Measurement of top-quark pair inclusive and differential cross-sections in the eμ channel in pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ using the ATLAS detector

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On behalf the ATLAS Collaboration

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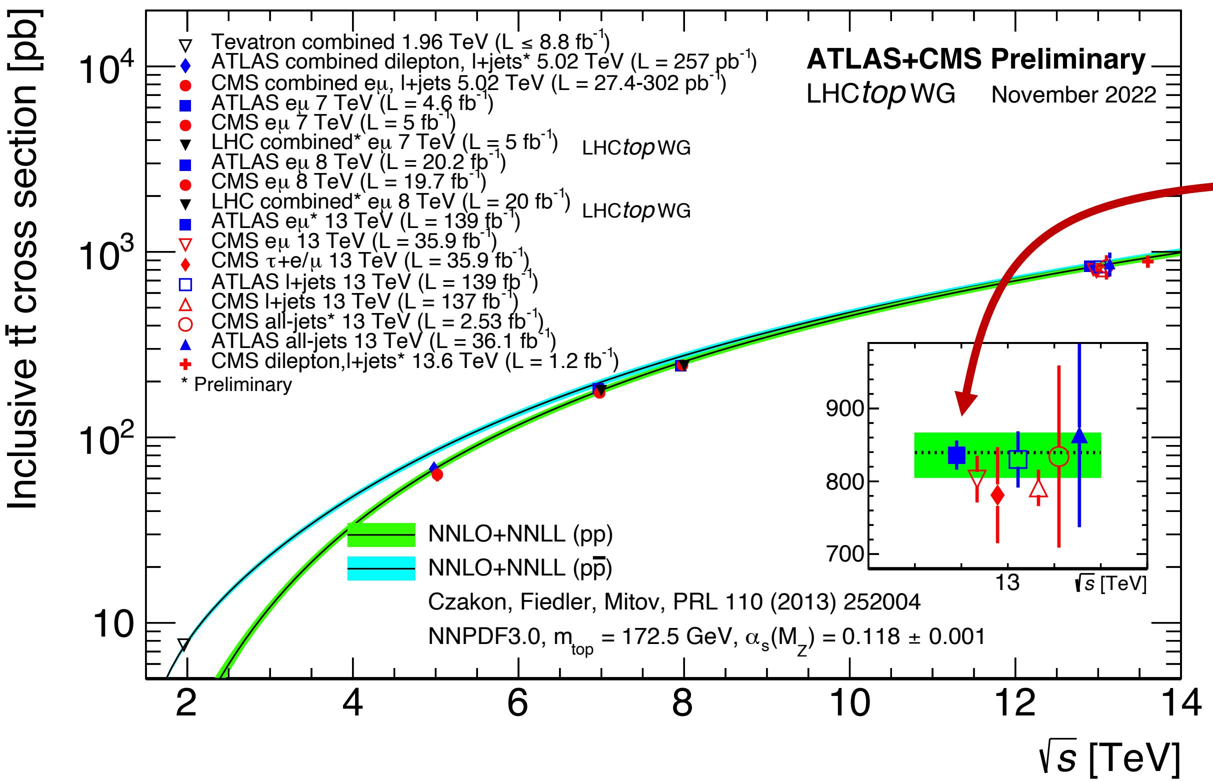
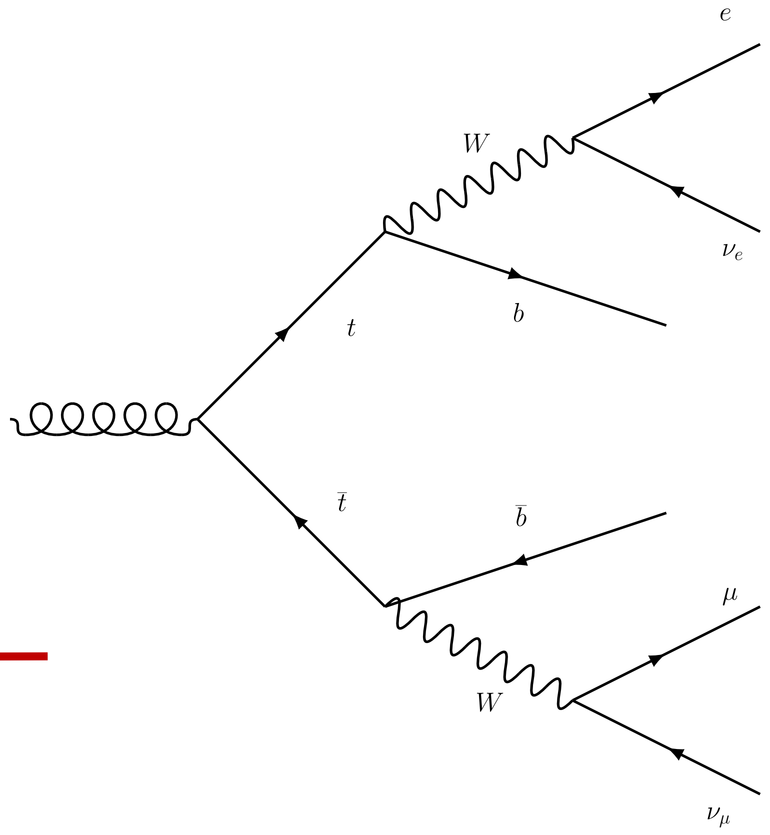
Introduction and context

- $e\mu$ channel has smallest backgrounds and smaller associated uncertainties
- New measurements of inclusive $\sigma_{t\bar{t}}$ using Full Run2 recorded by ATLAS
- Using huge statistical power of full Run2 to measure differential and double differential $\sigma_{t\bar{t}}$
- Test of different generators
- Testing SM, constraing SM parameters m_{top}, α_S, constraining PDFs... and also seeking hints of new physics.





Single lepton: p_T^l and $|\eta^l|$

Electron + muon system: $p_T^{e\mu}$, $m^{e\mu}$, $|y^{e\mu}|$ and $\Delta\phi^{e\mu}$

Sum quantities: $p_T^e + p_T^\mu$ and $E^e + E^\mu$

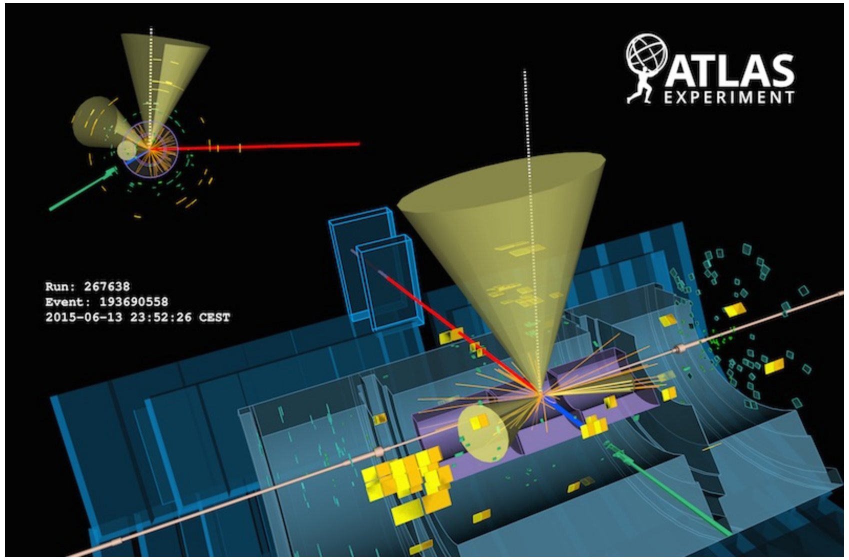
Double differential: $\Delta\phi^{e\mu} : m^{e\mu}$, $|y^{e\mu}| : m^{e\mu}$, $\Delta\phi^{e\mu} : p_T^{e\mu}$ and $\Delta\phi^{e\mu} : E^e + E^\mu$

Objects and event selection

Selections:

- Single electron
- Single muon
- No requirements on number of jets
- No requirements on MET, HT, M_{ll}
- Categorization in regions using the # of b-jets

- OS region → Signal region
- SS region → Control region



- **Electrons**:
  - $p_T > 27(25)^*$ GeV && $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
  - ID: Tight
  - Applied standard Overlap Removal**
  - $\sigma_{d_0}/|d_0|$ < 5 and $|\Delta z_0 \sin(\theta)|$ < 0.5 mm
- **Muons**:
  - $p_T > 27(25)^*$ GeV && $|\eta| < 2.5$
  - ID: Medium
  - Applied standard Overlap Removal**
  - $\sigma_{d_0}/|d_0|$ < 3 and $|\Delta z_0 \sin(\theta)|$ < 0.5 mm
- **Jets**:
  - $p_T > 25$ GeV && $|\eta| < 2.5$
  - JVT WP: Medium
  - Collection Name: AntiKt4EMTopoJets
- **b-tagging**:
  - WP with 70% of efficiency

