

Probing new physics at the LHC: searches for heavy top-like quarks with the ATLAS experiment

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Bellaterra, 28th of February, 2014

Four questions, one dissertation

- ▶ Why? bother with “new physics”

Four questions, one dissertation

- ▶ **Why?** bother with “new physics”
- ▶ **Where?** is all happening

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- ▶ **What?** are we looking at

Four questions, one dissertation

- ▶ **Why?** bother with “new physics”
- ▶ **Where?** is all happening
- ▶ **What?** are we looking at
- ▶ **How?**

Outline

Theoretical framework

The ATLAS experiment at the LHC

Monte Carlo simulation

Event reconstruction

Searches for $T\bar{T}$ in single lepton channel

Search for $T\bar{T}$ decaying to $Wb + X$

Search for $T\bar{T}$ decaying to $Ht + X$

Combined results

Conclusions and outlook

Standard Model as an effective theory

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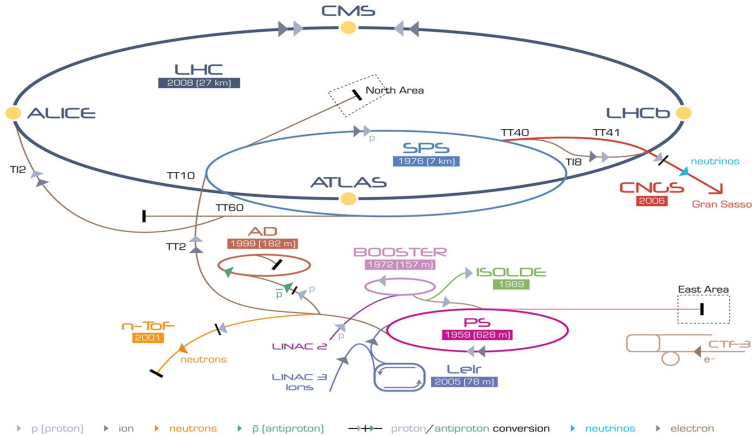
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The LHC complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF-3 Clic Test Facility CNGS CERN Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine Device
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-Tbf Neutrons Time Of Flight

The LHC complex



Parameter	designed	2010	2011	2012
Beam energy (TeV/c)	7	3.5	3.5	4
Beta function β^* (m)	0.55	2.0/3.5	1.5/1.0	0.6
Max. No. bunches/beam	2808	368	1380	1380
Max. No. protons/bunch	1.15×10^{11}	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}
Bunch spacing (ns)	25	150	75/50	50
Peak luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	1×10^{34}	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}
Emittance ε_n (μrad)	3.75	2.0	2.4	2.5
Max. $\langle \mu \rangle$	19	4	17	37

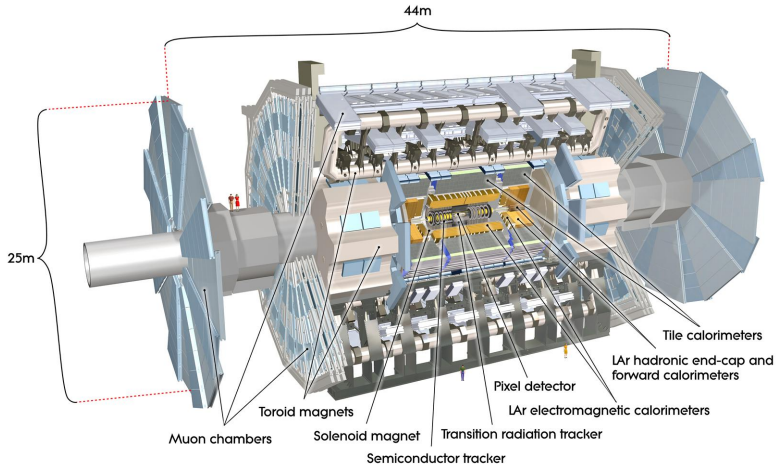


▶ p (proton) ▶ ion ▶ neutrons ▶ \bar{p} (antiproton) \leftrightarrow proton/antiproton conversion ▶ neutrinos ▶ electron

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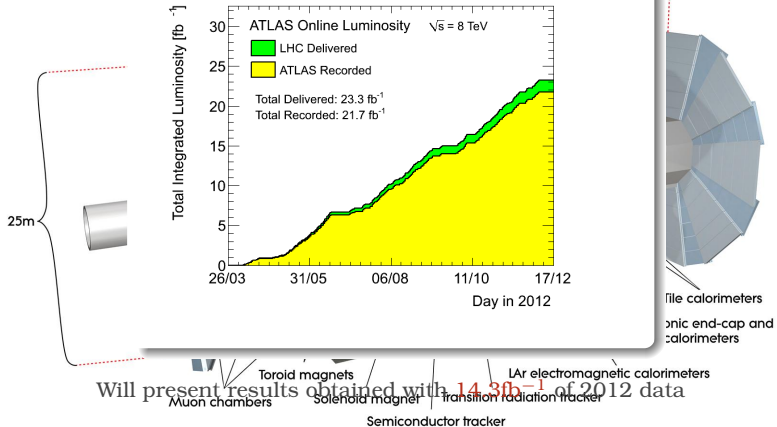
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The ATLAS Detector



The ATLAS Detector

In 2012 21.7fb^{-1} collected at $\sqrt{s} = 8\text{ TeV}$!



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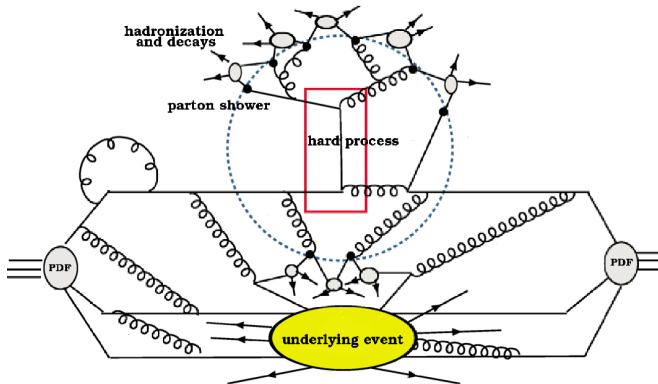
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Modelling of hadron collisions

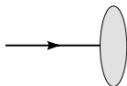
want to do physics at hadron colliders?
need a good understanding of incoming hadrons



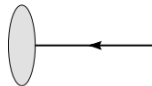
Modelling of hadron collisions

Drawings from [1]

$$E(p_1) = 4 \text{ TeV}$$



$$E(p_2) = 4 \text{ TeV}$$

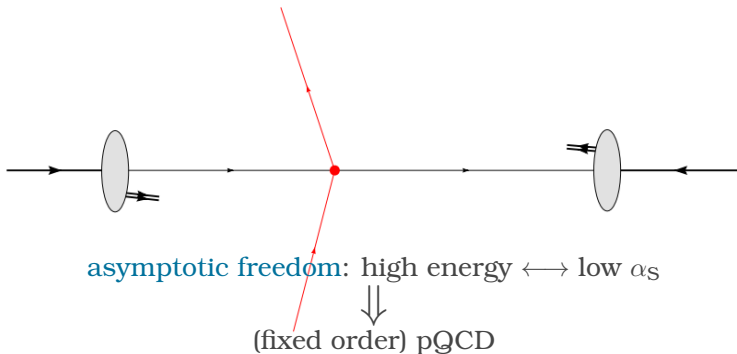


Quarks are distributed according to PDFs inside the proton

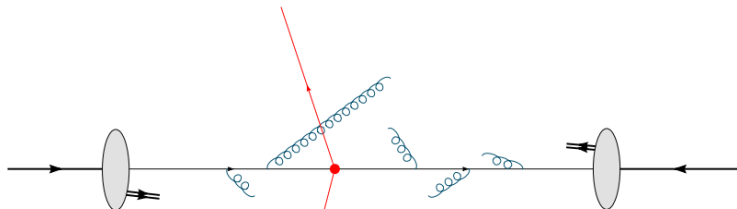


initial energy unknown

Hard scattering of two partons



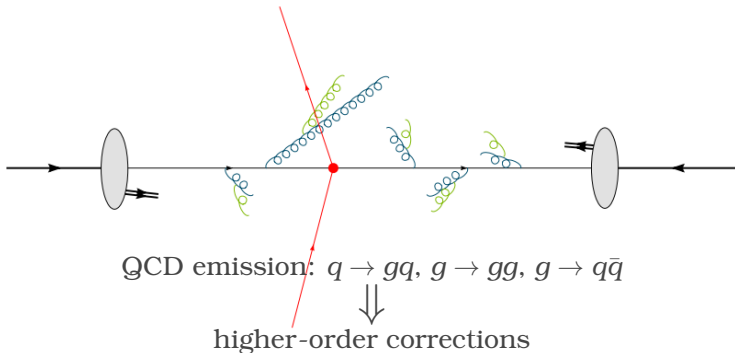
Parton showering



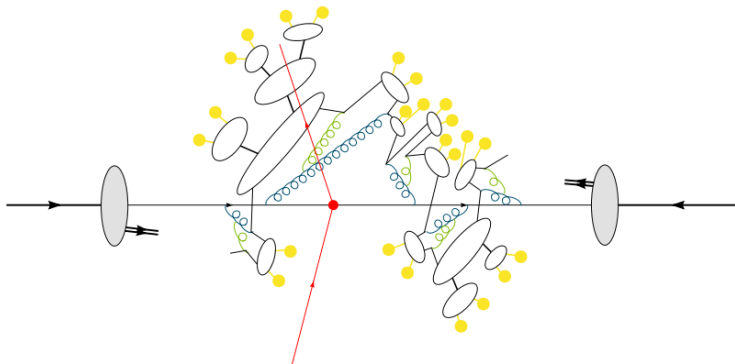
QCD emission: $q \rightarrow gq$, $g \rightarrow gg$, $g \rightarrow q\bar{q}$

