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

- **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
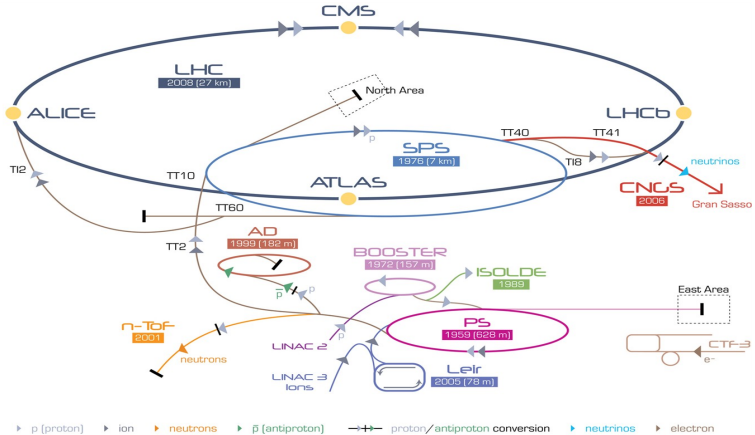
The LHC complex

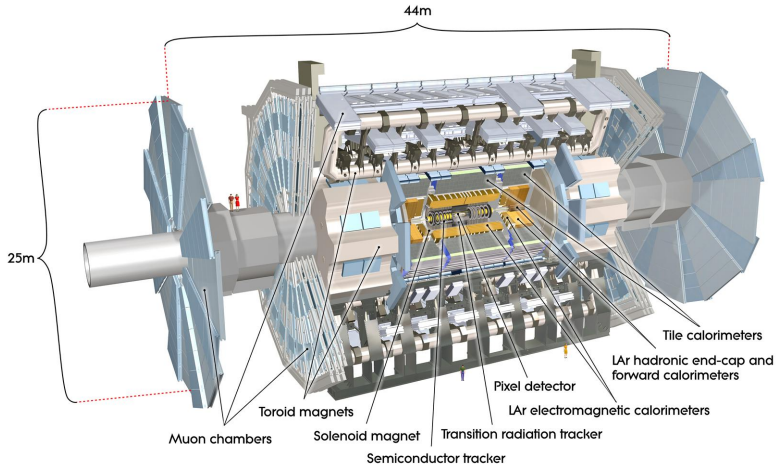| Parameter	designed	2010	2011	2012
Beam energy (TeV/c)	7	3.5	3.5	4
Beta function $\beta*$ (m)	0.55	2.0/3.5	1.5/1.0	0.6
Max. No. bunches/beam	2808	368	1380	1380
Max. No. protons/bunch	1.15×10^{11}	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}
Bunch spacing (ns)	25	150	75/50	50
Peak luminosity ($cm^{-2}s^{-1}$)	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

▸ p (proton)   ▸ ion   ▸ neutrons   ▸ p̄ (antiproton)   ⇥⊞⇤ proton/antiproton conversion   ▸ neutrinos   ▸ electron

LHC Large Hadron Collider   SPS Super Proton Synchrotron   PS Proton Synchrotron
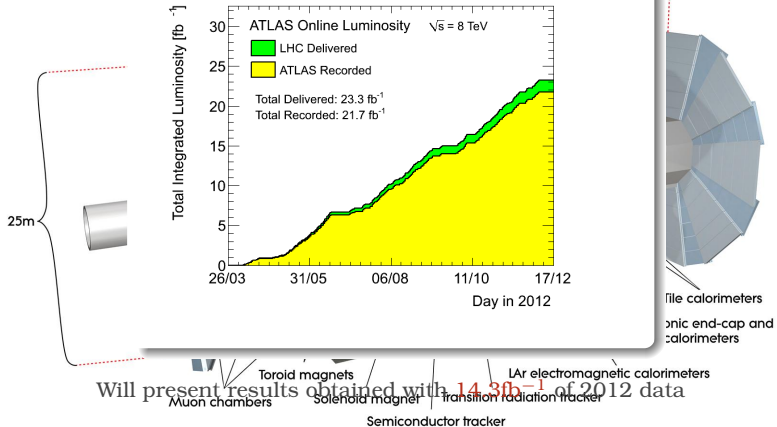
AD Antiproton Decelerator   CTF-3 Clic Test Facility   CNGS Cern Neutrinos to Gran Sasso   ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring   LINAC LINear ACcelerator   n-ToF Neutrons Time Of Flight

