Flavour physics and electroweak symmetry breaking results from ATLAS

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on behalf of the ATLAS Collaboration

Sixth Workshop on Theory, Phenomenology and Experiments in Flavour Physics (Villa Orlandi, Capri)
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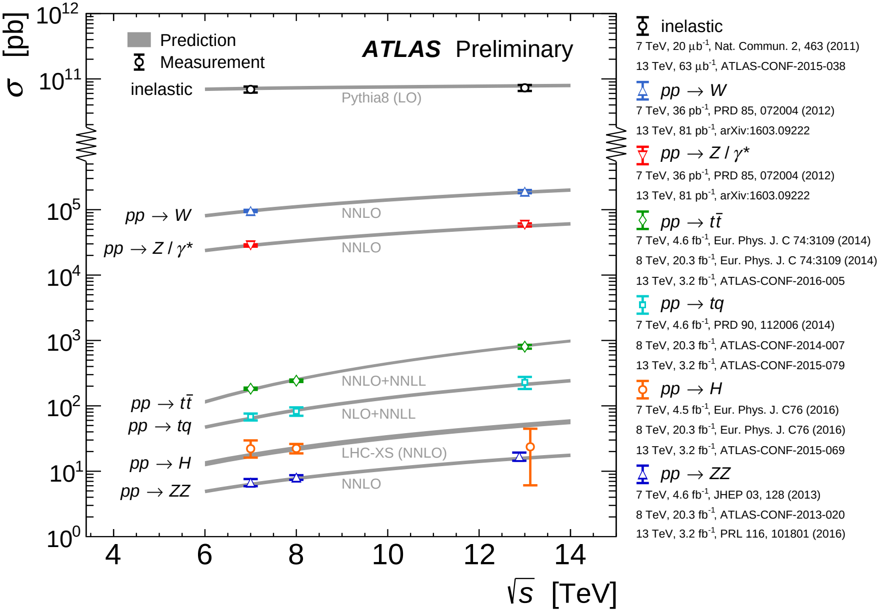
LHC: Discovery Machine

- The following have been there for decades:
  - Higgs fine-tuning problem can point to new EW scale physics
  - Dark Matter (WIMP "miracle") suggestive of new EW scale particle
- Strong motivation for direct exploration of new physics at the Electroweak Scale with Electroweak Couplings
  - Nothing to do with any specific model
- If you had a 13 TeV proton-proton collider, how much data would you need for this exploration?
  - Depends on the kind of new physics
  - Answer known for > 30 years: $\mathcal{O}(100\ \text{fb}^{-1})$, for a given scenario

Inclusive Cross-sections



Road map

- B-physics:
  - Measurement of $B_s^0 \to J/\psi\phi$ decay properties
  - Study of $B_{(s)}^0 \to \mu\mu$ decays
- Higgs
  - Lepton Flavour Violating Higgs decays
  - $ttH(H \to bb)$: all-hadronic and $H \to bb$ combination
- Anomalous couplings in $t \to W^+ b$
- FCNC decays with top
  - Search for $t \to Hq$
  - Search for single t-quark production via FCNC
  - Search for $t \to qZ$

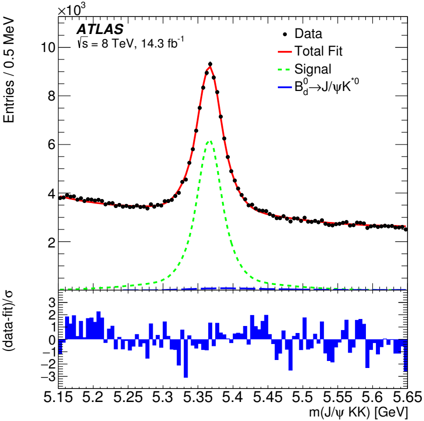
B-Physics

Measurement of $B_s^0 \to J/\psi\phi$ decay properties

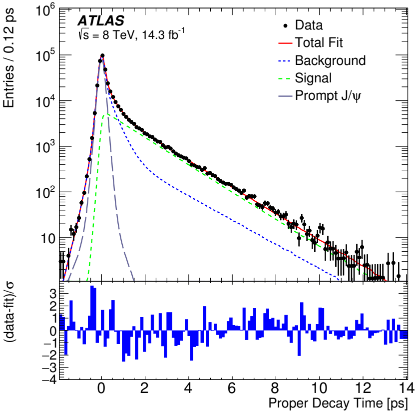
- $B_s^0 \to J/\psi\phi$ expected to be sensitive to BSM physics
- CP-violation phase: ϕ_s
  - CPV due to interference between:
    - Direct decay
    - Flavour oscillation + decay
- SM Predictions:
  - $\phi_s = -0.0364 \pm 0.0016$ [rads]
  - Indirect determination via global fits
  - SM precision much smaller than experimental
  - Experimental measurement a viable BSM search
- Method uses observables on the "opposite side" of the event to the B_s^0 candidate
- Observables include charge of tracks within a b-tagged jet or cone around μ/e on opposite side of event
- Distributions used to built per-candidate B_s tag probability (untagged events assigned probability of 0.5)

Full likelihood uses $m(\mu^+\mu^-K^+K^-)$, τ, $\delta\tau$, ϕ_T, $cos(\theta_T)$, $cos(\psi_T)$ and initial flavour probability used as input
arXiv:1601.03297 (January, 13)

Measurement of $B_s^0 \to J/\psi\phi$ decay properties

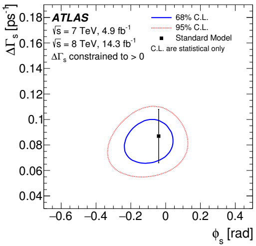


B_s^0 mass fit



B_s^0 proper decay time fit

Measurement of $B_s^0 \to J/\psi\phi$ decay properties

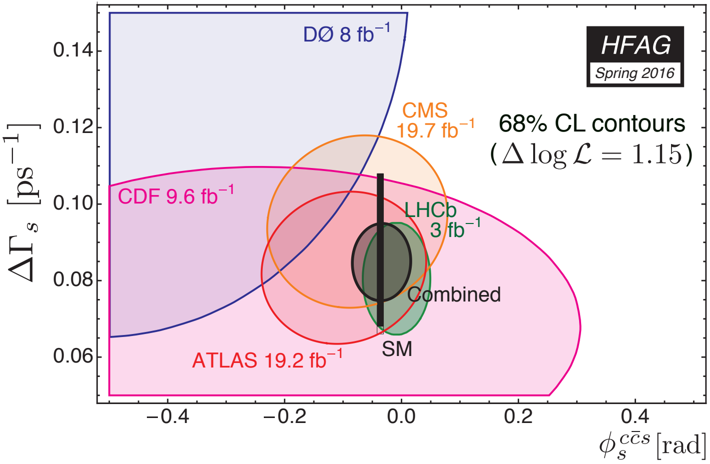


- New measurement (8 TeV) statistically combined with previous measurement (7 TeV, PRD 90 (2014) 052007)
- Simultaneous measurement of ϕ_s and $\Delta\Gamma_s$ consistent with Standard Model

Par	8 TeV data			7 TeV data			Run1 combined		
	Value	Stat	Syst	Value	Stat	Syst	Value	Stat	Syst
ϕ_s[rad]	-0.123	0.089	0.041	0.12	0.25	0.05	-0.098	0.084	0.040
$\Delta\Gamma_s[\mathrm{ps}^{-1}]$	0.096	0.013	0.007	0.053	0.021	0.010	0.083	0.011	0.007
$\Gamma_s[\mathrm{ps}^{-1}]$	0.678	0.004	0.004	0.677	0.007	0.004	0.677	0.003	0.003
$\lvert A_{\parallel}(0)\rvert^2$	0.230	0.005	0.006	0.220	0.008	0.009	0.227	0.004	0.006
$\lvert A_0(0)\rvert^2$	0.514	0.004	0.002	0.529	0.006	0.012	0.514	0.004	0.003
$\lvert A_S\rvert^2$	0.090	0.008	0.020	0.024	0.014	0.028	0.071	0.007	0.017
$\delta_\perp$ [rad]	4.46	0.48	0.29	3.89	0.47	0.11	4.13	0.33	0.16
$\delta_{\parallel}$ [rad]	3.15	0.13	0.05	[3.04, 3.23]		0.09	3.15	0.13	0.05
$\delta_\perp - \delta_S$ [rad]	-0.08	0.04	0.01	[3.02, 3.25]		0.04	-0.08	0.04	0.01

Measurement of $B_s^0 \to J/\psi\phi$ decay properties

Latest Heavy Flavour Averaging Group (HFAG) result on weak phase difference.



