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

Antonella Succurro

PhD candidate in Physics

Universitat Autònoma de Barcelona

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

Four questions, one dissertation

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

Four questions, one dissertation

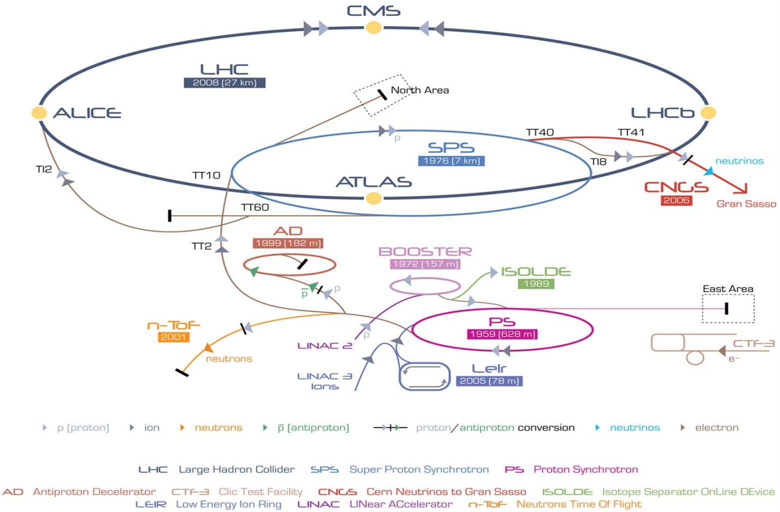
- Why? bother with “new physics”
- Where? is all happening
- What? are we looking at
- How?

Outline

Standard Model as an effective theory

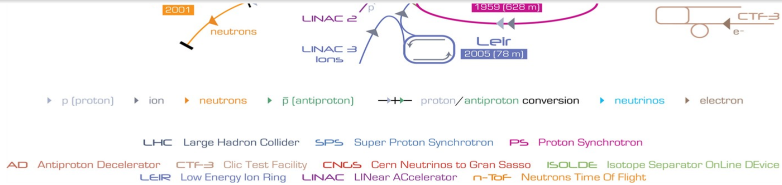
Outline

The LHC complex

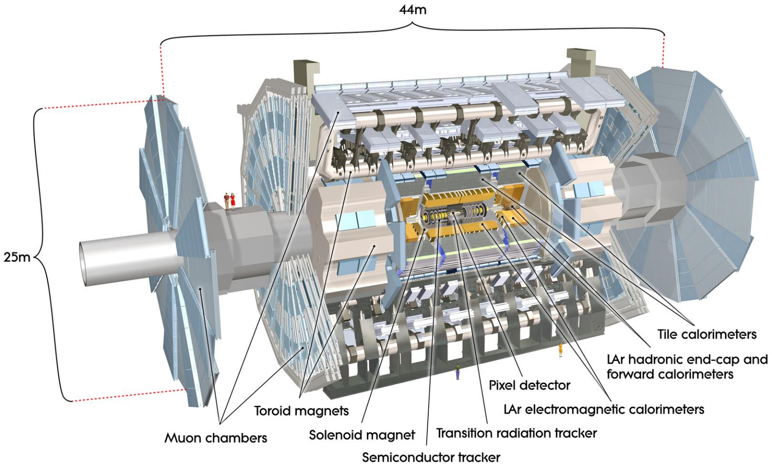


The LHC complex

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	1.15×10^{11}	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}
Bunch spacing (ns)	25	150	75/50	50
Peak luminosity ($cm^{-2}s^{-1}$)	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. $< \mu >$	19	4	17	37

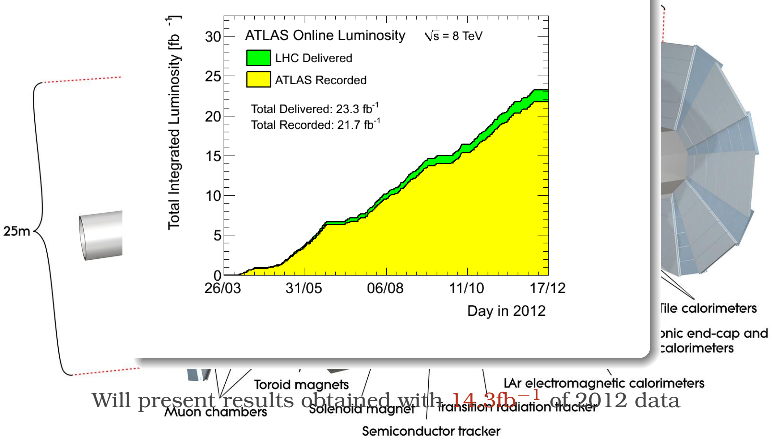


The ATLAS Detector



The ATLAS Detector

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

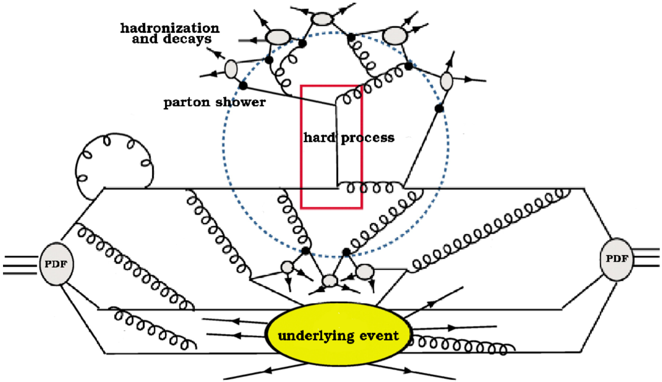


Will present results obtained with 14.3fb^{-1} of 2012 data

Outline

Modelling of hadron collisions

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

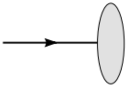


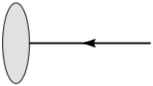
Modelling of hadron collisions

Drawings from [1]