** leading(sub-leading)*
*** see backup slides for any details*

Mis-ID lepton estimation

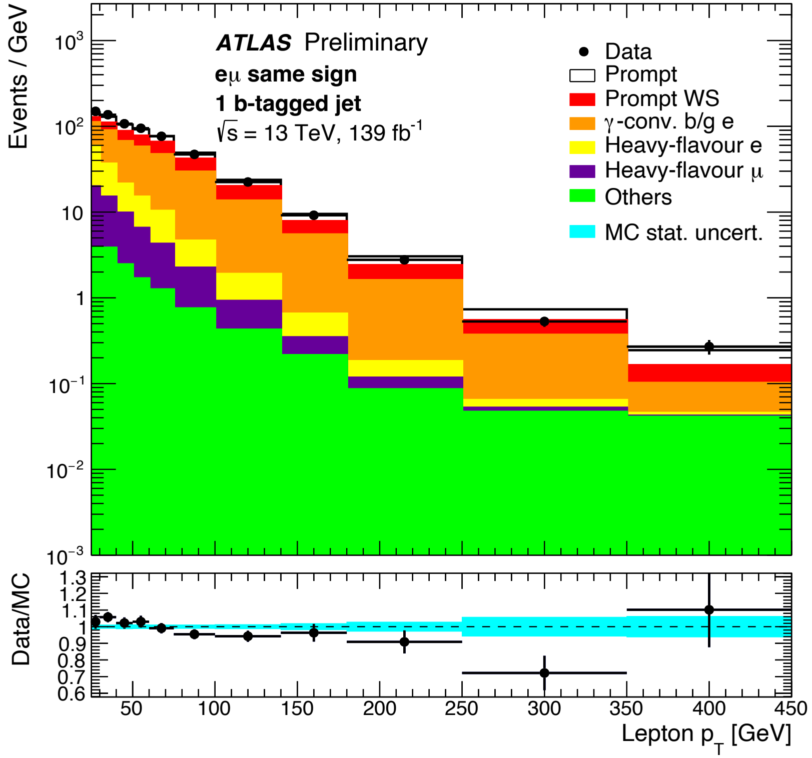
- The fake leptons background has been estimated by using a semi data-driven method (with the SS regions)

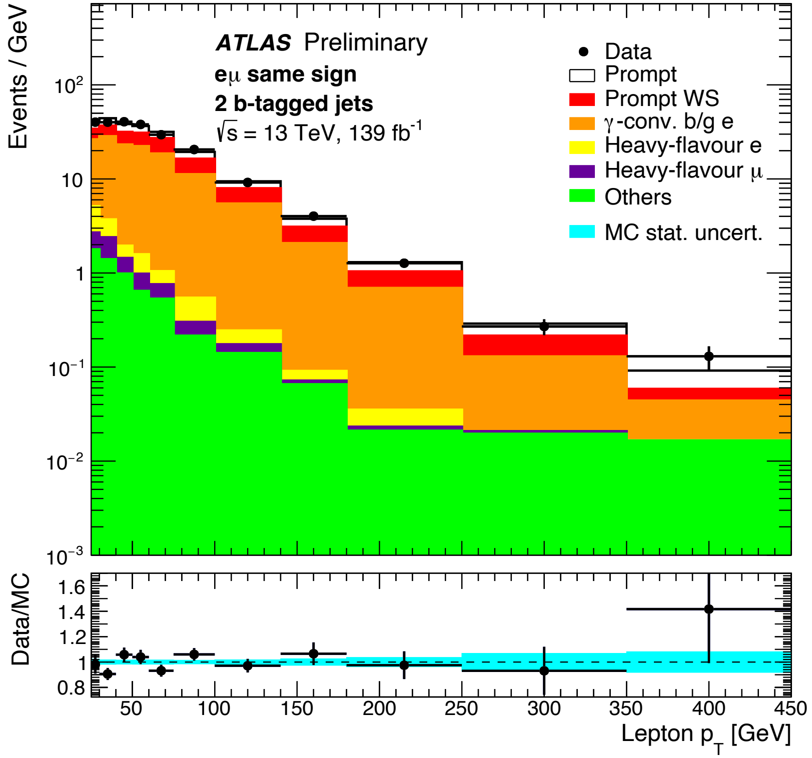
i = bin number

$$N_b^{i,mis-ID,OS} = \frac{N_b^{i,MC,mis-ID,OS}}{N_b^{i,MC,mis-IS,SS}} \cdot \left(N_b^{i,data,SS} - N_b^{i,MC,prompt\ RS,SS}\right)$$

b = Number of b-jet

From data = green
From MC = blue

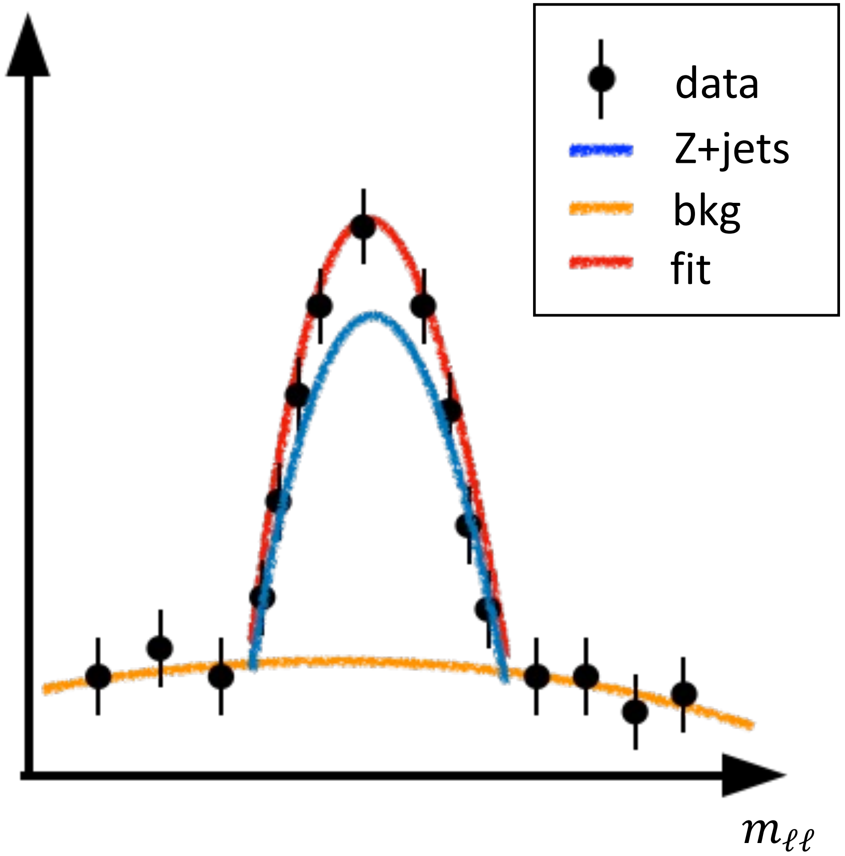




Fakes classes:
- Charge mis-identification
- Electron from Heavy Flavour
- Muon from Heavy Flavour
- Electron from γ conversions
- OTHERS

Z + jets estimation

- Observed a mismatch in total yield of $Z \to \tau\tau + jets$ events between data and MC which could be partly due to mismodelling in MC (cross section's theoretical QCD uncertainties)
- Fitted the different contribution ($Z \to ee$, $Z \to \mu\mu$) to extract a scale factor for 1 and 2-jet used for the $Z \to \tau\tau + jets$ background.
- The different contributions ($Z \to ll$ and *background*) are then fitted to the data varying weights with a bin-by-bin chi2 fit.



Fitting function:

$$f(m^{ll}) = n_Z \cdot hist(Z \to ll) + n_{bkg} \cdot hist(bkg)$$

Scale factor

Selection/number of *b*-jets	1 *b*-jet	2 *b*-jets
$Z \to ee$ + jets	1.206 ± 0.002	1.35 ± 0.01
$Z \to \mu\mu$ + jets	1.180 ± 0.001	1.310 ± 0.008
Total	1.189 ± 0.001	1.324 ± 0.006

Analysis strategy

Combined fit to extract cross-section and b-tagging efficiency. Low impact of b-tagging uncertainties

For total fiducial cross-section measurement

$$\begin{cases} N_1 = \mathcal{L}\,\sigma_{t\bar{t}}^{fid}\,G_{e\mu}\,2\varepsilon_b\,(1 - C_b\varepsilon_b) + N_1^{bkg} \\ N_2 = \mathcal{L}\,\sigma_{t\bar{t}}^{fid}\,G_{e\mu}\,C_b\varepsilon_b^2 + N_2^{bkg} \end{cases}$$

For differential cross-section measurement

$$\begin{cases} N_1^i = \mathcal{L}\,\sigma_{t\bar{t}}^i\,G_{e\mu}^i\,2\varepsilon_b^i\left(1 - C_b^i\varepsilon_b^i\right) + N_1^{i,bkg} \\ N_2^i = \mathcal{L}\,\sigma_{t\bar{t}}^i\,G_{e\mu}^i\,C_b^i\left(\varepsilon_b^i\right)^2 + N_2^{i,bkg} \end{cases}$$

$N_{1,2}^i$ total number of events in OS and OF dilepton $t\bar{t}$ channel for 1 b-tagged and 2 b-tagged jets (from data);
$\sigma_{t\bar{t}}^i$ is the absolute differential $t\bar{t}$ cross-section (fitted from data);
$G_{e\mu}^i = N_{e\mu}^{reco}/N_{e\mu}^{particle}$ is the lepton reconstruction efficiency (from MC);
ε_b^i is the b-tagging efficiency (fitted from data);
$C_b^i = \varepsilon_{bb}^i/\left(\varepsilon_b^i\right)^2 = 4N_{all}N_2/(N_1 + 2N_2)^2$ is the b-tagging correlation coefficient (from MC);
$N_{1,2}^{i,bkg}$ number of background events in OS and OF dilepton $t\bar{t}$ channel for 1 b-tagged and 2 b-tagged jets (from MC).
$A_{e\mu} = (N_{e\mu}^{particle}/N_{dilepton}) \cdot 1/BR(t\bar{t} \rightarrow e\mu)$ fraction of $t\bar{t}$ events with a true $e\mu$ pair within the fiducial region (from MC).
$E_{e\mu} = A_{e\mu} \cdot G_{e\mu} = N_{e\mu}^{reco}/N_{t\bar{t}}$ is the preselection efficiency (from MC).

