# Top Quark Pair Production At ATLAS

Lukas Heinrich
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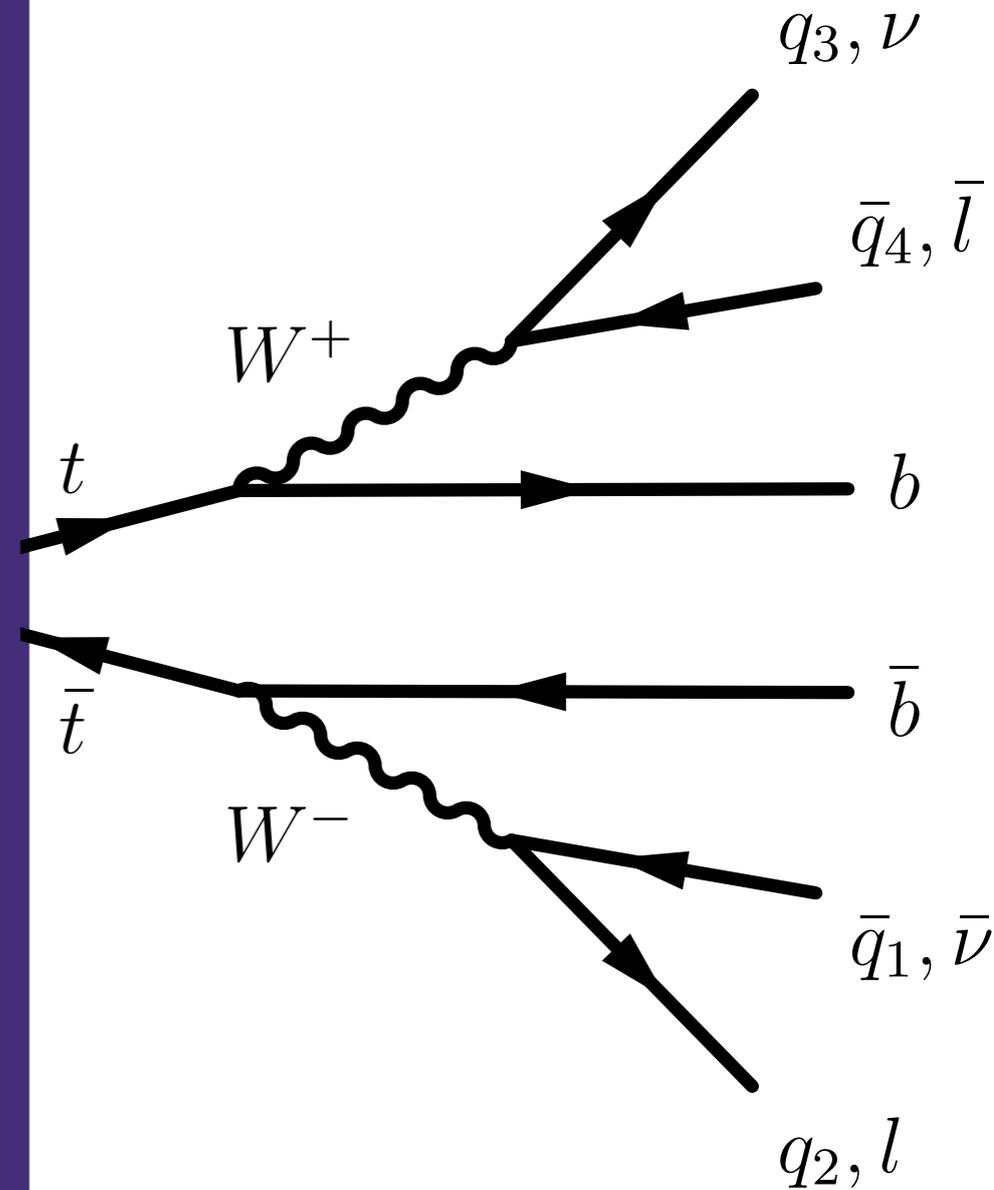
Top Quark Physics

- Top quark plays a special role in SM physics

  - only 'bare quark' system we can study

  - only quark with Yukawa coupling of order unity

    - prominent position in many SM extensions

    - stop crucial in SUSY

    - top partners   arXiv:1211.5663

- Must measure top properties
  such as cross section precisely.

  - benchmark process, background to many
    searches

  - may be sensitive to new physics itself

NEW YORK UNIVERSITY   arXiv:1303.4414
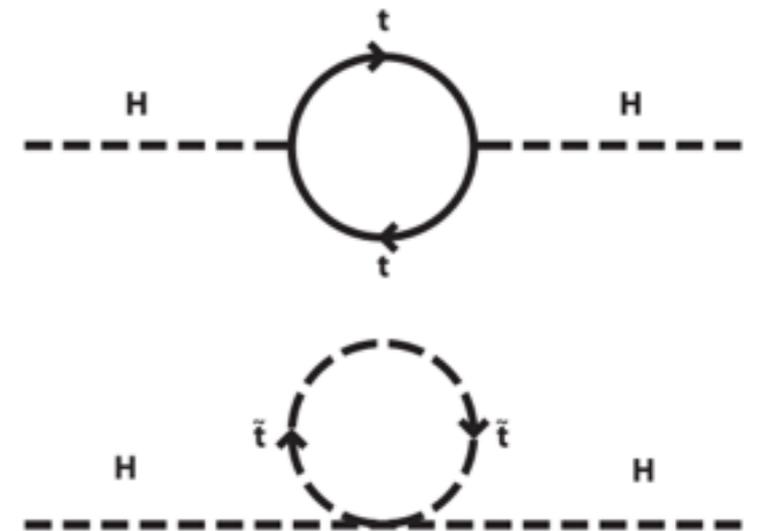
Top Quark Pair Production

- Top Quark Pairs are the main top production mode at the LHC, mainly through gluon fusion.
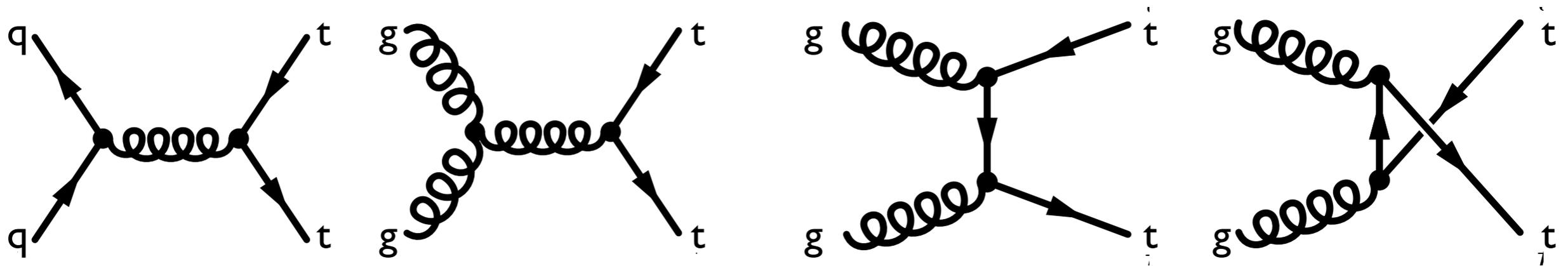
- Theoretical precision in inclusive cross-section prediction has reached NNLO level.