$E(p_1) = 4$ TeV

$E(p_2) = 4$ TeV



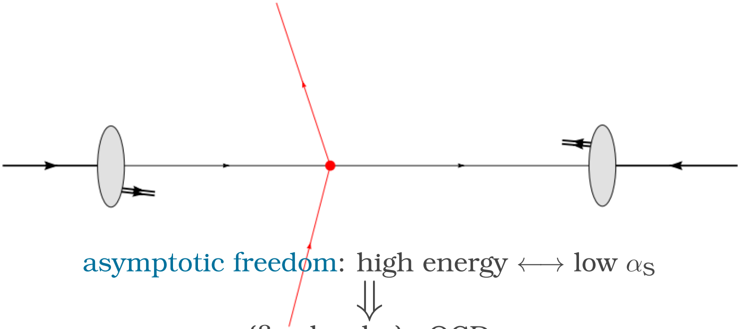


Quarks are distributed according to PDFs inside the proton

$\Downarrow$

intial energy unknown

Hard scattering of two partons

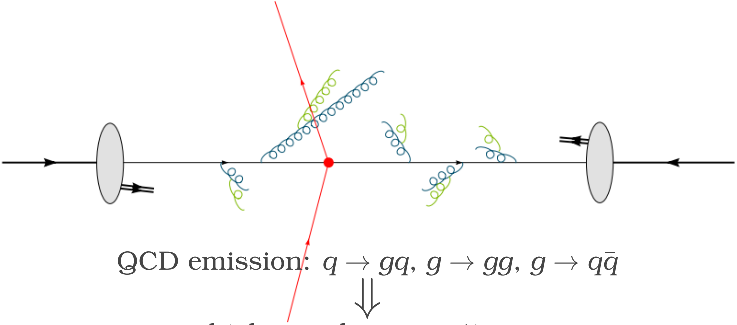


asymptotic freedom: high energy $\longleftrightarrow$ low α_S

$\Downarrow$

(fixed order) pQCD

Parton showering

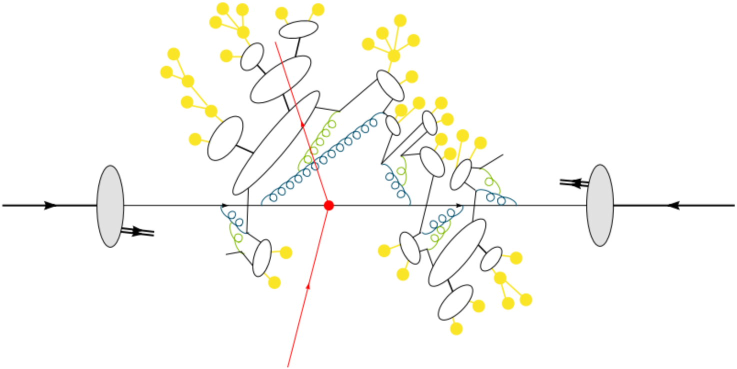


QCD emission: $q \to gq$, $g \to gg$, $g \to q\bar{q}$

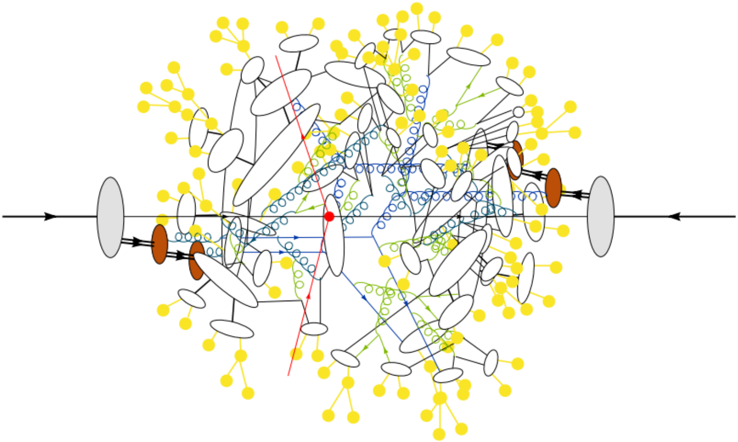
$\Downarrow$

higher-order corrections

Hadronization



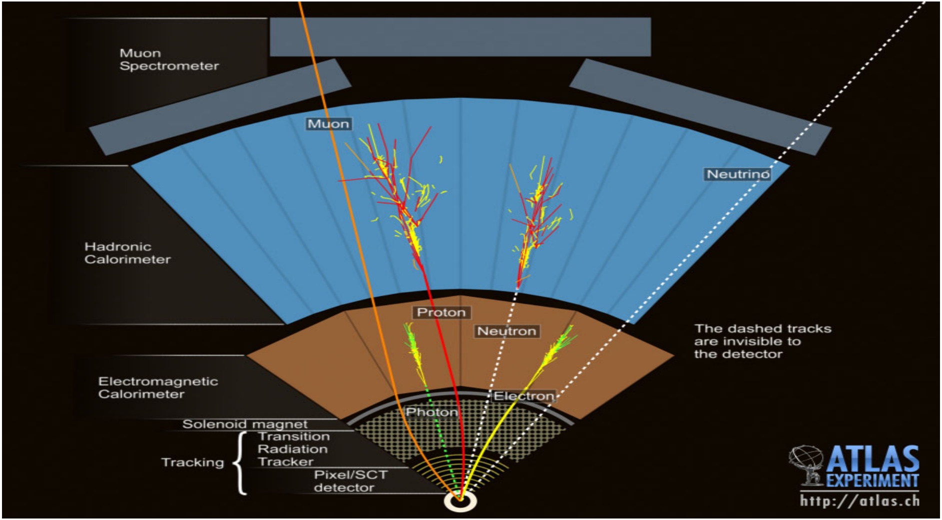
Underlying event simulation



Pile-up

Outline

Physics objects puzzle



One lepton

Many jets

Missing transverse energy

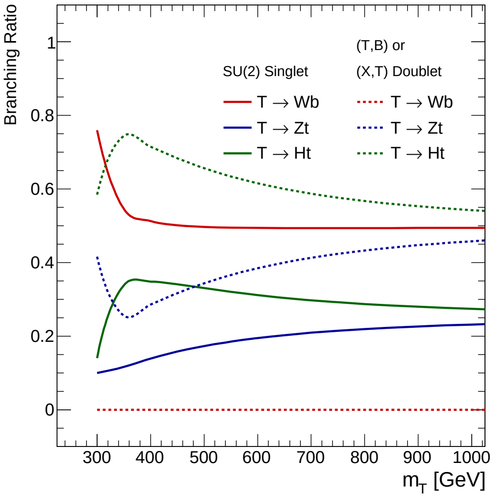
Outline

Available signatures

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

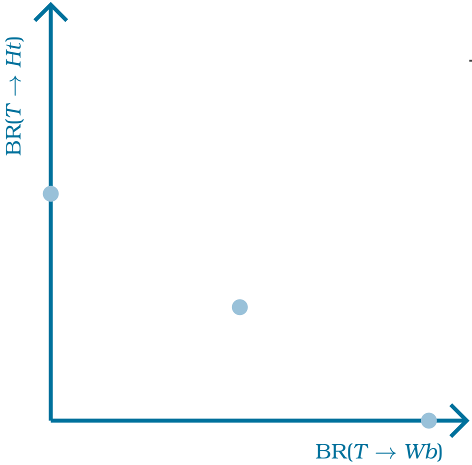


Model Independent Strategy

- Build a 2-dim plane to scan model mixing

BR($T \rightarrow Wb$)

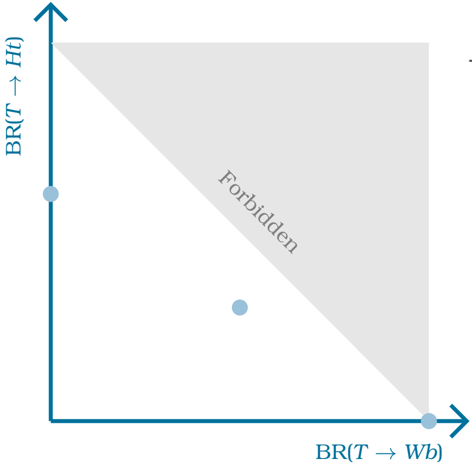
Model Independent Strategy



	$BR(T \to Wb)$	$BR(T \to Zt)$	$BR(T \to Ht)$
Chiral	1.0	0.0	0.0
Singlet	0.494	0.194	0.312
Doublet	0.000	0.383	0.617

- Build a 2-dim plane to scan model mixing

Model Independent Strategy



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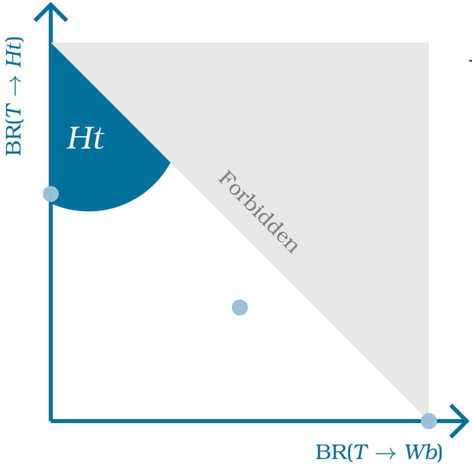
- Sum of BRs is 1[a]

[a] BR($T \to Zt$) = 1 - BR($T \to Ht$) - BR($T \to Wb$)

Model Independent Strategy



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- Different analyses are sensitive to different areas

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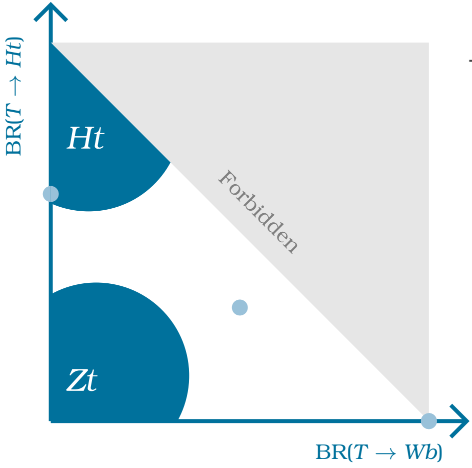
Model Independent Strategy



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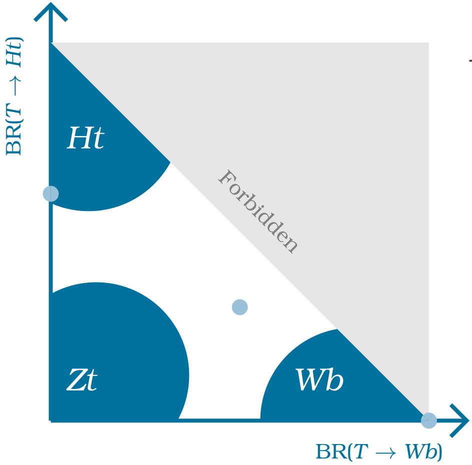

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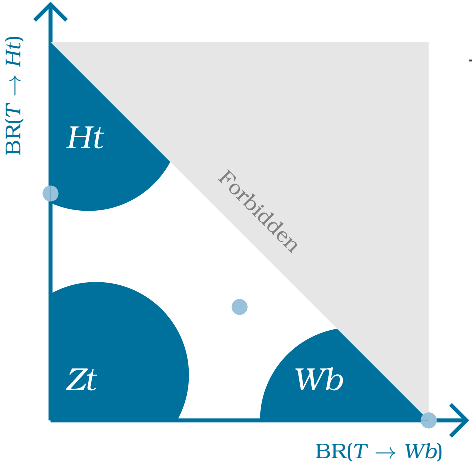
Model Independent Strategy



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- 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($T \to Zt$) = 1 - BR($T \to Ht$) - BR($T \to Wb$)

Preselection

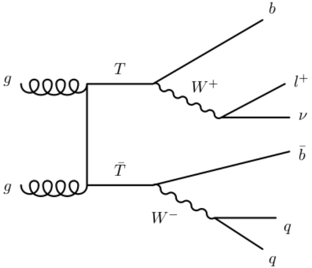
Two searches using common analysis framework:

