



ttbar cross section at the LHC

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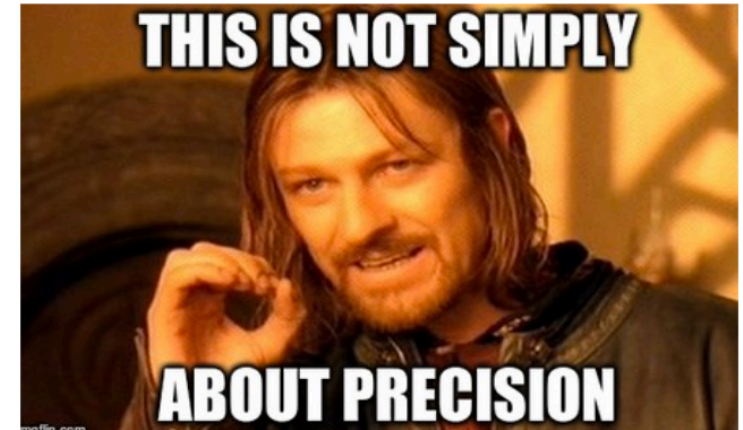
ATLAS and CMS results



Introduction



- Precision measurements of $t\bar{t}$ cross section.
 - Test theoretical predictions and modelling,
 - important for the top as a background for searches,
 - Search for new physics as deviations from Model (SM) predictions.



- Outlook:
 - “legacy” run I inclusive cross sections and search for new physics (SUSY),
 - Differential cross section at 8 TeV,
 - Inclusive and differential cross sections at 13 TeV.



Inclusive cross section at 7 and 8 TeV (ATLAS)

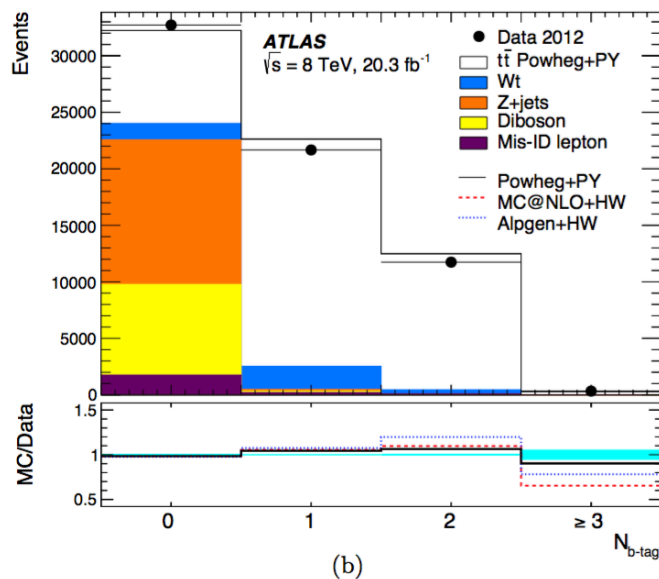


- Use $e\mu$ channel: most precise. [arXiv:1406.5375](https://arxiv.org/abs/1406.5375)
- Event selection: 1 isolated e and 1 isolated μ with opposite charge.
- 1 and 2 selected jet bins (including b-tagging (medium WP)) used to measure the cross section.

$$N_1 = L\sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{\text{bkg}}$$

$$N_2 = L\sigma_{t\bar{t}} \epsilon_{e\mu} C_b \epsilon_b^2 + N_2^{\text{bkg}}$$

Uncertainty \sqrt{s}	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	
	7 TeV	8 TeV
Data statistics	1.69	0.71
$t\bar{t}$ modelling and QCD scale	1.46	1.26
Parton distribution functions	1.04	1.13
Background modelling	0.83	0.83
Lepton efficiencies	0.87	0.88
Jets and b -tagging	0.58	0.82
Misidentified leptons	0.41	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26
Integrated luminosity	1.98	3.10
LHC beam energy	1.79	1.72
Total uncertainty	3.89	4.27



- In situ determination of the jet selection efficiency.

- Background estimations :

- Z+jets from same flavour channels,
- Fake lepton from same charge events.

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3 \text{ pb } (\sqrt{s} = 7 \text{ TeV}) \text{ and}$$

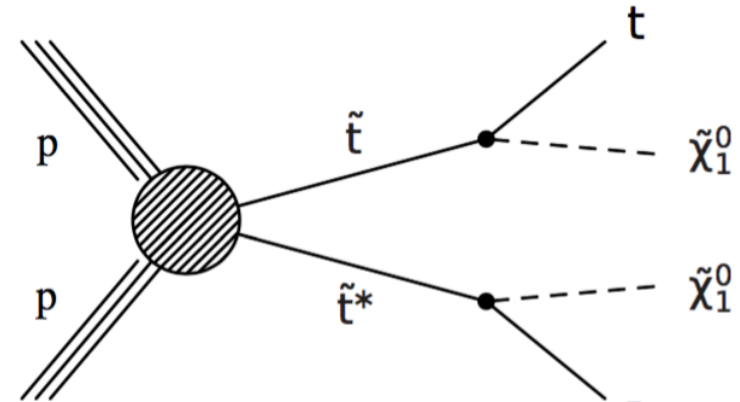
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2 \text{ pb } (\sqrt{s} = 8 \text{ TeV}),$$