$$\sigma_{pp \to t\bar{t}+X}(7 \text{ TeV}) = 177^{+10}_{-10} \text{ pb}$$

$$\sigma_{pp \to t\bar{t}+X}(8 \text{ TeV}) = 253^{+13}_{-15} \text{ pb}$$

Czakon, Mitov: arXiv:1207.0236

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# Signatures

- Top quark almost exclusively decays via $t \to Wb$

  - final states categorized in nature of W-decays

  - leptonic decays: high-pt lepton + MET

  - jets from any hadronic decays

  - always 2 b-jets
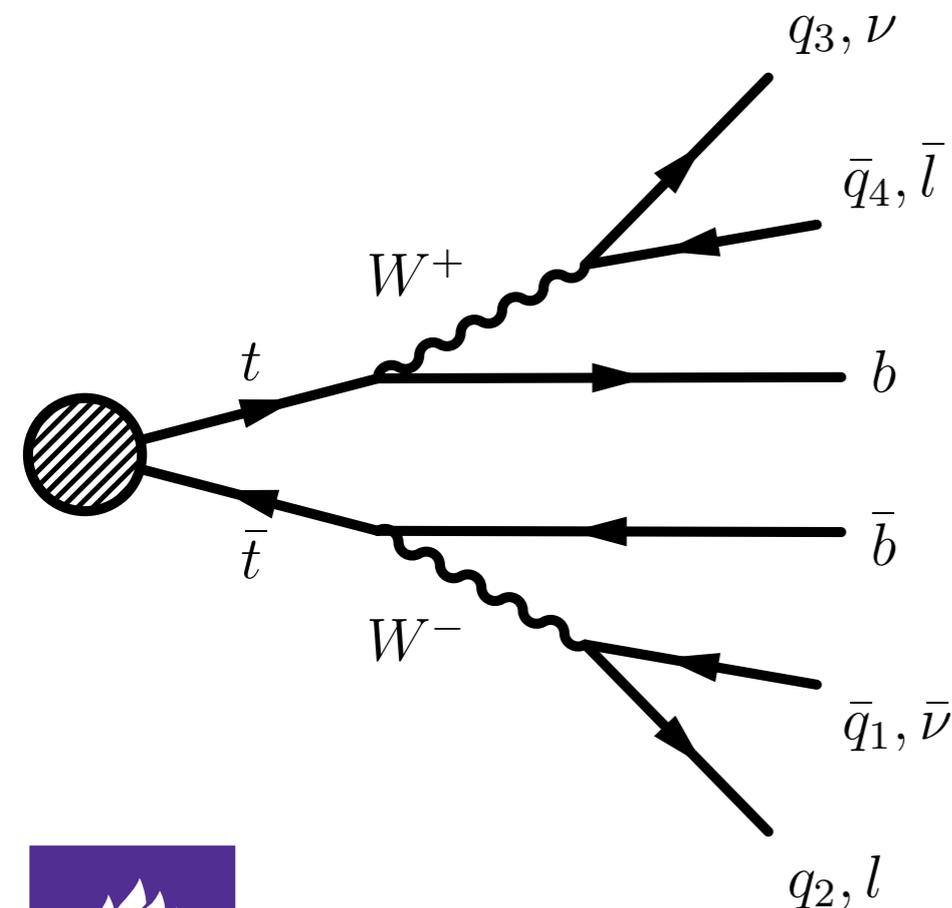
7 TeV

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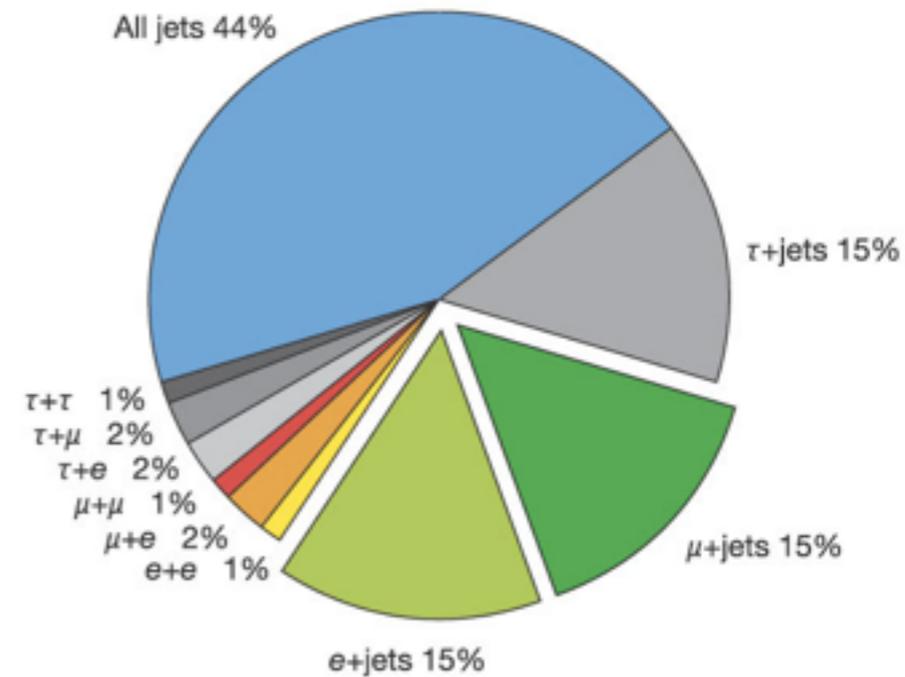
Four variables with large discriminating power:

- pseudo-rapidity of lepton

- leading jet p_T

- exp(-8xA): aplanarity A

- transverse energy of jets

single projective likelihood is constructed, shape for signal and background derived.

Cross-Section: Template fit is with systematics treated as nuisance parameter

Leading systematic: Generator Choice

$$\sigma_{t\bar{t}} = 179.0 \pm 9.8(\text{stat.} + \text{syst})$$
$$\pm 6.6(\text{lumi}) \, \text{pb}$$

Event Selection

- 25 (20) GeV e (μ)

- 25 GeV Missing E_T (MET)

- three or more jets w/ p_T > 25 GeV

- transverse mass m_T > 25 (60) GeV

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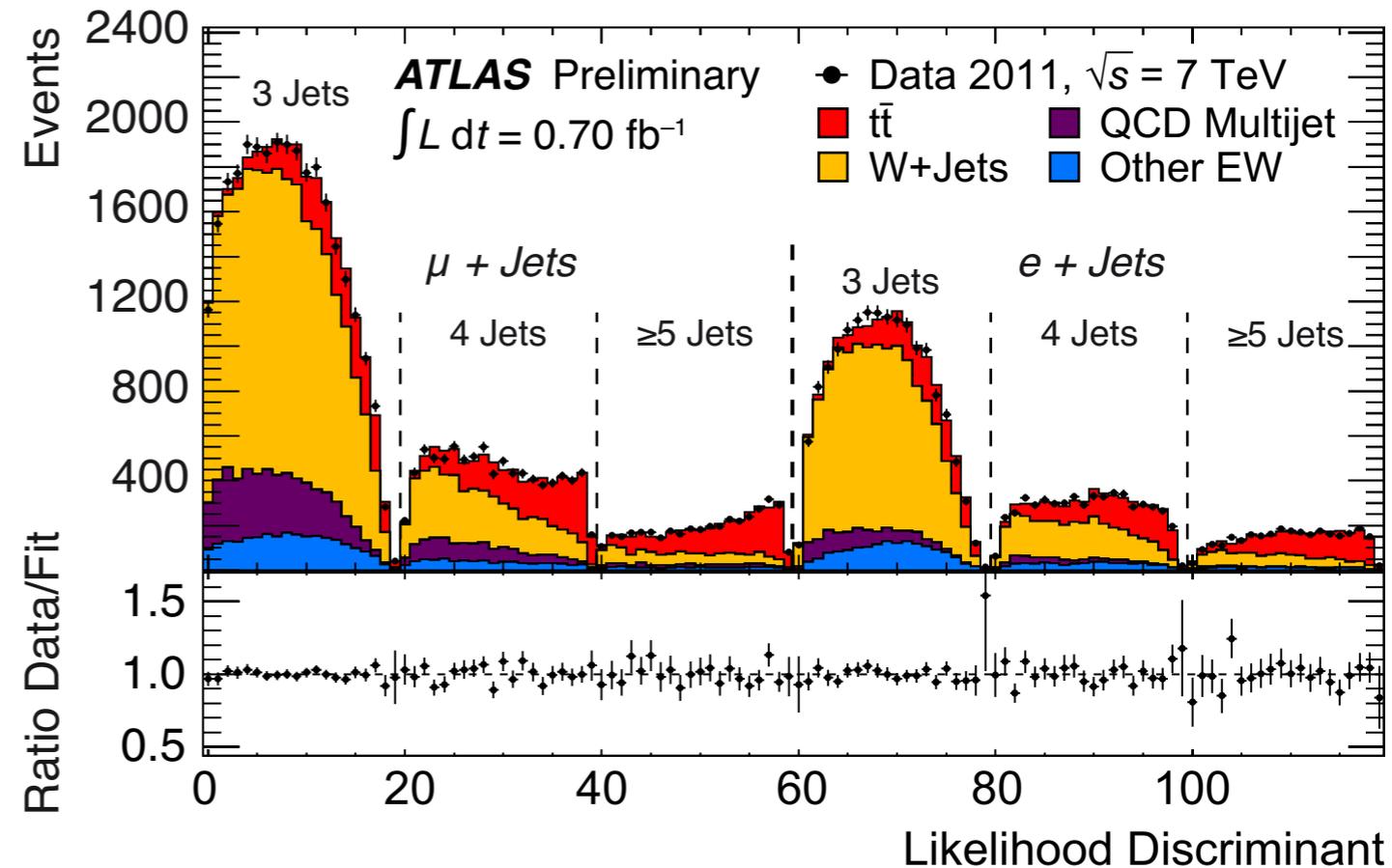
measures cross-section from likelihood fit on the event counts.

$$\mathcal{L}(\sigma_{\text{sig}}, L, \vec{\alpha}) = \prod_{i \in \{\text{channel}\}} \mathcal{P}\left(N_i^{\text{obs}} \mid N_{i,\text{tot}}^{\text{exp}}(\vec{\alpha})\right)$$

$$\times \quad \mathcal{G}(L_0 \mid L, \sigma_L) \times \prod_{j \in \text{syst}} \mathcal{G}_j(0 \mid \alpha_j, 1)$$

Leading systematic:

- Jet Energy Scale (JES)

- Final State Radiation (FSR)

Event Selection

- 2 opp. charge e or μ p_T > 25 GeV

- >60 GeV MET (in ee, μμ channels), H_T > 130 GeV (eμ)