Plot: HFAG Spring 2016

Study of $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ decays

Analysis strategy. BRs extracted applying the formula:

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \times \frac{f_u}{f_{d(s)}} \times \frac{1}{\mathcal{D}_{\rm norm}},$$

with $\mathcal{D}_{\rm norm} = \sum_k N^k_{J/\psi K^+} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}}\right)_k$

- From an unbinned ML fit to $m(\mu\mu)$ distribution
- From an unbinned ML fit to $m(\mu\mu K^\pm)$ distribution
- Hadronisation probabilities
- Trigger conditions and luminosity categories
- Acceptance and efficiencies form simulation

* k runs over the 4 mutually exclusive data categories (2012 data split in 3 trigger categories and whole 2011 data) and α_k is the relative integrated luminosity of the two channels for the 4 data categories

arXiv:1604.04263 (April, 14)

Study of $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ decays

Triggers (4 mutually exclusive categories for all channels):

- 2011 data based on di-muon trigger with $p_T > 4$ GeV
- 2012 data split into three mutually exclusive categories:
  - One muon with $p_T > 6$ GeV and second muon with $p_T > 4$ GeV
  - Both muons with $p_T > 4$ GeV and at least one with $|\eta| < 1.05$
  - Both muons with $p_T > 4$ GeV and $|\eta| > 1.05$

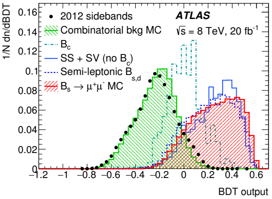
Selections:

- Combined muons with $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.5$
- Kaons (for $B^\pm \to J/\psi K^\pm$ and $B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$)
  - No particle-ID $\to$ Mass hypothesis to reconstruct kaons 4-momenta. $p_T(K) > 1$ GeV, $|\eta(K)| < 2.5$
- B_s^0, B^0, $B^\pm$, $J/\psi\phi$ candidates:
  - Di-muon vertex (w. or w/o J/ψ mass constraint)
  - Fiducial volume: $p_T(B) > 8$ GeV, $|\eta(B)| < 2.5$
  - $\mu^+\mu^-$ mass resolution and PV requirement

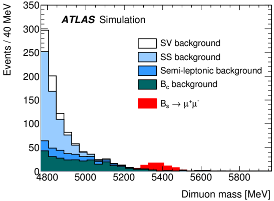
Study of $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ decays

Background composition:

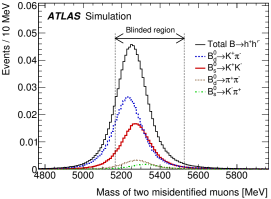
- **Combinatorial** background, the dominant component due to pairs of uncorrelated muons and characterised by a small dependence on the dimuon invariant mass
- **Partially reconstructed** $B \to \mu\mu X$ decays, characterised by non-reconstructed final-state particles (X) and thus accumulating in the low-mass sideband
- **Peaking** background, due to $B_s^0 \to hh'$ decays, with both hadrons misidentified as muons



Combinatorial bkg.



$B \to \mu\mu X$

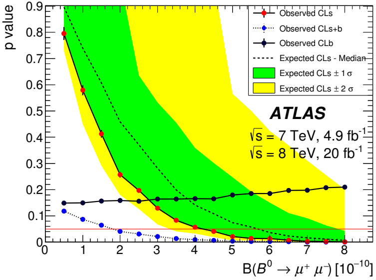


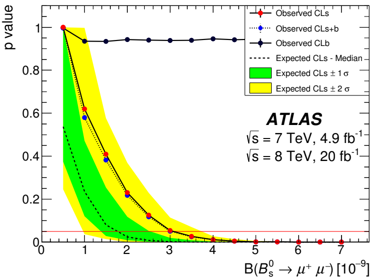
Peaking bkg.

Due to usage of multivariate analysis (BDT) for Combinatorial and Peaking backgrounds ATLAS managed to obtain better rejection of background than CMS or LHCb.

Study of $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ decays

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \cdot 10^{-9}$$



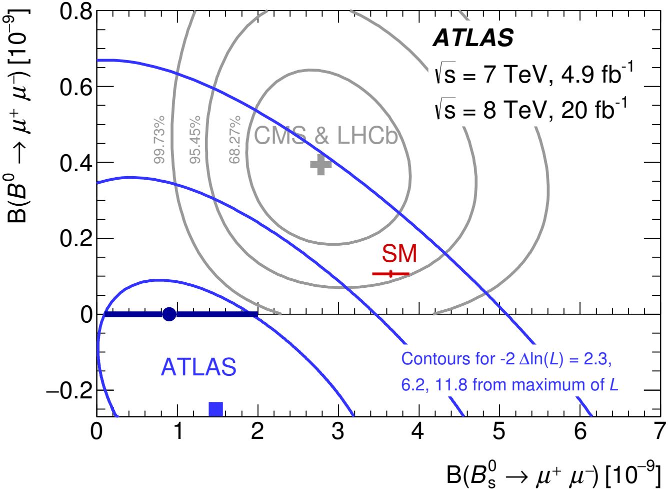


B^0:
Observed upper limit: $4.2 \cdot 10^{-10}$ at 95% CL
Expected upper limit: $5.7^{+2.1}_{-1.2} \cdot 10^{-10}$

B_s^0:
Observed upper limit: $3.0 \cdot 10^{-9}$ at 95% CL
Expected upper limit: $1.8^{+0.7}_{-0.4} \cdot 10^{-9}$

Study of $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ decays

BRs in the world...



The result is compatible to 2.0σ with the SM prediction.

Higgs

Lepton Flavour Violating Higgs decays

- Not present in initial formulations of the SM (neutrinos assumed to have exactly zero mass), but can occur in 2HDM and other models. Lepton number and Lepton Flavour number are accidental symmetries of the SM

- LFV is observed in ν oscillations
  - Requires modifications of the SM (e.g. add neutrino masses and ν_R). New physics phenomena could be related to LFV
  - The LFV of charged leptons expected as consequence of neutrino oscillations is too small to be experimentally observed at LHC
  - We hope to find additional manifestations $\rightarrow$ The Higgs and the Z bosons decays are excellent candidates

- The Higgs is a totally new playground for such searches

- 2.4σ excess in $H \rightarrow \mu\tau$ from CMS: Phys.Lett. B749 (2015)

- Z-boson is studied in this direction for a long while (last search at LEP)

arXiv:1604.07730 (April, 22)

Lepton Flavour Violating Higgs decays

Three new searches:

1. $H \to e\tau_{had}$ and $H \to \mu\tau_{had}$ (see dedicated analysis in JHEP11(2015)211)
2. $H \to e\tau_{lep}$ and $H \to \mu\tau_{lep}$
3. $Z \to \mu\tau_{had}$

(1), (3) use same techniques, similar to $H \to \tau\tau$ analysis
(1), (2) use same statistical combination.

	$\tau_{\rm lep}$ channels	$\tau_{\rm had}$ channels
Electrons	$I(E_{\rm T}, 0.3) < 0.13$ $I(p_{\rm T}, 0.3) < 0.07$	$I(E_{\rm T}, 0.2) < 0.06$ $I(p_{\rm T}, 0.4) < 0.06$
Muons	$I(E_{\rm T}, 0.3) < 0.14$ $I(p_{\rm T}, 0.3) < 0.06$	$I(E_{\rm T}, 0.2) < 0.06$ $I(p_{\rm T}, 0.4) < 0.06$

Summary of isolation requirements

Calorimeter based isolation:

$$I^{e(\mu)}(E_T, \Delta R) = \frac{\sum E_T^{cone\Delta R}}{E_T^e(p_T^\mu)}$$

Track based isolation:

$$I^{e(\mu)}(p_T, \Delta R) = \frac{\sum p_T^{cone\Delta R}}{E_T^e(p_T^\mu)}$$

arXiv:1604.07730 (April, 22)

Lepton Flavour Violating Higgs decays

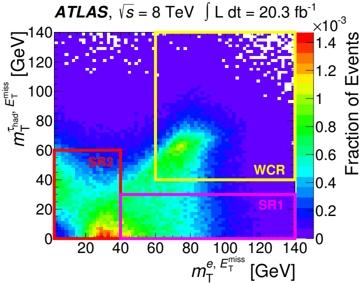
$H \to e\tau_{had}$ and $H \to \mu\tau_{had}$

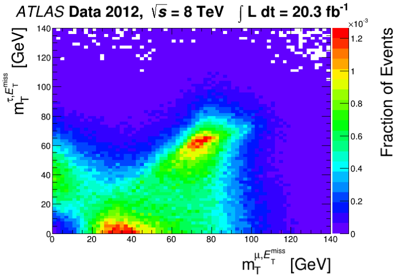
Background sources:
W+jets, t, $t\bar{t}$, $Z \to \tau\tau + jets$, $Z \to ee + jets$, Diboson, QCD, $H \to \tau\tau$