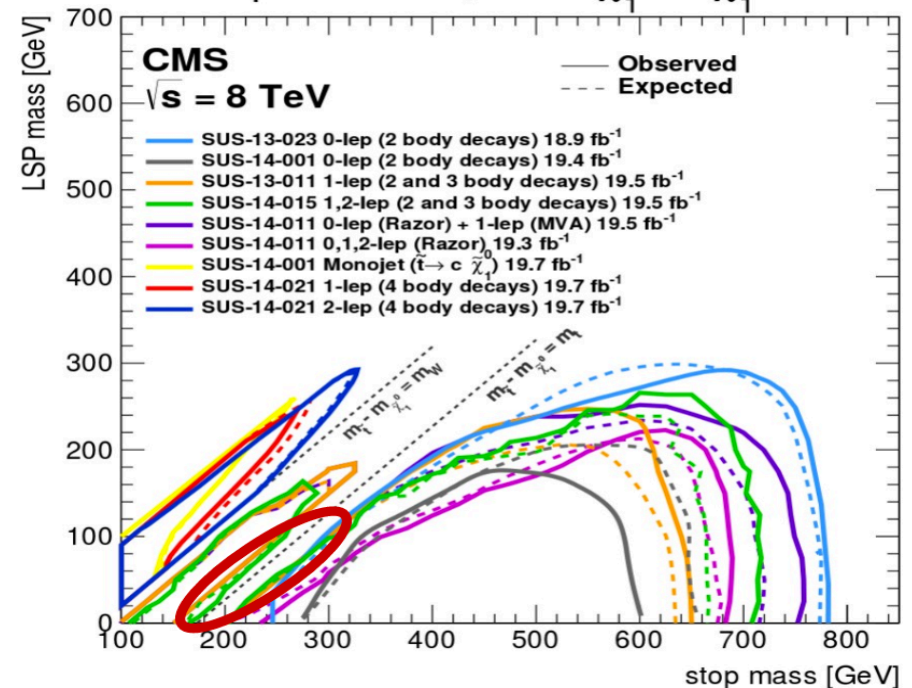
Search for SUSY stop pair production



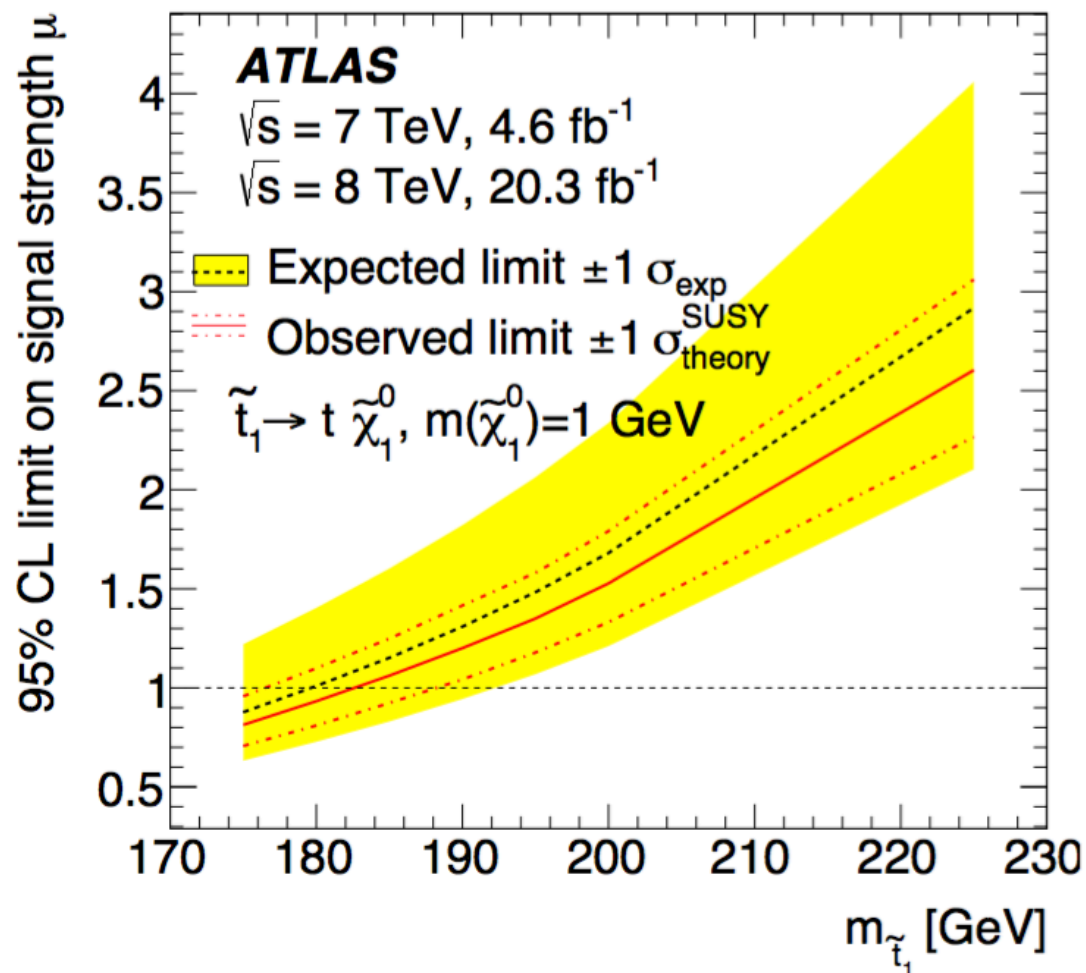
- Search for stop pair production, with stop decaying into a top quark and a neutralino.
- Direct searches insensitive for $m(\text{stop}) - m_{\tilde{\chi}_1^0} \approx m(\text{top}) \Rightarrow$ kinematics very similar to $t\bar{t}$ events.
- Search for a deviation from SM predictions in the precise measurement of the $t\bar{t}$ cross section (and spin correlation)



$\tilde{t}\tilde{t}^*$ production, $\tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0$



- Determination of **exclusion limits** on stop pair production from precise $t\bar{t}$ cross section.
- For **neutralino mass of 1 GeV**.
- Exclusion at 95% CL up to **177 GeV**.



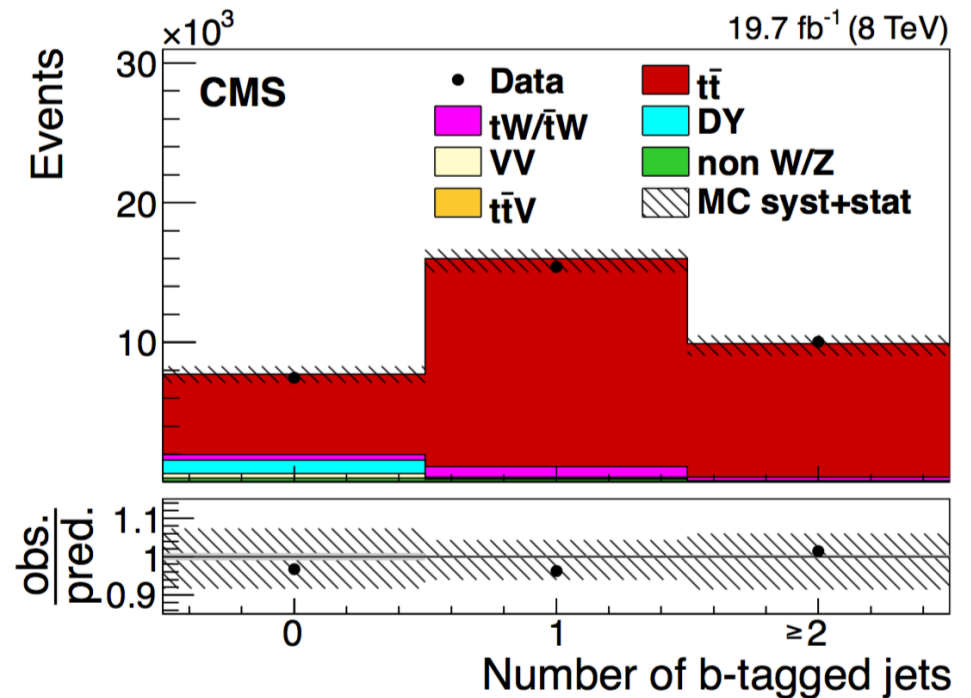


Event selection and cut&count analysis (xc)



arXiv:1603.0230

- Most precise channel : $e\mu$.
- Event selection : $e\mu$ trigger, 2 isolated leptons (electron+muon), at least 1-2 jets, with at least 1 b-tag (medium WP).
- Data-driven backgrounds:
 - Z+jets estimated from an in-peak control region in same-flavour events,
 - Fake-lepton backgrounds ($t\bar{t}$ semi-leptonic, W+jets) using same sign events.
- Main systematics from JES, lept. sel., b-tagging, signal modelling (top p_T , scale)



$$\sigma_{t\bar{t}} = 165.9 \pm 2.5 (\text{stat}) \pm 6.2 (\text{syst}) \pm 3.6 (\text{lumi}) \text{ pb, at } \sqrt{s} = 7 \text{ TeV.}$$

