Top-quark properties with the ATLAS detector at the LHC

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on behalf of the ATLAS collaboration

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ATLAS EXPERIMENT

EXCELENCIA SEVERO OCHOA

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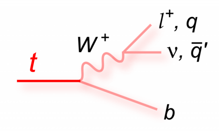
Introduction

The top-quark was

- introduced in 1973 to explain weak CP violation
- discovered in 1995 (CDF and D0 at Tevatron)

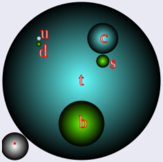
The LHC is a top-quark factory ⟶ See Shunshuke's talk on top-quark production!

Decay before hadronizing



⟶ Only chance to study a (almost) free quark

Heaviest particle discovered



⟶ Strongly impact electro-weak vacuum stability, BSM scenarios

Top-quark properties

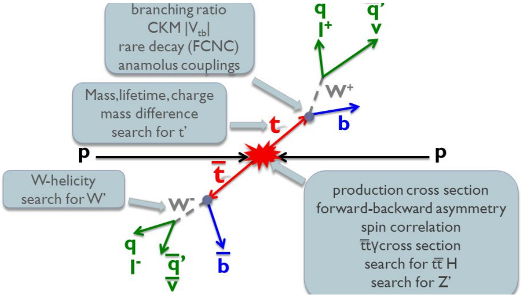
Properties:

- charge
- mass
- width
- spin
- couplings
- ... and more

$\longrightarrow$

Top-quark related free parameters:

- in the SM:
  - top-quark mass, m_t
  - three CKM matrix elements: V_{tu}, V_{tc}, V_{tb}
- in BSM scenarios:
  - couplings to new particles
  - new couplings to SM particles



Lots of different topics and analyses !

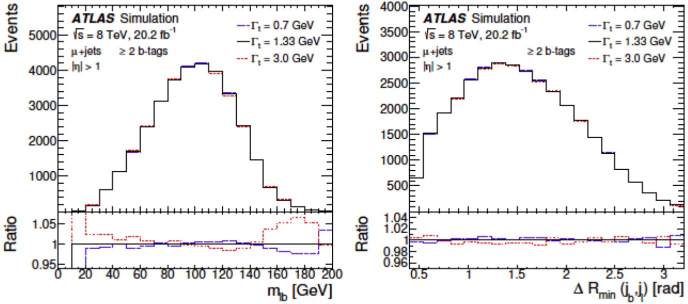
Only a selection of the most recent results reported here:
latest high precision SM results (8TeV) and searches (13TeV)

Decay width

EPJC 78 (2018) 129

ATLAS measured directly the decay width of the top quark:

- $t\bar{t}$ events, semileptonic final state, 8 TeV data
- Direct measurement less precise than indirect ones (top-quark mass spectrum experimental resolution)
- Combine m_{lb} (good sensitivity, smaller jet systematics) and $\Delta R_{\min}(j_b, j_l)$ (information on hadronic top)
- Important $t\bar{t}$ system reconstruction (Kinematic Likelihood)



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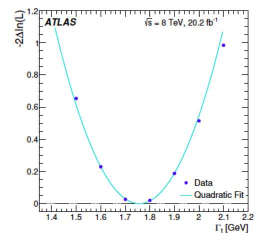
From a template fit (54 templates generated):

$$\Gamma_t = 1.76 \pm 0.33\ (\text{stat.})\ ^{+0.79}_{-0.68}\ (\text{syst.})\ \text{GeV}$$

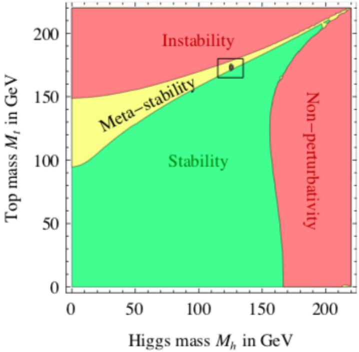
compatible with SM: expected $\Gamma_t = 1.32$ GeV
for a top-quark with mass of 172.5 GeV

Main errors (0.3-0.4 GeV each):
stat, jet scale/resolution, *b*-tag, hard generator

