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

Four questions, one dissertation

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- **Where?** is all happening
- **What?** are we looking at

Four questions, one dissertation

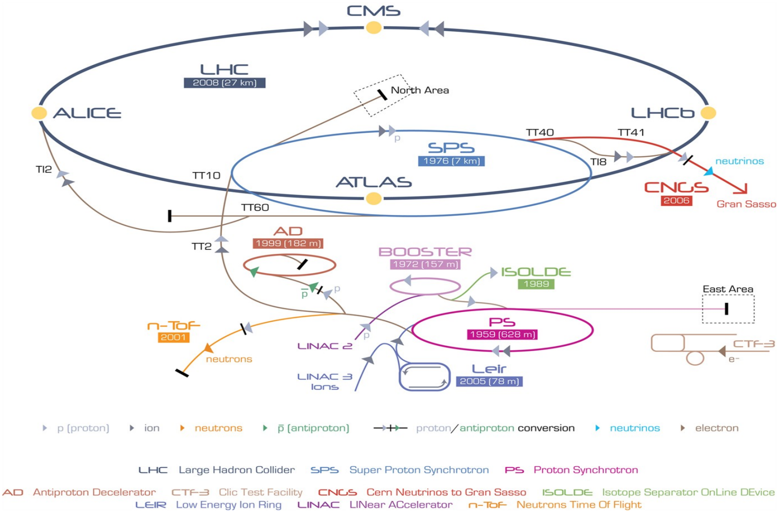
- **Why?** bother with “new physics”
- **Where?** is all happening
- **What?** are we looking at
- **How?**

