Top quark measurements at the LHC

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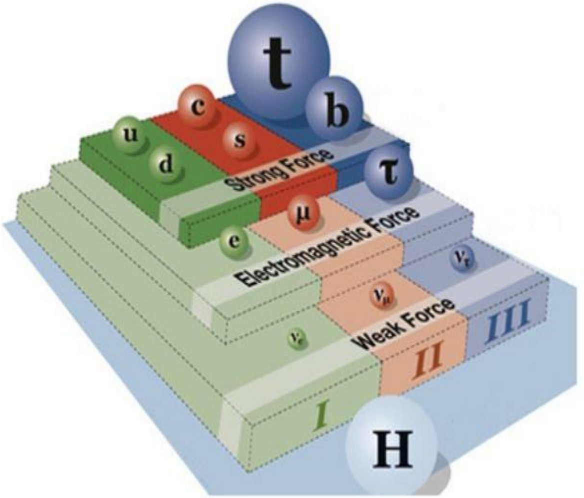
top-quark

The top has several features that make it a very interesting particle:



✓Heaviest particle discovered till now
-- $m^t = 173.34 \pm 0.27(\text{stat}) \pm 0.71(\text{syst})$ GeV
✓Decays before hadronization
-- Give access to the physics of a "free" quark
✓Intensively couples to the Higgs boson

The LHC is a top factory and allows:

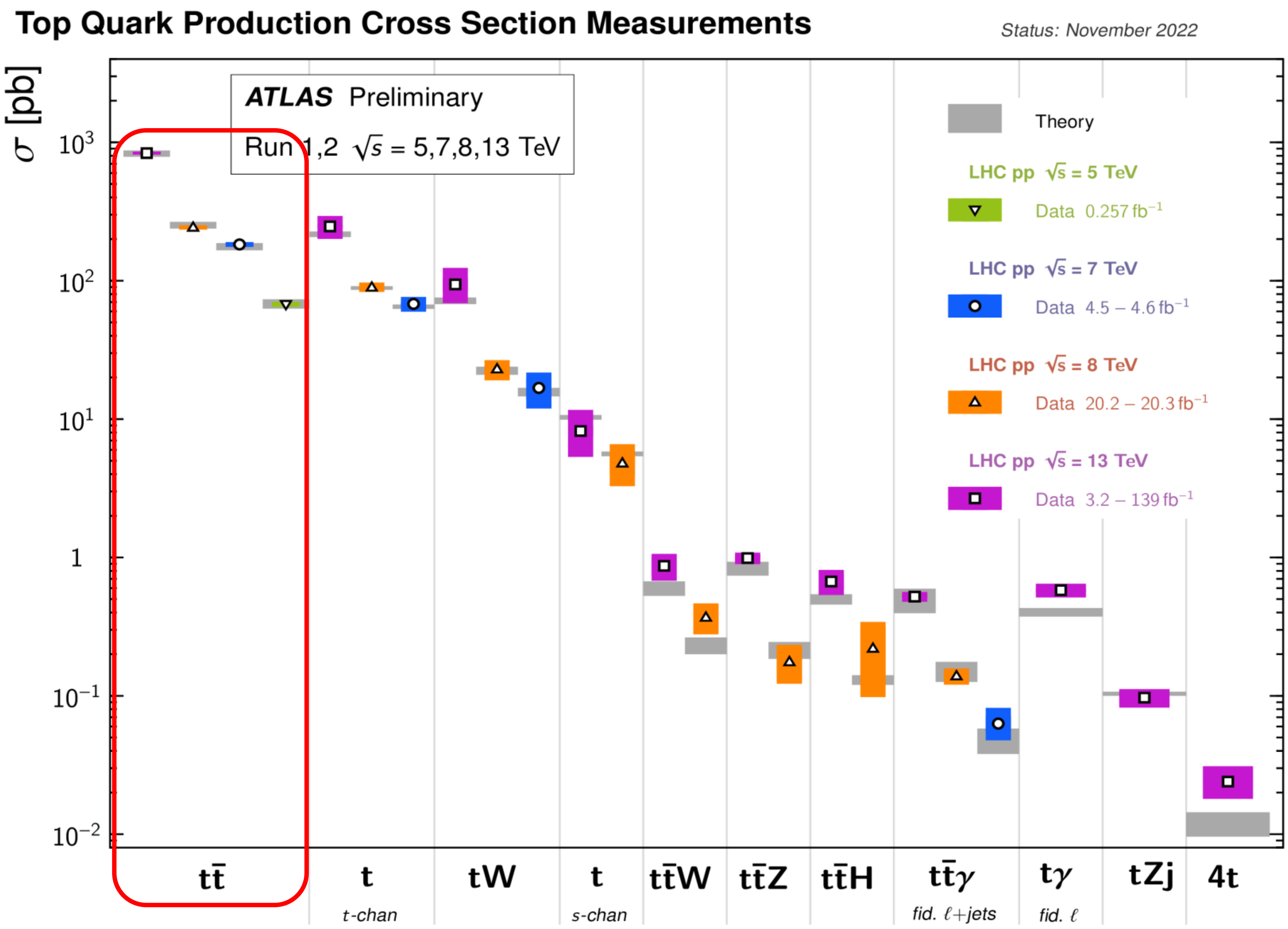
Over 200M top quark pairs in LHC Run2 13 TeV data
More coming with Run3 data taking

✓ Precise measurements of top pairs and single top production

✓ Observation of rare processes involving top

✓ Use the top quark as a "tool" to study the SM

Top pair production

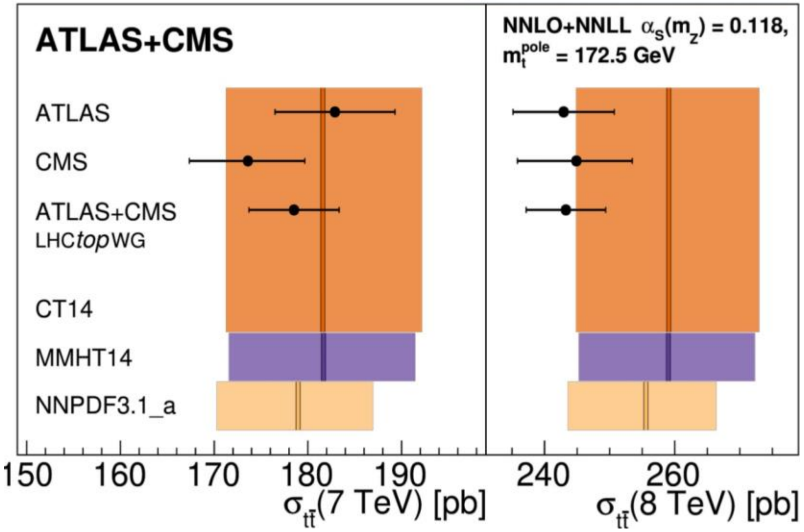


Top cross sections

arXiv:2205.13830

ATLAS+CMS combination 7/8 TeV

- inputs: eμ channel with best precision
- CONVINO tool to combine counting and PL fit

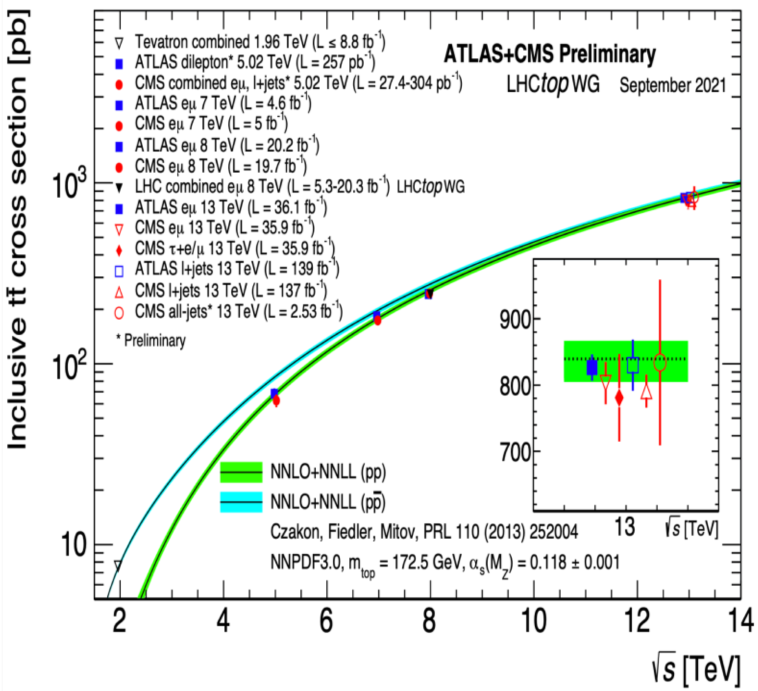


$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}\ ) \quad = \quad 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}\ ) \quad = \quad 243.3^{+6.0}_{-5.9}\ \text{pb},$$

- 25% reduction of uncertainties

$$\alpha_S(m_Z) = 0.1170^{+0.0021}_{-0.0018}$$

Measurements at 5.02 TeV

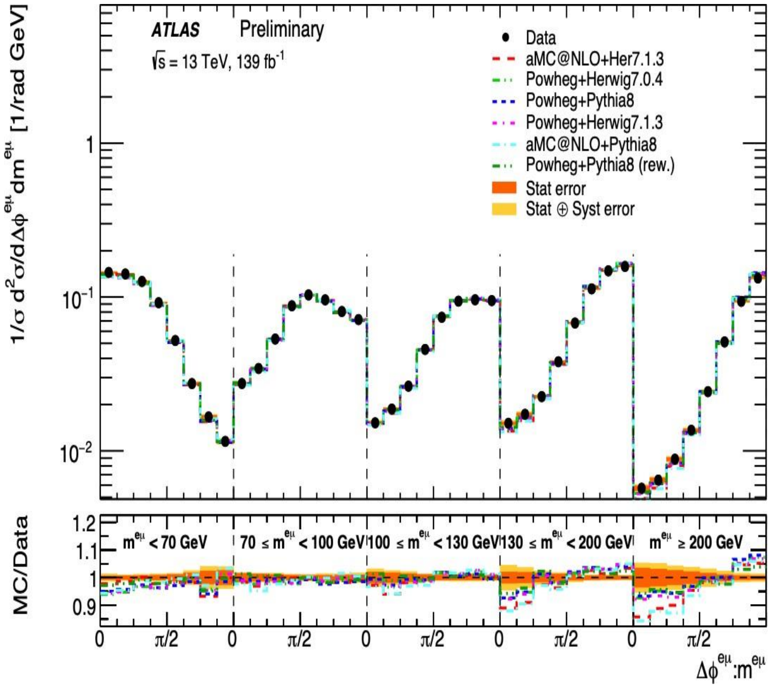


✓ Impressive agreement with QCD predictions from 5.02 to 13 TeV and a magnitude of cross section

Measurements in lepton channels

eμ channel

- ✓ Inclusive and 8 2D distributions
- ✓ For differential applied in each bin



$$\sigma_{t\bar{t}} = 836 \pm 1(stat) \pm 12(syst) \pm 16(lum + E_{cms})$$

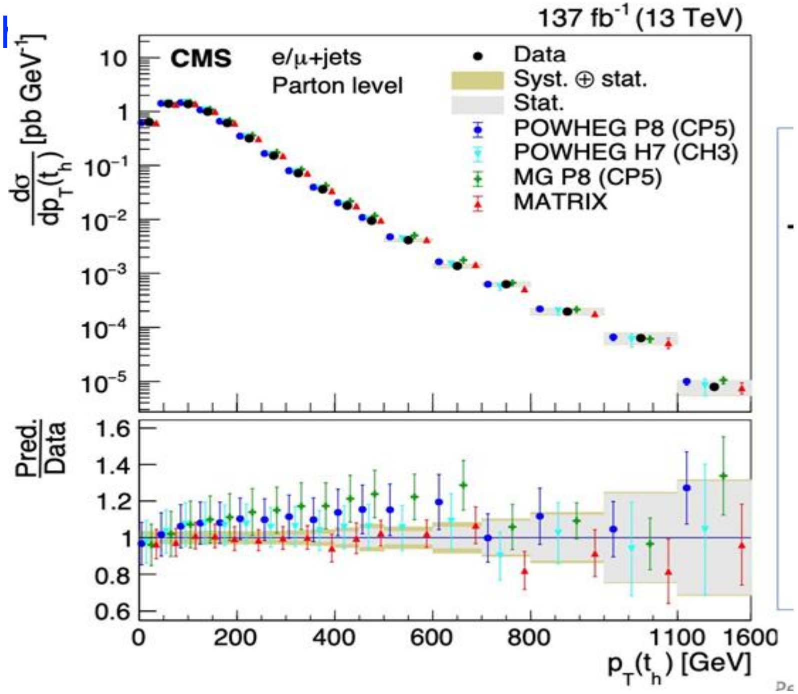
2.4% uncertainty

- Largest uncertainties from luminosity and Wt
- No improvement in precision compared to 36/fb result

Single lepton

PRD 104 (2021) 092013

- ✓ included resolved and boosted topologies
- ✓ Inclusive, parton and particle level
- ✓ Expanded PS compared to dilepton cl



$$\sigma_{t\bar{t}} = 791 \pm 1\,(\text{stat}) \pm 21\,(\text{syst}) \pm 14\,(\text{lumi})\,\text{pb}$$

3.2% uncertainty
most precise in this channel

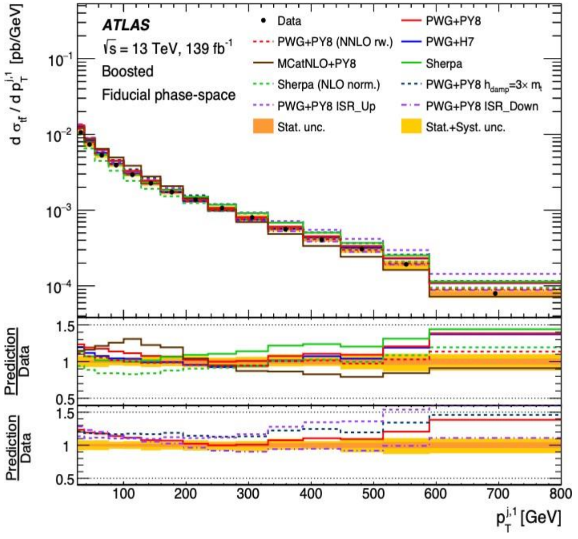
JHEP 06 (2022) 063

Measurements in boosted topology

arXiv:2205.02817

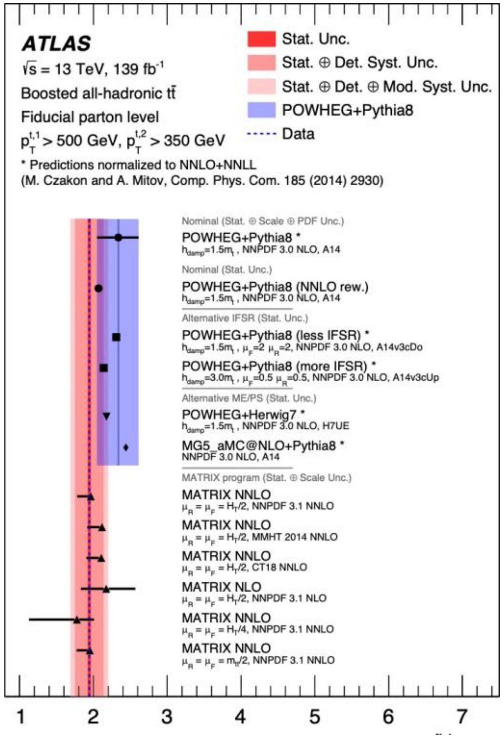
Single lepton channel

- Significant reduction of JES uncertainty due to in-situ JES calibration
- Problems with modelling additional jets and 2D distributions and azimuthal distances to hadronic top



pT of leading additional jet

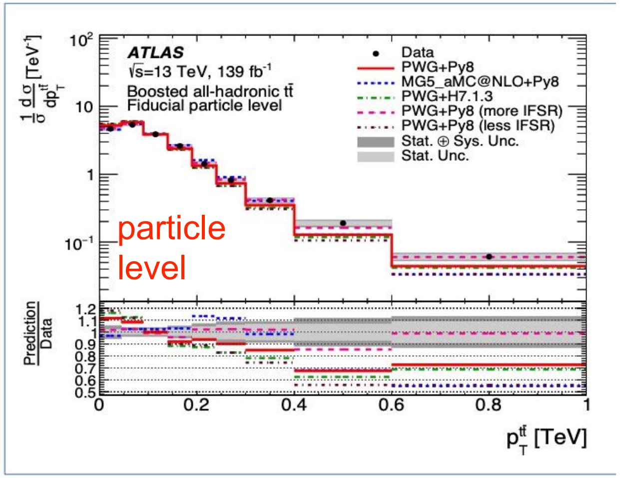
All-hadronic channel



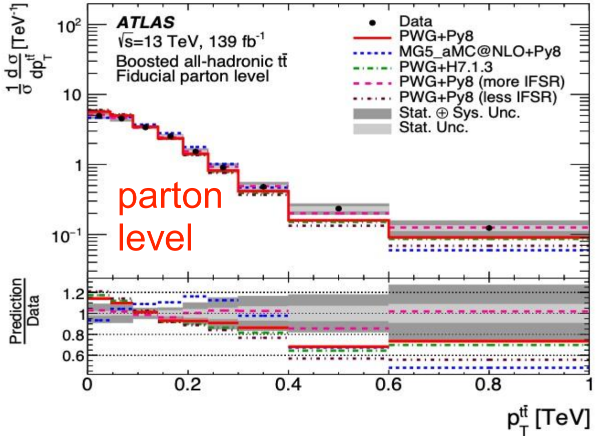
MATRIX reproduces the fiducial cross-section better than the NLO models.

Reweighing the NLO to NNLO top pT helps to reproduce data

tt system pT

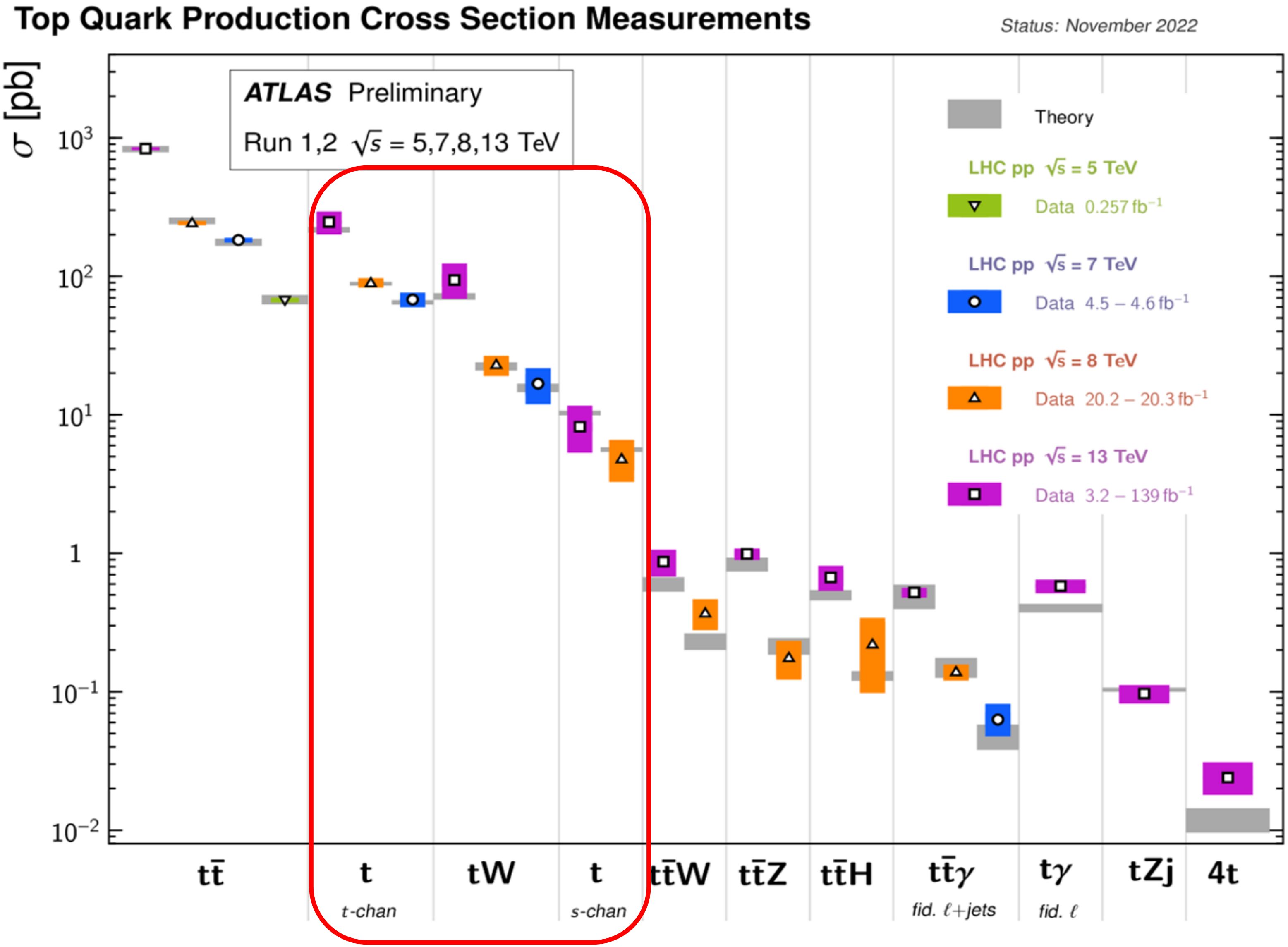


particle level

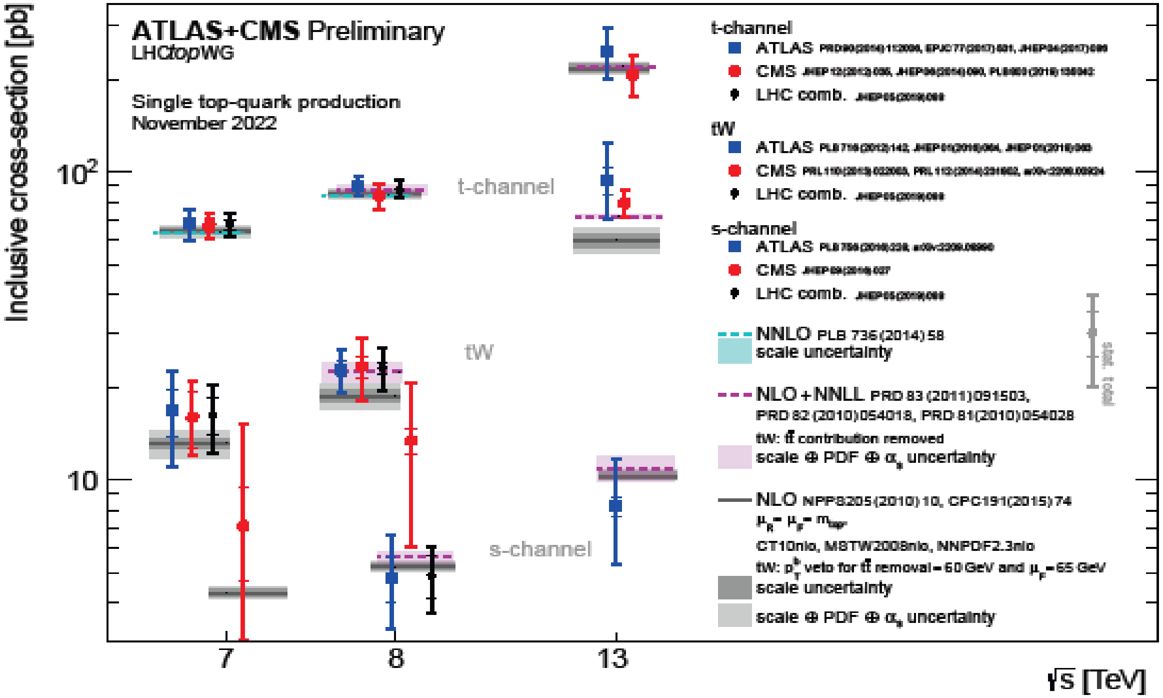


parton level

Single top production

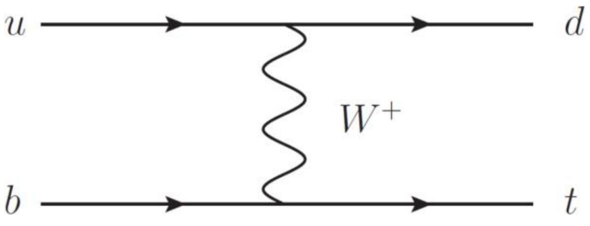


Single top production

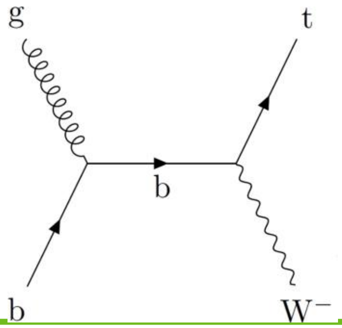


Inclusive xsec measurements are in good agreement w/ NLO+NNLL & NNLO prediction.