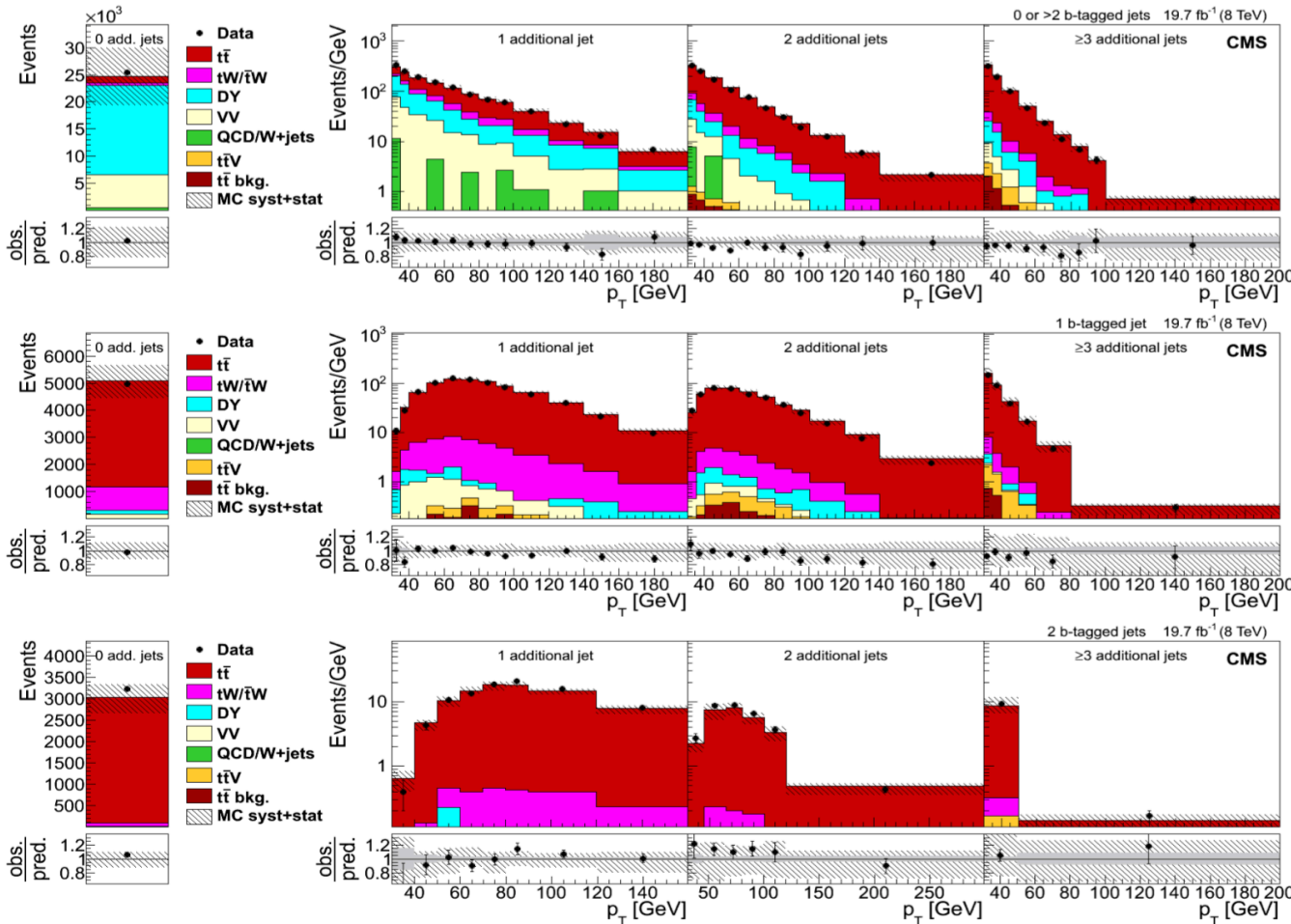
$$\sigma_{t\bar{t}} = 241.1 \pm 1.6 (\text{stat}) \pm 10.0 (\text{syst}) \pm 6.3 (\text{lumi}) \text{ pb, at } \sqrt{s} = 8 \text{ TeV.}$$



CMS bin likelihood fit



arXiv:1603.0230



- Main analysis : combine a likelihood fit (constrain of the systematics using nuisance parameters) with the ATLAS approach.
- Fit of jet p_T in various jet and btag jet mult. bins.
- Reduce systematics on b-tagging, JES and scale (vis. phase space).
- Dominant systematics : lept sel., trigger, JES, ttbar mod.

$$\sigma_{t\bar{t}} = 173.6 \pm 2.1 \text{ (stat)}_{-4.0}^{+4.5} \text{ (syst)} \pm 3.8 \text{ (lumi) pb, at } \sqrt{s} = 7 \text{ TeV and}$$

$$\sigma_{t\bar{t}} = 244.9 \pm 1.4 \text{ (stat)}_{-5.5}^{+6.3} \text{ (syst)} \pm 6.4 \text{ (lumi) pb, at } \sqrt{s} = 8 \text{ TeV,}$$

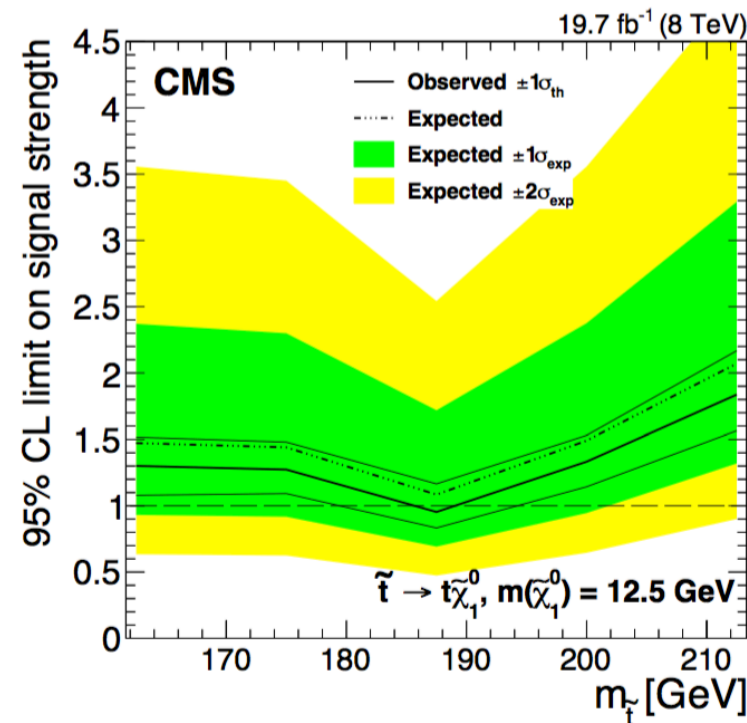
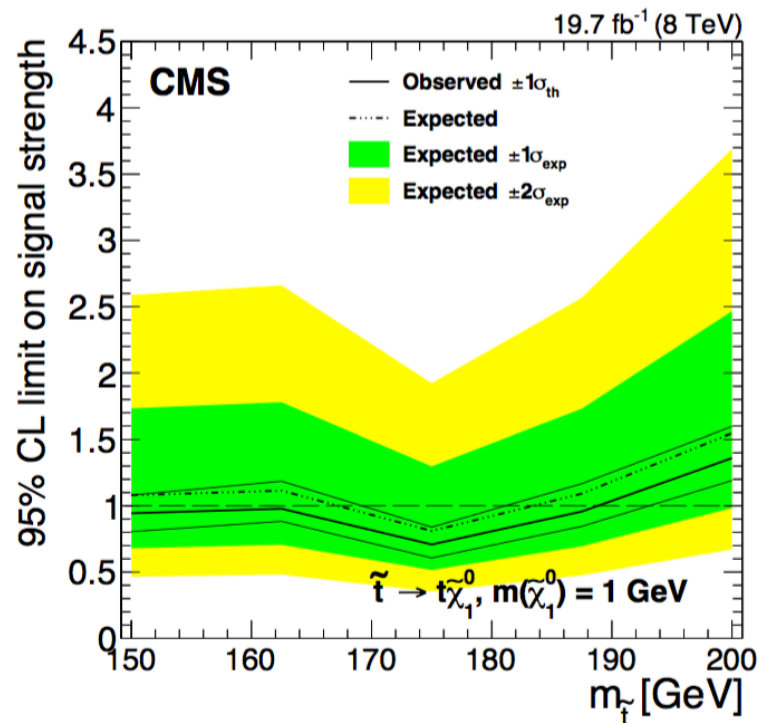


Limits on stop pair production



arXiv:1603.0230

- Compare the measured cross-section (cut&count) with the SM predictions, and SM+stop predictions.



- For neutralino mass of 1 GeV, exclusion up to 189 GeV,
- For neutralino mass of 12.5 GeV, exclusion in the range 185-189 GeV.



