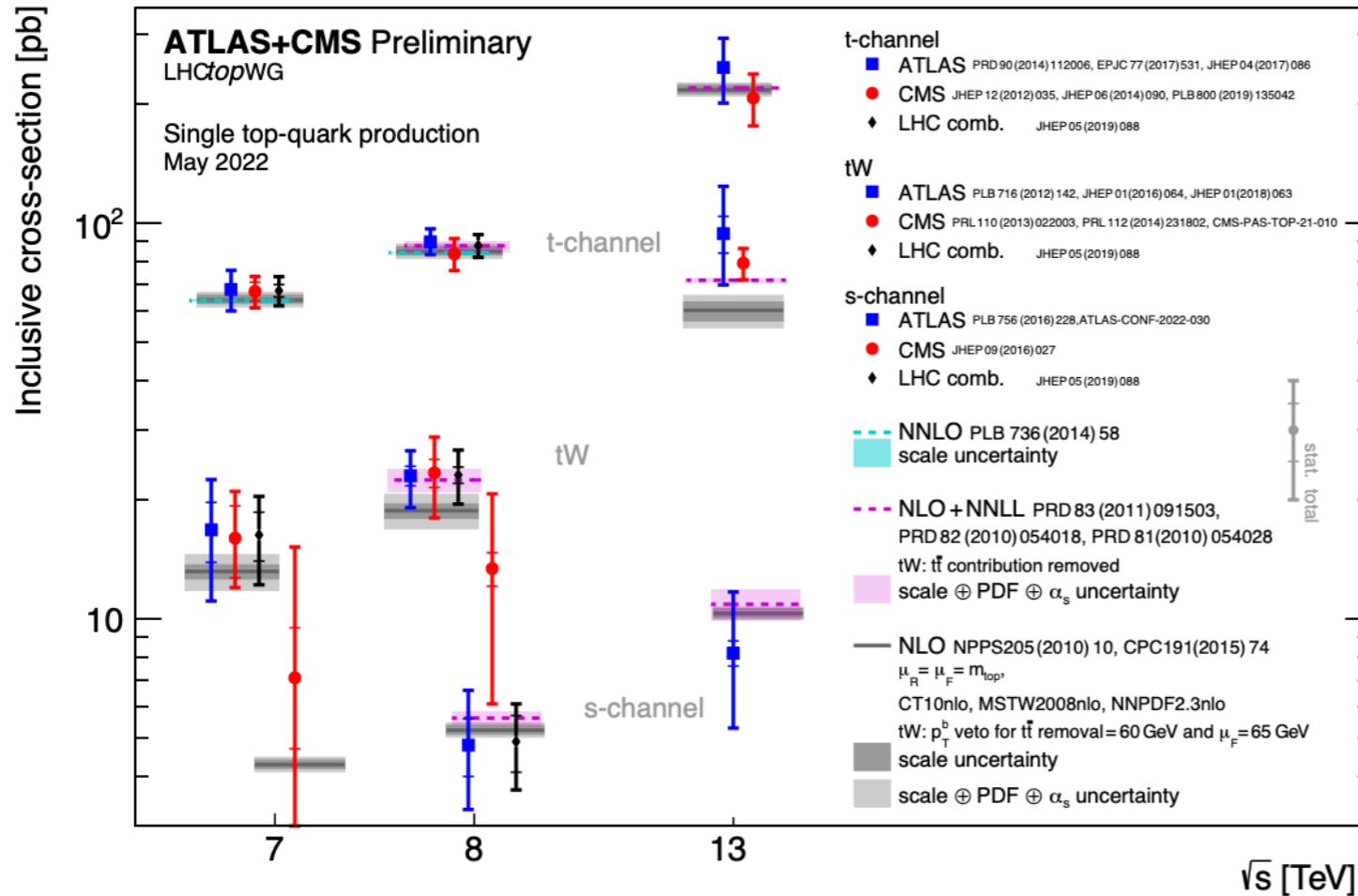
p-value:

Model	All bins	$m_{bl}^{minimax} > 160$ GeV
POWHEG-BOX $t\bar{t} + tW$ (DR)	0.71	0.40
POWHEG-BOX $t\bar{t} + tW$ (DS)	0.77	0.56
MG5_aMC $t\bar{t} + tW$ (DR)	0.14	0.17
MG5_aMC $t\bar{t} + tW$ (DR2)	0.02	0.08
POWHEG-BOX $\ell^+ \nu \ell^- \nu b\bar{b}$	0.92	0.95



Measuring s-channel process at the LHC

[ATLAS - arXiv:2209.08990](https://arxiv.org/abs/2209.08990)

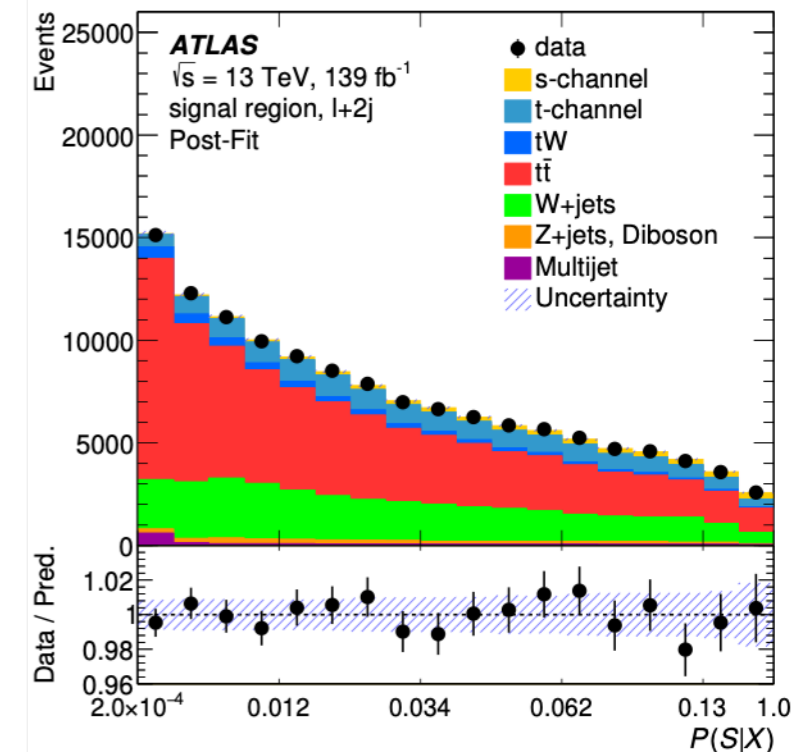


- t-channel is now a background
- **s-channel observed at Tevatron (2014)**
- signal to background ratio (s/b) decreases when center-of-mass energy increases
- **Evidence ($>3\sigma$) obtained at ATLAS 8 TeV and 13 TeV**

Search more difficult at 13 TeV than at 8 TeV:

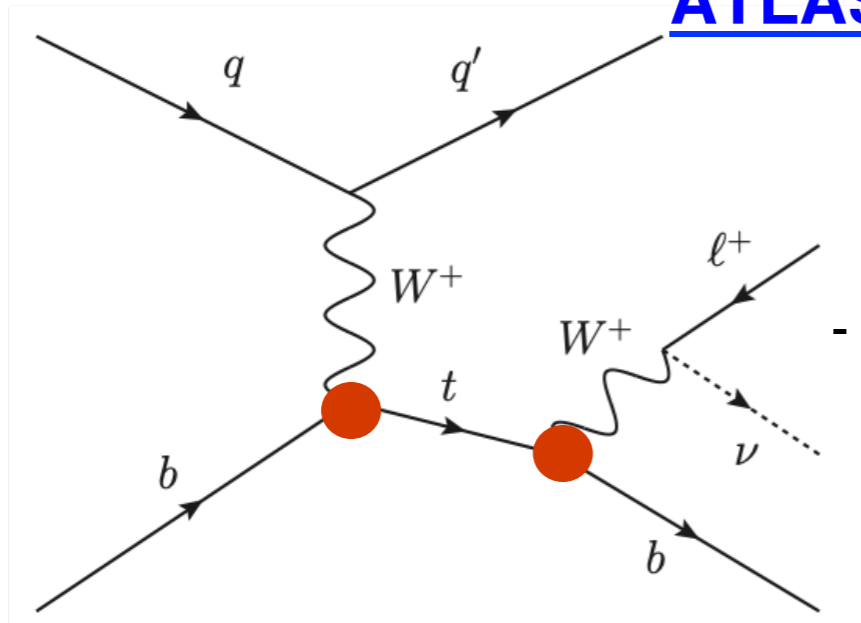
s-channel/ $t\bar{t}$ XS	
8 TeV	2,1 %
13 TeV	1,2 %

Advanced analysis methods need to be employed: ATLAS uses matrix element method



Wtb vertex: anomalous couplings

[ATLAS - JHEP12\(2017\)017](#)



Wtb vertex **involved both** in production and decay of **single top t-channel**

Effective lagrangian for the anomalous coupling at Wtb vertex:

$$L_{Wtb} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- + \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu}}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + h.c.$$

In the SM at tree level:

- $V_L = V_{tb} \sim 1$ (CKM element)
- $V_R = g_R = g_L = 0$

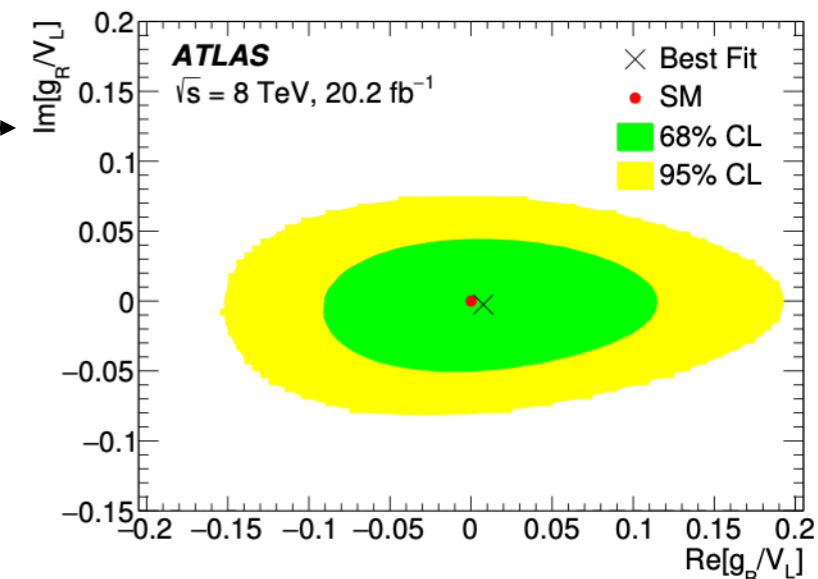
$$P_{L,R} = (1 \mp \gamma_5)/2$$

Left and right handed vectorial couplings

Left and right handed tensorial couplings

Imaginary coeff.: CP-violating
Only done with t-channel!

ATLAS, JHEP12(2017)017

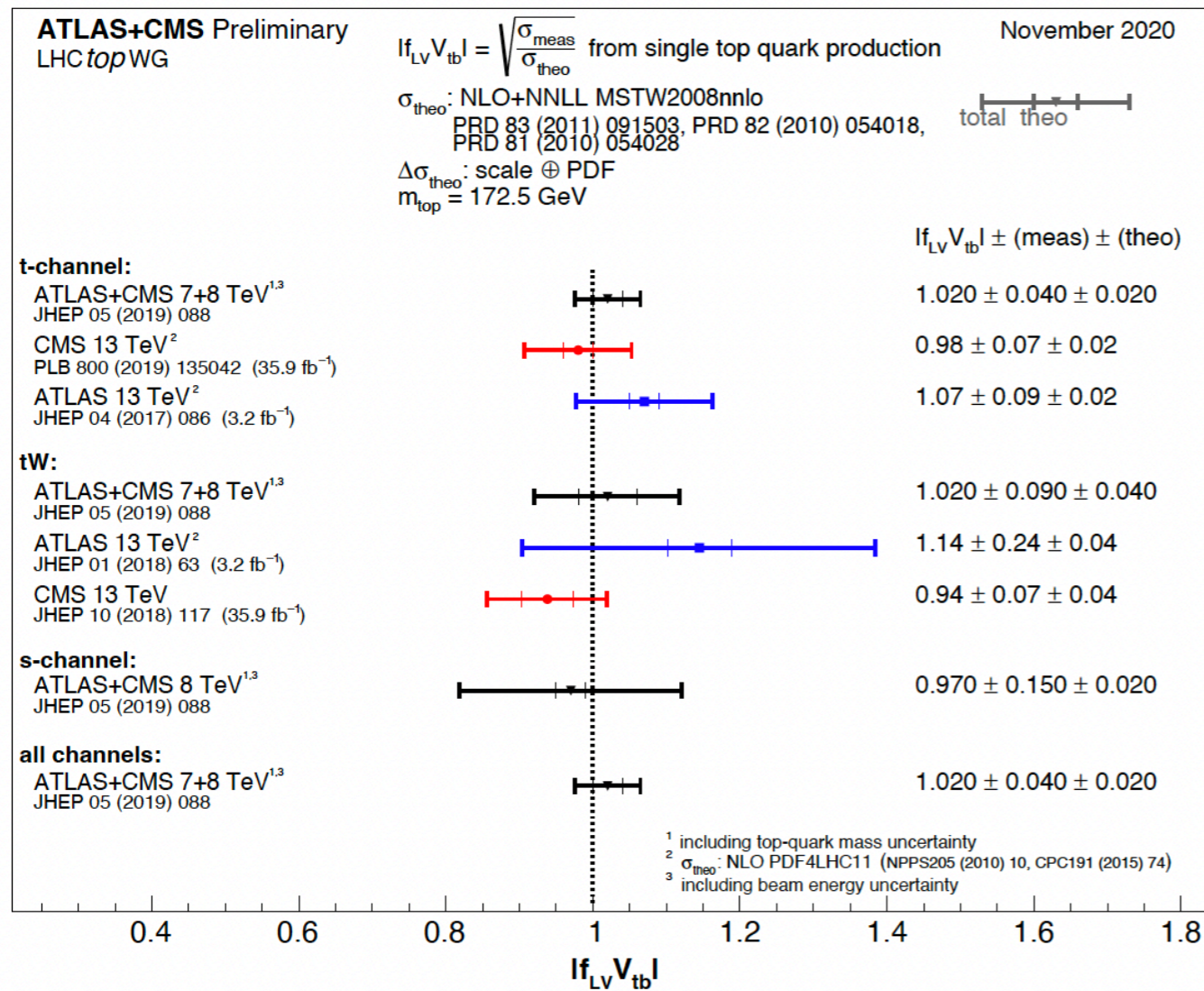


Measurements:

- Related to W helicity (mostly visible with ttbar), top quark polarization (single top production only)
- Impacts **angular distributions** defined in the top quark or W rest frame

Measurement of $|V_{tb}|$

Extraction of $|f_{LV} V_{tb}|$ (= $V_L W_{tb}$ coupling) from cross section measurements.



