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Recent highlights on top-quark physics with the ATLAS detector

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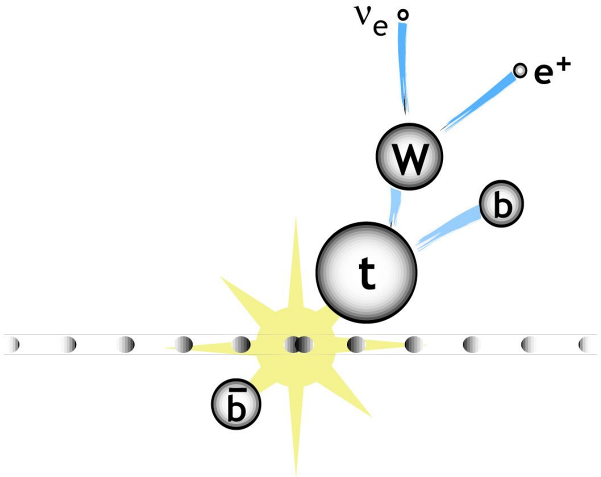
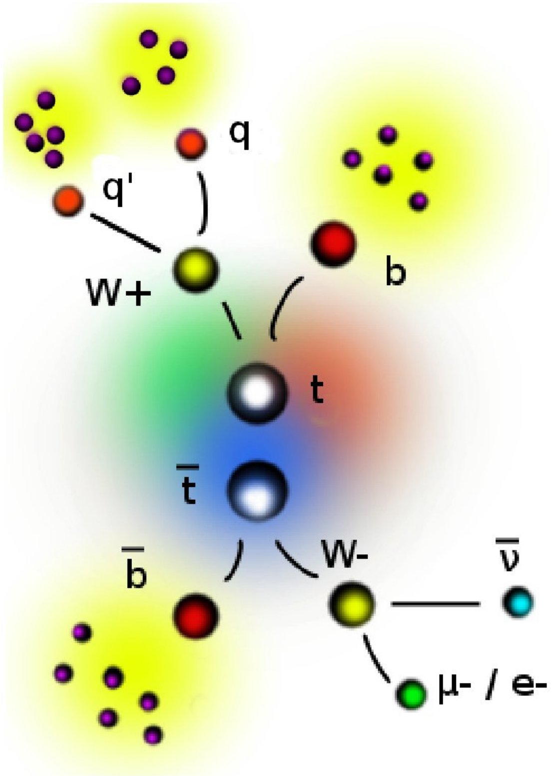
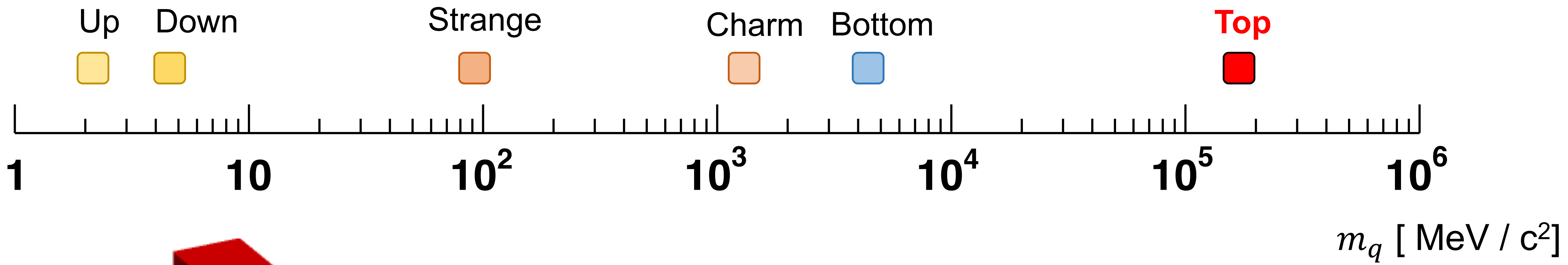
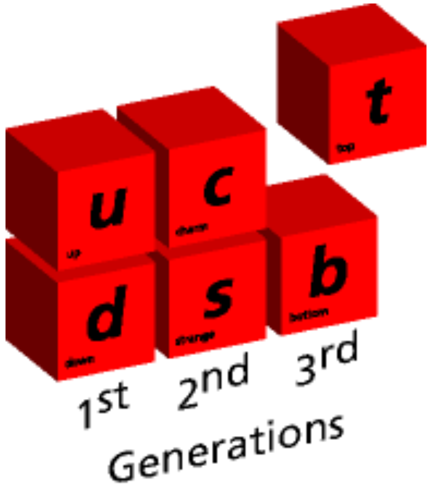


HEP Seminar Michigan State University,
December 8, 2020



The top quark





- Weak-isospin partner of the *b*-quark.
- Charge: +2/3 e
- Spin: ½
- By far the heaviest elementary particle: $m_t = 172.7 \pm 0.5$ GeV/c²

  0,3% precision!

  → large loop corrections

- Coupling to the Higgs boson: $y_t \approx 1$

- No bound states:

$$\tau_{\text{top}} \propto \left(\frac{M_W}{M_{\text{top}}}\right)^3$$

$$\tau_{\text{top}} \approx 4.7 \cdot 10^{-25}\ \text{s}$$

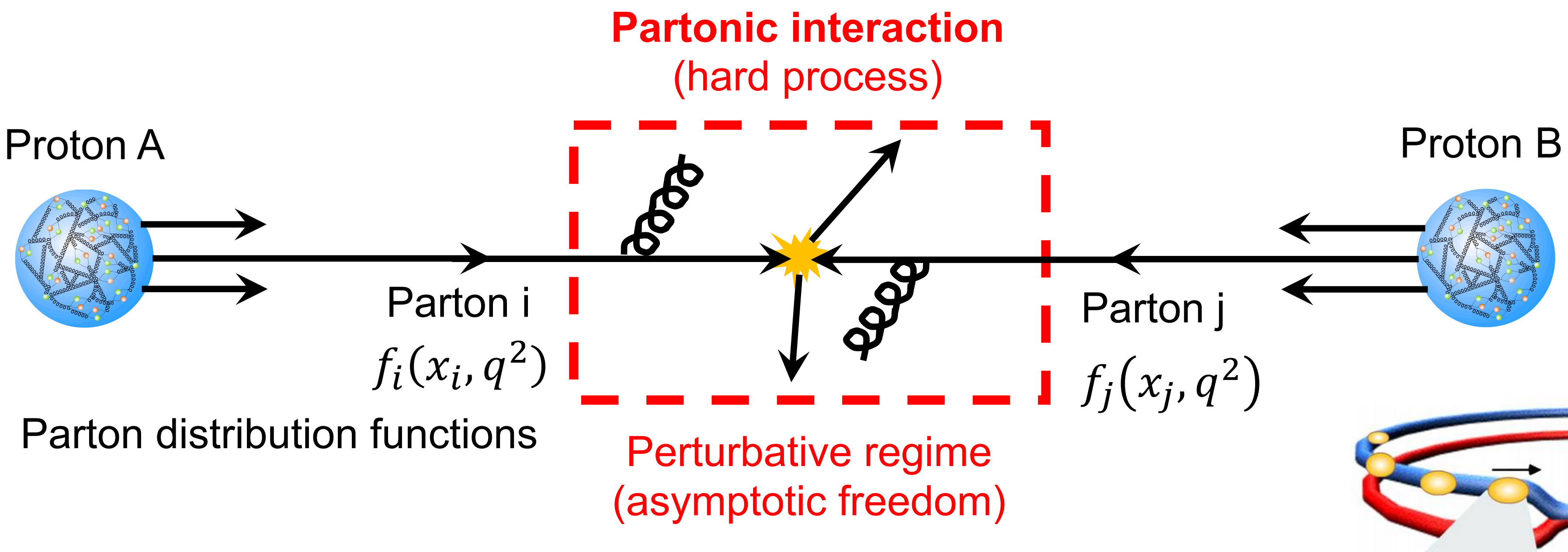
⇒ Top quark decays as a quasi free particle

⇒ Spin information and polarisation are accessible

(Spin decorrelation time: 10^{-21} s for hadrons)

High-p_T interactions in proton-proton collisions …

… described in the parton model



Partonic interaction
(hard process)

Proton A

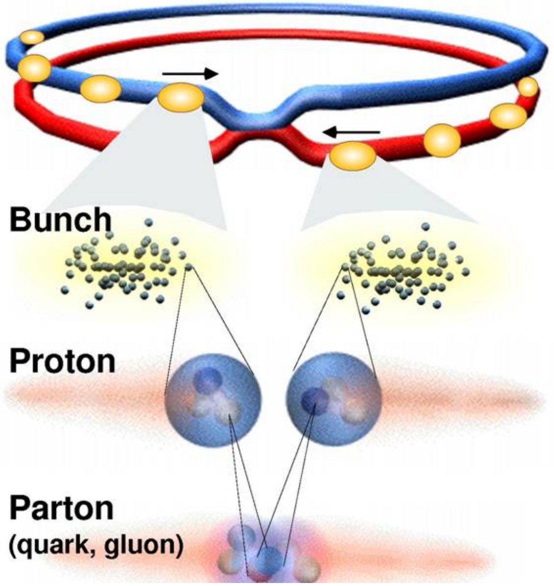
Proton B

Parton i
$f_i(x_i, q^2)$

Parton distribution functions

Parton j
$f_j(x_j, q^2)$

Perturbative regime
(asymptotic freedom)



Factorisation theorem

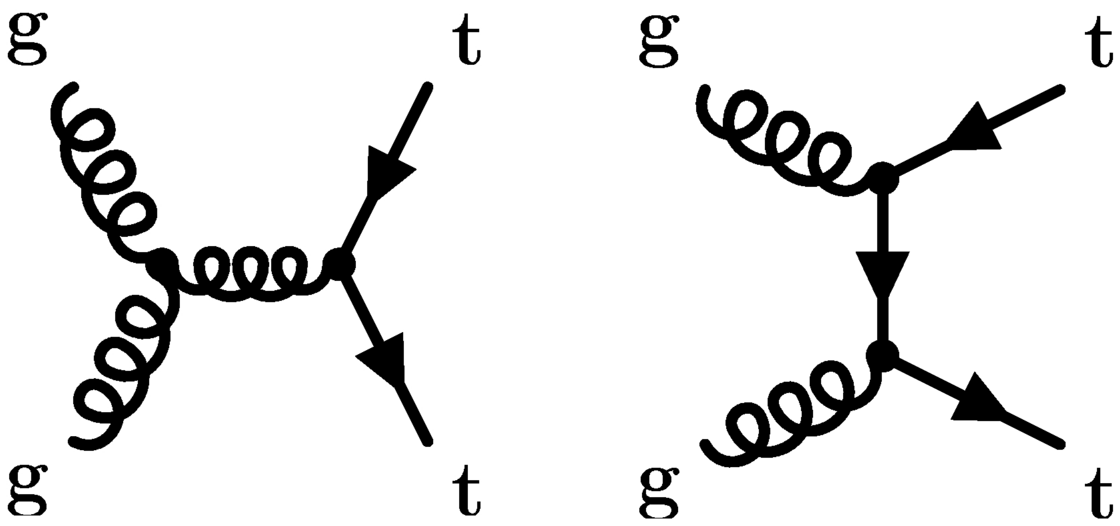
Partonic cross-section

$$\sigma(pp \to XY) = \sum_{i,j} \int d\hat{s}\, \mathcal{L}_{ij}(\hat{s}; s, \mu_f) \cdot \hat{\sigma}_{ij}(ij \to XY;\ \hat{s};\ \mu_f)$$

With $\mathcal{L}_{ij}(\hat{s}; s, \mu_f) = \frac{1}{s} \int_{\hat{s}}^{s} f_{i/A}\left(\frac{\tilde{s}}{s}\right) f_{j/B}\left(\frac{\hat{s}}{\tilde{s}}\right) \frac{1}{\tilde{s}}\, d\tilde{s}$ Parton luminosity

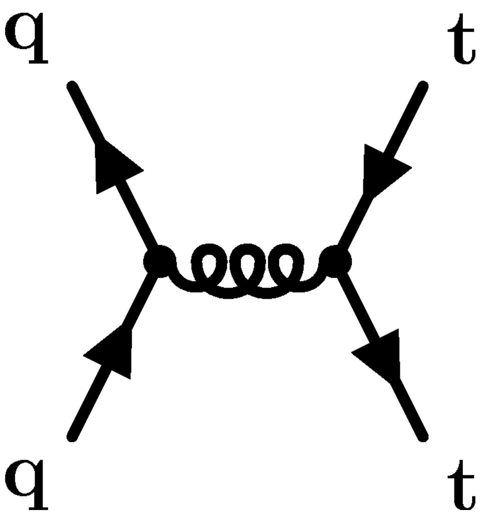
Top-quark-antiquark pair production

Gluon-gluon fusion



~90%

Quark-antiquark annihilation



~10%

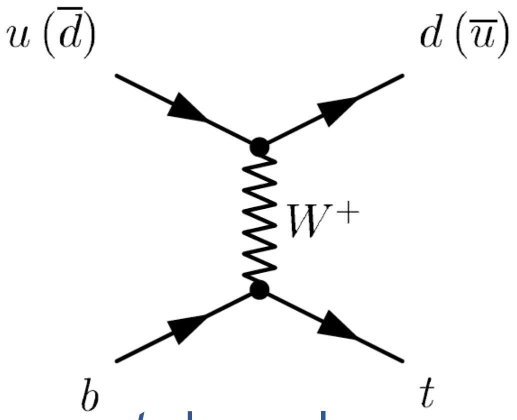
At the LHC at
$\sqrt{s} = 13$ TeV

Predicted total cross-section: $\sigma = 832\ ^{+20}_{-30}\ (\text{scale}) \pm\ 35$ (PDF and α_s) pb

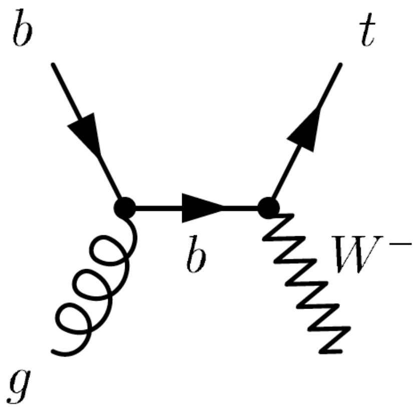
Relative uncertainty = 5.5%

... and more partonic top-quark processes

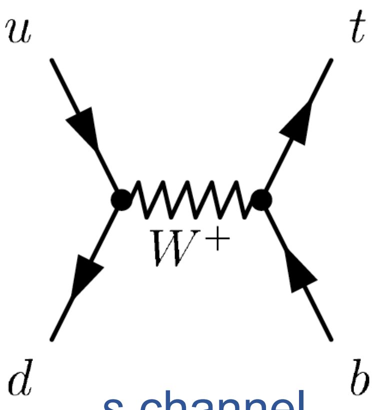
Single top-quark production



t-channel
(*tq* production)

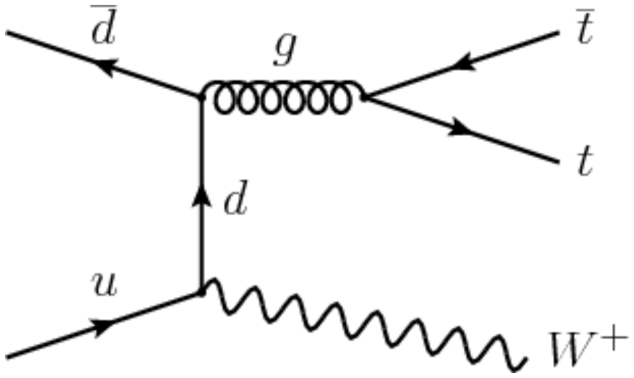


tW production

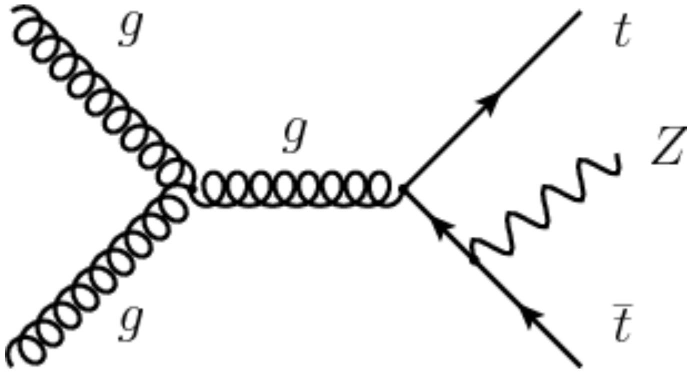


s-channel
($t\bar{b}$ production)

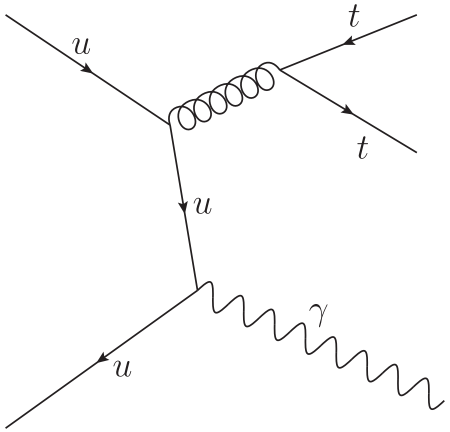
$t\bar{t} + W$ production



$t\bar{t} + Z$ production



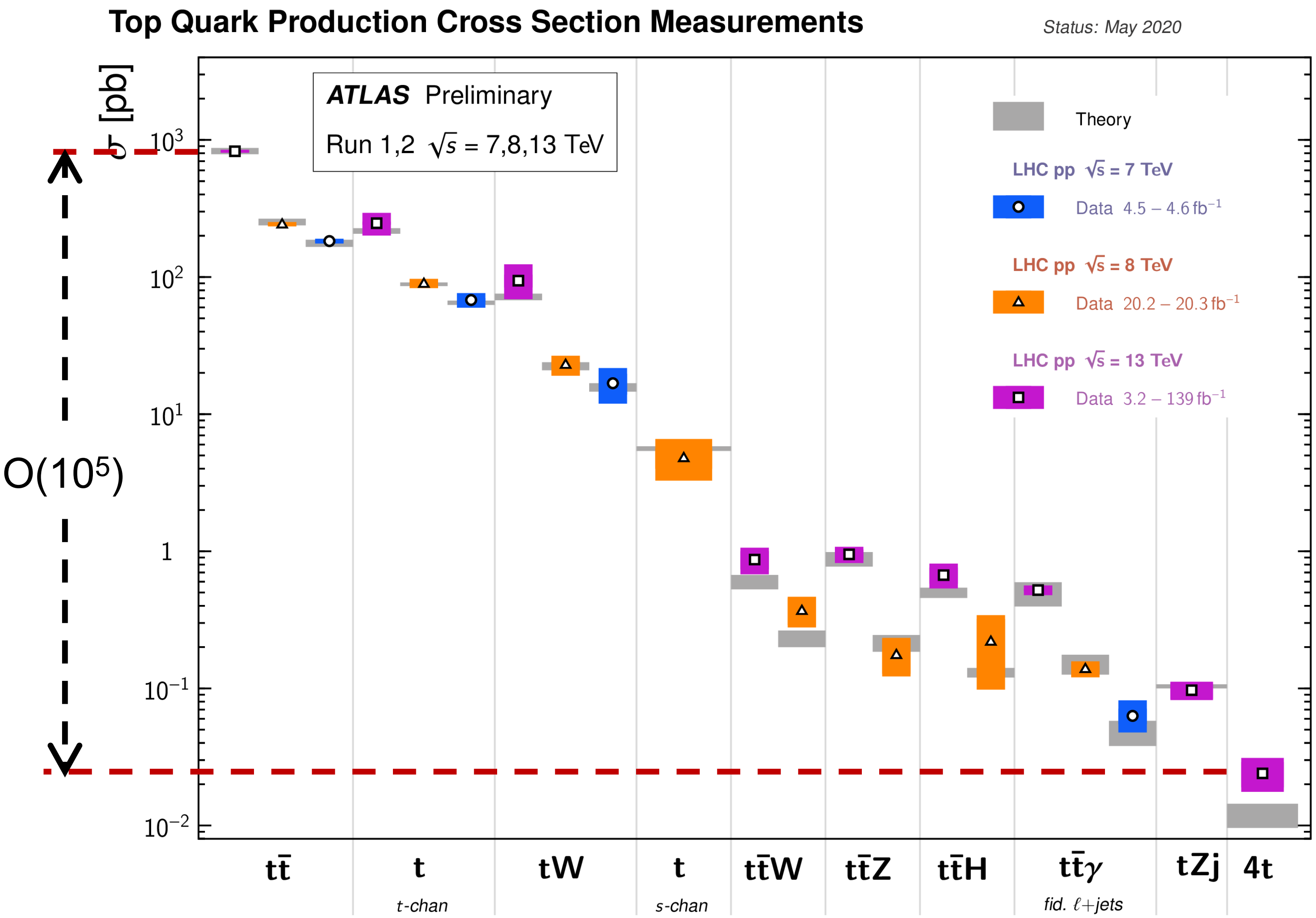
$t\bar{t} + \gamma$ production



The top-quark realm

- Cross-sections of top-quark processes span 5 orders of magnitude!
- In 139 fb-1 (Run 2 data set):
  - O(100M) $t\bar{t}$ events
  - O(1k) $t\bar{t}t\bar{t}$ events

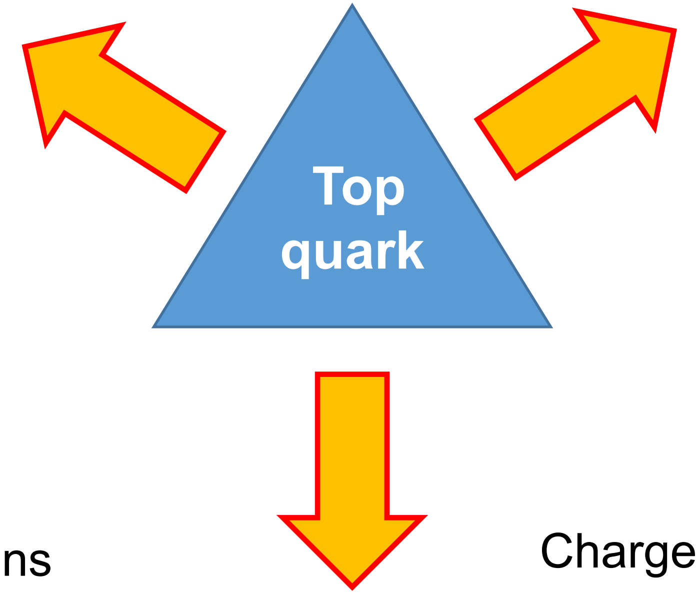
  produced



Processes discussed today:

Challenging the Standard Model with top quarks

Physics of the top quark and with top quarks.