Systematic uncertanties

The effect of each systematic uncertainty on the fiducial differential cross section has been determined by recalculating each element of the double tagging technique with the appropriate shift, and re-solving the equations to find the shifted fiducial cross section.

- **Detector and reconstructed objects** (electrons, muons, jets, b-jets, …):

  $G_{e\mu}$ - C_b - $N_{1,2}^{bkg}$ are affected
- $t\bar{t}$ (ME, PS, hdamp, ttbar+HF, top pT rew, ISR, FSR, PDF):

  $G_{e\mu}$ - C_b - $N_{1,2}^{bkg}$ are affected
- **Background** (Wt, Z+jets, fakes, diboson):

  $N_{1,2}^{bkg}$ is affected
- **Integrated luminosity**:

  $\mathcal{L}$ - $N_{1,2}^{bkg}$ are affected
- **Beam energy**:

  $G_{e\mu}$ - C_b - $N_{1,2}^{bkg}$ are affected
- **MC statistics**:

  $G_{e\mu}$ - C_b - $N_{1,2}^{bkg}$ are affected

$$N_1^i = \mathcal{L}\,\sigma_{t\bar{t}}^i\,G_{e\mu}^i\,2\varepsilon_b^i\left(1 - C_b^i\varepsilon_b^i\right) + N_1^{i,bkg}$$

$$N_2^i = \mathcal{L}\,\sigma_{t\bar{t}}^i\,G_{e\mu}^i\,C_b^i\left(\varepsilon_b^i\right)^2 + N_2^{i,bkg}$$

Systematic uncertainties – ttbar modelling

- Calculated either with alternative samples or through reweighing of nominal samples
- For each variation, each part of the double tagging technique is re-calculated and the equations solved again

- **Matrix element**
- **h_{damp} variation**
- **Parton shower**
- **Top pT reweighting**
- **$t\bar{t}$ + HF**
- **ISR**
- **FSR**
- **PDF**

Systematic uncertainty name	$\Delta C_b/C_b$ [%]	$\Delta G_{e\mu}/G_{e\mu}$ [%]	$\Delta E_{e\mu}/E_{e\mu}$ [%]
Matrix element	-0.10 ± 0.22	0.25 ± 0.11	0.29 ± 0.12
h_{damp}	-0.06 ± 0.08	-0.05 ± 0.04	-0.05 ± 0.05
Parton shower and hadronisation	0.16 ± 0.08	-0.26 ± 0.04	0.04 ± 0.05
top p_T reweighting	0.03 ± 0.08	0.22 ± 0.04	0.61 ± 0.05
$t\bar{t}$ + Heavy Flavour	-0.33 ± 0.08	0.01 ± 0.04	0.01 ± 0.05
ISR (high)	-0.01 ± 0.08	0.06 ± 0.04	0.35 ± 0.05
ISR (low)	0.04 ± 0.08	-0.13 ± 0.04	-0.35 ± 0.05
FSR (high)	0.05 ± 0.09	-0.07 ± 0.04	-0.12 ± 0.05
FSR (low)	-0.09 ± 0.15	0.10 ± 0.07	0.16 ± 0.09
PDF	0.02 ± 0.08	0.04 ± 0.04	0.42 ± 0.05

Results

Source of uncertainty	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix Element	0.12	0.17
h_{damp} variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + Heavy Flavour	0.34	0.34
top p_{T} reweighting	0.19	0.58
Parton distribution functions	0.04	0.43
Initial state radiation	0.11	0.37
Final state radiation	0.29	0.35
Electron energy scale	0.10	0.10
Electron efficiency	0.37	0.37
Electron isolation (in situ)	0.51	0.51
Muon momentum scale	0.13	0.13
Muon reconstruction efficiency	0.35	0.35
Muon isolation (in situ)	0.33	0.33
Lepton trigger efficiency	0.05	0.05
Vertex association efficiency	0.03	0.03
Jet energy scale/resolution	0.10	0.10
b-tagging efficiency	0.07	0.07
$t\bar{t}/Wt$ interference	0.37	0.37
Wt cross-section	0.52	0.52
Diboson background	0.18	0.18
$t\bar{t}V + t\bar{t}H$	0.03	0.03
Z+jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	1.90	1.90
Total uncertainty	2.3	2.4

Leading uncertainty: Luminosity (1.9%)

Sub-leading uncertainty: top pT reweighting (0.58%)

Sub-sub-leading uncertainty: Wt cross-section (0.52%)

it is very complicated to go below 2% accuracy due to the luminosity uncertainty

- Top pair total fiducial cross-section (2.3 % of uncertainty)

  $\mathbf{10.62 \pm 0.02\ (\mathit{stat}) \pm 0.13\ (\mathit{syst}) \pm 0.20\ (\mathit{lumi}) \pm 0.02\ (\mathit{beam})}$ **pb**

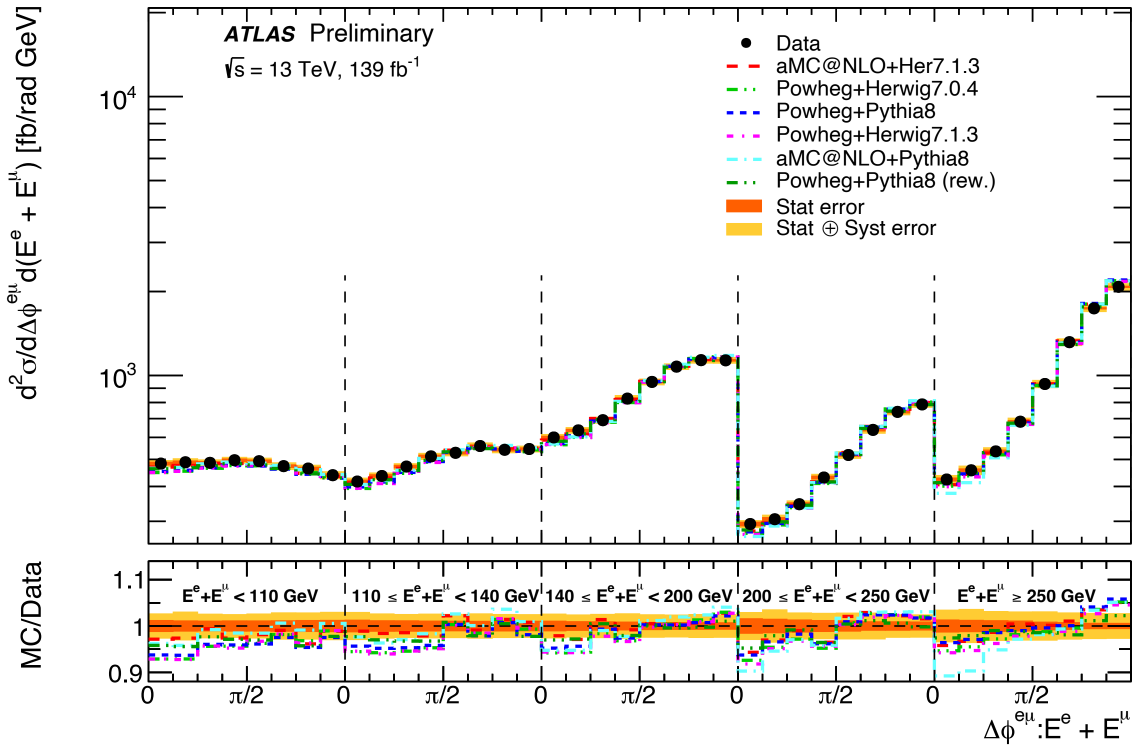
- Top pair total inclusive cross-section (2.4 % of uncertainty)

