Top quark production with the ATLAS detector at LHC

Les Rencontres de Physique de la Vallée d'Aoste LaThuile /23rd February-1st March 2014

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LHC & ATLAS



 Single top production



(On behalf of the ATLAS collaboration)

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Top quark production @ ATLAS





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Inclusive $\sigma_{t\bar{t}}$: dilepton - $\sqrt{s} = 8 \text{ TeV}$

- Require opposite sign (OS) eµ
- Bkg: single top (Wt) (from simul.), data-driven fake leptons (extrapol. from same sign lep. sample), Z+jets (extrapol. from Z→μμ sample)



$$N_{1} = L\sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_{b}(1 - C_{b}\epsilon_{b}) + N_{1}^{bkg}$$
$$N_{2} = L\sigma_{t\bar{t}} \epsilon_{e\mu} C_{b}\epsilon_{b}^{2} + N_{2}^{bkg}$$

• **"External" Syst dominated:** *Lumi* ~3.1%, *E_b*~1.7%, *tt modelling* ~1.5% *Elec. ID/isol* ~1.4%

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

 $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 4.8\%$



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Inclusive $\sigma_{t\bar{t}}$ - Summary at $\sqrt{s} = 7 \& 8 \text{ TeV}$



 $\sigma_{t\bar{t}} = 173.3 \pm 2.3 \text{ (stat.)} \pm 7.6 \text{ (syst.)} \pm 6.3 \text{ (lumi.) pb} \qquad \frac{\text{ATLAS-CONF-2012-134}}{\text{CMS-PAS-TOP-12-003}}$

 $\delta \sigma_{t\bar{t}} / \sigma_{t\bar{t}} \sim 5.8\%$

Systematics dominated, comparable to theory uncertainty

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Differential $d\sigma_{t\bar{t}}/dX$: I+jets $\sqrt{s} = 7$ TeV qqℓvbb

ATLAS-CONF-2013-099

- 1 isol. (e, μ), symmetric E_T and m_T^W cuts, \geq 4 central jets, \geq 1 b-tag
- Data-driven W+jets (normalize pre-tag with W+/Wasymmetry, extrapol. b-tag prob from 2-jet-bin) fake lep. (loose/tight matrix method), single top, dibosons (from sim.)
- Reconstruct tt with kinematic likel. fit $(m_t, m_W \text{ constraint}) \rightarrow \text{cut on quality of kine fit}$
- Unfold d(N-N_{bkg})/dX to full phase space (regularized unfolding, linearity tests), scale with L and $\sigma_{t\bar{t}} \rightarrow 1/\sigma_{t\bar{t}} d\sigma_{t\bar{t}}/dX$

- Combine (e,µ)+jets channels with minimal covariance estimator (BLUE) including correlations
 - Propagate syst uncertainties through unfolding: modify migration matrix & acceptances, fix data



Differential $d\sigma_{t\bar{t}}/dX$: I+jets $\sqrt{s} = 7$ TeV

$\int Ldt = 4.7 \, \text{fb}^{-1} \, (2011)$

• Syst dominated: <7% for $y_{t\bar{t}}$, 10-20% $p_{\tau,t\bar{t}}$, 2% to 11% for $p_{\tau,top}$, 3% to 6% $m_{t\bar{t}}$,



Inclusive σ_t , $\sigma_t \& \sigma_{\bar{t}}$: t-chan $\sqrt{s} = 7$ TeV

- 1 isol. lep (e or μ), 2 or 3 jets with |η|<4.5, E^{miss} cut, large m_T(W)*→ fake lep. veto, 1 b-tag
- Bkg: simulated tt/Wt/s-chan, W/Z+jets, data-driven fake lep (el-like jet template normalized with E^{miss} fit)

Phys. Lett B 717(2012) 330

 $\int Ldt = 1.04 \, \text{fb}^{-1} (2011)$

ATLAS-CONF-2012-056

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 Extract σ_{t, total} by binned max. likelihood fit of standard Neural Network distribution to data in 2-& 3-jet bins (12 and 18 kin. vars: jet-lep masses, jet y, E_T)

syst dominated
I/FSR~9%,
JES~7%, *b-tag*

$$|V_{tb}| = 1.13^{+0.14}_{-0.13}$$

$$\delta \sigma_t / \sigma_t \sim 24\%$$

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syst dominated JES~16%, $\sigma_t(t) = 53.2 \pm 1.7 \text{ (stat.)} \pm 10.6 \text{ (syst.) pb}$ b-tag, generator $\sigma_t(\bar{t}) = 29.5 \pm 1.5 \text{ (stat.)} \pm 7.3 \text{ (syst.) pb}$