Direct searches

Leptoquarks

Supersymmetry

Vector-like quarks

Heavy Higgs bosons

Indirect searches

Rare decays

CP violation

Flavour-changing neutral currents

Lepton-flavour violation

Top-quark + X production

Precision measurements

Spin correlations

Charge asymmetry

Polarisation

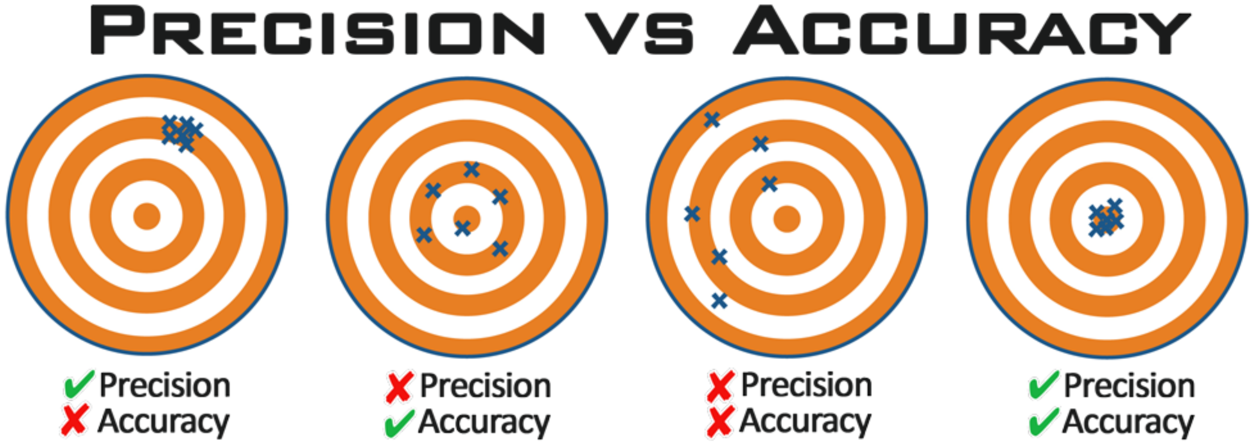
Differential and total cross-sections

W helicity in top-quark decay

Top-quark mass

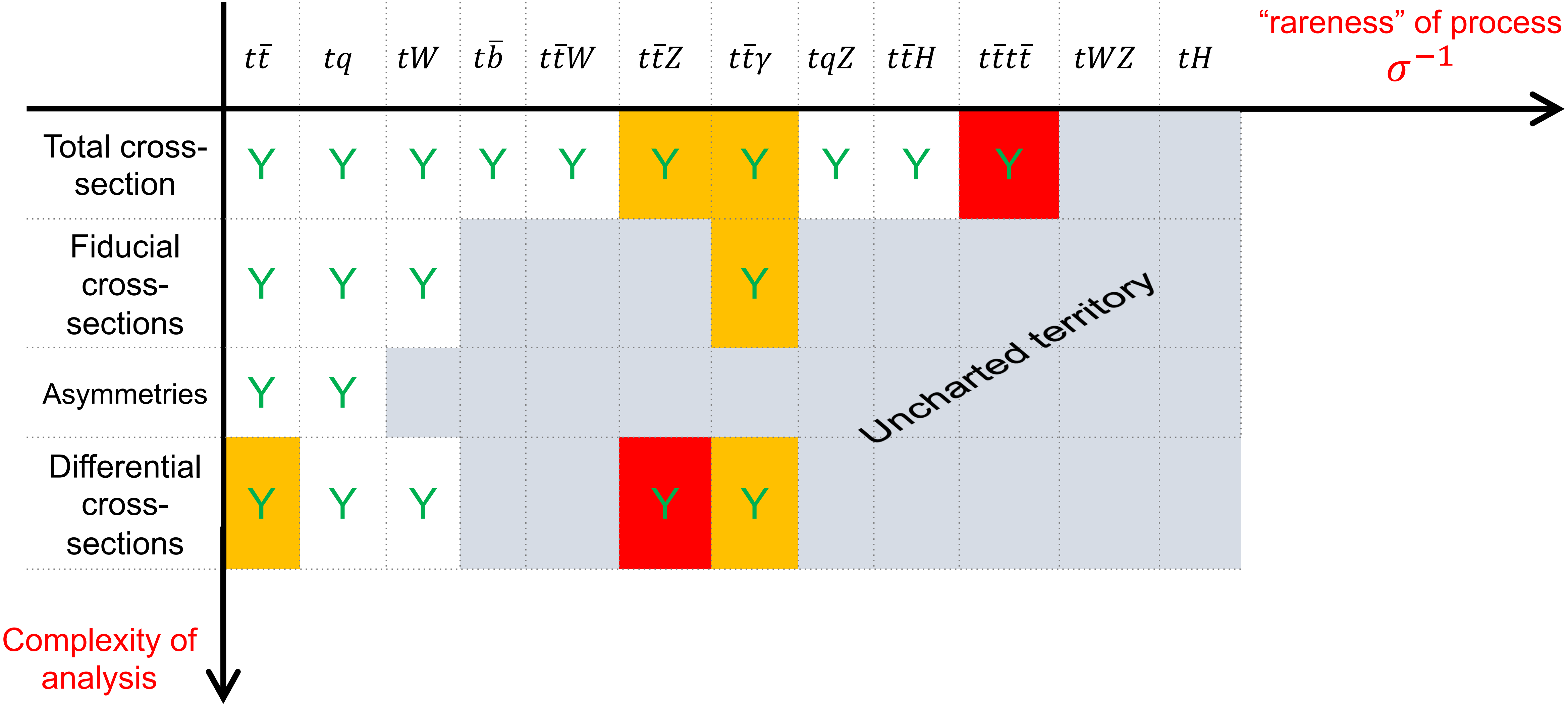
Top quarks as a tool

Precision measurements of top-quark properties



Reduce statistical and systematic uncertainties!

Pushing the frontiers of complexity



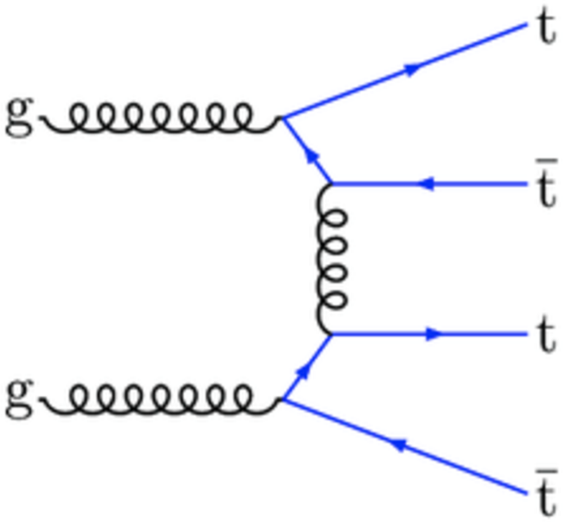
	$t\bar{t}$	tq	tW	$t\bar{b}$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}\gamma$	tqZ	$t\bar{t}H$	$t\bar{t}t\bar{t}$	tWZ	tH
Total cross-section	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		
Fiducial cross-sections	Y	Y	Y				Y					
Asymmetries	Y	Y										
Differential cross-sections	Y	Y	Y			Y	Y					

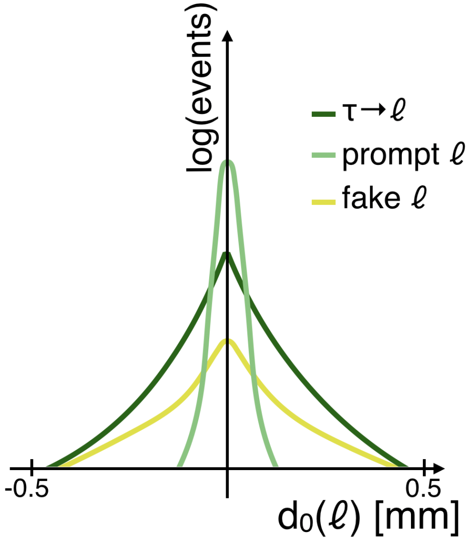
Part 1

Evidence for four-top-quark production

and

Test of the universality of τ and μ lepton couplings in W-boson decays



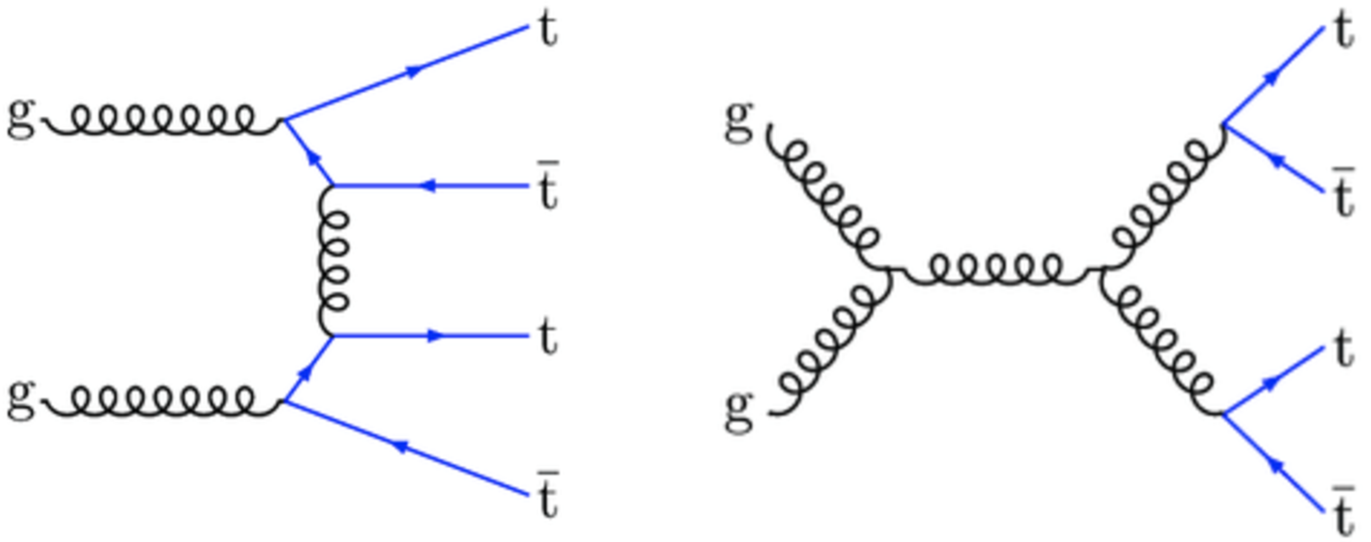


Four top-quarks production

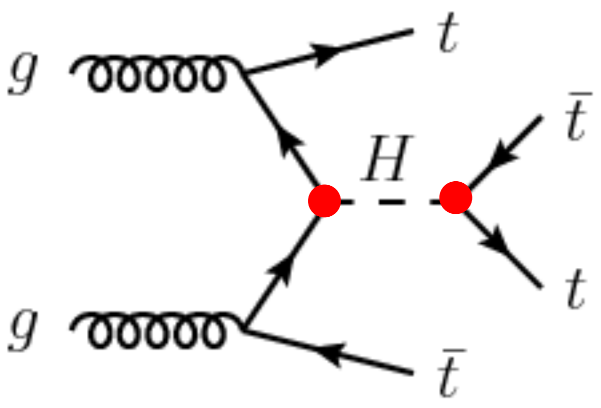
Very rare high-p_{T} scattering process:

In the SM at NLO (QCD and EWK corr.): $\sigma(t\bar{t}t\bar{t}) = 12.0 \pm 2.4$ (scale) fb [JHEP 02 (2018) 031]

Leading SM Feynman diagrams



Higgs boson contribution



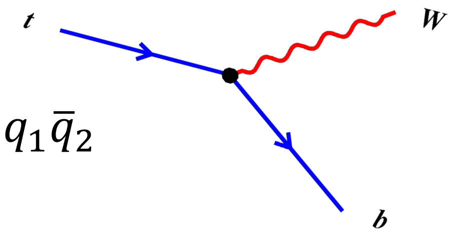
Sensitive to the top Yukawa coupling!

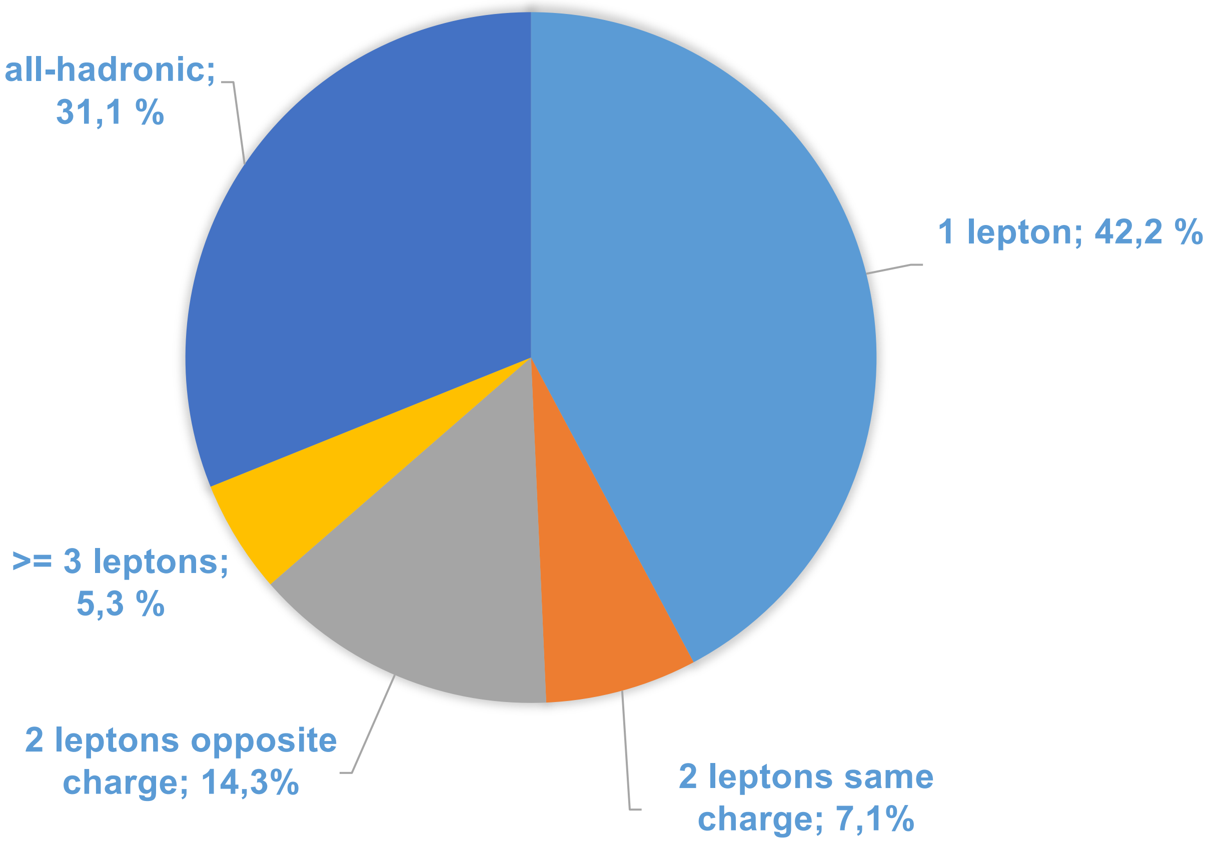
Phys. Rev. D 95 (2017) 053004

- SM process not yet observed!
- Sensitive to BSM physics, for example gluino pair production, two-Higgs-doublet models, contact interactions

Signatures and analysis channels

- 4-top-quarks final state contains 4 *W*-bosons: $W^+W^-W^+W^-$
- Categorize analysis channels according to *W*-boson decay modes: $W \rightarrow \ell\nu$ or $W \rightarrow q_1\bar{q}_2$





- Channels with best signal-to-background ratio:
  - 2 leptons with same-charge
  - ≥ 3 leptons
- Other channels suffer from large $t\bar{t}$ + jets ($b\bar{b}$ and $c\bar{c}$) background

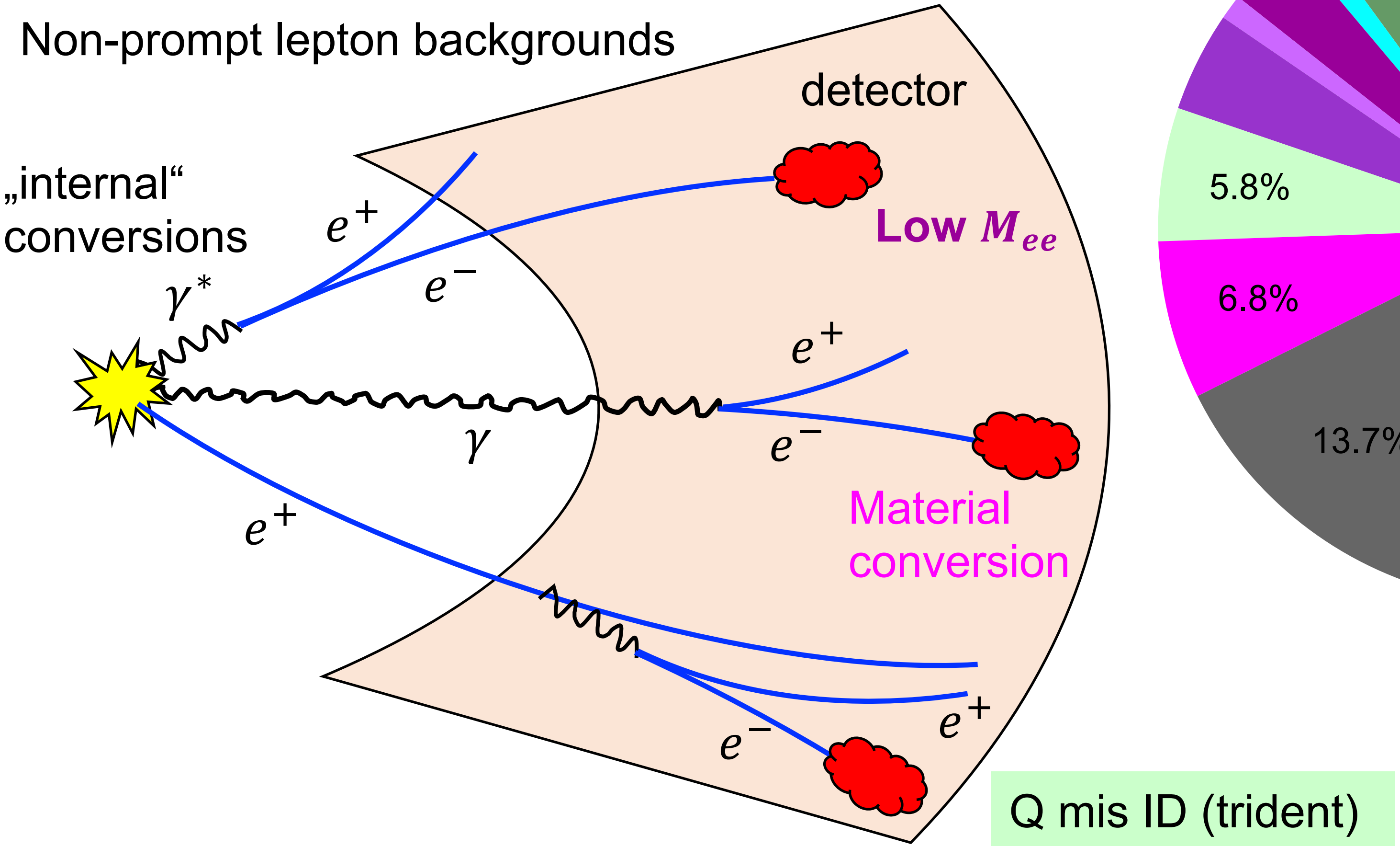
Background processes

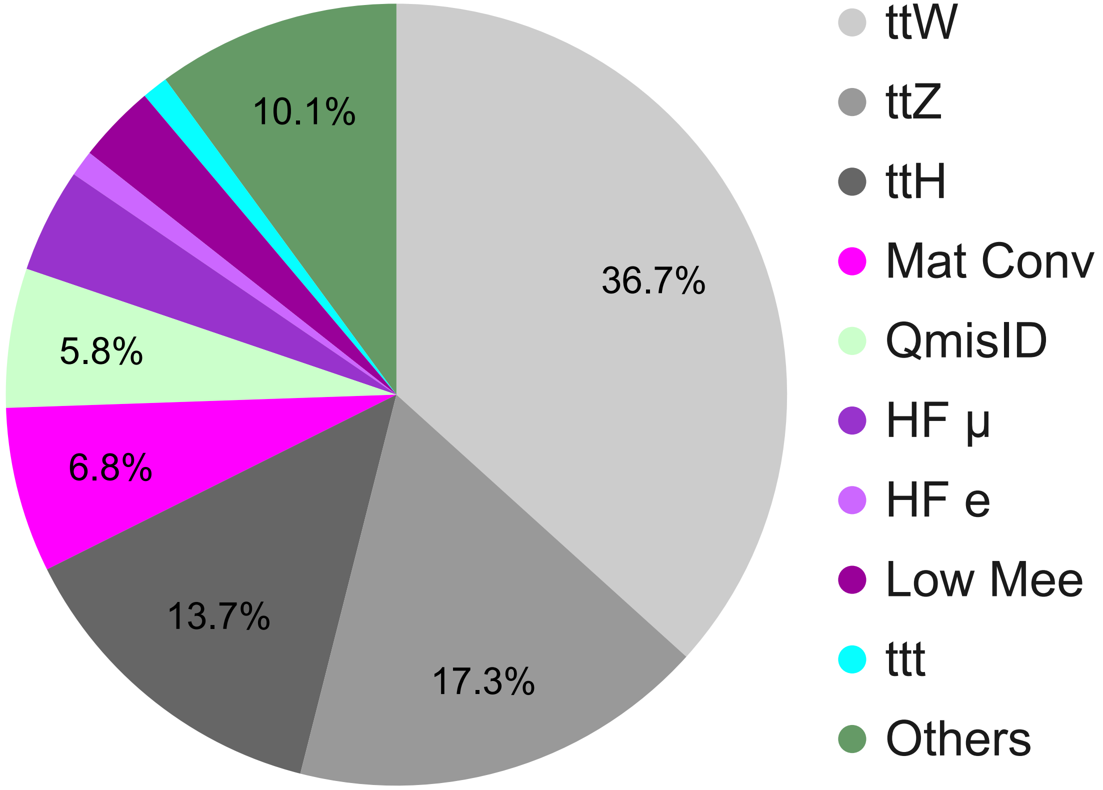
1) Hard-scattering processes with high-p_T prompt isolated (same-charge) leptons:

Major: $t\bar{t}W$+jets, $t\bar{t}Z$+jets, $t\bar{t}H$+jets, $t\bar{t}t$

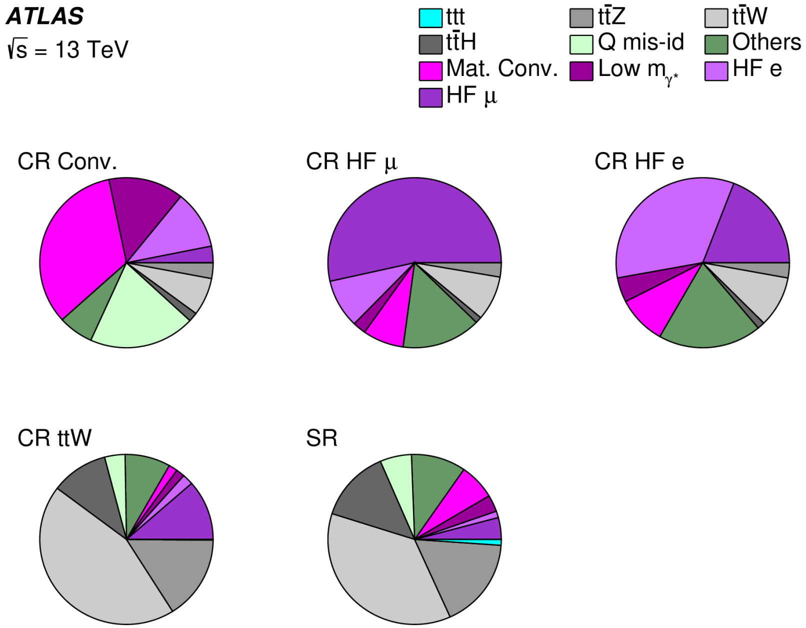
Minor: $t\bar{t}WW$, tWZ, tZq („Others“)

2) Non-prompt lepton backgrounds

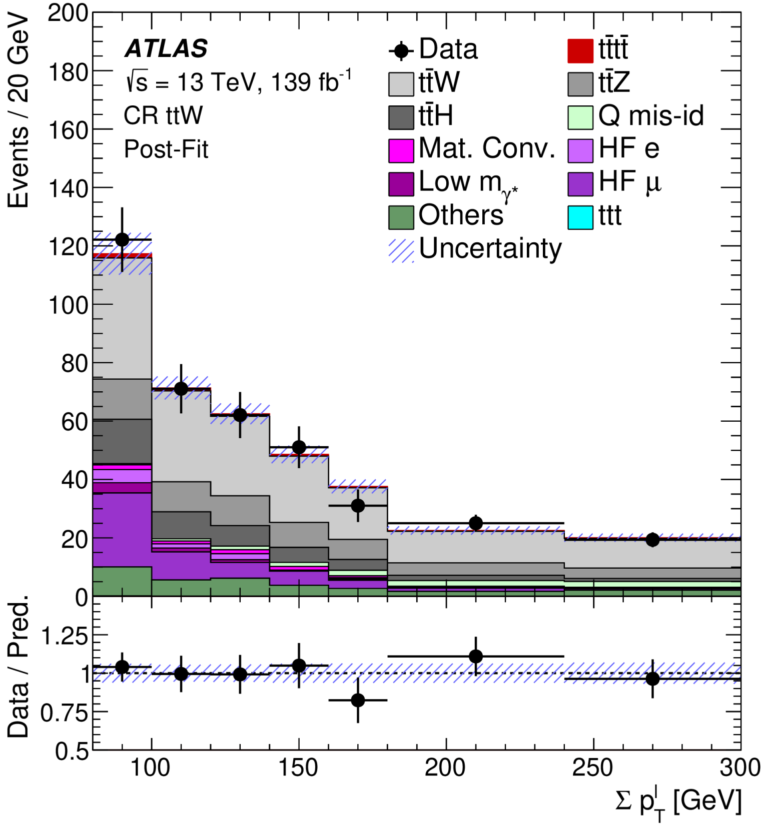




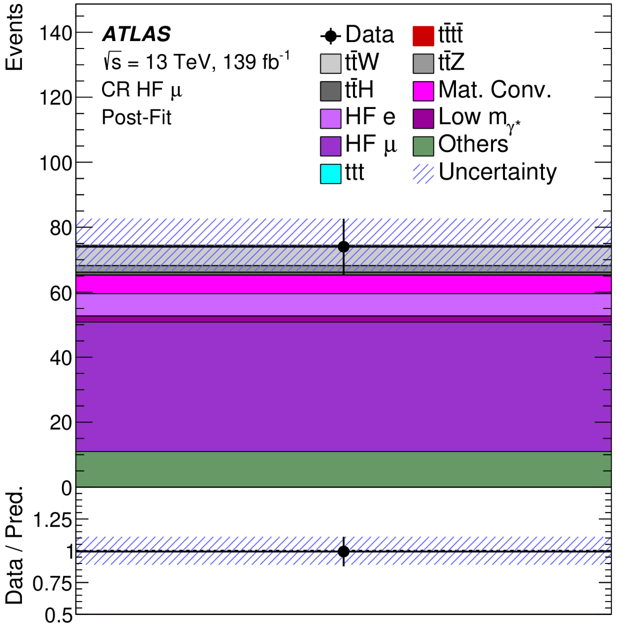
Background control regions



Control region for $t\bar{t}W$ events



Control region for muons from heavy-flavour decays (single bin)

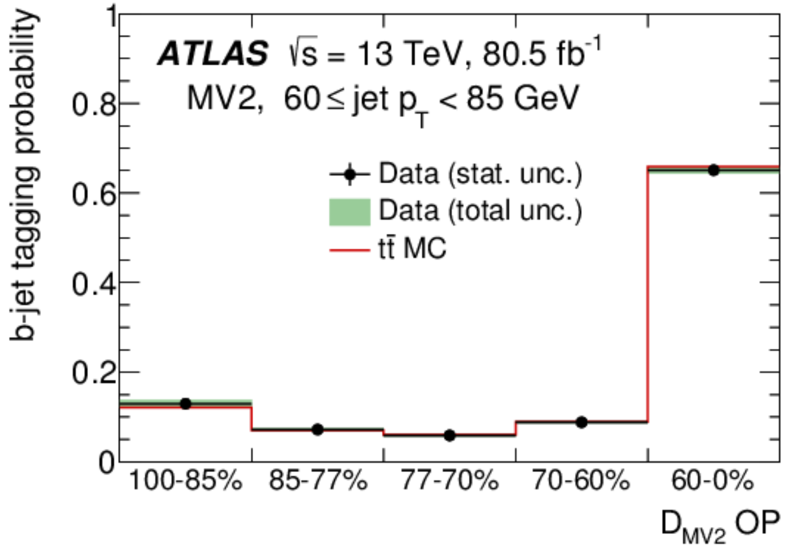


- Control regions are included in the final profile-likelihood fit
- Five backgrounds are free floating
  → normalisation factors are fitted

Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } m_{\gamma^*}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

Optimised signal-background separation

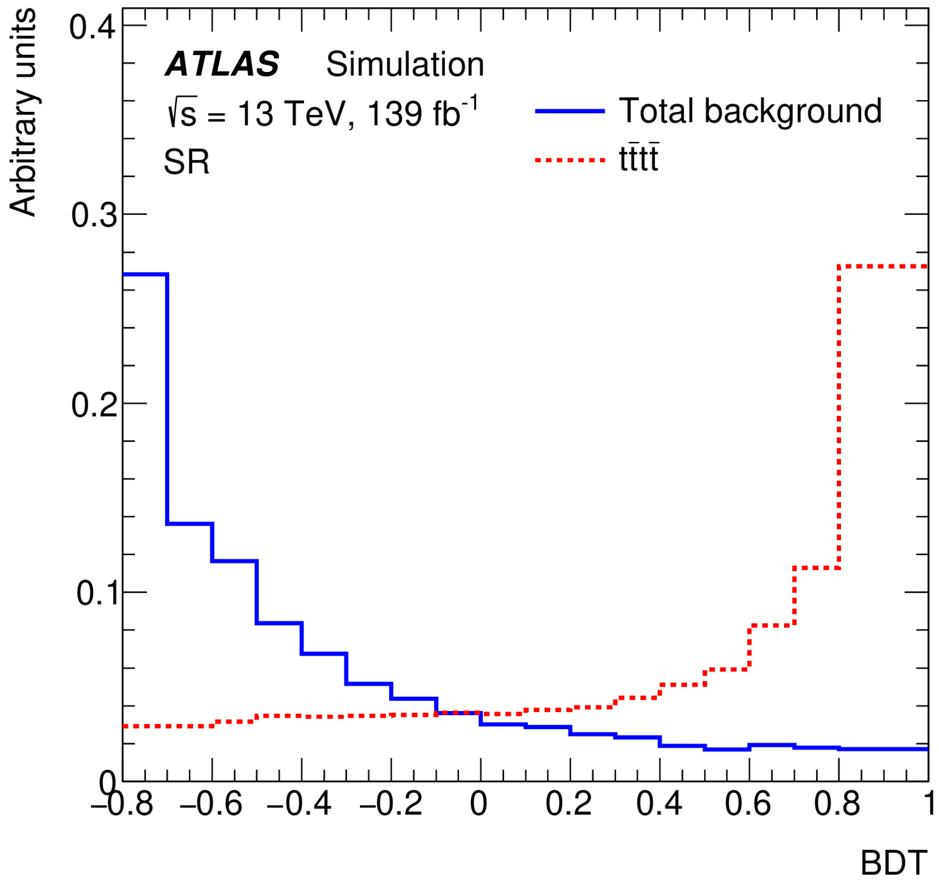
- Use Boosted Decision Tree (BDT) to separate signal from background events in the signal region (SR).
- Most important input variable:
  Sum of pseudo-continuous *b*-tagging score for all jets.



Eur. Phys. J C 79 (2019) 970

- Essentially counting *b*-jets in a clever way (signal has 4 b-jets).

Shapes of the BDT discriminant in the SR (signal versus background)



Evidence for four-top-quarks production

- Measured signal strength:

$$\mu(t\bar{t}t\bar{t}) = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}} = 2.0^{+0.9}_{-0.6}$$

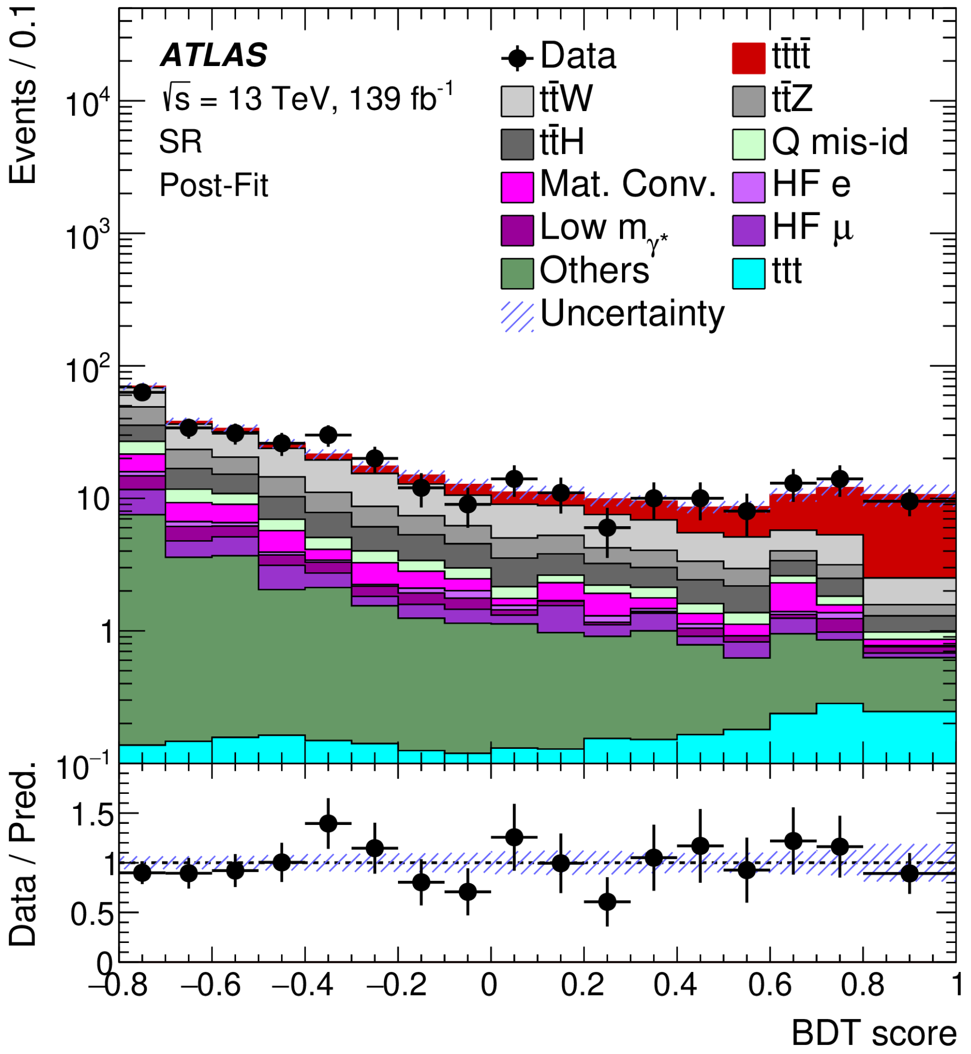
- Measured cross-section:

$$\sigma(t\bar{t}t\bar{t}) = 24 \pm 5\ (\text{stat})\ ^{+5}_{-4}\ (\text{syst})\ \text{fb}$$

predicted: $\sigma(t\bar{t}t\bar{t}) = 12.0\ \pm 2.4$ fb

- Strong evidence of 4.3 s.d. (2.4 s.d. expected) for this very rare process!

Consistent to 1.7 s.d. with the SM prediction.

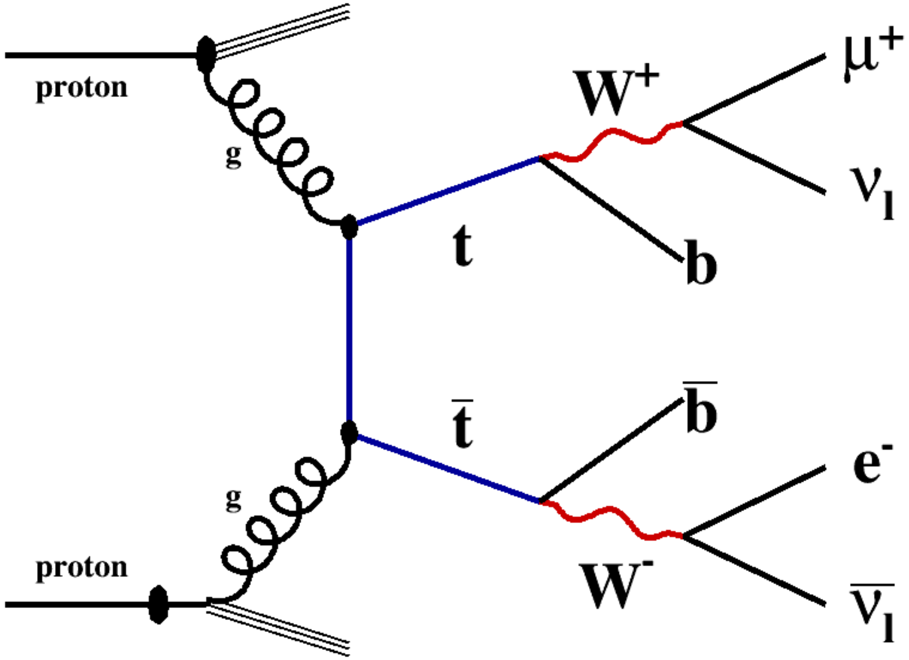


Eur. Phys. J. C 80 (2020) 1085 arXiv: 2007.14858

Top-quarks as a tool: a prime example

„Do research with top quarks, not on top quarks.“

Production of $t\bar{t}$ pairs is a copious source of on-shell *W*-boson pairs.



