

Searches for new physics using top quarks in ATLAS

With a very strong emphasis on tt resonance searches

Marcel Vos (IFIC Valencia)

Spanish meeting on LHC physics, Granada, october 2009

Looking for exotic physics with top quarks

tt resonance searches - an “early” analysis

ATLAS prospects for tt resonances – results of the traditional approach

ATLAS prospects for tt resonances – some new tools

Further exotic physics with tops

Top as a signature for new physics?

Wishful thinking?: Will the top and bottom quarks be the messenger by which Beyond The Standard Model physics reveals itself?

the top is too heavy, it's less constrained by (LEP) data

An experimentalist's view: of 12 known fermions, 7 potential signatures:

μ^\pm , e^\pm , τ^\pm , E_t^{miss} , uds(g), b/c and top

Quark signatures benefit from strong coupling (large production cross-section), but suffer from large Standard Model background

Bottom and top quarks can be identified efficiently. Top is the only quark that produces isolated leptons and where quarks can be easily distinguished from anti-quarks.



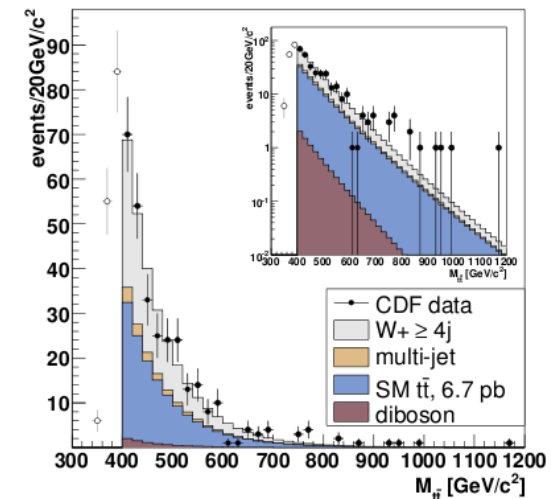
Tt resonance searches - early?

CDF arXiv:0709.0705

Tevatron

- Limited statistics
→ $8 \text{ fb}^{-1} \text{ ppbar @ } 1.96 \text{ TeV} = 64.000 \text{ } t \bar{t} \text{ pairs}$
- Tops produced at rest
→ *limited mass reach, heaviest observed pair ~ 1 Te*

~20 papers on tt resonance searches, limits $\sigma \times BR \sim 300 \text{ fb}$ for $0.7 < M < 1 \text{ TeV}$

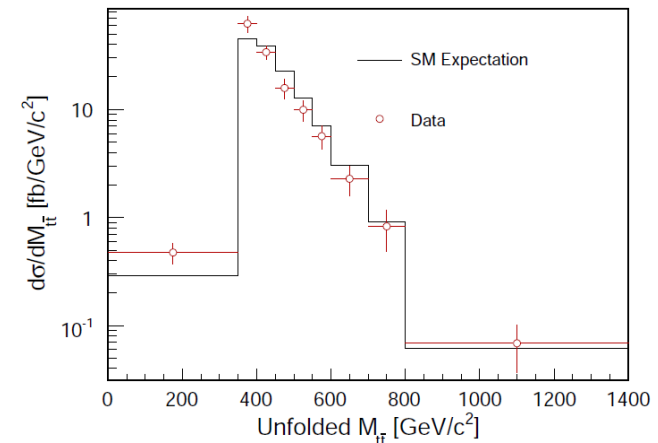


LHC early days:

- A top factory
→ $200 \text{ pb}^{-1} \text{ pp @ } 10 \text{ TeV} = 80.000 \text{ } t \bar{t} \text{ pairs}$
- Well above threshold
→ 1 in 5 tops has $p_T > 200 \text{ GeV}$
- But, will we understand the detector well enough
→ Definitely not to measure $d\sigma/dM_{tt}$

→ **no counting experiments**, but reconstruction of mass spectrum

does not depend crucially on understanding of luminosity, jet energy scale, alignment



(CDF, PRD 77, 051102, 2008!)

Tt resonance searches - early?

Resonances are present in many models (sequential Z', little Higgs, extra dimensions, ...)

Cross-sections and Branching Ratio can BOTH be sizeable (in some cases downright spectacular)

resonance X	Γ/M	B.R. ($X \rightarrow t\bar{t}$)	σ (1 TeV)	$\sigma \times BR$ (1 TeV)
sequential Z'	3.0%	11%	12.7 pb	1.39 pb
Little Higgs Z_H ($\cot \theta = 1$)	3.4%	13%	16.8 pb	2.10 pb
LR Twin Higgs Z_H	2.7%	8%	13.3 pb	1.0 pb
KK g^* (universal couplings)	20%	17%	1109 pb	190 pb
Basic RS g^*	15%	92%	30 pb	28 pb

LHC (14 TeV) cross-sections for different extensions of the Standard Model

Black holes ($2 \rightarrow 2$ a la Randall/Meade)	X	3% (tt)	30 nb	1 nb
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PRELIMINARY

ATLAS benchmark amplitudes for electroweak (narrow) and colored resonances (broad!) have been defined. **Colored resonances can be early physics.**

Production cross-section decreases rapidly with decreasing center-of-mass energy (forget about 7 TeV)

LHC cross-sections for the KK gluon in the basic RS setup for different center-of-mass energies

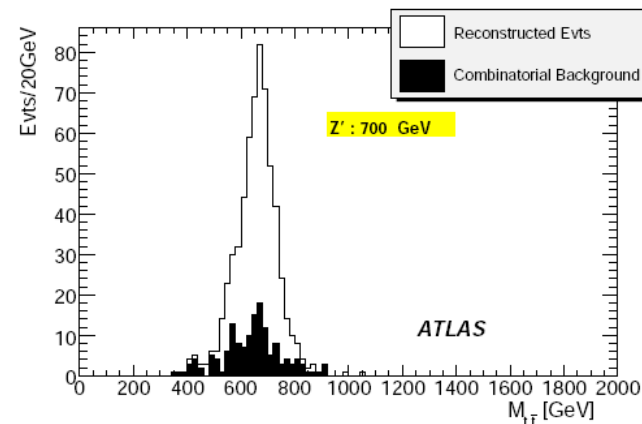
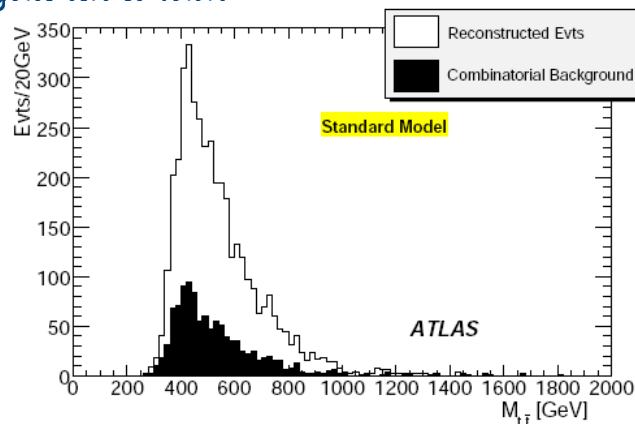
	10 TeV	7 TeV
1 TeV	4.0	1.6
2 TeV	0.142	0.038

The standard, resolved approach:

Thoroughly exercised on full simulation (ATL-PHYS-PUB-2006-033, ATLAS Collaboration, Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics, CERN-OPEN-2008-020).