The ATLAS Detector

44m

25m

Tile calorimeters

LAr hadronic end-cap and
forward calorimeters

Pixel detector

LAr electromagnetic calorimeters

Toroid magnets

Transition radiation tracker

Muon chambers

Solenoid magnet

Semiconductor tracker

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
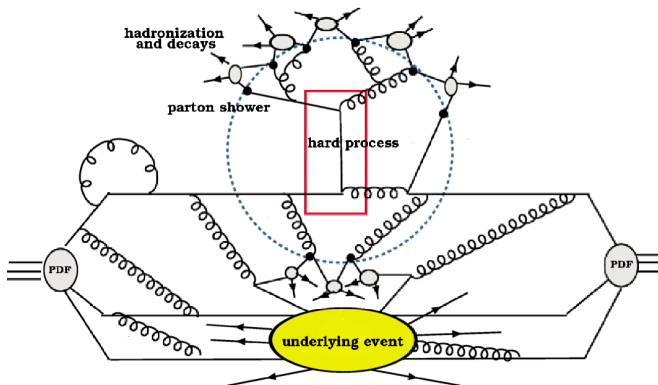
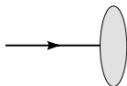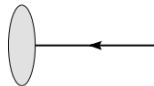# Modelling of hadron collisions

Drawings from [1]

$E(p_1) = 4$ TeV $E(p_2) = 4$ TeV

Quarks are distributed according to PDFs inside the proton
⇓
intial energy unknown

Hard scattering of two partons

asymptotic freedom: high energy $\longleftrightarrow$ low α_S

$\Downarrow$

(fixed order) pQCD

Parton showering

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

$\Downarrow$
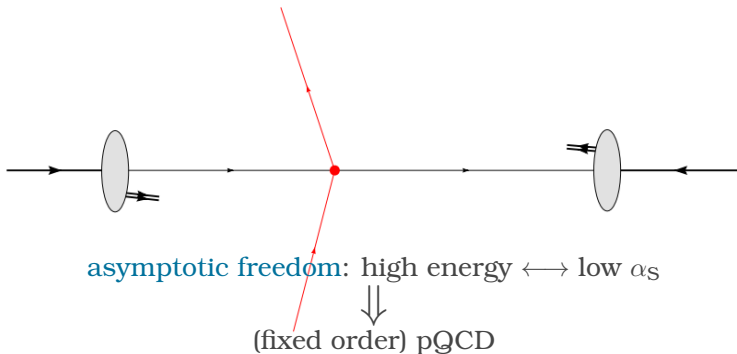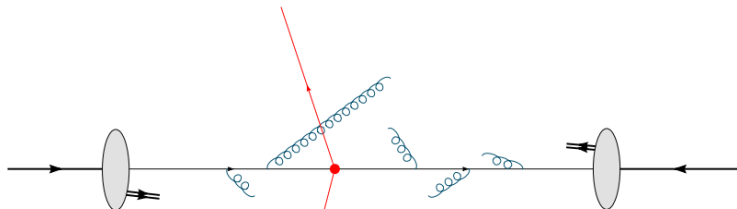
higher-order corrections