Outline

Standard Model as an effective theory

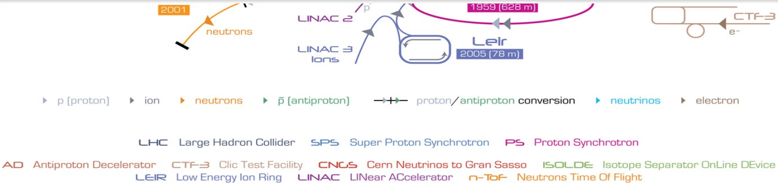
Outline

The LHC complex

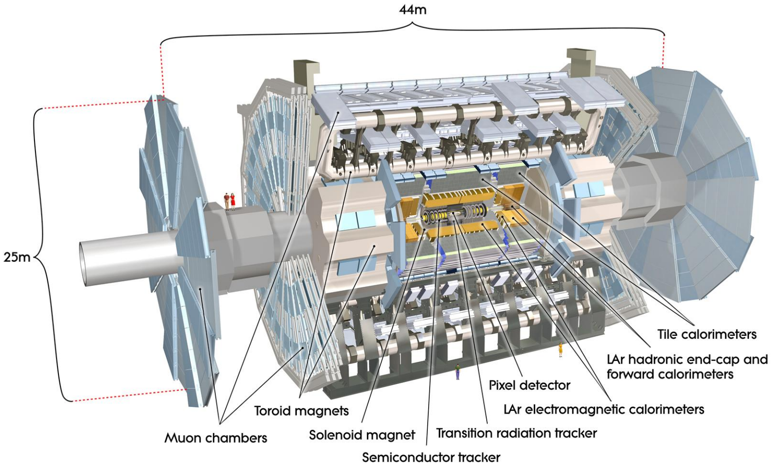


The LHC complex

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

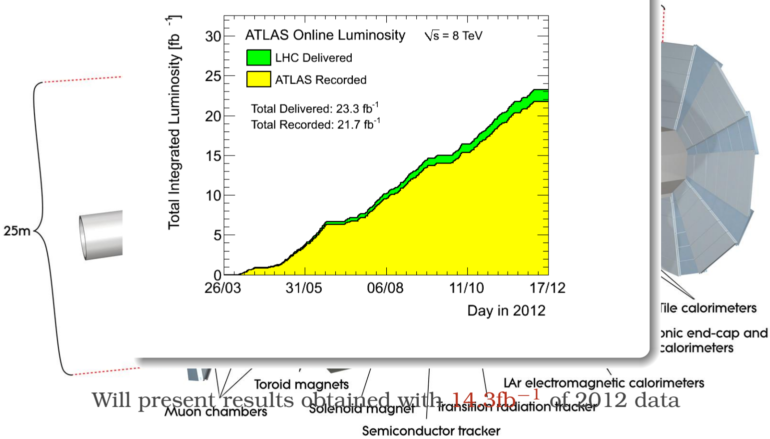


The ATLAS Detector



The ATLAS Detector

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

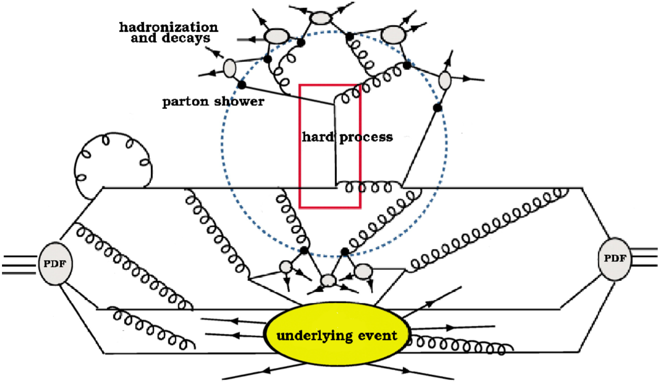


Will present results obtained with 14.3fb^{-1} of 2012 data

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

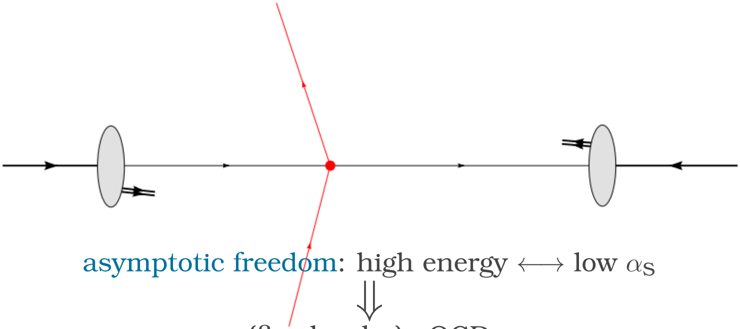
$E(p_2) = 4$ TeV

Quarks are distributed according to PDFs inside the proton

$\Downarrow$

intial energy unknown

Hard scattering of two partons

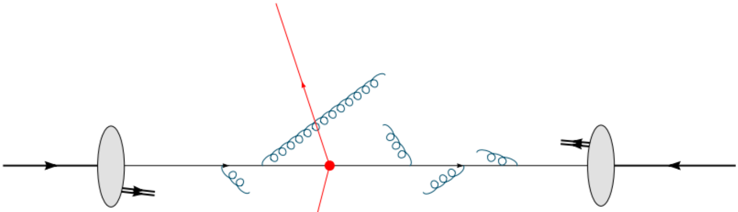


asymptotic freedom: high energy $\longleftrightarrow$ low α_S

$\Downarrow$

(fixed order) pQCD

Parton showering

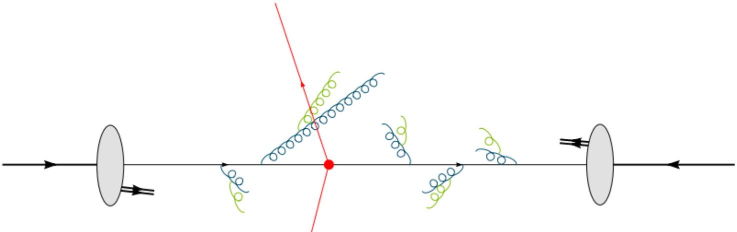


QCD emission: $q \to gq$, $g \to gg$, $g \to q\bar{q}$

$\Downarrow$

higher-order corrections

Parton showering

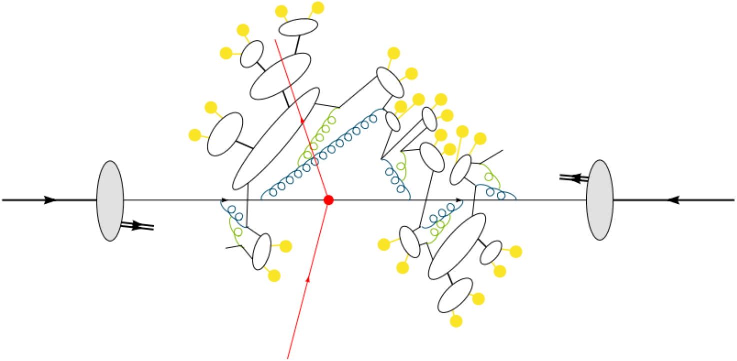


QCD emission: $q \to gq$, $g \to gg$, $g \to q\bar{q}$

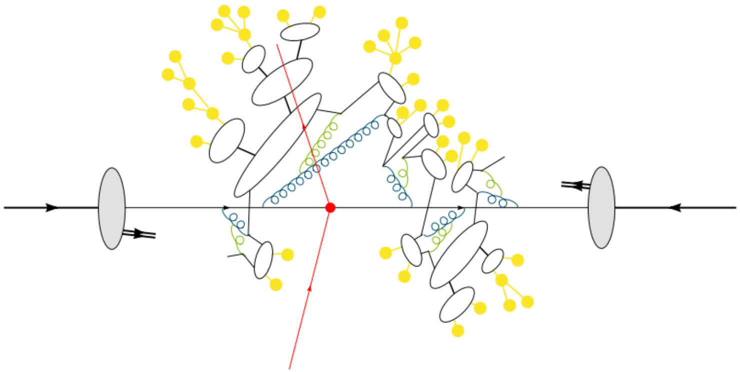
$\Downarrow$

higher-order corrections

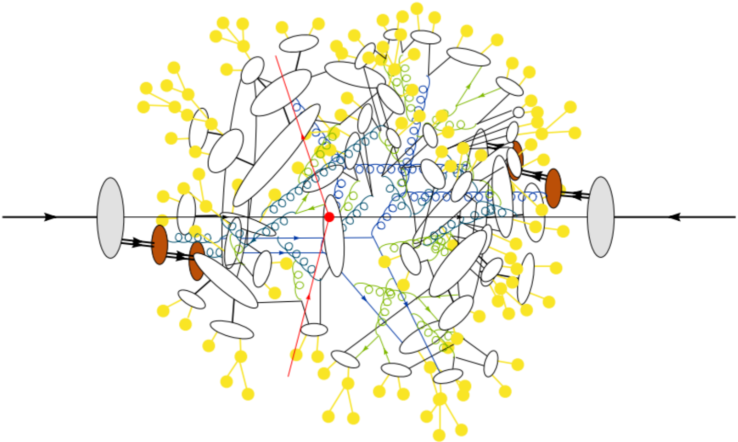
Hadronization



Final particle decays

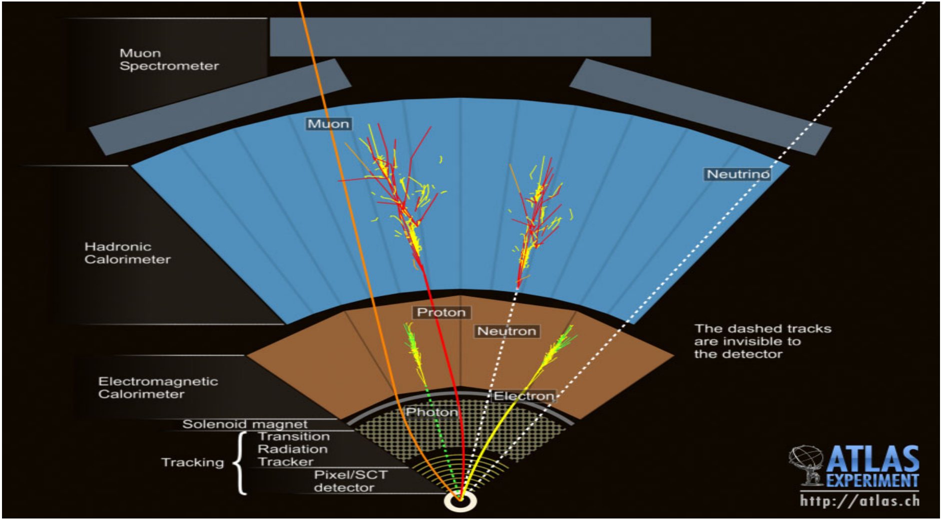


Underlying event simulation



Outline

Physics objects puzzle



One lepton

Many jets

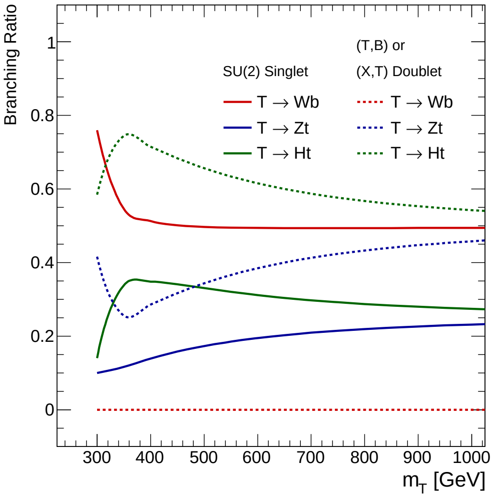
Missing transverse energy

Outline

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

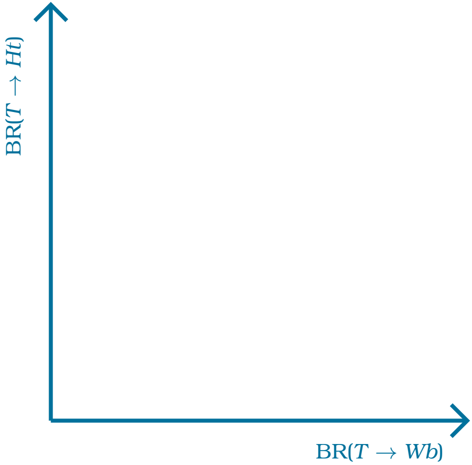


Model Independent Strategy

- Build a 2-dim plane to scan model mixing

$\mathrm{BR}(T \to Wb)$

Model Independent Strategy



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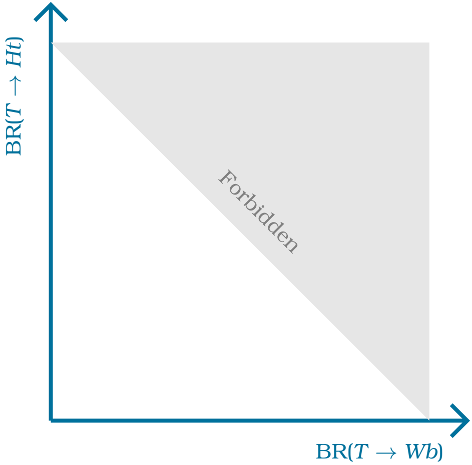
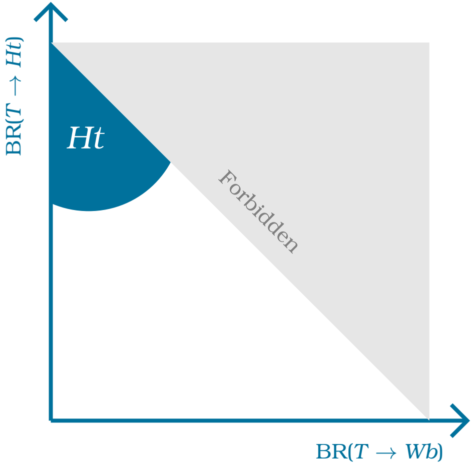


- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1[a]

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

Model Independent Strategy



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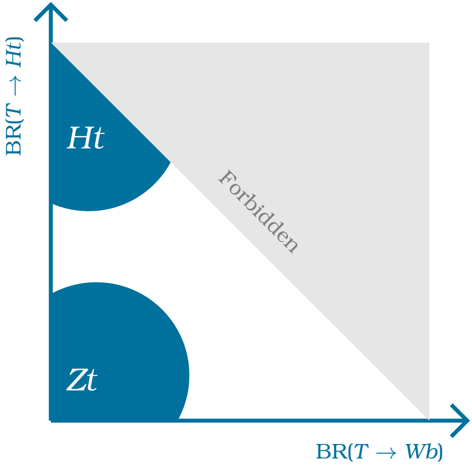

- Build a 2-dim plane to scan model mixing
- Sum of BRs is $1^{(a)}$
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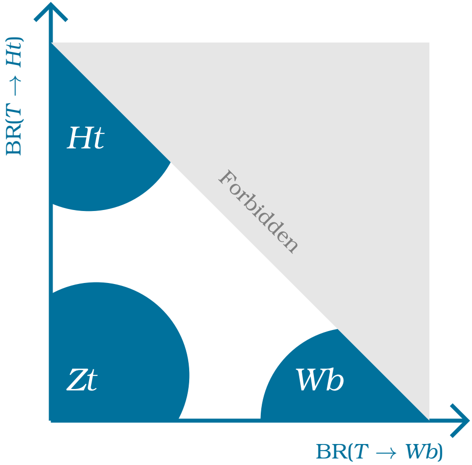
Model Independent Strategy



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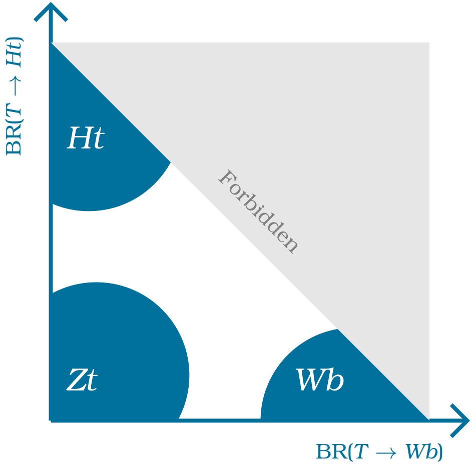

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- Set exclusion using CL_s technique [2, 3]

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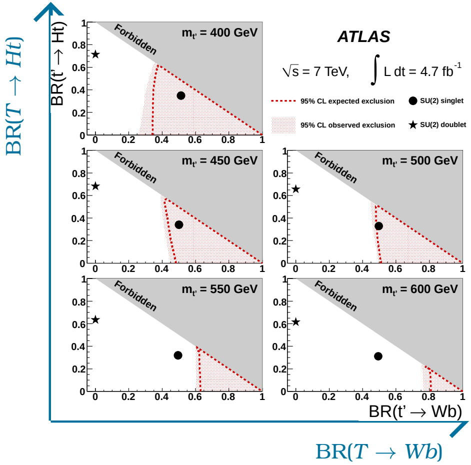
Model Independent Strategy



- 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]
- First published results at 7 TeV *Phys.Lett.* **B718** (2012) [4]

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

Preselection

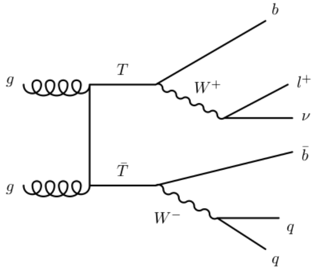
Two searches using common analysis framework:

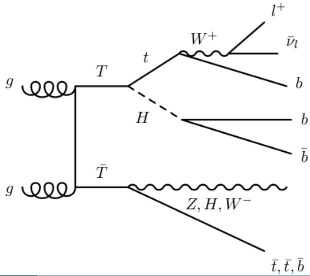
- $T\bar{T} \to Wb + X$ — ATLAS-CONF-2013-060 [5]
- $T\bar{T} \to Ht + X$ — ATLAS-CONF-2013-018 [6]

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:

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





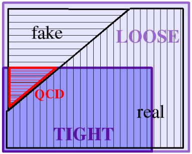
Background and signal modelling

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

	≥ 4 jets, ≥ 1 b-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

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

- 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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- 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

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- Diboson production generated with `HERWIG`
- NLO theoretical cross section

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

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

Background and signal modelling

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

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- $t\bar{t}$ 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

Background and signal modelling

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- $t\bar{t}$ 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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Background and signal modelling

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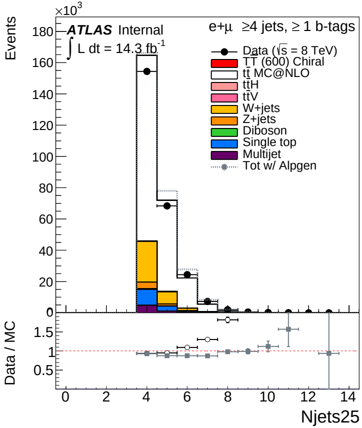
Yields for $t\bar{t}$ predicted with ALPGEN are ~3-8% higher than MC@NLO



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

- $T\bar{T}$ 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

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

Systematic uncertainties - Shape and Norm

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
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

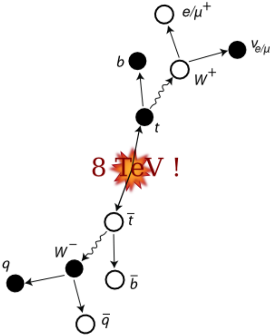
Outline

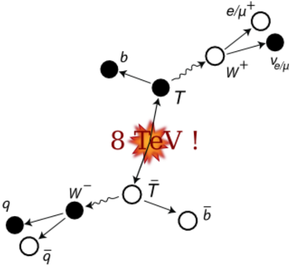
Strategy

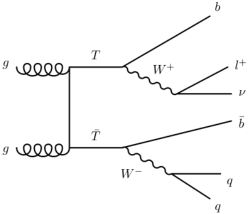
$T\bar{T} \rightarrow WbWb$

like

$t\bar{t} \rightarrow WbWb$







different boosted kinematics

$\Downarrow$

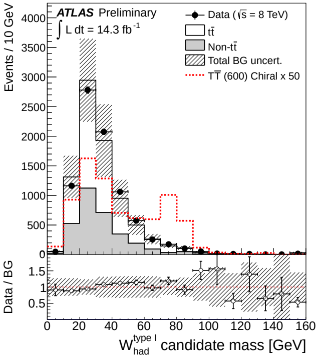
reconstruct the W boson from hadronic decay

