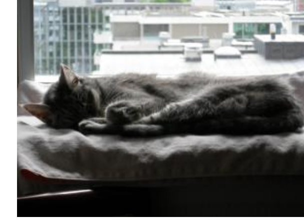
Measurement of the ttbar cross-section at 5.02 TeV

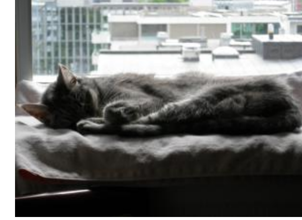


Richard Hawkings (CERN)

on behalf of the ATLAS Collaboration

LHC TopWG meeting, 20/5/2021

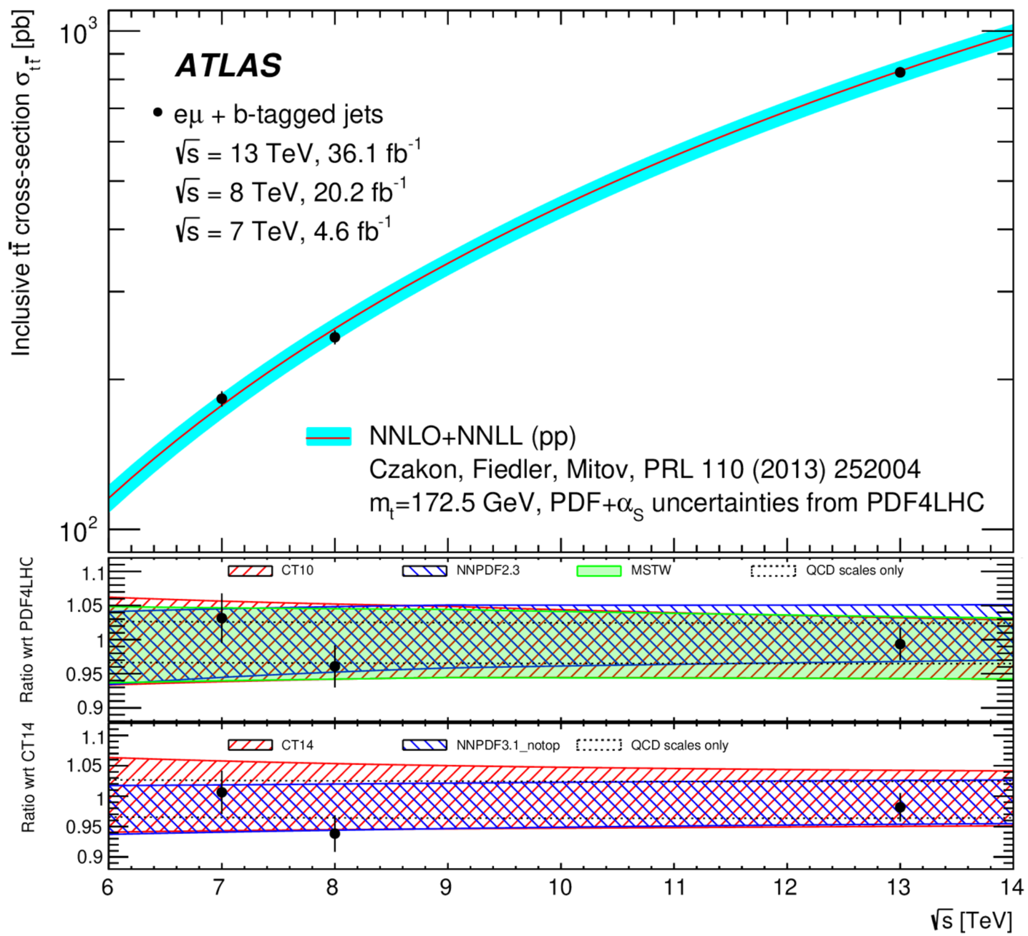
- New ATLAS ttbar x-sec analysis using dilepton decays in 2017 5 TeV data
  - CONF note ATLAS-CONF-2021-003, released for La Thuile 2021
- Brief presentation of the analysis and results
  - Object and event selection, analysis method
  - Results, systematics and comparison to theoretical predictions
- Also briefly discuss the recent CMS result from PAS TOP-20-004
  - And compare the two analyses' approaches and uncertainties
  - Thanks to Juan Gonzalez (CMS, Oviedo) for assistance

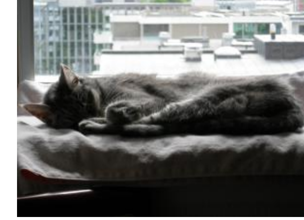


Introduction

- ttbar a 'standard candle' at LHC
  - Tests of QCD at high energies
  - Most precise measurements of inclusive cross-section from eμ
    - In nice agreement with NNLO+NNLL predictions at 7, 8 and 13 TeV
- Small data samples at $\sqrt{s}$=5.02 TeV
  - Add another point to the plot
  - Potential sensitivity to PDFs, through x-sec measurement and ratios
  - CMS l+jets/dilepton measurement using 27 pb^{-1} in 2015
    - Limited precision: ±12%
- ATLAS has 257 pb^{-1} from 2017
  - Should be able to improve, even using purely dilepton measurement

From 13 TeV eμ EPJ C 80 (2020) 528

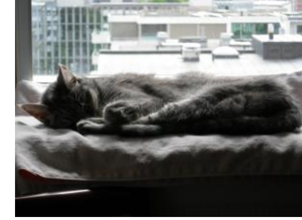




Dilepton ttbar measurement with low statistics

- 257 pb^{-1} sample recorded over 10 days in November 2017
  - Primarily pp reference data for heavy ion programme, also useful for SM physics
  - Low-μ data sample, with 0.5<μ<4, most with luminosity levelled to <μ>≈2
    - Optimal pileup for W-boson measurements (luminosity vs E_T^{miss} resolution)
  - Low single lepton trigger thresholds, fully efficient for p_T>15 GeV
    - Calorimeter noise thresholds optimised for low pileup, needs dedicated EM calibration
- Adapt the 'standard' eμ + b-tagged jet analysis for this sample:
  - Lower lepton p_T threshold to 18 GeV (c.f. 20 GeV at 13 TeV)
    - Going even lower brings more non-prompt leptons from b/c decays
  - Looser electron ID and use barrel-endcap transition region $1.37<|\eta|<1.52$
    - Electron efficiency/resolution not as good in this region, but we want more events
  - Add same flavour channels ee+$\mu\mu$
    - Include E_T^{miss} cut to fight $Z\rightarrow ll$ + b-jet background (not present in eμ channel)
- Simulation/event generators very similar to that used at $\sqrt{s}$=13 TeV
  - Only ttbar, Wt, t-channel, Z+jets, W+jets, diboson considered
    - ttV, ttH and other rare processes can be neglected
  - Dedicated low-μ calib. for electrons; muon/jets from 13 TeV but validated at 5 TeV