↓
higher-order corrections

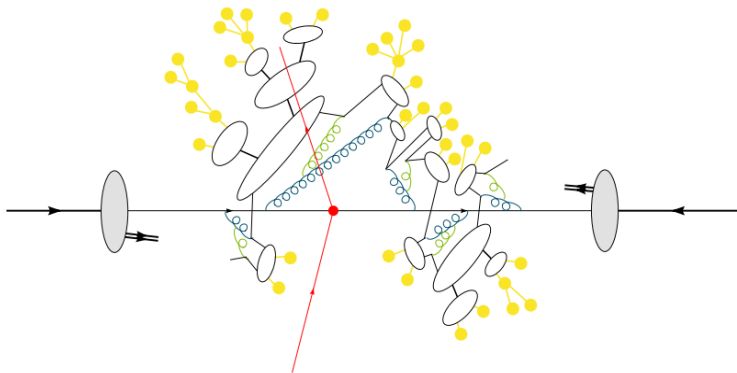
Parton showering



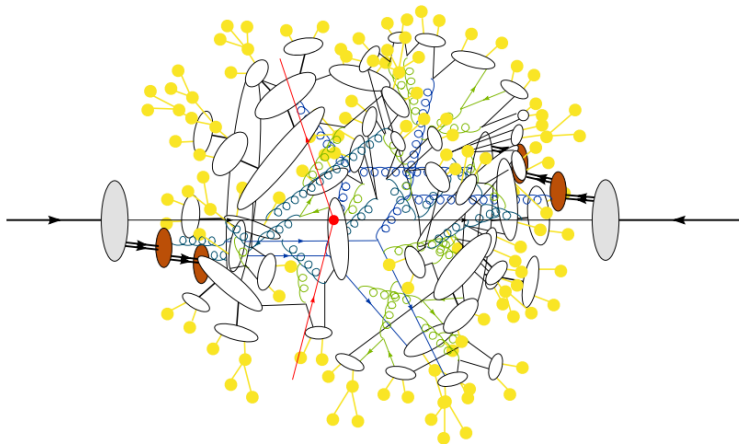
Hadronization



Final particle decays



Underlying event simulation



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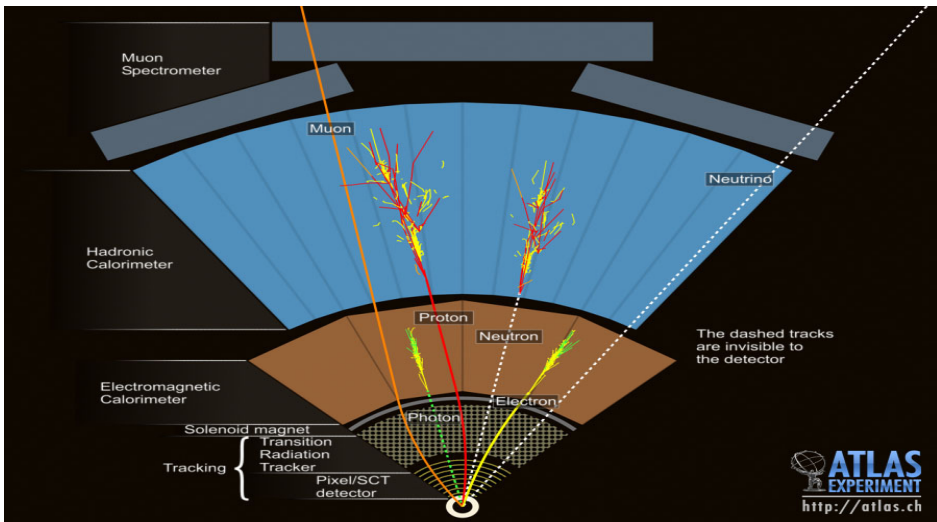
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Physics objects puzzle



One lepton

Many jets

Missing transverse energy

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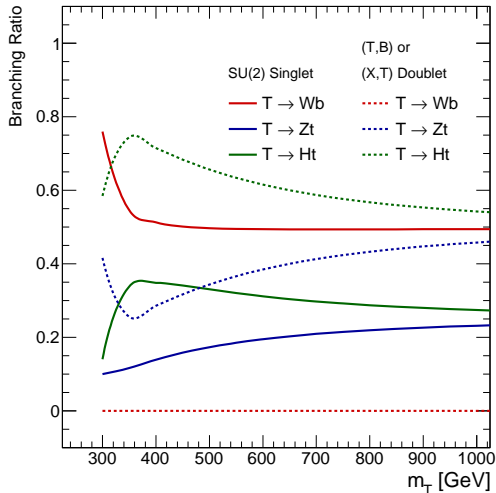
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Allowed decay modes

Singlet	Decay modes
$T(+2/3)$	$W^+ b, Ht, Zt$
$B(-1/3)$	$W^- t, Hb, Zb$
$X(+5/3)$	$W^+ t$
$Y(-4/3)$	$W^- b$
Doublet	Decay modes
$\begin{pmatrix} T \\ B \end{pmatrix}$	$W^+ b, Ht, Zt$ $W^- t, Hb, Zb$
$\begin{pmatrix} T \\ X \end{pmatrix}$	Ht, Zt $W^+ t$
$\begin{pmatrix} B \\ Y \end{pmatrix}$	Hb, Zb $W^- b$

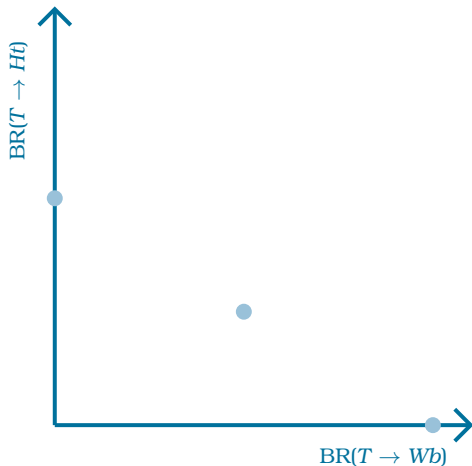


Model Independent Strategy

- Build a 2-dim plane to scan model mixing

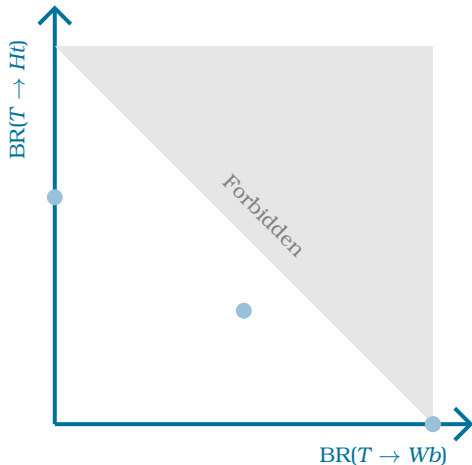


Model Independent Strategy



- Build a 2-dim plane to scan model mixing

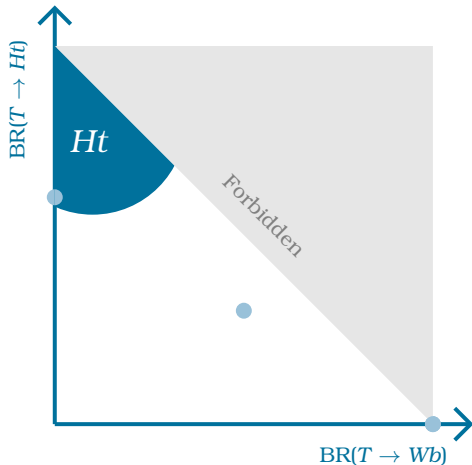
Model Independent Strategy



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1^(a)

$$^{(a)} \text{BR}(T \rightarrow Zt) = 1 - \text{BR}(T \rightarrow Ht) - \text{BR}(T \rightarrow Wb)$$

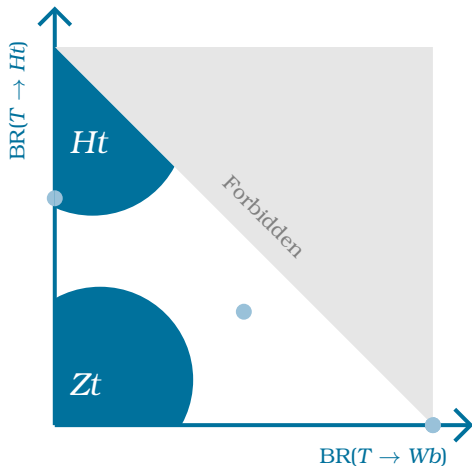
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- Build a 2-dim plane to scan model mixing
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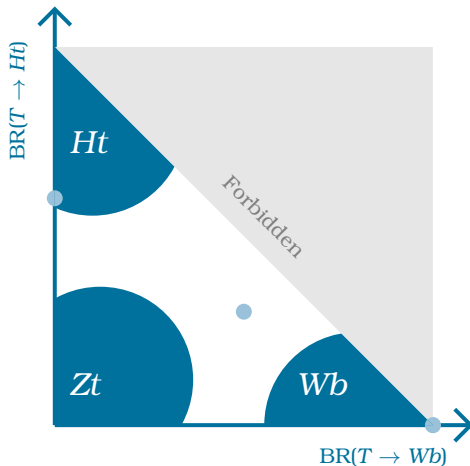
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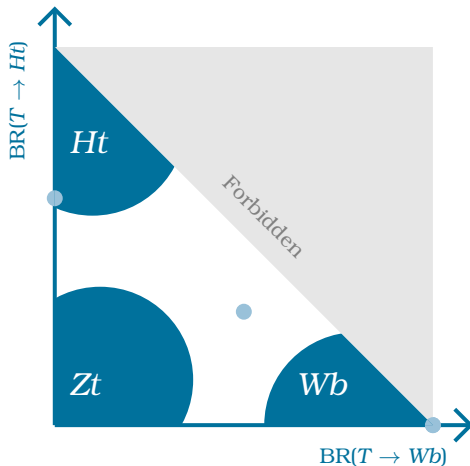
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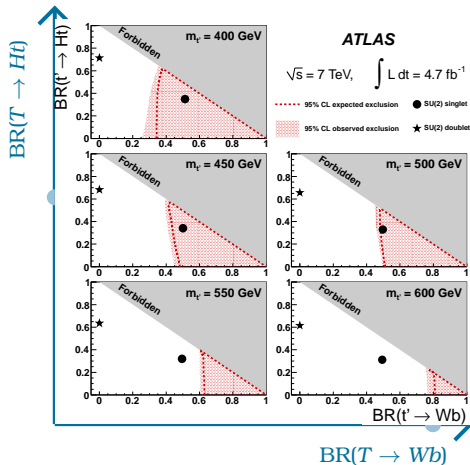
Model Independent Strategy



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1^(a)
- Different analyses are sensitive to different areas
- Set exclusion using CL_s technique [2, 3]

$$^{(a)} BR(T \rightarrow Zt) = 1 - BR(T \rightarrow Ht) - BR(T \rightarrow Wb)$$

Model Independent Strategy



- Build a 2-dim plane to scan model mixing
- Sum of BRs is $1^{(a)}$
- Different analyses are sensitive to different areas
- Set exclusion using CL_s technique [2, 3]
- First published results at 7 TeV *Phys.Lett.* **B718** (2012) [4]

$^{(a)} \text{BR}(T \rightarrow Zt) = 1 - \text{BR}(T \rightarrow Ht) - \text{BR}(T \rightarrow Wb)$

Preselection

Two searches using common analysis framework:

