Top quark production and properties

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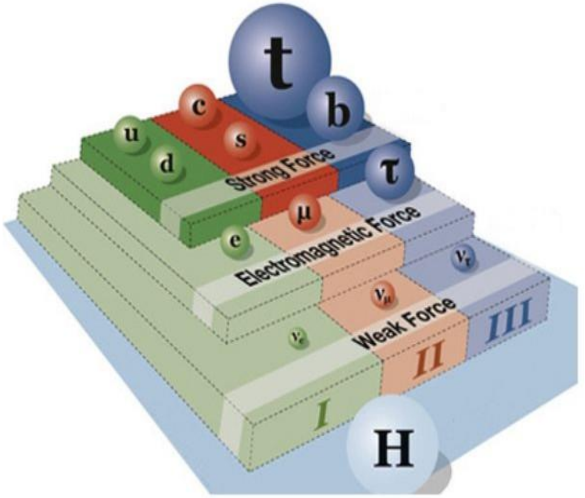
On behalf of ATLAS and CMS collaborations

RdV30: Windows on the Universe,
6-12 Aug 2023, Quy Nhon (Viet Nam)

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

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

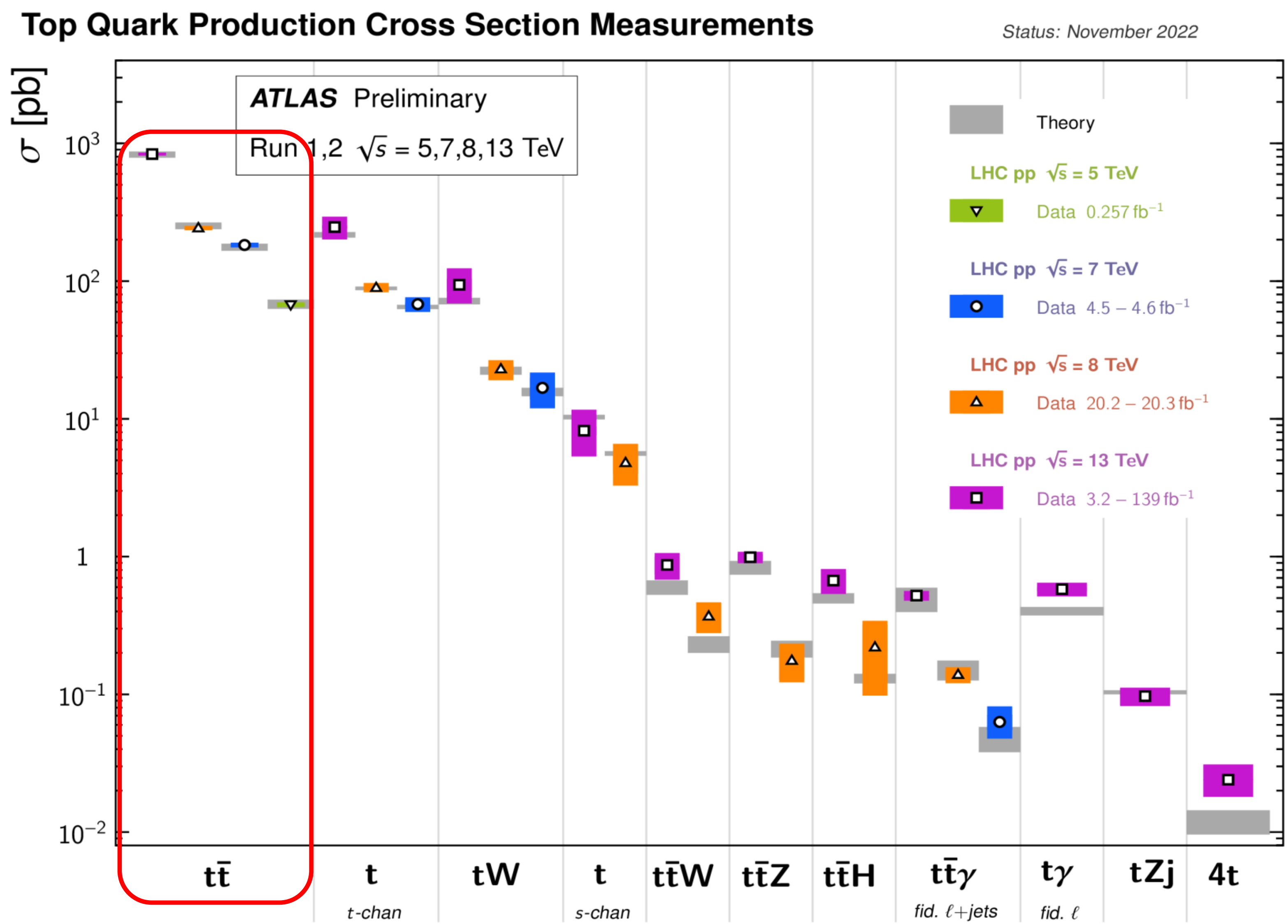


The LHC is a top factory and allows:

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

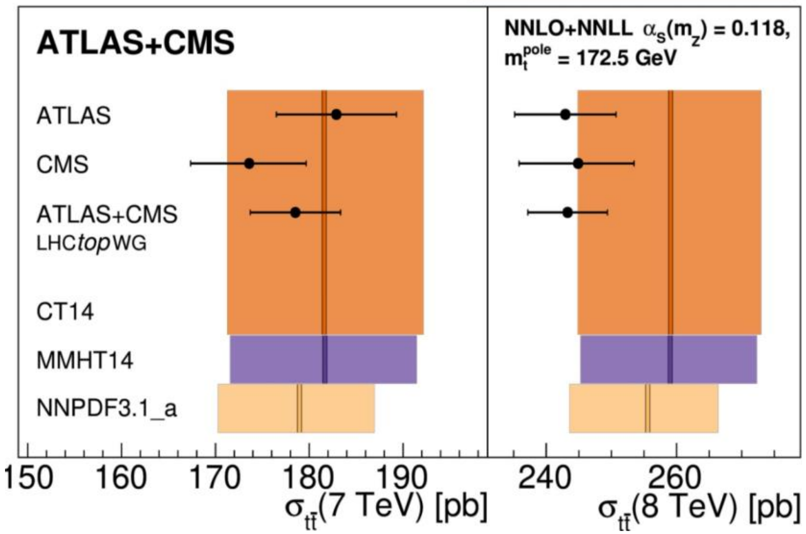
Top pair production



Top pair cross sections

ATLAS+CMS combination 7/8 TeV

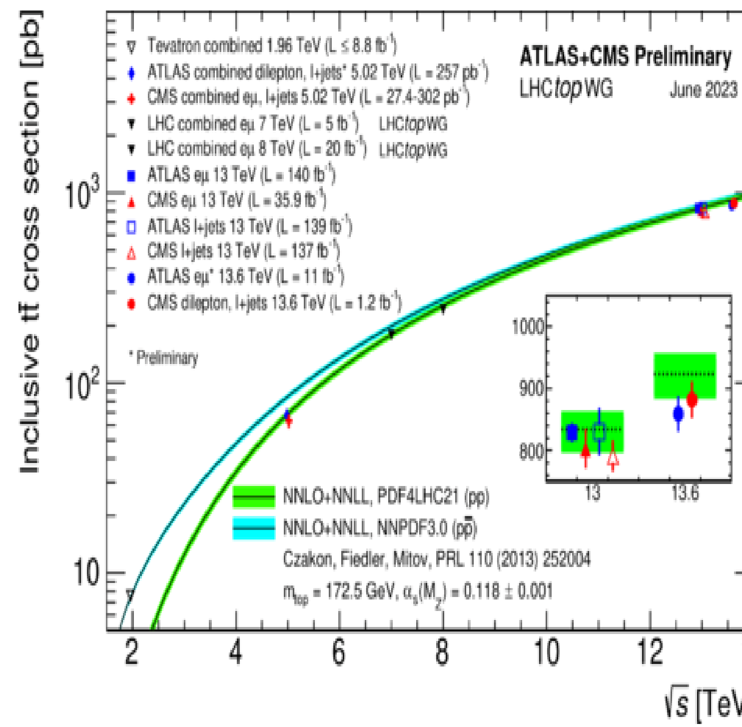
- inputs: eμ channel with best precision
- CONVINO tool to combine counting and PL fit



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

- 25% reduction of uncertainties

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

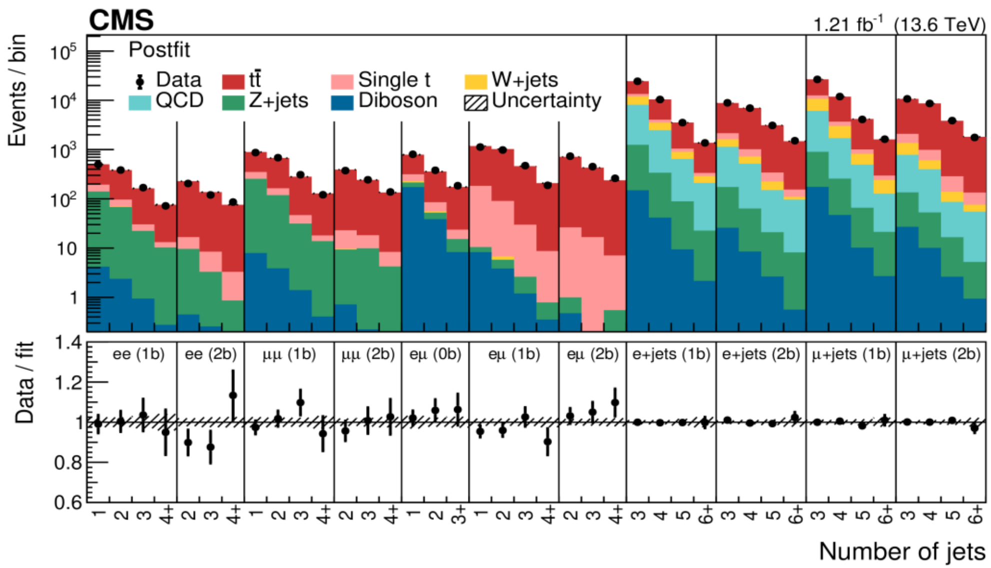


✓ **Impressive agreement with QCD predictions from 5.02 to 13.6 TeV and a magnitude of cross section**

First look at LHC run-3 data!

✓Very first measurements of **inclusive ttbar cross section at 13.6 TeV** by CMS:.

- ML fit to bins in # of leptons / lepton flavors / # of (b-)jets
- In-situ calibrations of lepton, JES, b-tag efficiencies.



Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3

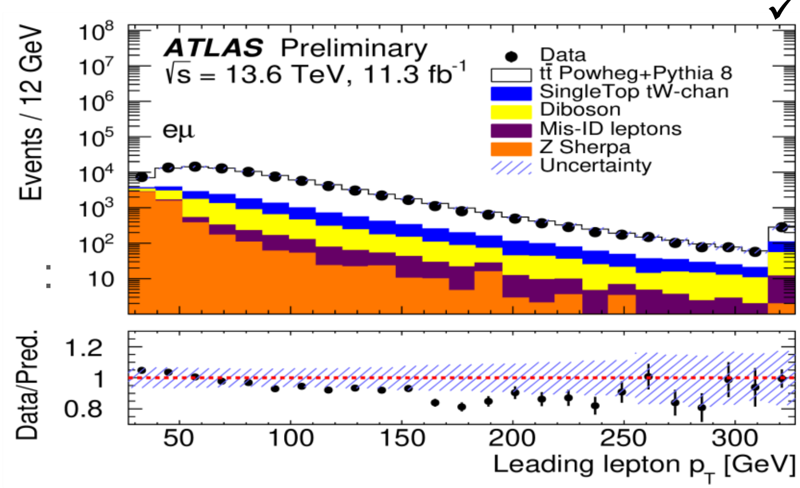
$$\sigma(t\bar{t}) = 887^{+43}_{-41}\,(\text{stat+syst}) \pm 53\,(\text{lumi})\ \text{pb}$$

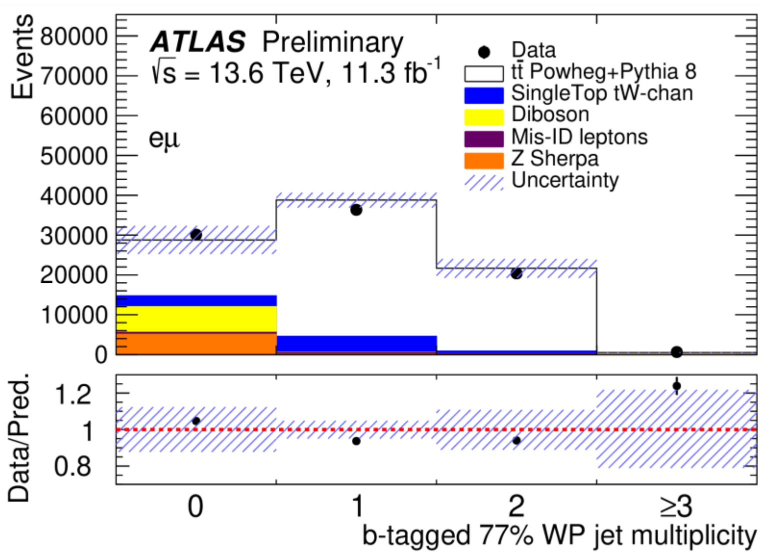
$$\textit{Theory:}\ \sigma(t\bar{t}) = 921^{+18}_{-16}\ \text{pb}$$

arXiv:2303.10680
Submitted to JHEP

Top pair & Z boson production at new energy

Top enriched eμ events





✓ **ATLAS measured inclusive ttbar, fiducial Z boson cross-sections, and the ratio at 13.6 TeV**

- Limited by the preliminary luminosity, but cancelled for the ratio!
- Measured values are consistent with the SM prediction using the PDF4LHC21 PDF set.

$$\sigma(t\bar{t}) = 859 \pm 4_{\text{(stat)}} \pm 22_{\text{(syst)}} \pm 19_{\text{(lumi)}}\ \text{pb}$$

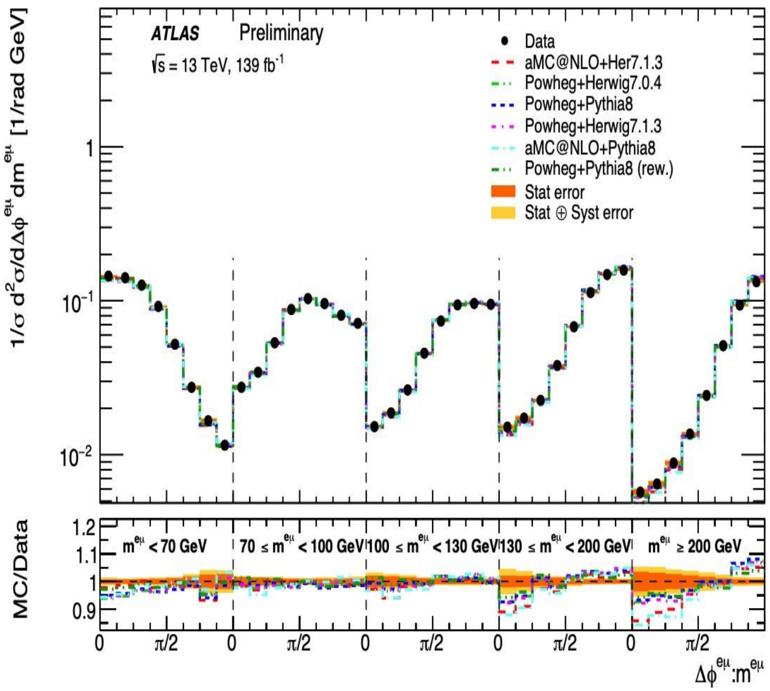
$$R_{t\bar{t}/Z} = 1.144 \pm 0.006_{\text{(stat)}} \pm 0.022_{\text{(syst)}} \pm 0.003_{\text{(lumi)}}$$

