

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

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*PhD candidate in Physics*



Bellaterra, 28th of February, 2014

# Four questions, one dissertation

- ▶ Why? bother with “new physics”

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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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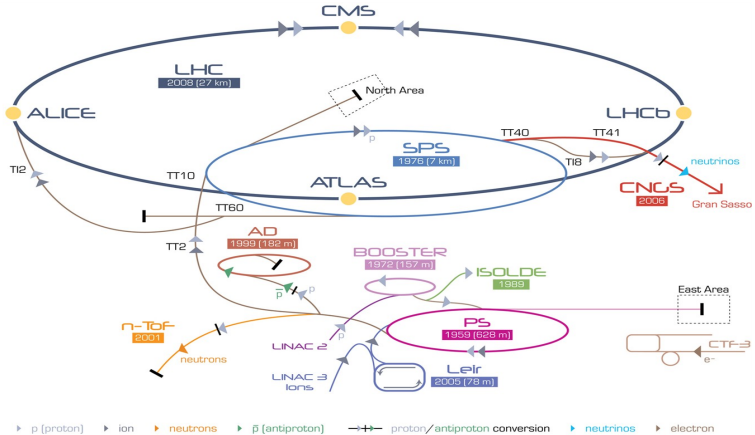
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# The LHC complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF-3 Clic Test Facility CNCS 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 $\beta^*$ (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	$1.15 \times 10^{11}$	$1.2 \times 10^{11}$	$1.45 \times 10^{11}$	$1.7 \times 10^{11}$
Bunch spacing (ns)	25	150	75/50	50
Peak luminosity ( $\text{cm}^{-2}\text{s}^{-1}$ )	$1 \times 10^{34}$	$2.1 \times 10^{32}$	$3.7 \times 10^{33}$	$7.7 \times 10^{33}$
Emittance $\varepsilon_n$ ( $\mu\text{rad}$ )	3.75	2.0	2.4	2.5
Max. $\langle \mu \rangle$	19	4	17	37

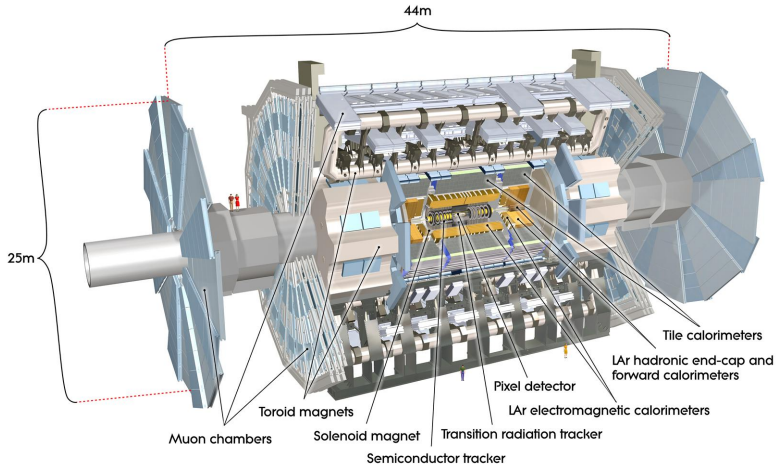


▶ p (proton)    ▶ ion    ▶ neutrons    ▶  $\bar{p}$  (antiproton)     $\leftrightarrow$  proton/antiproton conversion    ▶ neutrinos    ▶ electron

LHC Large Hadron Collider    SPS Super Proton Synchrotron    PS Proton Synchrotron

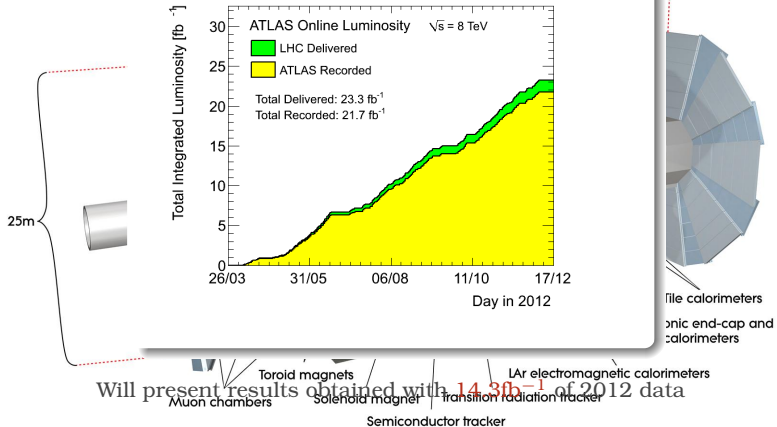
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# The ATLAS Detector



# The ATLAS Detector

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



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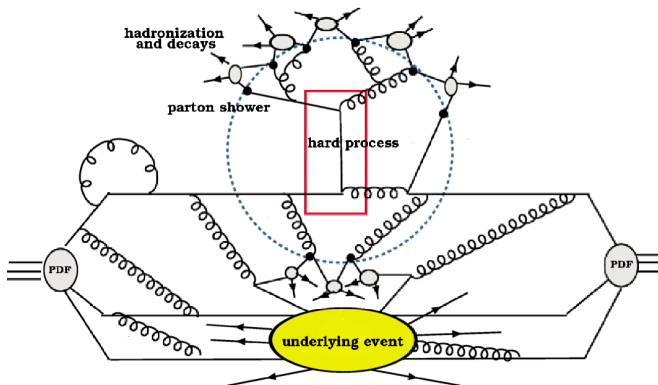
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# Modelling of hadron collisions

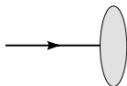
want to do physics at hadron colliders?  
need a good understanding of incoming hadrons



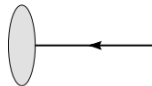
# Modelling of hadron collisions

Drawings from [1]

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



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

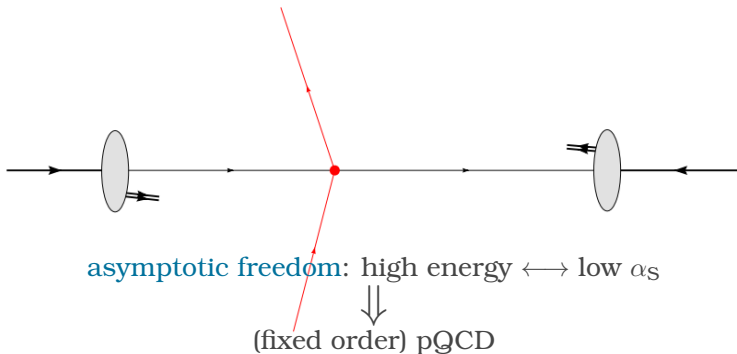


Quarks are distributed according to PDFs inside the proton



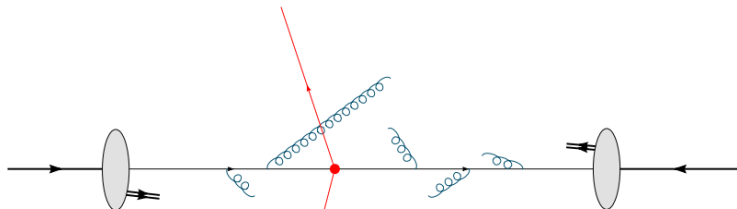
initial energy unknown

# Hard scattering of two partons





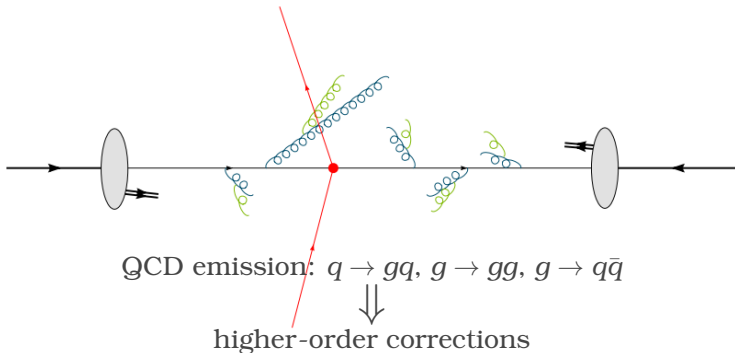
# Parton showering



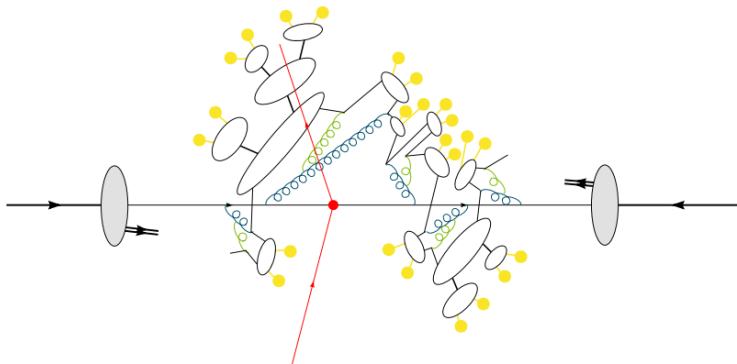
QCD emission:  $q \rightarrow gq$ ,  $g \rightarrow gg$ ,  $g \rightarrow q\bar{q}$

