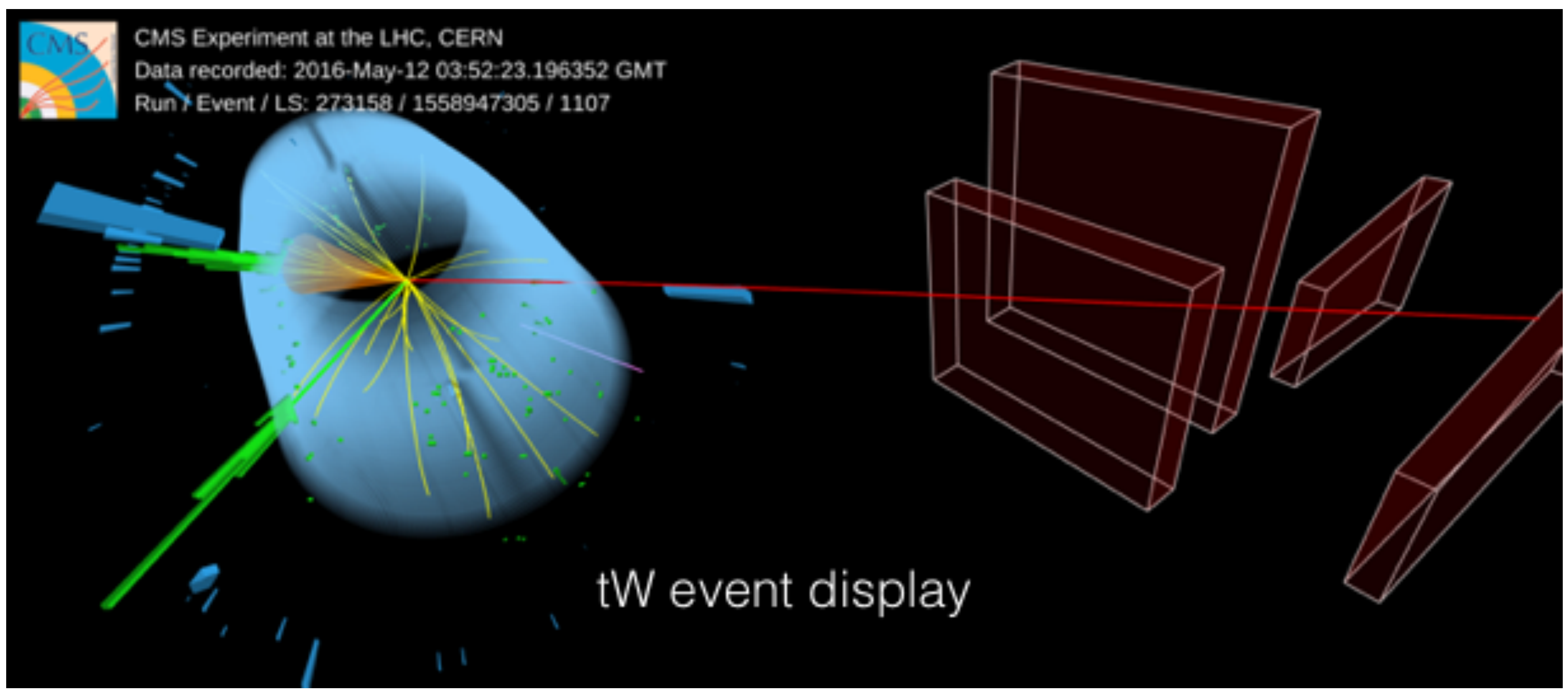
Review of single top quark physics

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**

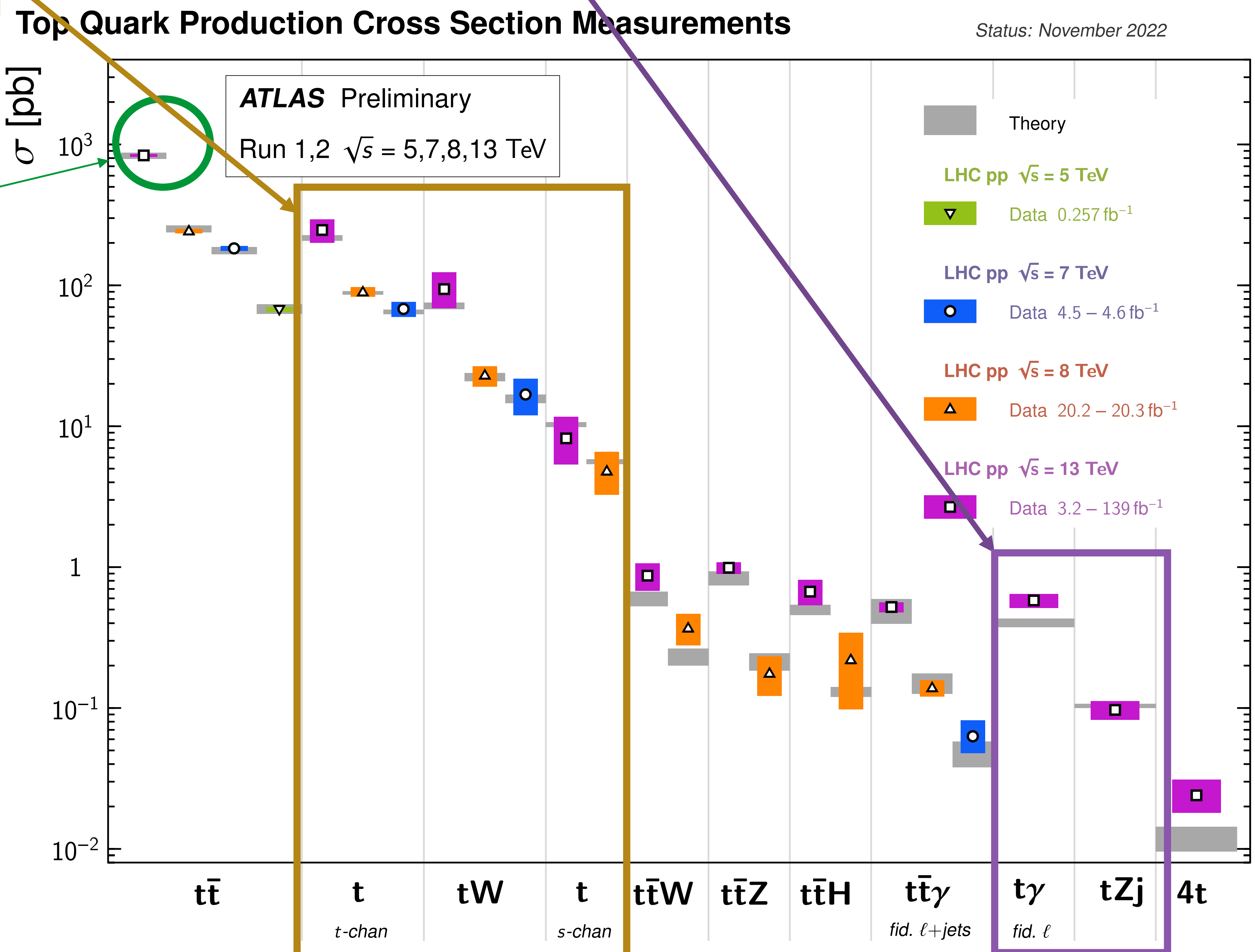
Processes considered in this seminar

Single top quark production

Processes involving **single top + gauge bosons**

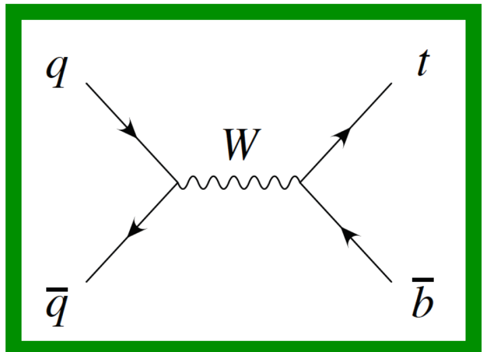
Consider "rare" top quark production

ttbar at 13 TeV: ~820 pb

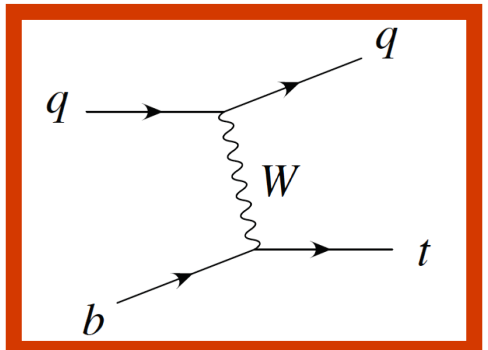


+tHj

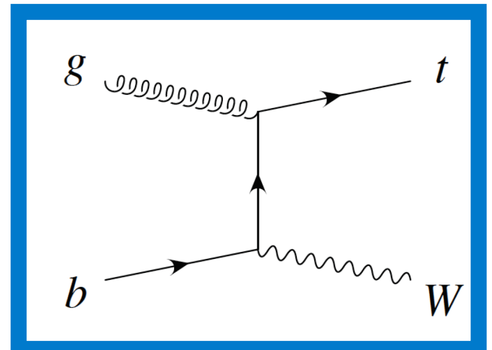
Single top quark cross sections



s-channel

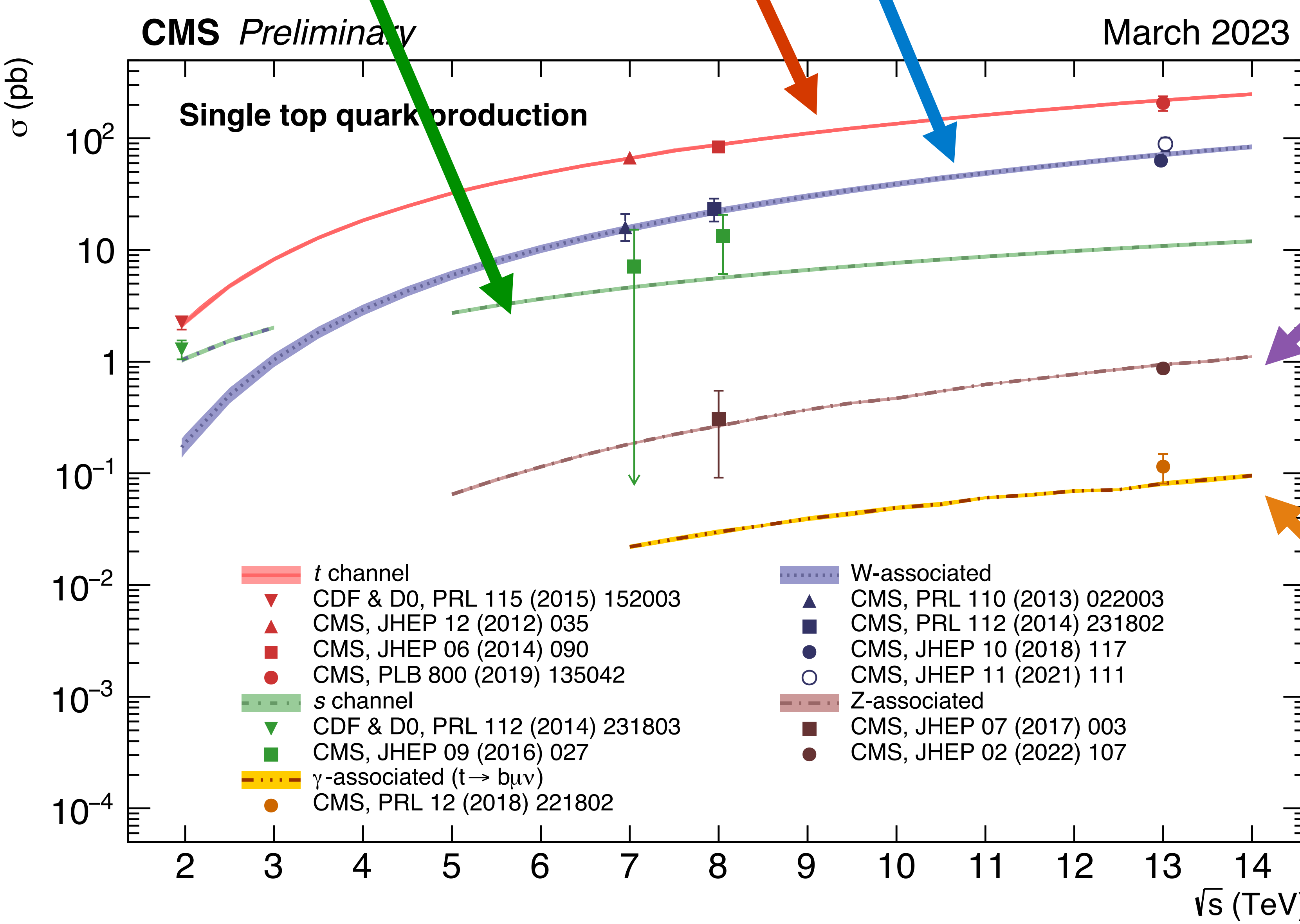


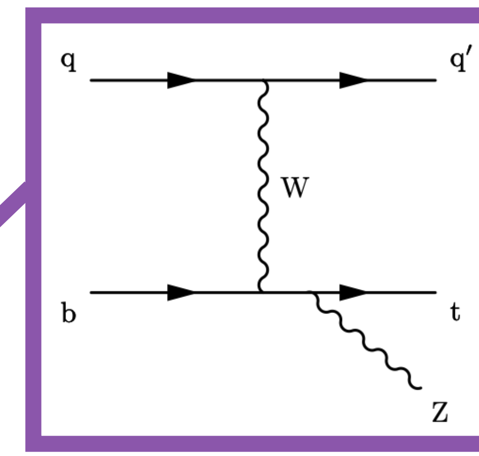
t-channel



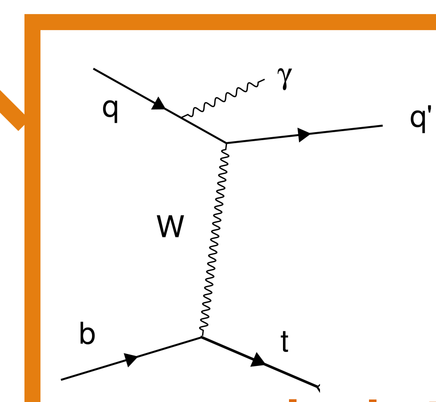
tW-channel

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





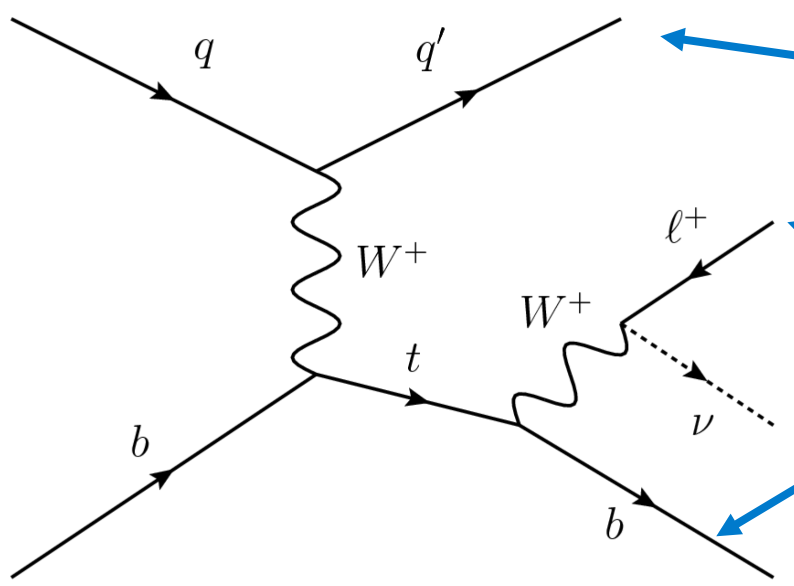
single top +Z



single top +photon

t-channel differential cross section

CMS - Eur. Phys. J. C 80 (2020) 370

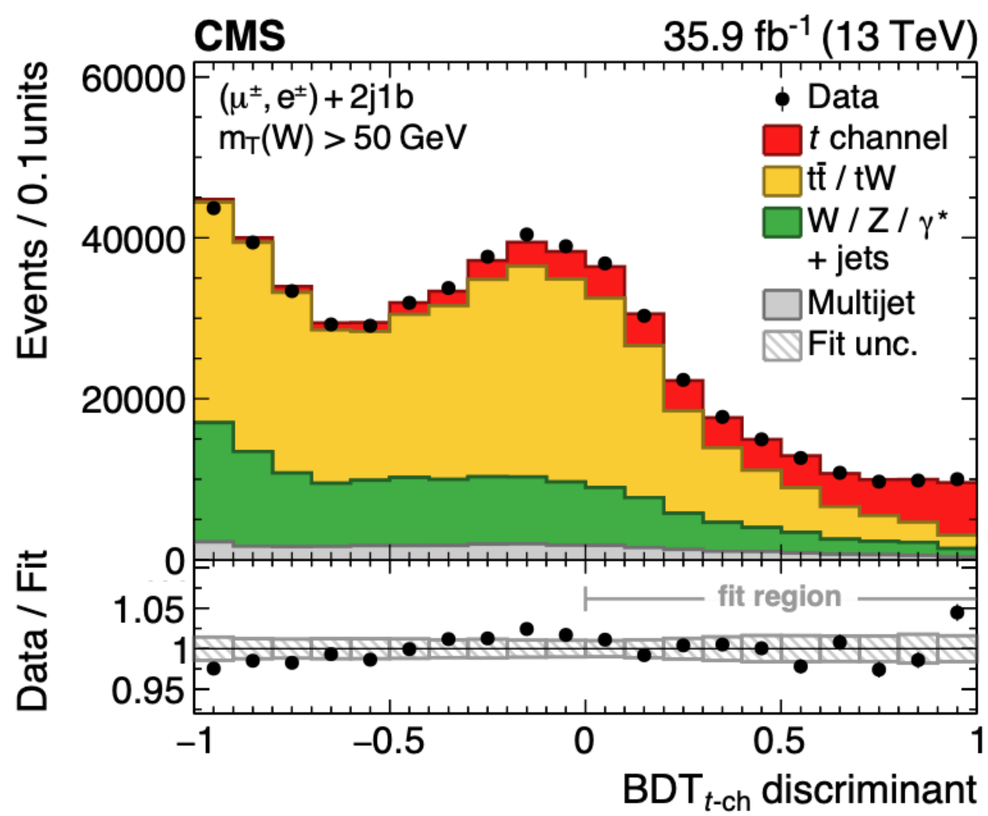


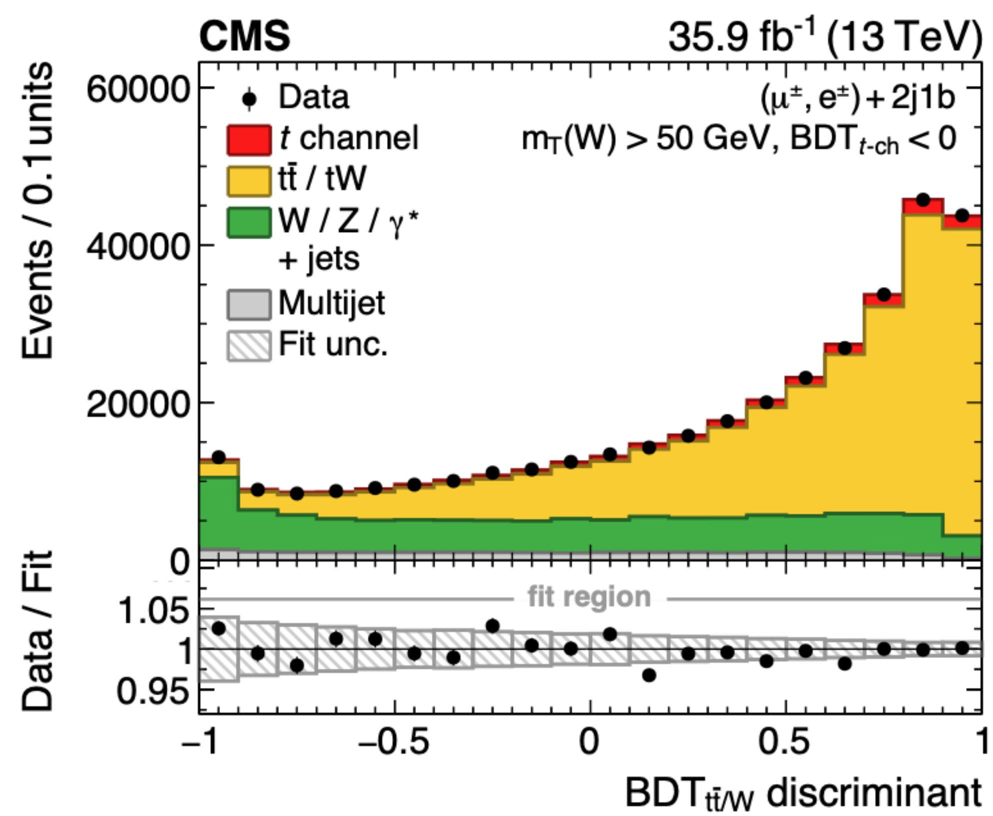
- Jet pT > 40 GeV in |η|<4.7: **t-channel** is an **electroweak** production: features a **forward jet**
- 1 Muon (electron) pT > 26 (35) GeV.
- One b-jet in |η|<2.4 (tracker acceptance)

- **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)