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

close-by jets $W_{\text{had}}^{\text{type II}}$

W boson reconstruction

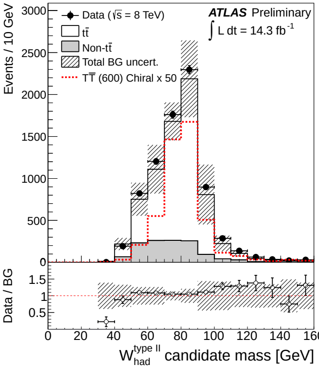
$W_{\text{had}}^{\text{type I}}$



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

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

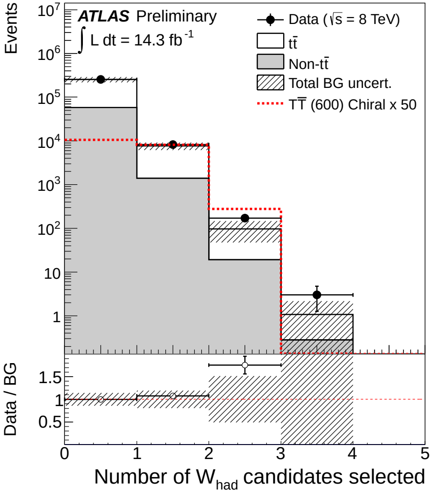
$W_{\text{had}}^{\text{type II}}$



W_{lep} reconstructed using lepton and "neutrino":
p_X, p_Y from E_T^{miss}, p_Z from $M_W^2 = (P_l + P_\nu)^2$

Event selection

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



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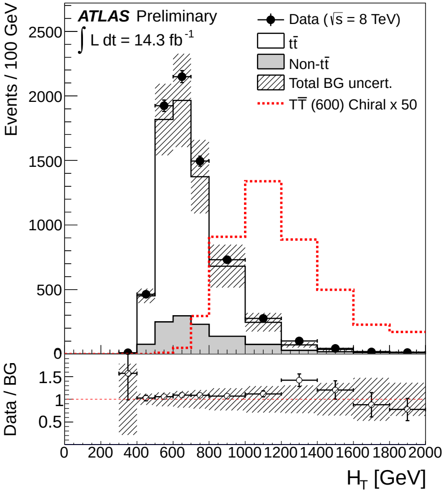

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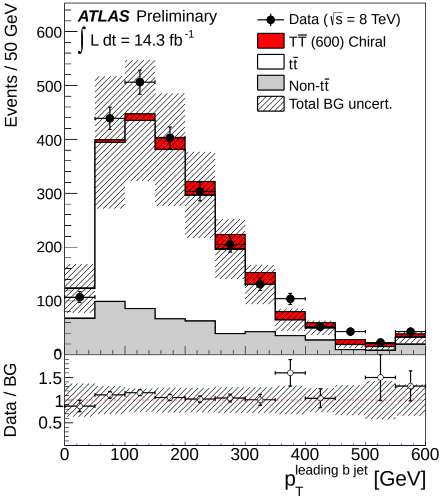

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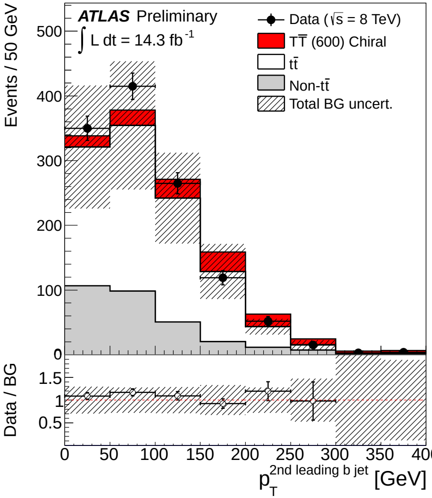

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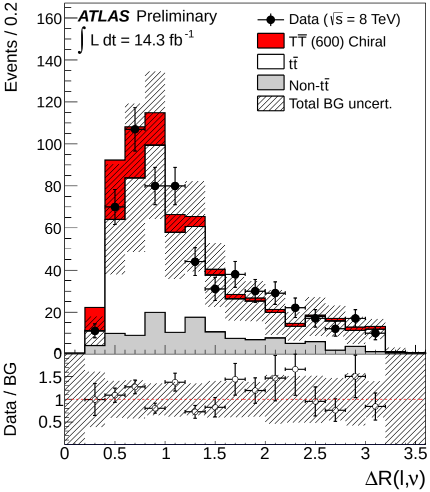

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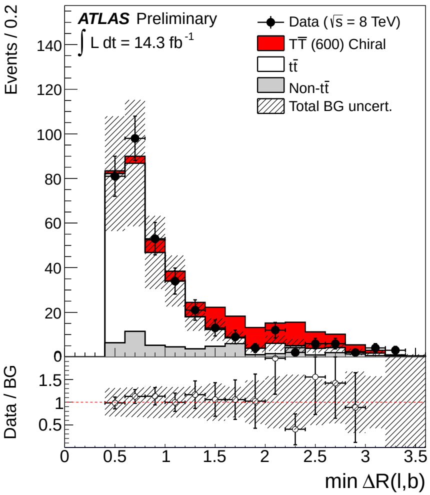

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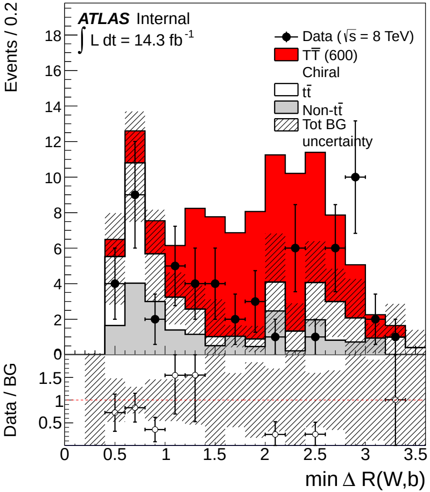


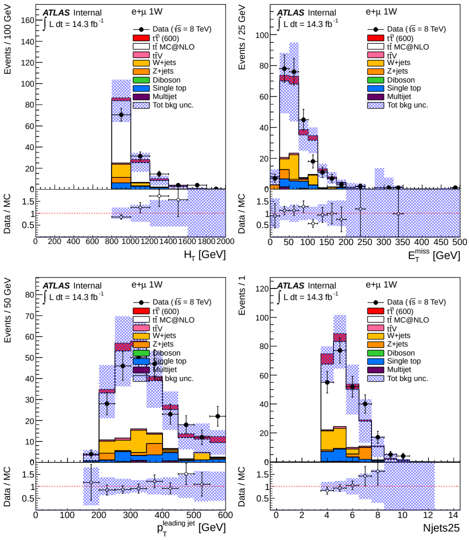
Comparison data vs prediction

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



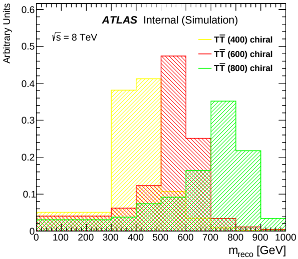
Yields in signal region

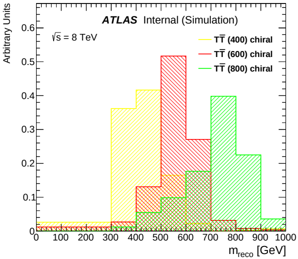
		Loose	Tight
	$t\bar{t}$	264 ± 80	10 ± 6
merged	$t\bar{t}V$	5.1 ± 1.8	0.5 ± 0.2
merged	W+jets	16 ± 11	6 ± 5
merged	Z+jets	1.1 ± 1.4	0.2 ± 0.5
merged	Single top	30 ± 7	4.4 ± 1.6
merged	Dibosons	0.21 ± 0.15	0.06 ± 0.05
	Tot.Bkg.	317 ± 90	21 ± 9
	Data	348	37
	$T\bar{T}$(600 GeV)		
	Chiral t'	88 ± 10	54 ±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

