Searches for new physics in the Single Top channel at the LHC

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On behalf of the ATLAS and the CMS Collaborations

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Single top quark: production and motivation

- Test of Standard Model predictions:
  - cross section $\propto |V_{tb}|^2$
  - test of the unitarity of the CKM matrix: hints for existence for a fourth generation
  - test of the b-quark structure function

- Probe and prepare for search for new physics

- Measure all three processes independently:
  - charged heavy boson W’, H^+
  - access to anomalous couplings

Theory prediction (NNLO)

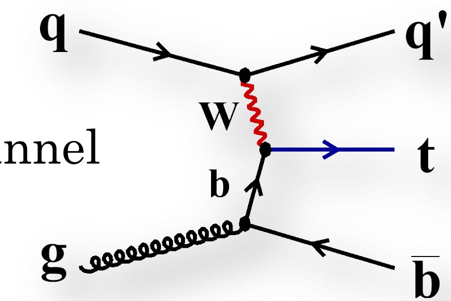
- t-channel: $64.6^{+3.2}_{-2.6}$ pb
- Wt-channel: 15.7 ± 1.3 pb
- s-channel: 4.6 ± 0.3 pb

❖ $M_{top} = 173.1 \pm 0.9$ GeV

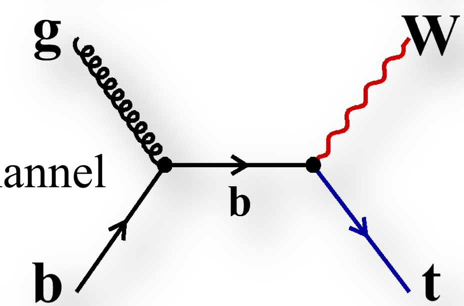
❖ Life-time ~ 10^{-25} s

❖ Decays to bW ~100%

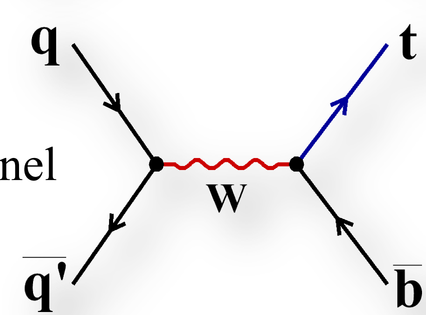
t-channel



Wt-channel



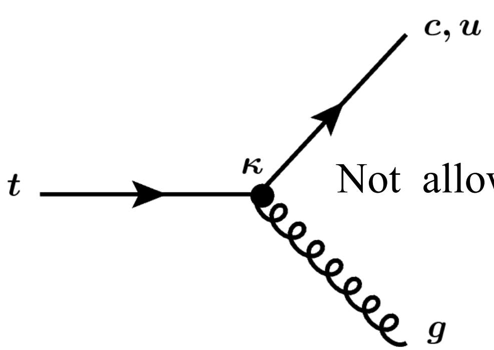
s-channel



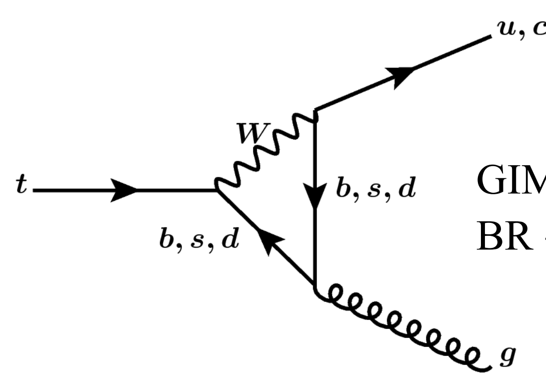
Search for Flavour Changing Neutral Currents at ATLAS using 2.05 fb^{-1}

Phys.Lett.B712, June 2012

- In the SM process, production is suppressed via GIM mechanism



Not allowed in SM

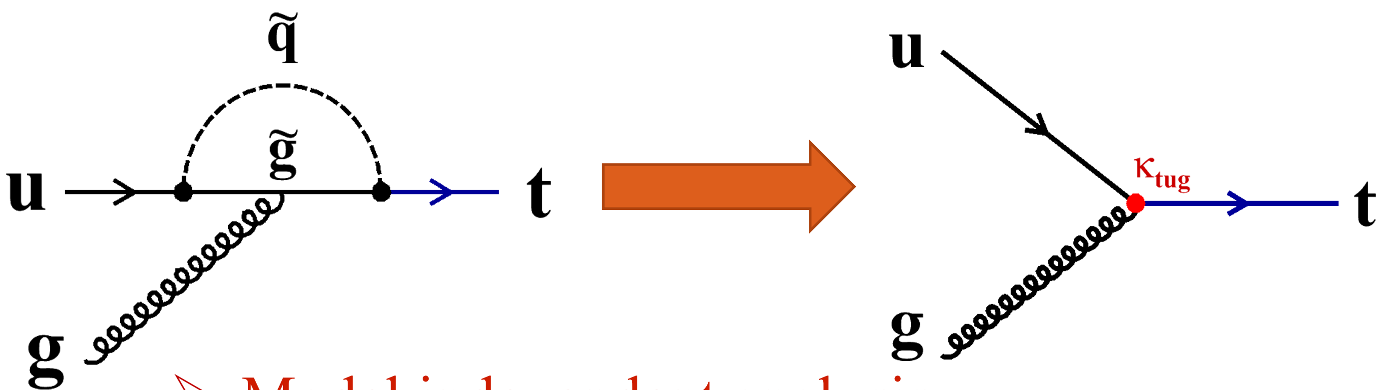


GIM mechanism
BR → 10^{-13}

- What do we want to know:
  - do quarks change their flavours when they couple with neutral force carriers (photon, Z, gluon)?
  - is there an enhancement to the predicted branching fractions (predicted excess depends highly on model; 5-8 orders)?
  - **is there any evidence for new physics?**

Analysis strategy

In this analysis we probe the coupling between the top quark and light quarks+gluon



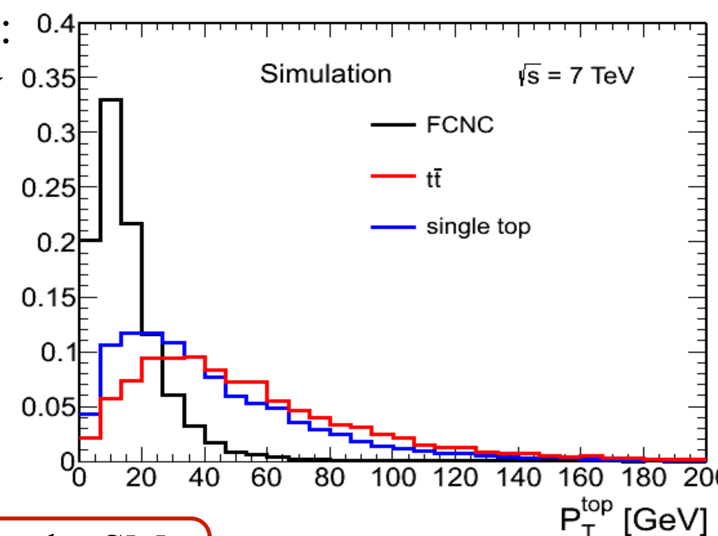
➢ Model independent analysis

Searching for FCNC in top quark **decay** is challenging:

- Limited by $t\bar{t}$ production cross-section and low branching fraction
- very difficult to separate signal from the multijet background

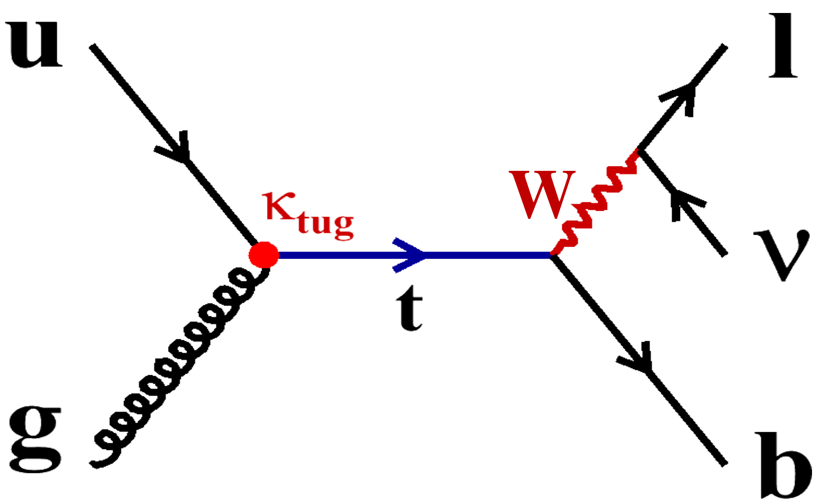
Top quark **production** via FCNC:

- higher cross-section
- no associated production
- the top quark has very low P_T compared with SM top quarks



Good variable to suppress the SM top-quark background

Event selection



- Lepton selection (electron / muon):
  - $P_T > 25$ GeV
- Missing transverse momentum
  - $E_T^{miss} > 25$ GeV
- Jets
  - $P_T > 25$ GeV
  - **exactly one jet**
  - one identified b-quark jet
- Extra background reduction
  - $M_T(l\nu) + E_T^{miss} > 60$ GeV

Dominant backgrounds:

- W+jets (W+c)
- Single top quark (t-channel)