Note:

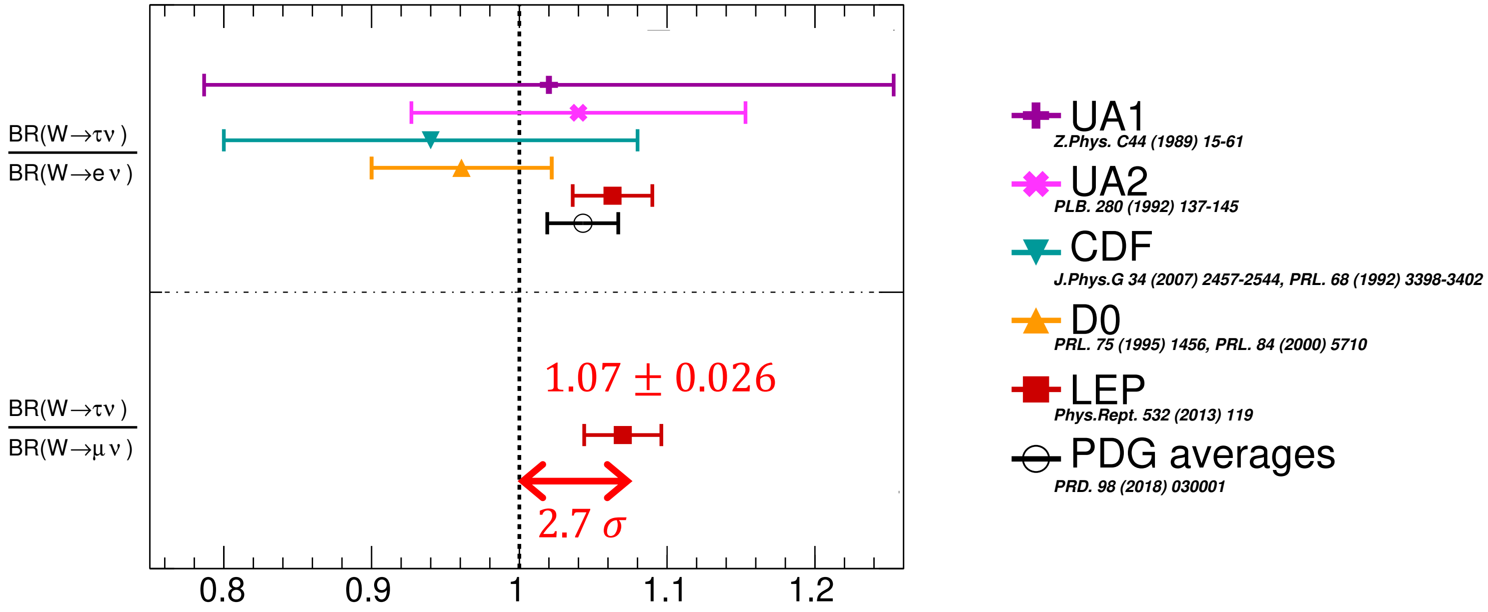
$$\frac{\sigma(t\bar{t})}{\sigma(WW)} \approx 10$$

Check universality of the weak coupling at *W* decay vertex by measuring:

$$R(\tau/\mu) = \frac{\mathcal{B}(W \rightarrow \tau\nu)}{\mathcal{B}(W \rightarrow \mu\nu)}$$

A long standing open issue

$R(\tau/\mu)$ measured at LEP II with W^+W^- pairs: discrepancy of 2.7 s.d. from 1 observed



Note:
Measurements of τ lifetime and branching ratios provide a very precise test of lepton-flavour universality at low energy:

$$\frac{g_\tau}{g_\mu} = 0.9999 \pm 0.0014$$

2nd, more recent motivation:
B factories and LHCb find 3.1 s.d. discrepancy in

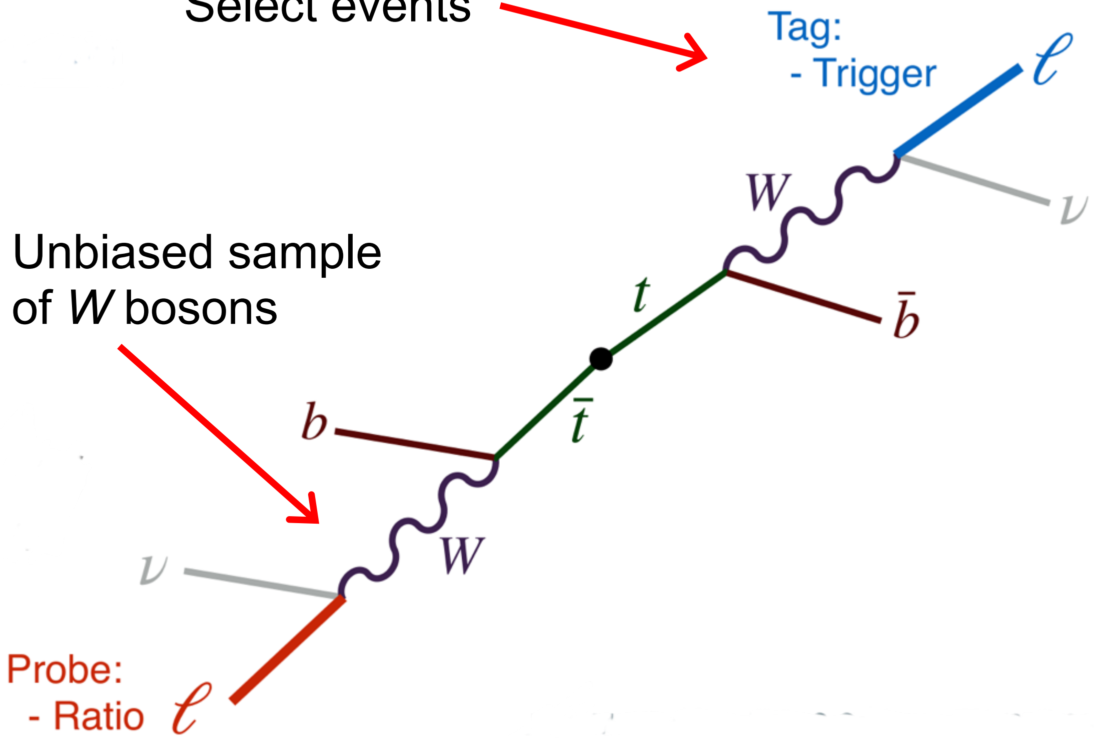
$$R(D^{(*)}) = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu\right)}{\mathcal{B}\left(\left(B \to D^{(*)}\mu\nu\right)\right)}$$

Analysis strategy

Tag-and-probe technique

Select events

Unbiased sample of *W* bosons



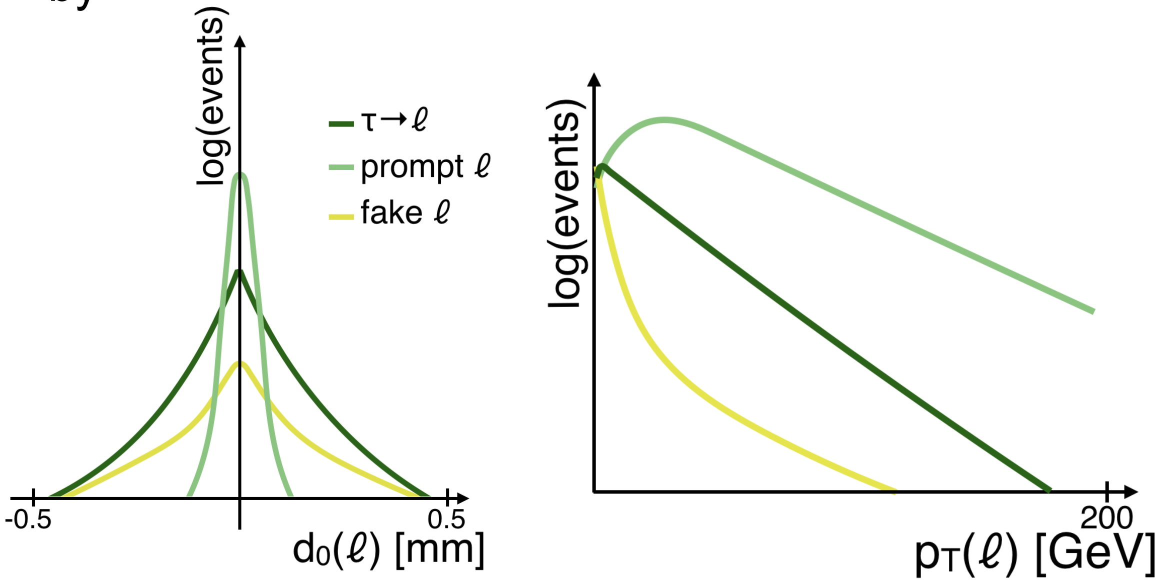
Measure τ leptons in their muon decay channel: $\tau \rightarrow \mu + \nu_\mu + \nu_\tau$

- ➢ Uncertainties in muon reconstruction efficiencies largely cancel

Separate

- ➢ prompt muons directly from *W* decay
- ➢ muons from the $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau\nu_\tau$ decay chain
- ➢ non-prompt muons

by



Transverse impact parameter $d_0(\mu)$

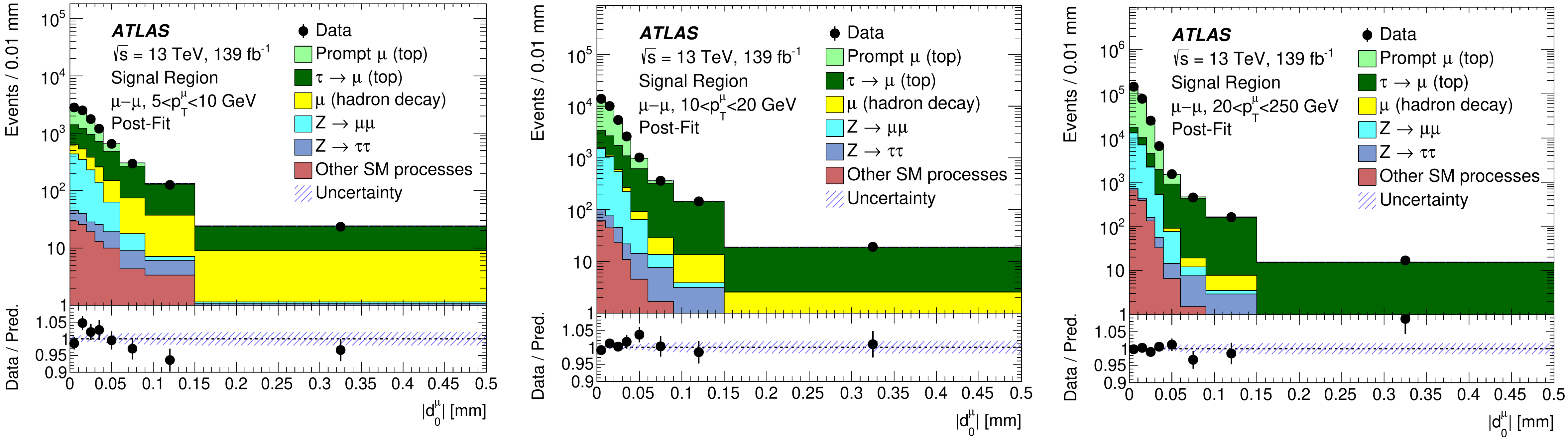
and

transverse momentum $p_\mathrm{T}(\mu)$

Maximum-likelihood fit …

… to 2D distribution in $|d_0(\mu)|$ and $p_{\mathrm{T}}(\mu)$ with 8 bins and 3 bins, respectively.

- Treat electron-tagged and muon-tagged events separately.

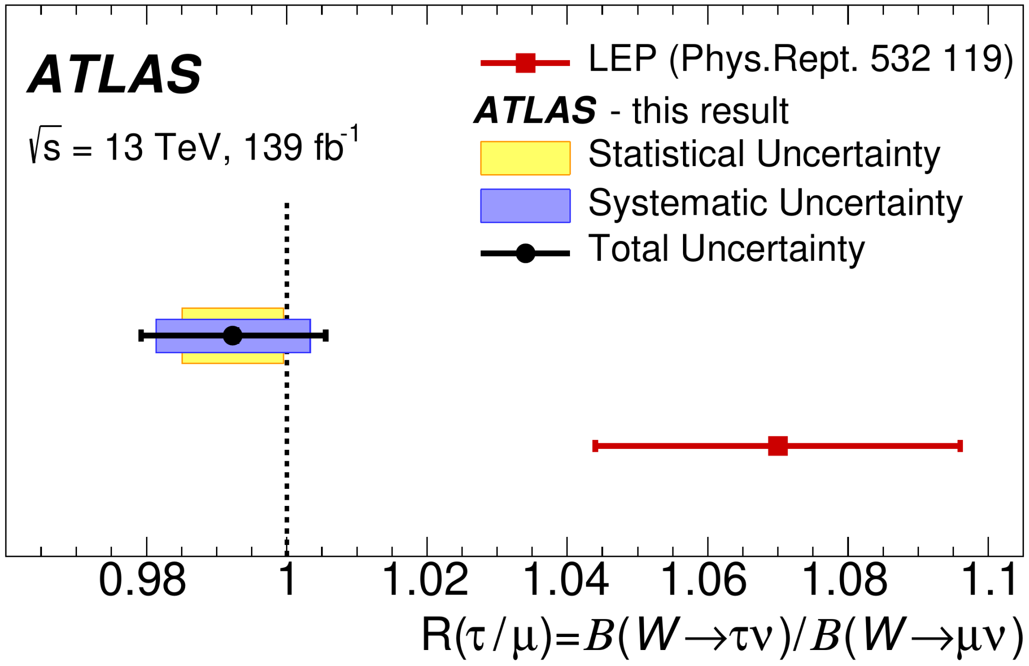


- The normalisation of the two main backgrounds, non-prompt muons from hadron decays and $Z \rightarrow \mu\mu$ are determined in control regions.

Result on $R(\tau/\mu)$

- Measured value:

$$\color{red}{R(\tau/\mu) = 0.992 \pm 0.013} \quad [\pm 0.07\ (\text{stat}) \pm 0.011\ (\text{syst})]$$



- In excellent agreement with the SM prediction.
- Most precise measurement of $R(\tau/\mu)$ to date. 🤙
- Almost twice the precision of the LEP II measurement.

Another example for the LHC as a precision experiment!

arXiv: 2007.14040 Accepted by Nature Physics.

Breakdown of uncertainties

Source	**Impact on $R(\tau/\mu)$**
Prompt d_0^{μ} templates	0.0038 🔵
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036 🔴
Muon isolation efficiency	0.0033 🔵
Muon identification and reconstruction	0.0030 🔵
$\mu_{(had.)}$ normalisation	0.0028 🔵
$t\bar{t}$ scale and matching variations	0.0027 🔴
Top p_{T} spectum variation	0.0026 🔴
$\mu_{(had.)}$ parton shower variations	0.0021 🔴
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^{μ} shape	0.0017 🔴
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau\to\mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072 🔵
Total	**0.013**

- Important uncertainties are of experimental nature (marked with 🔵).

  → improvements are possible with more data

- Improvements in modelling are less obvious and most likely longer term (marked with 🔴).

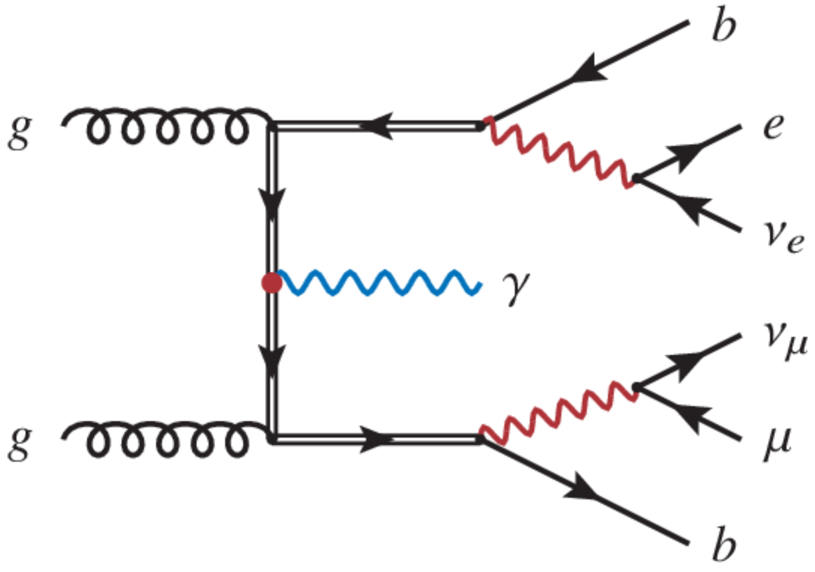
Part 2

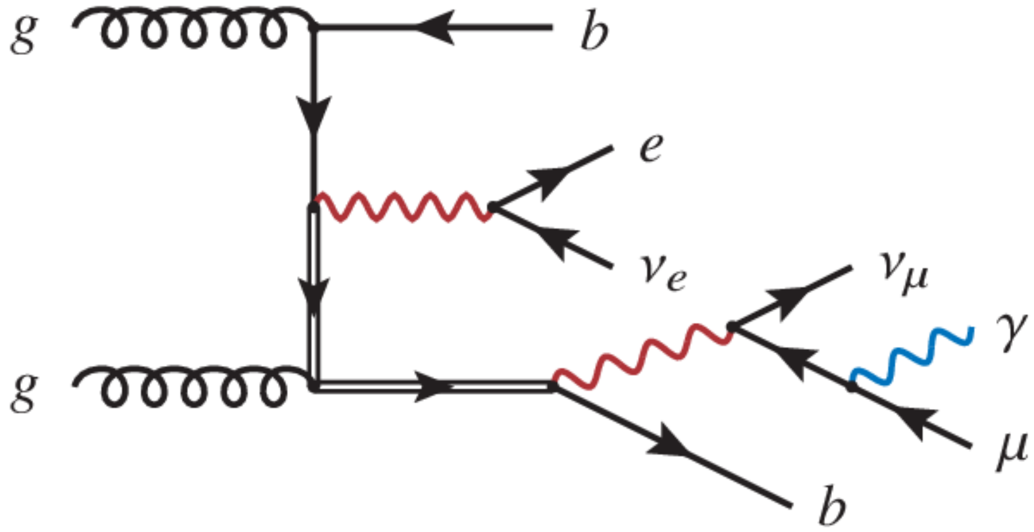
Measurements of $t\bar{t} + X$ production with $X = \gamma$ and $X = Z$

Measuring $t\bar{t}+\gamma$ and $tW+\gamma$ production

Main aim: comparison of differential distributions to a dedicated NLO computation: JHEP 10 (2018) 158

- Full computation of the $pp \rightarrow b e^{-} \bar{\nu}_e \bar{b} \mu^{+} \nu_\mu$ final state
- Includes $t\bar{t}+\gamma$ and $tW+\gamma$ interference and off-shell effects of W bosons and top quarks





- Partonic phase space has large acceptance for photons from final-state radiation.
- Analysis is not optimised for sensing the $t\gamma$ electroweak coupling

Inclusive cross-section measurement

- Main selection requirements:
    - 1 electron and 1 muon with $p_\mathrm{T} > 25$ GeV and $|\eta| < 2.5$
    - 1 isolated photon with $E_\mathrm{T} > 20$ GeV and $|\eta| < 2.37$
    - ≥ 2 jets with $p_\mathrm{T} > 25$ GeV and $|\eta| < 2.5$,
      at least one of them *b*-tagged
- Profile maximum-likelihood fit to

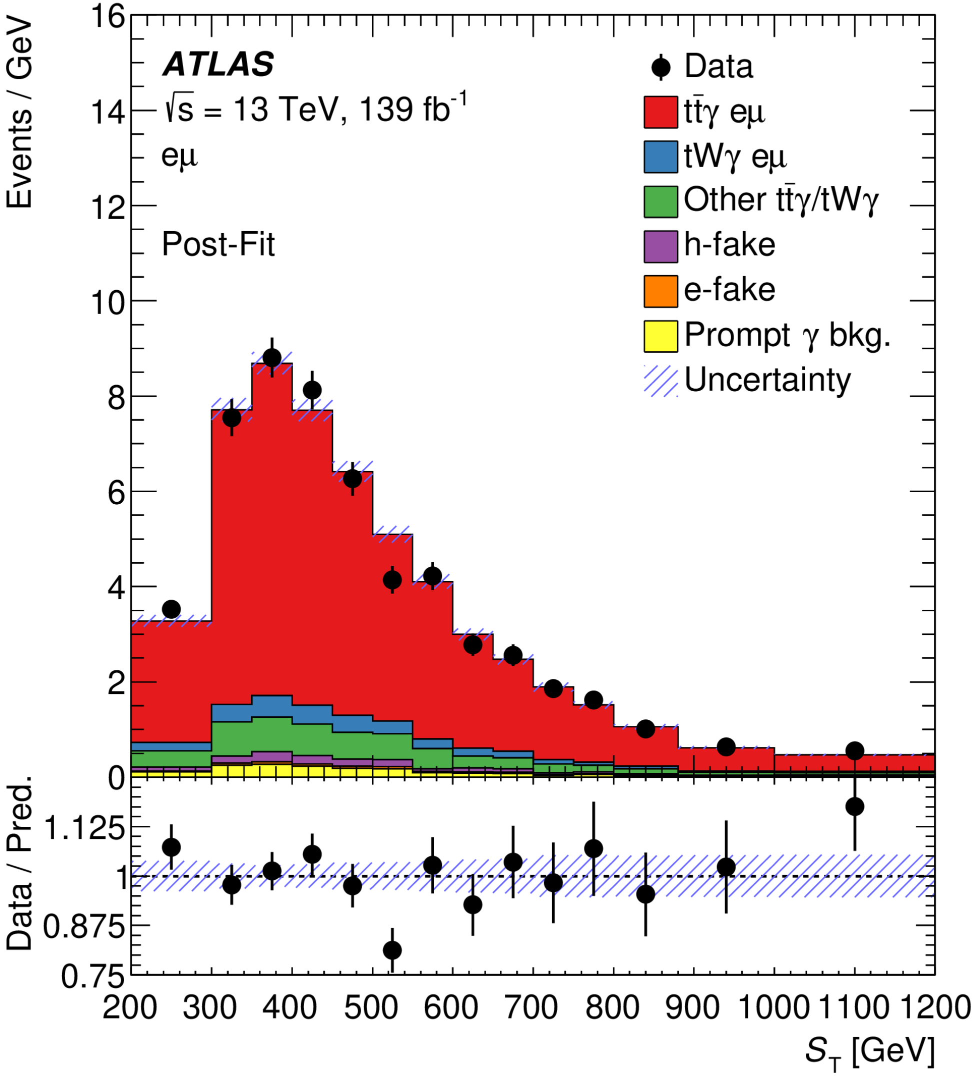
$$S_\mathrm{T} = \sum\nolimits_{\mathrm{jets}} p_\mathrm{T} + p_\mathrm{T}(e) + p_\mathrm{T}(\mu) + E_\mathrm{T}^{\mathrm{miss}}$$

- Result: fiducial cross-section

$$\sigma_{\mathrm{fid}}(t\bar{t}+\gamma) = 39.6 \pm 0.8\ (\mathrm{stat}) \pm {}^{+2.6}_{-2.2}\ (\mathrm{syst})\ \mathrm{fb}\ ^*$$

$$\sigma_{\mathrm{NLO}}(t\bar{t}+\gamma) = 38.5 \pm {}^{+0.56}_{-2.18}(\mathrm{scale}) \pm {}^{+1.04}_{-1.18}\ (\mathrm{PDF})\ \mathrm{fb}$$

Excellent agreement!