Inclusive cross section at 13 TeV (CMS)

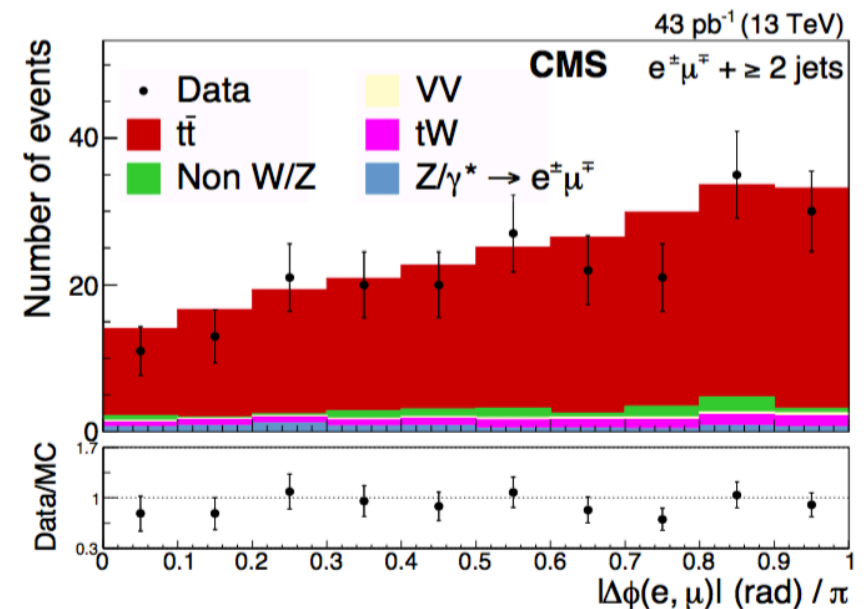
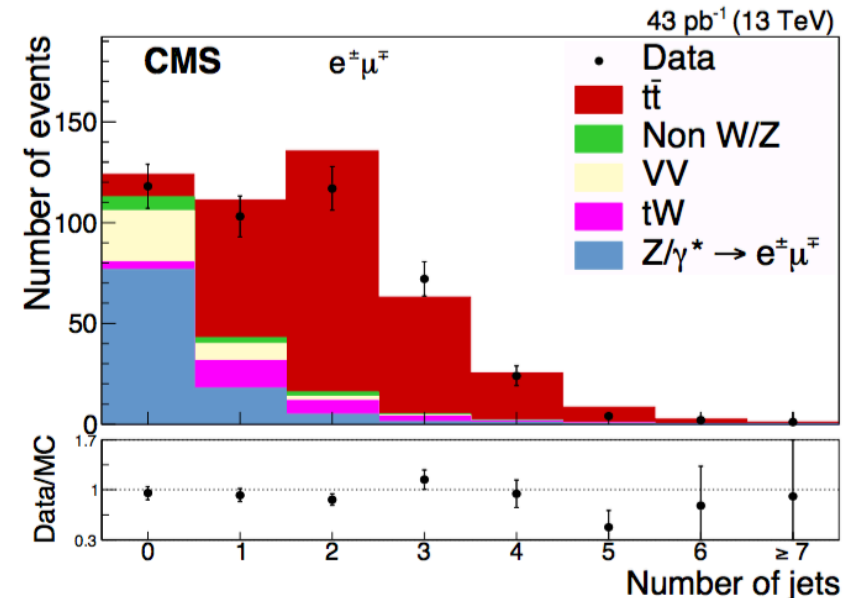


arXiv:1510.05302

- Inclusive cross section measurement in the $e\mu$ channel.
- Very similar approach as for the cut&count at 8 TeV. Main difference : **no b-tagging applied.**

$$\sigma = 746 \pm 58(\text{stat.}) \pm 53(\text{syst.}) \pm 36(\text{lumi.}) \text{pb}$$

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Trigger efficiencies	33	4.4
Lepton efficiencies	25	3.4
Lepton energy scale	<1	≤ 0.1
Jet energy scale	11	1.5
Jet energy resolution	<1	≤ 0.1
Pileup	5.2	0.7
QCD scales	1.4	0.2
NLO generator of $t\bar{t}$ signal	14	1.9
Modeling of $t\bar{t}$ signal	13	1.8
PDF	18	2.4
Single top tW background	13	1.8
VV background	3.5	0.5
Drell-Yan background	4.1	0.5
Nonprompt leptons background	7.6	1.0
Total systematic (w/o luminosity)	53	7.2
Integrated luminosity	36	4.8
Statistical uncertainty	58	7.8
Total	87	12





Inclusive cross section at 13 TeV (ATLAS)

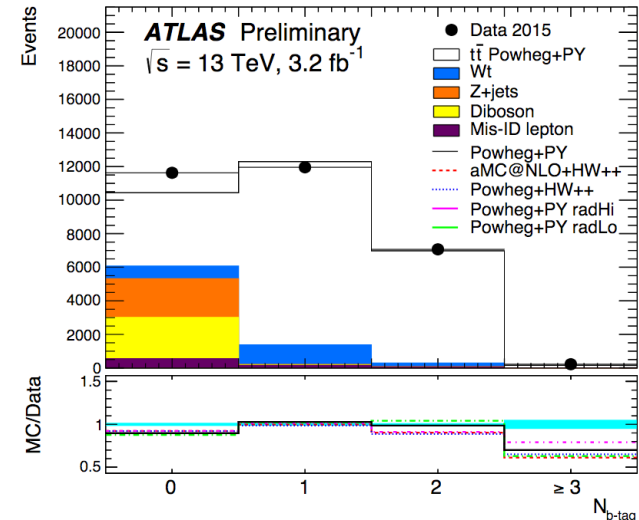
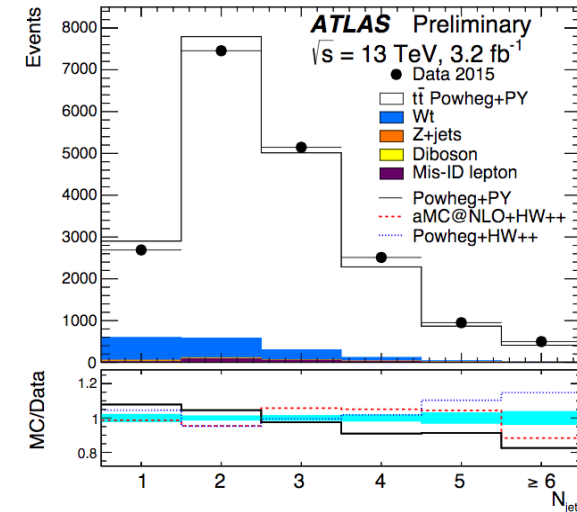


ATLAS-CONF-2016-005

- Similar to the 8TeV analysis strategy.