Trigger and topology:
Single electron, $E_T > 24$ GeV (single muon, $p_T > 26$ GeV). $p_T(\tau_{had}) > 45$ GeV and $|\eta^{e(\mu)} - \eta(\tau_{had})| < 2$. One ν collinear with the τ_{had}

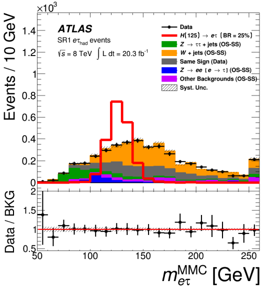
Missing Mass Calculator used as more sophisticated version of the collinear approximation:
NIM A654(2011)481

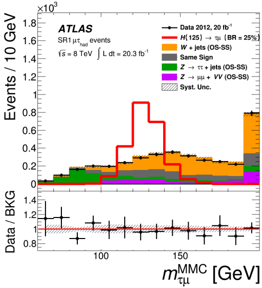
SR and CR definition based on $m_T^{(e(\mu),E_T^{miss})}$ and $m_T^{(\tau_{had},E_T^{miss})}$

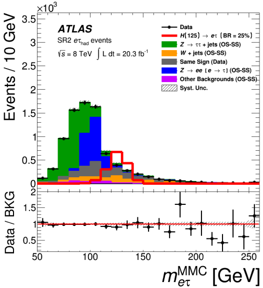


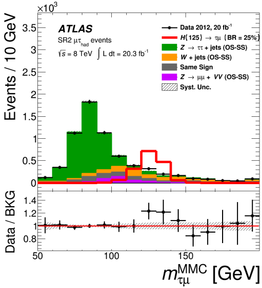


Lepton Flavour Violating Higgs decays









$H \to e\tau_{had}$ $H \to \mu\tau_{had}$

Lepton Flavour Violating Higgs decays

$H \rightarrow e\tau_{lep}$ & $H \rightarrow \mu\tau_{lep}$

Background sources (data-driven estimation):

- Symmetric components
  - SM sources with prompt e and μ
- Asymmetric components
  - Events with fake and non-prompt leptons
  - p_T dependent effects

Data samples:

$p_T^{\mu} \geq p_T^{e}$ (μe sample); $p_T^{e} > p_T^{\mu}$ ($e\mu$ sample)

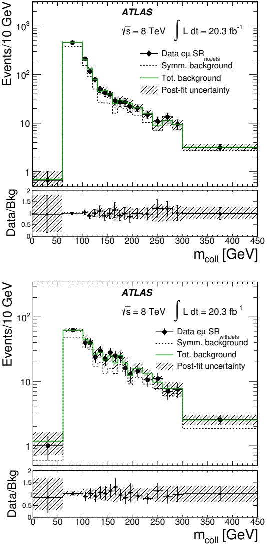
Topology:

One electron and one muon of opposite sign. 2ν collinear with the sub-leading lepton

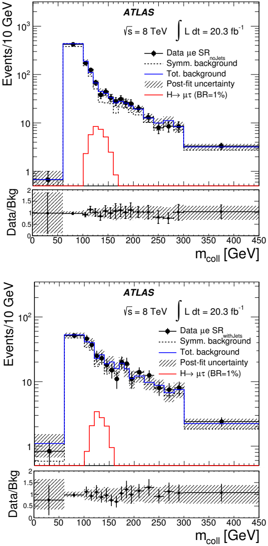
Final estimator (collinear mass):

$$m_{coll} = \sqrt{2p_T^{\ell 1}(p_T^{\ell 2} + E_T^{miss})(cosh\Delta\eta - cos\Delta\phi)}$$

Lepton Flavour Violating Higgs decays



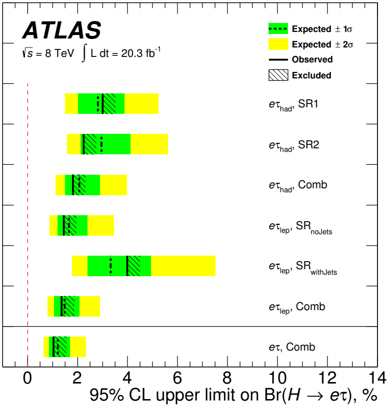
$e\mu$ channel



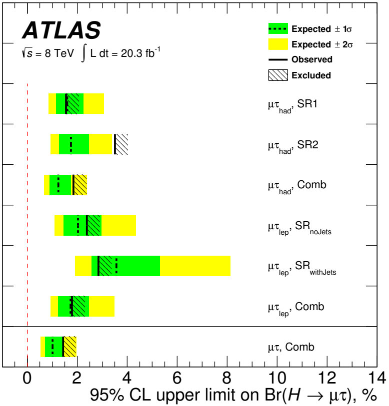
μe channel

Lepton Flavour Violating Higgs decays

LFV H combination. Upper limits on LFV decays of Higgs boson



$H \to e\tau$ hypothesis



$H \to \mu\tau$ hypothesis

* $\mu\tau_{had}$ channel is from JHEP11(2015)211

Fully hadronic $ttH(H \to bb)$

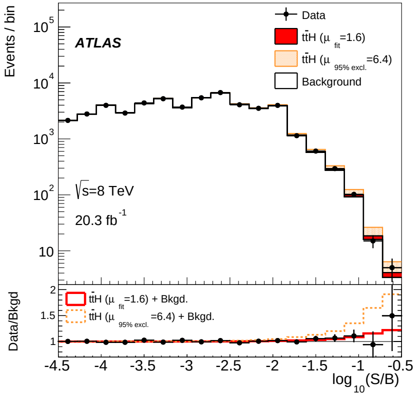
H coupling to top quarks "seen" in gluon fusion process, and loop in $\gamma\gamma$ decays but important to probe directly for model independent determination of coupling.
Analysis strategy:

- Largest BR among all ttH channels, but lowest purity due to large multijet production
- Preselection:
  - 5 jets $p_T > 55$ GeV, $|\eta| < 2.5$ each
  - At least one additional jet with $p_T > 25$ GeV, $|\eta| < 2.5$
  - Lepton veto
  - ≥ 2 b-tagged jets (@60% eff.)
- Data-driven multijet estimation (TRF_{MJ} method)
- Background sources:
  - Multijet
  - $t\bar{t}$+jets
- Output of a Boosted Decision Tree (BDT) used as final discriminant

EPJC75(2015)349 (update from April, 13: arXiv:1604.03812)

Fully hadronic $ttH(H \to bb)$

Event yields as a function of $\log_{10}(S/B)$



Signal strength:
$\mu\ (m_H = 125\ \text{GeV}) = 1.6 \pm 2.6$
Obs.(exp.) signal significance:
0.6(0.4)
Obs.(exp.) p-value:
27%(34%)

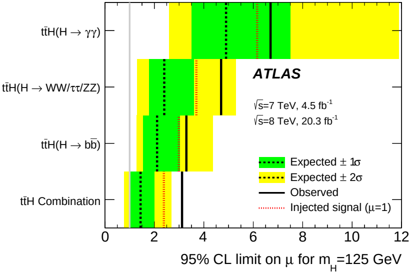
Observed and expected upper limits at 95% CL on $\sigma(ttH)$ relative to SM prediction:

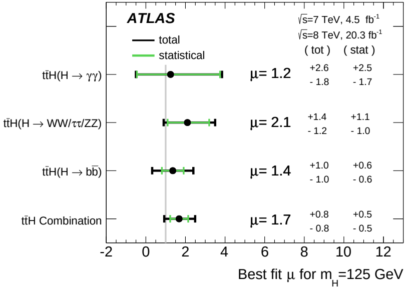
assuming the SM prediction for $\sigma(t\bar{t}H)$ is shown in the last column.