↓  
higher-order corrections

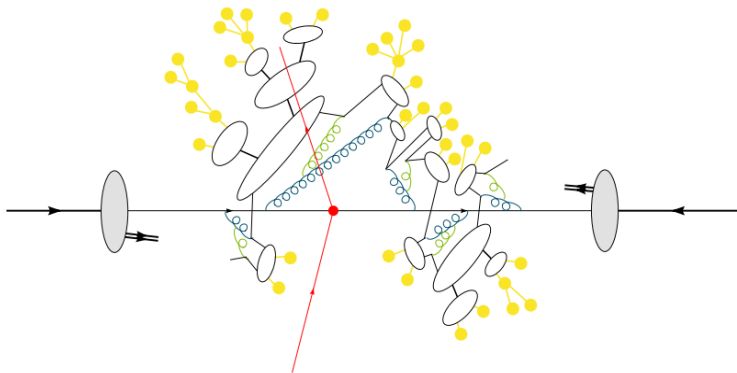
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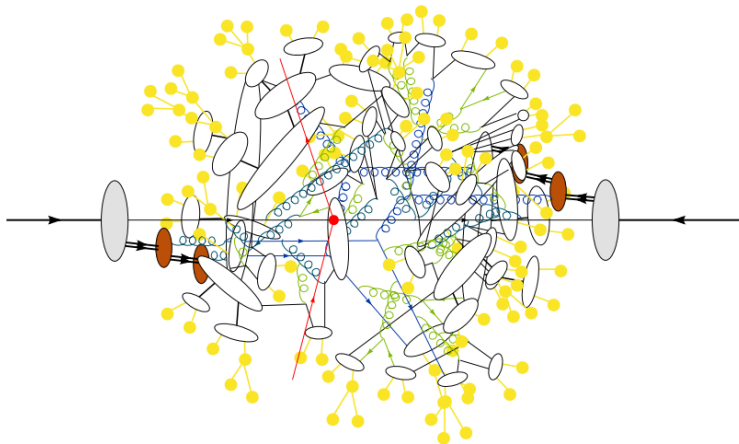
# Hadronization



# Final particle decays



# Underlying event simulation



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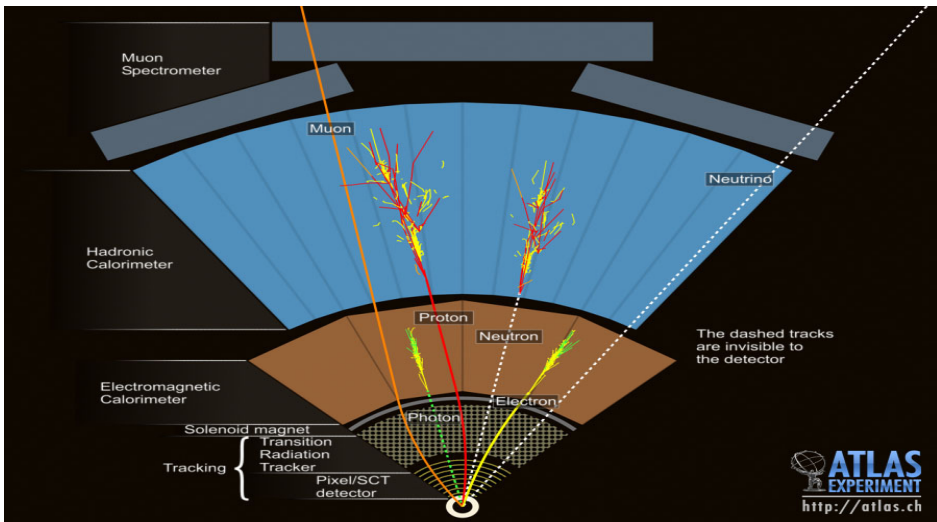
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# Physics objects puzzle



# One lepton



# Many jets

# Missing transverse energy

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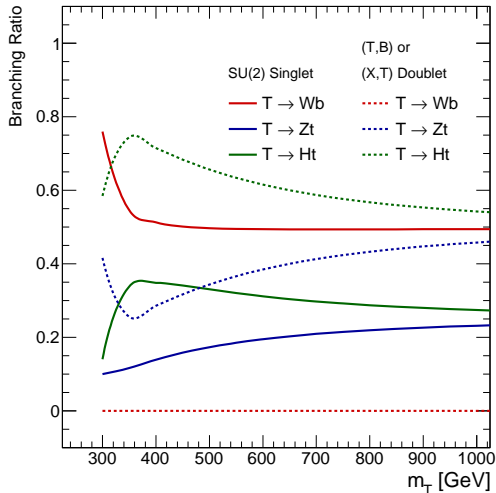
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# Allowed decay modes

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
$\begin{pmatrix} T \\ B \end{pmatrix}$	$W^+ b, Ht, Zt$ $W^- t, Hb, Zb$
$\begin{pmatrix} T \\ X \end{pmatrix}$	$Ht, Zt$ $W^+ t$
$\begin{pmatrix} B \\ Y \end{pmatrix}$	$Hb, Zb$ $W^- b$

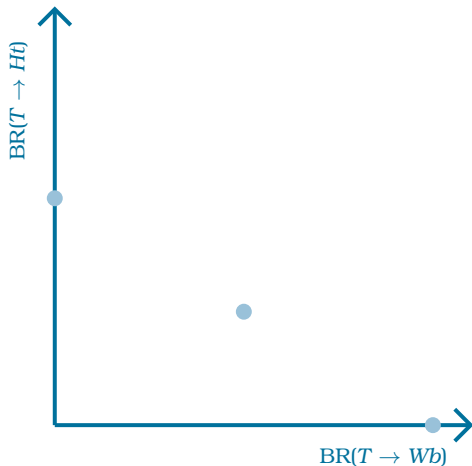


# Model Independent Strategy

- Build a 2-dim plane to scan model mixing

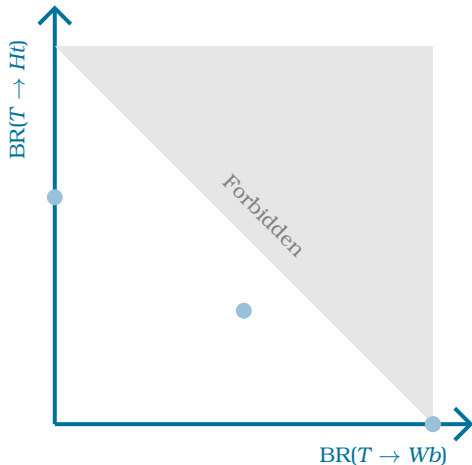


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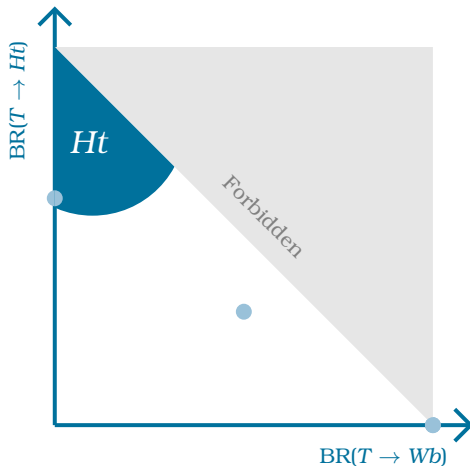
# Model Independent Strategy