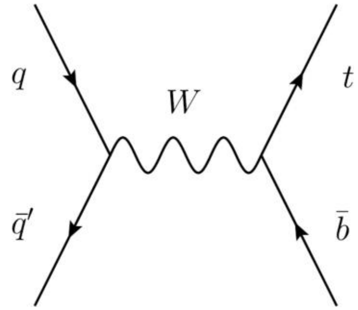
t-channel



tW-channel



s-channel



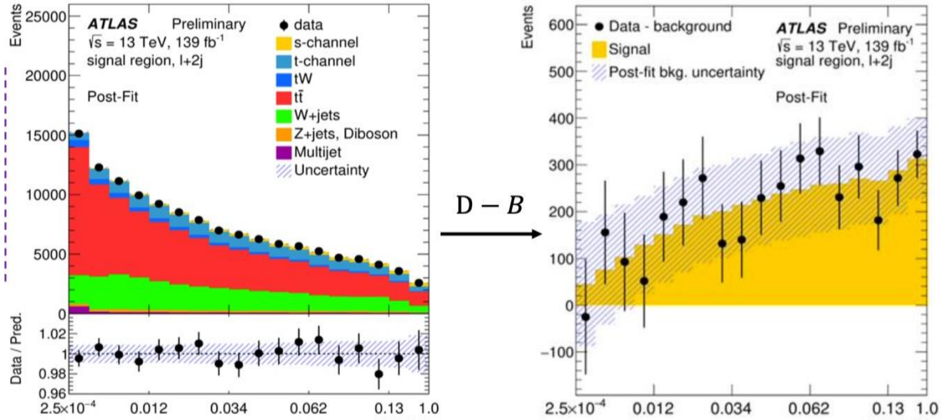
arXiv:2209.08990

Single top cross section

arXiv:2208.00924

s-channel

- ✓ Observed at Tevaton
- ✓ Very complicated at LHC:
  --small cross section, large backgrounds
- ✓ Matrix Element technique to separate S/B



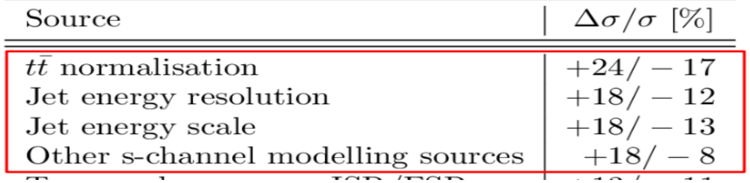
- **Result:**

$$\sigma_{\text{meas.}} = 8.2 \pm 0.6\,(\text{stat.})^{+3.4}_{-2.8}\,(\text{syst.})\text{ pb}$$

- Compatible with SM prediction:

Significance 3.3 (3.9) obs.(exp)

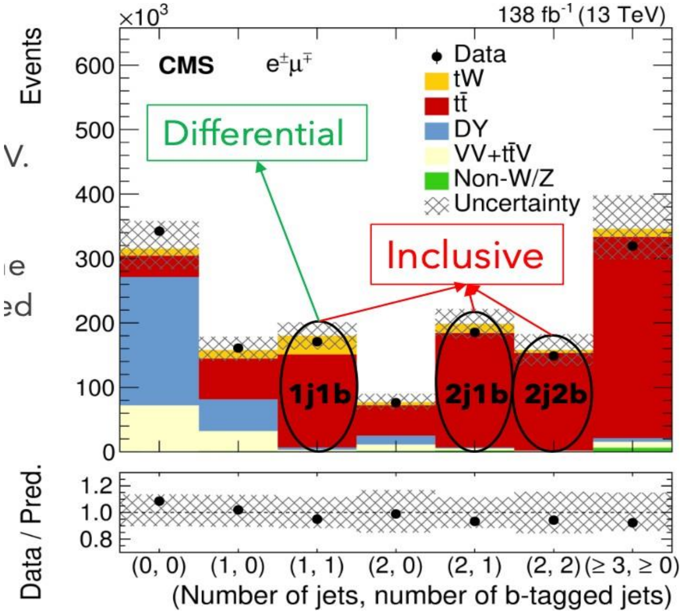
dominated by modelling and JES



Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	$+24/-17$
Jet energy resolution	$+18/-12$
Jet energy scale	$+18/-13$
Other s-channel modelling sources	$+18/-8$

tW channel

- ✓ Inclusive and differential XS in eμ channel



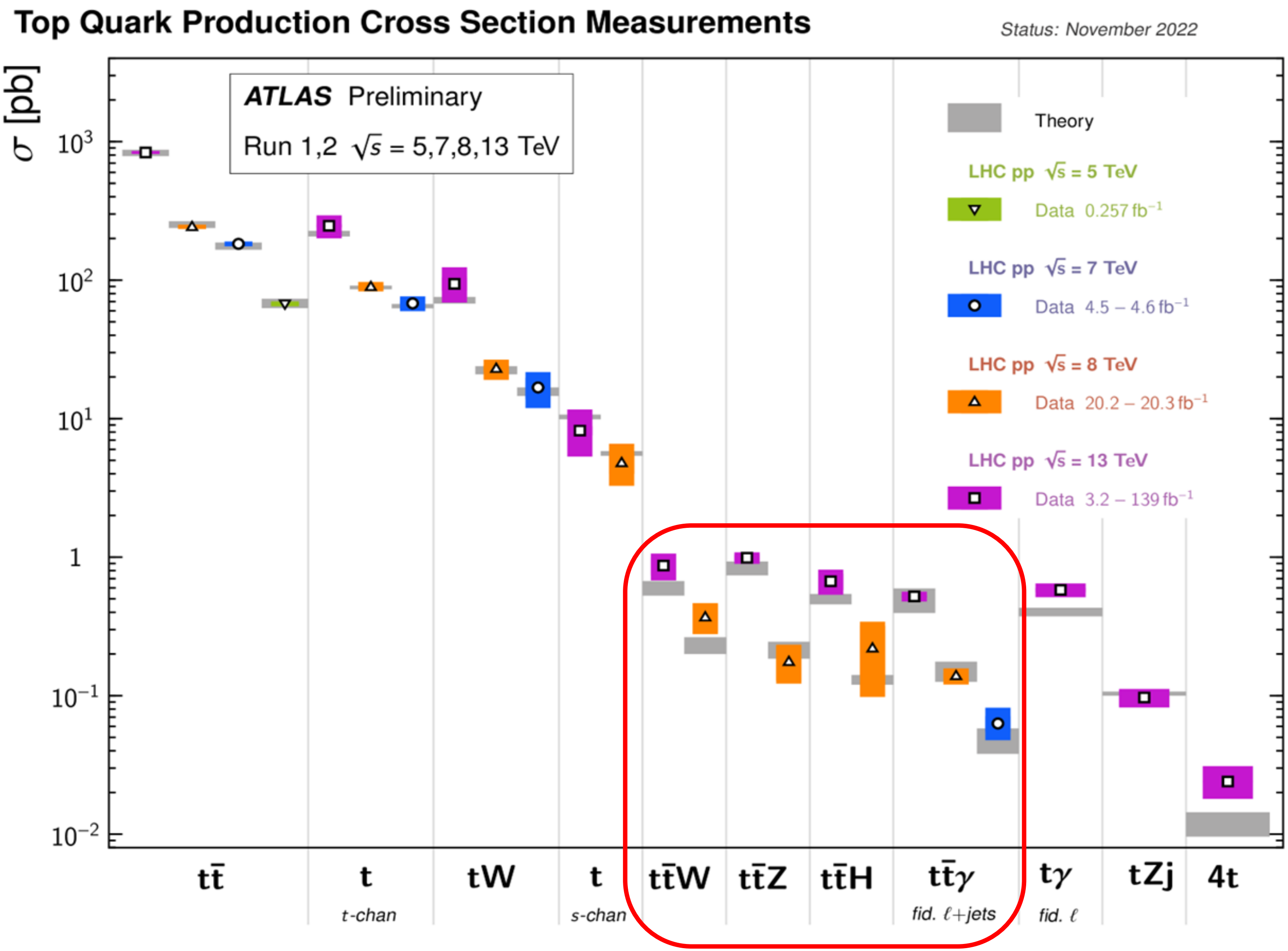
$$\sigma_{\text{tW}} = 79.2 \pm 0.8\,(\text{stat}) \pm^{7.0}_{7.2}\,(\text{syst}) \pm 1.1\,(\text{lumi})\text{ pb}$$

10% uncertainty

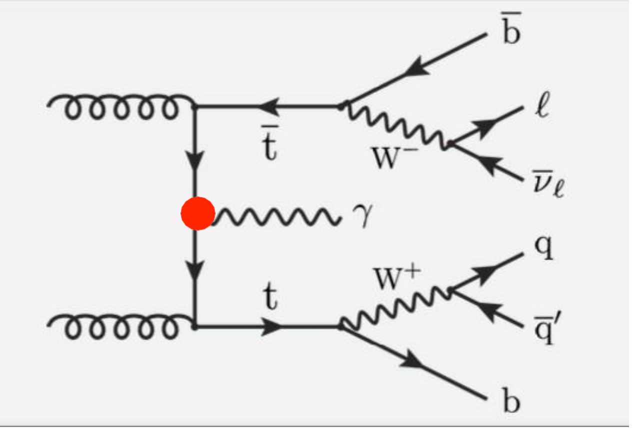
In agreement with predictions

- ➢ tW is also measured in single lepton channel by ATLAS (8 TeV) and CMS (13 TeV)
- ➢ Less precise than dilepton

tt + X production

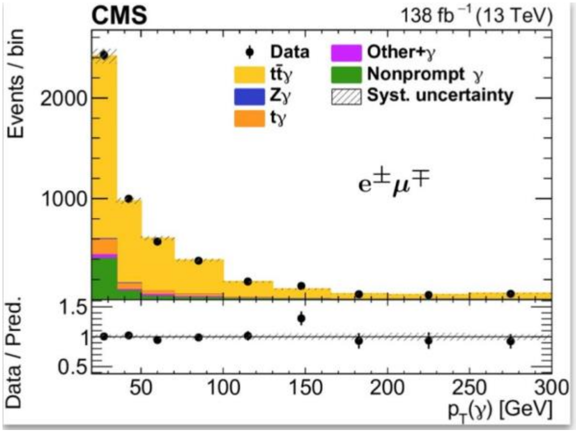


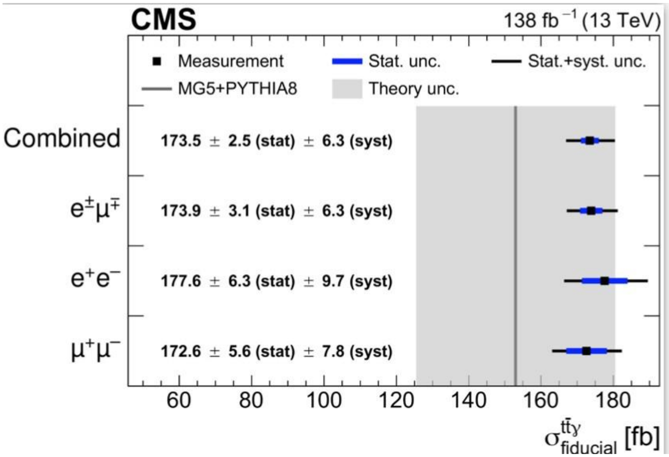
ttγ production



JHEP 05 (2022) 091

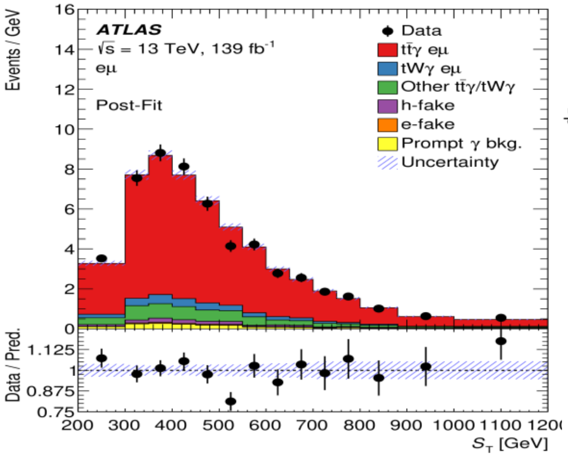
- New CMS measurement in dilepton channel

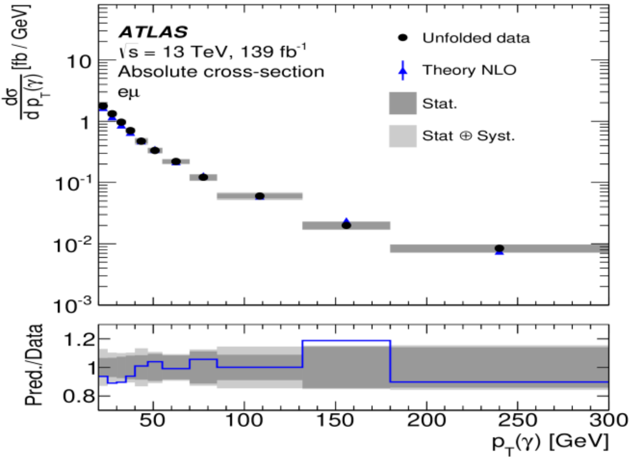




- Precision 4%
- Prediction from MG5aMC (LO+NLO k-factor) is lower

JHEP 09 (2020) 049

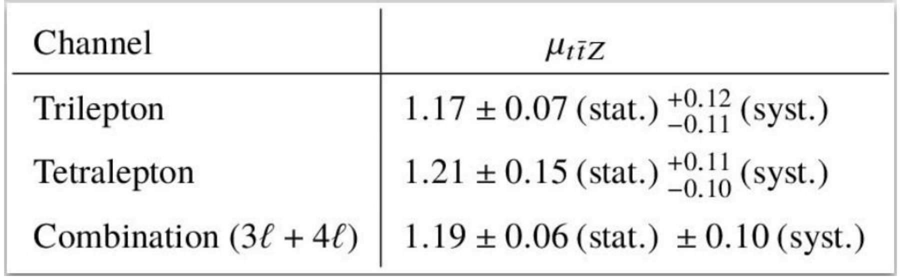




In agreement with the predictions from the SM

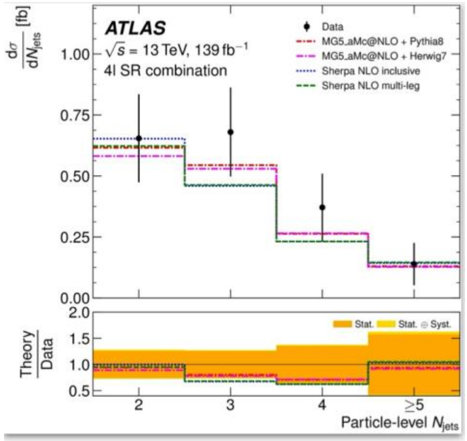
EPJC 81 (2021) 737

ttZ measurements

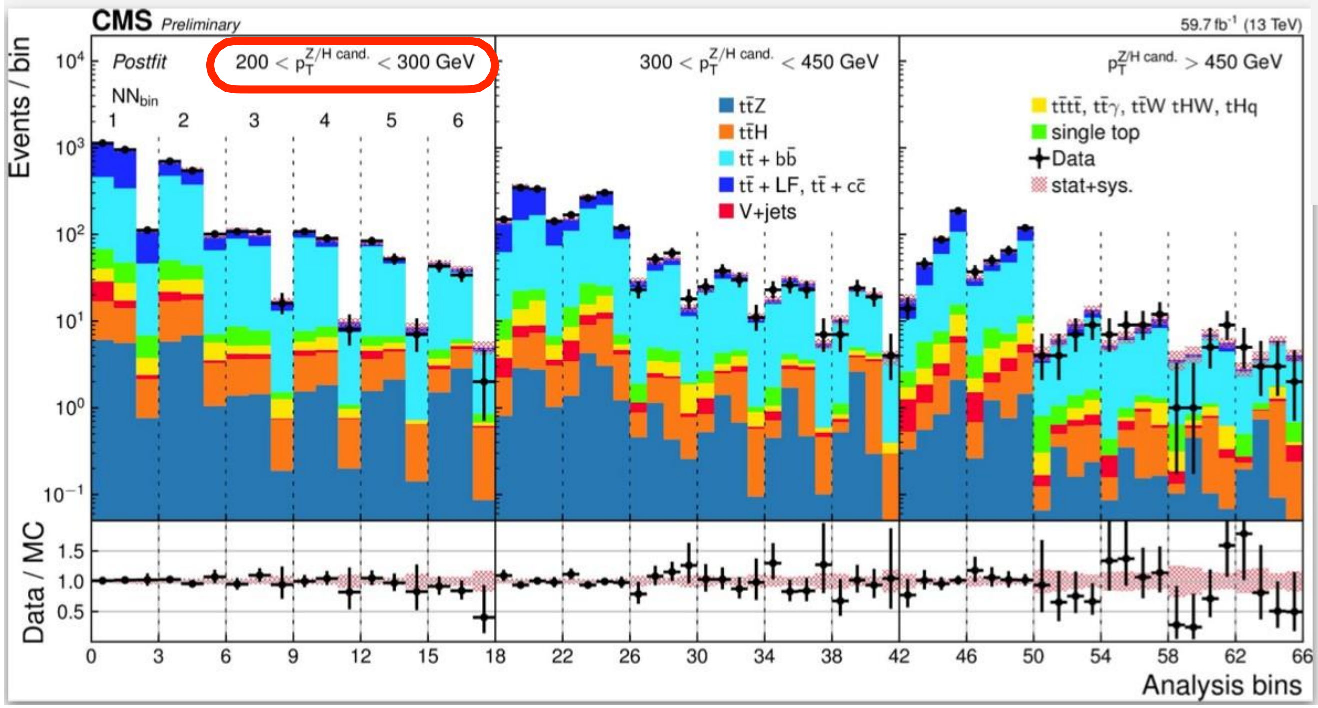


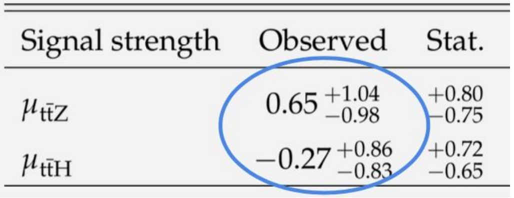
Channel	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combination ($3\ell + 4\ell$)	$1.19 \pm 0.06\,(\text{stat.}) \pm 0.10\,(\text{syst.})$

- ✓ Precision 10%
- ✓ Slightly higher than prediction



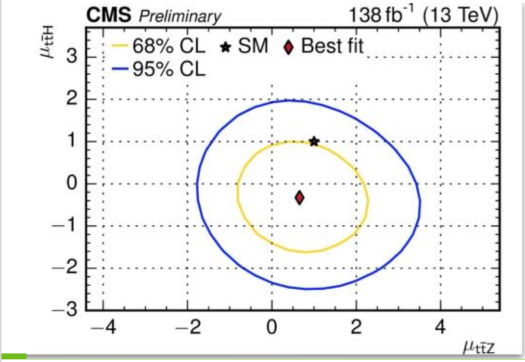
- ➢ Measurement of ttZ(bb) and ttH(bb) in boosted regime arXiv:2208.12837





Signal strength	Observed	Stat.
$\mu_{t\bar{t}Z}$	$0.65\,^{+1.04}_{-0.98}$	$^{+0.80}_{-0.75}$
$\mu_{t\bar{t}H}$	$-0.27\,^{+0.86}_{-0.83}$	$^{+0.72}_{-0.65}$

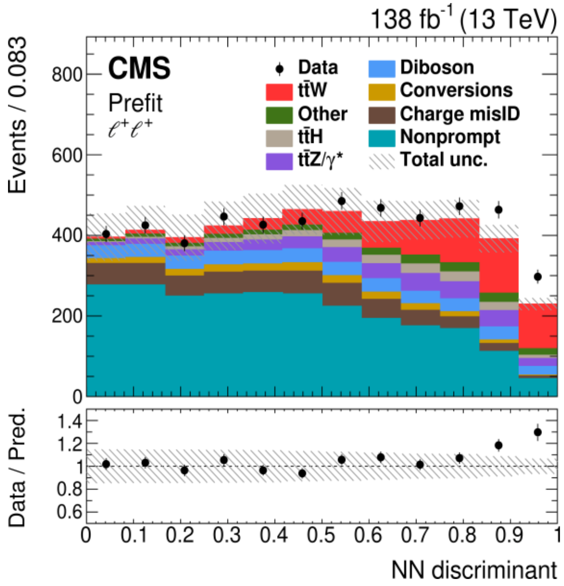
Limited by statistics

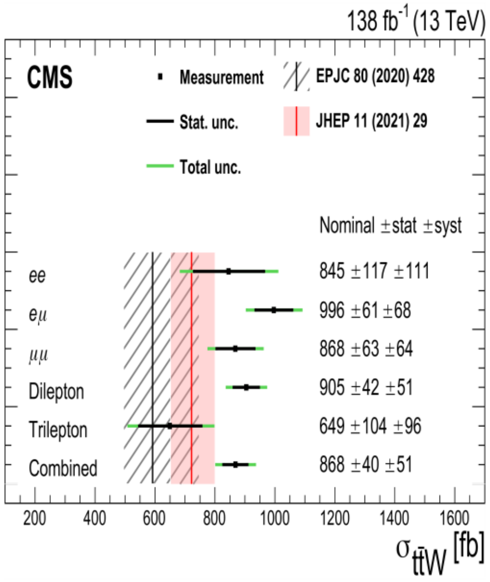


ttW measurement

2-lepton Same Sign and tri-lepton final states

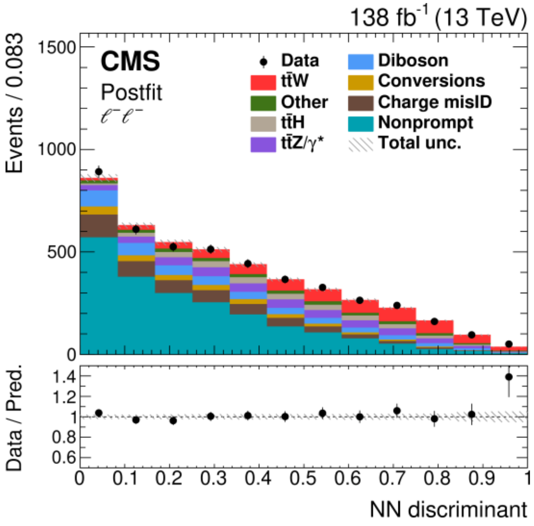
arXiv:2208.06485

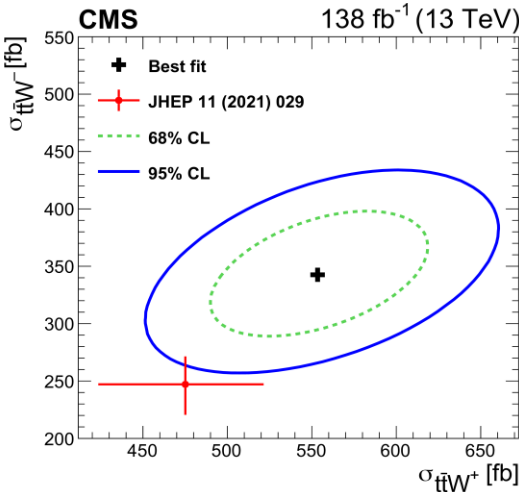




Combined cross section corresponds to $\mu_{ttW} = 1.47$

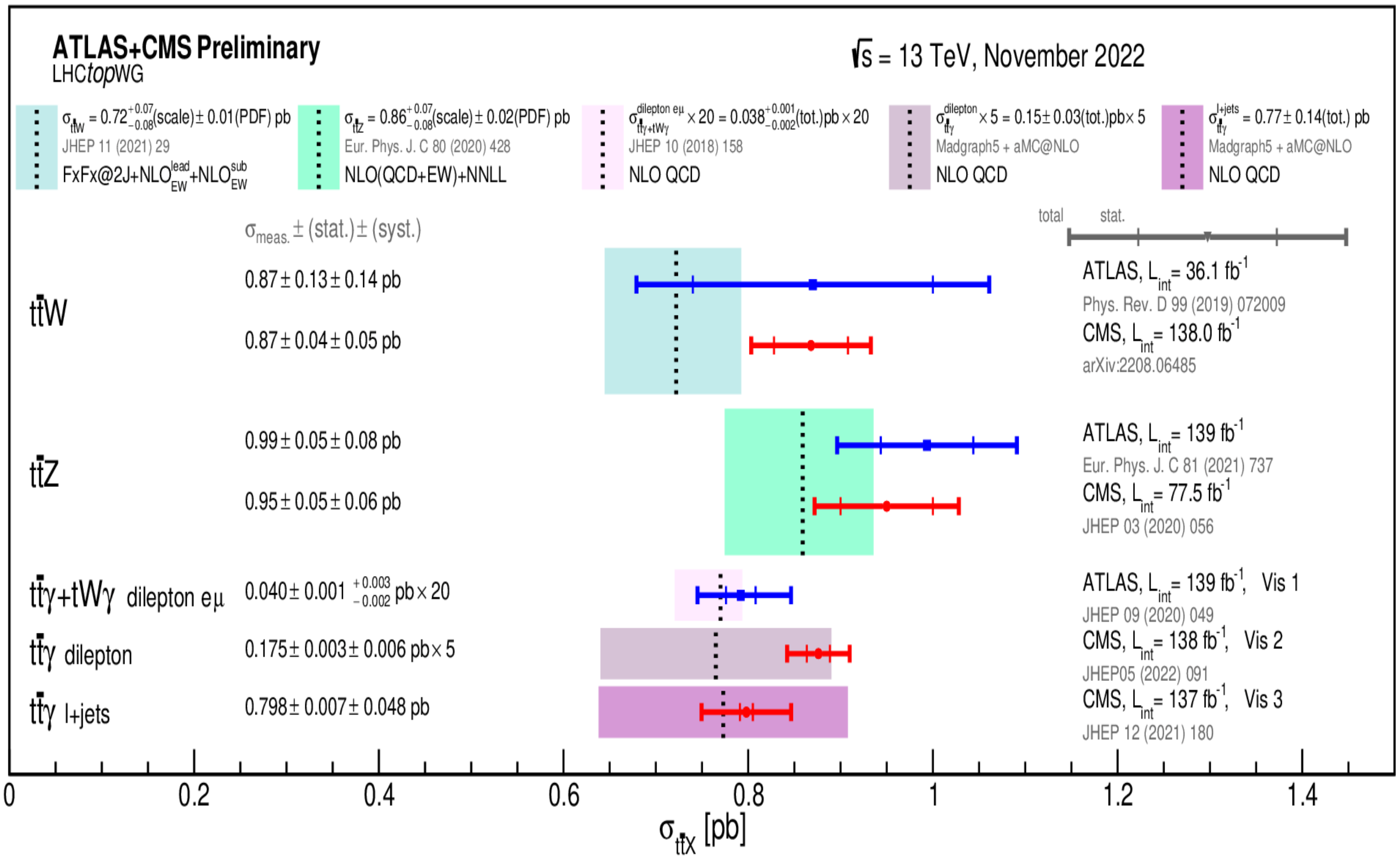
R(ttW+/ttW−) = 1.61 ± 0.15 (stat) $^{+0.07}/_{-0.05}$ (syst)