Parton showering

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

$\Downarrow$

higher-order corrections
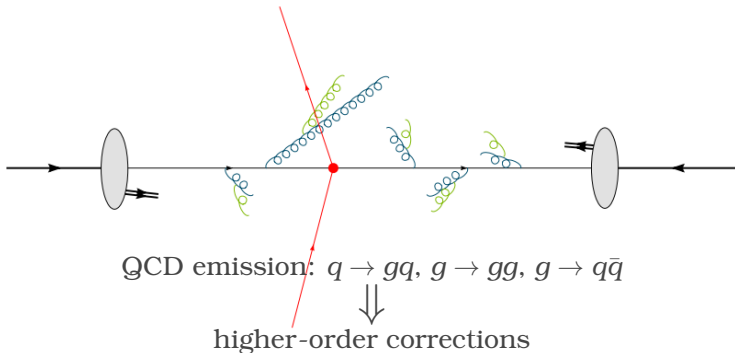
Hadronization
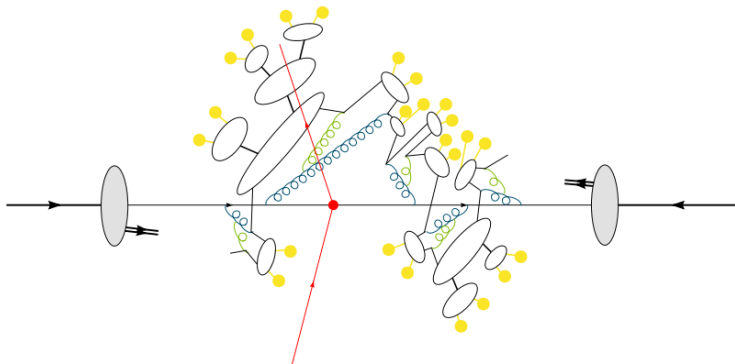
Final particle decays
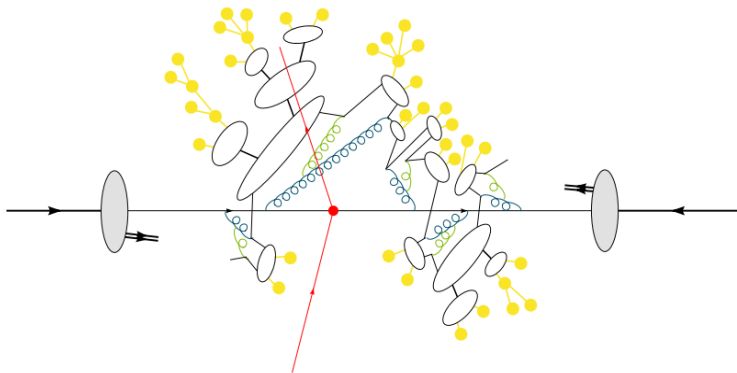
Underlying event simulation
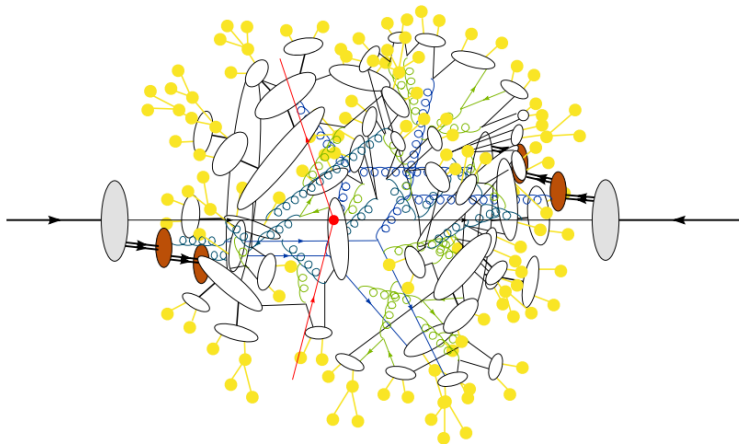
Outline