$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{t-ch.}}{\sigma_{t-ch}^{th}}}$$

Assumes $|V_{td}|, |V_{ts}| \ll |V_{tb}|$

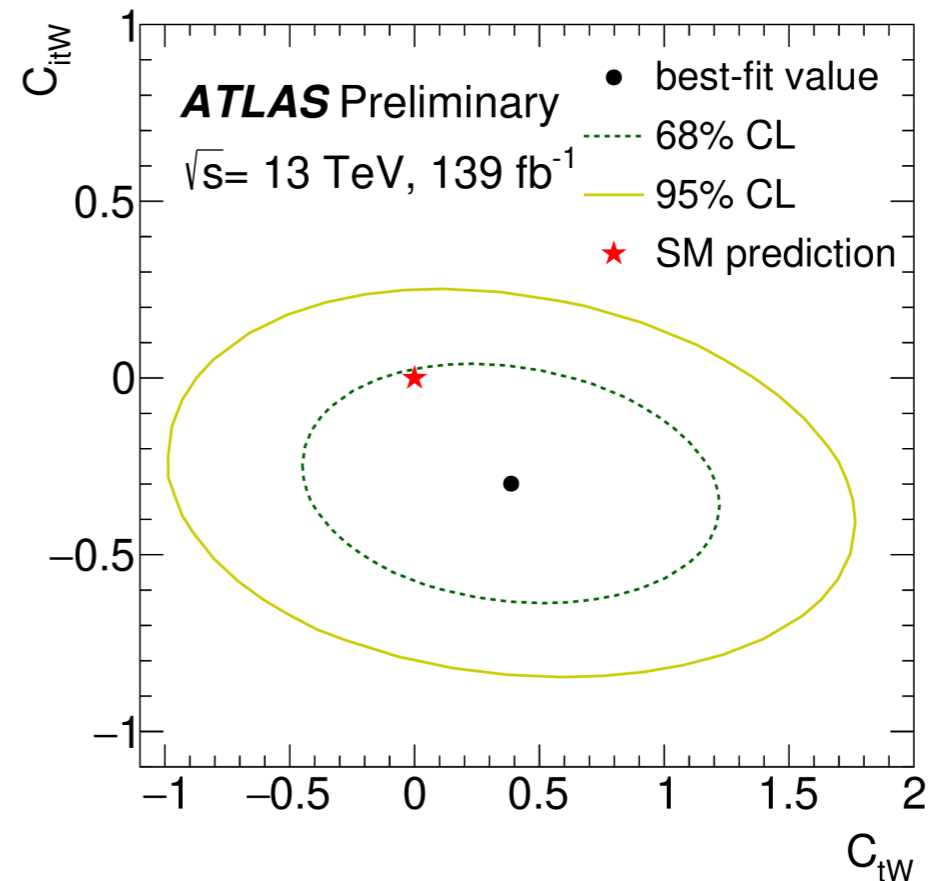
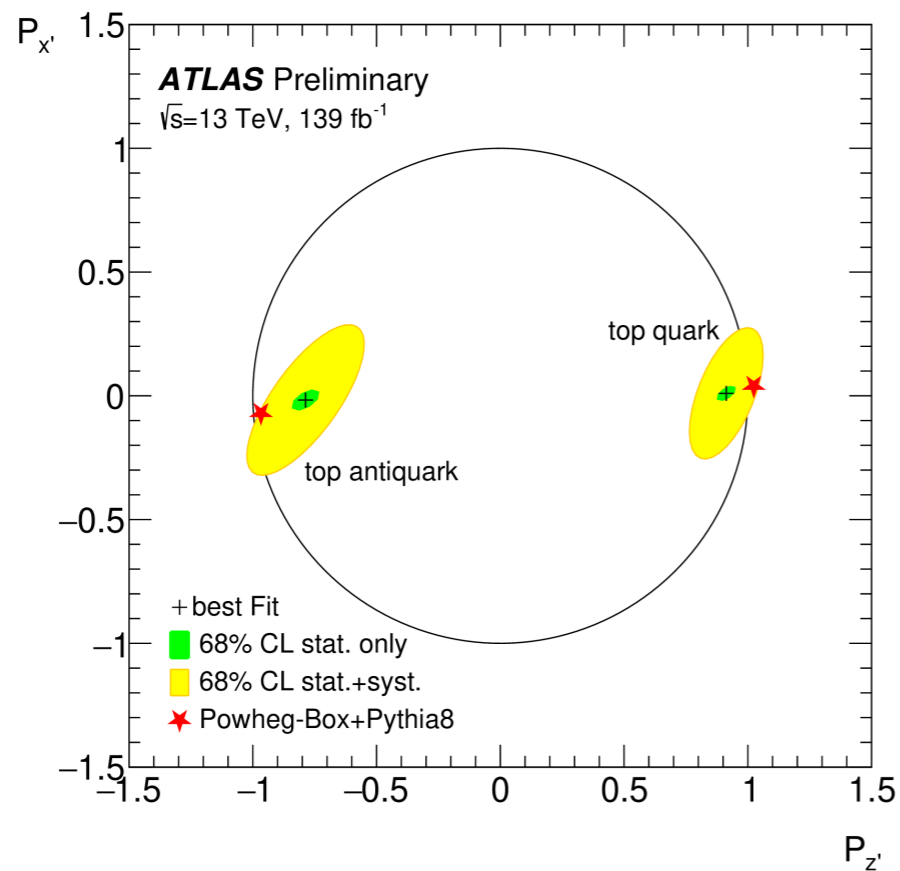
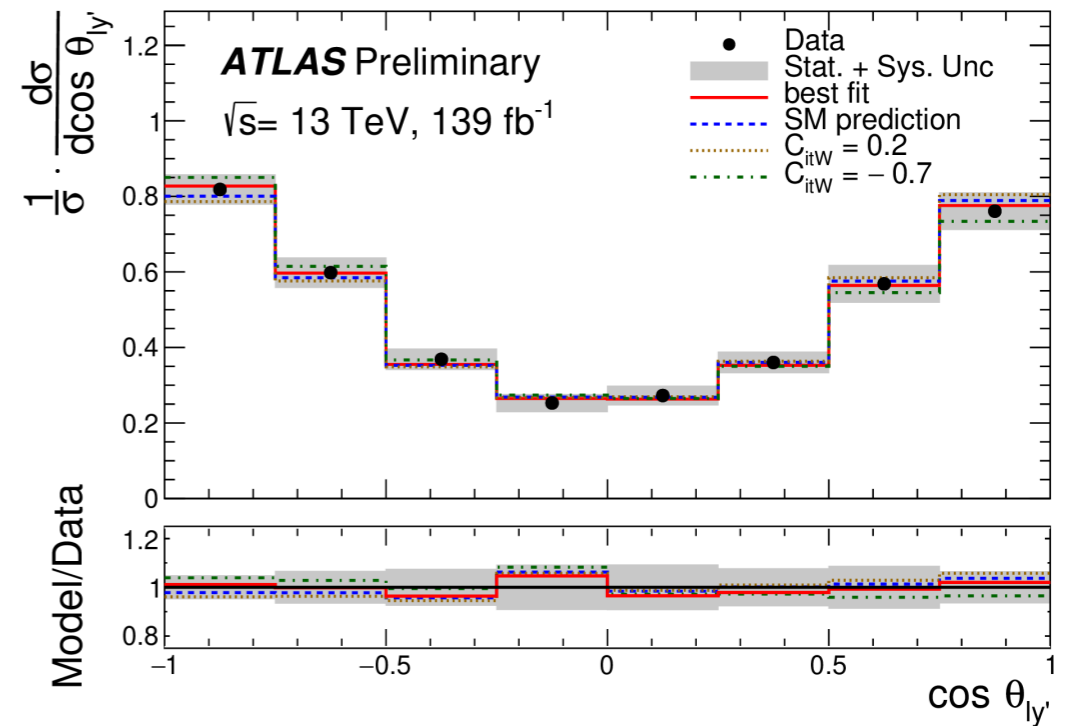
Combinations at 8TeV (t, tW and s-channels) provide the best precision.

Measurement without assumptions (t-channel measurement also measuring V_{td}, V_{ts}) lead to similar precision.

Top quark polarization

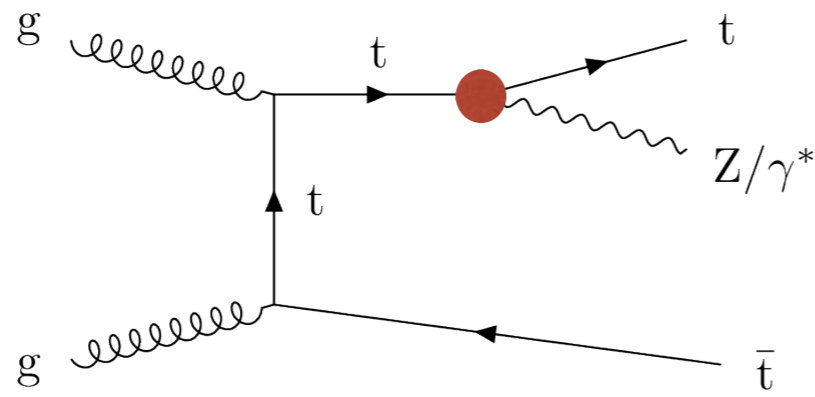
[ATLAS - JHEP 11 \(2022\) 040](#)

- Measure **angular distribution of the lepton in the top quark rest frame**
- Interpret results in term of top quark polarization along x' and z' directions ($P_{x'} \sim 0$, $P_{z'} \sim 1$)
- Extract **measurement of effective field theory couplings, tensor left** (aka g_L and $\text{Im}(g_L)$)