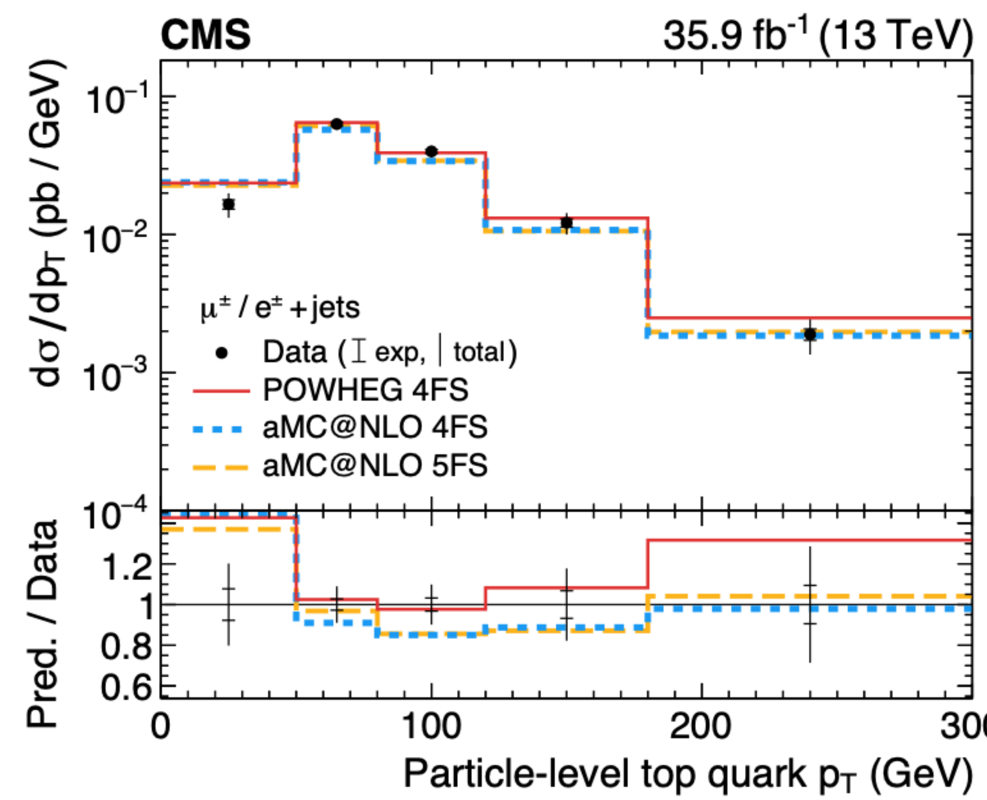


t-channel differential cross section

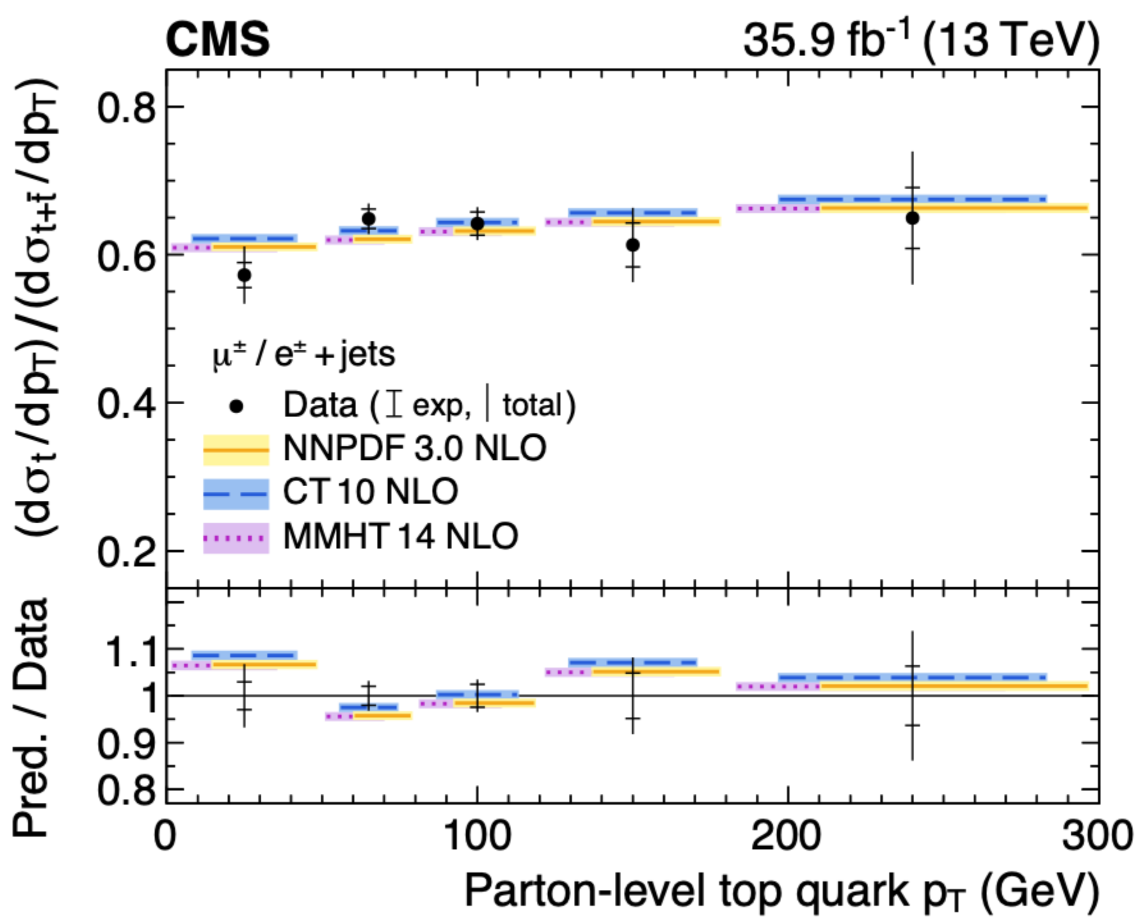
CMS - Eur. Phys. J. C 80 (2020) 370

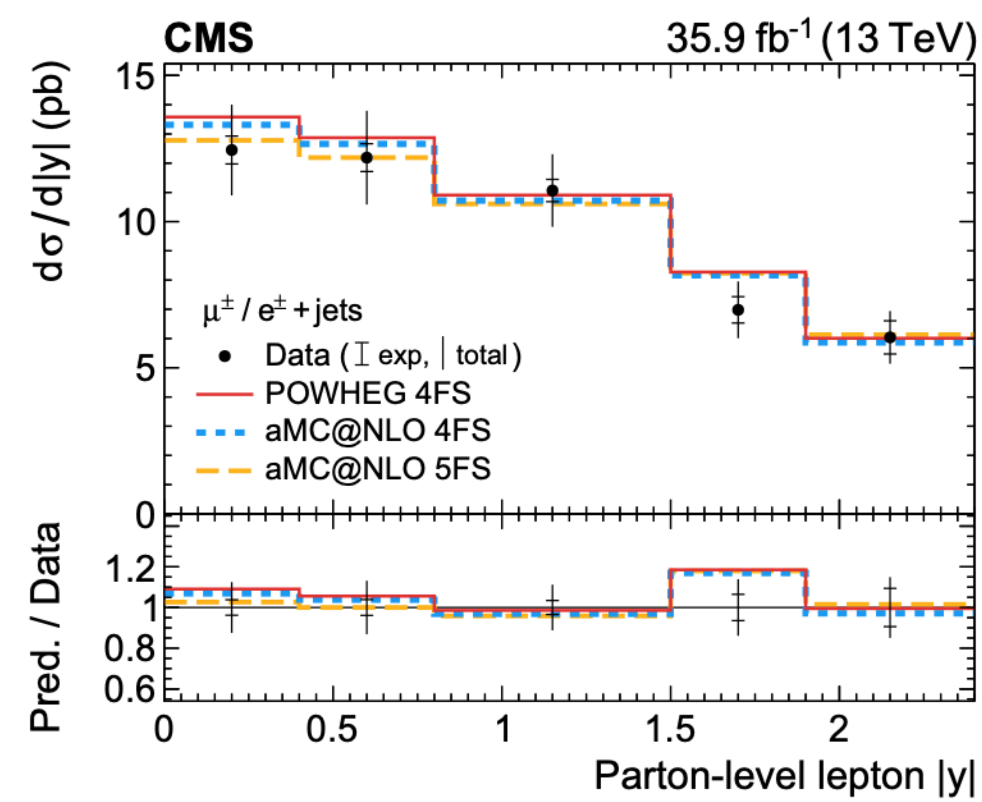
Differential cross sections:

- 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 pT

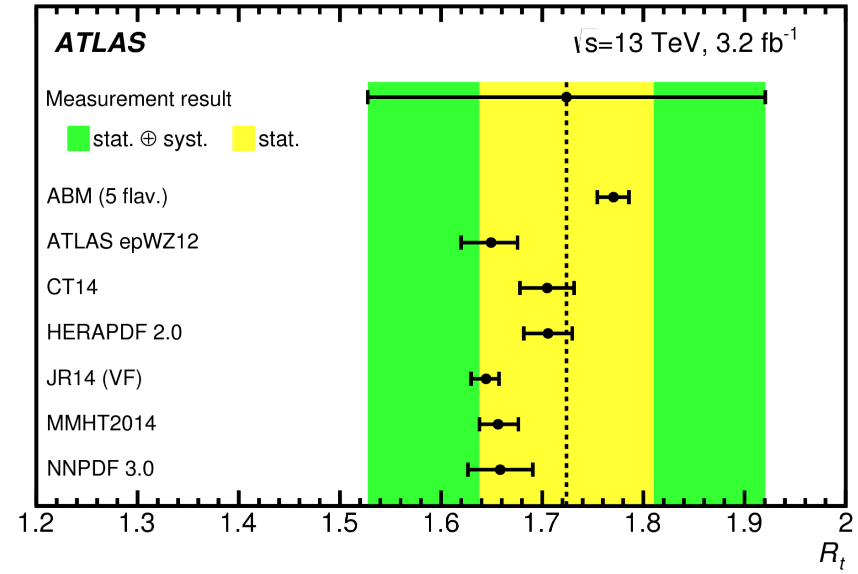




t-channel differential cross section 8 TeV

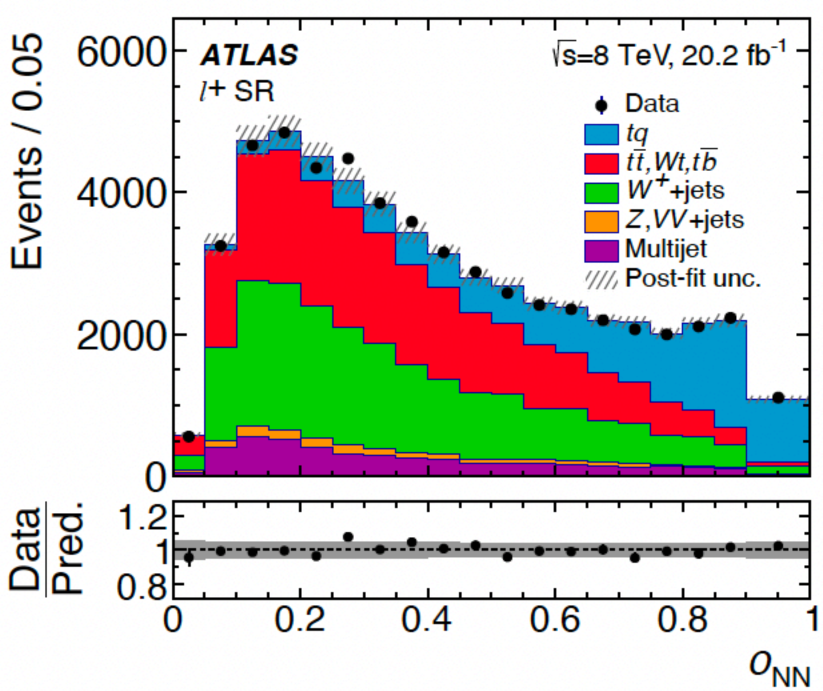
ATLAS - JHEP 04 (2017) 086, Eur. Phys. J. C 77 (2017) 531

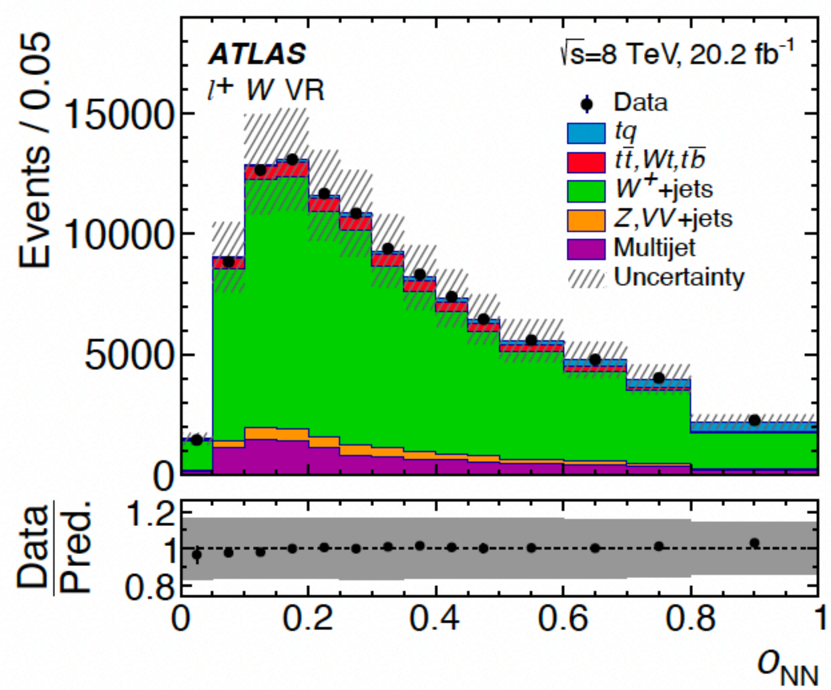
ATLAS 13TeV: inclusive cross section

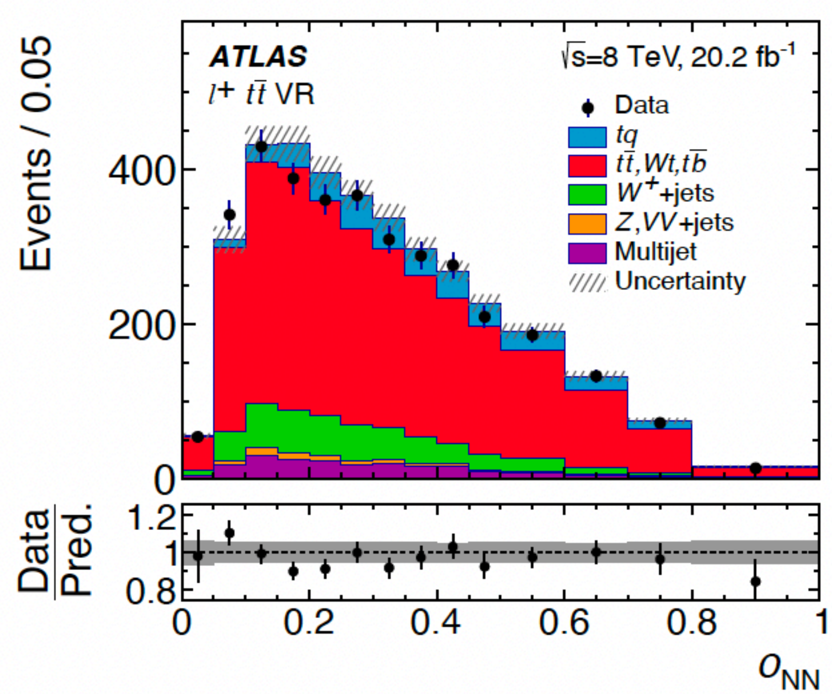


ATLAS 8 TeV, similar selection as CMS :

- 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.





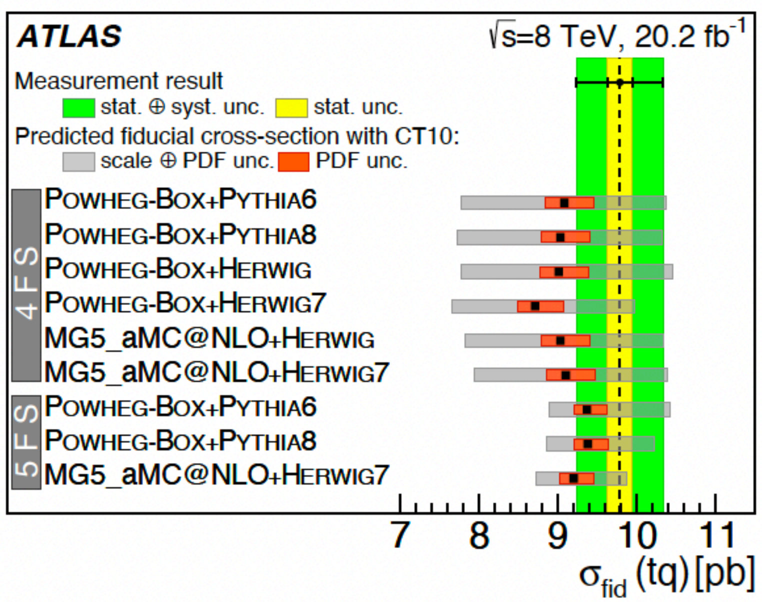


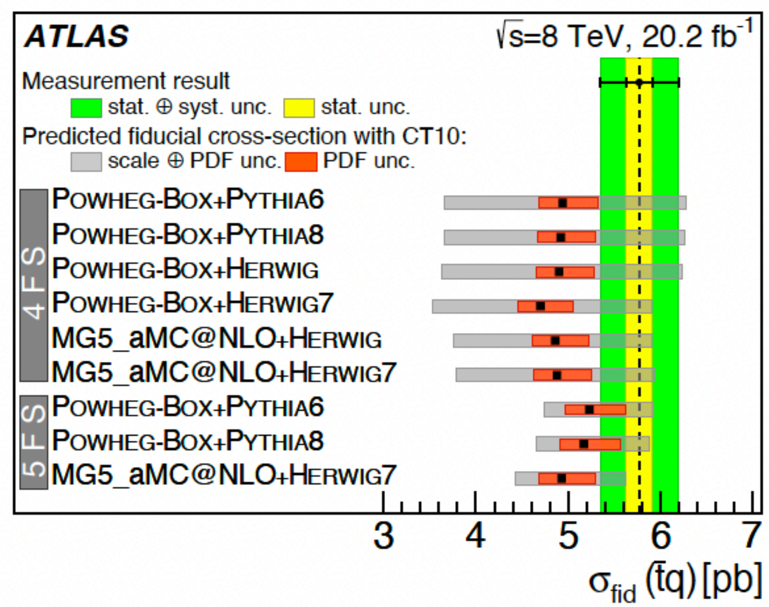
t-channel differential cross section

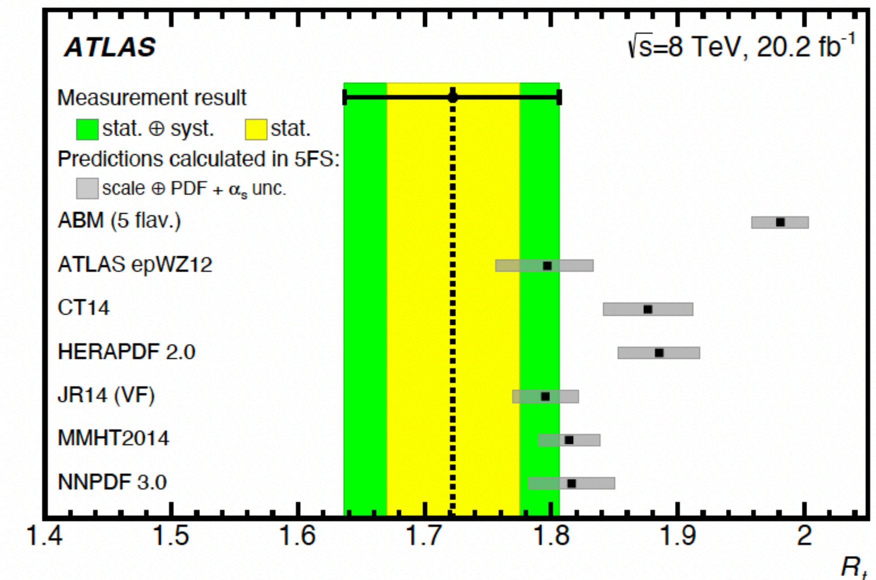
ATLAS - Eur. Phys. J. C 77 (2017) 531

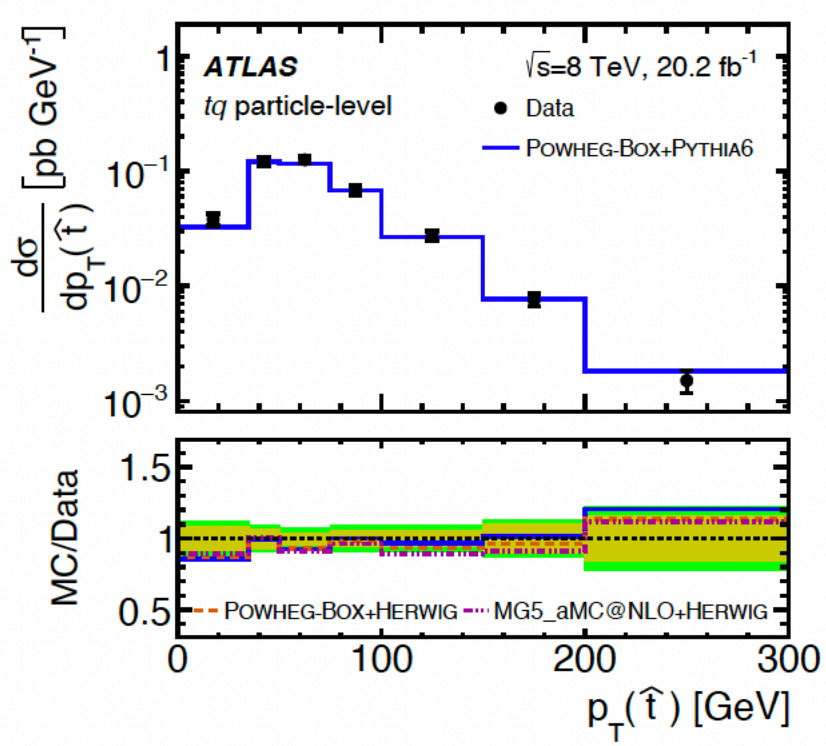
Fiducial and **differential** cross sections for **top** and **antitop**

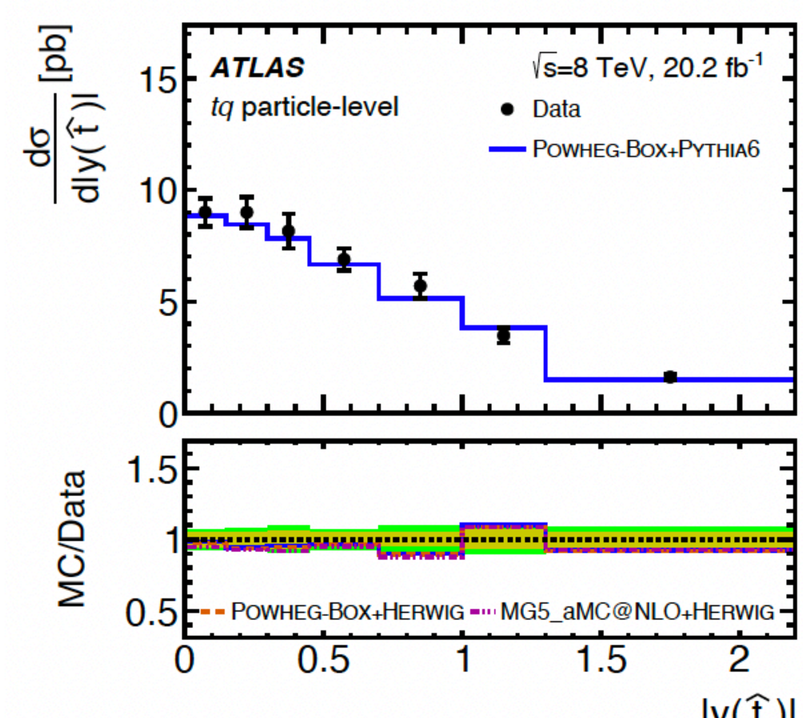
Ratio of top to antitop:
Tensions with data?