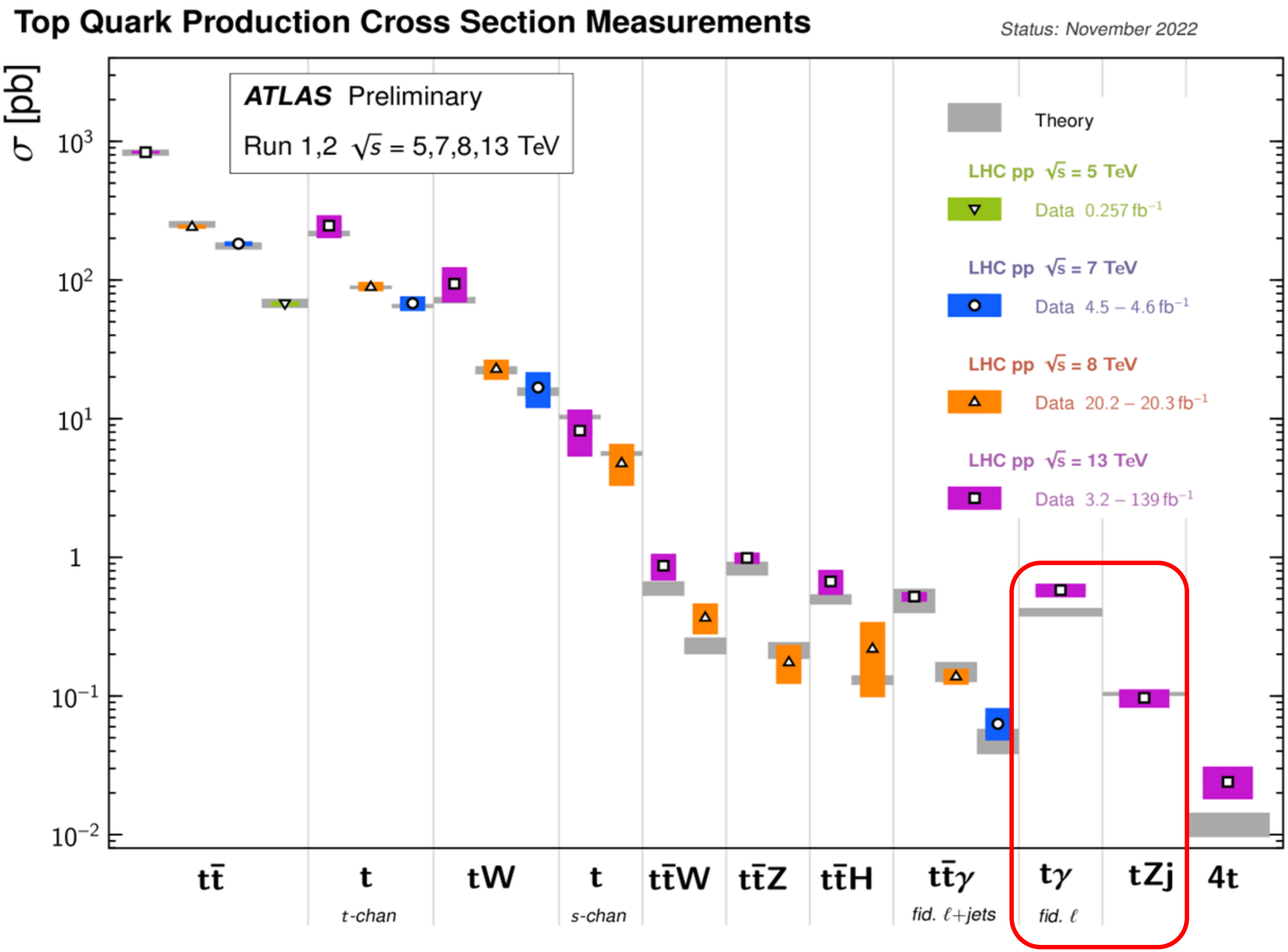


Significant deviation from prediction for ttW+/ttW- ratio = 1.94+0.37-0.24

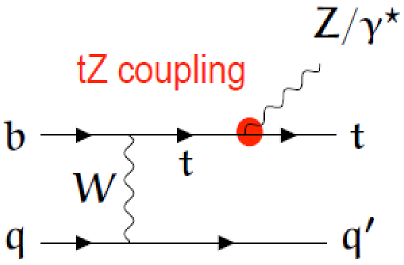
tt+X summary


ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, November 2022
σ_ttW = 0.72 +0.07 −0.08 (scale) ± 0.01(PDF) pb
JHEP 11 (2021) 29
FxFx@2J+NLO lead EW +NLO sub EW
σ_ttZ = 0.86 +0.07 −0.08 (scale) ± 0.02(PDF) pb
Eur. Phys. J. C 80 (2020) 428
NLO(QCD+EW)+NNLL
σ dilepton eμ ttγ+tWγ × 20 = 0.038 +0.001 −0.002 (tot.) pb × 20
JHEP 10 (2018) 158
NLO QCD
σ dilepton ttγ × 5 = 0.15 ± 0.03(tot.) pb × 5
Madgraph5 + aMC@NLO
NLO QCD
σ l+jets ttγ = 0.77 ± 0.14(tot.) pb
Madgraph5 + aMC@NLO
NLO QCD
σ_meas. ± (stat.) ± (syst.)
total
stat.
ttW
0.87 ± 0.13 ± 0.14 pb
ATLAS, L_int = 36.1 fb⁻¹
Phys. Rev. D 99 (2019) 072009
0.87 ± 0.04 ± 0.05 pb
CMS, L_int = 138.0 fb⁻¹
arXiv:2208.06485
ttZ
0.99 ± 0.05 ± 0.08 pb
ATLAS, L_int = 139 fb⁻¹
Eur. Phys. J. C 81 (2021) 737
0.95 ± 0.05 ± 0.06 pb
CMS, L_int = 77.5 fb⁻¹
JHEP 03 (2020) 056
ttγ+tWγ dilepton eμ
0.040 ± 0.001 +0.003 −0.002 pb × 20
ATLAS, L_int = 139 fb⁻¹, Vis 1
JHEP 09 (2020) 049
ttγ dilepton
0.175 ± 0.003 ± 0.006 pb × 5
CMS, L_int = 138 fb⁻¹, Vis 2
JHEP05 (2022) 091
ttγ l+jets
0.798 ± 0.007 ± 0.048 pb
CMS, L_int = 137 fb⁻¹, Vis 3
JHEP 12 (2021) 180
0
0.2
0.4
0.6
0.8
1
1.2
1.4
σ_ttX [pb]

t + X production



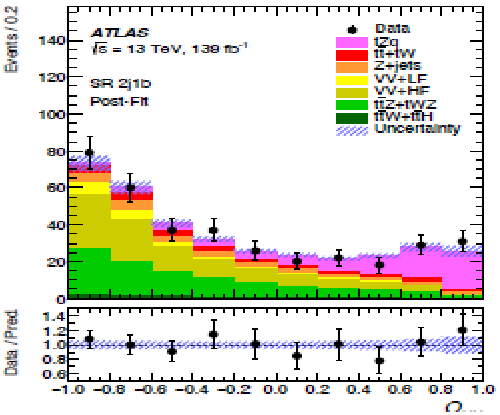
tZq production



Z(ll)

blν

forward jet

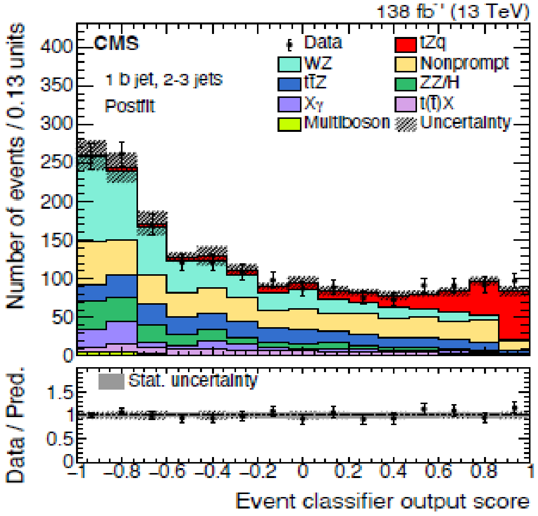


JHEP 07 (2020) 124

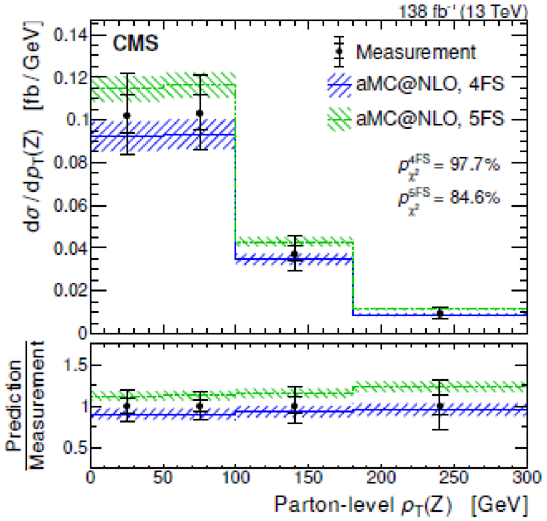
cross section measured with 14% uncertainty

- ✓ Observed by ATLAS and CMS
- ✓ New CMS analysis with full run2 data set

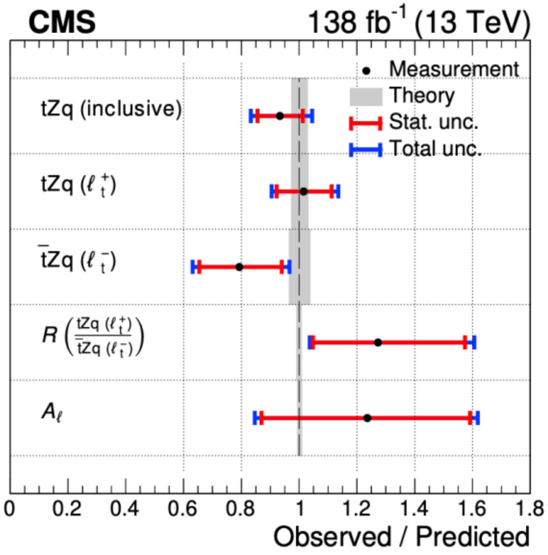
JHEP 02 (2022) 107



11% cross section uncertainty



first parton and particle level differential measurements



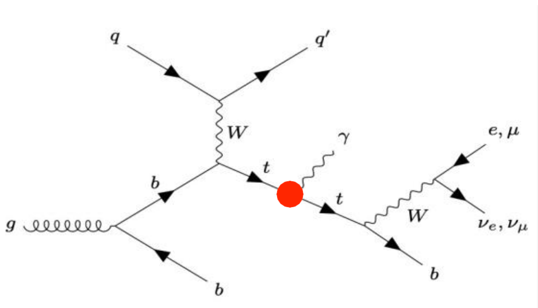
first measurement of ratio

$$R\left(\frac{\mathrm{tZq}\ (\ell_t^+)}{\bar{\mathrm{t}}\mathrm{Zq}\ (\ell_t^-)}\right)$$

Precision is expected to improve with more statistics in Run 3

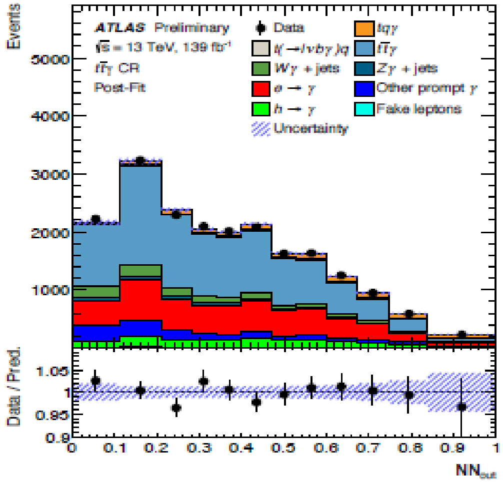
tqγ production

ATLAS-CONF-2022-013

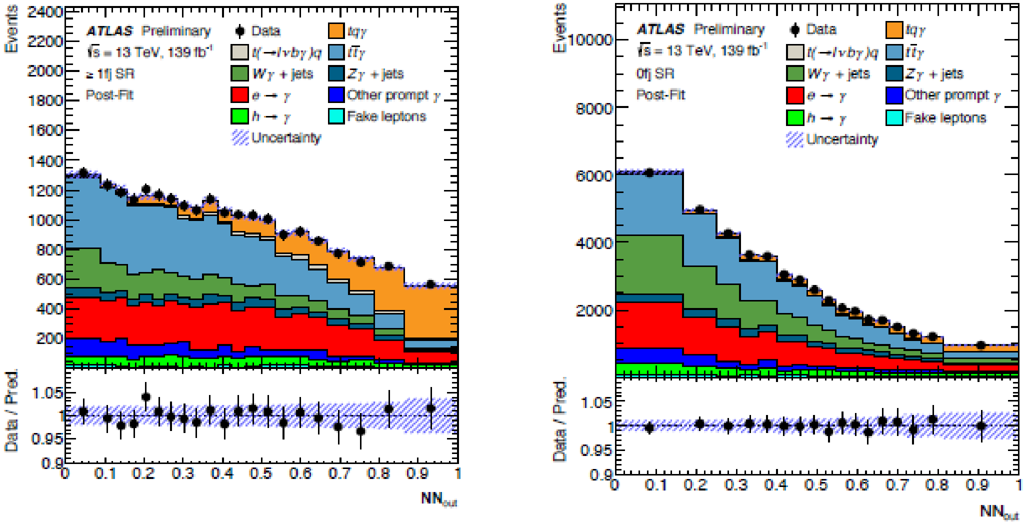


- ✓ **First evidence from CMS using ~36/fb of data**
- ✓ **New ATLAS analysis with full run 2 data**

Largest background from ttγ



Signal regions (NN)



Observed (expected) significance is 9.1σ (6.7σ)

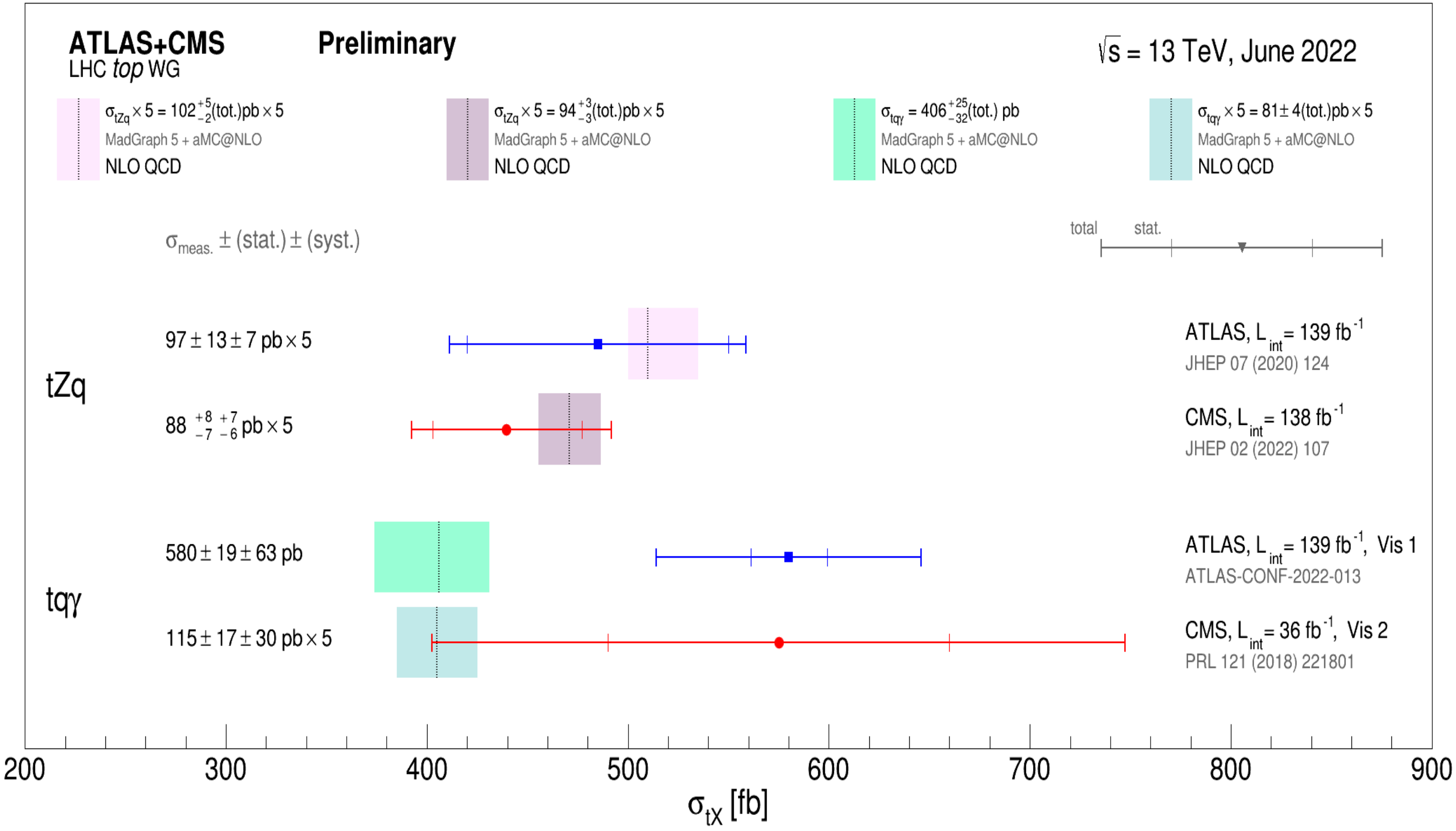
~40% higher that prediction

Parton level cross section: $\sigma(tq\gamma)\,\mathcal{B}(t \rightarrow \ell\nu b) = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})\text{fb}$

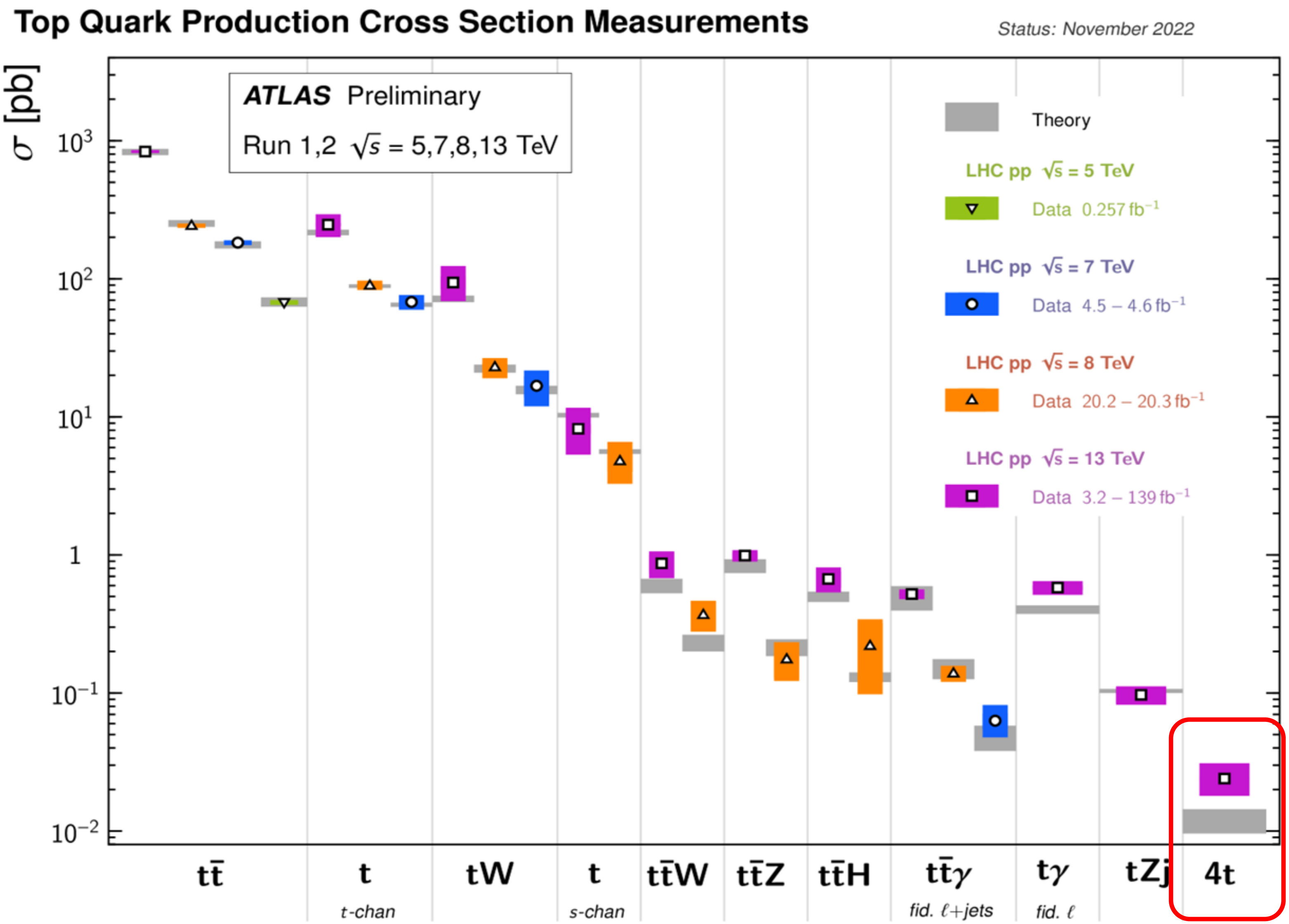
Particle level cross section $\sigma(tq\gamma)\,\mathcal{B}(t \rightarrow \ell\nu b) + \sigma(t \rightarrow \ell\nu b\gamma)q = 287 \pm 8(\text{stat.})^{+32}_{-31}(\text{syst.})\text{fb}$

Compatible with the SM within 2.5(1.9)σ at parton(particle) level

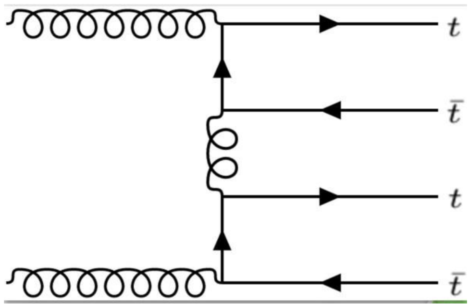
t+X summary


ATLAS+CMS
LHC top WG
Preliminary
$\sqrt{s}$ = 13 TeV, June 2022
$\sigma_{tZq} \times 5 = 102^{+5}_{-2}$(tot.)pb × 5
MadGraph 5 + aMC@NLO
NLO QCD
$\sigma_{tZq} \times 5 = 94^{+3}_{-3}$(tot.)pb × 5
MadGraph 5 + aMC@NLO
NLO QCD
$\sigma_{tq\gamma} = 406^{+25}_{-32}$(tot.) pb
MadGraph 5 + aMC@NLO
NLO QCD
$\sigma_{tq\gamma} \times 5 = 81 \pm 4$(tot.)pb × 5
MadGraph 5 + aMC@NLO
NLO QCD
$\sigma_{meas.} \pm$ (stat.) ± (syst.)
total
stat.
tZq
97 ± 13 ± 7 pb × 5
ATLAS, L_{int} = 139 fb^{-1}
JHEP 07 (2020) 124
$88 \, ^{+8}_{-7} \, ^{+7}_{-6}$ pb × 5
CMS, L_{int} = 138 fb^{-1}
JHEP 02 (2022) 107
tqγ
580 ± 19 ± 63 pb
ATLAS, L_{int} = 139 fb^{-1}, Vis 1
ATLAS-CONF-2022-013
115 ± 17 ± 30 pb × 5
CMS, L_{int} = 36 fb^{-1}, Vis 2
PRL 121 (2018) 221801
200
300
400
500
600
700
800
900
σ_{tX} [fb]

4-top production

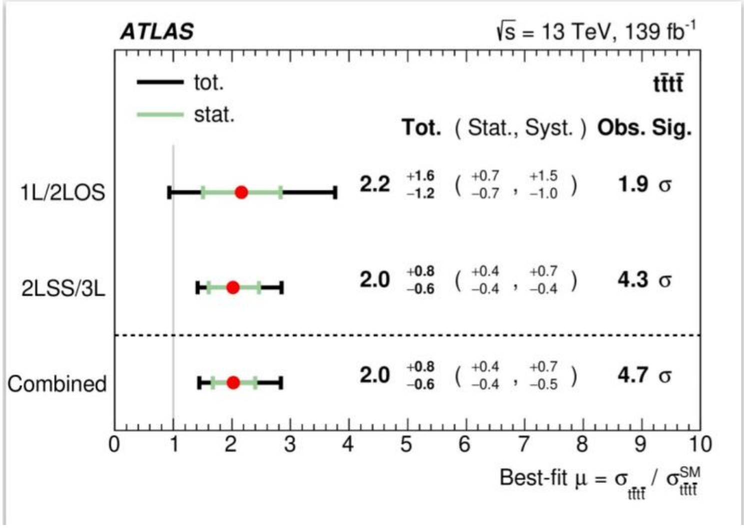


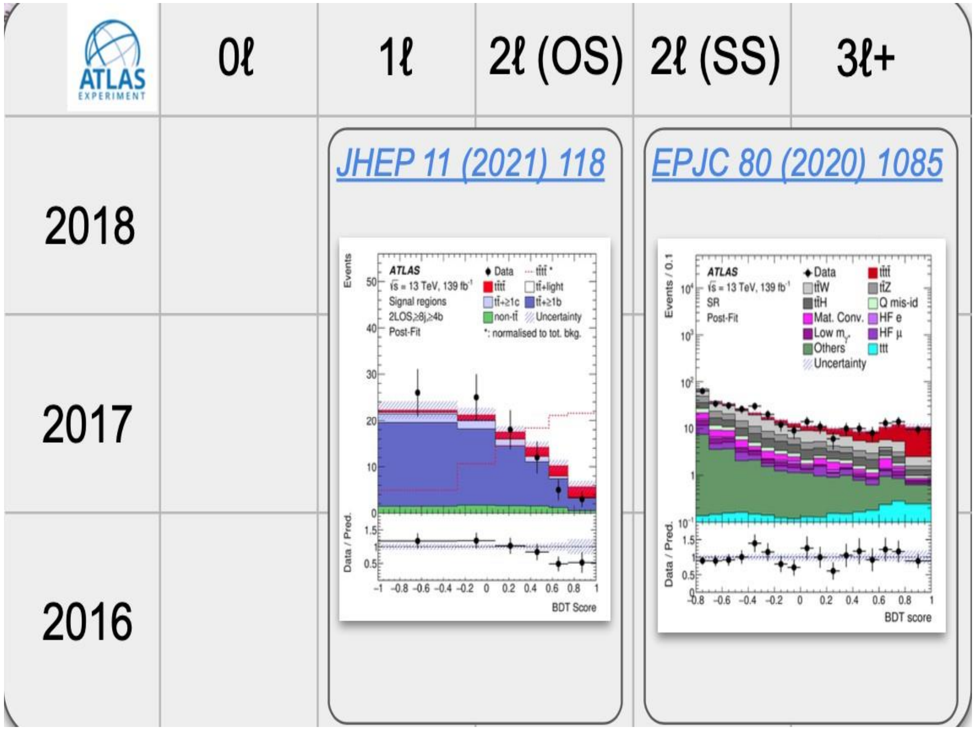
4-top searches



Heaviest particle final state

Many different final states





	0ℓ	1ℓ	2ℓ (OS)	2ℓ (SS)	3ℓ+
2018		JHEP 11 (2021) 118		EPJC 80 (2020) 1085	
2017					
2016					

