# Recent ATLAS and CMS results on top-quark physics

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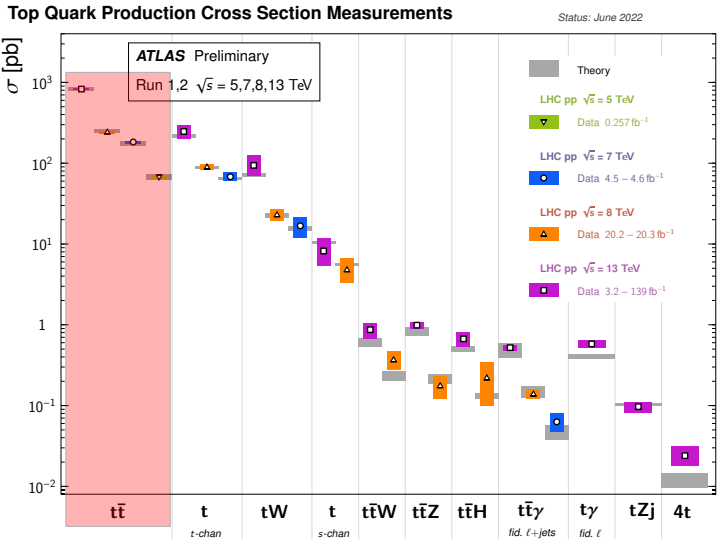
2022 LHC Days in Split



# Introduction

- Last LHC days conference happened at the end of Run 2 and many Top results were published since then...
- ...it is not possible to cover everything.
- Last month we had the **TOP quark 2022 conference**, where a significant number of new results were presented...
- ...focusing today on some of these "Hot off the press" results.
- Further analysis will be covered by **Jiri** and **Kerem**, particularly on BSM searches, which is not covered here.

# $t\bar{t}$ production



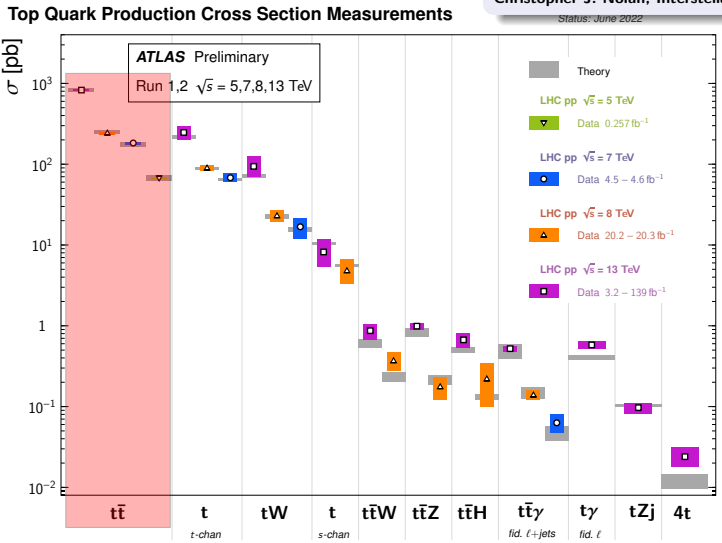

- CMS
  - Mass with profile likelihood approach: $\ell$+jets.
  - $\sqrt{s}$ =5.02 TeV inclusive cross-section.
  - Differencial cross-section with additional jets.
  - Charge asymmetry in 1$\ell$ boosted events.
  - Differencial cross-section $\ell$+jets.
  - Mass in boosted hadronic events.
  - Top pole mass in $t\bar{t}$+jets.
- ATLAS
  - Mass with template method: di-lepton.
  - $\sqrt{s}$ =5.02 TeV inclusive cross-section.
  - Polarization of W bosons in dilepton events.
  - Differencial cross-section dilepton.
  - Cross-section in boosted $\ell$+jets events.
  - Cross-section in boosted hadronic events.
  - Color reconnection sensitive measurement.
- Combination
  - $\sqrt{s}$ =7 and 8 TeV inclusive cross-section.

If unspecified, the results shown are for $\sqrt{s}$ =13 TeV $pp$ colisions.

# $t\bar{t}$ production

"Newton's third law

The only way humans have ever figured out of getting somewhere is to leave something behind."
**Christopher J. Nolan, Interstellar: The Complete Screenplay With Selected Storyboards**

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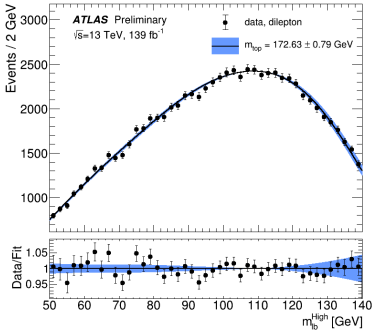
# ATLAS latest top quark mass measurement

ATLAS-CONF-2022-058

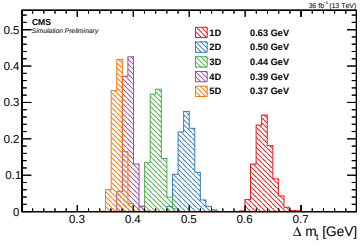



- Analysis on di-lepton events in full Run-2 dataset.
- DNN for assignment for $\ell - b$ pair: the one with largest DNN score.
- $m_{\ell b}^{\mathrm{High}}$: $\mathrm{DNN}^{\mathrm{High}} > 0.65$ & $p_{\mathrm{T}}^{\ell b} > 160$ GeV & $b$ is leading b-jet.
- Unbinned maximum-likelihood fit to data for $m_{\ell b}^{\mathrm{High}}$.
- Uncertainty dominated by JES, matrix element matching, color reconnection and the recoil effect on top quark decay (new).