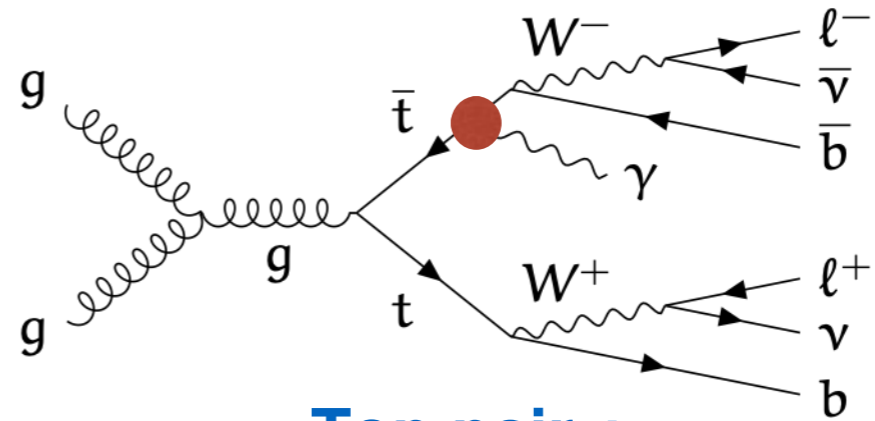


Processes with tops and gauge bosons

Larger cross section

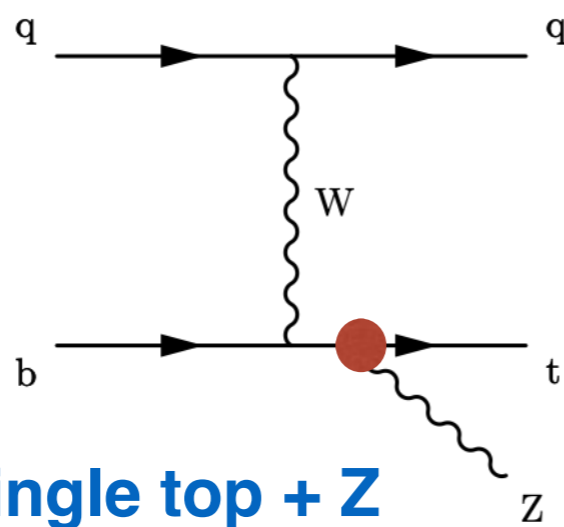


Top pair + Z

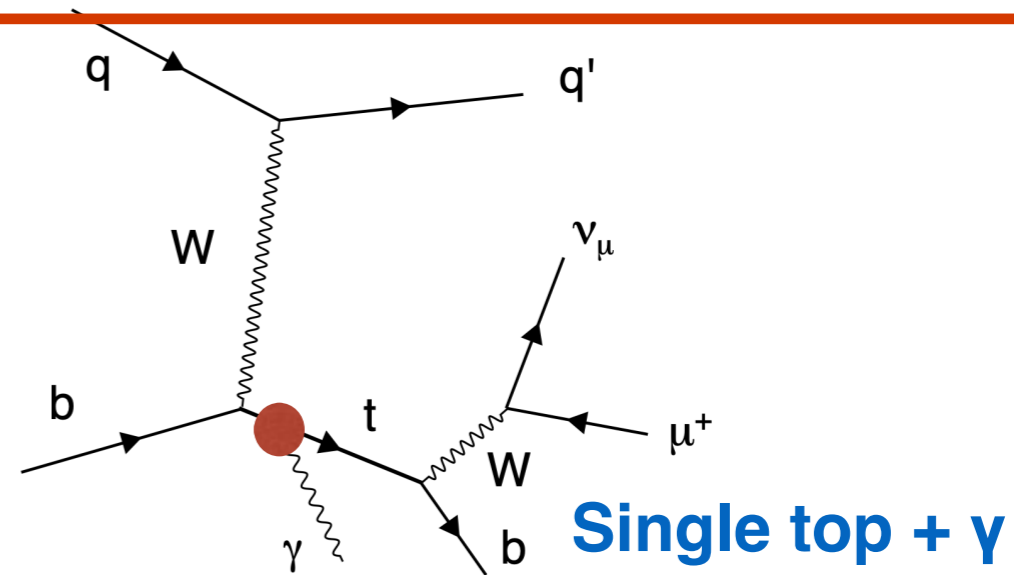


Top pair + γ

Smaller cross section



Single top + Z



Single top + γ

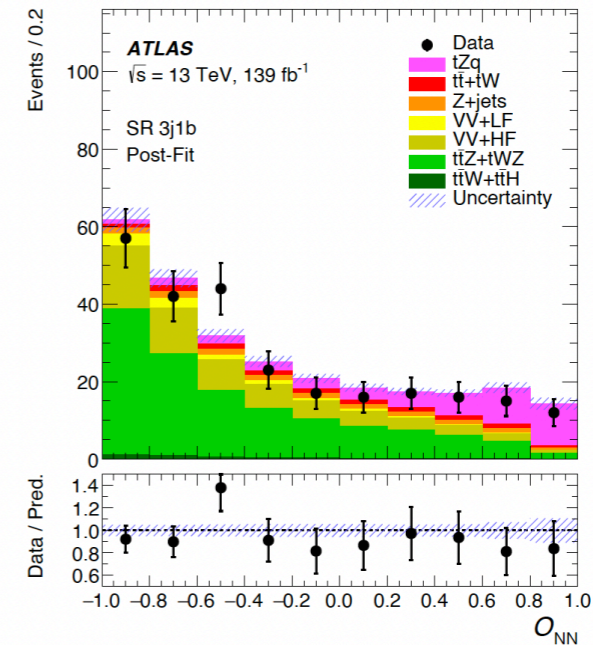
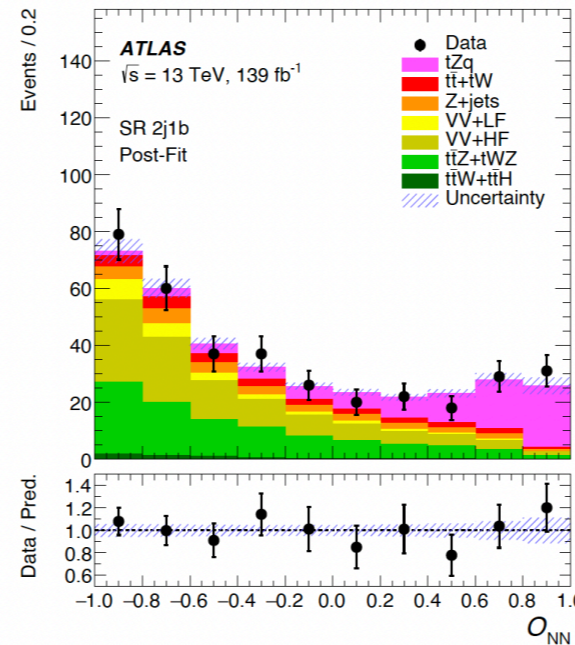
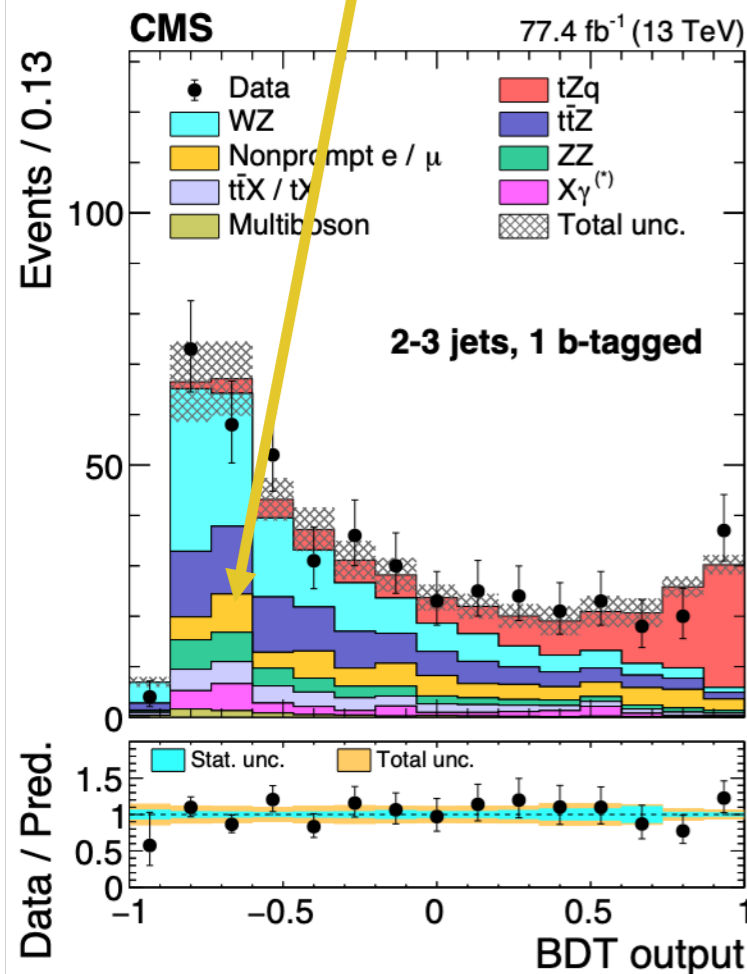
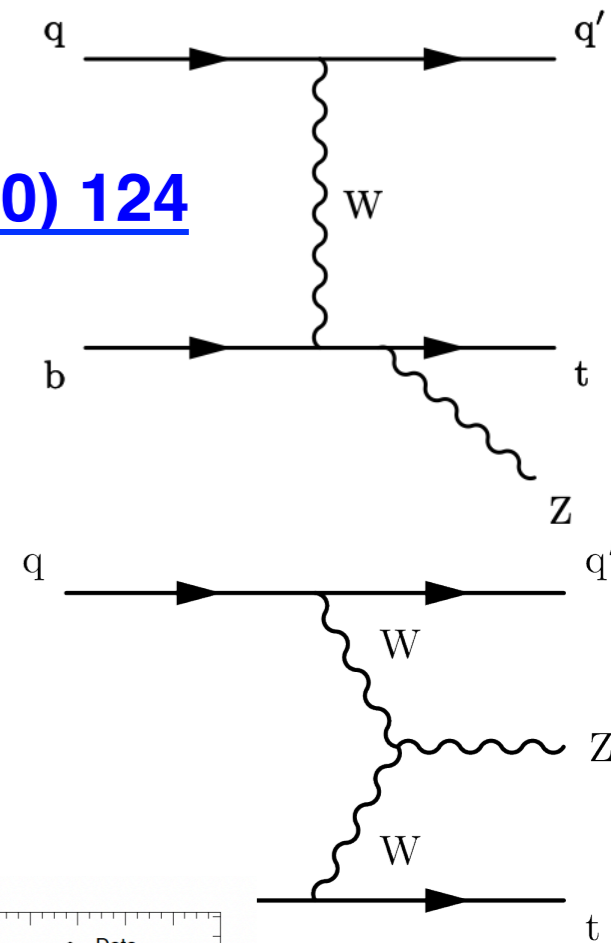
- Top pair + boson process is a background for single top + boson measurement
- **Test of SM predictions** (perturbative QCD, EW corrections)
- **Probe of the top - gauge boson coupling** (tZ in tZq , $t\gamma$ in $t\gamma q$)
- Search deviations from the SM within the framework of the **effective field theory**

Single top + Z (tZq)

CMS - PRL 122 (2019) 132003, ATLAS - JHEP 07 (2020) 124

Analysis performed in **3 ℓ final state (e or μ)**

- tZq is produced by EW interaction: make use of the **forward jet** ($|\eta| < 4.7$) to discriminate signal from background
- Need efficient **lepton identification to reject fake leptons**
- **Non prompt background** (ttbar and Z+jets): fake rate estimated in QCD jets data



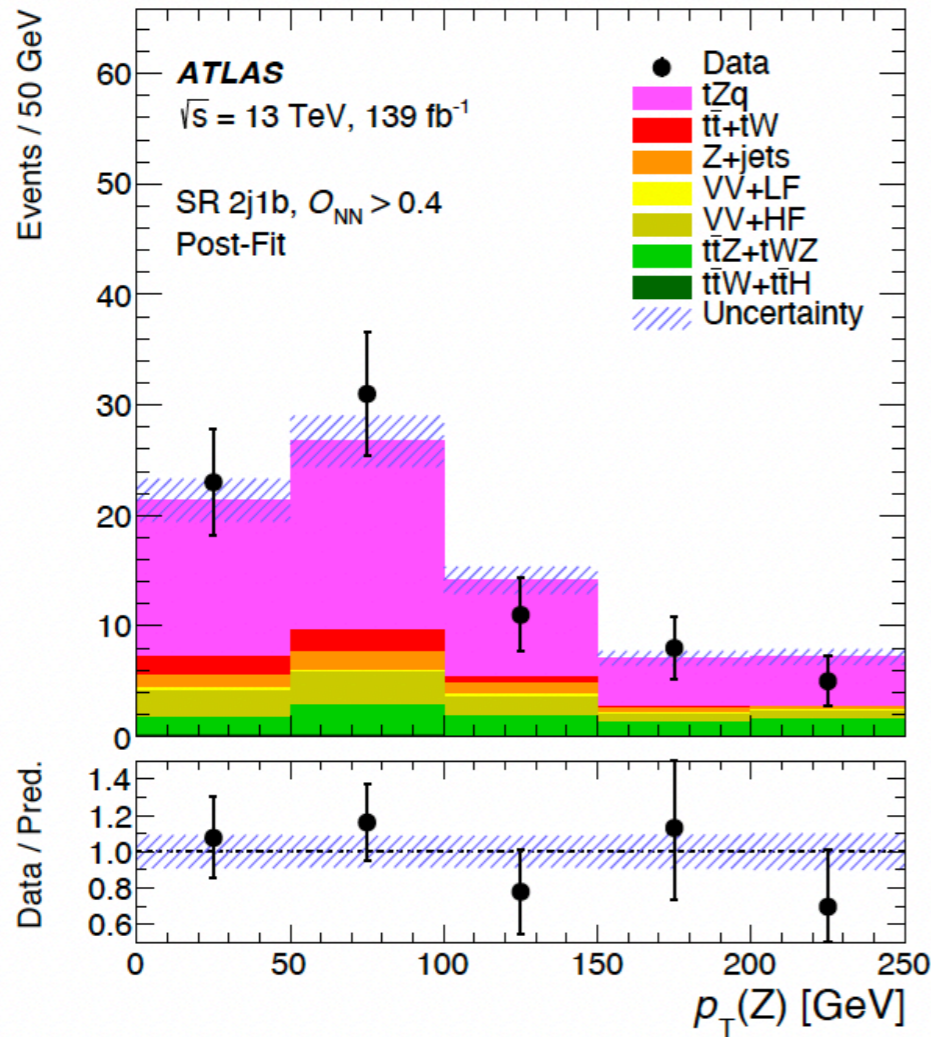
Signal extraction: **Fit of BDT (CMS) or NN output (ATLAS) in several event categories**

Observed at CMS and ATLAS ($>5\sigma$)

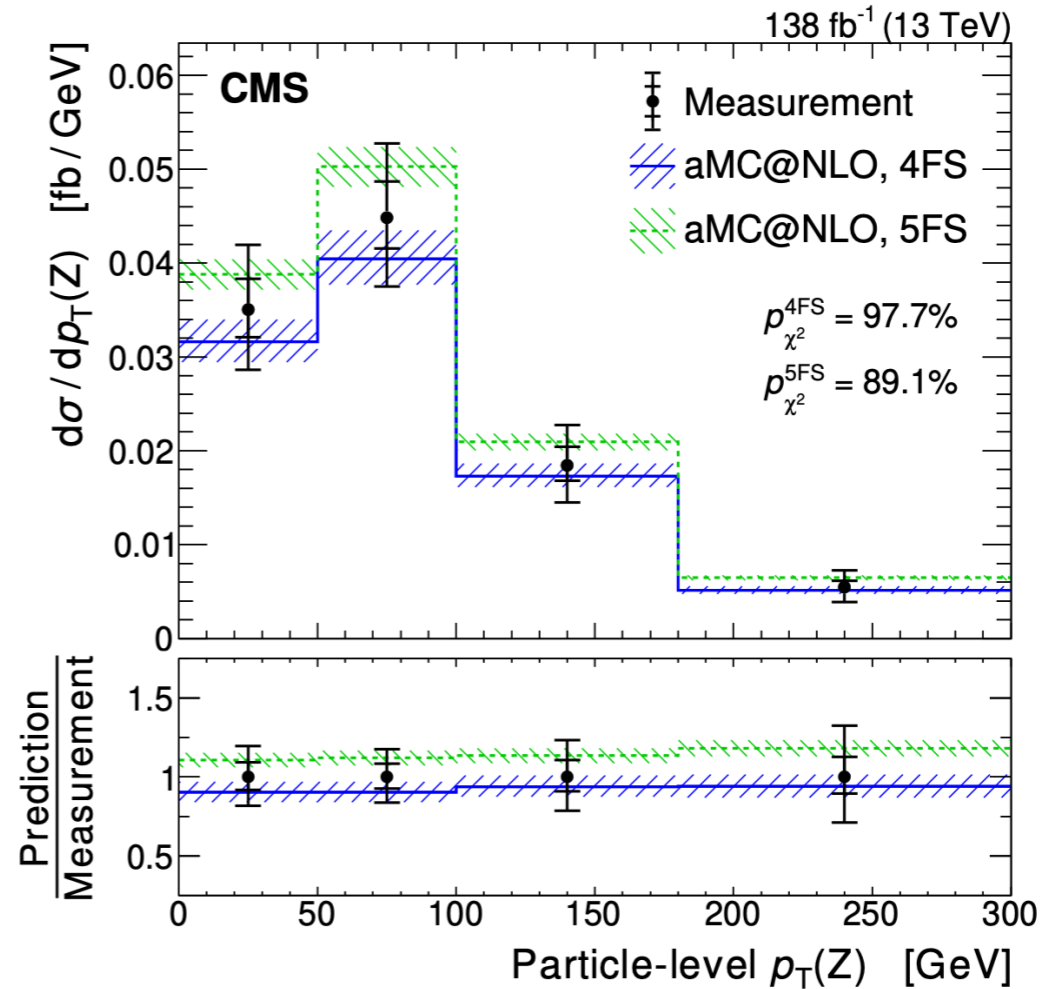
Single top + Z (tZq)

[CMS - JHEP 02 \(2022\) 107, ATLAS - PLB 780\(2018\)557-577](#)

Kinematic distributions at ATLAS



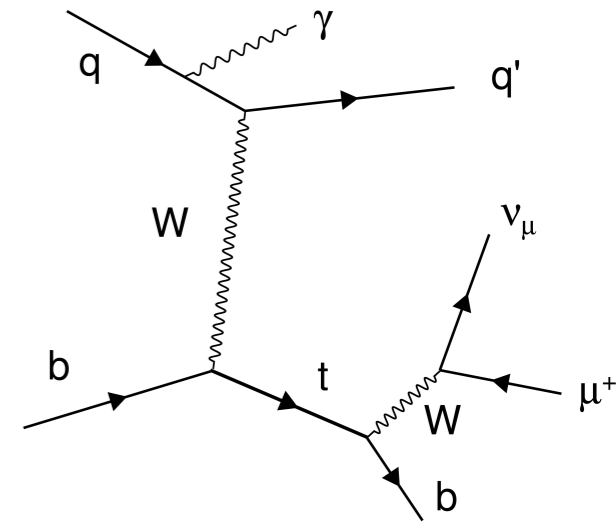
CMS differential measurement



Main uncertainties: Non-prompt background, jet energy scale, lepton efficiency, final state radiation and tZq QCD scale uncertainty (modeling uncertainties relatively smaller at ATLAS)

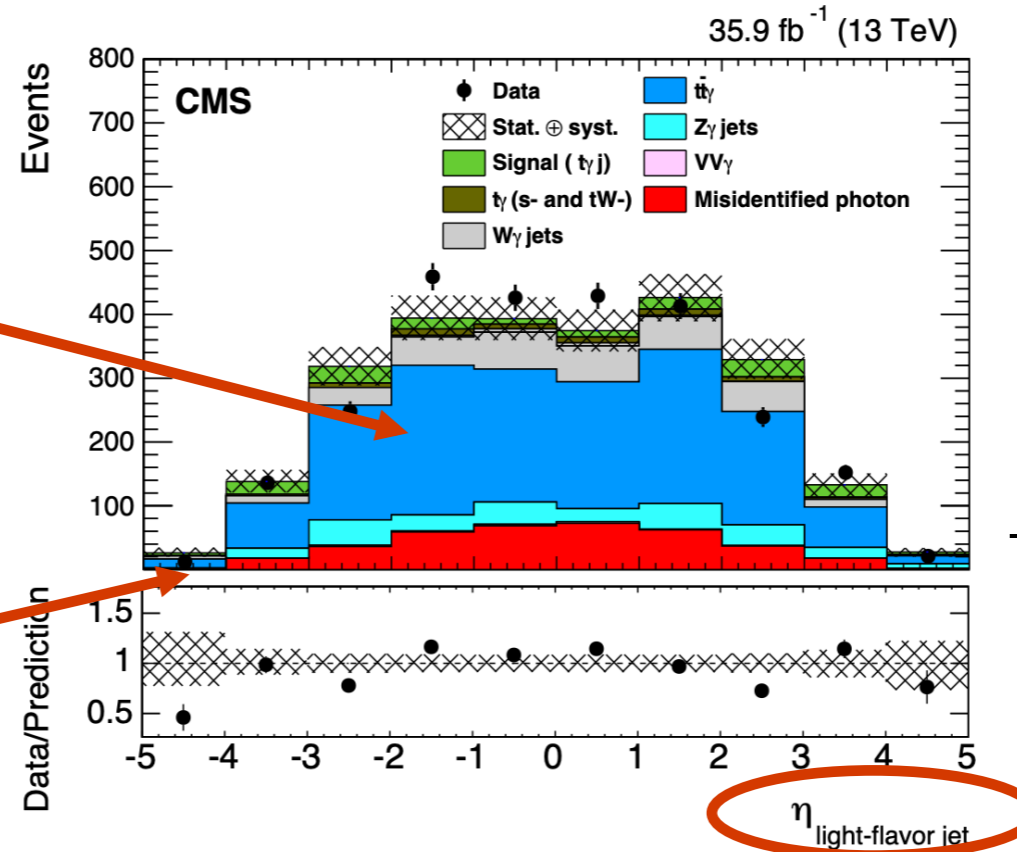
Single top + γ (t γ q)