	Observed	Expected if $\mu = 0$					Expected if $\mu = 1$
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Median
Upper limit on μ at 95%	6.4	2.9	3.9	5.4	7.5	10.1	6.4

ttH combination results

CL limits (left), μ measurements (right)





Analysis	95% CL upper limit							Signal strength
	Observed	Expected						
		-2σ	-1σ	median	$+1\sigma$	$+2\sigma$	median ($\mu = 1$)	μ
$t\bar{t}H(H \to \gamma\gamma)$	6.7	2.6	3.5	4.9	7.5	11.9	6.2	$1.2^{+2.6}_{-1.8}$
$t\bar{t}H(H \to$ leptons$)$	4.7	1.3	1.8	2.4	3.6	5.3	3.7	$2.1^{+1.4}_{-1.2}$
$t\bar{t}H(H \to b\bar{b})$	3.3	1.3	1.5	2.1	3.0	4.4	3.0	1.4 ± 1.0
$t\bar{t}H$ Combination	3.1	0.8	1.0	1.4	2.0	2.7	2.4	1.7 ± 0.8

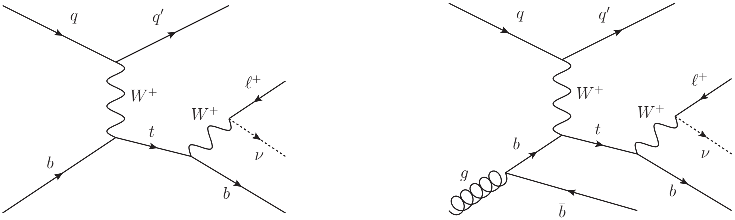
See also slide no. 51 (backup) for Log-likelihood contours of κ_F vs. κ_V

Anomalous couplings in $t \to W^+ b$

t-channel single top anomalous Wtb couplings

Defining the anomalous Wtb couplings:

- In the Standard Model: $\mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\frac{1}{2}(1-\gamma^5)tW_{\mu}^{-}$
- The most general lagrangian adds couplings V_R, g_L and g_R:
  $\mathcal{L}_{eff} = \frac{g}{\sqrt{2}}\bar{b}[\gamma^{\mu}(V_L P_L + V_R P_R) + \frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)]tW_{\mu}^{-}$
- Sensitive to new physics in complex coupling ratio g_R/V_L:

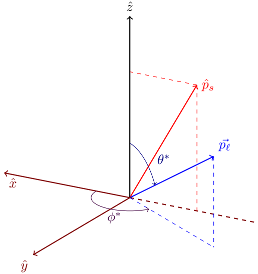


JHEP04(2016)023 (April 5)

t-channel single top anomalous Wtb couplings

Measurement definition: (see slide no. 52 (backup) for the analysis strategy)

- W helicity fractions $F_i = \frac{\Gamma_i}{\Gamma}$, $i \in [L, 0, R]$ sensitive to θ^* between $\vec{p}_\ell$ in the W frame and W momentum $\hat{q}$ in the t frame
- Top spin in t-channel production is $\approx 90\%$ polarized along spectator quark direction $\hat{p}_s$
- $\hat{q}$ and $\hat{p}_s$ define per-event 3D coordinates: $\hat{z} = \hat{q}$, $\hat{y} = \hat{p}_s \times \hat{q}$, $\hat{x} = \hat{y} \times \hat{q}$
- The W and b from polarized top decay have four possible helicity combinations
- Only amplitudes with matching b helicity interfere



The angular probability density is expressed with spherical harmonics, parameters $\vec{\alpha}$ and polarisation fraction P

$\alpha = (f_1, f_1^+, f_0^+, \delta_+, \delta_-)$

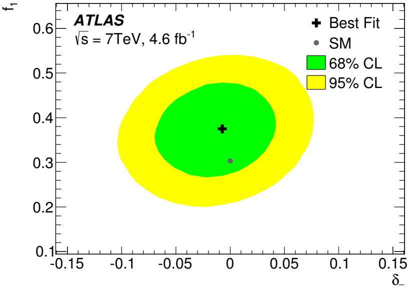
f_1 - fraction of decays containing transverse Ws

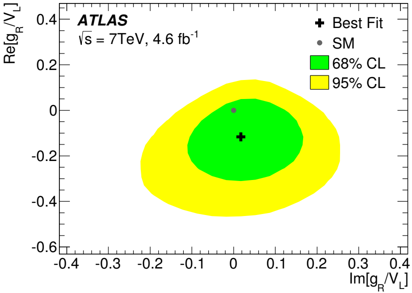
δ_- - phase between longitudinally and transversely polarised Ws with left-handed bs

f_1 & δ_- can be expressed in terms of $\frac{g_R}{V_L}$

t-channel single top anomalous Wtb couplings

Projections of the likelihood function into the fraction f_1 of decays containing transverse Ws vs. phase δ_- between longitudinally and transversely polarized Ws with left-handed bs (left); $Re\left[\frac{g_R}{V_L}\right]$ vs. $Im\left[\frac{g_R}{V_L}\right]$ (right)





$$f_1 = 0.37 \pm 0.05(stat.) \pm 0.05(syst.)$$
$$\delta_-/\pi = -0.014 \pm 0.023(stat.) \pm 0.028(syst.)$$

$$Re\left[\frac{g_R}{V_L}\right] = -0.13 \pm 0.07(stat.) \pm 0.10(syst.)$$
$$Im\left[\frac{g_R}{V_L}\right] = 0.03 \pm 0.06(stat.) \pm 0.07(syst.)$$
$$\rho\left(Re\left[\frac{g_R}{V_L}\right], Im\left[\frac{g_R}{V_L}\right]\right) = 0.11 \text{ (correlation)}$$

FCNC decays with top

Search for $t \to Hq$ FCNC decays

Much interest recently in flavour-violating Higgs interactions:

- Flavor-violating interactions could also be present in the quark sector
- If off-diagonal Yukawa coupling goes like $\lambda_{f_i f_j H} \sim \frac{\sqrt{m_{f_i} m_{f_j}}}{\nu}$
  $\to$ large effect expected in tcH interaction!
- $t \to Hq$ decays:
  - Highly suppressed in the SM: $\mathcal{B}(t \to Hc) \sim 10^{-15}$
  - Can receive large enhancements in BSM scenarios:
    e.g. $\mathcal{B}(t \to Hc) \sim 10^{-3}$ in 2HDM

JHEP12(2015)061 (December, 2015)

Search for $t \to Hq$

Strategies for $t\bar{t} \to WbHq$:

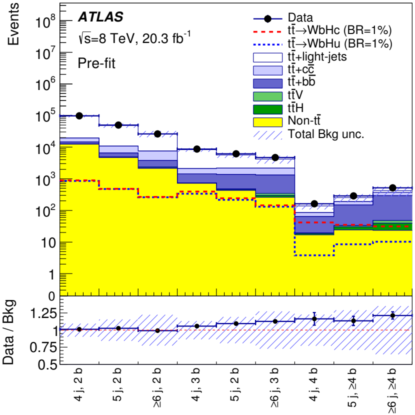
- $H \to b\bar{b}$:
  - $\mathcal{B}(H \to b\bar{b}) \sim 58\%$
  - Lepton+jets
  - Large background, some mass resolution
- $H \to WW^*$, $H \to \tau\tau$: see backup slides 53 and 54
  - $\mathcal{B}(H \to WW^*) \sim 21.5\%$, $\mathcal{B}(H \to \tau\tau) \sim 6.3\%$
  - SS dileptons, trileptons
  - Small background, essentially no mass resolution
- $H \to \gamma\gamma$: see backup slides (from slide no. 61)
  - $\mathcal{B}(H \to \gamma\gamma) \sim 0.2\%$
  - Diphoton+lepton+jets, diphoton+jets final states
  - Very small background, excellent mass resolution

Search for $t \to Hq$

$H \to b\bar{b}$ search: analysis strategy

- $t\bar{t} \to WbHq \to (\ell\nu)b(b\bar{b})q$: lepton+jets final state
- Event preselection:
  - Single lepton trigger
  - 1 lepton (e or μ), $p_T > 25$ GeV, $|\eta| < 2.5$
  - $\geq$4 jets, $p_T > 25$ GeV, $|\eta| < 2.5$
  - $\geq$2 b-tags
- Main background: $t\bar{t}(\to WbHq)$ + jets
- Categorise events according to jet (4, 5, $\geq$6) and b-tag (2, 3, $\geq$4) multiplicities:
  - Signal-rich regions: (4j, 3b) for $WbHu$ and $WbHc$; (4j, 4b) for $WbHc$
  - Rest for the Signal-depleted regions

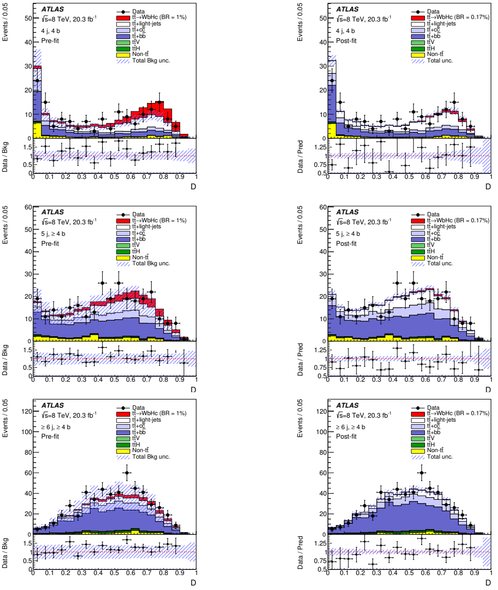
$H \to b\bar{b}$ search: signal and background modelling



Final discriminant: $\mathcal{D} = \frac{P^{sig}(x)}{P^{sig}(x)+P^{bkg}(x)}$

Search for $t \to Hq$

$H \to b\bar{b}$ search: results



Best-fit branching ratios:

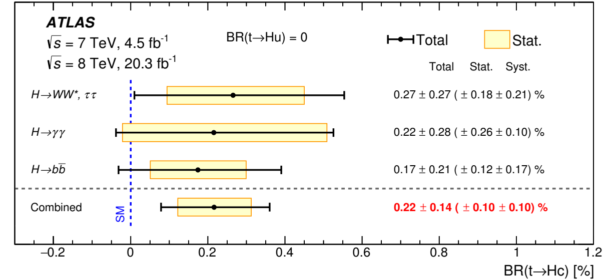
$\mathcal{B}(t \to Hc) =$
$[0.17 \pm 0.22 \pm 0.17]\%$
(assuming $\mathcal{B}(t \to Hu) = 0$)
$\mathcal{B}(t \to Hu) =$
$[-0.07 \pm 0.17 \pm 0.28]\%$
(assuming $\mathcal{B}(t \to Hc) = 0$)

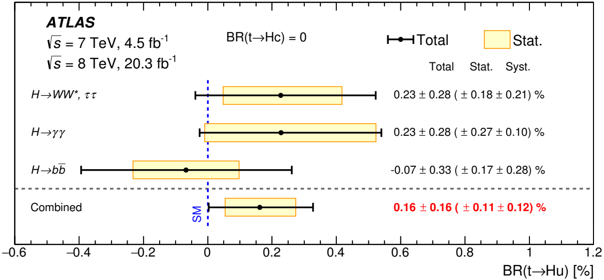
Obs.(exp.) limits
(@95% CL; one BR at a time):
$\mathcal{B}(t \to Hc) < 0.56\%(0.42\%)$
$\mathcal{B}(t \to Hu) < 0.61\%(0.64\%)$

No significant $t \to Hq$ excess
Most sensitive single search for
$t \to Hc$!

Search for $t \to Hq$

Combined results: best-fit branching ratios



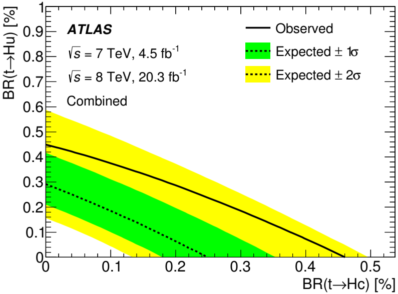


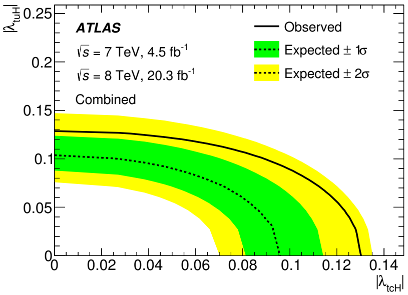
Search for $t \to Hq$

Combined results: 2D limits

Upper limits on the BRs can be translated* into upper limits on the non-flavour-diagonal Yukawa couplings $|\lambda_{tqH}|$ from

$$\mathcal{L}_{FCNC} = \lambda_{tcH}\bar{t}Hc + \lambda_{tuH}\bar{t}Hu + h.c.$$





Obs.(exp.) @95% CL upper limits on the coupling constants:

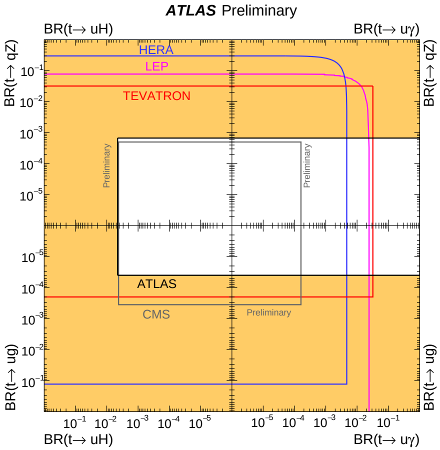
$|\lambda_{tcH}| < 0.13(0.10)$

$|\lambda_{tuH}| < 0.13(0.10)$

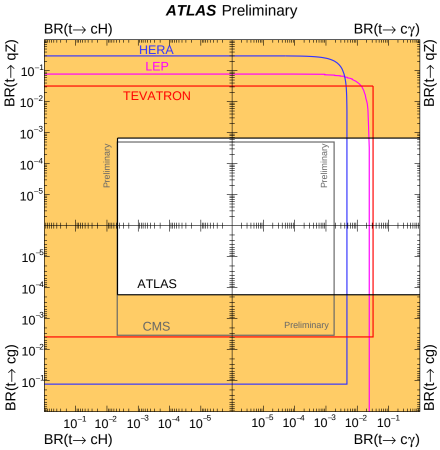
* $|\lambda_{tqH}| = (1.92 \pm 0.02)\sqrt{\mathcal{B}(t \to Hq)}$, from JHEP06(2014)008

Summary of the FCNC limits

Summary of the current 95% CL FCNC limits for $t \to qX$ decays ($q = u,\ c;\ X = g,\ Z,\ \gamma$ or H)



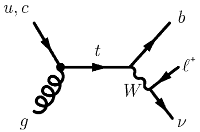
$t \to uX$



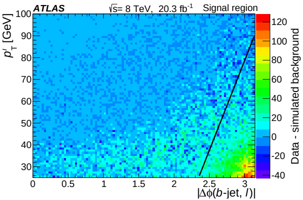
$t \to cX$

Search for single t-quark production via FCNC

Analysis strategy:

- 

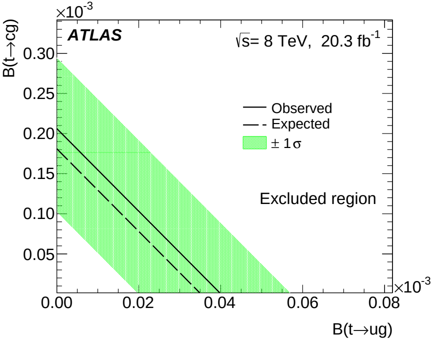
- Event preselection:
  - Exactly 1 isolated lepton, $p_T > 25$ GeV, $|\eta| < 2.5$
  - $E_T^{miss} > 30$ GeV
  - Exactly 1 jet, $p_T > 25$ GeV, $|\eta| < 2.5$
  - Exactly 1 b-tagged jet (@50% eff.)
  - $m_T(W) > 50$ GeV
  - Triangular cut: $p_T^\ell > 90\text{ GeV}\left(1 - \frac{\pi - |\Delta\phi(\ell, jet)|}{\pi - 2}\right)$
- Dominant background: W+jets
- Control region: same except 85% b-tagging eff.

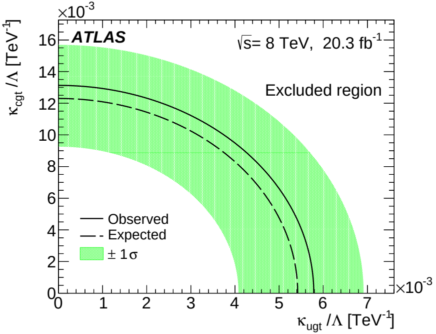


EPJC76(2016)55 (January)

Search for single t-quark production via FCNC

Observed 2D limits on the BRs and on the coupling constants





Observed upper limits @95% CL on the branching fractions:
$\mathcal{B}(t \to ug) < 4 \cdot 10^{-5}$
$\mathcal{B}(t \to cg) < 17 \cdot 10^{-5}$

Observed upper limits @95% CL on the coupling constants:
$\kappa_{ugt}/\Lambda < 5.8 \cdot 10^{-3}$ TeV^{-1}
$\kappa_{cgt}/\Lambda < 13 \cdot 10^{-3}$ TeV^{-1}

Search for $t \to qZ$

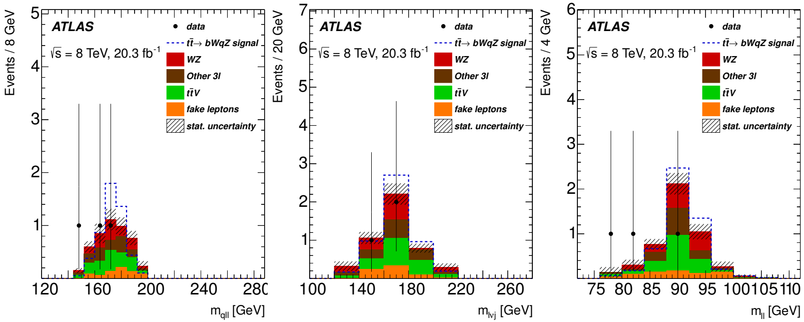
Analysis strategy:

- Searching for top quark pairs with one top decaying through FCNC and the other through the SM dominant mode ($t\bar{t} \to bWqZ \to b\ell\nu q\ell\ell$)
- Consider only Z boson decays to charged leptons, and W boson leptonic decays
- Final state topology:
  - 3 isolated leptons with $p_T > 15$ GeV, $|\eta| < 2.5$ each
  - 2 leptons must have mass within 15 GeV of m_Z^{PDG}
  - $\geq$2 jets with $p_T > 25$ GeV, $|\eta| < 2.5$
  - $E_T^{miss} > 20$ GeV
  - 1 or 2 b-tagged jets (@70% eff.)
- Background sources:
  - 3 real leptons (WZ, ZZ, $t\bar{t}V$, tZ, Tribosons)
  - Jets fake leptons (Z+jets, $t\bar{t}$, $Z\gamma$, single top, ...)