ATLAS-CONF-2023-006

Measurements in lepton channels

eμ channel

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



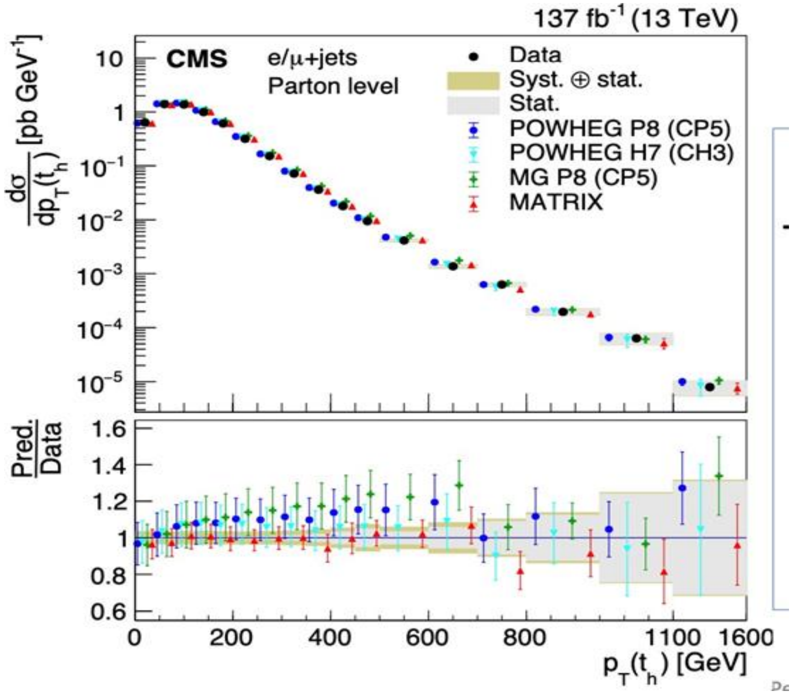
$$\sigma_{t\bar{t}} = 836 \pm 1(stat) \pm 12(syst) \pm 16(lum + E_{cms})$$

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 channel



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

3.2% uncertainty
most precise in this channel

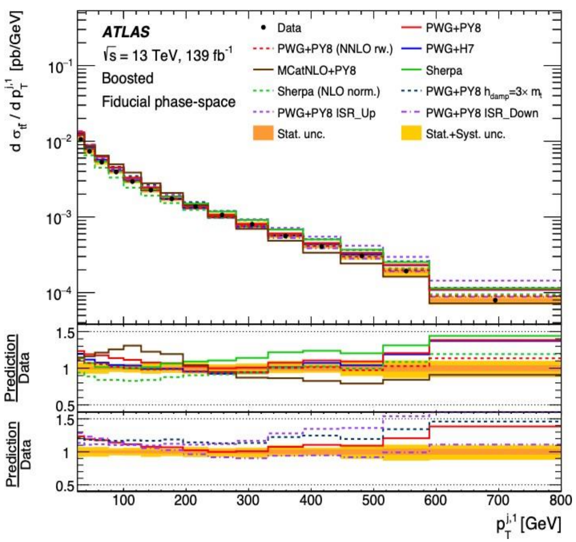
JHEP 06 (2022) 063

Measurements in boosted topology

arXiv:2205.02817

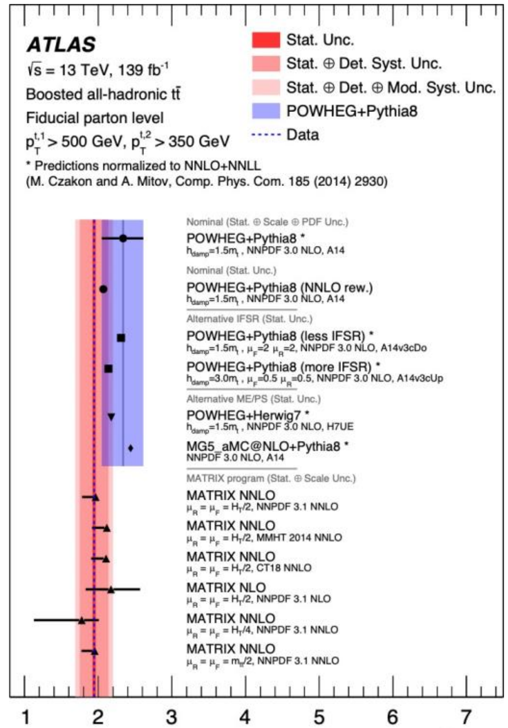
Single lepton channel

- 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

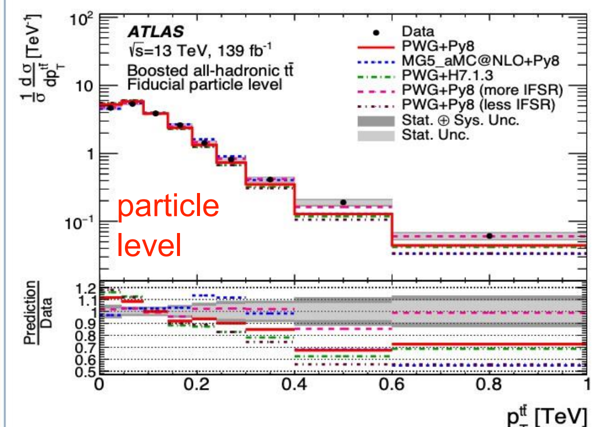
All-hadronic channel

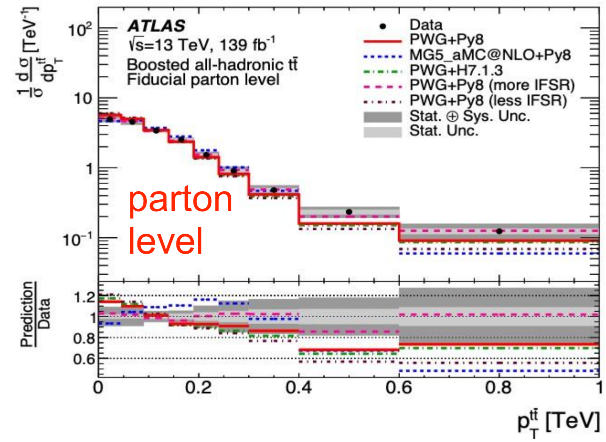


MATRIX reproduces the fiducial cross-section better than the NLO models.

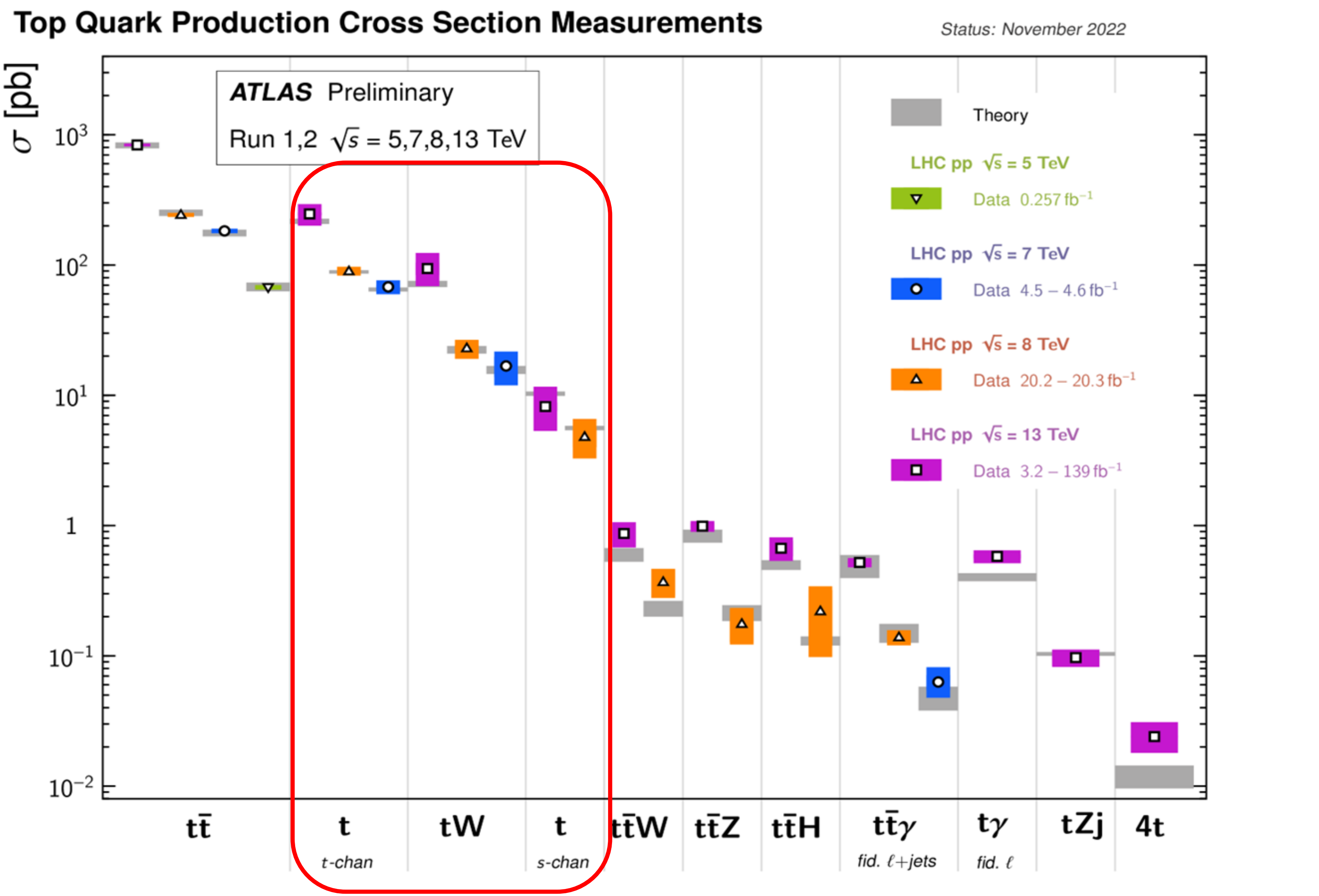
Reweighing the NLO to NNLO top pT helps to reproduce data

tt system pT

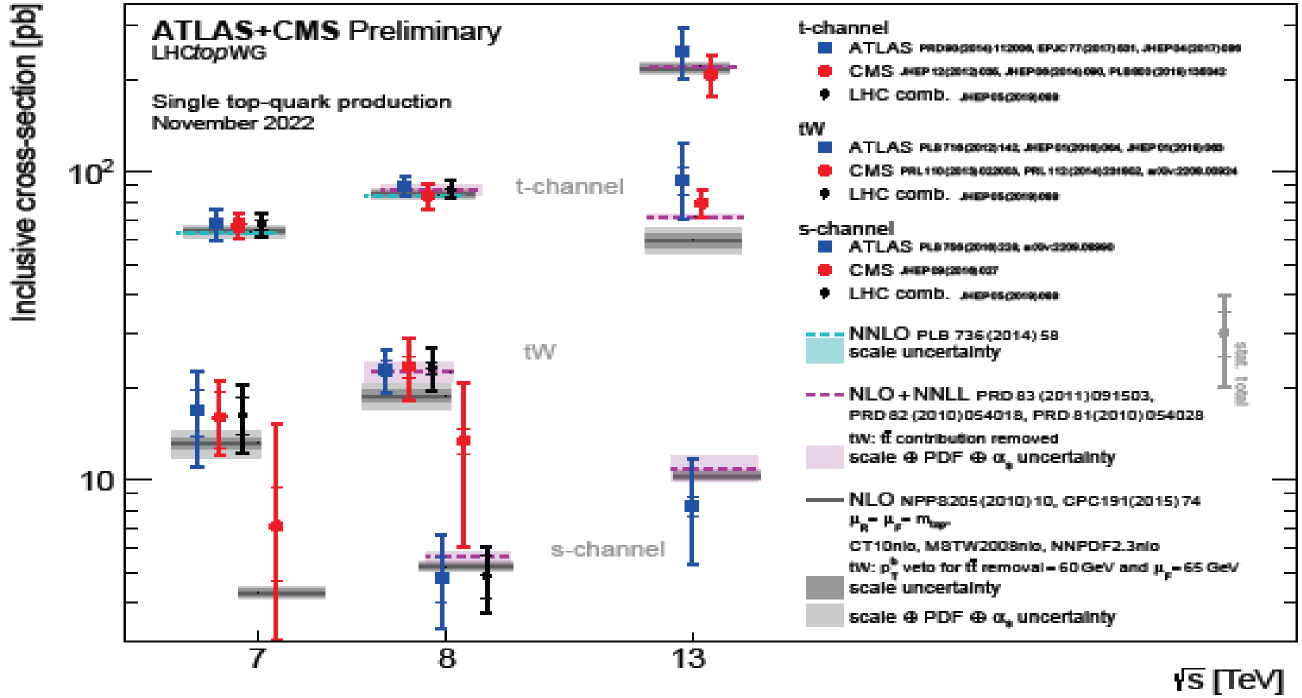




Single top production

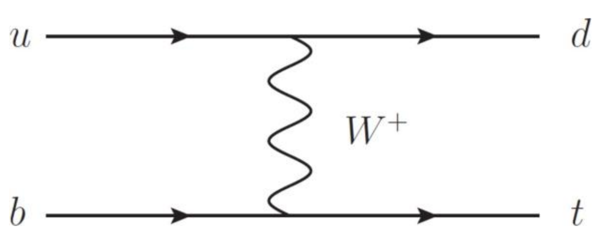


Single top production

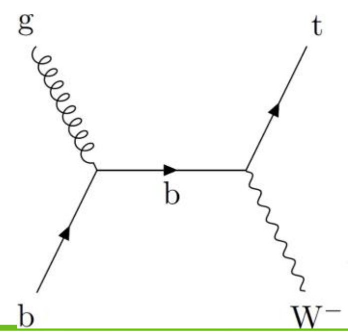


Inclusive xsec measurements are in good agreement w/ NLO+NNLL & NNLO prediction.

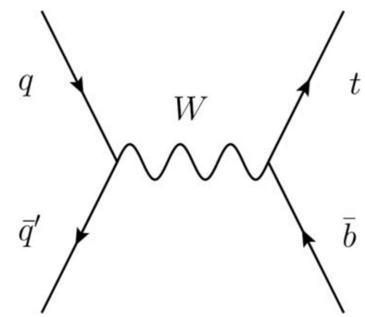
t-channel



tW-channel



s-channel

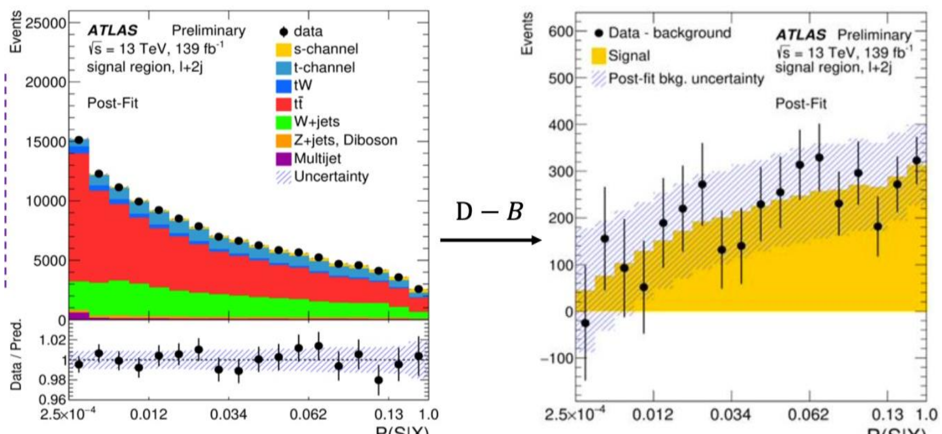


Single top cross section

JHEP 06 (2023) 191 — JHEP 07 (2023) 046

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:

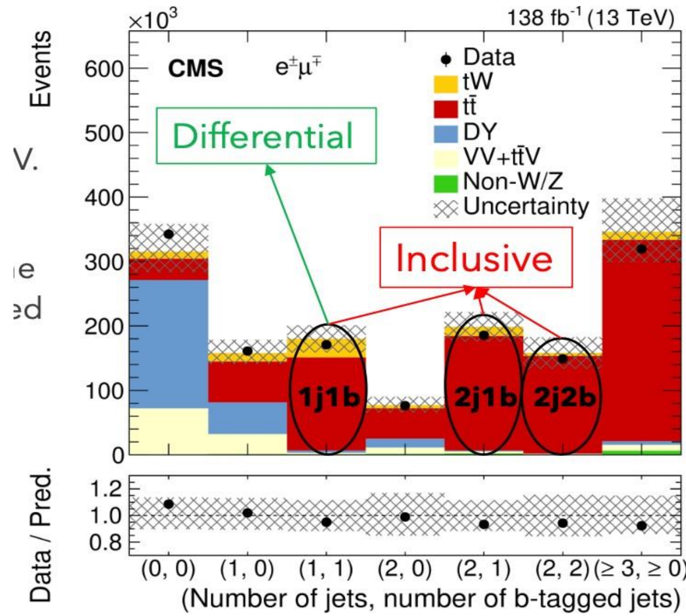
Significance 3.3 (3.9) obs.(exp)