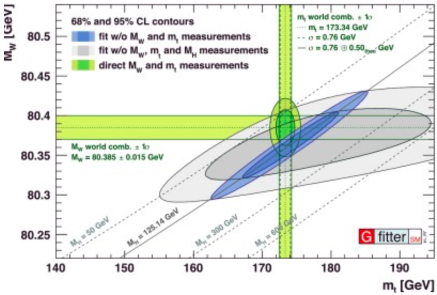


Mass

- top-quark mass is a free parameter of the SM
- important in SM checks, BSM theories and stability of EW vacuum



JHEP 08(2012)098



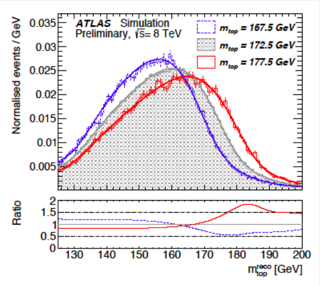
JHEP 12(2013)084

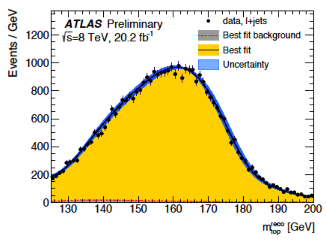
- Measurements reaching $\lesssim$ 1GeV exp. precision.
- Theoretical aspects become important: m_t is
  - a Lagrangian parameter (depends on re-normalisation scheme)
  - is not the mass implemented in Monte Carlo (m_t^{MC}) programs
    $\Delta(m_t^{\text{pole}} - m_t^{MC}) \lesssim$ 1GeV (PRD 77 (2008) 074010)

Direct measurements compare data to a template of MC simulations.
Template fit determines best m_t^{MC} value to describe data.

- m_t inferred from decay products
- $t\bar{t}$ and single-t, 7 and 8 TeV data, all-hadronic/semileptonic/dileptonic
- typically most precise m_t experimental results
- leading errors: jet energy scale and MC modelling

latest m_t^{MC} measurement uses l+jets channel at 8 TeV (ATLAS-CONF-2017-071)





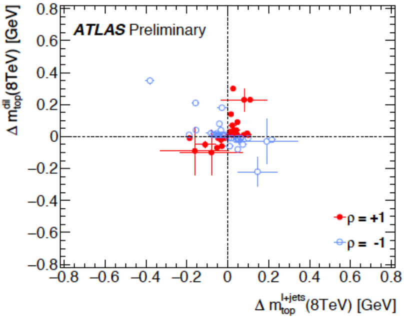
$$m_t^{MC} = 172.08 \pm 0.91(\text{stat}\oplus\text{syst})\ \text{GeV}$$

Direct top-quark mass combination

ATLAS-CONF-2017-071

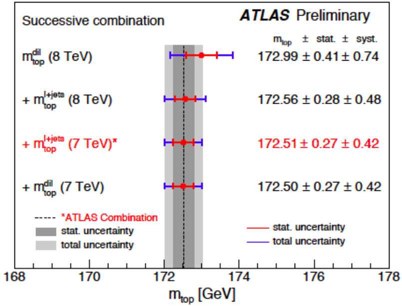
Various measurements at 7 and 8 TeV have been combined.
Correlations between measurements can reduce total uncertainty!

One point correspond to one systematic



Negative correlations reduce error!

l+jets and dilep combined at 7 and 8 TeV



Latest ATLAS combination of direct mass measurement:

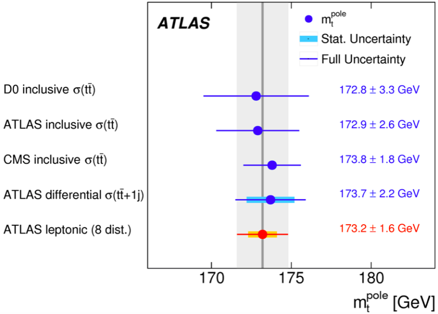
$$\sigma_{\text{exp}}(m_t^{MC}) \sim 0.5 \text{ GeV}$$

