# Measurement of differential cross-sections of $t\bar{t}$ production in the electron-muon channel with the full Run 2 data set

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On behalf the ATLAS Collaboration

LHC Top WG – 09.11.2022

# Outline



- Analysis motivation
- Object reconstruction and event selection
- Background estimation
- Analysis method
- Systematic uncertainties
- Results

# Analysis motivation

**MOTIVATION HIGHLIGHTS:**

- $e\mu$ channel has smallest backgrounds and smaller associated uncertainties
- New measurements of inclusive $\sigma_{t\bar{t}}$ using Full Run2
- Using huge statistical power of full Run2 to measure differential and double differential $\sigma_{t\bar{t}}$
- Test of different generators

NNLO+NNLL prediction @13 TeV

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

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

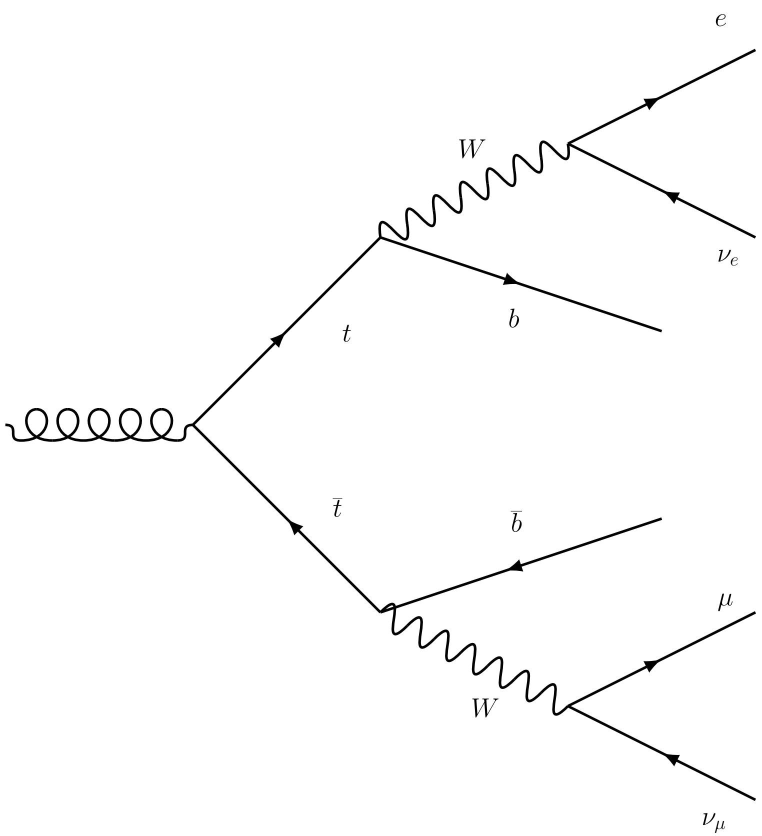
$$\sigma_{t\bar{t}} = 803 \pm 2(stat) \pm 25(syst) \pm 20(lumi)\ pb$$

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

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

## Respect to the previous dilepton analysis:

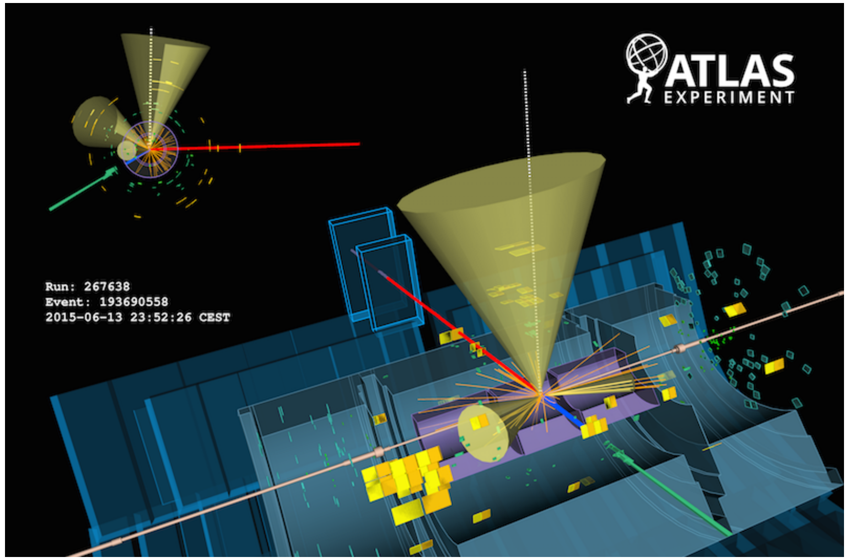
- Extended range of the variables;
- Finer binning;
- Two new double differential measurements.



# 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)
- Truth information on the leptons using the *MCTruthClassifier*

