Inclusive and differential cross-sections for dilepton $t\bar{t}$ production measured in $\sqrt{s} = 13\,\text{TeV}$ collisions with the ATLAS detector[1]

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[1] https://arxiv.org/pdf/2303.15340.pdf

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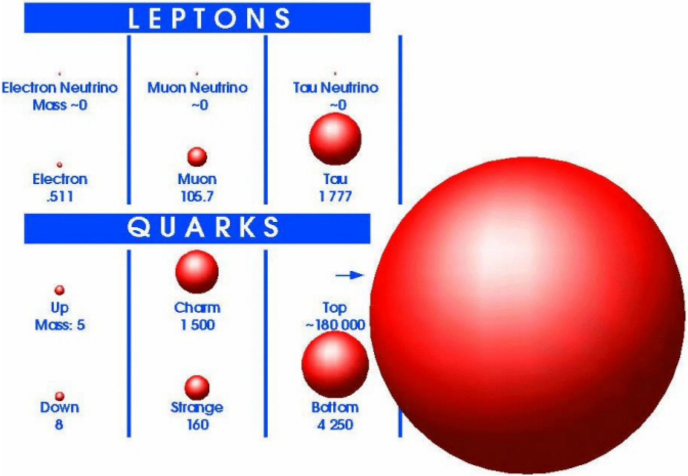
Introduction

The top quark

Why top quark?

- heaviest known elementary particle ($m_t \simeq 173\,\text{GeV}$) $\rightarrow$ large coupling to Higgs boson ($y_t = \frac{m_t}{v} \simeq 0.7$)



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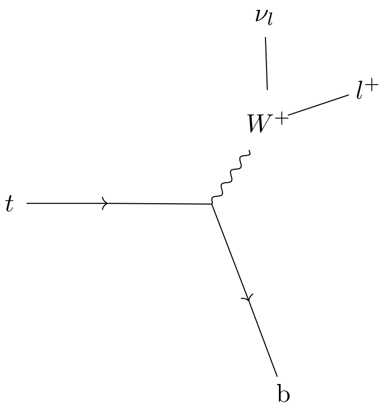

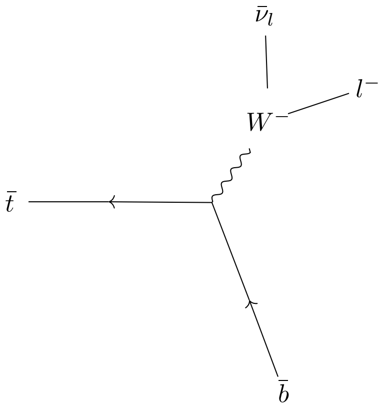

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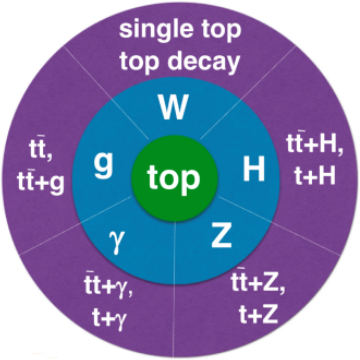

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- couples to all bosons

Why top-antitop pair production?

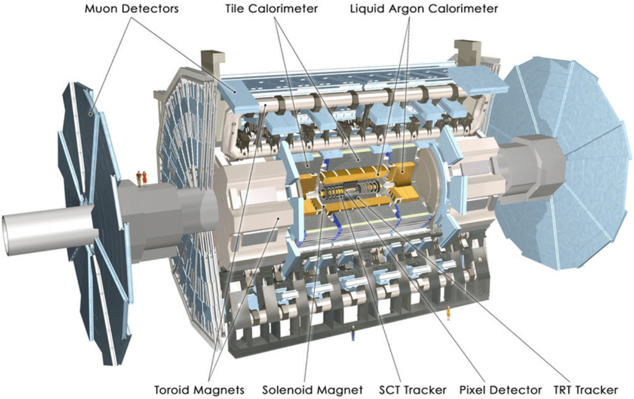
$\rightarrow$ test QCD model parameters: $\alpha_s, m_t, PDFs$...

Detector

ATLAS

= multi-purpose and multi-layer detector

- Inner Detectors (ID)
- Calorimeters (ECal + HCal)
- Muon Spectrometer (MS)



Signal and Event Reconstruction

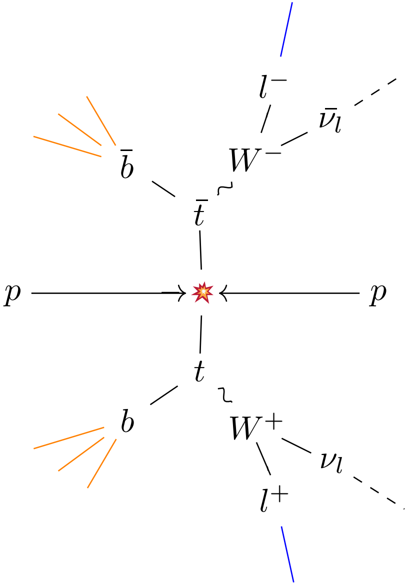
Signal

$$t\bar{t} \rightarrow W^{+}(\rightarrow l^{+}\nu_{l})bW^{-}(\rightarrow l^{-}\bar{\nu}_{l})\bar{b}$$

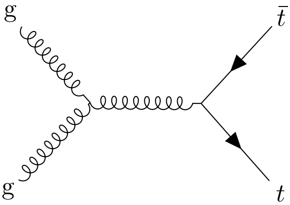
where $l^{+} = e^{+}, l^{-} = \mu^{-}$ or
$l^{+} = \mu^{+}, l^{-} = e^{-}$

Final state

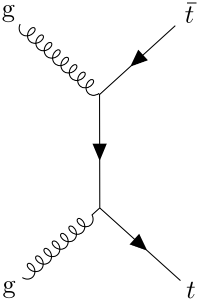
- 1 electron $e^{\mp}$
- 1 muon $\mu^{\pm}$
- 1-2 b-jets
- $\vec{E}_{T}^{miss}$



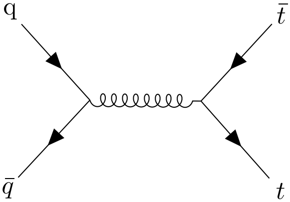
Signal



gluon fusion
(s-channel)

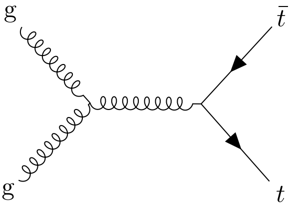


gluon fusion
(t-channel)



quark production

Signal



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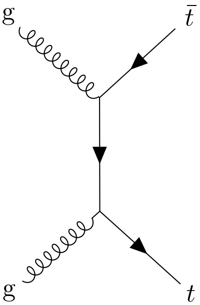