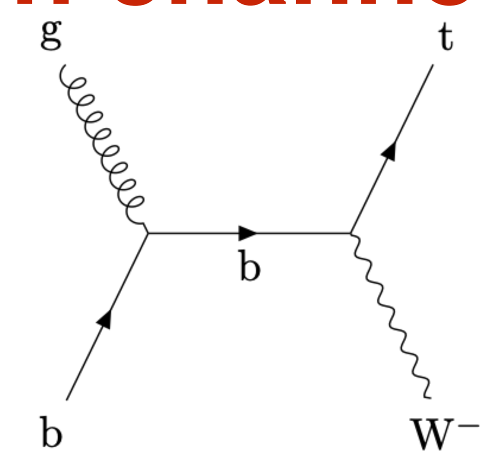






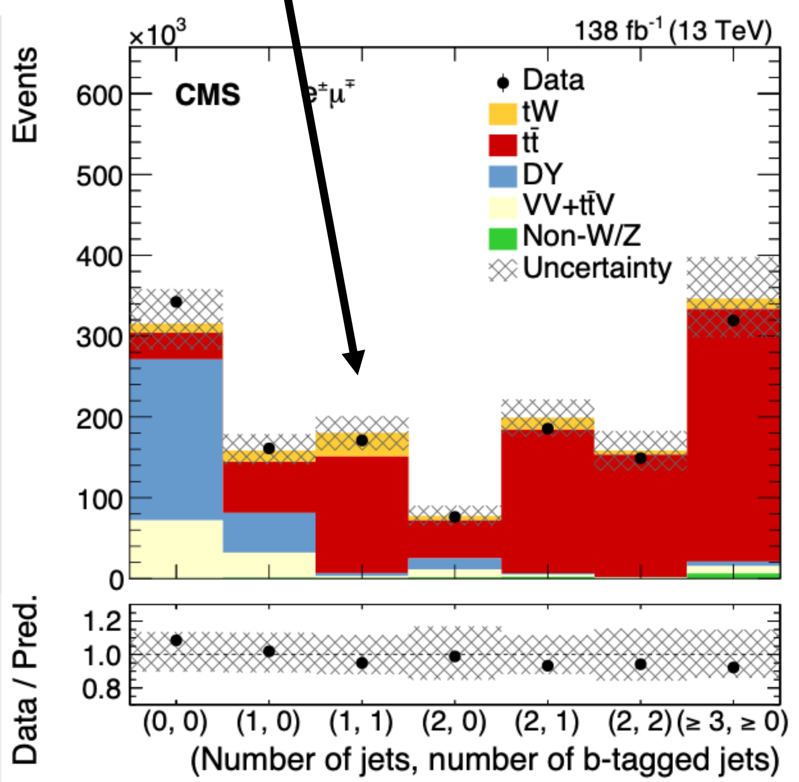
tW differential measurement in dilepton channel

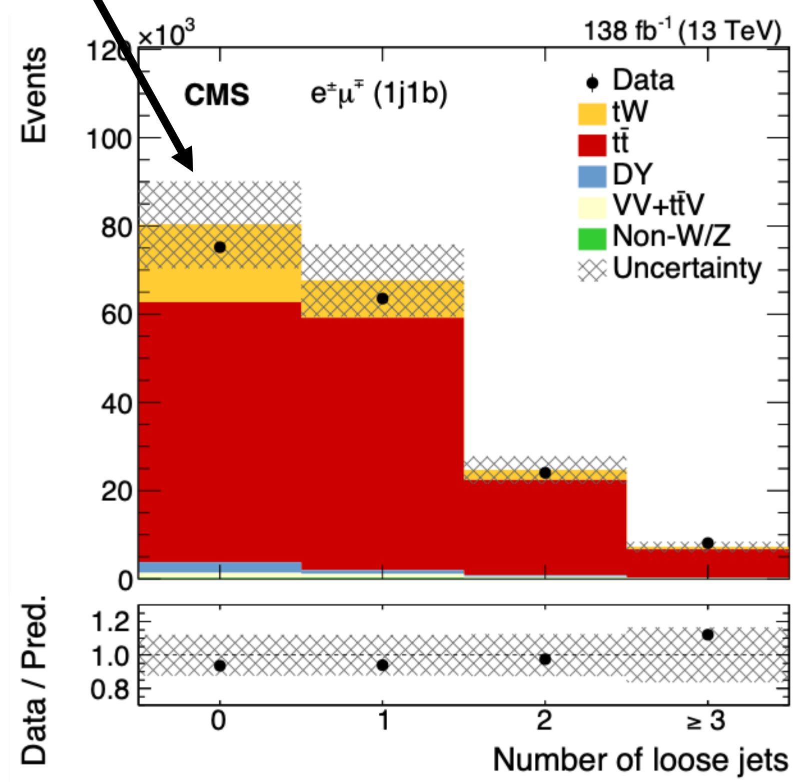
[CMS - arXiv:2208.00924]

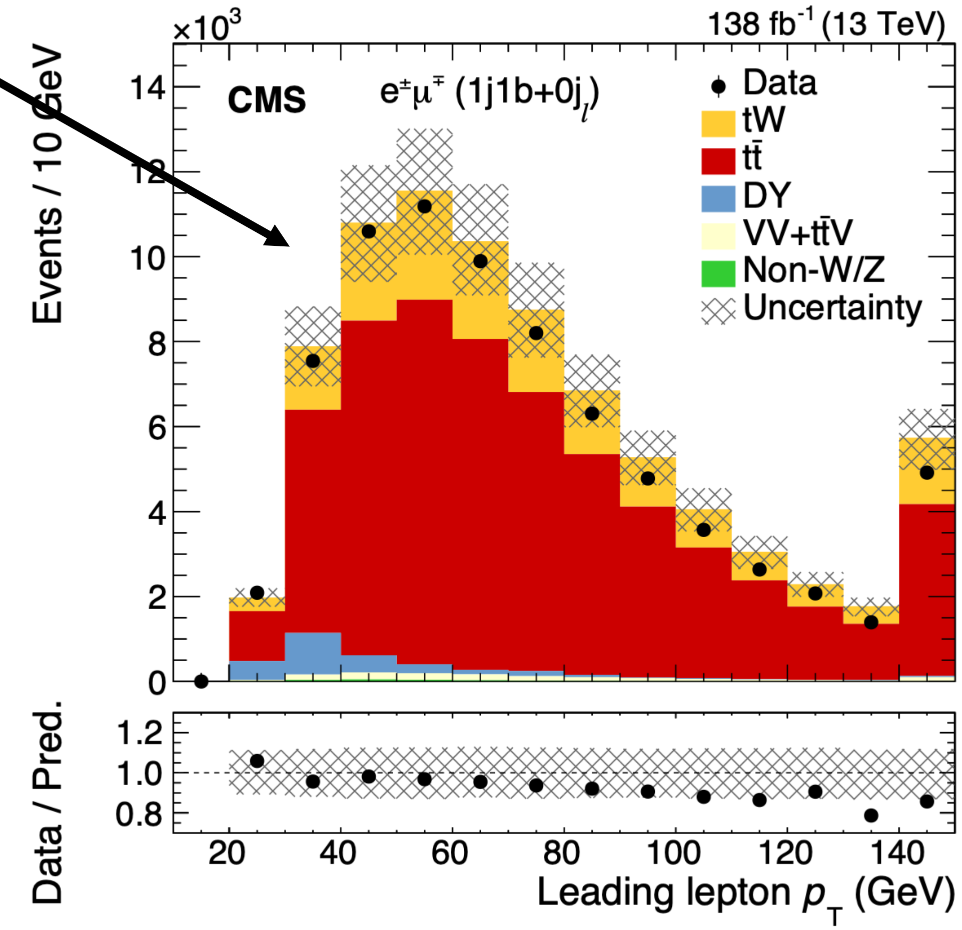


eμ channel analyzed:

- Two isolated leptons with pT>25, 20 GeV
- mll>20 GeV, jets pT>30 GeV
- **Signal region** defined as:
    - exactly 1 jet tagged as b-jet,
    - and 0 additional loose jets







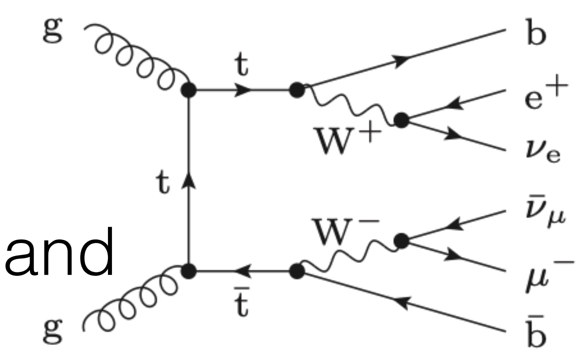
- **ttbar** and other background **estimated from simulation,** normalised by a fit to data

tW differential measurement in dilepton channel

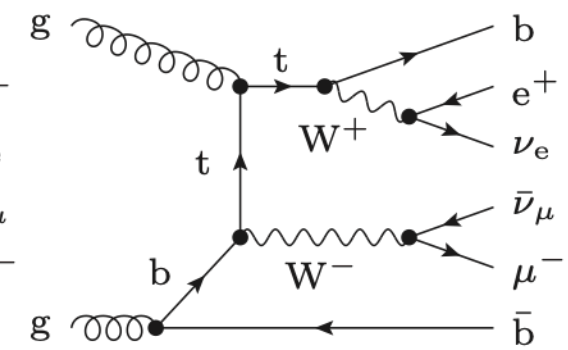
[CMS - arXiv:2208.00924, ATLAS - EPJC78(2018)186]

Interference between tW NLO and ttbar LO:

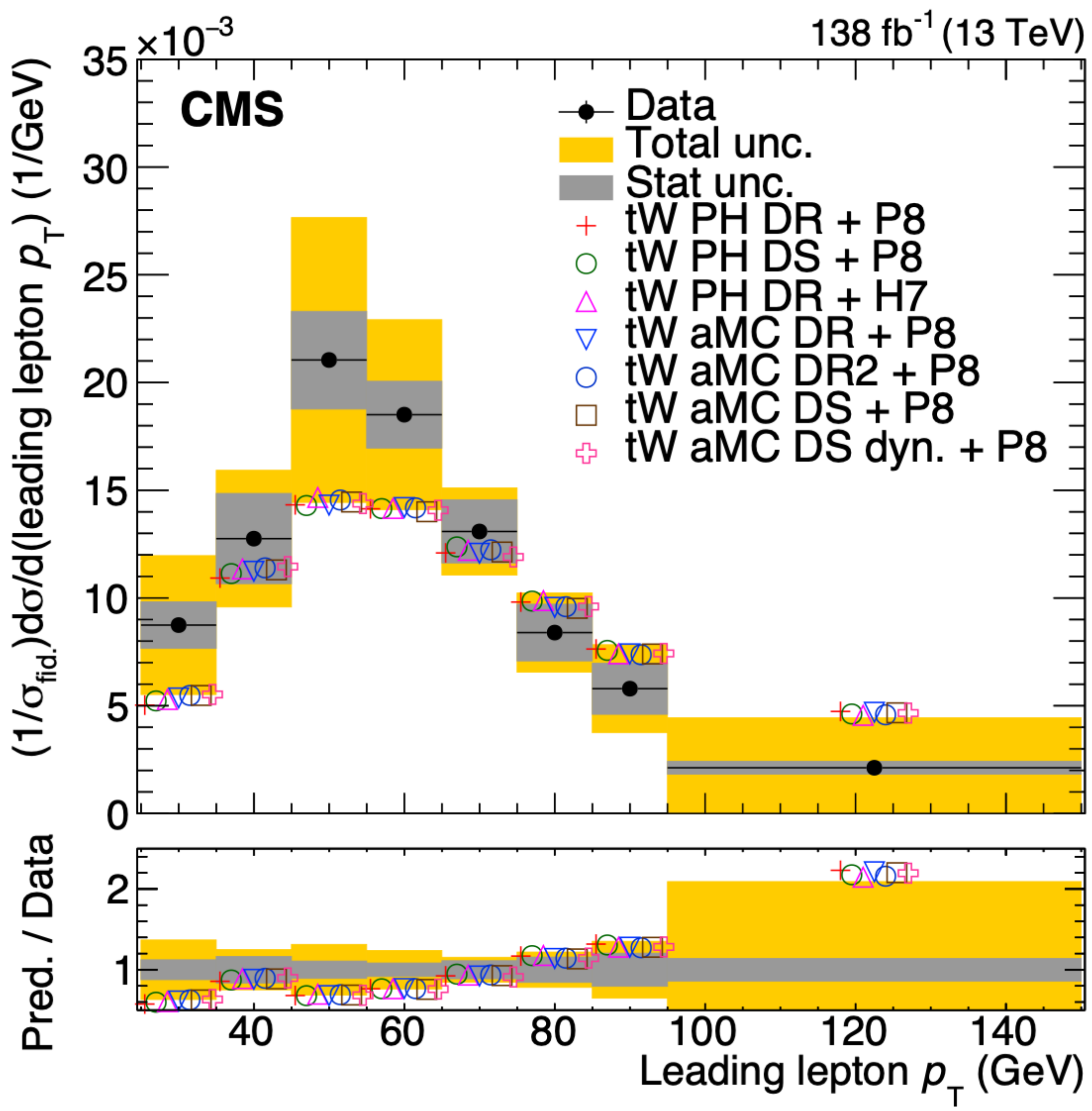
- comparisons of tW NLO predictions with ttbar resonance removed using DR (diagram removal) and DS (diagram subtraction) schemes.
- need more data to conclude.

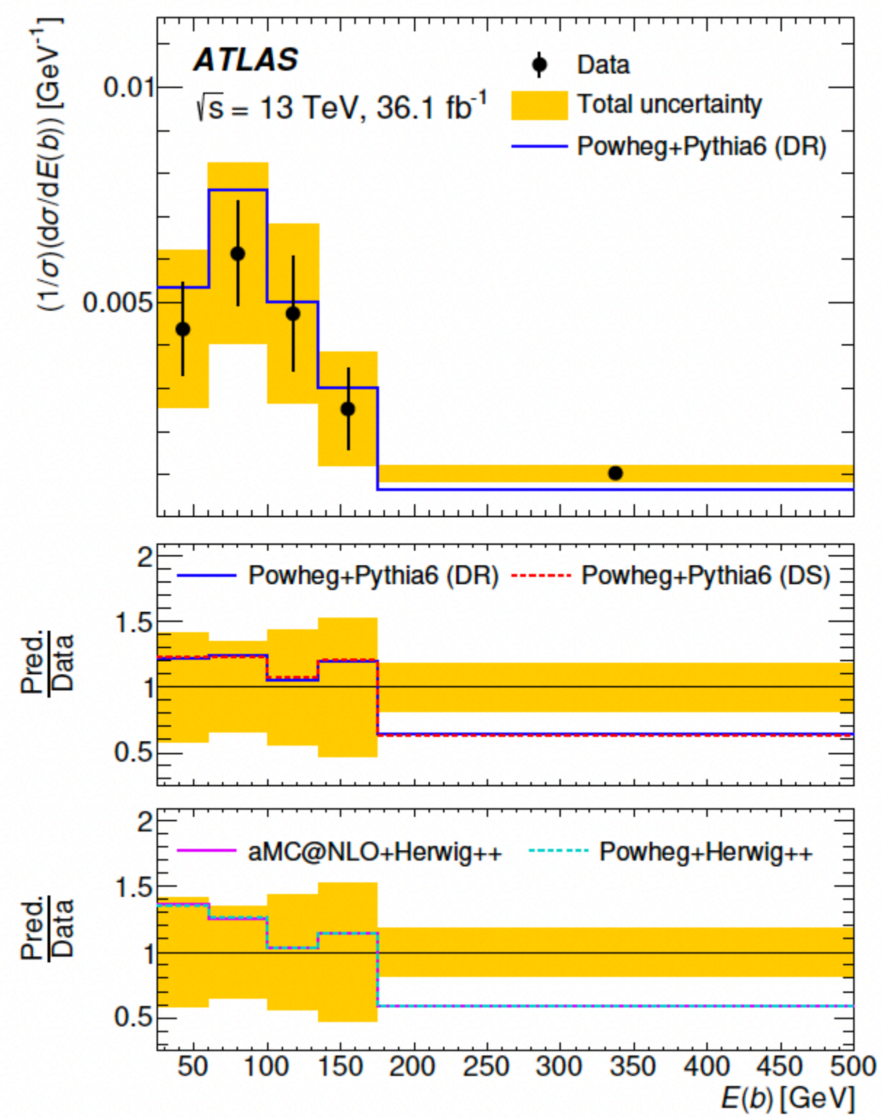


ttbar LO



tW NLO





Probing the interference between ttbar 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.

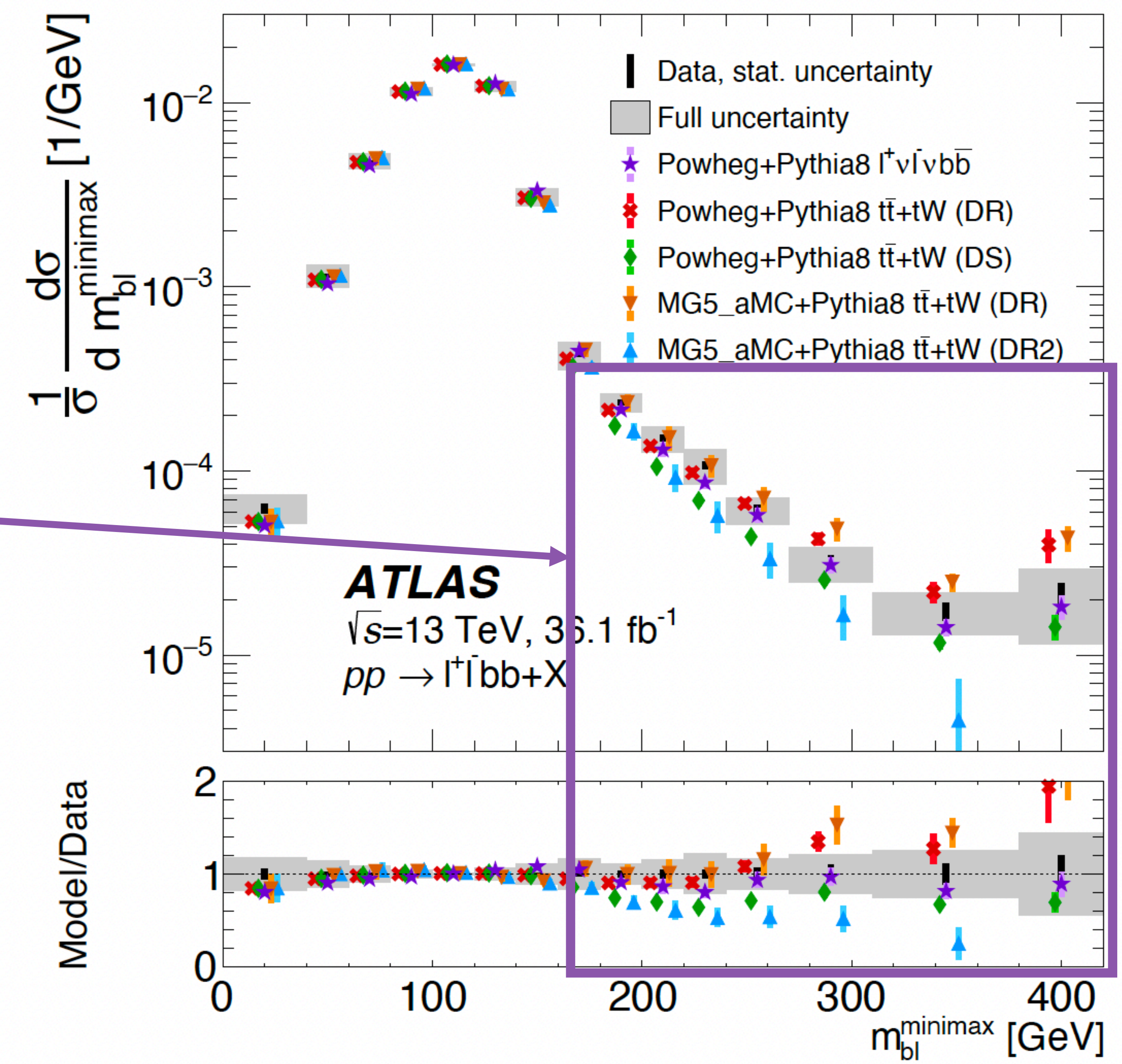
$$m_{b\ell}^{minimax} = min\Big(max(m_{b_1\ell_1}, m_{b_2\ell_2}), max(m_{b_1\ell_2}, m_{b_2\ell_1})\Big)$$