Top-quark mass from cross sections

EPJC 77 (2017) 804

Cross-section m_t measurements compare data to perturbative calculations.
$\sigma_{t\bar{t}}^{\mathrm{NNLO}}(m_t)$ and $\mathrm{d}\sigma_{t\bar{t}}^{\mathrm{NLO}}/\mathrm{dX}(m_t)$ continuously parametrised

- theoretically well defined m_t (can estimate theoretical errors)
- inclusive σ has low sensitivity, but $\mathrm{d}\sigma/\mathrm{dX}$ has higher
- unfolding to fiducial volume



Latest result from $t\bar{t}$ fiducial differential cross sections (EPJC 77 (2017) 804):

- $e^{\pm}\mu^{\mp}$+jets events at 8 TeV
- 8 fiducial distributions combined in fit
- $\sim$competitive with direct measurements (largest errors: stat. and bkgs):

$$m_t^{\mathrm{pole}} = 173.2 \pm 0.9\ \text{(stat)} \pm 0.8\ \text{(syst)} \pm 1.2\text{(theo) GeV}$$

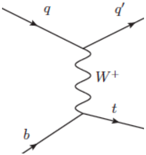
most precise m_t^{pole} measurement to date!

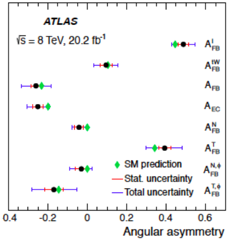
 JHEP 12 (2017) 017 - JHEP 04 (2017) 124

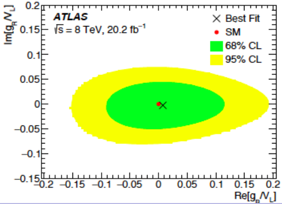
The *Wtb* interaction vertex controls the single-t production.

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,t W^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)\,t W^{-}_{\mu} + \text{h.c.}$$

in the SM: $V_L = V_{tb}$, while other couplings vanish







Measurements target t-channel production mode, leptonic top decay, using 8 TeV data:

- one lepton, missing energy, ==2 jets (one b-tag)
- angular asymmetries (JHEP 04 (2017) 124)
  - unfolded to parton level
- triple-differential decay rate (JHEP 12 (2017) 017)
  - simultaneous fits, no assumptions
  - limits set for all parameters

Results in agreement with SM

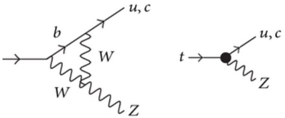
95% CL limits on g_R:
$\text{Im}\{g_R\} \in [-0.18, 0.06]$ (with V_L=1, $V_R = g_L = \text{Re}\{g_R\} = 0$)
$\text{Im}\{g_R/V_L\} \in [-0.07, 0.06]$, $\text{Re}\{g_R/V_L\} \in [-0.12, 0.17]$

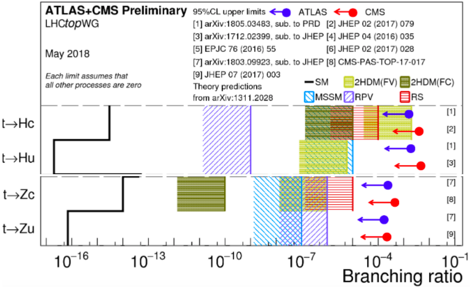
Flavour Changing Neutral Currents

Flavour-changing neutral currents (FCNC) are predicted to be experimentally unobservable in the SM
Evidence for FCNC is unambiguous sign of new physics.