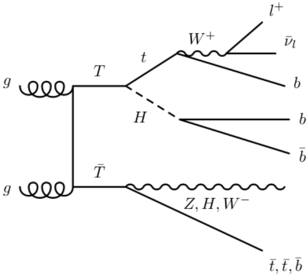
- $T\bar{T} \to Wb + X$
- $T\bar{T} \to Ht + X$

ATLAS-CONF-2013-060 [5]   ATLAS-CONF-2013-018 [6]

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

+ "orthogonality" requirements





Background and signal modelling

Yields in the preselection region "blinded" as: $H_T^{4j} < 800$ GeV (*)

	≥ 4 jets, ≥ 1 b-tags
$t\bar{t}$ MC@NLO	202042 ± 285
W+jets	35921 ± 525
Z+jets	5804 ± 146
Multi-jet	6264 ± 74
Single top	14375 ± 107
Diboson	548 ± 12
$t\bar{t}$V	680 ± 2
$t\bar{t}$H (125)	220 ± 1
Tot Bkg w/ MC@NLO	265854 ± 629
$T\bar{T}$ (600) chiral	36 ± 2
Data	256993 ± 507

(*) $H_T^{4j} = p_{\mathrm{T}}(l) + E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{j=1}^{4} p_{\mathrm{T}}(j)$

- $t\bar{t}$ pair production in association with jets generated with `MC@NLO+HERWIG`
- $m_t = 172.5$ 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 $t\bar{t}c\bar{c}$
- $m_t = 172.5$ GeV
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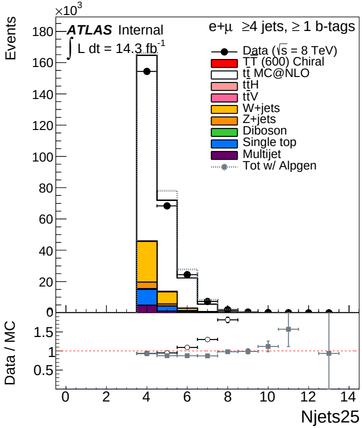
Yields for $t\bar{t}$ predicted with ALPGEN are ~3-8% higher than MC@NLO



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(*) $H_T^{4j} = p_{\mathrm{T}}(l) + E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{j=1}^{4} p_{\mathrm{T}}(j)$

- W and Z boson production in association with jets generated with up to five additional partons with `ALPGEN+HERWIG`

W+jets:

- Samples generated separately for W+light jets, $Wb\bar{b}$+jets, $Wc\bar{c}$+jets, and Wc+jets
- Normalized to data-driven prediction

Z+jets:

- Samples generated separately for Z+light jets, $Zb\bar{b}$+jets, and $Zc\bar{c}$+jets
- Inclusive NNLO theoretical cross section

Background and signal modelling

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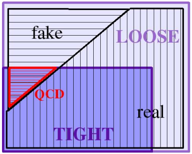
- QCD multi-jet events have high cross-section
- Data-drive estimation
- Matrix-method



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

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Single top:

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

Diboson:

- Diboson production generated with HERWIG
- NLO theoretical cross section

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$t\bar{t}V$:

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

$t\bar{t}H$:

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

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(*) $H_T^{4j} = p_{\mathrm{T}}(l) + E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{j=1}^{4} p_{\mathrm{T}}(j)$

- $T\bar{T}$ singlet production generated with `PROTOS+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

Systematic uncertainties - Shape and Norm

Systematic uncertainty	$T\bar{T} \to Wb + X$		$T\bar{T} \to Ht + X$	
	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

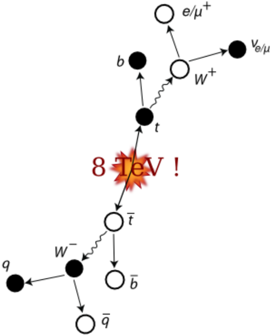
Outline

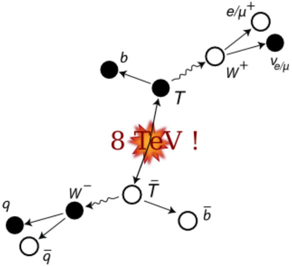
Strategy

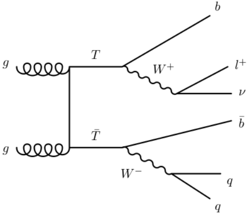
$$T\bar{T} \rightarrow WbWb$$

like

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







different boosted kinematics

$\Downarrow$

reconstruct the W boson from hadronic decay

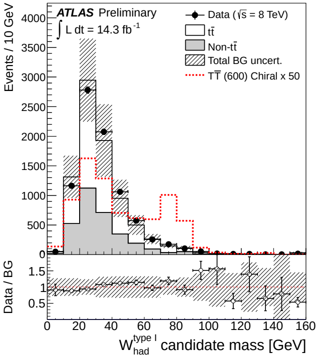
$$\Delta R \sim \frac{2m}{p_{\mathrm{T}}}$$

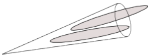
$\Downarrow$

reconstruct heavy quark mass

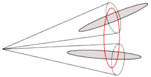
W boson reconstruction

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



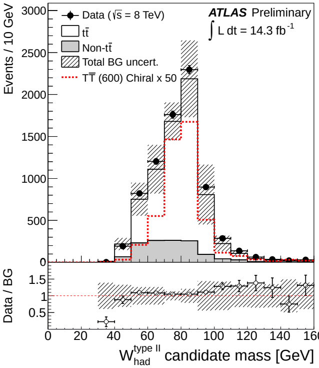


one jet
$p_T > 250$ GeV
$60 < M < 120$ GeV



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

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



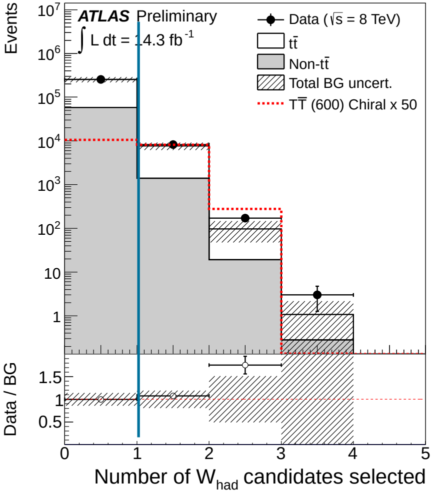
W_{lep} reconstructed using lepton and "neutrino":

p_X, p_Y from $E_{\mathrm{T}}^{\mathrm{miss}}$, p_Z from $M_W^2 = (P_l + P_\nu)^2$

Event selection

	LOOSE selection	
SR0	Preselection + Ortho Cut (*)	
SR1	+	$\geq 1\ W_{\mathrm{had}}$ candidates
SR2	+	$H_T^{4j} > 800$ GeV
SR3	+	$p_{\mathrm{T}}(b_1) > 160$ GeV
SR4	+	$p_{\mathrm{T}}(b_2) > 80$ GeV
SR5	+	$\Delta R(\ell, \nu) < 1.2$
	TIGHT selection	
SR5	LOOSE selection	
SR6	+	$\min\Delta R(\ell, b) > 1.4$
SR7	+	$\min\Delta R(W_{\mathrm{had}}, b) > 1.4$

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



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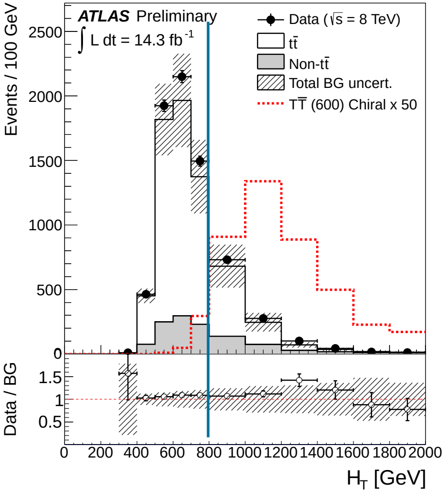
(*) reject events with $\geq$6 jets and $\geq$3 b-jets



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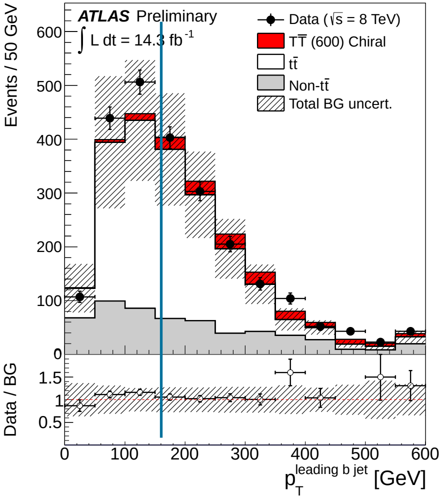