* Relative uncertainty: 6.3%

JHEP 09 (2020) 049

Differential cross-sections: Unfolding

$$\frac{d\sigma}{dX_k} = \frac{1}{\mathcal{L}_{int}\ \Delta X_k\ \varepsilon_k} \sum_j M_{jk}^{-1} \left(N_j^{\mathrm{obs}} - N_j^{b}\right) f_{e\mu,j} \left(1 - f_{\mathrm{out},j}\right)$$

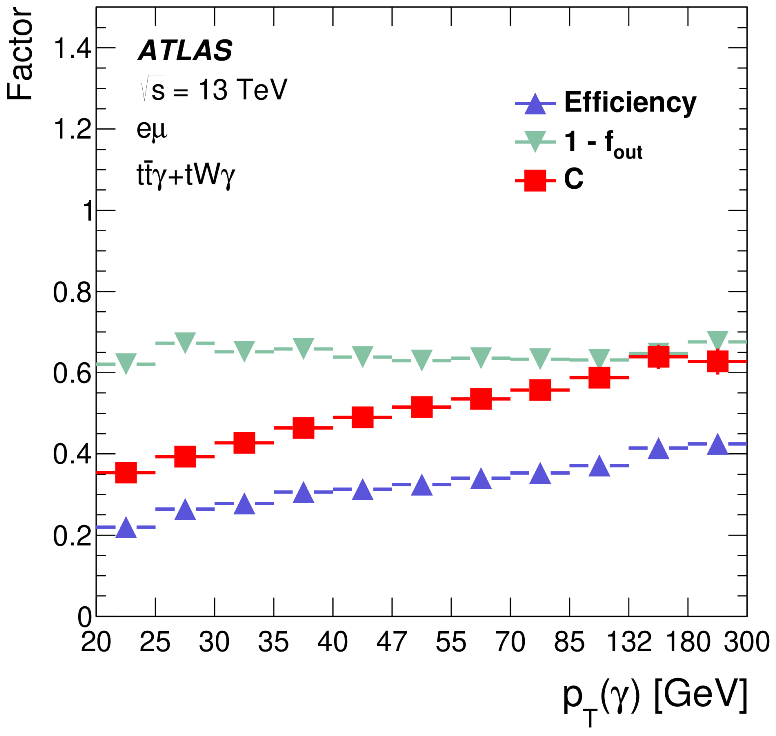
Bin at parton level

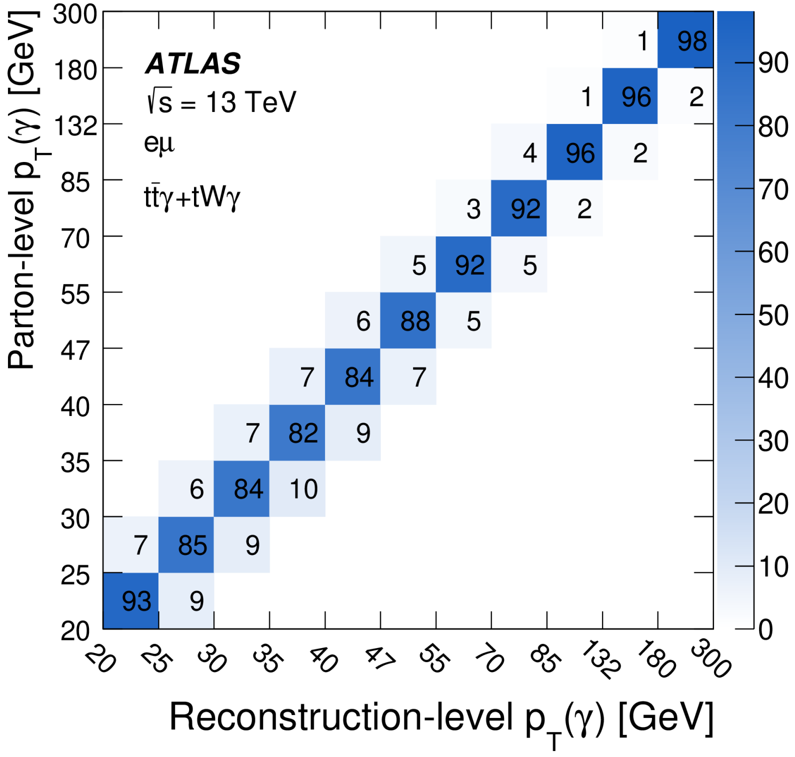
Selection efficiency of fiducial events

Bin at reconstruction level

Migration matrix

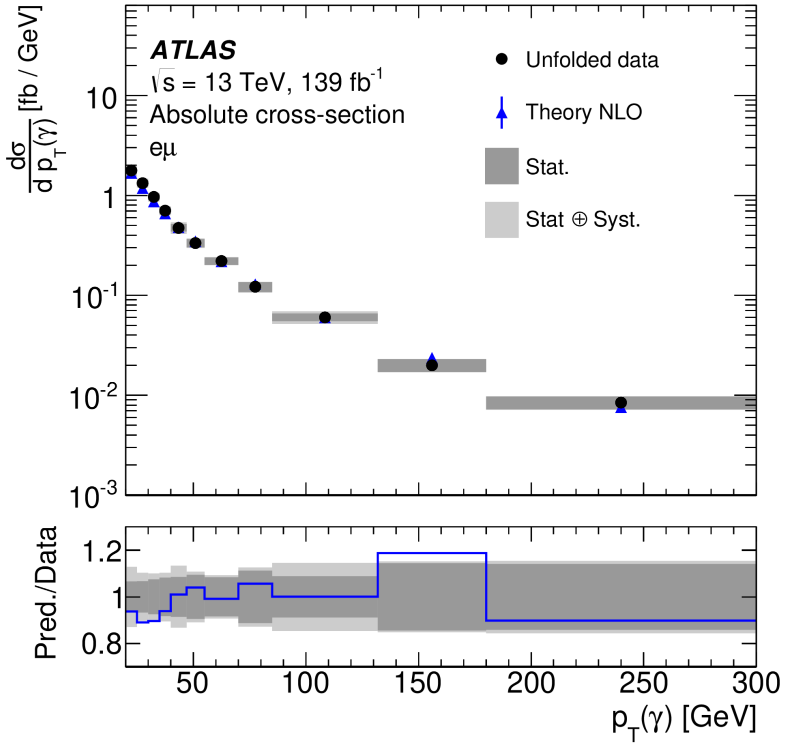
Fraction of events outside of the fiducial region, but selected at reconstruction level

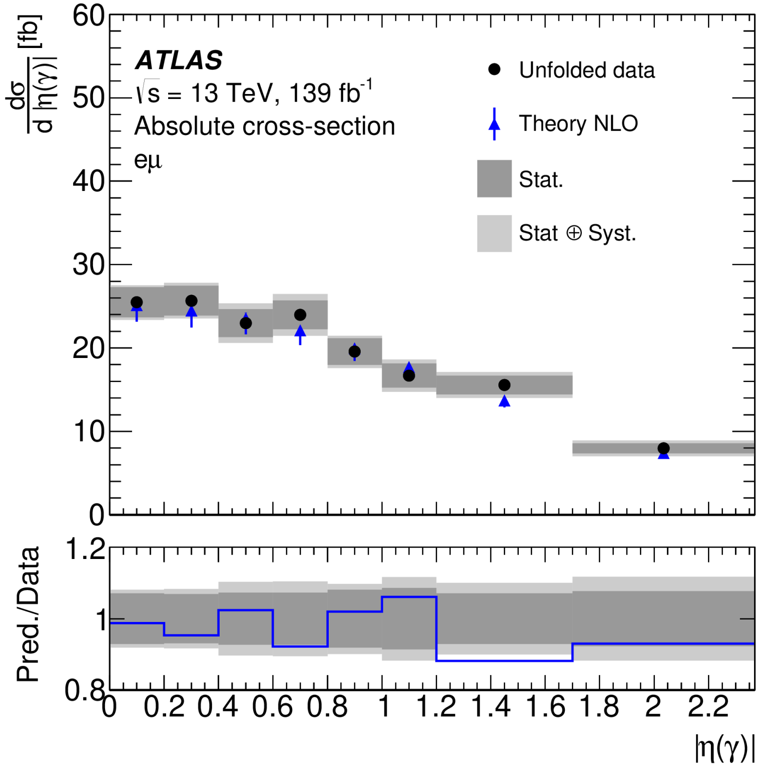


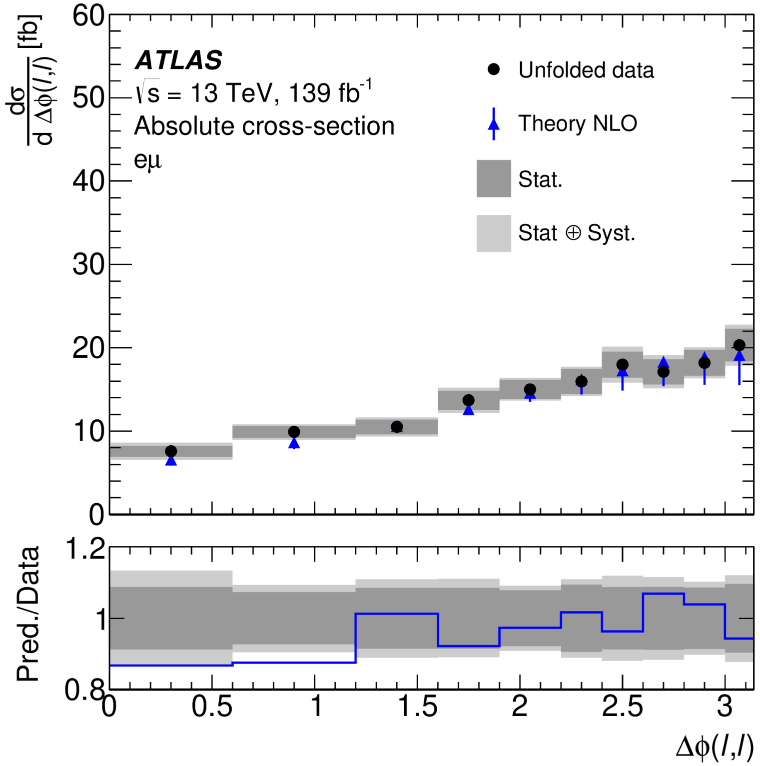


Absolute differential cross-sections

- Measured distributions: $p_\mathrm{T}(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)_\mathrm{min}$, $\Delta\phi(e,\mu)$, $|\Delta\eta(e,\mu)|$
- Uncertainties at the 10% level.
- Good agreement with NLO prediction!



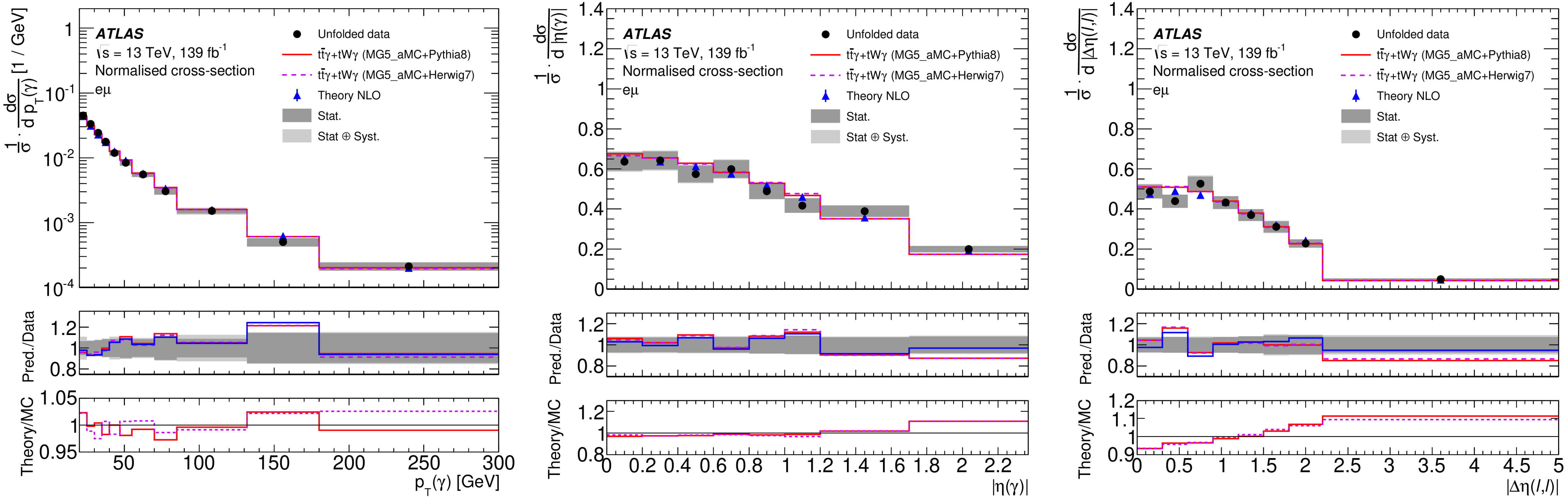




Predictions	$p_\mathrm{T}(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)_\mathrm{min}$		$\Delta\phi(\ell,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
Theory NLO	6.1/11	0.87	4.5/8	0.81	11.7/10	0.31	5.8/10	0.83	6.2/8	0.62

Normalised differential cross-sections

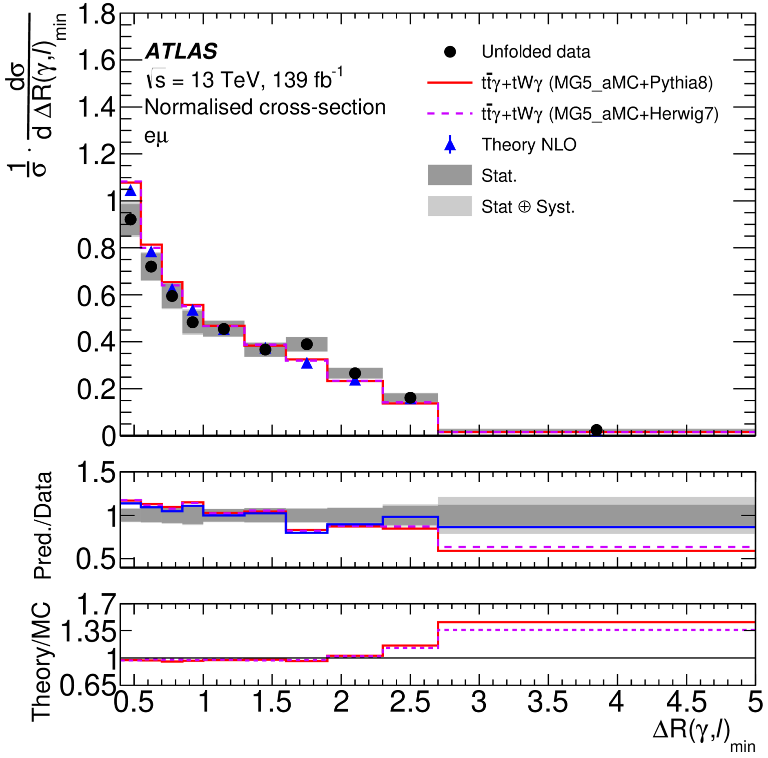
- Uncertainties slightly below 10%.
- Distributions of $p_{\mathrm{T}}(\gamma)$, $|\eta(\gamma)|$, $|\Delta\eta(e,\mu)|$ are well modelled by the fixed-order prediction and MG5_aMC@NLO.

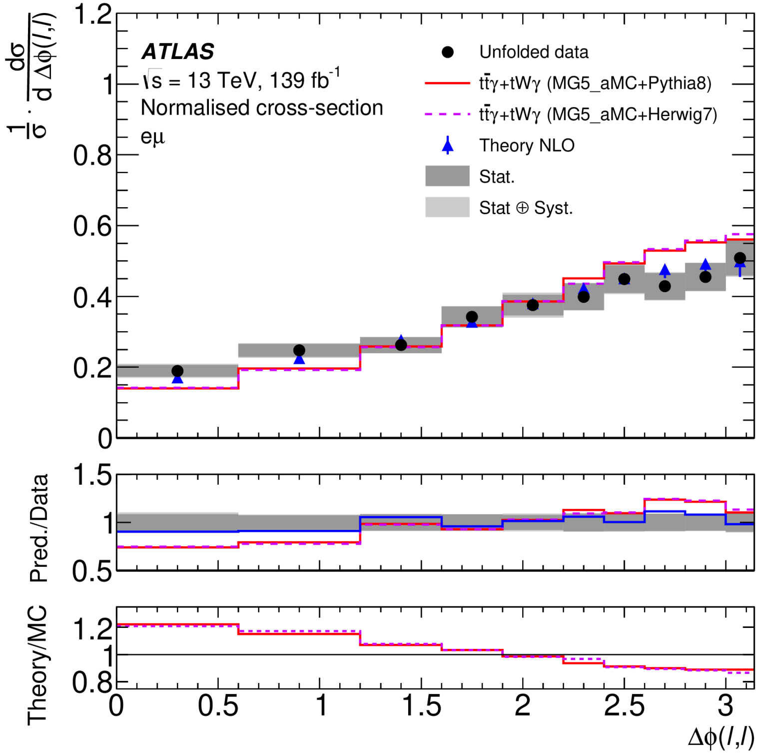


Predictions	$p_{\mathrm{T}}(\gamma)$ χ^2/ndf	$p_{\mathrm{T}}(\gamma)$ p-value	$\|\eta(\gamma)\|$ χ^2/ndf	$\|\eta(\gamma)\|$ p-value	$\Delta R(\gamma,\ell)_{\min}$ χ^2/ndf	$\Delta R(\gamma,\ell)_{\min}$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value	$\|\Delta\eta(\ell,\ell)\|$ χ^2/ndf	$\|\Delta\eta(\ell,\ell)\|$ p-value
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Pythia8)	6.3/10	0.79	7.3/7	0.40	20.1/9	0.02	30.8/9	<0.01	6.5/7	0.48
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Herwig7)	5.3/10	0.87	7.7/7	0.36	18.9/9	0.03	31.6/9	<0.01	6.8/7	0.45
Theory NLO	6.0/10	0.82	4.5/7	0.72	13.5/9	0.14	5.8/9	0.76	5.6/7	0.59

Normalised differential cross-sections

- Distributions of $\Delta R(\gamma,\ell)_{\min}$ and $\Delta\phi(e,\mu)$ not well modelled by MG5_aMC@NLO but well described by fixed-order calculation.



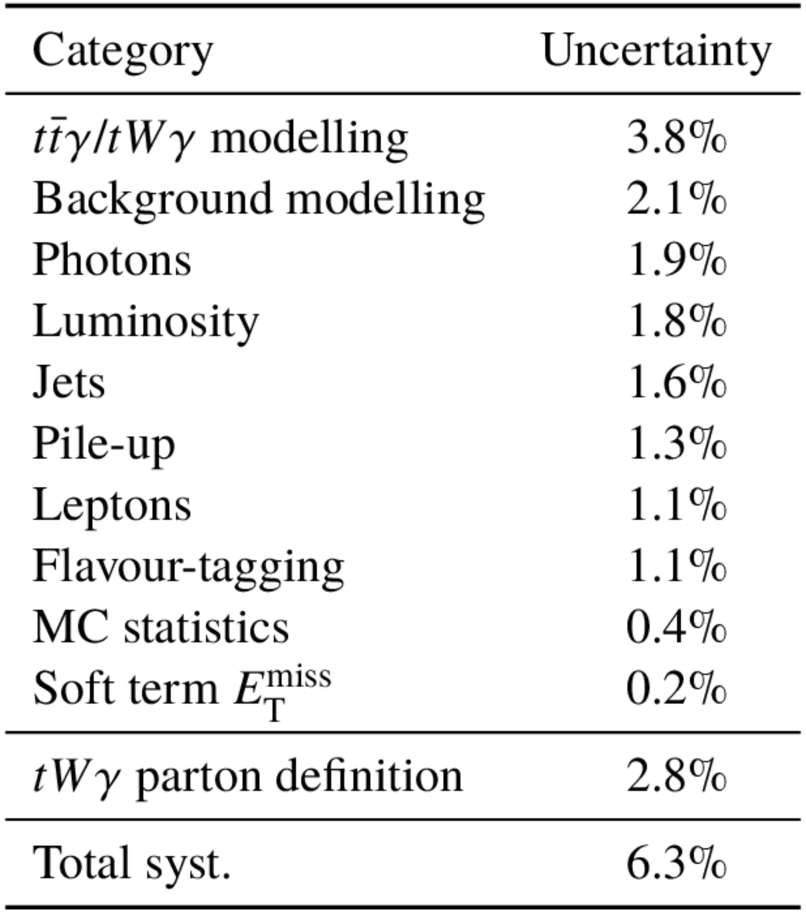


- $\Delta\phi(e,\mu)$ is sensitive to $t\bar{t}$ spin correlations.
- In $t\bar{t}$ production $\Delta\phi$ is neither well described by NNLO fixed-order calculations nor by MC generators.