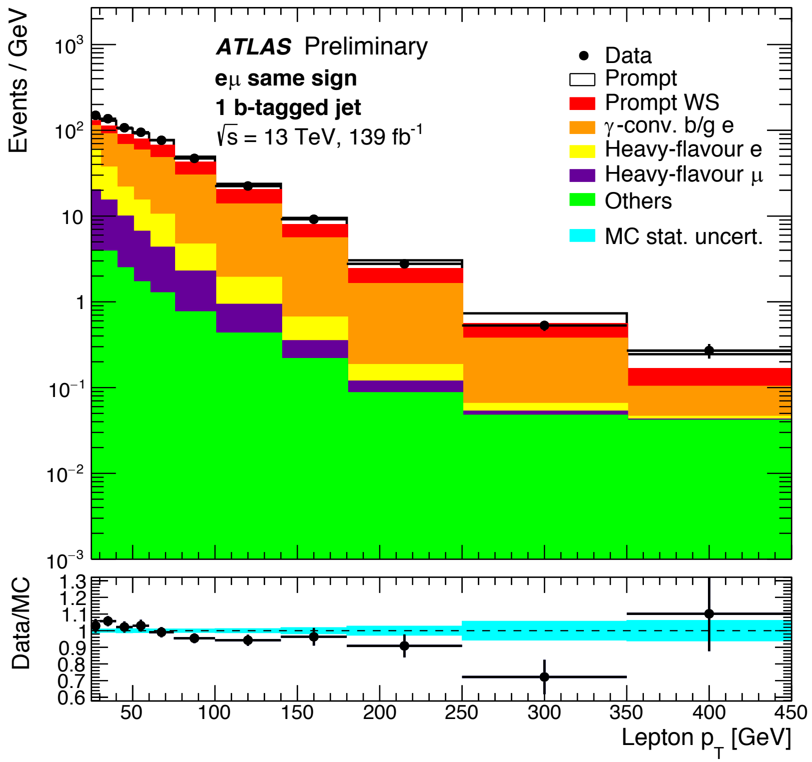
i = bin number

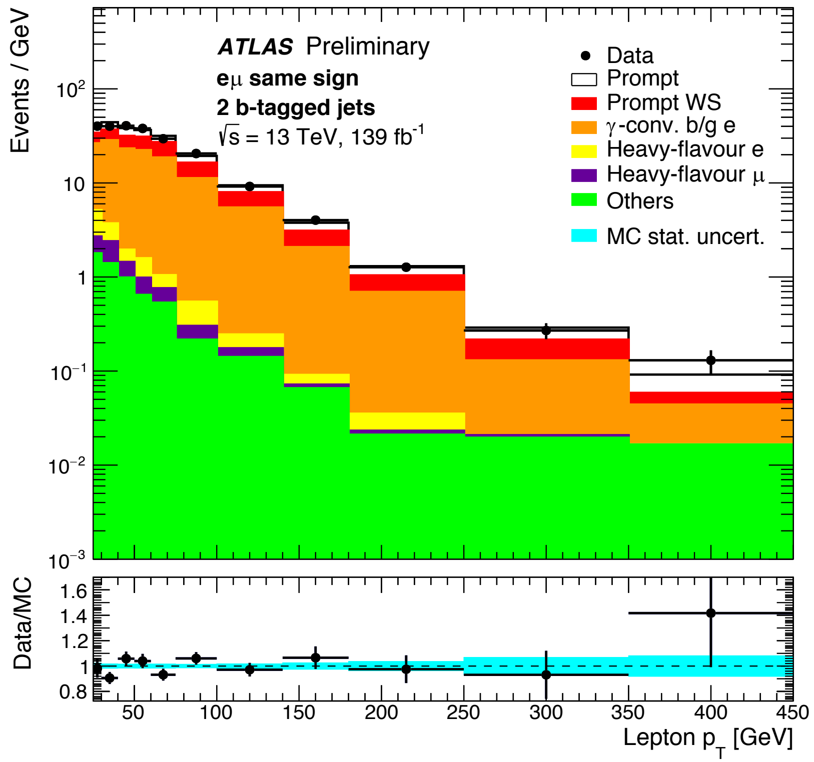
b = Number of b-jet

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

From data = green

From MC (using *MCTruthClassifier*) = blue



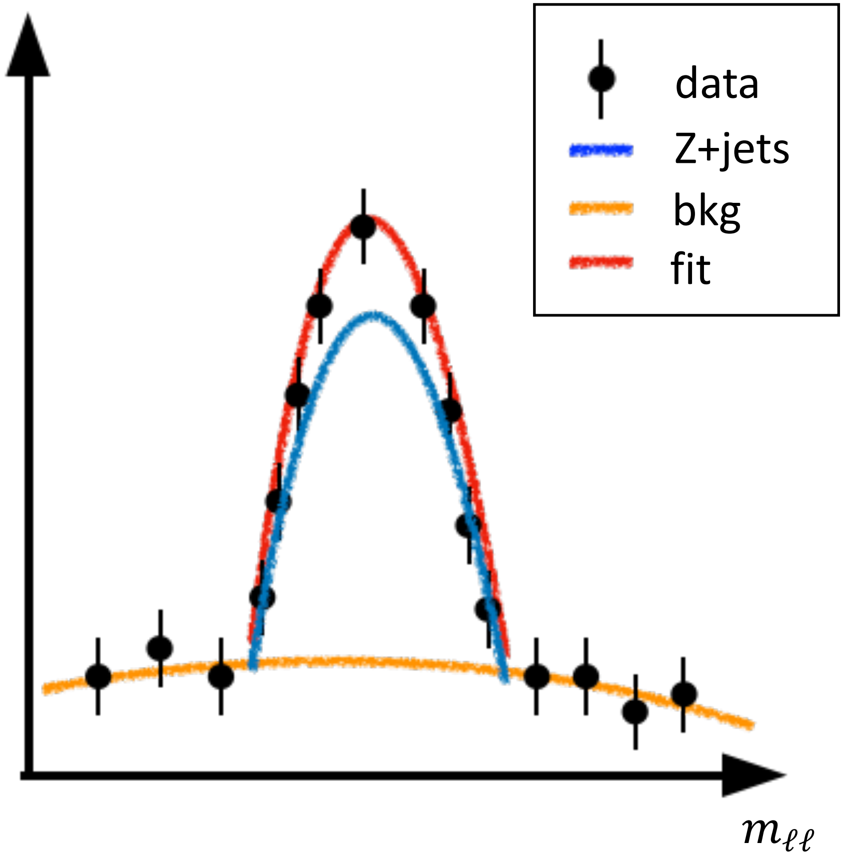




Fakes classes:

- Charge mis-identification
- Electron from Heavy Flavour
- Muon from Heavy Flavour
- Electron from $\gamma$ converions
- OTHERS

# Z + jets estimation

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



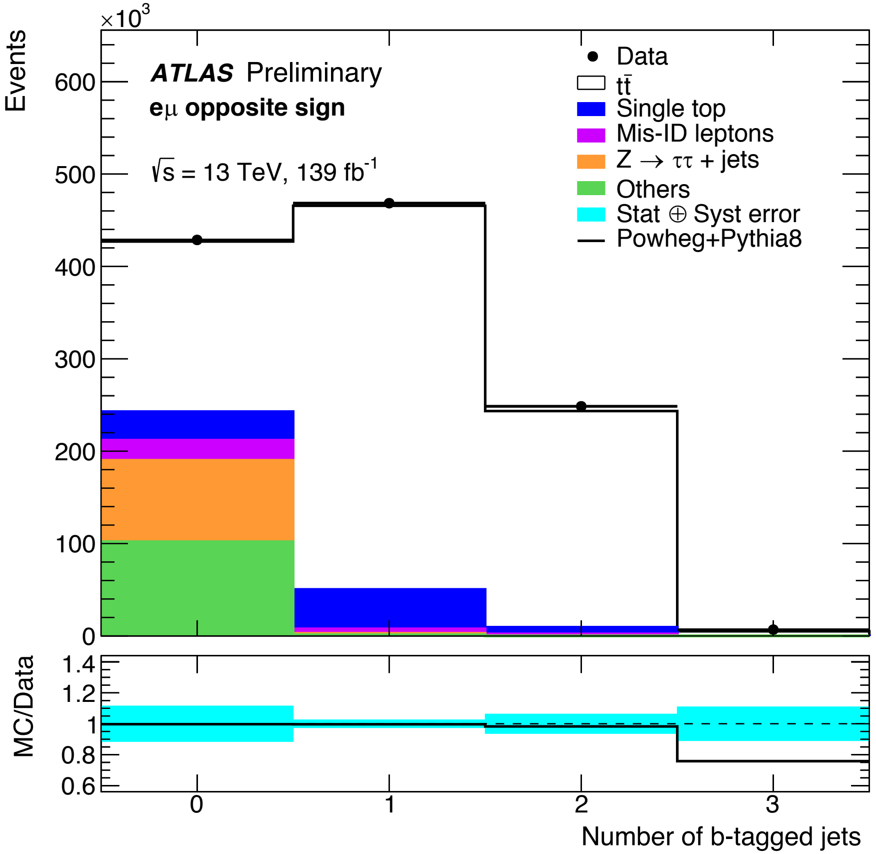

Fitting function:

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

Scale factor

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

# 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!

# Analysis strategy

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

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

$\boldsymbol{i}$ is the bin number of one of the kinematic variables used;
$N_{1,2}^i$ total number of events in OS and OF dilepton $t\bar{t}$ channel for 1 b-tagged and 2 b-tagged jets (from data);
$\mathcal{L}$ is the luminosity;
$\sigma_{t\bar{t}}^i$ 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);
$\varepsilon_b^i$ is the b-tagging efficiency (fitted from data);
$C_b^i = \varepsilon_{bb}^i/(\varepsilon_b^i)^2 = 4N_{all}N_2/(N_1 + 2N_2)^2$ 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).
$A_{e\mu} = (N_{e\mu}^{particle}/N_{dilepton}) \cdot 1/BR(t\bar{t} \to e\mu)$ 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).

For total inclusive cross-section measurement

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

$$\sigma_{t\bar{t}} = A_{e\mu}\sigma_{t\bar{t}}^{fid}$$

# Binning

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

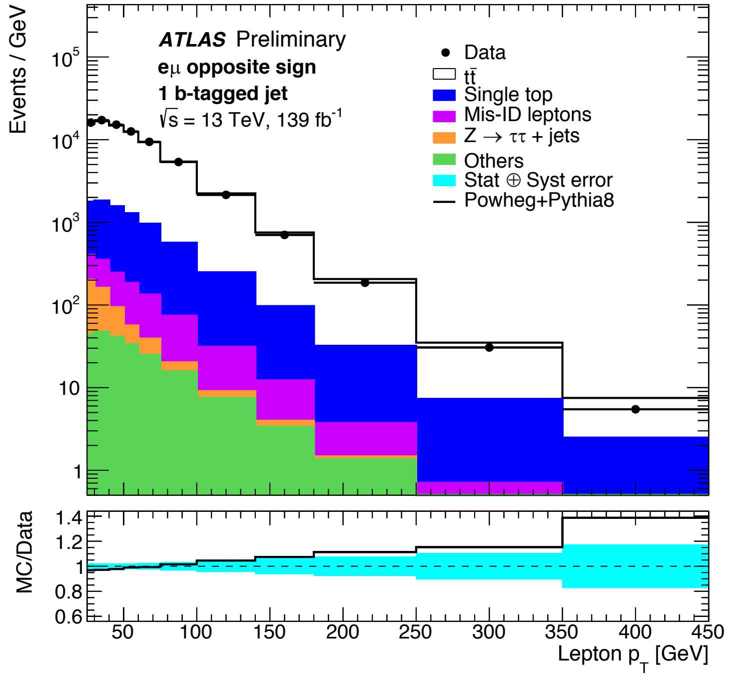
Binning choice:

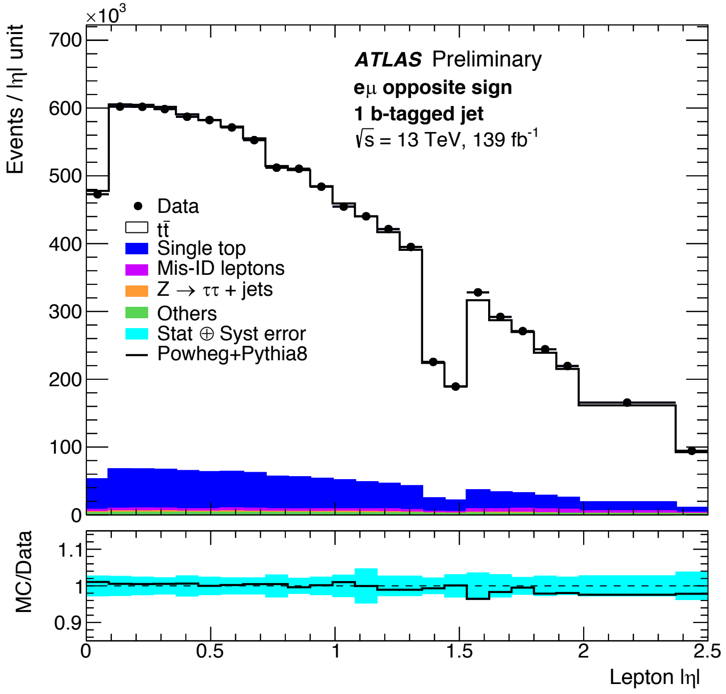
- Maximize the bin numbers for a variable while leaving 90% in the diagonal elements
- Good stat and not too high syst in each bin

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 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**

**$h_{damp}$**: 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 $\sim$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 – 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 |
| $h_{\text{damp}}$ | -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 |

# 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 $Z \to ll$ 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

# Results

| Source of uncertainty | $\Delta\sigma_{t\bar{t}}^{\text{fid}}/\sigma_{t\bar{t}}^{\text{fid}}$ (%) | $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%) |
|---|---|---|
| Data statistics | 0.15 | 0.15 |
| MC statistics | 0.04 | 0.04 |
| Matrix Element | 0.12 | 0.17 |
| $h_{\text{damp}}$ variation | 0.01 | 0.01 |
| Parton shower | 0.08 | 0.22 |
| $t\bar{t}$ + Heavy Flavour | 0.34 | 0.34 |
| top $p_{\text{T}}$ 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)

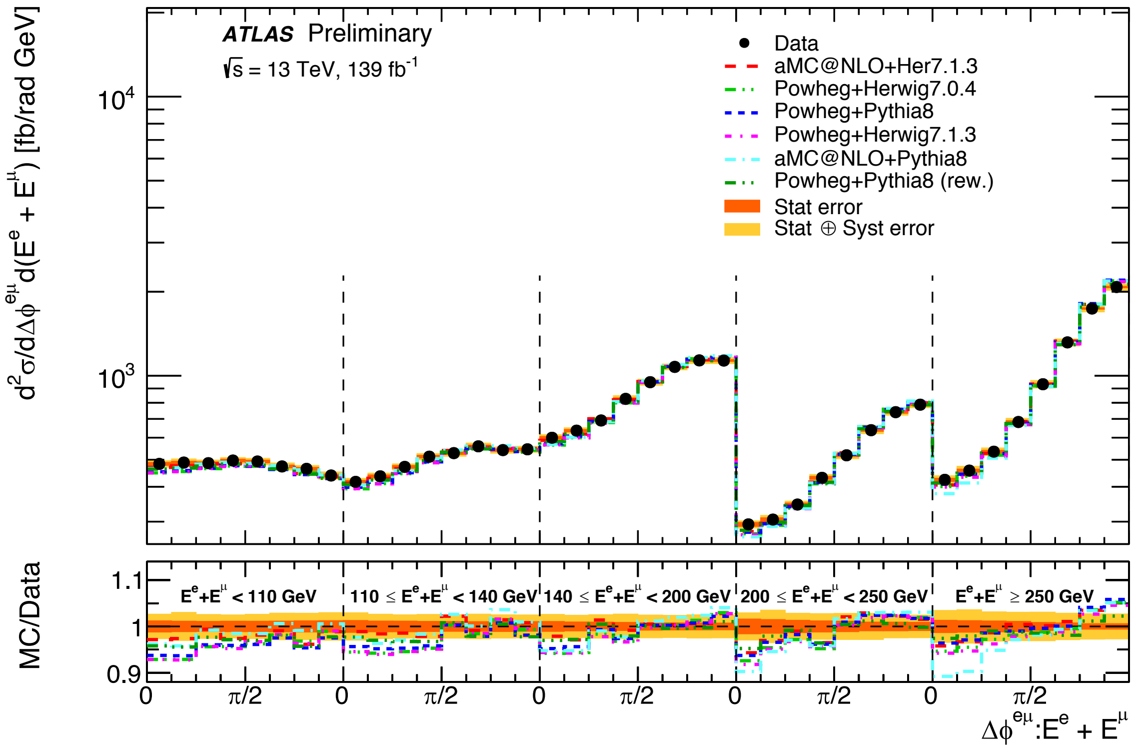
  $\mathbf{10.62 \pm 0.02\ (\mathit{stat}) \pm 0.13\ (\mathit{syst}) \pm 0.20\ (\mathit{lumi}) \pm 0.02\ (\mathit{beam})}$ **pb**