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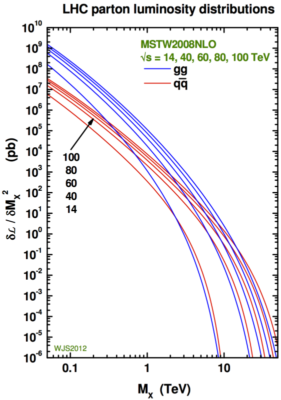
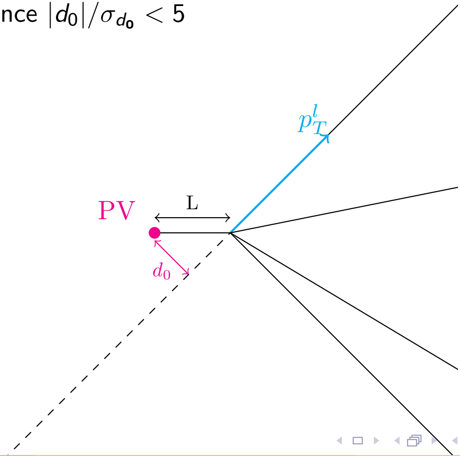


Event reconstruction: electron

1 electron $e^{\mp}$

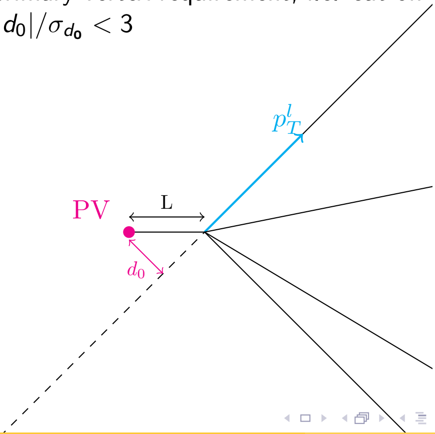
- matching energy cluster in ECal + track in ID
- tight selection criteria
- isolation requirement, with efficiency 90% computed on a $Z \to e^{+}e^{-}$ sample
- compatibility with the primary vertex requirement, i.e. cut on the impact parameter significance $|d_0|/\sigma_{d_0} < 5$



Event reconstruction: muon

1 muon $\mu^{\pm}$

- matching track in ID + track in MS
- medium selection criteria
- isolation requirement with efficiency of $\in [85\%, 98\%]$ depending on the transverse momentum $p_T^{\mu} \in [25, 100]$GeV
- compatibility with the primary vertex requirement, i.e. cut on the impact parameter significance $|d_0|/\sigma_{d_0} < 3$



Event reconstruction: jets

1-2 b-jets

- anti-k_T algorithm with $R = 0.4$
- $p_T > 25$ GeV
- $|\eta| < 2.5$

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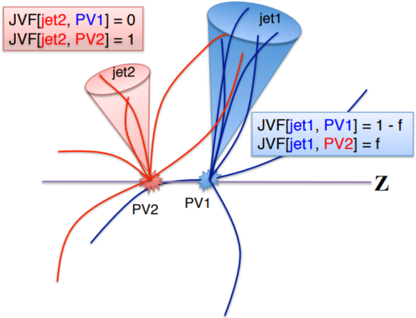
- anti-k_T algorithm with $R = 0.4$
- $p_T > 25$ GeV
- $|\eta| < 2.5$
- requirement to be compatible with the primary vertex, i.e. cut on JVT, with efficiency $\in [87\%, 95\%]$ depending on $p_T \in [25, 60]$GeV

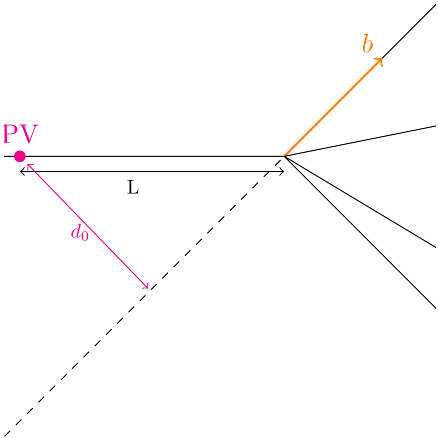
$$JVT = \frac{\sum_{j \in hard\ scattering} p_T^j}{\sum_j p_T^j}$$



Event reconstruction: jets

1-2 b-jets

- anti-k_T algorithm with $R = 0.4$
- $p_T > 25$ GeV
- $|\eta| < 2.5$
- requirement to be compatible with the primary vertex, i.e. cut on JVT, with efficiency $\in [87\%, 95\%]$ depending on $p_T \in [25, 60]$GeV
- b-tagging, with methods based on lifetimes, masses and decay topologies



Overlap removal

To avoid double counting, the following objects are discarded:

- any e-candidate sharing a track
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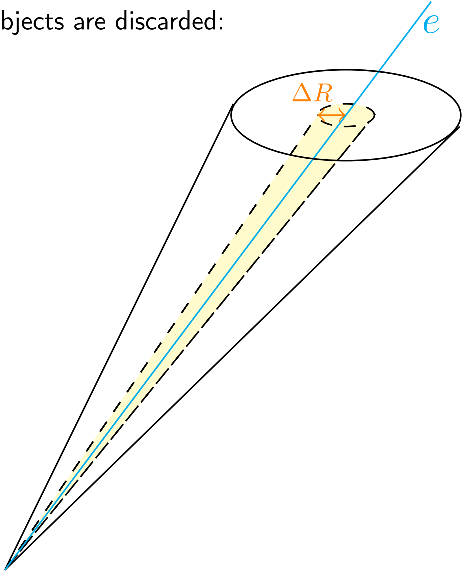
- any jet within $\Delta R = 0.2$ of an e-candidate



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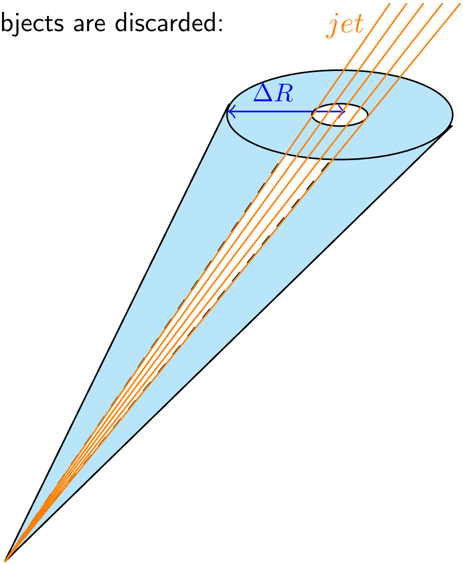

- any e-candidate sharing a track with a μ-candidate
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- e-candidates within $0.2 < \Delta R < 0.4$ around any remaining jet