CMS - Phys. Rev. Lett. 121 (2018) 221802

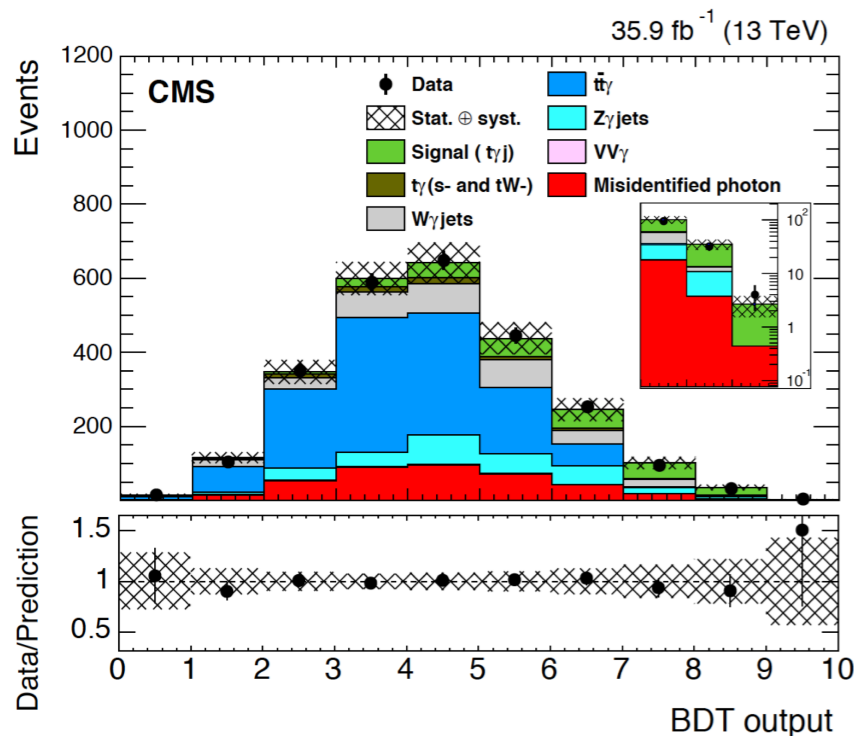


Dominant background tt+ γ
(dedicated CR is used)

Estimate **non-prompt photon** background with a **fake ratio method**



- Uses the **forward jet** to increase discrimination



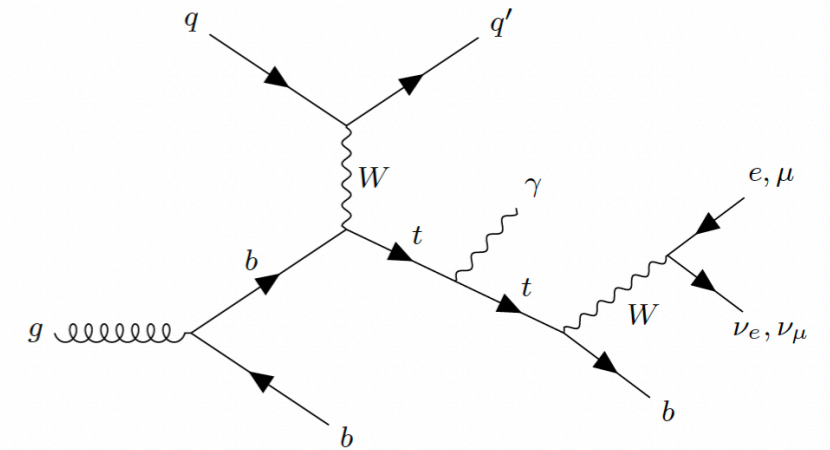
Extract signal with **BDT** using kinematics (noticeably **forward jet η**)

First evidence: significance 4.4σ (3.0σ expected)

Dominated by systematics: jet energy scale, b-tagging, t γ q modeling

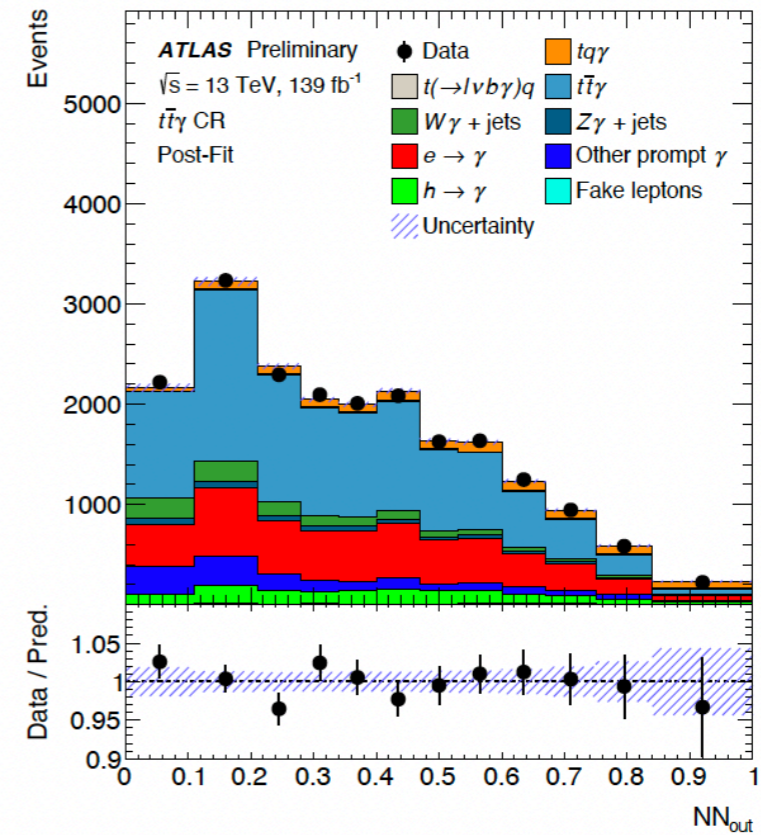
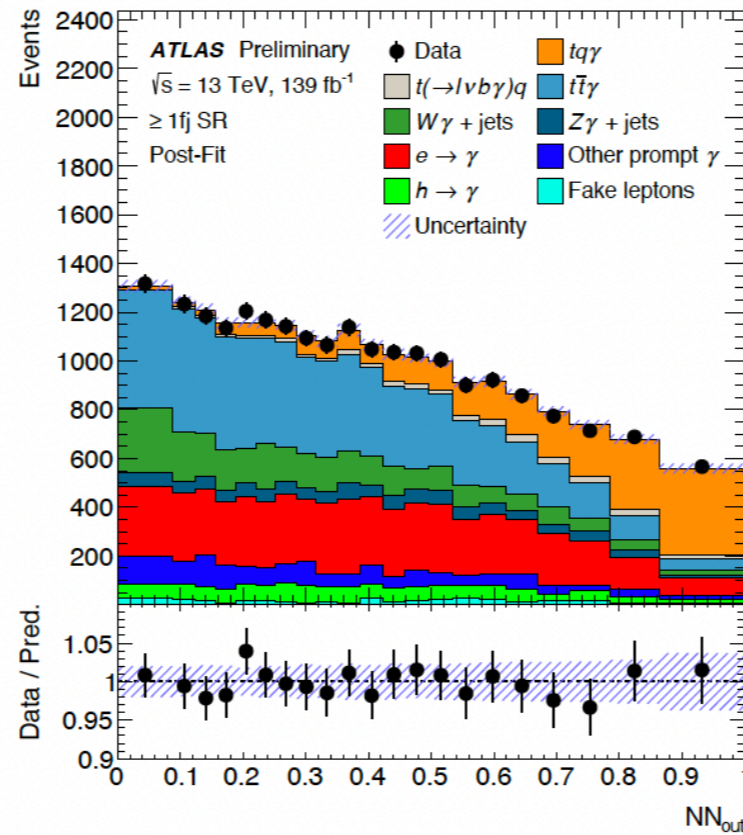
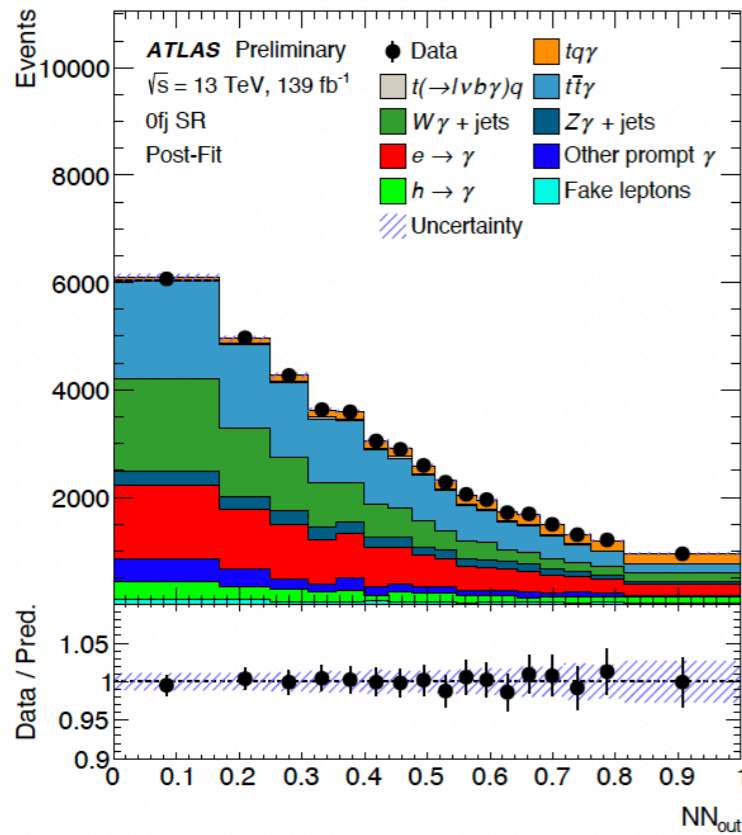
Observation of single top + γ (tyq)

[ATLAS-CONF-2022-013](#)



Similar analysis strategy at ATLAS
Signal extraction from fit of SR and CR (also $W\gamma$).

Signal is very clearly visible!

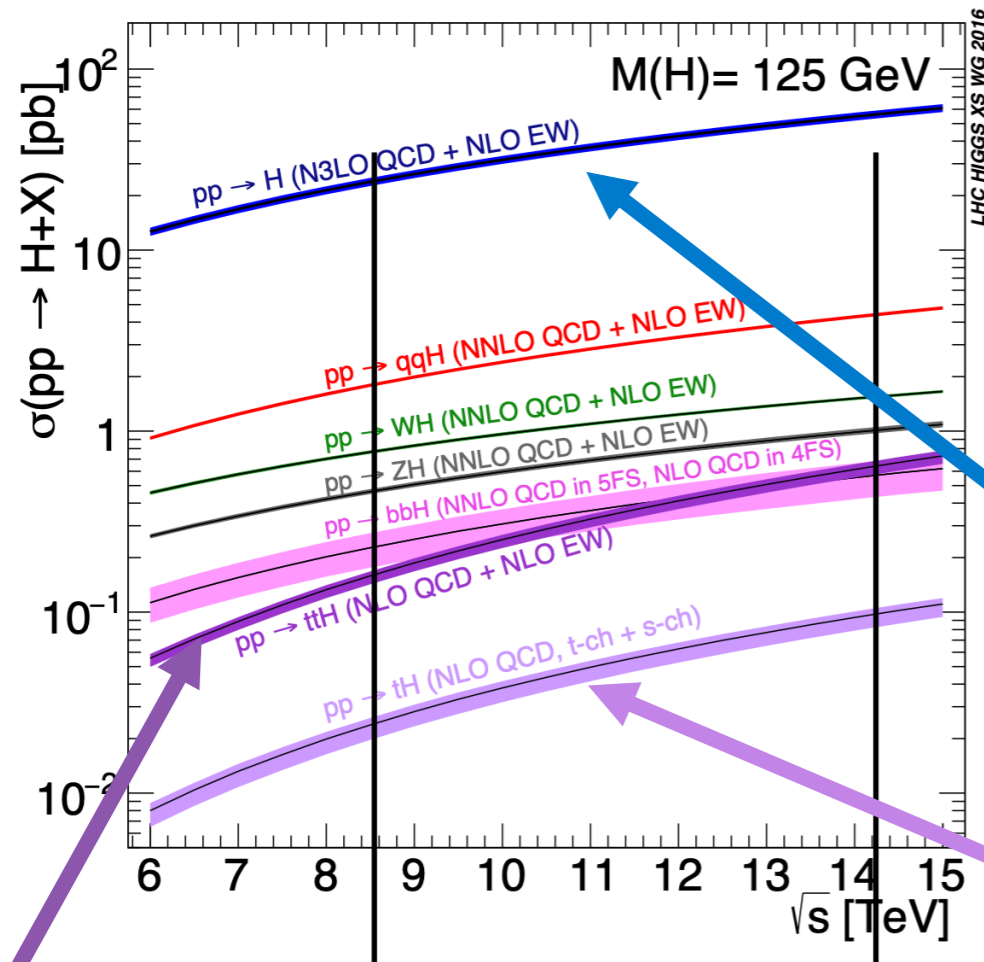


The measured fiducial parton-level cross section is $\sigma_{tq\gamma} \times \mathcal{B}(t \rightarrow \ell v b) = 580 \pm 19$ (stat.) ± 63 (syst.) fb.