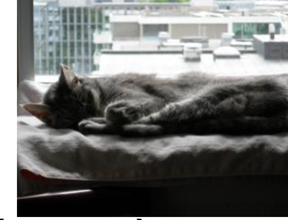
Event selection



- Object selection
  - Electrons: p_T>18 GeV, $|\eta|$<2.47 including transition, calorimeter + track isolation
  - Muons: p_T>18 GeV, $|\eta|$<2.5, calorimeter + track isolation
  - Jets: p_T>25 GeV, $|\eta|$<2.5, b-tagged with DL1r algorithm with 85% efi for b-jets
    - Highest efficiency WP, rejection of 3 against charm and 40 against light quark/gluon
  - Missing transverse momentum (E_T^{miss}) from electrons, muon, jets and soft tracks
- Require 2 opposite-sign leptons, ≥1 matched to single-lepton trigger
  - Redundant trigger gives high efficiency and small systematic uncertainty

Channel	**ee**	**eμ**	**$\mu\mu$**
Dilepton mass m_{ll}	>40 GeV	>15 GeV	>40 GeV
Missing trans. energy E_T^{miss}	>30 GeV	-	>30 GeV

  - Count numbers of events with exactly 1 or exactly 2 b-tagged jets
    - And any number (including zero) of un-tagged jets
    - Allows simultaneous measurement of σ_{tt} and jet selection * b-tagging efi, from data
  - Same-sign events used to control fake lepton background (in principle)



Numbers of selected events

- Events in each sample, classified by dilepton flavour and 1/2 b-tags (N_1,N_2)
  - Same-flavour events divided into 'off-Z' ($|m_{ll}-m_Z|>10$ GeV) and 'on-Z'
  - Background predictions come from final fit & include all systematic uncertainties

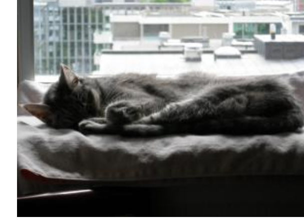
1 b-tagged jet

Event counts	$N^{ee}_{1,\mathrm{off-Z}}$	$N^{ee}_{1,\mathrm{on-Z}}$	$N^{e\mu}_{1}$	$N^{\mu\mu}_{1,\mathrm{off-Z}}$	$N^{\mu\mu}_{1,\mathrm{on-Z}}$
Data	46	109	120	66	92
Wt single top	4.0 ± 0.6	0.8 ± 0.1	13.9 ± 1.5	4.5 ± 0.5	0.9 ± 0.1
Z+jets	13.2 ± 1.4	74.9 ± 6.0	6.4 ± 1.6	23.3 ± 2.9	100.5 ± 8.3
Diboson	0.8 ± 0.2	2.3 ± 0.5	2.6 ± 0.5	0.9 ± 0.2	2.5 ± 0.5
Misidentified leptons	0.9 ± 0.4	0.1 ± 0.1	1.7 ± 0.9	0.2 ± 0.2	0.2 ± 0.1
Total background	18.9 ± 1.6	78.0 ± 5.9	24.6 ± 2.4	28.9 ± 2.9	104.1 ± 8.3

2 b-tagged jets

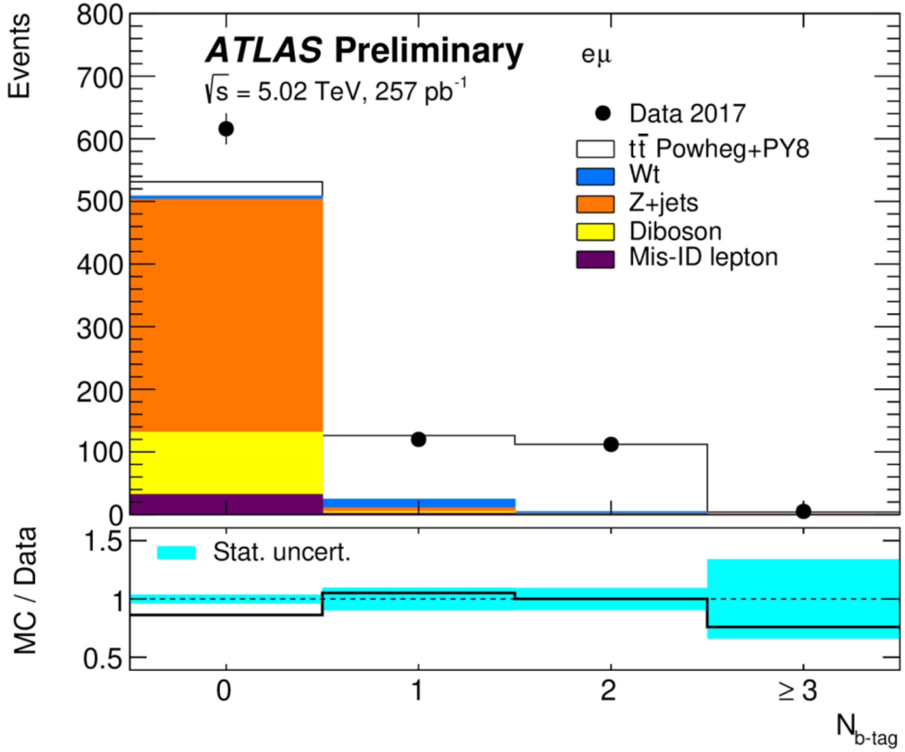
Event counts	$N^{ee}_{2,\mathrm{off-Z}}$	$N^{ee}_{2,\mathrm{on-Z}}$	$N^{e\mu}_{2}$	$N^{\mu\mu}_{2,\mathrm{off-Z}}$	$N^{\mu\mu}_{2,\mathrm{on-Z}}$
Data	30	13	112	30	15
Wt single top	0.9 ± 0.2	0.2 ± 0.1	3.0 ± 0.6	1.0 ± 0.3	0.2 ± 0.0
Z+jets	1.2 ± 1.0	6.8 ± 2.5	0.9 ± 0.4	1.9 ± 0.7	9.1 ± 3.5
Diboson	0.1 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.1
Misidentified leptons	0.2 ± 0.2	0.0 ± 0.0	0.6 ± 0.6	0.1 ± 0.1	0.0 ± 0.1
Total background	2.3 ± 1.1	7.2 ± 2.5	4.6 ± 0.9	3.1 ± 0.8	9.6 ± 3.5