Standard event selection for semi-leptonic events:

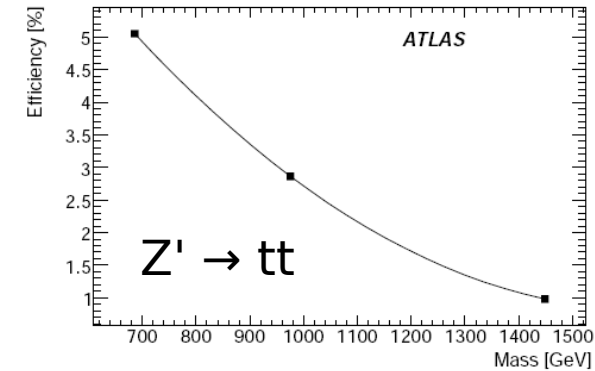
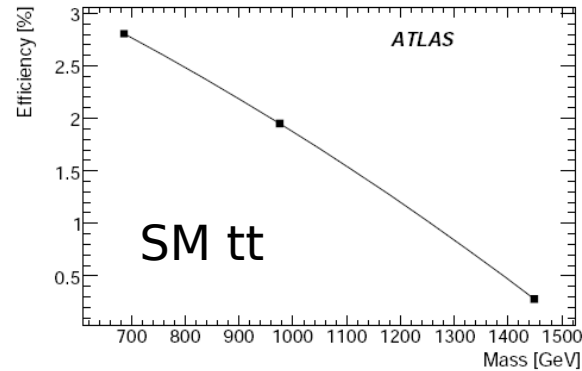
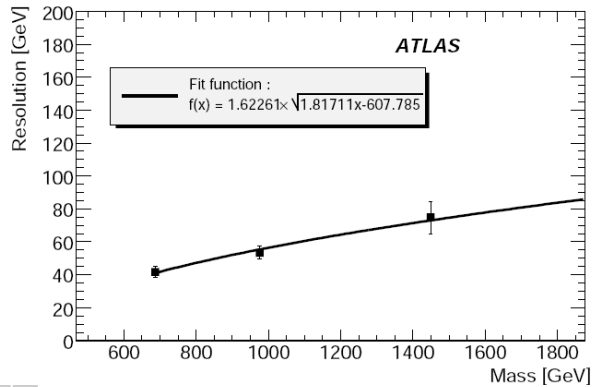
- exactly one isolated electron (muon),
- $|\eta| < 2.5$ and $p_T > 25$ GeV ($p_T > 20$ GeV)
- at least **four jets** with $|\eta| < 2.5$ and $p_T > 30$ GeV
- at least 2 jets tagged as b-jets
- $E_t^{\text{miss}} > 20$ GeV



Reconstruction: combine jets, lepton and E_{miss} to form top candidates

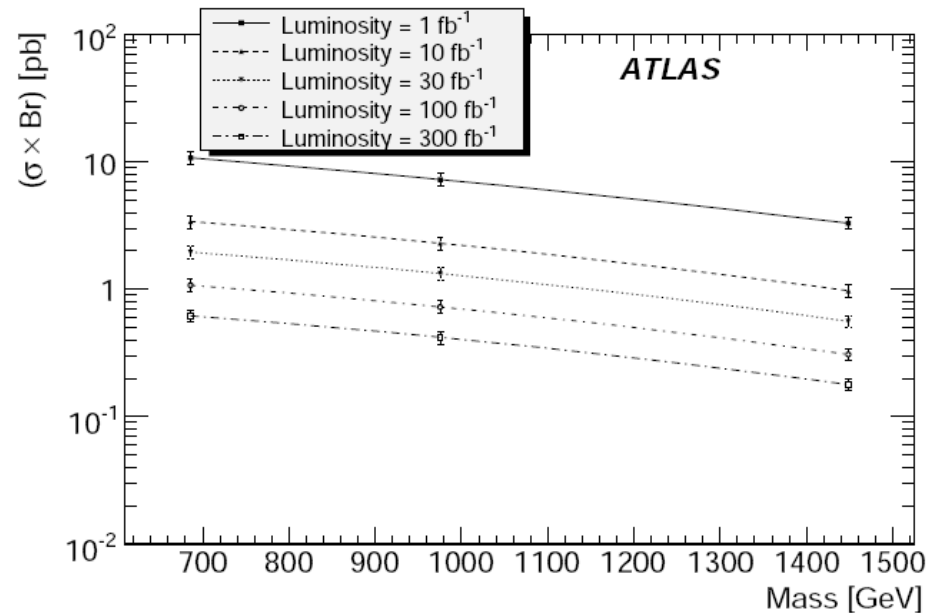
- **Hadronic W** \Rightarrow the jet combination with the smallest ΔR separation
- **Hadronic top** \Rightarrow add the nearest b-jet
- **Leptonic W** \Rightarrow solve for p_z^ν . (two solutions) using W-mass
- **Leptonic top** \Rightarrow Combine with remaining b-jet. Choose the neutrino solution that gives the leptonic top mass closest to the average mass of the hadronic top.

ATLAS tt resonance searches

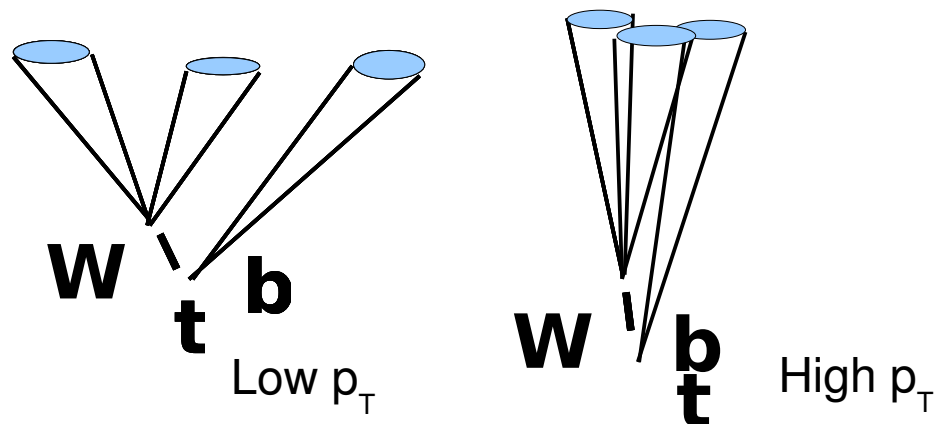
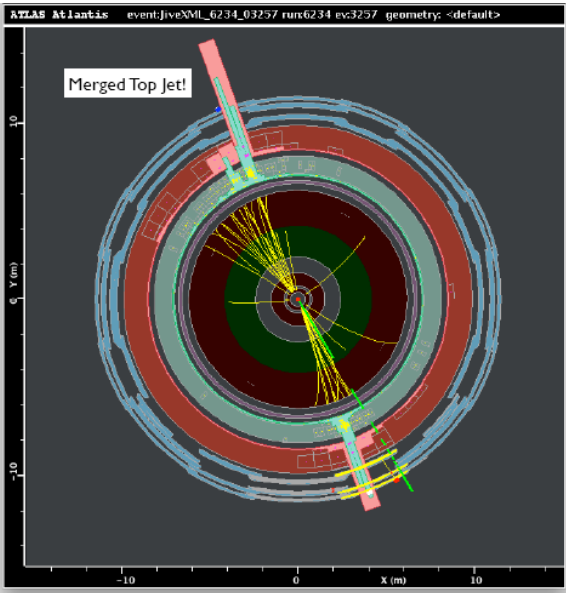


- Resonance mass resolution $\sim 5\%$ in mass range from 700 to 1500 GeV.
- A sharp efficiency drop towards larger resonance mass
 - 5 % @ 700 GeV
 - < 1 % @ 1500 GeV

The sensitivity of the standard approach for tt resonances versus mass and integrated luminosity

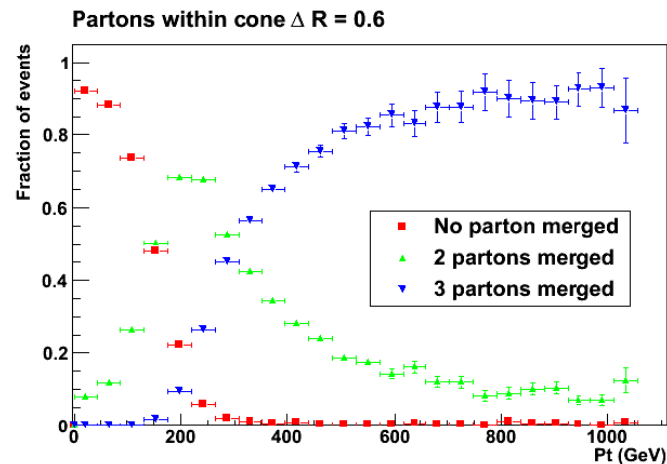


Reconstruction of high p_T tops



Problems for standard “resolved” top reconstruction at high p_T

- **Partons from top decay are not resolved by jet reconstruction algorithms**
- isolation of leptons (trigger)
- E_T^{miss} resolution in events with TeV jets
- tracking performance in jets (b-tagging)
- control samples (jet calibration, b-tag)



See also, among others:

K. Agashe et al., hep-ph/0612015

Randall, Lillie and Wang, JHEP 0709:074 (2007)

Kaplan et al., arXiv:0806.0848

The mono-jet alternative in a nut shell:

Reconstruct the hadronic top decay as a single jet

Tag it (to reduce non-top backgrounds)