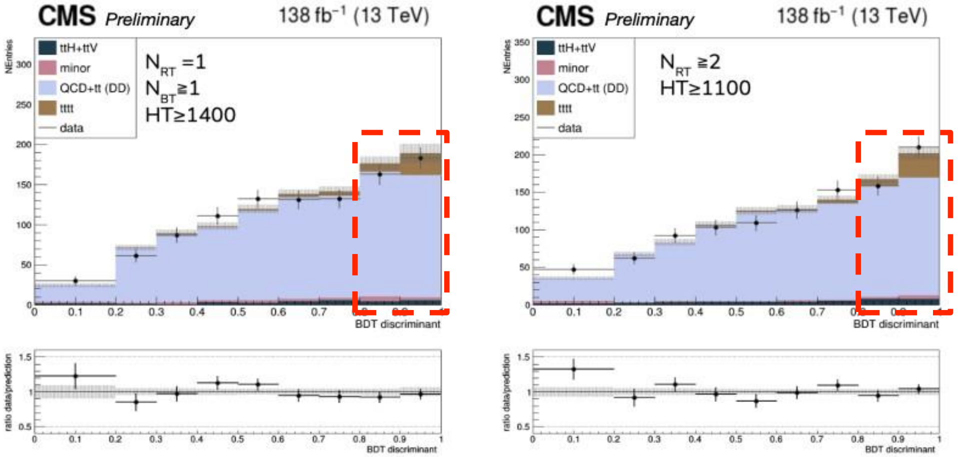
- ✓ Measured cross-section: $\sigma(tttt) = 24\,^{+7}/_{-6}$ fb (4.7σ)
- ✓ Predicted NLO QCD+EW: $\sigma(tttt) = 12.0\,^{+2.2}/_{-2.5}$ fb
- ✓ Compatible within 2σ

significance: 4.7σ

4-top searches

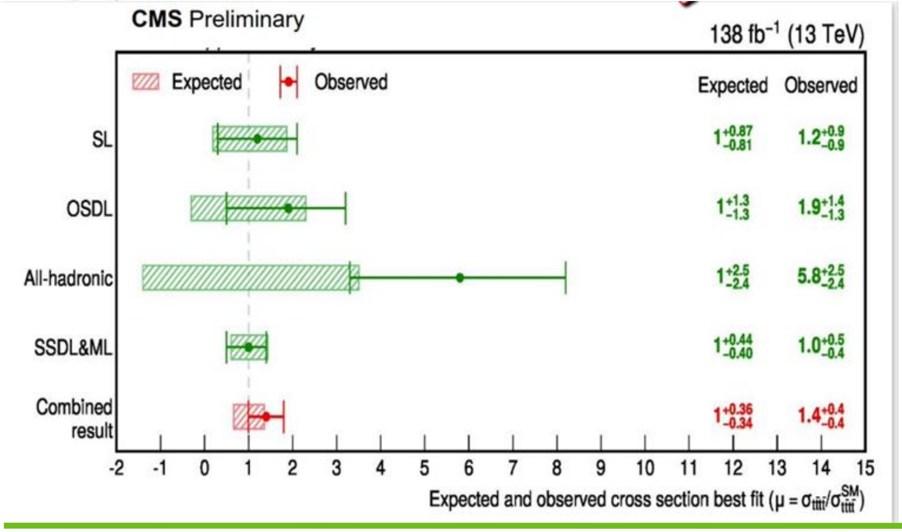
1-lepton, 2-lepton OS, all-hadronic channels

Channels with large tt+bb and multi jet (all-hadronic) backgrounds



Example post-fit S+B BDT discriminant distributions in most sensitive SR bins in Run II

Large excess in data in most sensitive regions in all-hadronic channel

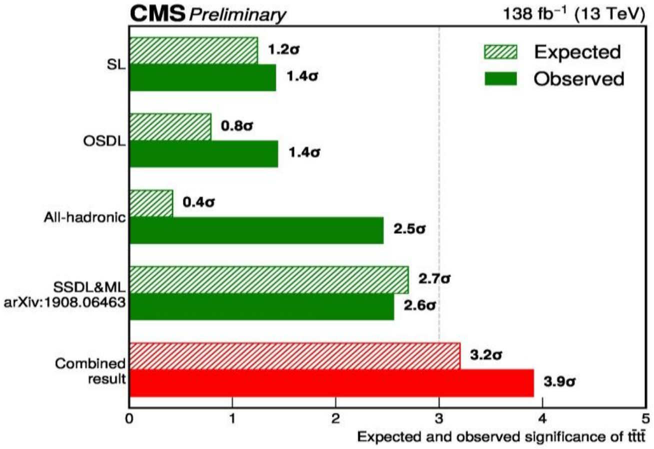


	Expected	Observed
SL	$1^{+0.87}_{-0.81}$	$1.2^{+0.9}_{-0.9}$
OSDL	$1^{+1.3}_{-1.3}$	$1.9^{+1.4}_{-1.3}$
All-hadronic	$1^{+2.5}_{-2.4}$	$5.8^{+2.5}_{-2.4}$
SSDL&ML	$1^{+0.44}_{-0.40}$	$1.0^{+0.5}_{-0.4}$
Combined result	$1^{+0.36}_{-0.34}$	$1.4^{+0.4}_{-0.4}$

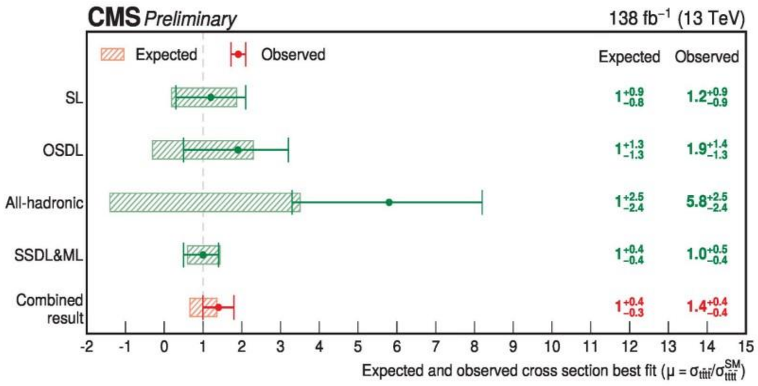
- ✓ Combined signal-strength: **μ(tttt) = 1.4 ± 0.4**
- ✓ significance: **3.9σ**
- ✓ Limited by data statistics and ttbb background modelling

4-top summary

Significance

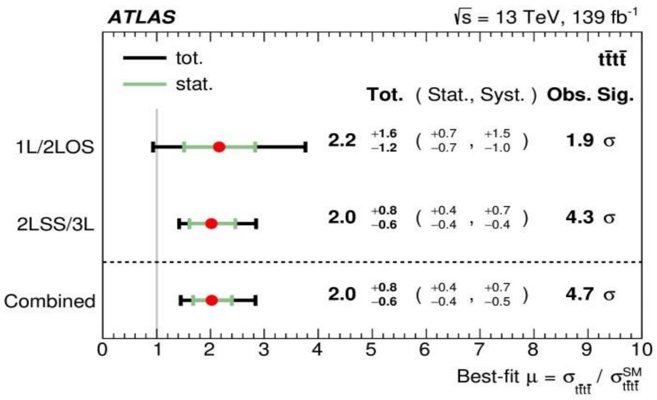


CMS-PAS-TOP-21-005



expected significance: 3.2 σ
observed significance: 3.9 σ

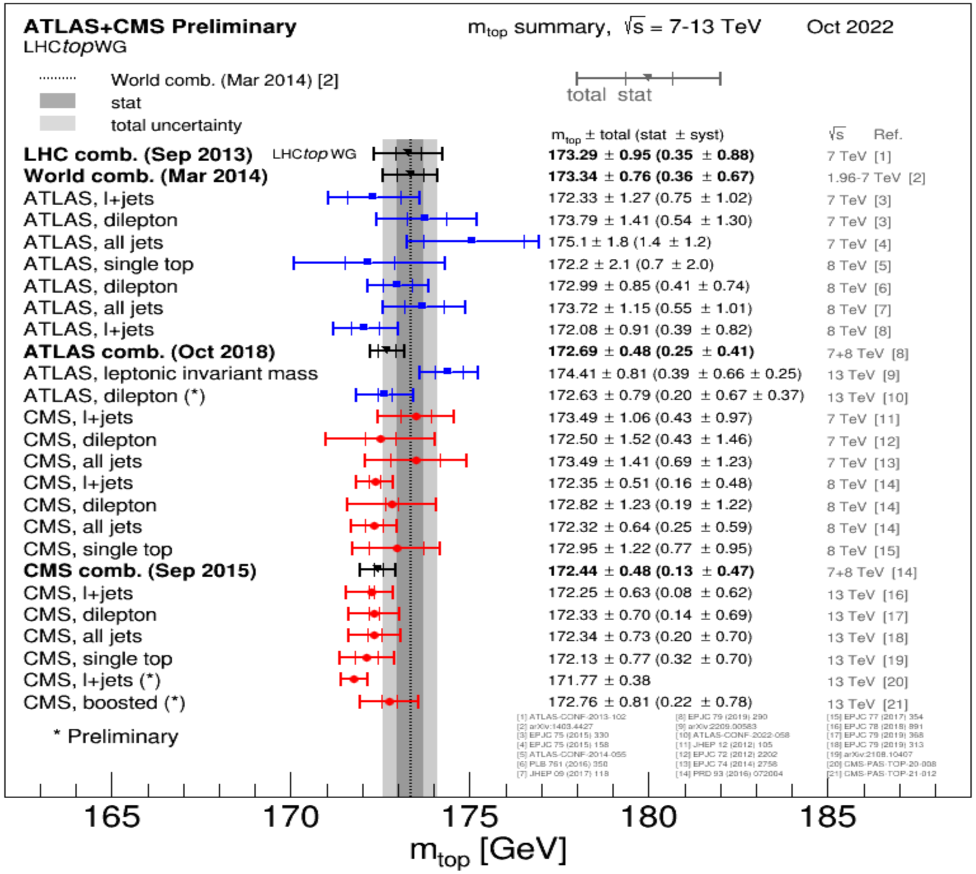
ATLAS JHEP 11 (2021) 118

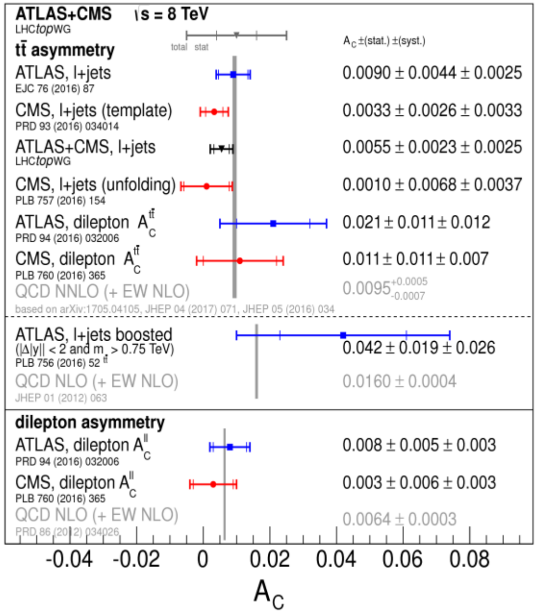


expected significance: 2.6 σ
observed significance: 4.7 σ

top quark properties

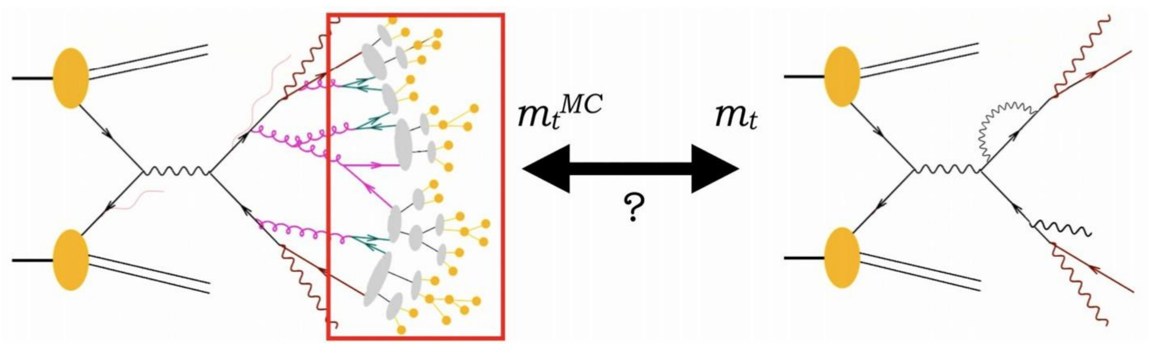
- ✓ Now at LHC is possible to reach un-precedent precisions for the property measurements
- ✓ Now measured not only in ttbar but also in single top and tt+X events

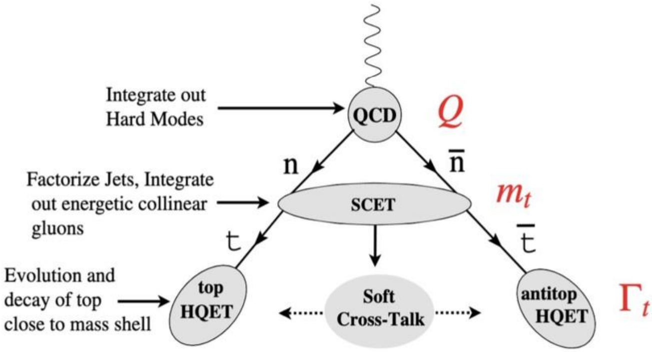




Top mass
Top spin
Top polarisation
Asymmetries
B-fragmentation
Color reconnection
CP properties………

Top mass





Direct

from reconstruct invariant mass of top quark decay products

- Most precise (~0.3 GeV)
- Depends on the details of the MC simulation

- CMS: tt+jets (36/fb)
- CMS: single top t-channel
- ATLAS ttbar soft muon tagging
- ATLAS ttbar dilepton

Indirect

measure observable directly sensitive to m_t (e.g. σ_{tt})

Compare to theory prediction in well-defined renormalisation **scheme** (pole, MS, MSR)

- ATLAS+CMS: m_t pole from combined σ_{tt} 7+8 TeV
- CMS: from tt+1j invariant mass
- CMS: : m_t running @NNLO revisited

“Third”

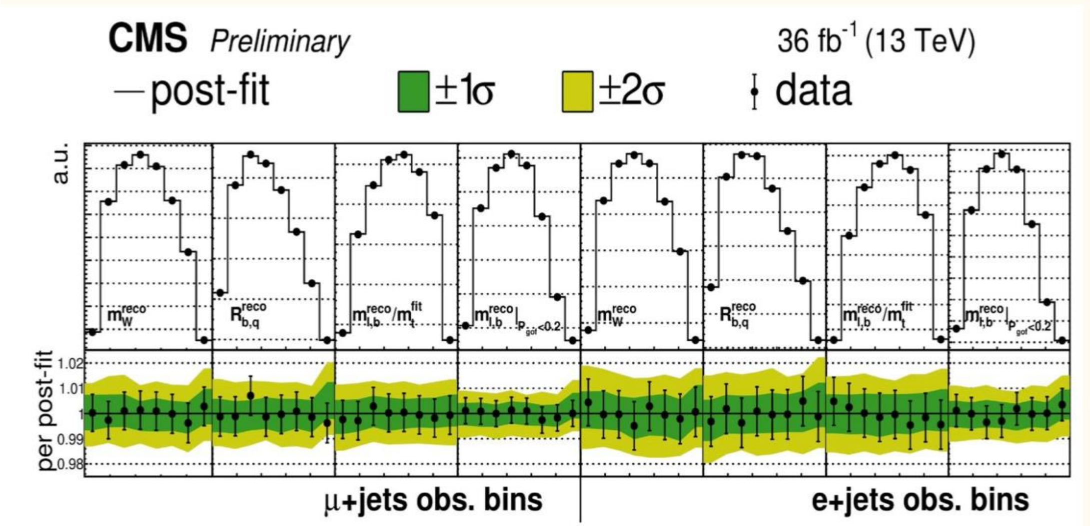
jet mass in boosted top decays can be calculated using SC-EFT

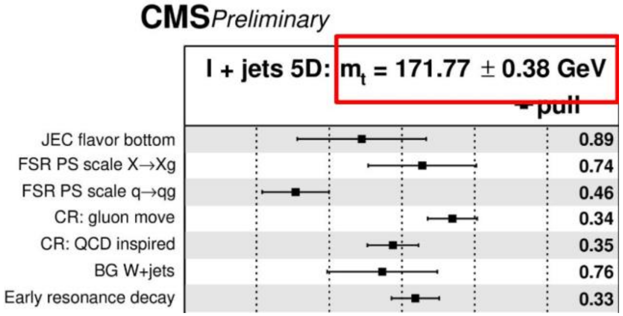
- CMS: top mass from boosted jet mass

CMS measurements

CMS-PAS-TOP-20-008

- ✓ tt l+jets: profile LH fit to 5 observables in different event categories

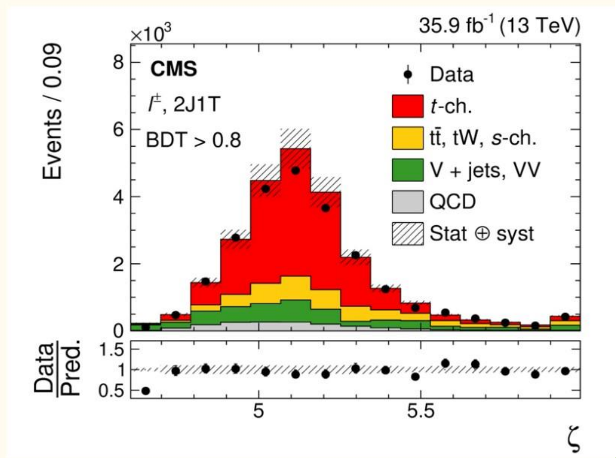




- Significant pull and constraint of FSR PS scale q->qg due to m_W^{rec}
- Alternative correlation scheme 172.14 ± 0.31 GeV

✓ Most precise measurement with 0.38 GeV uncertainty

- ✓ t-channel single top: ML fit to $\zeta=\ln(m_t/1\ \mathrm{GeV})$



$$m_t = 172.13^{+0.76}_{-0.77}\,\mathrm{GeV}$$

$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.9952^{+0.0079}_{-0.0104}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83^{+1.79}_{-1.35}\,\mathrm{GeV}$$

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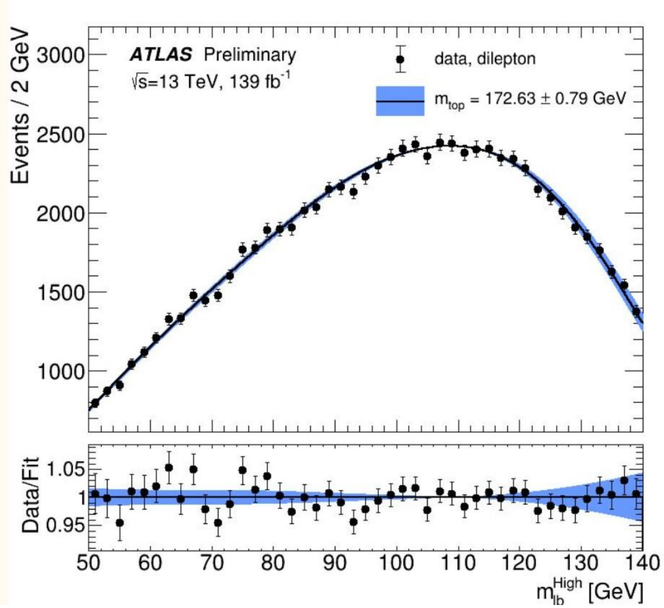
ATLAS measurements

Template method (similar to 8 TeV)

- DNN to select b/lepton pairings
- Select permutation with highest DNN score

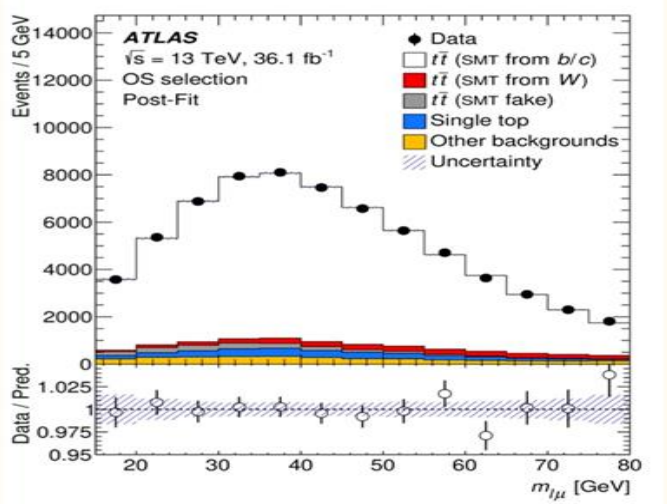


$$m_{top}^{dilepton} = 172.63 \pm 0.20\,(\text{stat}) \pm 0.67\,(\text{syst}) \pm 0.37\,(\text{recoil})\ \text{GeV}$$

✓ Dominant by modelling and JES

Top mass using soft muon tag

- Invariant mass $m_{l\mu}$ sensitive to m_t
- reduced sensitivity to JES
- sensitive to fragmentation modelling



$$174.41 \pm 0.39\,(\text{stat.}) \pm 0.66\,(\text{syst.}) \pm 0.25\,(\text{recoil})\ \text{GeV}$$

✓ consistent at 2σ level with previous results

- ➢ Ttbar modelling is the largest challenge for future measurements
- ➢ Require input from theory and experiments

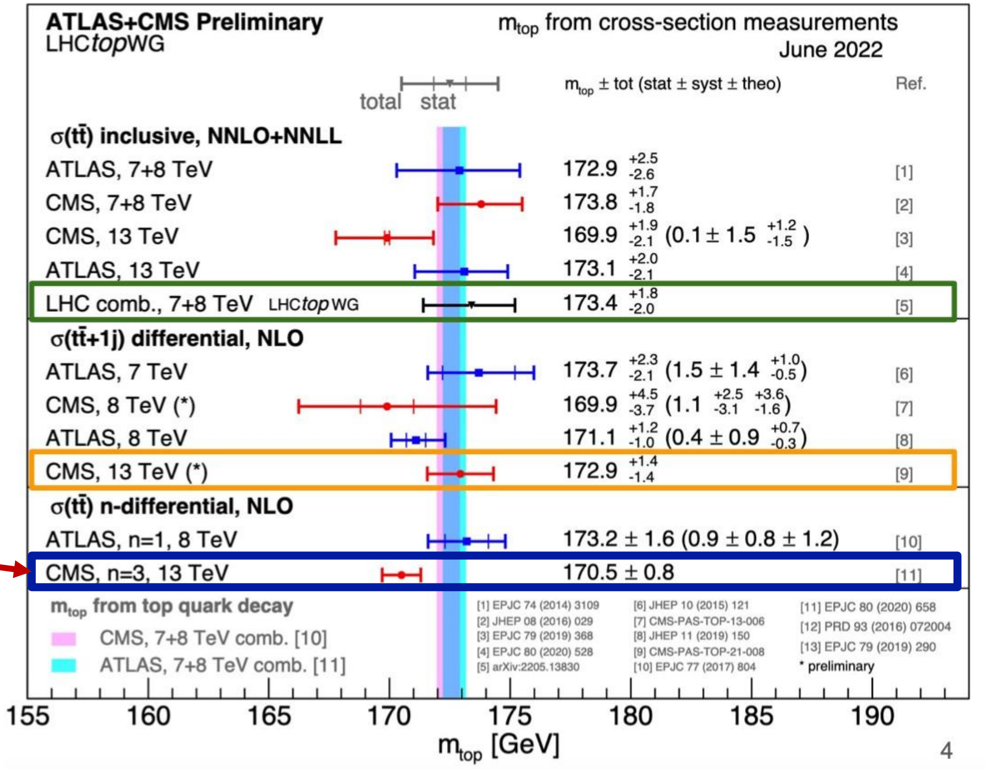
ATLAS-CONF-2022-058

arXiv:2209.00583

Summary: indirect measurements

Results obtained with different methods overall in good agreement

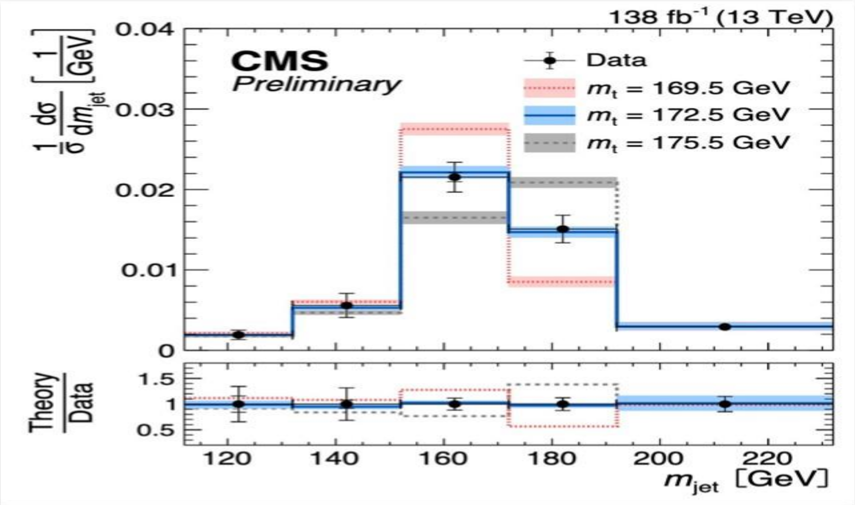
- CMS result from 3D cross section is the most precise result, to date, but may be significantly affected by threshold effects (can be 1.4 GeV).
- No consensus in theory community on the size of the effect



Theoretical advances needed
in order to obtain accurate and unambiguous results

Top mass from boosted jet mass

- ✓ XCone exclusive algorithm to reconstruct jets and sub-jets → improved resolution
- ✓ Dedicated calibration of FSR using substructure variables, and dedicated jet mass calibration
- ✓ Comparable precision to direct measurements



CMS-PAS-TOP-21-012

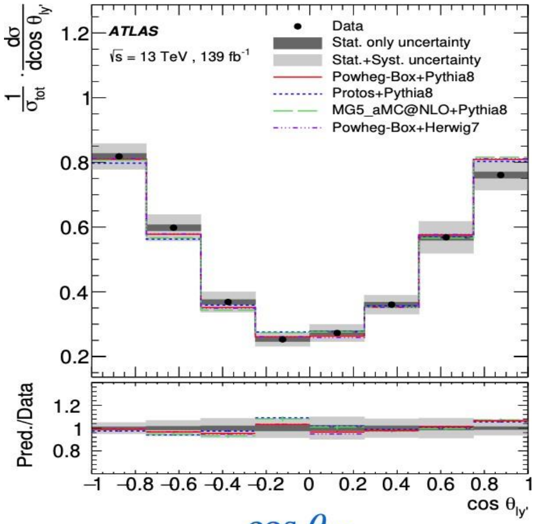
$$
\begin{aligned}
m_t &= 172.76 \pm 0.22\,(\mathrm{stat}) \pm 0.57\,(\mathrm{exp}) \pm 0.48\,(\mathrm{model}) \pm 0.24\,(\mathrm{theo})\ \mathrm{GeV} \\
&= 172.76 \pm 0.81\ \mathrm{GeV}.
\end{aligned}
$$

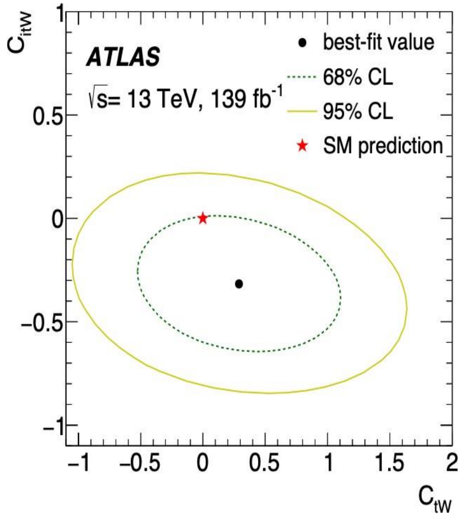
First top mass measurement in boosted regime.