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1<sup>(a)</sup>

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

# Model Independent Strategy

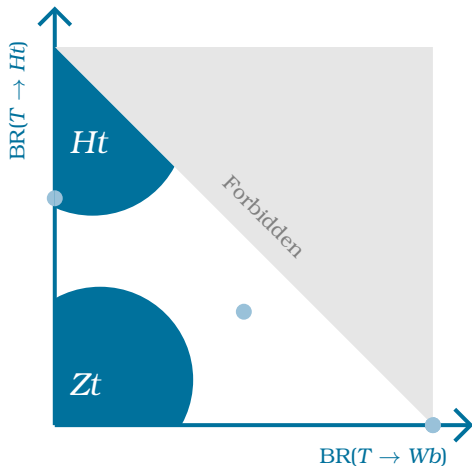


- Build a 2-dim plane to scan model mixing
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- Different analyses are sensitive to different areas

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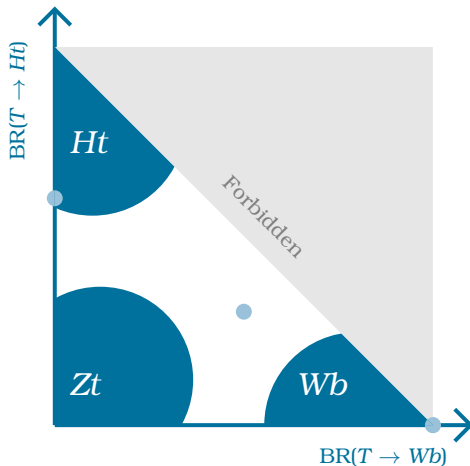
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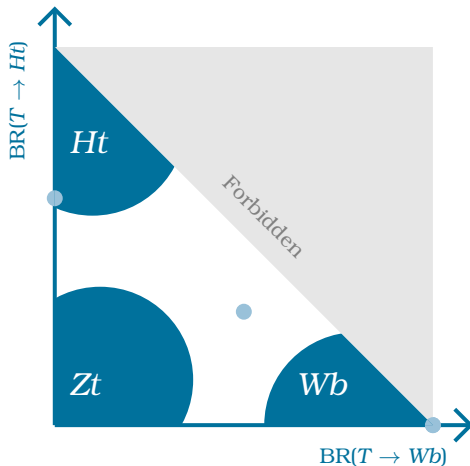
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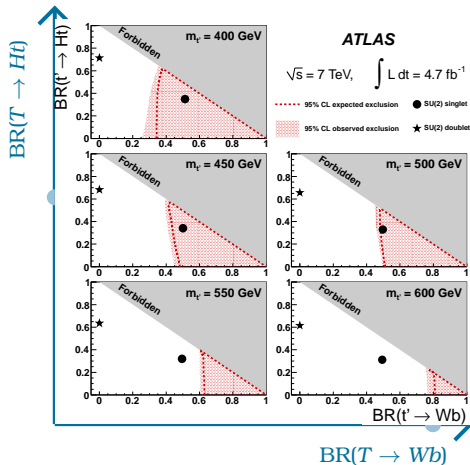
# Model Independent Strategy



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

<sup>(a)</sup>  $BR(T \rightarrow Zt) = 1 - BR(T \rightarrow Ht) - BR(T \rightarrow Wb)$

# 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:

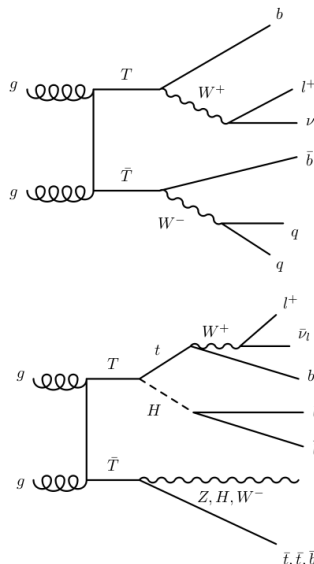
- $T\bar{T} \rightarrow Wb + X$       ►  $T\bar{T} \rightarrow Ht + X$

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	$\geq 4$ jets $\geq 1$ $b$ -tagged jets

## orthogonality requirements:

- $T\bar{T} \rightarrow Wb + X$ : reject events with  $\geq 6$  jets and  $\geq 3$   $b$ -jets
- $T\bar{T} \rightarrow Ht + X$ : reject events in the low  $b$ -tags channel with  $H_T < 700 \text{ GeV}$



# Background and signal modelling

Yields in the preselection region “blinded” as:

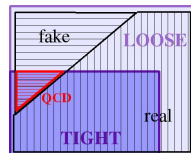
$$H_T^{Aj} < 800 \text{ GeV (*)}$$

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

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

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

- 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

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

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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

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

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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

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

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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

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

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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

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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

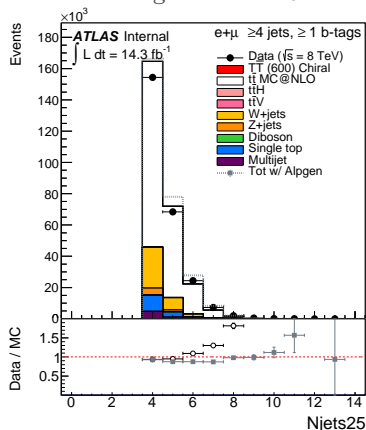
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$$(*) H_T^{4j} = p_T(l) + E_T^{\text{miss}} + \sum_{j=1}^4 p_T(j)$$

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



# Background and signal modelling

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$T\bar{T}$ (600) chiral	$36 \pm 2$
Data	$256993 \pm 507$

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

- ▶  $T\bar{T}$  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



# 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

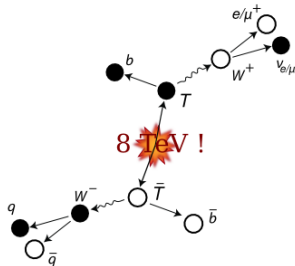
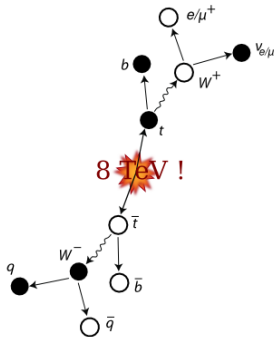
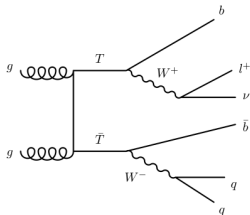
Conclusions and outlook

# Strategy

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

like

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



different **boosted kinematics**

reconstruct the W boson from hadronic decay

merged jets

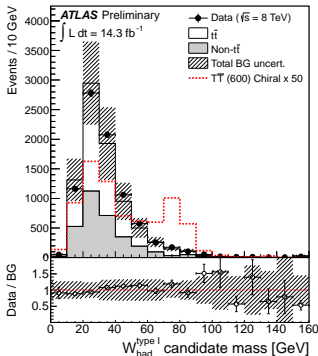
$W_{\text{had}}^{\text{type I}}$

close-by jets

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

# W boson reconstruction

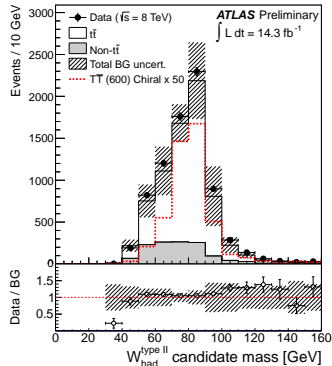
$W_{\text{had}}^{\text{type I}}$



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

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

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

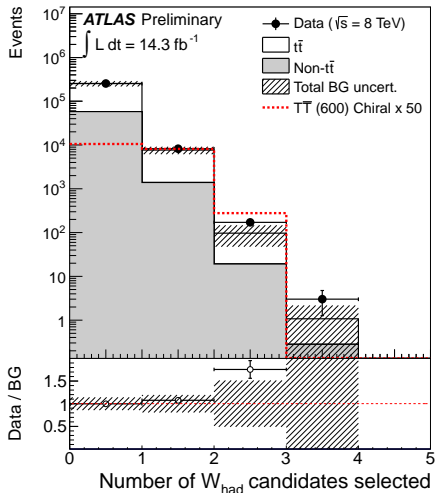


$W_{\text{lep}}$  reconstructed using lepton and “neutrino”:

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

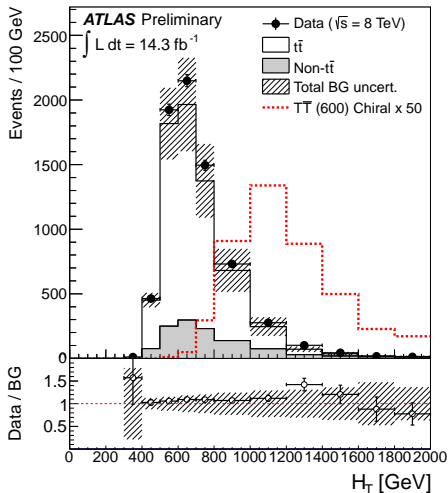
# Event selection

LOOSE selection		
SR0	Preselection	
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	+	$\min \Delta R(\ell, b) > 1.4$
SR7	+	$\min \Delta R(W_{\text{had}}, b) > 1.4$



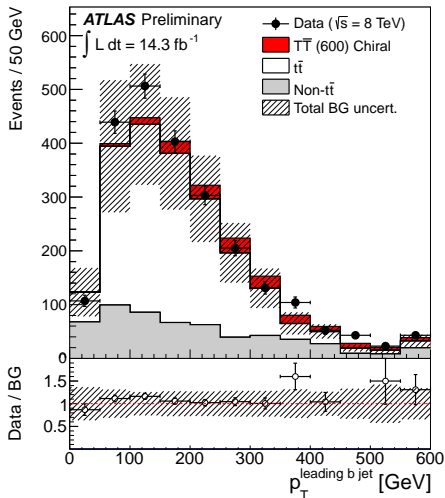
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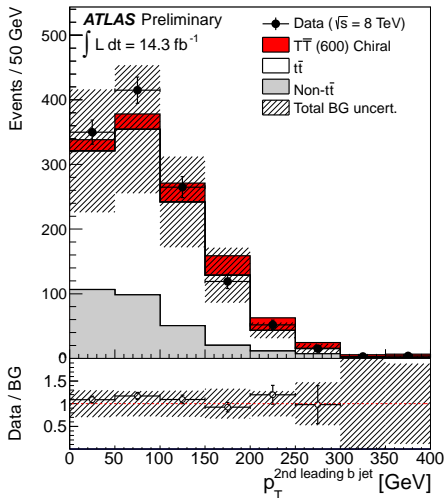
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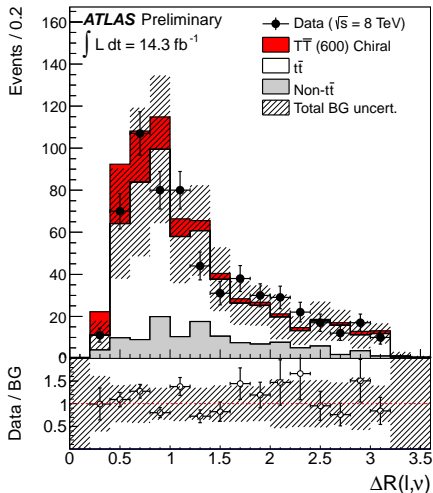
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# Event selection

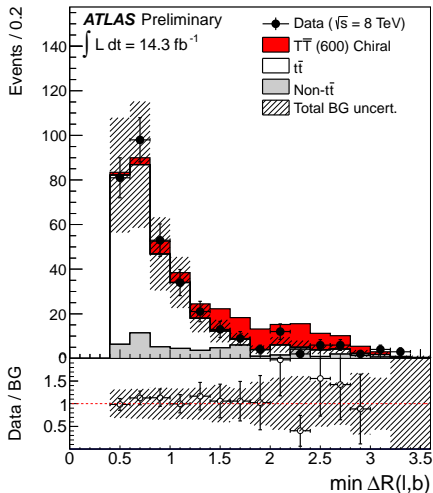
LOOSE selection		
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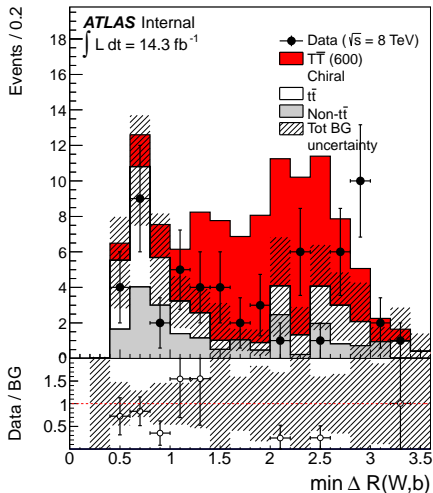
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# Comparison data vs prediction

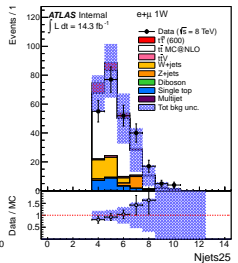
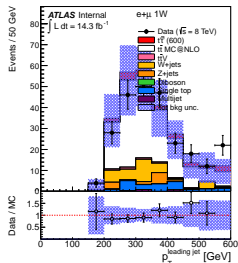
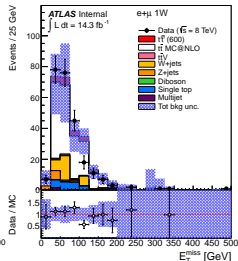
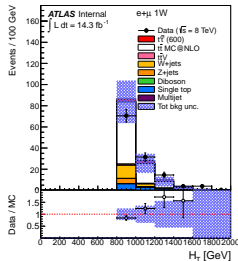
Check agreement between data and background prediction



Define regions depleted in signal

LOOSE but  $\Delta R(\ell, \nu) > 1.2$

$t\bar{t}'$ (600 GeV)	$18.47 \pm 1.48$	$+1.09$ $-1.64$
$t\bar{t}$	$173.13 \pm 8.82$	$+46.92$ $-48.59$
$W$ +jets	$30.64 \pm 9.78$	$+13.74$ $-12.43$
$Z$ +jets	$11.68 \pm 5.93$	$+5.89$ $-6.96$
Diboson	$0.29 \pm 0.19$	$+0.17$ $-0.17$
Single top	$21.46 \pm 2.54$	$+2.60$ $-2.54$
$t\bar{t}V$	$4.21 \pm 0.16$	$+1.33$ $-1.33$
Multijet	$0.49 \pm 0.91$	$\pm 0.25$
Total bkg.	$241.90 \pm 14.70$	$+53.57$ $-55.95$
Data	250	



# Yields in signal region

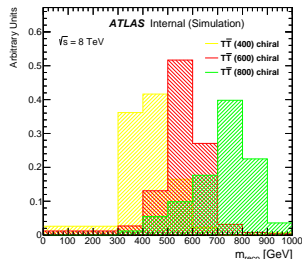
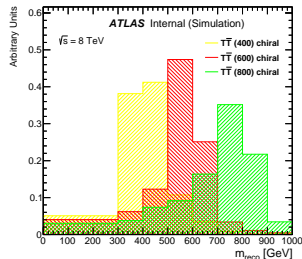
merged

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

Discriminating variable  $\Rightarrow$   $T$  reconstructed mass

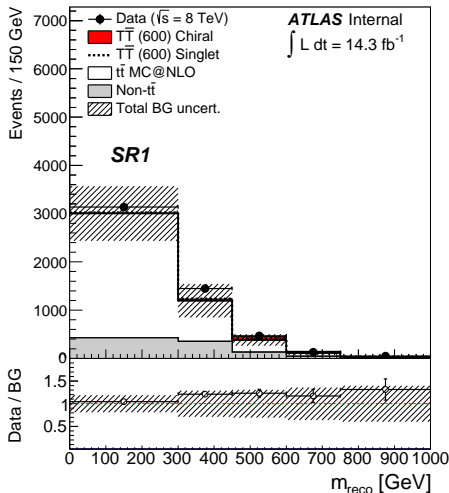


Pair  $b$ -jets and  $W$  boson candidates in order to get  
 $\min\Delta(M_{\text{lep}}, M_{\text{had}})$