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



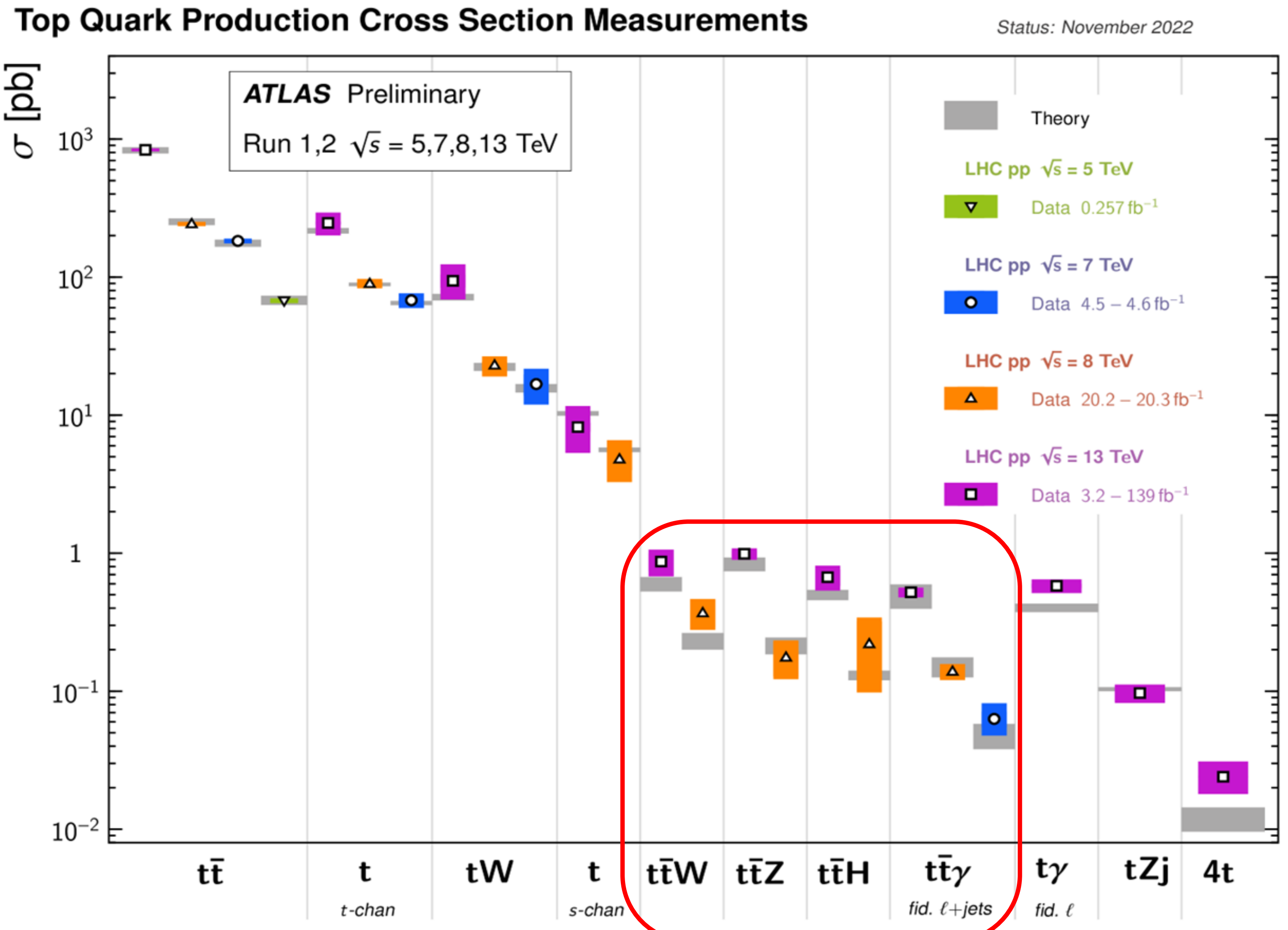
$$\sigma_{\text{tW}} = 79.2 \pm 0.8\,(\text{stat}) \pm^{7.0}_{7.2}\,(\text{syst}) \pm 1.1\,(\text{lumi})\ \text{pb}$$

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

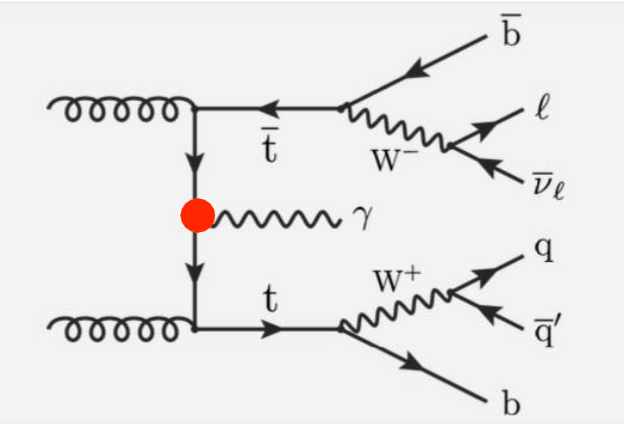
tt + X production

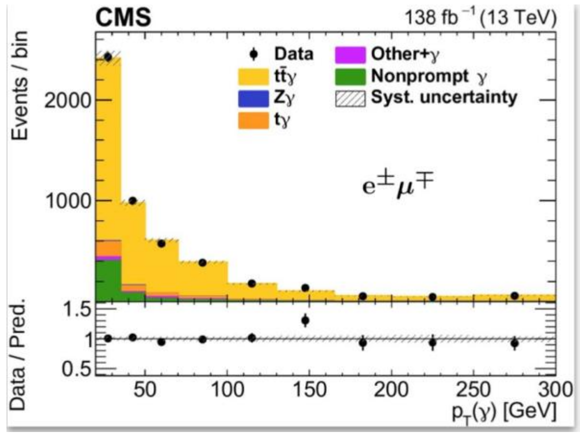


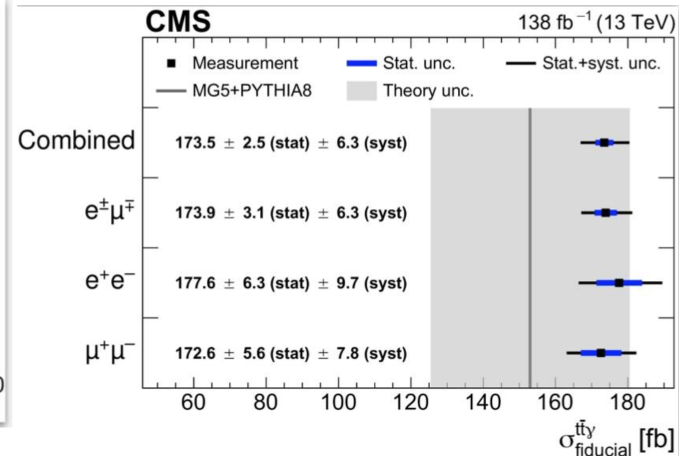
ttγ production

JHEP 05 (2022) 091

- New CMS measurement in dilepton channel

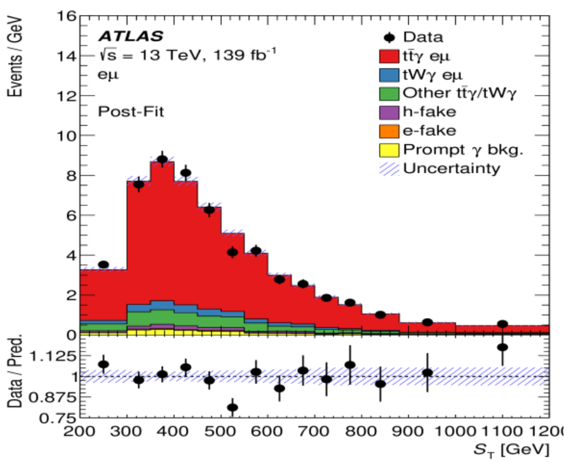


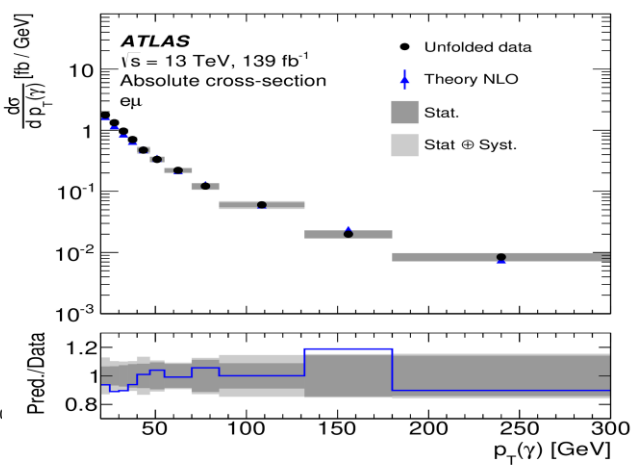




- Precision 4%
- Prediction from MG5aMC (LO+NLO k-factor) is lower

JHEP 09 (2020) 049





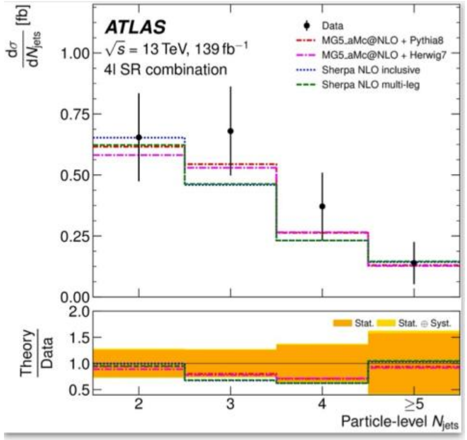
In agreement with the predictions from the SM

ttZ measurements

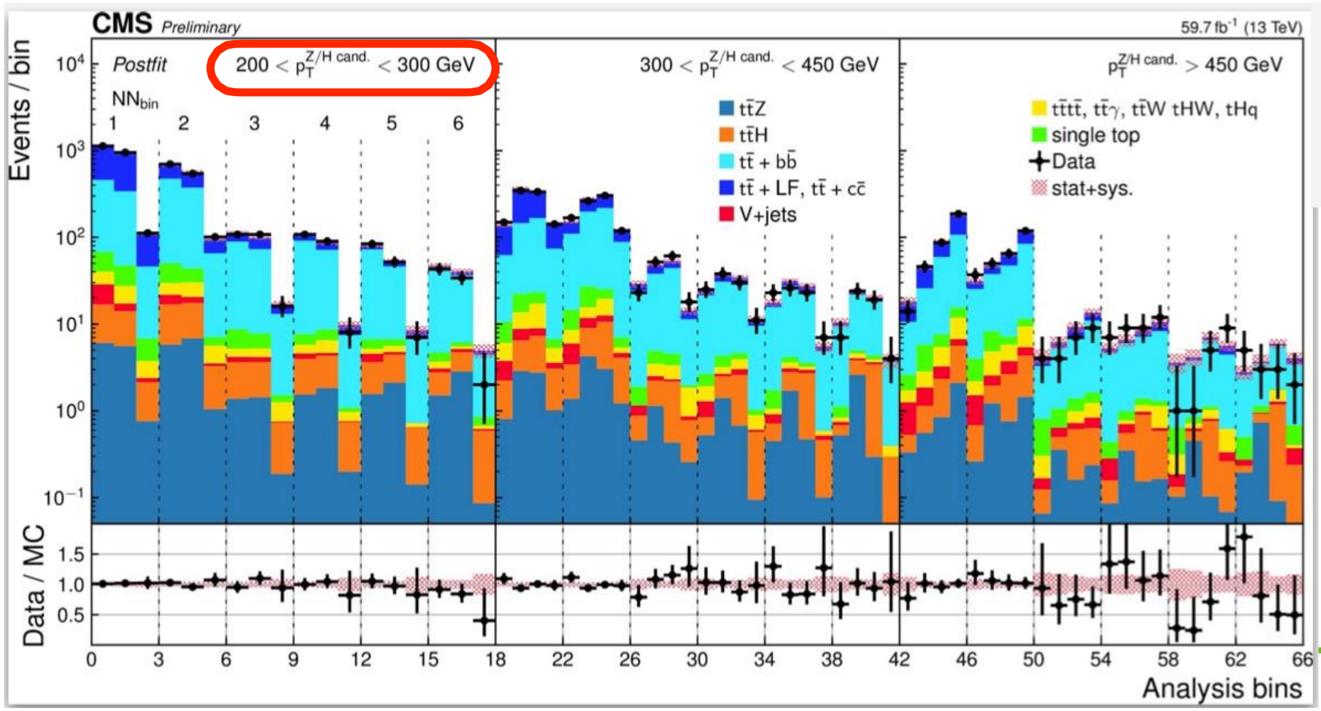
EPJC 81 (2021) 737

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

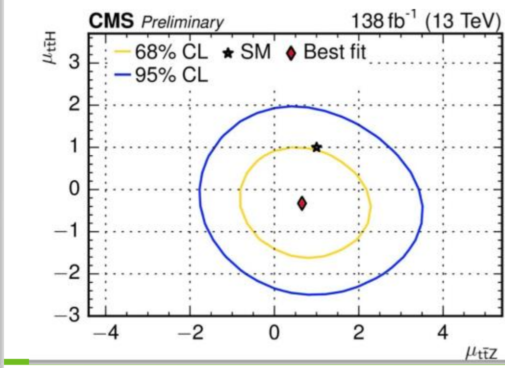


➢ Measurement of ttZ(bb) and ttH(bb) in boosted regime arXiv:2208.12837



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

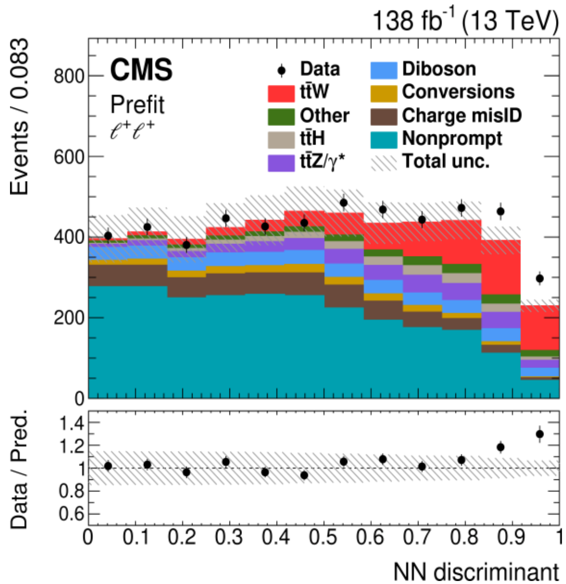
Limited by statistics

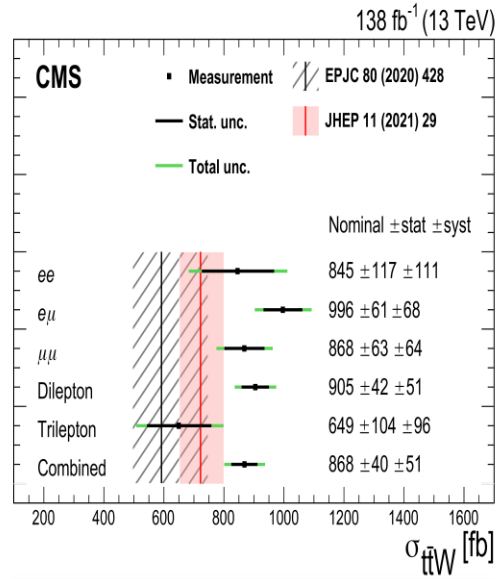


ttW measurement: CMS

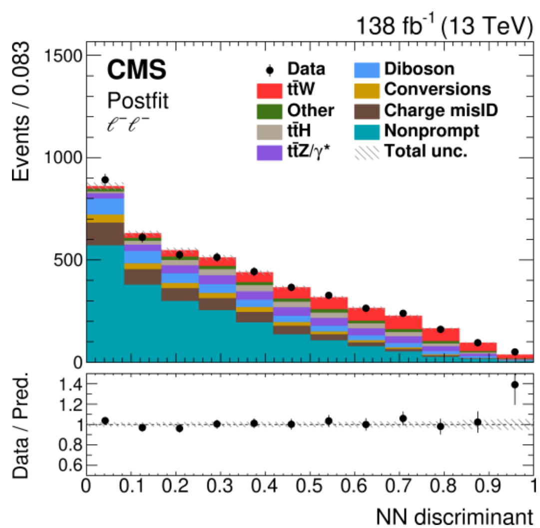
2-lepton Same Sign and tri-lepton final states