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

Sensitive to the interference

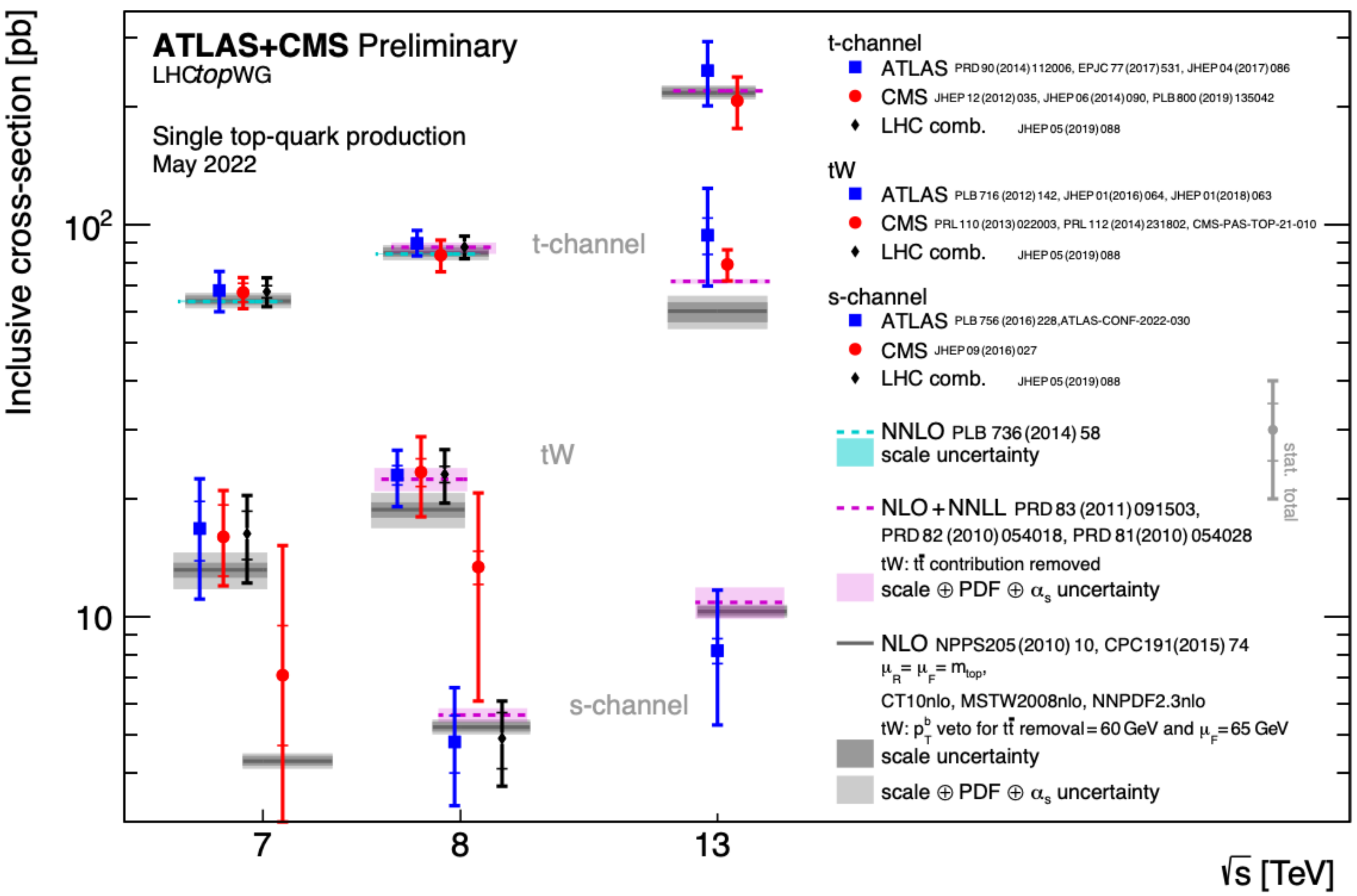
p-value:

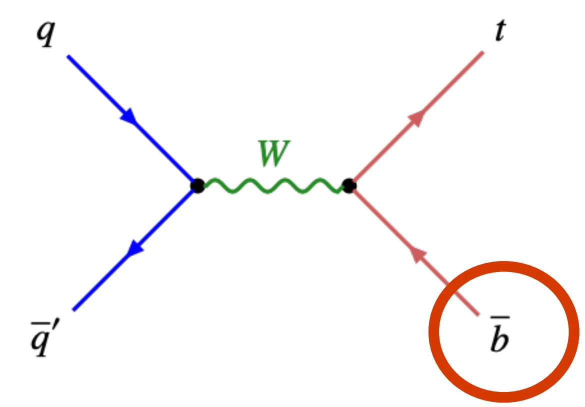
Model	All bins	$m_{b\ell}^{minimax}$ > 160 GeV
Powheg-Box $t\bar{t} + tW$ (DR)	0.71	0.40
Powheg-Box $t\bar{t} + tW$ (DS)	0.77	0.56
MG5_aMC $t\bar{t} + tW$ (DR)	0.14	0.17
MG5_aMC $t\bar{t} + tW$ (DR2)	0.02	0.08
Powheg-Box $\ell^+\nu\ell^-\nu bb$	0.92	0.95



Measuring s-channel process at the LHC

[ATLAS - arXiv:2209.08990]

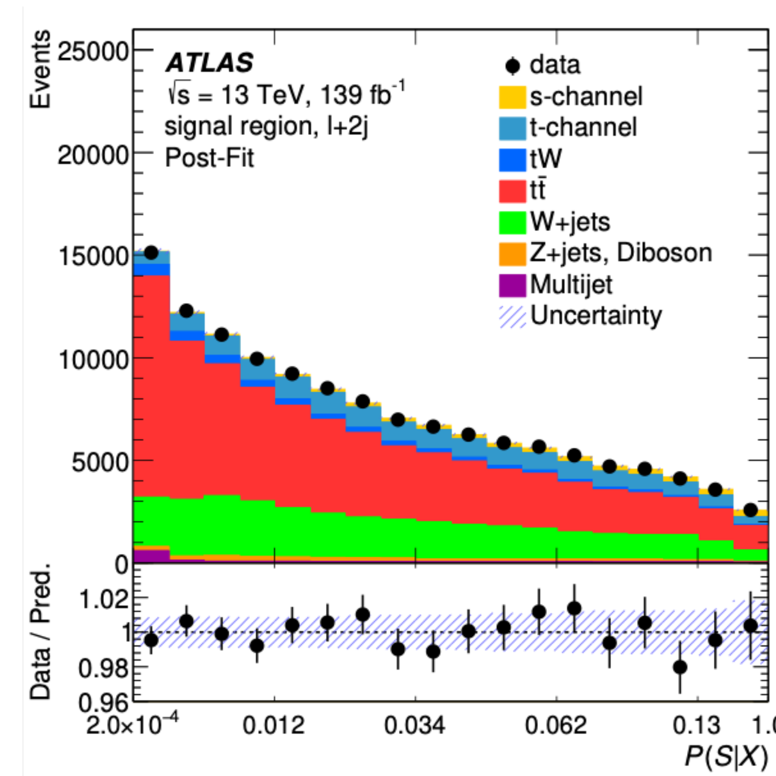




- t-channel is now a background
- **s-channel observed at Tevatron** (2014)
- signal to background ratio (s/b) decreases when center-of-mass energy increases
- **Evidence (>3σ) obtained at ATLAS** 8 TeV and 13 TeV

Search more difficult at 13 TeV than at 8 TeV:

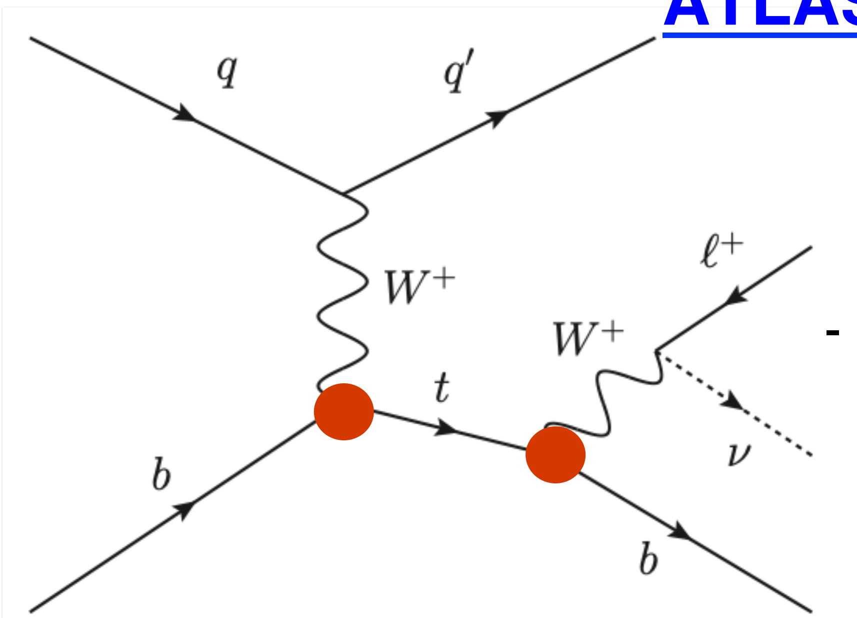
s-channel/ ttbar XS	
8 TeV	2,1 %
13 TeV	1,2 %



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:

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

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

Left and right handed vectorial couplings

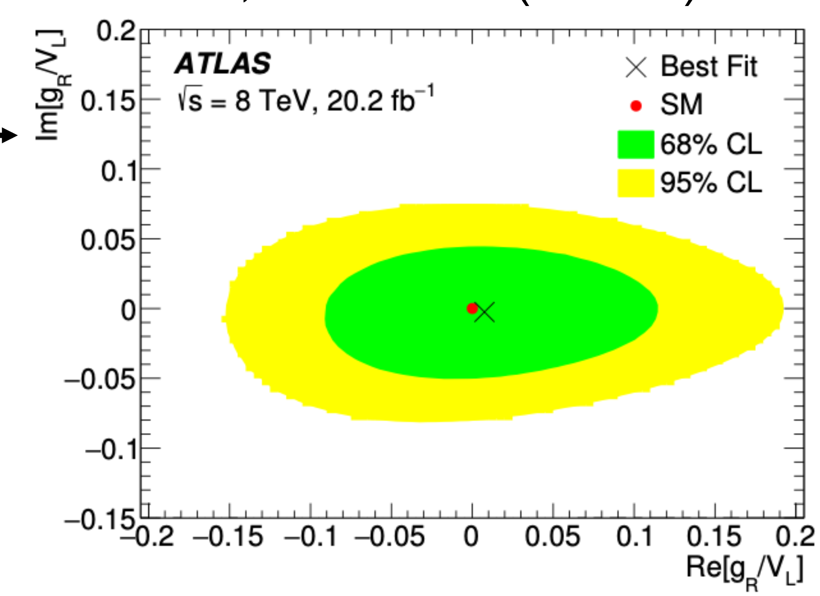
Left and right handed tensorial couplings

In the SM at tree level:

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

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

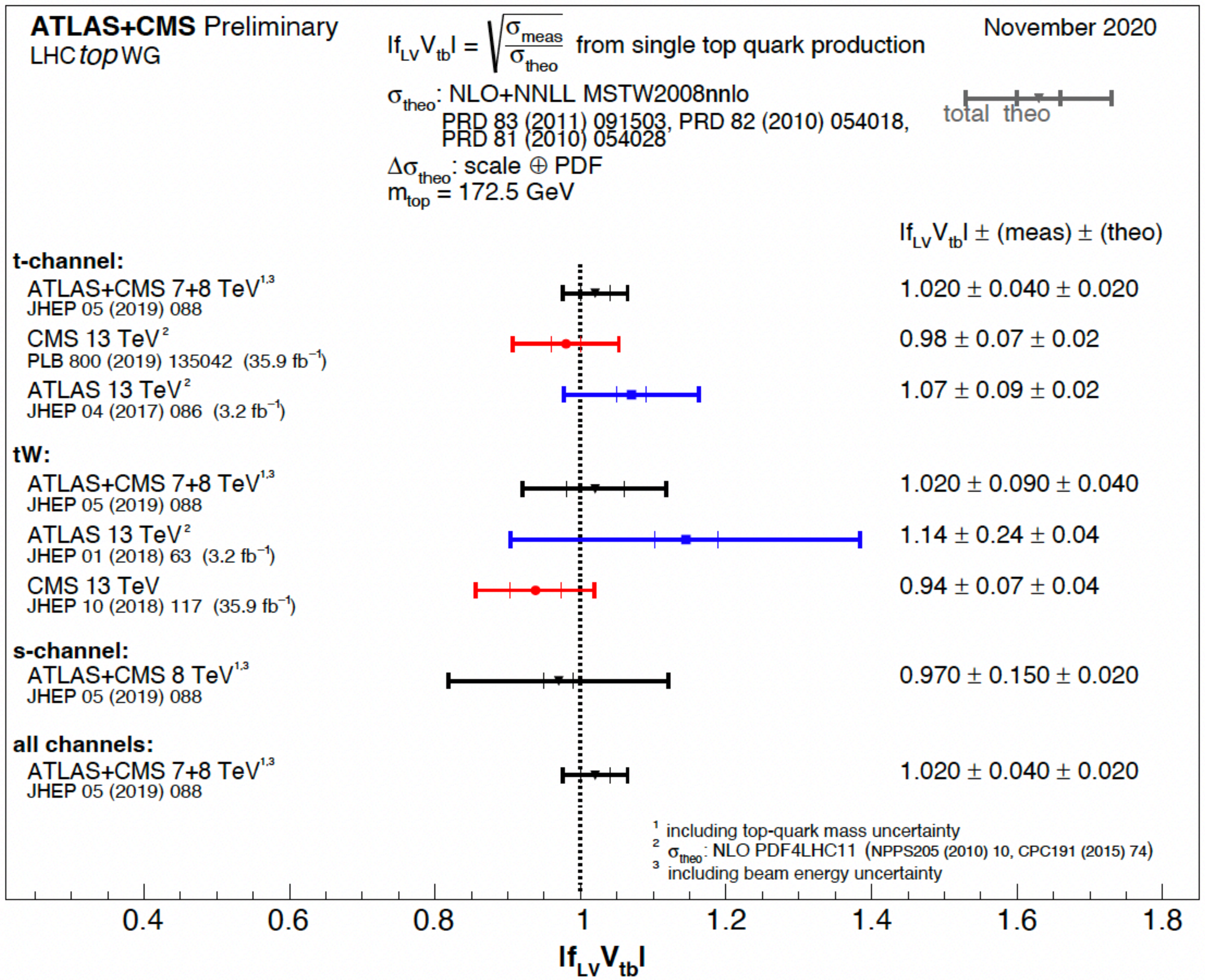
ATLAS, JHEP12(2017)017



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 |fLV Vtb| (= V_L Wtb coupling) from cross section measurements.

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

Assumes |Vtd|,|Vts| << |Vtb|

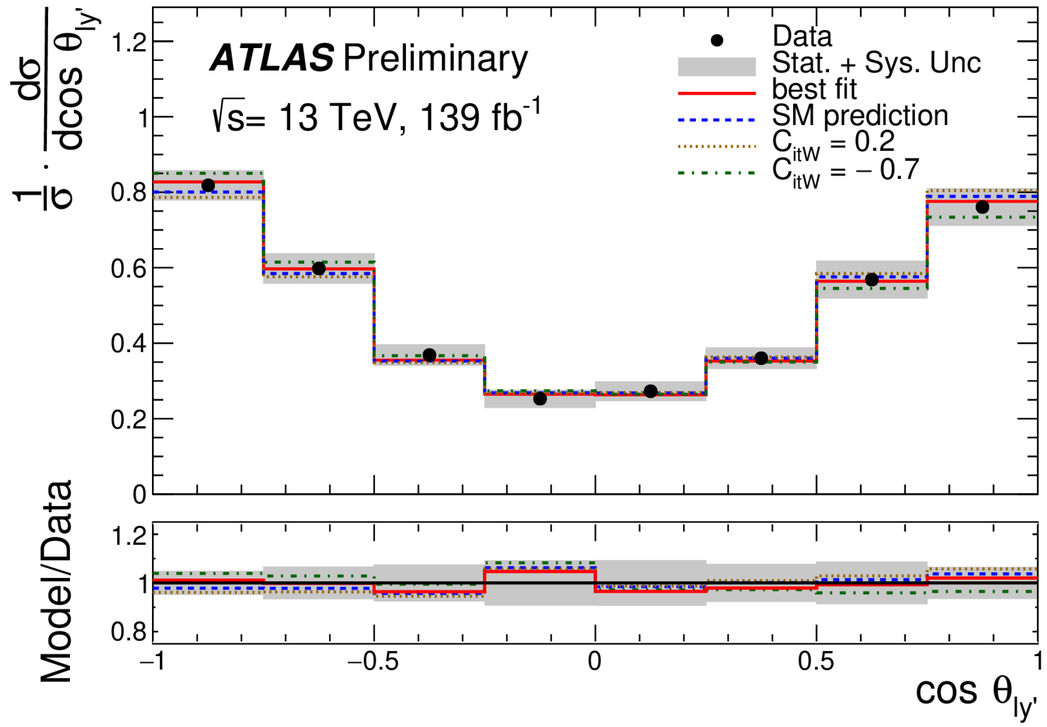
Combinations at 8TeV (t, tW and s-channels) provide the best precision.

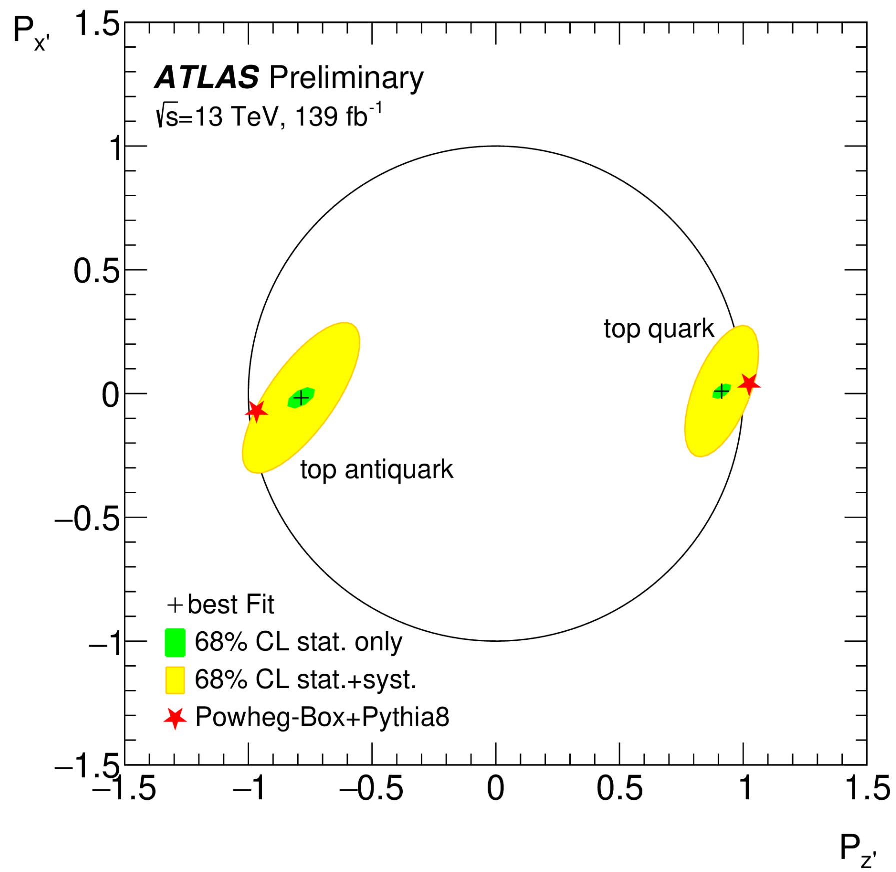
Measurement without assumptions (t-channel measurement also measuring Vtd,Vts) lead to similar precision.