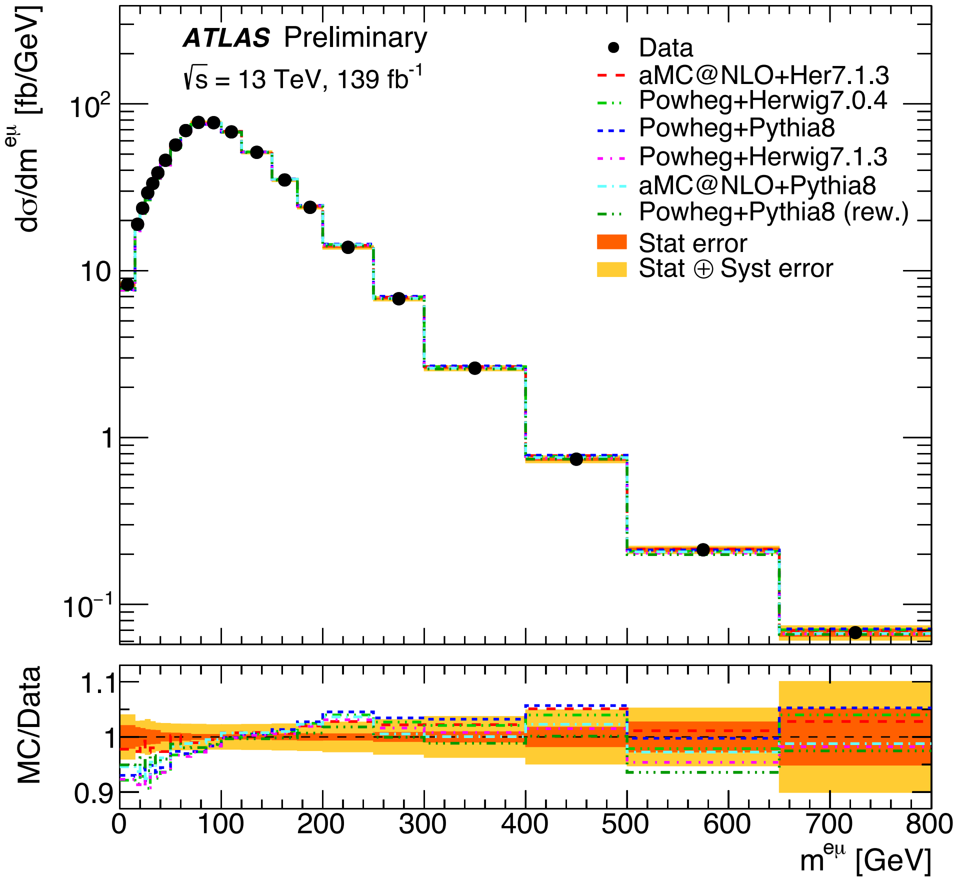
  $\mathbf{836 \pm 1\ (\mathit{stat}) \pm 12\ (\mathit{syst}) \pm 16\ (\mathit{lumi}) \pm 2\ (\mathit{beam})}$ **pb**

Results

- The dominating source of uncertainty is the Luminosity ($\sim 1.8\% - 2.1\%$) [absolute]
- Statistical uncertainty starts to contribute at high-pT or invariant mass
- Interference between $t\bar{t}$ and Wt is the main source of uncertainty in the last bin of many distributions

- In general, very low uncertainty ($2.5 - 3\%$) in most of the bins



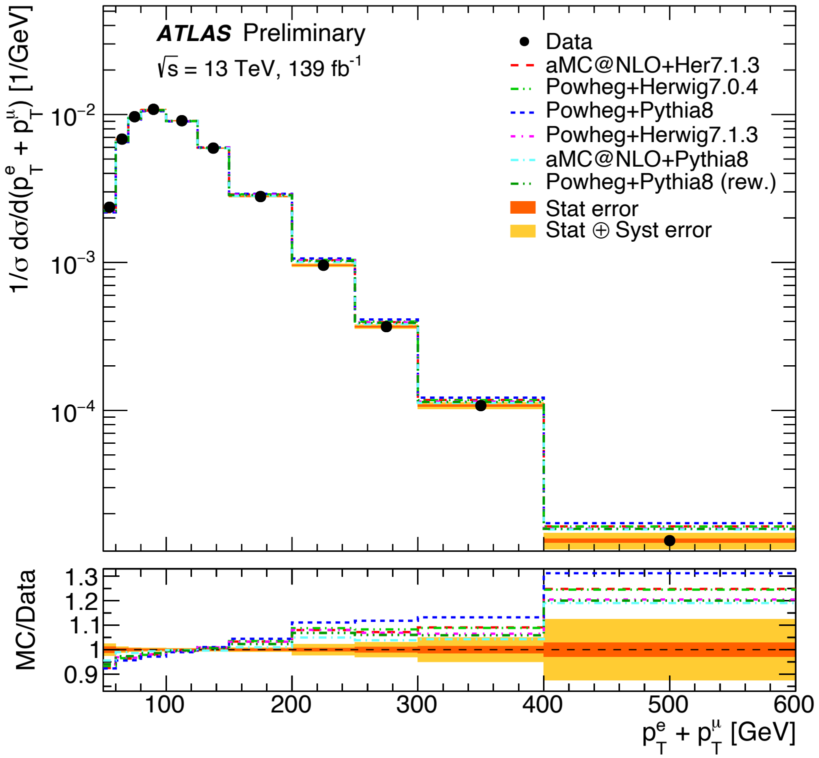


Test on different generators

χ^2 is performed for different generators on the normalised distributions.

$p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu}$		
$t\bar{t}$ generator	χ^2/ndof	P(χ^2)
Pow+Py8	131/9	< 0.01
Pow+Her7.0.4	83/9	< 0.01
aMCatNLO+Py8	14.38/9	0.11
Pow+Py8 - h_{damp} x 2	168/9	< 0.01
Pow+Py8 - Rad down	131/9	< 0.01
Pow+Py8 - PDF4LHC	125/9	< 0.01
Pow+Her7.1.3	75/9	< 0.01
Pow+Py8 - MEC off	37/9	< 0.01
Pow+Py8 - Rad up	140/9	< 0.01
Pow+Py8 - FSR up	144/9	< 0.01
Pow+Py8 - top p_{T} reweighting	42/9	< 0.01
Pow+Py8 - ISR up	120/9	< 0.01
Pow+Py8 - Heavy Flavour	131/9	< 0.01
MCatNLO+Her7.1.3	74/9	< 0.01
Pow+Py8 - ISR down	131/9	< 0.01
Pow+Py8 - FSR down	119/9	< 0.01

- Just few generators have a good description of the data.
- In some variables no generator can describe the data.
- No generator can describe the data in double differential distributions



Conclusions

- **Inclusive measurements compatible with previous ATLAS/CMS results and with the prediction**.
- Low uncertainty for the fiducial (2.3%) inclusive (2.4%) cross-section
- Very low uncertainty in all the bins of the differential cross-section (2.5-3% in most of the bins) [improvement wrt previous ATLAS differential measurements in the same channel]
- No generator that can described all the distributions
- In some cases it is difficult to find a generator that can describe the measured differential cross-section

- In the next days…
  - updated results using the new luminosity measurements
  - expected relative uncertainty on the inclusive cross-section of 1.8%
  - expected relative uncertainty on the differential cross-section of 1.5/2% in most of the bins

NNLO+NNLL prediction @13 TeV

$$\sigma_{t\bar{t}} = 832 \pm 35\,(scale)\,^{+20}_{-29}\,(PDF + \alpha_S)\,^{+23}_{-22}\,(m_{top})\;pb$$

This measurement @13 TeV

ATLAS $e\mu$ channel (139 fb^{-1}): [2.4%] - ATLAS-CONF-2022-061

$$\sigma_{t\bar{t}} = 836 \pm 1(stat) \pm 12(syst) \pm 16(lumi) \pm 2(beam)\;pb$$

Most precise/recent results @13 TeV

ATLAS $e\mu$ channel ($36.1\;fb^{-1}$): [2.40%] - EPJC 80 (2020) 528

$$\sigma_{t\bar{t}} = 826.4 \pm 3.6(stat) \pm 11.5(syst) \pm 15.7(lumi) \pm 1.9(beam)\;pb$$

CMS $e\mu$ channel ($35.9\;fb^{-1}$): [4.0%] - EPJC 79 (2019) 368

$$\sigma_{t\bar{t}} = 803 \pm 2(stat) \pm 25(syst) \pm 20(lumi)\;pb$$

CMS l+jets channel (137 fb^{-1}): [3.2%] - PRD 104 (2021) 092013

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

That's all!