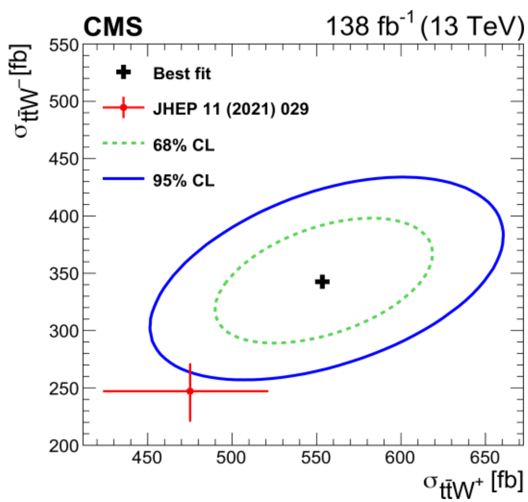
arXiv:2208.06485





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





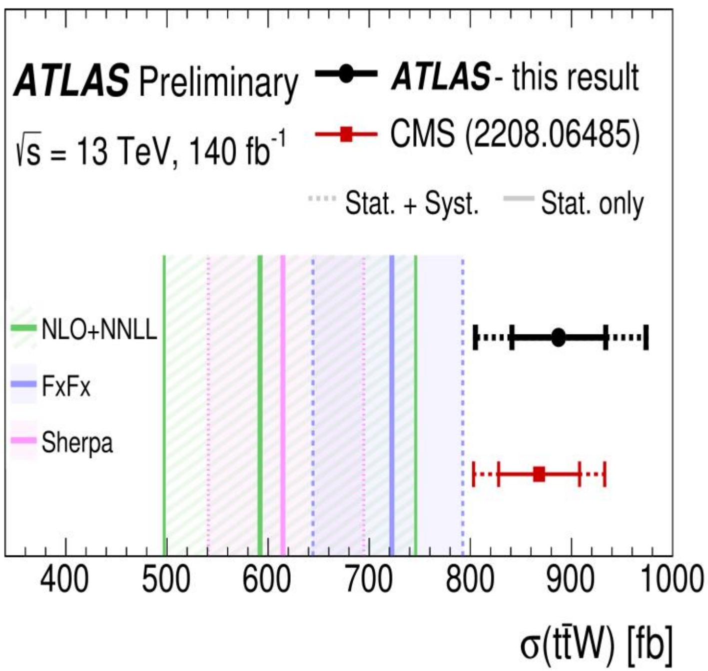
R(ttW+/ttW−) = 1.61 ± 0.15 (stat) $^{+0.07}/_{-0.05}$ (syst)

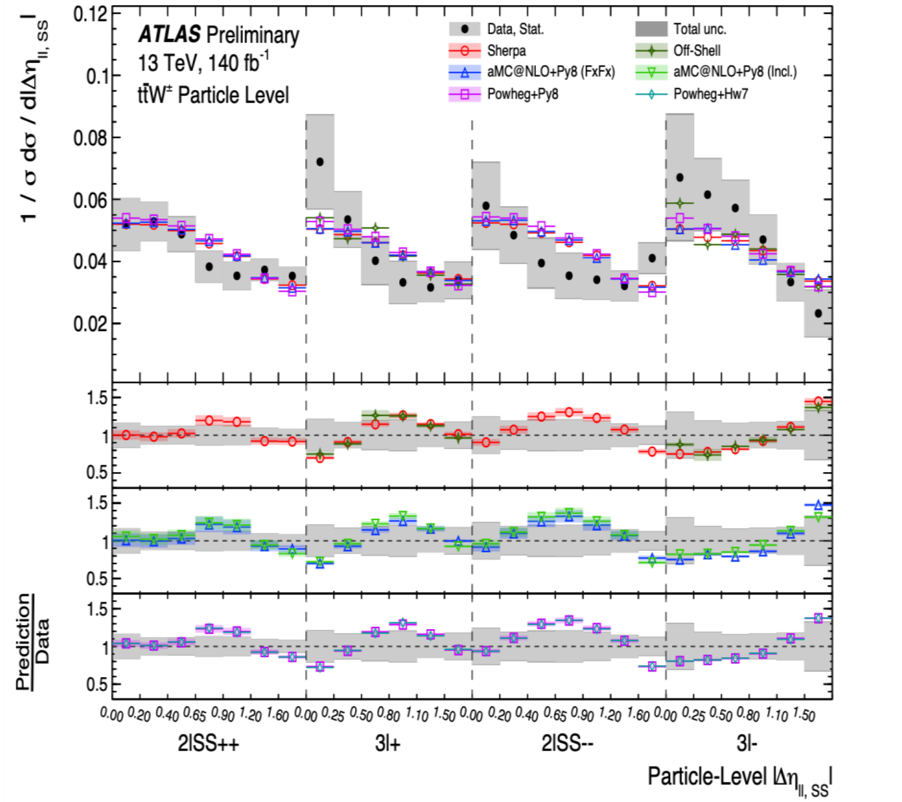
Significant deviation from prediction for ttW+/ttW- ratio = 1.94+0.37-0.24

ttW measurement: ATLAS

ATLAS-CONF-2023-019

- ✓ Inclusive cross section measurements for tt̄W, tt̄W+/–, and the ratio;
- ✓ Differential measurements for 9 kinematic observables; compatibility with data is tested by χ2.

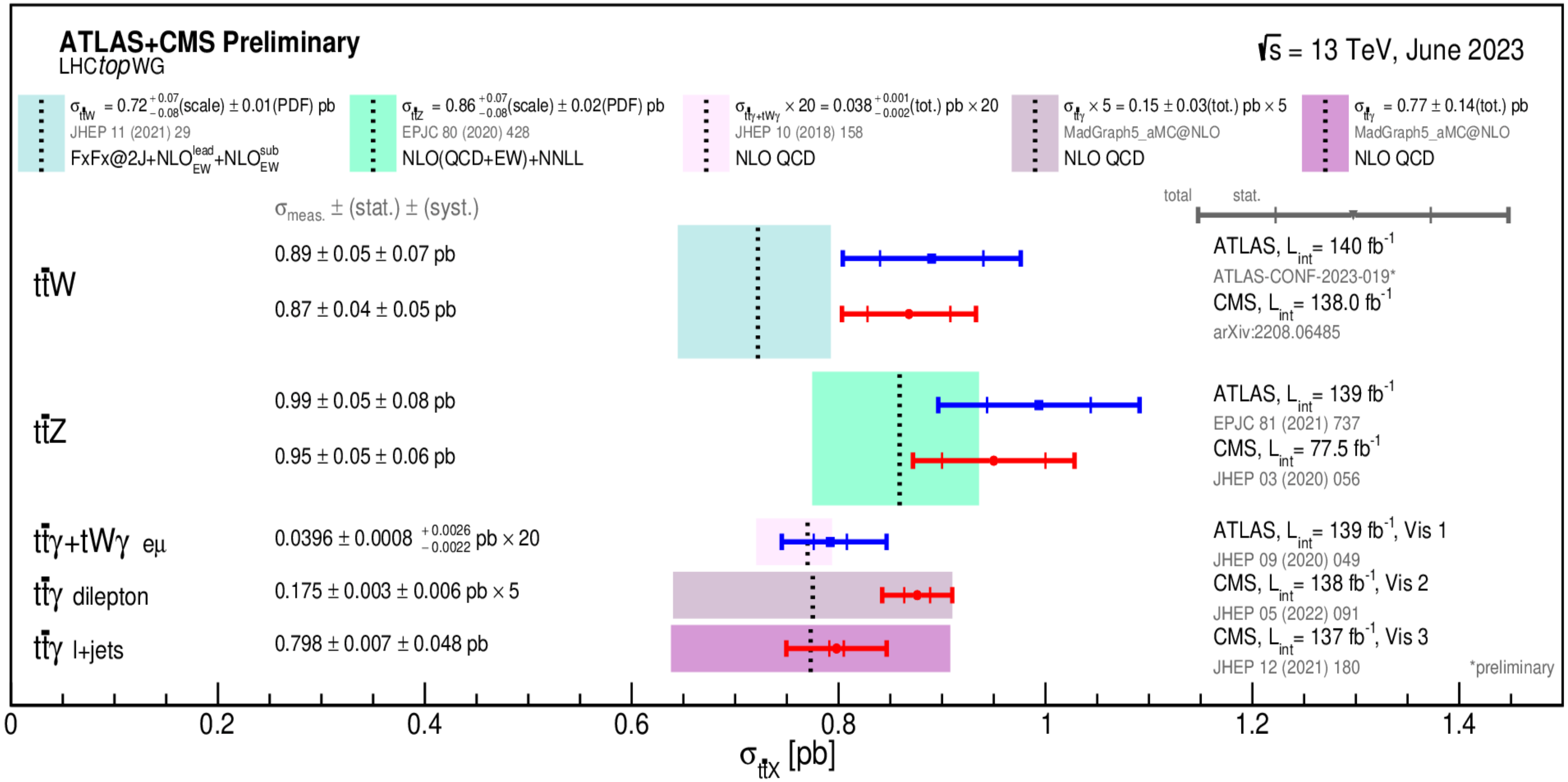




- ✓ Inclusive x-sec is compatible with CMS
- ✓ Larger than prediction.

Good agreement of data with MC setups

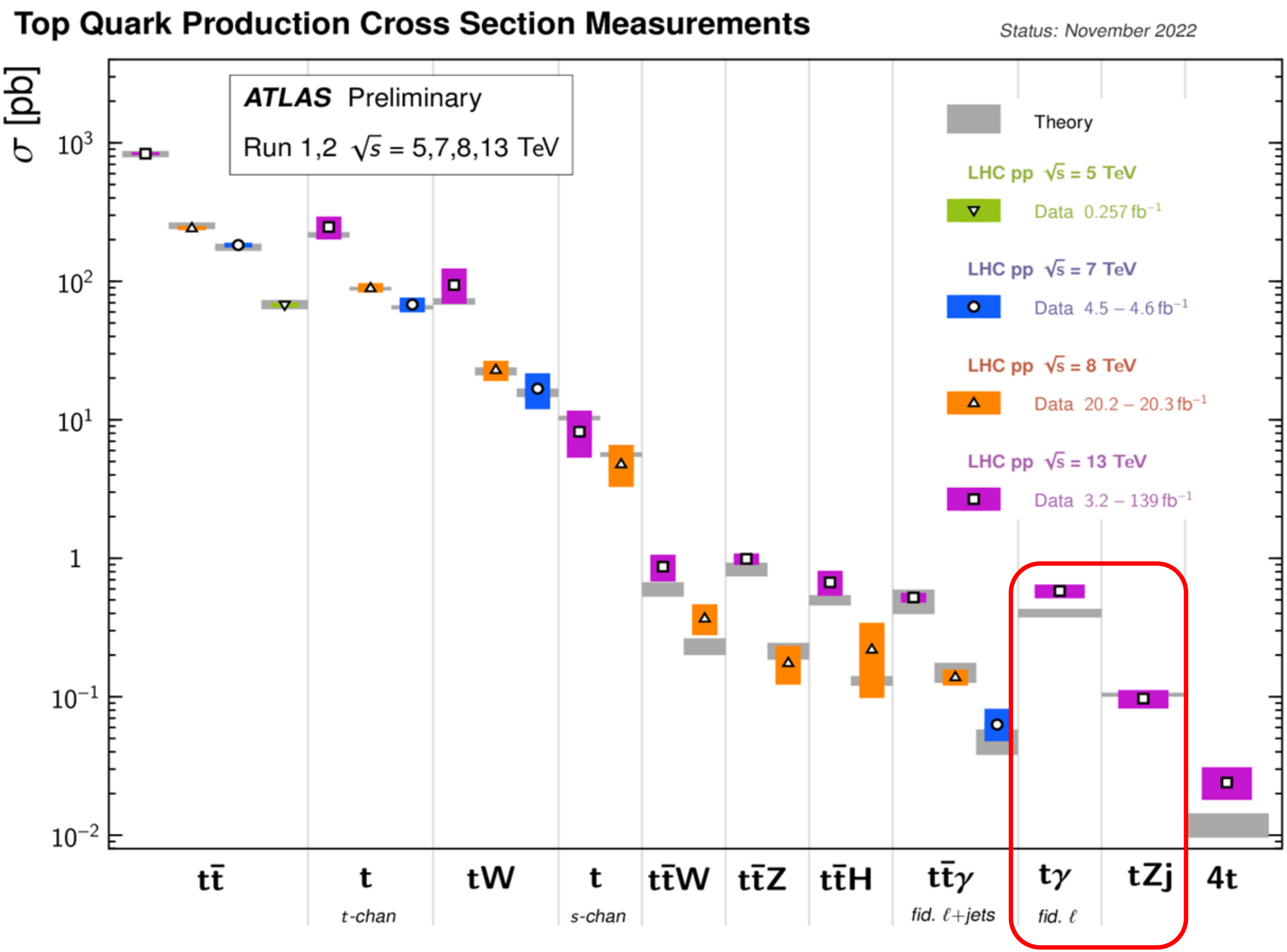
tt+X summary



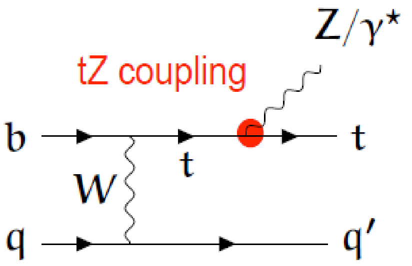
Sreelakshmi Sindhu: New results on ttW and 4-top production with the ATLAS experiment

Tae Jeong Kim: Top quark pair + heavy-flavor production at the LHC

t + X production



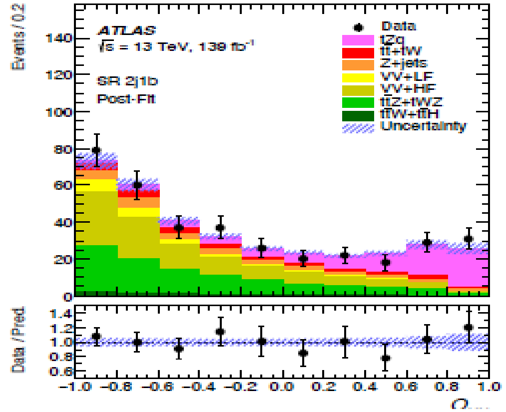
tZq production



Z(ll)

blν

forward jet

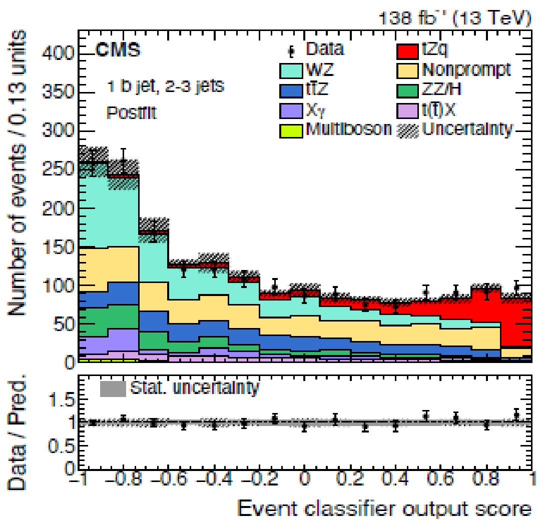


JHEP 07 (2020) 124

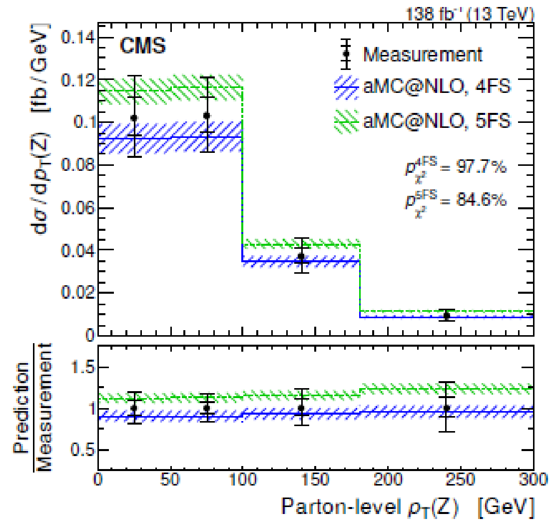
cross section measured with 14% uncertainty