- two jets p_T > 25 GeV

- separate b-tag selection requires at least 1 b-tagged jet

JHEP 1205 (2012) 059 arXiv:1202.4892

8 TeV

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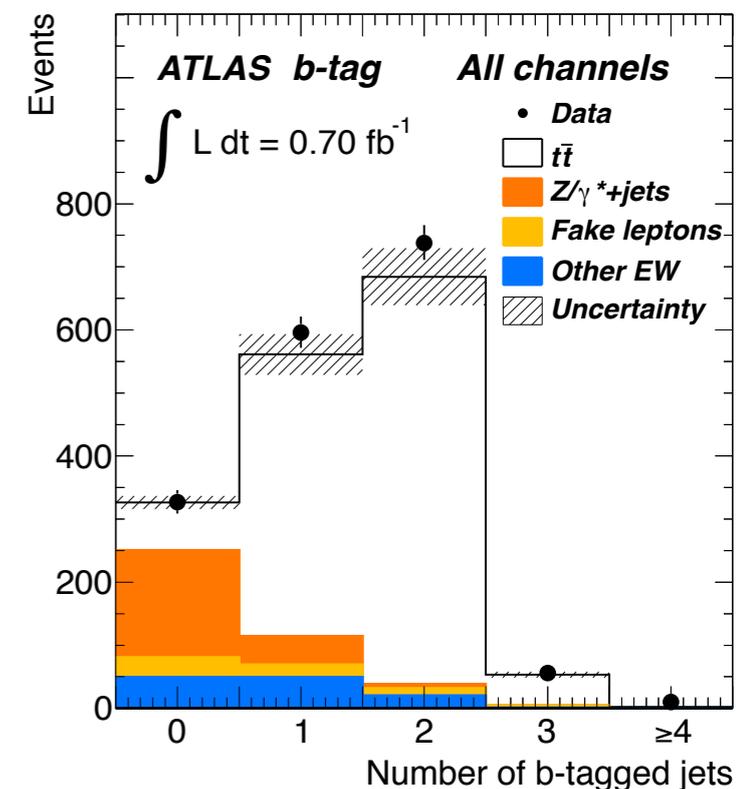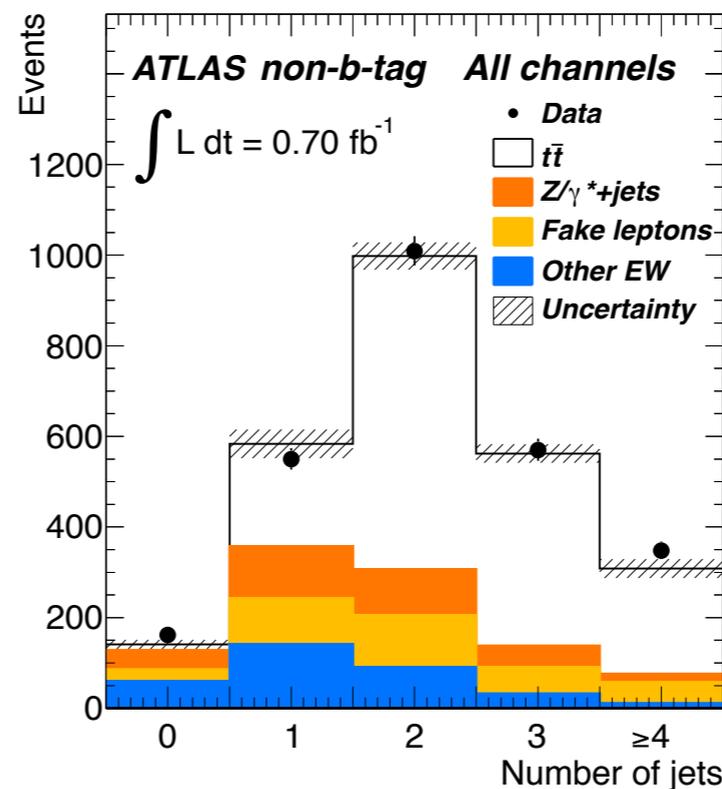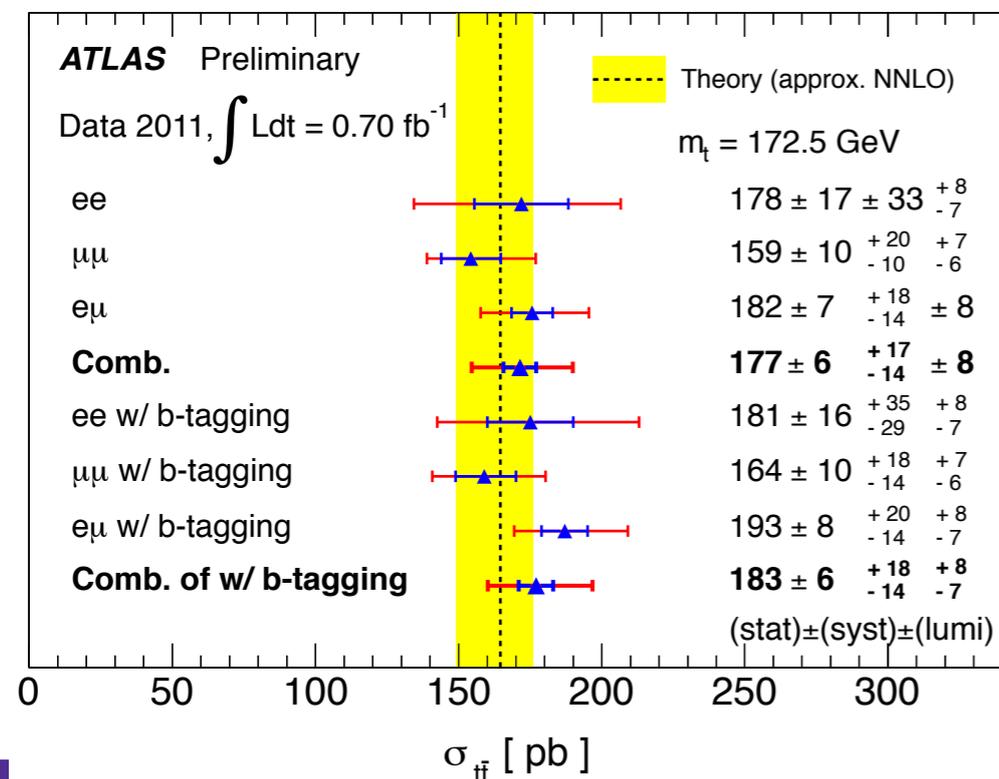
discriminant built from only two variables:

- aplanarity and lepton eta.

- binned likelihood fit of template shapes of discriminant (ttbar, W+jets, Other)

- Fit is simultaneous. (except W+Jets: floats freely in each channel)

- cross-section via: $\sigma_{t\bar{t}} = \dfrac{N_{t\bar{t}}}{\mathcal{L} \times BR \times \varepsilon_{\text{sig}}}$

Result is strongly dominated by systematics.

Main one (as in 7 TeV): Generator

$\sigma_{t\bar{t}} = 241 \pm 2 \text{ (stat.)} \pm 31 \text{ (syst.)} \pm 9 \text{ (lumi.) pb.}$

Event Selection

- exactly 40 GeV e or μ

- 30 (20) GeV MET for e(μ)-channel

- three or more jets w/ $p_T > 25$ GeV

- $m_T > 30$ GeV (e), m_T+MET > 60 GeV (μ)

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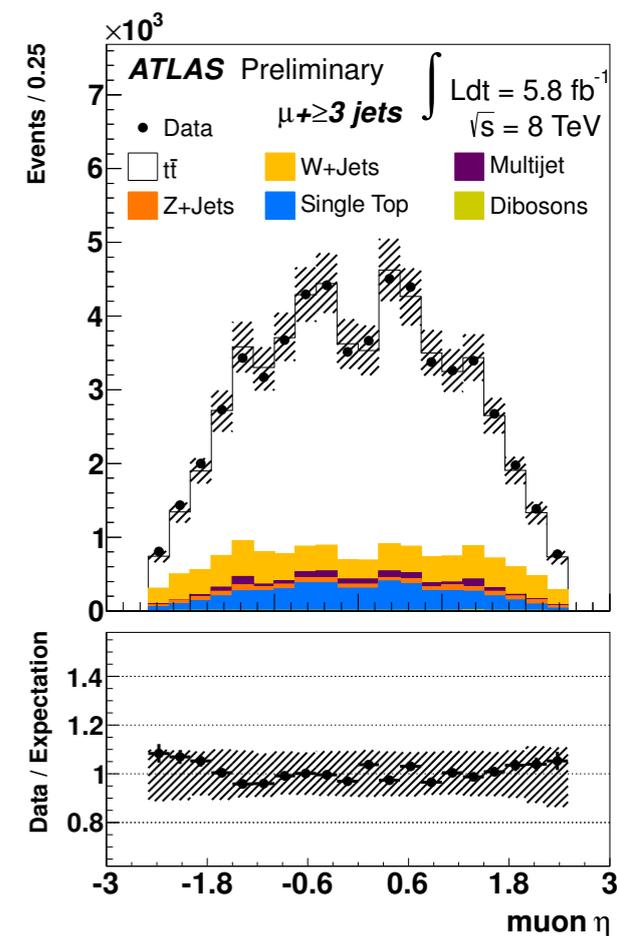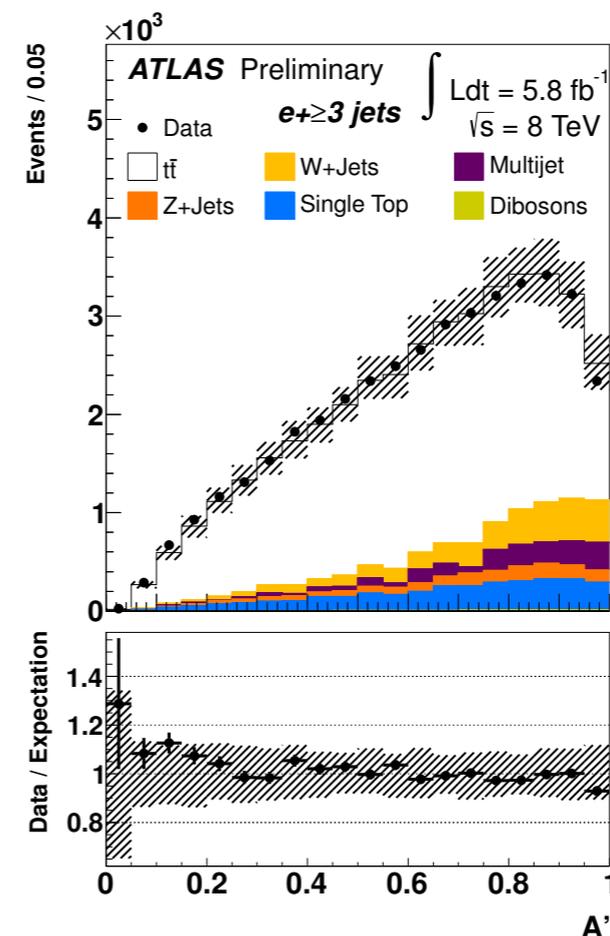
8 TeV eμ 20.3/fb

- robust analysis looking only at eμ sub channel on full 2012 dataset.