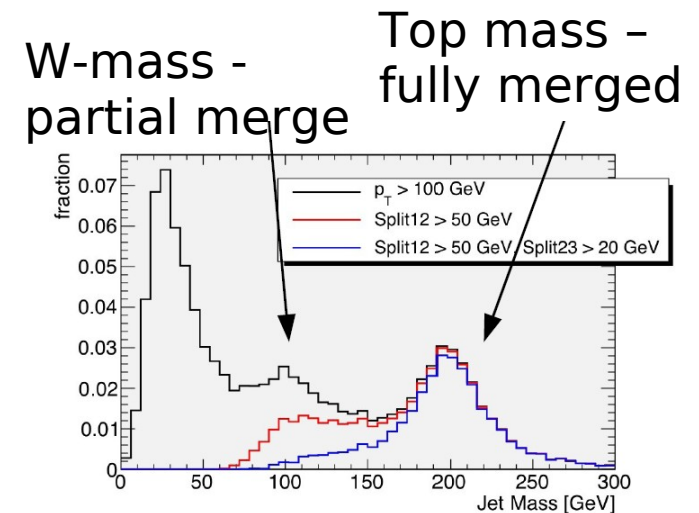
High p_T Hadronic Top Quark Identification

Part 1 : **Jet Mass and Ysplitter** *ATL-PHYS-CONF-2008-008*

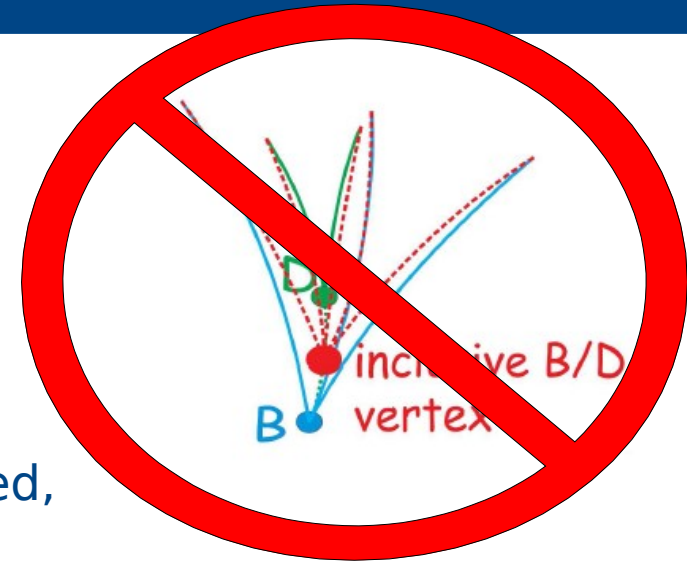
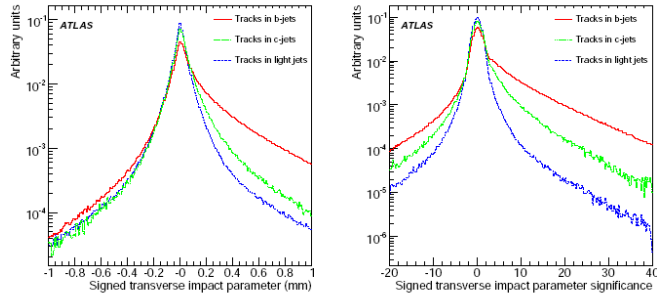
Part 2 : **the life-time signature** *ATL-PHYS-CONF-2008-016*

Many caveats apply:

- Resolved approach needed for $d\sigma/dM_{tt}$
- Early physics is in transition region

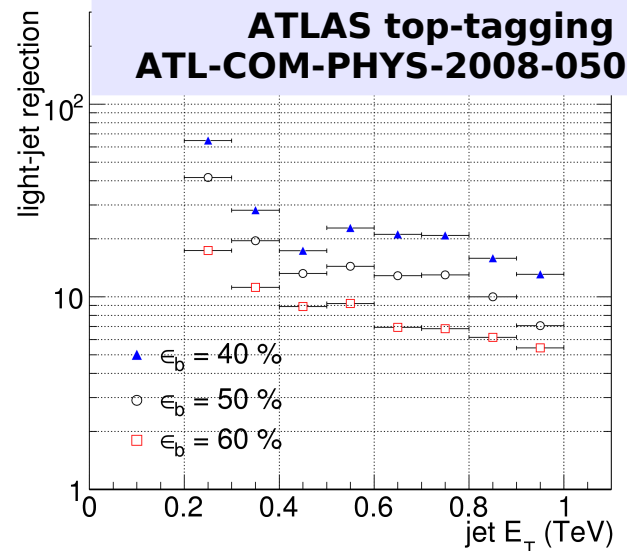
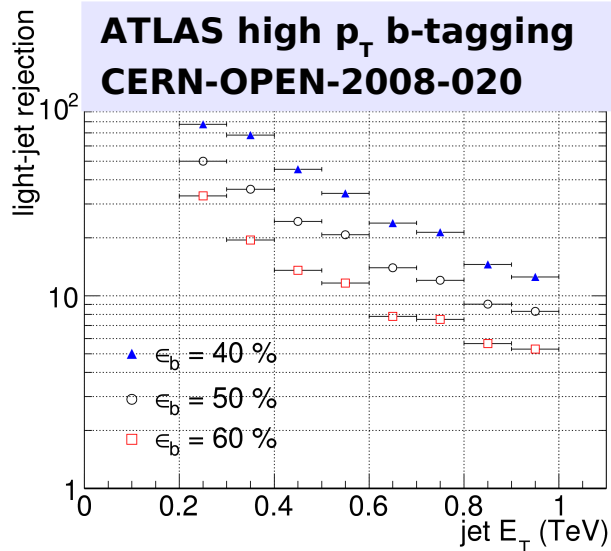


ATLAS flavour tagging



Early days: use simple, impact parameter based, self-calibrating b-tagging algorithms

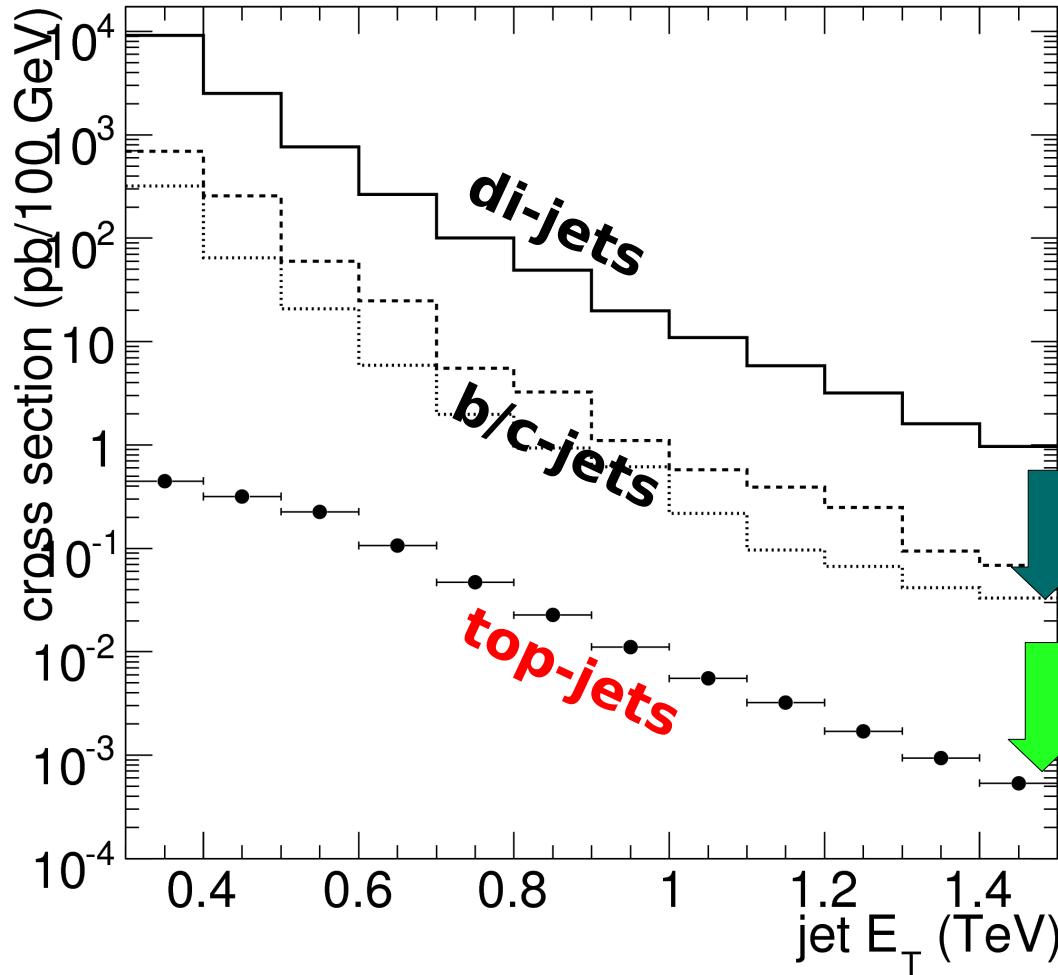
$$R_u < 100 \text{ for } \epsilon_b = 50 \%$$