Discriminating variable $\Rightarrow$ 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

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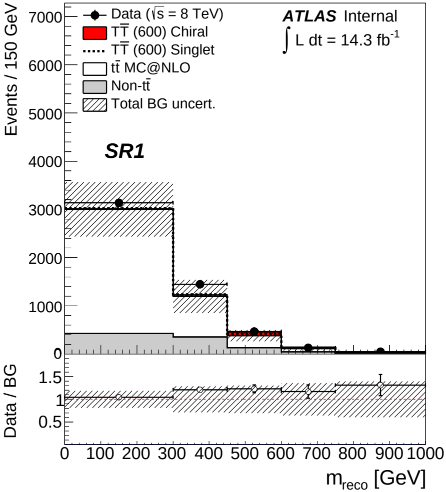

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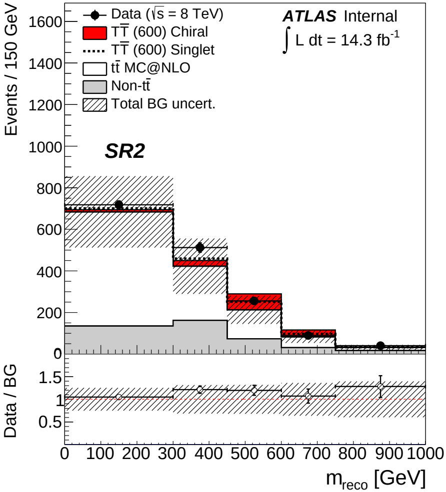

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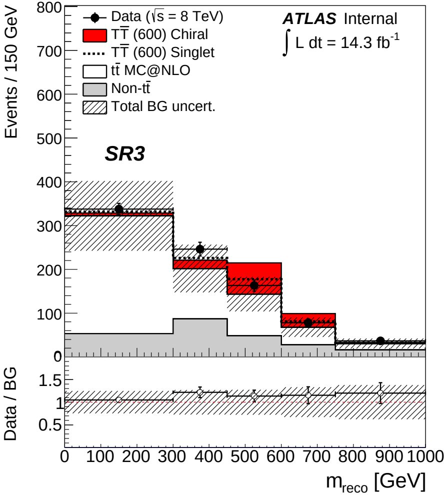

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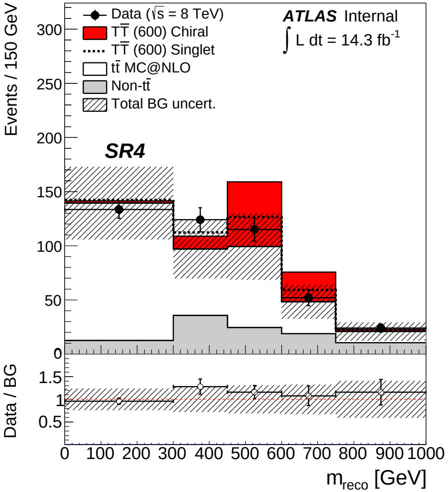

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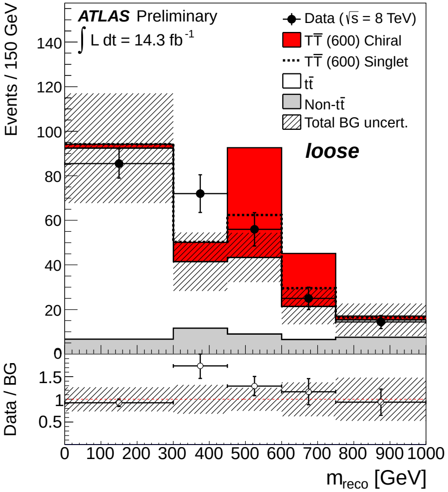

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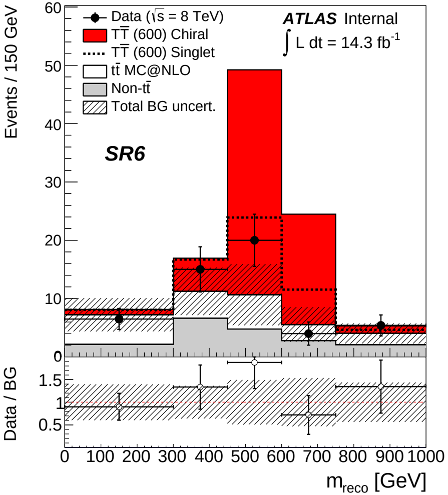

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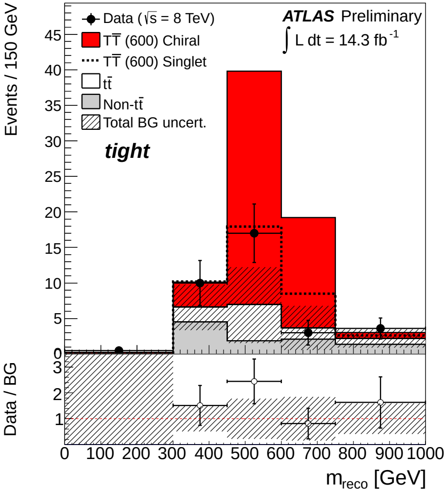
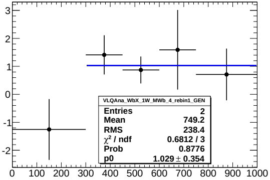
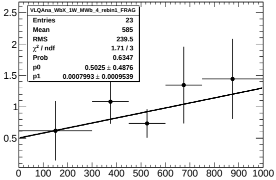
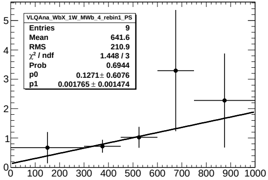


Most relevant systematic uncertainties

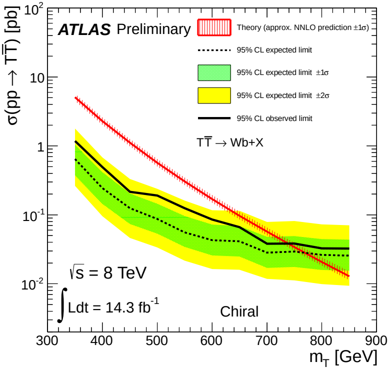
	$T\bar{T}$ (600 GeV)	$t\bar{t}$	Non-$t\bar{t}$
Total [%]	+14/-15	+59/-59	+42/-35
Main contributions [%]			
Jet energy scale	+6.6/-8.4	+15/-15	+33/-22
$t\bar{t}$ modelling: NLO MC generator	–	+48/-48	–
$t\bar{t}$ modelling: PS and fragm	–	+25/-25	–
$t\bar{t}$ modelling: ISR/FSR	–	+8.8/-8.8	–