➢ Additional material

Variables

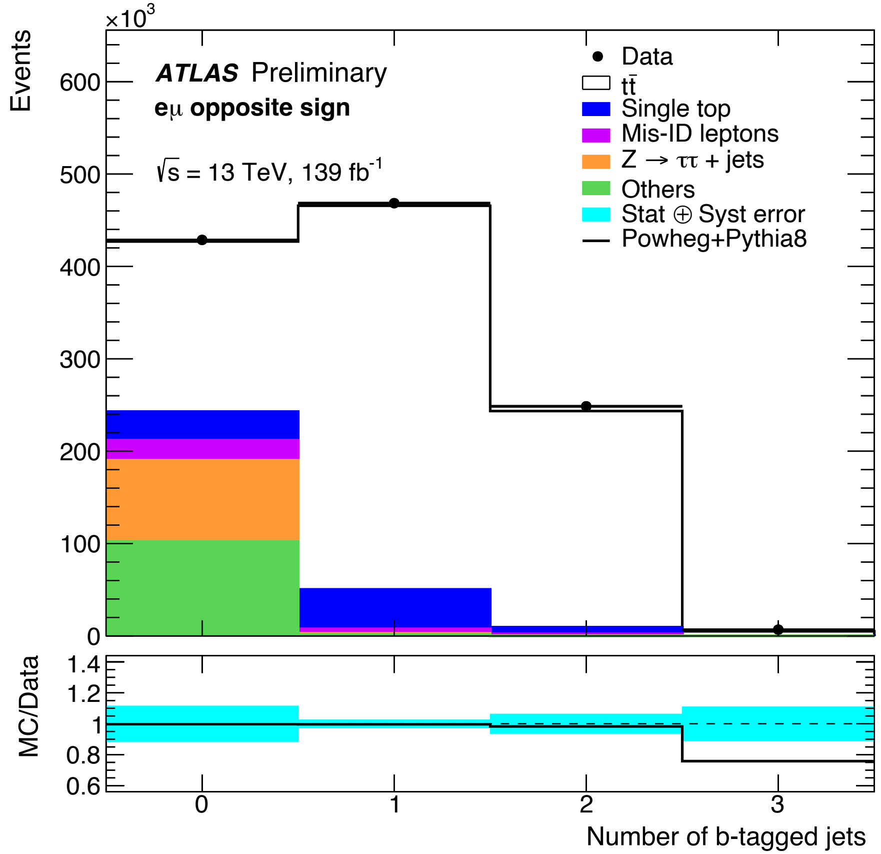
- p_T^l
  - Full Run2: (10 bins) 25, 30, 40, 50, 60, 75, 100, 140, 180, 250, 350 GeV
  - 36 fb-1: (11 bins) 20, 25, 30, 40, 50, 60, 80, 100, 120, 150, 200, 300 GeV
- $|\eta^l|$
  - Full Run 2: (24 bins) 0, 0.09, 0.18, 0.27, 0.36, 0.45, 0.54, 0.63, 0.72, 0.81, 0.9, 0.99, 1.08, 1.17, 1.26, 1.35, 1.44, 1.53, 1.62, 1.71, 1.8, 1.89, 1.98, 2.37, 2.5
  - 36 fb-1: 9 bins between 0, 2.5
- $m^{e\mu}$
  - Full Run 2: (21 bins) 0, 15, 20, 25, 30, 35, 40, 50, 60, 70, 85, 100, 120, 150, 175, 200, 250, 300, 400, 500, 650, 800 GeV
  - 36 fb-1: (12 bins) 0, 20, 40, 60, 80, 100, 120, 150, 200, 250, 300, 400, 500 GeV
- $E^e + E^\mu$
  - Full Run 2: (15 bins) 50, 60, 70, 80, 90, 110, 125, 160, 200, 250, 300, 370, 450, 550, 700, 900 GeV
  - 36 fb-1: (10 bins) 40, 80, 100, 120, 150, 200, 250, 300, 400, 500, 700 GeV
- $p_T^e + p_T^\mu$
  - Full Run 2: (11 bins) 50, 60, 70, 80, 100, 125, 150, 200, 250, 300, 400, 600 GeV
  - 36 fb-1: (8 bins) 40, 80, 100, 120, 150, 200, 250, 300, 400 GeV
- $p_T^{e\mu}$
  - Full Run 2: (10 bins) 0, 20, 30, 45, 60, 75, 100, 125, 150, 200, 300 GeV
  - 36 fb-1: (9 bins) 0, 20, 40, 60, 80, 100, 120, 150, 200, 300 GeV

- $\Delta\phi^{e\mu}$
  - Full Run 2: 30 bins between 0 and π
  - 36 fb-1: 10 bins between 0 and π
- $|y^{e\mu}|$
  - Full Run 2: 30 bins between 0, 2.5
  - 36 fb-1: 9 bins between 0, 2.5
- $|y^{e\mu}|$ vs $m^{e\mu}$
  - Full Run 2: (40 bins) 8 between [0, 2.5] x [0, 70, 100, 130, 200, inf] GeV
  - 36 fb-1: (32 bins) 8 between [0, 2.5] x [0, 80, 120, 200, 500] GeV
- $\Delta\phi^{e\mu}$ vs $m^{e\mu}$
  - Full Run 2: (40 bins) 8 between [0, π] x [0, 70, 100, 130, 200, inf] GeV
  - 36 fb-1: (32 bins) 8 between [0, π] x [0, 80, 120, 200, 500] GeV
- $\Delta\phi^{e\mu}$ vs $p_T^{e\mu}$
  - Full Run 2: (25 bins) 8 between [0, 1.65, 2.02,2.40,2.77, π] x [0, 40] + [0, π] x [40, 65, inf] GeV
  - 36 fb-1: -
- $\Delta\phi^{e\mu}$ vs $E^e + E^\mu$
  - Full Run 2: (40 bins) 10 between [0, π] x [0, 110, 140, 200, 250, inf] GeV
  - 36 fb-1: -

Overlap Removal

- Any electron candidates that share a track with a muon candidate are removed.
- Jets within $\Delta R < 0.2$ from an electron are removed.
- Electrons within the range $0.2 < \Delta R < 0.4$ of the remaining jets are rejected.
- Jets that have fewer than three tracks and are within $\Delta R < 0.2$ from a muon candidate are removed.
- Muons within $\Delta R < 0.4$ from any remaining jet, are discarded.

Event count



	OS		SS	
	N_1	N_2	N_1	N_2
$t\bar{t}$	415470 ± 130	234071 ± 94	-	-
Single t	42605 ± 76	7238 ± 31	-	-
Z+jets	1551 ± 66	96.9 ± 7.5	-	-
Diboson	1395.1 ± 9.4	49.5 ± 1.1	221.3 ± 2.4	10.50 ± 0.30
Charge mis-id lepton	1.88 ± 0.14	0.609 ± 0.061	851 ± 11	361.1 ± 7.0
Mis-identified lepton	4890 ± 100	1993 ± 67	2531 ± 57	899 ± 34
Other	1183.2 ± 4.1	800.8 ± 3.3	403.4 ± 1.7	236.4 ± 1.3
Total MC	467090 ± 190	244250 ± 120	4008 ± 58	1507 ± 36
Data	468450	248560	3995	1501
Data/MC	1.003 ± 0.002	1.017 ± 0.002	0.997 ± 0.021	0.996 ± 0.035

Good Data/MC agreement!

Binning

Migration matrices (reco-particle) have been built to check that around 90% of the events live in the diagonal elements.

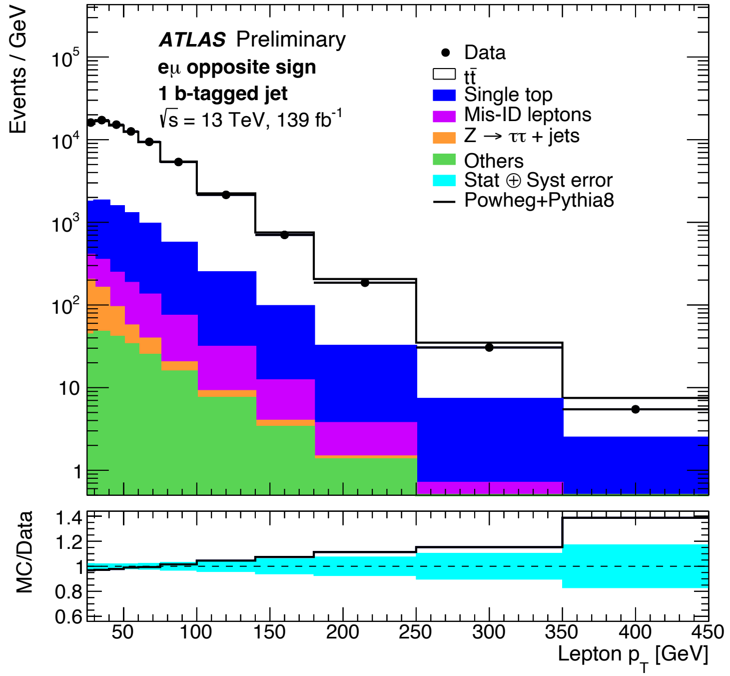
Binning choice:

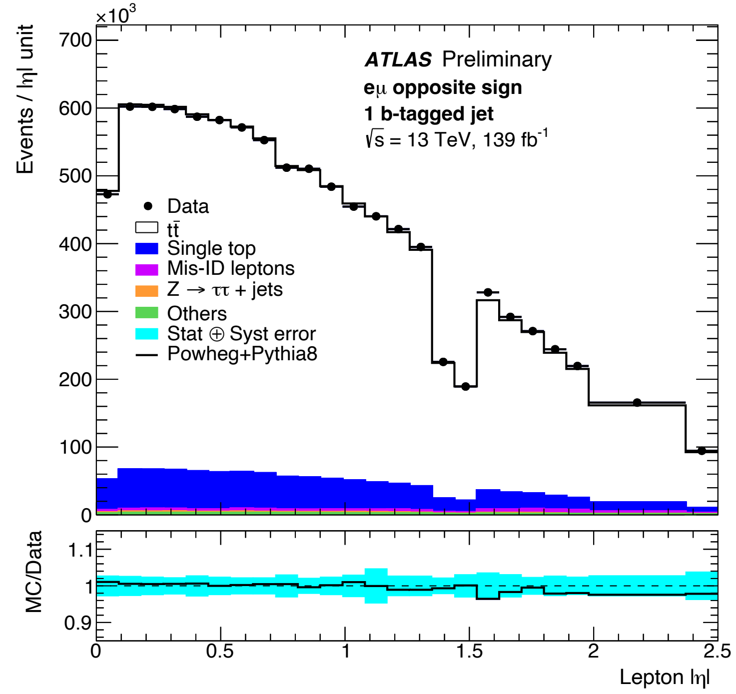
- Maximize the bin numbers for a variable while leaving 90% in the diagonal elements
- Good stat and not too high syst in each bin

Iterative procedure starting to small bins and merging them

With respect to the previous 36 fb^{-1} analysis

- p_T^l different binning
- $p_T^{e\mu}$ finer binning (from 9 to 10 bins)
- $p_T^e + p_T^\mu$ extended range (up to 600 GeV) + finer binning (from 8 to 11 bins)
- $E^e + E^\mu$ extended range (up to 900 GeV) + finer binning (from 10 to 15 bins)
- $m^{e\mu}$ extended range (up to 800 GeV) + finer binning (from 12 to 21 bins)
- $|\eta^l|$ finer binning (from 9 to 24 bins)
- $\Delta\phi^{e\mu}$ finer binning (from 10 to 30 bins)
- $|y^{e\mu}|$ finer binning (from 9 to 30 bins)
- $\Delta\phi^{e\mu} : m^{e\mu}$ finer binning in $m^{e\mu}$ (from 8x4 to 8x5 bins)
- $|y^{e\mu}| : m^{e\mu}$ finer binning in $m^{e\mu}$ (from 8x4 to 8x5 bins)
- $\Delta\phi^{e\mu} : p_T^{e\mu}$ completely new
- $\Delta\phi^{e\mu} : E^e + E^\mu$ completely new





Systematic uncertainties – detector and objects

- Calculated varying the nominal weights or the trees in the ntuples
- For each variation, each part of the double tagging technique is recalculated and the equations solved again

- Electron scale and resolution
- Electron efficiency
- **Electron isolation**
- Muon scale and resolution scale
- Muon reconstruction efficiency
- Muon trigger, TTVA efficiency
- **Muon isolation**
- **JVT**
- JES b-jes response
- JES effective NPs
- JES EtaInterCalibration
- JES flavor
- JES pileup
- JES PunchThrough
- JES HighPt
- MET soft term
- JER
- b-tagging

Other uncertainties: up/down variation within their uncertainties

Electron and muon isolation measured in-situ with ttbar and data events (instead of $Z \rightarrow ll$ events).
New scale factors and corresponding systematic uncertainty introduced
Eliminated the uncertainties releated to the $Z \rightarrow ll$ isolation SFs.

JVT uncertainty -> varying weight_jvt_UP/DOWN -> large impact on the xs measurement, due to high impact on $G_{e\mu} = N_{e\mu}^{reco}/N_{e\mu}^{particle}$;
JVT should not in principle affect $G_{e\mu}$ (we do not apply cuts on # of jets per event)
OR can play a foundamental role in this case (a change on JVT can change the number of good jets and then the OR can change the number of lepton per event);
An estimate of the JVT uncertainty is:

fraction of leptons removed in OR by jet passing JVT cut * relative change in jet JVT efficiency = $\sim 0.02 - 0.03\%$

The fraction of leptons that is changed varying the JVT cut is at most 2‰
We can assume that $G_{e\mu}$ is unaffected by the JVT cut

Systematic uncertainties – ttbar modelling

- Calculated either with alternative samples or through reweighing of nominal samples
- For each variation, each part of the double tagging technique is re-calculated and the equations solved again

- **Matrix element**
- **h_{damp} variation**
- **Parton shower**
- **Top pT reweighting**
- **$t\bar{t}$ + HF**
- **ISR**
- **FSR**
- **PDF**

h_{damp}: using an alternative Powheg + Pythia8 sample with varied h_damp $(= 3 \cdot m_{top})$ compared with Powheg + Pythia8

Parton shower: alternative sample Powheg + Herwig7.0.4 compared with Powheg + Pythia8

Top p_T reweighting: Top p_T corrected at truth level based on NNLO QCD + NLO EW and compared with nominal Powheg + Pythia8

$t\bar{t}$ +HF: increasing by ~30% the number of events with > 2 b-jets to match the prediction with the data

Matrix element: alternative sample aMC@NLO + Pythia8 compared with Powheg + Pythia8 with a particular tuning (MEC off)

ISR UP/DOWN: using Powheg + Pythia8 sample reweighed with *mR20mF20*Var3cDown/mc_weight_nominal* and *mR20mF20*Var3cUp/mc_weight_nominal*

FSR UP: using the nominal Powheg + Pythia8 sample reweighed with *isr:muRfac=10_fsr:muRfac=20*
FSR DOWN: usign the nominal Powheg + Pythia 8 sample reweighed with *isr:muRfac=10_fsr:muRfac=05*

PDF: using the nominal Powheg + Pythia8 sample reweighed to the PDF4LHC and its error set of 30 variations. The uncertainty is given by the quadrature sum of the different between the central value and the 30 variations

$$\delta^{PDF}\sigma = \sqrt{\sum_{k=1}^{N_{mem}} (\sigma^k - \sigma^0)^2}$$

Systematic uncertainties – background

- The background systematics are evaluated for one background at the time either by rescaling its yield or by comparing the nominal sample with an alternative one.

- Wt
- Z+jets
- Mis-ID leptons
- Dibosons
- ttV

Wt
Cross section (5.3%)
Interference between $t\bar{t}$ and Wt using alternative samples Powheg + Pythia8 to evaluate the diagram removal vs diagram subtraction scheme

Mis-ID Leptons
R factor (25% for 1 b-jet and 50% for 2 b-jet)
N_{prompt} (50%)
Data in Same Sign (data statistics)

Z+jets
Scale factor (5%) [the uncertainty from fit is less than 1%]
Modelling using alternative samples Powheg + Pythia8 to recalculate the $Z \rightarrow ll$ SFs and the $Z + \tau\tau$ shape

ttV
Cross section (13%)

Dibosons
Modelling using alternative sample Powheg + Pythia8
Scale reweighting of the nominal sample in order to change the factorisation and renormalisation scale
Flavour Compisition (40%) to take into account the light component (20%) and heavy component (30%) as done in tZ

Systematic uncertainties – others

- **Luminosity**
  - Yields of all samples varied of 1.7 % (UP/DOWN)
- **Beam energy**
  - Total cross-section: 0.23%
  - Differential cross-section: for the differential cross section: using aMC@NLO + Pythia8 sample reweighting the ttbar events using LHAPDF package in the same way as ATL-COM-PHYS-2018-1163

LHAPDF library [62]. The reweighting ratio is:

$$R = \frac{f(x_1^{mod}, Q^2) \cdot f(x_2^{mod}, Q^2)}{f(x_1, Q^2) \cdot f(x_2, Q^2)} \quad (30)$$

where x_1 and x_2 are the momentum fractions of the partons (also called Bjorken-x values), x_1^{mod} and x_2^{mod} are the shifted momentum fractions and Q^2 is the energy scale of the collision. The x_1^{mod} and x_2^{mod} are found as: $x_i^{mod} = x_i \cdot (1 \pm 0.001)$, where 0.001 comes from the LHC beam energy uncertainty of 0.1%

Comparison with generators (36 fb^{-1})