Predictions	$p_T(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)_{\min}$		$\Delta\phi(\ell,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Pythia8)	6.3/10	0.79	7.3/7	0.40	20.1/9	0.02	30.8/9	<0.01	6.5/7	0.48
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Herwig7)	5.3/10	0.87	7.7/7	0.36	18.9/9	0.03	31.6/9	<0.01	6.8/7	0.45
Theory NLO	6.0/10	0.82	4.5/7	0.72	13.5/9	0.14	5.8/9	0.76	5.6/7	0.59

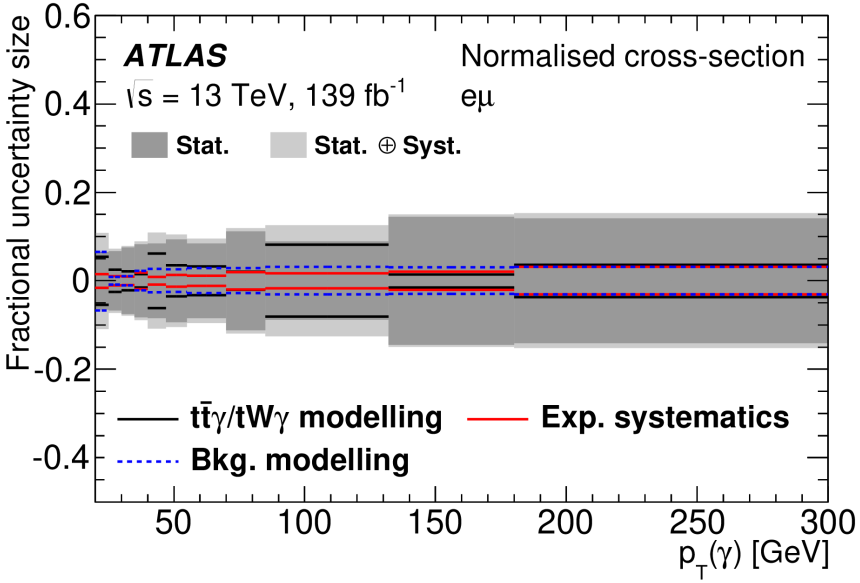
A word on the uncertainty breakdown

Inclusive cross-section



Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%
MC statistics	0.4%
Soft term $E_{\mathrm{T}}^{\mathrm{miss}}$	0.2%
$tW\gamma$ parton definition	2.8%
Total syst.	6.3%

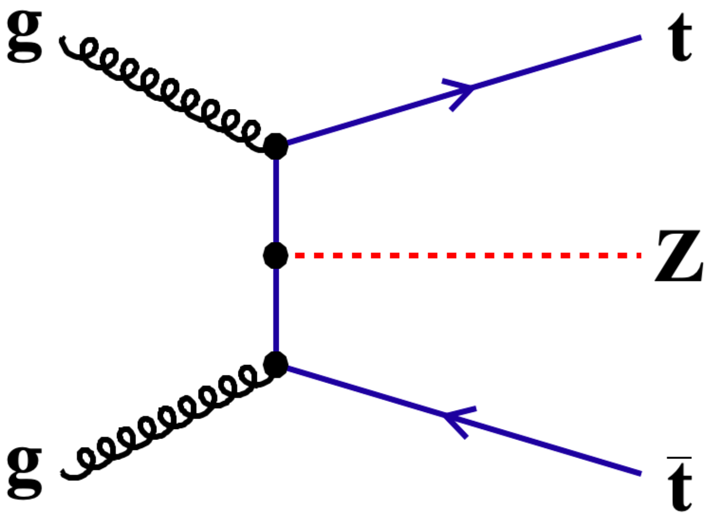
Differential cross-sections



- Statistical uncertainties are still sizeable
- More data will help (see projections for HL-LHC: ATL-PHYS-PUB-2018-049)
- Other systematics: experimental, signal and background modelling are at a similar level

Total and differential cross-sections of $t\bar{t} + Z$ production

- Probe the tZ coupling at high scales (LEP I probed top-quarks in loops)
- Sensitive to modifications in electroweak symmetry breaking mechanism

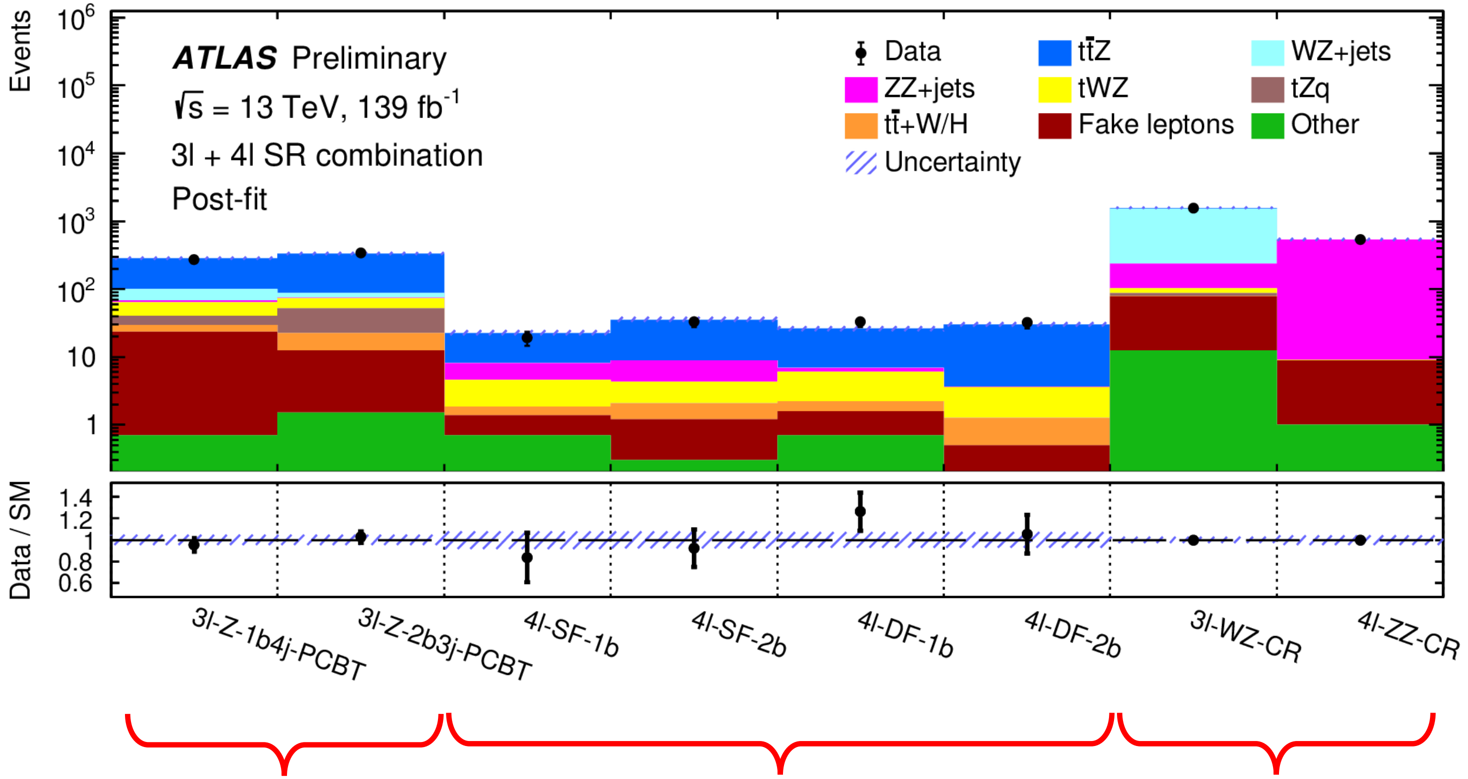


- Selection targets $Z \rightarrow e^{+}e^{-}$ / $\mu^{+}\mu^{-}$ and $t\bar{t} \rightarrow b\bar{b}\ell^{+}\nu\ell^{-}\bar{\nu}$ / $b\bar{b}\ell^{\pm}\nu jj$ decay channels
- Define 3-lepton and 4-lepton signal regions with p_{T} thresholds:
  3-lepton: $p_{\mathrm{T}}(\ell) > 27, 20, 20$ GeV
  4-lepton: $p_{\mathrm{T}}(\ell) > 27, 20, 10, 7$ GeV

  Low p_{T} thresholds correspond to large acceptance!
  Still room for improvement in the 3-lepton channel.
- Z-mass window requirement: $|m(\ell^{+}\ell^{-}) - m_{Z}| < 10$ GeV
- Requirements on N_{jets} and $N_{\mathrm{b-jets}}$

Total cross-section measurement

- Profile maximum-likelihood fit to event yields in 6 signal regions and 2 control regions



3 lepton
signal regions

4 lepton
signal regions

WZ + jets and
ZZ + jets
control regions

- Fitted signal strength $\mu(t\bar{t}Z) = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}}$

Fit configuration	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combined	$1.19 \pm 0.06\,(\text{stat.})\,\pm 0.10\,(\text{syst.})$

- Measured cross-section:

$$\sigma(t\bar{t}Z) = 1.05 \pm 0.05\ (\text{stat}) \pm 0.09\ \text{pb}$$

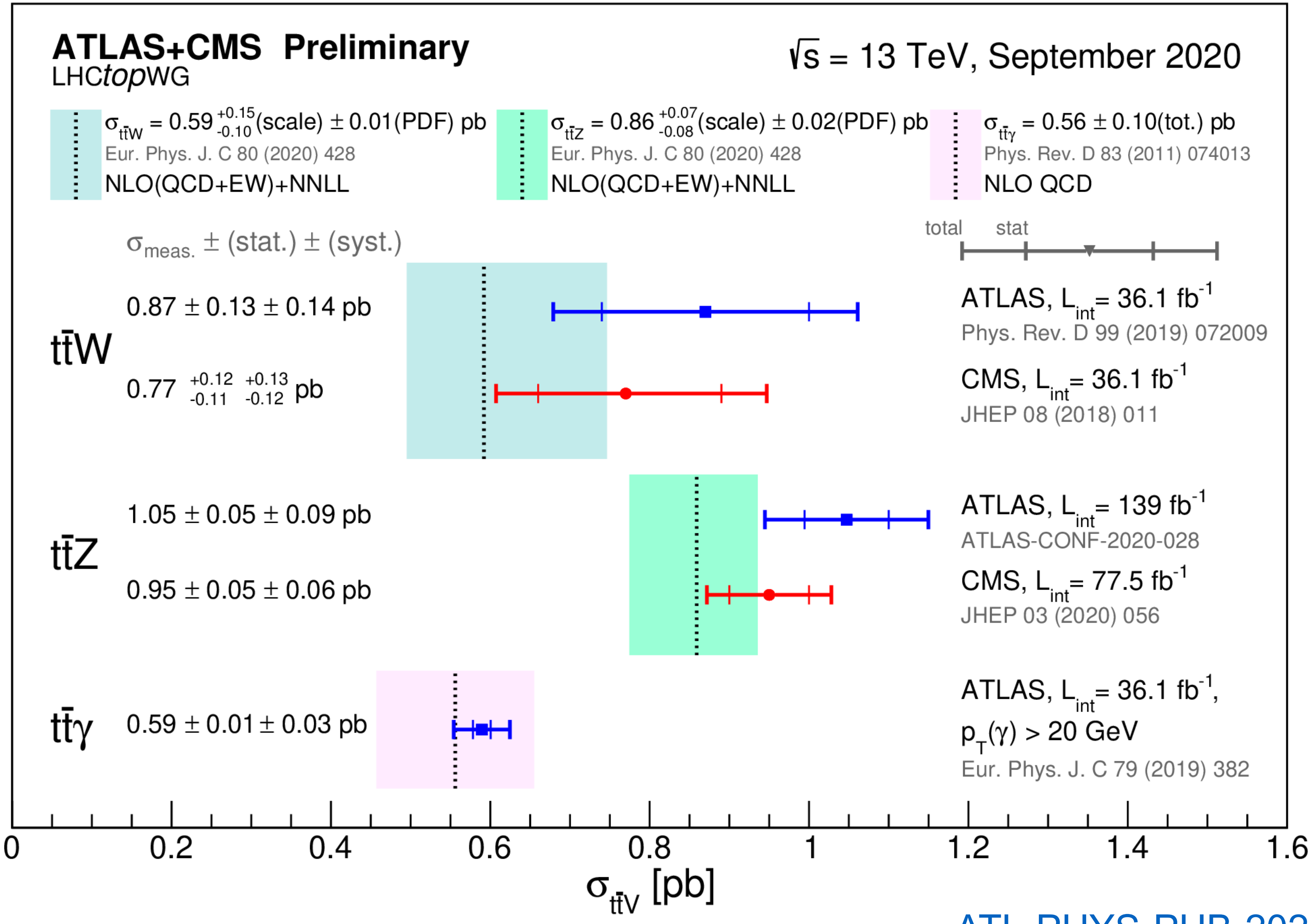
ATLAS-CONF-2020-028

Breakdown of uncertainties

Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
$WZ/ZZ+$jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Non-prompt/fake leptons	2.1
$t\bar{t}Z$ A14 tune	1.6
$t\bar{t}Z$ μ_{f}, μ_{r} scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematics	8.4
Data statistics	5.2
Total	9.9

- Systematic uncertainties dominate, but there is still some room to bring down the statistical uncertainty.
- Modelling uncertainties are important, in total 6.0%.

LHC $t\bar{t}+X$ Summary plot



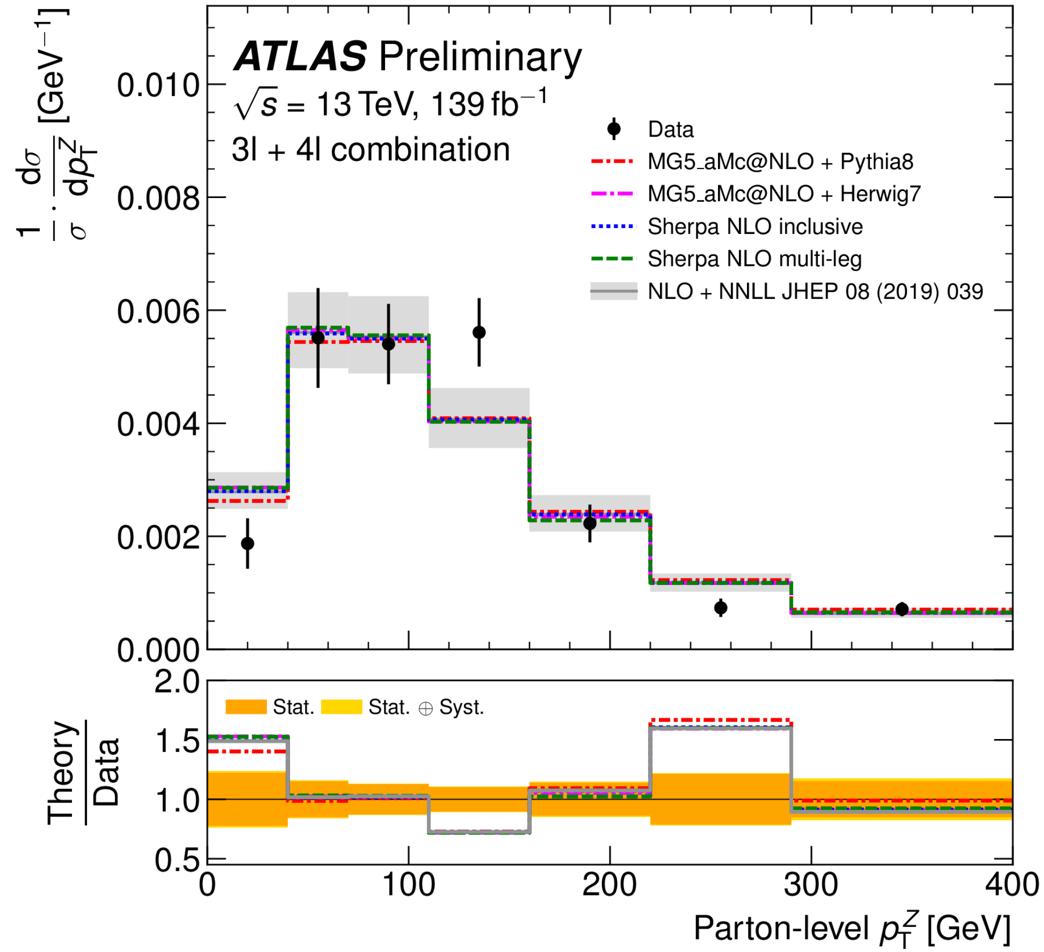
ATL-PHYS-PUB-2020-022

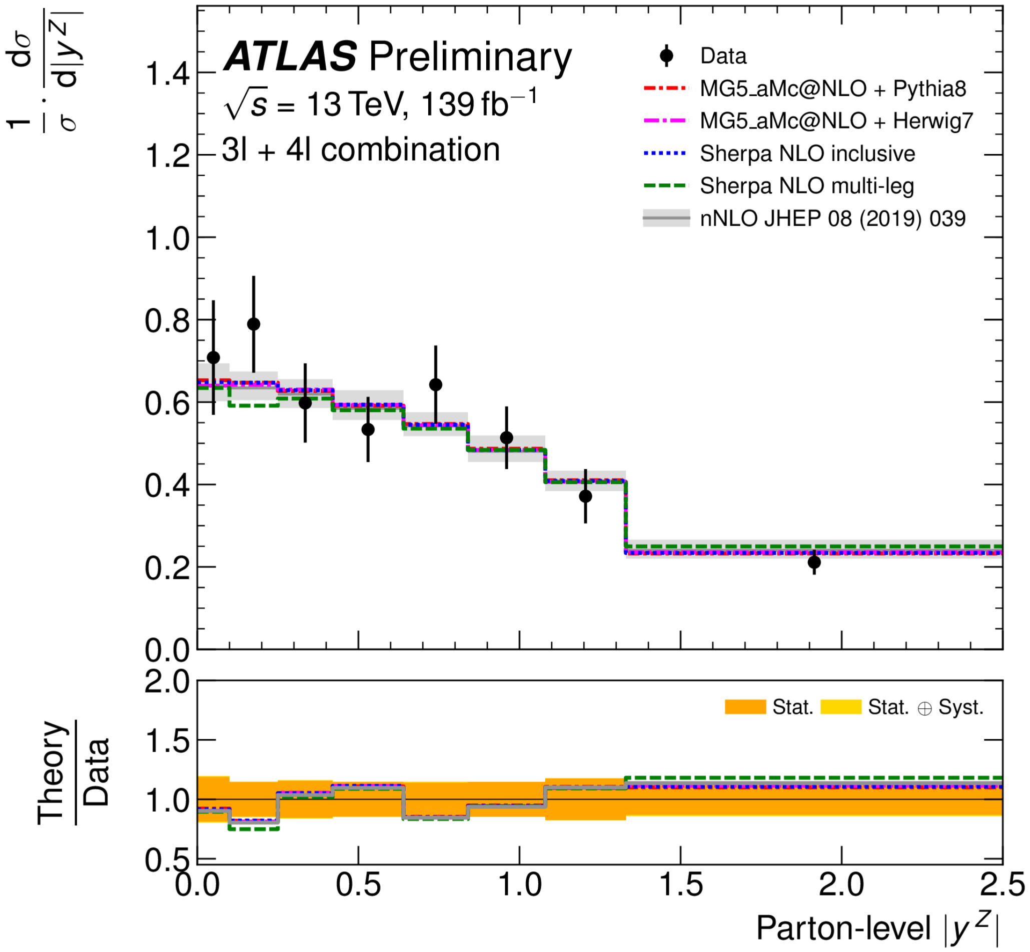
Differential cross-sections

- Unfolding to parton level and particle level (stable particles in Monte Carlo event generators).
- Absolute and normalised cross-sections.
- Considered variables:

	Variable	Definition
$3\ell + 4\ell$	p_T^{Z}	Transverse momentum of the Z boson
	$\|y^{Z}\|$	Absolute value of the rapidity of the Z boson
3ℓ	N_jets	Number of selected jets with $p_\mathrm{T} > 25$ GeV and $\|\eta\| < 2.5$
	$p_\mathrm{T}^{\ell,\mathrm{non-}Z}$	Transverse momentum of the lepton which is not associated with the Z boson
	$\|\Delta\phi(Z, t_\mathrm{lep})\|$	Azimuthal separation between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
	$\|\Delta y(Z, t_\mathrm{lep})\|$	Absolute rapidity difference between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
4ℓ	N_jets	Number of selected jets with $p_\mathrm{T} > 25$ GeV and $\|\eta\| < 2.5$
	$\|\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\|$	Azimuthal separation between the two leptons from the $t\bar{t}$ system
	$\|\Delta\phi(t\bar{t}, Z)\|$	Azimuthal separation between the Z boson and the $t\bar{t}$ system
	$p_\mathrm{T}^{t\bar{t}}$	Transverse momentum of the $t\bar{t}$ system