 $\delta \sigma t / \sigma t$ $\sim 25\%$ ATLAS Preliminary $\int L dt = 4.7 \text{ fb}^{-1} \text{ /s} = 7 \text{ TeV}$ data t - channel (top) s - channel (top) t - channel (top) s - channel (top) t - channel (top) s - channel (top) t - channel (top)t - channel (t

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0.6

0.4

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data

t-channel

W+light jets

tt.Wt.s-channel W+heavy flavour

Z+jets, diboson QCD multijet

ZZZ QCD + MC stat unc.

0.8

NN output

2.1

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Inclusive σ_t - Summary at $\sqrt{s} = 7 \& 8 \text{ TeV}$



• First ATLAS + CMS combination at $\sqrt{s} = 8$ TeV !

 $\sigma_{\text{t-ch.}} = 85 \pm 4 \,(\text{stat.}) \pm 11 \,(\text{syst.}) \pm 3 \,(\text{lumi.}) \,\text{pb}$ $\int \mathcal{L} dt = 5.8 \,(5.0) \,\text{fb}^{-1} \,(2012)$

ATLAS-CONF-2013-098 CMS-PAS-TOP-12-002

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Conclusions & Outlook

- Top quark physics analysis is in full swing thanks to the combined performance of LHC & detectors: a very rich program is well under way.
- By exploiting the LHC top quark factory **ATLAS** is testing top quark strong and electroweak inclusive production at unprecedented precisions
 - δσ_{tī}/σ_{tī} down to 4.8% compared to ~4% prediction uncertainty (NNLO+NNLL)
 - δσt/σt ~19% to 25% for t and Wt channel: still space for improvement and for s-channel observation
- Differential cross sections measurements test SM tt production and complement new physics searches in completely new phase space with 10%-20%% relative uncertainties.
- Stay tuned for more upcoming inclusive and differential results from RUN1!
- Look forward to Run 2 @ \sqrt{s} =13 TeV: uncharted kinematic phase space to be explored with ~factor 3 enhanced cross section
 - higher precision inclusive, exclusive ($t\bar{t}+X$) and differential cross section
 - fiducial measurements

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ollisions at LHC



Proton-Proton 2835 bunch/beam Protons/bunch $10^{10} 1 N_2 n_b$ Beam energy \propto 7 TeV (7x10¹² eV) $E_{cm}(Tev nit(sity) = 1, 90\% cme(s^{1/2})$





Selection of 1 in 10,000,000,000,000

 peak instantaneous luminosity:2.1 10³² cm⁻²s⁻¹

 delivered integrated luminosity~50 pb⁻¹ C : a Top producer ty proton bunches colliding at center of mass r √s) = 7 TeV in 27 Km tunnel

design: Ecm=14TeV, lumi 10³⁴cm⁻² s⁻¹ (~30 times Tevatron pp collider) RUN2 (start) 2015 Ecm = 13 IeV at start (14 to be decided later) peak lumi: 1.6 · 10³⁴ cm⁻² s⁻¹ ± 20% (Ldt -40-45 fb⁻¹ /exp per year RUN1

2012 E_{cm} =8 TeV peak lumi: 7.7 · 10³³ cm [Ldt -22 fb⁻¹ /exp

2011 E_{cm} =7 TeV peak lumi 2.10³³ cm⁻² s

[Ldt ~5.6 fb⁻¹/exp

 $N_{events}(\Delta t) = \int Ldt * cross section$

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Backgrounds estimates (single lepton+jets)



Backgrounds (di-lepton)

- Fake leptons : generalized single lepton
 - Get probability for loose "fake" and real leptons to be in signal region ← control samples enriched with real (in Z window) or "fake" (low ET^{miss}) leptons
 - Combine with N(di-lep) for all loose/tight pairs→fake tight (i.e. signal) lep





ATLAS-CONF-2011-100

 Z/γ* bkg (ee, μμ) : scale non-Z/γ*-bkgsubtracted data in Z-mass window control region with ratio of N(Z/γ*) in signal region to control region from simul.