$$m_{\mathrm{top}} = 172.63 \pm 0.20(\mathrm{stat}) \pm 0.67(\mathrm{syst}) \pm 0.37(\mathrm{Recoil})\ \mathrm{GeV}.$$

# CMS latest top quark mass measurement

CMS-PAS-TOP-20-008: $\ell$+jets




| histogram | | set label | | | | |
|---|---|---|---|---|---|---|
| observable | category | 1D | 2D | 3D | 4D | 5D |
| $m_{\mathrm{t}}^{\mathrm{fit}}$ | $P_{\mathrm{gof}} \geq 0.2$ | x | x | x | x | x |
| $m_{\mathrm{W}}^{\mathrm{reco}}$ | $P_{\mathrm{gof}} \geq 0.2$ | | x | x | x | x |
| $m_{\ell\mathrm{b}}^{\mathrm{reco}}$ | $P_{\mathrm{gof}} < 0.2$ | | | x | x | x |
| $m_{\ell\mathrm{b}}^{\mathrm{reco}} / m_{\mathrm{t}}^{\mathrm{fit}}$ | $P_{\mathrm{gof}} \geq 0.2$ | | | | x | x |
| $R_{\mathrm{bq}}^{\mathrm{reco}}$ | $P_{\mathrm{gof}} \geq 0.2$ | | | | | x |

- Analysis on $\ell$+jets on 2016 data (36 fb$^{-1}$).
- Maximize goodness-of-fit probability, $P_{\mathrm{gof}} = \exp(-\frac{1}{2}\chi^2)$, for jet-parton assignment in $2 \times 2$ permutations.
- Profile maximum-likelihood fit applied to up to 5 observables to extract top mass.
- Uncertainty dominated by b-jet energy calibration, final state radiation and color reconnection.
- $m_{\mathrm{top}} = 171.77 \pm 0.38$ GeV.

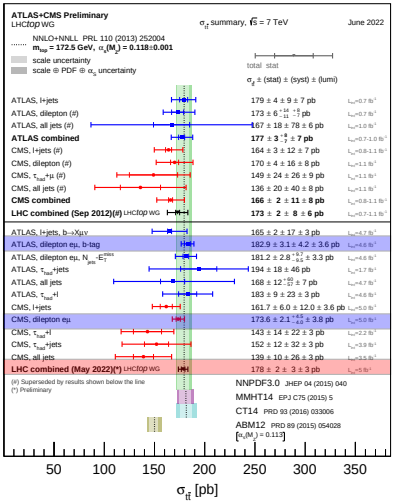
# ATLAS + CMS combination $t\bar{t}$ cross-section for $\sqrt{s}$ =7 and 8 TeV in $e\mu$ channel

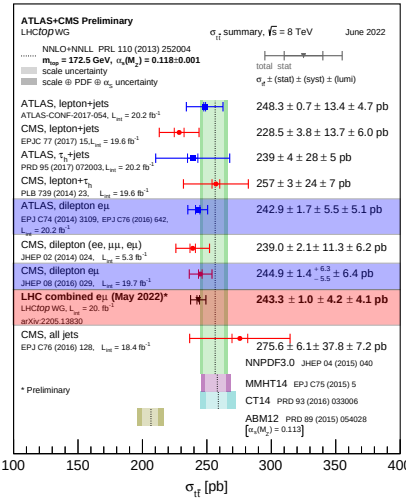
arXiv:2205.13830

7 TeV

## LHC top WG Summary plots

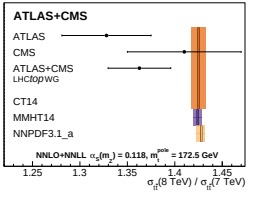
8 TeV

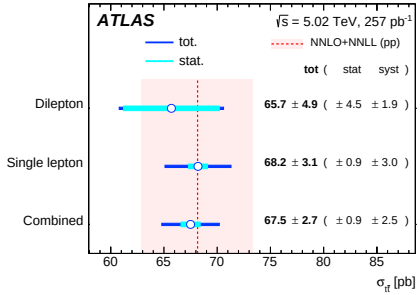


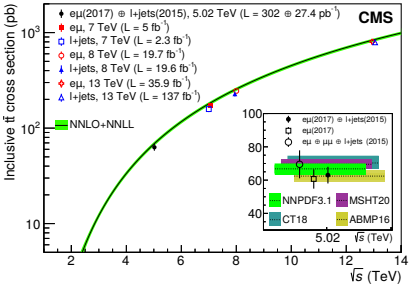




- Uncertainty after combining dominated by luminosity.
- The cross section ratio between the two years is compatible with SM.