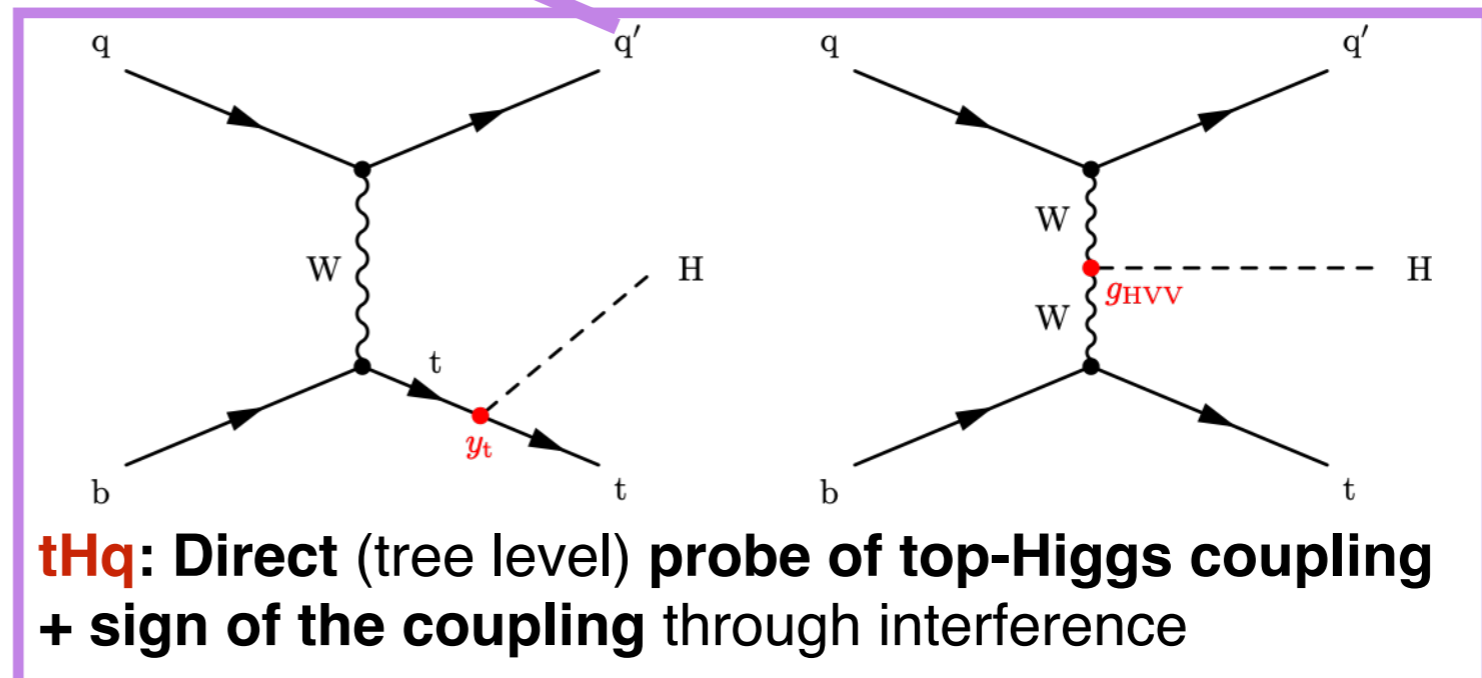
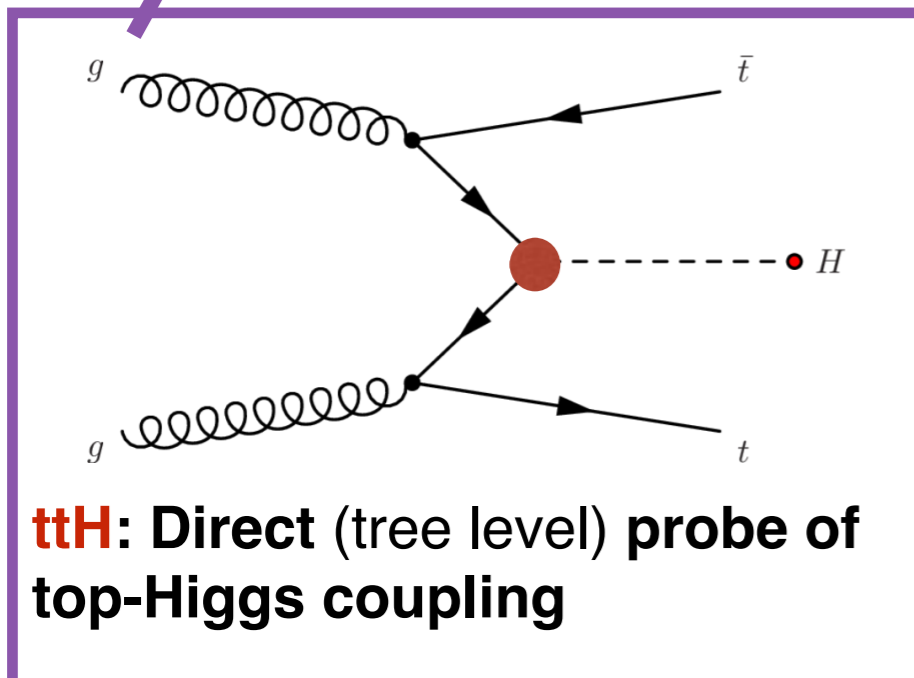
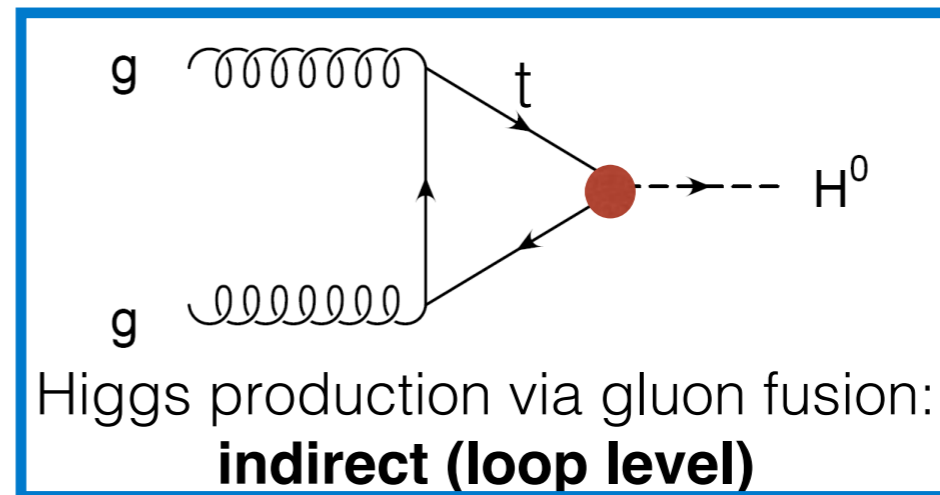
Observation: significance 9.1σ (6.7σ expected)

Dominated by systematics: ttgamma modeling, MC stat, ttbar modeling.

Top - Higgs coupling at the LHC



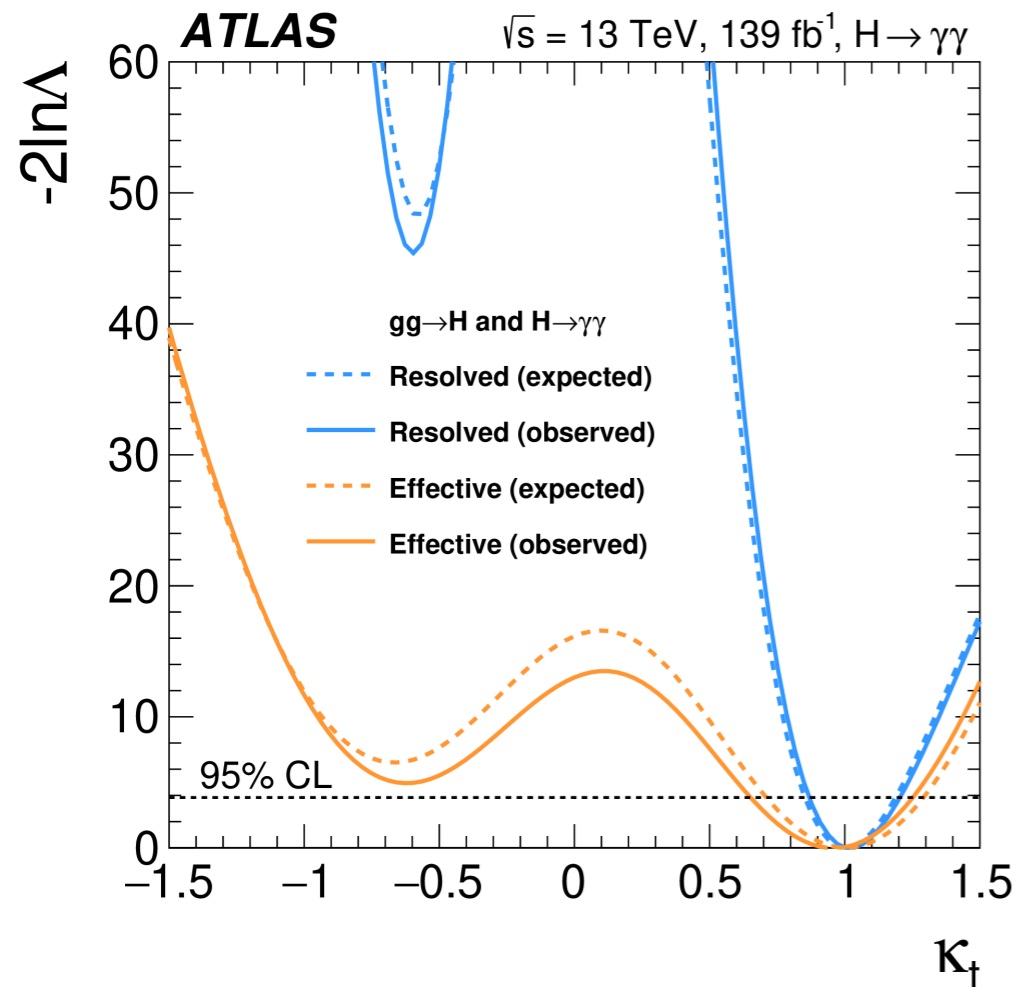
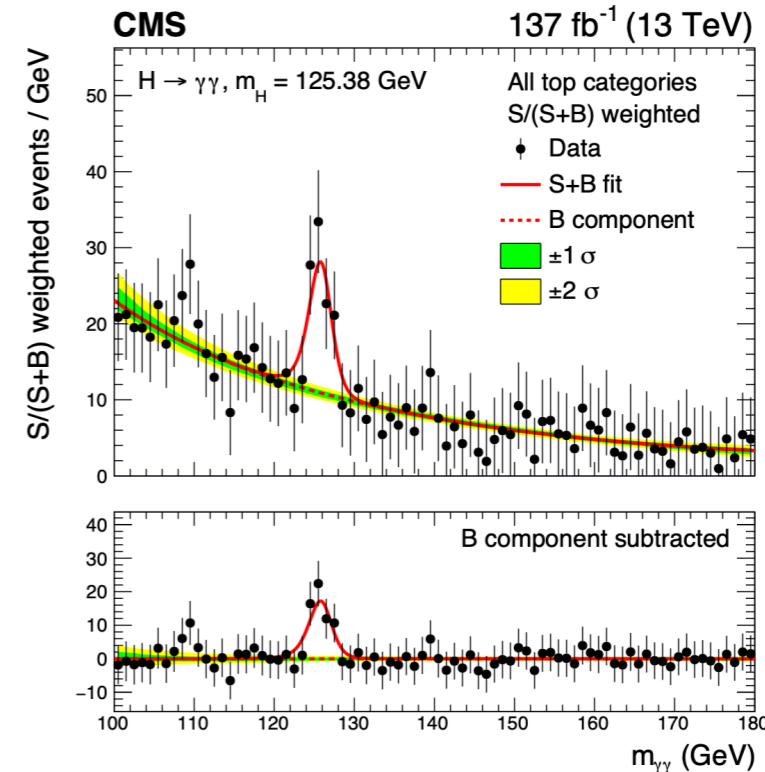
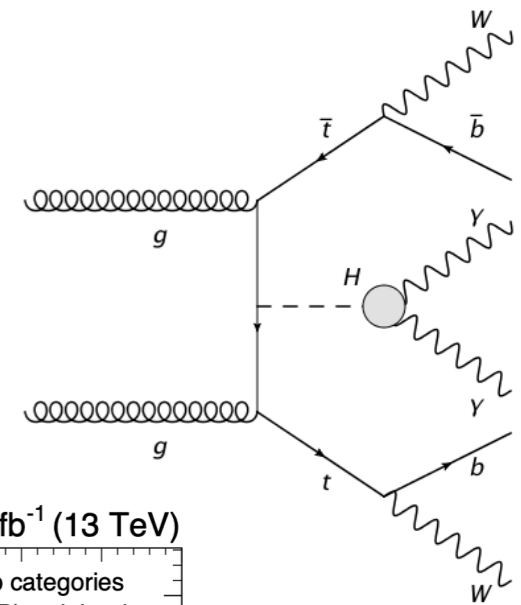
The Higgs boson generates fermion mass via its vacuum expectation value v : **Yukawa coupling**
- Top Yukawa coupling $\lambda_t = \sqrt{2} \cdot m_t/v \sim 1$
 - Measuring accurately λ_t is one of the priorities of the LHC



ttH, H → γγ

[CMS - JHEP 07 \(2021\) 027, ATLAS - arXiv:2207.0034](#)

- **Dedicated ttH category** in H → γγ measurements
- Look for **small signal peak (BR ~ 0.2%)** over large **background**
- **Photon identification:** reject jets faking photons with shower shape and isolation
- **Photon energy resolution ~1.2-1.6%** depending on categories: calibration is crucial
- Use **ML** in several **ttH** and **tH** categories



Data prefers **positive sign** of top-Higgs coupling

“Simplified template cross section”:

Measuring production mechanisms in kinematic bins at generator-level:

- **ATLAS:** $2.1_{-3.1}^{+4.2}$ times the standard model expectation
- **CMS:** $6.3_{-3.7}^{+3.4}$ times the SM expectation

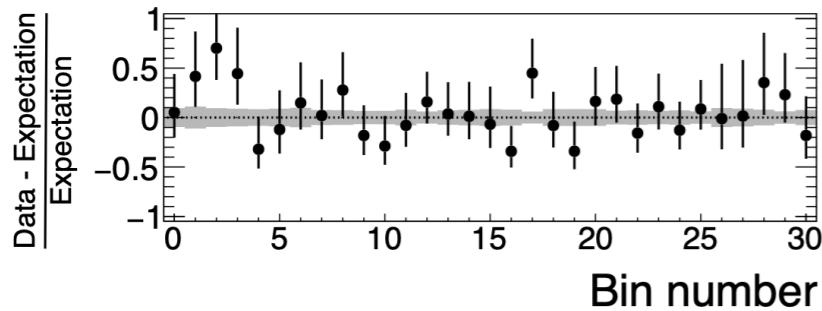
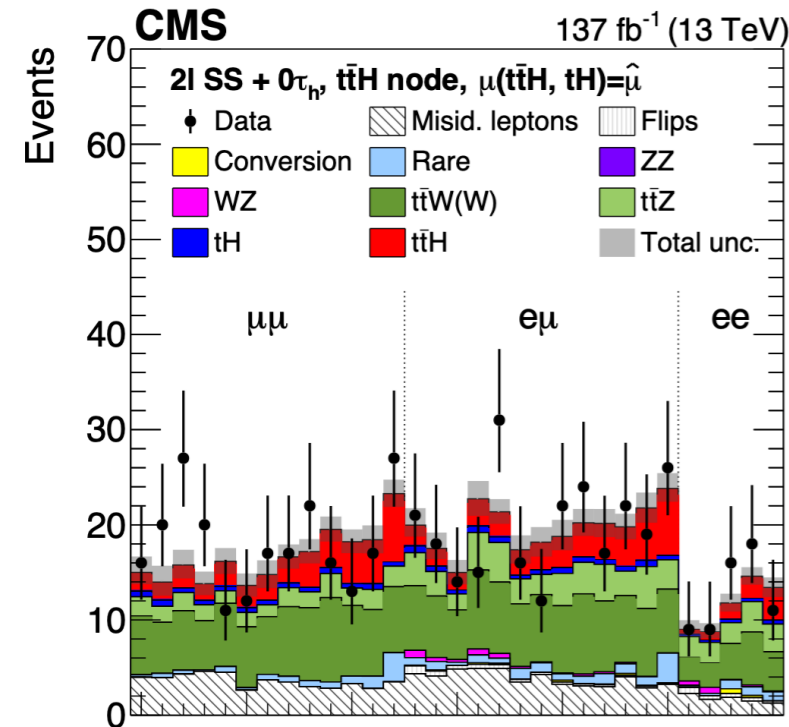
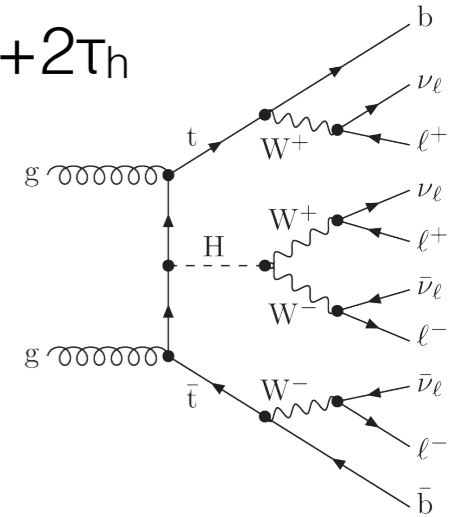
tH multilepton