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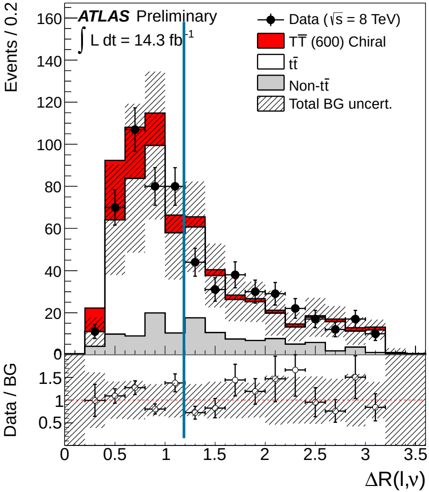

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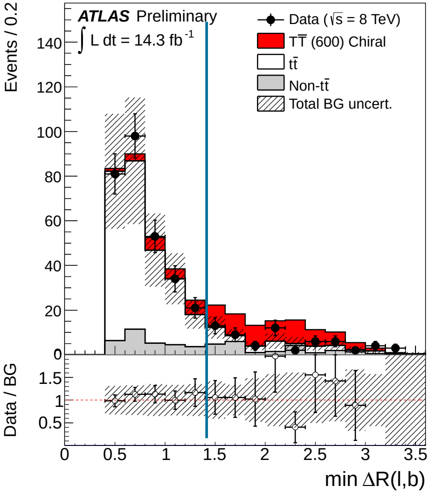

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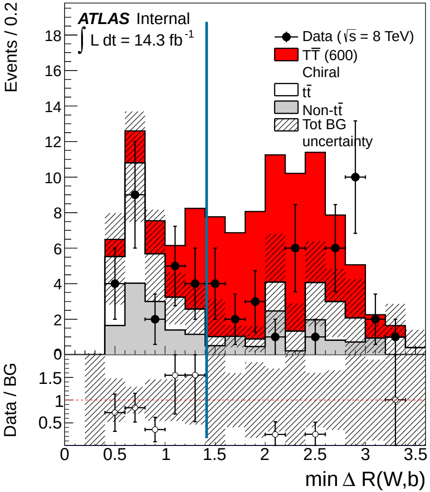
(*) reject events with $\geq$6 jets and $\geq$3 b-jets



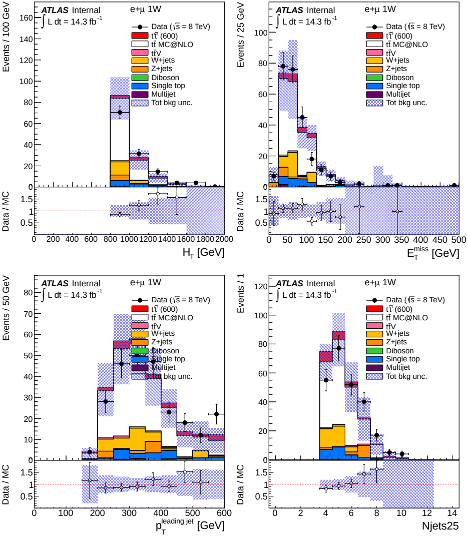
Comparison data vs prediction

(before unblinding)
Check agreement between data and background prediction

$\Downarrow$

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



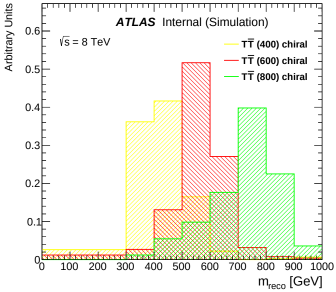
Signal to background discrimination

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

Discriminating variable ⇒ T reconstructed mass

$\Downarrow$

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	+	≥ 1 W_{had} candidates
SR2	+	$H_T^{4j} > 800$ GeV
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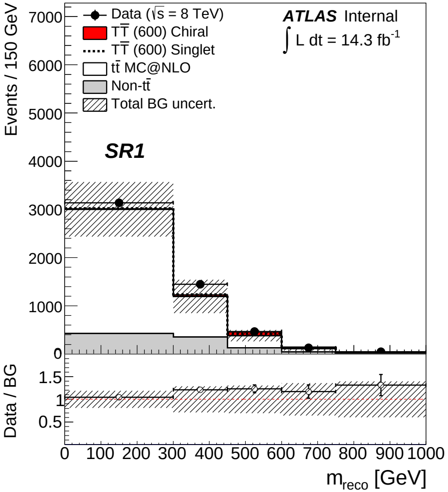

Reconstructed mass

	LOOSE selection	
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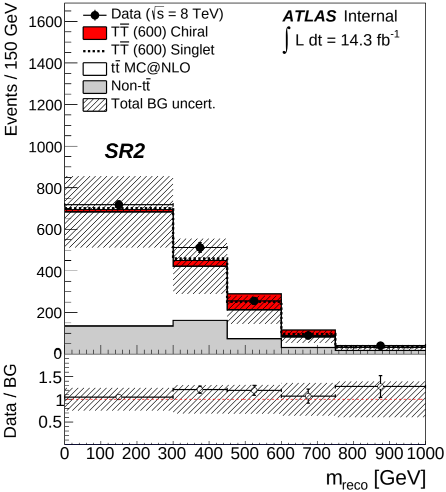

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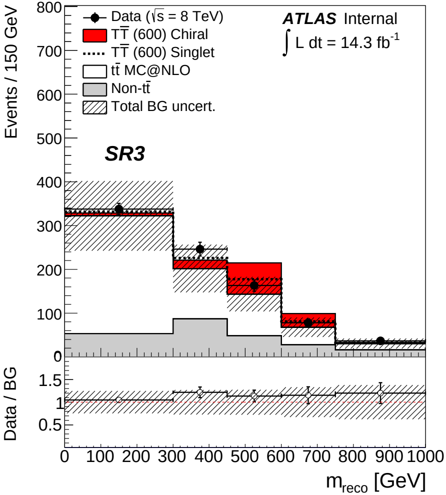

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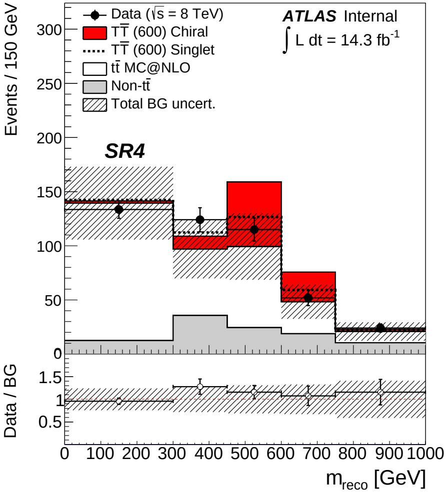

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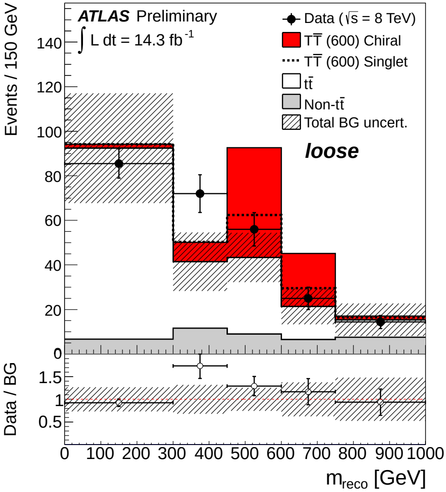

Reconstructed mass

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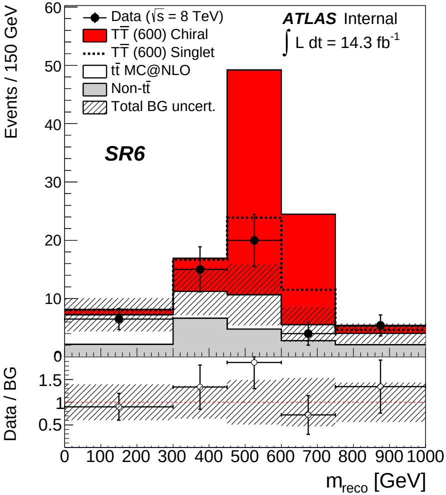

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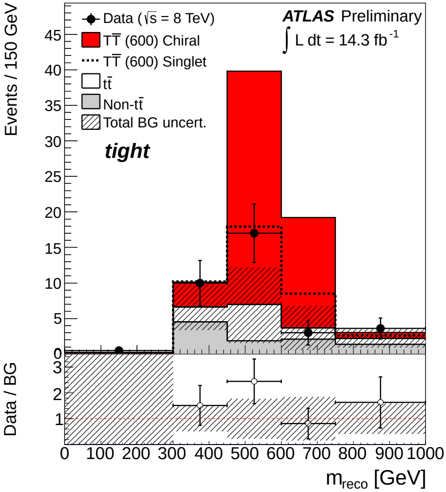
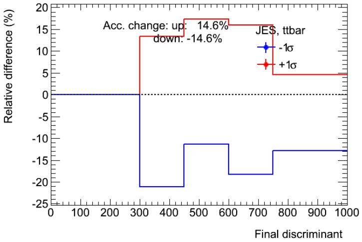
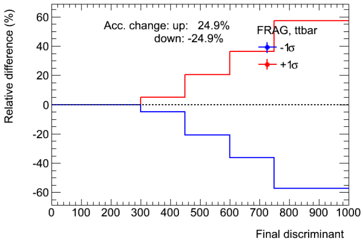