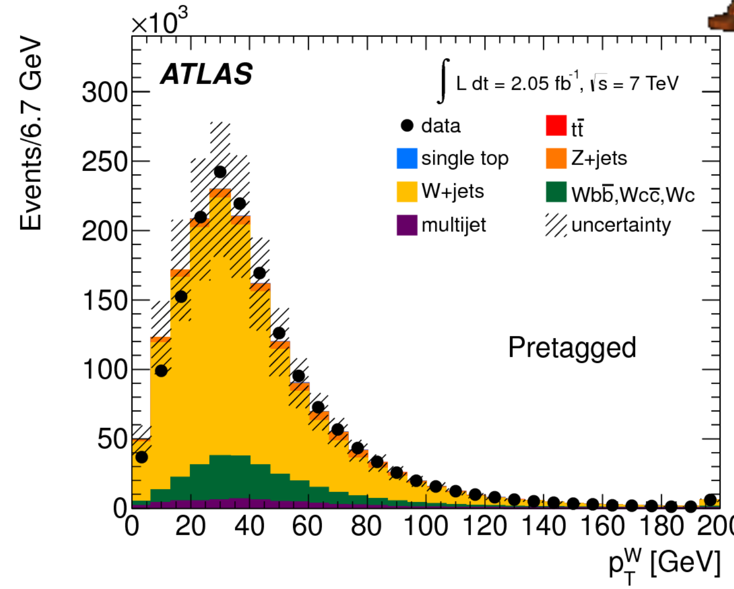
➢ Backgrounds estimated using the simulation and control regions

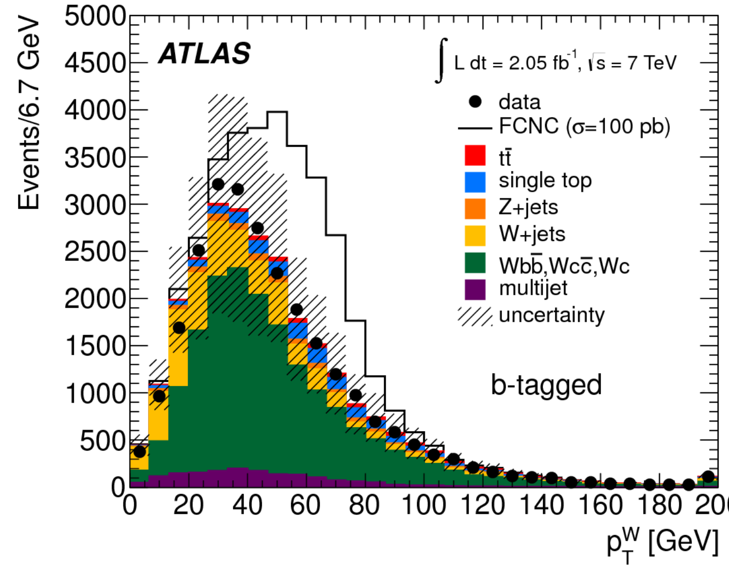
Event yields for 2.05 fb^{-1}

Process	Expected events		
SM single top	1460	±	150
$t\bar{t}$	660	±	70
W+light jets	4700	±	1100
$Wb\bar{b}/Wc\bar{c}$+jets	2700	±	1500
Wc + jets	12100	±	6700
Z+jets/diboson	700	±	170
Multijets	1600	±	800
Total background	24000	±	7000
Observed	26223		

- Multijets contribution estimated from data-driven method

➢ Shapes and yields agree within uncertainties





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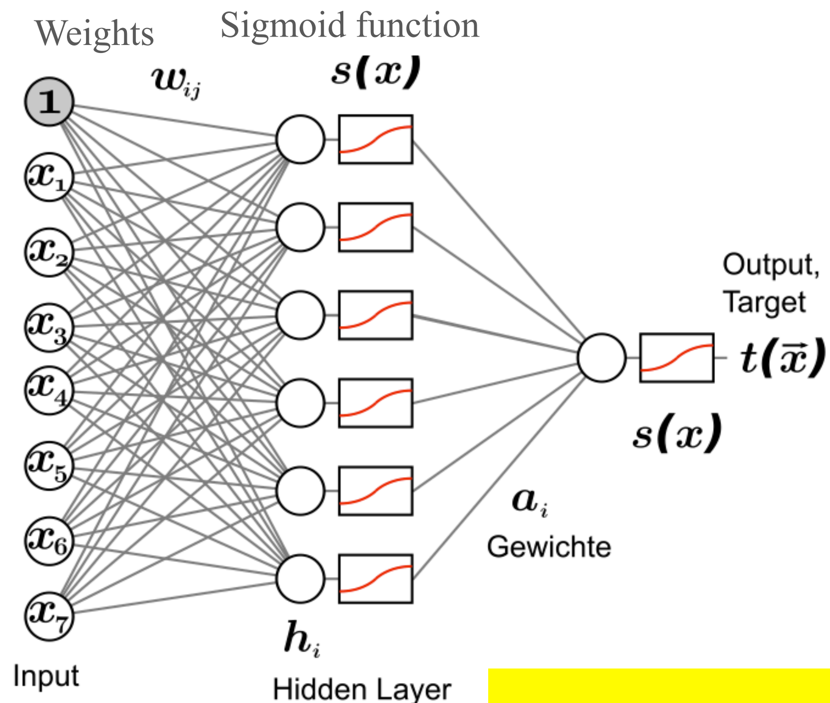
Neural Network

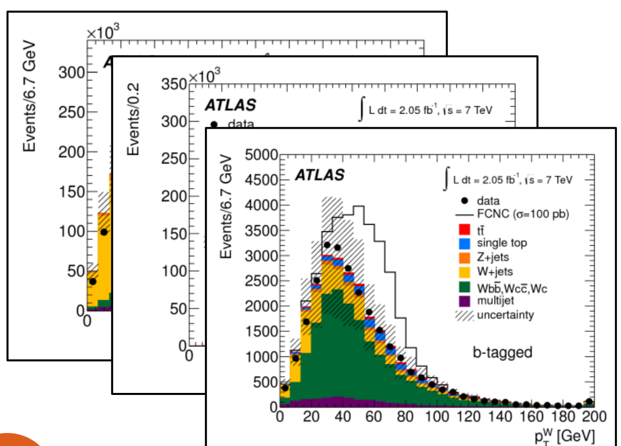


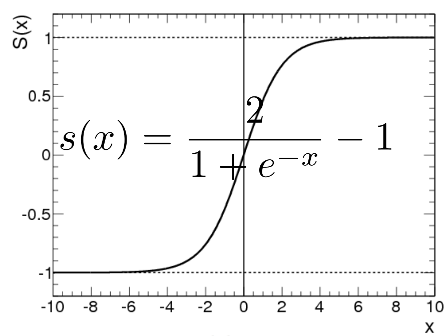
Signal signature:

- P_T (top) ~ 0
  (W and b are back-to-back)
- P(W) is large
- 4× more top than anti-top quarks

11 variables used to train the NN

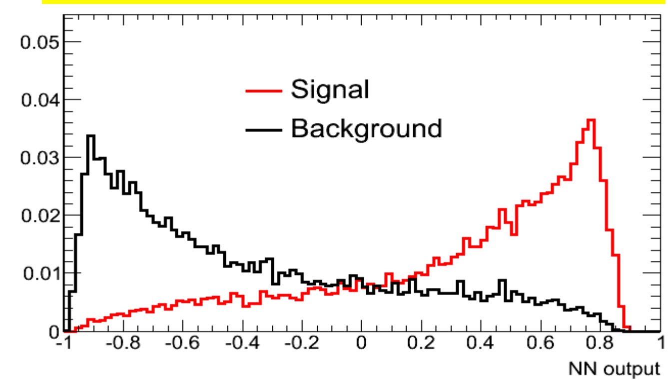
NN trained using MC events



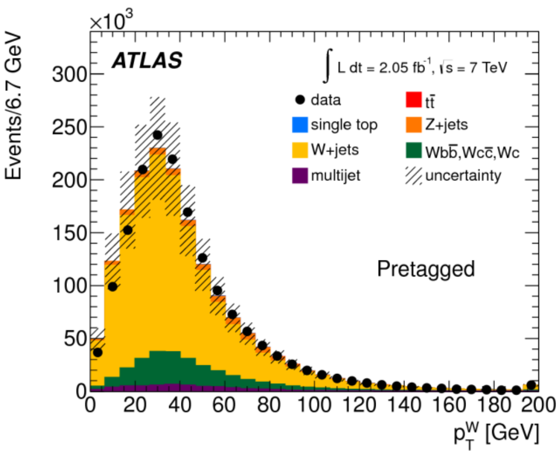


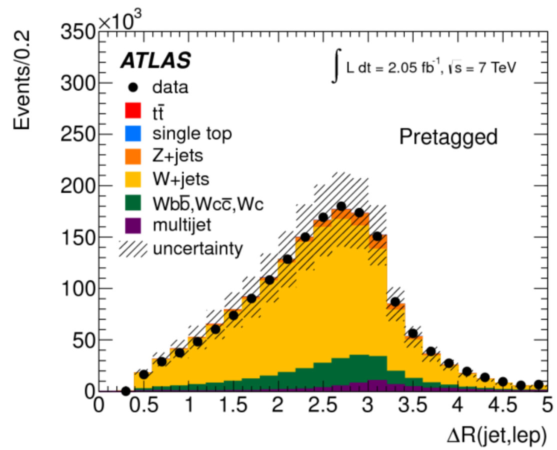
$$s(x) = \frac{2}{1+e^{-x}} - 1$$

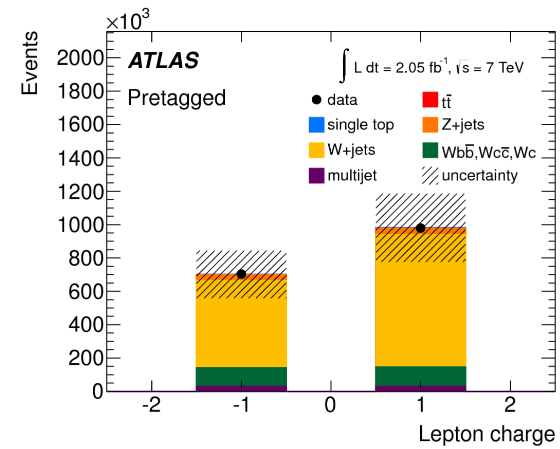
$$(-\infty, +\infty) \xrightarrow{s(x)} [-1, +1]$$