Generator	p_T^ℓ	$\lvert\eta^\ell\rvert$	$p_T^{e\mu}$	$m^{e\mu}$	$\lvert y^{e\mu}\rvert$	$\Delta\phi^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
N_{dof}	10	8	8	11	8	9	7	9
Powheg + PY8	43.7	19.5	8.6	44.3	11.4	14.4	32.5	18.4
Powheg + PY6 CT10	36.1	7.9	9.3	33.0	16.2	16.2	21.9	30.5
Powheg + HW7	34.8	15.9	11.5	62.7	9.4	17.3	23.0	14.7
Powheg + PY8 p_T rew.	20.2	14.7	2.3	38.3	8.4	12.7	9.4	14.0
Powheg + PY8 RadDn	40.0	24.2	6.1	44.3	9.2	16.3	29.0	20.1
Powheg + PY8 RadUp	33.0	16.3	21.9	35.3	12.3	6.4	26.7	16.5
Powheg + PY8 $\mu_{F,R} \times 2$	46.5	21.6	6.2	42.6	8.5	16.5	28.9	17.1
Powheg + PY8 $\mu_{F,R} \times 0.5$	39.8	17.3	11.4	38.0	10.7	10.9	27.6	14.2
Powheg + PY8 PDF4LHC15	43.4	14.6	7.4	39.0	6.2	13.5	28.0	15.9
Powheg + PY8 CT14	44.1	9.3	7.6	37.0	8.2	13.5	28.5	18.2
Powheg + PY8 MMHT	41.2	17.7	6.9	39.0	6.3	13.2	26.3	14.3
aMC@NLO + PY8	26.2	25.7	11.4	19.7	16.7	13.2	12.5	14.0
aMC@NLO + PY8 CT10	24.9	11.7	10.6	16.9	10.0	13.4	12.0	19.0
aMC@NLO + PY8 HERA2	17.1	96.6	6.9	26.0	68.5	12.5	6.1	38.4
Powheg + PY8	$4 \cdot 10^{-6}$	0.012	0.37	$6 \cdot 10^{-6}$	0.18	0.11	$3 \cdot 10^{-5}$	0.030
Powheg + PY6 CT10	$8 \cdot 10^{-5}$	0.45	0.32	$5 \cdot 10^{-4}$	0.039	0.062	$3 \cdot 10^{-3}$	$4 \cdot 10^{-4}$
Powheg + HW7	$1 \cdot 10^{-4}$	0.043	0.18	$3 \cdot 10^{-9}$	0.31	0.045	$2 \cdot 10^{-3}$	0.098
Powheg + PY8 p_T rew.	0.028	0.065	0.97	$7 \cdot 10^{-5}$	0.39	0.18	0.23	0.12
Powheg + PY8 RadDn	$2 \cdot 10^{-5}$	$2 \cdot 10^{-3}$	0.64	$6 \cdot 10^{-6}$	0.32	0.060	$1 \cdot 10^{-4}$	0.017
Powheg + PY8 RadUp	$3 \cdot 10^{-4}$	0.038	$5 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	0.14	0.70	$4 \cdot 10^{-4}$	0.057
Powheg + PY8 $\mu_{F,R} \times 2$	$1 \cdot 10^{-6}$	$6 \cdot 10^{-3}$	0.62	$1 \cdot 10^{-5}$	0.39	0.056	$1 \cdot 10^{-4}$	0.048
Powheg + PY8 $\mu_{F,R} \times 0.5$	$2 \cdot 10^{-5}$	0.027	0.18	$8 \cdot 10^{-5}$	0.22	0.28	$3 \cdot 10^{-4}$	0.12
Powheg + PY8 PDF4LHC15	$4 \cdot 10^{-6}$	0.067	0.49	$5 \cdot 10^{-5}$	0.62	0.14	$2 \cdot 10^{-4}$	0.068
Powheg + PY8 CT14	$3 \cdot 10^{-6}$	0.32	0.47	$1 \cdot 10^{-4}$	0.42	0.14	$2 \cdot 10^{-4}$	0.033
Powheg + PY8 MMHT	$1 \cdot 10^{-5}$	0.024	0.55	$5 \cdot 10^{-5}$	0.62	0.15	$5 \cdot 10^{-4}$	0.11
aMC@NLO + PY8	$3 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	0.18	0.049	0.034	0.15	0.086	0.12
aMC@NLO + PY8 CT10	$5 \cdot 10^{-3}$	0.16	0.23	0.11	0.27	0.15	0.10	0.025
aMC@NLO + PY8 HERA2	0.073	0	0.54	$6 \cdot 10^{-3}$	0	0.19	0.53	$1 \cdot 10^{-5}$

Comparison with generators (p_T)

χ^2 is performed for different generators on the normalised distributions

- Lepton p_T: only aMCatNLO+Py8 can describe the data but with a small χ^2 (P = 4%)
- $p_T^{e\mu}$: most of the gen. have a good χ^2 [better results from top p_T reweighting with 44%]
- $p_T^e + p_T^\mu$: only aMCatNLO+Py8 can describe the data with a probability of 11%

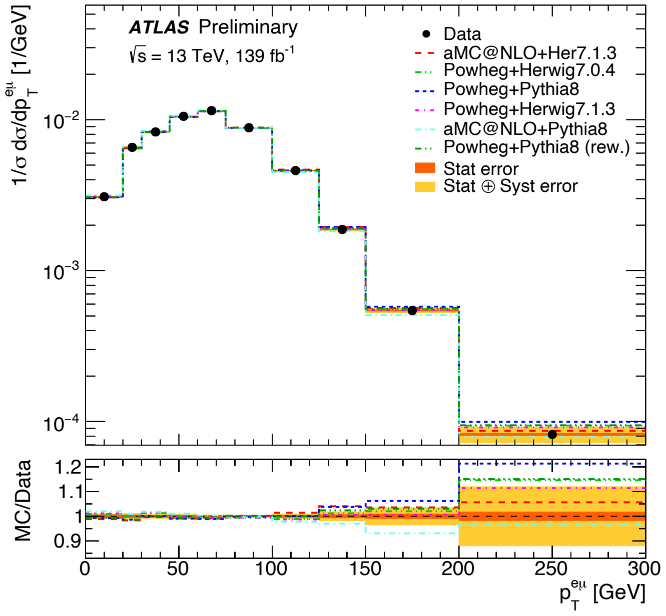
$$\chi^2 = V_{b-1}^T \cdot Cov_{b-1\,x\,b-1}^{-1} \cdot V_{b-1}$$

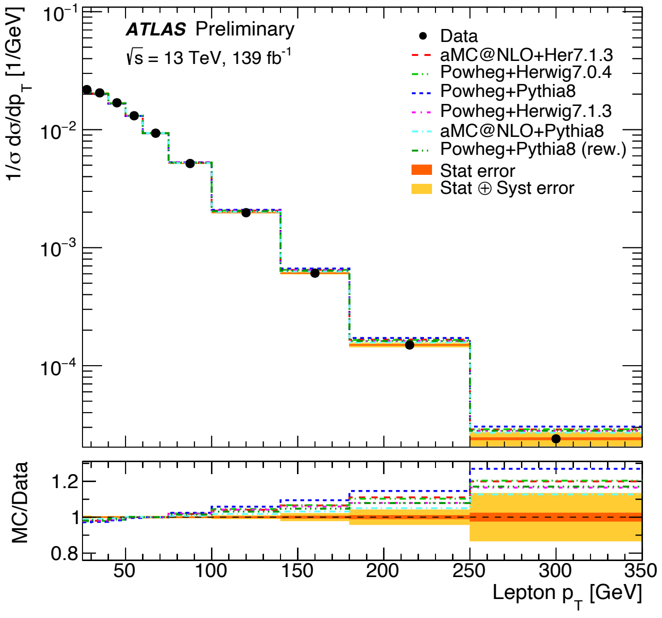
V_b is the vector of the differences between data and prediction

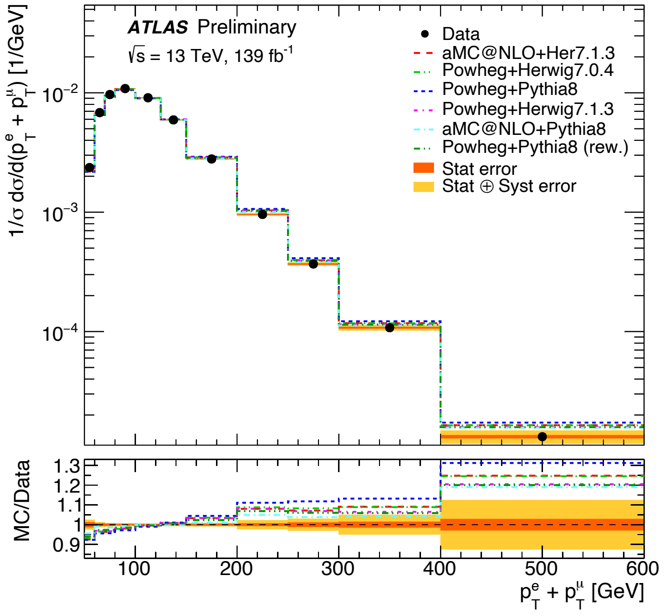
$b-1$ is the number of elements (bin) of a normalised variable

$Cov_{b\,x\,b}$ is total (stat+syst) covariance matrix

Similar results from the previous ATLAS analysis with an exception of $p_T^e + p_T^\mu$ (many gen. have a non negligible probability)







Comparison with generators (spatial distributions)

χ^2 is performed for different generators on the normalised distributions

- $\Delta\phi^{e\mu}$ and Lepton $|\eta|$: no one gen. can describe the data
- $|y^{e\mu}|$: many gen. have a χ^2 of the order of few %. Better results from Pow+Py8 with the PDH4LHC PDF set (prob. of 19%)