Most relevant systematic uncertainties

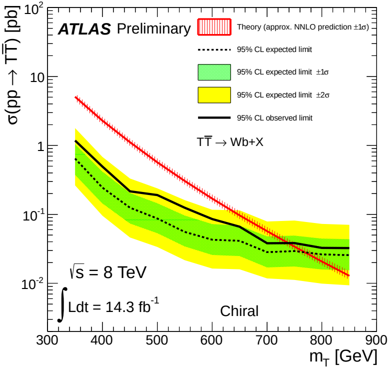
	$T\bar{T}$ (600 GeV)	$t\bar{t}$	Non-$t\bar{t}$
Total [%]	+14/-15	+59/-59	+42/-35
Main contributions [%]			
Jet energy scale	+6.6/-8.4	+15/-15	+33/-22
$t\bar{t}$ modelling: NLO MC generator	–	+48/-48	–
$t\bar{t}$ modelling: PS and fragm	–	+25/-25	–
$t\bar{t}$ modelling: ISR/FSR	–	+8.8/-8.8	–





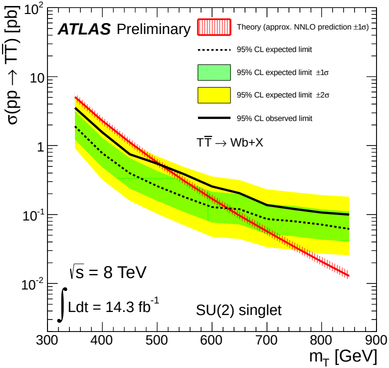
Benchmark results

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



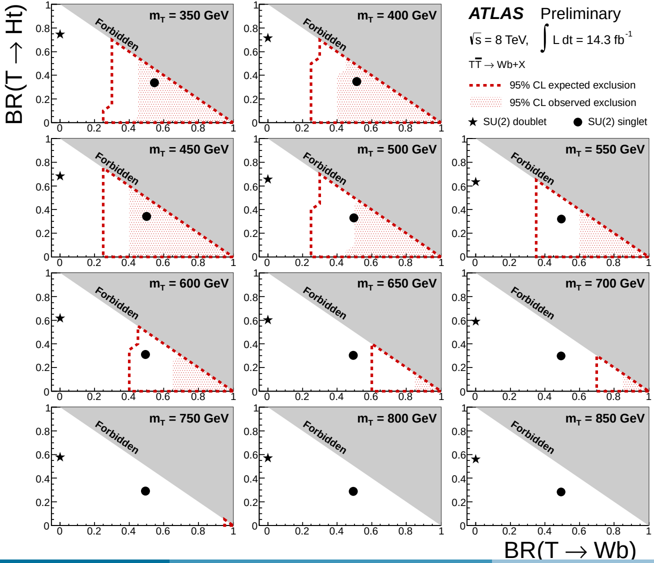
observed (expected) 95% CL limit
$m_T > 740\,(770)$ GeV

Singlet T



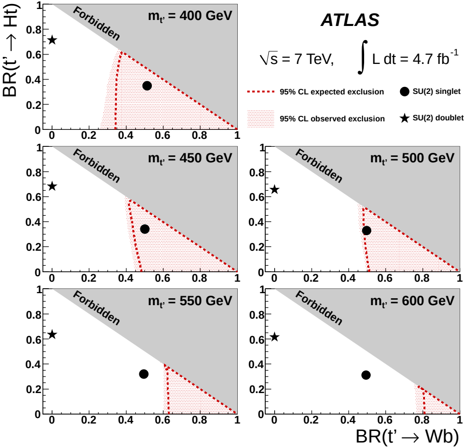
observed (expected) 95% CL limit
$m_T > 505\,(630)$ GeV

Model independent results



... updating 7 TeV results

First model-independent search
Phys.Lett. **B718** (2012) [4]

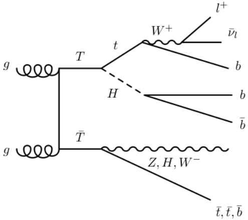


Outline

Strategy

$$T \rightarrow Ht \begin{array}{l} \nearrow bbWb \rightarrow bbbl\nu \\ \searrow WWWb \rightarrow qqqqbl\nu \end{array} \quad + \bar{T} \rightarrow Wb/Zt/Ht$$

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



SM Higgs boson
w/ $m_H = 125$ GeV
$\Downarrow$
BR($H \rightarrow bb$) = 60%
BR($H \rightarrow WW$) = 20%

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

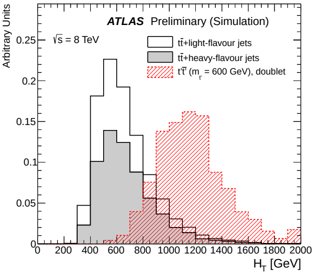
$$\Downarrow$$

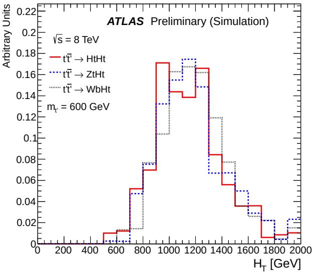
$$H_{\mathrm{T}} = p_{\mathrm{T}}(l) + E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{j=1}^{\mathrm{Njets}} p_{\mathrm{T}}(j)$$

peak $\sim 2m_T$

good signal/bkg discriminant

for all $Ht + X$ modes





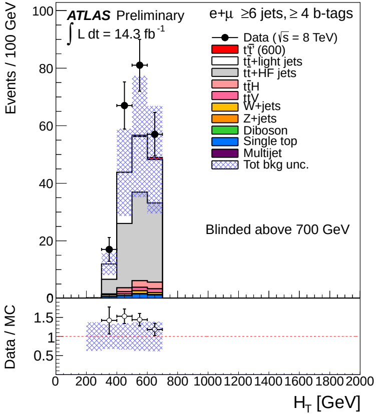
≥ 6 jets, ≥ 4 b-jets

Event selection

maximize signal acceptance

"2 b-TAGGED JETS"	$\geq$ 6 jets =2 b-tagged jets orthogonality cut: $H_{\mathrm{T}} < 700$ 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

$\rightarrow$ b-tagging by TRF in MC $\leftarrow$



heavy flavor component not well predicted

$\Downarrow$

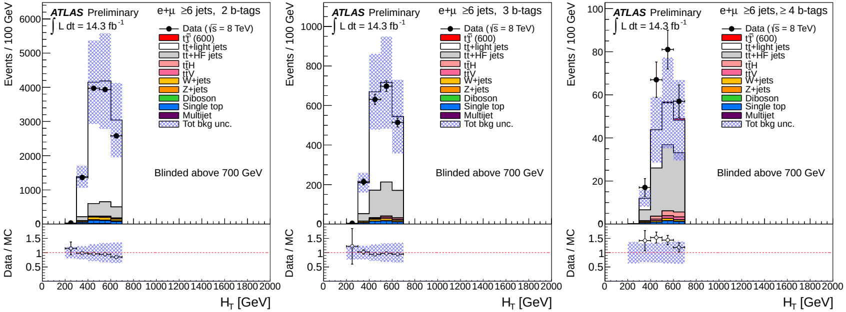
simultaneous fit to data of H_{T} variable

(good to have background enriched channels)

Scale of $t\bar{t}$ components

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

before. . .