► $T\bar{T} \rightarrow Wb + X$

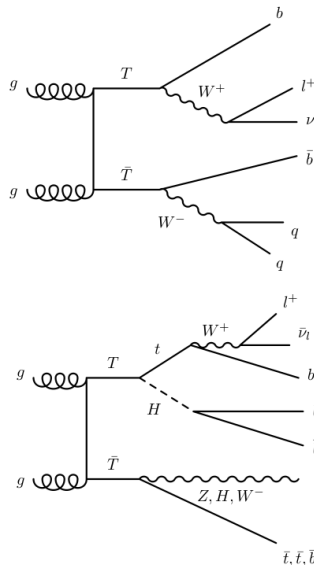
► $T\bar{T} \rightarrow Ht + X$

ATLAS-CONF-2013-060 [5]

ATLAS-CONF-2013-018 [6]

Preselection stage	Requirements
Single lepton	One electron or muon matching trigger
QCD rejection	$E_T^{\text{miss}} > 20 \text{ GeV}$ $E_T^{\text{miss}} + m_T > 60 \text{ GeV}$
Jet multiplicity	≥ 4 jets ≥ 1 b -tagged jets

+ “orthogonality” requirements



Background and signal modelling

Yields in the preselection region “blinded” as:

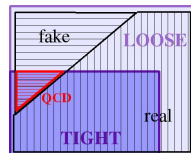
$$H_T^{Aj} < 800 \text{ GeV (*)}$$

$\geq 4 \text{ jets}, \geq 1 \text{ } b\text{-tags}$

Multi-jet	6264 ± 74
Single top	14375 ± 107
Diboson	548 ± 12
Z+jets	5804 ± 146
W+jets	35921 ± 525
$t\bar{t}V$	680 ± 2
$t\bar{t}H$ (125)	220 ± 1
$t\bar{t}$ MC@NLO	202042 ± 285
Tot Bkg w/ MC@NLO	265854 ± 629
$T\bar{T}$ (600) chiral	36 ± 2
Data	256993 ± 507

$$(*) H_T^{Aj} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

- QCD multi-jet events have high cross-section
- Data-drive estimation
- Matrix-method



$$N_{\text{fake}}^{\text{tight}} = \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} (N^{\text{loose}} \epsilon_{\text{real}} - N^{\text{tight}})$$

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- ▶ s-channel and Wt production generated with MC@NLO+HERWIG
- ▶ t -channel generated with ACERMC+PYTHIA
- ▶ $m_t = 172.5 \text{ GeV}$
- ▶ NNLO theoretical cross sections

$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

Background and signal modelling

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- Diboson production generated with HERWIG
- NLO theoretical cross section

$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

Background and signal modelling

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- ▶ Z boson production in association with jets generated with up to five additional partons with ALPGEN+HERWIG
- ▶ Samples generated separately for Z+light jets, $Zb\bar{b}$ +jets, and $Zc\bar{c}$ +jets
- ▶ Inclusive NNLO theoretical cross section

$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

Background and signal modelling

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- ▶ W boson production in association with jets generated with up to five additional partons with ALPGEN+HERWIG
- ▶ Samples generated separately for W+light jets, $Wb\bar{b}$ +jets, $Wc\bar{c}$ +jets, and Wc+jets
- ▶ Normalized to data-driven prediction

$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

Background and signal modelling

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- ▶ $t\bar{t}$ produced in association with a W or Z boson generated with MADGRAPH+PYTHIA
- ▶ $m_t = 172.5 \text{ GeV}$
- ▶ NLO theoretical cross section

$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

Background and signal modelling

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- ▶ $t\bar{t}$ produced in association with a Higgs boson generated with PYTHIA
- ▶ $m_t = 172.5 \text{ GeV}$, $m_H = 125 \text{ GeV}$
- ▶ Higgs decay modes considered:
 $H \rightarrow b\bar{b}, c\bar{c}, gg, W^+W^-$
- ▶ NLO theoretical cross section

$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

Background and signal modelling

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$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

- ▶ $t\bar{t}$ pair production in association with jets generated with MC@NLO+HERWIG

- ▶ $m_t = 172.5 \text{ GeV}$

- ▶ NNLO theoretical cross section

but

MC@NLO does not model well high-jet multiplicity regions!

- ▶ Additional samples generated with ALPGEN+HERWIG
- ▶ Separate samples are generated for $t\bar{t}$ +light jets with up to three additional light partons, and for $t\bar{t}$ +heavy-flavour jets including $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$
- ▶ $m_t = 172.5 \text{ GeV}$
- ▶ NNLO theoretical cross section

Background and signal modelling

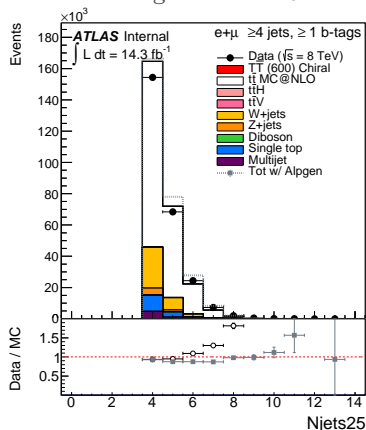
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$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

Yields for $t\bar{t}$ predicted with ALPGEN are
 $\sim 3\text{-}8\%$ higher than MC@NLO



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$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

- ▶ $T\bar{T}$ singlet production generated with PROTON+PYTHIA
- ▶ Branching ratio to each decay mode (Wb , Zt and Ht) is set to 1/3
- ▶ Events are reweighted at the analysis level in order to reproduce any desired branching ratio configuration
- ▶ m_T values generated from 350 GeV to 850 GeV in steps of 50 GeV
- ▶ $m_H = 125$ GeV, all Higgs boson decay modes are considered
- ▶ NNLO theoretical cross section

m_T (GeV)	$BR(T \rightarrow Wb)$	$BR(T \rightarrow Zt)$ Singlet	$BR(T \rightarrow Ht)$
600	0.494	0.194	0.312
600	0.000	Doublet 0.383	0.617

Systematic uncertainties - Shape and Norm

Systematic uncertainty	$T\bar{T} \rightarrow Wb + X$		$T\bar{T} \rightarrow Ht + X$	
	Status	Components	Status	Components
Luminosity	N	1	N	1
Lepton ID+reco+trigger	N	1	N	1
Jet vertex fraction efficiency	SN	1	SN	1
Jet energy scale	SN	1	SN	8
Jet energy resolution	SN	1	SN	1
b -tagging efficiency	SN	9	SN	9
c -tagging efficiency	SN	5	SN	5
Light jet-tagging efficiency	SN	1	SN	1
$t\bar{t}$ cross section	N	1	N	1
$t\bar{t}V$ cross section	N	1	N	1
$t\bar{t}H$ cross section	-	-	N	1
Single top cross section	N	1	N	1
Dibosons cross section	N	1	N	1
W +jets normalization	N	5	-	-
Z +jets normalization	N	1	-	-
V +jets normalization	-	-	N	1
Multijet normalization	-	-	N	1
$t\bar{t}$ modelling	SN	3	SN	3
V +jets modelling	SN	1	-	-
$t\bar{t}$ +heavy-flavour fractions	-	-	N	1

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Search for $T\bar{T}$ decaying to $Ht + X$

Combined results

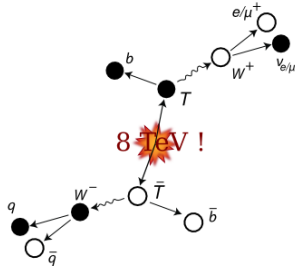
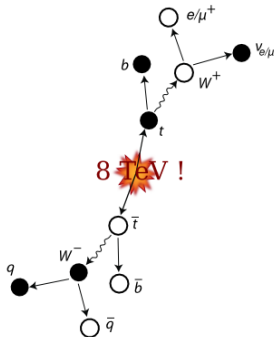
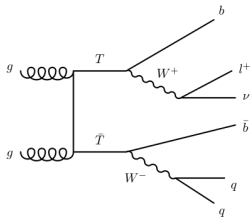
Conclusions and outlook

Strategy

$$T\bar{T} \rightarrow WbWb$$

like

$$t\bar{t} \rightarrow WbWb$$



different **boosted kinematics**

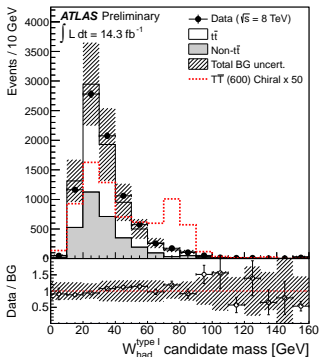
reconstruct the W boson from hadronic decay

$$\Delta R \sim \frac{2m}{p_T}$$

reconstruct heavy quark mass

W boson reconstruction

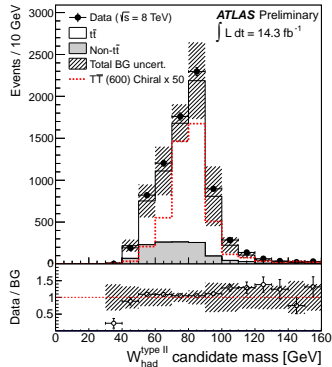
$W_{\text{had}}^{\text{type I}}$



one jet
 $p_T > 250 \text{ GeV}$
 $60 < M < 120 \text{ GeV}$

no $W_{\text{had}}^{\text{type I}}$
 di-jet system
 $\Delta R(j, j) < 0.8$
 $p_T > 200 \text{ GeV}$
 $60 < M < 120 \text{ GeV}$

$W_{\text{had}}^{\text{type II}}$



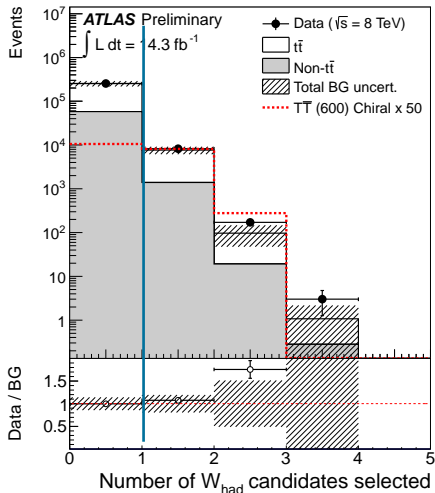
W_{lep} reconstructed using lepton and “neutrino”:

$$p_X, p_Y \text{ from } E_T^{\text{miss}}, p_Z \text{ from } M_W^2 = (p_l + p_\nu)^2$$