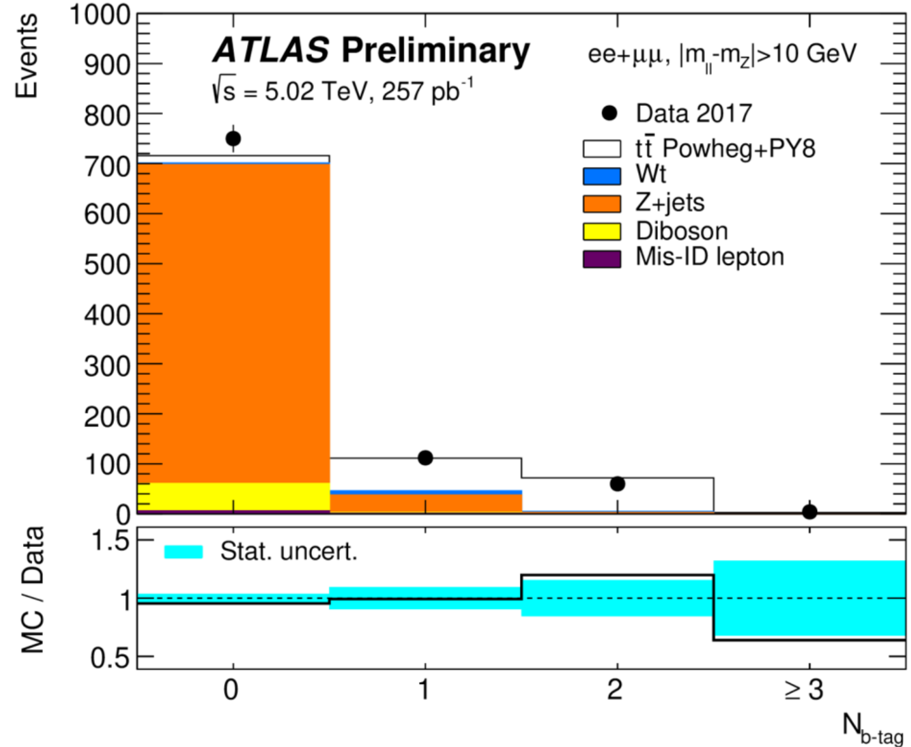
- $e\mu$ channel: 1/2 b-tag samples 80/96% pure ttbar, main background from Wt
- SF channels off-Z: 1/2 b-tag 60/94% pure ttbar, backgrounds Z+jets + Wt



Jet multiplicities

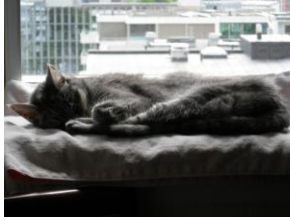
- Number of b-tagged jets in selected $e\mu$ (left) and off-Z $ee+\mu\mu$ (right) events