Top tagging



The abundance of heavy flavour ... (according to Pythia)



Lifetime signature

Jet substructure

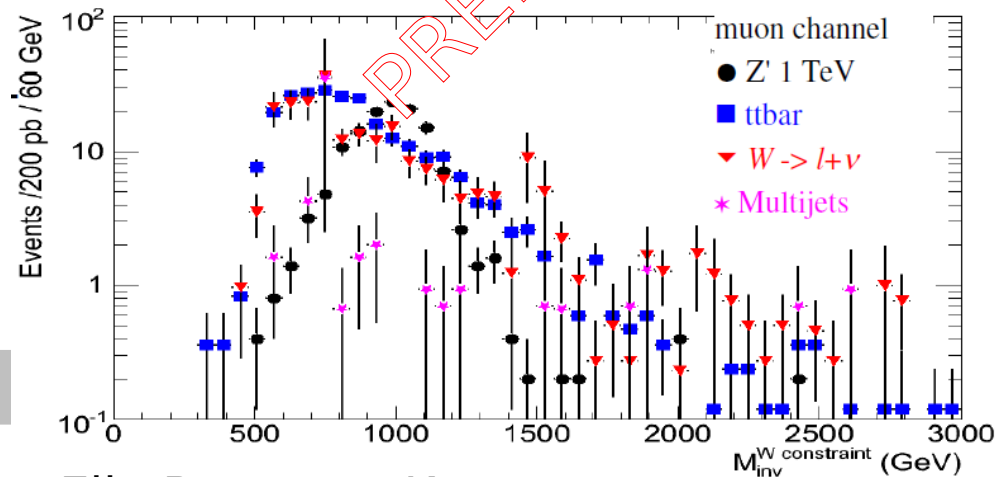
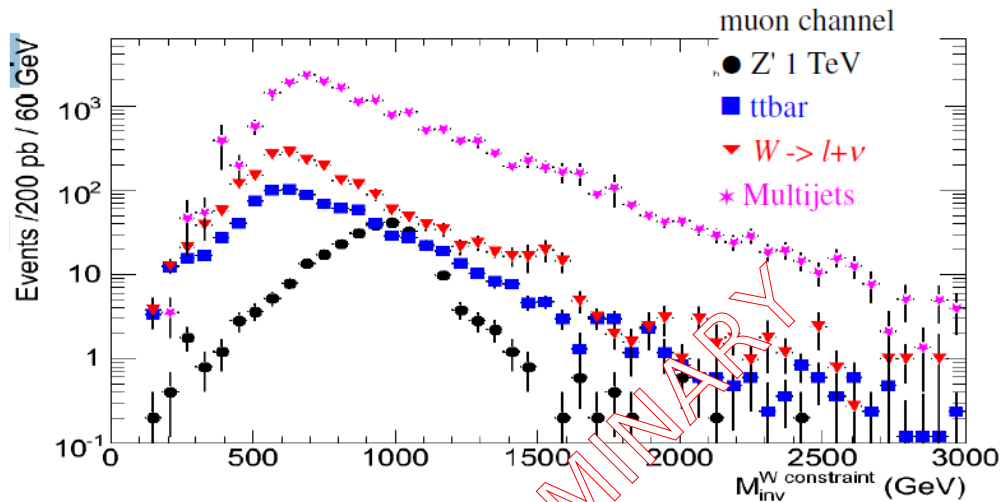
Results

Before selection

Existing selection is able to reduce QCD and W +jets backgrounds to the level of irreducible SM $t\bar{t}$ background at an acceptable efficiency

Detailed comparison of ATLAS potential among analyses and earlier publications is starting

After



Elin Bergeaas Kuutman

A bit further...

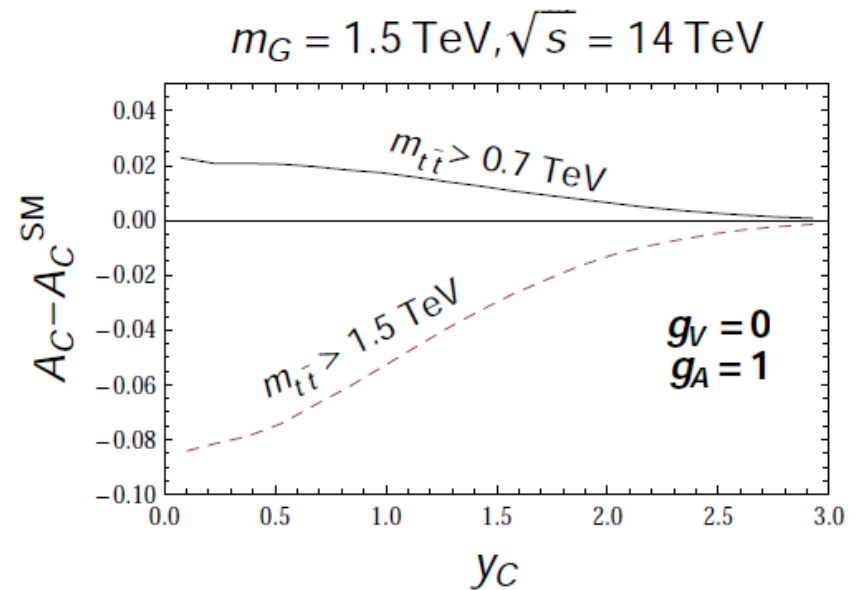
Smarter analysis may increase sensitivity

Paola Ferrario, German Rodrigo, Charge asymmetries of top quarks: A Window to new physics at hadron colliders, J.Phys.Conf.Ser.171 (2009) 012091

$$A_C(y_C) = \frac{N_t(|y| \leq y_C) - N_{\bar{t}}(|y| \leq y_C)}{N_t(|y| \leq y_C) + N_{\bar{t}}(|y| \leq y_C)}$$

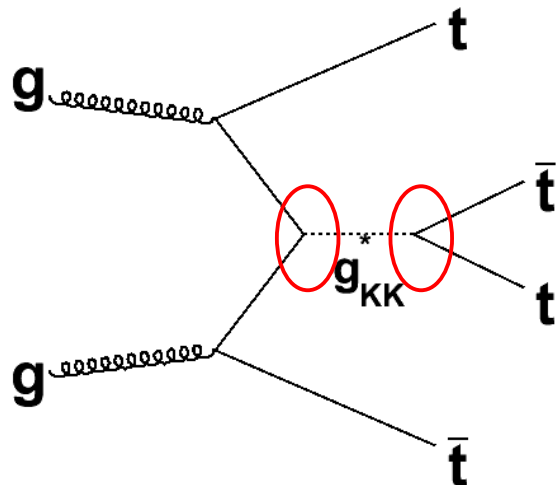
Good to get a grip on the background for very broad resonances

Requires efficiency versus η to be understood to some level



Outlook: $tt+X$

As soon as SM tt spectrum is understood, $tt+X$ studies start
Even looking for four tops!



What if only the top quark couples to new sector (significantly)?