Top polarisation

JHEP 11 (2022) 040

➢ Unfolded angular distributions to particle level compared to MC





cos $\theta_{ly'}$

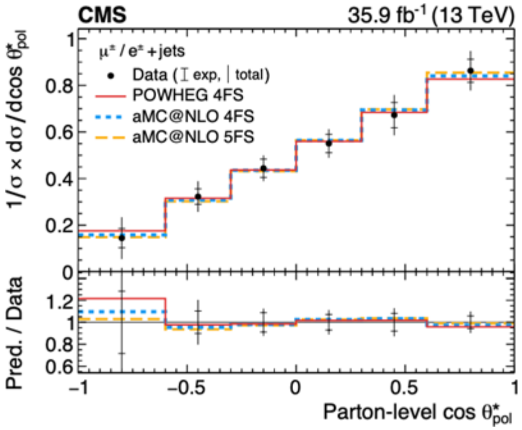
- ✓ Study of BSM effects in Wtb vertex
- ✓ Unfolded distributions give bounds on Wilson coefficients
- ✓ Consistent with SM prediction

✓ Spin asymmetry measurement

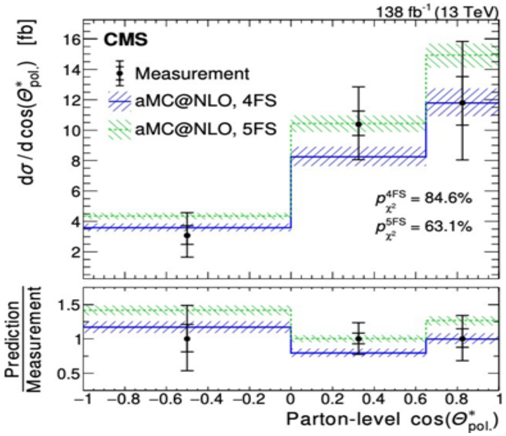
$$A_\ell = 0.440 \pm 0.031(\text{stat+exp}) \pm 0.062\,(\text{theo})$$

$$A_\ell = 0.54 \pm 0.16(\text{stat}) \pm 0.06\,(\text{syst})$$

t-ch



Statistically dominated



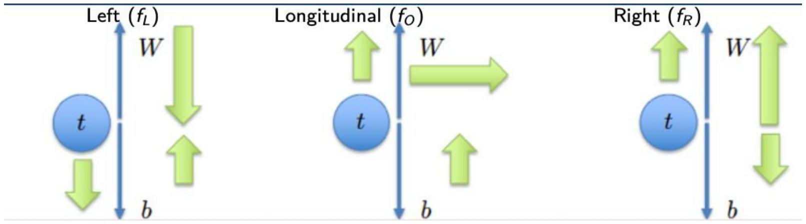
tZq

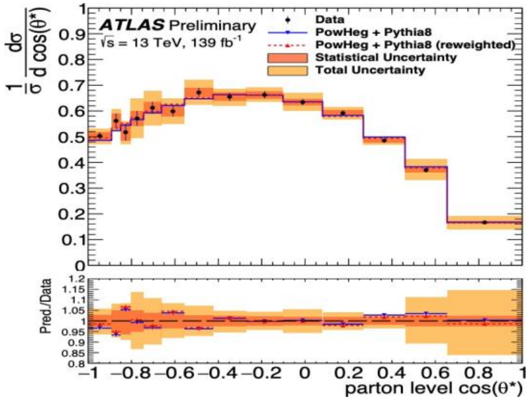
W polarization in top events

arXiv:2209.14903

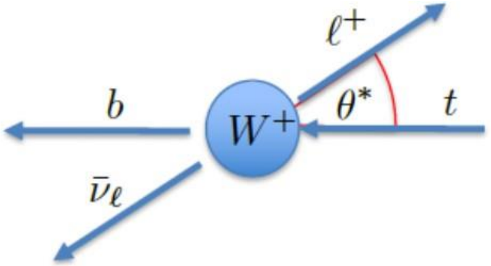
- ✓ Probe of Wtb vertex

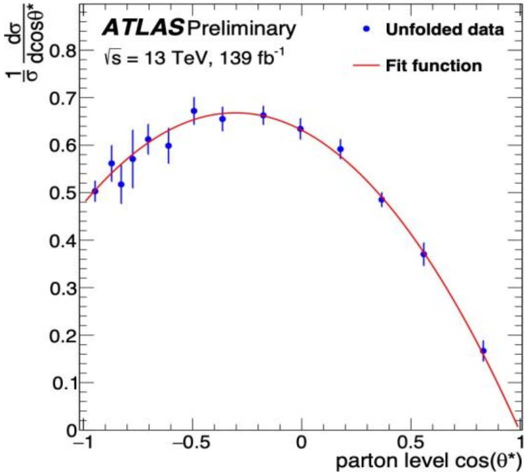
New method in dilepton channel: mesure absolute and normalised differential distributions in $\cos\theta^*$

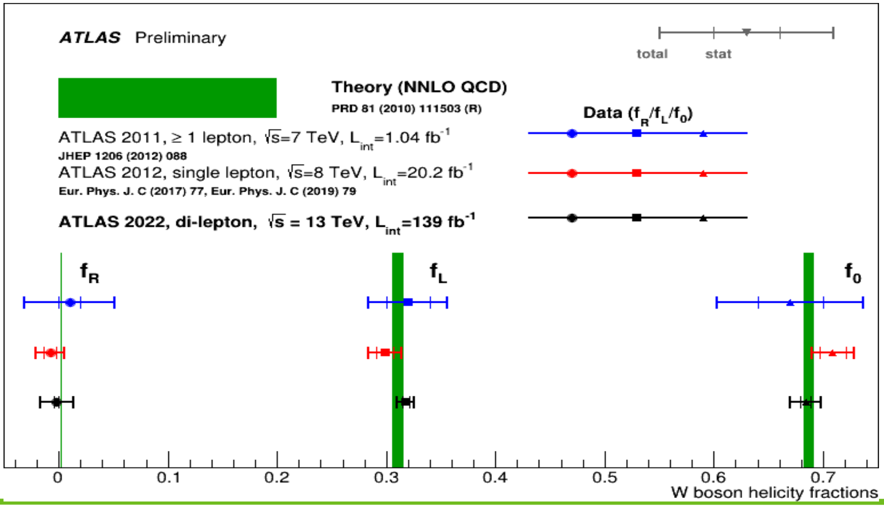




W rest frame







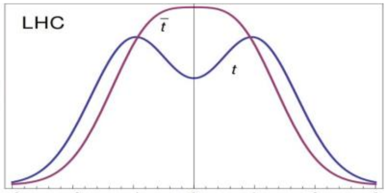
$$f_0 = \quad 0.684 \pm 0.015\ (\text{stat.} + \text{syst.})$$
$$f_L = \quad 0.318 \pm 0.008\ (\text{stat.} + \text{syst.})$$
$$f_R = -0.002 \pm 0.015\ (\text{stat.} + \text{syst.})$$

Systematically dominated

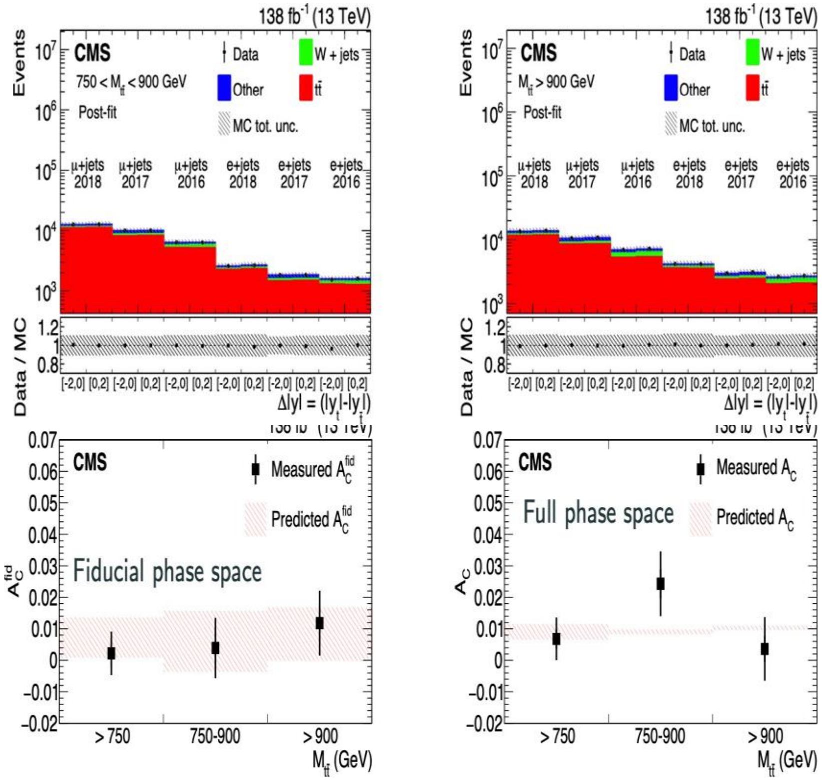
Charge asymmetry in tt

arXiv:2208.02751

- ✓ Central-forward in ttbar events
- ✓ No asymmetry at LO
- ✓ Higher order effects in qq̄→ t t



- Boosted regime, single lepton channel
- two Mtt̄ bins: [750, 900], [900, ∞]



Good agreement with prediction

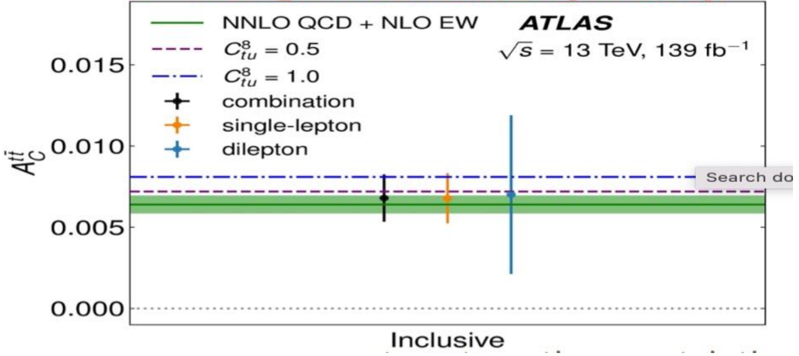
arXiv:2208.12095

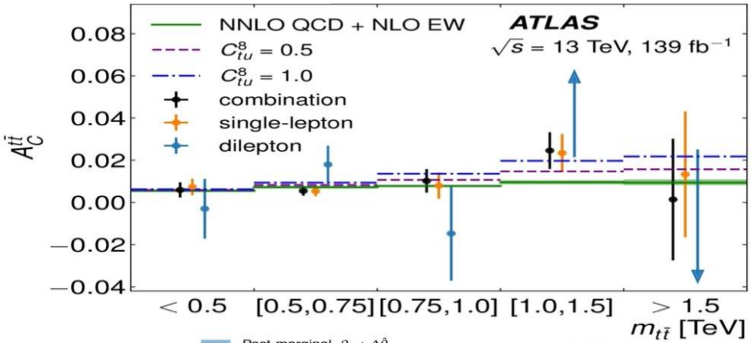
$$A_C = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{N(\Delta|y|>0)+N(\Delta|y|<0)}$$

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

- Single and dilepton channels
- Resolved and boosted regime

- A_{tt} = 0.0068 ± 0.0015(stat+syst.).
- 4.7 sigma from zero asymmetry





Expect improvement with additional data

Energy asymmetry in tt

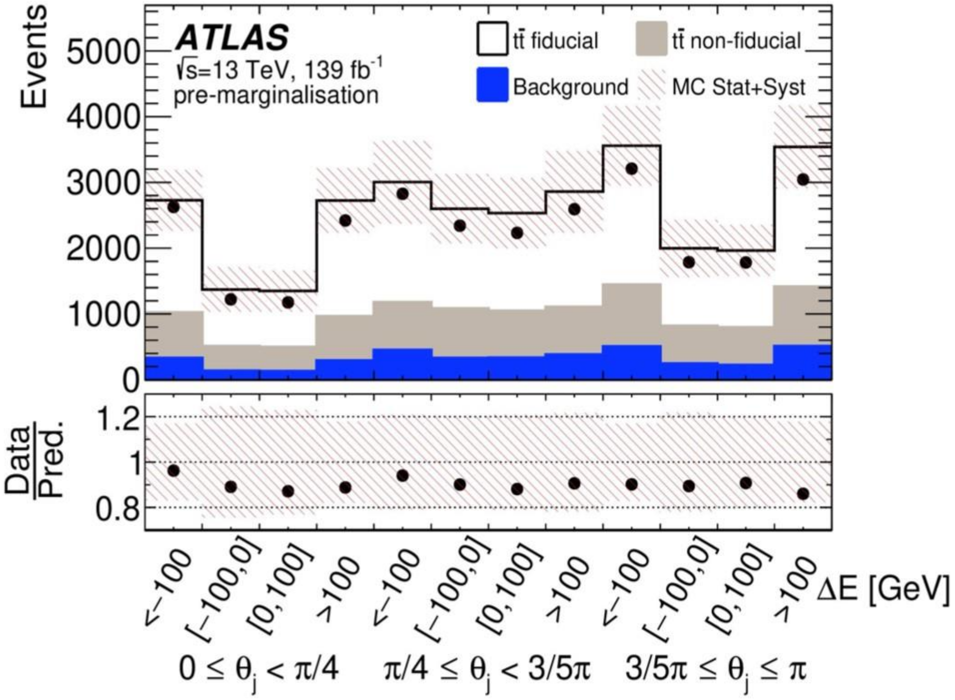
EPJC 82 (2022) 374

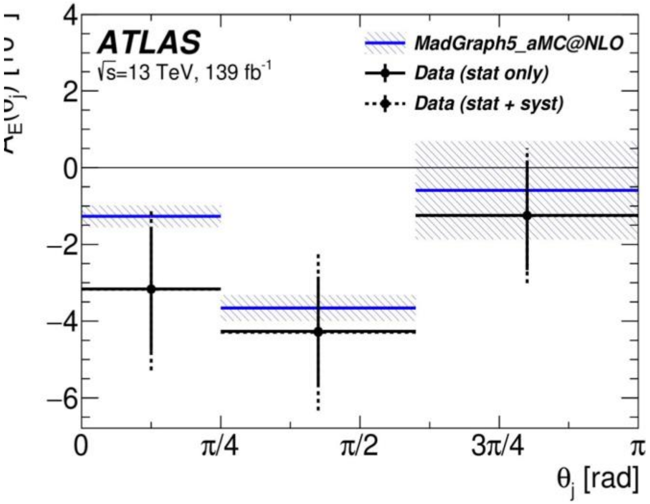
- ✓ Asymmetry between the energies of top and anti-top
- ✓ Measured in tt+j events in boosted regime

$$A_E(\theta_j) \equiv \frac{\sigma^{\mathrm{opt}}(\theta_j|\Delta E > 0) - \sigma^{\mathrm{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\mathrm{opt}}(\theta_j|\Delta E > 0) + \sigma^{\mathrm{opt}}(\theta_j|\Delta E < 0)}$$

$$\sigma^{\mathrm{opt}}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)$$

Angle between the jet and z-axis
Effect increases with jet pT





Agrees with prediction
Statistically limited

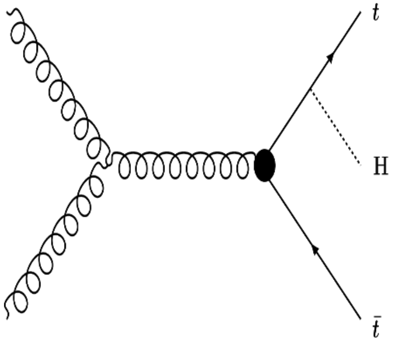
Search for new physics

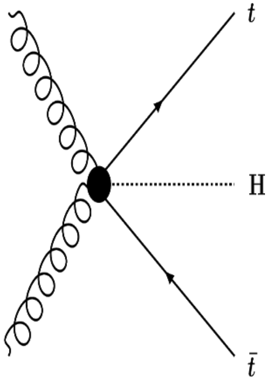
Tool to search for new physics:

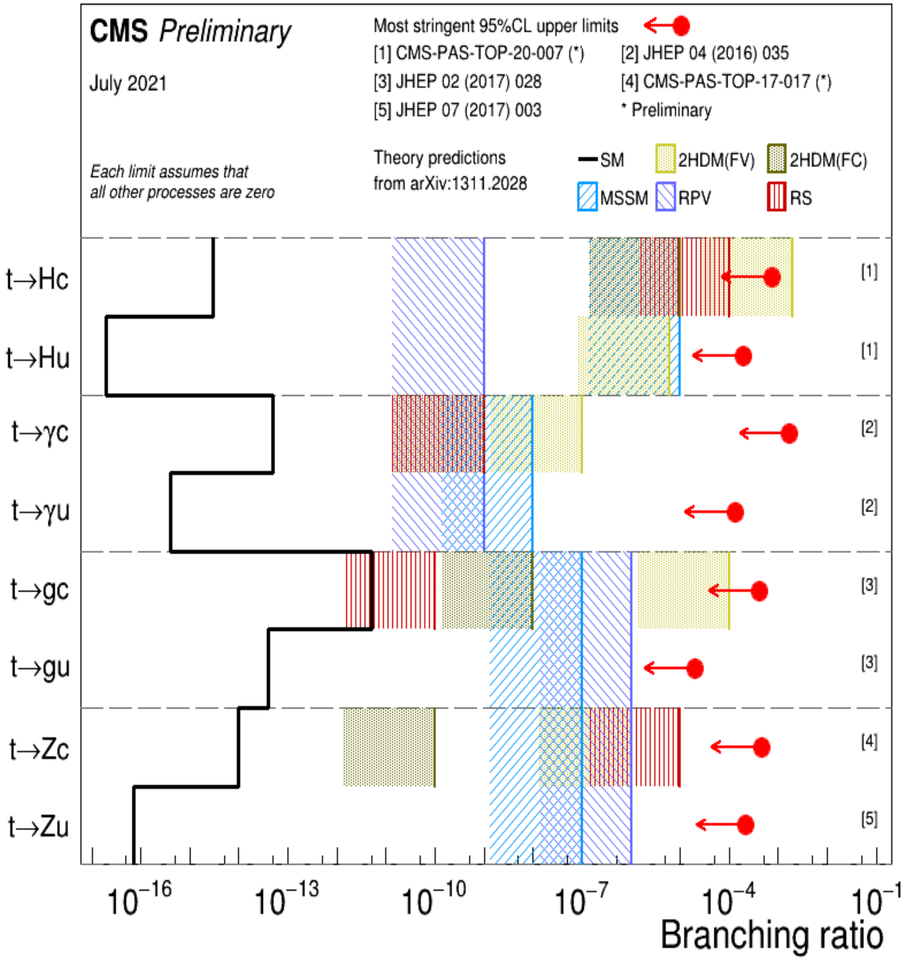
✓Many BSM models are expected to involve top quarks

- ➢ Possible to perform direct searches for new resonances and FCNC

✓Use the precise measurements to set a limit on new operators in an EFT framework







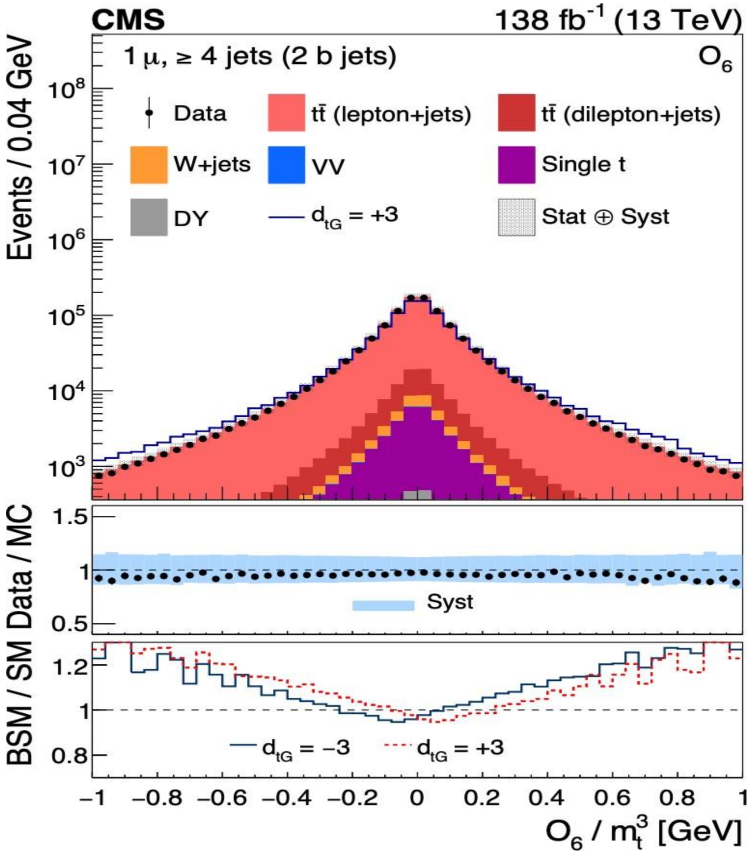
CP violation in ttbar

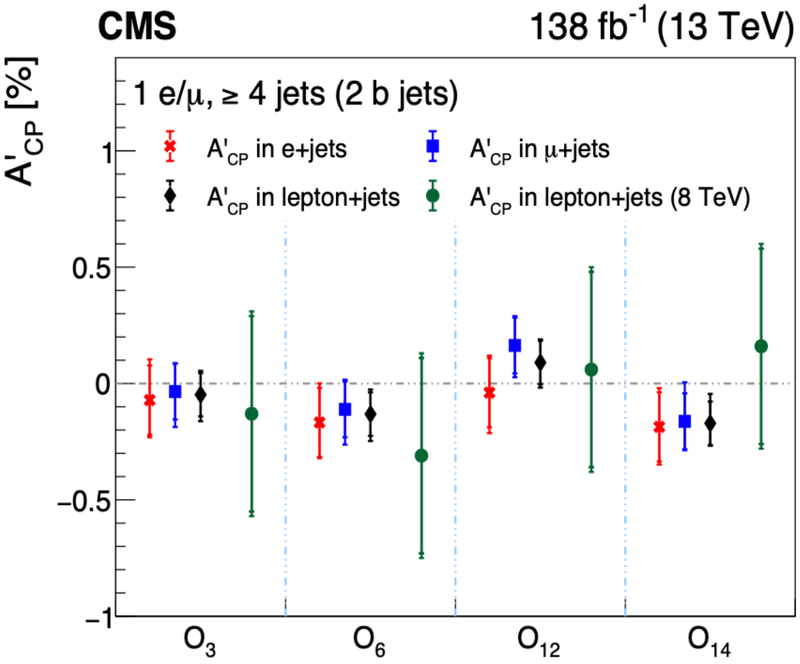
arXiv:2205.02314

- ✓ Construct 4 CP-sensitive observables
- ✓ Define and measure asymmetry

$$A_{CP} = \frac{N(O_i>0)-N(O_i<0)}{N(O_i>0)+N(O_i<0)},$$

$$i = 3, 6, 12, 14$$





0.04 ± 0.10 (stat) ± 0.07 (syst)

In agreement with SM value of zero

Searches for FCNC

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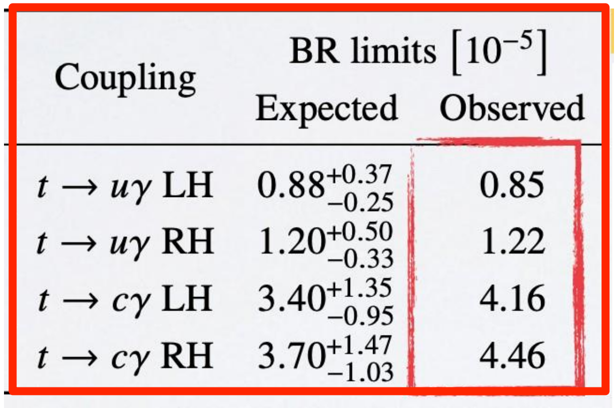
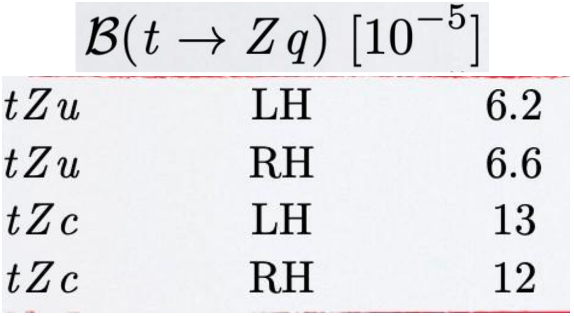
arXiv:2208.11415

arXiv:2205.02537

✓ Improved limit by factors 3.3 to 5.4 from previous analysis



Coupling	BR limits $[10^{-5}]$ Expected	BR limits $[10^{-5}]$ Observed
$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46

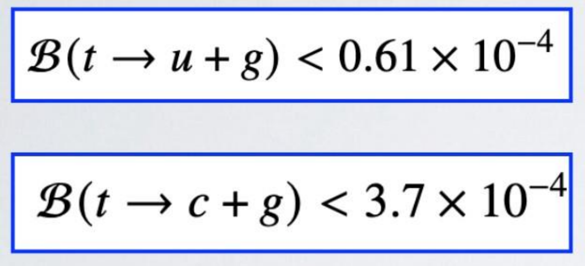


$\mathcal{B}(t \to Zq)\ [10^{-5}]$

tZu	LH	6.2
tZu	RH	6.6
tZc	LH	13
tZc	RH	12

✓ Improved limit by factors 3 to 5 from previous analysis

Improved limit by x2 from 8 TeV analysis



$\mathcal{B}(t \to u + g) < 0.61 \times 10^{-4}$

$\mathcal{B}(t \to c + g) < 3.7 \times 10^{-4}$

Large impact from systematics

$\mathcal{B}(t \to uH) < 0.94 \times 10^{-3}$
$\mathcal{B}(t \to cH) < 0.69 \times 10^{-3}$ H →ττ

$\mathcal{B}(t \to uH) < 0.79 \times 10^{-3}$
$\mathcal{B}(t \to cH) < 0.94 \times 10^{-3}$ H →bb

$\mathcal{B}(t \to uH) < 0.19 \times 10^{-3}$
$\mathcal{B}(t \to cH) < 0.73 \times 10^{-3}$ H →γγ