With 13 TeV data, ATLAS looked for

- $t \to Hc$ and $t \to Hu$ with:
  $H \to VV, \tau_{\rm lep}\tau_{\rm lep}$ New! arXiv:1805.03483
  $H \to \gamma\gamma$ JHEP10 (2017) 129
- $t \to Zc$ and $t \to Zu$.
  New! arXiv:1803.09923





Limits can be set on effective couplings.
in the FCNCTop framework (PRD 91 (2015) 074017) $\longrightarrow$ coefficients $C^{(t\ ,\ {u \atop c})}_{u\ ,\ {\phi \atop B/W}}$

FCNC - $t \to Hq$ at 13 TeV

arXiv:1805.03483

Various analyses carried out, distinguished by H decay mode

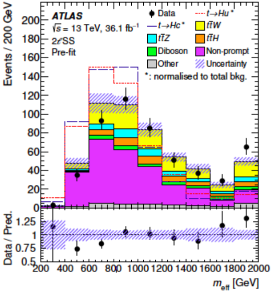
- $t\bar{t} \to HqWb \to WWqWb$ like event selection
- Multileptonic final states:
    - 2 leptons with same sign (2lSS)
    - at least four jets, one or two b-tagged
    - no hadronic τ candidates

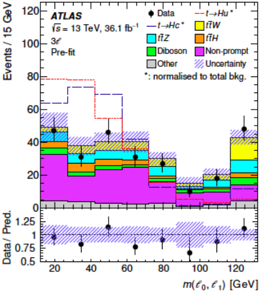
  or

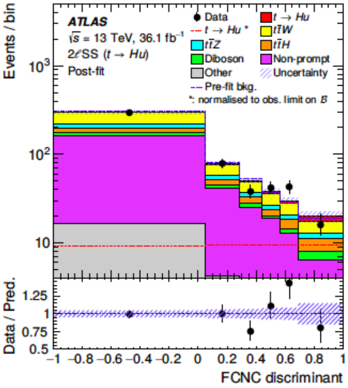
    - 3 leptons (3l)
    - at least two jets, at least one b-tagged
    - lepton pairs invariant mass cuts (hadrons and Z decay and $t\bar{t}Z$ bkgs)
- Signal composition:

  $\sim$80% $H \to WW$, $\sim$15% $H \to \tau\tau$, $\sim$5% $H \to ZZ$
- Boosted decision trees (BDT)

  11(16) variables for 2lSS (3l)



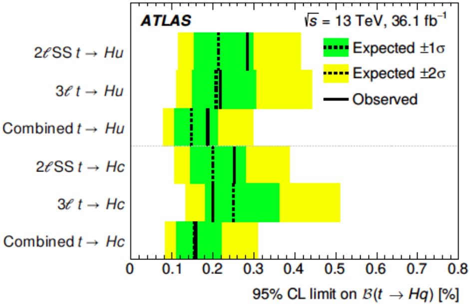




← BDT example in 2*l*SS, $t \to Hu$

channel-by-channel limits on BRs

↓



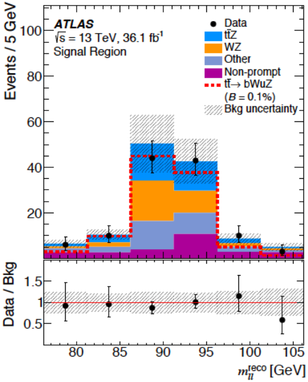
No $t \to Hq$ signal observed.

Limits at 95% CL:

$\mathcal{B}(t \to Hu) < 0.19\%$ (stat + syst)

$\mathcal{B}(t \to Hc) < 0.16\%$ (stat + syst)

- $t\bar{t} \to ZqWb \to l_1 l_2 q l_3 \nu b$ selection
  - exactly 3 leptons
  - at least two jets, exactly one *b*-tagged
  - missing energy
  - system reconstruction with likelihood
  - cuts on invariant masses of top-quarks and *W* boson candidates
- Main bkgs: VV, $t\bar{t}Z$, tZ, non-prompt leptons.
- Data driven bkg estimation with 5 control regions reduce systematics.



No $t \to Zq$ observed

Limits at 95% CL:
$\mathcal{B}(t \to Zu) < 0.017\%$ (stat + syst)
$\mathcal{B}(t \to Zc) < 0.024\%$ (stat + syst)

Most stringent limits to date!