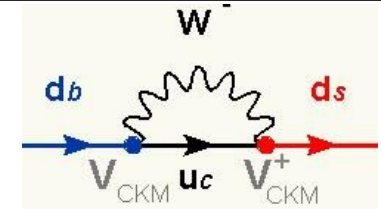
top compositeness, Lillie, Shu, Tait; Kumar, Tait, Vega-Morales; Pomarol, Serra

Relatively easy to isolate (same-sign lepton), but will we ever be able to reconstruct such events?

ad-hoc working group with A-I Etiennev, G. Servant (Saclay) and E. Bussato (Cl. Ferrand)

Searches for rare top decays

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} \quad V_{ij} = \begin{bmatrix} 0.97383 & 0.2272 & 0.00396 \\ 0.2271 & 0.97296 & 0.04221 \\ 0.00814 & 0.04161 & 0.999100 \end{bmatrix}$$



Standard Model: the Wtb coupling is purely left-handed at tree level, its strength governed by $V_{tb} \sim 0.999$

(assuming three generations of quarks and the unitarity of CKM matrix)

New physics may lead to departure from the SM value for V_{tb} or new radiative contributions

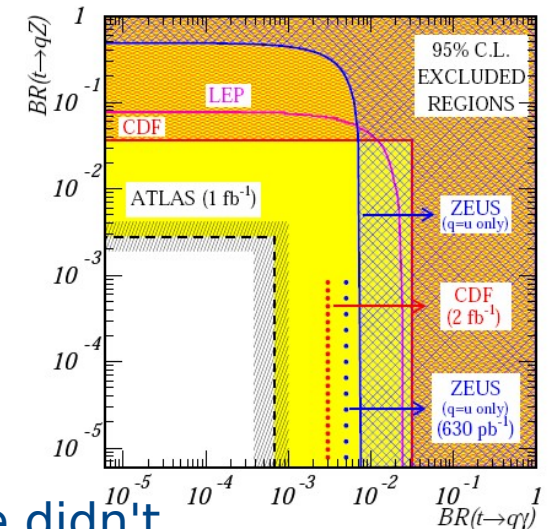
Flavor Changing Neutral Current (FCNC) are strongly suppressed in the SM by the (GIM) mechanism, but may appear at tree-level in SUSY, 2 Higgs Doublet Models and models with exotic vector-like quarks

Process	SM	QS	2HDM	MSSM	RPV SUSY
$t \rightarrow uZ$	8×10^{-7}	1.1×10^{-4}	x	2×10^{-6}	3×10^{-5}
$t \rightarrow u\gamma$	3.7×10^{-16}	7.5×10^{-9}	x	2×10^{-6}	1×10^{-6}
$t \rightarrow uZ$	3.7×10^{-14}	1.5×10^{-7}	x	8×10^{-5}	2×10^{-4}
$t \rightarrow cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	2×10^{-6}	3×10^{-5}
$t \rightarrow c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	2×10^{-6}	1×10^{-6}
$t \rightarrow cZ$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	8×10^{-5}	2×10^{-4}

Are these extremely small branching ratios accessible experimentally?

We hadn't gotten very close, so far.

	LEP	HERA	Tevatron
BR ($t \rightarrow qZ$)	7.8%	49%	3.7%
BR ($t \rightarrow q\gamma$)	2.4%	0.75%	3.2%
BR ($t \rightarrow qg$)	17.0%	13%	0.1-1%



But, then we didn't have a top factory!

Study of ATLAS sensitivity to FCNC top decays, SN-ATLAS-2007-059

Spanish involvement

My, hopefully incomplete, list of Spanish institutes involved in (ATLAS) exotic physics with tops

Granada

J.A. Aguilar Saavedra → anomalous couplings

IFAE theory

J. Serra → top compositeness

IFIC: experiment

E. Ros → convenor ATLAS exotics 2007-2009

M. Vos → convenor ATLAS exotics / Jet + X 2009-2010

→ coordinator tt resonance searches

M. Villaplana, E. Oliver, directed by S. Gonzalez de la Hoz and J. Salt → Ph.D. Thesis on first data

IFIC: theory

G. Rodrigo, P. Ferrario → asymmetries



Summary

Top quarks may be abundantly produced through resonant new physics channel → searches for (strongly interacting) $t\bar{t}$ resonance are “early physics”

high $p_T \neq$ low p_T

ATLAS has developed top reconstruction/tagging algorithms based on jet substructure and lifetime

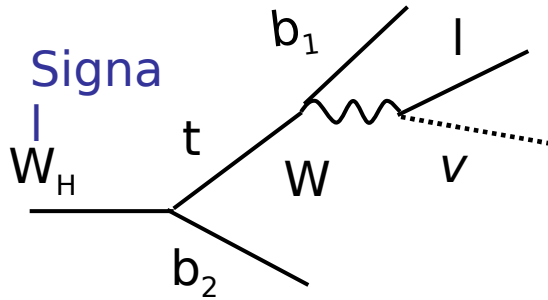
MC paper on ATLAS prospects for $t\bar{t}$ resonances to be finalized by the end of the year.

Hopefully, competitive limits (or discovery) will follow soon after.

$t\bar{t}$ resonances pave the way for a large number of $t\bar{t}+X$ searches



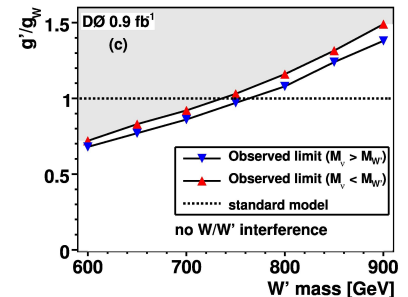
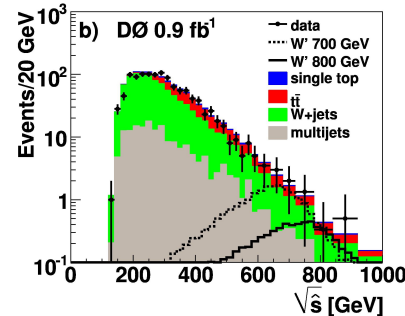
$W_H \rightarrow tb$, the topology that has it all



Dominant backgrounds:
 tt , W +jets, single top

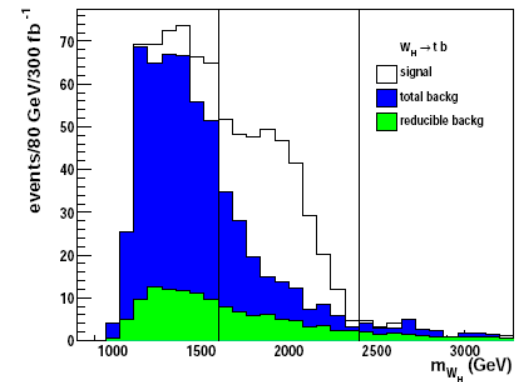
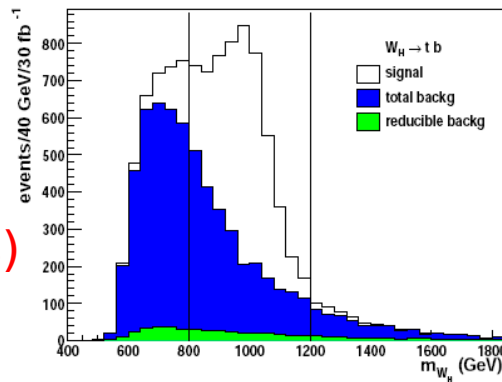
D0 collaboration, Search for W -prime Boson Resonances
 Decaying to a Top Quark and a Bottom Quark.

$m(W') > 700$ GeV



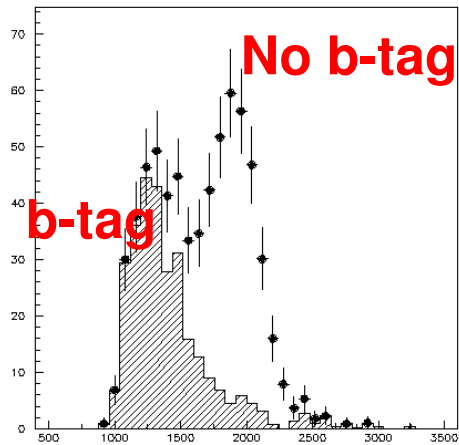
ATLAS fast simulation Littlest Higgs $W_H \rightarrow tb$

discovery up to 2.5 TeV
 ($\cot \theta = 1$, PHYS-PUB-2006-003)
 $ZH \rightarrow tt$ and $ZH \rightarrow bb$ more difficult

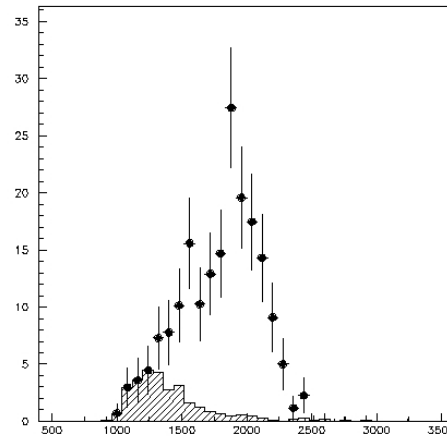


Full simulation study within more challenging LR Twin Higgs model (PHYS-PUB-2008-004)