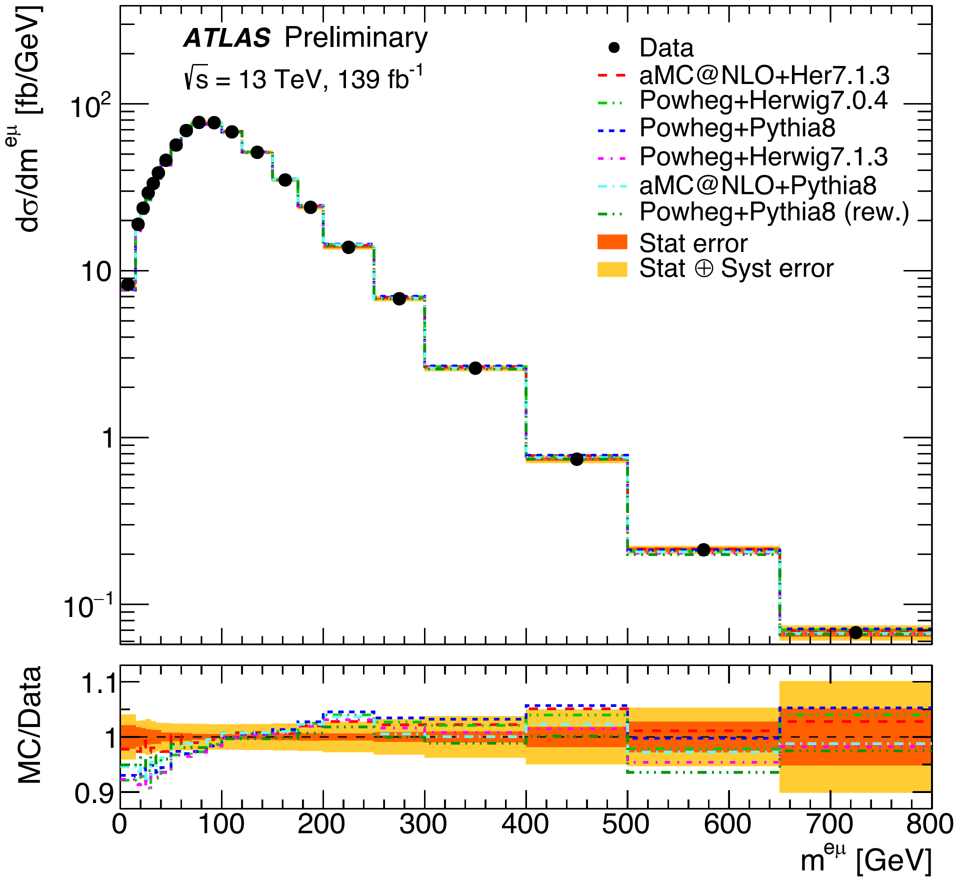
- Top pair total inclusive cross-section (2.4 % of uncertainty)

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



# Comparison with generators ($p_T$)

$\chi^2$ is performed for different generators on the normalised distributions

- Lepton $p_T$: only aMCatNLO+Py8 can describe the data but with a small $\chi^2$ (P = 4%)
- $p_T^{e\mu}$: most of the gen. have a good $\chi^2$ [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%

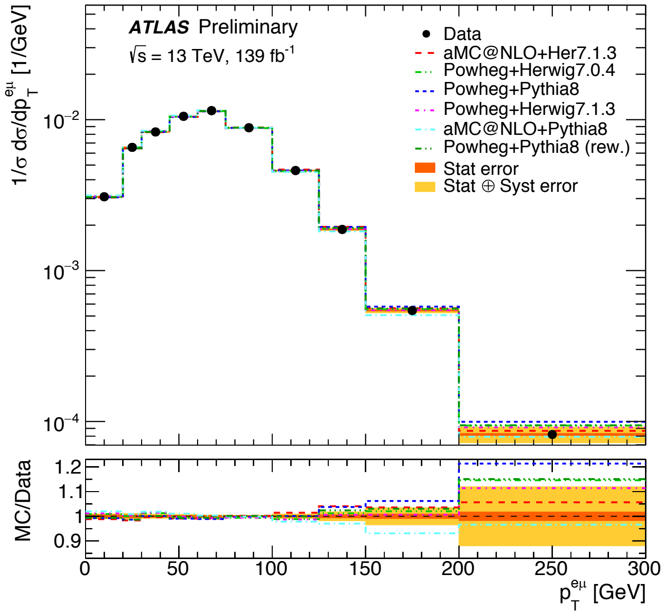
$$\chi^2 = V_{b-1}^T \cdot Cov_{b-1\,x\,b-1}^{-1} \cdot V_{b-1}$$

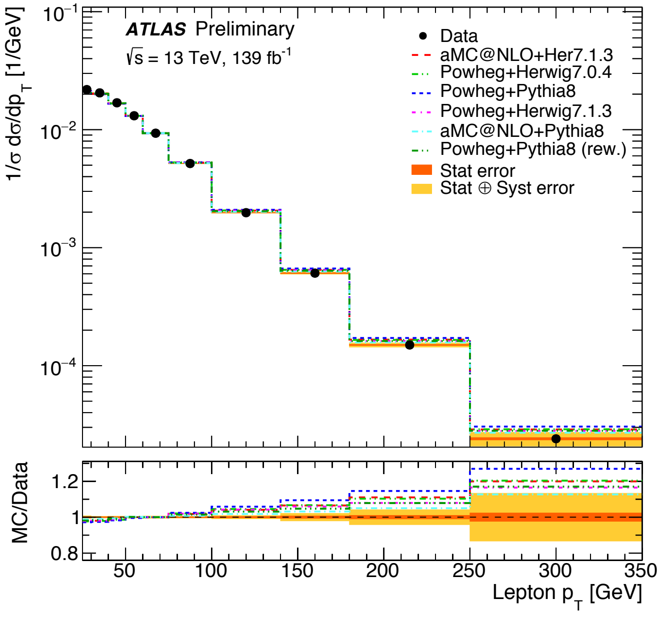
$V_b$ is the vector of the differences between data and prediction