EPJC76(2015)12 (December, 2015)

Search for $t \to qZ$

Reconstructed masses of the top quarks and Z boson after the final selection



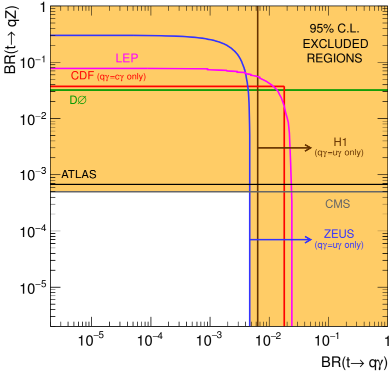
The test statistics for comparison the observed data events:

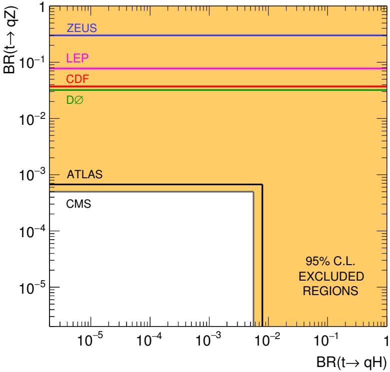
$X_d = \text{n } ln(1 + \frac{s}{b})$

Search for $t \to qZ$

Results

No evidence for signal found





@95% CL limits on the $\mathcal{B}(t \to qZ)$:

Observed: $7 \cdot 10^{-4}$

Expected: $8 \cdot 10^{-4}$

(-1σ): $6 \cdot 10^{-4}$

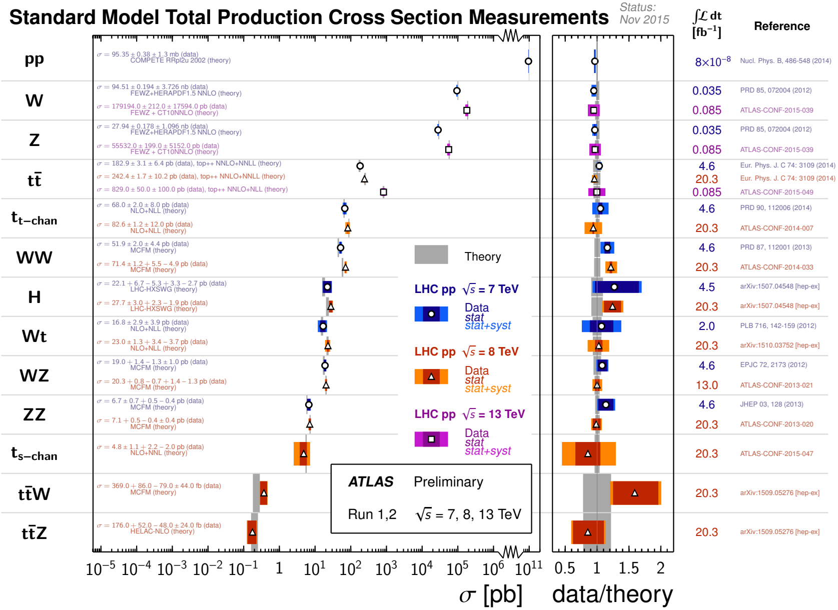
$(+1\sigma)$: $12 \cdot 10^{-4}$

Conclusions

- ATLAS has published to date more than 500 physics papers
- LHC is exploring a new energy frontier
- Direct and indirect search campaign for physics beyond the Standard Model is in full play
- LHC plan is to take data in 2016, 2017 and 2018 at full steam before another long shutdown period
- New results coming soon with 2016 data

Backup slides

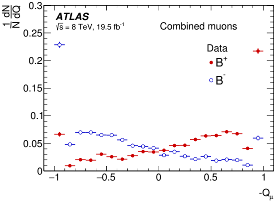
Standard Model Total Production Cross Section Measurements



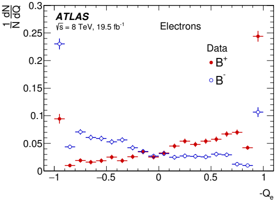
Measurement of $B_s^0 \to J/\psi\phi$ decay properties

Analysis uses "opposite side tagging" calibrated with $B^\pm \to J/\psi K^\pm$

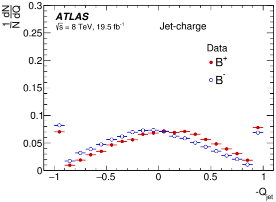
- Method uses observables on the "opposite side" of the event to the B_s^0 candidate
- Observables include charge of tracks within a b-tagged jet or cone around μ/e on opposite side of event
- Distributions used to built per-candidate B_s tag probability (untagged events assigned probability of 0.5)



μ cone charge



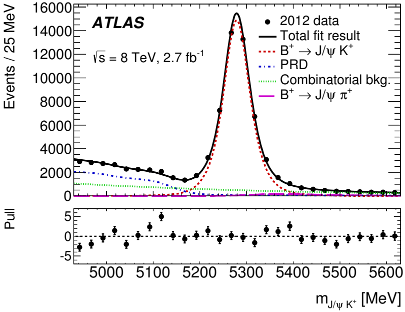
e cone charge



b-tagged jet charge

Study of $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ decays

$B^\pm$ yield extraction



$J/\psi K^+$ invariant mass

- $B^\pm \to J/\psi K^\pm$ and $B^\pm \to J/\psi\pi^\pm$ yields are simultaneously extracted $\to$ Measure their BRs ratio
- Ratio is the weighted average of the ratios in the 4 trigger categories

Category	$N_{J/\psi K^+}$	$N_{J/\psi\pi^+}$
T_1	$46\,860 \pm 290 \pm 280$	$1\,420 \pm 230 \pm 440$
T_2	$5\,200 \pm 84 \pm 100$	$180 \pm 51 \pm 89$
T_3	$2\,512 \pm 91 \pm 42$	$85 \pm 77 \pm 30$
2011	$95\,900 \pm 420 \pm 1\,100$	$3\,000 \pm 340 \pm 1\,140$

$$\frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 0.035 \pm 0.003 \pm 0.012$$

World average: 0.040 ± 0.004

Lepton Flavour Violating Higgs decays

$Z \to \mu\tau_{had}$

Background sources:

W+jets, t, $t\bar{t}$, $Z \to \tau\tau + jets$, $Z \to \mu\mu + jets$, Diboson, QCD, $H \to \tau\tau$ (new w.r.t. $H \to e\tau_{had}$)

Trigger and topology:

Single muon ($p_T > 24$ GeV). μ and τ are back to back. One ν collinear with the τ_{had}

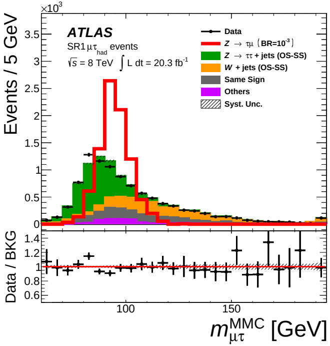
SR and CR definition based on $m_T^{(e,E_T^{miss})}$ and $m_T^{(\tau_{had},E_T^{miss})}$:

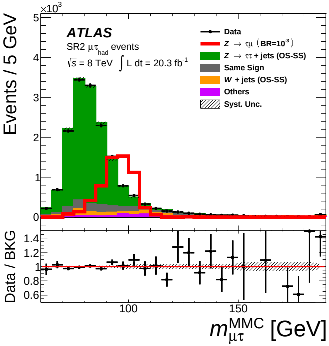
Cut	SR1	SR2	WCR	TCR
$p_{\mathrm{T}}(\mu)$	>30 GeV	>30 GeV	>30 GeV	>30 GeV
$p_{\mathrm{T}}(\tau_{\mathrm{had}})$	>30 GeV	>30 GeV	>30 GeV	>30 GeV
$\lvert\eta(\mu) - \eta(\tau_{\mathrm{had}})\rvert$	<2	<2	<2	<2
$m_{\mathrm{T}}^{\mu,E_{\mathrm{T}}^{\mathrm{miss}}}$	>30 GeV and <75 GeV	<30 GeV	>60 GeV	–
$m_{\mathrm{T}}^{\tau_{\mathrm{had}},E_{\mathrm{T}}^{\mathrm{miss}}}$	<20 GeV	<45 GeV	>40 GeV	–
N_{jet}	–	–	–	>1
$N_{b-\mathrm{jet}}$	0	0	0	>0