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Inclusive $\sigma_{t\bar{t}}$ - LHC at $\sqrt{s} = 7$ TeV



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Inclusive $\sigma_{t\bar{t}}$ vs \sqrt{s} : from Tevatron to LHC

Inclusive tt cross section [pb]



Overall good agreement with predictions

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Inclusive $\sigma_{tt+heavy flavour}$:dilepton - $\sqrt{s} = \text{TeV}^{\int Ldt} \sim 4.7 \text{ fb}^{-1}$ (2011)



Large sensitivity to fraction of tt+b+X Large uncertainty on fraction of tt+b+X

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Jet shapes in dilepton and ℓ +jets $\sqrt{s} = 7 \text{ TeV}$ [Lat = 1.8 fb⁻¹ (2011)

ATLAS $\sqrt{s} = 7 \text{ TeV}$

30 GeV < p_ < 40 Ge

0.05

@ NLO/Da

L dt = 1.8 fb

MC@NLO+Herwia

PowHeg+Pythia

MC@NLO+Herwig

PowHeg+Pythia

b-jets (R = 0.4)

light jets (R = 0.4)

A

✓ Data (stat ⊕ sys)



- standard bkg estimates
- **Define** isolated (no other jet within DR=0.8), JVF>0.75 **b-jets** & light jets (non-b-tagged jet pair with m(jj) closest to *m_W*) **samples**
- Correct dX/dr to fiducial phase space in five p_T bins (30 GeV to 150 GeV)

 $<\rho(\mathbf{r})> = 1/\Delta \mathbf{r} < \sum \mathbf{p}_{\mathsf{T}}$ (clusters in Δr)/ $\sum p_T$ (all clusters)>_{jets}

X= $\langle \Psi(\mathbf{r}) \rangle = \langle \sum p_T \rangle$ (clusters **up to r**)/ $\sum p_T$ (all clusters)>_{jets}

• Syst dominated: JES (2 to 8%), cluster en. (2 to 10%), pile-up (2 to 10%)

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R



Eur. Phys. J. C. (2013) 73:2676

jets larger t

and low p_T

ATLAS $|\sqrt{s} = 7 \text{ Te}$

0.2

Ψ (r)

in₆b- jets at b-jets

[⊥] dt**≠Ψ**(r)>

Data (stat 🕀 sy

MC@NLO+Her

PowHeg+Pythia

Data (stat

system) MC@NLO+Her

PowHeg+Pythia

light jets (R = 0.4)

Differential $dN_{t\bar{t}}/dN_{jets}$: I+jets $\sqrt{s} = 7$ TeV Unfolding and corrections

$$\vec{N}_{\text{part}} = \vec{f}_{\text{part!reco}} \cdot \mathbf{M}_{\text{part}}^{\text{reco}} \cdot \vec{f}_{\text{reco!part}} \cdot \vec{f}_{\text{accpt}} \cdot (\vec{N}_{\text{reco}} - \vec{f}_{\text{bgnd}})$$



ATLAS Week

Results: ATLAS & CMS (7 TeV, l+jets) – p_T(top)





- Powheg+Herwig describes ATLAS & CMS data reasonably well over the full p_{T} range
- p_τ(top) < 200 GeV: disagreement btw ATLAS & CMS</p>
 - CMS: softer spectrum in data, best described by Approx. NNLO
 - ATLAS: disagreement with Approx. NNLO
- CMS: Similar behaviour for dileptons, both at 7 & 8 TeV

TOPLHCWG, 28.11.13

session 28-29th Nov. 2013

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Top quark production @ ATLAS

Results: ATLAS & CMS (7 TeV, *l*+jets) – p_T(top) <u> </u>

First attempt at direct data comparison: data/NLO prediction (MCFM)



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Top quark production @ ATLAS

Inclusive σ_t : Wt-channel $-\sqrt{s} = 7$ TeV $\int Ldt = 2.05 \text{ fb}^{-1} (20)$

Phy.Lett. B 716 (2012) 142-159

- OS leptons (e or μ), ≥1 central high p_T jet, E_T^{miss}
 > 50 GeV, (ee/μμ) veto Z-lke (mass window), cut on ∑Δφ(lep, E_T^{miss}) ← veto Z→ττ
- Bkg: simulated $t\bar{t}$, diboson, data-driven $Z \rightarrow ee/\mu\mu$ (extrapol. low ($E_{\tau^{miss}}, M(\ell\ell)$) plane), $Z \rightarrow \tau\tau$ (extrapol from bkg region) fake dilept. (matrix method)
- Extract σ_{Wt} by simultaneous binned max. likelihood fit of Boosted Decision Tree outputs in 1-jet, 2-jet, ≥3-jet bin (22 kine. vars) constraining syst as nuisance pars