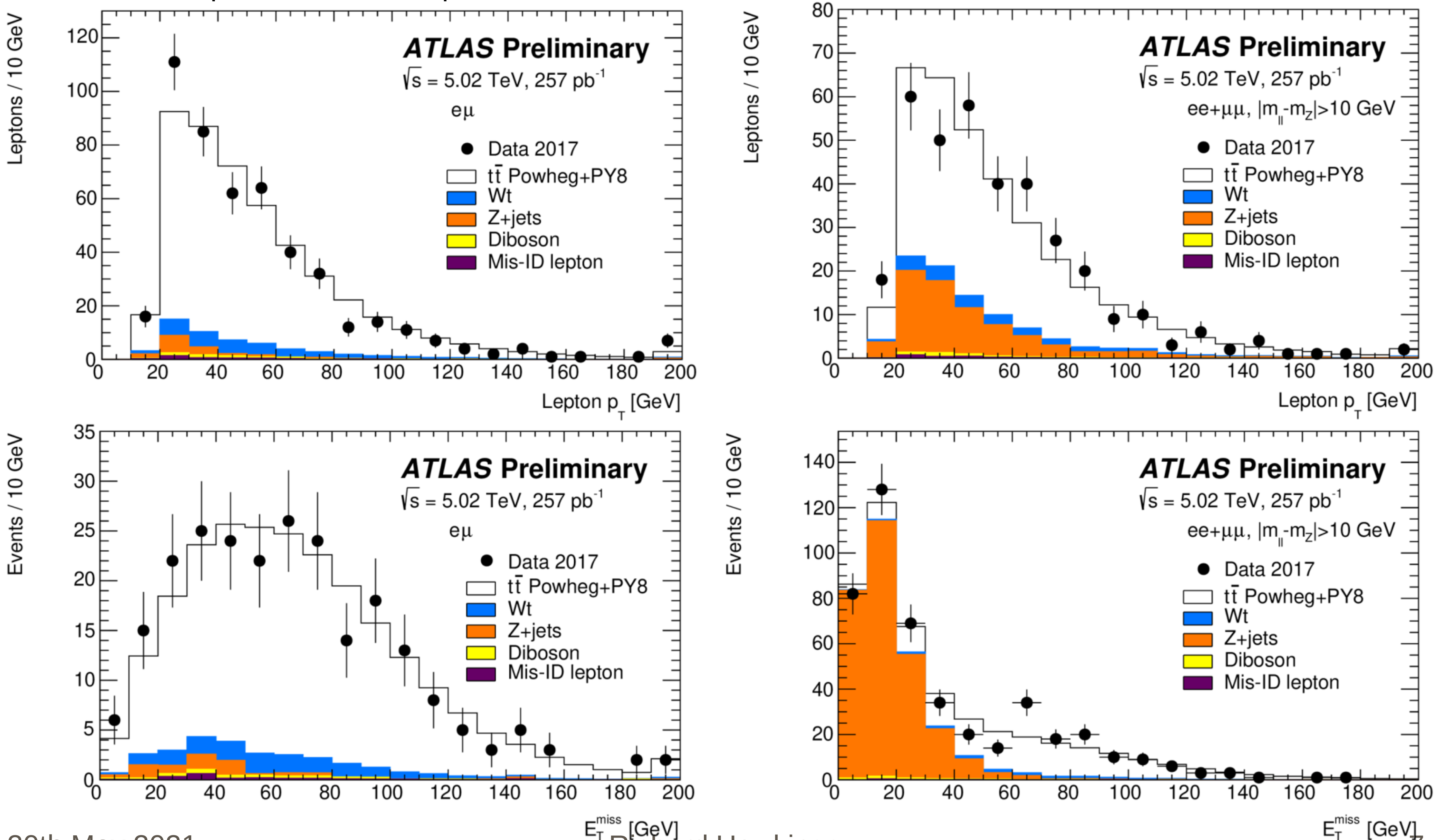


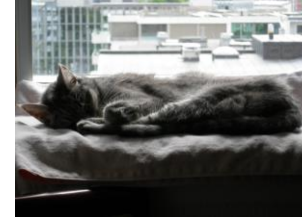
  - ttbar prediction uses reference value of 68.2 pb (top++, CT10/MSTW/NNPDF2.3)
- Good agreement with predictions within statistical uncertainty of data
  - Except for 0 b-tag bin, not used in fit
    - Discrepancies also seen at other energies, Z+jets or diboson modelling?

Lepton and event kinematics



- Lepton p_T (top) and E_T^{miss} (bottom) – good agreement within statistics





Fit to extract ttbar cross-section

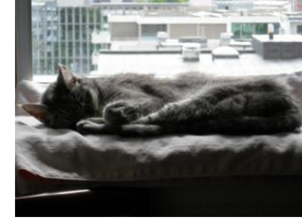
- For eμ channel, use same double-tagging formalism as for 7, 8, 13 TeV

$$
\begin{aligned}
N_1^{e\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu} 2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) &+ \sum_{k=\mathrm{bkg}} s_1^k\, N_1^{e\mu,k} \\
N_2^{e\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu} C_b^{e\mu}(\epsilon_b^{e\mu})^2 &+ \sum_{k=\mathrm{bkg}} s_2^k\, N_2^{e\mu,k}
\end{aligned}
$$

  - $\varepsilon_{e\mu}$ is dilepton selection efficiency, ε_b is probability to select and b-tag jet from top
  - Tagging correlation $C_b \approx 1$, backgrounds k=Wt, Z+jets, diboson, misidentified leptons scaled by scale factors s_k
- For ee/$\mu\mu$ channels, split data into 6 mass bins [40,71,81,101,151,∞ GeV]

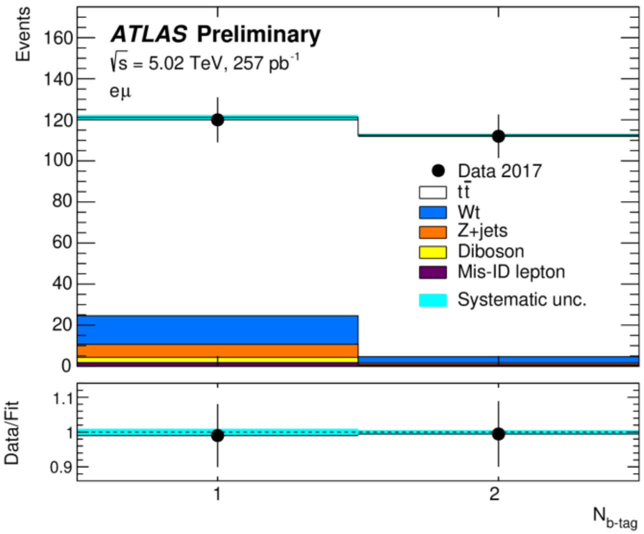
$$
\begin{aligned}
N_{1,m}^{\ell\ell} &= L\sigma_{t\bar{t}}\,\epsilon_{\ell\ell}\, 2\epsilon_b^{\ell\ell}(1 - C_b^{\ell\ell}\epsilon_b^{\ell\ell})\, f_{1,m}^{\ell\ell,t\bar{t}} &+ \sum_{k=\mathrm{bkg}} s_1^k\, f_{1,m}^{\ell\ell,k}, \\
N_{2,m}^{\ell\ell} &= L\sigma_{t\bar{t}}\,\epsilon_{\ell\ell}\, C_b^{\ell\ell}(\epsilon_b^{\ell\ell})^2\, f_{2,m}^{\ell\ell,t\bar{t}} &+ \sum_{k=\mathrm{bkg}} s_2^k\, f_{2,m}^{\ell\ell,k}
\end{aligned}
$$

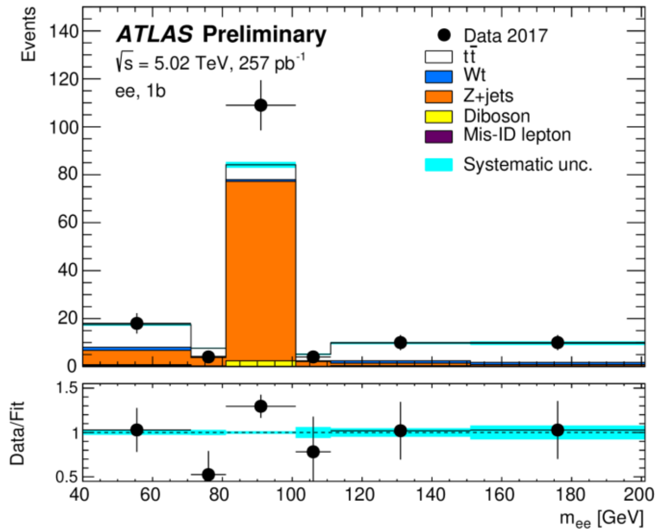
  - Normalised distributions $f_{1,m}$ and $f_{2,m}$ distribute event counts as function of m_{ll}
- Fit all channels together, floating σ_{tt}, ε_b^{ll} and R^Z_1, R^Z_2 ≡ Z+jets scale factors
  - Lepton efficiencies ε_{ll}, correlations C_b, mass distributions $f_{i,m}$ and Wt, diboson and misidentified leptons taken from simulation
    - Corresponds to a template fit in m_{ll} with ttbar and Z+jets components floating