☐ All searches except tgq are statistically limited

$t \to uZ$
$t \to u\gamma$
$t \to ug$
$t \to uH$

$t \to cZ$
$t \to c\gamma$
$t \to cg$
$t \to cH$

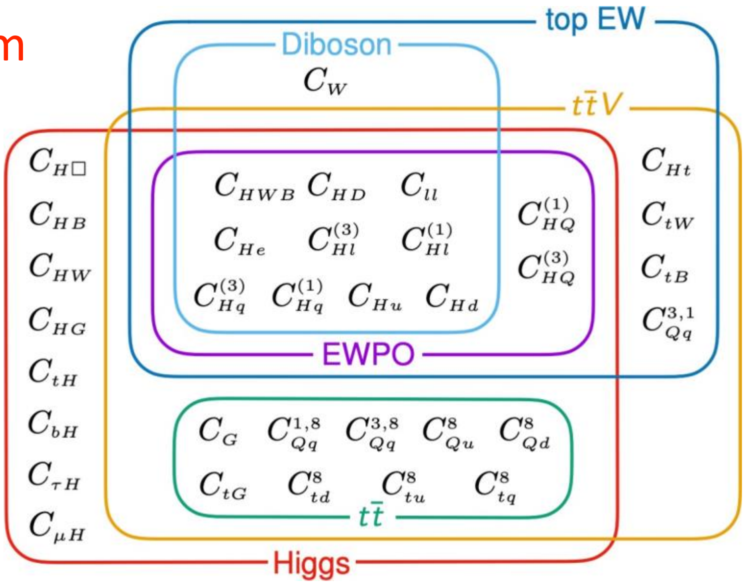
gained sensitivity by including regions sensitive to couplings in top production and decay

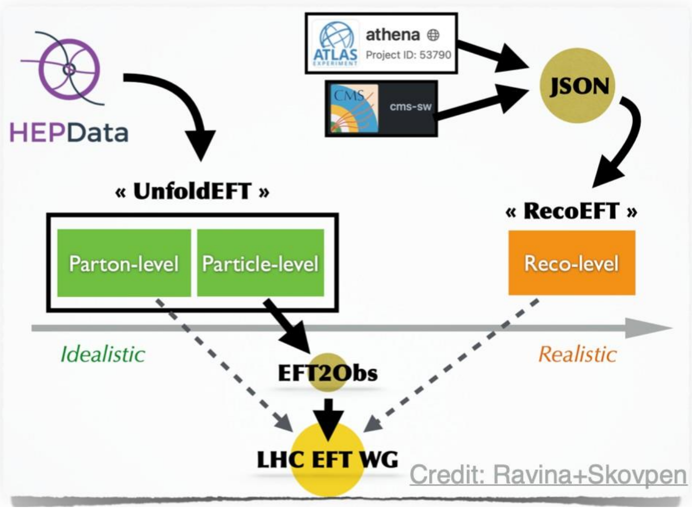
EFT

EFT fits: multidimensional management problem

- ☐ Many Top analysis include and even designed to provide EFT interpretations
- ☐ Global fit is the goal but there are many steps to go and
  - Practical difficulties
    - Different statistical methods (IBU vs FBU, PL vs toys, …)
    - Proper treatment of statistical and systematic correlations
    - Measurements delivered on different timelines
    - Interpretations: different assumptions on "backgrounds" → EFT effects - Hard without coordination!
  - ➢ Signal model :
    - SMEFT@LO or @NLO?
    - Which operators?
    - Linear/quadratic terms?
    - EFT uncertainties and validity constraints

➢ Run 3 is a good opportunity to solve these issues and perform a global fit across different physics groups and experiments



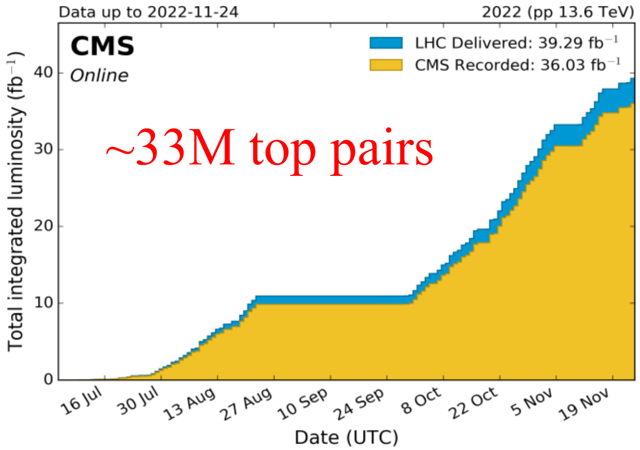


Credit: Ravina+Skovpen

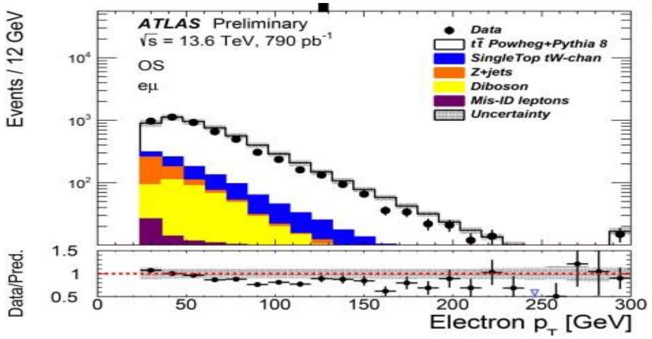
Run3 started!

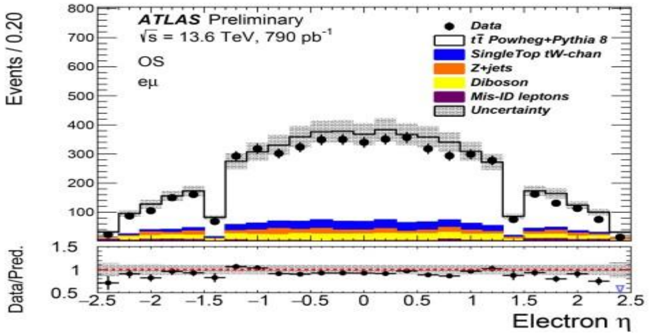
CMS-PAS-TOP-22-012

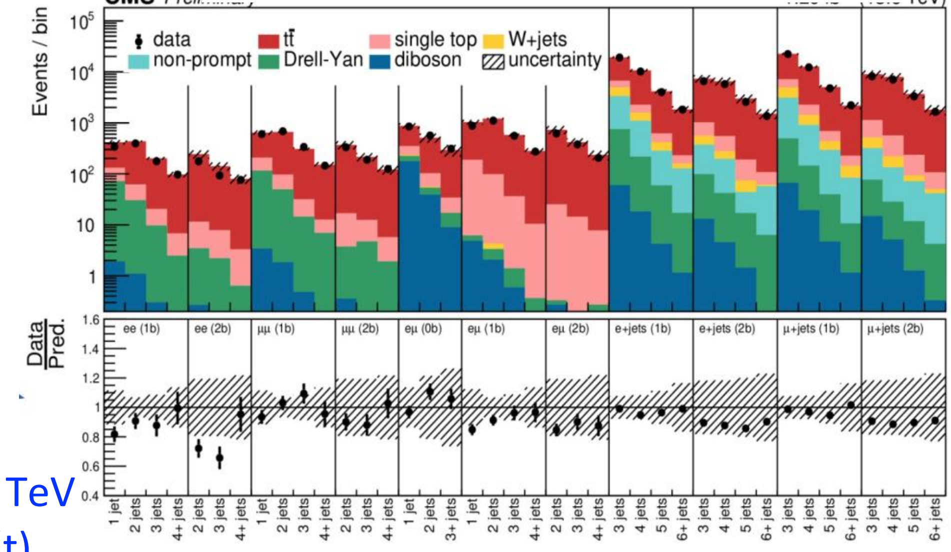
- ✓ Top quark is still there!
- ✓ Allows to exercise the analysis chain and validate the performance of all components



~33M top pairs







$$\sigma_{t\bar{t}} = 887^{+43}_{-41}(\mathrm{stat+sys}) \pm 53(\mathrm{lumi})\ \mathrm{pb}$$

- ✓ Assuming ~250/fb per experiment at 13.6 TeV
- ✓ And cross section ~920 pb (tt) + ~330 pb (t)
- ✓ Run 3 will provide twice more ttbar and single top data sets

Summary

- ✓ CMS and ATLAS provided many results with full Run2 dataset:
  - ➢ High precision measurements
  - ➢ Searching for very rare processes
  - ➢ Measuring the top properties and couplings
  - ➢ Setting constraints to new physics
- ✓ So far, all measurements of top quark showed good agreement with SM predictions
- ✓ What can we learn from Run2?
  - ➢ Theoretical advancements are still necessary to improve simulation and to understand / reduce uncertainties
  - ➢ Machine learning has significant role in top physics!
- ✓ What do we expect for Run3?
  - ➢ Measurements in t(t)+X final states and FCNC searches are statistically limited
  - ➢ More data will allow for reaching higher jet pT or higher masses sensitive to BSM and EFT parameters

More results with more data are coming…..

References

- ✧ LHCTopWG https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG
- ✧ ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- ✧ CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Backup

OPERATORS AND PHYSICS IMPLICATIONS

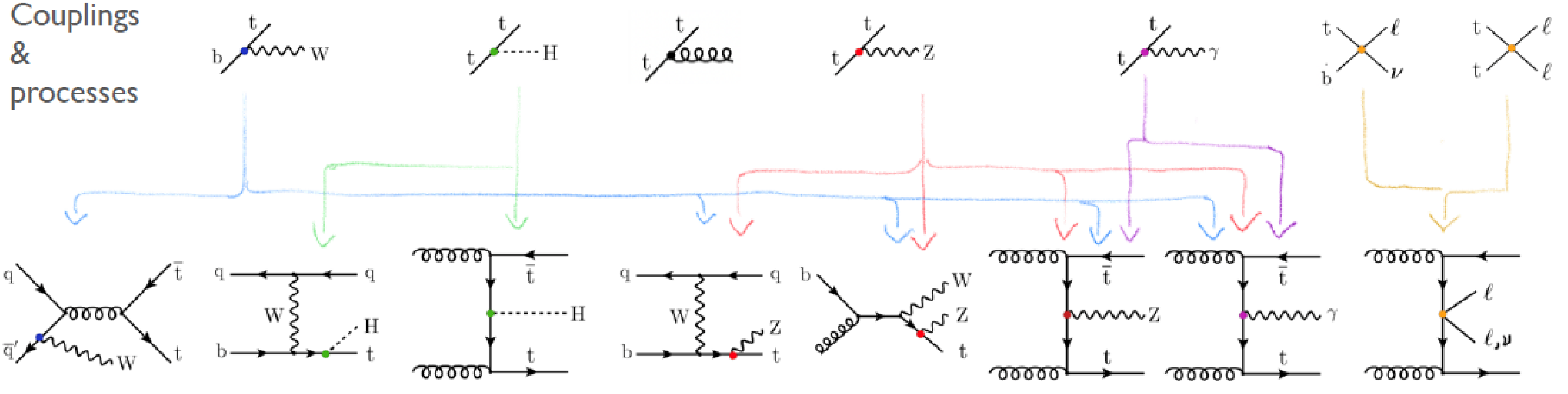
SMEFT Lagrangian

$$\mathcal{L} = \mathcal{L}_{4,\mathrm{SM}} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \boxed{\frac{1}{\Lambda^2}\mathcal{L}_6} + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Operators

$\mathcal{O}_{\phi\mathrm{tb}}$	$i(\tilde{\phi}\, D_\mu\, \phi)\,(\bar{t}_R\, \gamma^\mu\, b_R) + \mathrm{h.c.}$	$\mathcal{O}_{\mathrm{tB}}$	$i(\bar{q}_L \sigma^{\mu\nu}\, t_R)\, \tilde{\phi}\, B_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(3)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I \phi)\,(\bar{q}_L\, \gamma^\mu\, \tau^I q_L)$	$\mathcal{O}^1_{qq}$	$(\bar{q}_L\, \gamma_\mu\, q_L)\,(\bar{q}_L\, \gamma^\mu q_L)$
$\mathcal{O}_{\mathrm{t}\phi}$	$(\phi^\dagger \phi)\, \bar{q}_L\, t_R\, \tilde{\phi} + \mathrm{h.c.}$	$\mathcal{O}_{\mathrm{tG}}$	$i(\bar{q}_L \sigma^{\mu\nu} \lambda^a\, t_R)\, \tilde{\phi}\, G^a_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(1)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)\,(\bar{q}_L\, \gamma^\mu\, q_L)$	$\mathcal{O}^8_{qq}$	$(\bar{q}_L\, \gamma_\mu T^A\, q_L)\,(\bar{q}_L\, \gamma^\mu T^A\, q_L)$

Couplings & processes



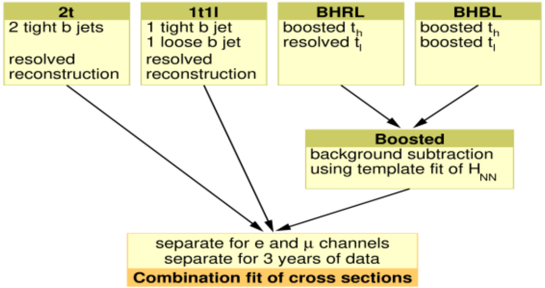
Parametrized predictions

$$N\left(\frac{\vec{c}}{\Lambda^2}\right) = S_0 + \sum_j S_{1j}\frac{c_j}{\Lambda^2} + \sum_j S_{2j}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} S_{3jk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

Differential and double-differential σ($t\bar{t}$) in lepton + jets arXiv:2108.02803

- ✓ High precision measurement of differential and double-differential cross sections
- ✓ For the first time the full spectra of differential cross sections are determined

-- combine of resolved and boosted $t\bar{t}$ topologies


2t
2 tight b jets
resolved reconstruction

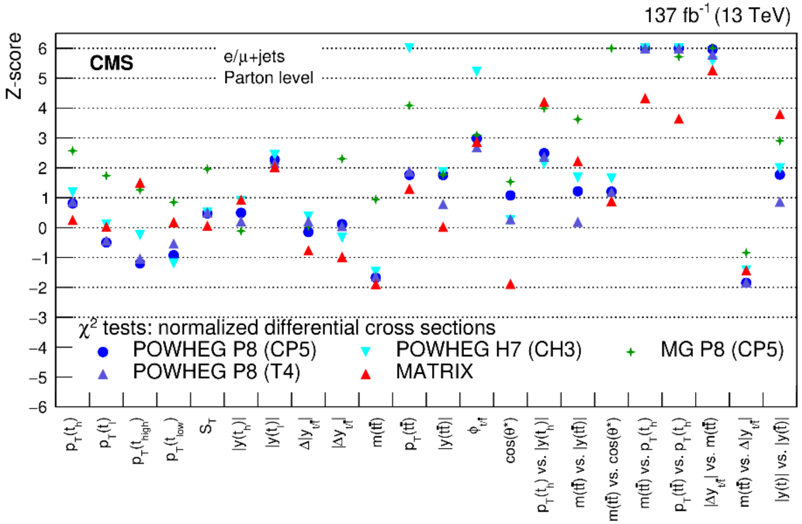
1t1l
1 tight b jet
1 loose b jet
resolved reconstruction

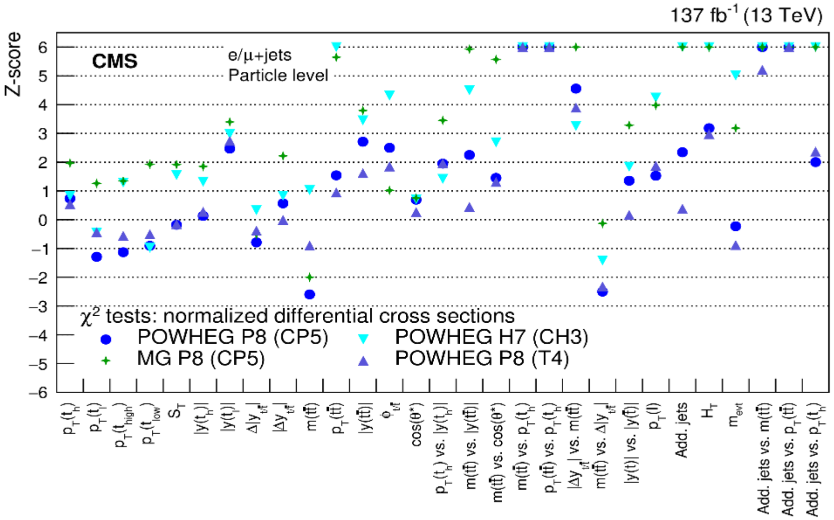
BHRL
boosted t_h
resolved t_l

BHBL
boosted t_h
boosted t_l

Boosted
background subtraction using template fit of H_{NN}

separate for e and μ channels
separate for 3 years of data
Combination fit of cross sections





Most of the predictions are in good agreement with the measurement, except:

- ➢ M($t\bar{t}$) vs. pT(th) and pT($t\bar{t}$) vs. pT(th) shows largest disagreements.
- ➢ At particle level add. jets vs. kinematic observable are difficult to describe by NLO.

Inclusive cross section: **791 ± 1 (stat.) ± 21 (syst.) ± 14 (lumi.) pb**

- ✓ most precise measurement in lepton + jets channel
- ✓ Dominanted by: JES and b-tagging

$t\bar{t}cc/bb$ and $t\bar{t}jj$ production

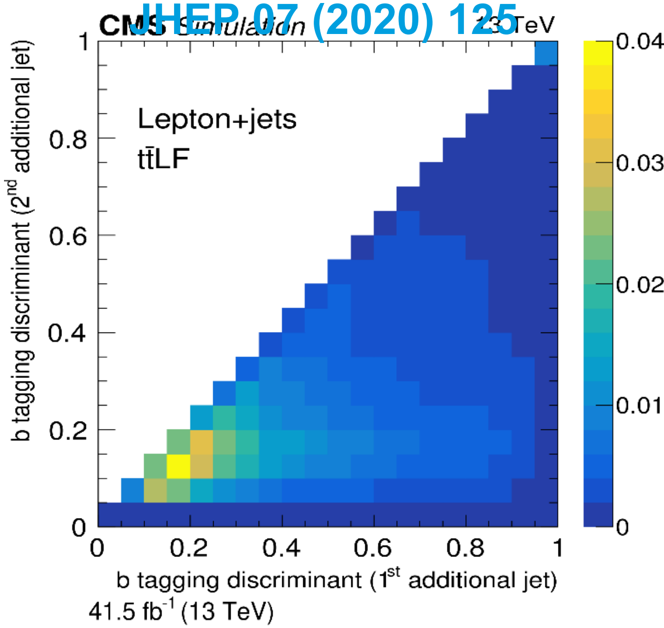
PLB 820 (2021) 136565

JHEP 07 (2020) 125

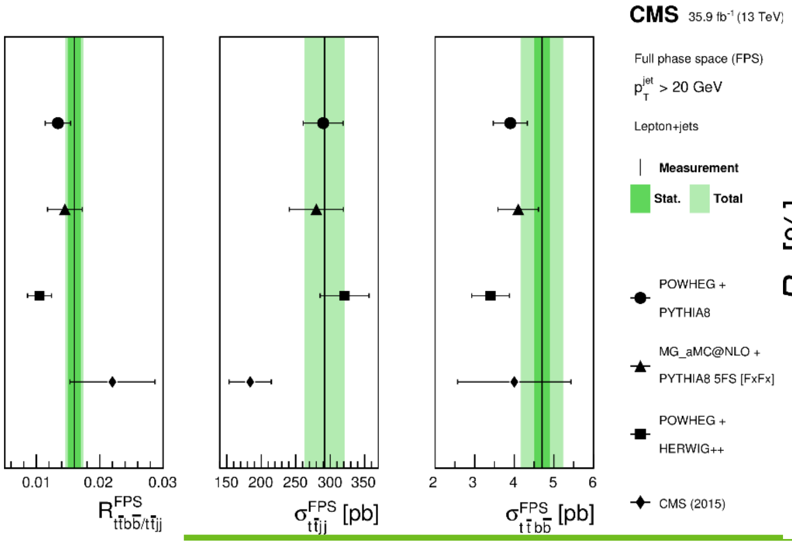
- Test the state-of-art predictions at NLO
- Irreducible background to ttH, $H \rightarrow bb$
- $\boldsymbol{ttb\bar{b}}$ and $\boldsymbol{ttj\bar{j}}$ measurement
  - $\sigma_{t\bar{t}bb}$ and $\sigma_{t\bar{t}bb}/\sigma_{t\bar{t}jj}$ extracted simultaneously

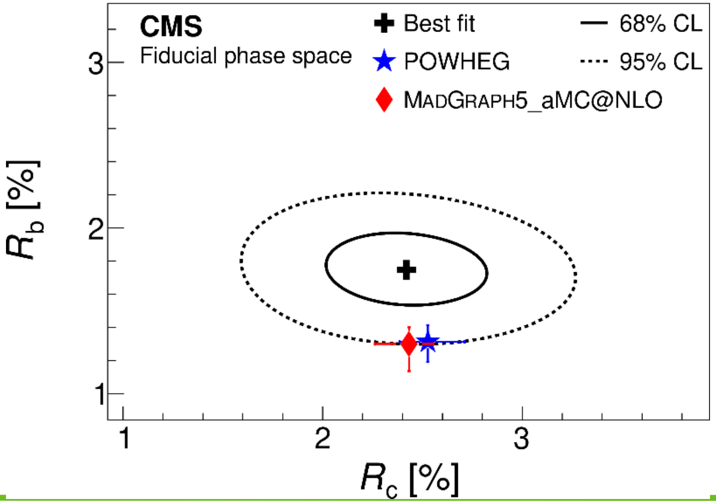
from a 2D discriminant

  - PowhegPythia8 and MG_aMC@NLO+Pythia8 provide the best description



- **First** measurement of $\boldsymbol{ttc\bar{}}$ $\boldsymbol{\epsilon}$ production
  - Simultaneous extraction of $\sigma_{t\bar{t}bb}$, $\sigma_{tt\bar{c}c}$ and $\sigma_{t\bar{t}LL}$ using a template fit procedure





Precision dominated by : MC modelling, JES, c-tagging

tW production in ℓ+jets

CMS-PAS-TOP-20-002

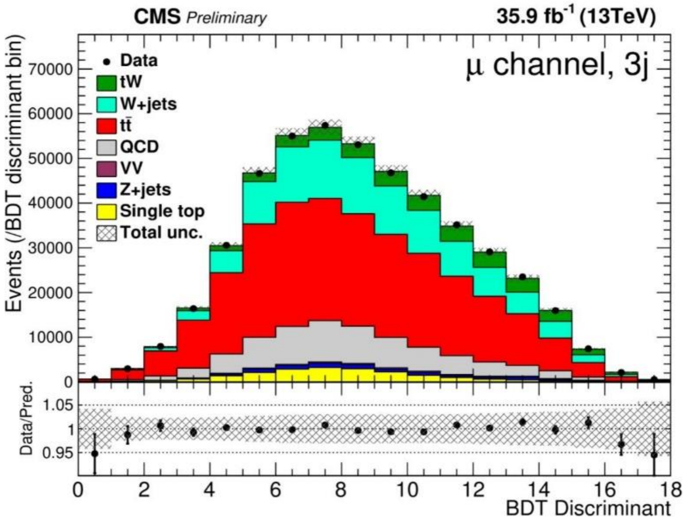
➢ Categories based on jet multiplicity and 1 b-tagged jet: 2J1T (W+Jets). **3J1T** (tw Signal region) and 4J1T (ttbar)

➢ Data-driven background

✓ One BDT is trained per lepton flavor in signal (3J1T) region and evaluation in all regions

✓ Simultaneous ML fit performed in all categories using BDT discriminants

✓ Dominant uncertainty:
Background estimation, JES and modeling



Measured (expected) signal strength:

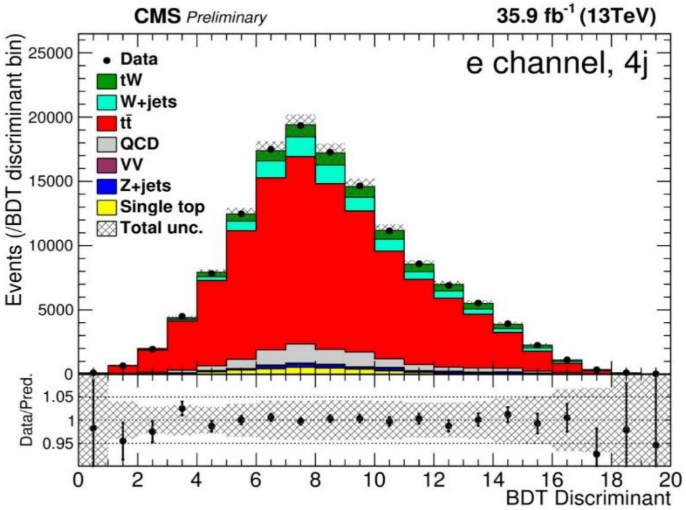
$\mu = 1.24 \pm 0.18\ (1.00 \pm 0.17)$

Cross section:

σ_{tW} = 89 ± 4 (stat.) ± 12 (syst.) pb

σ_{SM} = 72 ± 4 pb

✓ Observed (expected) significance is 7.4 (6.8) standard deviations

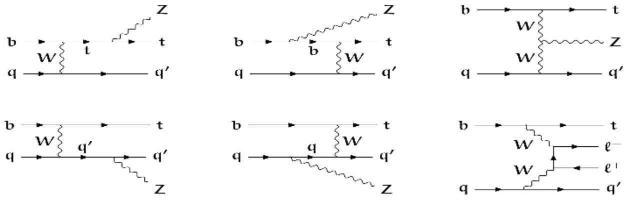


First observation of tW production in ℓ+jets

Inclusive and differential tZq

CMS-PAS-TOP-20-010

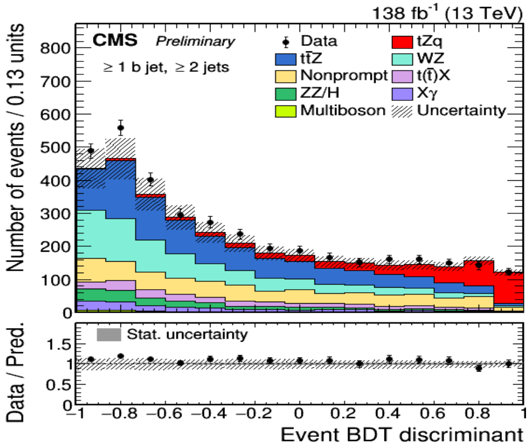
- ✓ Full run2 dataset
- ✓ 3 leptons with improved lepton MVA
- ✓ constraining nonprompt background
- ✓ multiclass NN or BDT



Inclusive tZq cross-section:

$$\sigma_{\mathrm{tZq}} = 87.9\ ^{+7.5}_{-7.3}\,(\mathrm{stat})\ ^{+7.3}_{-6.0}\,(\mathrm{syst})\ \mathrm{fb}\ .$$

Improvement 30%
w.r.t.earlier measurements



Partial tZq cross-sections:

$$\sigma_{\mathrm{tZq}(\ell_t^+)} = 62.2\ ^{+5.9}_{-5.7}\,(\mathrm{stat})\ ^{+4.4}_{-3.7}\,(\mathrm{syst})\ \mathrm{fb}\ ,$$

$$\sigma_{\bar{\mathrm{t}}\mathrm{Zq}(\ell_t^-)} = 26.1\ ^{+4.8}_{-4.6}\,(\mathrm{stat})\ ^{+3.0}_{-2.8}\,(\mathrm{syst})\ \mathrm{fb}\ ,$$

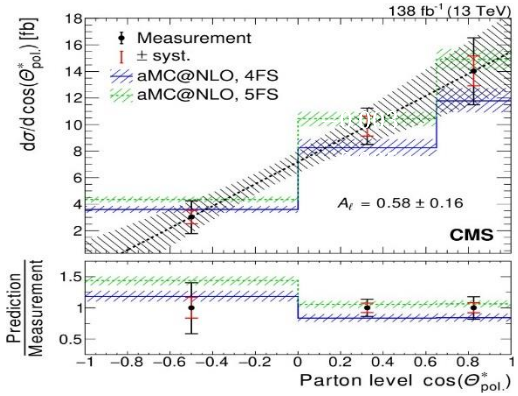
$$R = 2.37\ ^{+0.56}_{-0.42}\,(\mathrm{stat})\ ^{+0.27}_{-0.13}\,(\mathrm{syst})\ .$$

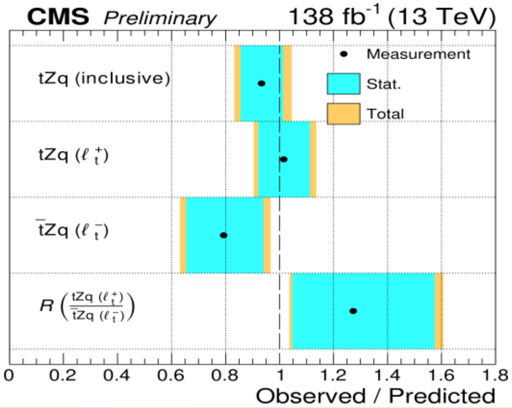
First time!