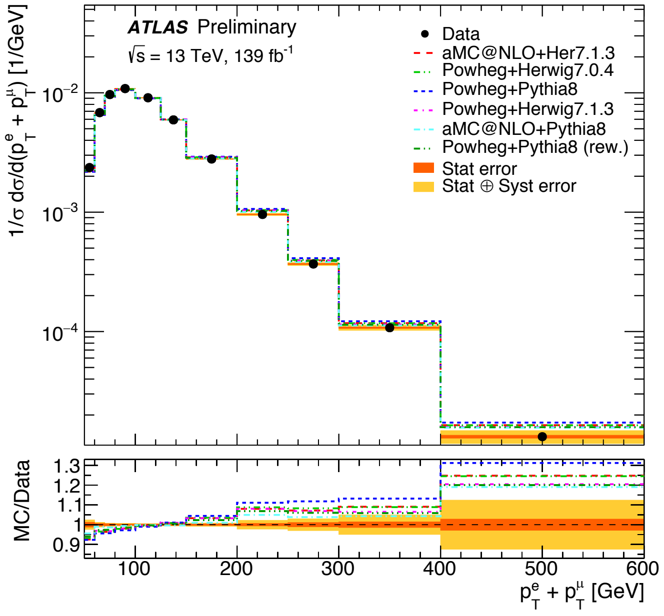
$b-1$ is the number of elements (bin) of a normalised variable

$Cov_{b\,x\,b}$ 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)

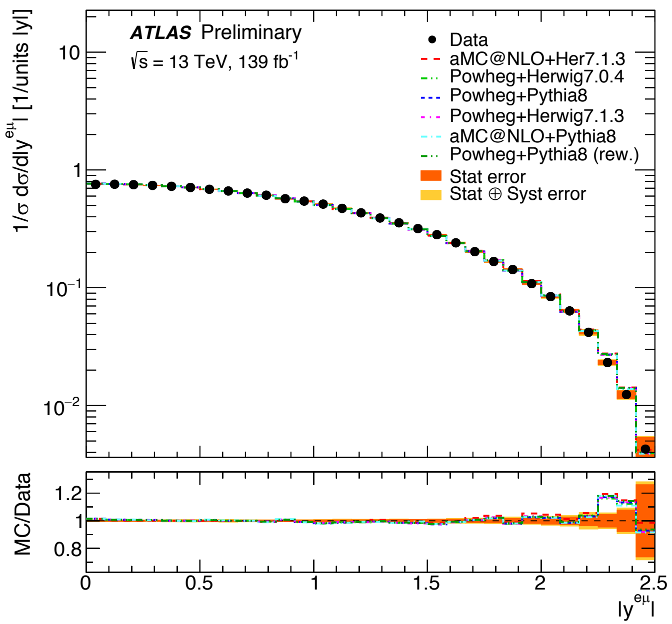
$\chi^2$ is performed for different generators on the normalised distributions

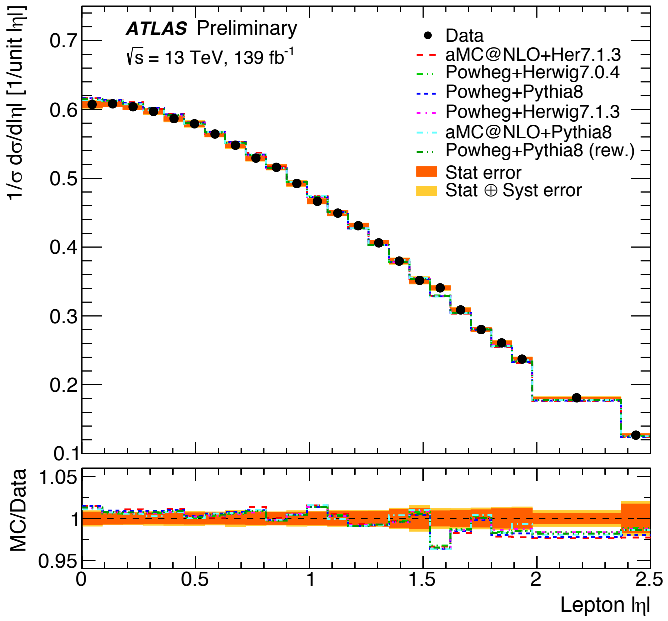
- $\Delta\phi^{e\mu}$ and Lepton $|\eta|$: no one gen. can describe the data
- $|y^{e\mu}|$: many gen. have a $\chi^2$ of the order of few %. Better results from Pow+Py8 with the PDH4LHC PDF set (prob. of 19%)