Event selection

LOOSE selection		
SR0	Preselection + Ortho Cut (*)	
SR1	+	$\geq 1 W_{\text{had}}$ candidates
SR2	+	$H_T^{Aj} > 800 \text{ GeV}$
SR3	+	$p_T(b_1) > 160 \text{ GeV}$
SR4	+	$p_T(b_2) > 80 \text{ GeV}$
SR5	+	$\Delta R(\ell, \nu) < 1.2$
TIGHT selection		
SR5	LOOSE selection	
SR6	+	$\min \Delta R(\ell, b) > 1.4$
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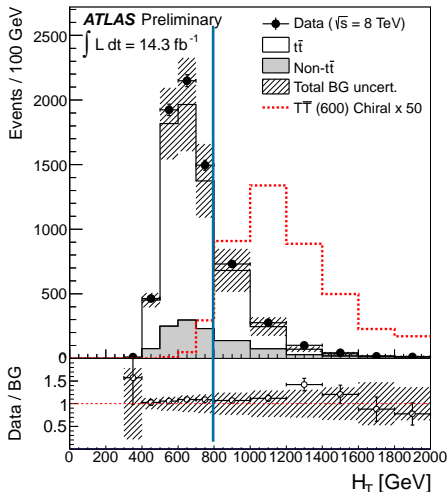
(*) reject events with ≥ 6 jets and ≥ 3 b -jets



Event selection

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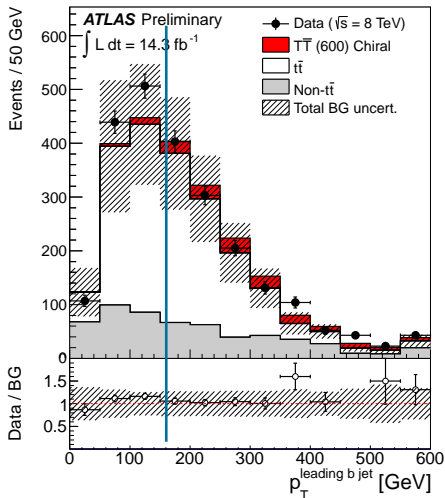
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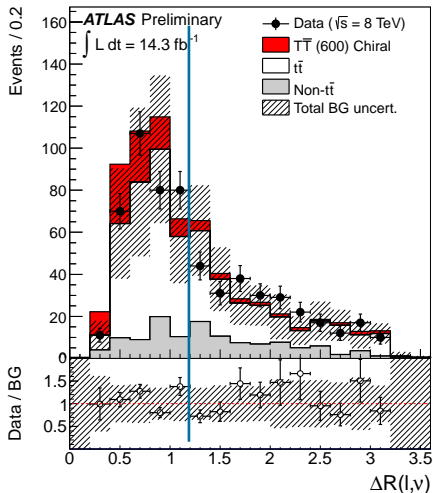
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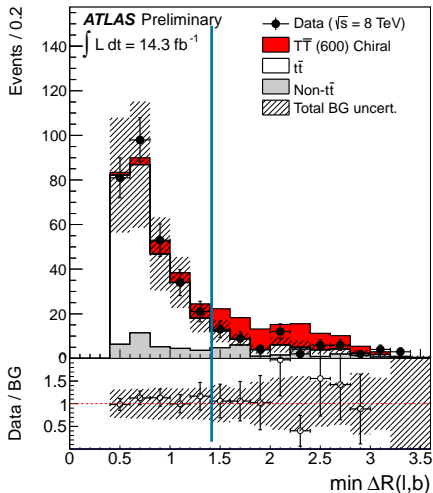
(*) reject events with ≥ 6 jets and ≥ 3 b -jets



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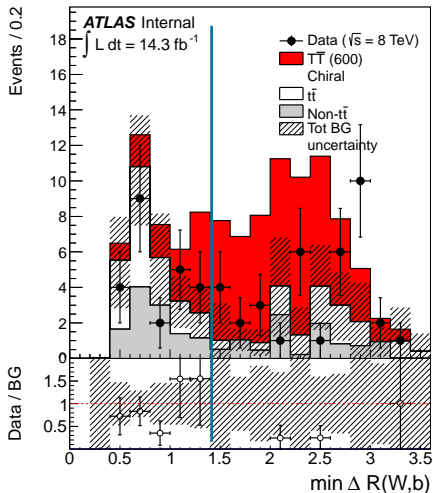
(*) reject events with ≥ 6 jets and ≥ 3 b -jets



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(*) reject events with ≥ 6 jets and ≥ 3 b -jets



Comparison data vs prediction

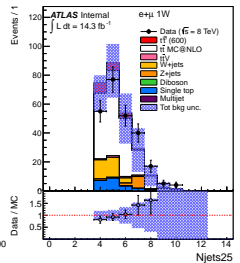
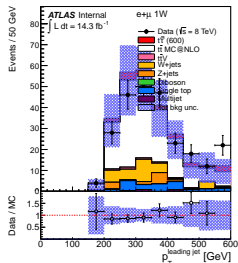
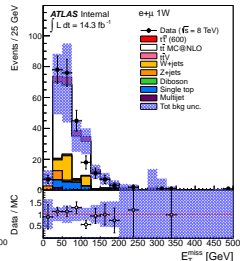
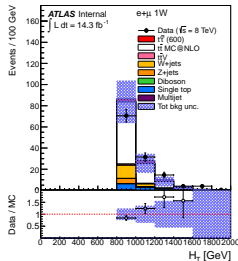
(before unblinding)

Check agreement between data and background prediction



Define regions depleted in signal

	LOOSE but $\Delta R(\ell, \nu) > 1.2$			
$t\bar{t}$ (600 GeV)	18.47 ± 1.48	$+1.09$ -1.64		
$t\bar{t}$	173.13 ± 8.82	$+46.92$ -48.59		
W+jets	30.64 ± 9.78	$+13.74$ -12.43		
Z+jets	11.68 ± 5.93	$+5.89$ -6.96		
Diboson	0.29 ± 0.19	$+0.17$ -0.17		
Single top	21.46 ± 2.54	$+2.60$ -2.54		
$t\bar{t}V$	4.21 ± 0.16	$+1.33$ -1.33		
Multijet	0.49 ± 0.91	± 0.25		
Total bkg.	241.90 ± 14.70	$+53.57$ -55.95		
Data	250			



Signal to background discrimination

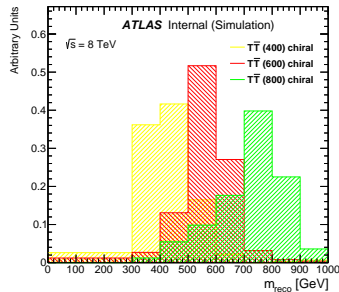
merged

	LOOSE	TIGHT
$t\bar{t}$	264 ± 80	10 ± 6
$t\bar{t}V$	5.1 ± 1.8	0.5 ± 0.2
W+jets	16 ± 11	6 ± 5
Z+jets	1.1 ± 1.4	0.2 ± 0.5
Single top	30 ± 7	4.4 ± 1.6
Dibosons	0.21 ± 0.15	0.06 ± 0.05
Tot.Bkg.	317 ± 90	21 ± 9
Data	348	37
<hr/>		
$T\bar{T}(600 \text{ GeV})$		
Chiral t'	88 ± 10	54 ± 7
T Singlet	41 ± 4	20.3 ± 2.2

Discriminating variable $\Rightarrow T$
reconstructed mass

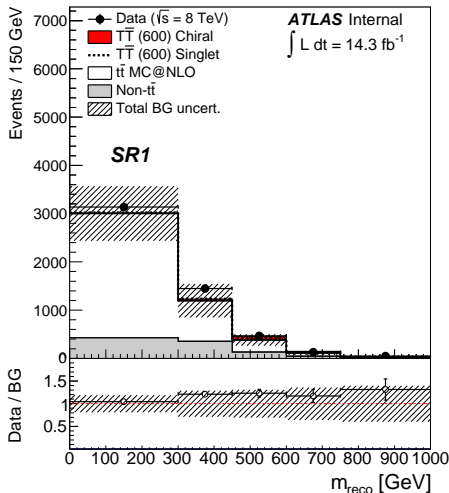


Pair b -jets and W boson candidates
in order to get
 $\min\Delta(M_{\text{lep}}, M_{\text{had}})$