- cross section extraction from tag counting

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

total # of events   selection efficiency   b-jet selection + combinatorics   background

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

- simultaneous fit of b-jet efficiency (selection+tagging) and cross section minimizes systematic uncertainties. Only 1- and 2-tag bins participate

ATLAS-CONF-2013-097

Event Selection

- exactly one electron $E_T > 25$ GeV
- exactly one muon $p_T > 25$ GeV
- one or two b-tagged jets with $p_T > 25$ GeV
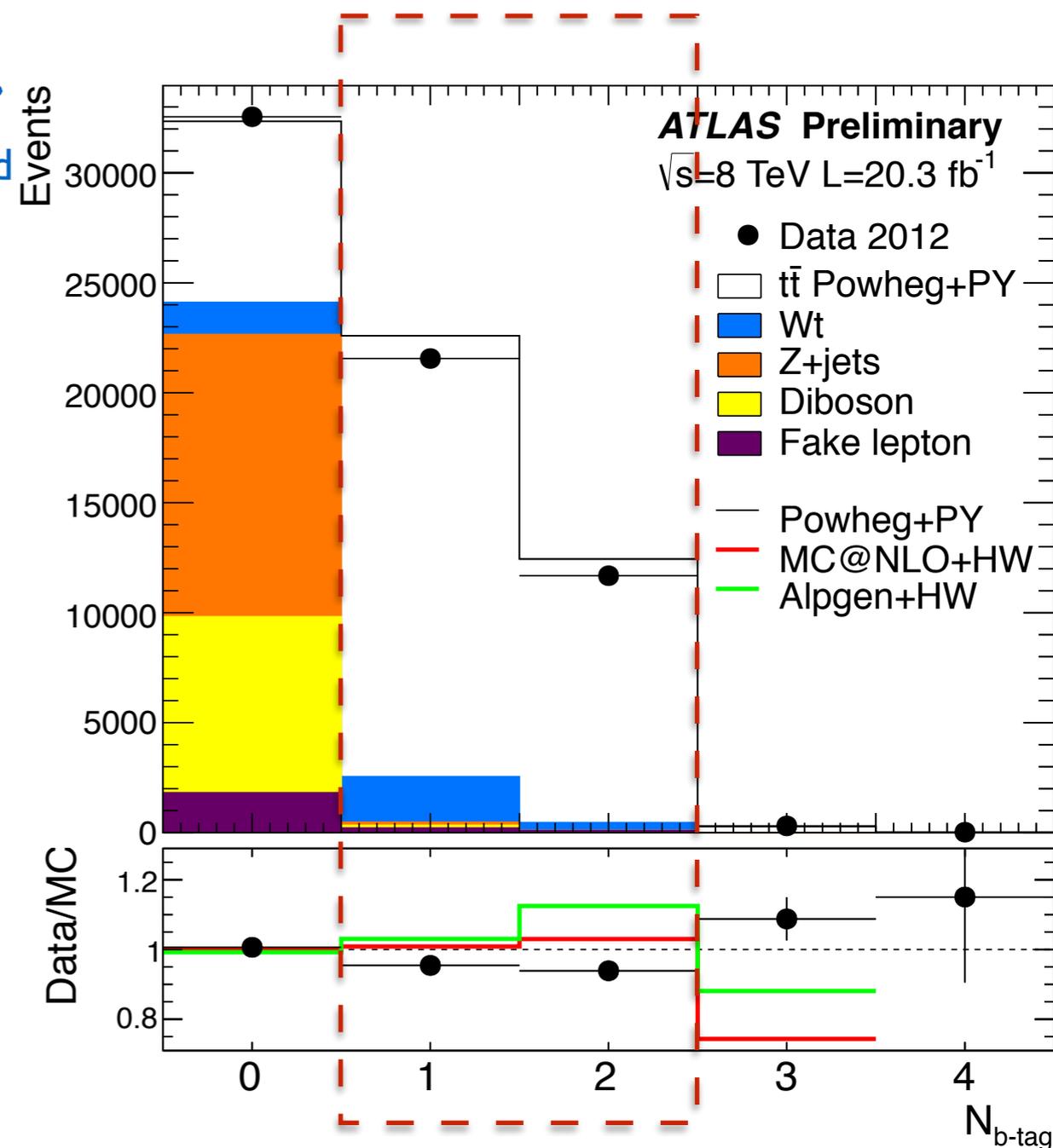
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backgrounds are estimated with data-driven and Monte-Carlo methods.

- Wt single top and Diboson: MC norm. to NNLO, NLO respectively.

- Z+jets: MC simulation w/ data-driven normalization (from Z→ee,Z→μμ)

- Fake leptons: estimated from background subtracted same-sign events and same-sign → opp. scale factor

- most precise measurement of top pair cross section at the LHC at 8 TeV

$$\sigma_{t\bar{t}} = 237.7 \pm 1.7(\text{stat.})$$
$$\pm 7.4(\text{syst.})$$
$$\pm 7.4(\text{lumi.})$$
$$\pm 4.0(\text{beam energy})$$

Event counts	N_1	N_2
Data	21559	11682
Wt single top	2070 ± 220	360 ± 120
Dibosons	120 ± 90	3^{+6}_{-3}
$Z(\to \tau\tau \to e\mu)$+jets	210 ± 10	8 ± 1
Misidentified leptons	240 ± 70	110 ± 60
Total background	2640 ± 250	480 ± 140

Uncertainty	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\epsilon_b/\epsilon_b$ (%)
Data statistics	-	-	0.72	1.7	0.57
$t\bar{t}$ modelling	0.91	-0.61	1.52	3.6	0.61
Initial/final state radiation	-0.76	0.26	1.23	2.9	0.37
Parton density functions	1.08	-	1.09	2.6	0.06
QCD scale choices	0.30	-	0.30	0.7	0.00
Single-top modelling	-	-	0.38	0.9	0.56
Single-top/$t\bar{t}$ interference	-	-	0.15	0.4	0.25
Single-top Wt cross-section	-	-	0.70	1.7	0.24
Diboson modelling	-	-	0.42	1.0	0.19
Diboson cross-sections	-	-	0.03	0.1	0.01
Z+jets extrapolation	-	-	0.05	0.1	0.02
Electron energy scale/resolution	0.43	0.01	0.48	1.1	0.03
Electron identification/isolation	1.28	0.00	1.42	3.4	0.05
Muon momentum scale/resolution	0.01	0.01	0.05	0.1	0.02
Muon identification/isolation	0.50	0.00	0.52	1.2	0.01
Lepton trigger	0.15	0.00	0.16	0.4	0.01
Jet energy scale	0.46	0.07	0.49	1.2	0.11
Jet energy resolution	-0.44	0.04	0.59	1.4	0.08
Jet reconstruction/vertex fraction	0.02	0.01	0.04	0.1	0.01
b-tagging	-	0.13	0.42	1.0	0.09
Pileup modelling	-0.30	0.05	0.28	0.7	0.05
Misidentified leptons	-	-	0.38	0.9	0.12
Total systematic	2.29	0.69	3.12	7.4	1.02
Integrated luminosity	-	-	3.11	7.4	0.11
LHC beam energy	-	-	1.70	4.0	0.00
Total uncertainty	2.29	0.69	4.77	11.3	1.17

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differential cross-section

The large dataset obtained in Run I allows for differential cross-section measurements in various variables.

ATLAS analysis performe...

- standard l+jets fina...
- differential measure...

Basics

- detector and reco...
  measured values away from true values. using
  Monte Carlo we can obtain a *migration matrix*
  that describes con...

fraction of events from bin j (tr...
reconstructed in bin i due to ...

$$N_i = \sum_j M_{ij} N$$

acceptance

events

ATLAS Simulation Preliminary √s = 7 TeV e+jets

correlation: 0.85 — Parton-level p_T^t [GeV] — Reconstructed p_T^t [GeV]

ATLAS Simulation Preliminary √s = 7 TeV μ+jets

correlation: 0.84 — Parton-level p_T^t [GeV] — Reconstructed p_T^t [GeV]

ATLAS Simulation Preliminary √s = 7 TeV e+jets

correlation: 0.86 — Parton-level $m_{t\bar{t}}$ [GeV] — Reconstructed $m_{t\bar{t}}$ [GeV]

ATLAS Simulation Preliminary √s = 7 TeV μ+jets

correlation: 0.85 — Parton-level $m_{t\bar{t}}$ [GeV] — Reconstructed $m_{t\bar{t}}$ [GeV]
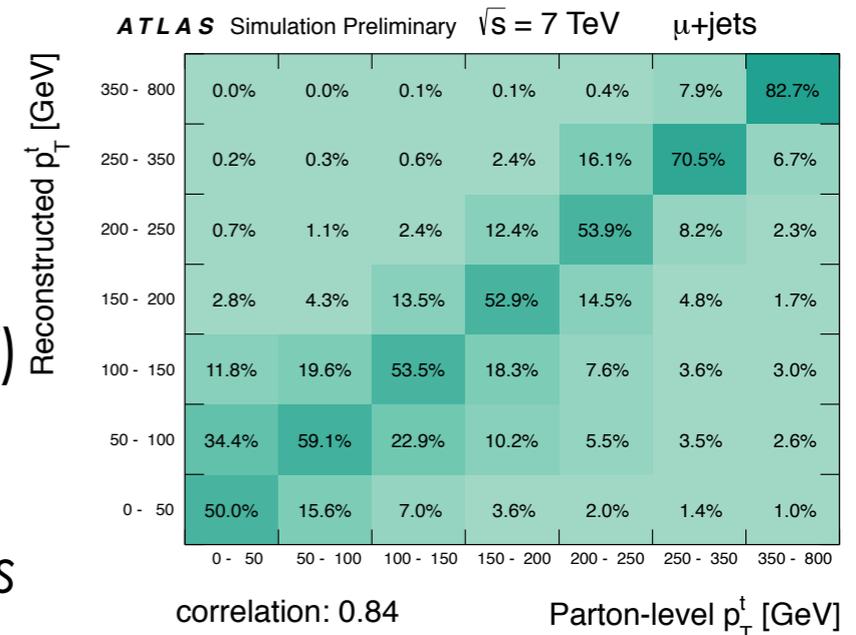
differential cross-section