$$R_{8/7} = 1.363 \pm 0.015(\text{stat.}) \pm 0.028(\text{syst.})$$



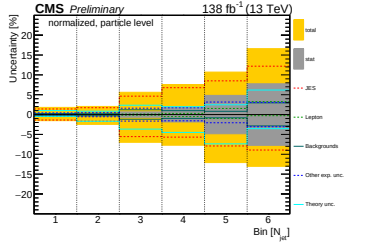


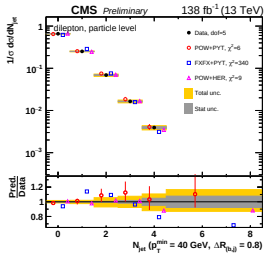



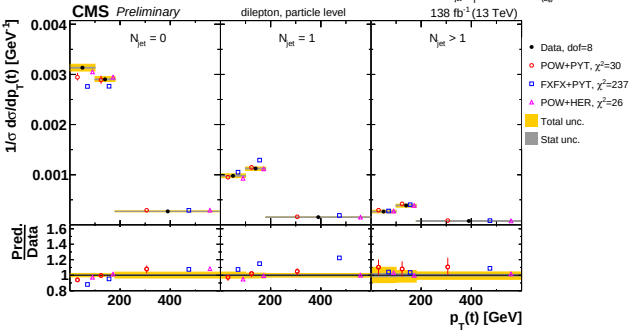

- $\ell$+jets + $ee/\mu\mu/e\mu$
- $\sigma_{t\bar{t}} = 67.5 \pm 2.7$ pb
- Uncertainty dominated by V+jets modelling in $\ell$+jets.

- $e\mu$ (2017) + $\mu\mu/e\mu$ + $\ell$+jets (2015)
- $\sigma_{t\bar{t}} = 63.0 \pm 5.1$ pb
- Uncertainty dominated by jets energy scale and resolution.

Compatible with SM prediction: $\sigma_{t\bar{t}} = 66.8 \pm 3.1$ pb




## CMS-PAS-TOP-20-006

- Uncertainty dominated by JES.
- Combined di-lepton analysis: $ee$, $e\mu$, $\mu\mu$.
- Single-/Multi-differencial $\sigma$.
- At parton and particle level.
- Obtain for several variables:
  - number of jets.
  - $y_t$ and $y_{t\bar{t}}$.
  - $\eta_t$ and $\eta_{t\bar{t}}$.
  - $p_{\mathrm{T,t}}$, $p_{\mathrm{T,\bar{t}}}$ and $p_{\mathrm{T,t\bar{t}}}$.
  - $p_{\mathrm{T},\ell\ell}$, $\eta_{\ell\ell}$ and $m_{\ell\ell}$.
  - $m_{b\bar{b}}$ and $m_{\ell\ell b\bar{b}}$.
  - ...
  - See backup 3D differencial: $\left[N_{\mathrm{jet}}^{0,1,2,3+} \times m(t\bar{t}) \times |y(t\bar{t})|\right]$.

# W-bosons polarization in di-lepton events

ATLAS-CONF-2022-063

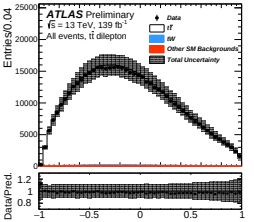
- Analysis combining $ee/\mu\mu/e\mu$ events.
- The Neutrino Weighting method used to reconstruct the top and anti-top quarks.
- Extraction from $\cos\theta^*$: angle between $\ell$ and respective $b$ in $t \to b\ell\nu$ (W rest frame)

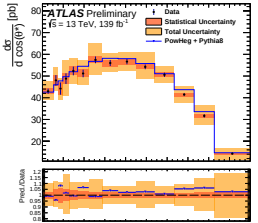
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) f_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 f_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 f_R$$

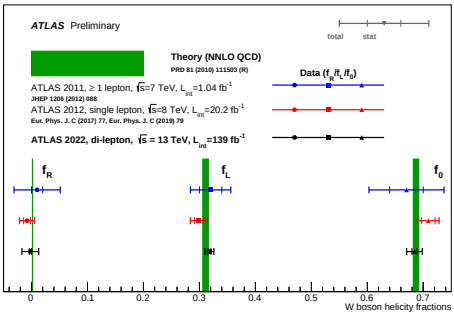
- Differential cross-section calculation:

$$\frac{d\sigma}{d\cos\theta^*} = \frac{1}{\mathfrak{L}\cdot\Delta X_i\cdot\epsilon_i^{\text{sel}}}\sum_j R_{ij}^{-1}\cdot\left(N_j^{obs} - N_j^{bkg}\right)$$

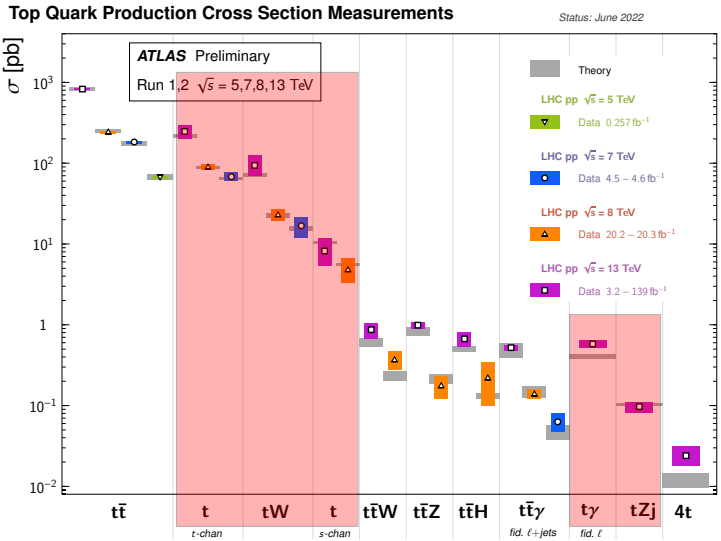
  - $R_{ij}$ is the migration matrix (backup) from reconstructed $\cos\theta^*$ to parton level.
- Uncertainty dominated by jet energy calibration and $t\bar{t}$ modelling.