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

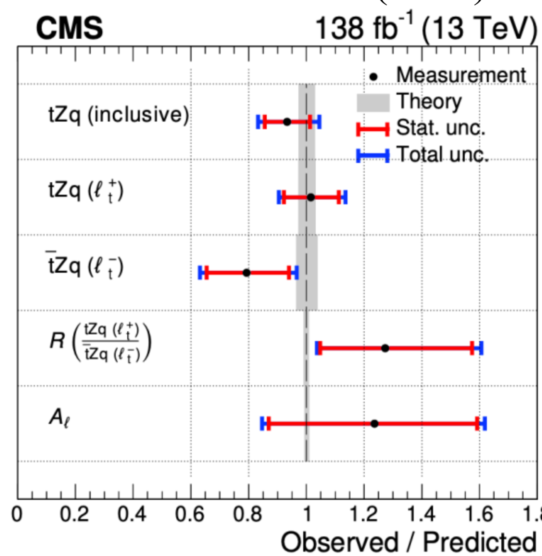
JHEP 02 (2022) 107



11% cross section uncertainty



first parton and particle level differential measurements



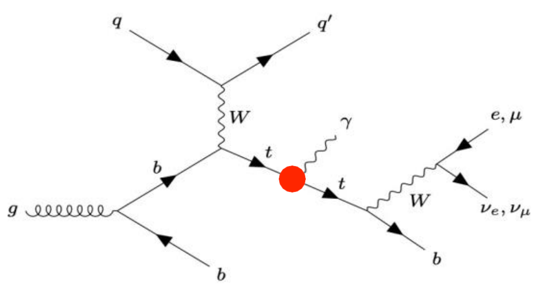
first measurement of ratio

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

Precision is expected to improve with more statistics in Run 3

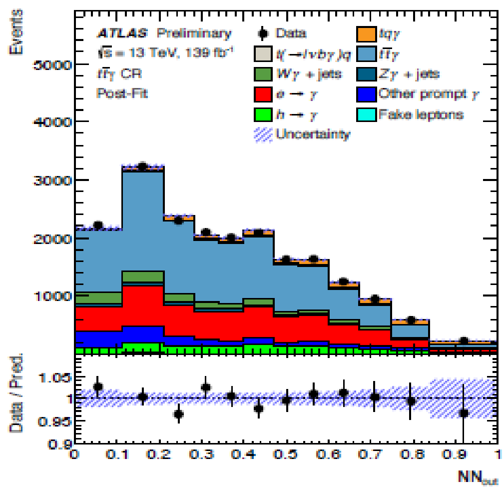
tqγ production

arXiv:2302.01283
Submitted to PRL

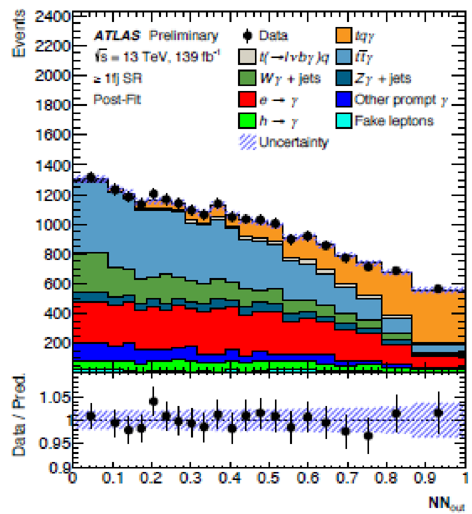


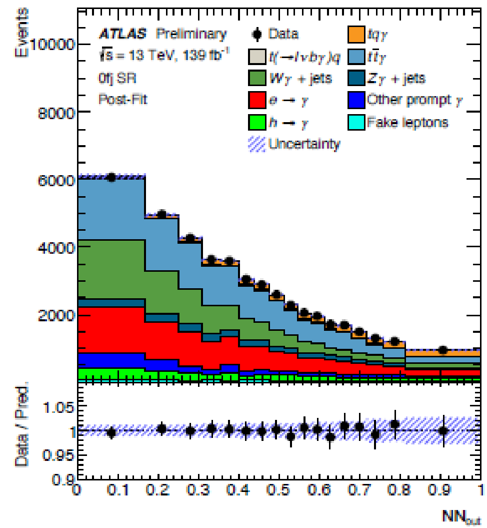
- ✓ **First evidence from CMS using ~36/fb of data**
- ✓ **New ATLAS analysis with full run 2 data**

Largest background from ttγ



Signal regions (NN)





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

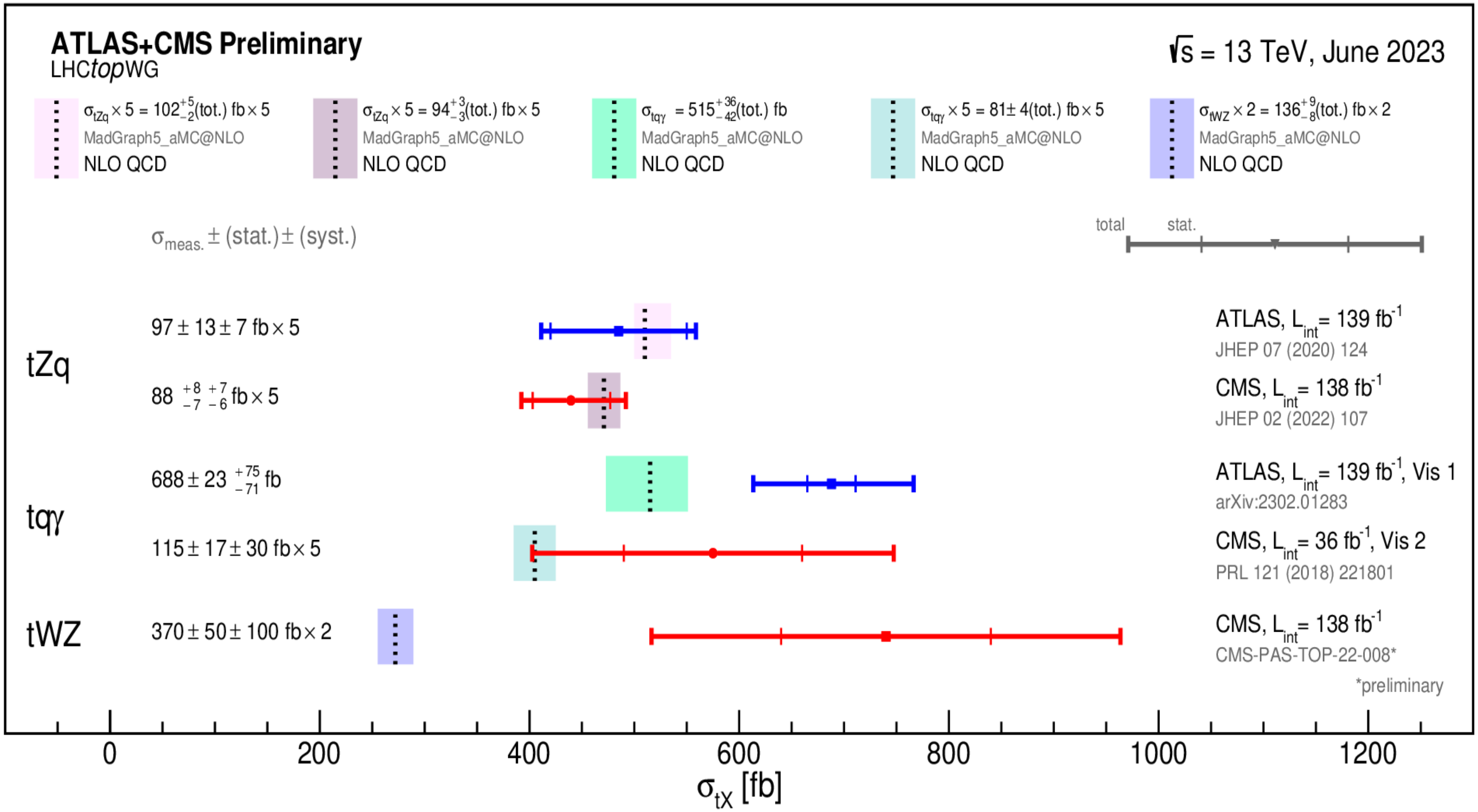
~40% higher that prediction

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

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

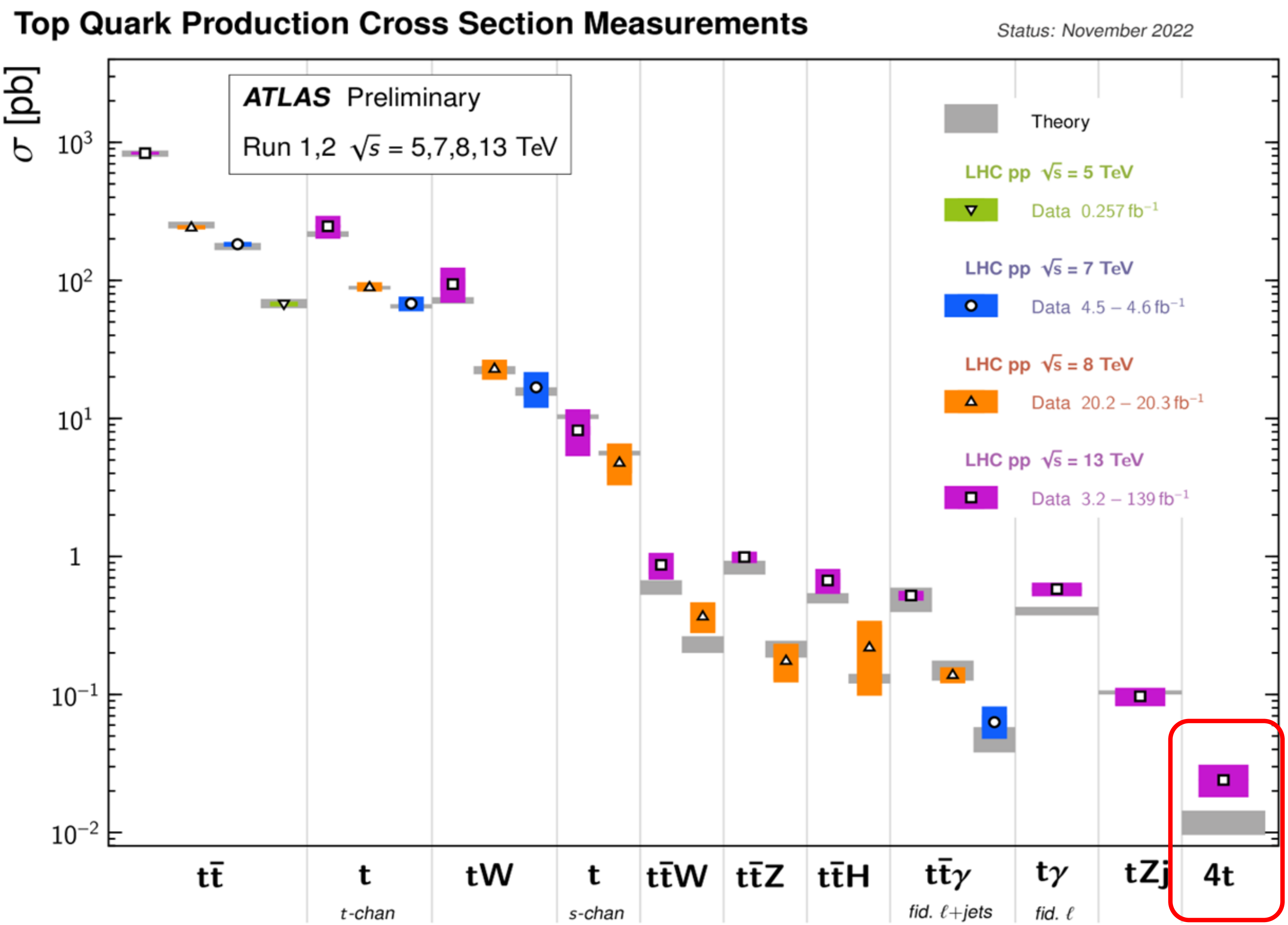
Compatible with the SM within 2.5(1.9)σ at parton(particle) level

t+X summary

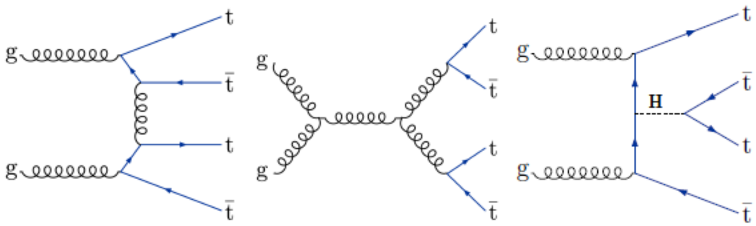


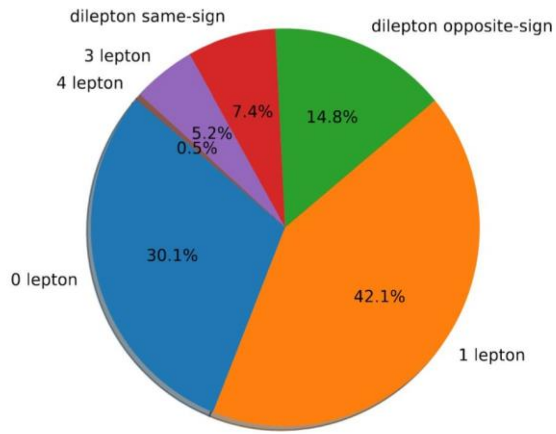
ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, June 2023
σtZq × 5 = 102 +5 −2 (tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtZq × 5 = 94 +3 −3 (tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtqγ = 515 +36 −42 (tot.) fb
MadGraph5_aMC@NLO
NLO QCD
σtqγ × 5 = 81± 4(tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtWZ × 2 = 136 +9 −8 (tot.) fb × 2
MadGraph5_aMC@NLO
NLO QCD
σmeas. ± (stat.) ± (syst.)
total
stat.
tZq
97 ± 13 ± 7 fb × 5
ATLAS, Lint = 139 fb-1
JHEP 07 (2020) 124
88 +8 −7 +7 −6 fb × 5
CMS, Lint = 138 fb-1
JHEP 02 (2022) 107
tqγ
688 ± 23 +75 −71 fb
ATLAS, Lint = 139 fb-1, Vis 1
arXiv:2302.01283
115 ± 17 ± 30 fb × 5
CMS, Lint = 36 fb-1, Vis 2
PRL 121 (2018) 221801
tWZ
370 ± 50 ± 100 fb × 2
CMS, Lint = 138 fb-1
CMS-PAS-TOP-22-008*
*preliminary
0
200
400
600
800
1000
1200
σtX [fb]

4-top production



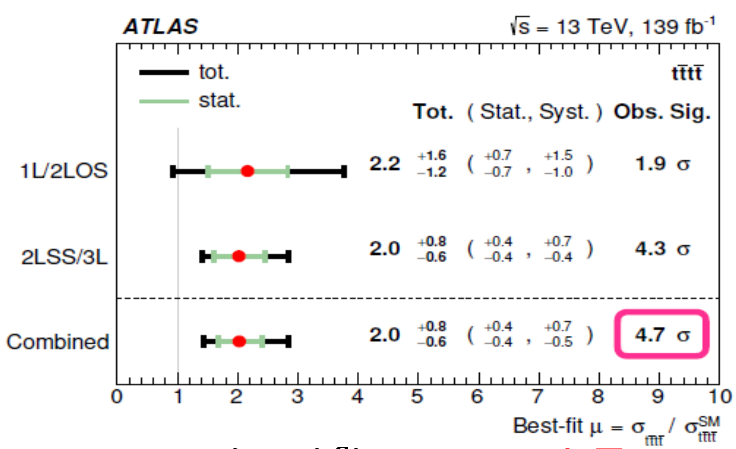
4-top searches



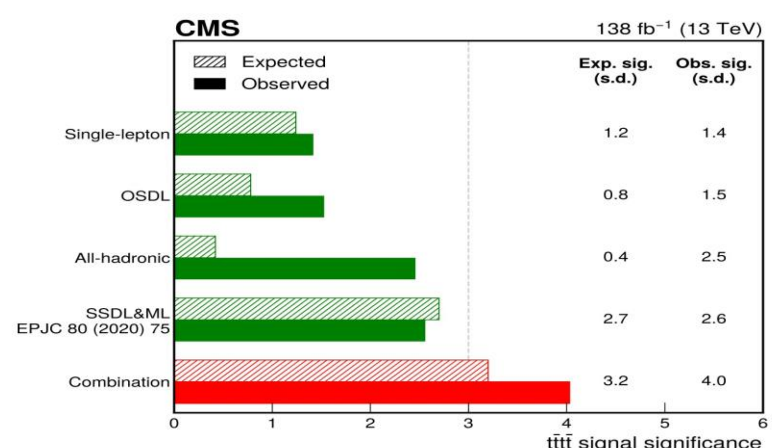


- ✓ Very rare production in SM
- ✓ Heaviest particle final state
- ✓ Many different final states
- ✓ Sensitivity to the top quark Yukawa coupling
- ✓ Important input to effective field theory interpretations

Evidences from both experiments!