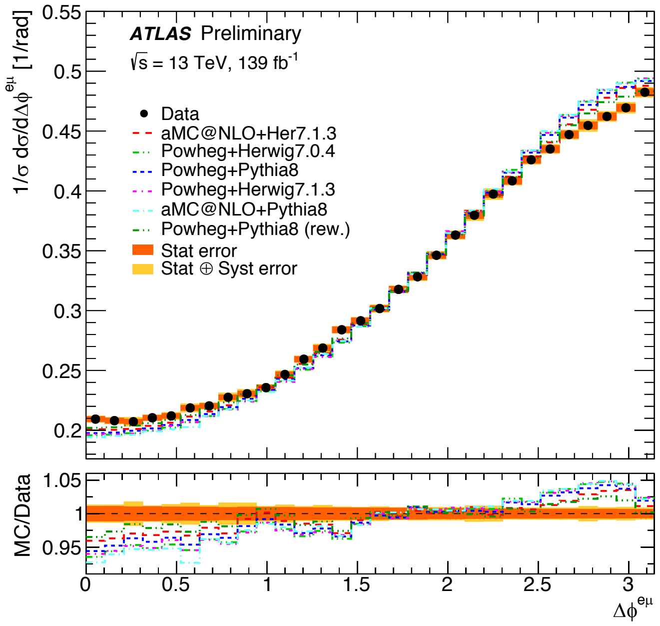
$$\chi^2 = V_{b-1}^T \cdot Cov_{b-1\,x\,b-1}^{-1} \cdot V_{b-1}$$

$V_b$ 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)

$\chi^2$ 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

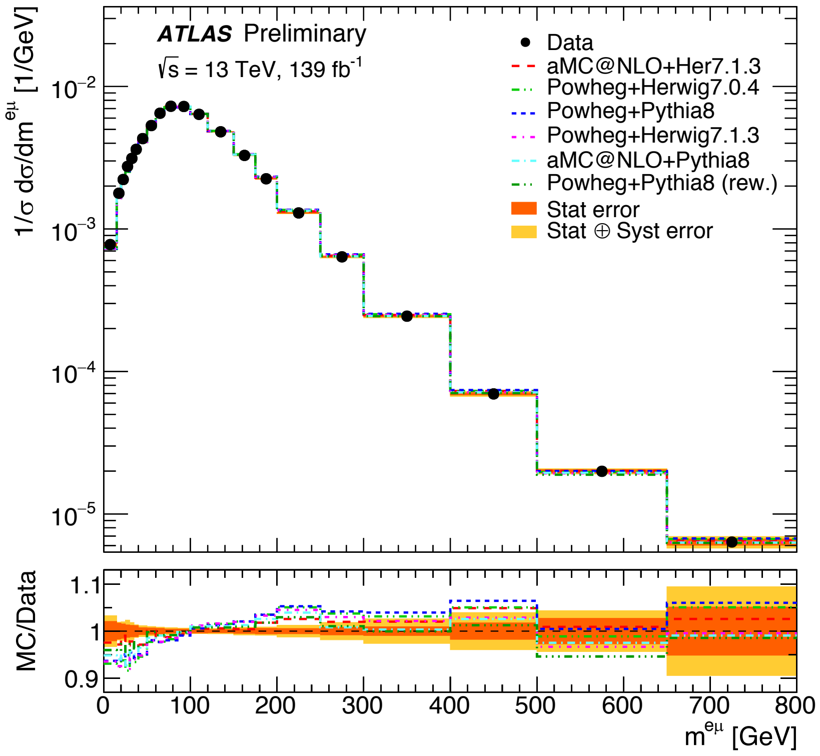
$$\chi^2 = V_{b-1}^T \cdot Cov_{b-1\,x\,b-1}^{-1} \cdot V_{b-1}$$

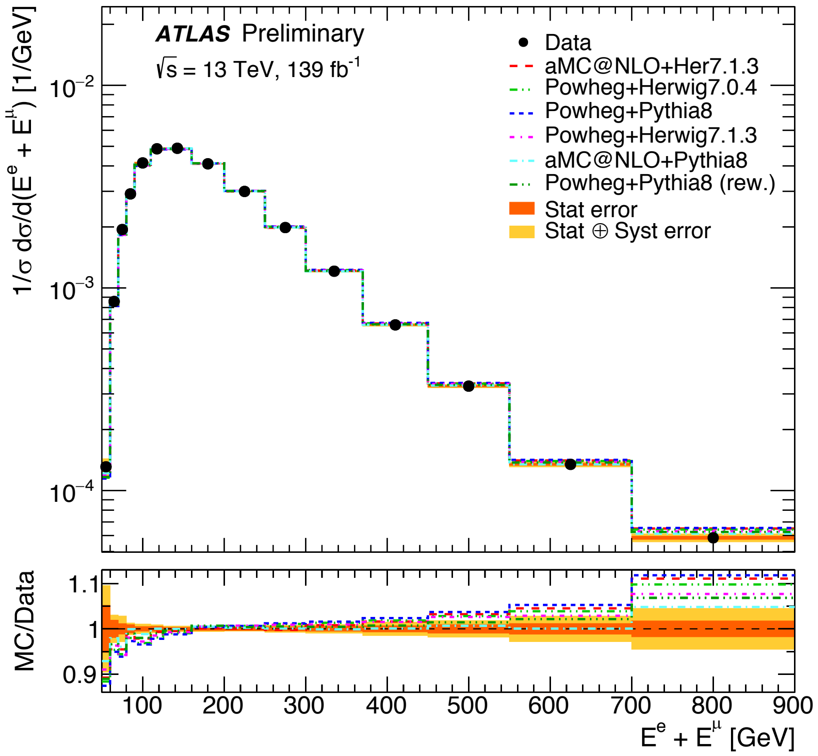
$V_b$ is the vector of the differences between data and prediction

$b-1$ 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)