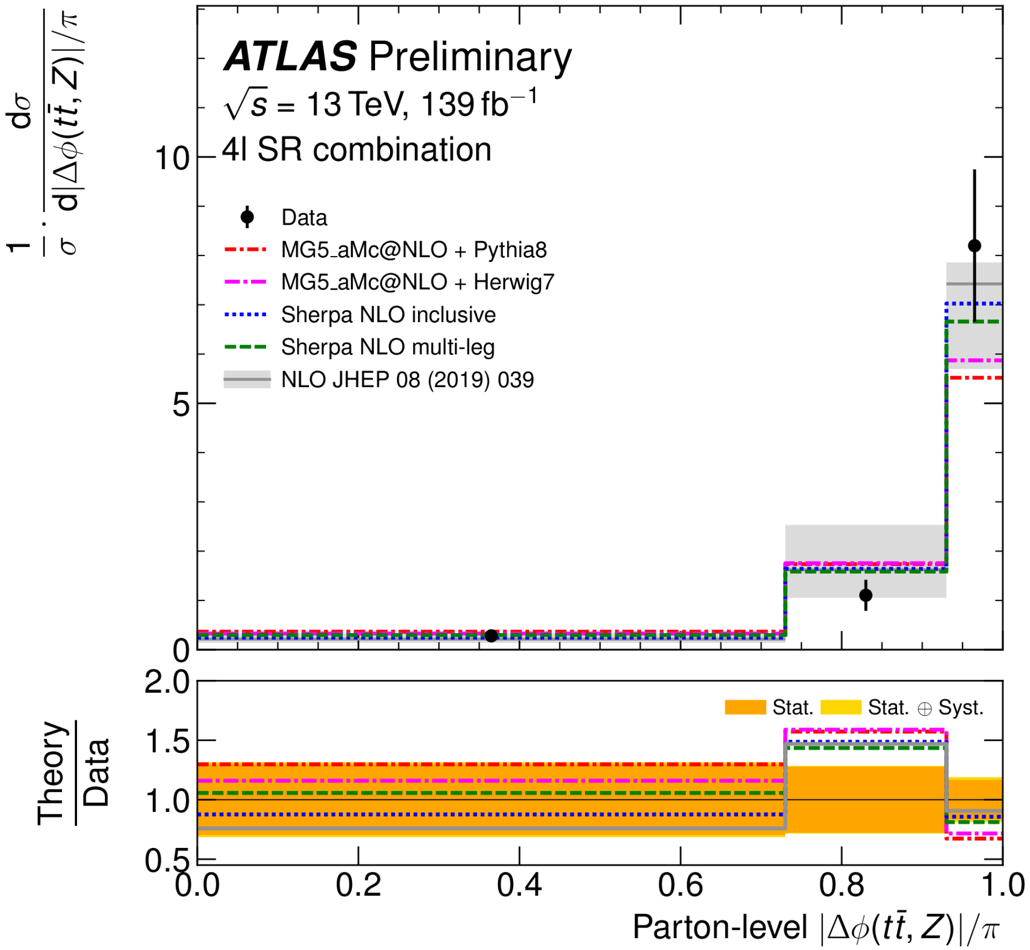
$p_{\mathrm{T}}(Z)$ and $|y(Z)|$

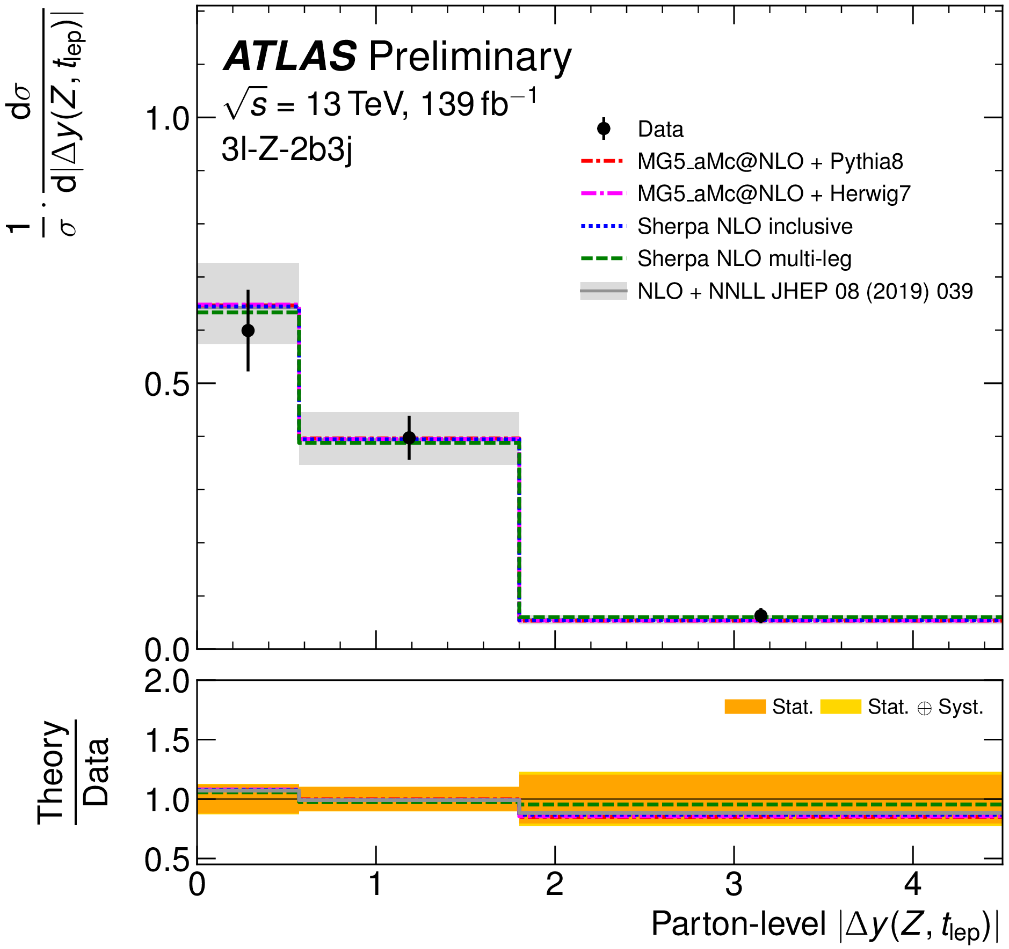




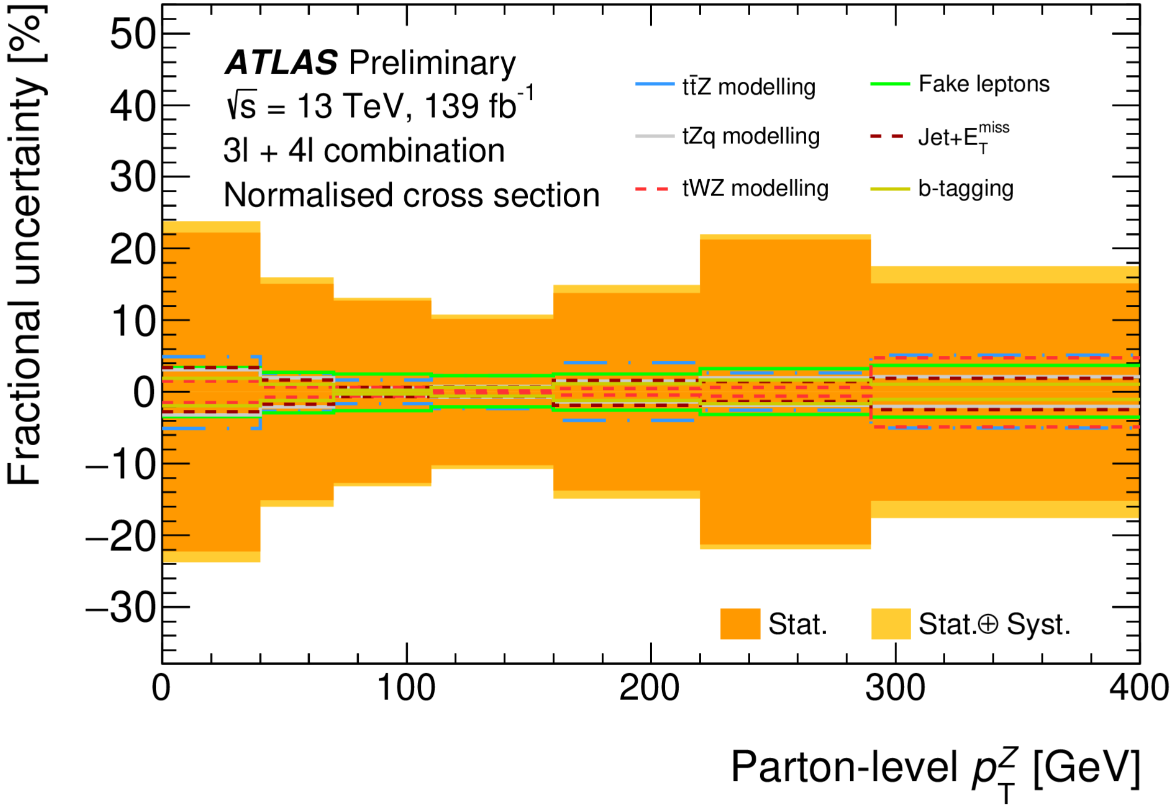
Shows relative large deviations in 3 bins, but no trend.

$|\Delta\phi(Z, t_{\mathrm{lep}})|$ and $|\Delta y(Z, t_{\mathrm{lep}})|$





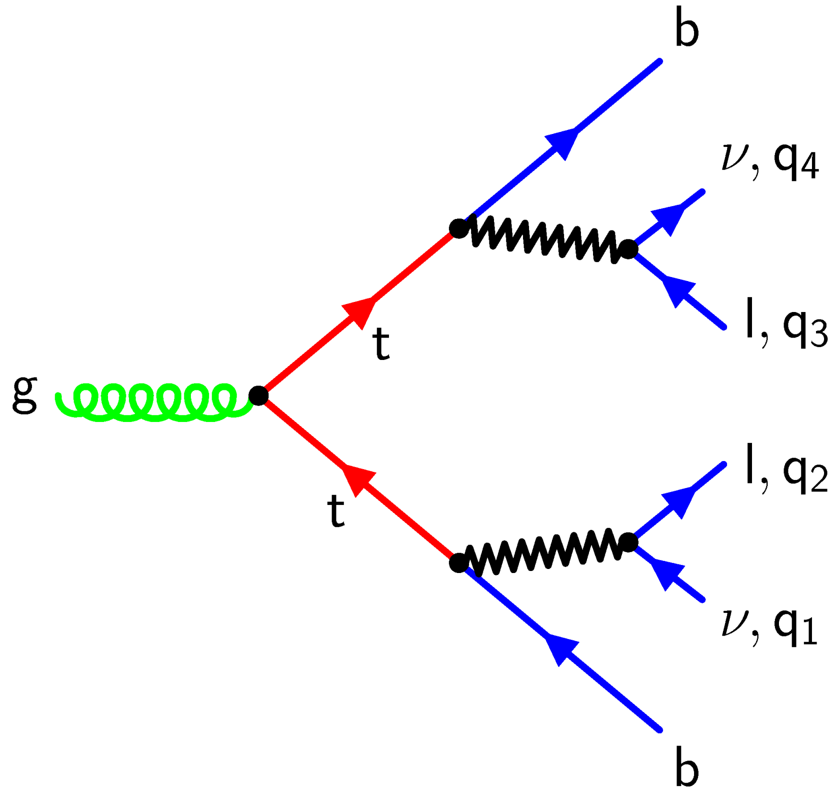
Uncertainties of differential measurements

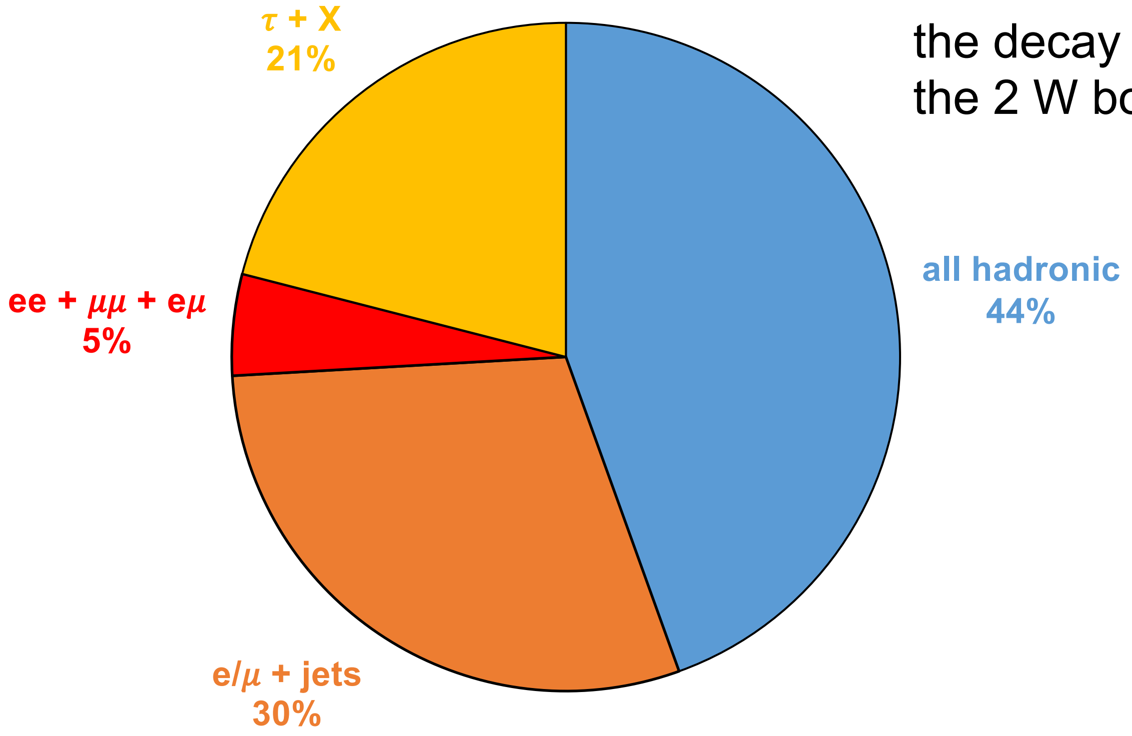


- Uncertainties are at the level of 10 to 20%.
- Statistical uncertainties clearly dominate.
- Next iteration of the analysis is in preparation:
  - Will focus on an interpretation in Effective Field Theory (EFT)
  - Implement improvements in lepton identification and lower p_{T} thresholds for leptons.

Part 3

Differential cross-sections of $t\bar{t}$ production





Categorize $t\bar{t}$ final states according to the decay modes of the 2 W bosons

Three analyses covering three main channels

Channel	$e\mu$	$e/\mu+$ jets	all hadronic
Publication	Eur. Phys. J. C 80 (2020) 528	Eur. Phys. J. C 79 (2019) 1028	arXiv: 2006.09274
HEPData	ins1759875	Record: 95748	Not available
Background level	9%	11%	30%
Main backgrounds	tW production	tW, $W+$ jets and multijet production	Multijet production
Topology	leptonic variables only	Resolved and boosted $t\bar{t}$ system reconstructed	Resolved only $t\bar{t}$ system reconstructed
Unfolding method	Bin-by-bin	Iterative Bayesian	Iterative Bayesian

- All analysis use an integrated luminosity of 36 fb^{-1} recorded in 2015 and 2016.
- Analyses are complementary in various ways: background composition, background level, topology, access to the $t\bar{t}$ system and resolution.

Disclaimer: Today: Will not discuss the experimental details, but compare main results.

Objectives

Excess the matrix element (ME) of the hard scattering process:

- Sensitivity to physics beyond the standard model
- Study modelling with NLO ME generators
- Variables:
  $p_{\mathrm{T}}(t)$, $|y(t)|$, $|y(t\bar{t})|$, $m(t\bar{t})$

Study the modelling of extra radiation by parton-shower generators and the matching between NLO ME generators and parton-shower programs:

- Variable: $p_{\mathrm{T}}(t\bar{t})$ and N_{jets}

Differential cross-sections

Parameter extraction

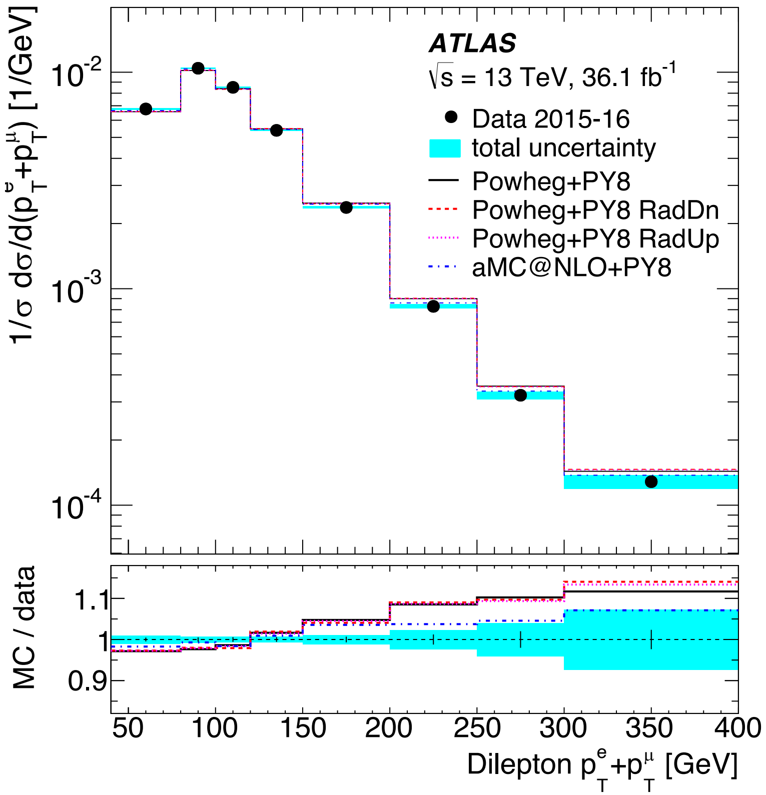
1) Top-quark mass: Use $p_{\mathrm{T}}(t)$ and $m(t\bar{t})$
2) Parton distribution functions (PDFs): Use $|y(t)|$, $|y(t\bar{t})|$, $m(t\bar{t})$

Predictions

- Generator setups: Use NLO matrix-element (ME) generator matched to a parton-shower generator
- Nominal setup: Powheg-Box ver. 2 (PWG) + Pythia 8.210 (PY8)
    - Scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \sqrt{m_t^2 + p_{\mathrm{T}}(t)^2} =: \mu_{\mathrm{nominal}}$
    - PDF set: NNPDF3.0NLO for the ME calculation, NNPDF2.3LO for the parton shower
    - Matching scale: $h_{\mathrm{damp}} = 1.5\, m_t$
    - Variant „Radiation up" with settings: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = 0.5\, \mu_{\mathrm{nominal}}$, $h_{\mathrm{damp}} = 1.5\, m_t$, Var3c=Up of the A14 tune
    - Variant "Radiation down" with settings: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = 2.0\, \mu_{\mathrm{nominal}}$, Var3c=Down of the A14 tune
- PWG+Herwig 7
- MadGraph5_aMC@NLO (ver. 2.3.3.p1) + PY8
- Sherpa 2.2.1, 1st emission at NLO, up to 4 additional parton emissions at LO
- Fixed-order calculations at NNLO by M. Czakon and A. Mitov et al.
- Caveat: Quantitative comparisons with the predictions (χ^2/d.o.f. and p-values) do not include uncertainties in the predictions.

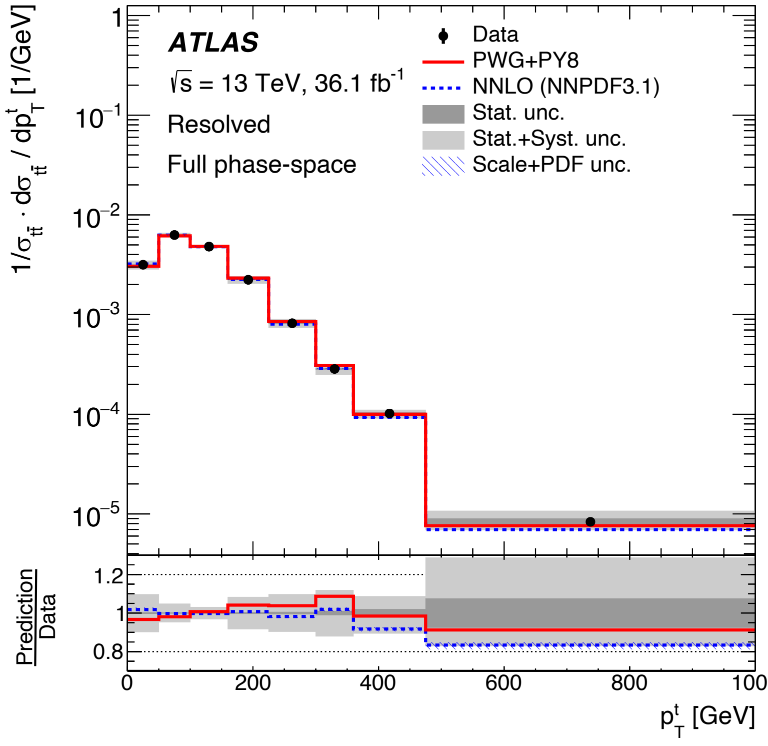
Top quark $p_{\mathrm{T}}(t)$

$e\mu$ channel



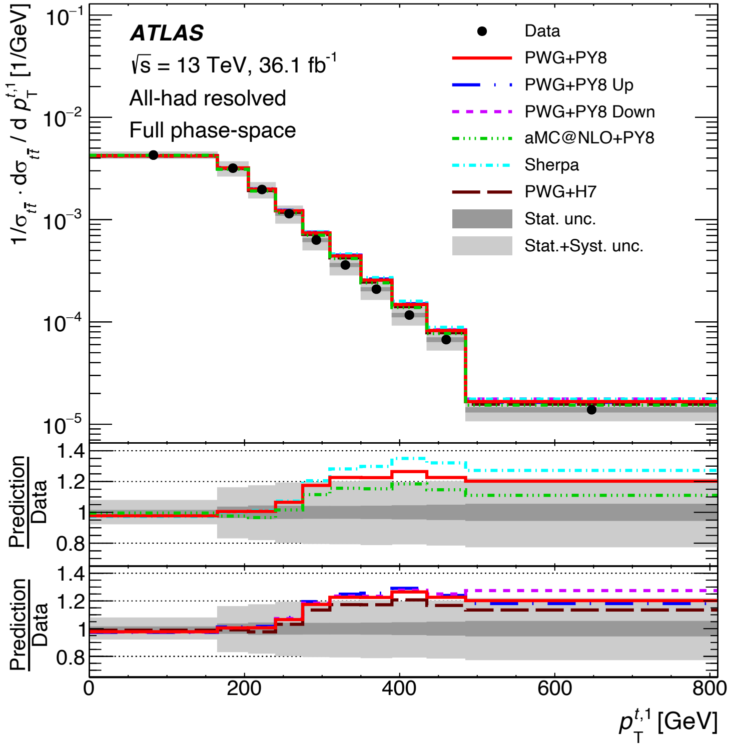
- $p_{\mathrm{T}}(\ell)$ related to $p_{\mathrm{T}}(t)$
- None of the generators describes the data well, but MG5aMC does better than PWG

e/μ + jets channel



- Both PWG+PY8 and the NNLO FO calculation model $p_{\mathrm{T}}(t)$ well.