Data can be *unfolded* by inverting migration matrix.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \frac{1}{\Delta X}\frac{M_{ij}^{-1}(N_i - B_i)}{\epsilon_j \cdot BR \cdot L}$$

- largest systematic uncertainties from ISR/FSR, JES, b-tagging,

Results

ATLAS-CONF-2013-099

- generally observed softer p_T spectrum than predicted

- more central production than predicted

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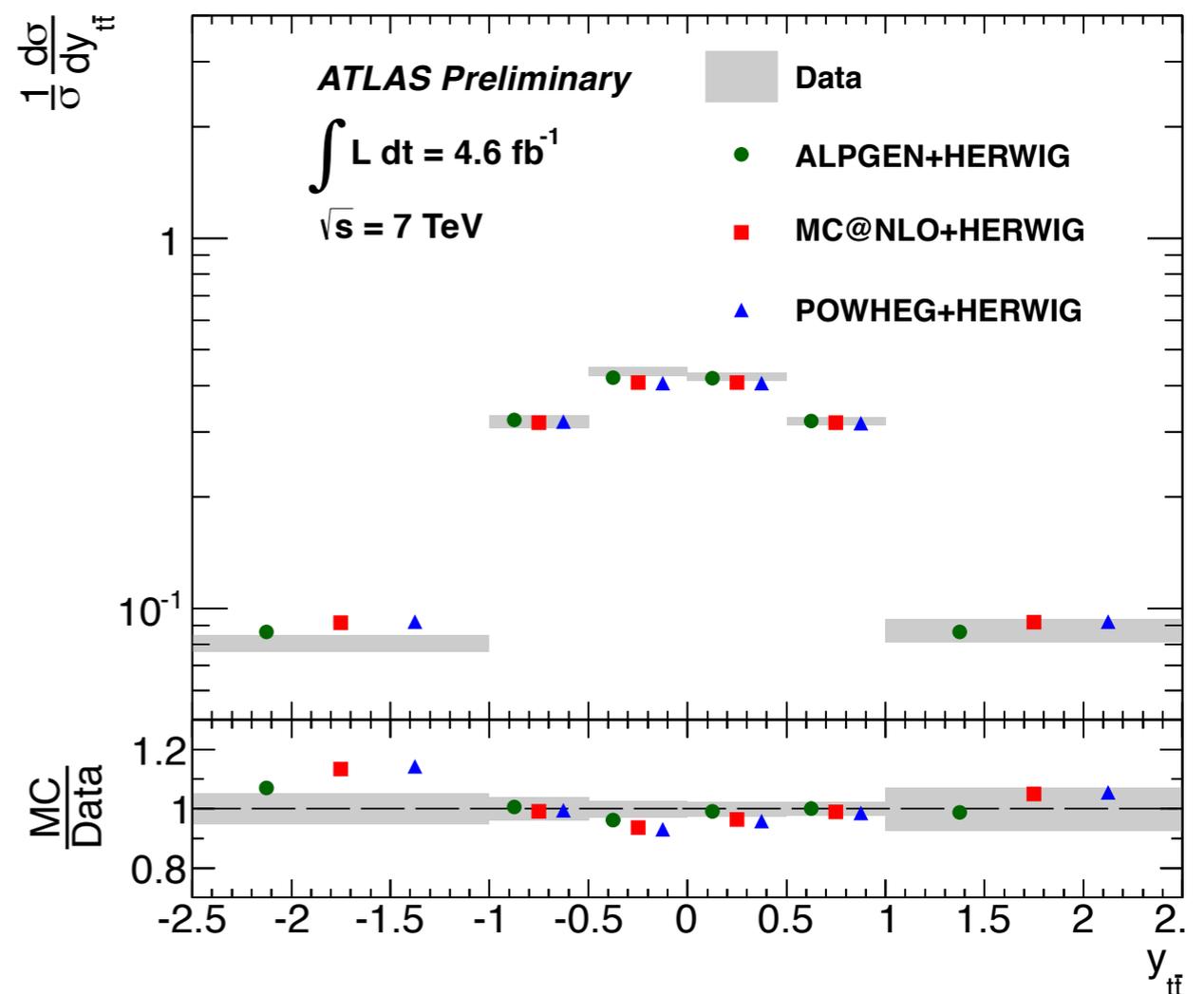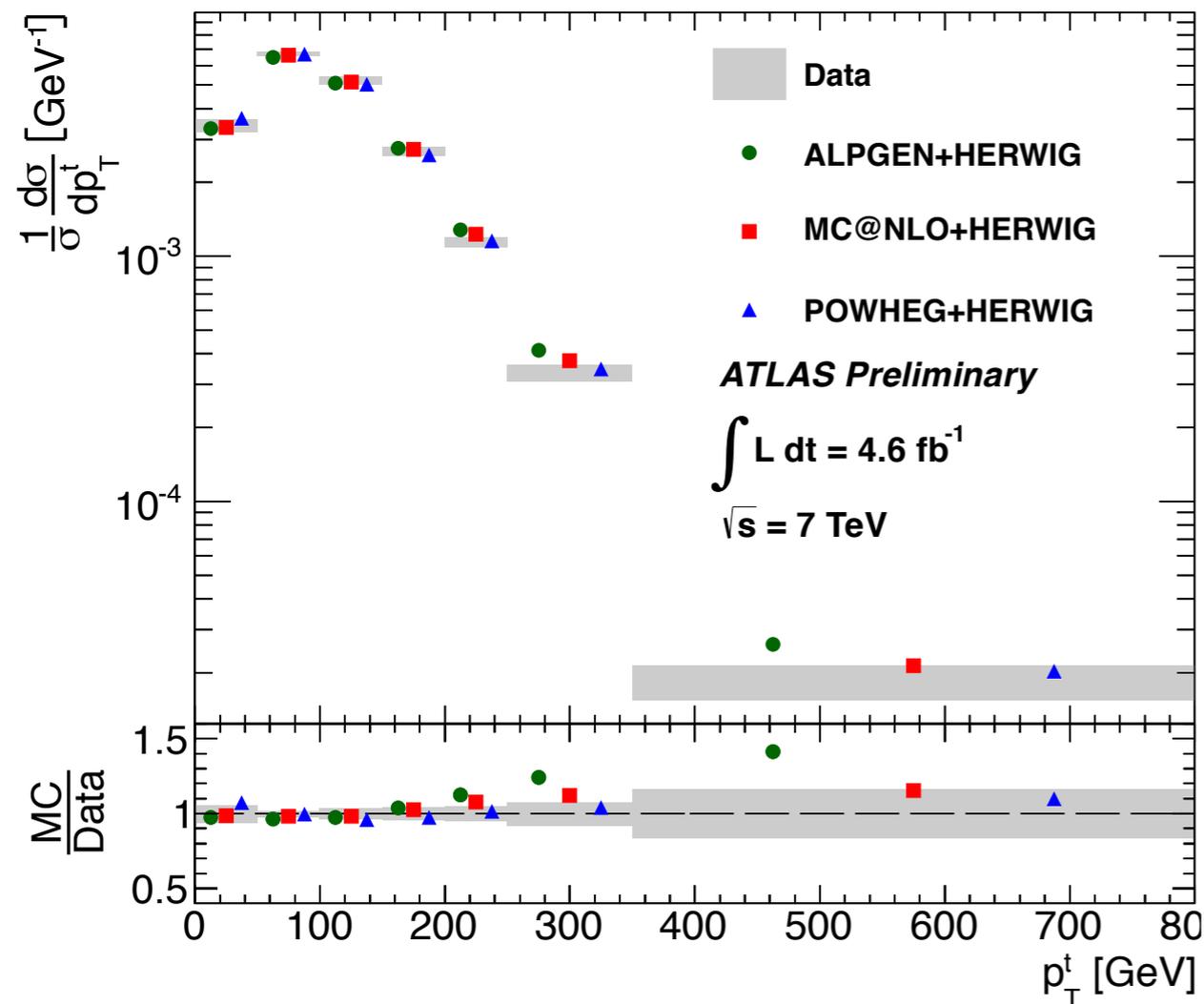
differential cross-section

Results (cont'd)

- compared to NLO(+NNLL) predictions, $m_{t\bar{t}}$ is systematically softer

- comparing different NLO PDF sets, HERAPDF consistently is preferred.

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Conclusion

ATLAS Preliminary — 12 Sep 2013

Data 2012, $\sqrt{s}$ = 8 TeV

Channel & Lumi.