# Single top and t+X production




- ATLAS
  - Single top cross-section in the s-channel **(link)**.
  - Polarization measurements of single top in t-channel (**link**).
  - Observation of $t\gamma$ in t-channel (**link**).
- CMS
  - Inclusive and differencial cross-section measurement in Wt-channel (**link**).
  - Charge asymmetry measurement in single top boosted events. (**link**)

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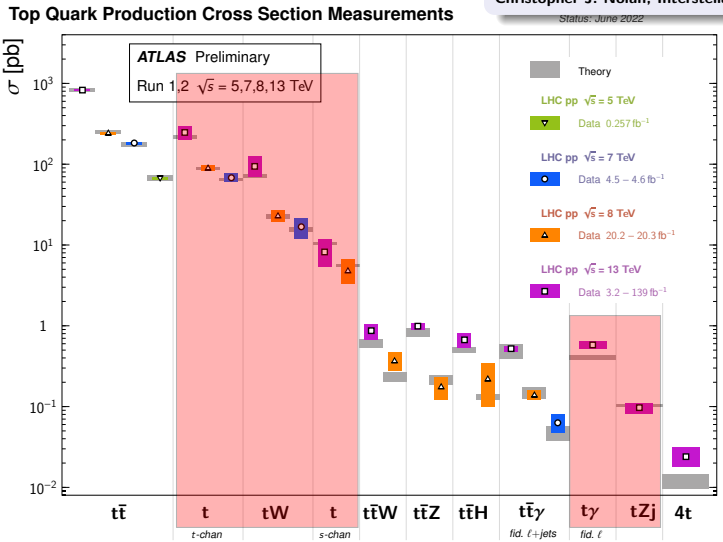


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  - Charge asymmetry boosted events. (**link**)

Newton's third law

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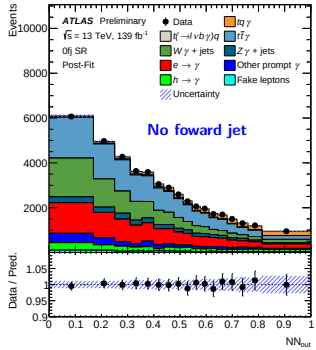
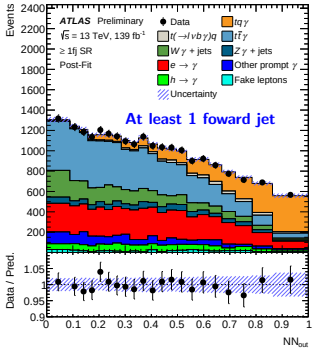
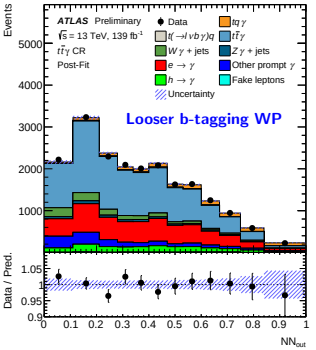
# Observation of $tq\gamma$ production

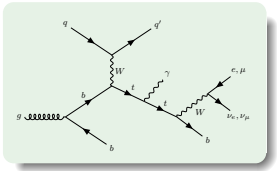
ATLAS-CONF-2022-013



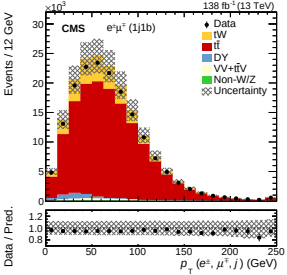



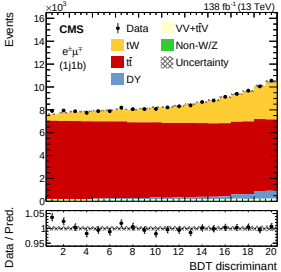

- Analysis with 1 electron or muon, 1 b-jet and 1 photon
- $\sigma(pp \to tq\gamma) \times \mathfrak{B}(t \to \ell\nu q) = 580 \pm 19(stat) \pm 63(syst)$ fb.
- The observed (expected) significance of $tq\gamma$ is $9.1\sigma(6.7\sigma)$.
- Agreement with SM prediction: $406^{+25}_{-32}$ fb.
- About 40% higher cross-section consistent with CMS results.
  - arXiv:1808.02913