Lepton Flavour Violating Higgs decays

$Z \to \mu\tau_{had}$ results

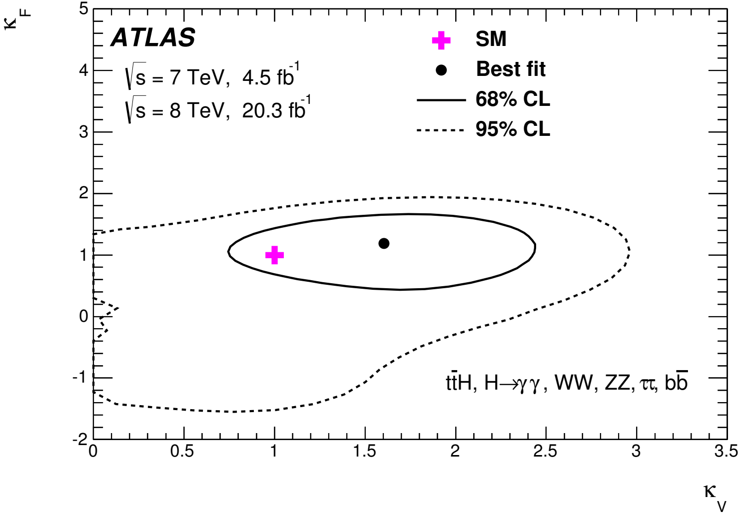
$Br(Z \to \mu\tau)[10^{-5}]$	SR1	SR2	Combined
Expected limit	$2.6^{+1.1}_{-0.7}$	$6.4^{-1.8}_{+2.8}$	$2.6^{+1.1}_{-0.7}$
Observed limit	1.5	7.9	1.7
Best fit	$-2.1^{+1.2}_{-1.3}$	$2.6^{+2.9}_{-2.6}$	$-1.6^{+1.3}_{-1.4}$





ttH combination results

Log-likelihood contours of κ_F vs. κ_V



t-channel single top anomalous Wtb couplings

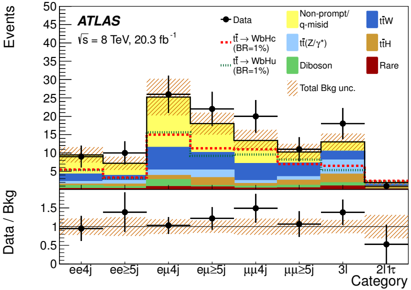
Analysis strategy:

- Event selection:
  - 1 isolated lepton, $p_T > 25$ GeV, $|\eta| < 2.47$;
    excludes $1.37 < |\eta(e)| < 1.52$ and $|\eta(\mu)| < 2.5$
  - 2 jets, $p_T > 30$ GeV, $|\eta| < 4.5$;
    or $p_T > 35$ GeV in $2.75 < |\eta(e)| < 3.5$; $\Delta R(j, \ell) > 0.2$
  - 1 b-tagged jet (@55% eff.)
  - $E_T^{miss} > 30$ GeV
  - $m_T(\ell, E_T^{miss}) > 30$ GeV
  - $p_T^{\ell} >$40 GeV$\left(1 - \frac{\pi - \Delta\phi(j1,\ell)}{\pi - 1}\right)$
- Background: $t\bar{t}$, single top, diboson, Z+jets, W+jets

Search for $t \to Hq$

$H \to WW^*$, $H \to \tau\tau$ search: analysis strategy

- Reinterpretation of $t\bar{t}H$ multileptons (see arXiv:1506.05988)
- Event categories:
  - $2\ell 0\tau_{had}$: sensitive to $t\bar{t} \to WbHq \to \ell^{\pm}\ell^{\pm}qqb2\nu$ $(ee,\ e\mu,\ \mu\mu) \times (4\ \text{j},\ \geq 5\ \text{j})$
  - 3ℓ: sensitive to $t\bar{t} \to WbHq \to \ell^{\pm}\ell^{\pm}\ell^{\mp}qb3\nu$
  - $2\ell 01\tau_{had}$: sensitive to $t\bar{t} \to WbHq \to \ell^{\pm}\ell^{\pm}\tau^{\mp}qb3\nu$

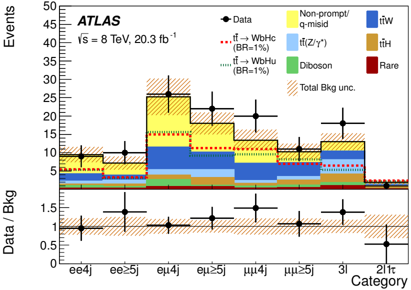


$H \to WW^*$, $H \to \tau\tau$ search: results

Best-fit branching ratios:

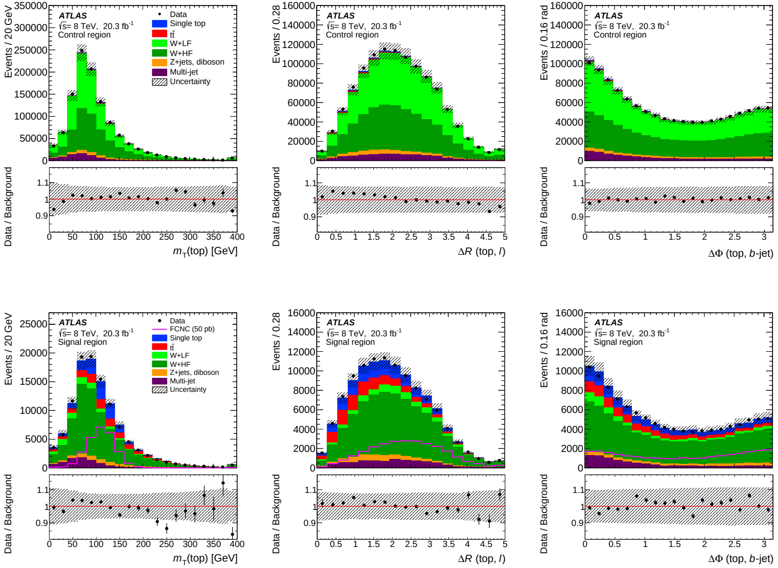
$\mathcal{B}(t \to Hc) = [0.28^{+0.18}_{-0.17}(stat.)^{+0.22}_{-0.19}(syst.)]\%$ (assuming $\mathcal{B}(t \to Hu) = 0$)

$\mathcal{B}(t \to Hu) = [0.23^{+0.19}_{-0.18}(stat.)^{+0.23}_{-0.20}(syst.)]\%$ (assuming $\mathcal{B}(t \to Hc) = 0$)



Search for single t-quark production via FCNC

Important discriminating variables in Control (top) and Signal (bottom) regions



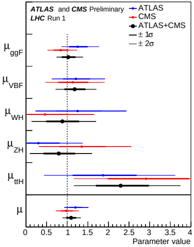
Higgs couplings results

Higgs couplings from ATLAS & CMS

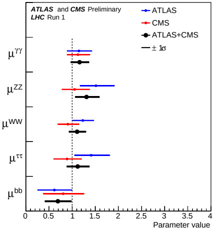
Based on event rates from all accessible combinations of Higgs productions and decays

Assuming a single Higgs state with the SM tensor structure,

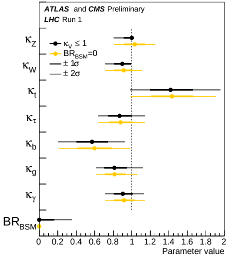
$m_H = 125.09 \pm 0.21(stat.) \pm 0.11(syst.)$



Production modes, $\mu_{decay} = 1$



Decay modes, $\mu_{prod} = 1$



Test BSM in loops:

Global signal strength for production and decay modes

$\mu = 1.09 \pm 0.07_{stat.} \pm 0.04_{exp.syst.} \pm 0.03_{th.bkg.} \pm 0.07_{th.signal}$

$k_V \leq 1$ $BR_{BSM} \leq 34\%$	or	H $BR_{BSM} = 0$ SM p-value
95% CL		11%

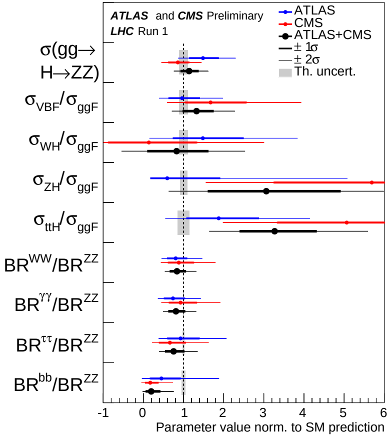
ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002