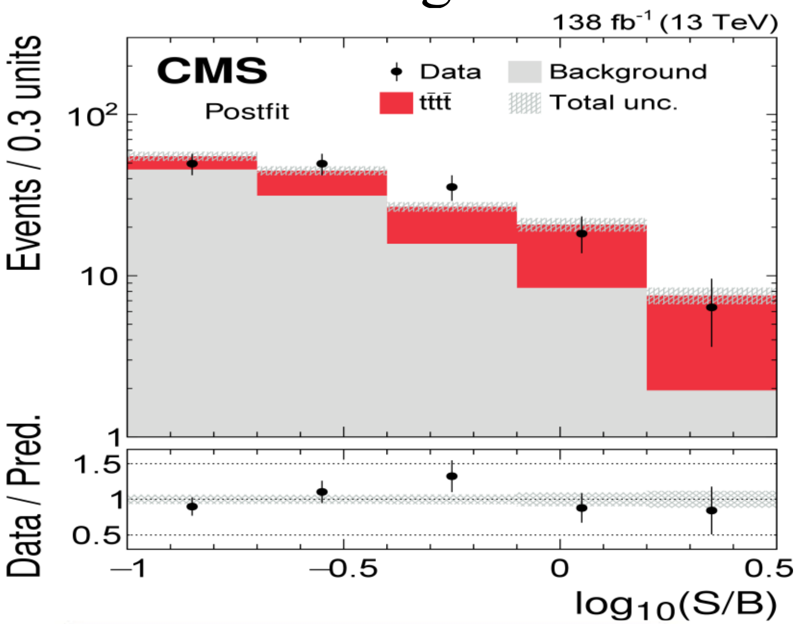
significance: 4.7σ

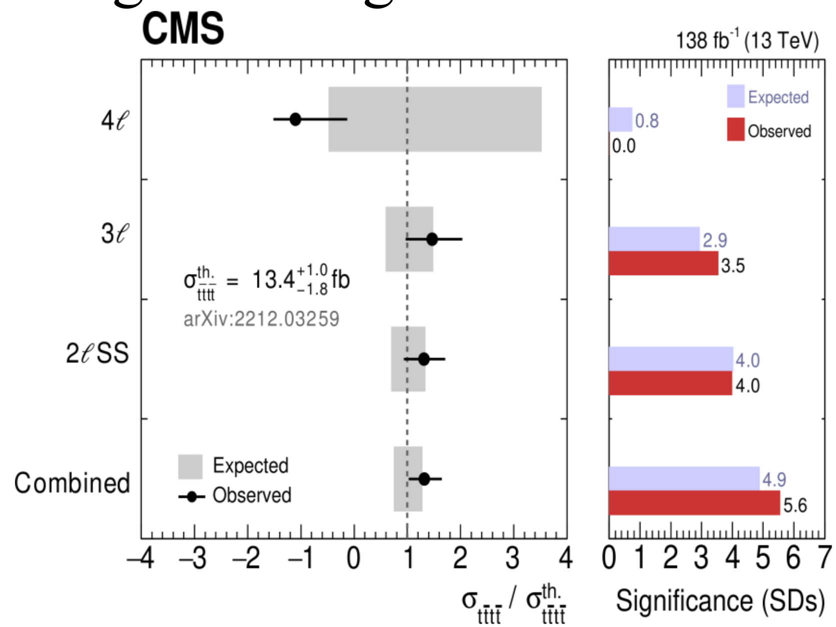


significance: 4.0σ

Observation of 4-top productions: CMS

- ✓ Re-analyze/re-optimize the analysis of full Run-2 data in same-sign 2ℓ, 3ℓ, 4ℓ channels.
- ✓ Simultaneous binned profile likelihood fit to signal & control regions to extract the signal strength.





$\sigma_{t\bar{t}t\bar{t}} = 17.9^{+3.7}_{-3.5}\,(\text{stat})^{+2.4}_{-2.1}\,(\text{syst})$ fb

Prediction: $\sigma_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8}$ fb

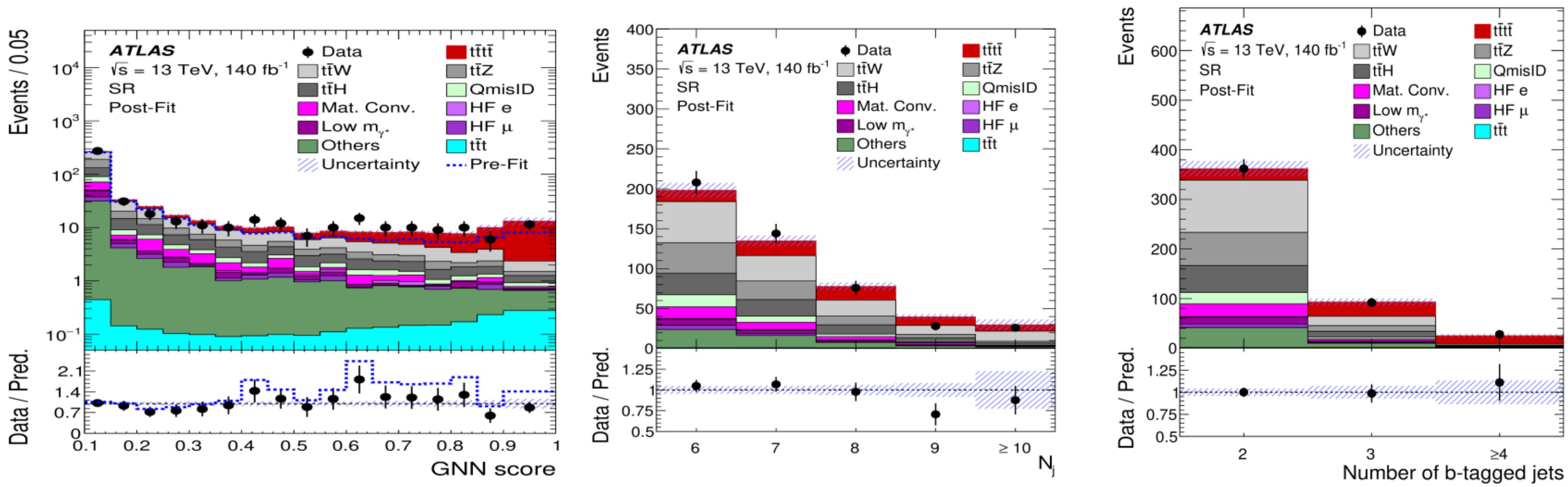
arXiv:2305.13439
Submitted to PLB

- ✓ **Significance: 5.5σ (obs) / 4.9σ (exp)**
- ✓ Slightly larger than prediction, but still compatible.

Observation of 4-top productions: ATLAS

- ✓ Same-sign 2ℓ & 3ℓ, ≥6 jets, ≥2 b-jets.
- ✓ Graph Neural Network (GNN) trained to separate signal from background.
- ✓ Signal extraction by simultaneous fits to GNN scores in signal and control regions

Also gives the first limits on 3-tops:
$\sigma(t\bar{t}t) < 41$ fb
$\sigma(t\bar{t}tW) < 30$ fb
$\sigma(t\bar{t}tq) < 100$ fb
@ 95% CL, $\mu(4t) = 1.9$



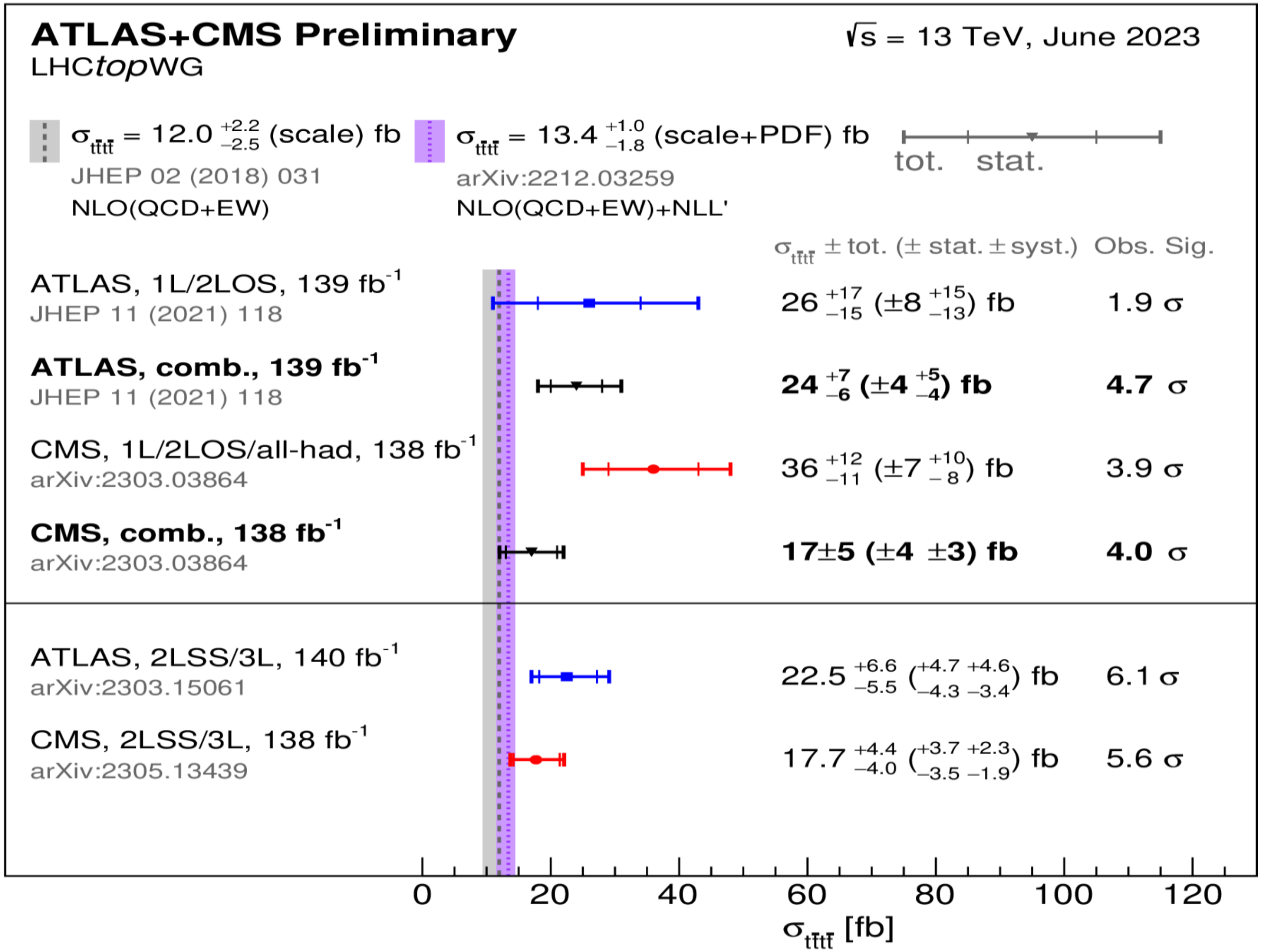
- ✓ **Significance: 6.1σ (obs) / 4.3σ (exp)**
- ✓ Compatible with SM prediction within 1.9σ

Signal strength: $\mu = 1.9 \pm 0.4\,(\text{stat})^{+0.7}_{-0.4}\,(\text{syst})$

$\Rightarrow \sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.6}$ fb

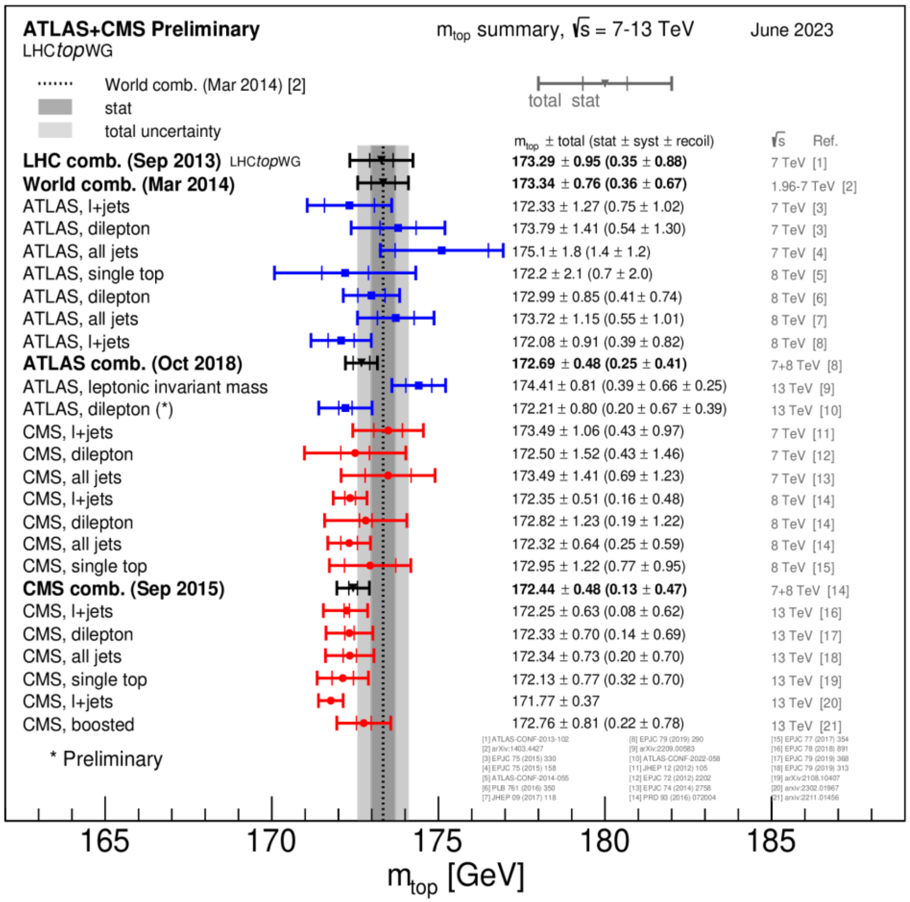
EPJC 83 (2023) 496

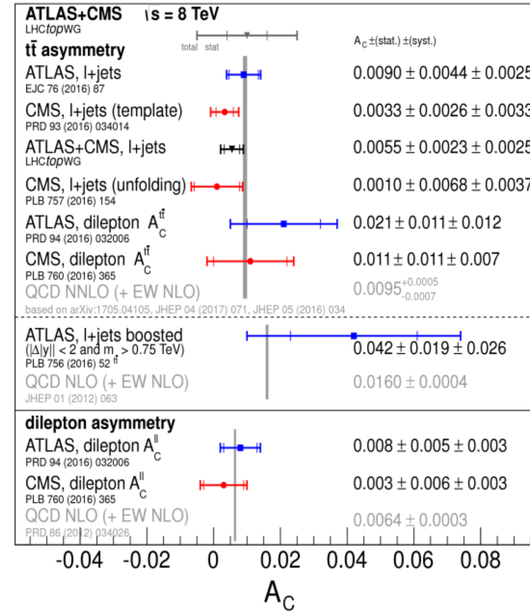
4-tops summary



Top quark properties

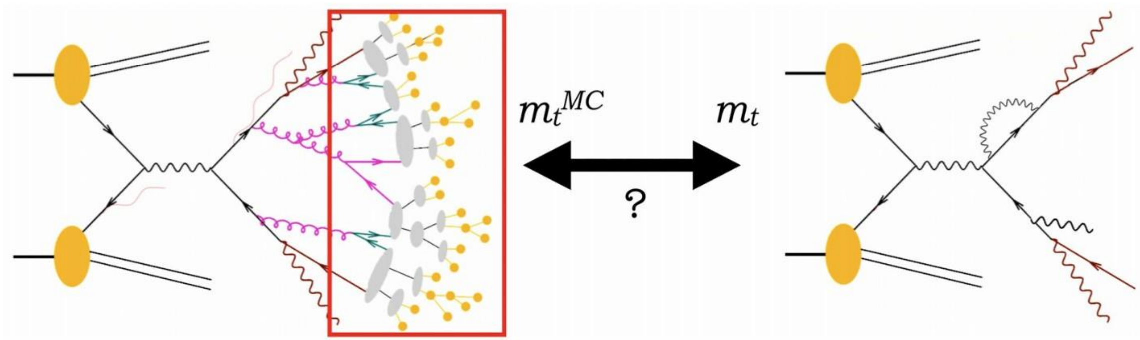
- ✓ Now at LHC is possible to reach un-precedent precisions for the property measurements
- ✓ Now measured not only in ttbar but also in single top and tt+X events