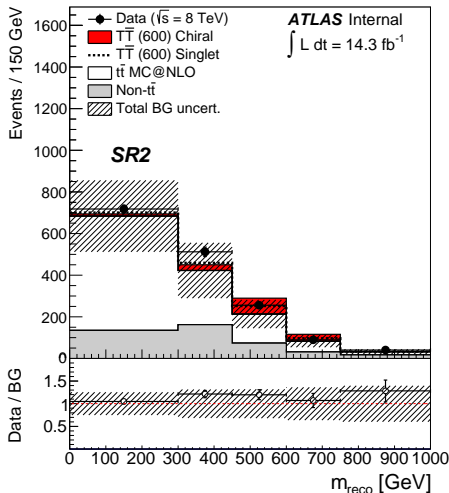
Reconstructed mass

LOOSE selection		
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SR1	+	$\geq 1 W_{\text{had}}$ candidates
SR2	+	$H_T^{Aj} > 800 \text{ GeV}$
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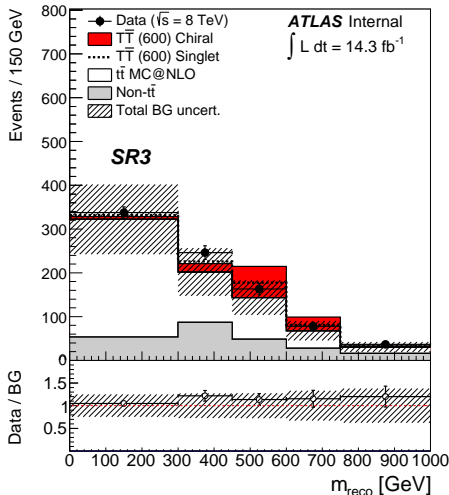
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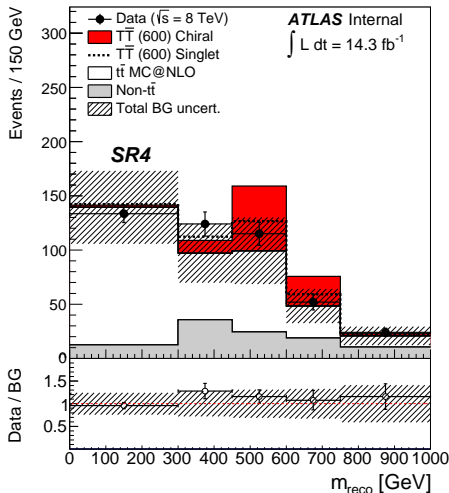
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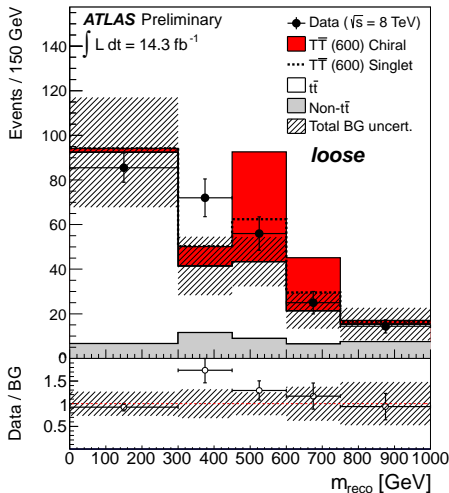
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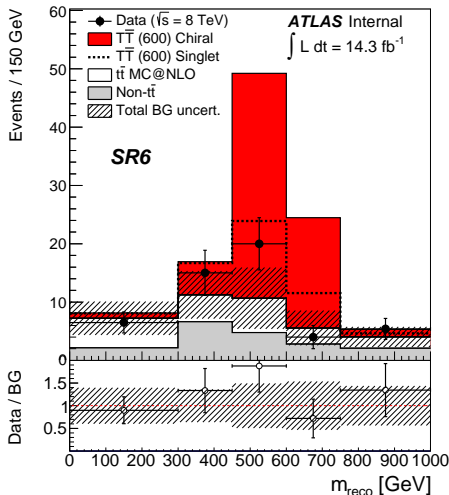
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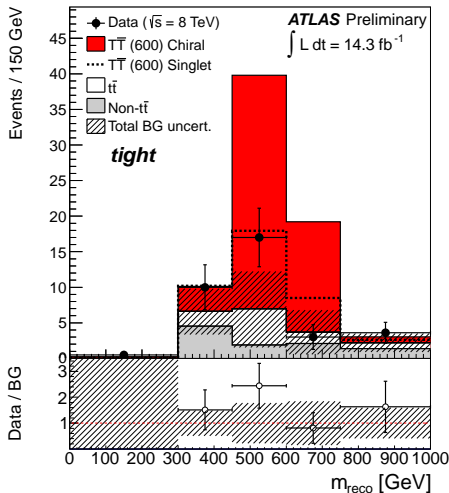
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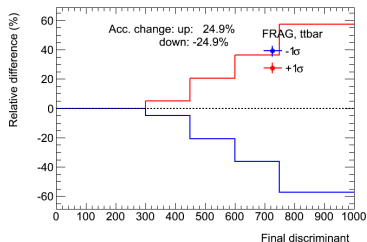
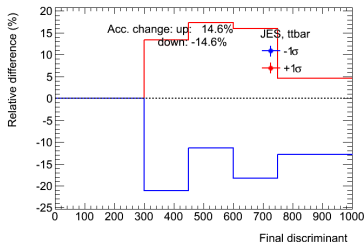
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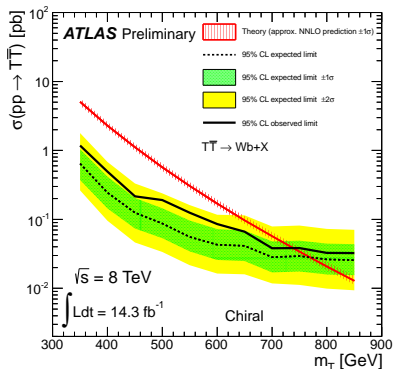
Most relevant systematic uncertainties

	$T\bar{T}$ (600 GeV)	$t\bar{t}$	Non- $t\bar{t}$
Total [%]	+14/-15	+59/-59	+42/-35
Main contributions [%]			
Jet energy scale	+6.6/-8.4	+15/-15	+33/-22
$t\bar{t}$ modelling: NLO MC generator	—	+48/-48	—
$t\bar{t}$ modelling: PS and fragm	—	+25/-25	—
$t\bar{t}$ modelling: ISR/FSR	—	+8.8/-8.8	—



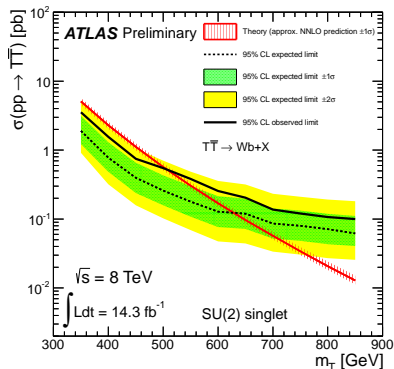
Benchmark results

Chiral T /Vector-like $Y(-4/3)$



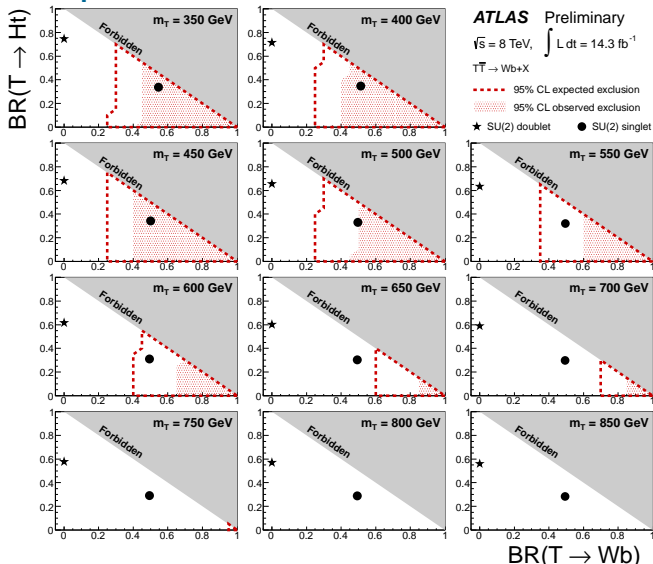
observed (expected) 95% CL limit
 $m_T > 740$ (770) GeV

Singlet T



observed (expected) 95% CL limit
 $m_T > 505$ (630) GeV

Model independent results



Outline

Theoretical framework

The ATLAS experiment at the LHC

Monte Carlo simulation

Event reconstruction

Searches for $T\bar{T}$ in single lepton channel

Search for $T\bar{T}$ decaying to $Wb + X$

Search for $T\bar{T}$ decaying to $Ht + X$

Combined results

Conclusions and outlook

Strategy

$$T \rightarrow Ht \begin{cases} \nearrow bbWb \rightarrow bbb\nu \\ \searrow WWWb \rightarrow qqql\nu \end{cases} + \bar{T} \rightarrow Wb/Zt/Ht$$

as a minimum 6 total jets in the event ($T\bar{T} \rightarrow HtWb$)

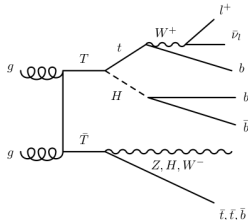


$$H_T = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^{N_{\text{jets}}} p_T(j)$$

peak $\sim 2m_T$

good signal/bkg discriminant

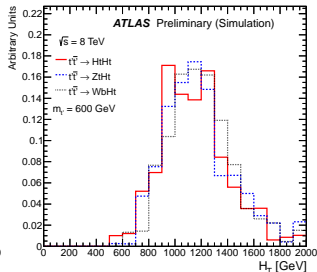
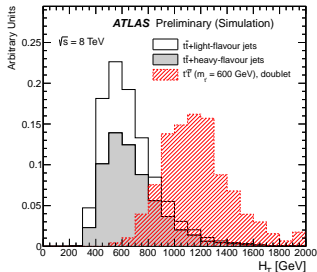
for all $Ht + X$ modes



SM Higgs boson
w/ $m_H = 125 \text{ GeV}$



$$\begin{aligned} \text{BR}(H \rightarrow bb) &= 60\% \\ \text{BR}(H \rightarrow WW) &= 20\% \end{aligned}$$



≥ 6 jets, ≥ 4 b -jets

Event selection

maximize signal acceptance

"2 b -TAGGED JETS"	≥ 6 jets =2 b -tagged jets orthogonality cut: $H_T < 700$ GeV
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"3 b -TAGGED JETS"	≥ 6 jets =3 b -tagged jets
----------------------	--------------------------------------

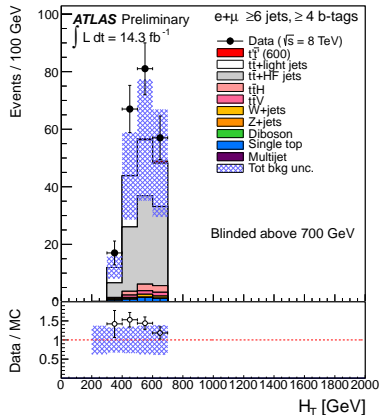
" ≥ 4 b -TAGGED JETS"	≥ 6 jets ≥ 4 b -tagged jets
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→ b -tagging by TRF in MC ←

heavy flavor component not well predicted



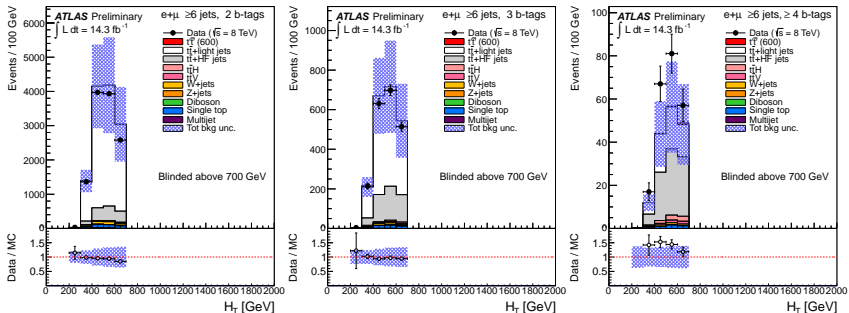
simultaneous fit to data of H_T variable
(good to have background enriched channels)



Scale of $t\bar{t}$ components

 $t\bar{t} + \text{light: } 0.87 \pm 0.02 \text{ (stat.)}$
 $t\bar{t} + \text{HF: } 1.35 \pm 0.11 \text{ (stat.)}$

before...