[Eur. Phys. J. C 81 \(2021\) 378](#)

Most sensitive event categories: 2 leptons of same sign ($2\ell_{ss}$), 3ℓ , $2\ell_{ss}+1\tau_h$ (hadronic tau), $1\ell+2\tau_h$

Signal extraction:

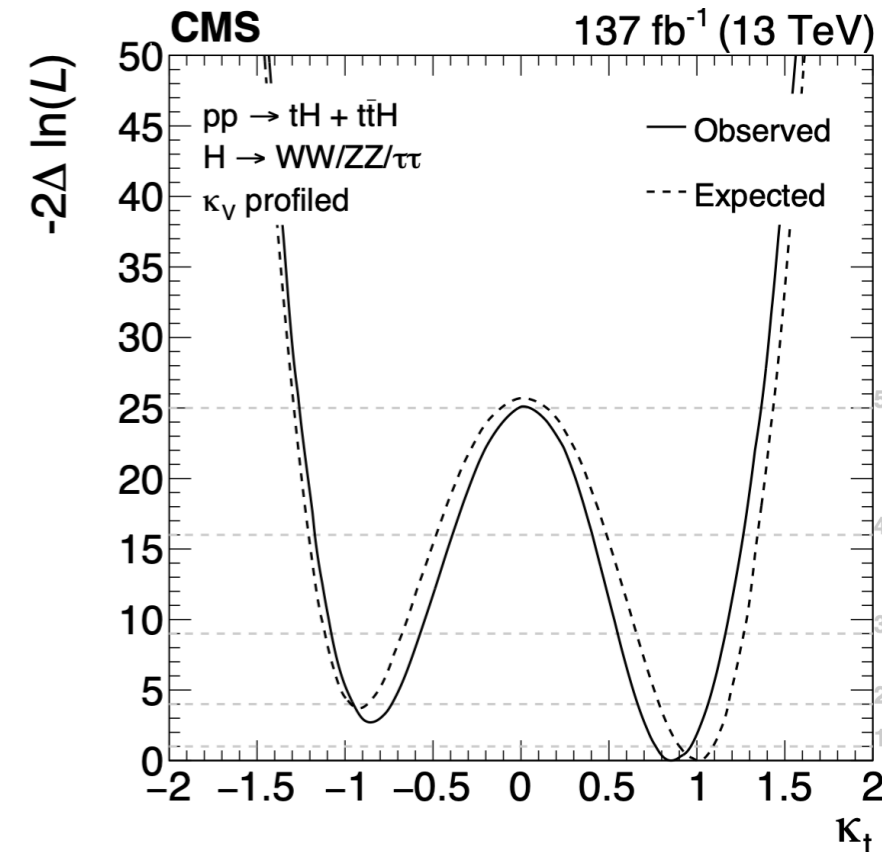
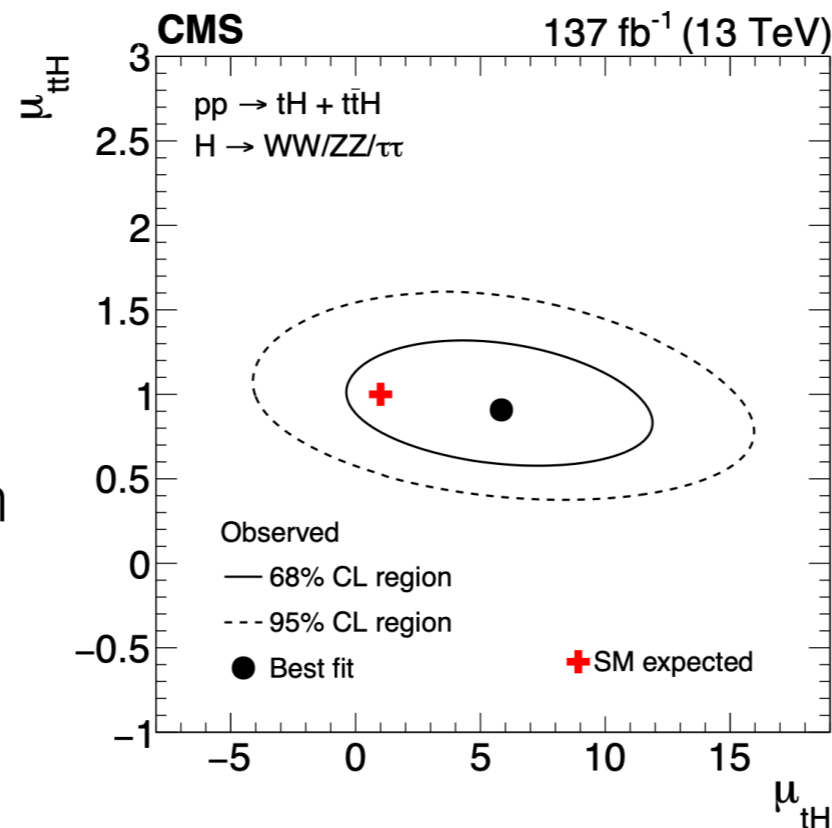
- Deep neural networks and BDTs



Simultaneous fit of ttH and tH signal strengths:

- Sensitivity to tH: 5-10x SM

Data prefers **positive sign** of top-Higgs coupling



CMS combination: $\mu_{tH} = 6 \pm 2.5$

Projections on κ_t : 3% precision at the HL-LHC (10% today) ([Nature 607 \(2022\) 60-68](#))

Conclusions

Single top cross sections

- **Differential** cross sections measured in **t-channel and tW channel**
- t-channel used for **top quark property** measurements
- **s-channel still to be observed at the LHC**

Top quark properties

- Properties of **Wtb vertex** (V_{tb} , CP-even/odd) and top quark polarization are explored
- **EFT framework** is gaining popularity

Top quark production associated with Z/ γ bosons

- **SM top quark - gauge boson coupling** well established
- Background for processes involving top and Higgs
- **Deviations searched for** with the Effective Field Theory framework

Top quark Yukawa coupling with tH process

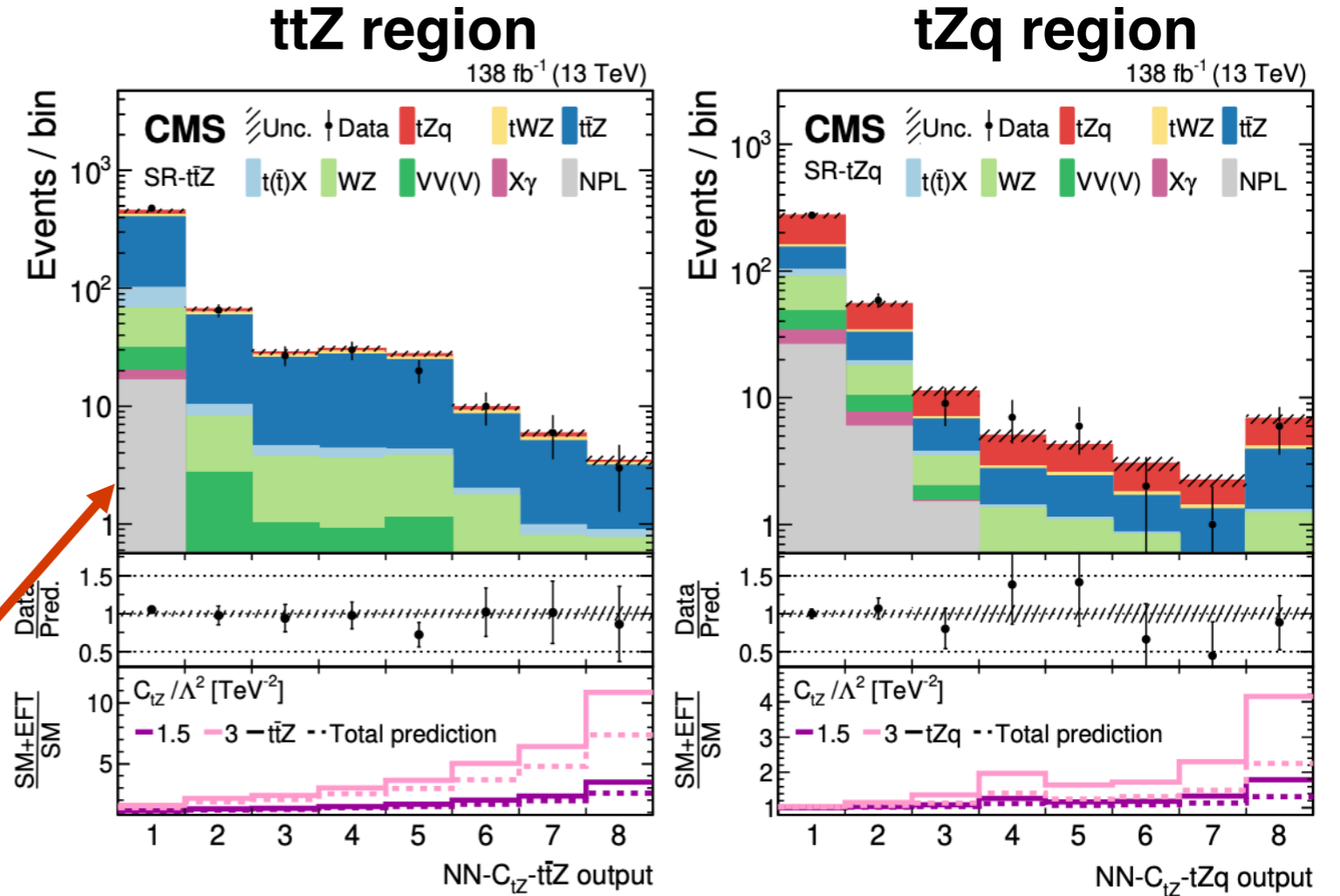
- **Top - Higgs coupling measured** with **ttH+tH** production
- **tH process still to be observed**

Back-up slides

top-Z couplings with Machine learning

[JHEP 12 \(2021\) 083](#)

- Neural network to **produce 3 classes of SM events:** enriched in ttZ events, tZq events and other events.
- Neural network to **discriminate SM signal from backgrounds.**
- Neural network to **discriminate new physics from SM.**
- **Simultaneous fit of 5 coefficients** in the **Effective Field theory** modifying top-Z coupling, parametrising deviations from SM.



WC / Λ^2 [TeV^{-2}]	95% CL confidence intervals			
	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
c_{tZ}	[-0.97, 0.96]	[-0.76, 0.71]	[-1.24, 1.17]	[-0.85, 0.76]
c_{tW}	[-0.76, 0.74]	[-0.52, 0.52]	[-0.96, 0.93]	[-0.69, 0.70]
$c_{\varphi Q}^3$	[-1.39, 1.25]	[-1.10, 1.41]	[-1.91, 1.36]	[-1.26, 1.43]
$c_{\varphi Q}^-$	[-2.86, 2.33]	[-3.00, 2.29]	[-6.06, 14.09]	[-7.09, 14.76]
$c_{\varphi t}$	[-3.70, 3.71]	[-21.65, -14.61] \cup [-2.06, 2.69]	[-16.18, 10.46]	[-19.15, 10.34]

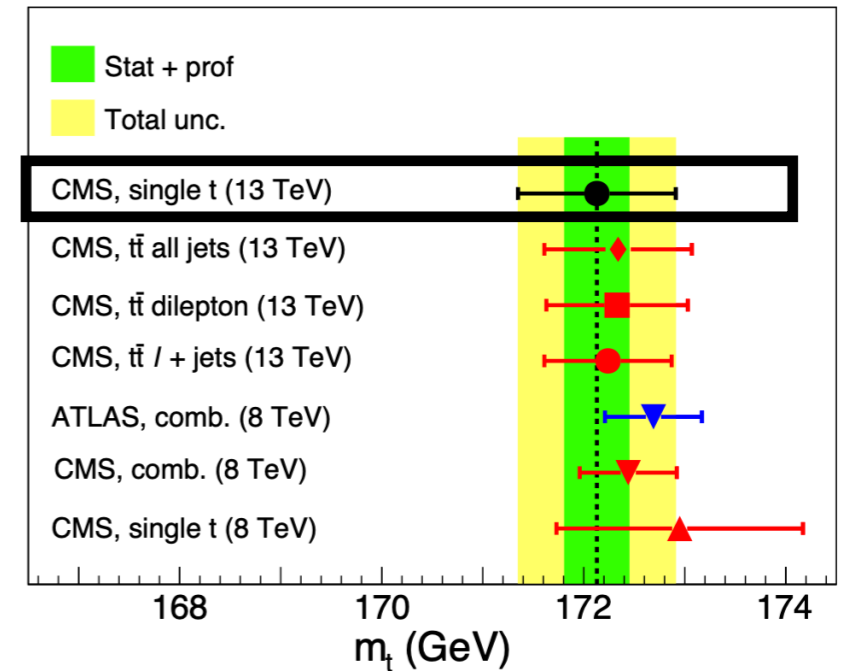
$$L = L_{SM} + \sum_i \frac{a_i}{\Lambda^2} O_i + \sum_j \frac{b_j}{\Lambda^4} O_j + \dots$$

top quark mass with t-channel

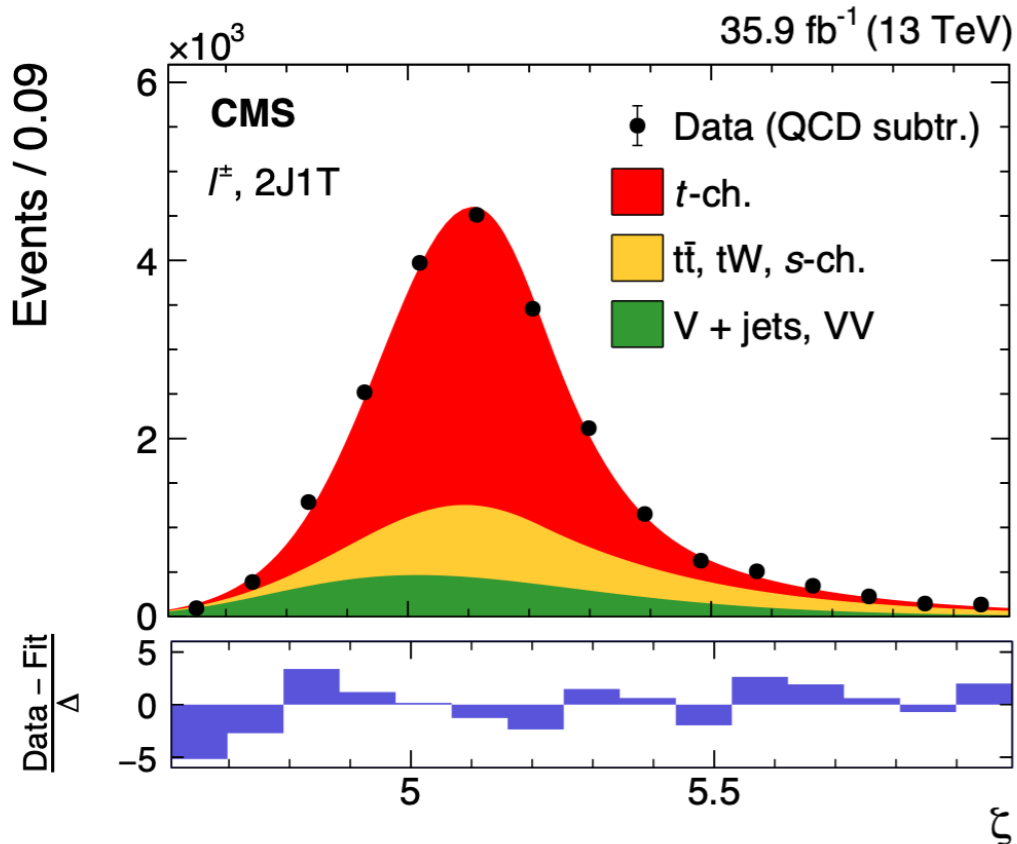
[JHEP 12 \(2021\) 161](#)