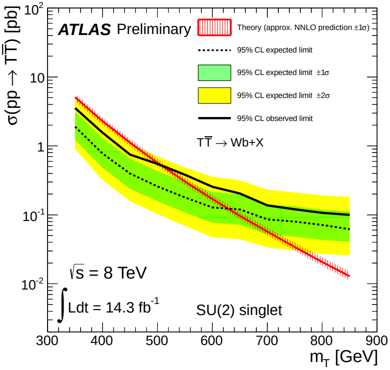






Results


ATLAS Preliminary
Theory (approx. NNLO prediction ±1σ)
95% CL expected limit
95% CL expected limit ±1σ
95% CL expected limit ±2σ
95% CL observed limit
TT̄ → Wb+X
√s = 8 TeV
∫Ldt = 14.3 fb⁻¹
Chiral
σ(pp → TT̄) [pb]
m_T [GeV]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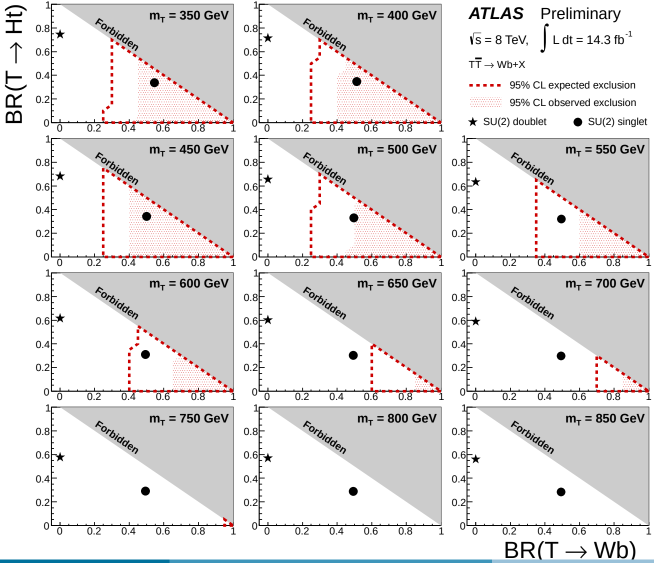
TT̄ → Wb+X
√s = 8 TeV
∫Ldt = 14.3 fb⁻¹
SU(2) singlet
σ(pp → TT̄) [pb]
m_T [GeV]

Results


ATLAS Preliminary
√s = 8 TeV, ∫ L dt = 14.3 fb⁻¹
TT̄ → Wb+X
95% CL expected exclusion
95% CL observed exclusion
SU(2) doublet
SU(2) singlet
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Forbidden
BR(T → Ht)
BR(T → Wb)

Outline

Strategy

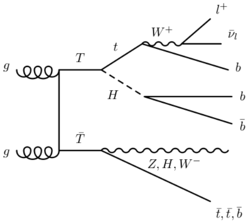
$$T\bar{T} \to Ht + X$$

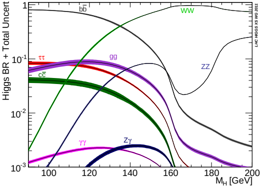
$$T \to Ht \begin{array}{l} \nearrow bbWb \to bbbl\nu \\ \searrow WWWb \to qqqbl\nu \end{array} \quad + \ \bar{T} \to Wb/Zt/Ht$$

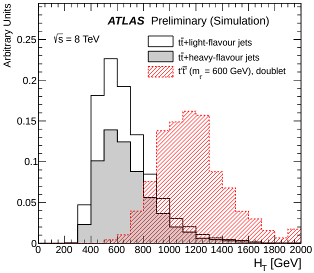
as a minimum 6 total jets in the event ($T\bar{T} \to HtWb$)

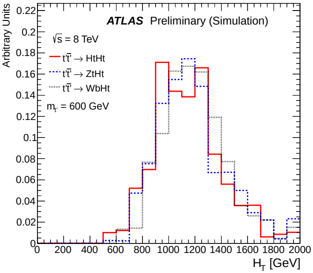
$$\Downarrow$$

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







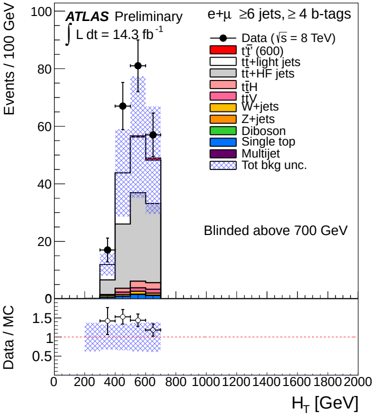


$\geq$ 6 jets, $\geq$ 4 b-jets

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

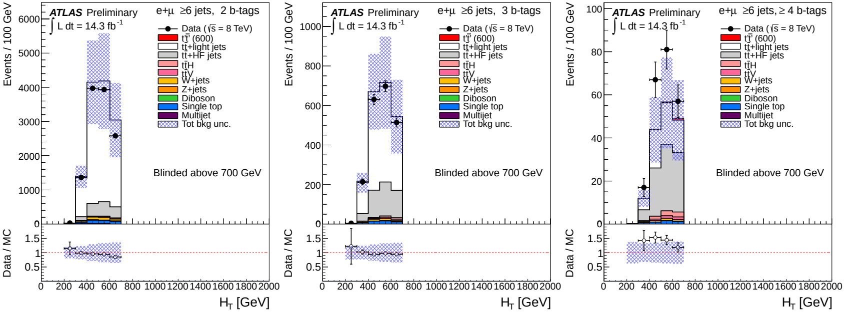


bad modeling $\Rightarrow$ Simultaneous fit to data of H_T variable

Scale of $t\bar{t}$ components

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

before...

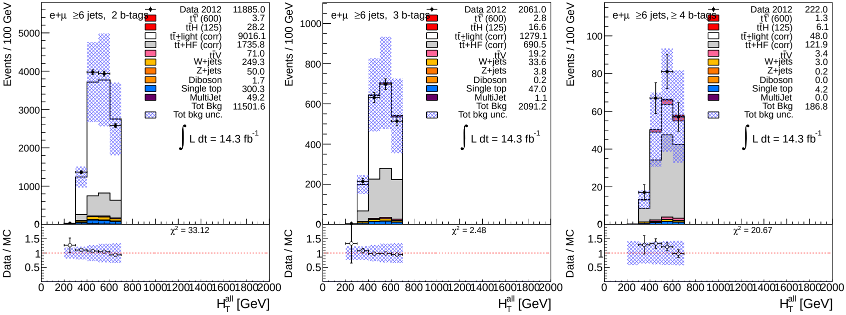


Maximum yields discrepancy below 5%

Scale of $t\bar{t}$ components

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

. . . after



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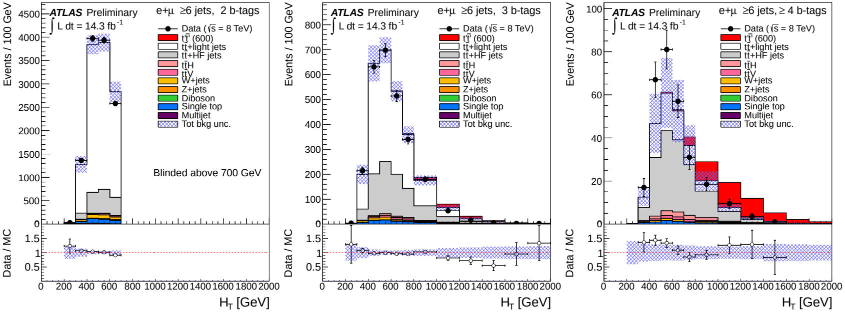
final