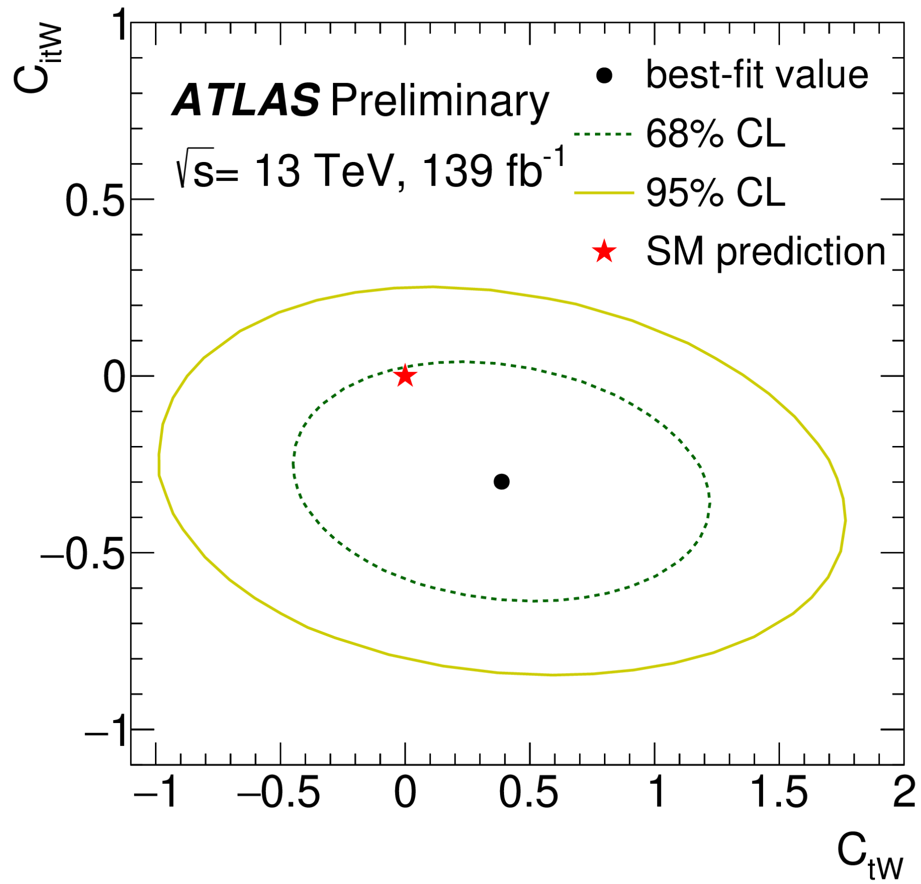
Top quark polarization

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 (Px’~0, Pz’~1)
- Extract **measurement of effective field theory couplings, tensor left** (aka gL and Im(gL))

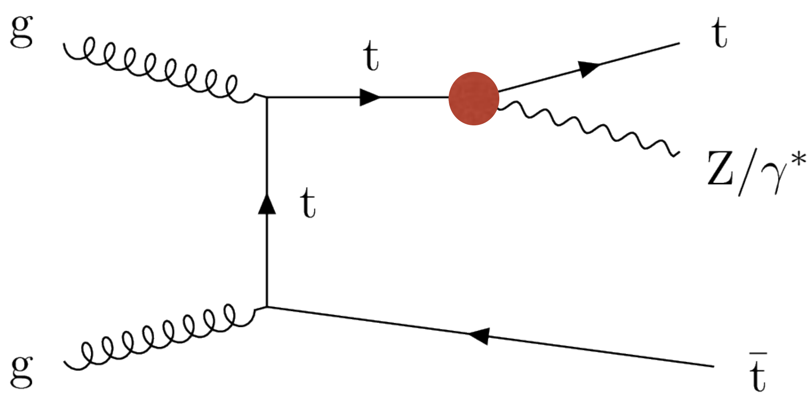




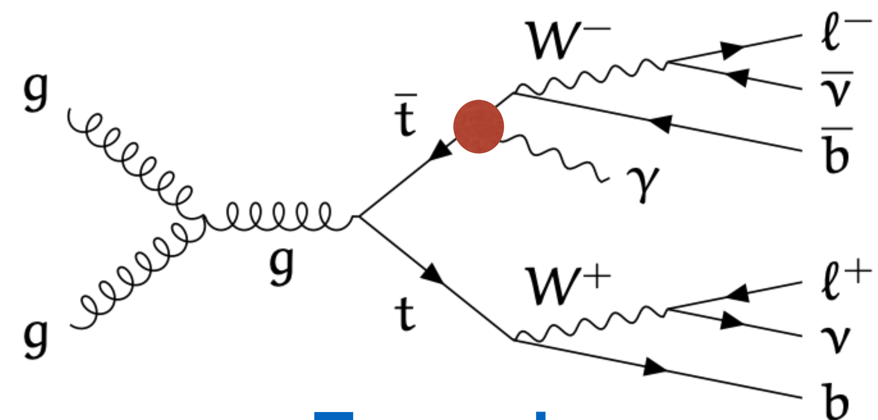


Processes with tops and gauge bosons

Larger cross section

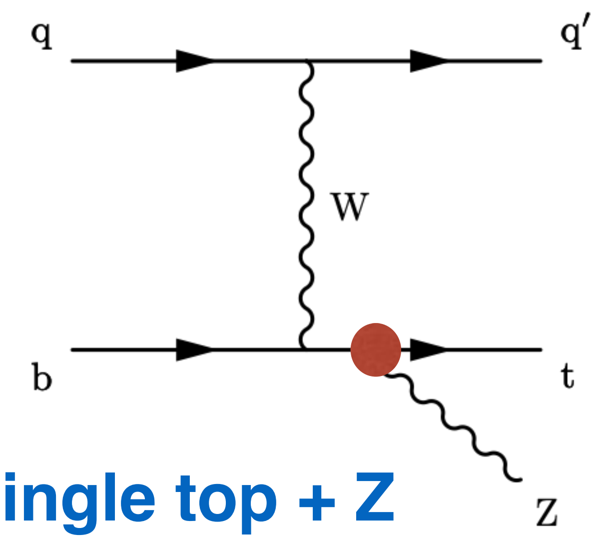


Top pair + Z

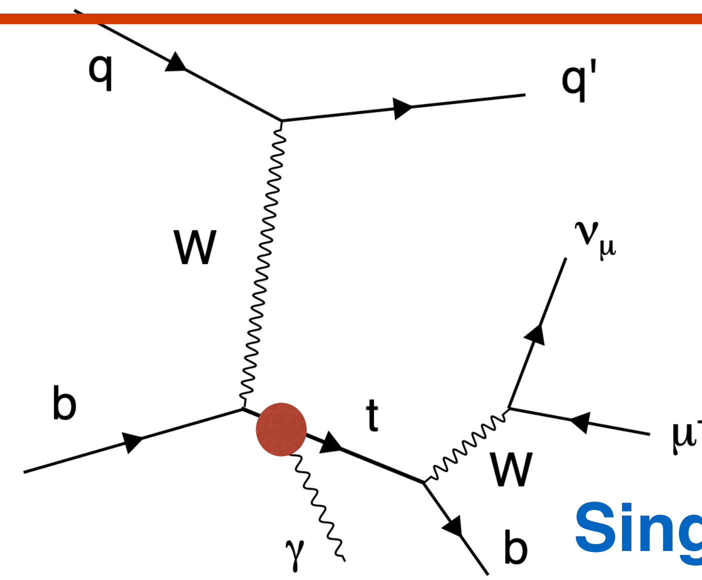


Top pair + γ

Smaller cross section



Single top + Z

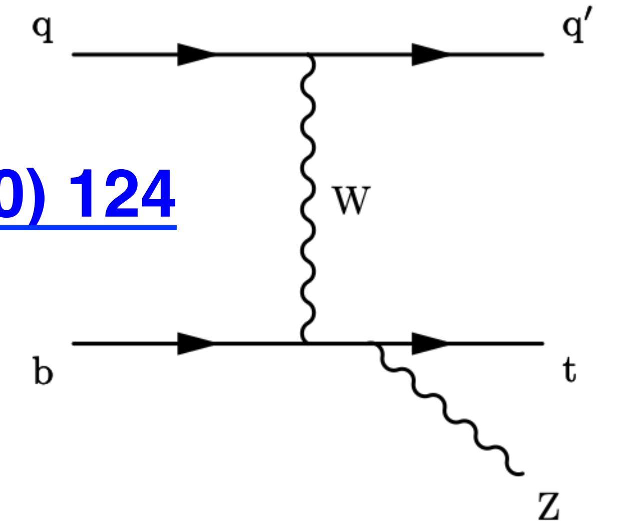


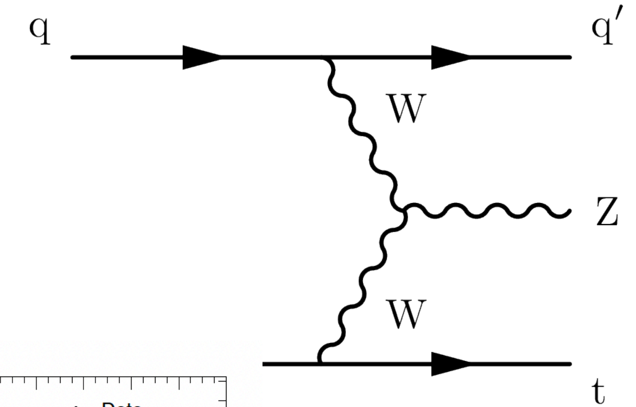
Single top + γ

- 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, tγ in tγq)
- Search deviations from the SM within the framework of the **effective field theory**

Single top + Z (tZq)

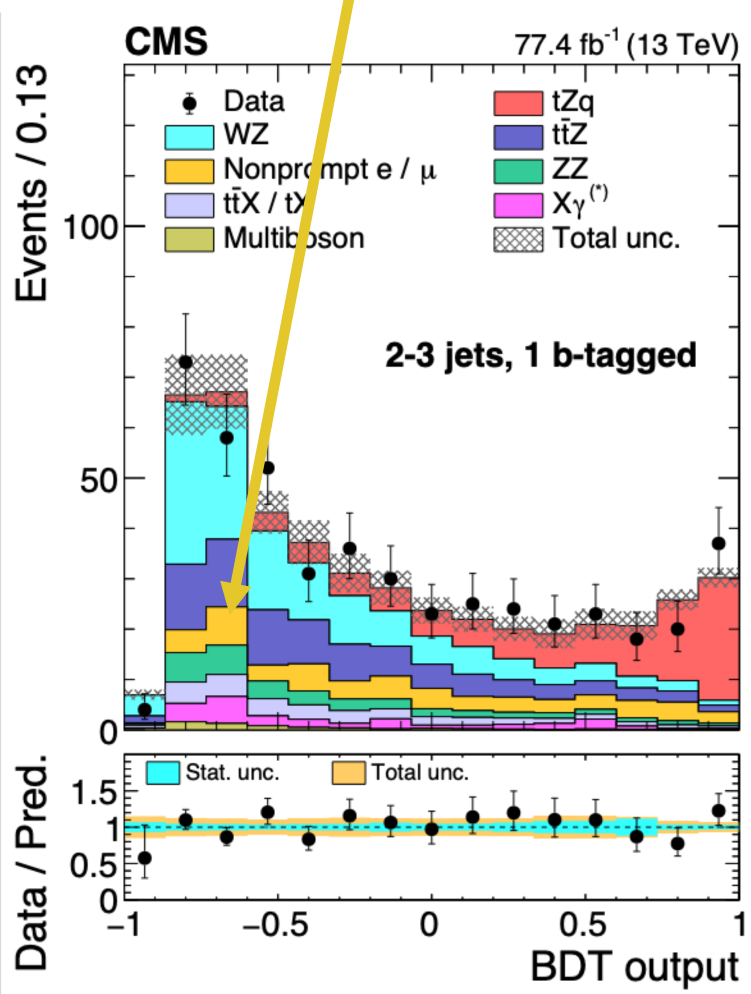
CMS - PRL 122 (2019) 132003, ATLAS - JHEP 07 (2020) 124

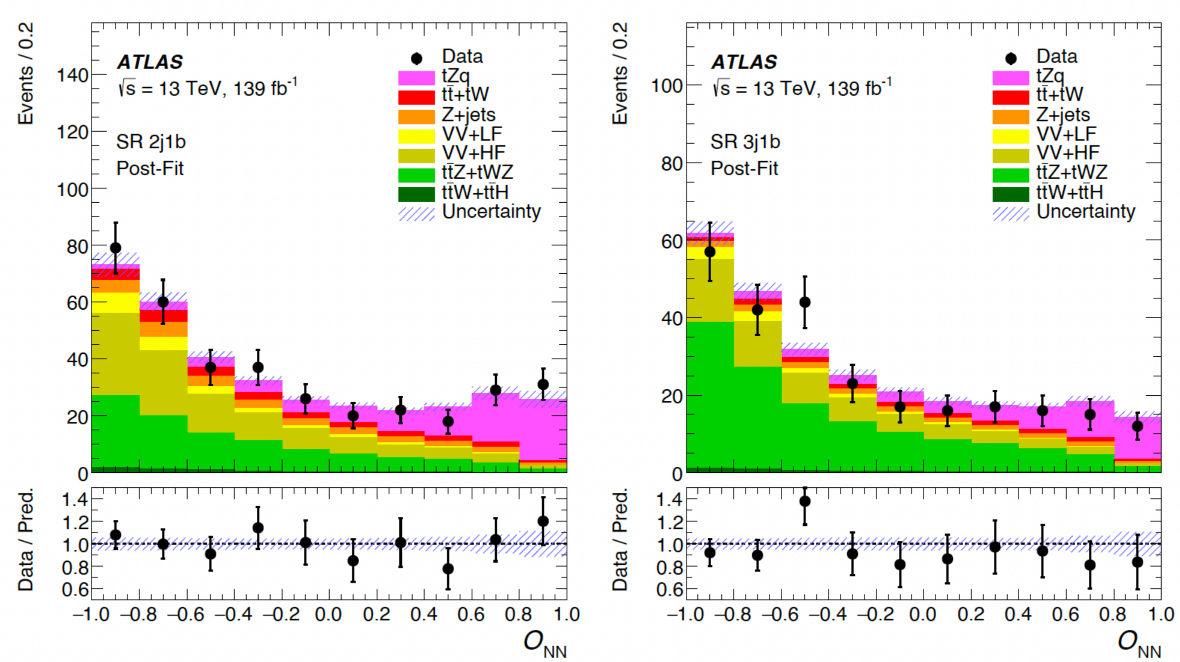




Analysis performed in **3ℓ final state (e or μ)**

- tZq is produced by EW interaction: make use of the **forward jet** (|η|<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





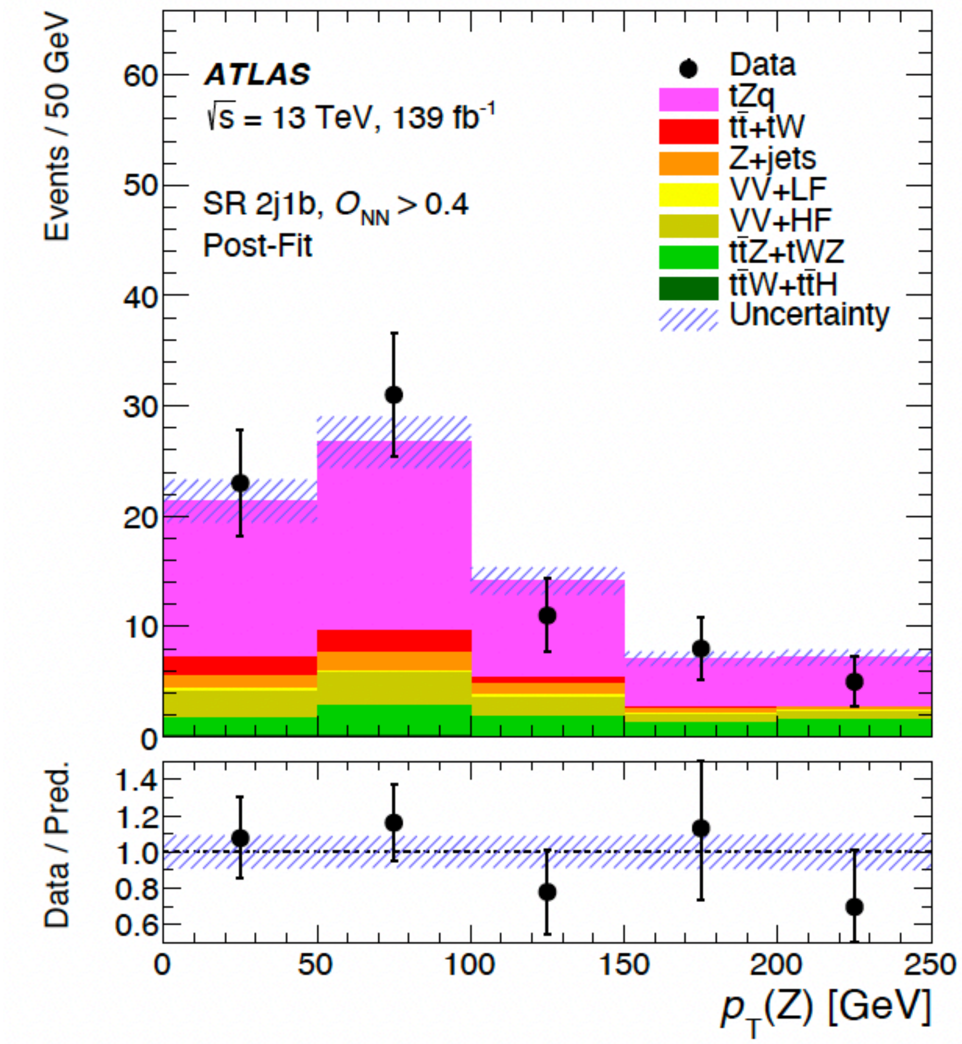
Signal extraction: **Fit of BDT (CMS) or NN output (ATLAS) in several event categories**

Observed at CMS and ATLAS (>5σ)

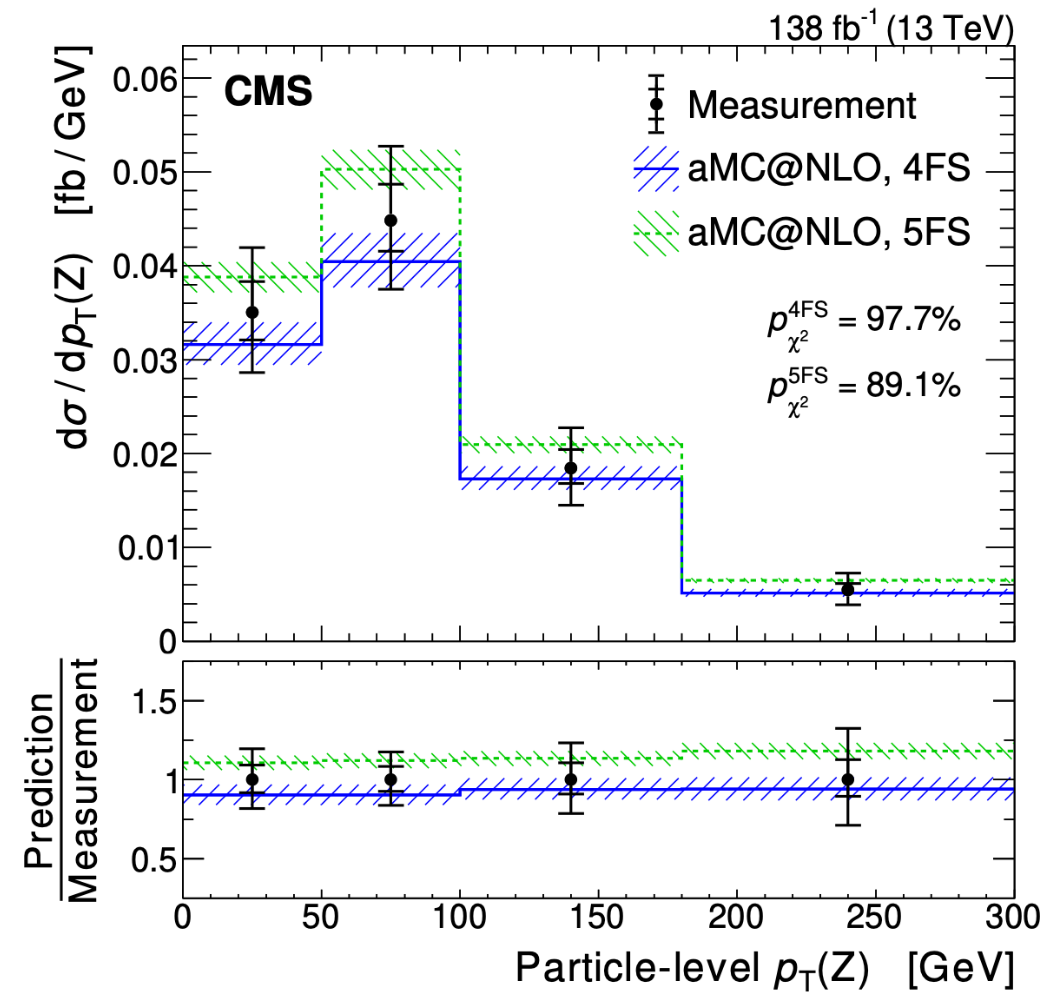
Single top + Z (tZq)