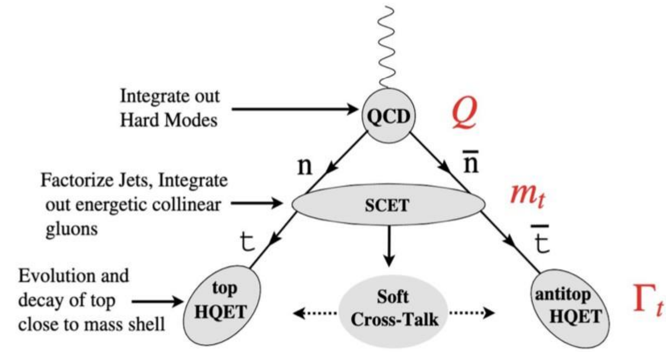




Top mass
Top spin
Top polarisation
Asymmetries
B-fragmentation
Color reconnection
CP properties………

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

Indirect

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

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

"Third"

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

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

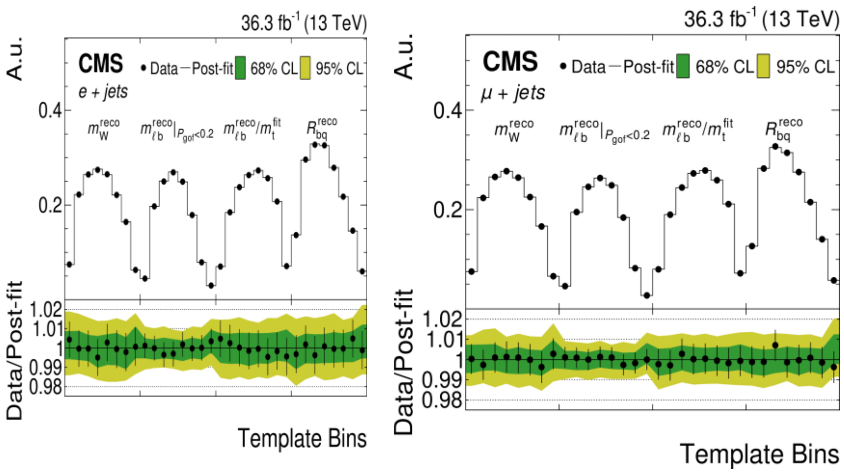
- ATLAS+CMS: m_t pole from combined σ_{tt} 7+8 TeV
- CMS: from tt+1j invariant mass
- CMS: : m_t running @NNLO revisited

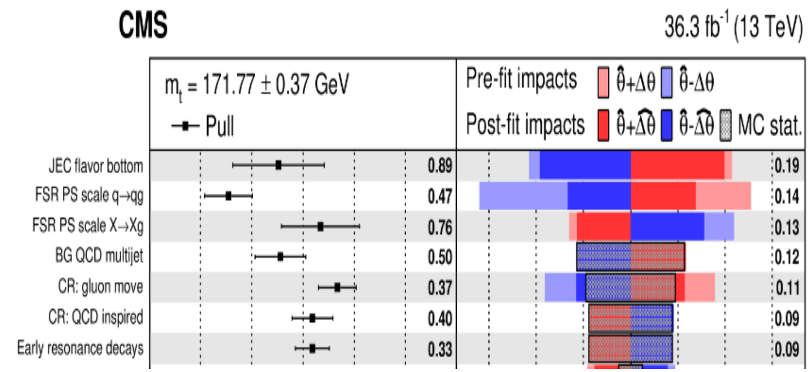
- CMS: top mass from boosted jet mass

CMS measurements

arXiv:2302.01967
Submitted to EPJC

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

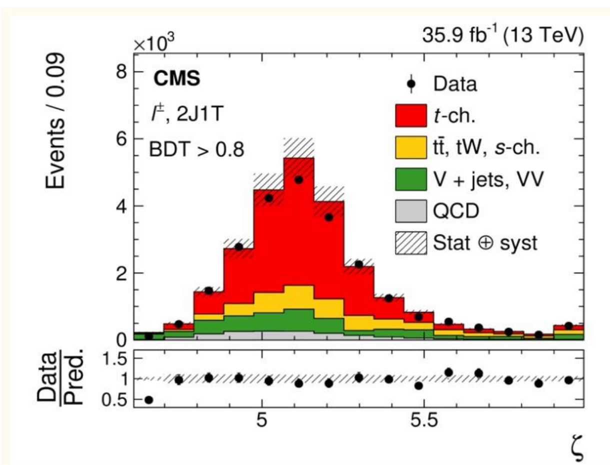




- Significant pull and constraint of FSR PS scale q->qg due to m_W^{reco}

✓ Most precise measurement with 0.37 GeV uncertainty

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



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

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

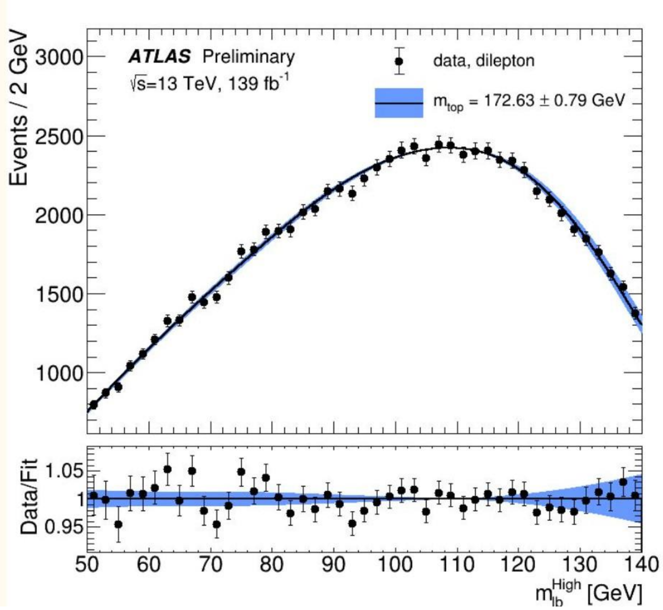
$$\Delta m_t = m_t - m_{\bar{t}} = 0.83^{+1.79}_{-1.35}\text{ GeV}$$

JHEP 12 (2021) 161

ATLAS measurements

Template method (similar to 8 TeV)

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

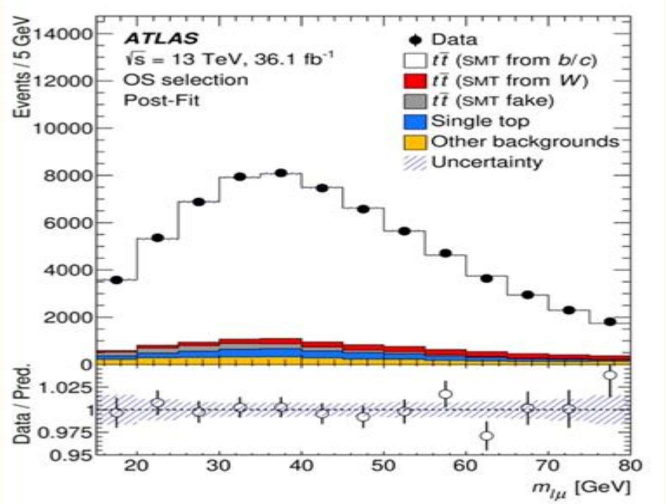


$$m_{top}^{dilepton} = 172.63 \pm 0.20\,(stat) \pm 0.67\,(syst) \pm 0.37\,(recoil)\ \text{GeV}$$

✓ 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

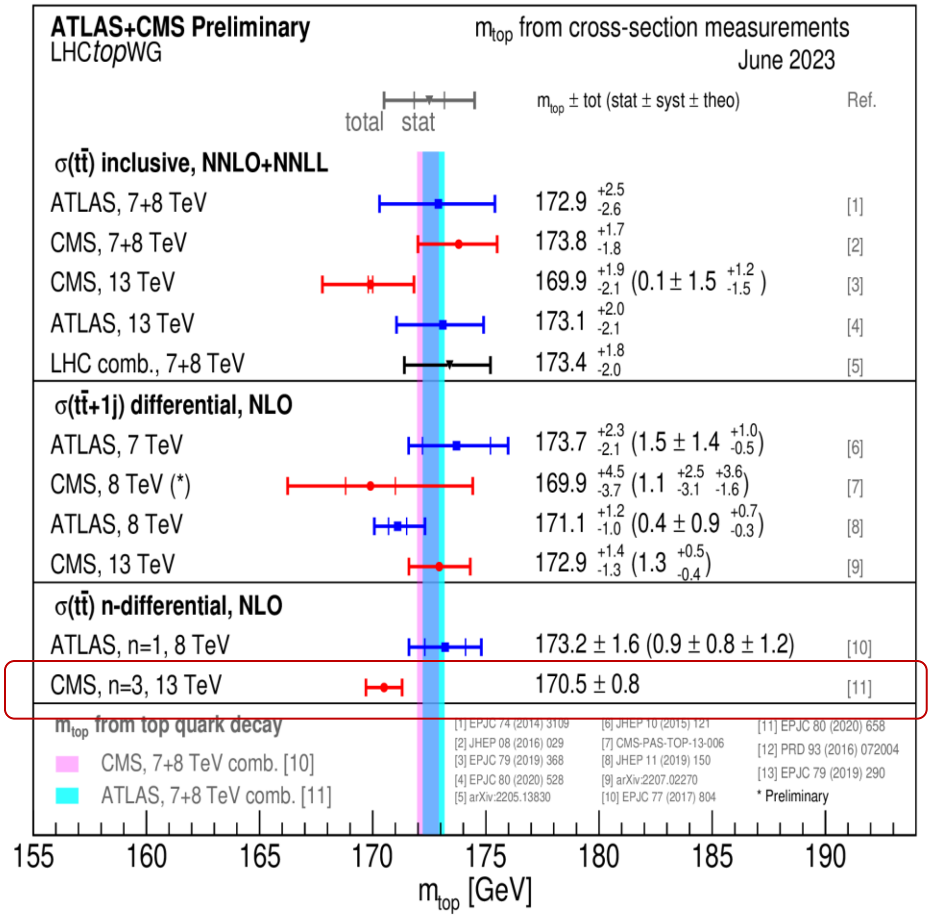
ATLAS-CONF-2022-058

JHEP 06 (2023) 019

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



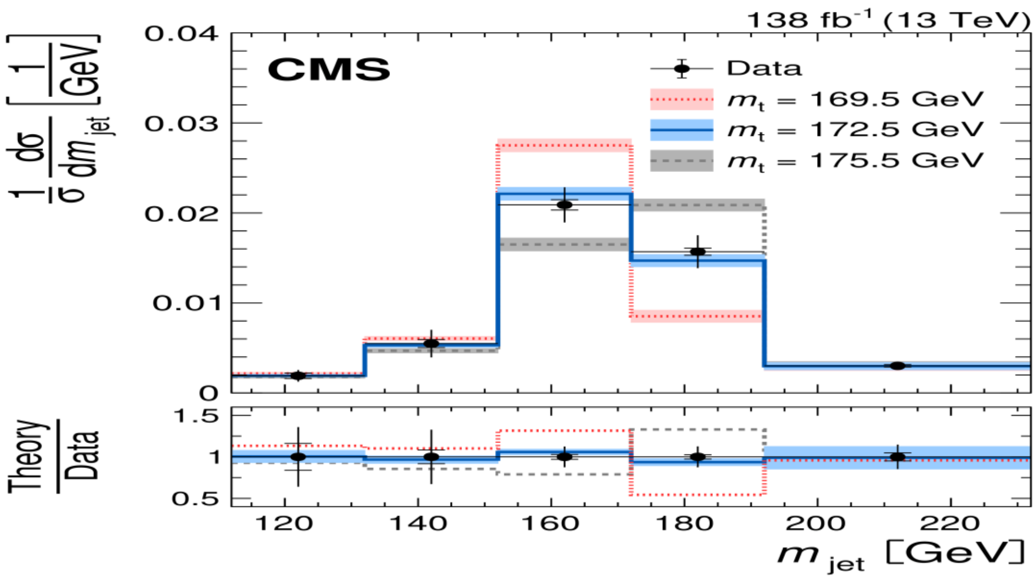
Theoretical advances needed
in order to obtain accurate and unambiguous results

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



EPJC 83 (2023) 560

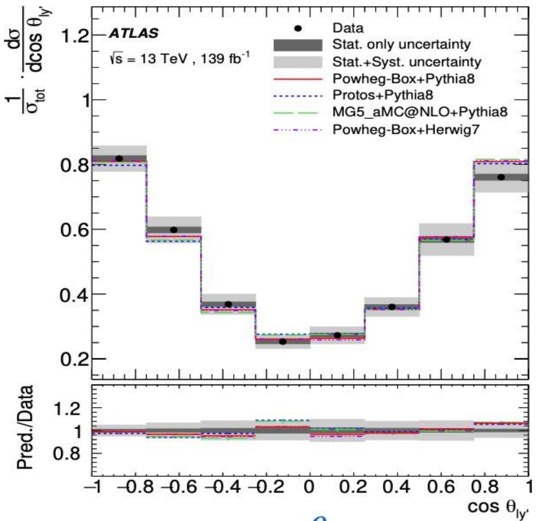
$$m_t = 172.76 \pm 0.22\,(\text{stat}) \pm 0.57\,(\text{exp}) \pm 0.48\,(\text{model}) \pm 0.24\,(\text{theo})\,\text{GeV} = 172.76 \pm 0.81\,\text{GeV}.$$

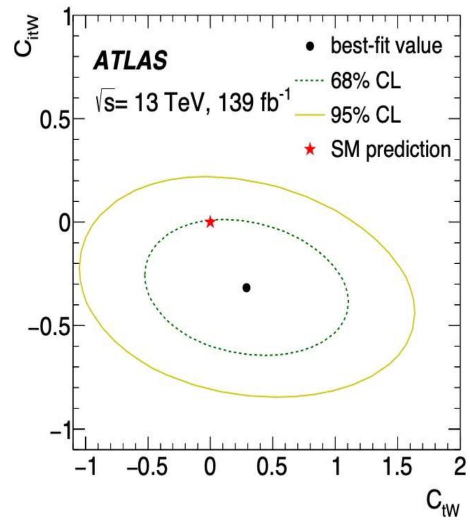
First top mass measurement in boosted regime.

Top polarisation

JHEP 11 (2022) 040

✓ Unfolded angular distributions to particle level compared to MC





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

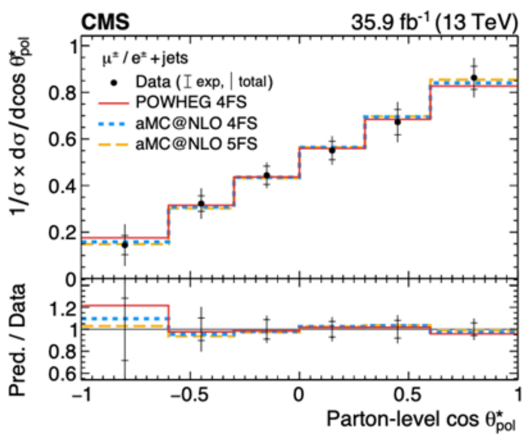
$\cos\theta_{ly'}$

✓ Spin asymmetry measurement

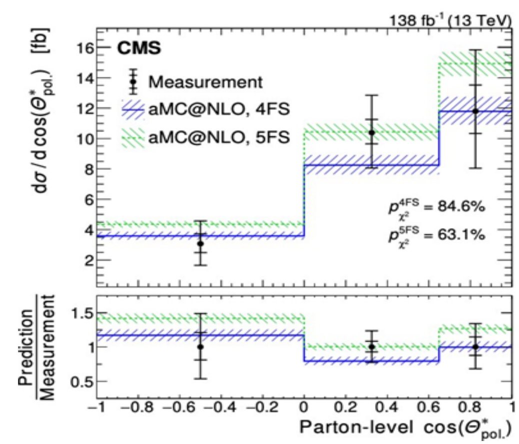
$$A_\ell = 0.440 \pm 0.031(\text{stat+exp}) \pm 0.062\,(\text{theo})$$