Measurement at 13 TeV:

- Main channel usually $t\bar{t}$ dilepton, but single top t-channel starts to be competitive
- Optimize selection with boosted decision tree
- Unbinned fit of $\ln(m_t)$ as discriminant variable
- Calibration of extracted m_t with true m_t



Main syst. uncertainties:

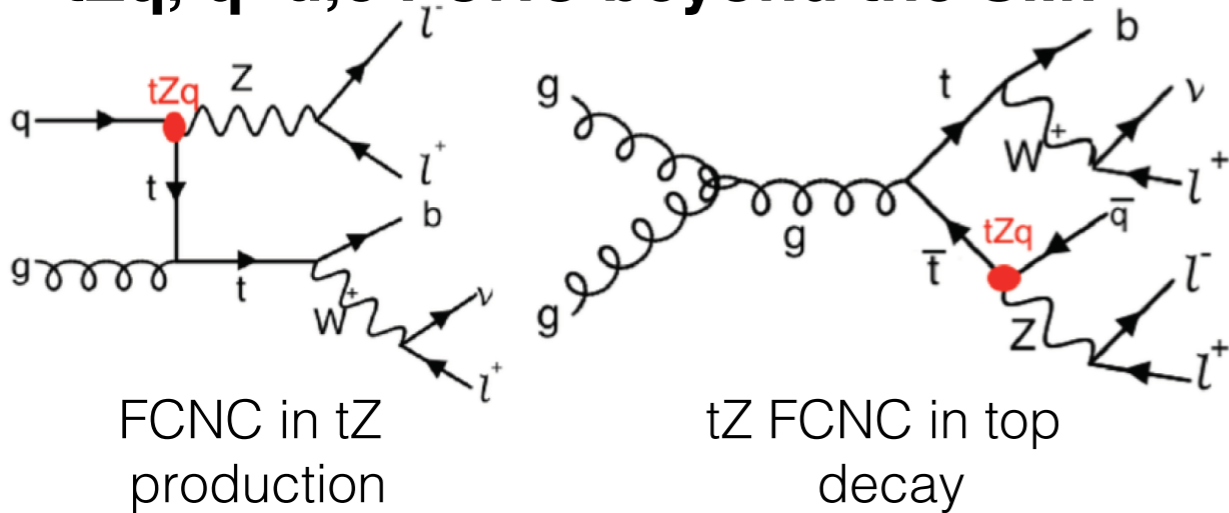


- Jet energy scale
- Color reconnection in hadron shower
- b-quark fragmentation model

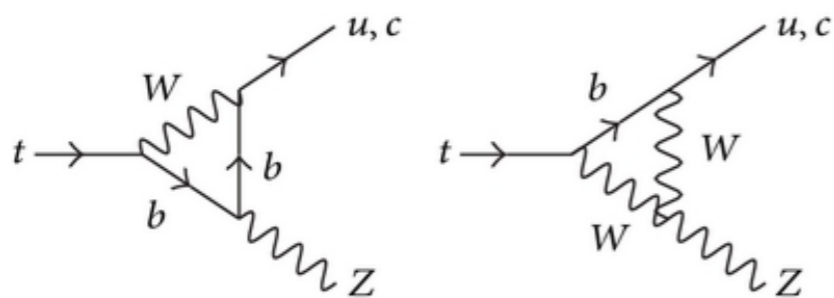
Source	δm_{t+}	δm_{t-}	δm_{t-}
Statistical	± 0.19	± 0.23	± 0.33
Statistical + profiled systematic	± 0.32	± 0.37	± 0.58
Correlation group intercalibration	± 0.09	± 0.07	± 0.12
Correlation group MPFinSitu	± 0.02	± 0.02	± 0.01
Correlation group uncorrelated	± 0.39	± 0.17	± 0.83
Total (quadrature sum)	± 0.40	± 0.18	± 0.84
JES	< 0.01	< 0.01	< 0.01
JER	< 0.01	< 0.01	< 0.01
Unclustered energy	< 0.01	< 0.01	< 0.01
Muon efficiencies	< 0.01	< 0.01	< 0.01
Electron efficiencies	± 0.01	± 0.01	± 0.01
Pileup	± 0.14	± 0.04	± 0.34
b tagging	± 0.20	± 0.18	± 0.22
QCD multijet background	± 0.02	± 0.01	± 0.02
Mass calibration	± 0.11	± 0.13	± 0.20
Int. luminosity	< 0.01	< 0.01	< 0.01
CR model and ERD	± 0.24 (0.017)	± 0.39 (0.027)	± 0.68 (0.048)
Flavor-dependent JES			
Gluon	$+0.52$	$+0.75$	-0.03
Light quark (uds)	-0.18	-0.18	-0.23
Charm	$+0.01$	$+0.08$	$+0.11$
Bottom	-0.48	-0.29	-0.31
Total (linear sum)	-0.13	-0.72	-0.46
b frag. Bowler-Lund	± 0.03	± 0.06	± 0.08
b frag. Peterson	$+0.14$	$+0.11$	$+0.19$
b quark hadronization model			
Semileptonic b hadron decays	$+0.18$	± 0.17	± 0.19
Total (quadrature sum)	$+0.23$ -0.18	$+0.21$ -0.18	$+0.28$ -0.21
Signal modeling			
ISR	± 0.01	± 0.01	< 0.01
FSR	± 0.28	± 0.31	± 0.20
μ_R and μ_F scales	± 0.09	± 0.13	± 0.03
PDF+ α_S	± 0.06	± 0.06	± 0.07
Total (quadrature sum)	± 0.30	± 0.34	± 0.21
ISR	± 0.11 (0.008)	± 0.02 (0.001)	± 0.22 (0.016)
FSR	± 0.10 (0.007)	± 0.14 (0.010)	± 0.40 (0.028)
ME-PS matching scale	± 0.10 (0.007)	± 0.10 (0.006)	± 0.10 (0.008)
μ_R and μ_F scales	± 0.03	± 0.03	± 0.01
PDF+ α_S	< 0.01	< 0.01	< 0.01
Top quark p_T reweighting	-0.04	-0.08	-0.04
UE	± 0.07 (0.005)	± 0.04 (0.003)	± 0.17 (0.012)
Total (quadrature sum)	± 0.20	$+0.18$ -0.20	± 0.50
Signal shape	± 0.05	± 0.03	± 0.04
t \bar{t} bkg. shape	± 0.07	± 0.04	± 0.05
EW bkg. shape	± 0.03	± 0.01	± 0.02
Total (quadrature sum)	± 0.09	± 0.05	± 0.07
Parametric shapes			
Total externalized systematic	$+0.69$ -0.71	$+0.97$ -0.65	$+1.32$ -1.39
Grand total	$+0.76$ -0.77	$+1.04$ -0.75	$+1.44$ -1.51

Flavour Changing Neutral Currents

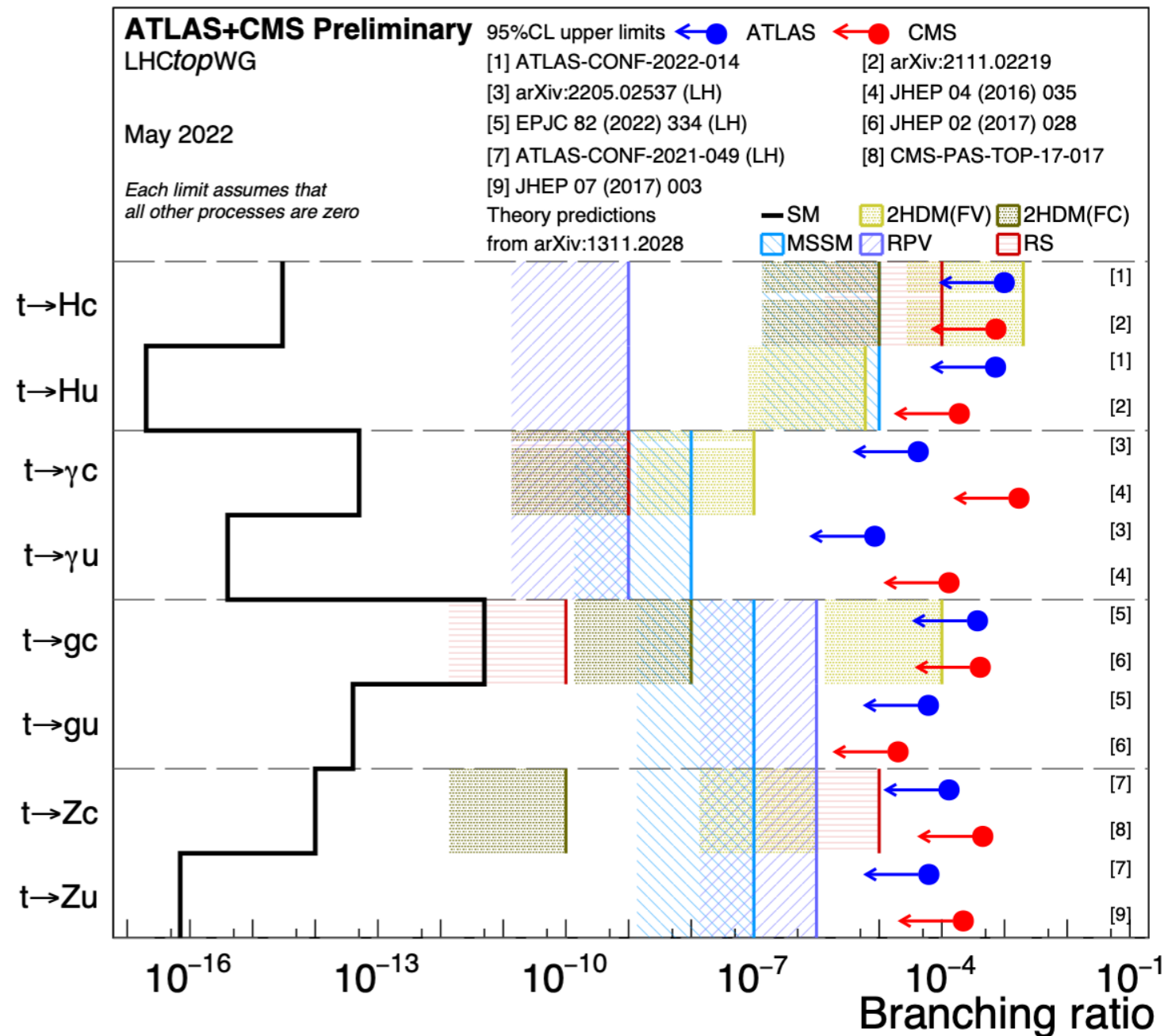
tZq , $q=u,c$ FCNC beyond the SM:



SM tZq coupling, $q=u,c$ via loops are suppressed by GIM mechanism)

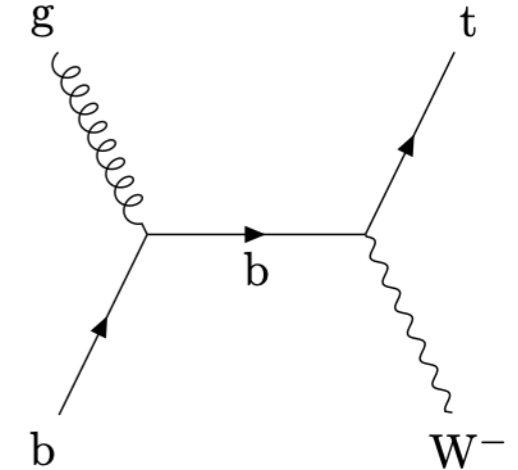


Summary: approaching sensitivity to several BSM models



tW cross section in lepton+jets channel

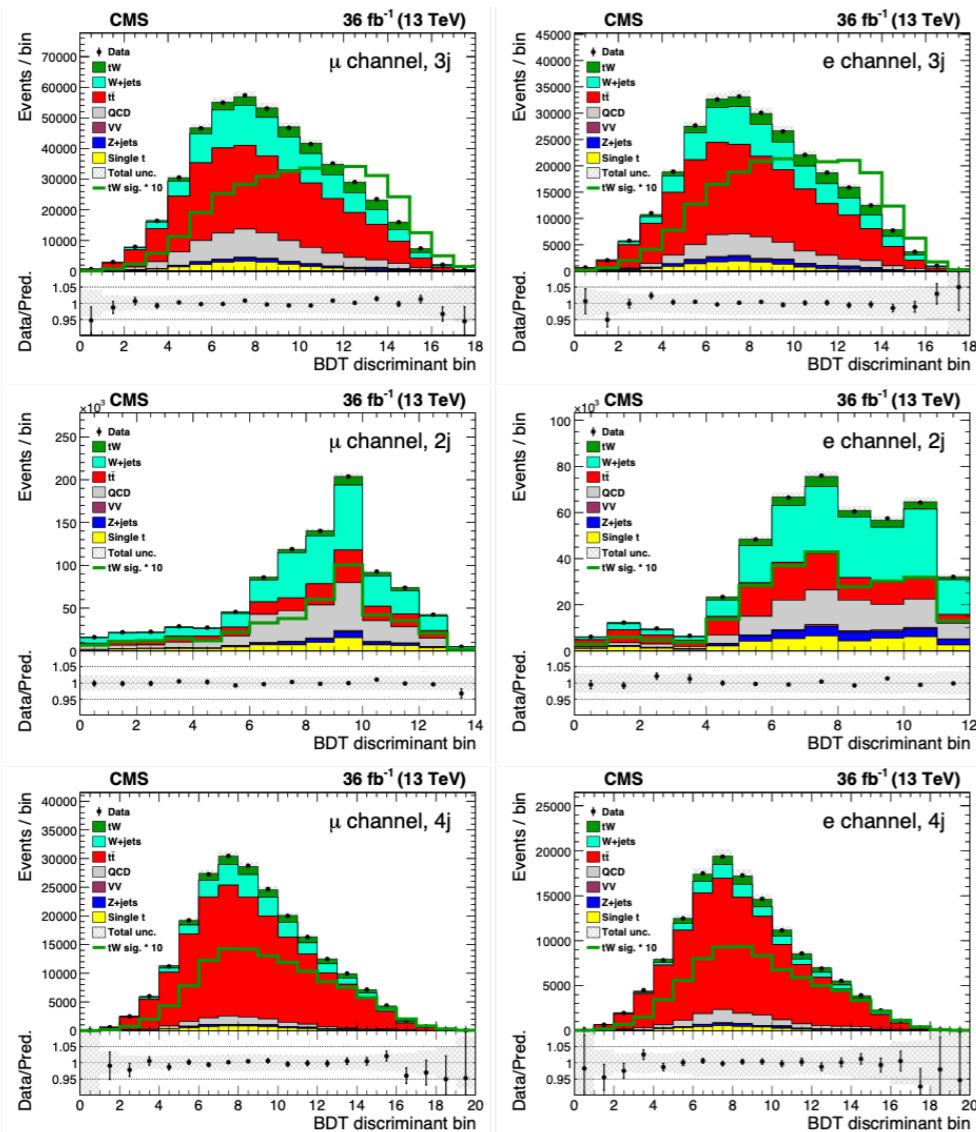
[JHEP 11 \(2021\) 111](#)