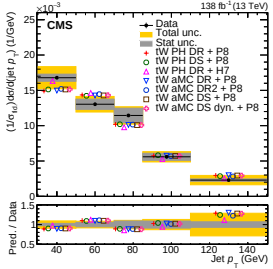


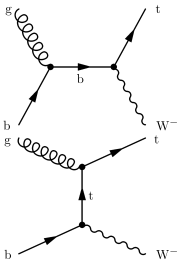
# Cross-section for single top tW channel

arXiv:2208.00924



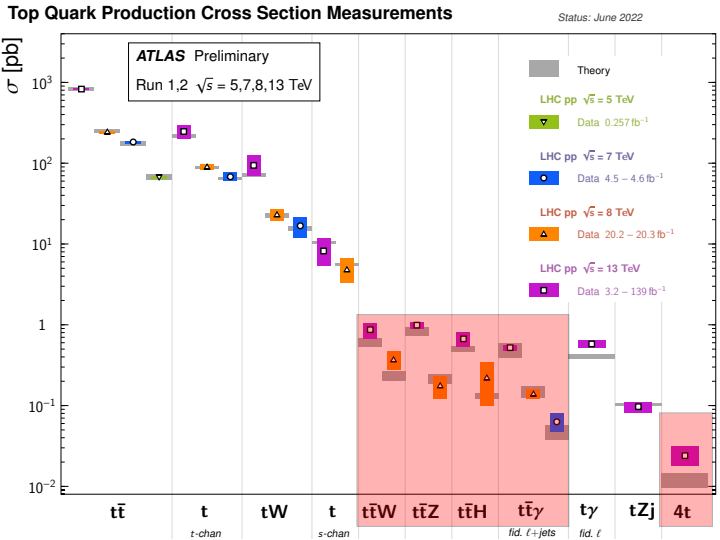




- Analysis uses events with $e^{\pm}\mu^{\mp}$ pair and 1 b-tagged jet.
- No strong discrimination between $tW$ and $t\bar{t}$: BDT trained with 6 variables in 1j1b region.
- Uncertainty dominated by jet energy calibration and $t\bar{t}$ and tW modelling ($\mu_R$, $\mu_F$,FSR).
- Inclusive cross-section: $\sigma_{tW} = 79.2 \pm 0.9(\mathrm{stat})^{+7.7}_{-8.0}(\mathrm{syst}) \pm 1.2(\mathrm{lumi})$ fb.
- Differential cross-section obtained for 6 physical observables including $p_T(\mathrm{jet})$.
  - Leading lepton $p_{\mathrm{T}}$, $\Delta\varphi(e^{\pm},\mu^{\mp})$, $p_{\mathrm{z}}(e^{\pm},\mu^{\mp},j)$, $m(e^{\pm},\mu^{\mp},j)$, $m_{\mathrm{T}}(e^{\pm},\mu^{\mp},j),\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$.

# $t\bar{t} + X$ and 4 tops production




- CMS
  - Inclusive cross-section measurement in $t\bar{t}W$ (**link**).
  - Inclusive and differencial cross-section measurement in $t\bar{t}\gamma$ (**link**).
  - Four tops production (**link**).
- ATLAS
  - Charge asymmetry measurement in $t\bar{t}W$. (**link**)
  - Charge asymmetry measurement in $t\bar{t}\gamma$. (**link**)

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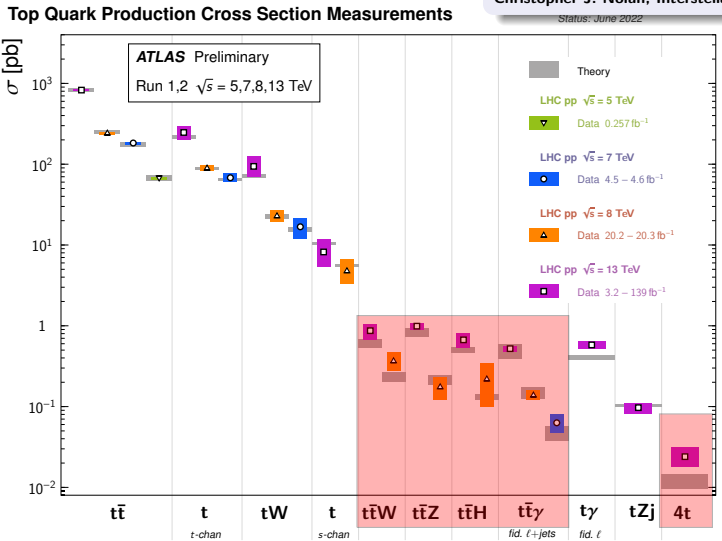


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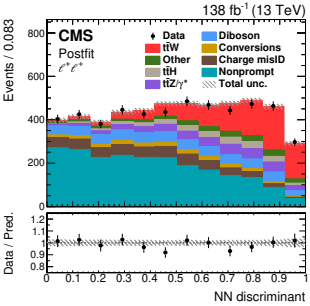
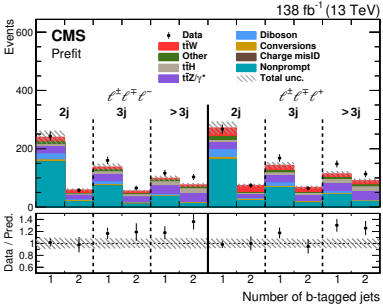
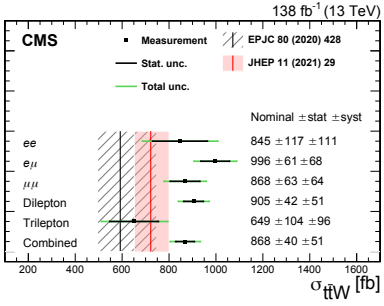
# CMS latest $t\bar{t}W$ measurement: cross-section