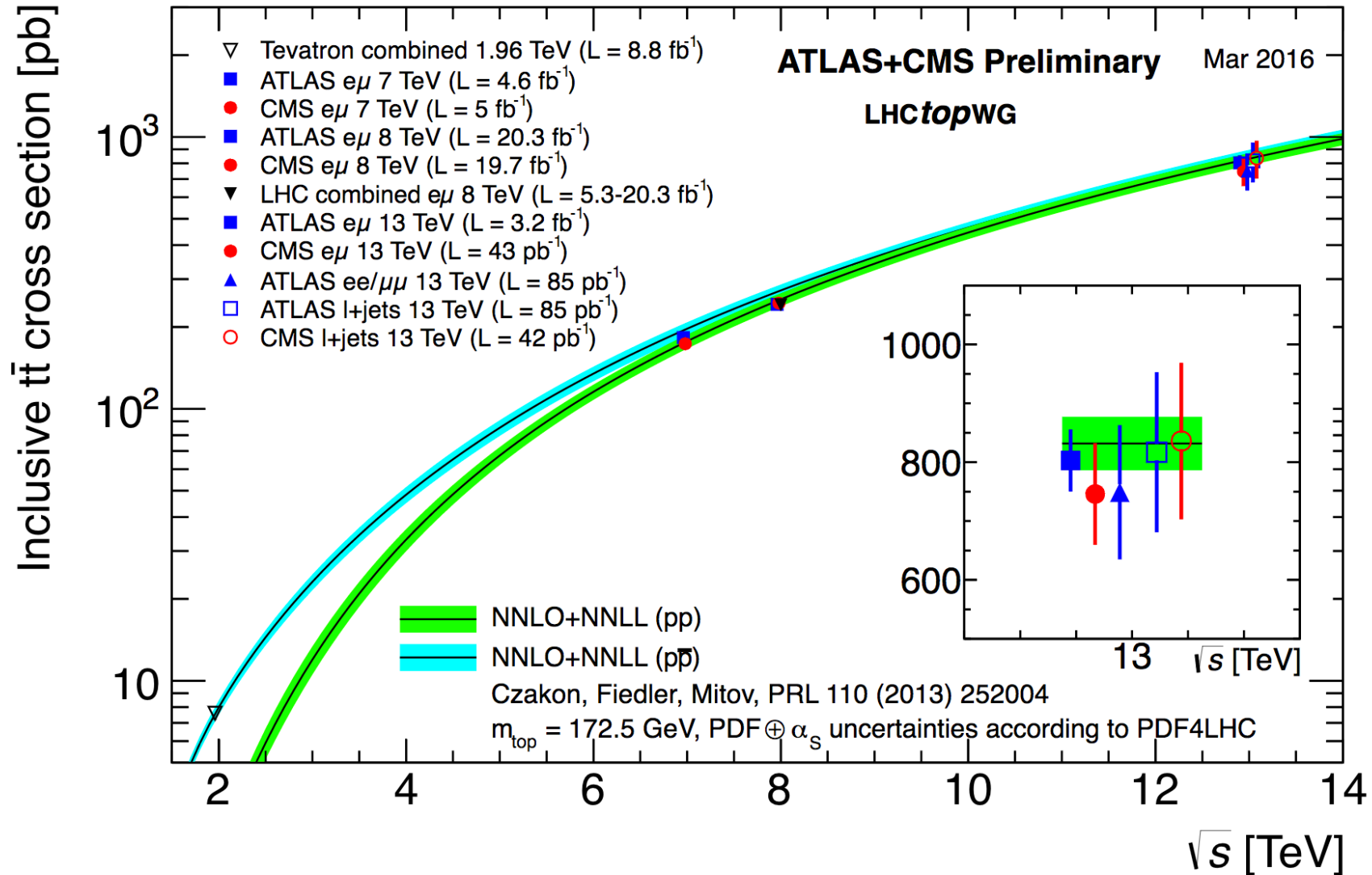
$$\sigma_{t\bar{t}} = 803 \pm 7 \text{ (stat)} \pm 27 \text{ (syst)} \pm 45 \text{ (lumi)} \pm 12 \text{ (beam)} \text{ pb,}$$

Uncertainty (inclusive $\sigma_{t\bar{t}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			0.9
$t\bar{t}$ NLO modelling	0.7	-0.1	0.8
$t\bar{t}$ hadronisation	-2.4	0.4	2.8
Initial/final state radiation	-0.3	0.1	0.4
$t\bar{t}$ heavy-flavour production	-	0.4	0.4
Parton distribution functions	0.5	-	0.5
Single-top modelling	-	-	0.3
Single-top/ $t\bar{t}$ interference	-	-	0.6
Single-top Wt cross-section	-	-	0.5
Diboson modelling	-	-	0.1
Diboson cross-sections	-	-	0.0
Z+jets extrapolation	-	-	0.2
Electron energy scale/resolution	0.2	0.0	0.2
Electron identification	0.3	0.0	0.3
Electron isolation	0.4	-	0.4
Muon momentum scale/resolution	-0.0	0.0	0.0
Muon identification	0.4	0.0	0.4
Muon isolation	0.2	-	0.3
Lepton trigger	0.1	0.0	0.2
Jet energy scale	0.3	0.1	0.3
Jet energy resolution	-0.1	0.0	0.2
b -tagging	-	0.1	0.3
Misidentified leptons	-	-	0.6
Analysis systematics	2.7	0.6	3.3
Integrated luminosity	-	-	5.5
LHC beam energy	-	-	1.5
Total uncertainty	2.7	0.6	6.7
Uncertainty (fiducial $\sigma_{t\bar{t}}^{\text{fid}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}^{\text{fid}}/\sigma_{t\bar{t}}^{\text{fid}}$ (%)
$t\bar{t}$ NLO modelling	0.5	-0.1	0.6
$t\bar{t}$ hadronisation	-1.6	0.4	1.9
Parton distribution functions	0.1	-	0.1
Other uncertainties (as above)	0.8	0.4	1.5
Analysis systematics ($\sigma_{t\bar{t}}^{\text{fid}}$)	1.8	0.6	2.5
Total uncertainty ($\sigma_{t\bar{t}}^{\text{fid}}$)	1.8	0.6	6.3





ttbar LHC cross sections





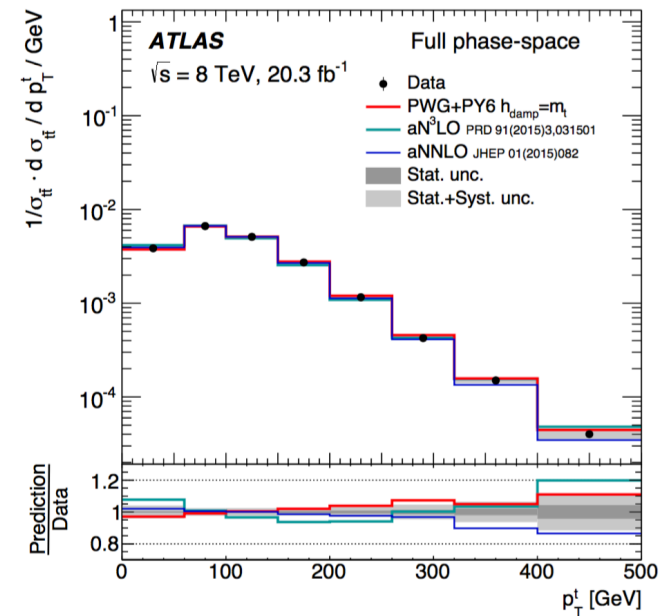
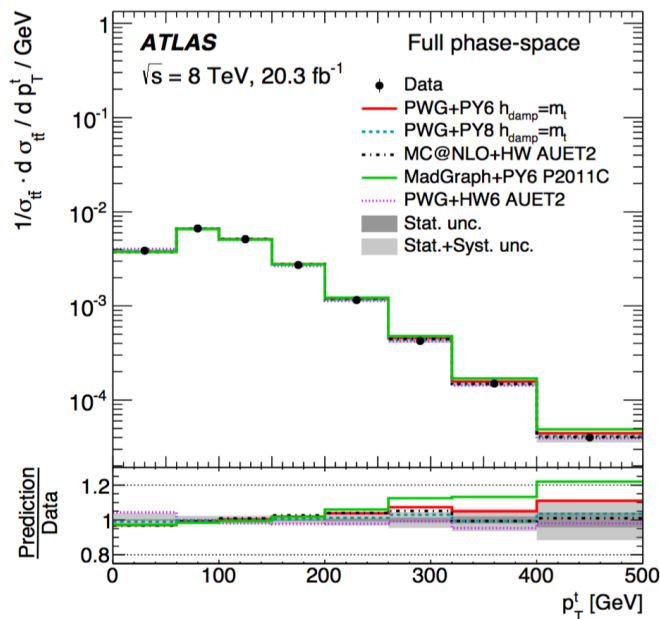
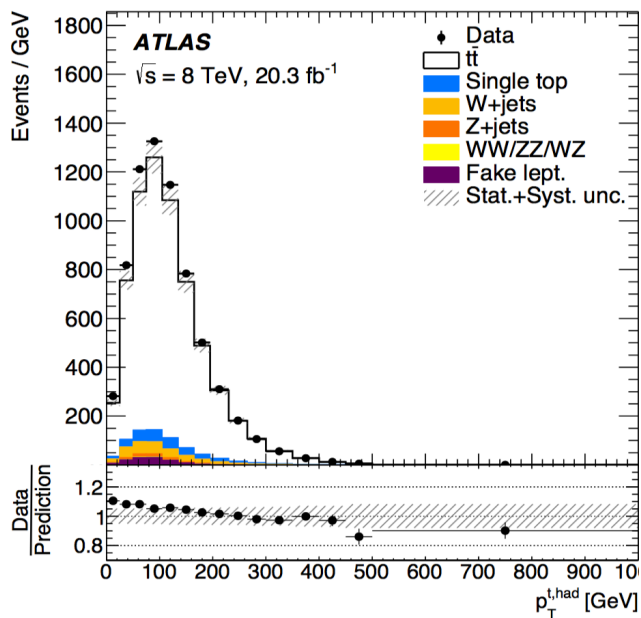
Differential cross section at 8 TeV (ATLAS)



arXiv:1511.04716

- Differential cross section in the **semi-leptonic channel**.
- DD for W+jets and multijet backgrounds.
- (pseudo) top reconstructed using constrains on W mass. **Unfolded at parton level**.