Now, for something a bit more complex: $t\bar{b}b\bar{b}$

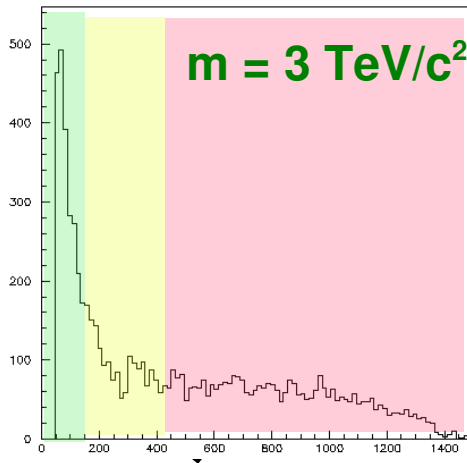


Events ($L = 30 \text{ fb}^{-1}$)



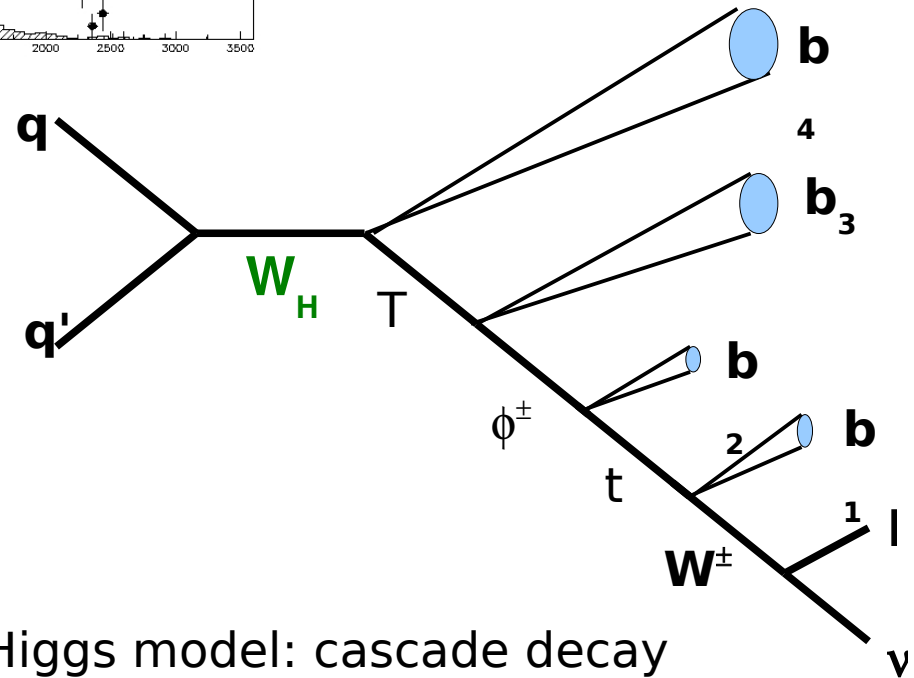
2 TeV no b-tag b-tag

N_{sig}	301	120
N_{tt}	48	4.8
N_{wj}	1.9	-
N/\sqrt{B}	43	55



1500 GeV/c

P_T spectrum of b-jets



LR Twin Higgs model: cascade decay

$$W_H \rightarrow T\bar{b} \rightarrow \phi^\pm b\bar{b} \rightarrow t+3b \rightarrow b\bar{b} + l + E_t^{\text{miss}}$$

And more spectacular

RS warped extra dimensions

L. Randall, R. Sundrum, A Large Mass Hierarchy from a Small Extra Dimension. Physical Review Letters 83 (1999): 3370-3373

L. Randall, Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions. New York: HarperCollins (2005).

“possibly the most attractive”

When SM gauge bosons penetrate the bulk, Kaluza Klein towers of excited states appear. The KK gluon has some quite attractive features for experimentalists

couples strongly to quarks:

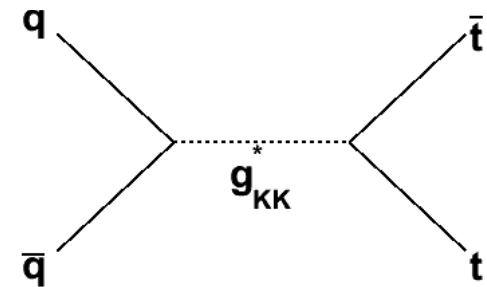
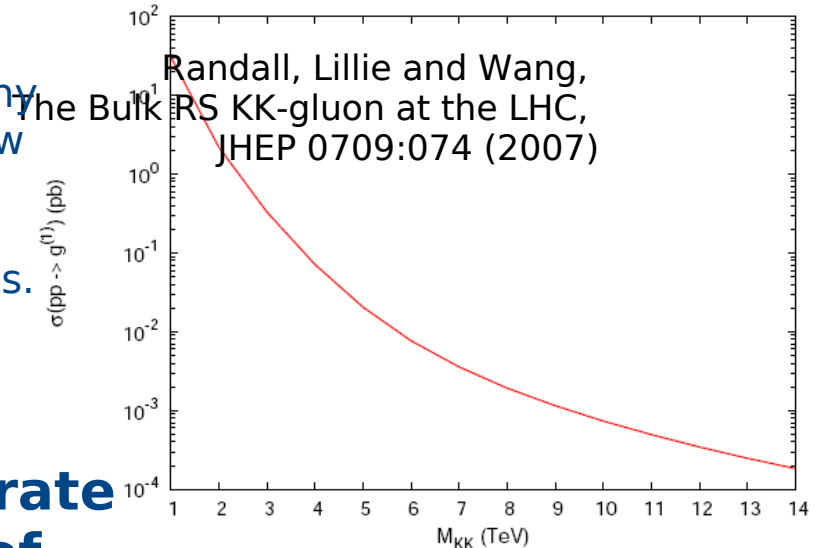
large cross-section: 15 pb for $m(g_{KK}^*) = 1 \text{ TeV} @ 10 \text{ TeV}$

but, by the same token:

not a narrow resonance! Basic RS model: $\Gamma = 0.17 M$

Large branching fraction into $t\bar{t}$

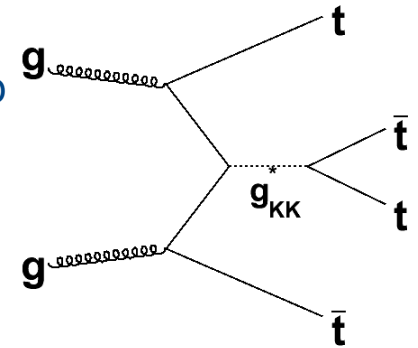
Basic RS scenario: 92.6 %



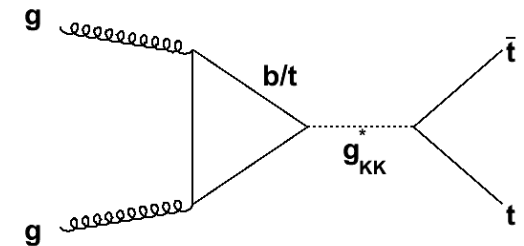
Tt + missing ET, tt + jets, tt + additional leptons

Or even four tops!