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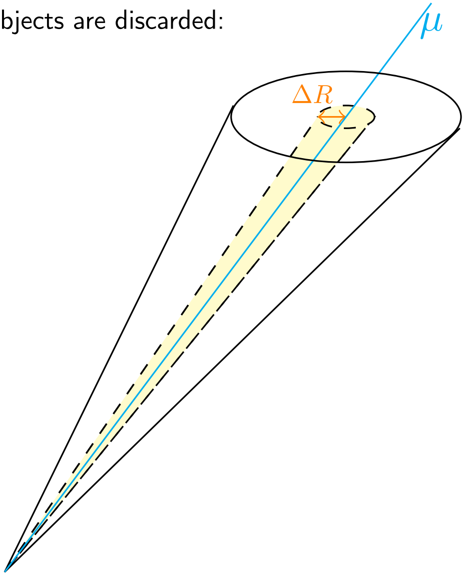
- jets that have fewer than three tracks and are within $\Delta R = 0.2$ of a μ-candidate



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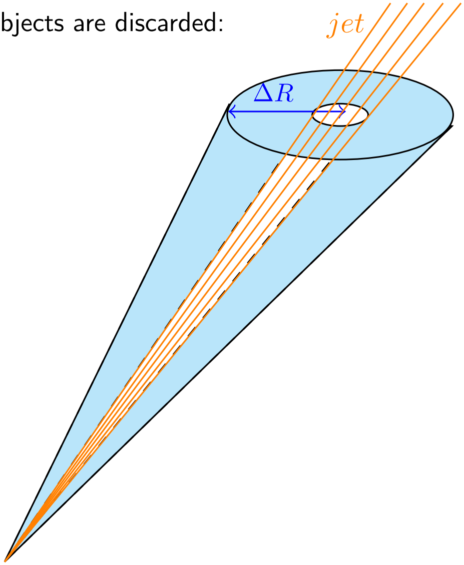
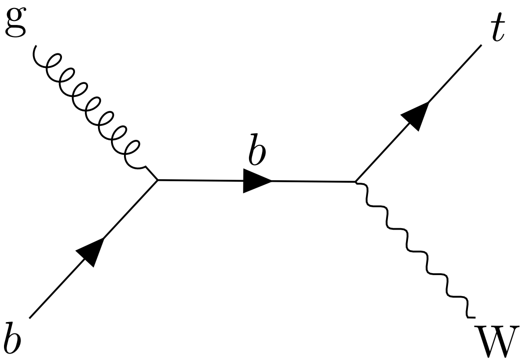
- jets that have fewer than three tracks and are within $\Delta R = 0.2$ of a μ-candidate
- μ-candidates within $\Delta R = 0.4$ around any remaining jet



Background

Background

- Wt



Background

- Wt
- misidentified leptons, including:
  - electrons from the conversion of a photon radiated from a prompt electron
  - electrons from heavy flavour hadrons decays
  - muons from heavy flavour hadrons decays
  - leptons with wrongly reconstructed charge

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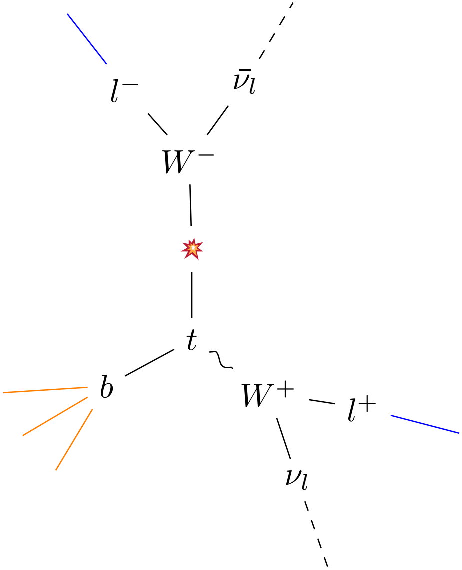
- Z+jets
- $t\bar{t}V$, where $V \in \{W, Z\}$
- $t\bar{t}H$

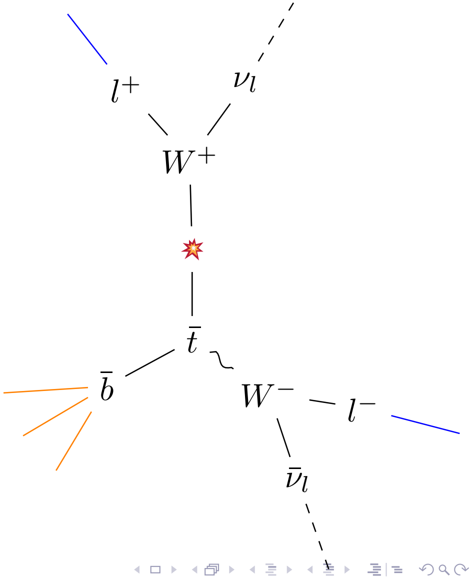
Background

- Wt reducible
- misidentified leptons, including: reducible
  - electrons from the conversion of a photon radiated from a prompt electron
  - electrons from heavy flavour hadrons decays
  - muons from heavy flavour hadrons decays
  - leptons with wrongly reconstructed charge
- VV, where $V \in \{W, Z\}$ reducible
- Z+jets irreducible
- $t\bar{t}Z$ irreducible and $t\bar{t}W$ reducible
- $t\bar{t}H$ reducible

Background: Wt

- *Wt*





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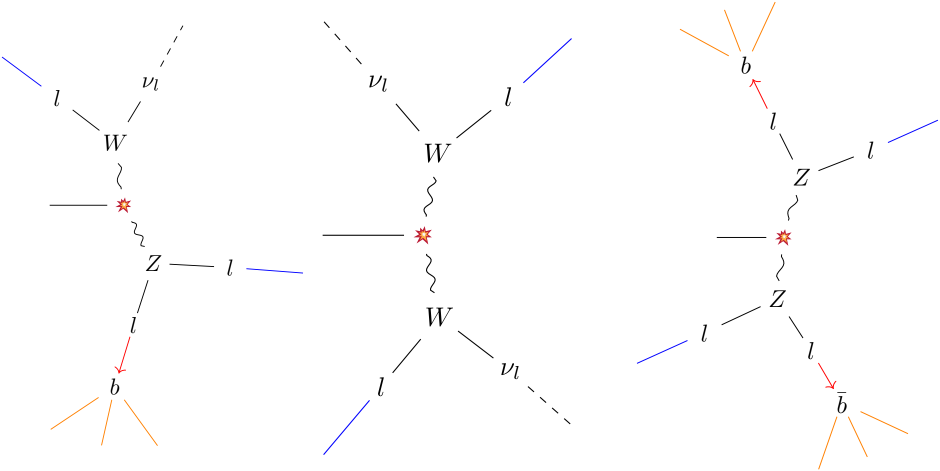
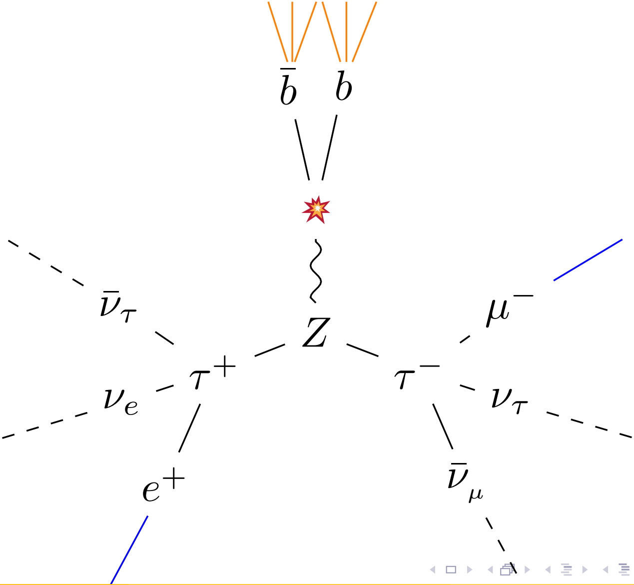