NNLO+NNLL (top++ 2.0) PDF4LHC m_{top} = 172.5 GeV

scale uncertainty
scale+PDF uncertainty

stat. uncertainty
total uncertainty

$\sigma_{t\bar{t}} \pm$(stat) $\pm$(syst) $\pm$(lumi) $\pm$(E_{beam})

Single lepton 5.8 fb^{-1} — 241 $\pm$ 2 $\pm$ 31 $\pm$ 9 pb

Dilepton (eμ) 20.3 fb^{-1} — 238 $\pm$ 2 $\pm$ 7 $\pm$ 7 $\pm$ 4 pb

$\sigma_{t\bar{t}}$ [pb]
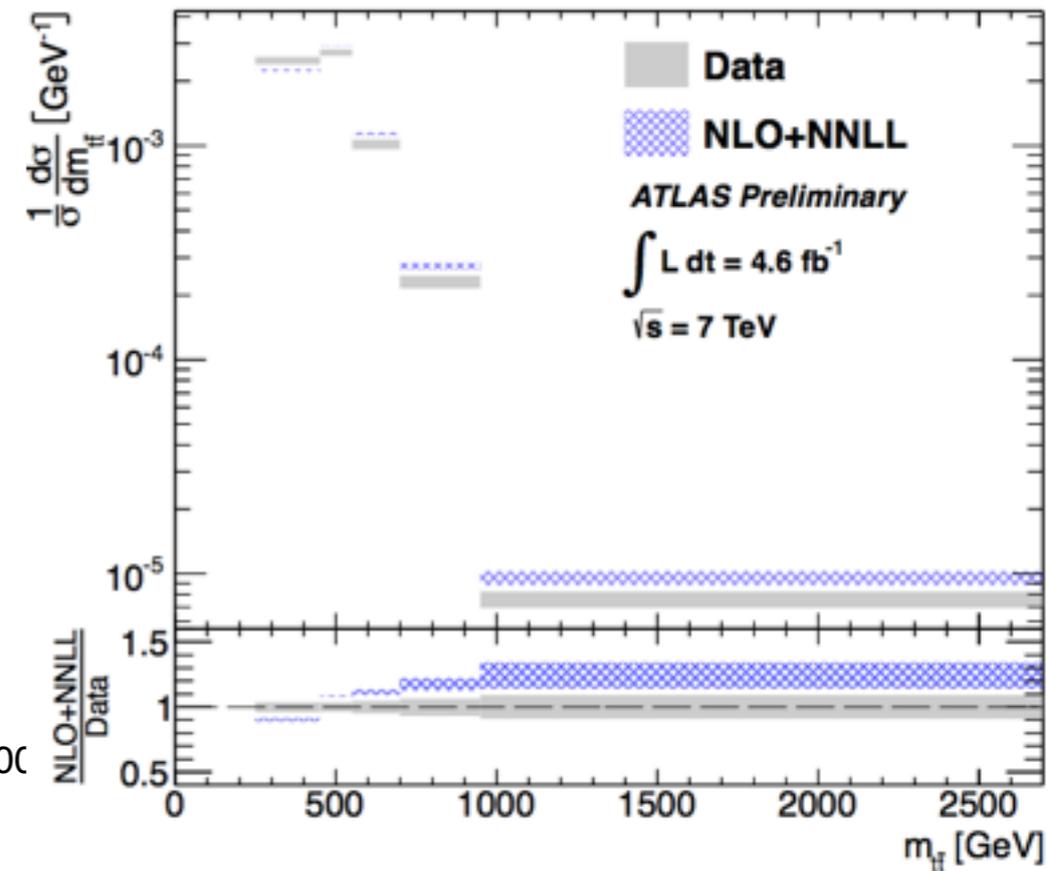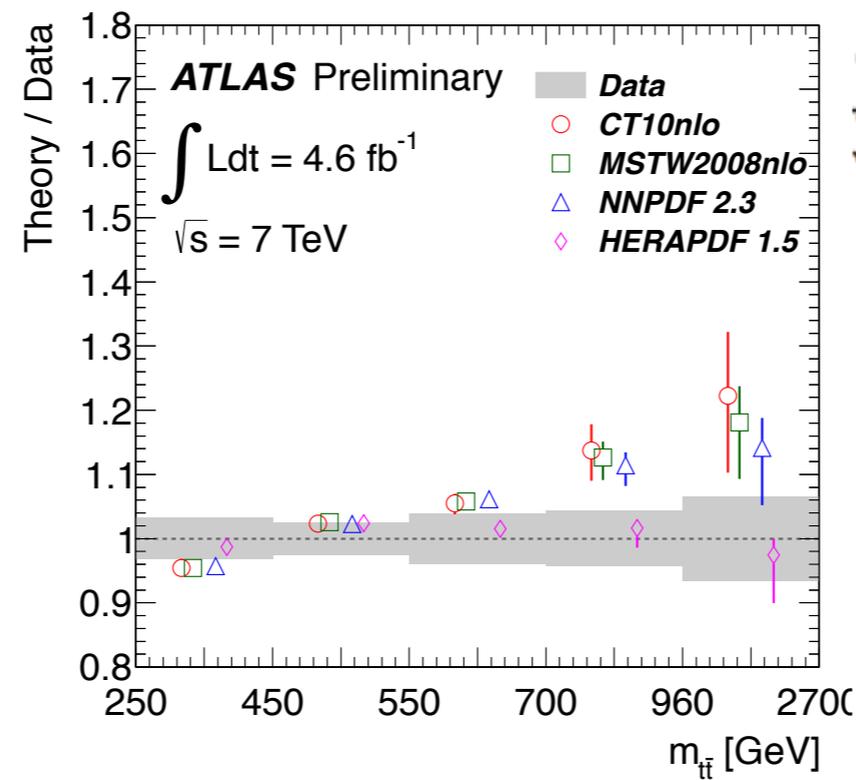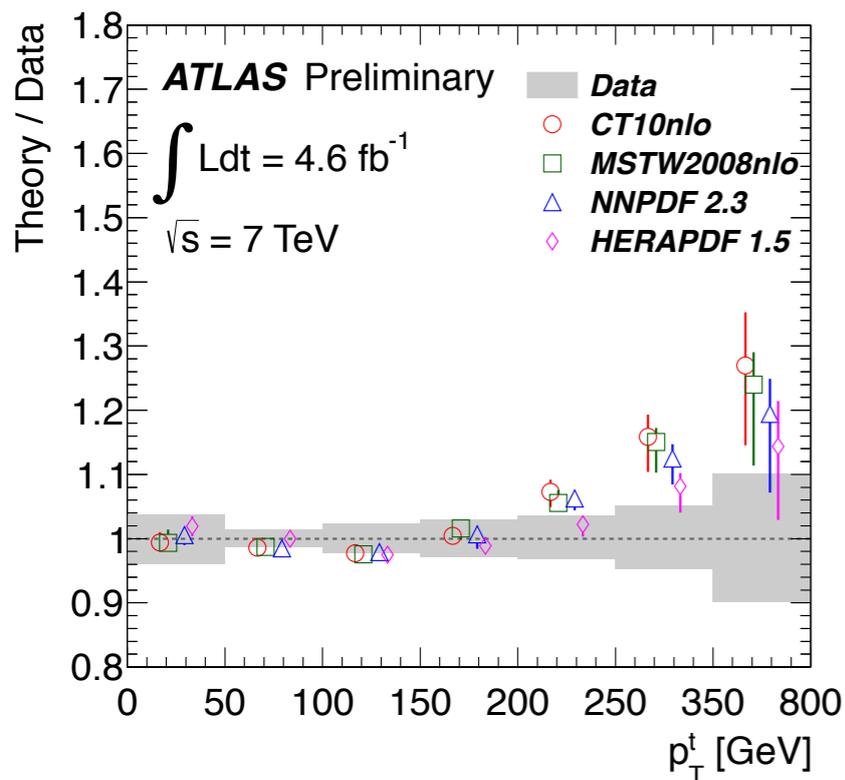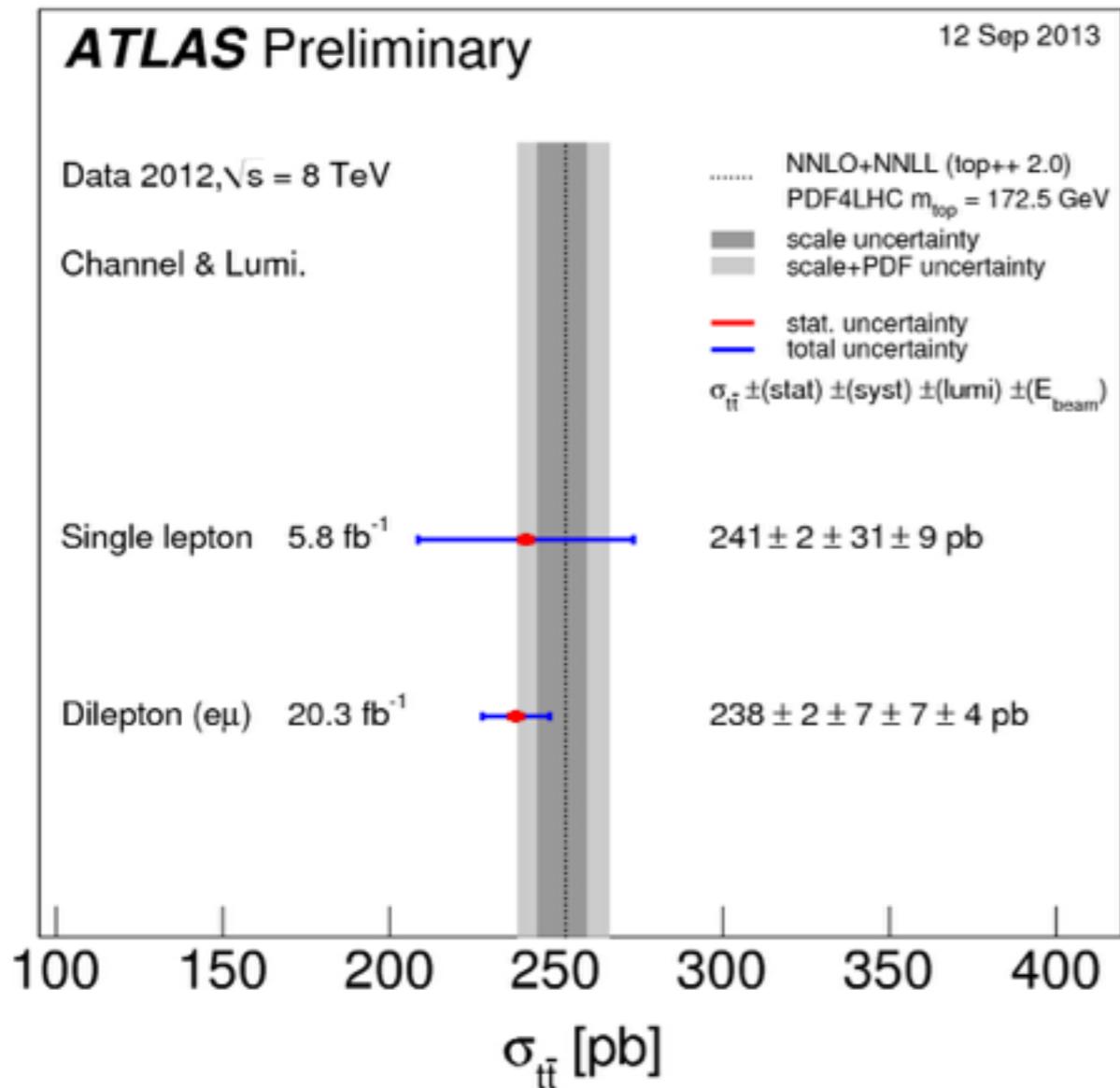
- The Top Quark Pair Cross-Section has been studied in various final states at both 7 and 8 TeV c.o.m. energy

- The most precise analyses are not limited by statistics but systematics in the few%-range

- Results are in agreement with SM predictions and some reach NNLO sensitivity

- differential cross-section measurements measured at 7 TeV.