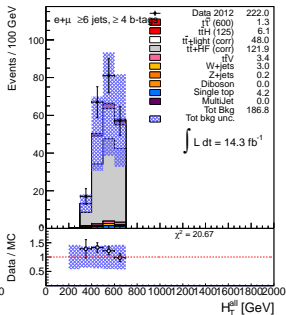
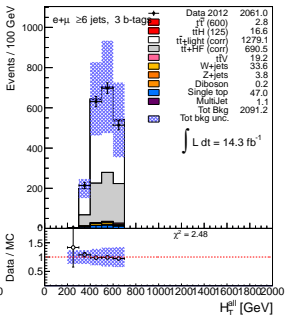
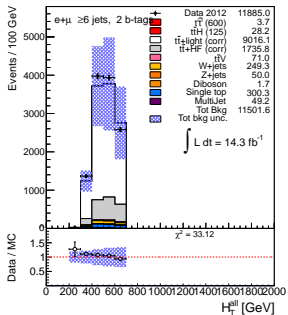
Maximum yields discrepancy below 5%

Scale of $t\bar{t}$ components

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$$t\bar{t}+\text{HF}: 1.35 \pm 0.11 \text{ (stat.)}$$

... after



Maximum yields discrepancy below 5%

Comparison data vs prediction

Blinding cut: $H_T < 700$ GeV

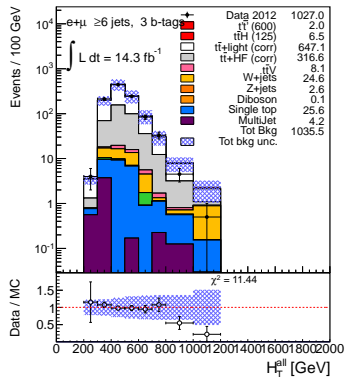
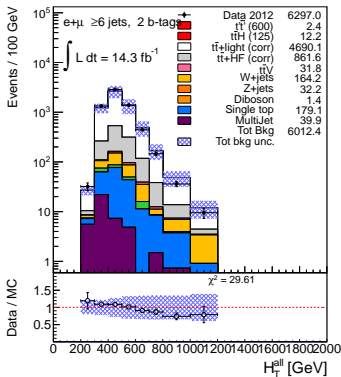


Define special blinded regions to check H_T modeling:

at most two jets with $p_T > 60$ GeV, $H_T < 1.2$ TeV

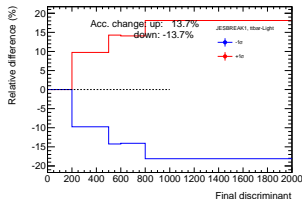
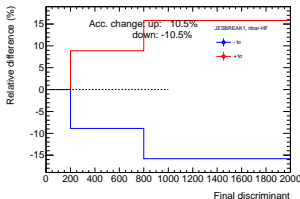
2 b -tagged jets

3 b -tagged jets



Most relevant systematic uncertainties

	$T\bar{T}$	$t\bar{t}H$ (125)	$t\bar{t}$ -HF	$t\bar{t}$ -Light	W+jets	Z+jets	Single top	Diboson	$t\bar{t}V$	Multijet
Total [%]	+21.9/-24.0	+25.2/-30.0	+57.3/-58.4	+42.0/-44.1	+60.0/-61.0	+65.2/-66.2	+31.7/-32.9	+68.2/-70.2	+37.6/-38.8	+50.0/-50.0
Main contributions [%]										
BTAGBREAKS	+20.4/-22.7	+18.7/-21.6	+15.8/-17.8	+12.2/-13.1	+13.5/-15.0	+13.0/-13.9	+15.9/-17.8	+22.0/-27.4	+16.4/-18.6	-
JES "baseline"	+3.1/-3.1	+7.3/-7.3	+10.5/-10.5	+13.7/-13.7	+18.1/-18.1	+18.2/-18.2	+19.9/-19.9	+5.2/-5.2	+8.4/-8.4	-
ttbar iqopt2	-	-	+6.9/-6.9	+20.1/-20.1	-	-	-	-	-	-
ttbar ktfac	-	-	+7.5/-9.2	+13.8/-17.0	-	-	-	-	-	-
ttbar qfac	-	-	+0.7/-0.7	+1.6/-1.6	-	-	-	-	-	-
ttbarHF	-	-	+50.0/-50.0	+13.0/-13.0	-	-	-	-	-	-

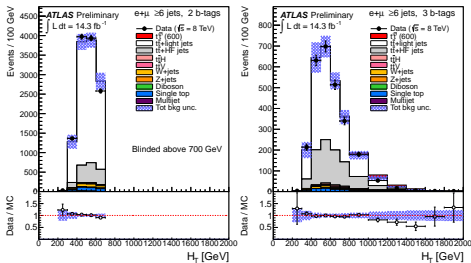


Introduce the scaling factors as **nuisance parameters**

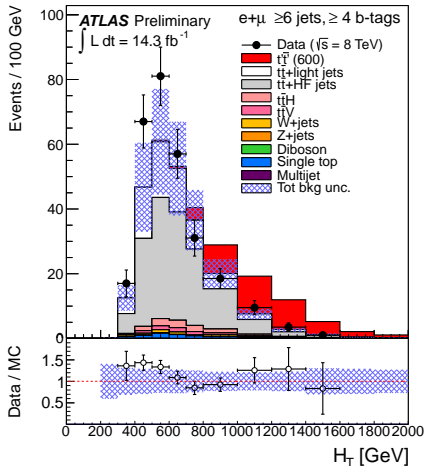


total uncertainty on $t\bar{t}$ +HF reduced by $\sim 20\%$

Yields in signal regions

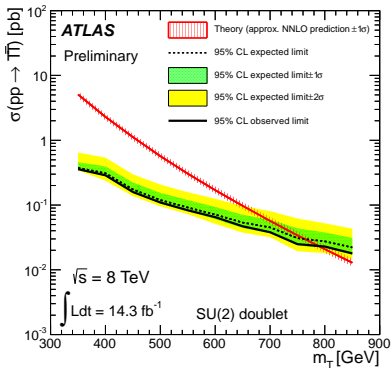


	2 b-tags	3 b-tags	≥ 4 b-tags
$t\bar{t}$ +HF	1500 ± 900	900 ± 400	170 ± 70
$t\bar{t}$ +LF	9600 ± 1000	1900 ± 350	75 ± 22
W+jets	250 ± 130	50 ± 30	5 ± 3
Z+jets	50 ± 40	9 ± 6	0.5 ± 0.9
Single top	300 ± 70	75 ± 18	7 ± 3
Diboson	1.7 ± 0.6	0.3 ± 0.1	0.03 ± 0.03
$t\bar{t}V$	70 ± 20	36 ± 12	7 ± 3
$t\bar{t}H$	28 ± 4	31 ± 6	12 ± 3
Multijet	49 ± 23	1.7 ± 0.8	0.15 ± 0.06
Tot. Bkg.	11860 ± 260	2990 ± 210	270 ± 60
Data	11885	2922	318
$T\bar{T}$ (600)			
doublet	4.3 ± 1.2	94 ± 7	79 ± 18
singlet	2.3 ± 0.4	61 ± 7	36 ± 9



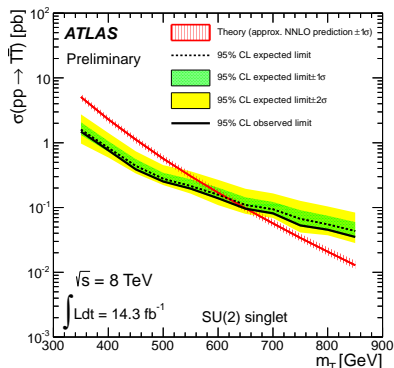
Benchmark results

Doublet



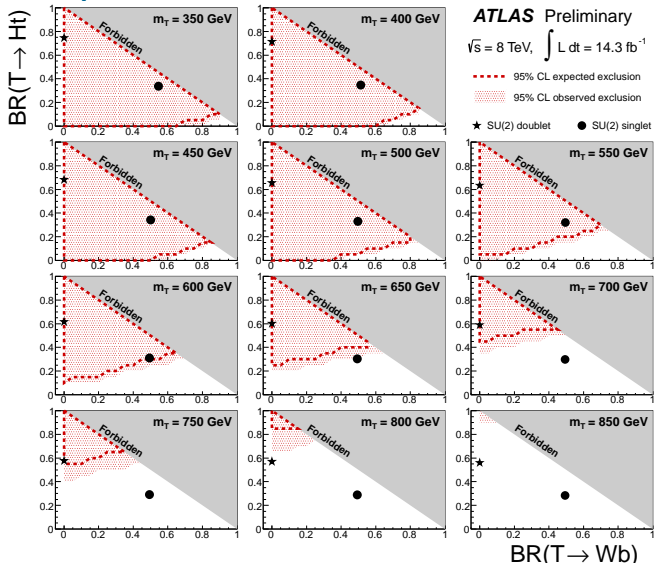
observed (expected) 95% CL limit
 $m_T > 790$ (745) GeV

Singlet



observed (expected) 95% CL limit
 $m_T > 640$ (615) GeV

Model independent results



Outline

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Search for $T\bar{T}$ decaying to $Ht + X$

Combined results

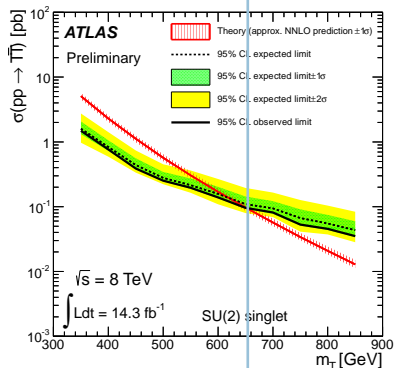
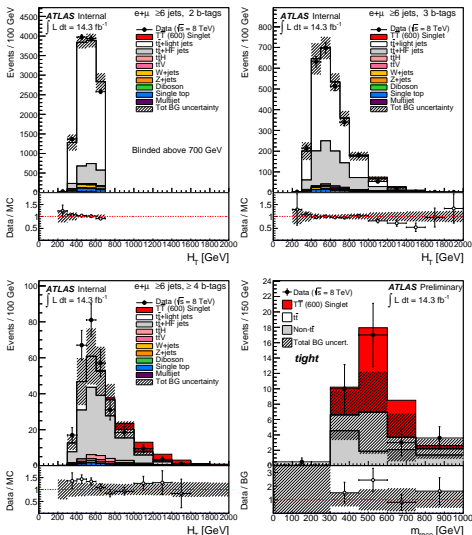
Conclusions and outlook

Combination of $T\bar{T} \rightarrow Wb + X$ and $T\bar{T} \rightarrow Ht + X$

The search channels do **not** overlap

↓
can be combined in the statistical analysis
(consistent **syst unc** treatment)

$T\bar{T} \rightarrow Ht + X$ only: 640 GeV

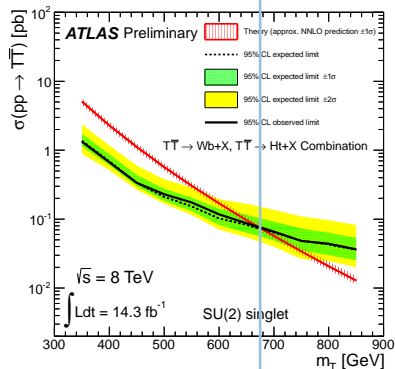
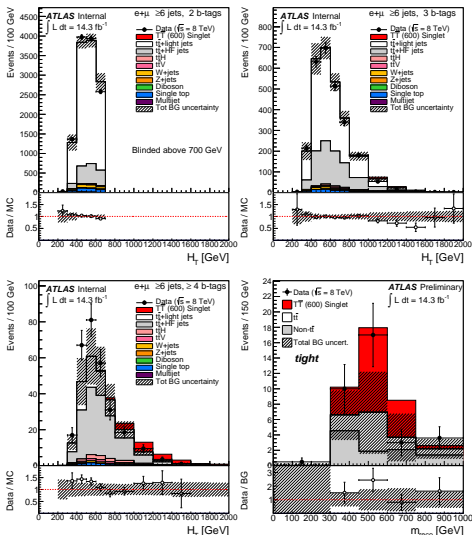