 $\sigma_{Wt} = 16.8 \pm 2.9 \text{ (stat)} \pm 4.9 \text{ (syst) pb}$

significance: 3.3 **s.d.**

δσwt/σwt ~34%

• **Syst dominated:** JES~16%, parton shower 15%, generator 10%

• Assuming $|V_{tb}| >> |V_{ts}|$, $|V_{td}|$ determine V_{tb} ← ratio of measured to predicted σ_t $|V_{tb}| = 1.03^{+0.16}_{-0.19}$

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Top quark production @ ATLAS



Inclusive σ_t : t-chan $\sqrt{s} = 7$ TeV

Phys. Lett B 717(2012) 330

- 1 isol. lep (e or μ), 2 or 3 jets with |η|<4.5, E^{miss} cut, large m_T(W)*→ fake lep. veto, 1 b-tag
- Bkg: simulated tt/Wt/s-chan, W/Z+jets, data-driven fake lep (electron-like jet template normalized with E^{miss} fit)
- Extract σ_t and bkg norm by binned max. likelihood fit of Neural Network (NN) distribution to data in 2- & 3-jet bins (12 and support 18 kin. vars: jet-lep masses, jet rapidities, E_T)

$$\sigma_t = 83 \pm 4 \,(\text{stat.})^{+20}_{-19} \,(\text{syst.}) \,\text{pb}: \, \delta\sigma_t/\sigma_t \sim 24\%$$

- Dominated by syst.(I/FSR~14%,,b-tag eff~13%JES~7%)
- Assuming |V_{tb}| >> |V_{ts}|, |V_{td}| determine V_{tb} ← ratio of measured to predicted σ_t

$$|V_{tb}| = 1.13^{+0.14}_{-0.13}$$

If $|V_{tb}| < 1$ $|V_{tb}| > 0.75$ at 95%CL

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Top quark production @ ATLAS







band from MC stat+fakes uncert.

*
$$m_{\rm T}(W) = \sqrt{2p_T(\ell)E_{\rm T}^{\rm miss}\left[1 - \cos\Delta\phi\left(\ell, E_{\rm T}^{\rm miss}\right)\right]}$$

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Ratio of $\sigma_t / \sigma_{\bar{t}}$: t-chan $\sqrt{s} = 7$ TeV $\int Ldt = 4.7 \, \text{fb}^{-1} (2011)$

- 1 isol. lep (e or μ), 2 or 3 jets with $|\eta| < 4.5$, E_T^{miss} cut, large $m_T(W)^* \rightarrow$ fake lep. veto, 1 b-tag
- Bkg: simulated tt/Wt/s-chan, W/Z+jets, data-driven **fake lep** (electron-like jet template normalized with E_T^{miss} fit)
- **Extract** σ_t and σ_{anti-t} by binned max. likelihood fit of standard NN distribution to data in 2- & 3-jet bin with pos and neg lep (e,µ)

syst dominated JES~16%, b-tag,generator

Events

 $\delta \sigma_t / \sigma_t$ $\sigma_t(t) = 53.2 \pm 1.7 \text{ (stat.)} \pm 10.6 \text{ (syst.) pb}$ ~20% $\sigma_t(\bar{t}) = 29.5 \pm 1.5 \text{ (stat.)} \pm 7.3 \text{ (syst.) pb}$ ~25%



ATLAS-CONF-2012-056



Single top Combination @ 8 TeV ATLAS & CMS

| Source | Uncertainty (pb) |
|--------------------------------|------------------|
| Statistics | 4.1 |
| Luminosity | 3.4 |
| Simulation and modelling | 7.7 |
| Jets | 4.5 |
| Backgrounds | 3.2 |
| Detector modelling | 5.5 |
| Total systematics (excl. lumi) | 11.0 |
| Total systematics (incl. lumi) | 11.5 |
| Total uncertainty | 12.2 |

ATLAS+CMS Preliminary, $\sqrt{s} = 8 \text{ TeV}$



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