Higgs couplings from ATLAS & CMS

Using $gg \to H \to ZZ$ as a reference:

$$\sigma_{prod} \times BR_{decay} = \sigma(gg \to H \to ZZ) \times \frac{\sigma_{prod}}{\sigma_{ggF}} \times \frac{BR_{decay}}{BR_{ZZ}}$$

- The most model-independent results
  - Insensitive to theory uncertainty on inclusive σ_{prod}
  - Independent of the total Higgs width
- p-value in 16% compatibility with the SM
- $\sigma_{ttH}/\sigma_{ggF}$: 2.4$\sigma$ excess over SM prediction, mainly due to ttH, $H \to$ multi-lepton events
- BR^{bb}/BR^{ZZ}: 2.5σ deficit w.r.t. SM. Pulled down by excesses in $\sigma_{ttH}/\sigma_{ggF}$ and σ_{ZH}/σ_{ggF}

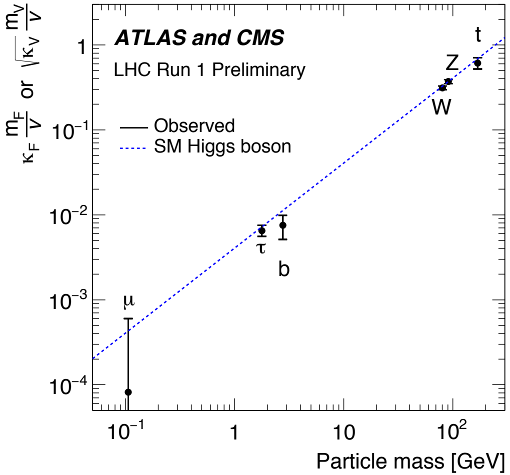


Higgs couplings from ATLAS & CMS

Coupling modifiers in the κ-framework

$\sigma_{prod} \times BR_{decay} = \frac{\sigma_{prod}(\vec{\kappa}) \cdot \Gamma_{decay}(\kappa)}{\Gamma_H}$, where $\kappa^2_{prod} = \frac{\sigma_{prod}}{\sigma^{SM}_{prod}}$, $\kappa^2_{decay} = \frac{\Gamma_{prod}}{\Gamma^{SM}_{prod}}$ and $\Gamma_H = \frac{\kappa^2_H \Gamma^{SM}_H}{1 - BR_{BSM}}$

κ denotes the modification of the SM coupling related to the physics beyond the SM



$$t \to qH(\gamma\gamma)$$

Search for $t \to qH(\gamma\gamma)$

Flavour Changing Neutral Current (FCNC) involving light u, c quarks are highly suppressed in the Standard Model (GIM mechanism)

Analysis strategy:

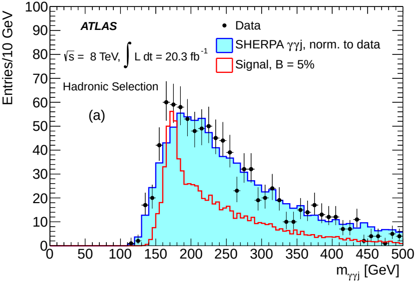
- Search in $pp \to t\bar{t}$: one of the top decays to cH, the other decays to Wb
- Besides from the standard $H \to \gamma\gamma$ inclusive selection
  - Two high p_T (30/40 GeV/c) isolated photons (tight identification criteria)
  - Add cuts on jets and invariant masses to fully reconstruct the final state
- One b-tagged jet + 3 jets: hadronic channel (at 7 and 8 TeV)
- One jet + lepton (e/μ), a neutrino and a b-tagged jet: leptonic channel (8 TeV only)

JHEP06(2014)008 (June 2014)

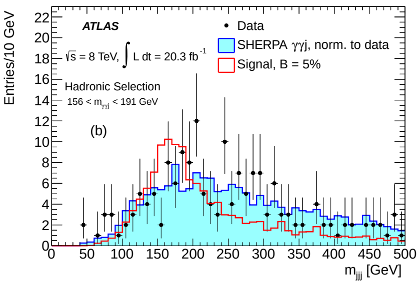
Search for $t \to qH(\gamma\gamma)$

Hadronic channel

Invariant mass distributions for all selected events before mass cut:



(a): $\gamma\gamma j$ (b-tagged)



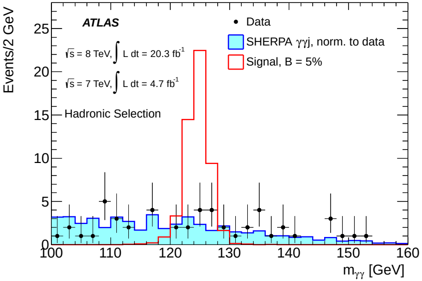
(b): jjj

Search for $t \to qH(\gamma\gamma)$

Hadronic channel

Efficiency for $t \to cH$ signal simulation and number events for data:

	$t \to cH$ (%)		Data (events)	
	7 TeV	8 TeV	7 TeV	8 TeV
$\gamma\gamma$ selection	34.5	34.2	23683	118500
$N_{jets} \geq 4$	15.2	15.1	227	1349
Mass requirements	5.9	6.1	36	210
At least 1 b-tag	4.2 ± 0.1	4.0 ± 0.1	7	43

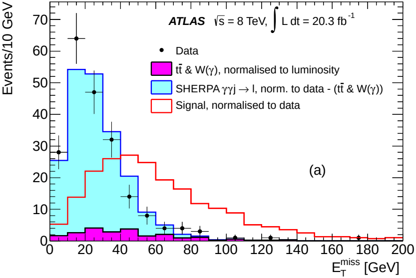


$m_{\gamma\gamma}$ invariant mass distribution

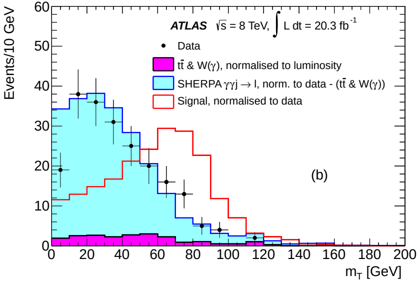
Search for $t \to qH(\gamma\gamma)$

Leptonic channel

Missing transverse energy E_T^{miss} and transverse mass m_T distributions of the W candidates:



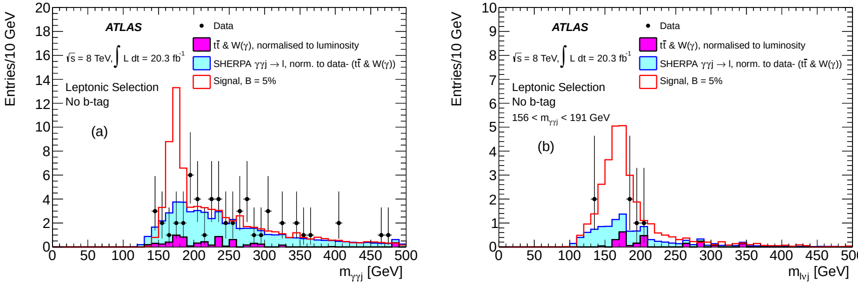
(a): $\gamma\gamma j$ (b-tagged)



(b): jjj

Leptonic channel

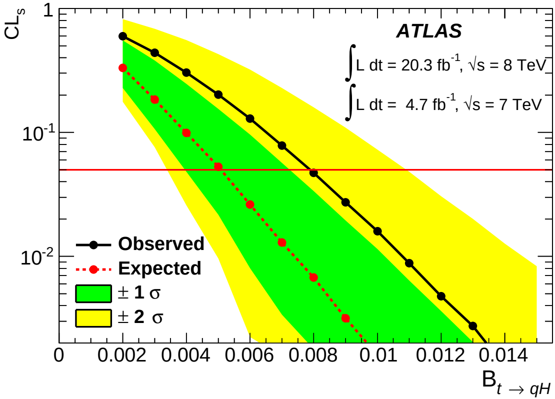
Invariant mass distributions for all selected events before mass cut, and without *b*-tagging requirement:



	$t \to cH$	$t\bar{t}$ & $W(\gamma)$	$S_{\gamma\gamma j \to \ell}$	Data
	(%)	Events		
$\gamma\gamma$ selection	34.9	313.7	—	118500
1 lepton	6.0	21.8	188.2	210
$N_{jets} \geq 2$, $m_T > 30$ GeV	3.8	3.4	18.8	30
Mass requirements	1.9	1.2	3.5	4
At least 1 *b*-tag	1.3 ± 0.1	0.9 ± 0.5	0.5 ± 0.2	1

Search for $t \to qH(\gamma\gamma)$

Evolution of CLs as a function of the branching fraction B of the t to qH decay for the observation of a signal at 125.5 GeV



$\mathcal{B}(t \to qH) < 0.79\%$ observed at 95% CL (0.51% expected)