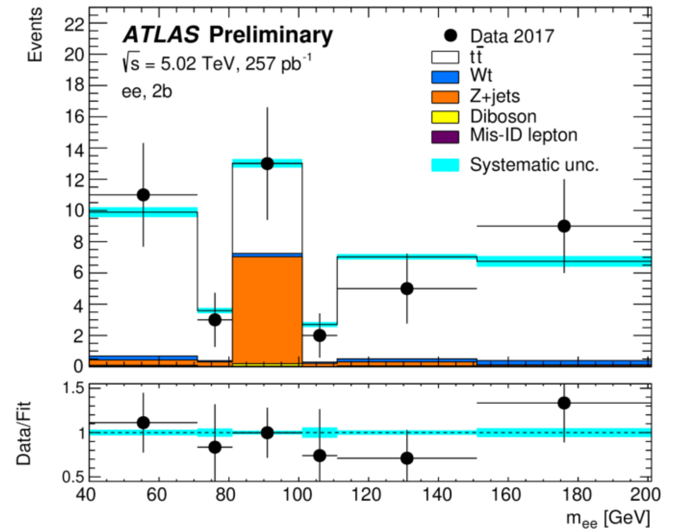


Fit results

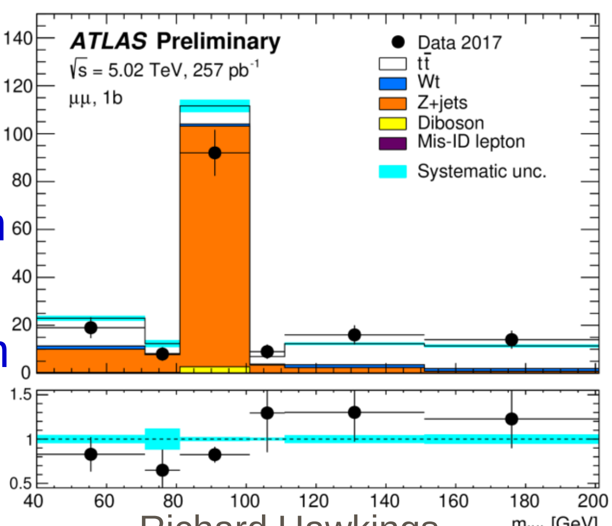
- Data compared to 'post-fit' prediction, cyan bands show systematics

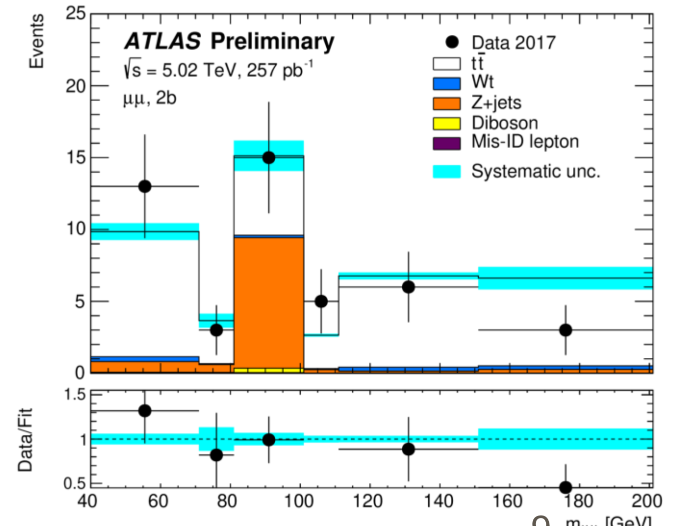




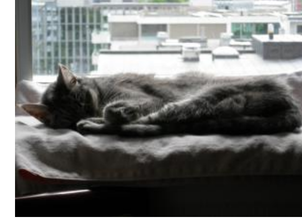


- Description generally good
  - Some tension in $Z\rightarrow ee$+1b vs $Z\rightarrow \mu\mu$+1b
  - But does not affect ttbar-rich region off-Z
  - Likely a statistical fluctuation
  - Disappears when relaxing cut to E_T^{miss}>20 GeV



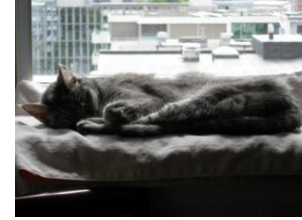


Statistical and systematic uncertainties



Uncertainty	σ (%)
Data statistics	6.8
generator	1.2
hadronisation	0.2
Initial/final state radiation	1.0
heavy-flavour production	0.2
Parton distribution functions	0.3
Electron energy scale	0.1
Electron energy resolution	0.1
Electron identification	0.6
Electron charge misidentification	0.0
Electron isolation	0.5
Muon momentum scale	0.1
Muon momentum resolution	0.0
Muon identification	0.3
Muon isolation	0.6
Lepton trigger	0.2
Jet energy scale	0.1
Jet energy scale extrapolation	0.0
Jet energy resolution	0.1
Pileup jet veto	0.0
b-tagging efficiency	0.1
b-tag mistagging	0.1
E_T^{miss} soft particle modelling	0.1
Single-top cross-section	1.0
Single-top/ interference	0.2
Single-top modelling	0.4
Z+jets extrapolation	0.7
Diboson cross-sections	0.3
Misidentified leptons	0.7
Simulation statistics	0.2
Integrated luminosity	1.8
Beam energy	0.3
Total uncertainty	7.5