  - generally good agreement

  - sensitivity to theory input observed (generator, PDF sets, etc.)

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BACKUP

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44m

25m

Tile calorimeters

LAr hadronic end-cap and forward calorimeters

Pixel detector

LAr electromagnetic calorimeters

Toroid magnets

Transition radiation tracker

Muon chambers

Solenoid magnet

Semiconductor tracker
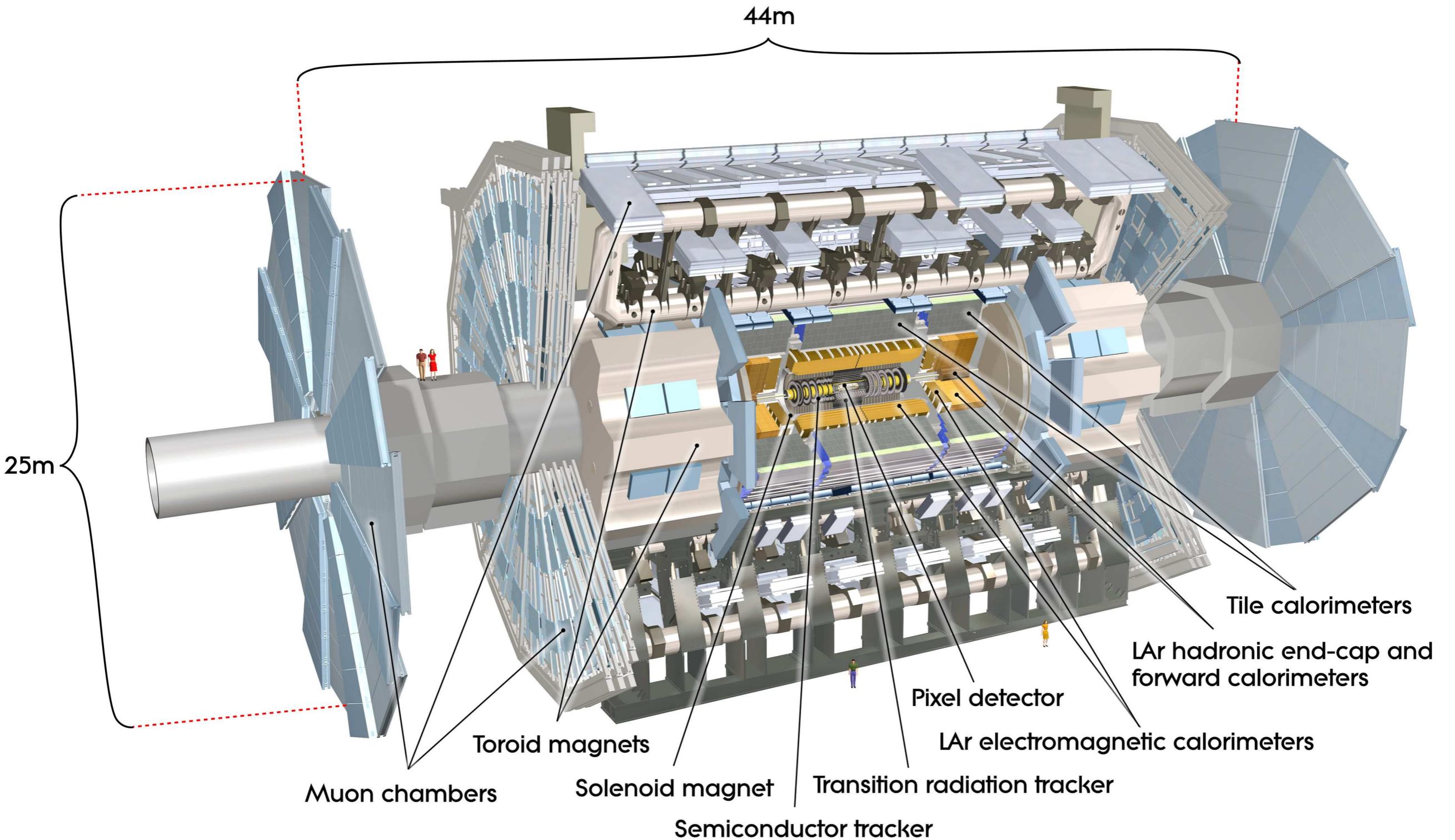
7 TeV all-hadronic 1.02/fb

- very challenging channel

- mapping of jets onto topology of top quark pairs -> kinematic fit.

- χ^2-distribution used as discriminating variable:

- templates from simulation, cross-section from binned template fit

- Main Systematics

  - JES, ISR/FSR, b-tagging

Event Selection

- no high-p_T muons or electrons
- one tau$_{had}$ candidate
- 5(6) jets p_T > 55(30) GeV
- 2 b-tagged jet
- $E_T^{miss} / \sqrt{H_T} < 3$

$$\chi^2 = \frac{\left(m_{j_1,j_2} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m_{j_1,j_2,b_1} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m_{j_3,j_4} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m_{j_3,j_4,b_2} - m_t\right)^2}{\sigma_t^2},$$

$\sigma_{t\bar{t}} = 167 \pm 18 \, (\text{stat.}) \pm 78 \, (\text{syst.}) \pm 6 \, (\text{lum.}) \, \text{pb}$

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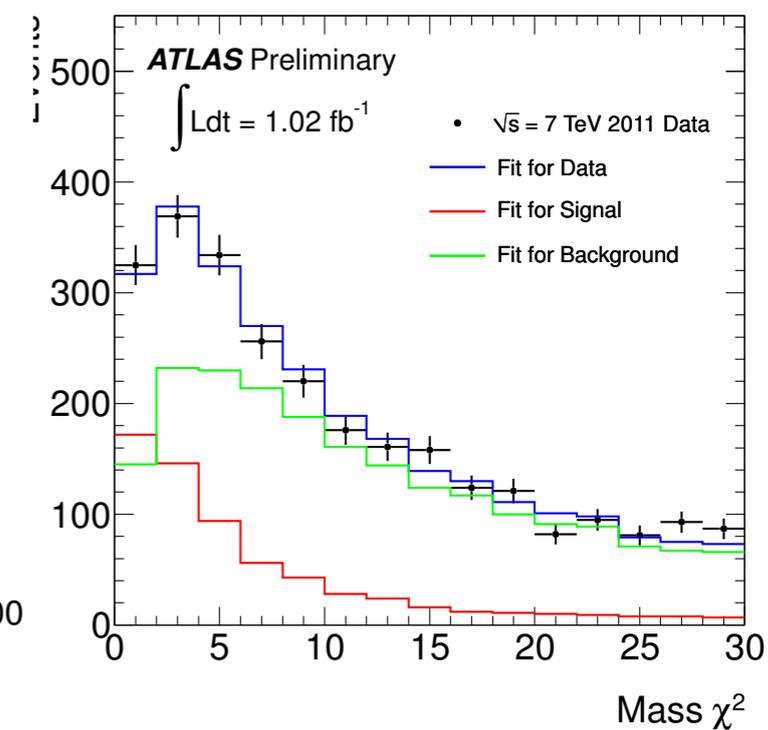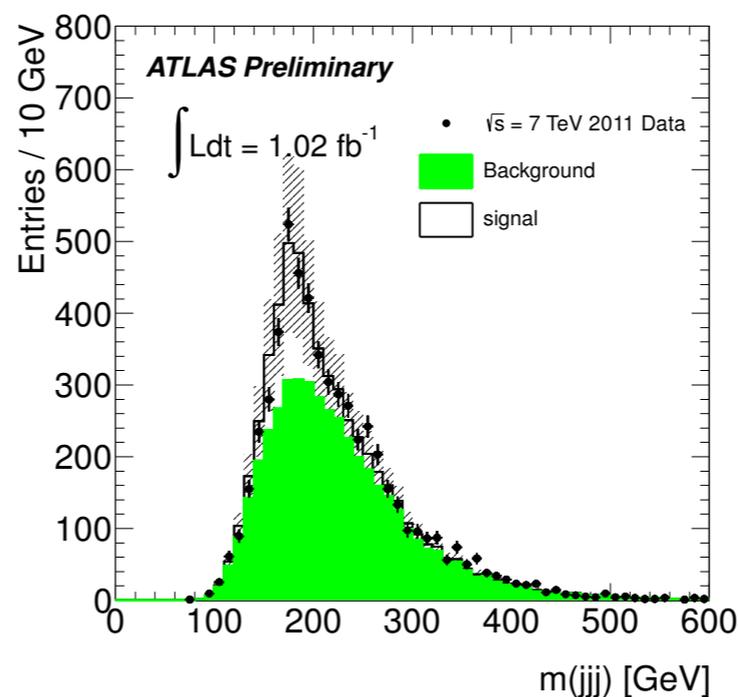
7 TeV tau+jets 1.67/fb

- hadronic tau decays

- tau candidate from particles to ttbar topology.