(see also: top compositeness, Lillie, Shu, Tait; Kumar, Tait, Vega-Mo



Scenario	g^q	$g_L^b = g_L^t$	g_R^b	g_R^t	$\Sigma(g_{KK}^* \rightarrow qq)$	$\Sigma(g_{KK}^* \rightarrow bb)$	$\Sigma(g_{KK}^* \rightarrow tt)$	$\Gamma g^*/Mg^*$
Basic RS	-0.2	1	-0.2	4	1.7%	5.7%	92.6%	0.153
$kr_{IR} = 5$	-0.4	-0.2	-0.4	0.6	68.1%	10.6%	21.3%	0.016
$kr_{IR} = 20$	-0.8	-0.6	-0.8	-0.2	78.5%	15.3%	6.1%	0.054
SO(5), N=0	-0.2	2.76	-0.2	0.07	2.0%	49.1%	48.9%	0.130
SO(5), N=1	-0.2	2.76	-0.2	0.07	0.7%	16.0%	15.9%	0.400
E_1	-0.2	1.34	0.55	4.9	1.1%	7.4%	91.4%	0.235
E_2	-0.2	1.34	3.04	4.9	0.9%	29.7%	69.4%	0.310
E_3	-0.2	1.34	0.55	3.25	2.2%	14.2%	83.6%	0.123
E_4	-0.2	1.34	3.04	3.25	1.3%	46.6%	52.1%	0.198



From: Baur and Orr, arXiv:0803.1160

Basic RS: Randall, Lillie and Wang, JHEP 0709:074 (2007)

Large brane kinetic terms: H. Davoudias, J.L. Hewett, T.G. Rizzo, Phys. Rev. D 68, 045002 (2003), M. S. Carena, E. Ponton, T. M. P. Tait and C. E. M. Wagner, Phys. RevD 67 (2003), Phys. Rev. D 71 (2005)

Custodial symmetry (SO(5) x U(1))_x: M. S. Carena, E. Ponton, J. Santiago and C. E. M. Wagner, Phys. Rev. D 76, 035006 (2007)

A^b_{FB} inspired: A. Djouadi, G. Moreau, and R.K. Singh, Nucl. Phys. B 797 (2008)

The high p_T alternative

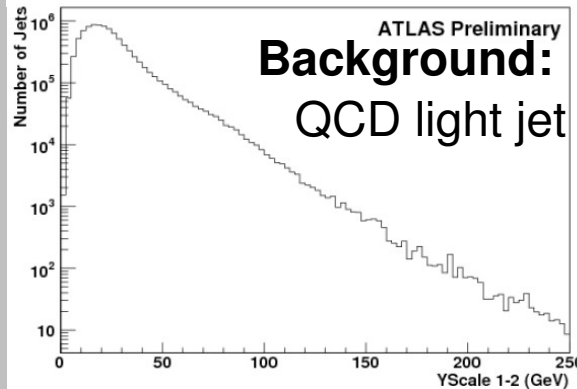
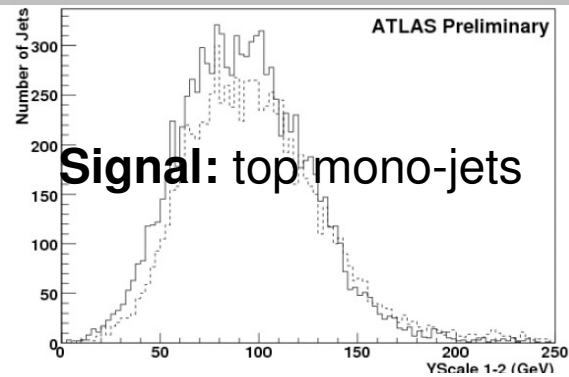
ATLAS NOTE
ATL-COM-PPV-2008-001
February 4, 2008

High p_T Hadronic Top Quark Identification
Part I: Jet Mass and Y-Splitter

Constan Dinu
Columbia University

Abstract

At the LHC, objects with masses at the electroweak scale will for the first time be produced with very large transverse momenta. In many cases these objects are produced in association with a hard jet. The interesting new experimental phenomenology requires the development and testing of new tools, since the usual reconstruction methods would simply reconstruct a single jet. This note describes the application of the Y-splitter algorithm to compare with the jet mass to identify high transverse momentum jets (recoiling hadrons etc).



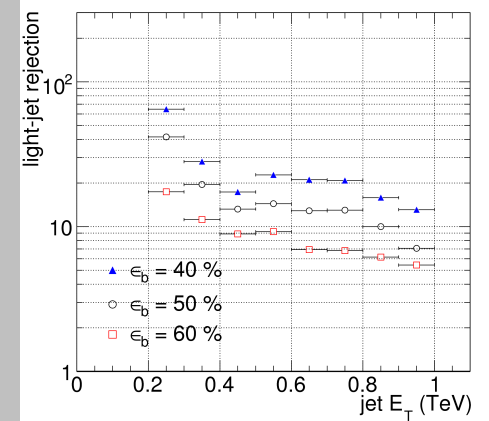
ATLAS NOTE
ATL-PPV-TEB-2008-000
June 6, 2008

High p_T Hadronic Top Quark Identification
Part II: the Lifetime signature

M. Vos
IFIC (C/ Universitat CSIC), Valencia, Spain

Abstract

At the LHC top quarks will for the first time be produced at hard and with very large transverse momenta. For hadronic decays of top quarks at large p_T the three jet decay into a single jet, or top quark. Identification of these objects using the overwhelming QCD jet background requires the development of specially experimental strategies. In this note the use of event tagging algorithms based on the lifetime information for the identification of top quarks will be explained.



ATLAS flavour tagging

Selection:

- good (low fake rate) tracks
- reliable (precise IP) tracks

Assign category: shared hits

Clean track collection: remove V0s (neutral two track vertices, mostly conversions)

Calculate impact parameter significance

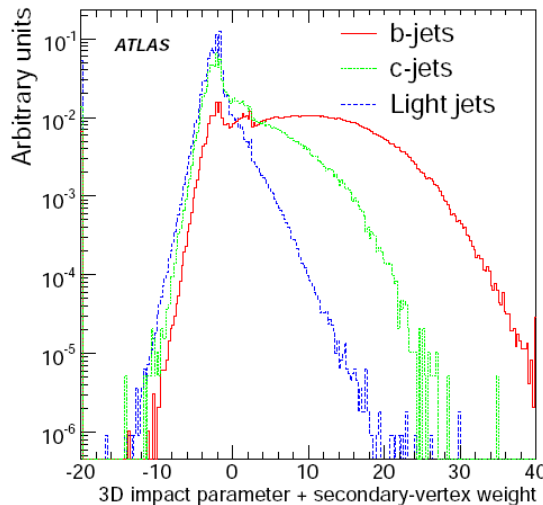
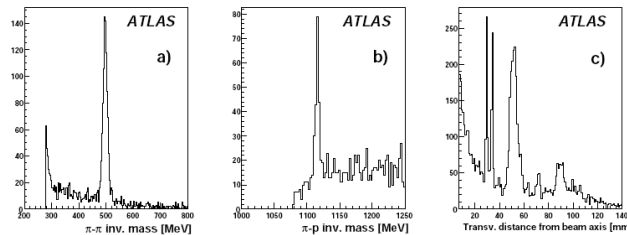
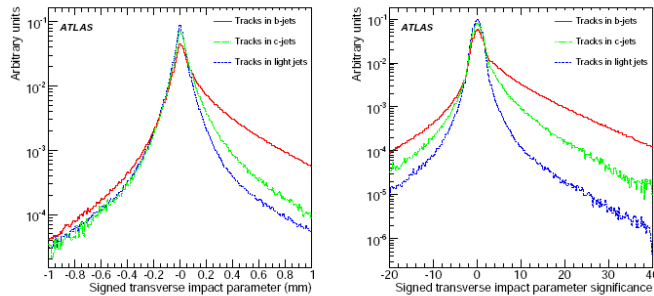
$$\text{significance} = d_0 / \sigma$$

Determine likelihood

PDF \rightarrow MC significance distribution for b-, c- and light jets

Construct jet likelihood

Sum 3D impact parameter $\log(\text{likelihood})$ of all (good) tracks in the jet



Heavy flavour (top): a background to many...

Examples of ATLAS exotic physics studies

ATLAS Collaboration, Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics, CERN-OPEN-2008-020, Geneva, 2008, to appear

Z' and W' searches:

SM tt is an important background.