Spin asymmetry:

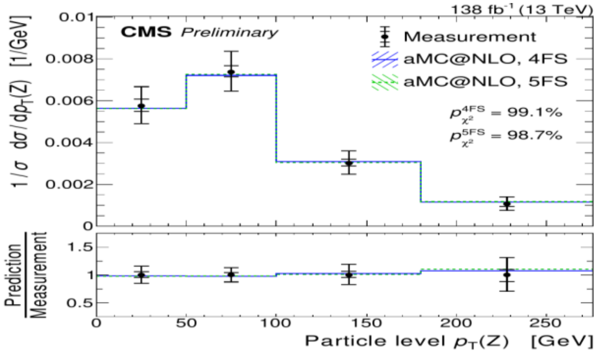
$$A_\ell = 0.58\ ^{+0.15}_{-0.16}\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})\ .$$

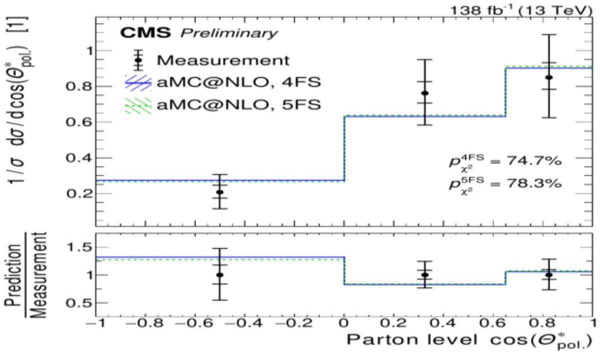
Agreement with SM prediction:





Differential tZq cross-section:





In general, observe good agreement between measurement and prediction.

Rare top production: $t\bar{t}V$

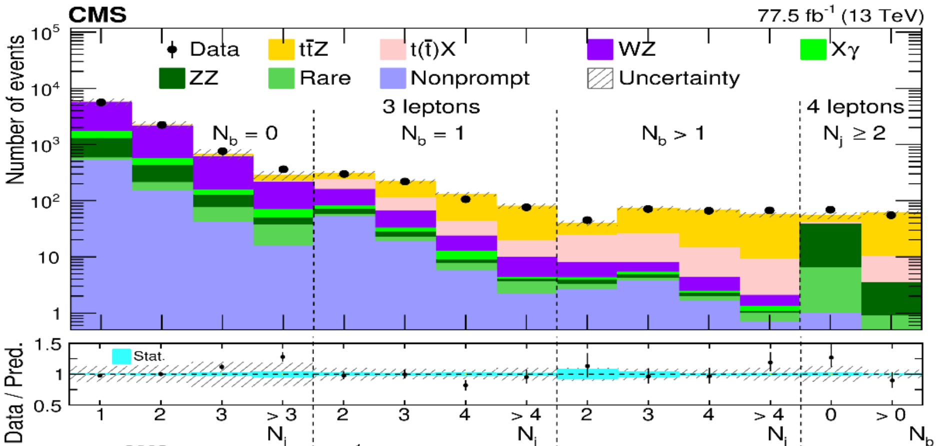
arXiv: 2107.01508

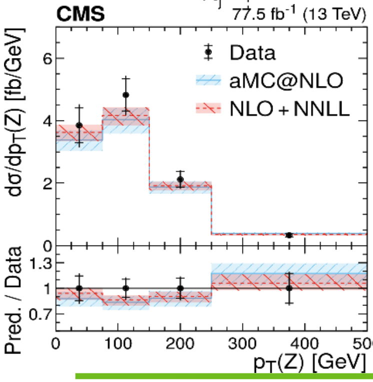
$t\bar{t}Z$ production JHEP 03 (2020) 056

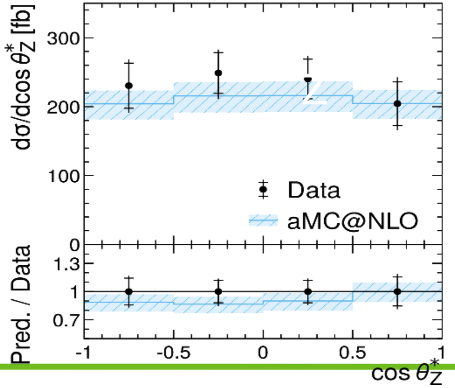
- ➢ Targets 3 or 4 isolated lepton channel with Z to l^+l^-
- ➢ Inclusive cross section already systematic limited

$$\sigma(t\bar{t}Z) = 0.95 \pm 0.05\ (\text{stat}) \pm 0.06\ (\text{syst})\ \text{pb}$$

- ➢ Dominated by signal/background MC modelling
- ➢ Differential cross sections are measured fist time



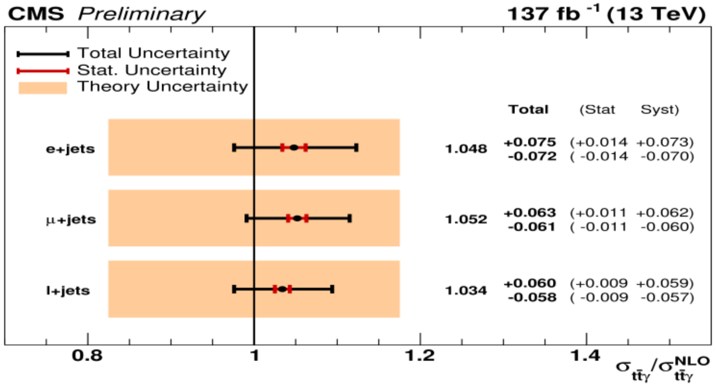


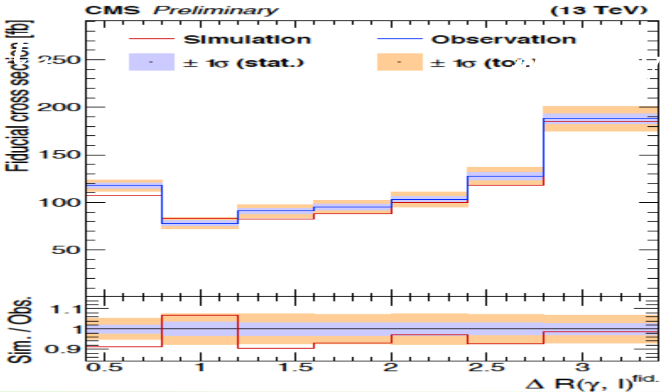


$t\bar{t}\gamma$ production

- ✓ Measured in lepton+jets channel

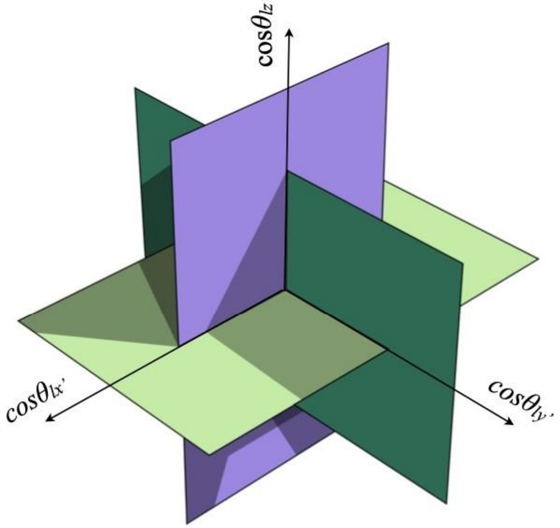
  800 ± 46 (syst) ± 7 (stat) fb,
- ✓ Precision limited by MC modelling
- ✓ Differential cross sections measured in several kinematic observables
- ✓ Good agreement with SM prediction





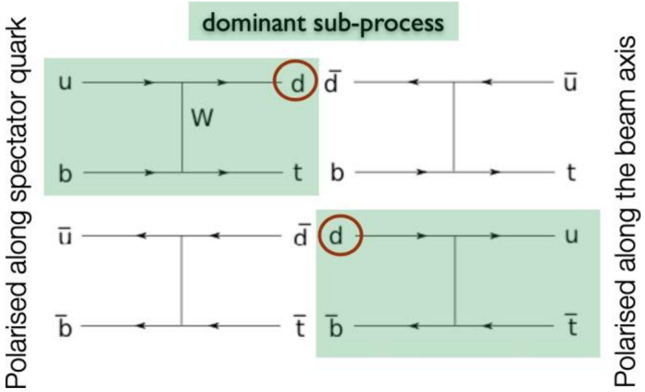
Top polarisation

Top quarks in t-channel are strongly polarised



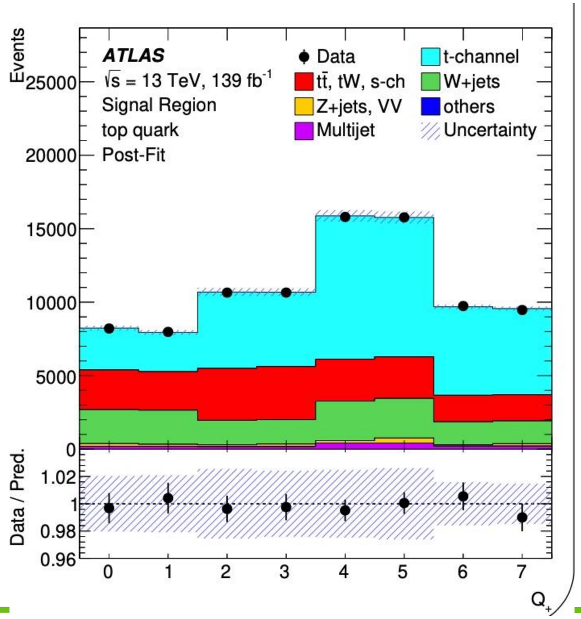
t-quark along spectator quark direction

anti-t opposite incoming quark direction



Signal regions defined by sign of $\cos\theta_{li}$ and lepton charge

$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

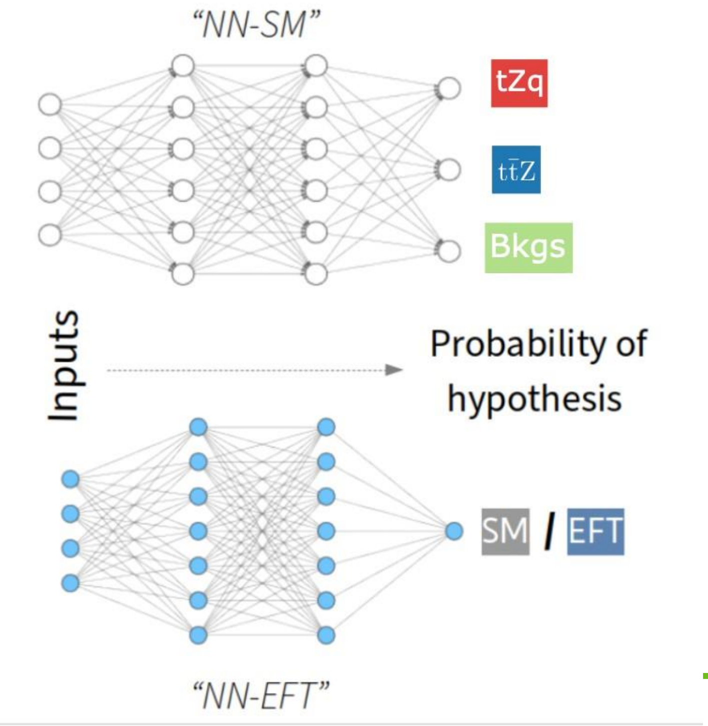


Template fit result: strong polarisation along z-axis

Machine learning in Top

Conclusions

- ML has **significant role** in top physics!
- Wide array of strategies and applications, very **active field of research**
  - CMS example [CMS-TOP-21-001]
  - ATLAS example [ATLAS-CONF-2022-049]
- Many **new developments** on-going
  - **DCTR** [PhysRevD.101.091901]
  - But also **much more**! E.g. [TOP22, M. Fenton]



Search for CP Violation

CMS-PAS-TOP-20-005

- CP violation in SM is insufficient to describe the matter-antimatter asymmetry of the universe
- In the SM, CPV in the production and decay of top quark pairs is predicted to be very small
- Simple CP odd observables

$$A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}.$$

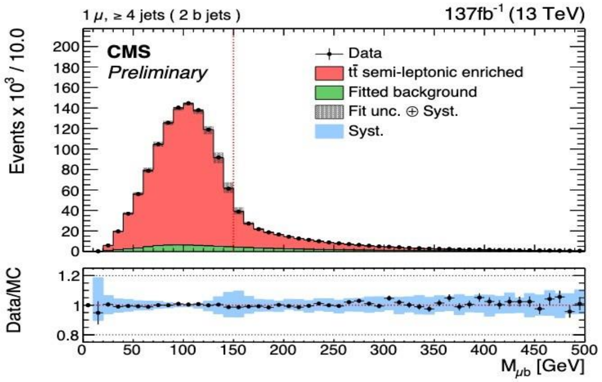
- chromo-electric dipole moment (CEDM) of top quark in top pair production induces CPV

✓ Lepton + jets final states [137 fb^{-1}]

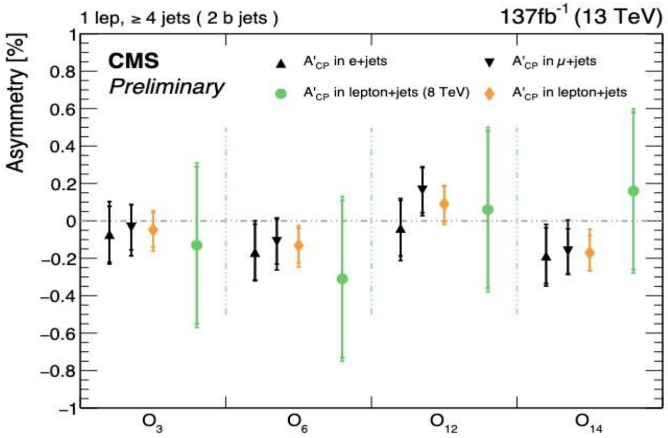
✓ Observables; O_3, O_6, O_{12} and O_{14}

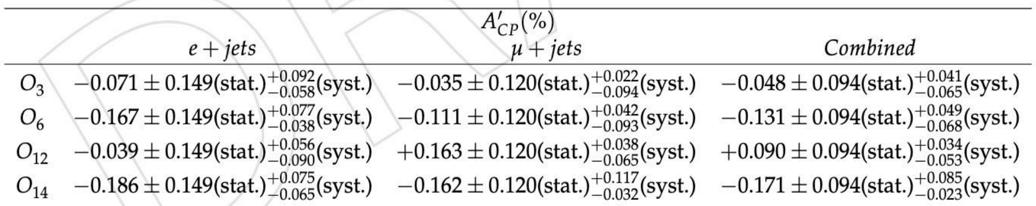
✓ Top quark and antiquark candidates are reconstructed usin
a χ^2 sorting algorithm

✓ The background contribution in the signal region is estimat
from a fit to the mass distribution



- There is no significant evidence of CPV in each observable
  - Consistent with the SM prediction

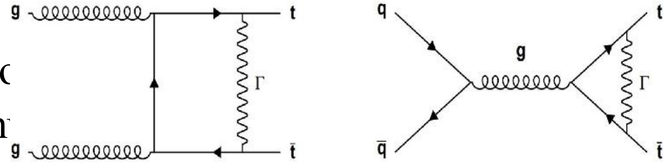




	$A'_{CP}(\%)$ $e + jets$	$\mu + jets$	Combined
O_3	$-0.071 \pm 0.149(\text{stat.})^{+0.092}_{-0.058}(\text{syst.})$	$-0.035 \pm 0.120(\text{stat.})^{+0.022}_{-0.094}(\text{syst.})$	$-0.048 \pm 0.094(\text{stat.})^{+0.041}_{-0.065}(\text{syst.})$
O_6	$-0.167 \pm 0.149(\text{stat.})^{+0.077}_{-0.038}(\text{syst.})$	$-0.111 \pm 0.120(\text{stat.})^{+0.042}_{-0.093}(\text{syst.})$	$-0.131 \pm 0.094(\text{stat.})^{+0.049}_{-0.068}(\text{syst.})$
O_{12}	$-0.039 \pm 0.149(\text{stat.})^{+0.056}_{-0.090}(\text{syst.})$	$+0.163 \pm 0.120(\text{stat.})^{+0.038}_{-0.065}(\text{syst.})$	$+0.090 \pm 0.094(\text{stat.})^{+0.034}_{-0.053}(\text{syst.})$
O_{14}	$-0.186 \pm 0.149(\text{stat.})^{+0.075}_{-0.065}(\text{syst.})$	$-0.162 \pm 0.120(\text{stat.})^{+0.117}_{-0.032}(\text{syst.})$	$-0.171 \pm 0.094(\text{stat.})^{+0.085}_{-0.023}(\text{syst.})$

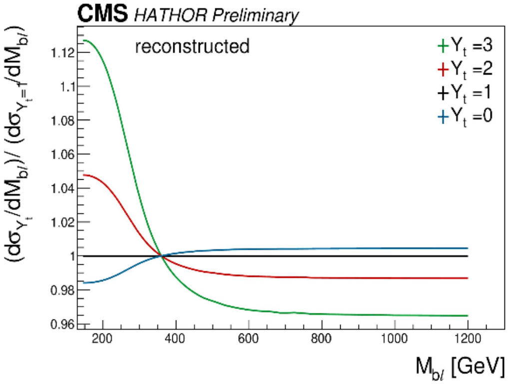
Measurement of the y^t

- ✓ Measure the Yukawa (y^t) coupling in $t\bar{t}$ production.
  - ✓ Exploit the large effect that the radiation of a virtual H bos
- ✓ $t\bar{t}$ predictions for different values of y^t obtained as event-based m HATHOR:
  - ✓ Applied on POWHEG predictions

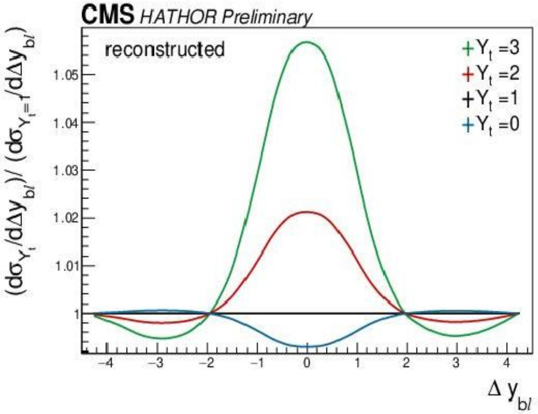


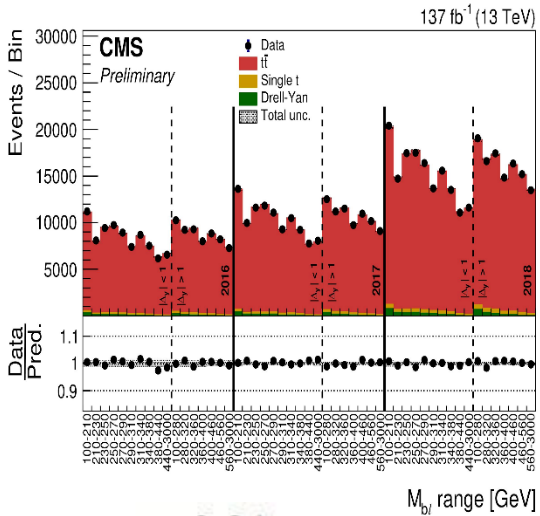
$$R_{\mathrm{EW}}(M_{t\bar{t}}, \Delta y_{t\bar{t}}) = \frac{d^2\sigma_{\mathrm{HATHOR}}}{dM_{t\bar{t}}\, d\Delta y_{t\bar{t}}} \Bigg/ \frac{d^2\sigma_{\mathrm{LO\ QCD}}}{dM_{t\bar{t}}\, d\Delta y_{t\bar{t}}}$$

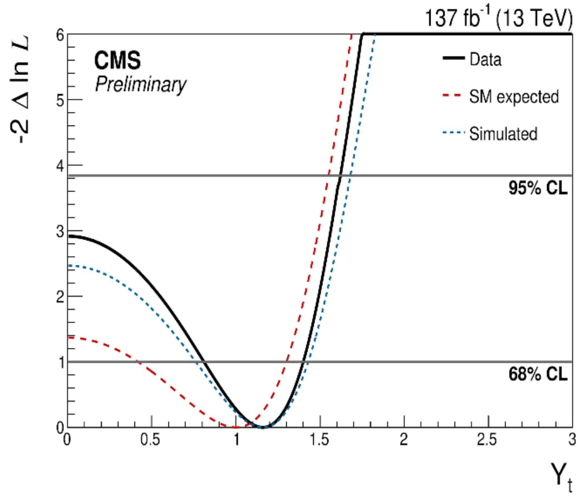
- ✓ The comparison with an additive approach is taken as uncertainty



- ✓ Event collected in the diletopn channel, >=2bjets
- ✓ Variables used based on partial system reconstruction: M ($l^+ + l^-$ + 2 b-jets) and Δy_{bl} : requires the correct matching of b and l







$$Y_t = 1.16^{+0.24}_{-0.36}$$

Compatible with the result in l+jets

$$Y_t = 1.07^{+0.34}_{-0.43}$$

PRD 102 (2020) 092013

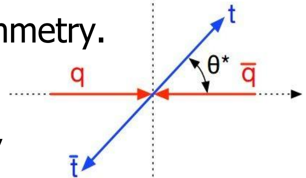
PRD 100 (2019) 072002

$t\bar{t}$ forward-backward asymmetry

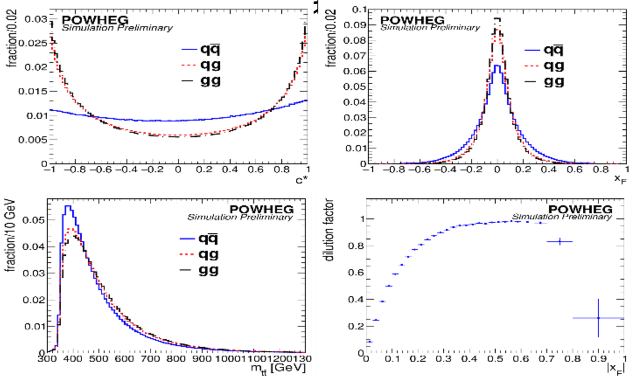
JHEP 06 (2020) 146

- ✓ NLO interference terms in $t\bar{t}$ production from qq initial state creates a forward-backward asymmetry.