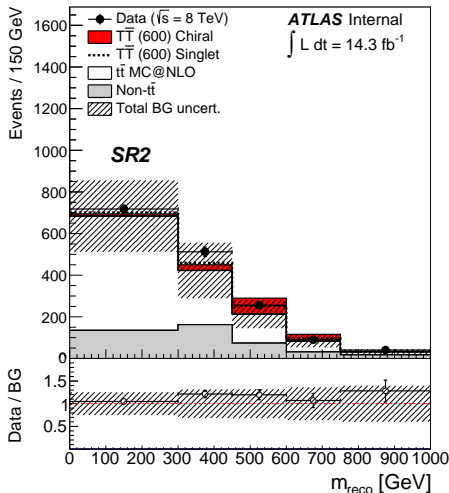
# Reconstructed mass

LOOSE selection		
SR0	Preselection	
SR1	+	$\geq 1 W_{\text{had}}$ candidates
SR2	+	$H_T^{Aj} > 800 \text{ GeV}$
SR3	+	$p_T(b_1) > 160 \text{ GeV}$
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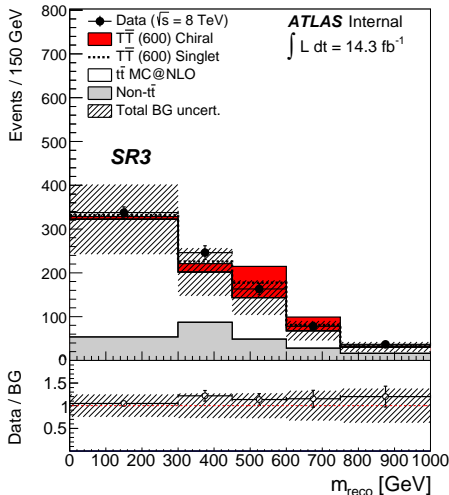
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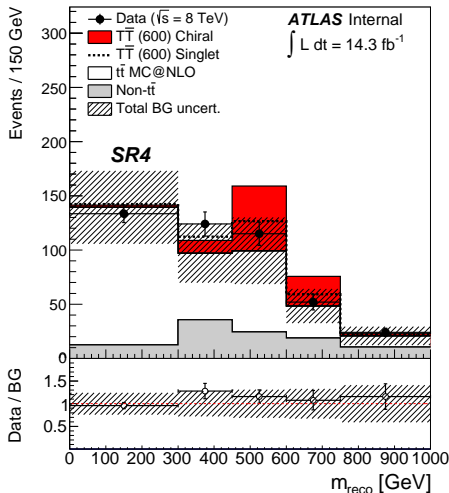
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# Reconstructed mass

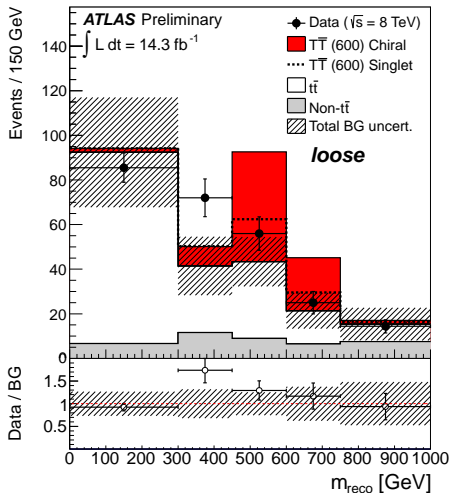
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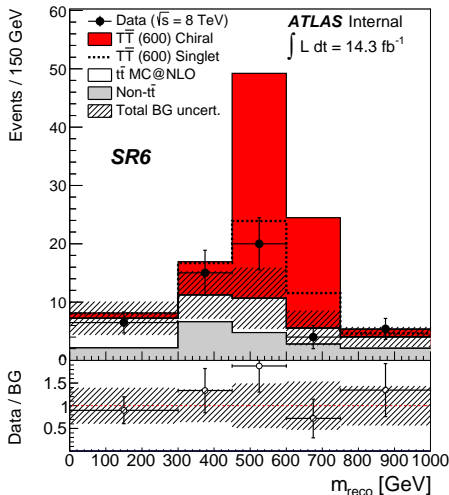
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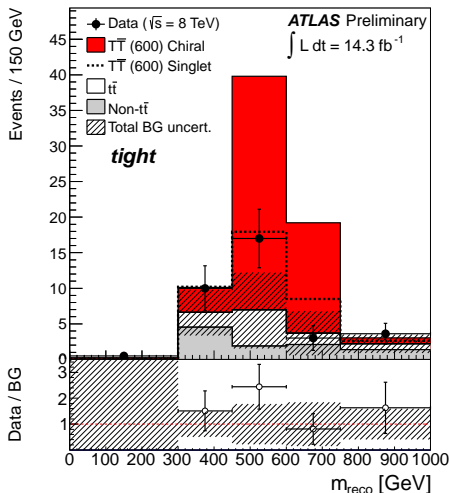
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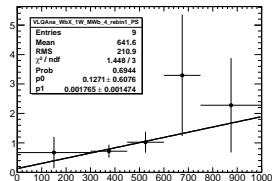
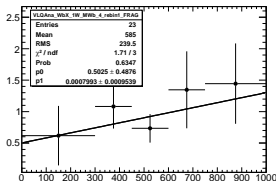
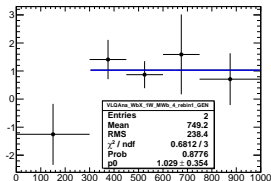
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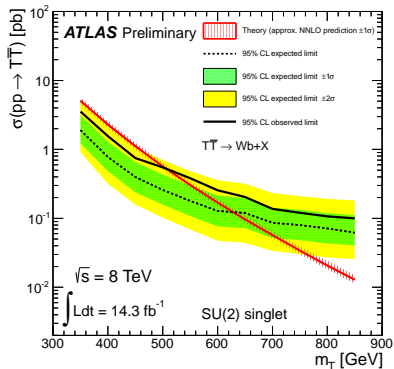
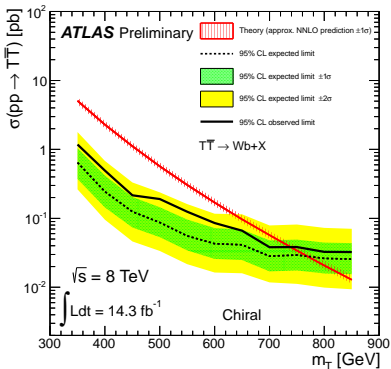


# Most relevant systematic uncertainties

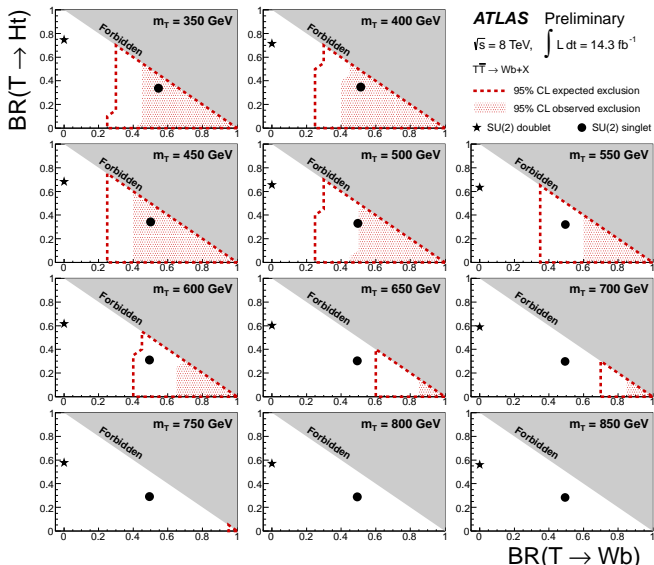
	$T\bar{T}$ (600 GeV)	$t\bar{t}$	Non- $t\bar{t}$
Total [%]	+14/-15	+59/-59	+42/-35
Main contributions [%]			
Jet energy scale	+6.6/-8.4	+15/-15	+33/-22
$t\bar{t}$ modelling: NLO MC generator	—	+48/-48	—
$t\bar{t}$ modelling: PS and fragm	—	+25/-25	—
$t\bar{t}$ modelling: ISR/FSR	—	+8.8/-8.8	—



# Results



## Results



# Outline

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Monte Carlo simulation

Event reconstruction

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

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

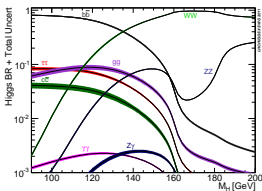
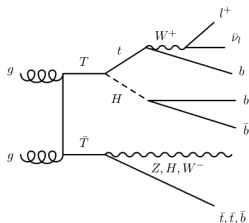
Search for  $T\bar{T}$  decaying to  $Ht + X$