Search for scalar lepto-quarks and right-handed W-bosons in di-lepton+jets final states:

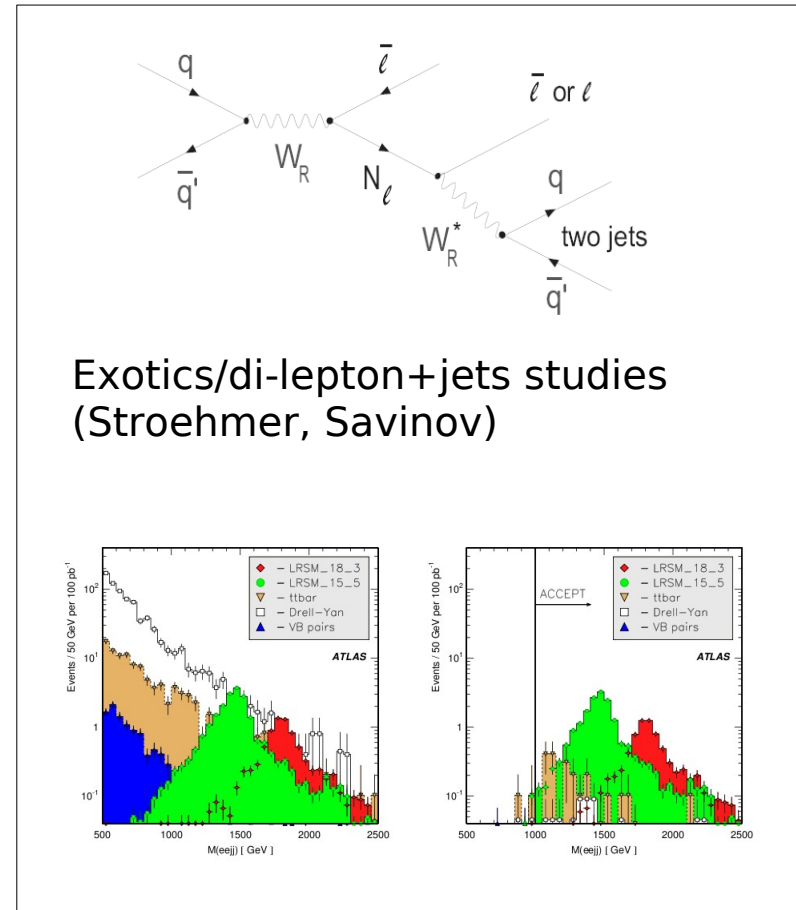
SM tt is the dominant background for LRSM
important also for lepto-quarks

Vector-boson scattering:

SM tt and tW events are an important background

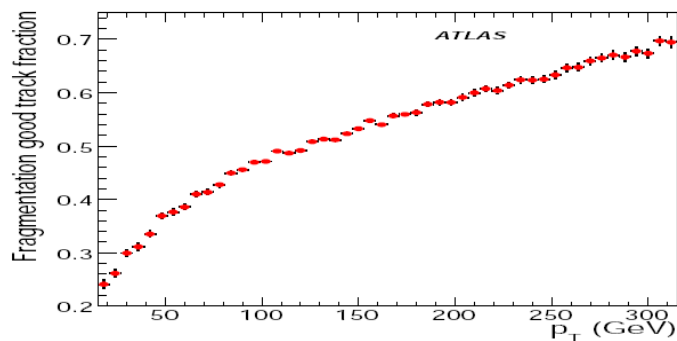
Black holes:

SM tt among important backgrounds



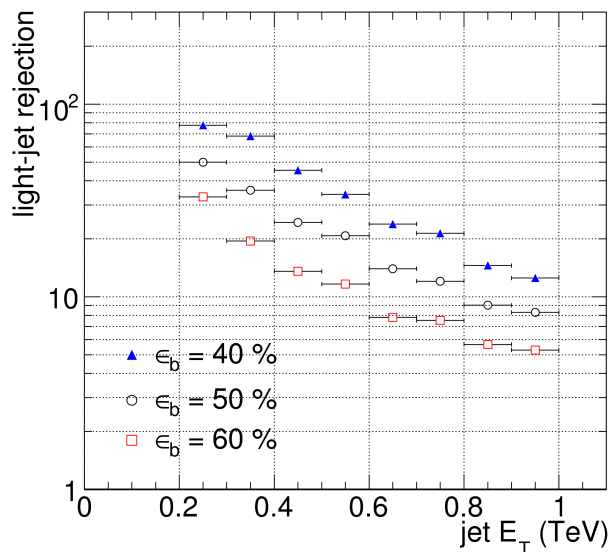
Event selection reduces SM tt sample to a tiny fraction with extraordinary properties (E_{miss}, #jets, p_T of final state objects)

High p_T b-tagging



More and more fragmentation tracks “dilute” the signal from ~ 5 B/D decay tracks

B-hadrons fly too far (impact parameter approximately constant)



	$R_B > 2.9$ (%)	$R_B > 5.1$ (%)
$E_T > 100$ GeV	12.2	3.9
$E_T > 200$ GeV	21.1	7.9

Tracking efficiency for tracks from displaced vertex in dense jet core strongly degraded

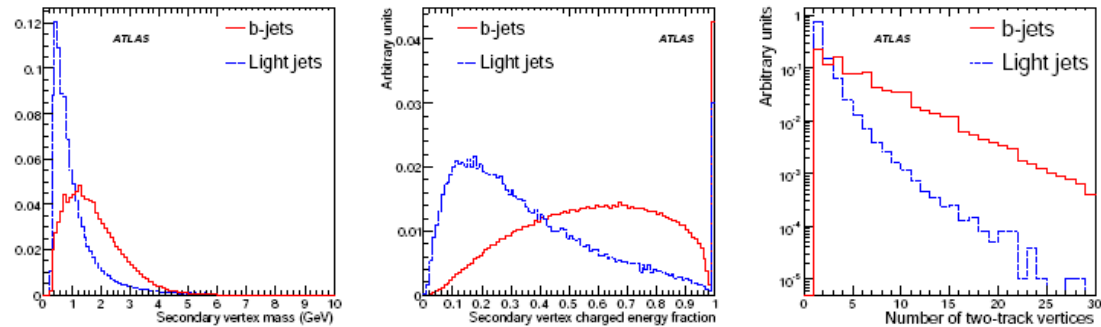
Flavour tagging performance suffers

ATLAS flavour tagging: SV

JetFitter

SV1

Add secondary vertex information (lifetime, but also mass and topology)



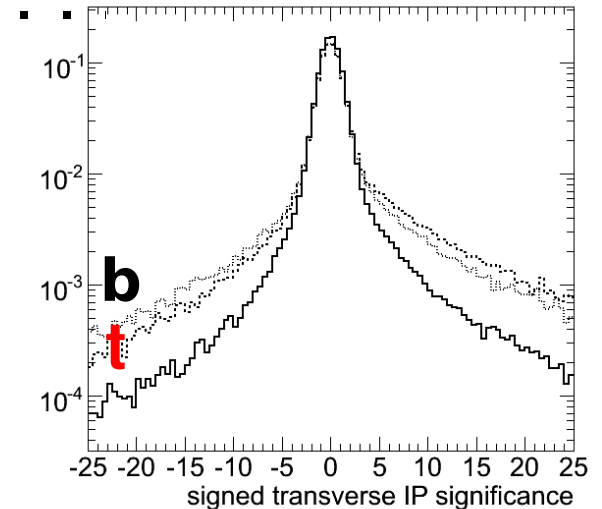
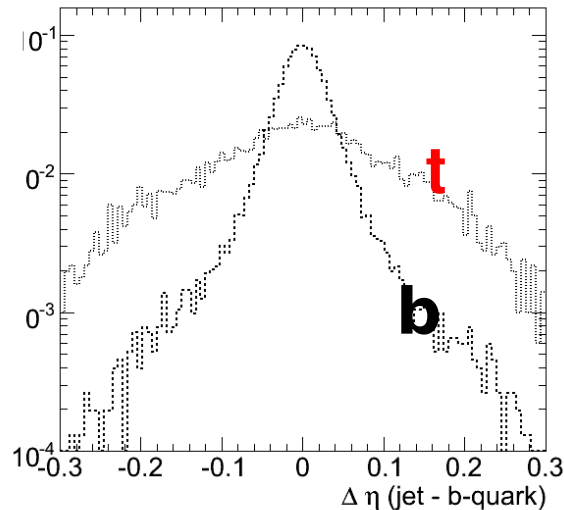
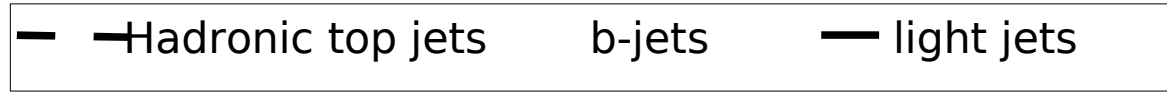
<-----> sophisticated

JetProb	IP2D	IP3D	IP3D+SV1	IP3D + JetFitter
83 ± 1	116 ± 2	190 ± 3	458 ± 13	555 ± 17
30 ± 0	42 ± 0	59 ± 1	117 ± 2	134 ± 2

Light jet rejection ($R_u = 1/\epsilon_u$) for two values of the b-tag efficiency

The lifetime signature

Very high p_T jets
 challenge the tracking
 pattern recognition.
 High p_T B-decay products
 challenge the pixel
 detector two-track
 resolution



What about top-jets. Does the “noise” from close-by W-decay affect the tagging performance?

- jet direction no longer as readily identified with B-hadron flight path
- impact parameter sign more often incorrect
- additional tracks without life-time information dilutes the likelihood