- Largest uncertainty from data statistics: 6.8%
  - Integrated luminosity: 1.8%
    - ΔL/L=1.6% but some backgrounds taken from simulation
  - ttbar generator (aMC@NLO+PY8 vs Powheg+PY8) + initial/final state radiation uncertainties around 1%
  - Background uncertainties
    - Wt cross-section from theory, varied by 9.5%
    - Z+jets rate normalised in Z→ee/$\mu\mu$ with E_T^{miss} cut, but extrapolated to Z->$\tau\tau$→eμ without E_T^{miss} cut
  - Misidentified leptons
    - Same-sign dilepton sample too small to constrain it, taken from simulation with 50%/100% (1b/2b) errors
  - Lepton identification and isolation
    - Measured/cross-checked in-situ with 5 TeV Z→ll
  - Jet uncertainties small by design, jet calibration checked using Z+jet balance studies at 5 TeV
- Total non-lumi systematic 2.4%, total error 7.5%
  - C.f. 1.4% non-lumi systematic at 13 TeV



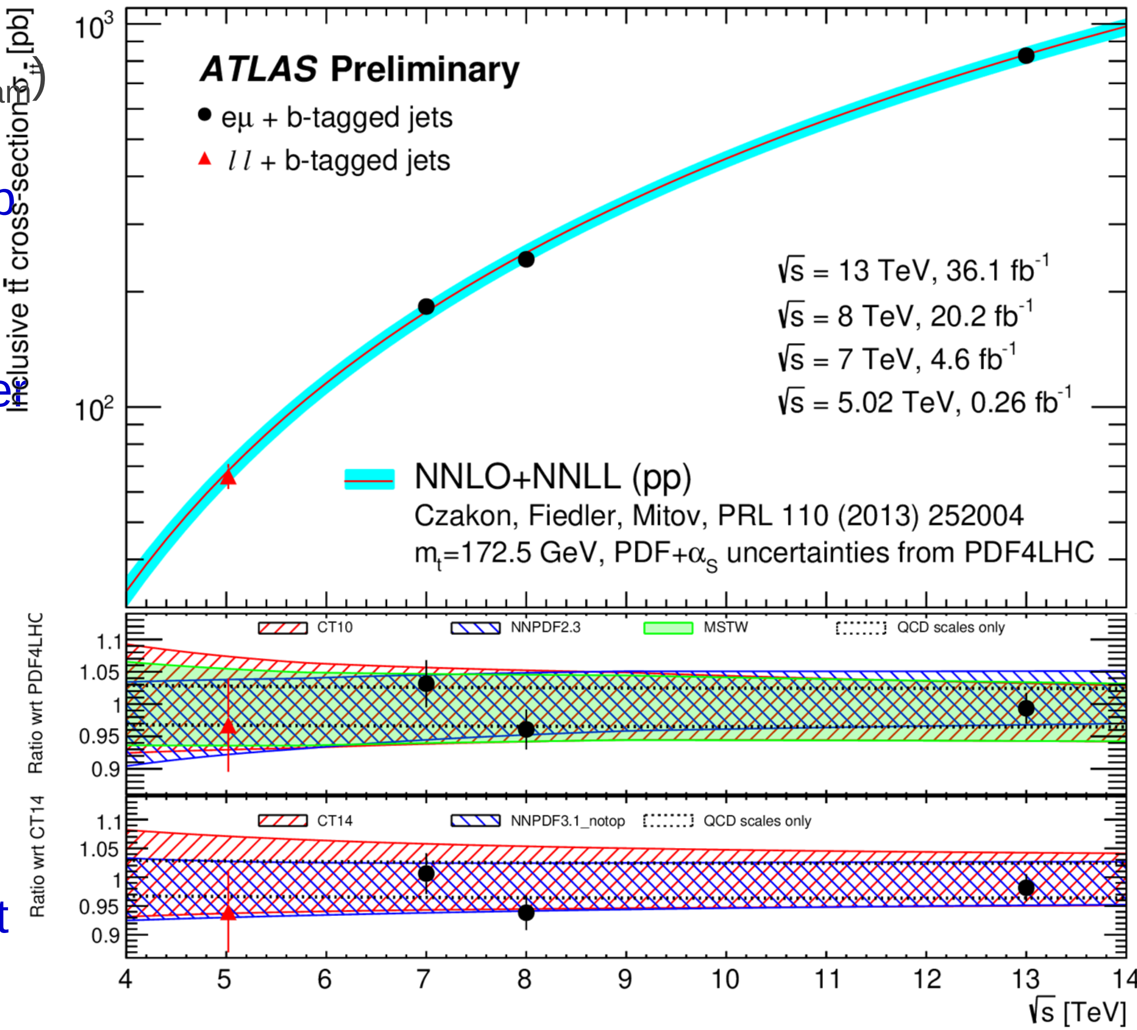
ttbar cross-section result

- Final result:

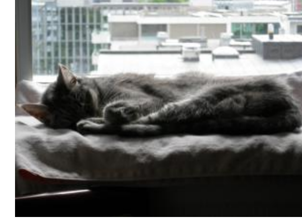
$$\sigma_{t\bar{t}} = 66.0 \pm 4.5 \pm 1.6 \pm 1.2 \pm 0.2\ \text{pb}$$

(±stat, ±syst, ±lumi, ±E_{beam})