- Template Fit of number of tracks in tau-jet -> estimate on $N_{tt \to tau(\to had)+jets}$

- Cross-section from

$$\sigma_{t\bar{t}} = N_\tau / (\mathcal{L} \cdot \varepsilon).$$

- main systematics

  - ISR/FSR, Generator

$$194 \pm 18 (\text{stat.}) \pm 46 (\text{syst.}) \text{ pb}$$

Eur. Phys. J. C, 73 3 (2013) 2328 arXiv:1211.7205

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Event Selection

- 5 jets with $p_T > 20$ GeV
- at least 2 b-tagged jets
- MET significance $S_{MET} > 8$
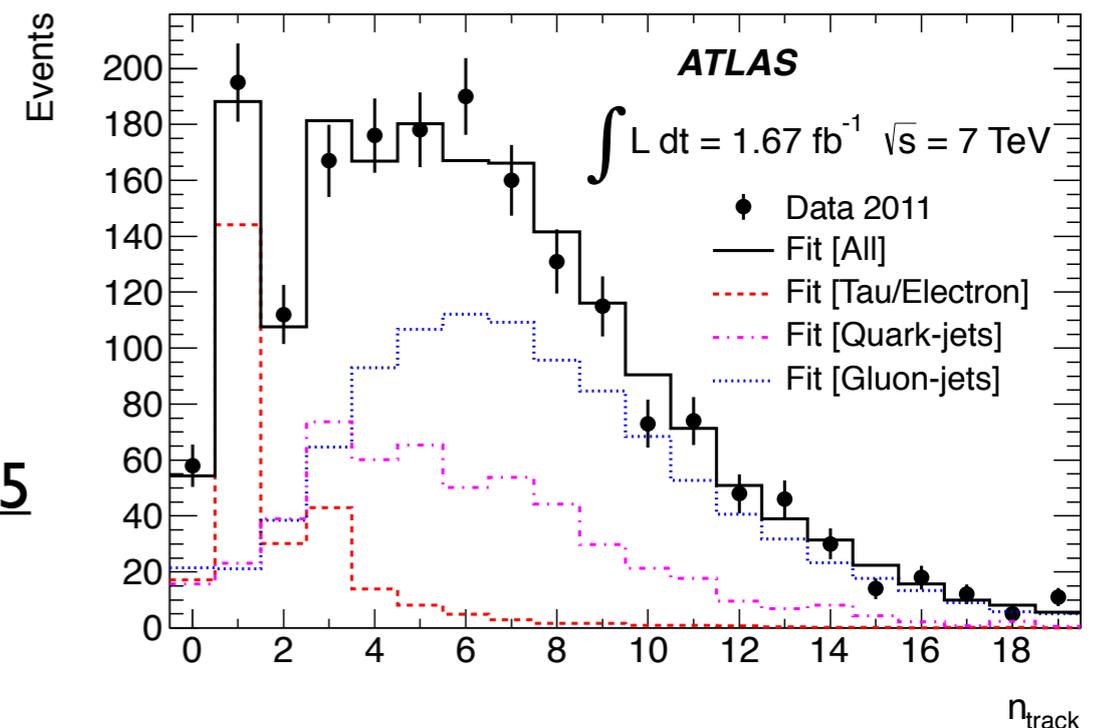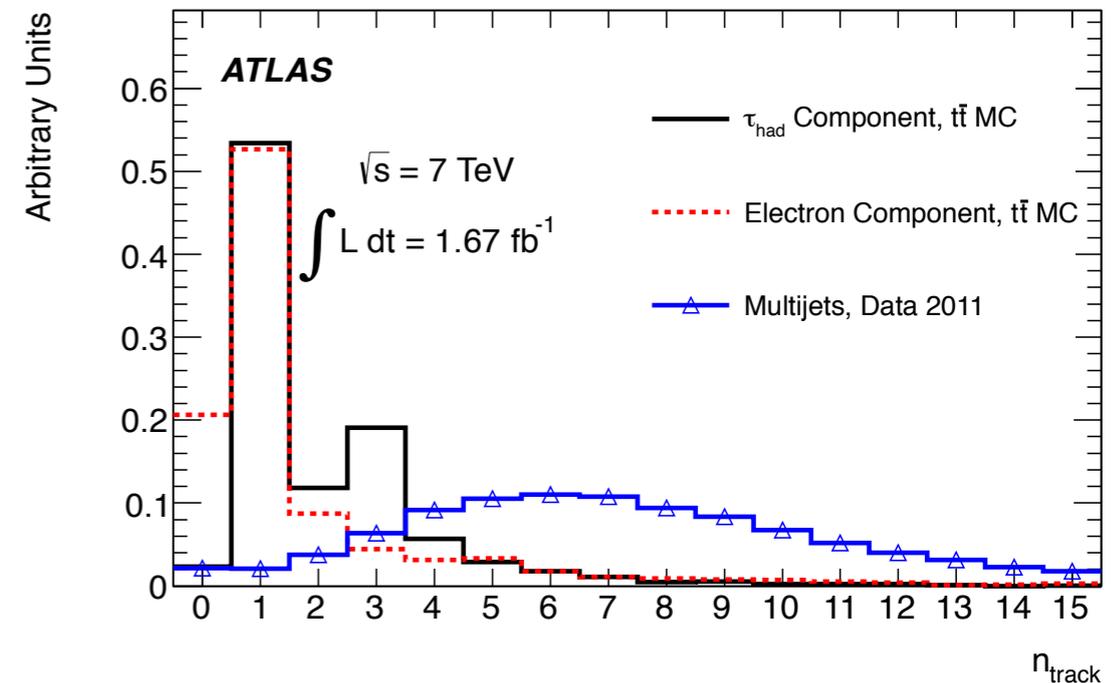
7 TeV tau$_{had}$+e(μ) 2.05/fb

Boosted Decision Tree (BDT) optimized to separate taus and jets (BDT$_j$) used.

Background shapes from control samples (no b-tags).

χ^2-fit to find signal contribution

Cross sections via $\sigma_{t\bar{t}} = N_\tau / (\mathcal{L} \cdot \varepsilon)$

Separate analyses for 1- and 3-prong tau decays. Afterwards: BLUE combination

Main systematic: b-tagging.

$\sigma_{t\bar{t}} = 186 \pm 13 \text{ (stat.)} \pm 20 \text{ (syst.)} \pm 7 \text{ (lumi.)}$ pb

Event Selection
- single e (>25 GeV) or mu (20 GeV)
- one tau$_{had}$ candidate
- two jets p$_T$ > 25 GeV w/o tau-overlap
- MET > 30 GeV
- 1 b-tagged jet

ATLAS+CMS Preliminary $\sigma_{t\bar{t}}$ summary, $\sqrt{s}$ = 7 TeV TOPLHCWG

.... NNLO+NNLL (top++ 2.0), PDF4LHC m_{top} = 172.5 GeV — stat. uncertainty
scale uncertainty — total uncertainty
scale ⊕ PDF ⊕ α_s uncertainty $\sigma_{t\bar{t}}$ ±(stat) ±(syst) ±(lumi)

ATLAS, l+jets $179 \pm 4 \pm 9 \pm 7$ pb L_{int}=0.7 fb⁻¹
ATLAS, dilepton $173 \pm 6 {}^{+14}_{-11} {}^{+8}_{-7}$ pb L_{int}=0.7 fb⁻¹
ATLAS, all jets (*) $167 \pm 18 \pm 78 \pm 6$ pb L_{int}=1.0 fb⁻¹
ATLAS combined $177 \pm 3 {}^{+8}_{-7} \pm 7$ pb L_{int}=0.7-1.0 fb⁻¹
CMS, l+jets (*) $164 \pm 3 \pm 12 \pm 7$ pb L_{int}=0.8-1.1 fb⁻¹
CMS, dilepton (*) $170 \pm 4 \pm 16 \pm 8$ pb L_{int}=1.1 fb⁻¹
CMS, τ_{had}+μ (*) $149 \pm 24 \pm 26 \pm 9$ pb L_{int}=1.1 fb⁻¹
CMS, all jets (*) $136 \pm 20 \pm 40 \pm 8$ pb L_{int}=1.1 fb⁻¹
CMS combined $166 \pm 2 \pm 11 \pm 8$ pb L_{int}=0.8-1.1 fb⁻¹
LHC combined (Sep 2012) $173 \pm 2 \pm 8 \pm 6$ pb L_{int}=0.7-1.1 fb⁻¹

ATLAS, l+jets, b→Xμν $165 \pm 2 \pm 17 \pm 3$ pb L_{int}=4.7 fb⁻¹
ATLAS, τ_{had}+l $186 \pm 13 \pm 20 \pm 7$ pb L_{int}=2.1 fb⁻¹
ATLAS, τ_{had}+jets $194 \pm 18 \pm 46$ pb L_{int}=1.7 fb⁻¹
ATLAS, all jets $168 \pm 12 {}^{+60}_{-57} \pm 7$ pb L_{int}=4.7 fb⁻¹
CMS, l+jets $158 \pm 2 \pm 10 \pm 4$ pb L_{int}=2.2-2.3 fb⁻¹
CMS, dilepton $162 \pm 2 \pm 5 \pm 4$ pb L_{int}=2.3 fb⁻¹
CMS, τ_{had}+l $143 \pm 14 \pm 22 \pm 3$ pb L_{int}=2.2 fb⁻¹
CMS, τ_{had}+jets $152 \pm 12 \pm 32 \pm 3$ pb L_{int}=3.9 fb⁻¹
CMS, all jets $139 \pm 10 \pm 26 \pm 3$ pb L_{int}=3.5 fb⁻¹

(*) Superseded by results shown below the line

50 100 150 200 250 300 350

$\sigma_{t\bar{t}}$ [pb]

NEW

- aplanarity:
  eigenvector of
$$M_{ij} = \frac{\sum_{k=1}^{N'_{\text{objects}}} p_{ik} p_{jk}}{\sum_{k=1}^{N'_{\text{objects}}} p_k^2},$$

- transverse mass:
$$m_T(W) = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

- H_T: scalar p_T sum of all objects + MET