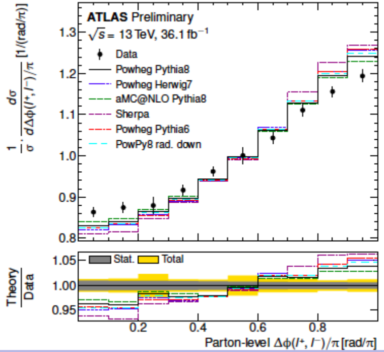
$\longrightarrow$

Limits on effective coupling set:
$C_{u\ B/W}^{(tu)} < 0.25$ (stat + syst)
$C_{u\ B/W}^{(tc)} < 0.30$ (stat + syst)

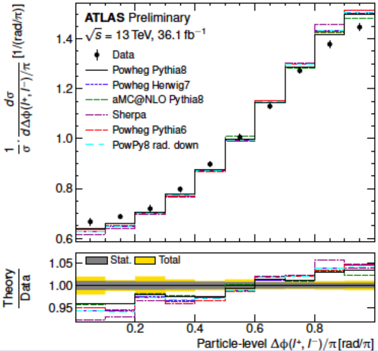
 ATLAS-CONF-2018-027

The spin information of the top-quark is passed directly to its decay products.
($\Gamma_t \sim 5 \cdot 10^{-25} s < \tau_{\text{hadronization}} \sim 10^{-23} s <$ spin decorrelation time $10^{-21} s$)
In $t\bar{t}$ events top-quark spins are correlated in the SM

- most recent result from ATLAS uses 36.1 fb^{-1} of 13 TeV data
- $e^{\pm}\mu^{\mp}$+jets final state
- differential cross section as function of $\Delta\phi = \Delta\phi(e^{\pm}, \mu^{\mp})$
- four $m_{t\bar{t}}$ intervals and inclusive : $[0, 450, 550, 800, \infty]$ (GeV)
- unfolding to parton and particle level



PARTON LEVEL



PARTICLE LEVEL

 ATLAS-CONF-2018-027

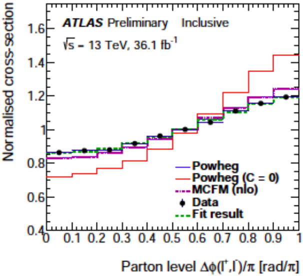
Extract the fraction of SM-like spin correlation(f_{SM}) at parton level

$$N = f_{SM} N_{\text{SM}} + (1 - f_{SM}) N_{\text{no-SM}}$$

Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

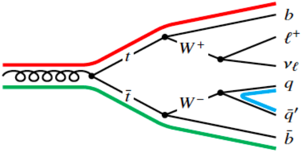
in inclusive $m_{t\bar{t}}$ range:
$f_{SM} = 1.250 \pm 0.026\text{(stat)} \pm 0.063\text{(syst)}$

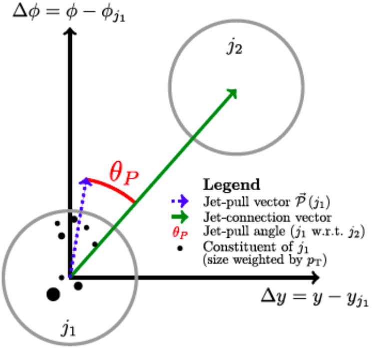
- largest error from MC modelling
- significance of 3.7σ (3.2σ with theoretical unc)
- Known effect, now significant (7 TeV result PRL 108 (2012) 212001)



arXiv:1805.02935 at 13 TeV

Weighted angular moments from jet constituents encode the colour connections between parton that seed the jets.