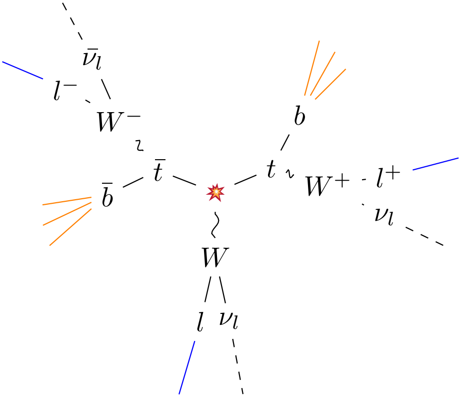
Background: Z+jets

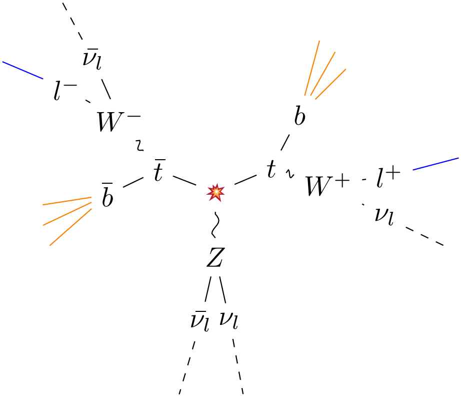
- Z+jets



Background: $t\bar{t}V$

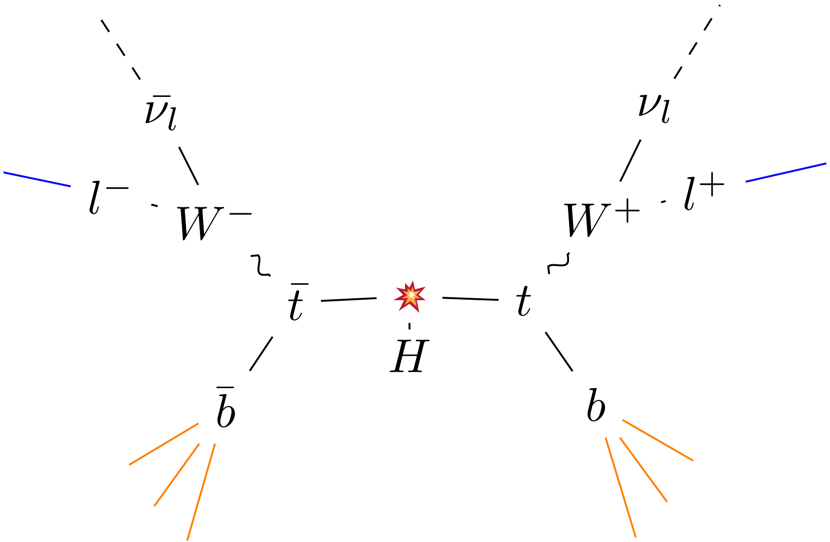
- $t\bar{t}V$





Background: $t\bar{t}H$

- $t\bar{t}H$



Background estimation

- Wt: simulation
- misidentified leptons
    - e from the conversion of a γ radiated from a prompt-e simulation
    - e from heavy flavour hadrons decays simulation+data-driven
    - μ from heavy flavour hadrons decays simulation+data-driven
    - leptons with wrongly reconstructed charge simulation+data-driven
- VV, where $V \in \{W, Z\}$: simulation
- Z+jets: simulation + data-driven
- $t\bar{t}V$, where $V \in \{W, Z\}$: simulation
- $t\bar{t}H$: simulation

Background estimation: data-driven techniques

misidentified leptons: wrongly reconstructed charge

$\rightarrow$ from the events in data with same-sign $e\mu$

misidentified leptons: non-prompt leptons from hadron decays

$\rightarrow$ from the leptons in data that fail the impact parameter requirement

$$N_{bkg}^{SR} = \frac{N_{data}^{CR}}{N_{MC}^{CR}} N_{MC}^{SR}$$

Background estimation: data-driven techniques

misidentified leptons: wrongly reconstructed charge
→ from the events in data with same-sign $e\mu$

misidentified leptons: non-prompt leptons from hadron decays
→ from the leptons in data that fail the impact parameter requirement

$$N^{SR}_{bkg} = \frac{N^{CR}_{data}}{N^{CR}_{MC}} N^{SR}_{MC}$$

$Z \rightarrow \tau\tau$+jets
→ from samples of $Z \rightarrow \mu^+\mu^-$ + jets (CR1) and $Z \rightarrow e^+e^-$ +jets (CR2)
→ average to find the scaling factor $K_{ll+jets}$

$$K_{ll+jets} = \frac{1}{2}\left(\frac{N^{CR1}_{data}}{N^{CR1}_{MC}} + \frac{N^{CR2}_{data}}{N^{CR2}_{MC}}\right)$$

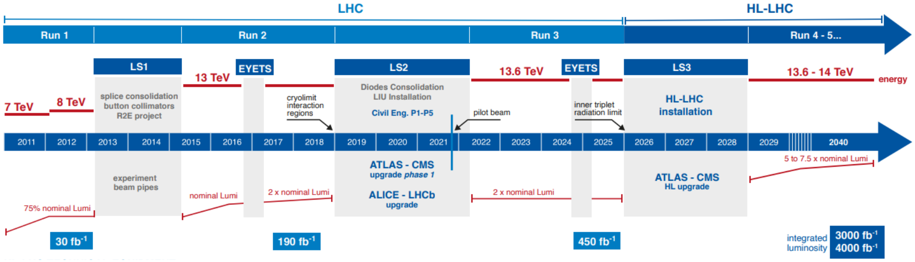
$$N^{SR}_{Z\rightarrow\tau\tau+jets} = K_{ll+jets} N^{SR}_{MC}$$