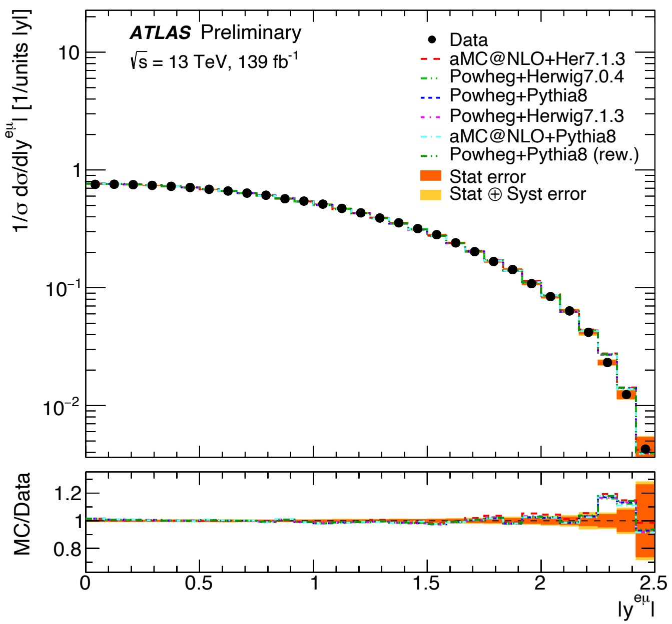
$$\chi^2 = V_{b-1}^T \cdot Cov_{b-1\,x\,b-1}^{-1} \cdot V_{b-1}$$

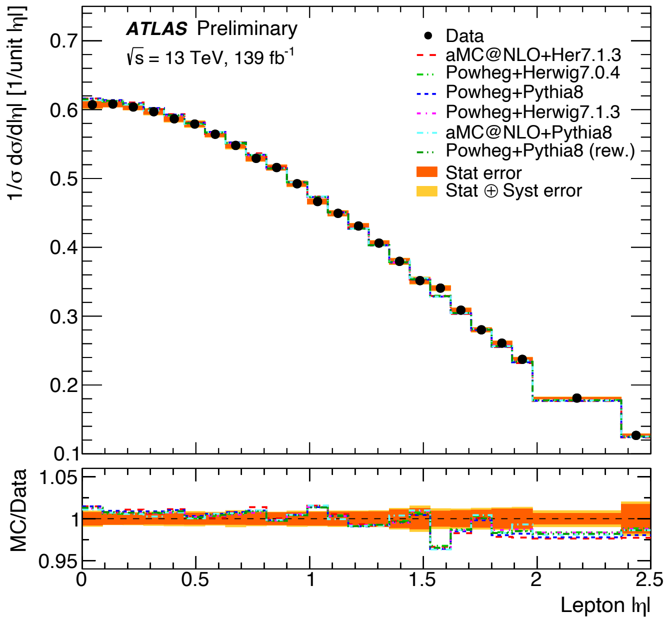
V_b is the vector of the differences between data and prediction

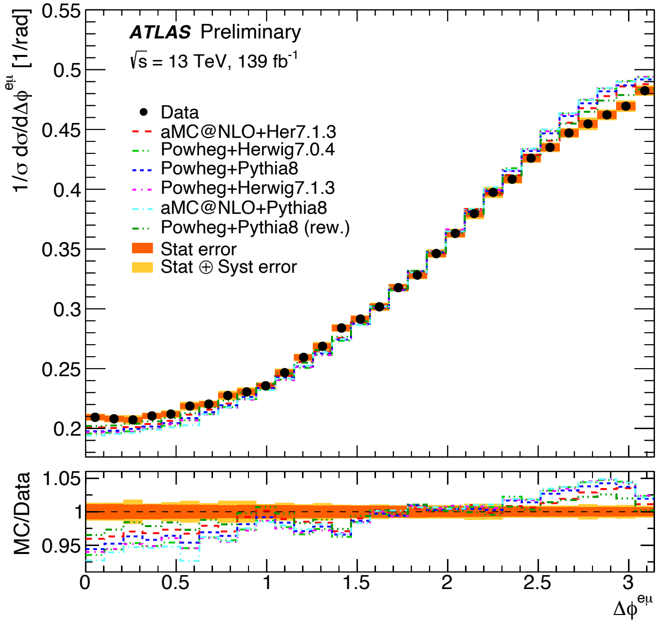
$b-1$ is the number of elements (bin) of a normalised variable

$Cov_{b\,x\,b}$ is total (stat+syst) covariance matrix

Different results from the previous ATLAS analysis (with ~1/3 bins)







Comparison with generators (mass and energies)

χ^2 is performed for different generators on the normalised distributions

- $m^{e\mu}$: only aMCatNLO+Herwig7.1.3 can describe the data with a probability of 6%
- $E^e + E^\mu$: better description from aMCatNLO+Py8 and Pow+Py8 with MEC off while other gen. cannot describe the data

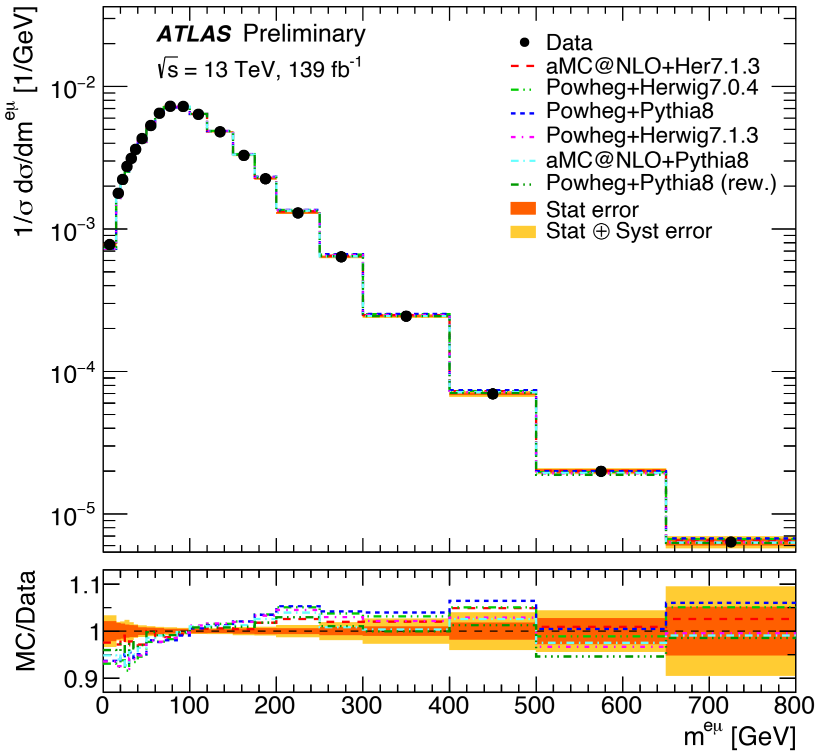
$$\chi^2 = V_{b-1}^T \cdot Cov_{b-1\,x\,b-1}^{-1} \cdot V_{b-1}$$

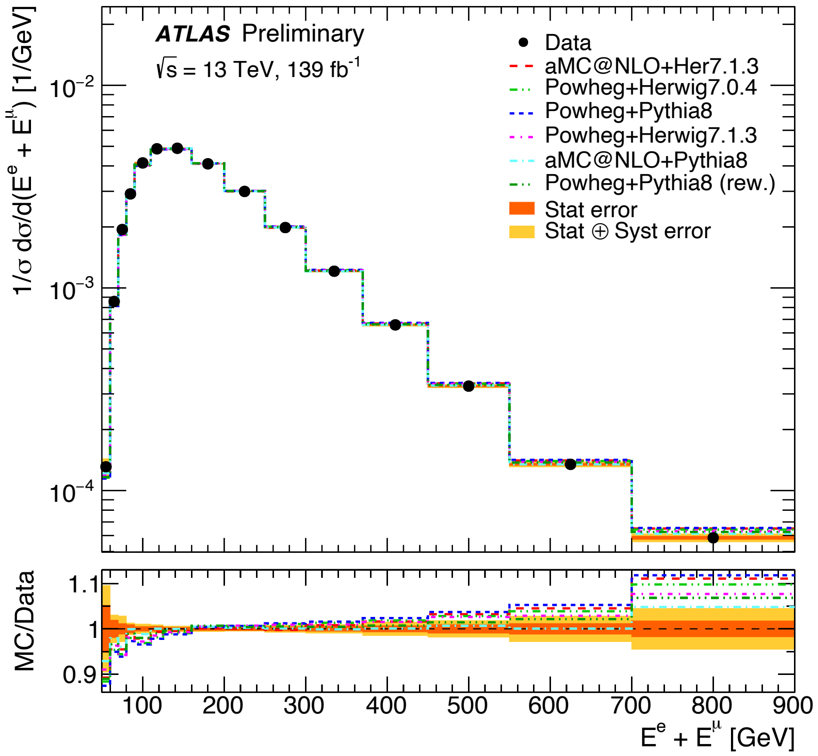
V_b is the vector of the differences between data and prediction

$b-1$ is the number of elements (bin) of a normalised variable

$Cov_{b\,x\,b}$ is total (stat+syst) covariance matrix

Similar results from the previous ATLAS





Test on different generators (spatial distributions)

χ^2 is performed for different generators on the normalised distributions

- Double differential measurements: no one of the analysed generator can describe the data

$$\chi^2 = V_{b-1}^T \cdot Cov_{b-1\,x\,b-1}^{-1} \cdot V_{b-1}$$

V_b is the vector of the differences between data and prediction
$b-1$ is the number of elements (bin) of a normalised variable
$Cov_{b\,x\,b}$ is total (stat+syst) covariance matrix

Quite different results wrt the previous ATLAS analysis (with less bins)