CMS - JHEP 02 (2022) 107, ATLAS - PLB 780(2018)557-577

Kinematic distributions at ATLAS



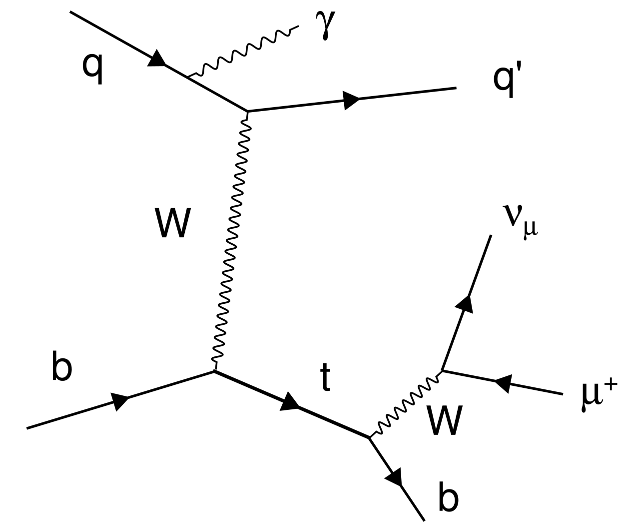
CMS differential measurement



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

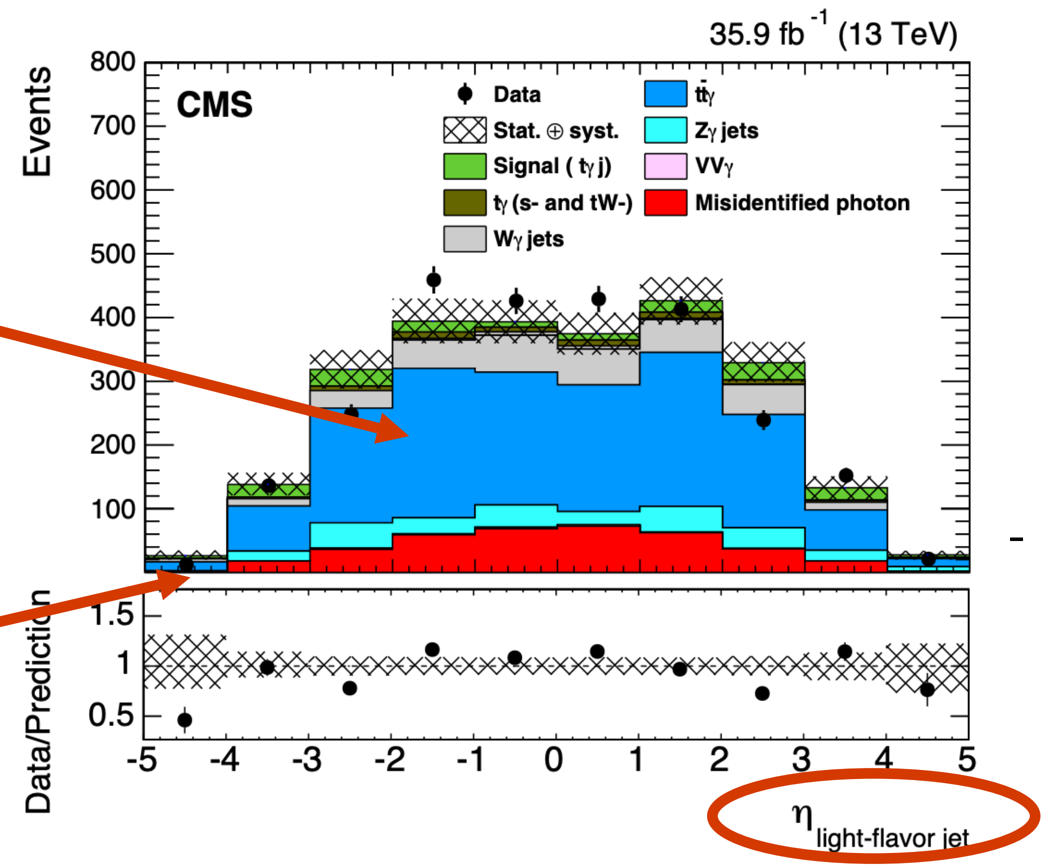
Single top + γ (tγq)

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

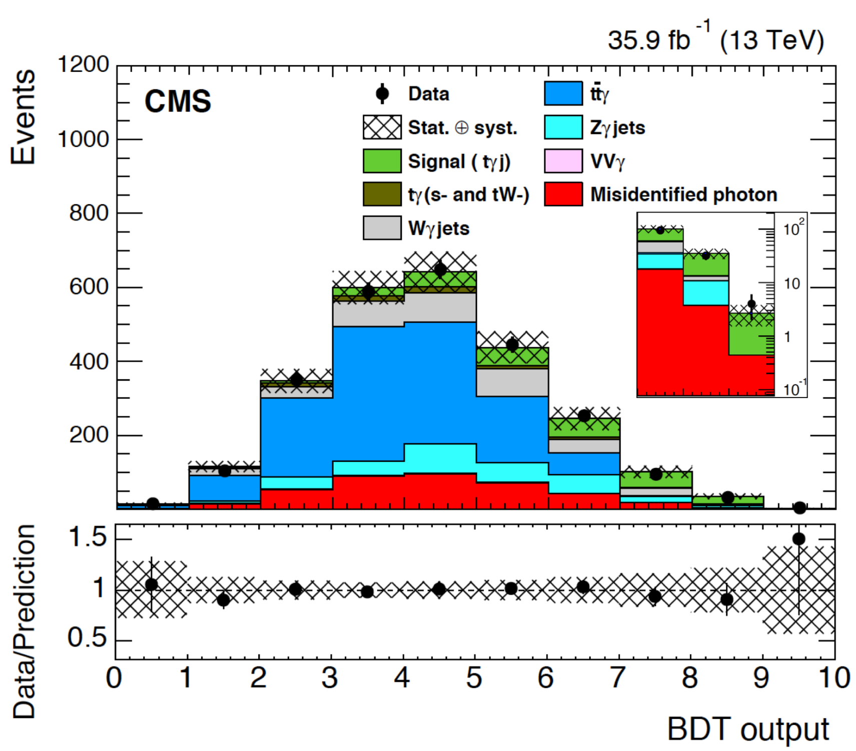


Dominant background tt+γ (dedicated CR is used)

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



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



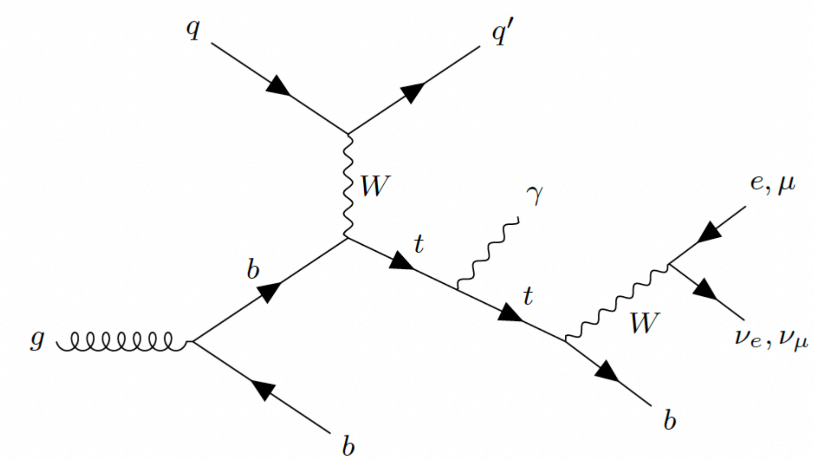
Extract signal with **BDT** using kinematics (noticeably **forward jet η**)

First evidence: significance 4.4σ (3.0σ expected)

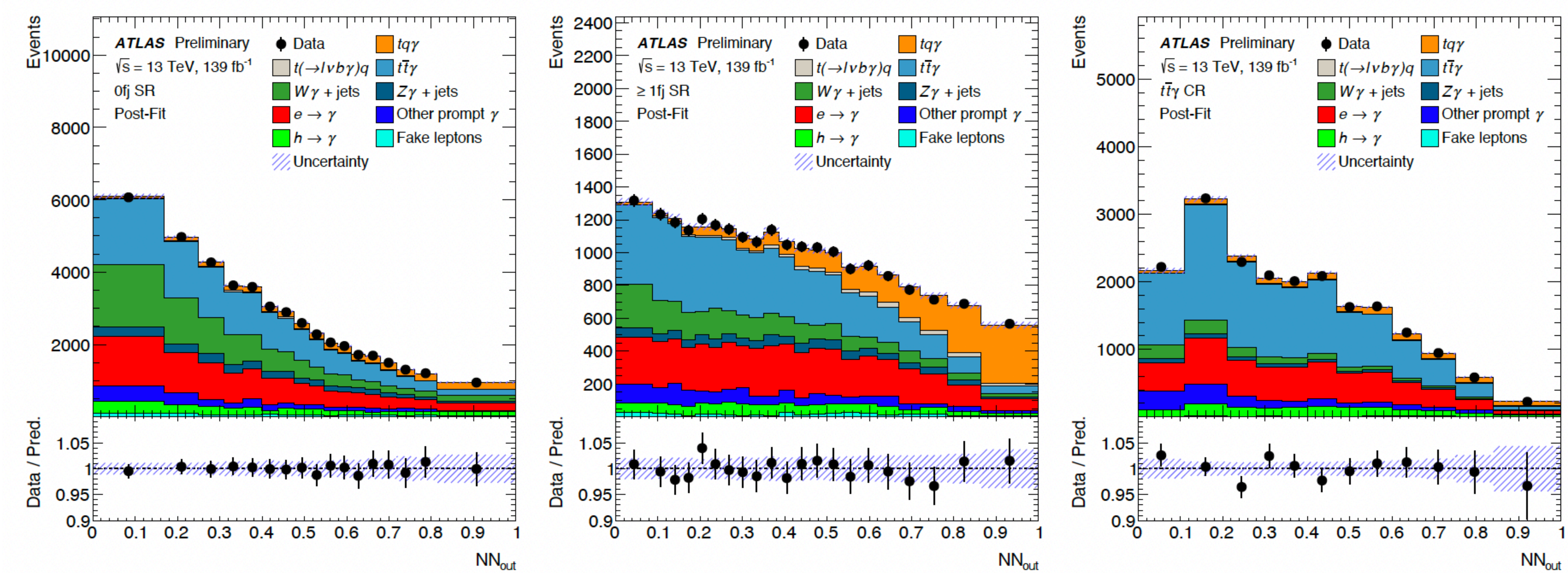
Dominated by systematics: jet energy scale, b-tagging, tγq modeling

Observation of single top + γ (tγq)

ATLAS-CONF-2022-013



Similar analysis strategy at ATLAS
Signal extraction from fit of SR and CR (also Wγ).
Signal is very clearly visible!

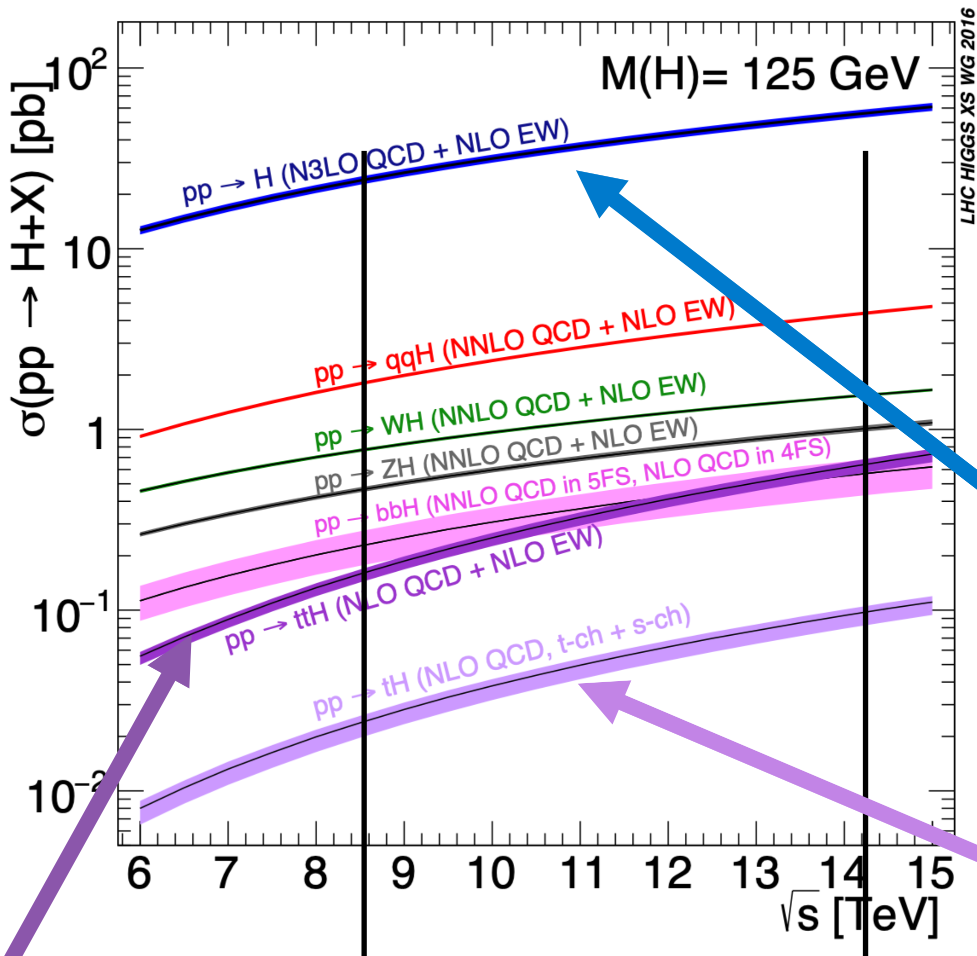


The measured fiducial parton-level cross section is $\sigma_{tq\gamma} \times \mathcal{B}(t \to \ell\nu b) = 580 \pm 19\,(\text{stat.}) \pm 63\,(\text{syst.})$ fb.

Observation: significance 9.1σ (**6.7**σ expected)

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

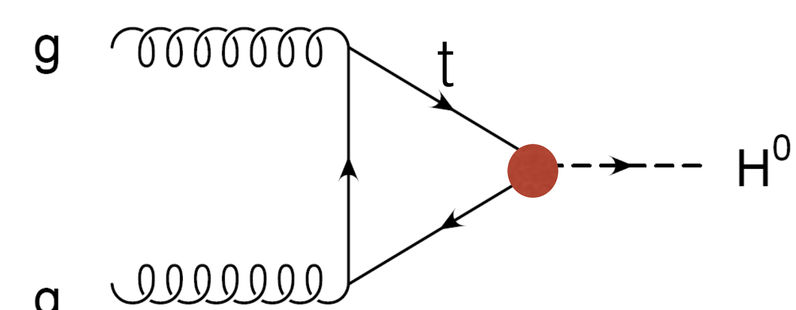
Top - Higgs coupling at the LHC



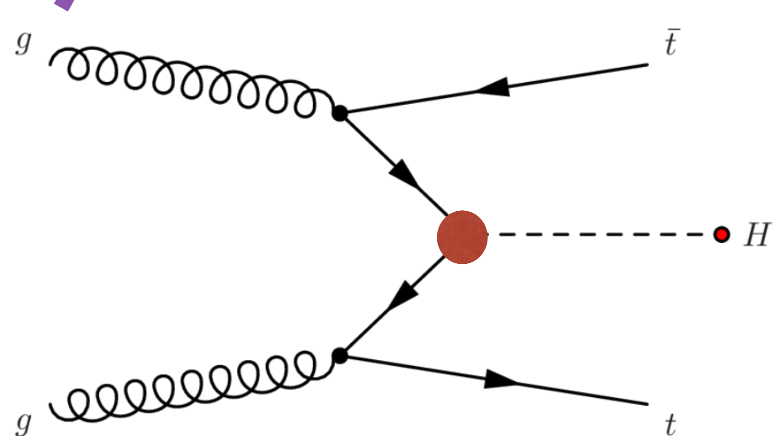
The Higgs boson generates fermion mass via its vacuum expectation value v: **Yukawa coupling**

- Top Yukawa coupling $\lambda_t = \sqrt{2}.\ m_t/v \sim 1$

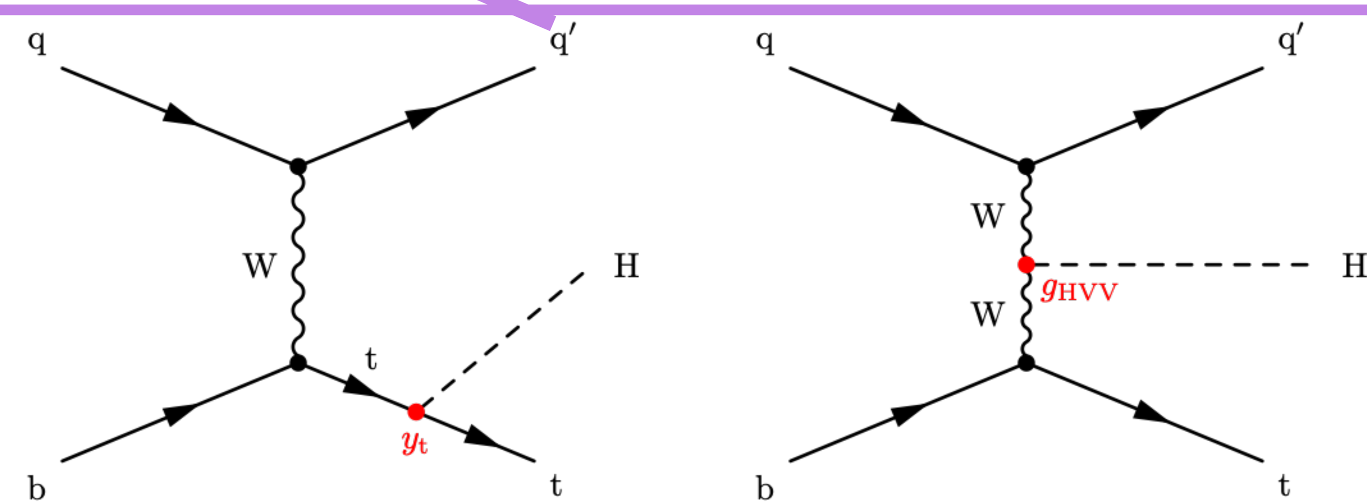
- Measuring accurately λ_t is one of the priorities of the LHC



Higgs production via gluon fusion:
indirect (loop level)



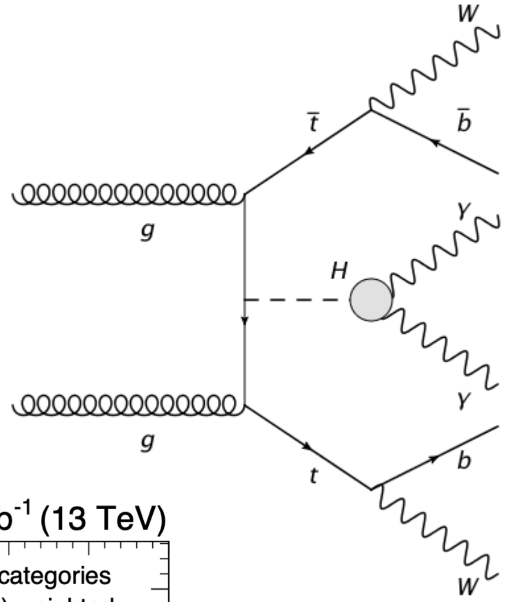
ttH: Direct (tree level) **probe of top-Higgs coupling**



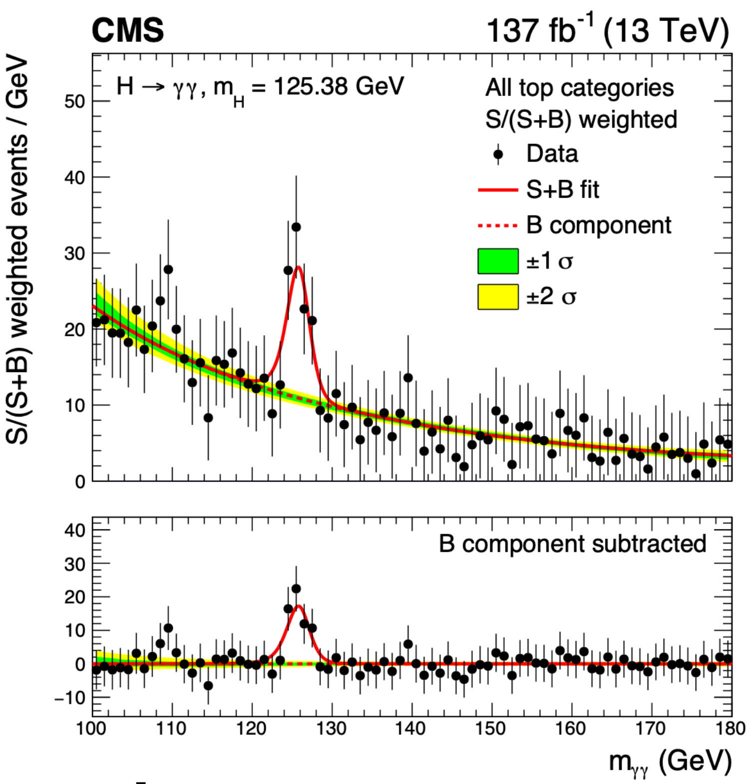
tHq: Direct (tree level) **probe of top-Higgs coupling + sign of the coupling** through interference