Data and simulations

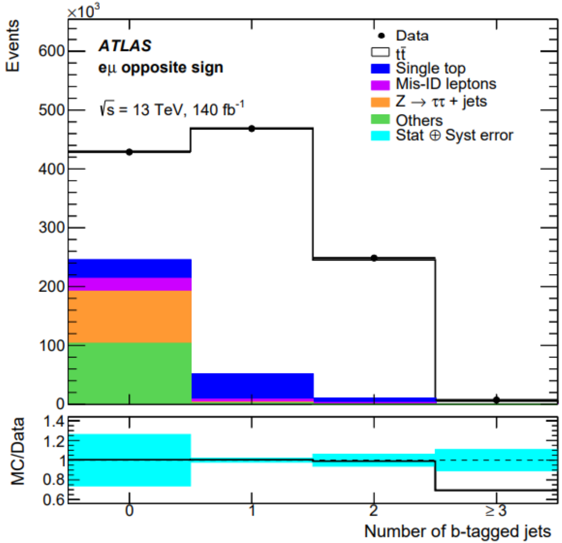
Data and simulations

Data
DAQ period: 2015-2018 (Run 2)
Center-of-mass energy: $\sqrt{s} = 13$ TeV
Integrated luminosity: $\mathcal{L} = 140\,\text{fb}^{-1}$

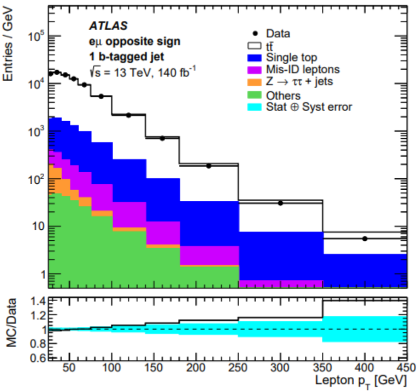
Simulations
GEANT4: detector behaviour
PYTHIA 8.186: pile-up
EVTGEN1.6.0: charm and bottom showers
POWHEG BOX: $t\bar{t}$ at NLO
+ many others...

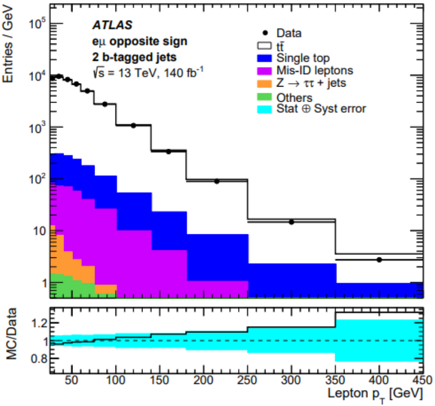


Data distribution: number of b-jets



Data distribution: lepton transverse momentum (OS events)





Analysis

Differential cross-sections

(Double) Differential cross-section distributions of kinematic variables:

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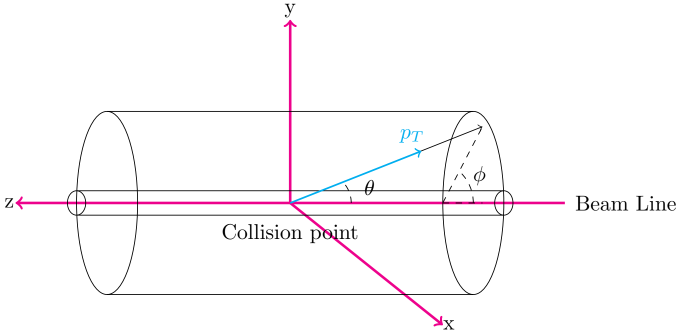
- single-lepton transverse momentum, $p_T^l, l \in \{e, \mu\}$

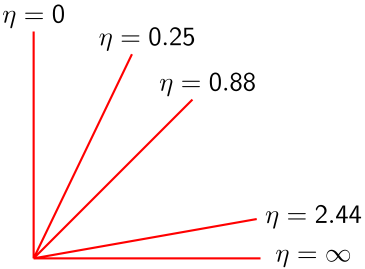


Differential cross-sections

(Double) Differential cross-section distributions of kinematic variables:

- single-lepton transverse momentum, $p_T^l, l \in \{e, \mu\}$
- single-lepton pseudorapidity $|\eta^l|, l \in \{e, \mu\}$

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$



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- single-lepton transverse momentum, $p_T^l, l \in \{e, \mu\}$
- single-lepton pseudorapidity $|\eta^l|, l \in \{e, \mu\}$
- $e\mu$-system invariant mass $m^{e\mu}$

$$m^{e\mu} = \sqrt{(E^e + E^\mu)^2 - (\vec{p}^e + \vec{p}^\mu)^2} \sim \sqrt{2 p_T^e p_T^\mu} \sqrt{(cosh(\Delta\eta^{e\mu}) - cos(\Delta\Phi^{e\mu}))}$$

Differential cross-sections

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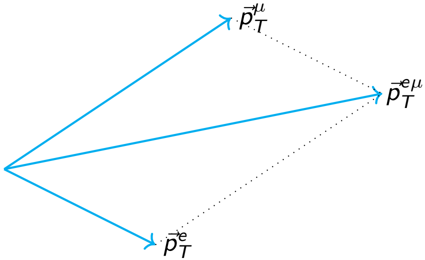
- $e\mu$-system invariant mass $m^{e\mu}$
- $e\mu$-system transverse momentum $p_T^{e\mu}$



$$p_T^{e\mu} \sim \sqrt{2 p_T^e p_T^\mu cos(\Delta\Phi^{e\mu})}$$

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- $e\mu$-system invariant mass $m^{e\mu}$
- $e\mu$-system transverse momentum $p_T^{e\mu}$
- $e\mu$-system rapidity $Y^{e\mu}$

$$Y = \frac{1}{2} \ln \left(\frac{E^{e\mu} + p_{||}^{e\mu}}{E^{e\mu} - p_{||}^{e\mu}} \right)$$

$$\beta \to 1 \quad Y \sim \eta$$

Differential cross-sections

(Double) Differential cross-section distributions of kinematic variables:

- single-lepton transverse momentum, $p_T^l, l \in \{e, \mu\}$
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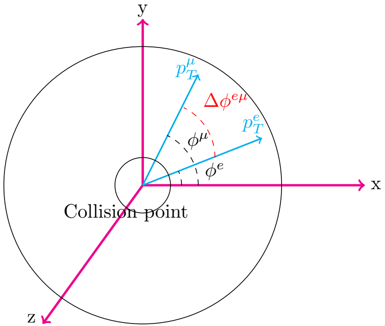
- $e\mu$-system invariant mass $m^{e\mu}$
- $e\mu$-system transverse momentum $p_T^{e\mu}$
- $e\mu$-system rapidity $Y^{e\mu}$
- azimuthal angular separation of leptons $|\Delta\phi^{e\mu}|$



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- sum of lepton energies $E^e + E^\mu$

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- $e\mu$-system transverse momentum $p_T^{e\mu}$
- $e\mu$-system rapidity $Y^{e\mu}$
- azimuthal angular separation of leptons $|\Delta\phi^{e\mu}|$
- sum of lepton energies $E^e + E^\mu$
- scalar sum of lepton transverse momenta $p_T^e + p_T^\mu$

Differential cross-sections: analysis

$$N_1^i = L\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i(1-\epsilon_b^i C_b^i) + N_{1,bkg}^i$$
$$N_2^i = L\sigma_{t\bar{t}}^i G_{e\mu}^i (\epsilon_b^i)^2 C_b^i + N_{2,bkg}^i$$