Maximum yields discrepancy below 5%

Comparison data vs prediction

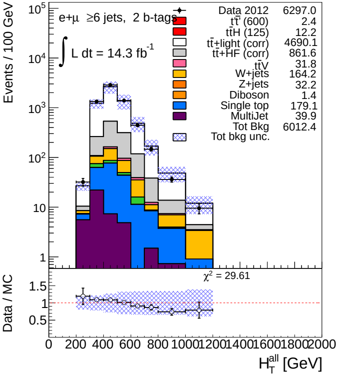
Blinding cut: $H_{\mathrm{T}} < 700$ GeV

$\Downarrow$

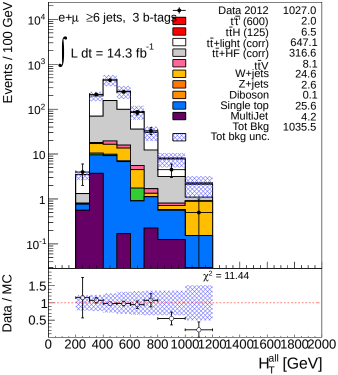
Define special blinded regions to check H_{T} modeling:

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

2 b-tagged jets

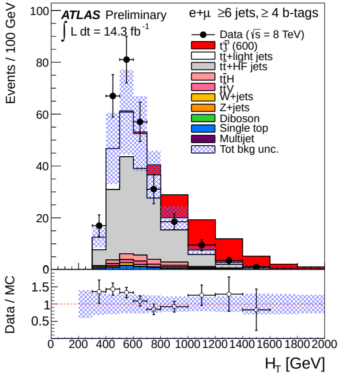


3 b-tagged jets



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

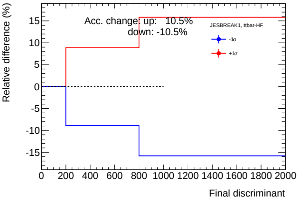


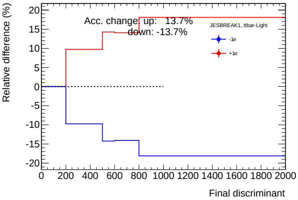
Introduce the scaling factors as nuisance parameters

Most relevant systematic uncertainties

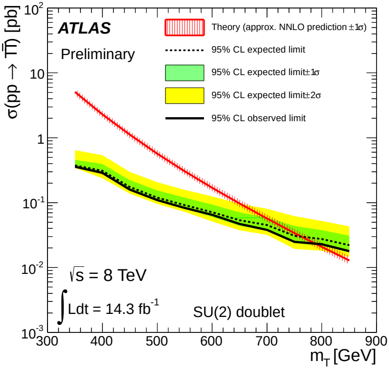
... before fitting the nuisance parameters

	$T\bar{T}$	$t\bar{t}$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	–	–	–	–	–	–

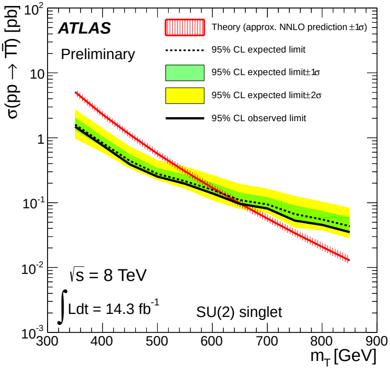




Results

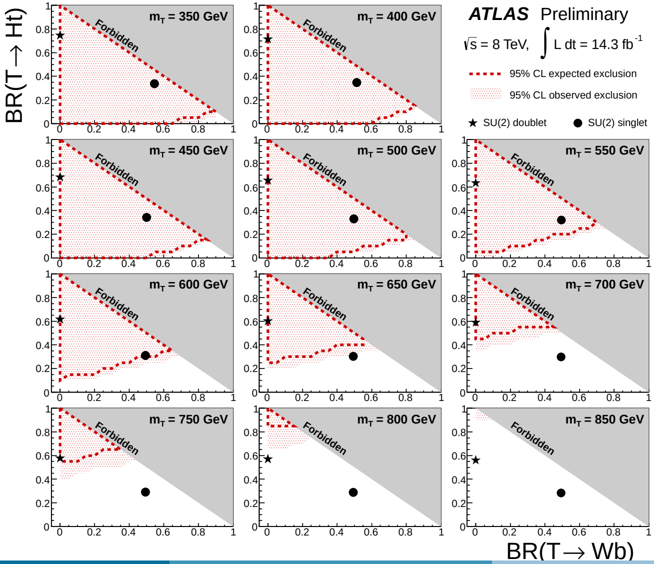


ATLAS
Preliminary
Theory (approx. NNLO prediction ±1σ)
95% CL expected limit
95% CL expected limit±1σ
95% CL expected limit±2σ
95% CL observed limit
√s = 8 TeV
∫Ldt = 14.3 fb⁻¹
SU(2) doublet
σ(pp → TT̄) [pb]
m_T [GeV]



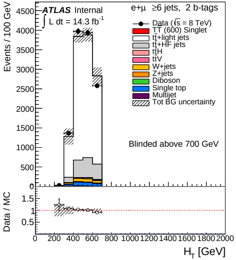
ATLAS
Preliminary
Theory (approx. NNLO prediction ±1σ)
95% CL expected limit
95% CL expected limit±1σ
95% CL expected limit±2σ
95% CL observed limit
√s = 8 TeV
∫Ldt = 14.3 fb⁻¹
SU(2) singlet
σ(pp → TT̄) [pb]
m_T [GeV]

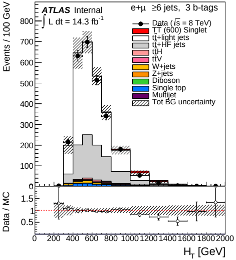
Results

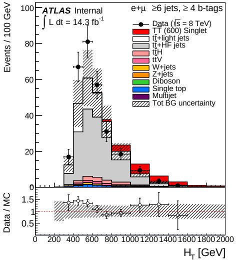

ATLAS Preliminary
√s = 8 TeV, ∫ L dt = 14.3 fb-1
95% CL expected exclusion
95% CL observed exclusion
SU(2) doublet
SU(2) singlet
mT = 350 GeV
mT = 400 GeV
mT = 450 GeV
mT = 500 GeV
mT = 550 GeV
mT = 600 GeV
mT = 650 GeV
mT = 700 GeV
mT = 750 GeV
mT = 800 GeV
mT = 850 GeV
Forbidden
BR(T→Ht)
BR(T→Wb)