Maximum yields discrepancy below 5%

Scale of $t\bar{t}$ components

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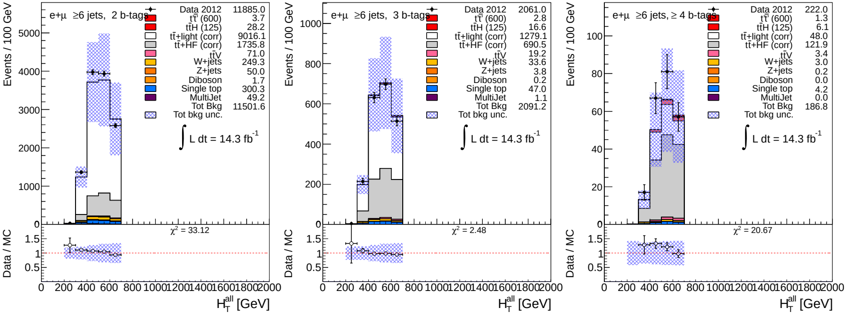
... after



Maximum yields discrepancy below 5%

Comparison data vs prediction

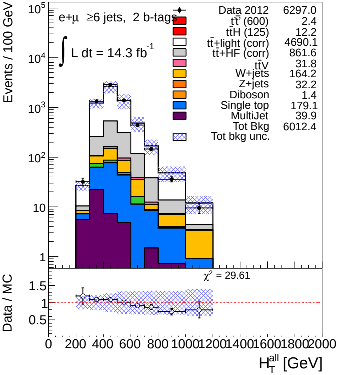
Blinding cut: $H_{\mathrm{T}} < 700$ GeV

$\Downarrow$

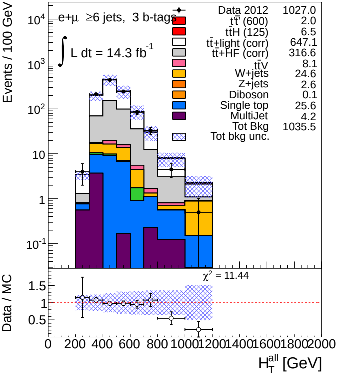
Define special blinded regions to check H_{T} modeling:

at most two jets with $p_{\mathrm{T}} > 60$ GeV, $H_{\mathrm{T}} < 1.2$ TeV

2 b-tagged jets

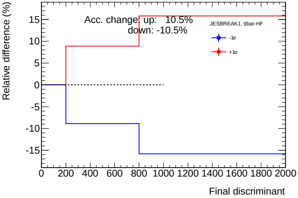


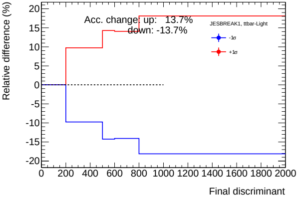
3 b-tagged jets



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 [%]					
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	–	–	–	–	–	–



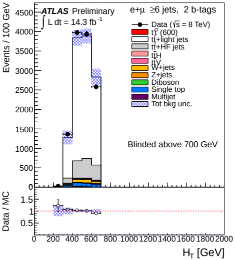


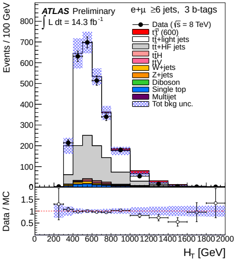
Introduce the scaling factors as nuisance parameters

$\Downarrow$

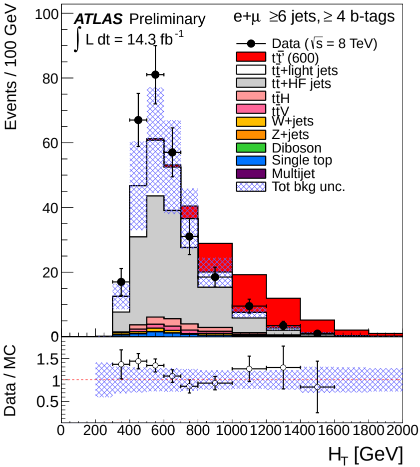
total uncertainty on $t\bar{t}$+HF reduced by $\sim 20\%$

Yields in signal regions



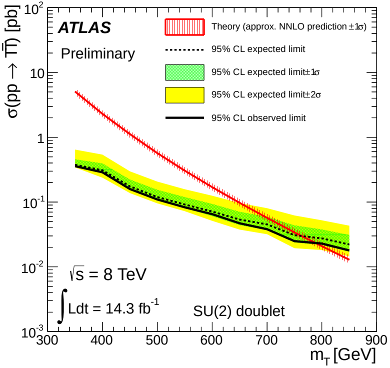


	2 b-tags	3 b-tags	$\geq$ 4 b-tags
$t\bar{t}$+HF	1500 ± 900	900 ± 400	170 ± 70
$t\bar{t}$+LF	9600 ± 1000	1900 ± 350	75 ± 22
W+jets	250 ± 130	50 ± 30	5 ± 3
Z+jets	50 ± 40	9 ± 6	0.5 ± 0.9
Single top	300 ± 70	75 ± 18	7 ± 3
Diboson	1.7 ± 0.6	0.3 ± 0.1	0.03 ± 0.03
$t\bar{t}V$	70 ± 20	36 ± 12	7 ± 3
$t\bar{t}H$	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



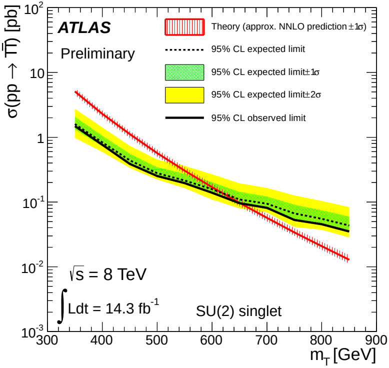
Benchmark results

Doublet



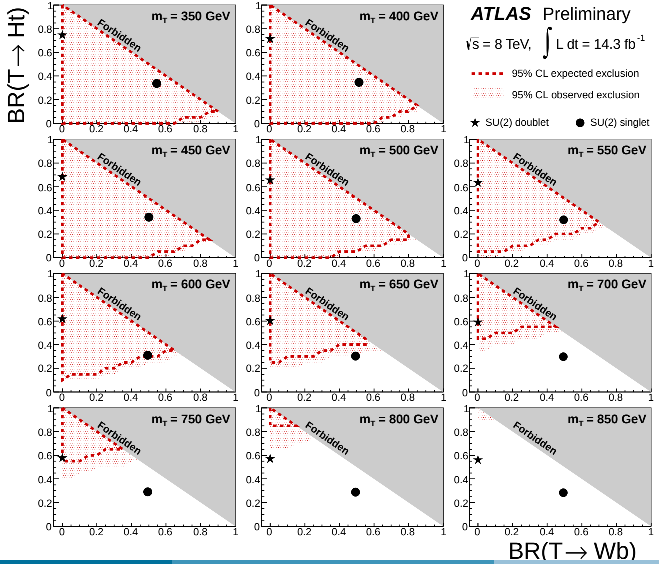
observed (expected) 95% CL limit
$m_T > 790\,(745)$ GeV

Singlet



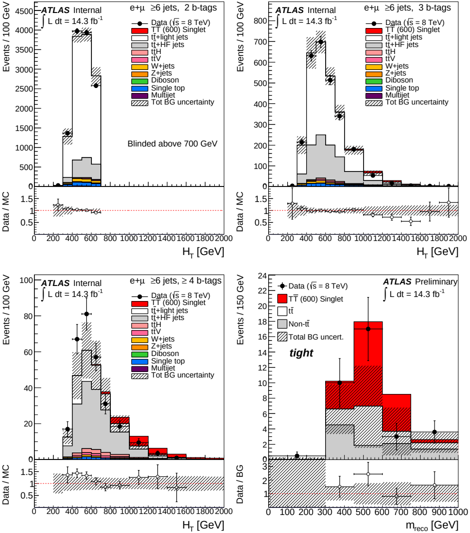
observed (expected) 95% CL limit
$m_T > 640\,(615)$ GeV