Cut	Event selection
Single lepton trigger	Electrons (isolated): $p_T > 60$ (24) GeV Muons (isolated): $p_T > 36$ (24) GeV
Primary vertex	≥ 5 tracks with $p_T > 0.4$ GeV
Exactly one isolated lepton	Muons: $p_T > 25$ GeV, $ \eta < 2.5$ Electrons: $p_T > 25$ GeV $ \eta < 2.47$, excluding $1.37 < \eta < 1.52$
Jets	≥ 4 jets $p_T > 25$ GeV, $ \eta < 2.5$ ≥ 2 b -tagged jets at $\epsilon_b = 70\%$



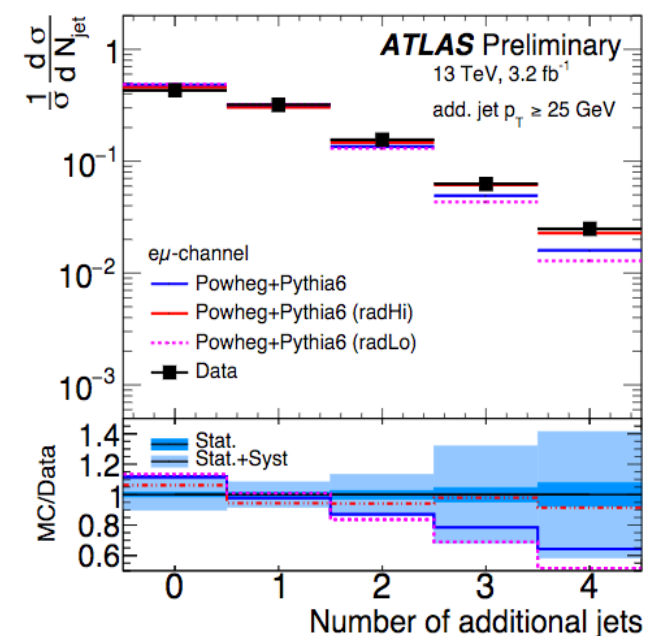
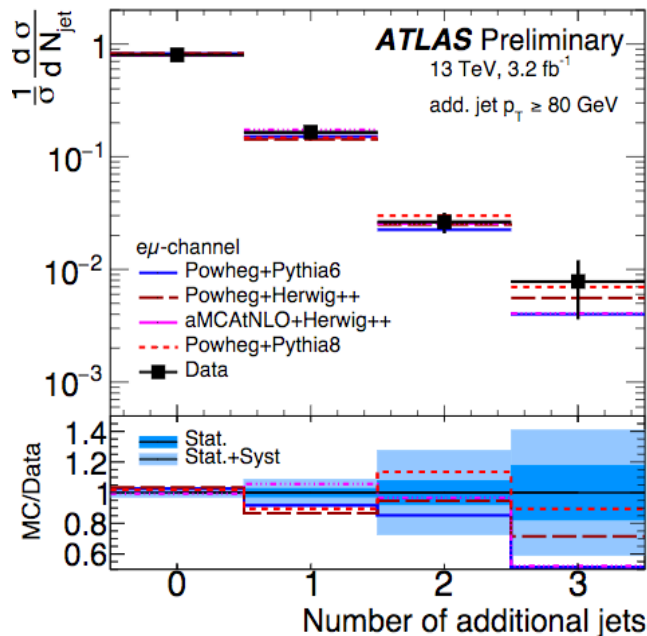
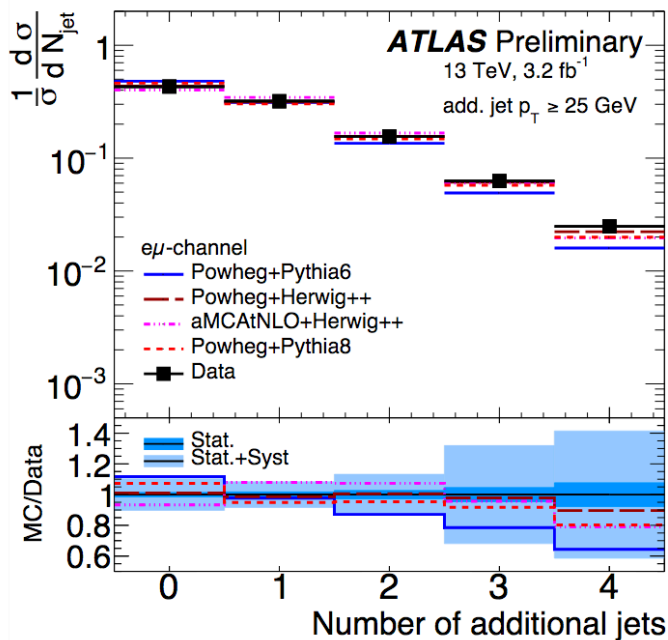
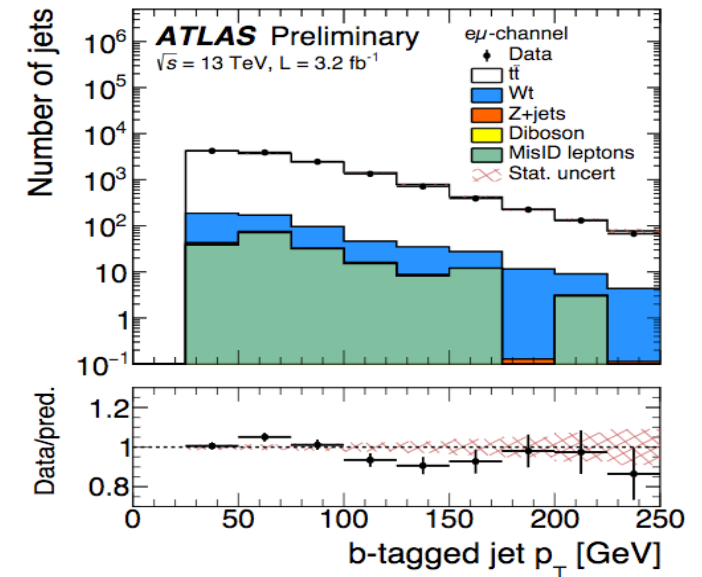


Differential cross section at 13 TeV (ATLAS)



ATLAS-CONF-2015-065

- Differential cross section at 13 TeV, as a function of jet multiplicity.
- Important test of the modelling of extra jets.
- Use dilepton events. Similar selection+2 b-tagged jets (medium WP). No top reconstruction needed, **unfolding at particle level**.