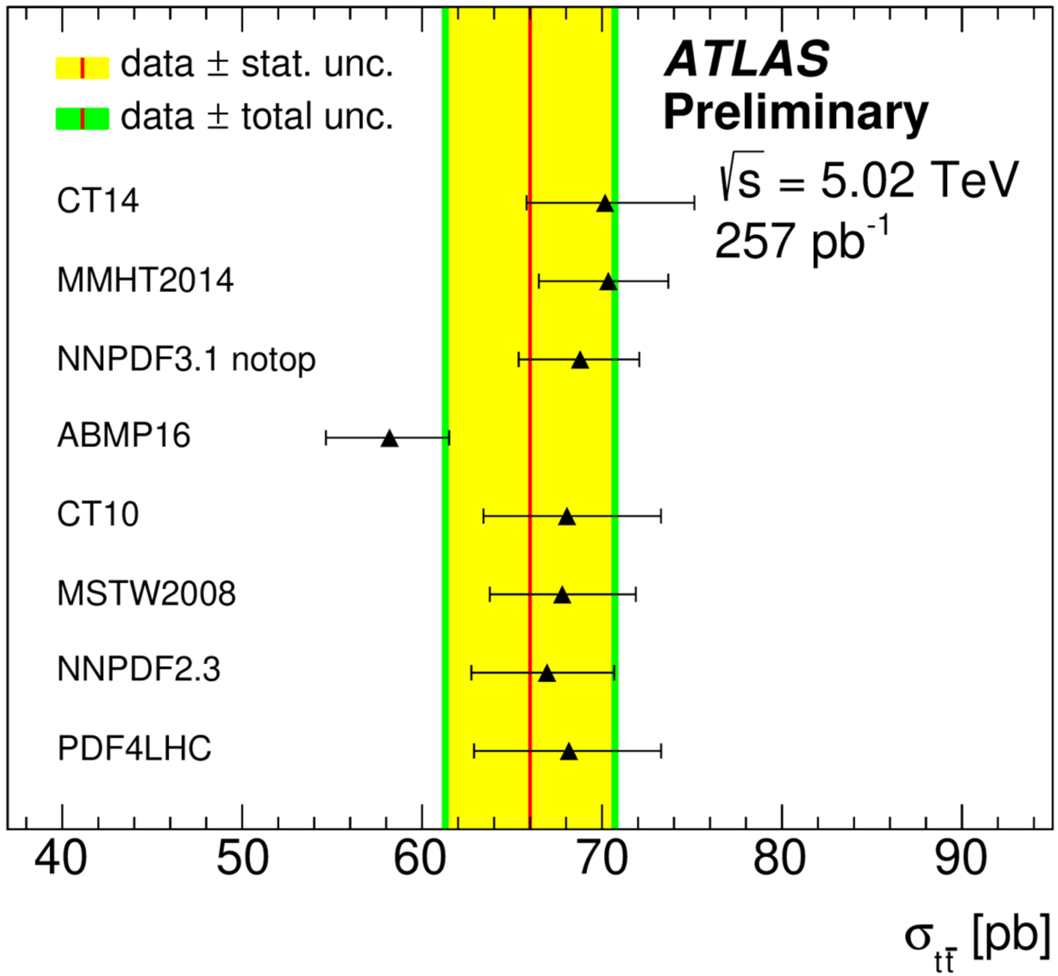
  - In good agreement with prediction: 68.2±4.8 (PDF+α_S) $^{+1.9}_{-2.3}$ (scale) pb
    - NNLO+NLLL pred. from top++
    - CT10/MSTW/NNPDF2.3 PDF sets
  - QCD predictions agree with data over >1 order of magnitude
- Various cross-checks
  - Extracted values of ϵ_b, R^Z_1 and R^Z_2 agree with simulation
  - Consistent results with eμ (±8.5%) and ee+$\mu\mu$ (±13.2%) data alone
  - Results stable vs E_T^{miss} cut
  - Inclusive Z→ee and Z→$\mu\mu$ yields wrt simulation consistent to 1%
    - Validates lepton efficiencies



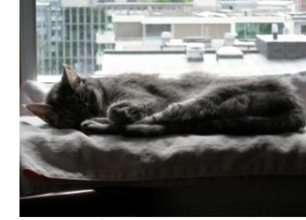
Comparison to PDF predictions



- Comparison with PDF predictions
  - Modern PDFs CT14, MMHT2014, NNPDF3.1_notop and ABMP16
  - Pre-LHC CT10, MSTW2008 and NNPDF2.3 used to make the 'PDF4LHC' envelope cross-section prediction
- Result compatible with all of them
  - Including ABMP16 which gives a lower central value
- Stronger constraints could come from a more precise measurement
  - E.g. add l+jets, combine with CMS?
  - Could also look at ratios to 13 TeV