Combination of $T\bar{T} \rightarrow Wb + X$ and $T\bar{T} \rightarrow Ht + X$

The search channels do **not** overlap

↓
can be combined in the statistical analysis
(consistent **syst unc** treatment)

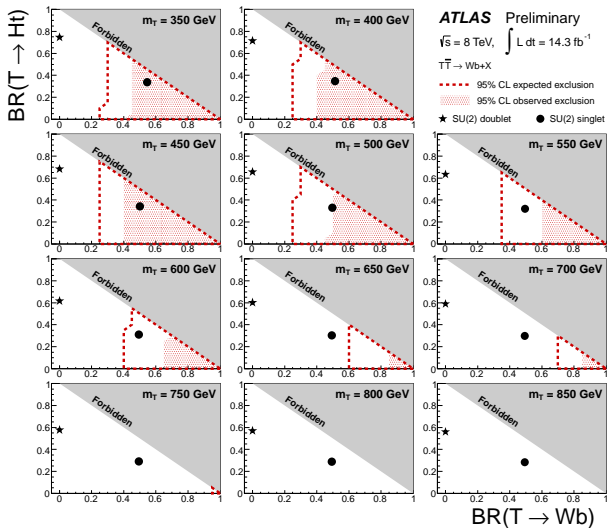
combination: 670 GeV



Combined results

Individual analyses probe different areas

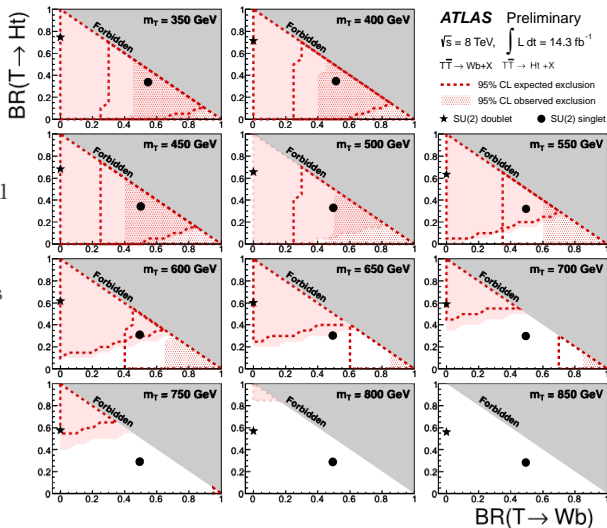
- $T\bar{T} \rightarrow Wb + X$ analysis alone very optimized for the bottom right corner



Combined results

Individual analyses probe different areas

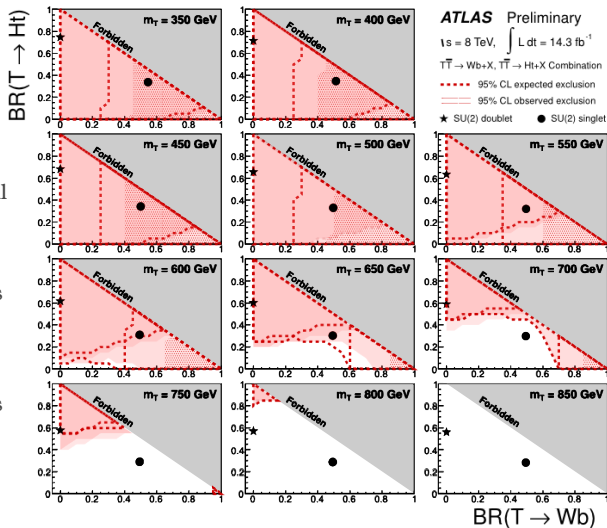
- ▶ $T\bar{T} \rightarrow Wb + X$ analysis alone very optimized for the bottom right corner
- ▶ $T\bar{T} \rightarrow Ht + X$ gives general good coverage, brings complete exclusion up to 450 GeV and almost excludes 650 GeV singlets



Combined results

Individual analyses probe different areas

- ▶ $T\bar{T} \rightarrow Wb + X$ analysis alone very optimized for the bottom right corner
- ▶ $T\bar{T} \rightarrow Ht + X$ gives general good coverage, brings complete exclusion up to **450 GeV** and almost excludes 650 GeV singlets
- ▶ full combination reaches complete exclusion up to almost **600 GeV** and excludes 650 GeV singlets

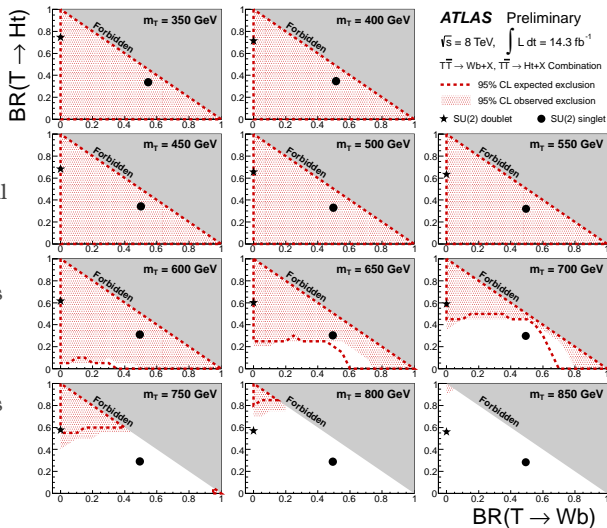


Combined results

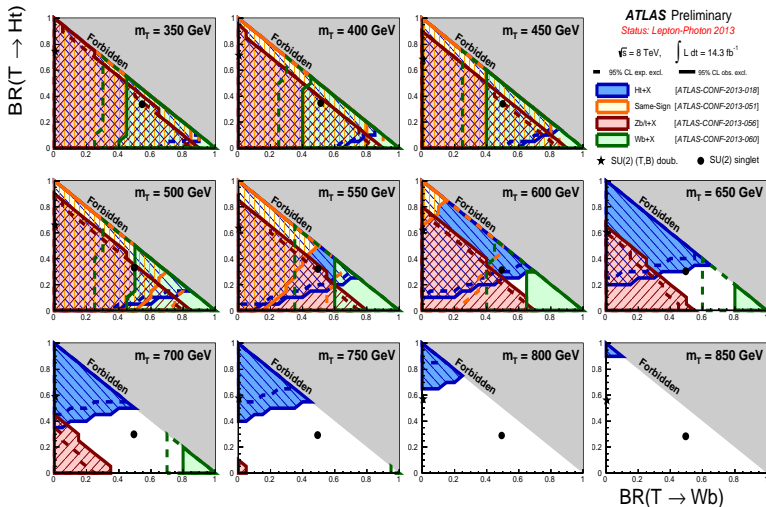
Individual analyses probe different areas

- ▶ $T\bar{T} \rightarrow Wb + X$ analysis alone very optimized for the bottom right corner
- ▶ $T\bar{T} \rightarrow Ht + X$ gives general good coverage, brings complete exclusion up to **450 GeV** and almost excludes 650 GeV singlets
- ▶ full combination reaches complete exclusion up to almost **600 GeV** and excludes 650 GeV singlets

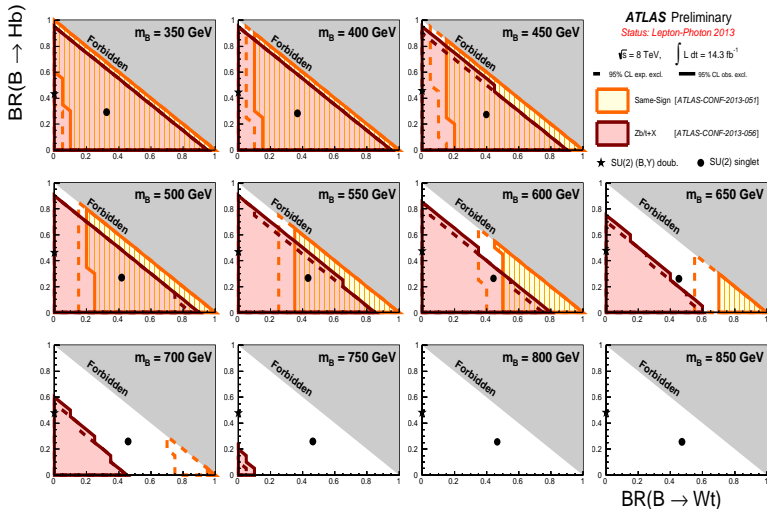
... but there's more from **ATLAS Exotics!**



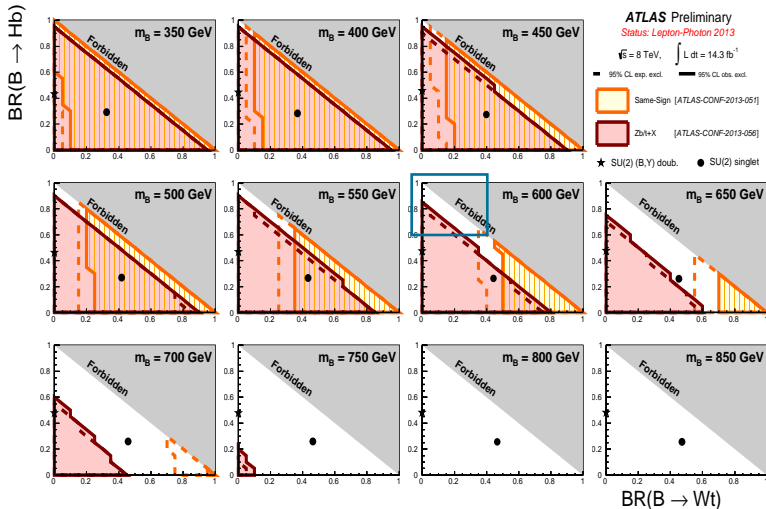
ATLAS “worst case scenario” coverage



ATLAS “worst case scenario” coverage



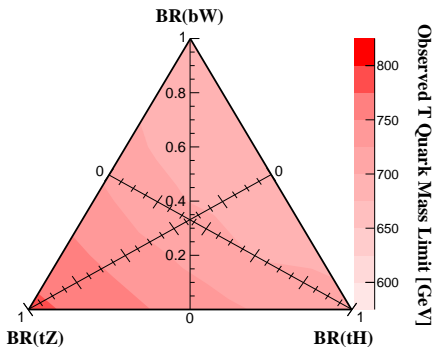
ATLAS “worst case scenario” coverage



Comparison to CMS results

Inclusive $T\bar{T}$ searches CMS-PAS-B2G-12-015 [7]