- $N_{1,2}^i$: numbers of selected data events with 1,2 b-tagged jets in the i-th bin
- $N_{1,2}^i$: numbers of predicted background events with 1,2 b-tagged jets in the i-th bin
- L: integrated luminosity
- $\sigma_{t\bar{t}}^i$: cross-section of $t\bar{t}$ production resulting in OS $e\mu$ in the fiducial region in the i-th bin
- $G_{e\mu}^i$: reconstruction efficiency

$$G_{e\mu}^i = \frac{N_{MC,sel}^i}{N_{MC,gen}^i}$$

- ϵ_b^i: combined probability for a b-jet from a t-decay to be reconstructed as a jet, to fall within the detector and selection acceptance and be tagged as b-jet
- C_b^i: b-tagging correlation coefficient that corrects the probability of tagging the second jet after having tagged the first one

Differential cross-sections: analysis

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

$$N_2^i = L\sigma_{t\bar{t}}^i G_{e\mu}^i (\epsilon_b^i)^2 C_b^i + N_{2,bkg}^i$$

$\rightarrow$ unknown variables ϵ_b^i, $\sigma_{t\bar{t}}^i$ determined with a $-\ln[\mathcal{L}]$ fit

Differential cross-sections: analysis

$$\mathcal{L} = e^{-\left(L\sigma^i_{t\bar{t}} G^i_{e\mu} 2\epsilon^i_b (1-\epsilon^i_b C^i_b) + N^i_{\mathbf{1},bkg}\right)} \frac{\left(L\sigma^i_{t\bar{t}} G^i_{e\mu} 2\epsilon^i_b (1-\epsilon^i_b C^i_b) + N^i_{1,bkg}\right)^{N^i_{\mathbf{1}}}}{N^i_1!}$$

$$-\ln[\mathcal{L}] = \left(L\sigma^i_{t\bar{t}} G^i_{e\mu} 2\epsilon^i_b (1-\epsilon^i_b C^i_b) + N^i_{1,bkg}\right) - (N^i_1) \ln\left[L\sigma^i_{t\bar{t}} G^i_{e\mu} 2\epsilon^i_b (1-\epsilon^i_b C^i_b) + N^i_{1,bkg}\right]$$

$$-\ln\left[\pi_{G^i_{e\mu}}\right] - \ln\left[\pi_{C^i_b}\right] - \ln\left[\pi_L\right]$$

- parameters of interest: ϵ^i_b, $\sigma^i_{t\bar{t}}$
- observables: $N^i_1, N^i_{1,bkg}$
- nuisance parameters: G^i_μ, C^i_b, L
- ancillary likelihood functions: $\pi_{G^i_{e\mu}}, \pi_{C^i_b}, \pi_L$
  = Gaussian distributions for G^i_μ, C^i_b, L, in order to take into account uncertainties on these quantities

Total cross-section

Fiducial region total cross-section
= kinematic + geometric region with a good and well-known performance

$p_T^{l,leading} > 27$ GeV

$p_T^{l,subleading} > 25$ GeV

$|\eta_T^{\mu}| < 2.5$

$|\eta_T^{e}| < 1.37$ U $1.52 < |\eta_T^{e}| < 2.47$

Inclusive total cross-section
= in the full phase space

Total fiducial cross-section: analysis

Substitute $i-th$ bin with the entire fiducial region:

$$N_1^{fid} = \mathcal{L}\sigma_{t\bar{t}}^{fid} G_{e\mu}^{fid} 2\epsilon_b^{fid}(1-\epsilon_b^{fid} C_b^{fid}) + N_{1,bkg}^{fid}$$

$$N_2^{fid} = \mathcal{L}\sigma_{t\bar{t}}^{fid} G_{e\mu}^{fid} (\epsilon_b^{fid})^2 C_b^{fid} + N_{2,bkg}^{fid}$$

Total inclusive cross-section: analysis

Consider the detector acceptance:

$$N_1^{fid} = \mathcal{L}\sigma_{t\bar{t}}^{incl} E_{e\mu}^{fid} 2\epsilon_b^{fid}(1 - \epsilon_b^{fid} C_b^{fid}) + N_{1,bkg}^{fid}$$

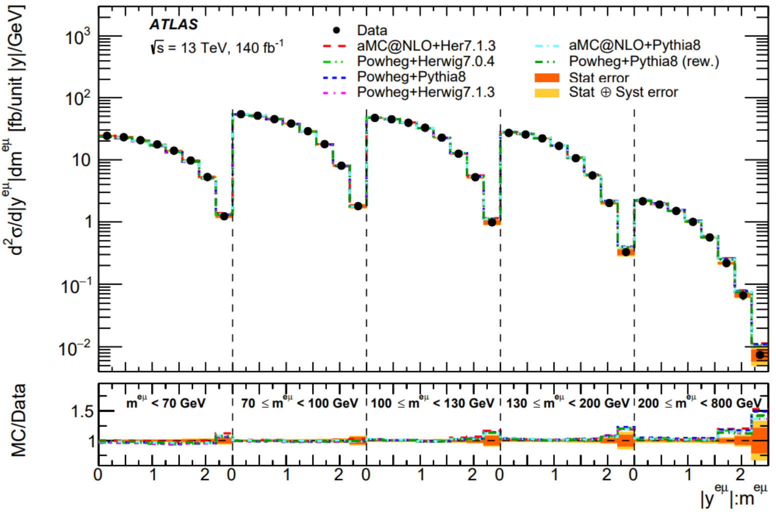
$$N_2^{fid} = \mathcal{L}\sigma_{t\bar{t}}^{incl} E_{e\mu}^{fid} (\epsilon_b^{fid})^2 C_b^{fid} + N_{2,bkg}^{fid}$$

where $E_{e\mu} = A_{e\mu} G_{e\mu}$ and $A_{e\mu} = \frac{N_{e\mu}^{t\bar{t},fid}}{N^{t\bar{t}}}$

- $A_{e\mu}$ acceptance
- $N_{e\mu}^{t\bar{t},fid}$: number of particle-level opposite sign $e\mu$ events in the fiducial region in a simulated $t\bar{t}$ sample
- $N^{t\bar{t}}$: total number of events in the simulated $t\bar{t}$ sample