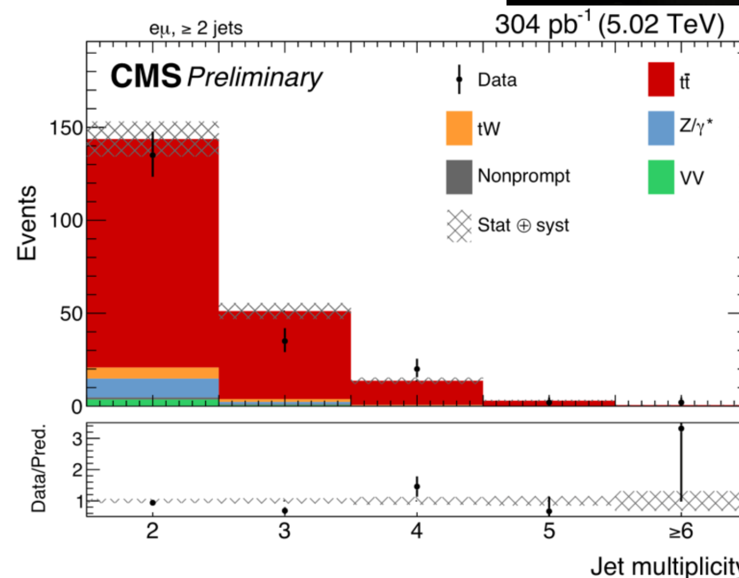
New CMS measurement with 2017 data

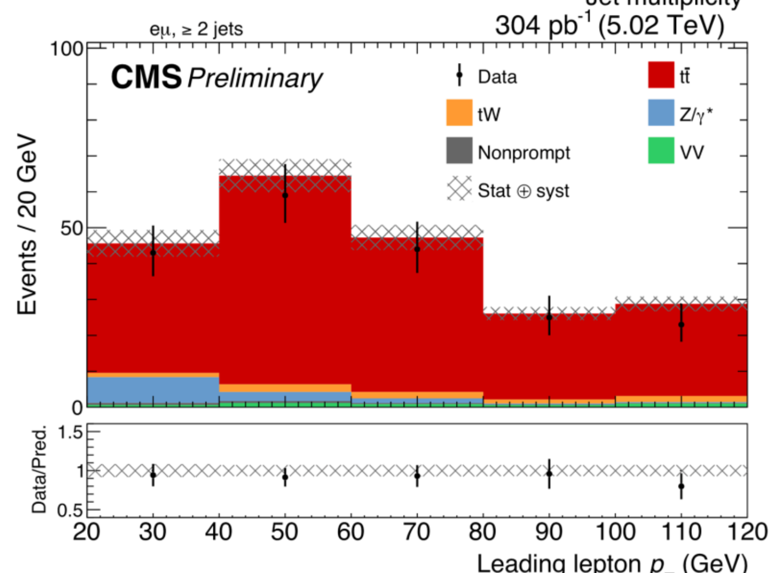


- New result using 304 pb^{-1} recorded in 2017
  - CMS PAS TOP-20-004
  - Based on eμ dilepton channel only
- Event selection: OS eμ + 2 jets
  - Leading lepton p_T>20 GeV, other p_T>10 GeV
  - Jets with p_T>25 GeV and $|\eta|$<2.4, no leptons in jet
  - No b-tagging requirement
    - Except in lepton+jet overlap removal
- Signal extracted using selected event count:

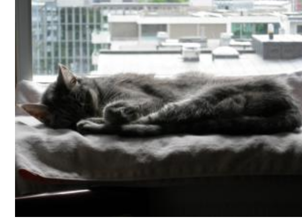
$$\sigma_{t\bar{t}} = \frac{N - N_{\rm bkg}}{\varepsilon \mathcal{A} \mathcal{B} \mathcal{R} \mathcal{L}}$$

  - ε=signal efficiency, A=acceptance, BR=branching ratio to eμ (including τ contributions), L=lumi
  - Z+jets (Drell-Yan) background estimated from data using same flavour events
  - Wt, VV, fake lepton backgrounds from simulation





CMS 2017 eμ result



- Event yield dominated by ttbar (89%):

Process	Event yield		
tW	8	$\pm$ 0.1	$\pm$ 2
Nonprompt leptons	1.7	$\pm$ 0.1	$\pm$ 0.9
DY	10	$\pm$ 0.1	$\pm$ 3
VV	4	$\pm$ 0.1	$\pm$ 1
Total background	24	$\pm$ 0.2	$\pm$ 4
$t\bar{t}$	187	$\pm$ 1	$\pm$ 8
Data	194		

  - Largest systematics from jet energy scale/resl. and Drell-Yan background modelling
- Result:

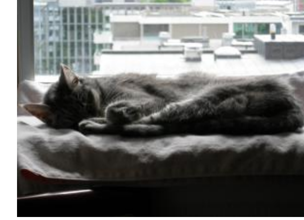
$$\sigma_{t\bar{t}} = 60.3 \pm 5.0\ (\text{stat}) \pm 2.8\ (\text{syst}) \pm 0.9\ (\text{lumi})\ \text{pb}$$

  - 2017 eμ result is combined with 2015 l+jets measurement on 27 pb^{-1} to give

$$\sigma_{t\bar{t}} = 62.6 \pm 4.1\ (\text{stat}) \pm 3.0\ (\text{syst+lumi})\ \text{pb}$$

    - 2017 eμ result has 73% weight in combination

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
tW	1.0
Nonprompt leptons	0.4
Drell–Yan	1.8
VV	0.8
Trigger efficiency	1.3
L1 prefiring	1.4
Electron efficiency	1.6
Muon efficiency	0.6
JES	2.2
JER	1.2
μ_R, μ_F scales	0.2
PDF$\oplus\alpha_S(m_Z)$	0.3
Final state radiation	1.1
Initial state radiation	< 0.1
h_{damp}	1.0
Underlying event tune	0.7
Total systematic	4.3
Integrated luminosity	1.5
Statistical uncertainty	8.2



Comparison of results and uncertainties

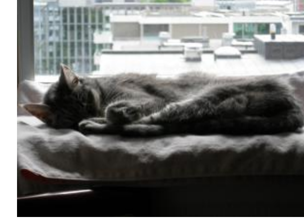
Results	σ_{tt} (± stat, ± syst+lumi)
ATLAS 2017 ll	66.0 ± 4.5 ± 2.0 pb
CMS 2017 eμ	60.3 ± 5.0 ± 2.9 pb
CMS 2017 eμ + 2015 l+jets	62.6 ± 4.1 ± 3.0 pb

Results in excellent agreement ☺

Uncertainties (%)	ATLAS 2017	CMS 2017
ttbar modelling	1.6	1.7
Background modelling	1.5	2.2
Trigger	0.2	1.9
Lepton efficiency/scale	1.0	1.7
Jets, E_T^{miss}, b-tagging	0.2	2.5
Total expt. systematic	**2.4**	**4.3**
Integrated luminosity	1.8	1.5
Data statistics	6.8	8.2
Total uncertainty	**7.5**	**9.1**

- ATLAS dilepton result has significantly smaller systematics
  - In particular for jets (double tag technique), also for leptons and trigger
    - Also slightly smaller statistical uncertainty (use of same-flavour events), which is the dominant effect, as systematics << statistical error for both analyses
  - CMS combined measurement has uncertainty of 7.9%, c.f. ATLAS 2017 7.5%
  - Neither measurement has exploited 2017 l+jets data yet

Conclusions and outlook



- Presented a new ATLAS measurement of ttbar cross-section at $\sqrt{s}$=5.02 TeV
  - Based on eμ+b-tagged jets technique used at 7, 8, 13 TeV, extended to also include same flavour channels, and optimised for low-statistics sample
  - Result has an uncertainty of 7.5%, dominated by data statistical uncertainty
  - Agrees with NNLO+NNLL predictions derived using several modern PDF sets
  - Also agrees with a recent CMS measurement with 7.9% uncertainty, from combination of 2017 eμ and 2015 l+jets (10x smaller sample)

- To fully exploit the 5.02 TeV data samples, analysis of 2017 l+jets events and combination of ATLAS and CMS results would be useful
  - May then allow discrimination between different PDF sets
  - Ratio measurements e.g. between 13 and 5 TeV could also be useful