arXiv:2208.06485



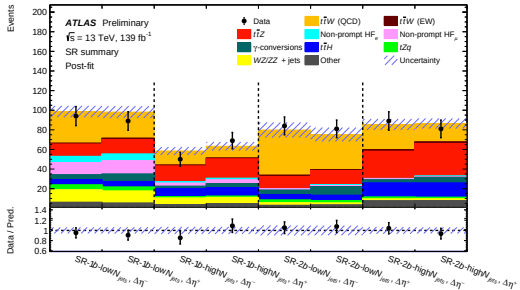



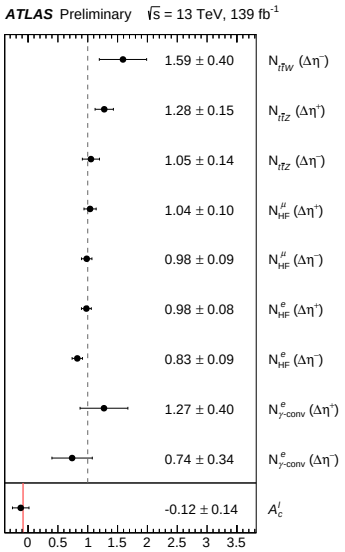




- Analysis of $2\ell$ and $3\ell$ final state
- In $2\ell$, DNN to discriminate signal from background.
- In $3\ell$. sum of lepton charge required to be $\pm 1$
- Uncertainty dominated by $t\bar{t}W$ modelling and ttH normalization.
- $\sigma_{t\bar{t}W} = 868 \pm 40(\text{stat}) \pm 51(\text{syst})$ fb
- $\frac{\sigma(t\bar{t}W^+)}{\sigma(t\bar{t}W^-)} = 1.61 \pm 0.15(\text{stat})^{+0.07}_{-0.05}(\text{syst})$

# ATLAS latest $t\bar{t}W$ measurement: Q asymmetry

ATLAS-CONF-2022-062

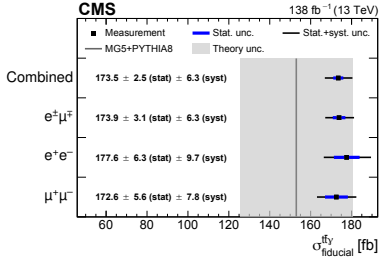


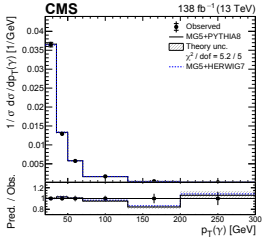



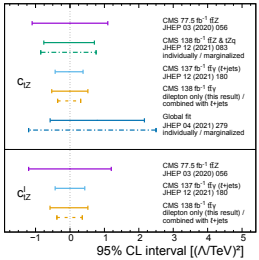

- Analysis of only $3\ell$ final state.
- BDT to discriminate which same-sign lepton originate from W boson.
- Uncertainty dominated by jet energy resolution and $t\bar{t}V$ modelling.
- $A_C^t = \frac{N\left(\Delta_y^t > 0\right) - N\left(\Delta_y^t < 0\right)}{N\left(\Delta_y^t > 0\right) + N\left(\Delta_y^t < 0\right)}, \quad \Delta_y^t = |y_t| - |y_{\bar{t}}|.$
- $A_C(t\bar{t}W) = -0.123 \pm 0.136(\text{stat}) \pm 0.051(\text{syst})$
- $A_C^{\text{SM}}(t\bar{t}W) = -0.084^{+0.005}_{-0.003}(\text{scale}) \pm 0.006(\text{MCstat})$

# CMS latest $t\bar{t}\gamma$ measurement: cross-section

arXiv:2201.07301



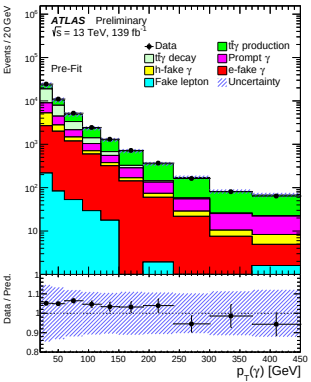



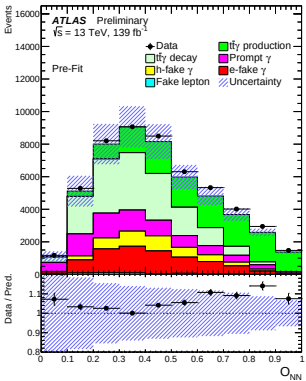




- Analysis of $2\ell + 1\gamma + \geq 1b$-jet final state.
- Same flavour leptons exclude $m(Z)$.
- Profile likelihood fit on the distribution of the photon $p_{\mathrm{T}}$.
- Uncertainty dominated by $t\bar{t}\gamma$ modelling and efficiency of photon selection and b-tagging.
- $\sigma_{\mathrm{fid}}(pp \to t\bar{t}\gamma) = 175.2 \pm 2.5(\mathrm{stat}) \pm 6.3(\mathrm{syst})$ fb
- $\sigma_{\mathrm{SM}}(pp \to t\bar{t}\gamma) = 155 \pm 27$ fb.
- EFT interpretation made with best limit on Wilson coefficients, $c_{tZ}$ and $c^{\mathrm{I}}_{tZ}$