Physics objects puzzle
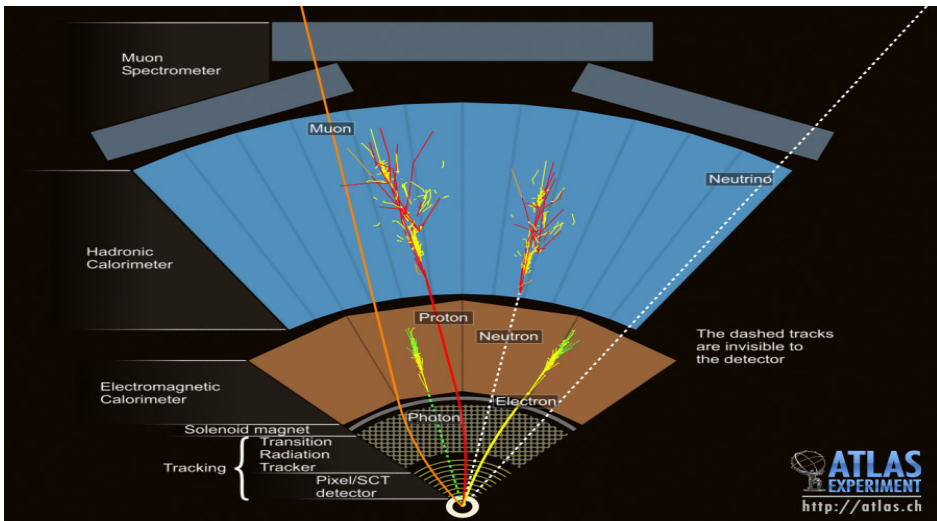
One lepton

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
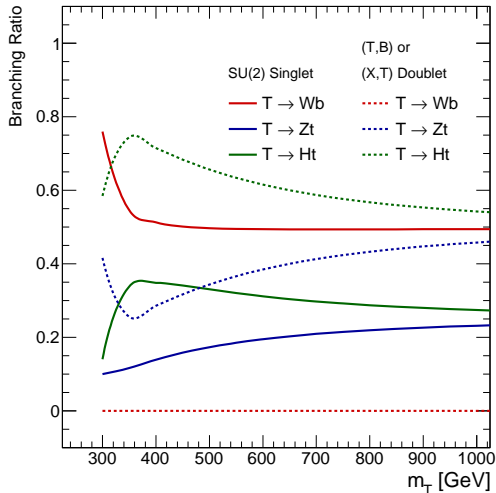
BR($T \to Wb$) →

Model Independent Strategy

- Build a 2-dim plane to scan model mixing

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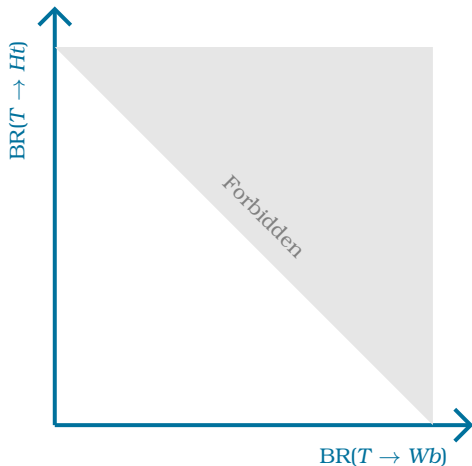
- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1[a]

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

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

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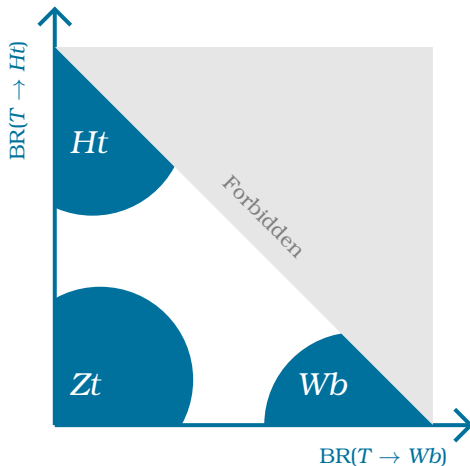
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Model Independent Strategy

- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1[a]
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- Set exclusion using CL_s technique [2, 3]