$\chi^2$ is performed for different generators on the normalised distributions

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

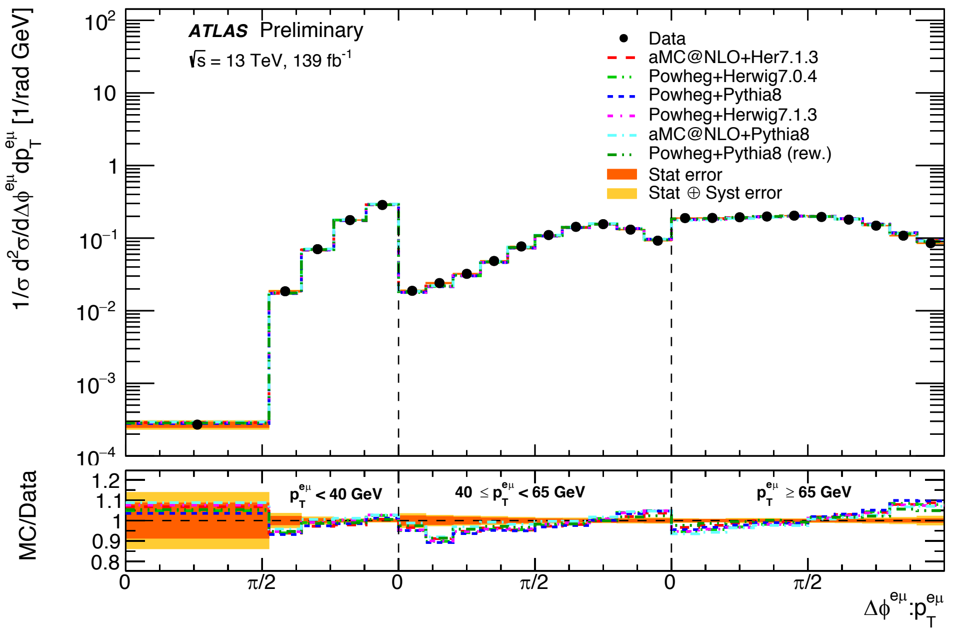
$$\chi^2 = V_{b-1}^T \cdot Cov_{b-1\,x\,b-1}^{-1} \cdot V_{b-1}$$

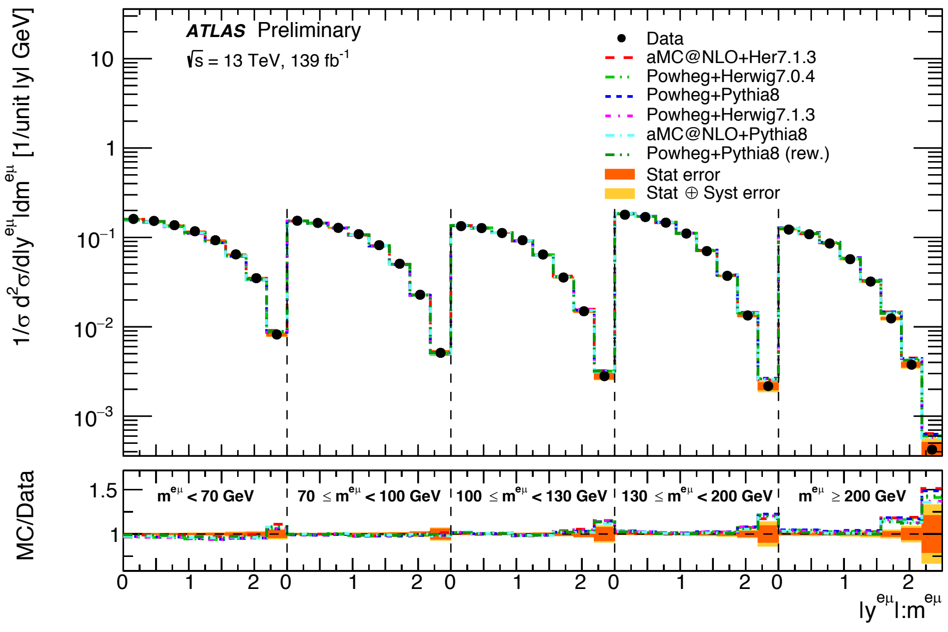
$V_b$ is the vector of the differences between data and prediction

$b-1$ 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)



# Conclusions

- Inclusive measurements compatible with previous ATLAS/CMS results and with the prediction.
- This analysis has measurements with very low uncertainty in the fiducial (2.3%) inclusive (2.4%) but also in all the bins of the differential cross-section (2.5-3% in most of the bins).
- There is no generator that can described all the distributions and in some cases it is difficult to find a generator that can describe the measured differential cross-section
- Respect to the previous measurements we have:
  - better accuracy on the fiducial cross-section;
  - same uncertainty of the previous measurement inclusive cross-section (using 36 $fb^{-1}$);
  - finer binning (and extended range) of the (double) differential distributions;
  - two new double differential cross-section measurements.

*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.

# 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%

# Test on different generators

$\chi^2$ is performed for different generators on the normalised distributions.

$p_T^e + p_T^\mu$

| $t\bar{t}$ generator | $\chi^2$/ndof | P($\chi^2$) |
|---|---|---|
| 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 | $< 0.01$ |

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

$V_b$ 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

- 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

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

| Generator | $p_T^\ell$ | $\lvert\eta^\ell\rvert$ | $p_T^{e\mu}$ | $m^{e\mu}$ | $\lvert y^{e\mu}\rvert$ | $\Delta\phi^{e\mu}$ | $p_T^e + p_T^\mu$ | $E^e + E^\mu$ |
|---|---|---|---|---|---|---|---|---|
| $N_{dof}$ | 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 | $1 \cdot 10^{-5}$ |