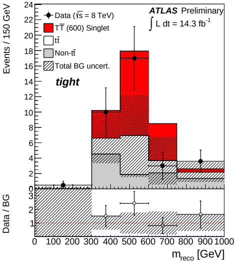
Outline

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





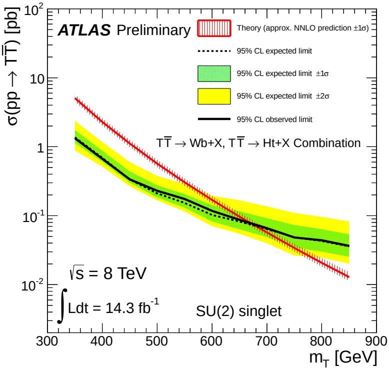




The searches are orthogonal

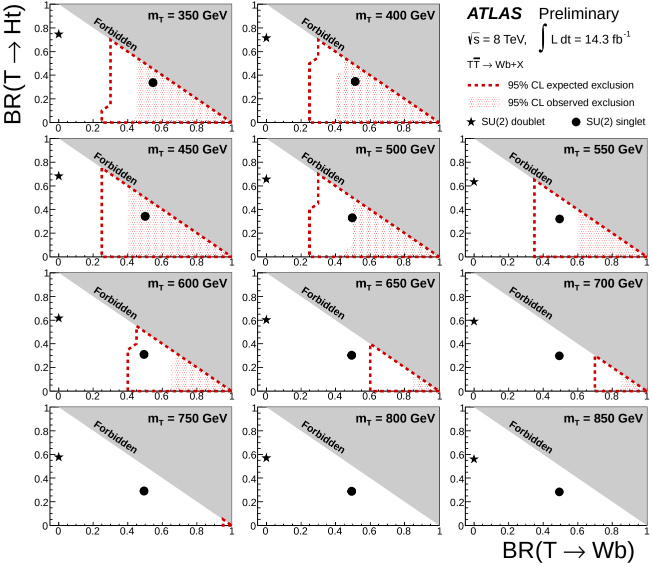
$\Downarrow$

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



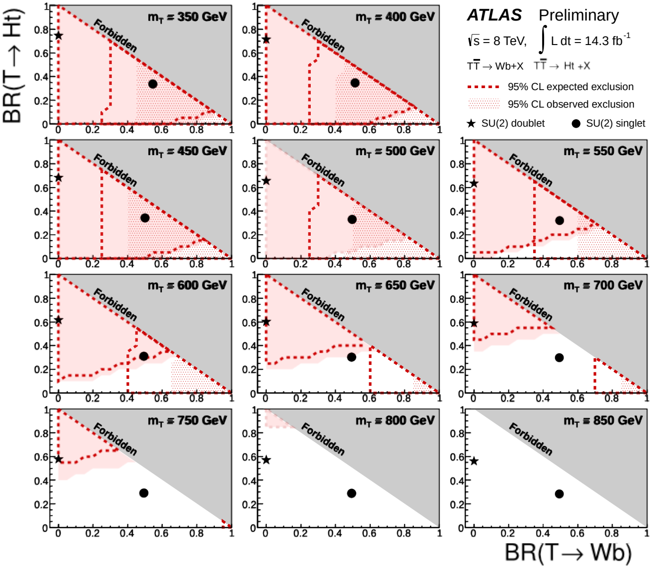
Results

aaaa

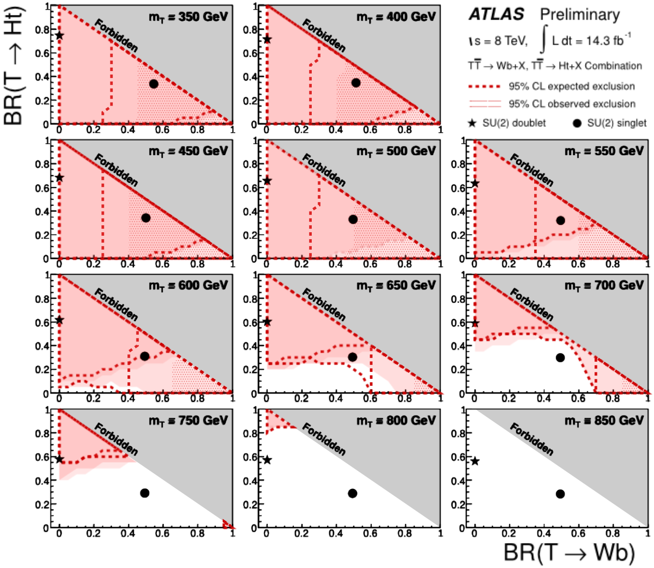


Results

aaaa



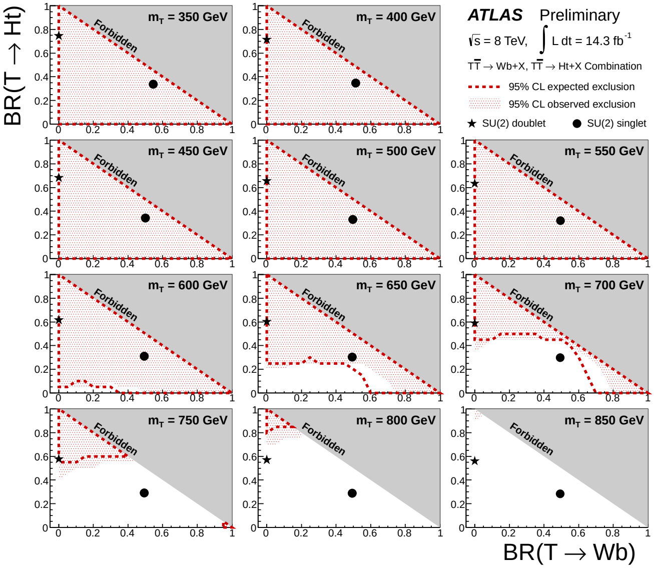
Results



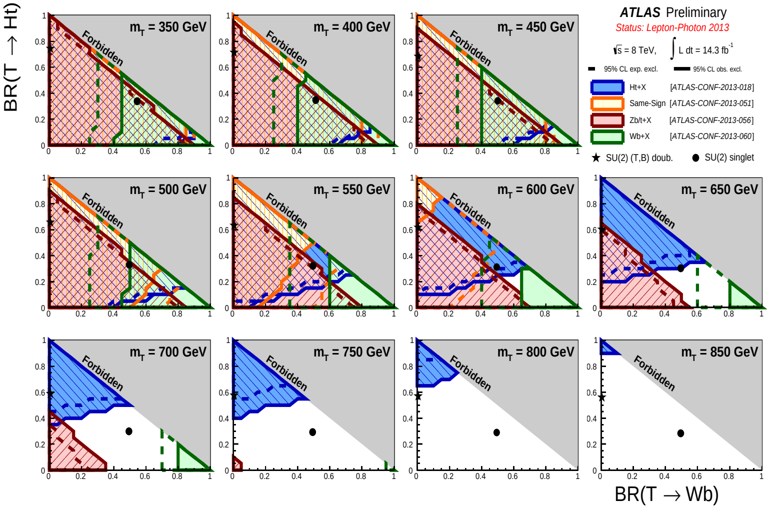
aaaa

Results

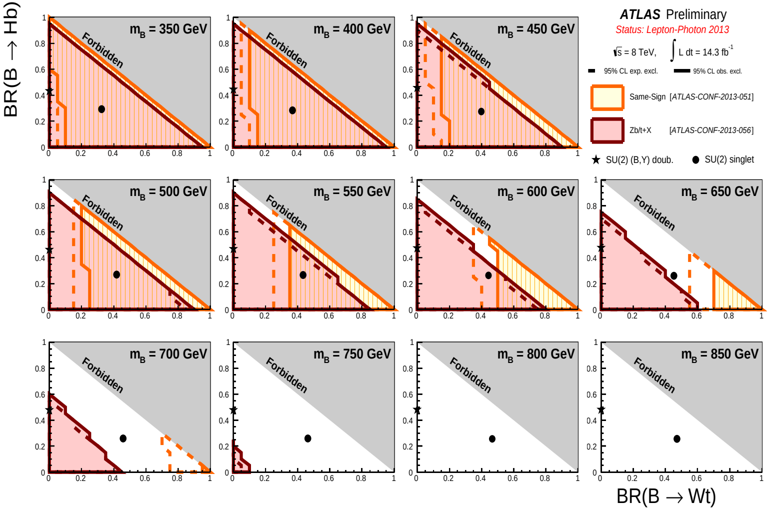
aaaa



ATLAS BR coverage



ATLAS BR coverage



Outline

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[4] ATLAS Collaboration.
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[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.
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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.
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[7] 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 [7].

$T\bar{T} \to Wb + X$ 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 ≥ 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