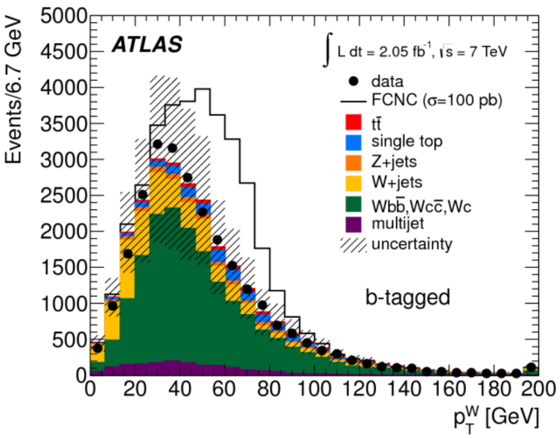


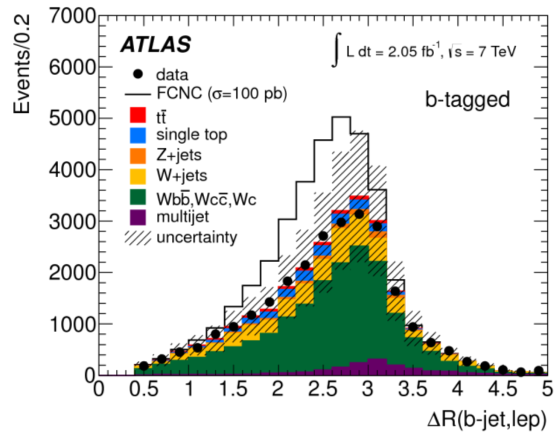
Best variables used to train the NN

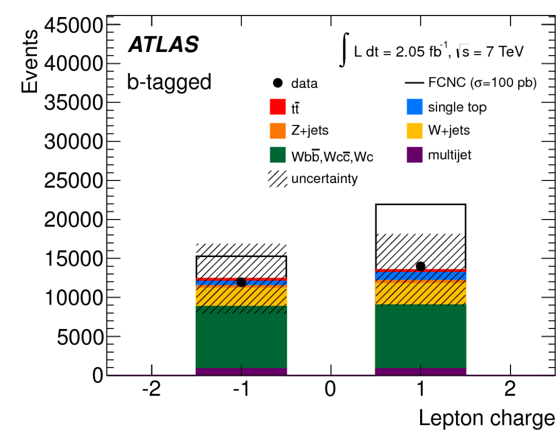






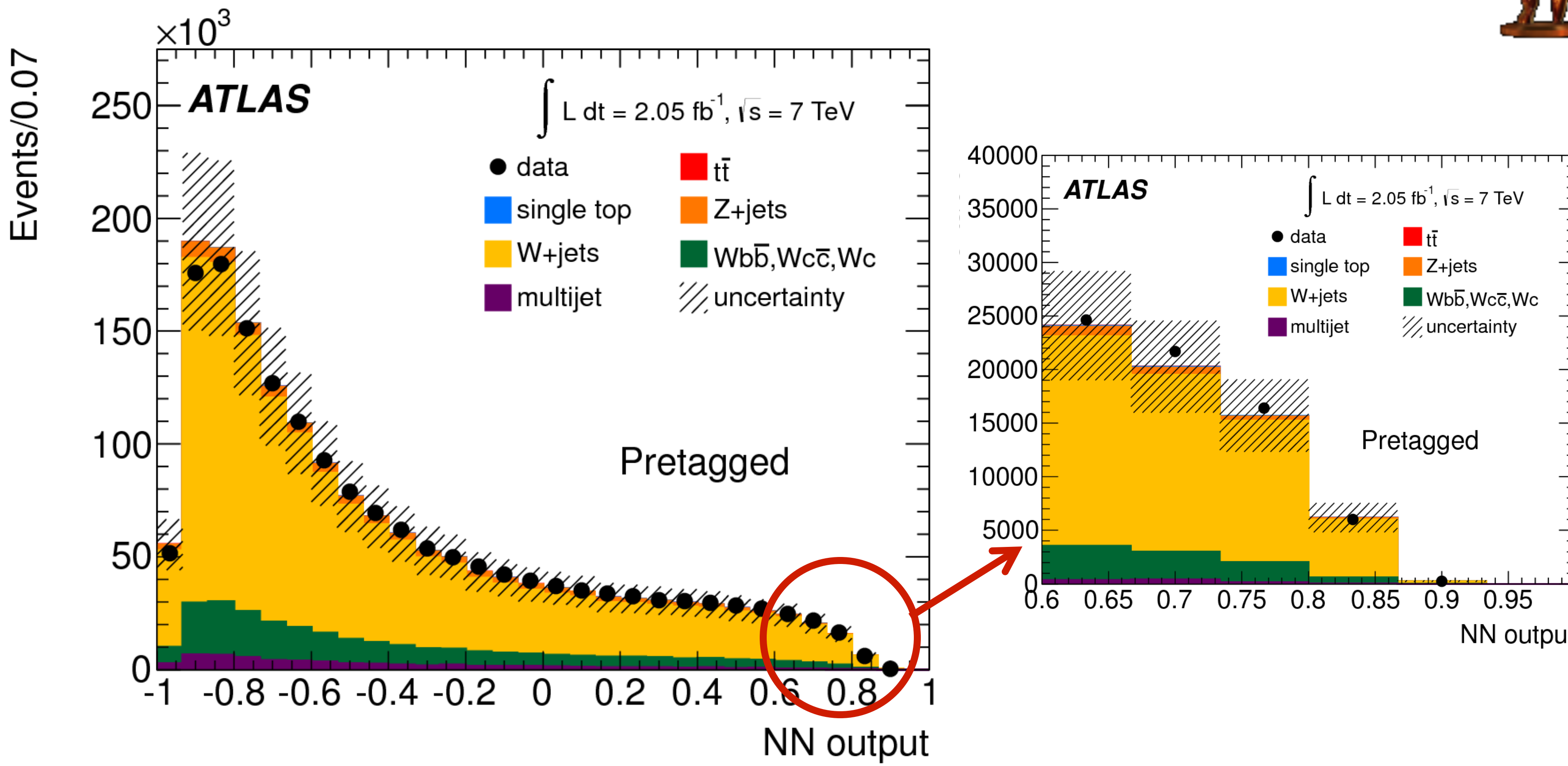






- Data agrees very well with MC

NN validation in the pretagged region



- The trained NN in tagged samples is applied on the pretagged sample
- Very good agreement between data and MC

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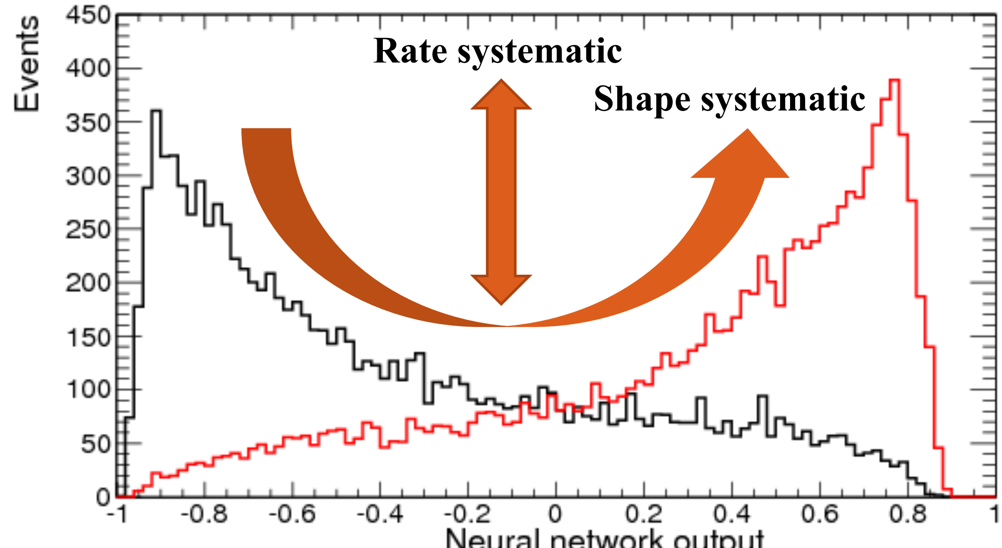
Signal extraction

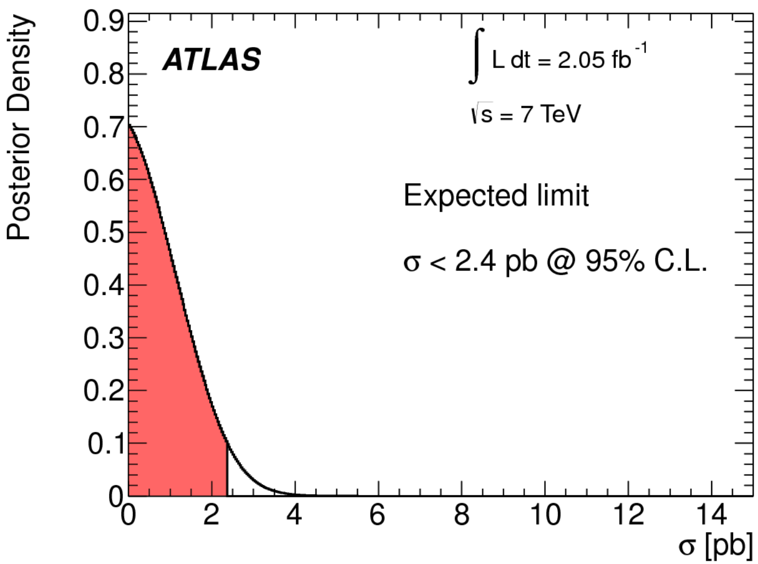
- **Bayesian statistics** is used to calculate the signal posterior probability density function
- Binned Likelihood performed on the full NN output distributions
- Type of systematic uncertainties:
  - rate systematic uncertainties of each background processes
  - shape systematics which affects the signal and background templates
- Systematics uncertainties are included as nuisance parameters taking into account the correlations between electron and muon channels
- Systematic uncertainties included with **Gaussian priors**