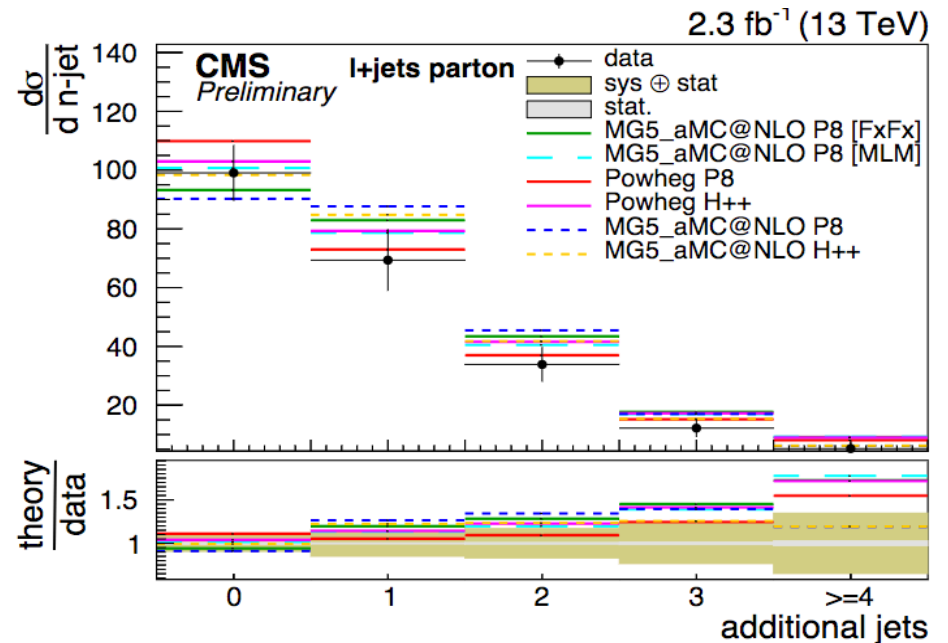
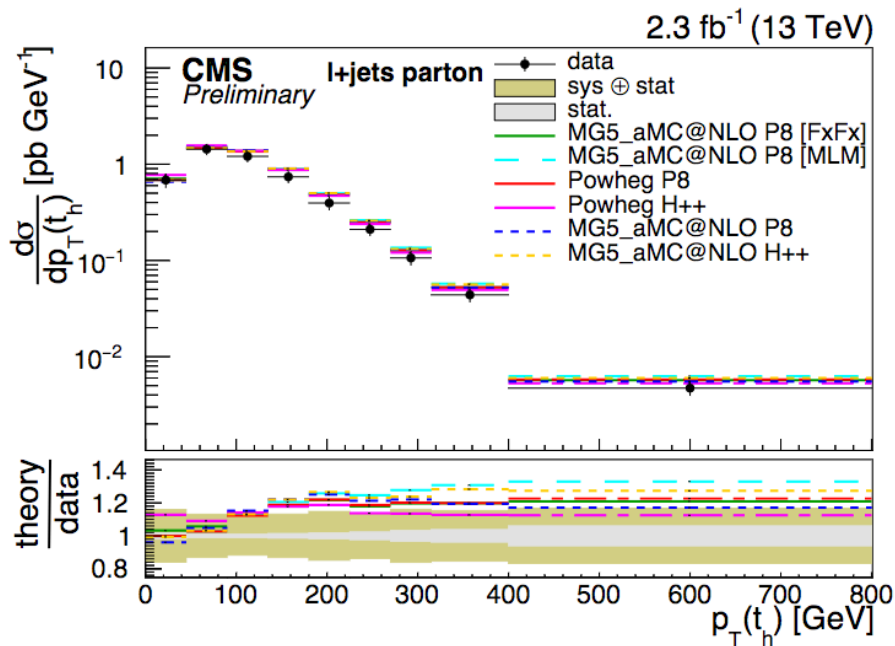
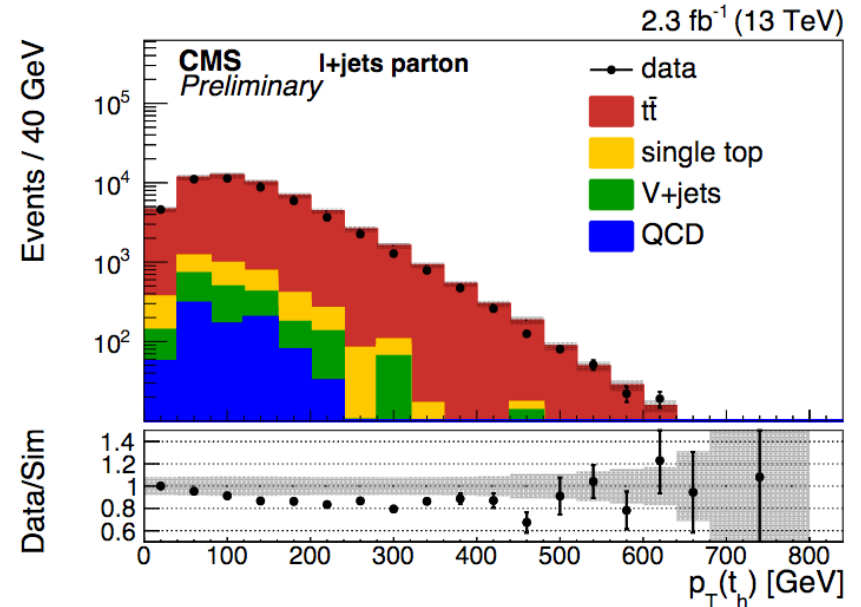


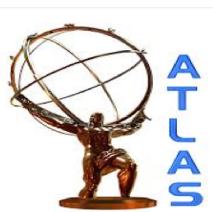
Differential cross section at 13 TeV (CMS)



CMS PAS TOP-16-008

- Differential cross section as a function of various observables.
- **Semi-leptonic channels**: single μ/e triggers, one isolated μ/e , ≥ 4 jets and ≥ 2 b-tagged jets.
- **Top reconstruction and unfolding** to particle and parton levels.





Conclusion



- **ttbar cross section measurements:**
 - benchmark analysis for top precision measurements,
 - can even be used for calibrating the detectors (see b-tagging talks),
 - allows for deep comparisons with theoretical predictions ! (and fiducial)
- **But also indirect measurements of :**
 - α_S ,
 - Top quark pole mass, etc...
- **And searches !**
 - stop pair production,
 - chromo-Magnetic and Electric dipole moments,
 - anomalous couplings, etc...
- With more work on systematics, we should be able to do **even more precise measurements** ($\sim 4\%$ for the moment).
- High luminosity will help ! (if LHC works well)