# ATLAS latest $t\bar{t}\gamma$ measurement: Q asymmetry

ATLAS-CONF-2022-049




- Analysis of only $1\ell + 1\gamma + \geq 4$ jets, with $\geq 1$ b-jet in the final state.
- Kinematic fit algorithm to reconstruct $p_{\mathrm{Z}}^{\nu}$
- NN to separate $t\bar{t}\gamma$ from backgrounds using 21 variables.
- Uncertainty dominated by b-tagging/jets, $\not{E}_{\mathrm{T}}$ and MC statistics.
- $A_C^t = \dfrac{N\left(\Delta_y^t > 0\right) - N\left(\Delta_y^t < 0\right)}{N\left(\Delta_y^t > 0\right) + N\left(\Delta_y^t < 0\right)}, \quad \Delta_y^t = |y_t| - |y_{\bar{t}}|.$
- $A_C(t\bar{t}\gamma) = -0.006 \pm 0.024(\mathrm{stat}) \pm 0.018(\mathrm{syst})$
- $A_C^{\mathrm{MC}}(t\bar{t}\gamma) = -0.014 \pm 0.001$ for MadGraph5_aMC@NLO in same phase-space.

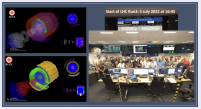
# Summary and outlook

- ATLAS and CMS have an extensive and strong top quark sector program.
- All these measurements are discussed in great detail in the TOP QUARK conference last month.
- More to come still from Run 2 of LHC data taking in the near future.
- Also, coming up next: check out specific detector presentations for ATLAS and CMS.
- Meanwhile...

# Summary and outlook

## Meanwhile...

- After several years of break with several improvements to all detectors.
- The factory is back on producing top quarks for LHC Run 3 of data taking ...
- ...this time at a new record energy of $\sqrt{s} = 13.6$ TeV.


- And...

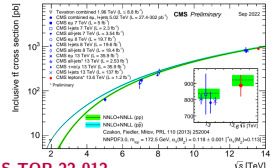
# Summary and outlook

## And...

- We are already starting to analyse Run 3 data and some of it is already public.

### Conclusion

- We are excited to kick off the study of top quark physics at a new energy frontier!
- CMS data taking has begun, and data is rapidly becoming available for analysis
- We present a novel early measurement which uses multiple channels to constrain efficiencies *in situ*
- **Top quark physics has arrived @ LHC Run-3!**




**E. Raken @ TOP22** / **CMS-PAS-TOP-22-012**

First measurement of top quark production by CMS at $\sqrt{s}$ = 13.6 TeV!

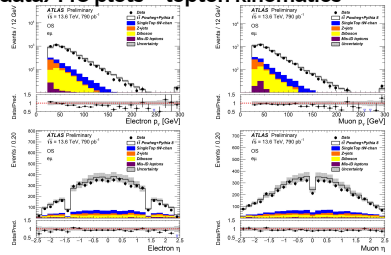
$$\sigma_{t\bar{t}} = 887^{+43}_{-41}(\text{stat} + \text{sys}) \pm 53(\text{lumi})\,\text{pb}$$

CMS-PAS-TOP-22-012 (online very soon!)



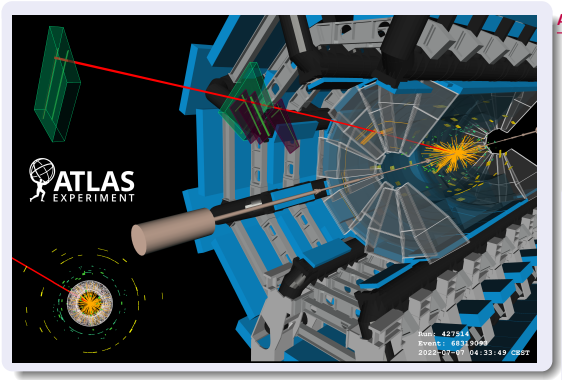
**B. Ravina @ TOP22** / **FTAG-2022-003**