CMS preliminary $\sqrt{s} = 8 \text{ TeV}$ 19.6 fb^{-1}



“doublet”
790 obs

“singlet”
670 obs

“chiral”
740 obs

Scenario	Branching Fractions			expected limit (GeV)	observed limit (GeV)
	T→bW	T→tH	T→tZ		
(0)	0.5	0.25	0.25	773	696
(1)	0.0	0.0	1.0	813	782
(2)	0.0	0.2	0.8	798	766
(3)	0.0	0.4	0.6	790	747
(4)	0.0	0.6	0.4	783	731
(5)	0.0	0.8	0.2	773	715
(6)	0.0	1.0	0.0	770	706
(7)	0.2	0.0	0.8	794	758
(8)	0.2	0.2	0.6	786	739
(9)	0.2	0.4	0.4	777	717
(10)	0.2	0.6	0.2	767	698
(11)	0.2	0.8	0.0	766	694
(12)	0.4	0.0	0.6	786	734
(13)	0.4	0.2	0.4	776	705
(14)	0.4	0.4	0.2	766	693
(15)	0.4	0.6	0.0	762	690
(16)	0.6	0.0	0.4	779	703
(17)	0.6	0.2	0.2	771	693
(18)	0.6	0.4	0.0	769	687
(19)	0.8	0.0	0.2	779	695
(20)	0.8	0.2	0.0	777	689
(21)	1.0	0.0	0.0	785	700

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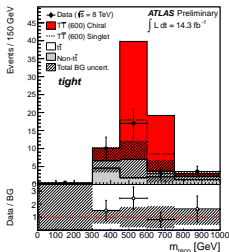
Search for $T\bar{T}$ decaying to $Ht + X$

Combined results

Conclusions and outlook

Conclusions and outlook

both searches are being updated with the full 20 fb^{-1} statistics

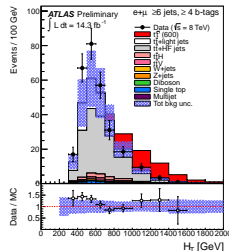


- poor MC bkg's statistical population in the TIGHT channel
- larger MC samples available
- possible optimization of the H_T^{4j} cut
- explorable option: larger anti- k_t jets

Best up-to-date 95% CL obs limit on chiral T and vector-like Y (740 GeV)

- poor modeling of $t\bar{t}$ +HF by ALPGEN
- b -tagging calibration sub-optimal for analyses with high- p_T objects
- $t\bar{t}$ -based calibrations being developed
- potential high gain in sensitivity with **profiling**
- easily optimizable for a $B\bar{B} \rightarrow Hb + X$ analysis

Best up-to-date 95% CL obs limit on doublet T



Outlook

all four ATLAS searches are being updated
with the full 20 fb^{-1} statistics,
plus two new channels: $B\bar{B} \rightarrow Wt + X$ and $B\bar{B} \rightarrow Hb + X$

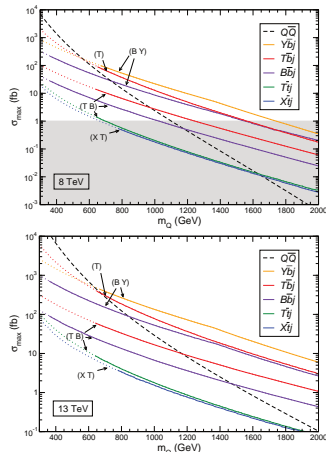
LHC Run-II:

- ↗ $\sqrt{s}=14 \text{ TeV}$
- ↗ $\sim 100 \text{ fb}^{-1}$ in 3 years
- ↘ higher pile-up

To-do:

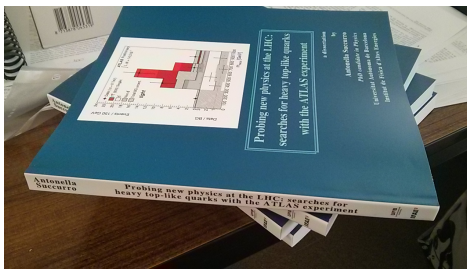
- ▶ continue on the road of full combination
- ▶ design searches for single production

plots from [8]



Thank you!

Thank you for your attention!



References I

- [1] S. Gieseke.
Parton shower monte carlos.
- [2] Thomas Junk.
Confidence level computation for combining searches with small statistics.
Nucl.Instrum.Meth., A434:435–443, 1999.
- [3] Alexander L. Read.
Presentation of search results: The CL(s) technique.
J.Phys., G28:2693–2704, 2002.
- [4] ATLAS Collaboration.
Search for pair production of heavy top-like quarks decaying to a high- p_T W boson and a b quark in the lepton plus jets final state at $\sqrt{s} = 7$ TeV with the ATLAS detector.
Phys.Lett., B718:1284–1302, 2012.

References II

[5] ATLAS Collaboration.

Search for pair production of heavy top-like quarks decaying to a high- p_T W boson and a b quark in the lepton plus jets final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector.

ATLAS-CONF-2013-060, Jun 2013.

[6] ATLAS collaboration.

Search for heavy top-like quarks decaying to a higgs boson and a top quark in the lepton plus jets final state in pp collisions at $\sqrt{s} = 8$ tev with the atlas detector.

ATLAS-CONF-2013-018, Mar 2013.

[7] Inclusive search for a vector-like T quark by CMS.

Technical Report CMS-PAS-B2G-12-015, CERN, Geneva, 2013.

[8] J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Perez-Victoria.

A handbook of vector-like quarks: mixing and single production.
2013.

[9] M. Lamont.

The First Years of LHC Operation for Luminosity Production.

in Proceedings of 4th International Particle Accelerator Conference (IPAC 2013), 2013.

BACKUP SLIDES

LHC parameters

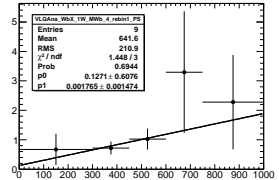
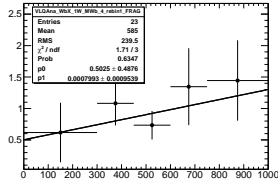
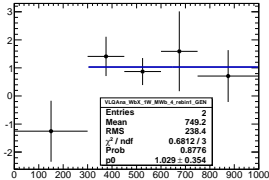
Parameter	designed	2010	2011	2012
Beam energy (TeV/c)	7	3.5	3.5	4
Beta function β^* (m)	0.55	2.0/3.5	1.5/1.0	0.6
Max. No. bunches/beam	2808	368	1380	1380
Max. No. protons/bunch	1.15×10^{11}	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}
Bunch spacing (ns)	25	150	75/50	50
Peak luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	1×10^{34}	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}
Emittance ε_n (μrad)	3.75	2.0	2.4	2.5
Max. $\langle \mu \rangle$	19	4	17	37

Table: Overview of some parameters for the LHC performance comparing the design values with their time evolution during the first long run operation in 2010-2013 [9].

$T\bar{T} \rightarrow Wb + X$ 7 TeV vs 8 TeV

Selection	7 TeV	8 TeV
Preselection	One electron or muon ⁽⁺⁾	
	$E_T^{\text{miss}} > 35(20)$ GeV for electron (muon) channel	$E_T^{\text{miss}} > 20$ GeV
	$E_T^{\text{miss}} + m_T > 60$ GeV	
	≥ 3 jets for $W_{\text{had}}^{\text{type I}}$ ≥ 4 jets for $W_{\text{had}}^{\text{type II}}$	≥ 4 jets ^(*)
	≥ 1 b -tagged jets ^(**)	
Loose selection	orthogonality cut reject events with ≥ 6 and ≥ 3 b -tagged jets	
	Preselection	
	≥ 1 W_{had} candidates ^(x)	
	$H_T^{4j} > 750$ GeV	$H_T^{4j} > 800$ GeV

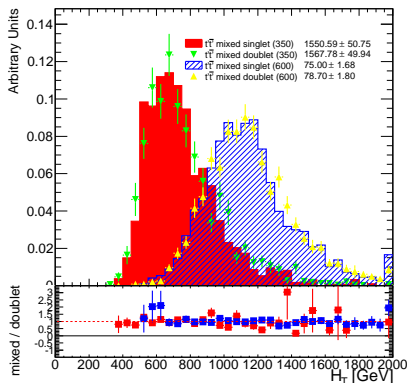
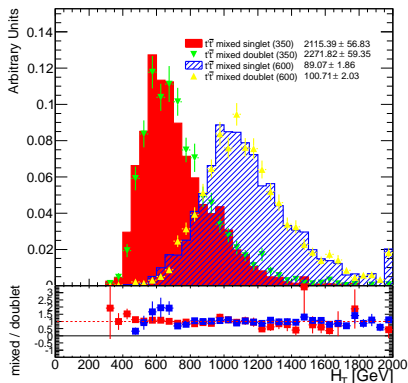
$t\bar{t}$ modeling systematic uncertainties



Doublet vs singlet

MC simulated for **singlet** T with $\text{BR} = 1/3$ for every decay mode

- Mixing between SM quarks and T is **left-handed** for singlets, **right-handed** for doublets



Discrepancies in yields below 5% in “ ≥ 4 b -TAGGED JETS”

Treatment of sys unc in combination

Systematic uncertainty		$T\bar{T} \rightarrow Wb + X$		$T\bar{T} \rightarrow Ht + X$	
		Status	Components	Status	Components
Fully Correlated	Luminosity	N	1	N	1
	Lepton ID+reco+trigger	N	1	N	1
	Jet vertex fraction efficiency	SN	1	SN	1
	Jet energy resolution	SN	1	SN	1
	b -tagging efficiency	SN	9	SN	9
	c -tagging efficiency	SN	5	SN	5
	Light jet-tagging efficiency	SN	1	SN	1
	$t\bar{t}$ cross section	N	1	N	1
	$t\bar{t}V$ cross section	N	1	N	1
	$t\bar{t}H$ cross section	-	-	N	1
	Single top cross section	N	1	N	1
	Dibosons cross section	N	1	N	1
	W +jets normalization	N	5	-	-
	Z +jets normalization	N	1	-	-
	V +jets normalization	-	-	N	1
Uncorrelated	Multijet normalization	-	-	N	1
	$t\bar{t}$ modelling	SN	3	SN	3
	V +jets modelling	SN	1	-	-
Correlate	$t\bar{t}$ +heavy-flavour fractions	-	-	N	1
JES w/ BASELINE	Jet energy scale	SN	1	SN	8