Combined results

Conclusions and outlook

# Strategy

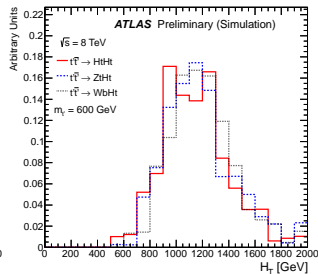
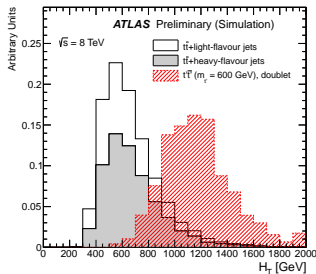
$$T\bar{T} \rightarrow Ht + X$$



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

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

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



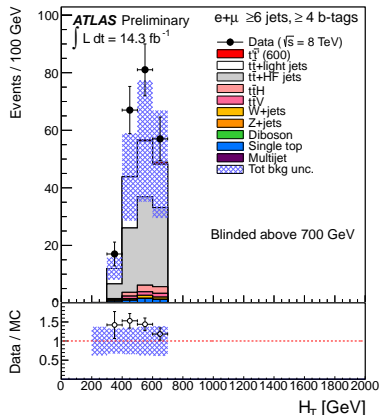
$\geq 6$  jets,  $\geq 4$   $b$ -jets



# Event selection

maximize signal acceptance

"2 $b$ -TAGGED JETS"	$\geq 6$ jets =2 $b$ -tagged jets orthogonality cut: $H_T < 700$ GeV
"3 $b$ -TAGGED JETS"	$\geq 6$ jets =3 $b$ -tagged jets
" $\geq 4$ $b$ -TAGGED JETS"	$\geq 6$ jets $\geq 4$ $b$ -tagged jets



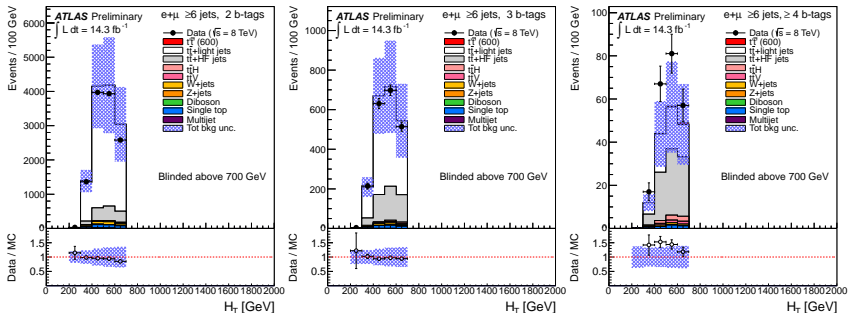
bad modeling  $\Rightarrow$  Simultaneous fit to data of  $H_T$  variable

# 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...



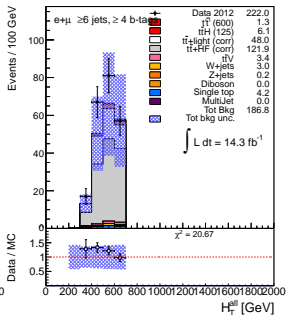
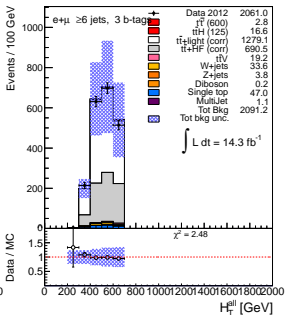
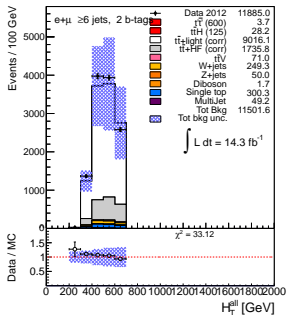
Maximum yields discrepancy below 5%

# Scale of $t\bar{t}$ components

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

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

... after



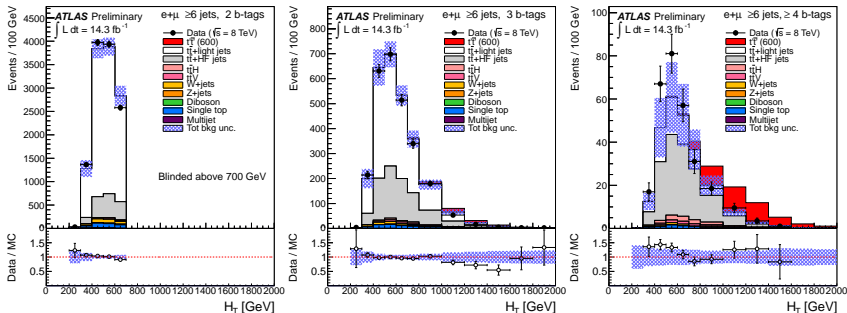
Maximum yields discrepancy below 5%

# Scale of $t\bar{t}$ components

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

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

final



Maximum yields discrepancy below 5%

# Comparison data vs prediction

Blinding cut:  $H_T < 700$  GeV

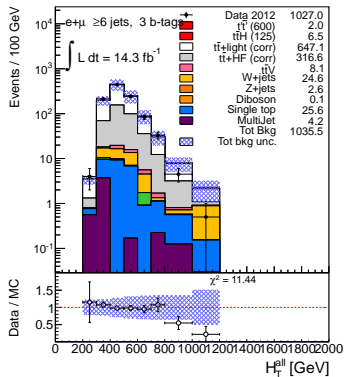
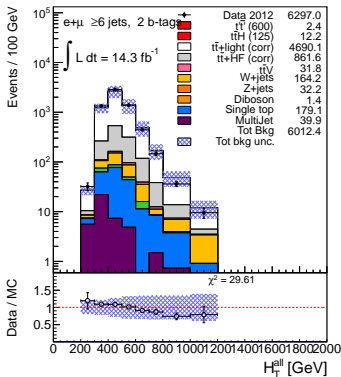


Define special blinded regions to check  $H_T$  modeling:

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

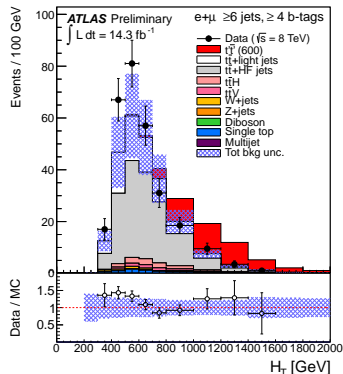
2  $b$ -tagged jets

3  $b$ -tagged jets



# Yields in signal regions

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

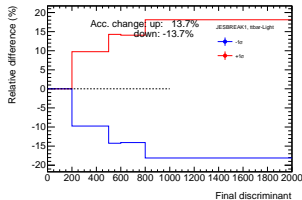
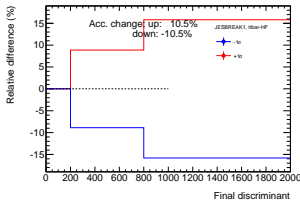


Introduce the scaling factors as **nuisance parameters**

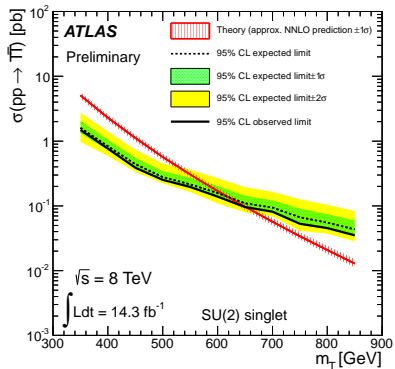
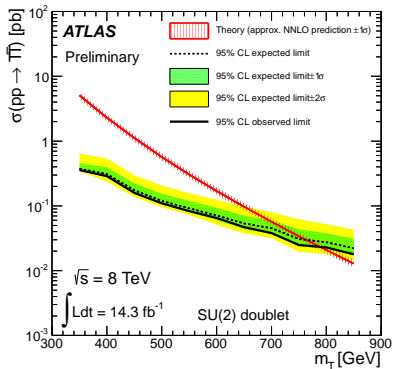
# Most relevant systematic uncertainties

... before fitting the nuisance parameters

	$T\bar{T}$	$t\bar{t}H$ (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 [%]										
BTAGBREAK8	+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	-	-	-	-	-	-