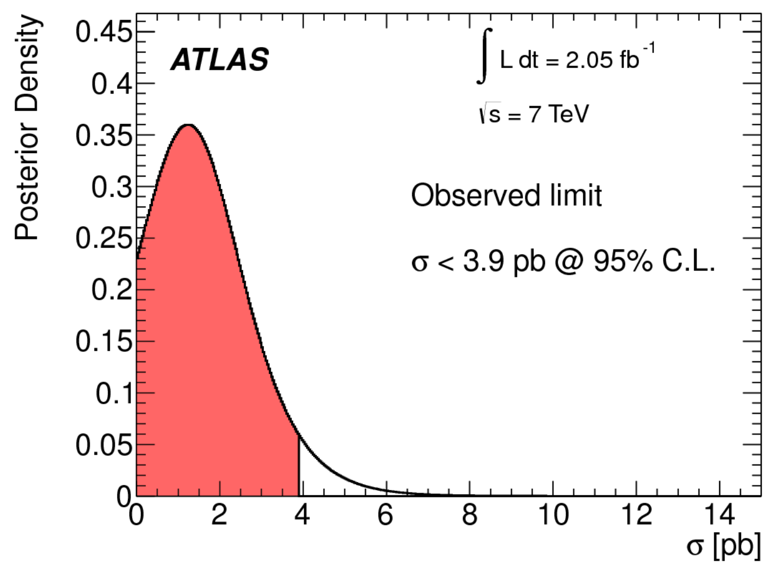


Cross section upper limit

- Pseudo-data sets are created from the background templates
- Signal is not included (Null hypothesis)

No signal is observed and an upper limit at 95% C.L. is calculated (red shaded area)



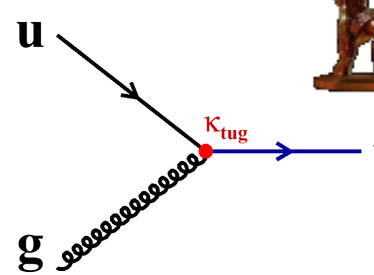


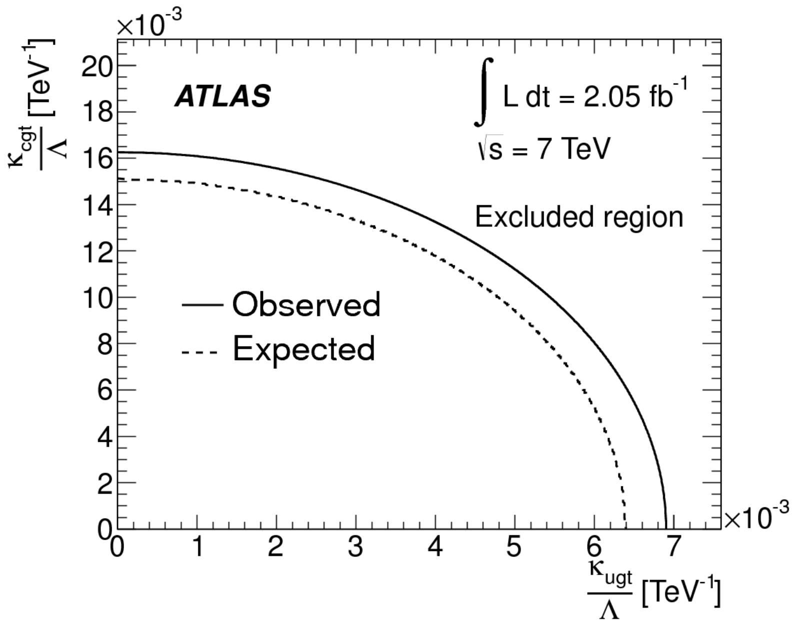
- The expected upper limit is **2.4 pb**
- The observed upper limit is **3.9 pb**

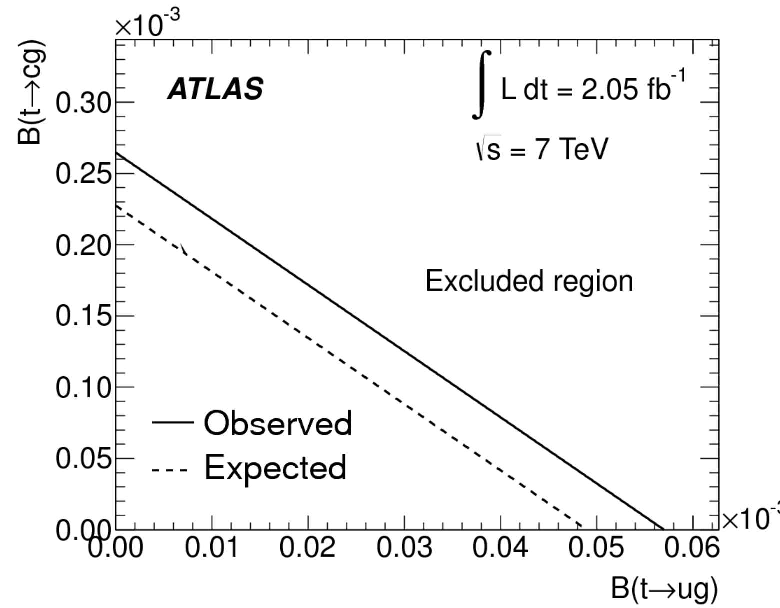
Dominant systematic uncertainties:
- Jet energy scale
- ISR/FSR
- b-tagging efficiency and mis-tag rate

Interpretation of the results

$$\mathcal{L}_1 = g_s \sum_{q=u,c} \frac{\kappa_{gqt}}{\Lambda} \bar{t}\sigma^{\mu\nu}\lambda^a (f_q^L P_L + f_q^R P_R) G_{\mu\nu}^a q + h.c.$$







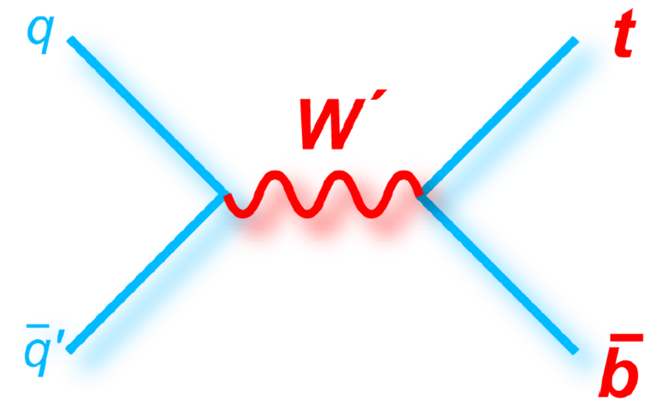
$\kappa_{ugt}/\Lambda < 6.9 \cdot 10^{-3}\ \mathrm{TeV}^{-1}$ $\mathrm{Br}(t \to ug) < 5.7 \cdot 10^{-5}$

$\kappa_{cgt}/\Lambda < 1.6 \cdot 10^{-2}\ \mathrm{TeV}^{-1}$ $\mathrm{Br}(t \to cg) < 2.7 \cdot 10^{-4}$

Search for *tb* resonances at ATLAS using 1.04 fb^{-1}

- Extensions to SM predict extra W boson (**W'**)
- **W'** can have right-, left-handed coupling depends on the model

- **W'** is searched in ***tb*** resonance since many models predict it more strongly coupled to the third generation than the first and second generation
- Easier to suppress the background



A right-handed W'_R with SM like couplings is chosen as a benchmark model in the search for ***tb*** resonances

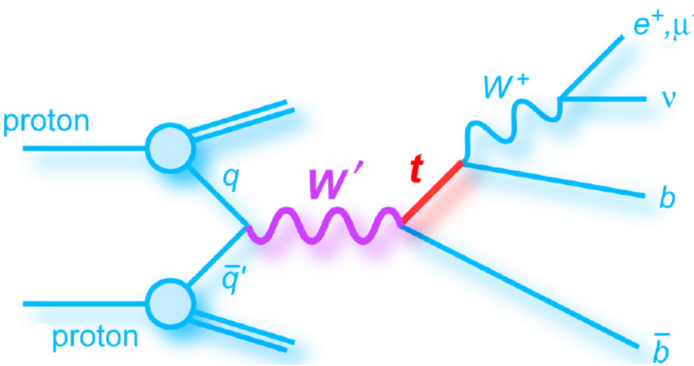
Phys.Rev.Lett. 109 (2012) 081801

NLO calculations

$m_{W'_R}$ [GeV]	$\mathcal{B}(W' \to tb)$	$\sigma \times \mathcal{B}$ [pb]
500	0.298	54.6 ± 2.1
750	0.319	10.9 ± 0.6
1000	0.326	2.92 ± 0.18
1250	0.328	0.91 ± 0.07
1500	0.330	0.31 ± 0.03
1750	0.331	0.11 ± 0.01
2000	0.332	0.04 ± 0.01

Z. Sullivan, Phys. Rev. D 66, 075011(2002)

Event Selection



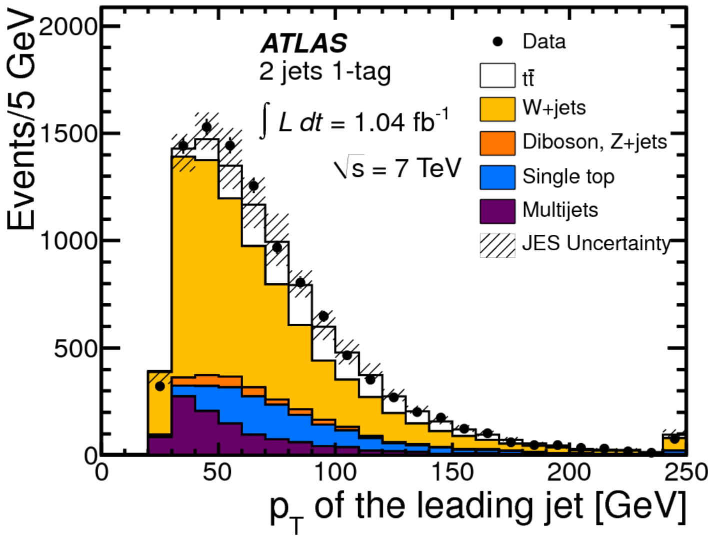
- One isolated lepton (electron / muon):
  - $P_T > 25$ GeV
- Missing transverse momentum
  - $E_T^{miss} > 25$ GeV
- Jets:
  - $P_T > 25$ GeV
  - **exactly two jets**
  - at least one identified b-quark jet
- Extra background reduction
  - $M_T(l\nu) + E_T^{miss} > 60$ GeV