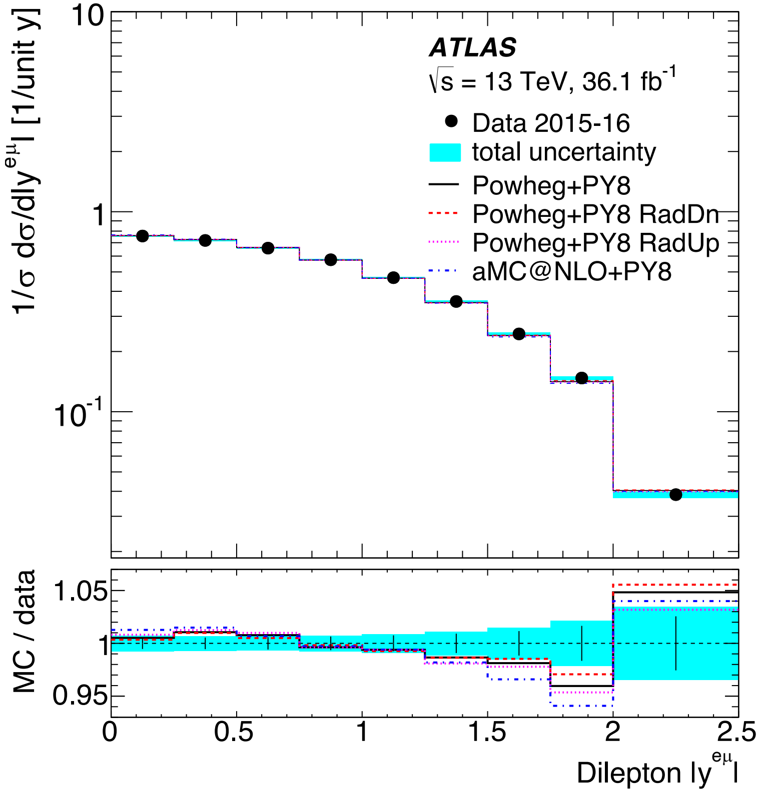
All-hadronic channel



- All generators show the same trend of underestimating the cross-section at high $p_{\mathrm{T}}(t)$.
- MG5aMC and PWG+H7 do better than the nominal PWG+PY8 and Sherpa.

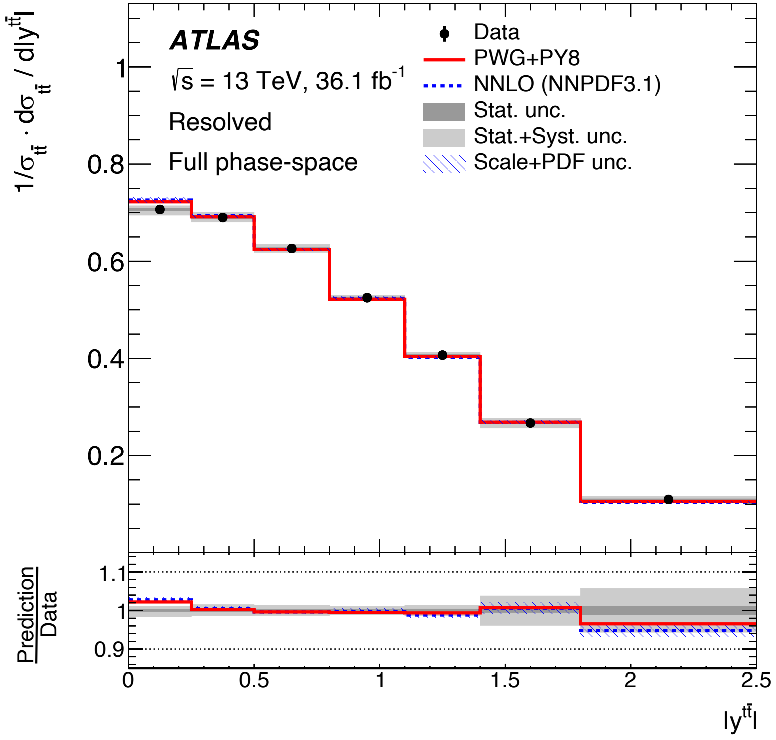
Rapidity of the $t\bar{t}$ system: $|y(t\bar{t})|$

$e\mu$ channel



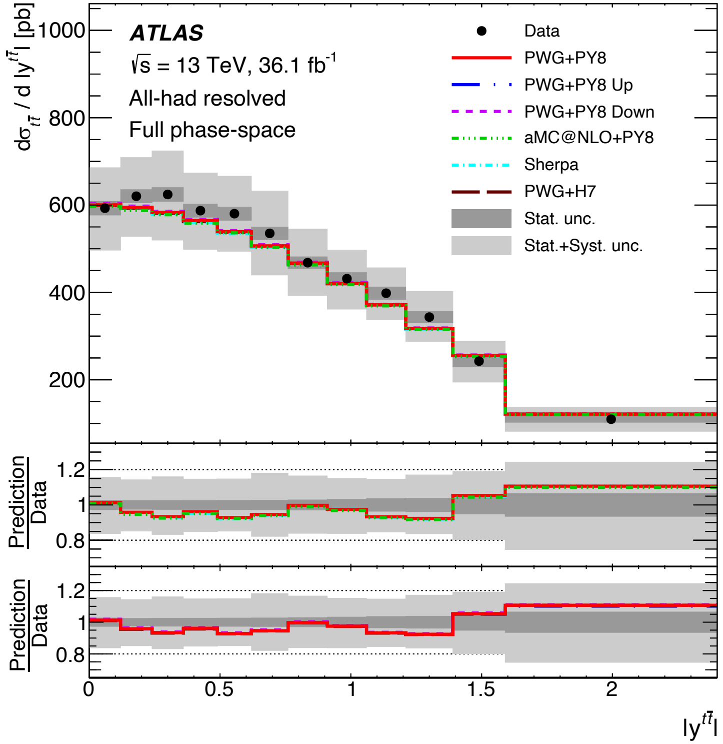
- All generator setups show a trend to lower cross-sections at high $|y(t\bar{t})|$. ⟹ parton shower and ME generator may be not the driving issue

e/μ + jets channel



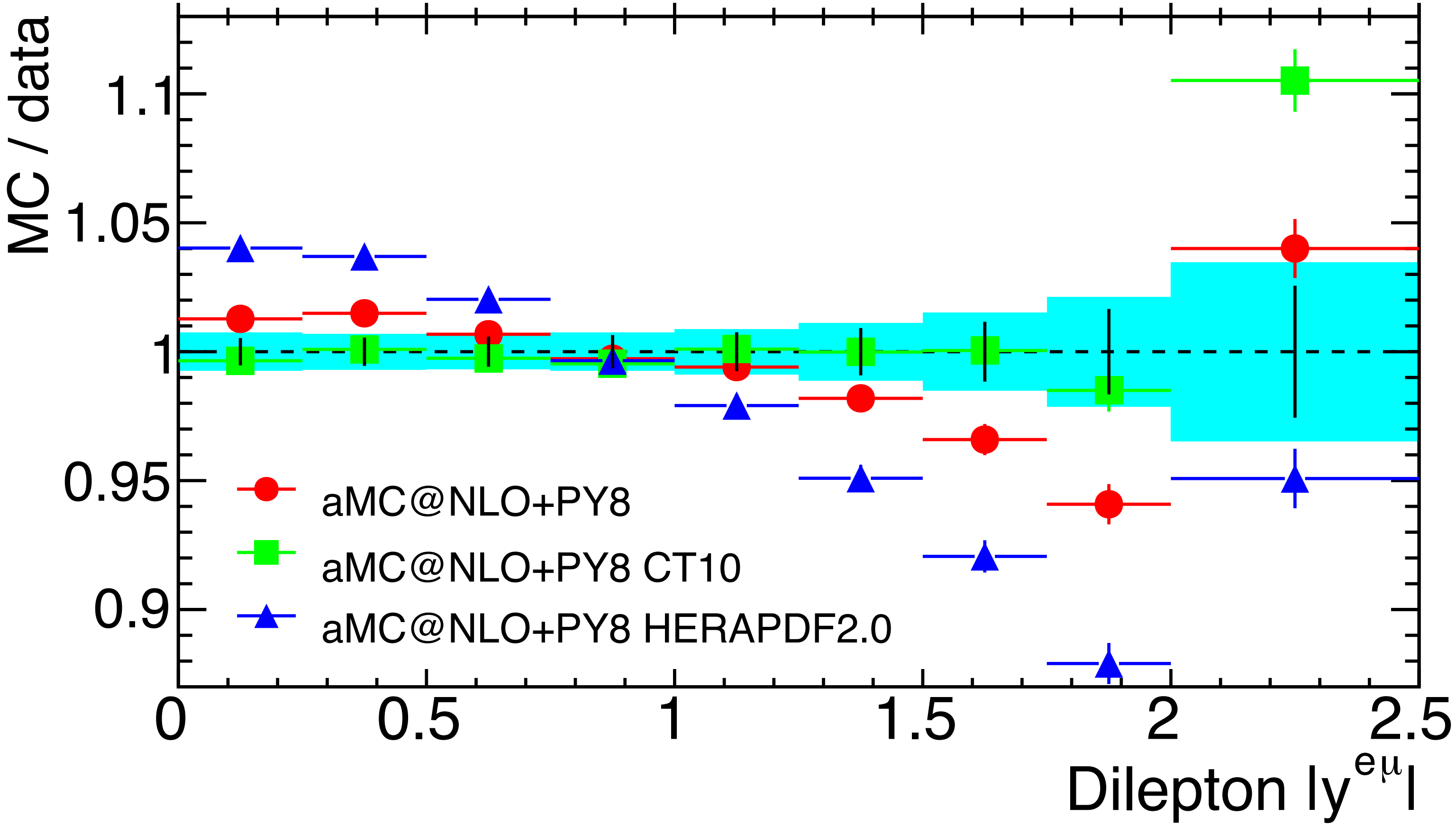
- No trend visible.

All-hadronic channel



- Uncertainties are too large to draw conclusions

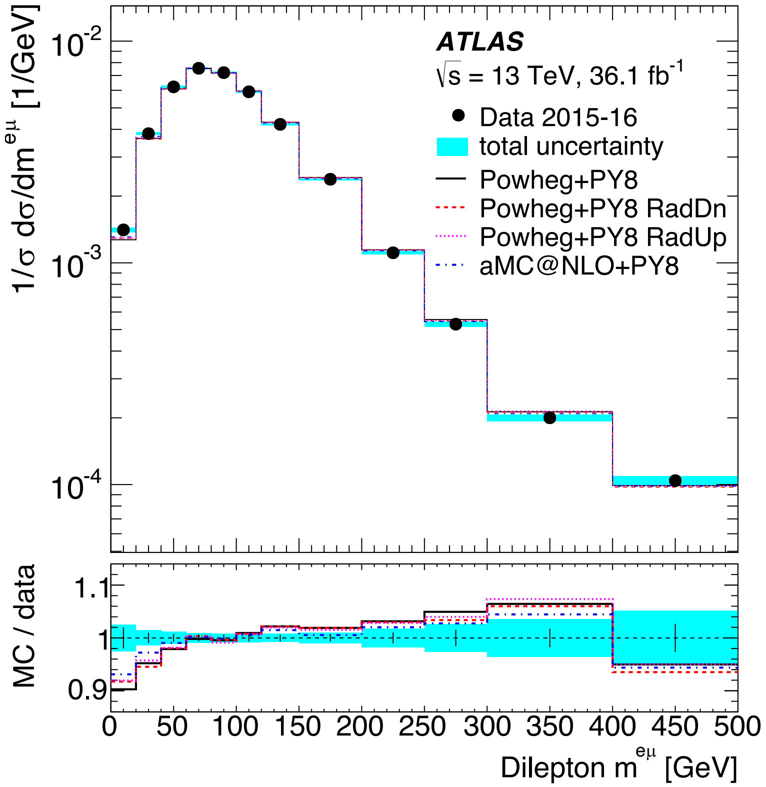
$|y(e\mu)|$ for different PDFs



With MG5aMC the CT10 PDF set gives a better description of the data than the default NNPDF3.0NLO and HERAPDF2.0.

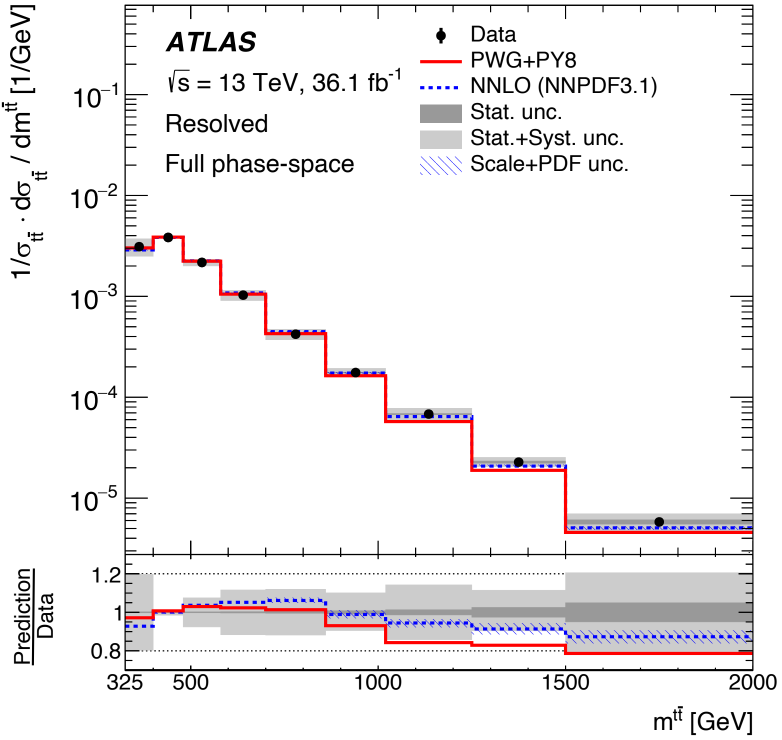
Mass of the $t\bar{t}$ system: $m(t\bar{t})$

$e\mu$ channel



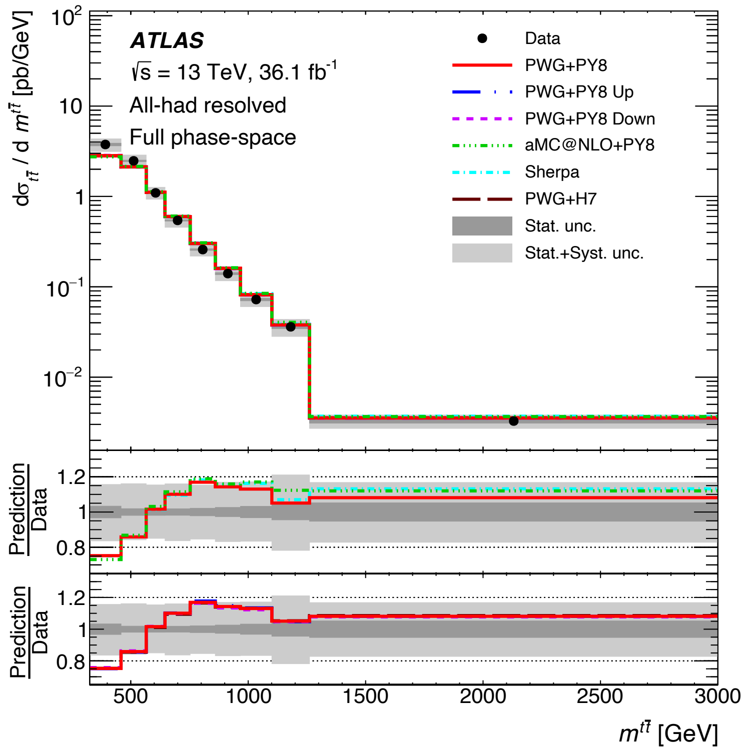
- Distribution is badly described by PWG+PY8 (p-value = $6{\times}10^{-6}$)
- MG5aMC+PY8 does better (p-value =0.049)

e/μ + jets channel



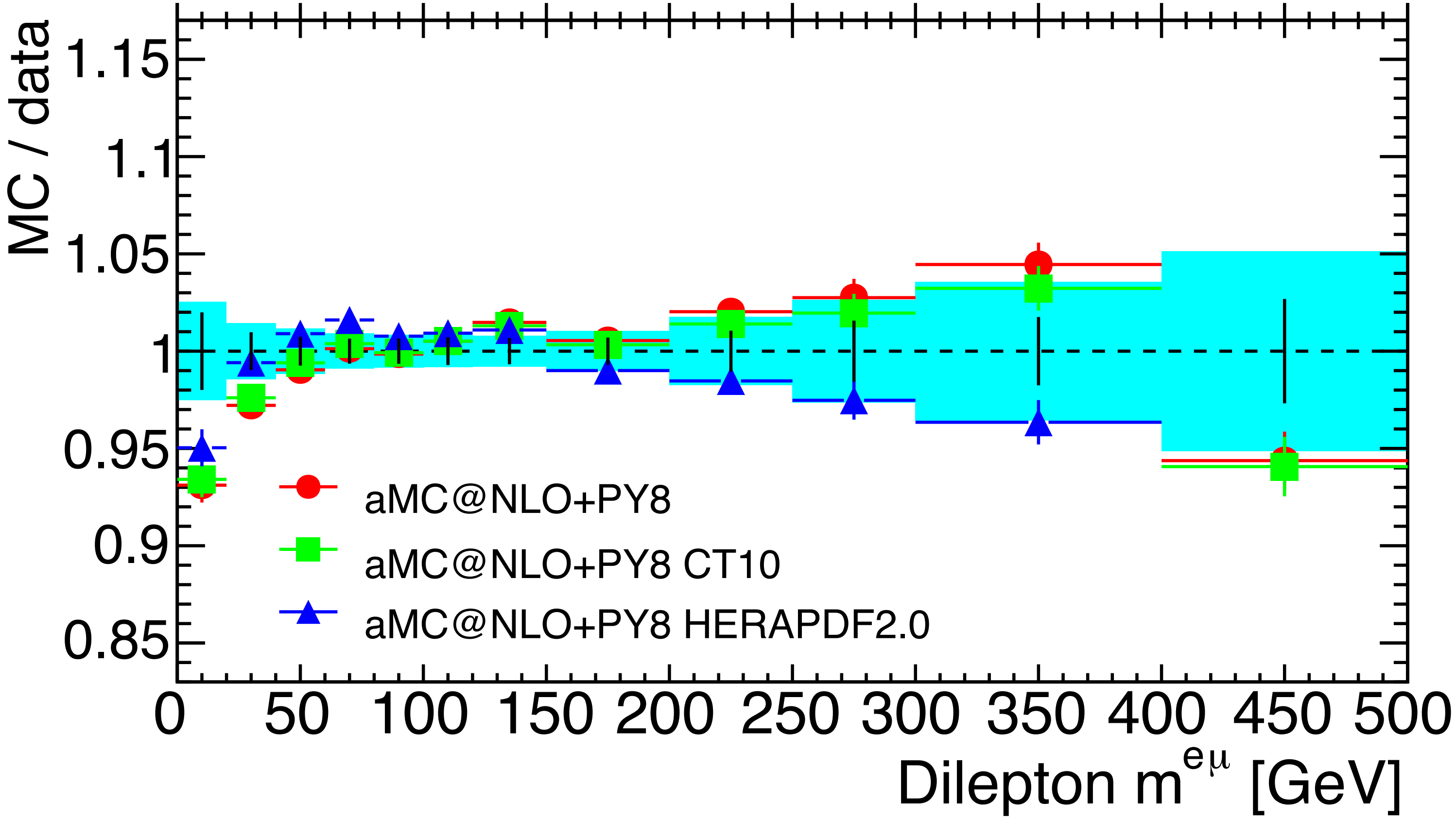
- Distribution is badly described by PWG+PY8 and all other MC setups (not shown)
- χ^2/d.o.f. = 32.1/8
- P-value < 0.01

All-hadronic channel



- Within the large uncertainties the modelling is acceptable.

$m(t\bar{t})$ for different PDFs



- With MG5aMC the CT10 PDF set gives a slightly better description (p-value = 0.11) of the data than the default NNPDF3.0NLO (p-value =0.049) and HERAPDF2.0 (p-value $= 6\times10^{-3}$).
- This study demonstrates sensitivity of the measurements to the PDFs.
- Good motivation to be included in PDF fits.

Summary

- ATLAS is exploiting the full statistical power of the Run 2 data set.
- Recent highlights in the top-quark sector:
  - Evidence for 4-top-quarks production
  - Test universality of $W\tau$ and $W\mu$ weak couplings
  - Differential cross-section measurements of $t\bar{t}+\ \gamma$ and $t\bar{t}+Z$ production
  - Comprehensive measurements of differential cross-sections of $t\bar{t}$ production