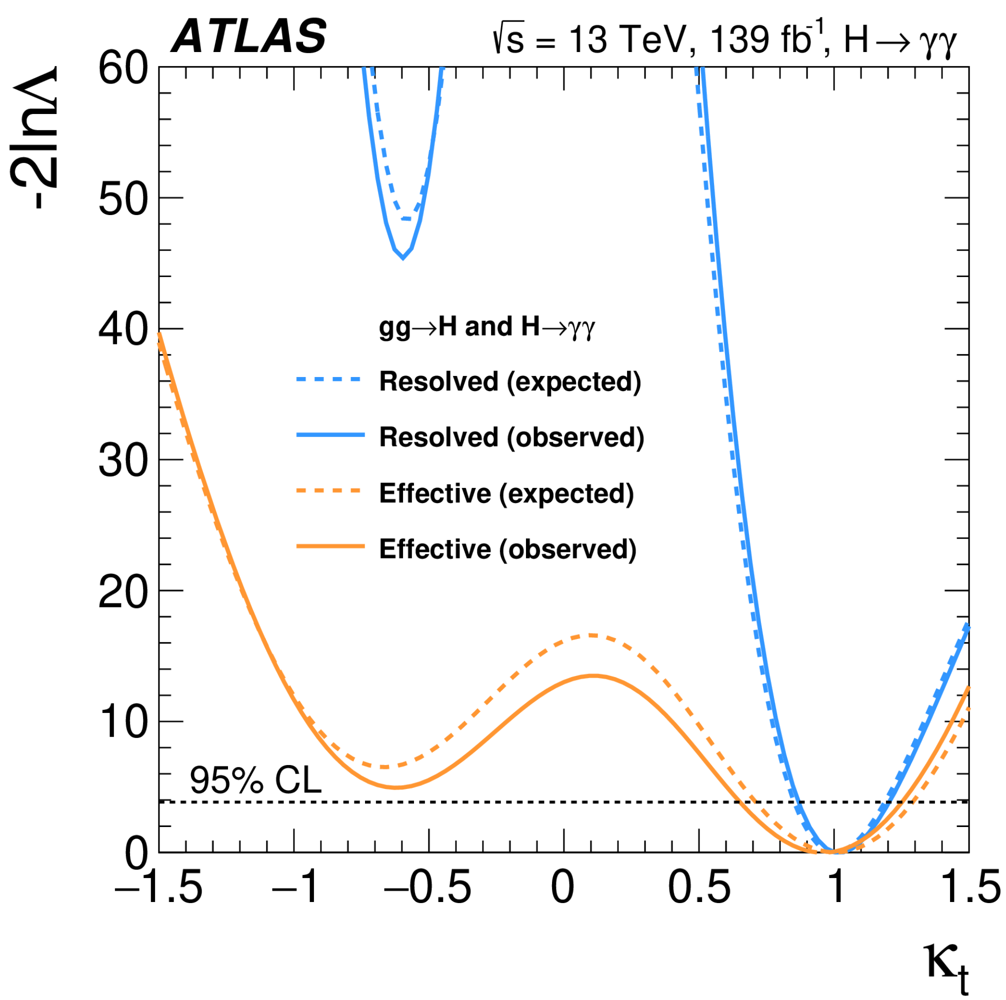
tH,H→γγ

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



- **Dedicated tH 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**



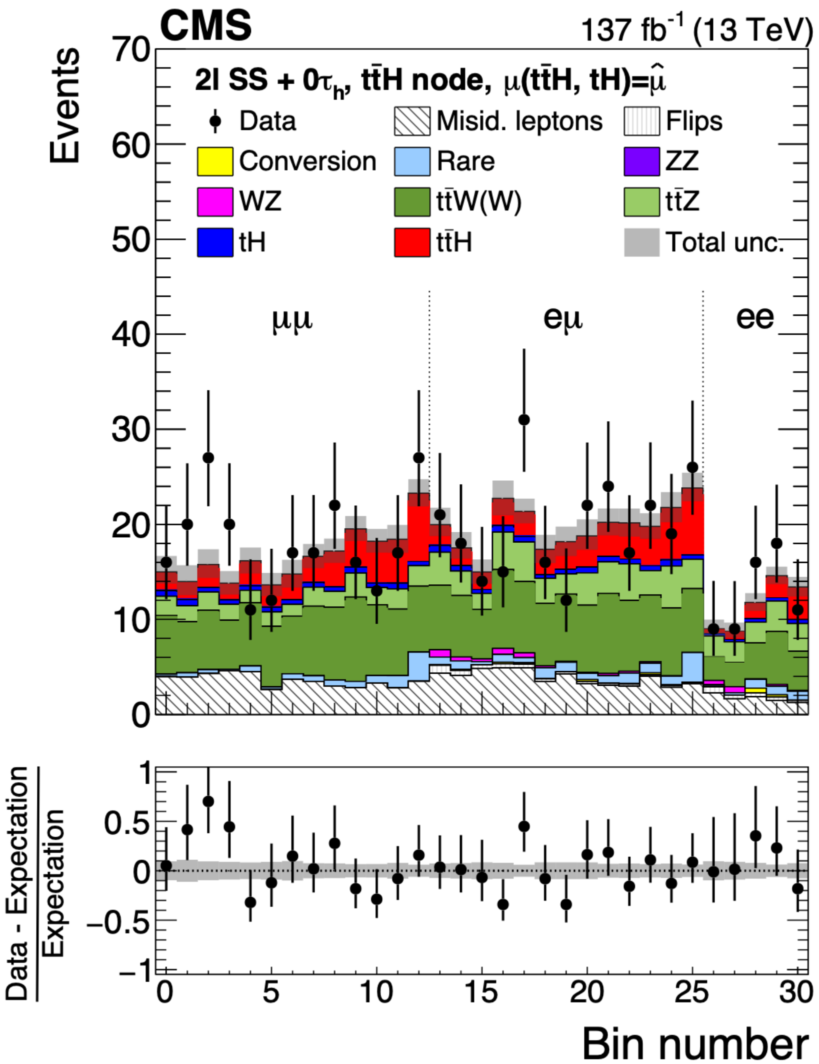


Data prefers **positive sign** of top-Higgs coupling

"Simplified template cross section":
Measuring production mechanisms in kinematic bins at generator-level:
- **ATLAS:** $2.1^{+4.2}_{-3.1}$ times the standard model expectation
- **CMS:** $6.3^{+3.4}_{-3.7}$ times the SM expectation

tH multilepton

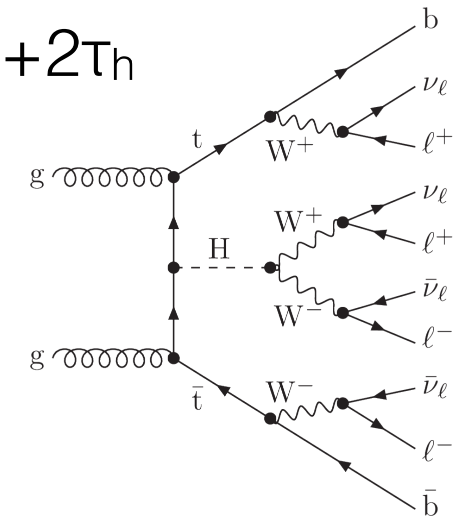
Eur. Phys. J. C 81 (2021) 378



Most sensitive event categories: 2 leptons of same sign (2ℓss), 3ℓ, 2ℓss+1τ_h (hadronic tau), 1ℓ+2τ_h

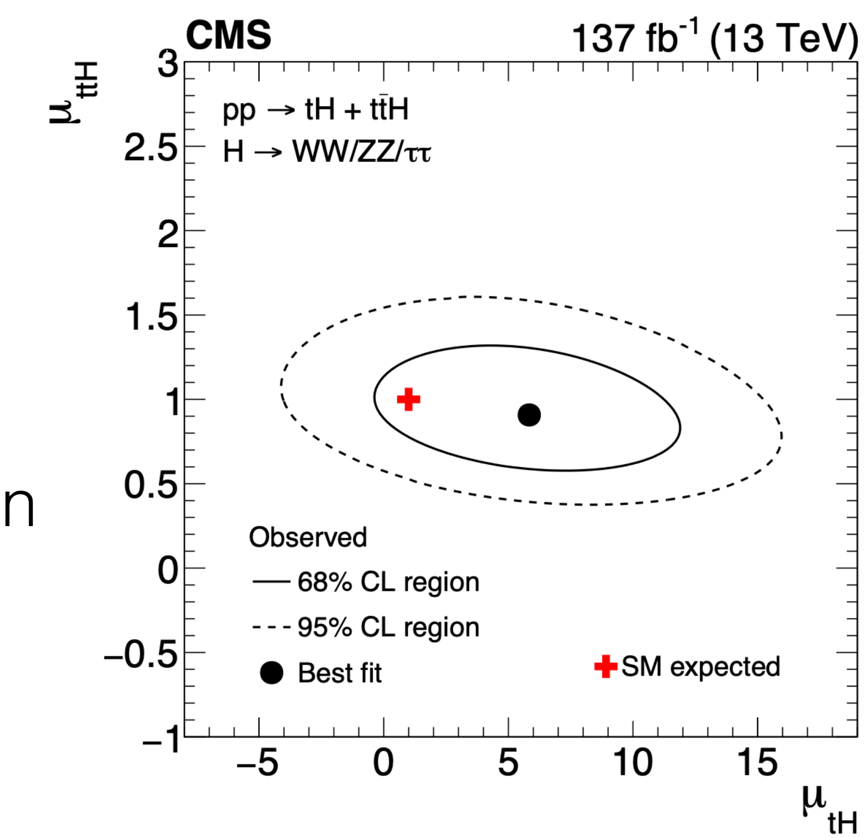
Signal extraction:

- Deep neural networks and BDTs

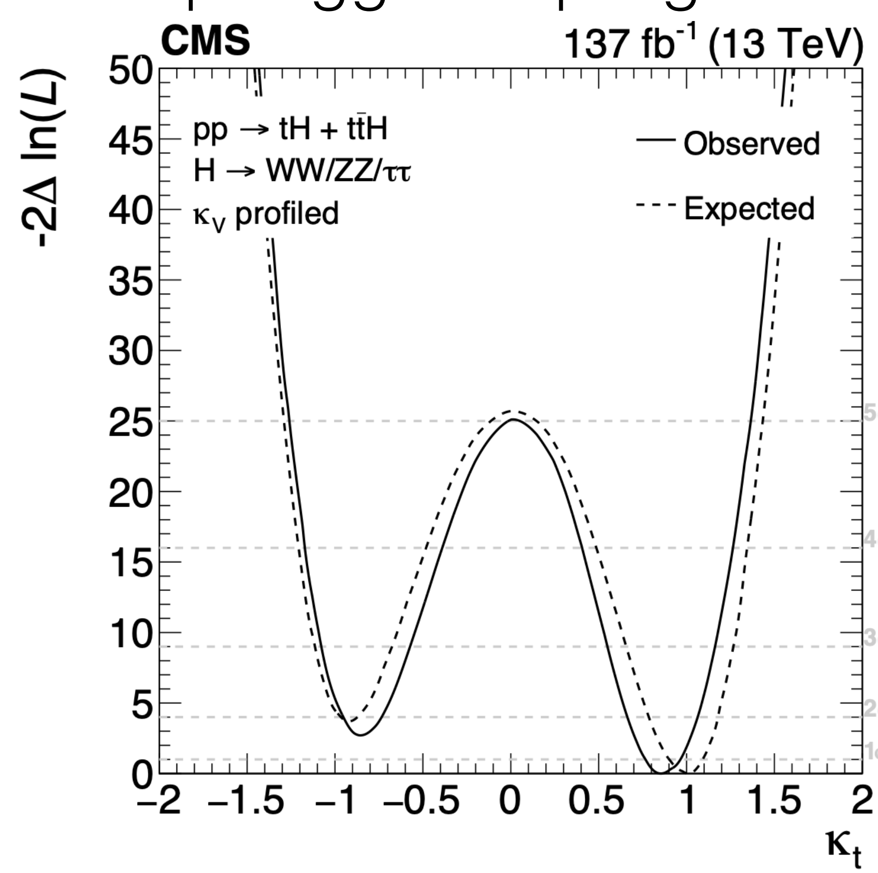


Simultaneous fit of ttH and tH signal strengths:

- Sensitivity to tH: 5-10x SM



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



CMS combination: μ_{tH}=6±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** (Vtb, 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.

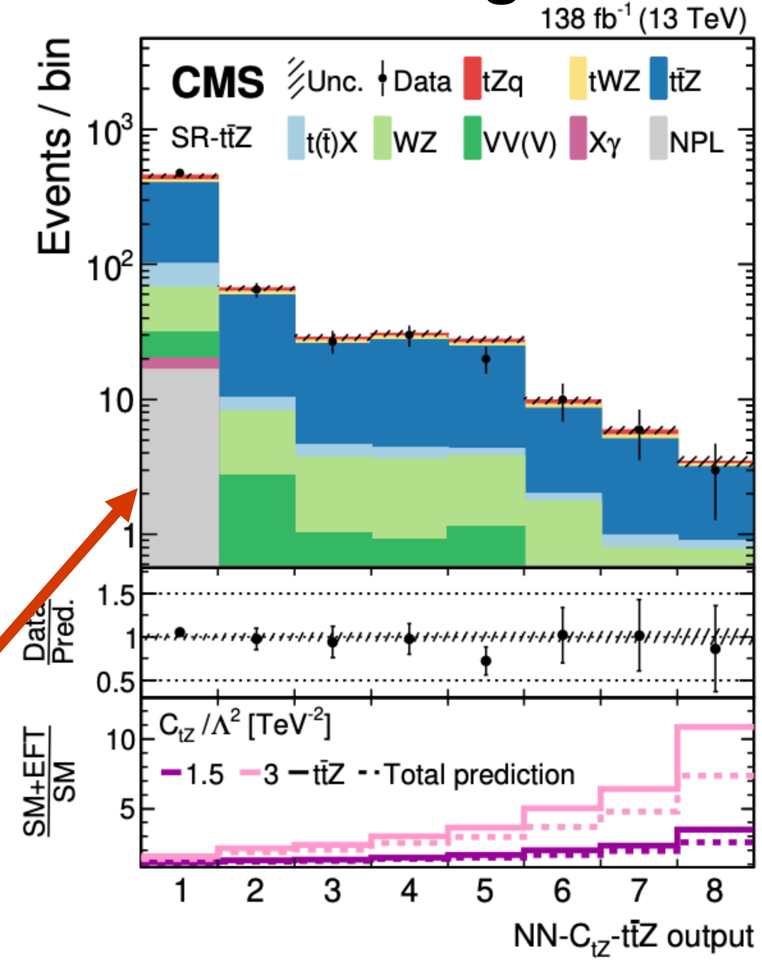
- Neural network to **discriminate SM signal from backgrounds.**

- Neural network to **discriminate new physics from SM**.

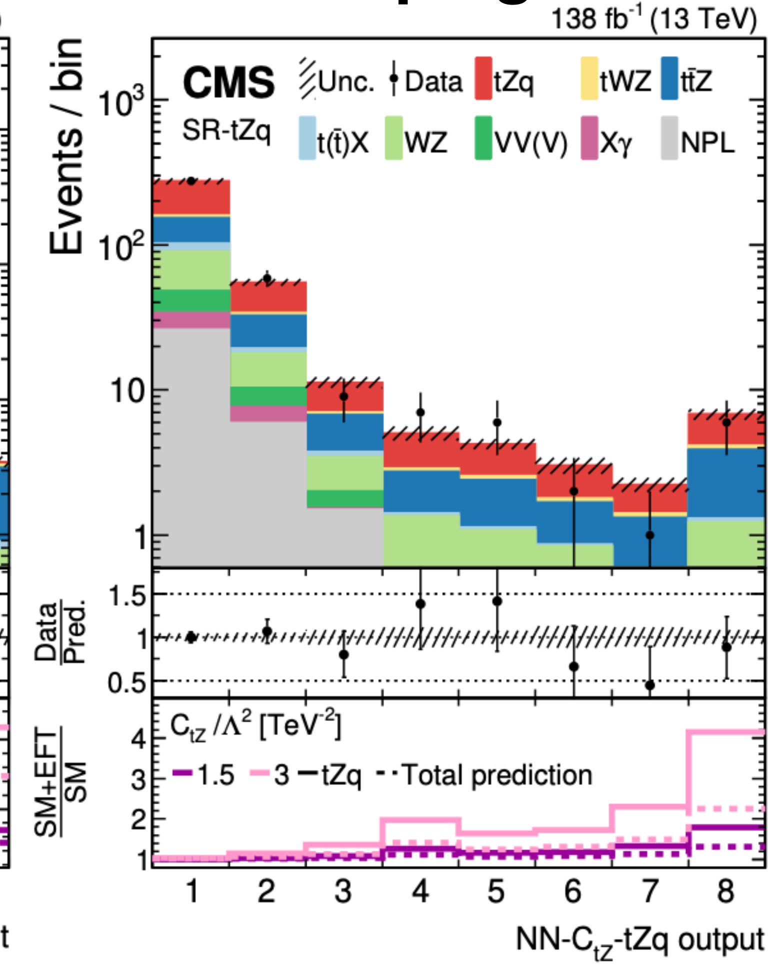
- **Simultaneous fit of 5 coefficients** in the **Effective Field theory** modifying top-Z coupling, parametrising deviations from SM.

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

ttZ region



tZq region



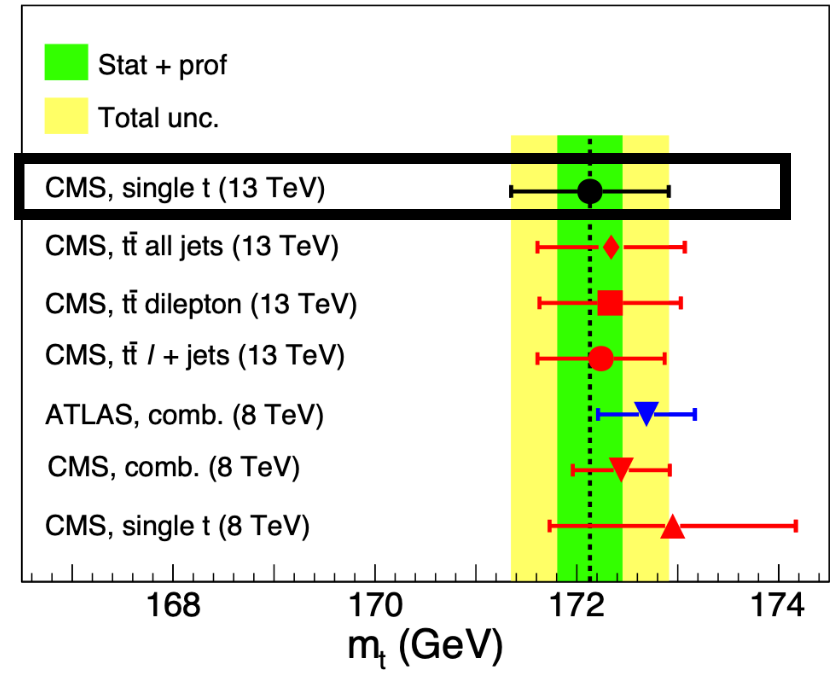
WC/Λ^2 [TeV^{-2}]	95% CL confidence intervals			
	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
c_{tZ}	[−0.97, 0.96]	[−0.76, 0.71]	[−1.24, 1.17]	[−0.85, 0.76]
c_{tW}	[−0.76, 0.74]	[−0.52, 0.52]	[−0.96, 0.93]	[−0.69, 0.70]
$c^3_{\varphi Q}$	[−1.39, 1.25]	[−1.10, 1.41]	[−1.91, 1.36]	[−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] ∪ [−2.06, 2.69]	[−16.18, 10.46]	[−19.15, 10.34]

top quark mass with t-channel

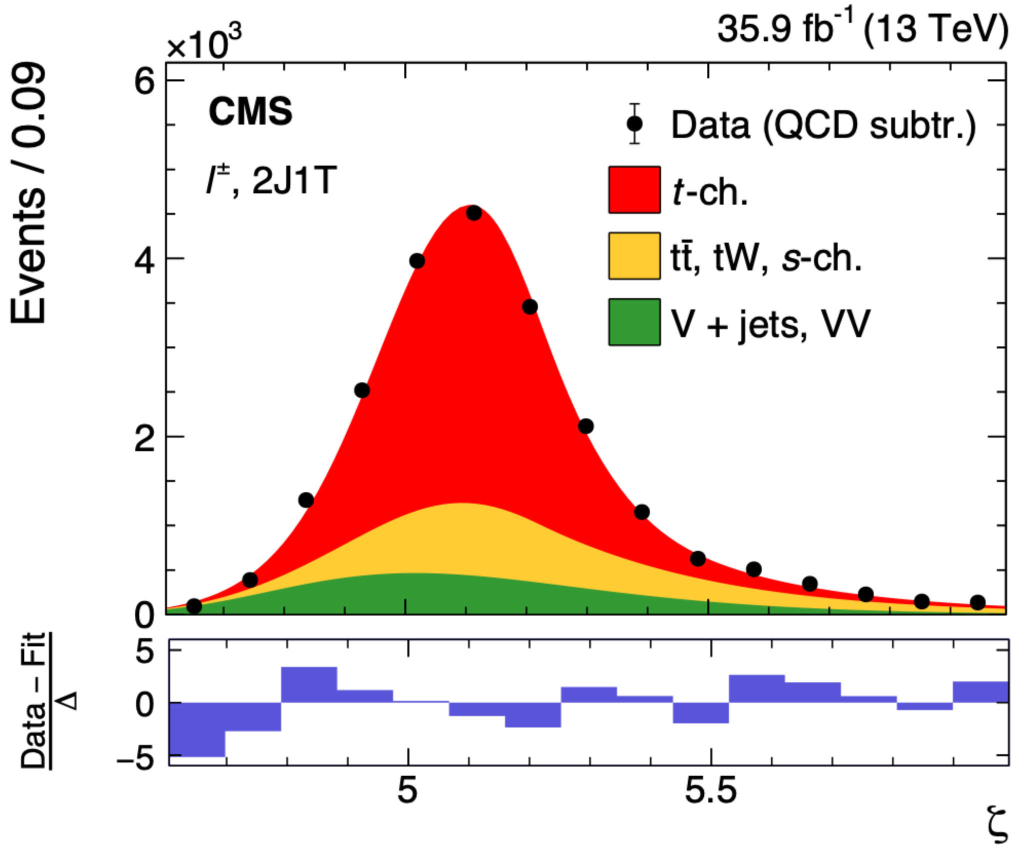
JHEP 12 (2021) 161

Measurement at 13 TeV:

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



Main syst. uncertainties:



Jet energy scale

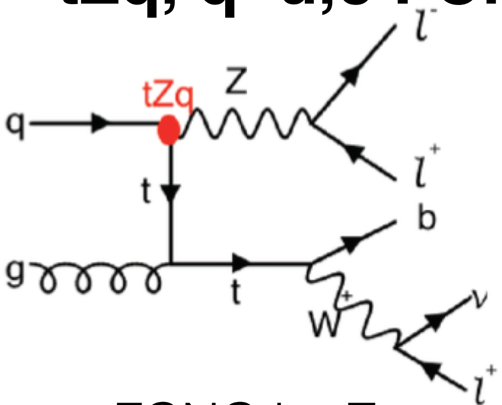
Color reconnection in hadron shower

b-quark fragmentation model

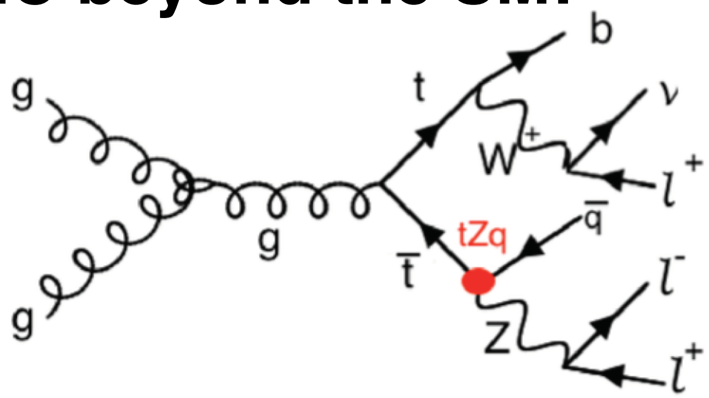
Source		$\delta m_{l^\pm}$	δm_{l^+}	δm_{l^-}
Statistical		±0.19	±0.23	±0.33
Statistical + profiled systematic		±0.32	±0.37	±0.58
JES	Correlation group intercalibration	±0.09	±0.07	±0.12
	Correlation group MPFInSitu	±0.02	±0.02	±0.01
	Correlation group uncorrelated	±0.39	±0.17	±0.83
	Total (quadrature sum)	±0.40	±0.18	±0.84
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 quark hadronization model	b frag. Bowler–Lund	±0.03	±0.06	±0.08
	b frag. Peterson	+0.14	+0.11	+0.19
	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
tt̄ modeling	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
Parametric shapes	Signal shape	±0.05	±0.03	±0.04
	tt̄ 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
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:

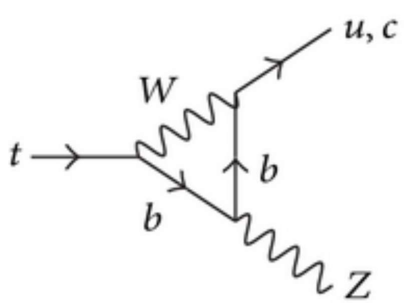


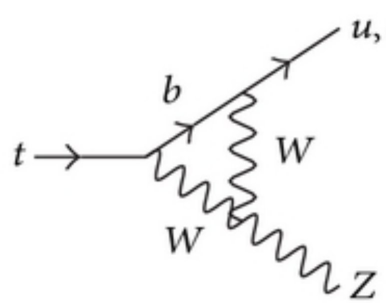
FCNC in tZ production



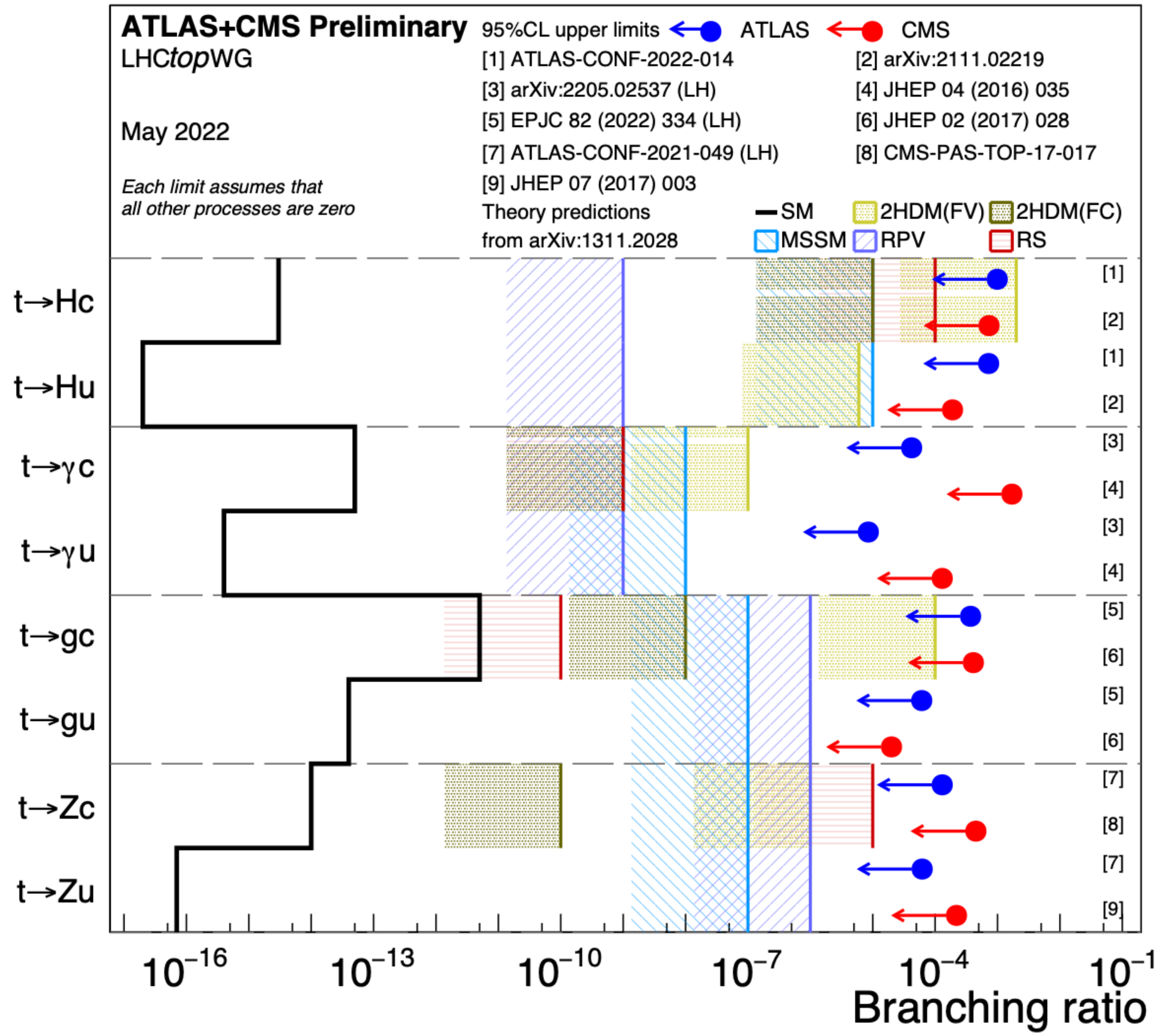
tZ FCNC in top decay

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



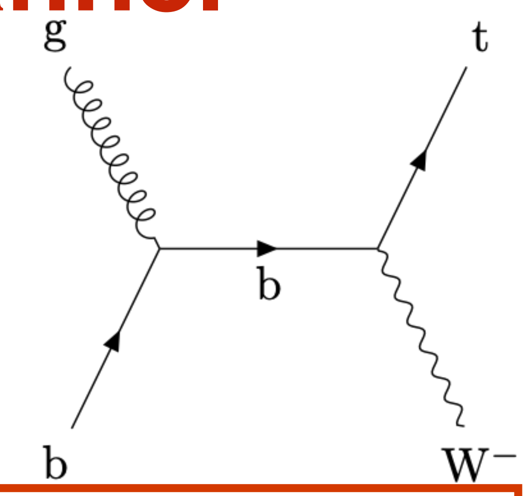


Summary: approaching sensitivity to several BSM models

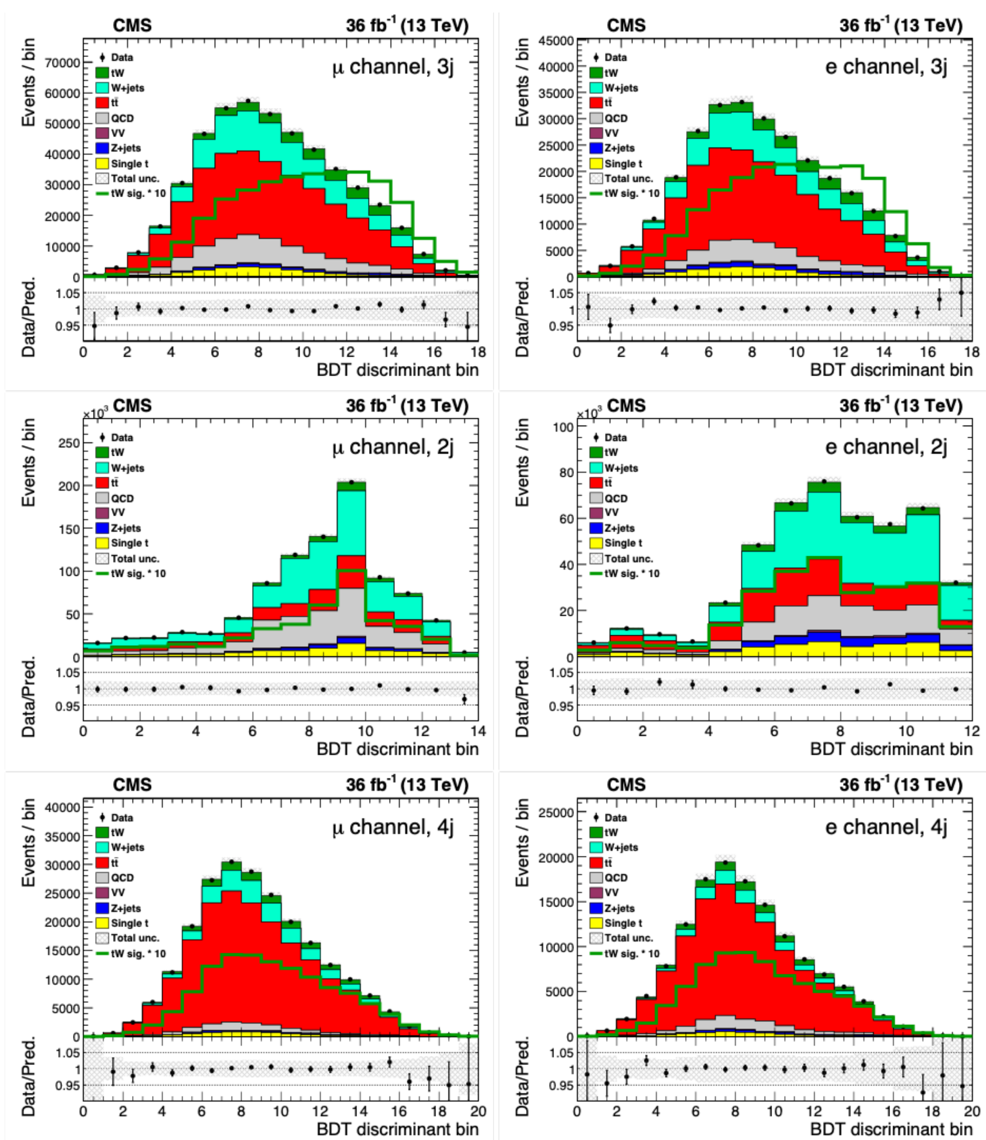


tW cross section in lepton+jets channel

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 (>5σ)

Cross section: $89 \pm 4\,(\text{stat}) \pm 12\,(\text{syst})$ pb

Source	Relative uncertainty (%)
Experimental	
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
Normalization	
QCD multijet normalization	7
W+jets normalization	6
Z+jets normalization	3
Single t normalization	1
$t\bar{t}$ normalization	1
VV normalization	<1
Theoretical	
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**"

Wilson coefficients

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

Dimension 4 operators in the SM Lagrangian

Dimension 6 operators

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

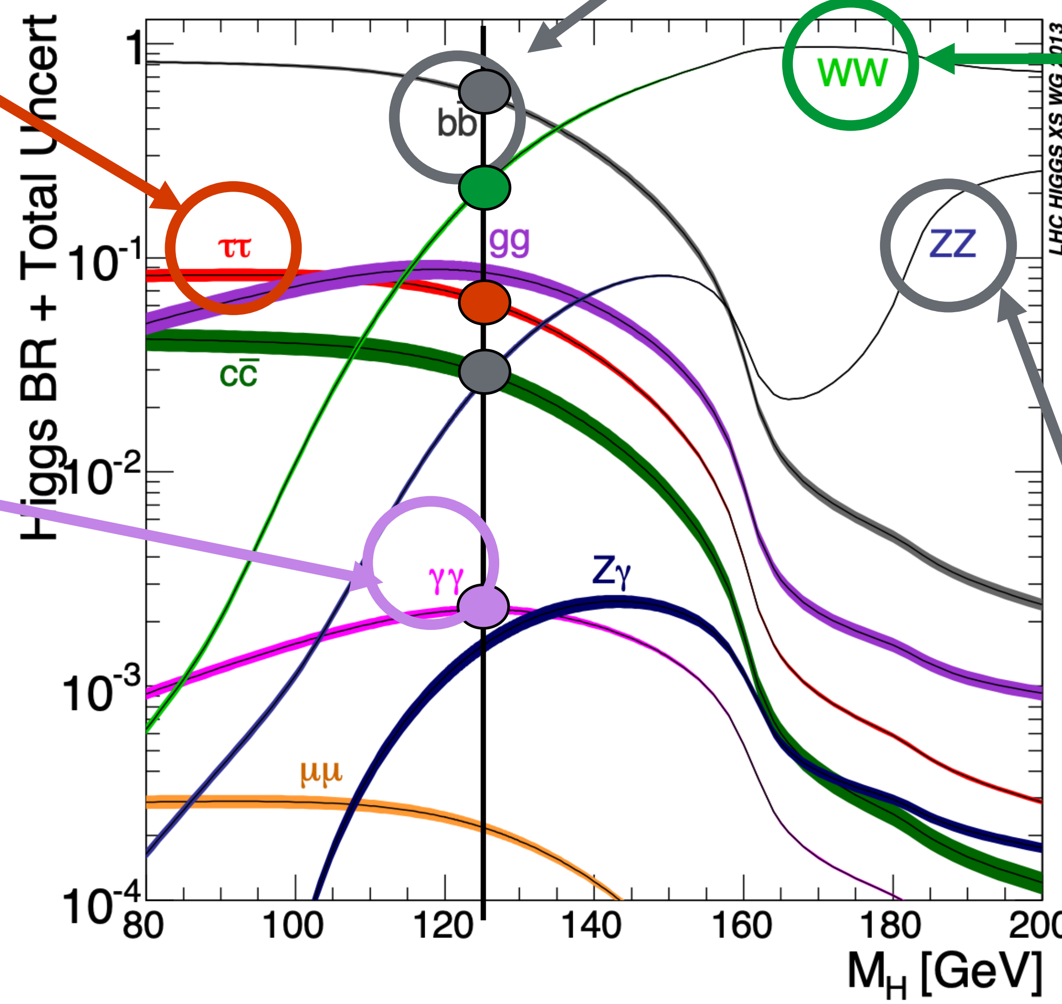
Higgs boson decay

Higgs decay width at 125 GeV: Γ~4 MeV

H→bb (57.7%)
- Large branching ratio
- But large jets background

H→ττ (6.3%)
- Hadronic or leptonic τ decay

H→WW (21.5%)



H→γγ (~0.2%)
- Excellent mass resolution,
- But low branching ratio

H→ZZ (2.6%)
- ZZ→4l: excellent mass resolution

H→WW (and H→ZZ), **H→ττ final state:** tackled with the "**multilepton**" analysis

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

CMS - arXiv:2208.02686

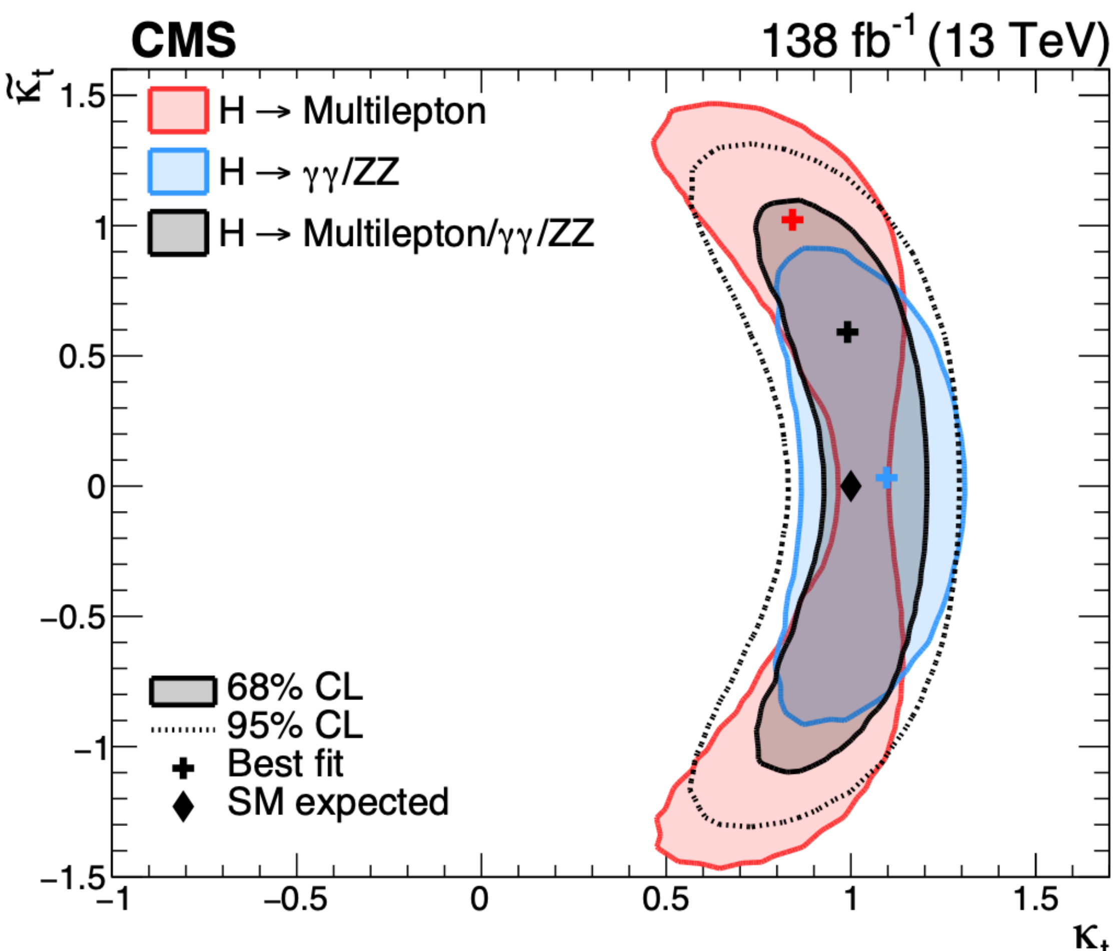
Why universe is there a matter/antimatter asymmetry in the Universe ?

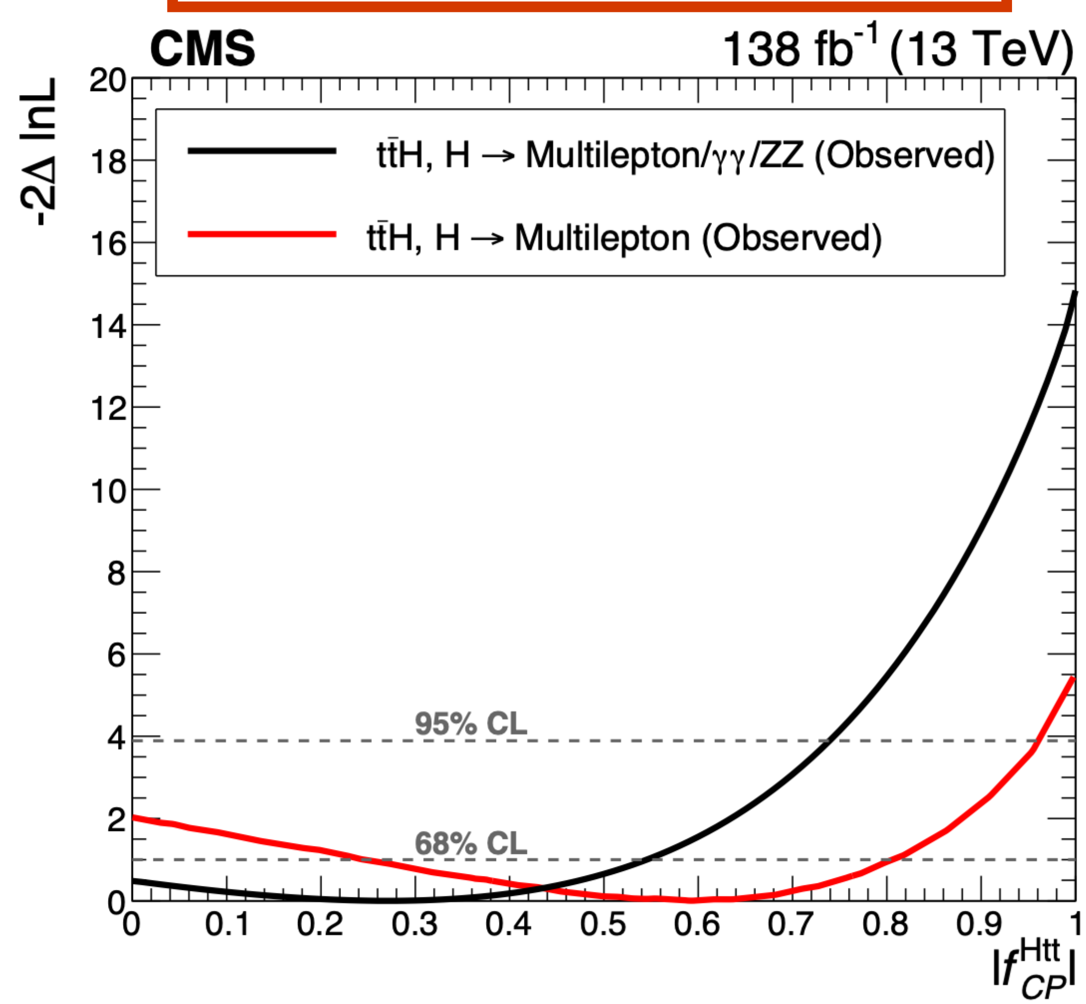
- Skharov conditions: baryogenesis needs **CP violation** (not only)
- Amount of CP violation in the SM is not sufficient: new sources are searched for.
- The top quark impacts electroweak baryogengesis if its Yukawa coupling is CP-violating (see for instance arXiv:1512.08922)

$$f_{\mathrm{CP}}^{\mathrm{Htt}} = \frac{|\tilde{\kappa}_{\mathrm{t}}|^2}{|\kappa_{\mathrm{t}}|^2 + |\tilde{\kappa}_{\mathrm{t}}|^2} \operatorname{sign}(\tilde{\kappa}_{\mathrm{t}}/\kappa_{\mathrm{t}})$$

$$\mathcal{L}(Hf\bar{f}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5\right)\psi_f\, H$$

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





negative values tested