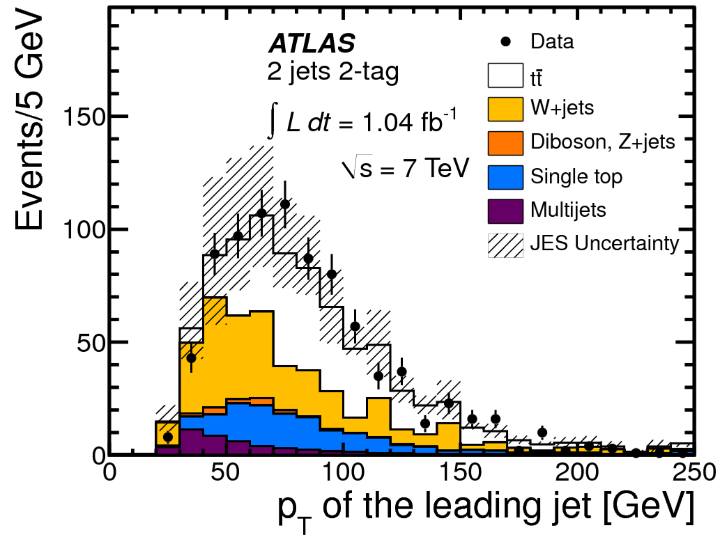
Samples	Single-tagged	Double-tagged
$W+$ jets	5970 ± 1000	290 ± 180
Multijets	1120 ± 560	47 ± 47
$t\bar{t}$	1560 ± 130	360 ± 30
Single top	1240 ± 90	120 ± 10
Diboson, Z+jets	320 ± 120	14 ± 2
Total prediction	10200 ± 1200	830 ± 190
Data	10428	844

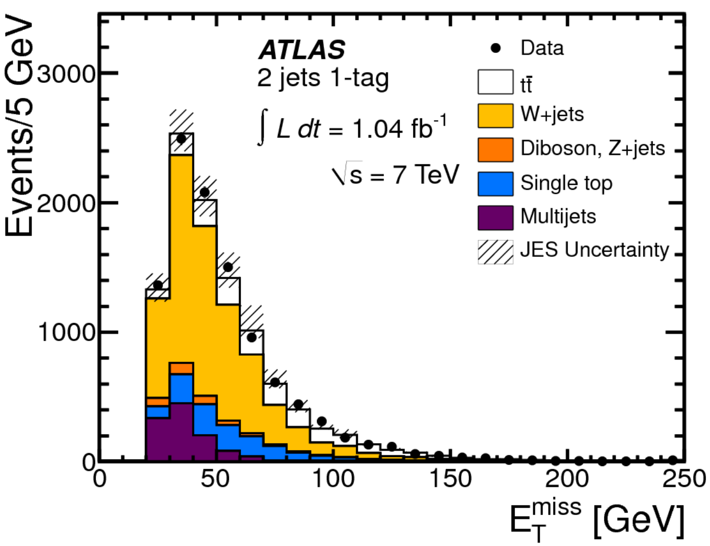
➢ Background and data yields agree within uncertainties

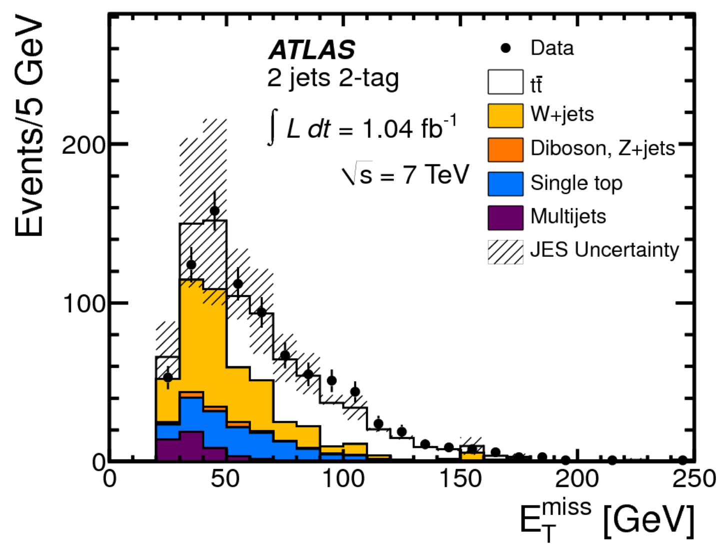
Kinematic plots

Single-tagged **Double-tagged**





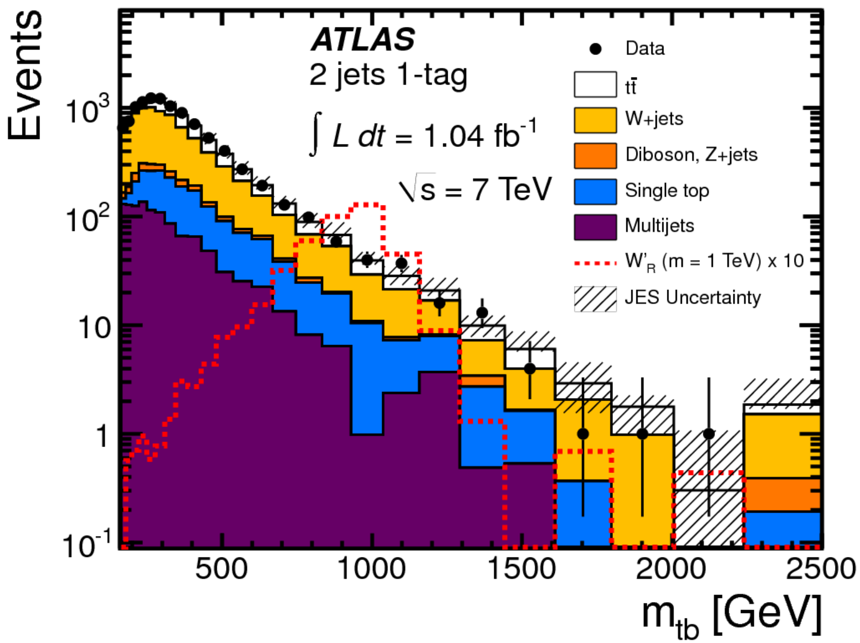




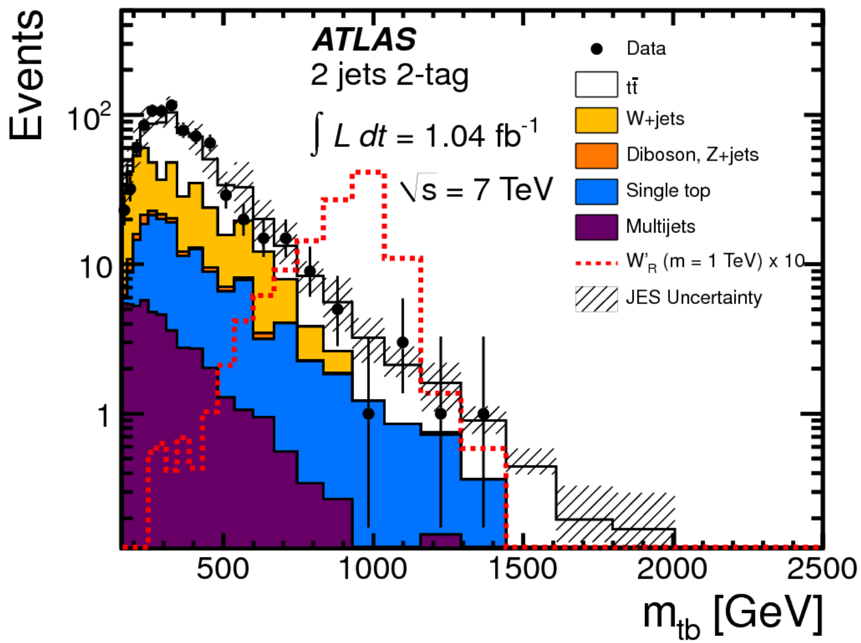
Search for *tb* resonances

- Data and MC compared using the invariant mass distributions for the ***tb*** system
- Single and double tagged events used separately