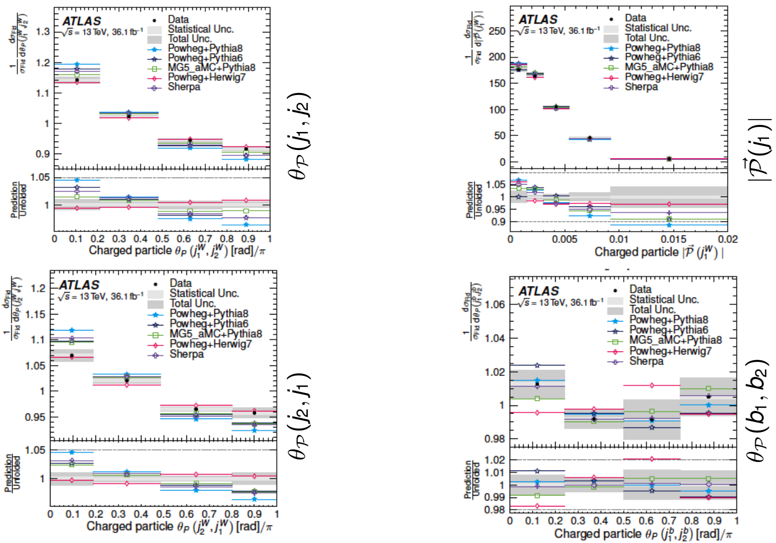
- recent ATLAS measurement on 36.1 fb^{-1} of 13 TeV data
- semileptonic final state
- jet-pull angle and magnitude, from jet-pull vector:

$$\vec{\mathcal{P}}(j) = \sum_{i \in j} \frac{|\vec{\Delta r}_i| \cdot p_T^i}{p_T^j} \vec{\Delta r}_i$$

- (b_1, b_2) and (j_1^W, j_2^W) dijet systems

Colour flow in $t\bar{t}$ events

arXiv:1805.02935 at 13 TeV



No prediction exists which describe well all observables taken into account.

Conclusions

ATLAS program on top-quark physics is wide and top-quark properties are an important part of it.

Summarising:

- almost all 8 TeV analyses have been published
  - top-quark SM parameters precisely measured at 8 TeV
- first 13 TeV results becoming public
  - no sign of new physics in the top-quark sector
  - stronger limits put on BSM theories parameters space

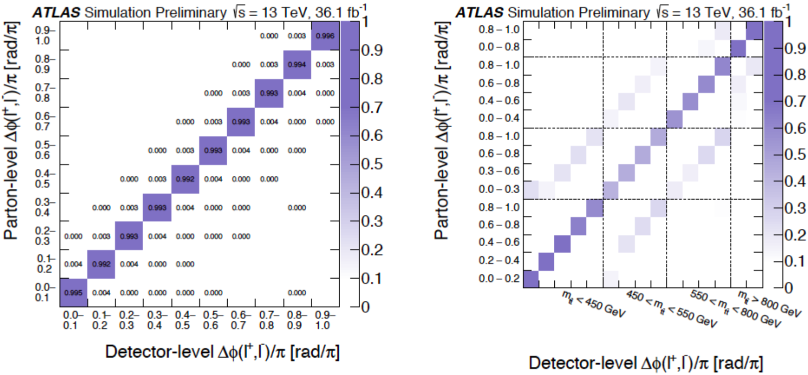
To conclude:

- Top-quark properties measurements entered precision era
  Typical largest uncertainties from:
  - jet energy scale
  - MC modelling
- Significant trends in top-quark modelling observed
- TOP2018 conference next week $\leftarrow$ new interesting results coming!

BACK-UP

ATLAS-CONF-2018-027

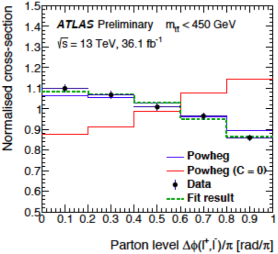
Unfolding correlation matrices



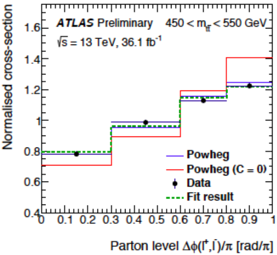
Spin correlations

ATLAS-CONF-2018-027

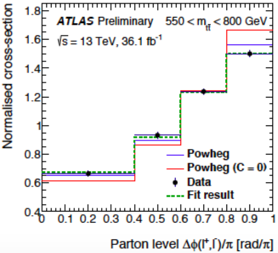
Unfolded parton-level observables

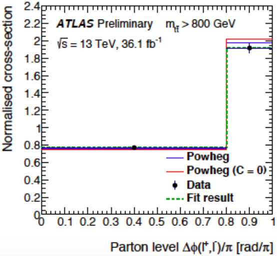


(a)