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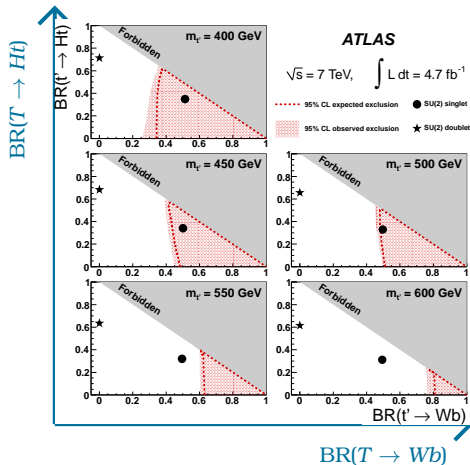
Model Independent Strategy

- 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]

$^{(a)}$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	$E_T^{miss} > 20$ GeV $E_T^{miss} + m_T > 60$ GeV
Jet multiplicity	≥ 4 jets ≥ 1 b-tagged jets

orthogonality requirements:

▶ $T\bar{T} \to Wb + X$: reject events with ≥ 6 jets and ≥ 3 b-jets

▶ $T\bar{T} \to Ht + X$: reject events in the low b-tags channel with $H_T < 700$ 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

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

- QCD multi-jet events have high cross-section
- Data-drive estimation
- Matrix-method
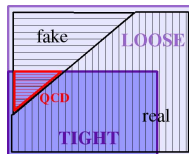
$$N_{\text{fake}}^{\text{tight}} = \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}}(N^{\text{loose}}\epsilon_{\text{real}} - N^{\text{tight}})$$

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

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▶ Diboson production generated with
  `HERWIG`

▶ NLO theoretical cross section

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

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

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

Background and signal modelling

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▶ W boson production in association with jets generated with up to five additional partons with ALPGEN+HERWIG

▶ Samples generated separately for W+light jets, $Wb\bar{b}$+jets, $Wc\bar{c}$+jets, and Wc+jets

▶ Normalized to data-driven prediction

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

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

Background and signal modelling

Yields in the preselection region "blinded" as:
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$T\bar{T}$ (600) chiral	36 ± 2
Data	256993 ± 507

▶ $t\bar{t}$ 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

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

Background and signal modelling

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

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

▶ $m_t = 172.5$ 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

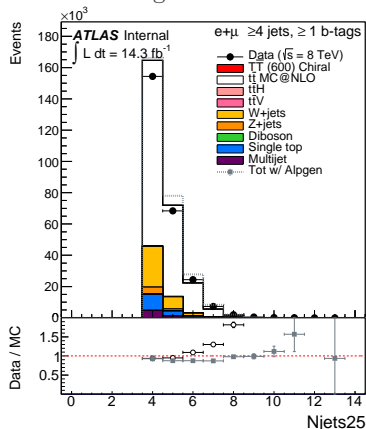▶ NNLO theoretical cross section

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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$3-8% higher than MC@NLO

Background and signal modelling

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

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

$T\bar{T} \to WbWb$

like

$t\bar{t} \to WbWb$
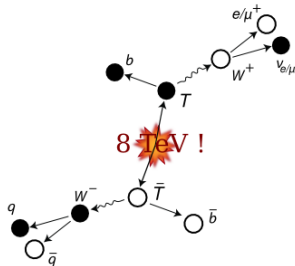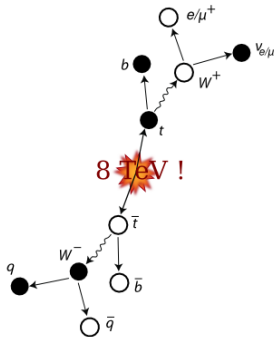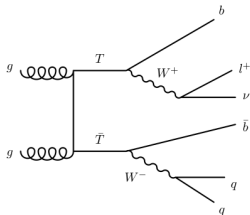
different boosted kinematics

⇓

reconstruct the W boson from hadronic decay

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

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

Outline

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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] 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	1.15×10^{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

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].