Single-tagged



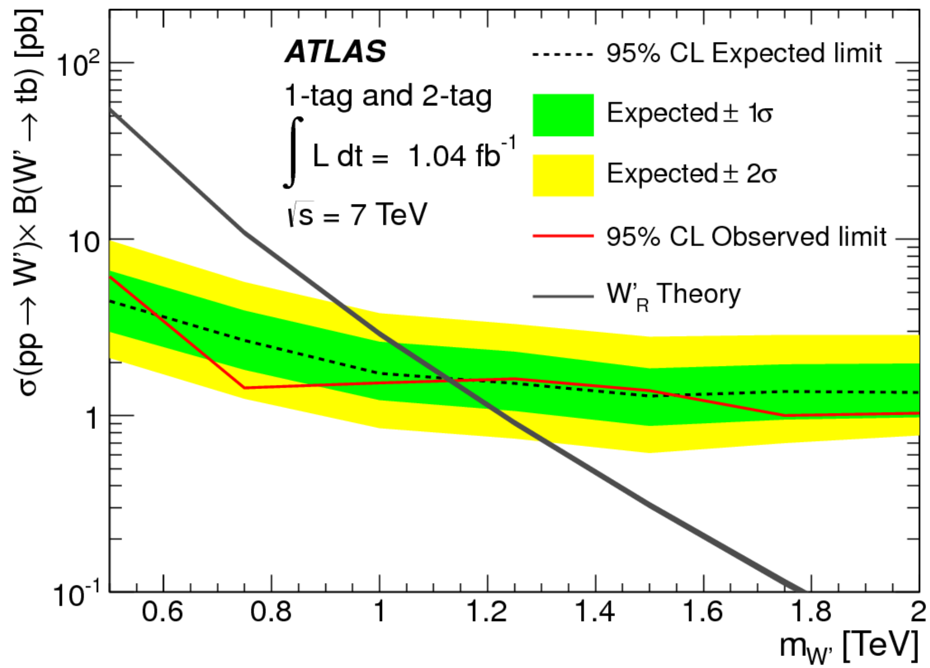
Double-tagged



➢ **No significant excess is observed**

Limits on the W'_R mass

- **Bayesian approach** is used to calculate the cross section upper limits at 95% C.L.
- Binned Likelihood performed on the full **m_{tb}** distributions using 1tag and 2tag distributions
- Shape and normalization systematic uncertainties are considered
- Systematic uncertainties included with **Gaussian priors**
- Observed cross section upper limit **6.1-1.0** pb for ***W'$_R$*** masses between 0.5 and 2.0 TeV
- Observed mass lower limit $M_{W'_R}$ > **1.13** TeV

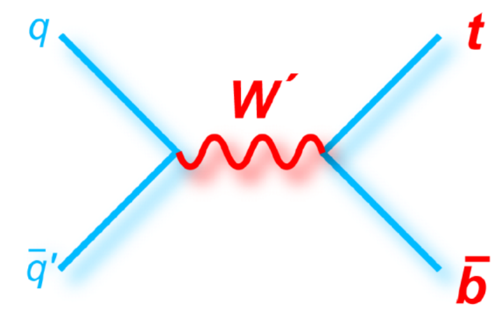


Dominant systematic uncertainties:
- Jet energy scale
- b-tagging scale factor uncertainties
- background cross section uncertainties

Search for W' resonances at CMS using 5 fb^{-1}

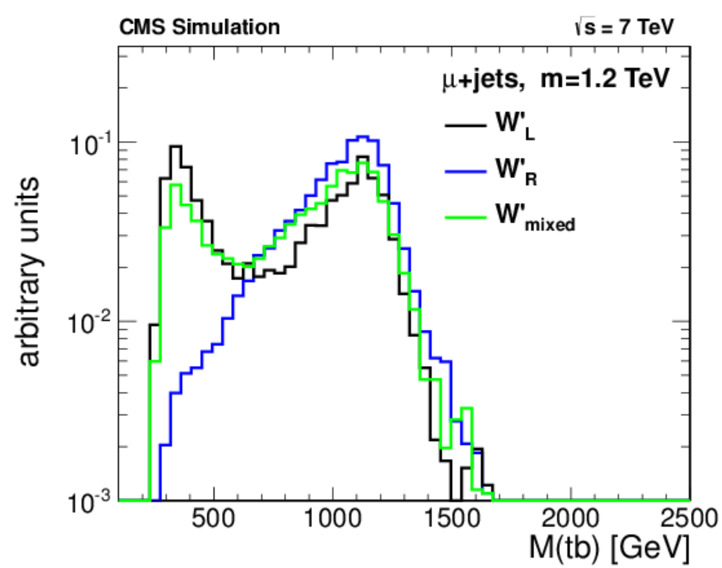
arXiv:1208.0956v1 [hep-ex]

A search for **W'** is done including an arbitrary combination of left- and right-handed couplings to fermions



- SM **W** boson and **W'** boson with left-handed couplings both contribute to single top quark production, the interference can be 5-20%

- D0 searched for **W'** boson assuming both left-handed and right-handed couplings:
  - cross section upper limits are 0.10-1.3 pb for masses between 0.6 and 1 TeV
  - lower limit on the W' mass is 916 GeV assuming SM-like couplings



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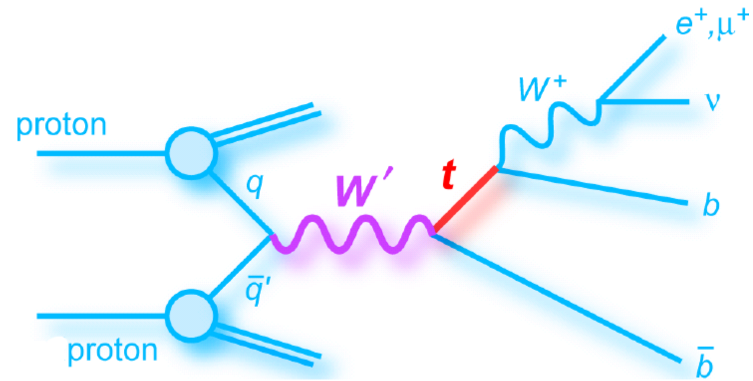
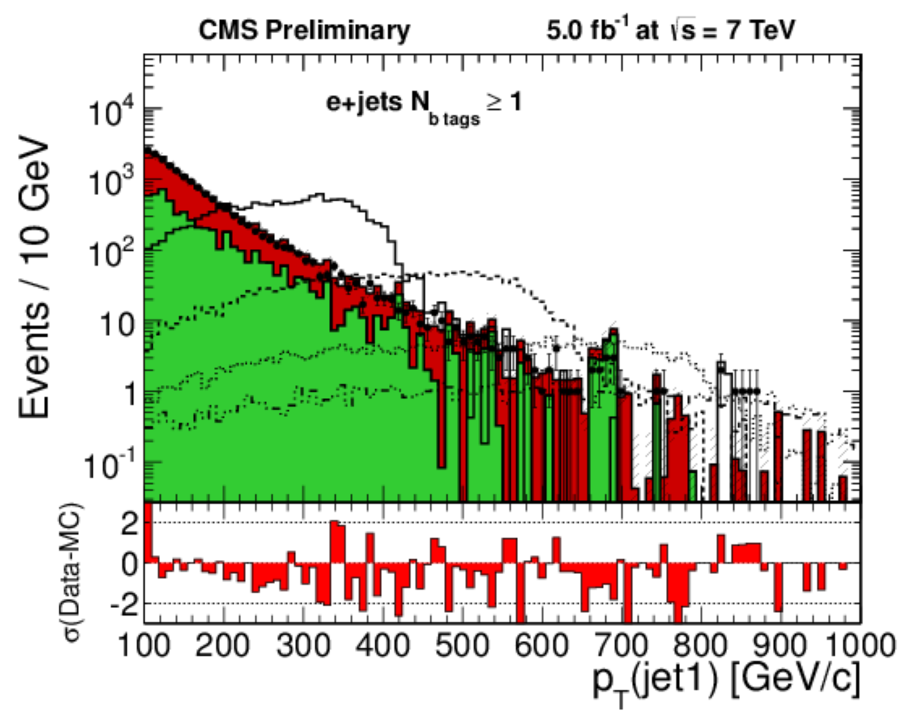
Event Selection

- One isolated high P_T lepton (electron / muon)
  - $P_T > 35$ GeV for electrons
  - $P_T > 32$ GeV for muons
- Missing transverse momentum
  - $E_T^{miss} > 20$ (35) GeV for muon (electron) channel
- At least two Jets
  - $P_T > 100$ GeV for the leading jet
  - $P_T > 40$ GeV for the second leading jet
- At least one identified b-quark jet
- Additional cuts:
  - $P_T^{top} > 75$ GeV
  - $P_T^{jet1,jets2} > 100$ GeV
  - $130 < M_{top} < 210$ GeV





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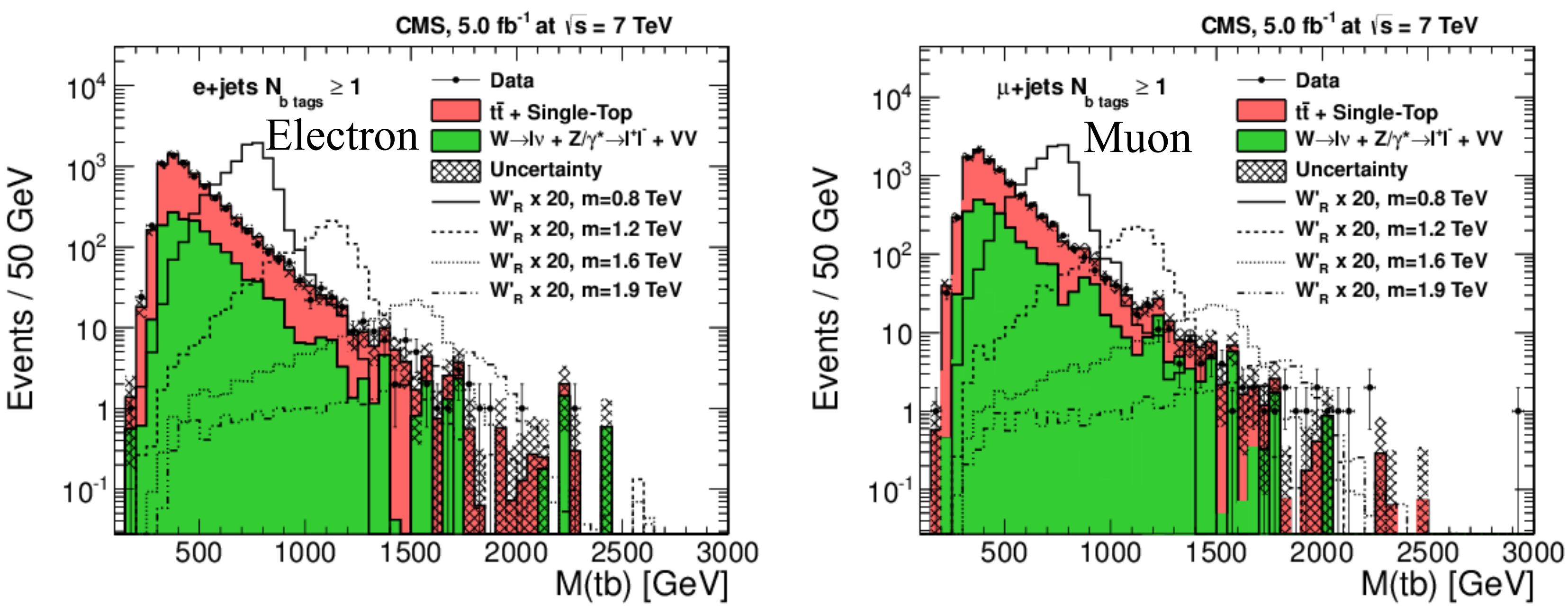
Event Yields