(b)

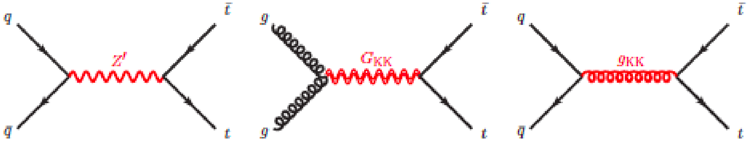




Heavy particles to top-quarks

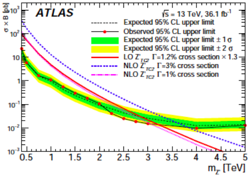
arXiv:1804.10823

In BSM scenarios, the top-quark can interact with undiscovered particles.

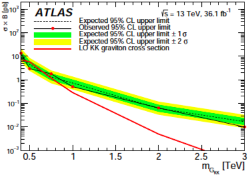


- Signature for such particles is deviation from the $t\bar{t}$ invariant mass ($m_{t\bar{t}}$)
- Most recent ATLAS analysis used 36.1 fb^{-1}of 13 TeV data
- l+jets final state, resolved and boosted top-quark categories

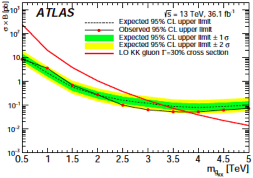
No deviations from SM. Upper limits set on masses and couplings.



$m_{Z'} \gtrsim 3$TeV



$m_{G_{KK}} \begin{array}{l} < 0.45 \text{ TeV} \\ > 0.65 \text{ TeV} \end{array}$



$m_{g_{KK}} \gtrsim 3.5$TeV

New phenomena in leptons + *b*-jets events arXiv:1807.11883

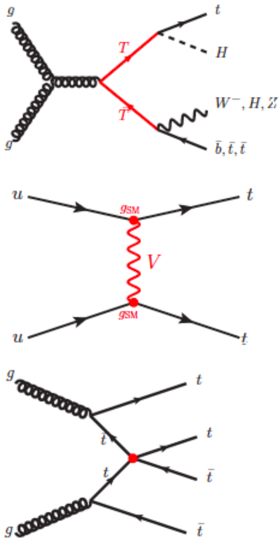
Search for new physics with final states:

- $l^{\pm}l^{\pm}$+*b*-jets (2*l* SS)
- *lll*+*b*-jets (3*l* SS)

using 36 $\text{fb}^{-1}$of 13 TeV data
Possible sources:

- vector-like quarks (T, B) to top-quarks
- same sign top-quark production
- four-top-quark production

Various signal/validation regions defined.



No signal observed

95% CL limits set

- $m_{T/B} > 1$TeV
- $\sigma_{tt} < 89$ fb (assuming $m_V = 1$TeV)
- $\sigma_{tttt} < 69$ fb (and constraints on exotic productions)

Main errors: jets scale, *b*-jet, bkgs norm

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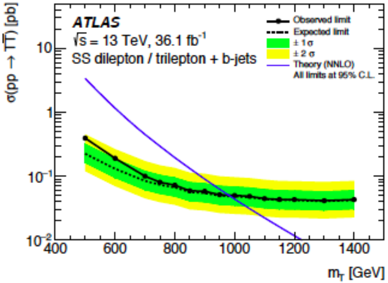
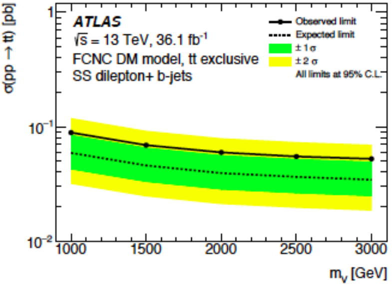
- same sign top-quark production
- four-top-quark production





Various signal/validation regions defined.

No signal observed

95% CL limits set

- $m_{T/B} > 1$TeV
- $\sigma_{tt} < 89$ fb (assuming $m_V = 1$TeV)
- $\sigma_{tttt} < 69$ fb (and constraints on exotic productions)

Main errors: jets scale, *b*-jet, bkgs norm