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

t-ch



Statistically dominated



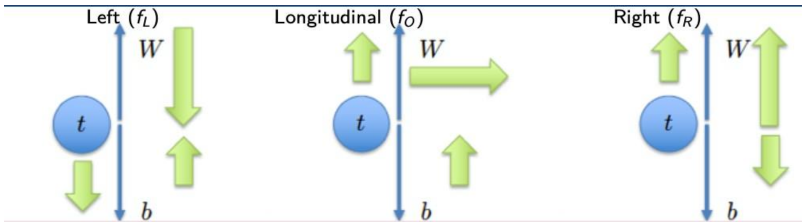
tZq

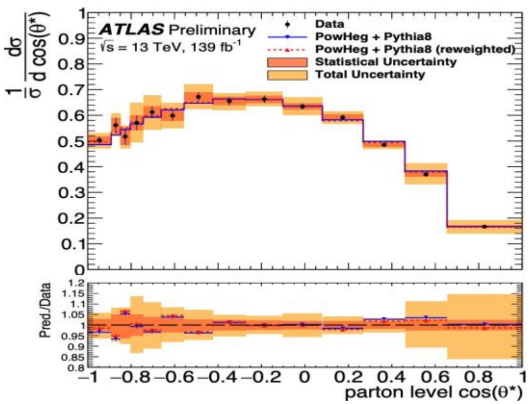
W polarization in top events

arXiv:2209.14903

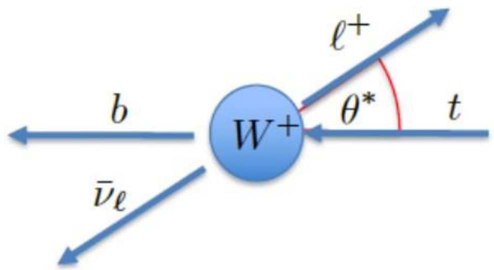
✓ Probe of Wtb vertex

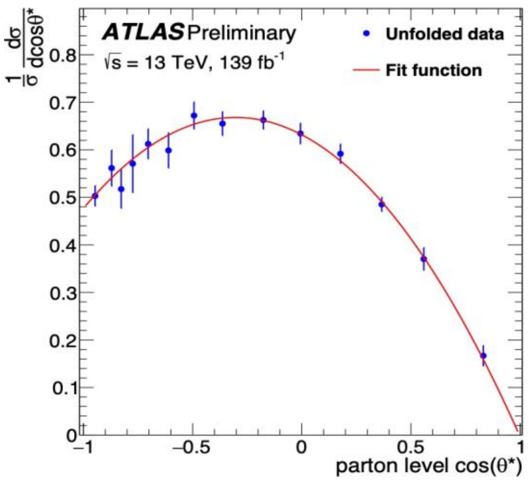
New method in dilepton channel: mesure absolute and normalised differential distributions in $\cos\theta^*$

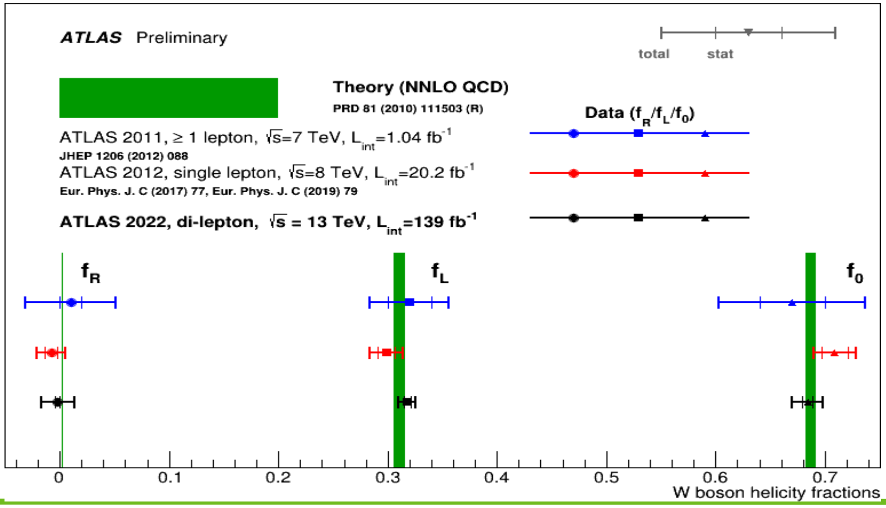




W rest frame







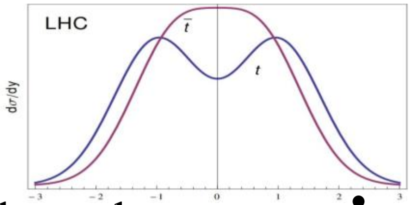
$$f_0 = \quad 0.684 \pm 0.015\ (\text{stat.} + \text{syst.})$$
$$f_L = \quad 0.318 \pm 0.008\ (\text{stat.} + \text{syst.})$$
$$f_R = -0.002 \pm 0.015\ (\text{stat.} + \text{syst.})$$

Systematically dominated

Charge asymmetry in tt

arXiv:2208.02751 | arXiv:2208.12095

- ✓ Central-forward in ttbar events
- ✓ No asymmetry at LO
- ✓ Higher order effects in $q\bar{q} \rightarrow t\ t$



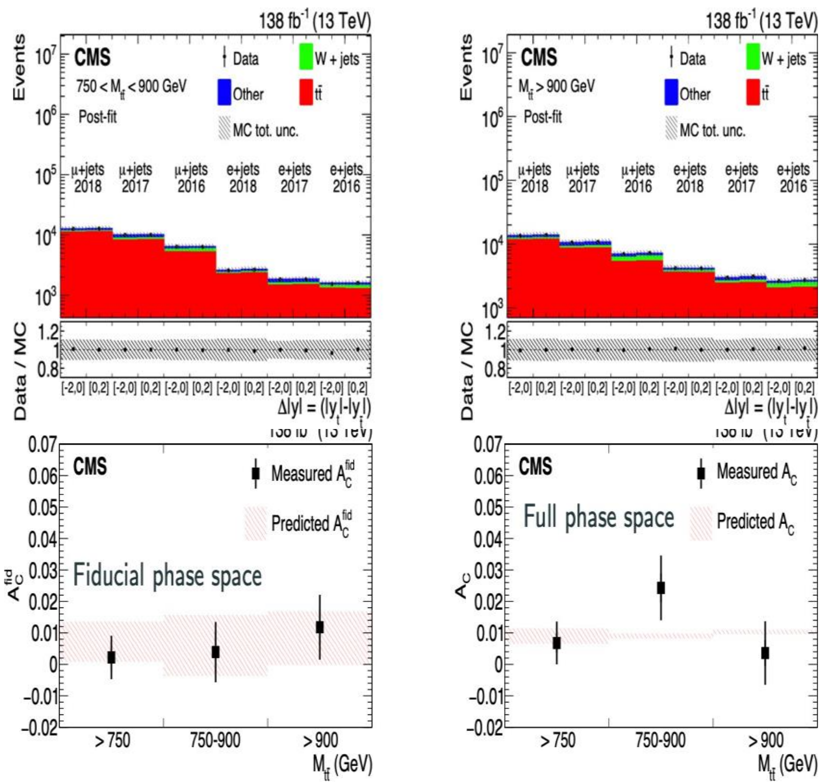
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

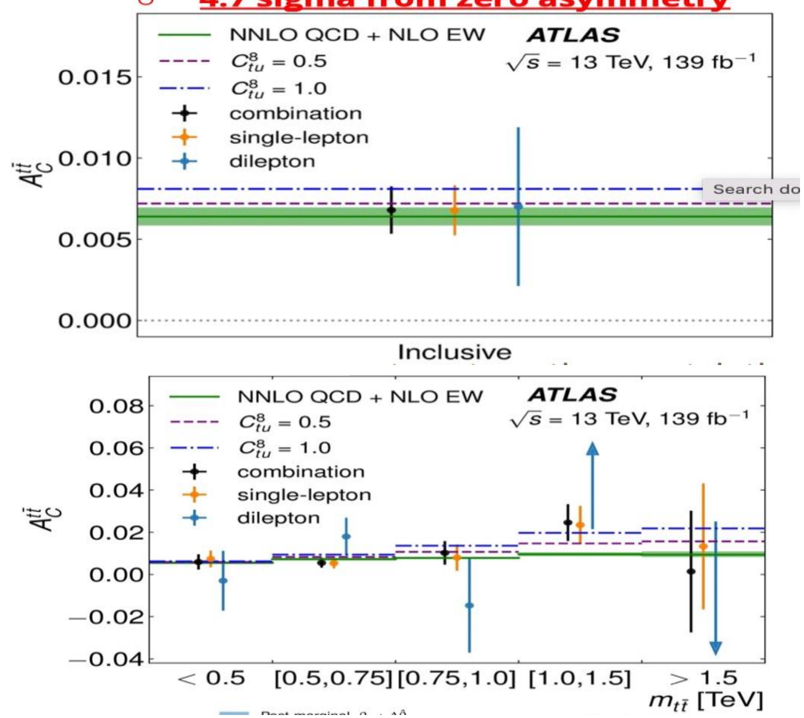
$(\Delta|y| = |y_t| - |y_{\bar{t}}|)$

- Boosted regime, single lepton channel
- two $M_{t\bar{t}}$ bins: [750, 900], [900, ∞]

- Single and dilepton channels
- Resolved and boosted regime

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





Good agreement with prediction

Expect improvement with additional data

Energy asymmetry in tt

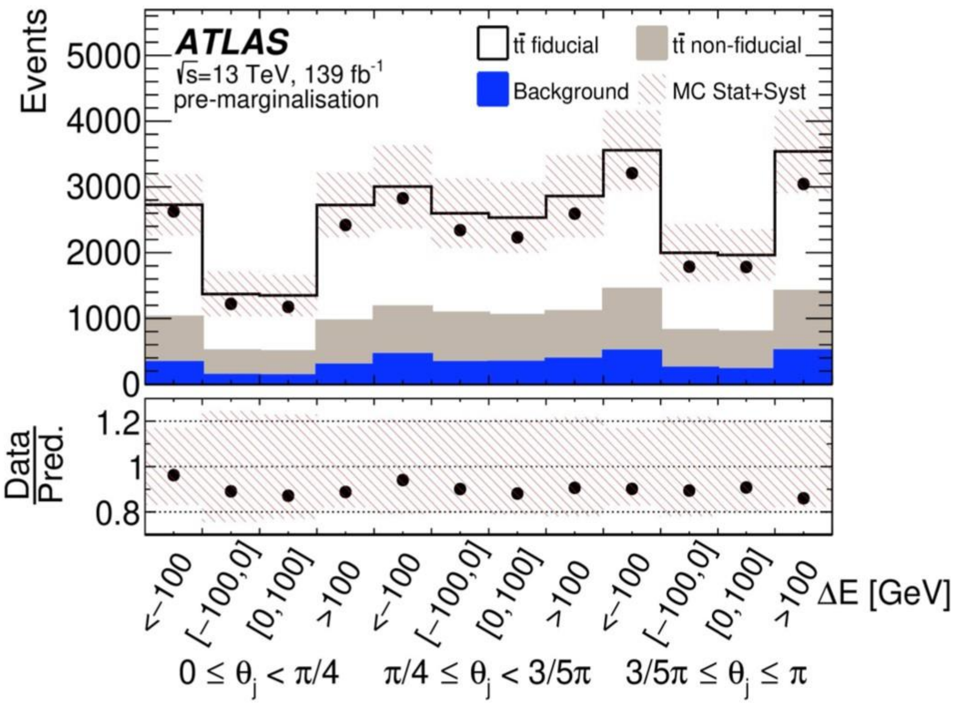
EPJC 82 (2022) 374

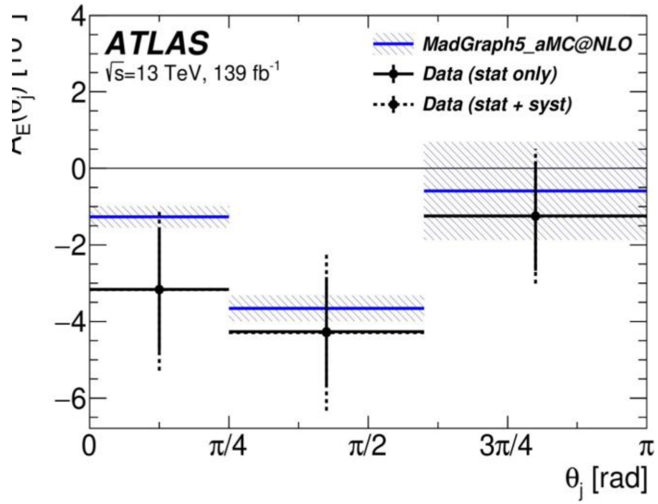
- ✓ Asymmetry between the energies of top and anti-top
- ✓ Measured in tt+j events in boosted regime

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

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

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



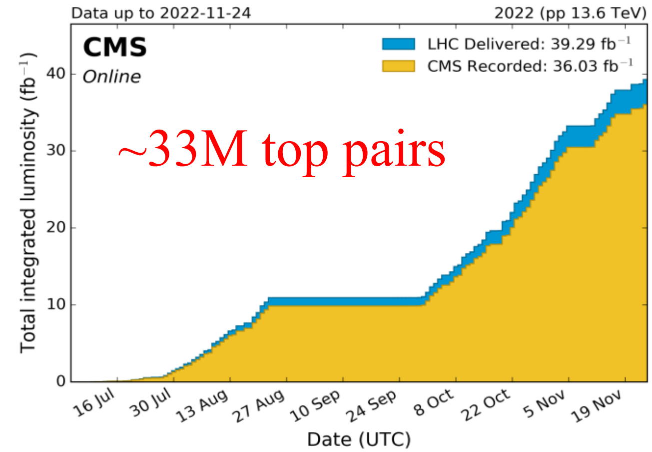


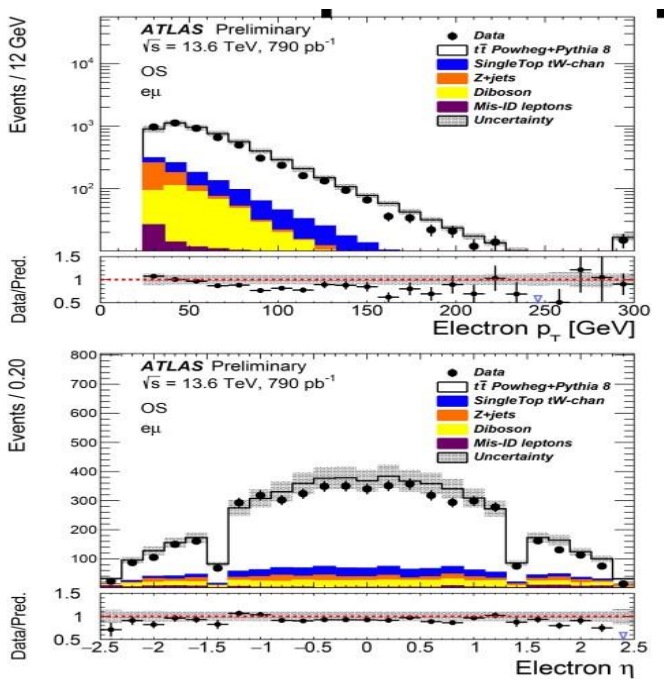
Agrees with prediction

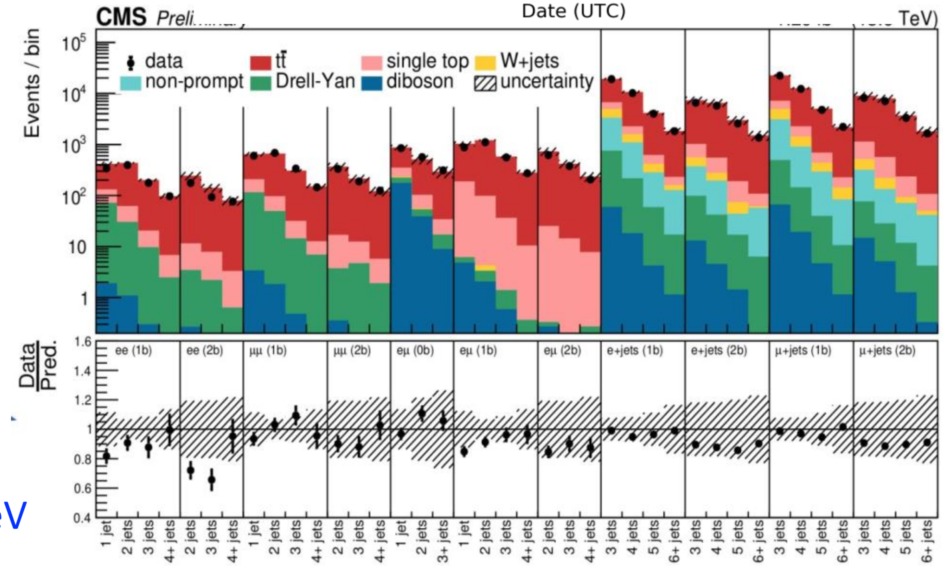
Statistically limited

Run3 started!

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







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

- ✓ 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

- ✓ ATLAS and CMS 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
- ✓ The very first look of the Run-3 data gives the results at the highest CM energy in record!
- ✓ 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