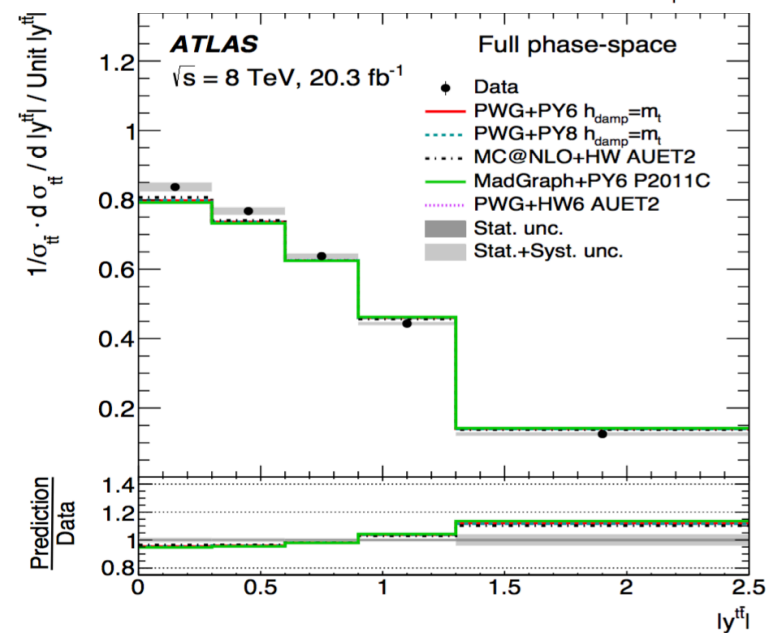
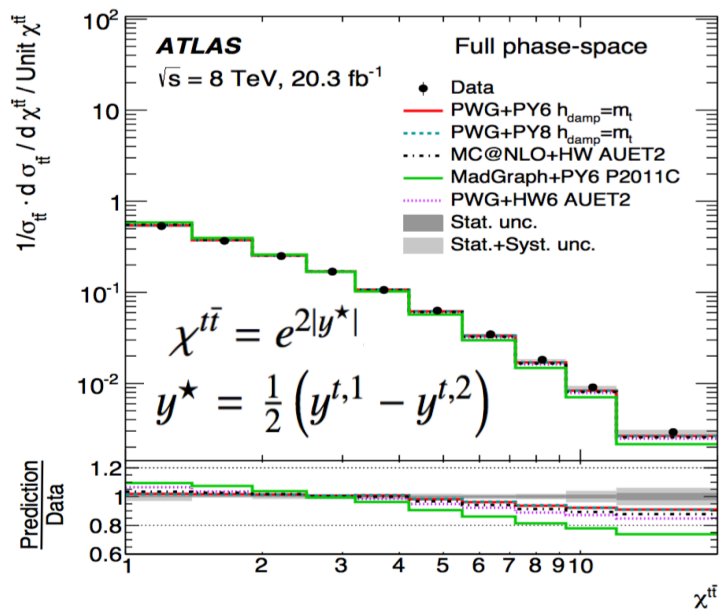
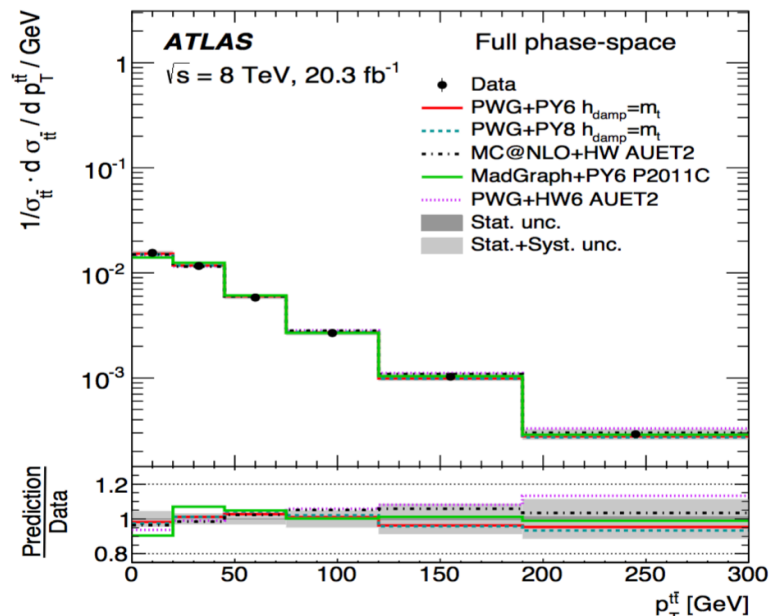
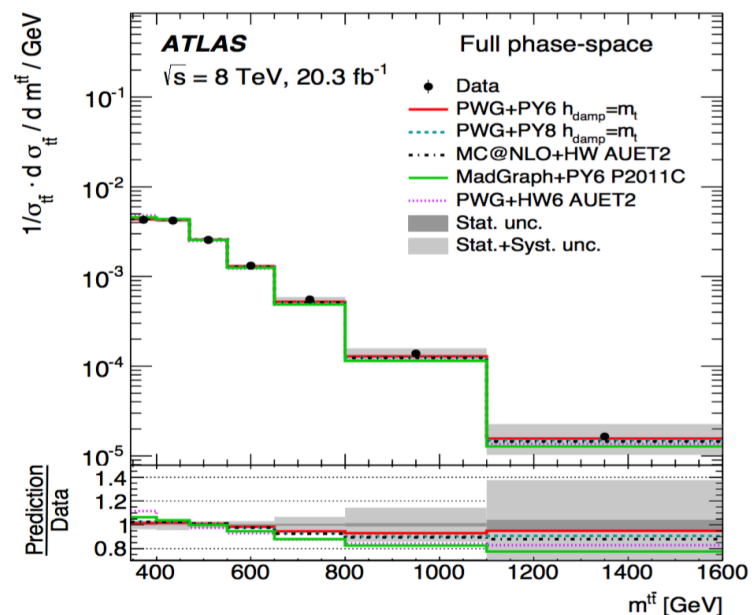




Backups



Differential cross section at 8 TeV





Comparisons of systematics



ATLAS

\sqrt{s}	7 TeV			8 TeV		
Uncertainty (inclusive $\sigma_{t\bar{t}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			1.69			0.71
$t\bar{t}$ modelling	0.71	-0.72	1.43	0.65	-0.57	1.22
Parton distribution functions	1.03	-	1.04	1.12	-	1.13
QCD scale choice	0.30	-	0.30	0.30	-	0.30
Single-top modelling	-	-	0.34	-	-	0.42
Single-top/ $t\bar{t}$ interference	-	-	0.22	-	-	0.15
Single-top Wt cross-section	-	-	0.72	-	-	0.69
Diboson modelling	-	-	0.12	-	-	0.13
Diboson cross-sections	-	-	0.03	-	-	0.03
Z +jets extrapolation	-	-	0.05	-	-	0.02
Electron energy scale/resolution	0.19	-0.00	0.22	0.46	0.02	0.51
Electron identification	0.12	0.00	0.13	0.36	0.00	0.41
Muon momentum scale/resolution	0.12	0.00	0.14	0.01	0.01	0.02
Muon identification	0.27	0.00	0.30	0.38	0.00	0.42
Lepton isolation	0.74	-	0.74	0.37	-	0.37
Lepton trigger	0.15	-0.02	0.19	0.15	0.00	0.16
Jet energy scale	0.22	0.06	0.27	0.47	0.07	0.52
Jet energy resolution	-0.16	0.08	0.30	-0.36	0.05	0.51
Jet reconstruction/vertex fraction	0.00	0.00	0.06	0.01	0.01	0.03
b -tagging	-	0.18	0.41	-	0.14	0.40
Misidentified leptons	-	-	0.41	-	-	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27	1.66	0.59	2.26
Integrated luminosity	-	-	1.98	-	-	3.10
LHC beam energy	-	-	1.79	-	-	1.72
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	0.75	3.89	1.66	0.59	4.27
Uncertainty (fiducial $\sigma_{t\bar{t}}^{\text{fid}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}^{\text{fid}}/\sigma_{t\bar{t}}^{\text{fid}}$ (%)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
$t\bar{t}$ modelling	0.84	-0.72	1.56	0.74	-0.57	1.31
Parton distribution functions	0.35	-	0.38	0.23	-	0.28
QCD scale choice	0.00	-	0.00	0.00	-	0.00
Other uncertainties (as above)	0.88	0.21	1.40	1.00	0.17	1.50
Analysis systematics ($\sigma_{t\bar{t}}^{\text{fid}}$)	1.27	0.75	2.13	1.27	0.59	2.01
Total uncertainty ($\sigma_{t\bar{t}}^{\text{fid}}$)	1.27	0.75	3.81	1.27	0.59	4.14

CMS

Source	Uncertainty [%]	
	7 TeV	8 TeV
Trigger	1.3	1.2
Lepton ID/isolation	1.5	1.5
Lepton energy scale	0.2	0.1
Jet energy scale	0.8	0.9
Jet energy resolution	0.1	0.1
$tW/\bar{t}W$	1.0	0.6
DY	1.4	1.3
$t\bar{t}$ bkg.	0.1	0.1
$t\bar{t}V$	0.1	0.1
Diboson	0.2	0.6
W +jets/QCD	0.1	0.2
b -tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
μ_R, μ_F scales	0.3	0.6
ME/PS matching	0.1	0.1
MADGRAPH vs POWHEG	0.4	0.5
Hadronisation (JES)	0.7	0.7
Top quark p_T modelling	0.3	0.4
Colour reconnection	0.1	0.2
Underlying event	0.1	0.1
PDF	0.2	0.3
Integrated luminosity	2.2	2.6
Statistical	1.2	0.6
Source	Uncertainty [%]	
	7 TeV	8 TeV
Total (visible)	+3.6 -3.4	+3.7 -3.4
Q^2 scale (extrapol.)	+0.1 -0.4	+0.2 -0.1
ME/PS matching (extrapol.)	+0.1 -0.1	+0.3 -0.3
Top quark p_T (extrapol.)	+0.5 -0.3	+0.6 -0.3
PDF (extrapol.)	+0.1 -0.1	+0.1 -0.1
Total	+3.6 -3.5	+3.7 -3.5



Top mass from cross section