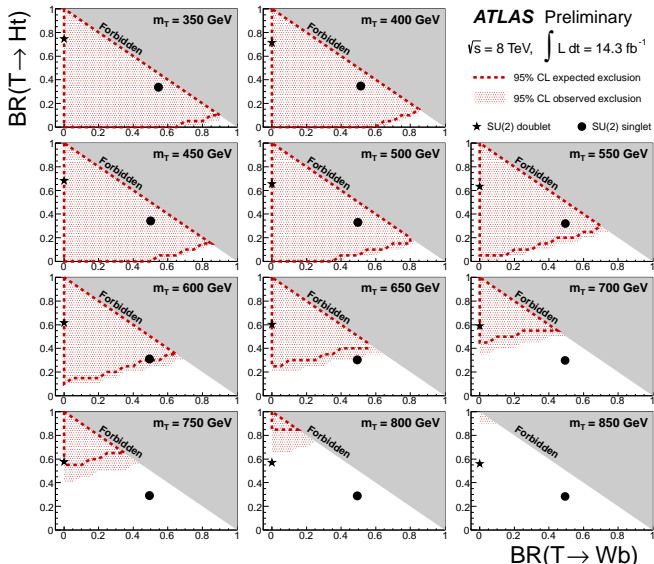


# Results





## 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**

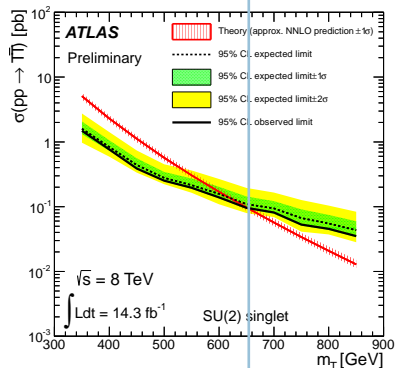
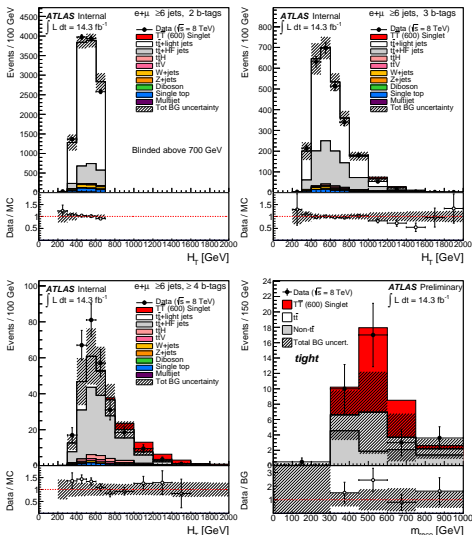
Conclusions and outlook

# 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

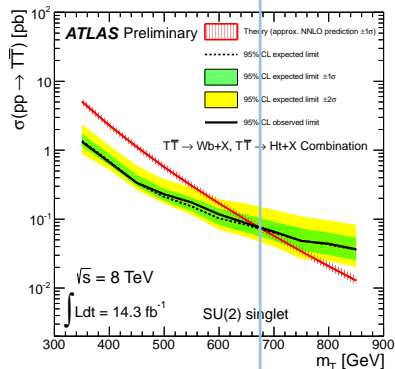
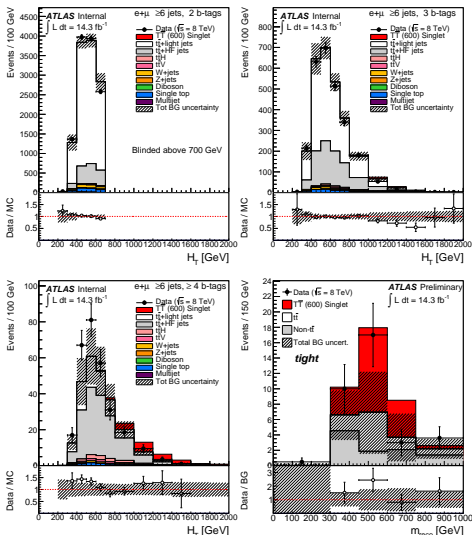


# Combination of $T\bar{T} \rightarrow Wb + X$ and $T\bar{T} \rightarrow Ht + X$

The search channels do **not** overlap

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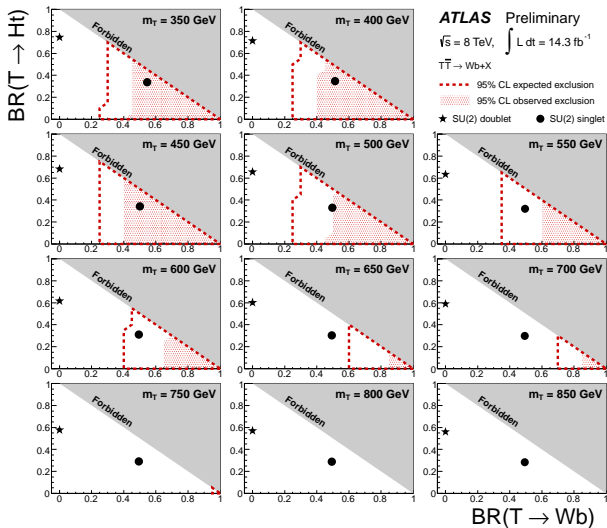
combination: 670 GeV



# Combined results

Individual analyses probe different areas

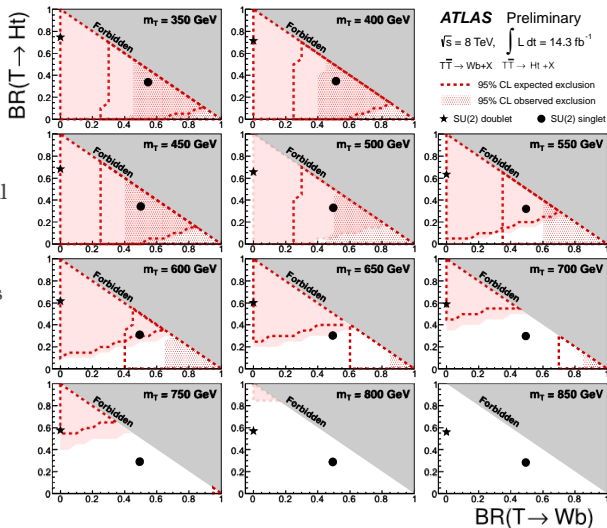
- $T\bar{T} \rightarrow Wb + X$  analysis alone very optimized for the bottom right corner



# Combined results

Individual analyses probe different areas

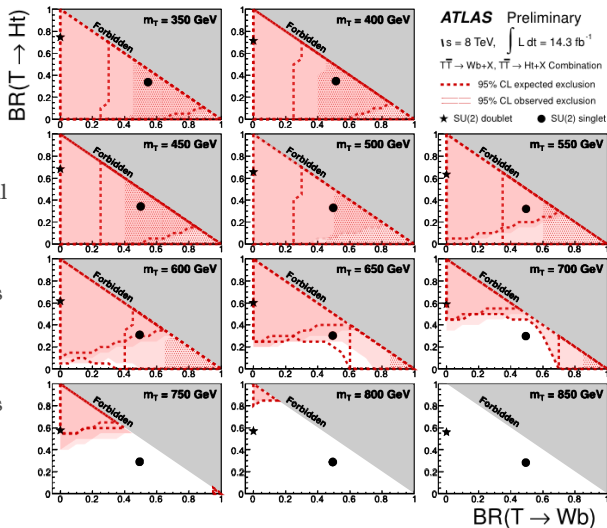
- ▶  $T\bar{T} \rightarrow Wb + X$  analysis alone very optimized for the bottom right corner
- ▶  $T\bar{T} \rightarrow Ht + X$  gives general good coverage, brings complete exclusion up to 450 GeV and almost excludes 650 GeV singlets



# Combined results

Individual analyses probe different areas

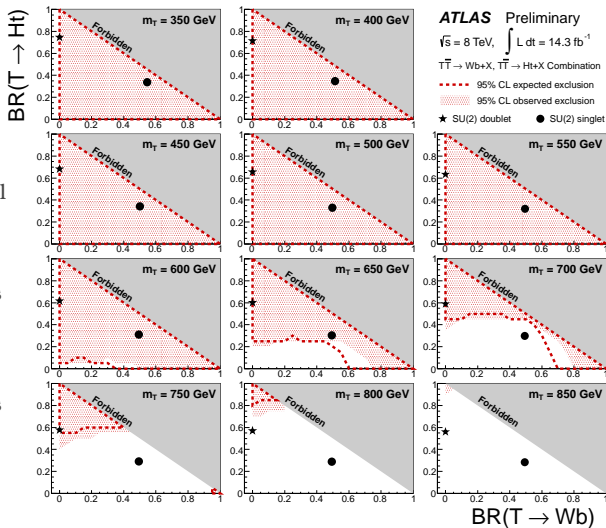
- ▶  $T\bar{T} \rightarrow Wb + X$  analysis alone very optimized for the bottom right corner
- ▶  $T\bar{T} \rightarrow Ht + X$  gives general good coverage, brings complete exclusion up to **450 GeV** and almost excludes 650 GeV singlets
- ▶ full combination reaches complete exclusion up to almost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