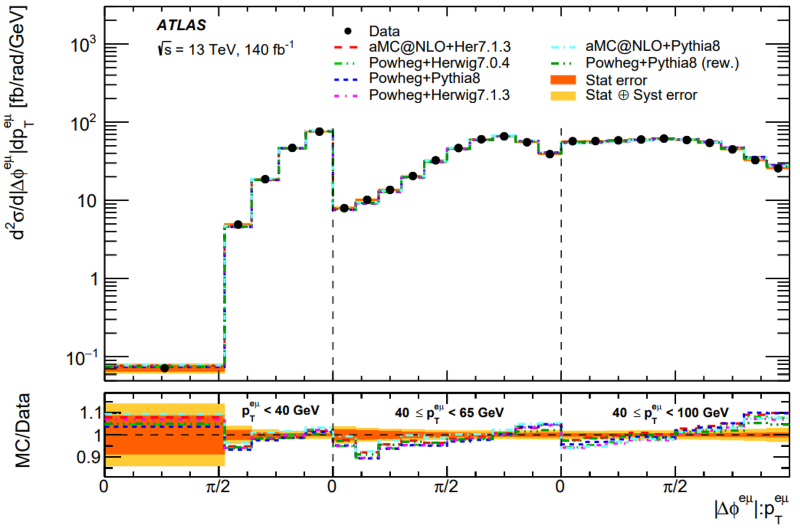
Results

Double differential cross-section: $|y^{e\mu}| : m^{e\mu}$



;

Double differential cross-section: $|\Delta\phi^{e\mu}| : p_T^{e\mu}$



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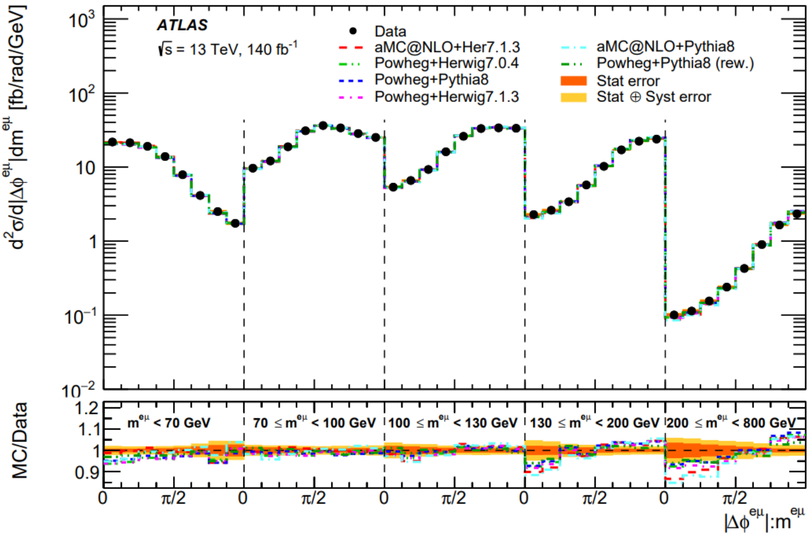
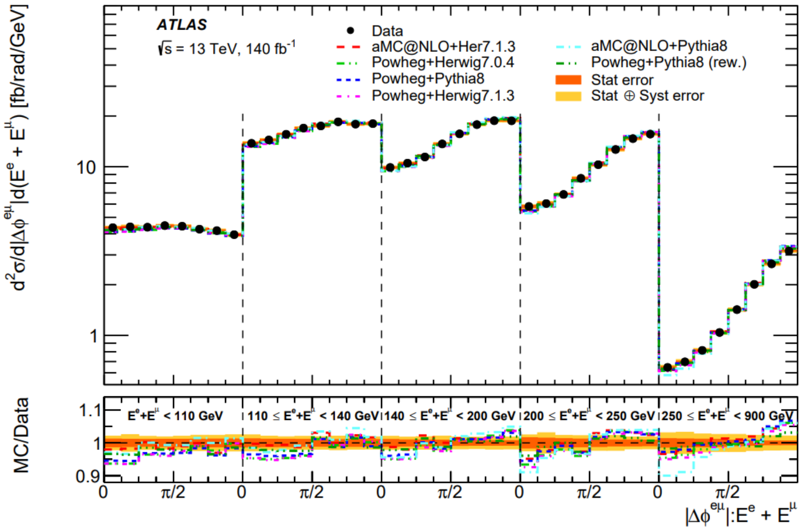
Double differential cross-section: $|\Delta\phi^{e\mu}|$: $m^{e\mu}$



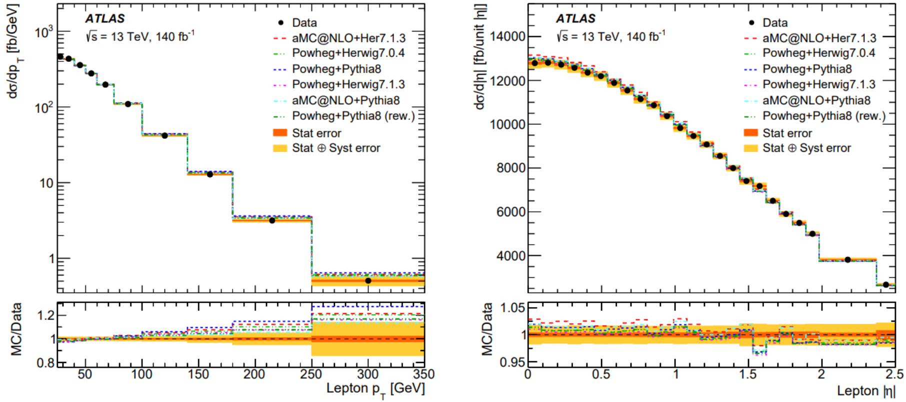
;

Double differential cross-section: $|\Delta\phi^{e\mu}|$: $E^e + E^\mu$



;

Differential cross-section: $p_T^l, |\eta|^l$



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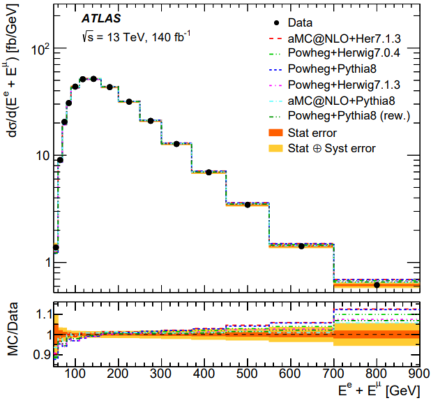
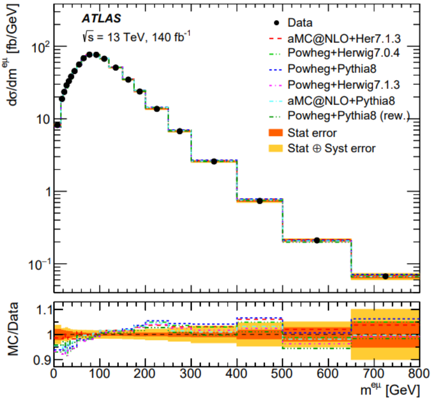
Differential cross-section: $E^e + E^\mu$, $m^{e\mu}$