- A **BDT** is trained against ttbar, exploiting the difference in jet kinematics
- tW extraction likelihood fit of the **3 regions**: 2 jets (W+jets control region), 3 jets (signal region) and 4 jets (ttbar control region)

First observation of tW process in l+jets channel ($>5\sigma$)

Cross section: 89 ± 4 (stat) ± 12 (syst) pb



Source	Relative uncertainty (%)
<i>Experimental</i>	
Jet energy scale	6
b tagging efficiency	4
Luminosity	3
Lepton energy scale	2
Trigger efficiency	1
Jet energy resolution	1
b tagging misidentification rate	<1
Unclustered energy	<1
Pileup	<1
<i>Normalization</i>	
QCD multijet normalization	7
W+jets normalization	6
Z+jets normalization	3
Single t normalization	1
tt normalization	1
VV normalization	<1
<i>Theoretical</i>	
h_{damp}	4
Diagram removal/diagram subtraction	3
Underlying event tune	3
Colour reconnection model	1
Parton distribution function	1
Matrix element/parton shower matching	1
Final-state radiation	<1
Initial-state radiation	<1
Total systematic uncertainty	14
Statistical uncertainty	5
Total uncertainty	15

Searching for deviations with the EFT

Effective Field Theory:

- **New physics at higher energy scale Λ** would manifest itself at the electroweak scale as **small deviations relative to the SM**, that can be detected
- Construct all the **operators** involving SM fields with new interactions, respecting gauge invariance: SM-EFT
- This approach is mostly “**model-independent**”

$$L = L_{SM} + \sum_i \frac{a_i}{\Lambda^2} O_i + \sum_j \frac{b_j}{\Lambda^4} O_j + \dots$$

Dimension 4 operators in the SM Lagrangian

Dimension 6 operators

Wilson coefficients

- **Real** part of Wilson coefficient is **CP-conserving**, **imaginary** part is **CP-violating**

Higgs boson decay

Higgs decay width at 125 GeV: $\Gamma \sim 4$ MeV

$H \rightarrow bb$ (57.7%)

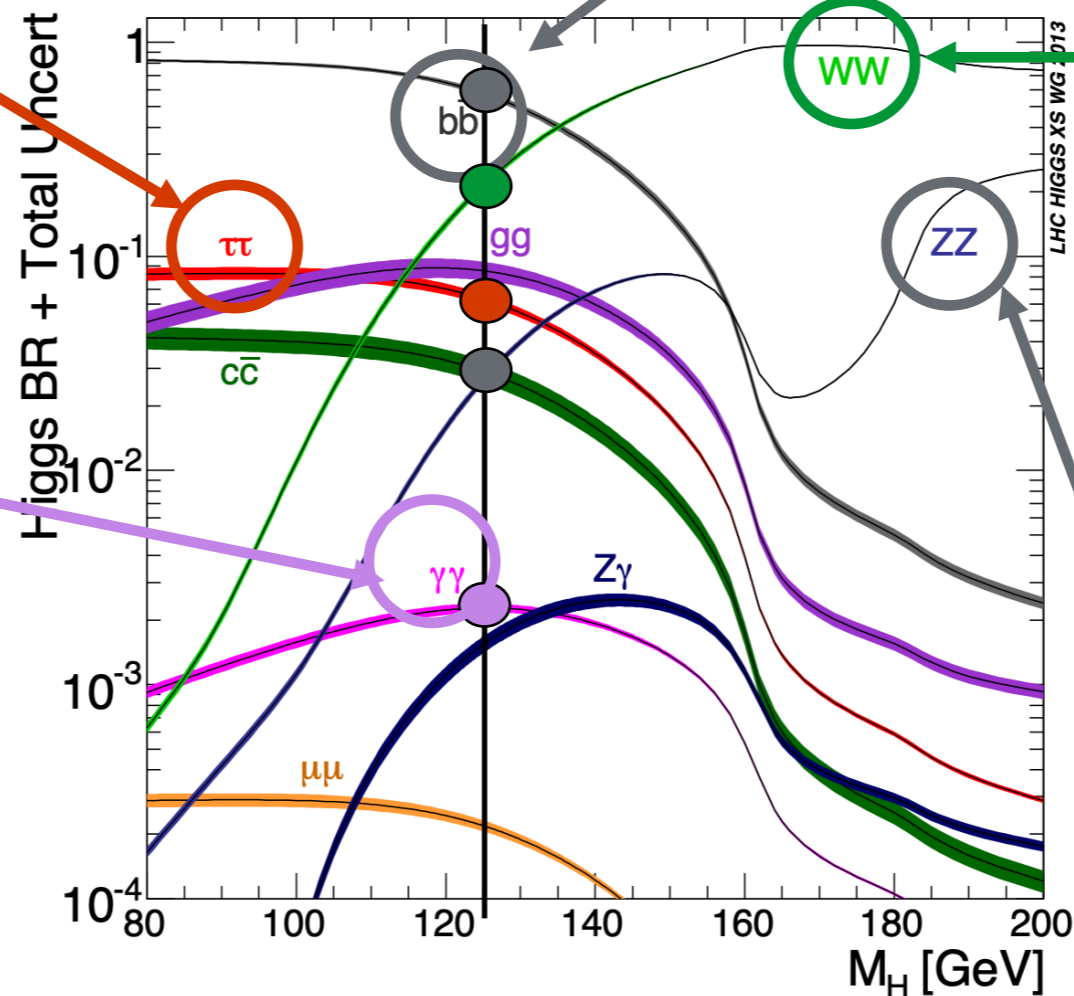
- Large branching ratio
- But large jets background

$H \rightarrow \tau\tau$ (6.3%)

- Hadronic or leptonic τ decay

$H \rightarrow \gamma\gamma$ ($\sim 0.2\%$)

- Excellent mass resolution,
- But low branching ratio



$H \rightarrow WW$ (21.5%)

$H \rightarrow ZZ$ (2.6%)
 - $ZZ \rightarrow 4l$: excellent mass resolution

$H \rightarrow WW$ (and $H \rightarrow ZZ$), $H \rightarrow \tau\tau$ final state:
 tackled with the “**multilepton**” analysis

CP violation in top coupling with $t\bar{t}H$

[CMS - arXiv:2208.02686](#)

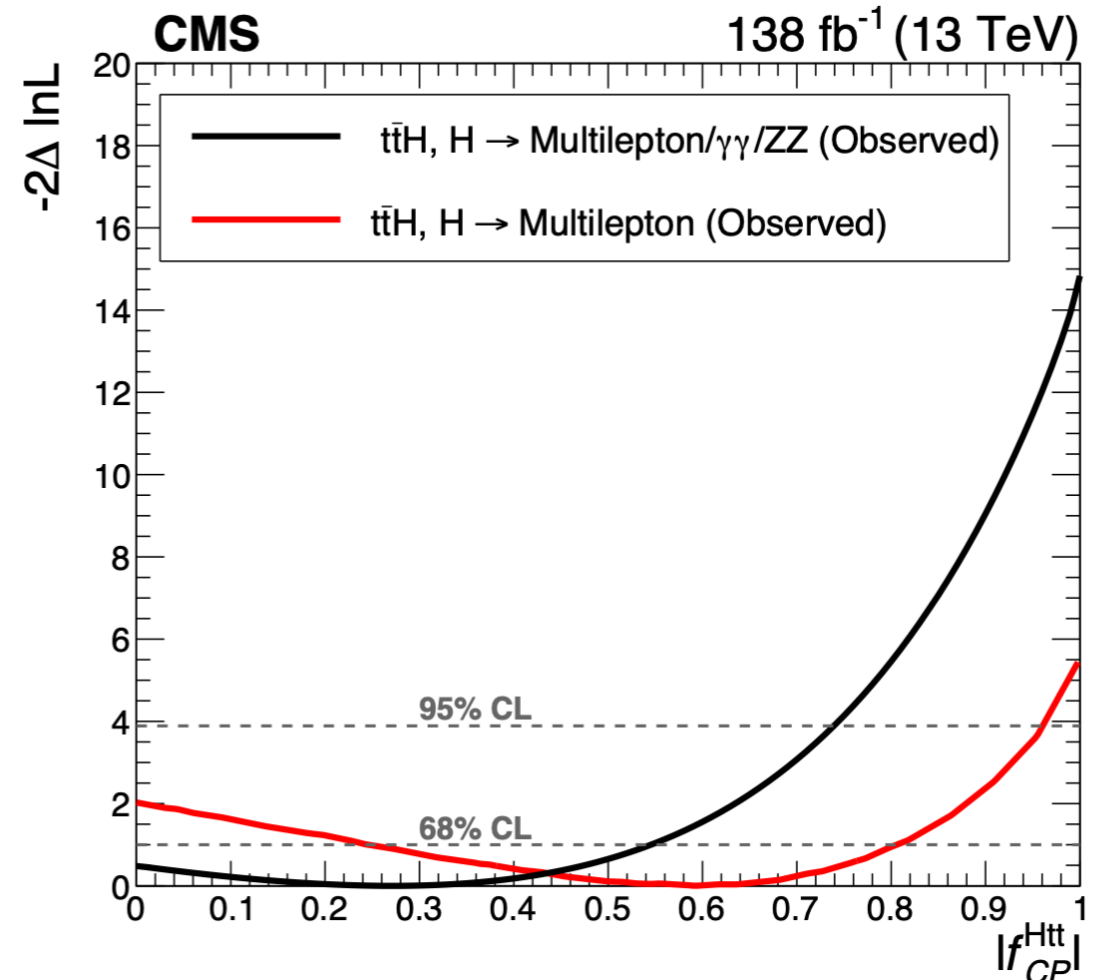
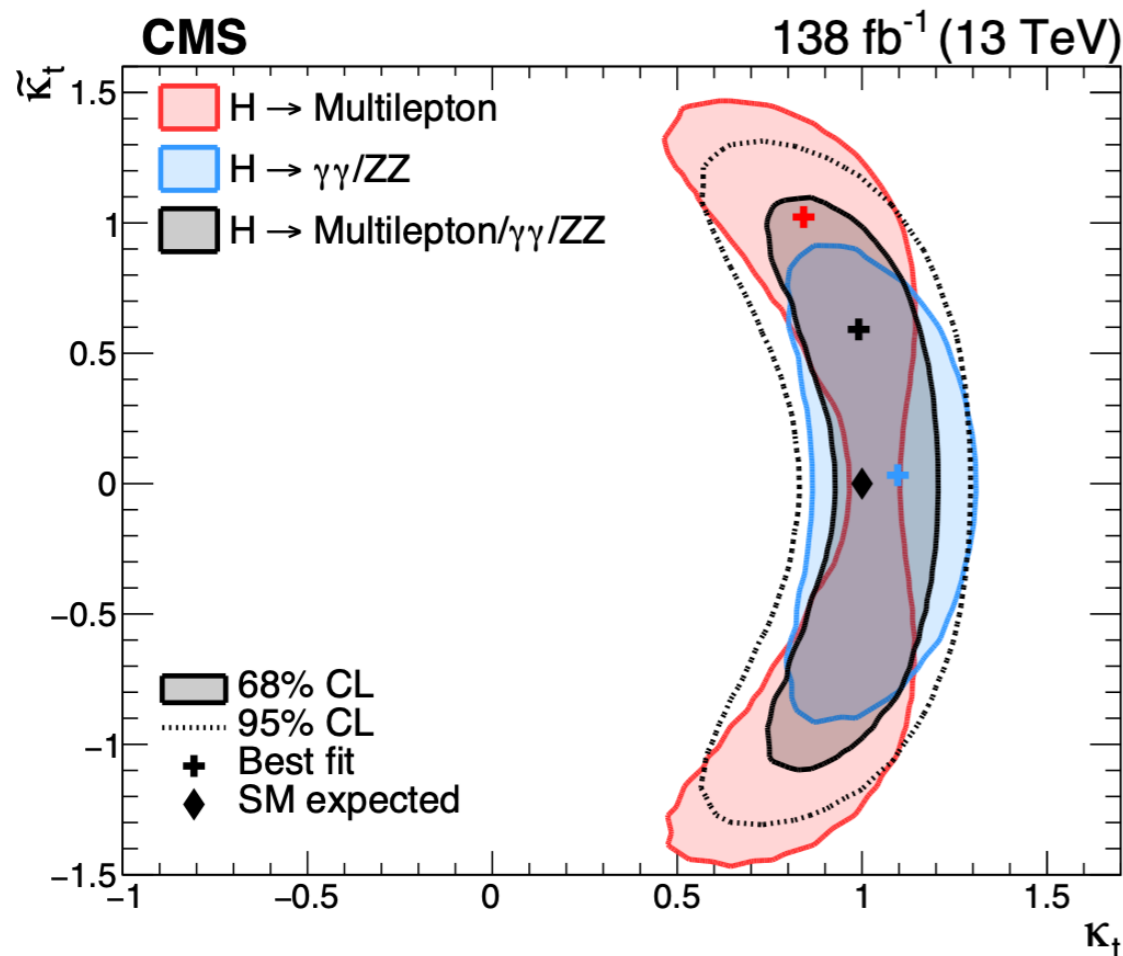
Why universe is there a matter/antimatter asymmetry in the Universe ?

- Sakharov conditions: baryogenesis needs **CP violation** (not only)
- Amount of CP violation in the SM is not sufficient: new sources are searched for.
- The top quark impacts electroweak baryogenesis if its Yukawa coupling is CP-violating (see for instance arXiv:1512.08922)

$$\mathcal{L}(Hff) = -\frac{m_f}{v} \bar{\psi}_f (\kappa_f + i \tilde{\kappa}_f \gamma_5) \psi_f H$$

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \text{sign}(\tilde{\kappa}_t/\kappa_t)$$

$$|f_{CP}^{Htt}| < 0.55 \text{ at 68\% confidence level}$$



negative values tested