### First data/MC plots – lepton kinematics



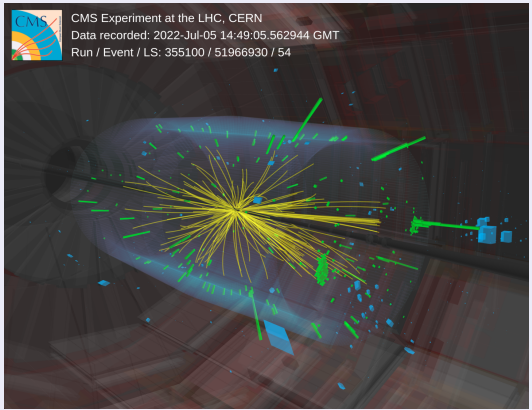

## Finally...

## And...



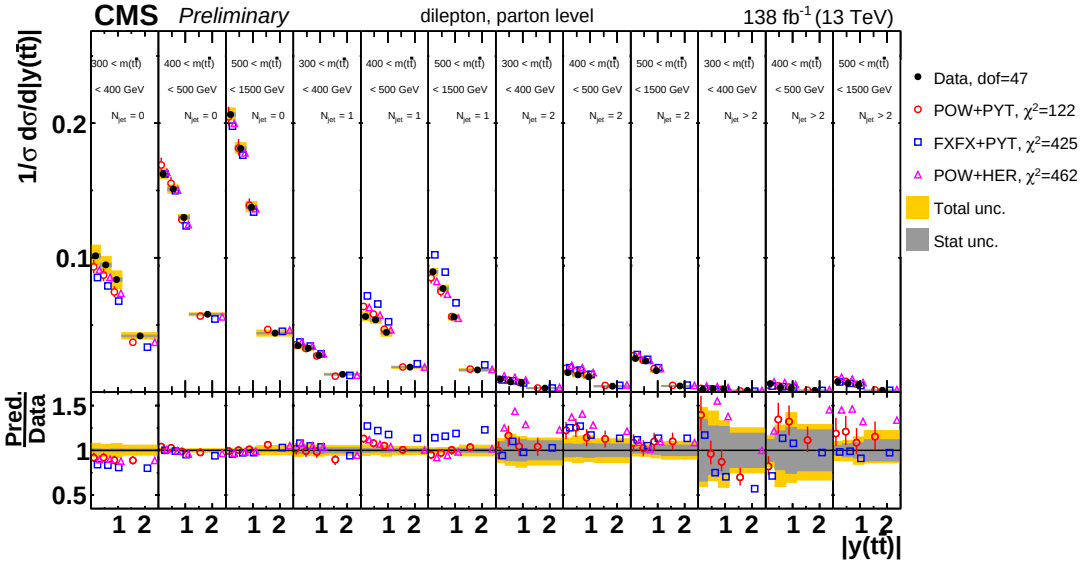



## Thank you

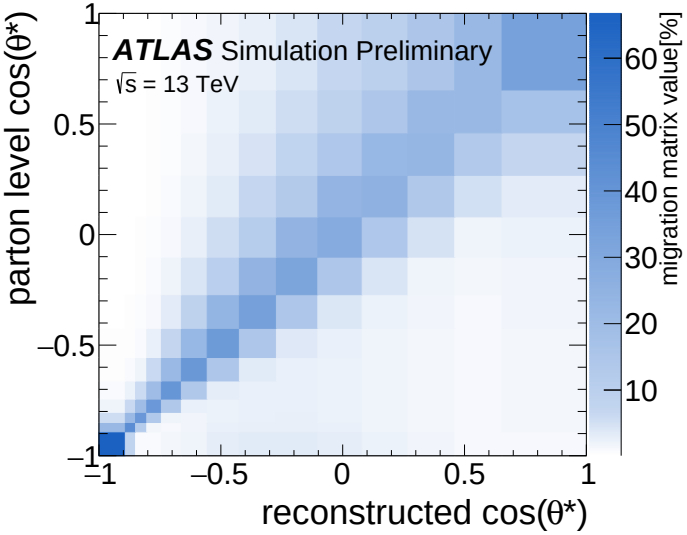



## for your attention

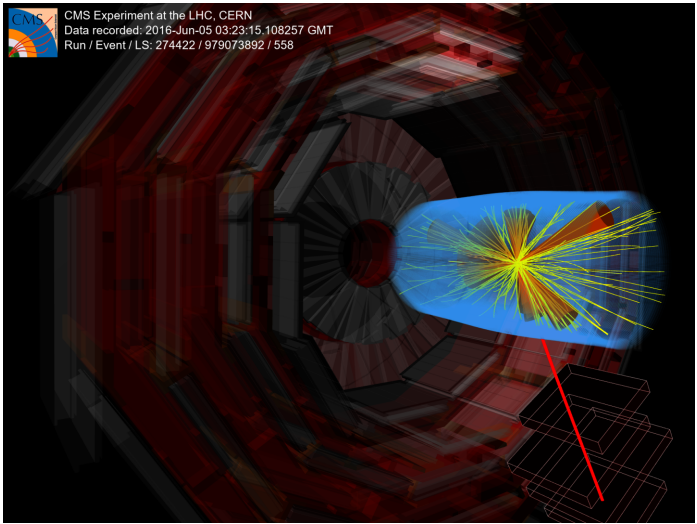
# Backup: 3D differencial cross-section for CMS di-lepton measurement



# Backup Migration matrix $R_{ij}$ for ATLAS W-boson polarization

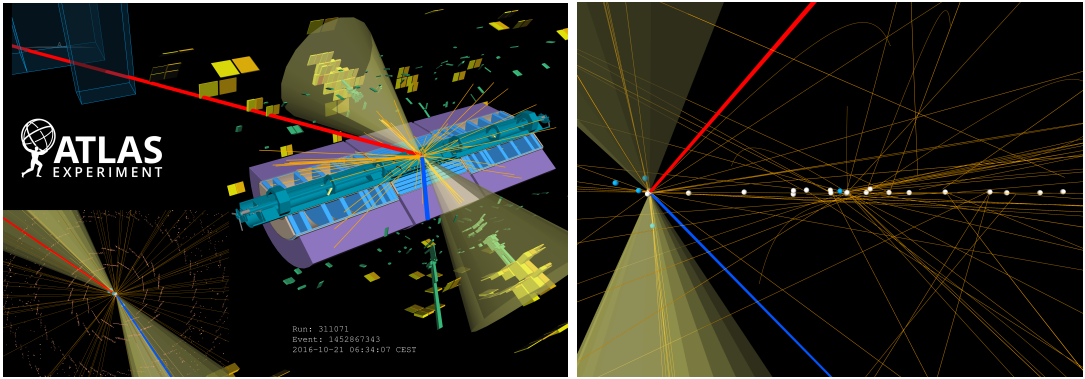


# CMS high-jet multiplicity event 



# ATLAS $e\mu$ event with vertex separation





# CMS $tW$ candidate event