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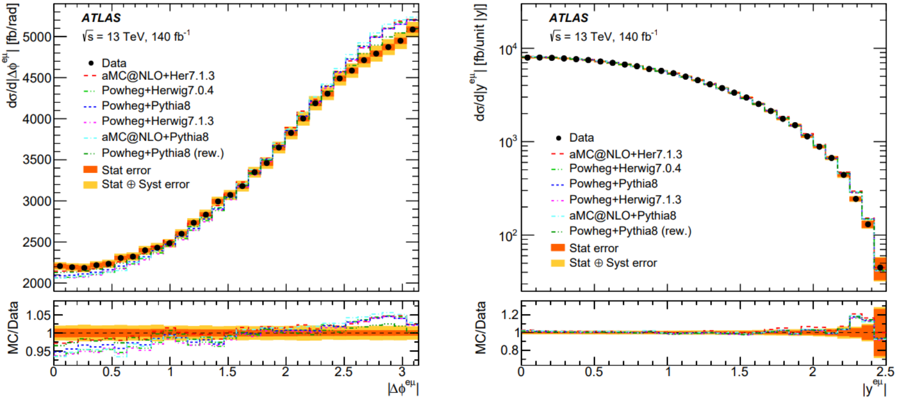
Differential cross-section: $|\Delta\phi^{e\mu}|$, $|y^{e\mu}|$



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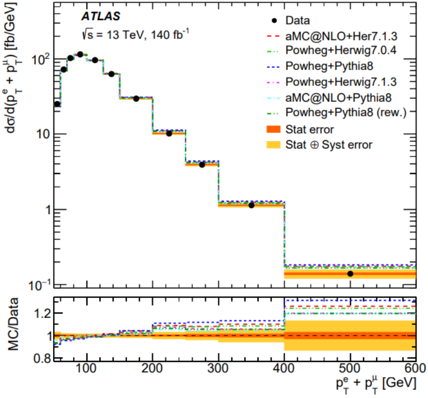
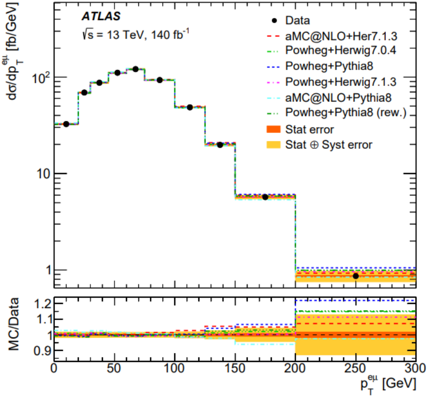
Differential cross-section: $p_T^e + p_T^\mu$, $p_T^{e\mu}$





;

Total cross-sections

Total fiducial region cross-section

$$\sigma_{t\bar{t}}^{fid} = 10.53 \pm 0.02(stat) \pm 0.13(syst) \pm 0.10(lumi) \pm 0.02(beam)\text{pb}$$

Total inclusive cross-section

$$\sigma_{t\bar{t}}^{fid} = 829 \pm 1(stat) \pm 13(syst) \pm 8(lumi) \pm 2(beam)\text{pb}$$

Uncertainties

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	0.16
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	0.34	0.34
$t\bar{t}V$ and $t\bar{t}H$	0.03	0.03
Z + jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	0.93	0.93
Total uncertainty	1.6	1.8

statistic
systematic
beam energy
luminosity
dominant

- associated with generators (theoretical assumptions, detector modelling, etc...) $\rightarrow$ estimated by changing the values of parameters in the simulations or using alternative generators
- background $\rightarrow$ data-driven methods and simulations
- detector-related $\rightarrow$ data-driven, 'up' and 'down' variations

Conclusions

- The process $t\bar{t}$ in the $e\mu$ **dileptonic channel** has been studied

$$t\bar{t} \rightarrow W^{+}(\rightarrow l^{+}\nu_{l})bW^{-}(\rightarrow l^{-}\bar{\nu}_{l})\bar{b}$$

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- **Events reconstruction** and **events selection** are needed to get a sample of events for the analysis
- A study of the different processes contributing to **background** has been done, predicting their yields by means of simulations and data-driven techniques
- The **cross-section** of the process has been measured in many ways - double differential, differential, total fiducial, total inclusive
  $\rightarrow$ **wider range** for differential distributions thanks to larger dataset
  $\rightarrow$ **higher precision** thanks to reduced L uncertainty

Backup

Efficiencies estimation: data-driven techniques

The lepton trigger, reconstruction and selection efficiencies are evaluated both from simulation and with data-driven techniques.

e.g. lepton isolation requirement

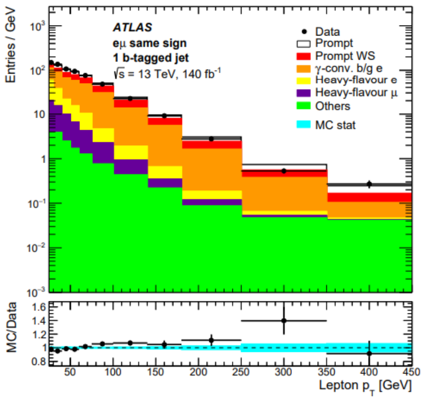
1. selection of $Z \to l^+ l^-$ events
2. selection of opposite sign $e\mu$ events with the isolation requirement applied only to one of the two leptons
3. the fraction of signal events where the other lepton fails the requirement gives the inefficiency of the isolation requirement

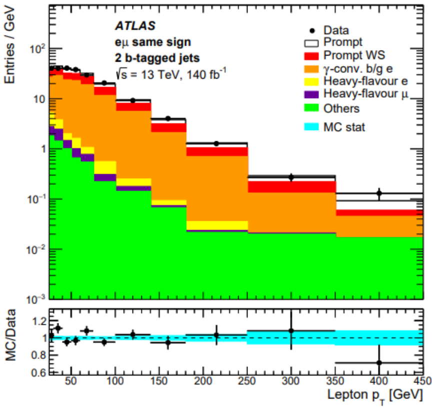
Particle-level objects

= simulated stable particles without any simulation of the interaction with the detector components

- compute the reconstruction efficiency $G^i_{e\mu} = \frac{N^i_{MC,sel}}{N^i_{MC,gen}}$
- compute the fiducial region acceptance $A_{e\mu} = \frac{N^{t\bar{t},fid}_{e\mu}}{N^{t\bar{t}}}$
- choose the binning for (double) differential cross-sections such that at least 90% of the events populate the diagonal of the migration matrix

Data distribution: lepton transverse momentum (SS events)





Validation of the analysis: bootstrapping

→ **bootstrapping**

For each bin i:

1. take the data sample, i.e two numbers N_1^i, N_2^i
2. generate a set of 1000 weights $w_k, k \in [0, 1000]$ obtained from fluctuations of a Poisson distribution with $\mu = 1$
3. get 1000 pseudo-esperiments by assigning each weight to N_1^i, N_2^i
4. do the analysis on the weighted samples and get 1000 values for the cross-section in the i-th bin
5. compare the average cross-section over the 1000 values with the values obtained from the simulations to check any possible bias in the analysis

Differential cross-sections: analysis

+ Normalized differential and double-differential cross-sections

$$\sigma^i_{t\bar{t},norm} = \frac{\sigma^i_{t\bar{t}}}{\sum_j \sigma^j_{t\bar{t}}}$$

pro: large reduction of systematic uncertainties
contra: introduction of bin-to-bin correlations