Model independent results



Outline

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

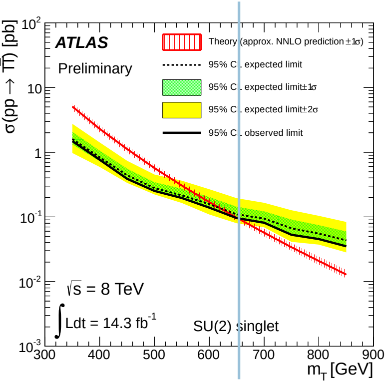


The search channels do not overlap

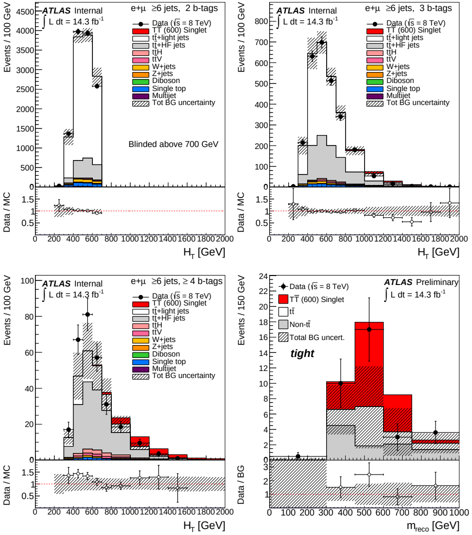
⇓

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

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



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

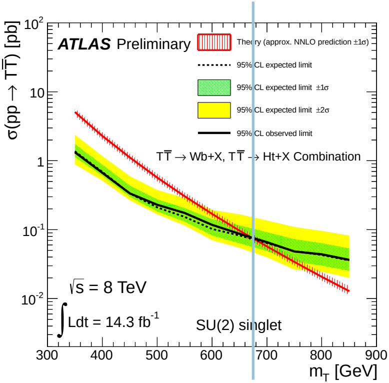


The search channels do not overlap

⇓

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

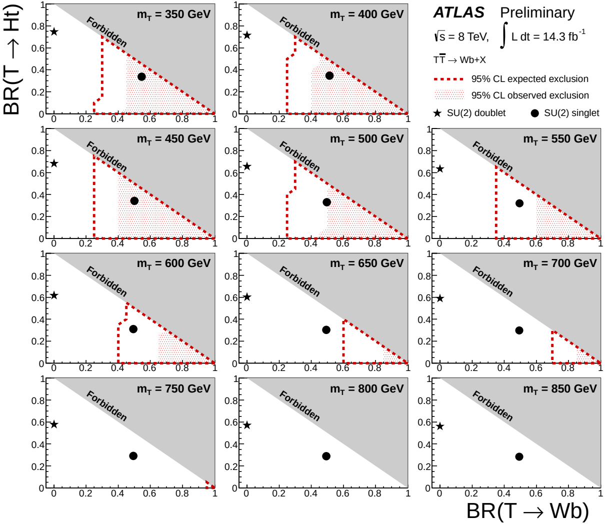
combination: 670 GeV



Combined results

Individual analyses probe different areas

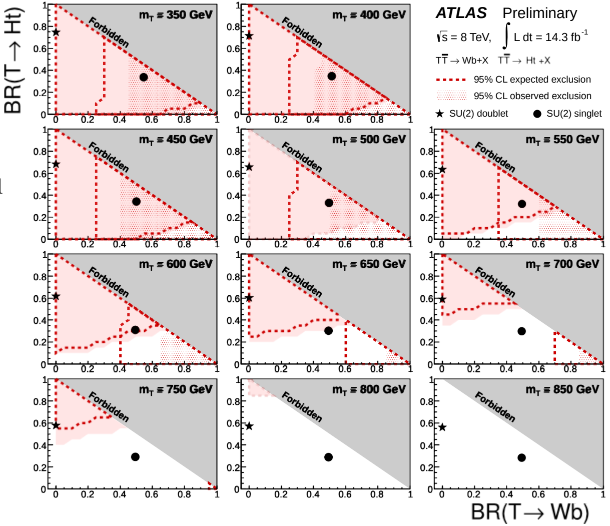
- $T\bar{T} \to Wb + X$ analysis alone very optimized for the bottom right corner



Combined results

Individual analyses probe different areas

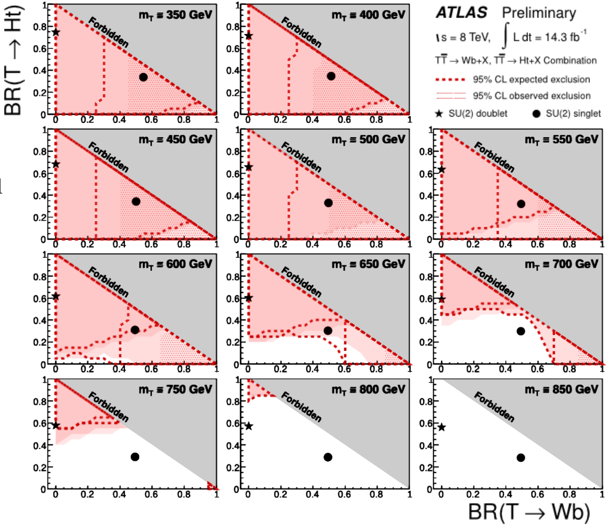
- $T\bar{T} \to Wb + X$ analysis alone very optimized for the bottom right corner
- $T\bar{T} \to Ht + X$ gives general good coverage, brings complete exclusion up to 450 GeV and almost excludes 650 GeV singlets



Combined results

Individual analyses probe different areas

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

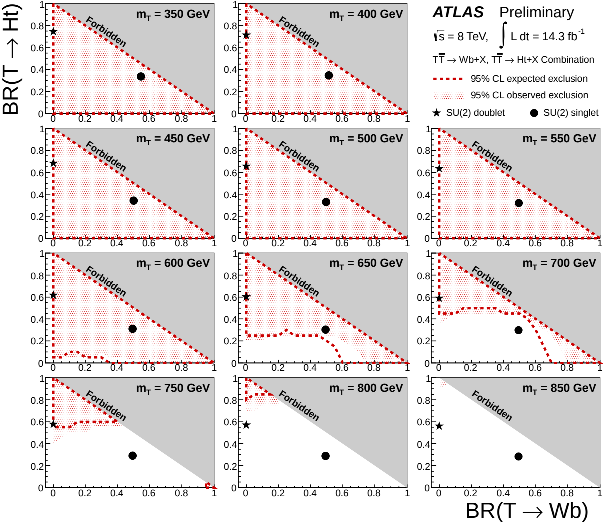


Combined results

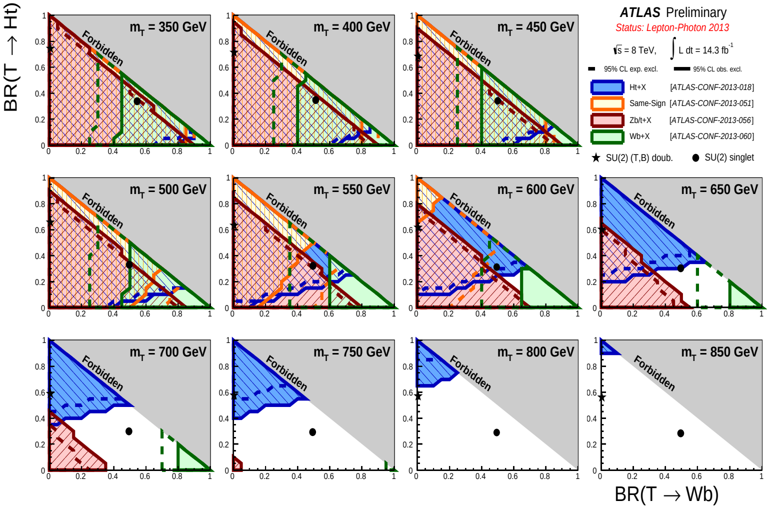
Individual analyses probe different areas

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

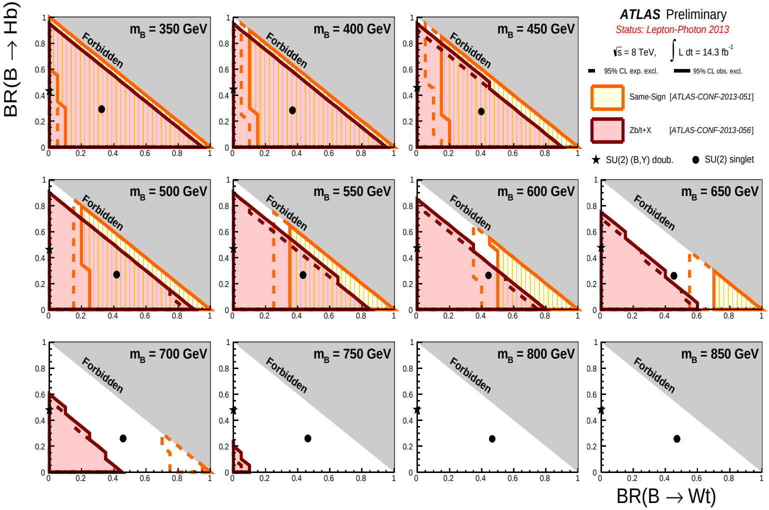
... but there's more from ATLAS Exotics!



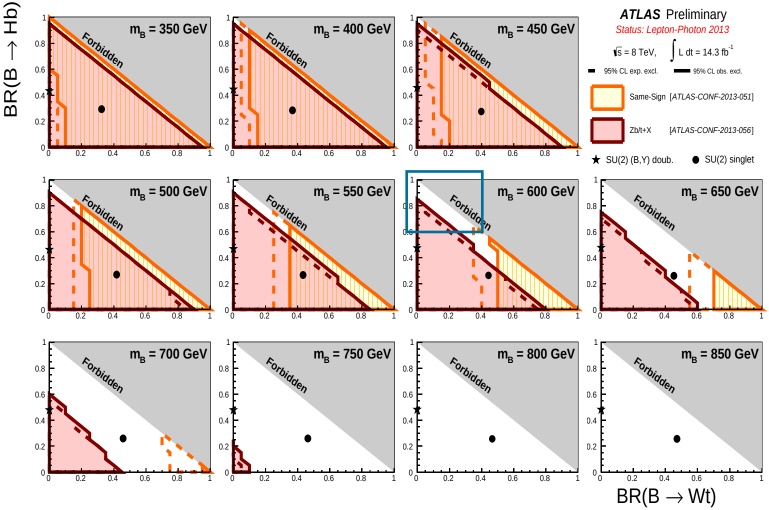
ATLAS “worst case scenario” coverage



ATLAS “worst case scenario” coverage

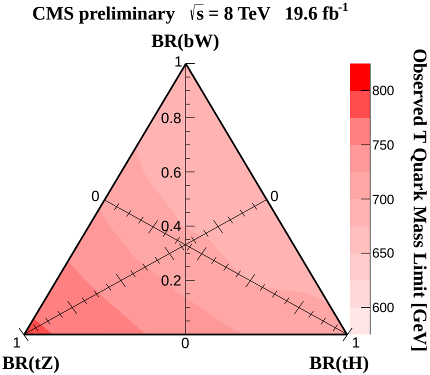


ATLAS “worst case scenario” coverage



Comparison to CMS results

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



"doublet" 790 obs

"singlet" 670 obs

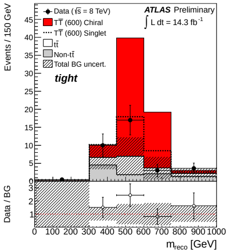
"chiral" 740 obs

	Branching Fractions			expected	observed
Scenario	T→bW	T→tH	T→tZ	limit (GeV)	limit (GeV)
(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