Process	Number of events					
	e+jets			μ+jets		
	b-tagged jets		Additional	b-tagged jets		Additional
Signal	=1	≥ 1	selection	$= 1$	≥ 1	selection
W'_R (0.8 TeV)	405	631	463	539	838	605
W'_R (1.2 TeV)	63	90	68	76	109	81
W'_R (1.6 TeV)	11	14	11	11	15	11
W'_R (1.9 TeV)	3	4	3	3	4	3
						Background
$t\bar{t}$	8496	10659	4795	13392	16957	6692
t-channel	587	686	300	1047	1223	442
s-channel	46	73	32	81	134	51
tW-channel	549	628	270	886	1007	395
$W(\rightarrow)\ell\nu$+jets	4588	4760	1404	8673	9023	2350
$Z\gamma^*(\rightarrow \ell\ell)$+jets	164	173	68	388	414	135
Diboson	51	52	17	77	79	27
Multijet QCD	104	225	0	121	121	0
Total background	14585±3199	17256±3780	6886±1371	24665±4917	28958±5765	10092±1807
Data	14337	16758	6638	23979	28392	9821

- Background and data yields agree within uncertainties

tb invariant mass analysis

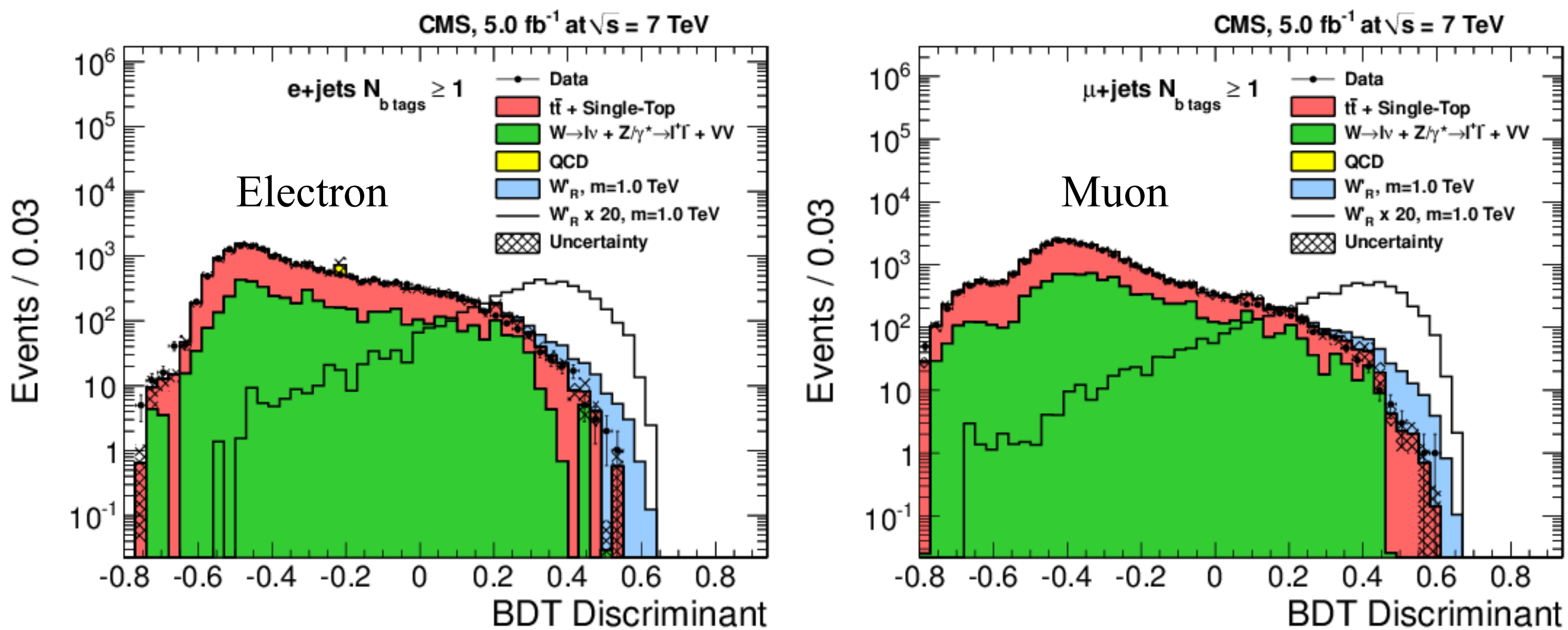
- The top quark invariant mass built from the combination of the **W** boson with the jets closest to the 172.5 GeV
- The **W'** invariant mass is constructed from the top quark and the highest P_T jet remaining after constructed the top quark



➤ Good agreement between data and predicted background

BDT analysis

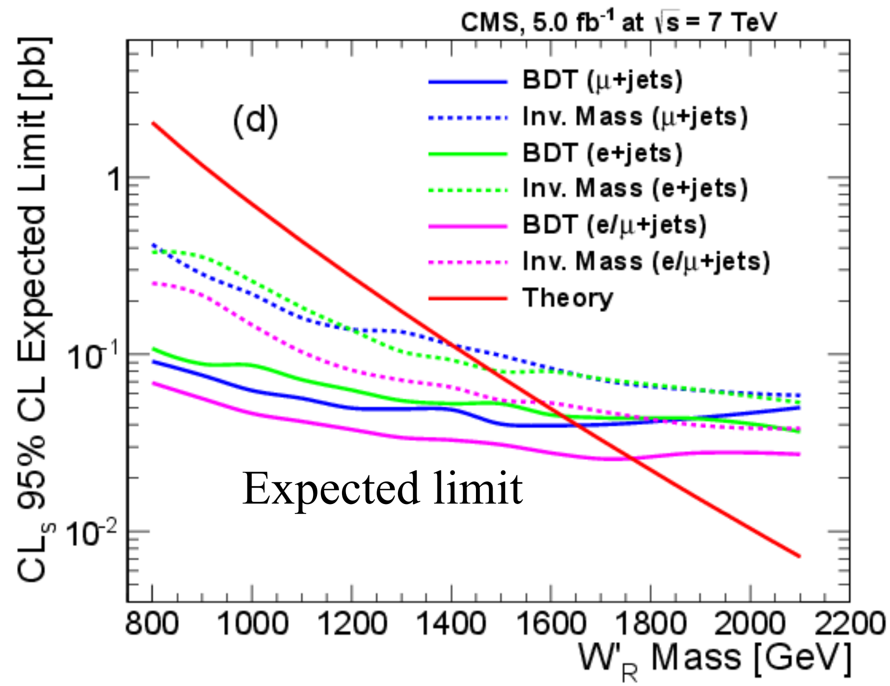
- Boosted Decision Tree (BDT) used to distinguish between the signal **W'** and the background
- BDT is trained at each **W'** mass point and for each type of coupling separately for electron and muon channels
- 39 kinematic variables used to train BDT



Cross section upper limit

- The **CLs method** is used to calculate cross section upper limits at 95% C.L.
- Binned Likelihood performed on the full **W'** Invariant mass distributions and BDT distributions
- Both shape and normalization systematic uncertainties taken into account

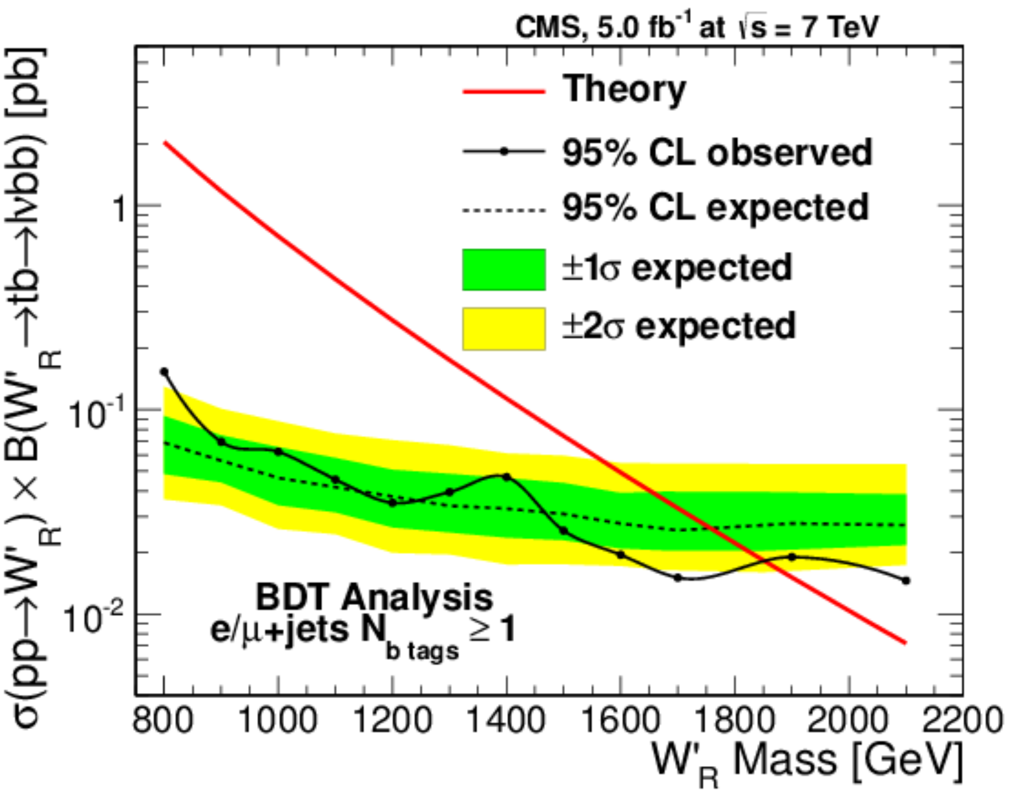
- Systematic uncertainties included with log-normal priors
- W+ light quarks jets and W+ heavy quark jets has the largest impact on the cross section limit estimation
- Less dominant systematic uncertainties
  - jet energy scale
  - b-tagging efficiency
  - mis-tag rate