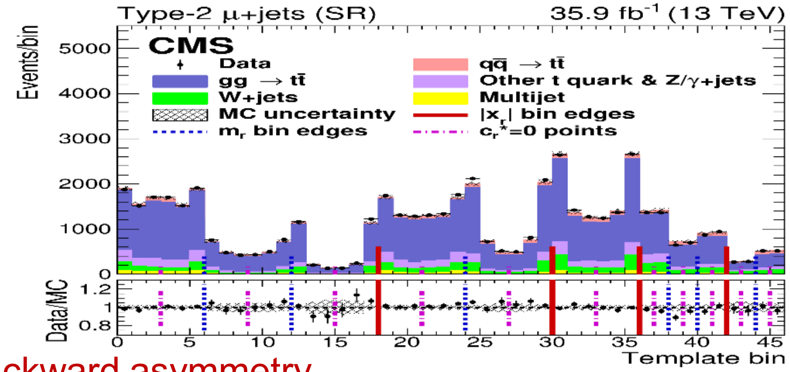
$$A_{\mathrm{FB}} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$

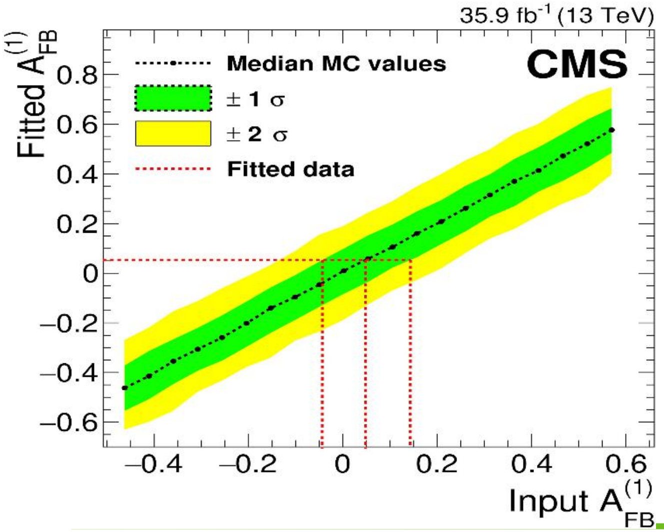


- ✓ Quantity never measured before @LHC, where the charge asymmetry is measured as a proxy
- ✓ Use variables sensitive to the difference between qq, qg and gg initial state to build templates and separate the qq
- ✓ Extract A_{FB} and anomalous chromoelectric and chromomagnetic dipole moments



- ✓ Events collected in the l+jets channel
- ✓ Both resolved and boosted topologies.
- ✓ Profile likelihood-fit to the 3D template to extract AFB and the anomalous moments separately





forward-backward asymmetry

$$A_{\mathrm{FB}}^{(1)} = 0.048\,^{+0.095}_{-0.087}\,(\mathrm{stat})\,^{+0.020}_{-0.029}\,(\mathrm{syst}),$$

chromomagnetic moments

$$\hat{\mu}_t = -0.024^{+0.013}_{-0.009}\,(\mathrm{stat})\,^{+0.016}_{-0.011}\,(\mathrm{syst}),$$

anomalous chromoelectric

$$|\hat{d}_t| < 0.03 \text{ at 95\% confidence level.}$$

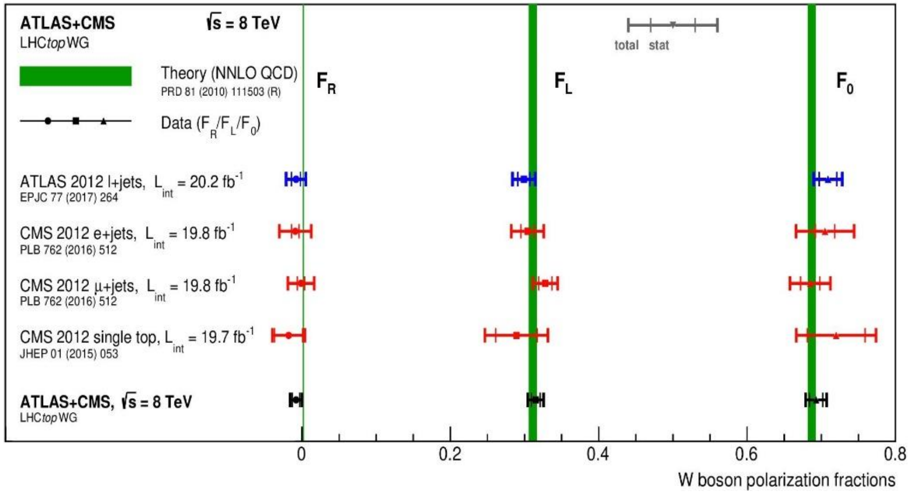
Consistent with the SM and previous CMS results

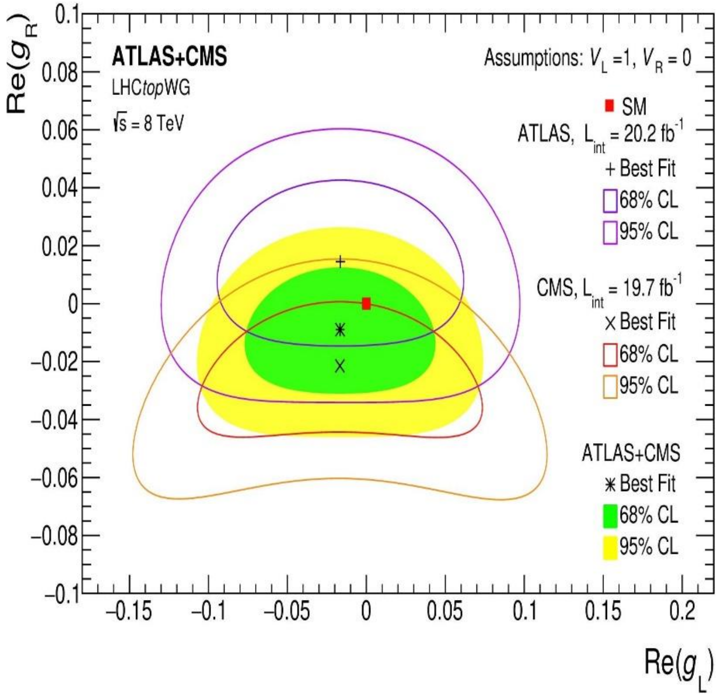
W polarization in ATLAS and CMS

JHEP 08 (2020) 051

- ✓ Combination of the W boson polarization in top quark decays, on Run1(8 TeV, 20fb^{-1}) data.
  - ✓ W boson polarization determined by the V-A structure of the tWb vertex

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$





- ➢ Combination of the polarization fractions from 4 measurements

- ✓ Combination Improvement > 20% wrt the most precise measurement
- ✓ Measurement used to set limits on the anomalous coupling in the tWb vertex

	95% CL interval		
Coupling	ATLAS	CMS	ATLAS+CMS combination
Re(V_R)	$[-0.17, 0.25]$	$[-0.12, 0.16]$	$[-0.11, 0.16]$
Re(g_L)	$[-0.11, 0.08]$	$[-0.09, 0.06]$	$[-0.08, 0.05]$
Re(g_R)	$[-0.03, 0.06]$	$[-0.06, 0.01]$	$[-0.04, 0.02]$

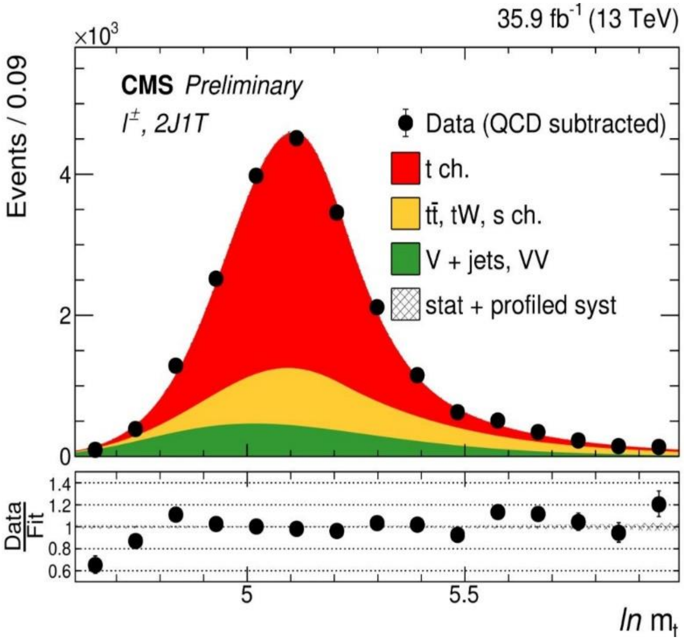
Mass measurement in single top events

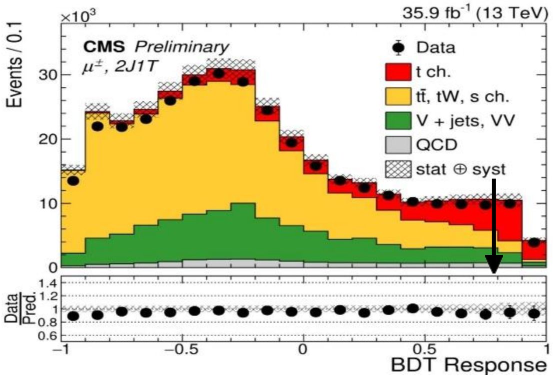
CMS-PAS-TOP-19-009

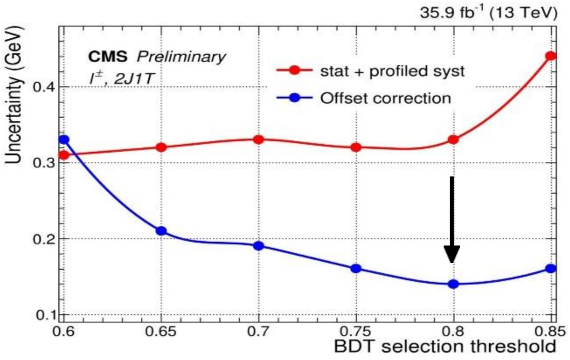
- ✓ BDT discriminator and cut optimization
- ✓ Data-driven QCD is subtracted from the data
- ✓ Simultaneous ML fit using $\boldsymbol{y = ln(m_t)}$ distributions in μ and e final states, validated in control region

$$F(y) = f_{t-ch}\, F_{t-ch}(y\,;\, y_0) + f_{Top}\, F_{Top}(y\,;\, y_0) + f_{EWK} F_{EWK}(y)$$

- ✓ y_0, f_{t-ch}, f_{Top} and f_{EWK} are allowed to float during the fit







mass results:

Sub GeV precision

$$m_t = 172.13 \pm 0.32\,(\text{stat}+\text{prof})\,^{+0.69}_{-0.70}\,(\text{syst})\ \text{GeV} = 172.13^{+0.76}_{-0.77}\ \text{GeV}$$

$$m_t = 172.62 \pm 0.37\,(\text{stat}+\text{prof})\,^{+0.97}_{-0.65}\,(\text{syst})\ \text{GeV} = 172.62^{+1.04}_{-0.75}\ \text{GeV},$$

$$m_{\bar{t}} = 171.79 \pm 0.58\,(\text{stat}+\text{prof})\,^{+1.32}_{-1.39}\,(\text{syst})\ \text{GeV} = 171.79^{+1.44}_{-1.51}\ \text{GeV}.$$

Masses ratio and difference (a check for CPT Invariance)

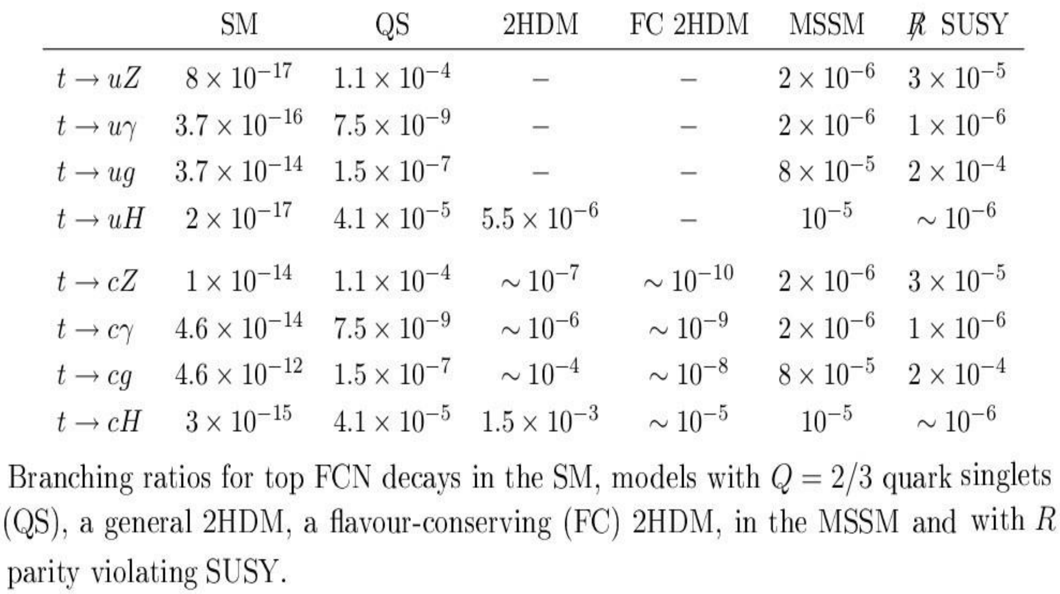
$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.995 \pm 0.004\,(\text{stat}+\text{prof})\,^{+0.002}_{-0.004}\,(\text{syst}) = 0.995^{+0.005}_{-0.006}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69\,(\text{stat}+\text{prof})\,^{+0.35}_{-0.74}\,(\text{syst})\ \text{GeV} = 0.83^{+0.77}_{-1.01}\ \text{GeV}$$

Precision limited by : JES and modelling

Search for FCNC in the top sector

- Flavor changing neutral currents (FCNC) allow for transitions between quarks of different flavor but same electric charge
- FCNC processes are highly suppressed in the SM due to the GIM mechanism
  - Small contributions appear at one loop level
- Many extensions of the SM predict the presence of FCNC and give rise to detectable FCNC amplitude



	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

Branching ratios for top FCN decays in the SM, models with $Q = 2/3$ quark singlets (QS), a general 2HDM, a flavour-conserving (FC) 2HDM, in the MSSM and with R parity violating SUSY.

Any evidence of FCNC will indicate the existence of new physics

Search for FCNC tHq interaction by H→γγ

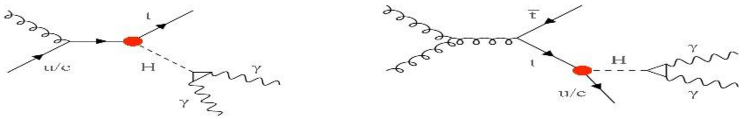
CMS-PAS-TOP-20-007

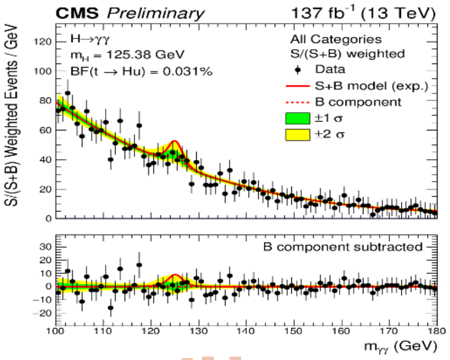
- Signal modeling: effective Lagrangian

$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t}\kappa_{Hqt}\left(F^{L}_{Hq}P_{L} + F^{R}_{Hq}P_{R}\right)qH + \text{h.c.},$$

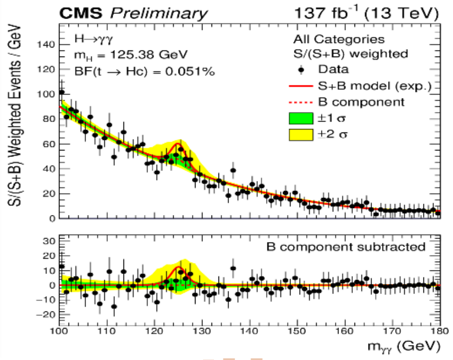
- Production & decay
- Signal regions: 2 photons, 100 < $m_{\gamma\gamma}$ < 180 GeV
  - leptonic: ≥1 jet, ≥1ℓ
  - hadronic: ≥3 jet, ≥1 b-jet
- Strategy
  - 8 BDTs: (u, c) × (lep, had) × (res, non-res bkg)
  - 7 categories defined by BDT score
  - 14 $m_{\gamma\gamma}$ distributions to fit
- Dominant uncertainties:

  b-tagging and γ identification
- Data compatible with absence of signal
- Upper limits on the signal cross sections are translated to the strength of the tqH anomalous couplings and related branching fractions

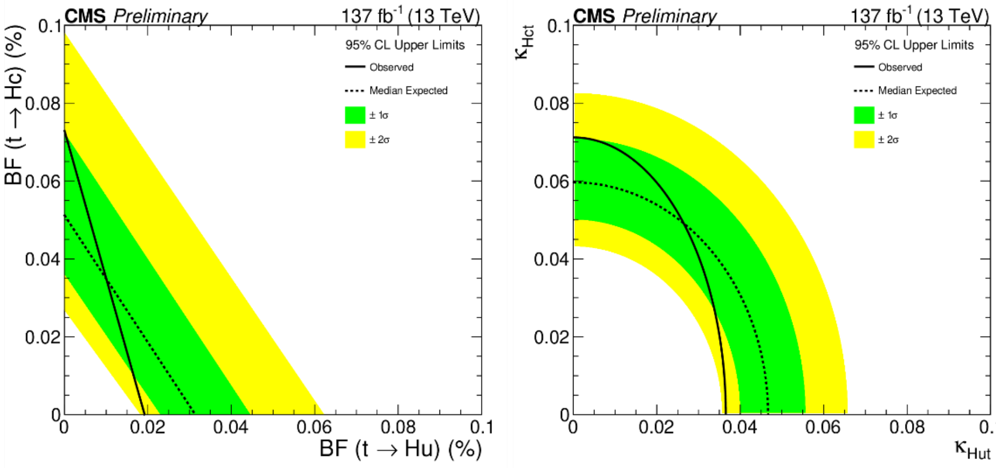




tHu



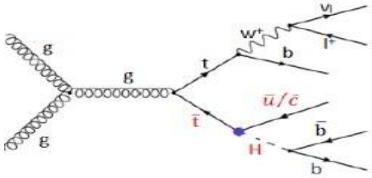
tHc



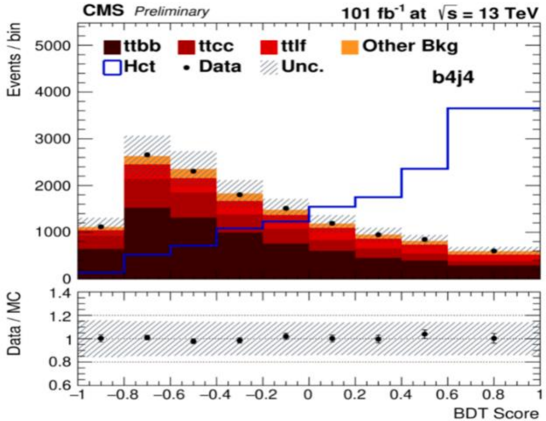
- **Upper limits**
  - B(t→Hu) < 1.9×10⁻⁴ (exp. 3.1×10⁻⁴)
  - B(t→Hc) < 7.3×10⁻⁴ (exp. 5.1×10⁻⁴)

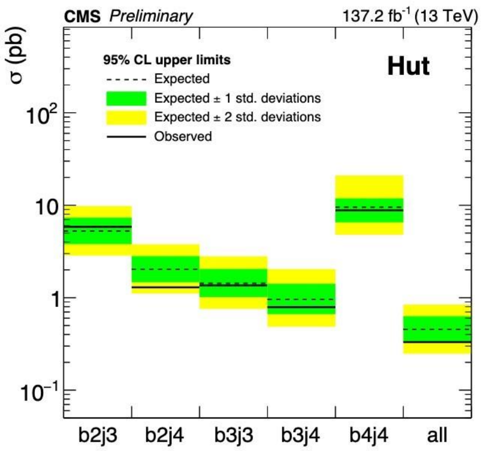
Search for FCNC tHq interaction by H→bb

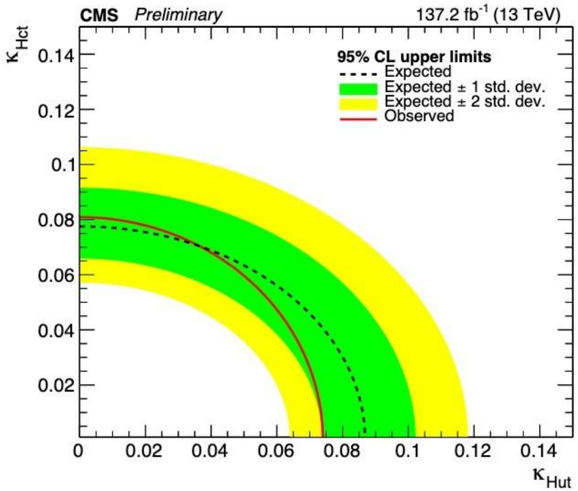
CMS-PAS-TOP-19-002

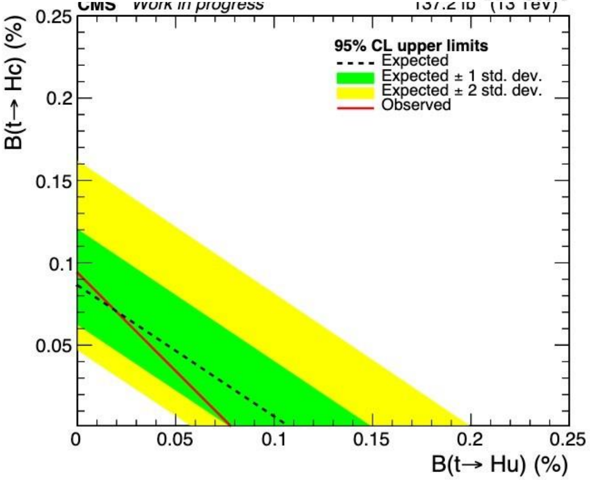


- Production & decay
- Signal region: 1ℓ , ≥3 jet, ≥2 b-jet
- A deep neural network is used to associate the reconstructed objects to the matrix-element partonic final state
- BDTs are used to distinguish the signal from the background event
- All bjet-jet categories are combined
- No significant excess with respect to the SM background expectations: 95% CL limits are set on the xs, couplings and BRs
- Significant improve with respect to the early run-2 search









- Upper limits:
  - B(t→Hu) < 7.9×10^{-4} (exp: 11×10^{-4})
  - B(t→Hc) < 9 .4×10^{-4} (exp: 8.6×10^{-4})

Search for CLFV interactions

CMS-PAS-TOP-19-006

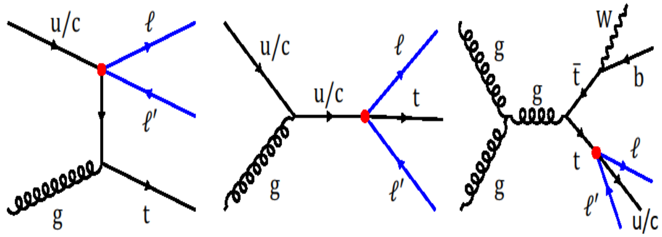
- In the SM, lepton flavor is conserved in all interactions
- Many new physics models predict sizable CLFV (neutrino mass, multi-Higgs doublet models,…)
- If the new physics responsible for the CLFV is at scales beyond what the LHC can directly probe, the SM Lagrangian can be extended by dimension-6 operators

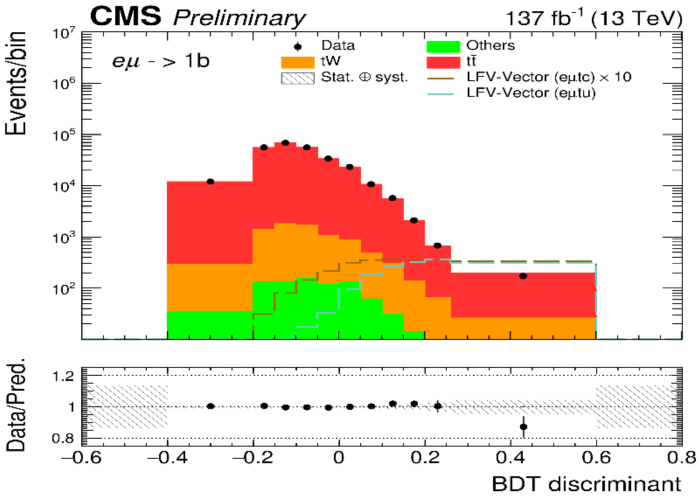
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \ldots ,$$

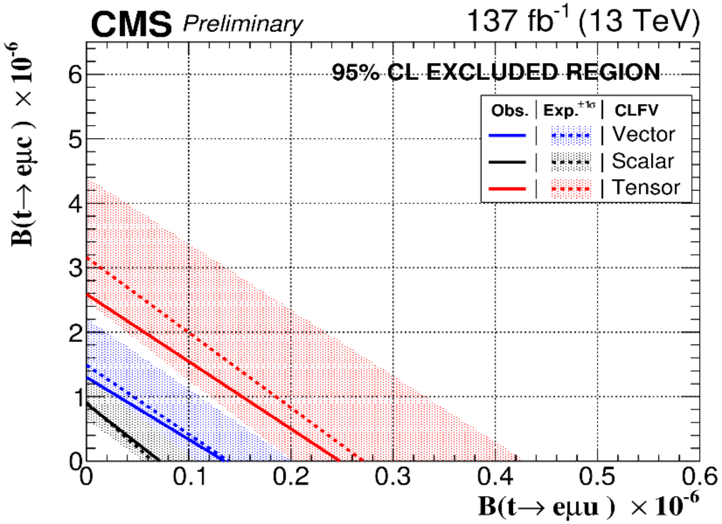
- ✓ Search for CLFV in eμ final state [137 fb^{-1}]
- ✓ Production & decay
- ✓ Signal: CLFV vector, scalar and tensor
- ✓ BDT is used to discriminate signal from BG events
- ✓ Data consistent with SM expectation
  - ✓ Upper limits are set at 95% CL

Production

Decay







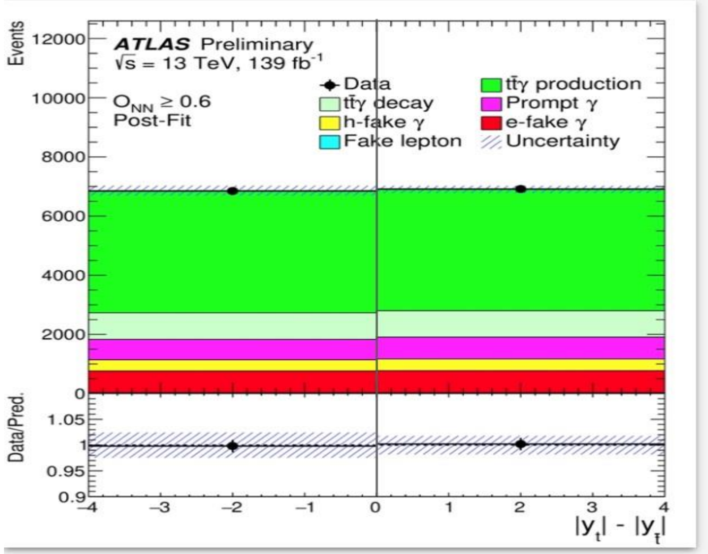
Asymmetry in ttγ and ttW

ttγ

Asymmetry from ISR/FSR interference

Similar definition as in tt

Much lower statistics, 2 bins



A_C= −0.006 ± 0.024(stat) ± 0.018(syst)

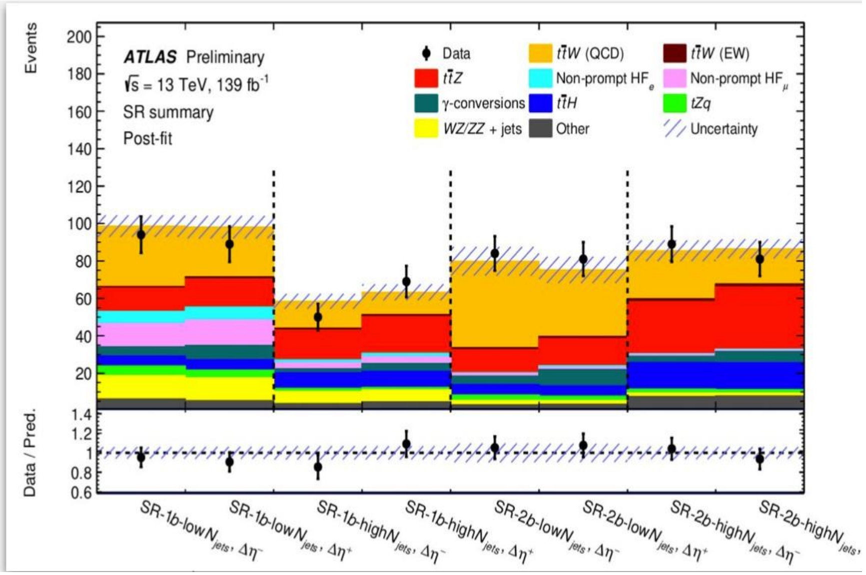
in agreement with prediction from MG5aMC

A_C= −0.014 ± 0.001(scale)

ttW

Expected to be larger than in tt due qq initial stat

3-lepton channel, lepton as proxy for top



Fiducial result unfolded to particle-

A_C = −0.112 ± 0.170 (stat) ± 0.055 (syst)

in agreement with Sherpa NLO+EW simulation

Statistically dominated analyses, Run 3 data will help