Outline

Conclusions and outlook

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



↘ poor MC bkgs statistical population in the TIGHT channel

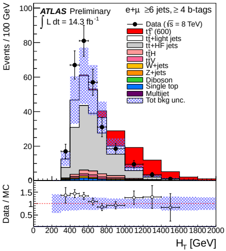
↗ larger MC samples available
↗ possible optimization of the H_T^{4j} cut
↗ explorable option: larger anti-k_t jets

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 $B\bar{B} \to Hb + X$ analysis

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



Outlook

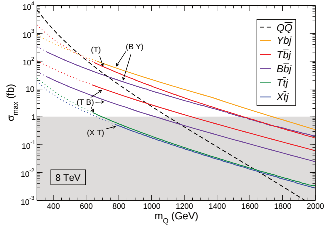
all four ATLAS searches are being updated
with the full 20 fb^{-1} statistics,
plus two new channels: $B\bar{B} \to Wt + X$ and $B\bar{B} \to Hb + X$

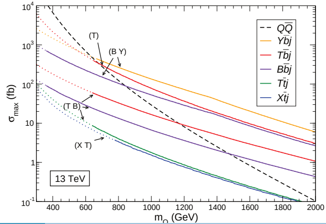
LHC Run-II:

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

To-do:

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

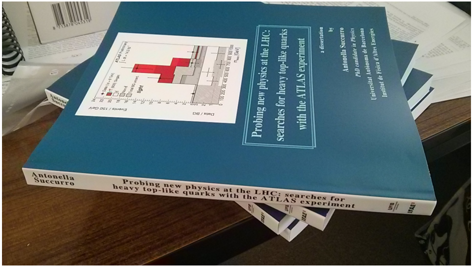




plots from [8]

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 $\beta*$ (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 ($cm^{-2}s^{-1}$)	$1{\times}10^{34}$	$2.1{\times}10^{32}$	$3.7{\times}10^{33}$	$7.7{\times}10^{33}$
Emittance ε_n (μrad)	3.75	2.0	2.4	2.5
Max. $< \mu >$	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].

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

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

Neutrino reconstruction

Neutrino 4-momentum unknown

$\Downarrow$

$E_{\mathrm{T}}^{\mathrm{miss}}$ X and Y components + a bit of algebra:

$$(P_l + P_\nu)^2 = P_W^2 = M_W^2$$

$\Downarrow$

two possible p_{Z_ν} solutions for the Z component of the neutrino momentum:

$$p_{Z_\nu} = \frac{\lambda \pm \sqrt{\delta}}{2}$$

Choose the solution giving $\min|m_{\mathrm{reco}}^{\mathrm{had}} - m_{\mathrm{reco}}^{\mathrm{lep}}|$
(this implies also b-jets association!)

- If no real solution, $\nu \sim$ collinear to $l \Rightarrow \eta_\nu$ set equal to η_l

$$\begin{aligned}\lambda &= 2\beta\frac{p_{Z_l}}{E_l^2 - p_{Z_l}^2};\\ \delta &= \lambda^2 - 4\gamma;\\ \gamma &= -\frac{\beta^2 - E_l^2(p_{X_\nu}^2 + p_{Y_\nu}^2)}{E_l^2 - p_{Z_l}^2};\end{aligned}$$

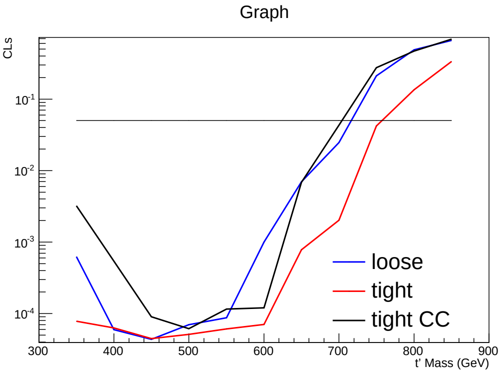
$$\begin{aligned}\beta &= \alpha + p_{X_\nu}p_{X_l} + p_{Y_\nu}p_{Y_l};\\ \alpha &= \frac{1}{2}(M_W^2 - M_l^2).\end{aligned}$$

Statistical analyses

In the 7 TeV analysis three configurations have been tested:

- LOOSE selection using m_{reco} and profiling of overall $t\bar{t}$ yield ("LOOSE")
- TIGHT selection using m_{reco} ("TIGHT")
- TIGHT selection considering just the overall yield and not the shape of m_{reco} ("TIGHT cut-and-count")

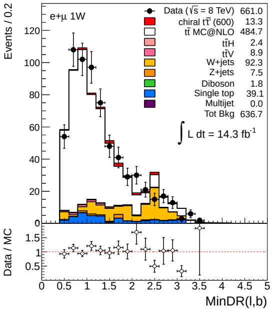
Look at expected value of CL_s as a function of m_T for best performance:



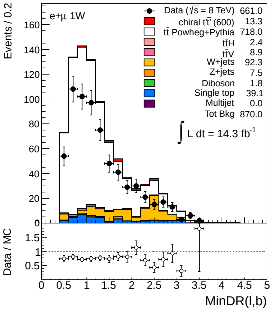
Generator choice for $t\bar{t}$

Comparison data to background prediction w/ different $t\bar{t}$ generators
e.g. in SDR3 (*loose* selection with reversed b-jet p_T cuts)

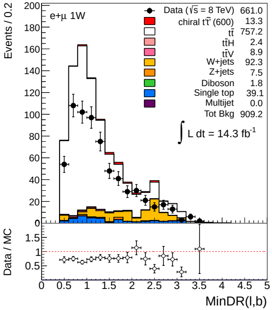
MC@NLO



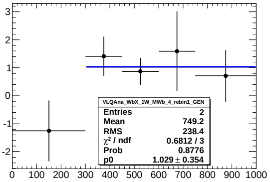
POWHEG+PYTHIA

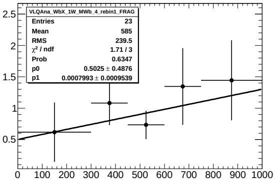


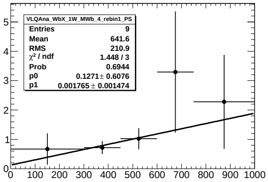
ALPGEN+HERWIG



$t\bar{t}$ modeling systematic uncertainties



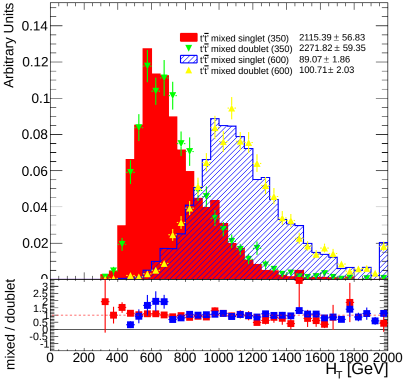


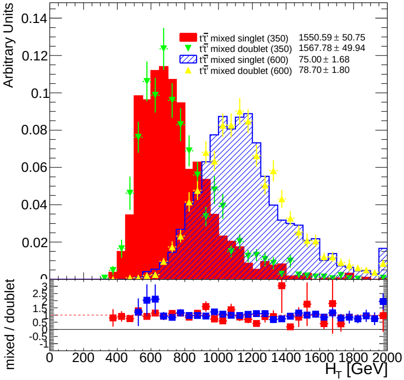


Doublet vs singlet

MC simulated for singlet T with 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 "$\geq$4 b-TAGGED JETS"

Treatment of sys unc in combination

	Systematic uncertainty	$T\bar{T} \to Wb + X$ Status	$T\bar{T} \to Wb + X$ Components	$T\bar{T} \to Ht + X$ Status	$T\bar{T} \to Ht + X$ 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
	Multijet normalization	-	-	N	1
Uncorrelated	$t\bar{t}$ modelling	SN	3	SN	3
	V+jets modelling	SN	1	-	-
	$t\bar{t}$+heavy-flavour fractions	-	-	N	1
Correlate JES w/ BASELINE	Jet energy scale	SN	1	SN	8