➢ **BDT gives better results than invariant mass analysis**

Results from the BDT analysis

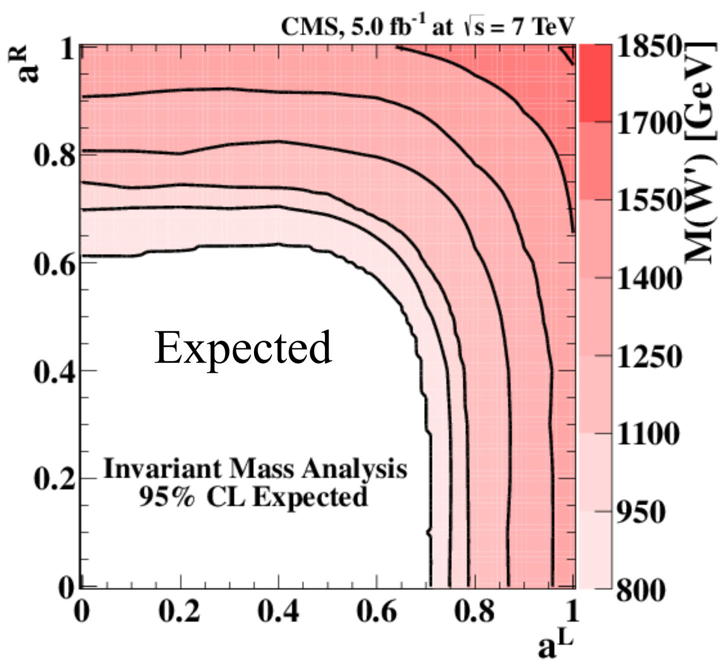
- For **W'** boson with right-handed couplings to fermions, lower mass limit is **1.85 TeV**
- For the W' boson with left-handed coupling, the lower mass limit is **1.85 TeV** without interference with SM

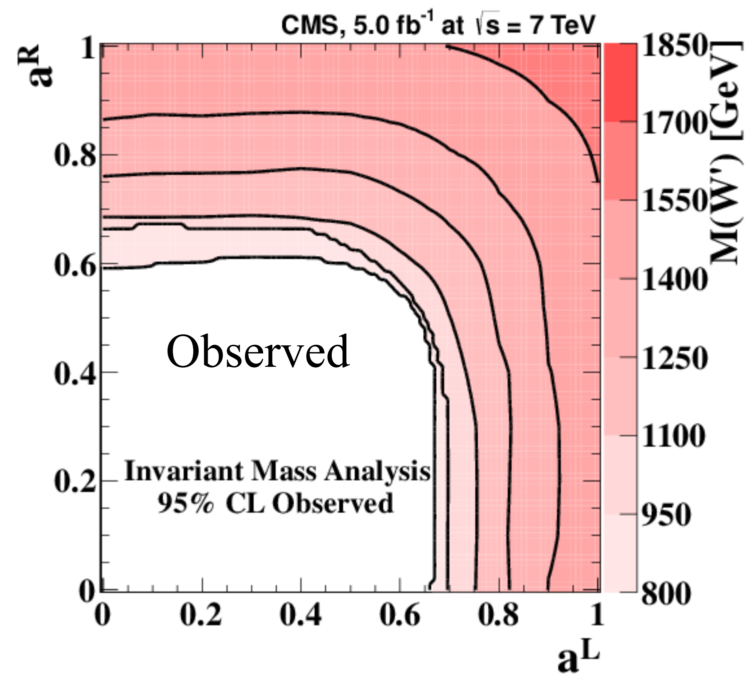


Interpreting the result

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \overline{f}_i \gamma_\mu \left(a^R_{f_i f_j}(1+\gamma^5) + a^L_{f_i f_j}(1-\gamma^5) \right) W'^\mu f_j + \text{H.c.}$$

- The coupling with ***ud*** quarks are assumed to be equal to the coupling with ***tb*** quarks
- The cross section upper limits are converted to upper limits on the coupling assuming arbitrarily combinations of $\boldsymbol{a^R}$ and $\boldsymbol{a^L}$ for each mass point





Muhammad Alhroob

Summary

Search for FCNC:

- 2.05 fb^{-1} of ATLAS data collected in 2011 used
- neural network: σ_{FCNC} < **3.9 pb** @ 95% C.L
- improves the previous limits on the branching fractions by a factor of 4 and a factor of 15 for ***ugt*** and ***cgt*** channels, respectively

Search for $\mathbf{W'_R}$ at ATLAS using 1.04 fb^{-1} of data collected in 2011:

- invariant mass of ***tb*** system is used to perform the analysis
- $M_{W'_R}$ > **1.13 TeV**

Search for W' at CMS using 5.0 fb^{-1} of data collected in 2011:

- CLs method used to calculate the cross section upper limits @95% C.L for $\mathbf{W'_R}$, $\mathbf{W'_L}$ and arbitrary combination of left- and right handed couplings to fermions
- BDT used to suppress the background: mass lower limit **1. 85 TeV** @95% C.L.
- the results of the ***tb*** invariant mass analysis used to calculate the upper limits on the left-handed and right-handed couplings for the first time

Q&A

Thank you.

Input variables for NN

Variable	Significance (σ)
p_T^W	57
ΔR(b-jet,lep)	28
Lepton charge	22
m_{top}	20
m_{b-jet}	15
η_{b-jet}	12
$\Delta\phi$(W,b-jet)	11
p_T^{lep}	12
p_T^{b-jet}	6.5
$\cos\theta^*$	5.7
ΔR(W,b-jet)	5.0

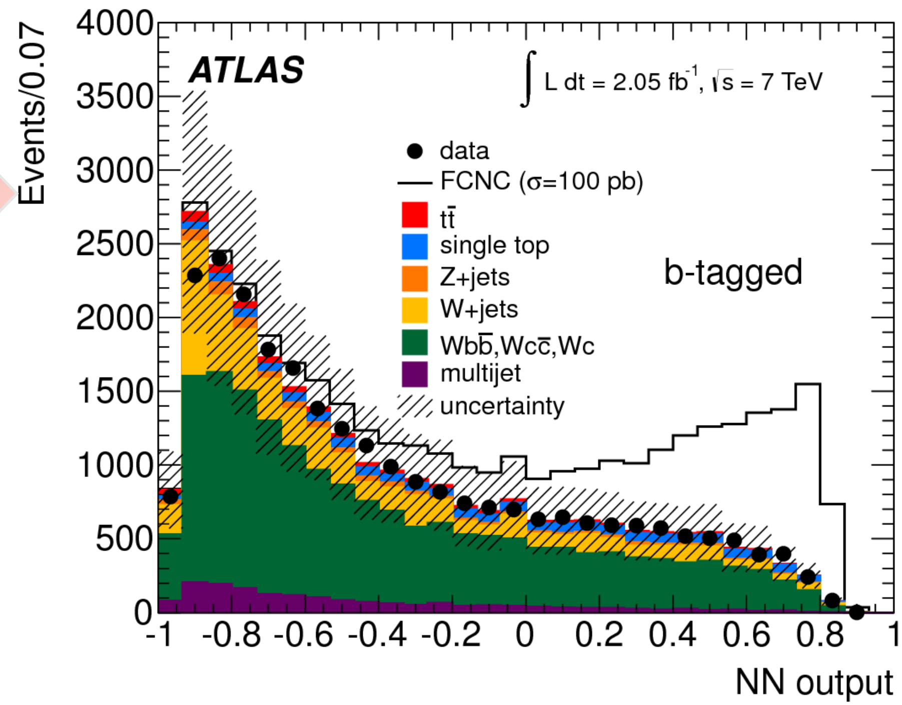
11 discriminating variables

Significance

NN

Signal signature:

- P_T (top) ~ 0 (W and b are back-to-back)
- P(W) is large
- 4× more top than anti-top quarks



- Six background templates, one for each background process
- One signal template

Input variables for BDT

Object kinematics	Event kinematics
η(jet1)	Aplanarity(alljets)
p_T(jet1)	Sphericity(alljets)
η(jet2)	Centrality(alljets)
p_T(jet2)	M(btag1,btag2,W)
η(jet3)	M(jet1,jet2,W)
p_T(jet3)	M(alljets)
η(jet4)	M(alljets,W)
η(lepton)	M(W)
p_T(lightjet)	M(alljets,lepton,E_T^{miss})
p_T(lepton)	M(jet1,jet2)
η(notbest1)	M_T(W)
p_T(notbest1)	p_T(jet1,jet2)
p_T(notbest2)	p_T(jet1,jet2,W)
E_T^{miss}	p_z/H_T(alljets)
Top quark reconstruction	**Angular correlations**
$M(W, \text{btag1})$ ("btag1" top mass)	$\Delta\phi$(lepton,jet1)
$M(W, \text{best1})$ ("best" top mass)	$\Delta\phi$(lepton,jet2)
$M(W, \text{btag2})$ ("btag2" top mass)	$\Delta\phi$(jet1,jet2)
$p_T(W, \text{btag1})$ ("btag1" top p_T)	cos(best,lepton)$_{\text{besttop}}$
$p_T(W, \text{btag2})$ ("btag2" top p_T)	cos(light,lepton)$_{\text{besttop}}$
	ΔR(jet1,jet2)