# Combined results

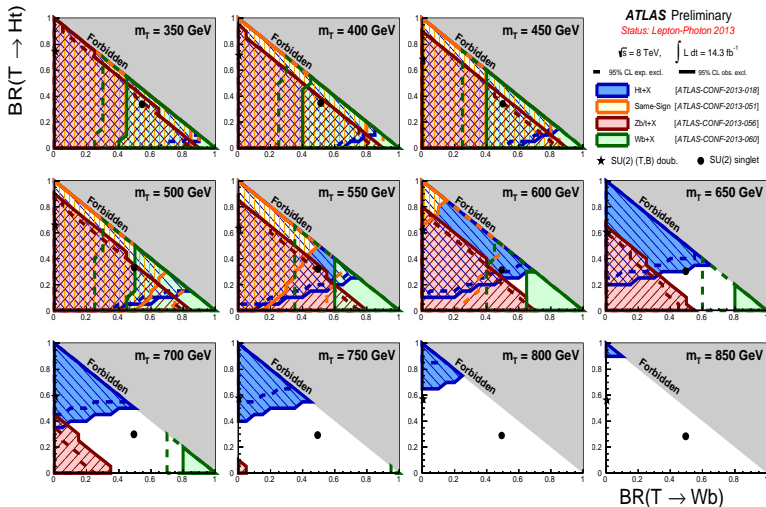
Individual analyses probe different areas

- ▶  $T\bar{T} \rightarrow Wb + X$  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!**

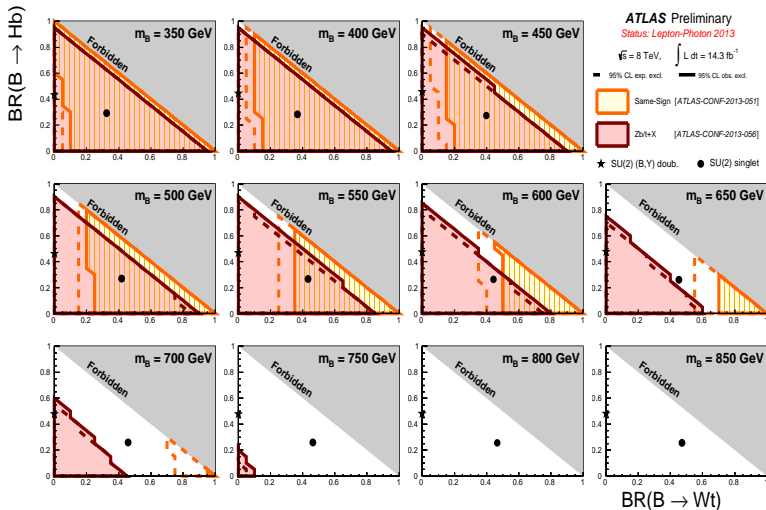




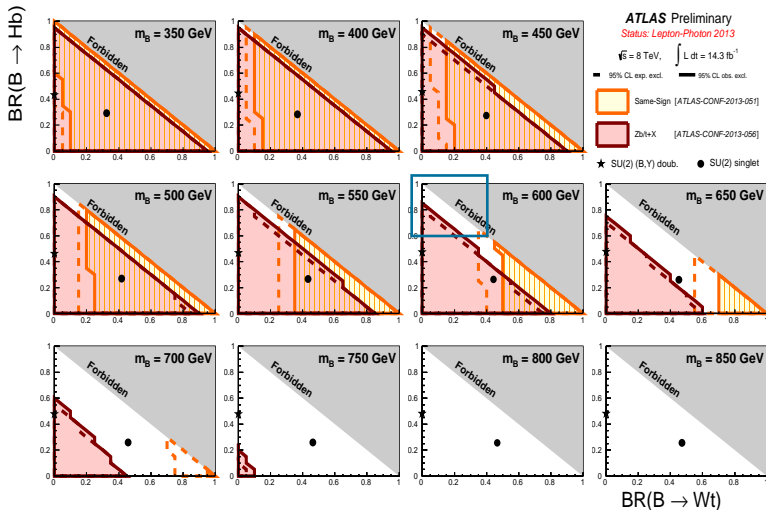
# ATLAS “worst case scenario” coverage



# ATLAS “worst case scenario” coverage



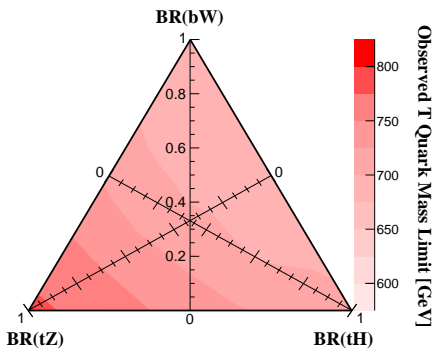
# ATLAS “worst case scenario” coverage



# Comparison to CMS results

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

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



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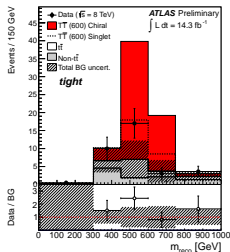
Search for  $T\bar{T}$  decaying to  $Ht + X$

Combined results

Conclusions and outlook

# Conclusions and outlook

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

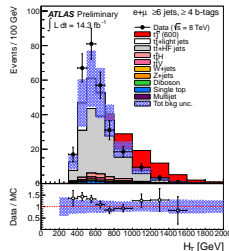


- poor MC bkg's statistical population in the TIGHT channel
- larger MC samples available
- possible optimization of the  $H_T^{4j}$  cut
- explorable option: larger anti- $k_t$  jets

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  $20 \text{ fb}^{-1}$  statistics,  
plus two new channels:  $B\bar{B} \rightarrow Wt + X$  and  $B\bar{B} \rightarrow Hb + X$

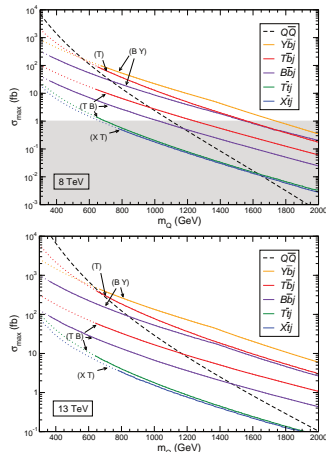
LHC Run-II:

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

To-do:

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

plots from [8]



# 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 $\beta^*$ (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	$1.15 \times 10^{11}$	$1.2 \times 10^{11}$	$1.45 \times 10^{11}$	$1.7 \times 10^{11}$
Bunch spacing (ns)	25	150	75/50	50
Peak luminosity ( $\text{cm}^{-2}\text{s}^{-1}$ )	$1 \times 10^{34}$	$2.1 \times 10^{32}$	$3.7 \times 10^{33}$	$7.7 \times 10^{33}$
Emittance $\varepsilon_n$ ( $\mu\text{rad}$ )	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 <sup>(+)</sup>	
	$E_T^{\text{miss}} > 35(20)$ GeV for electron (muon) channel	$E_T^{\text{miss}} > 20$ GeV
	$E_T^{\text{miss}} + m_T > 60$ GeV	
	$\geq 3$ jets for $W_{\text{had}}^{\text{type I}}$ $\geq 4$ jets for $W_{\text{had}}^{\text{type II}}$	$\geq 4$ jets <sup>(*)</sup>
	$\geq 1$ $b$ -tagged jets <sup>(**)</sup>	
Loose selection	orthogonality cut reject events with $\geq 6$ and $\geq 3$ $b$ -tagged jets	
	Preselection	
	$\geq 1$ $W_{\text{had}}$ candidates <sup>(x)</sup>	
	$H_T^{4j} > 750$ GeV	$H_T^{4j} > 800$ GeV

# 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