tt resonance searches & rare decays

A comment about top as a SM background for BSM searches
Two example of BSM physics where tops are the signal...

searches for rare top decays

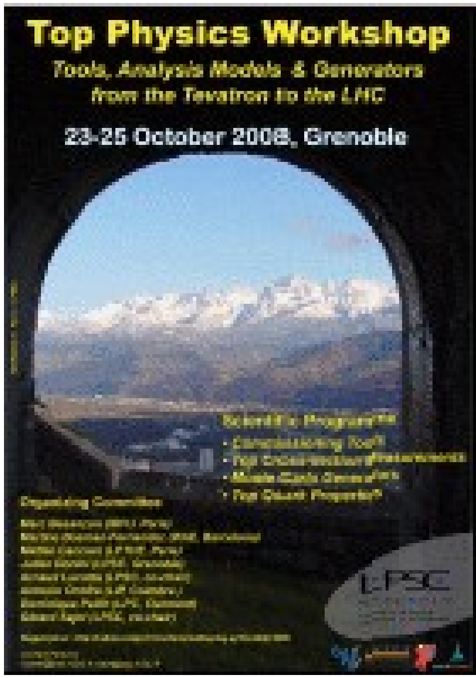
tt resonance searches

- A popular model: the KK gluon
- Brief overview of Tevatron results
- **ATLAS tt resonance searches:**

  a comment on the possibility of di-lepton
  the traditional approach...
  ... and the alternative

Some concluding remarks

Marcel Vos, IFIC Valencia



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:

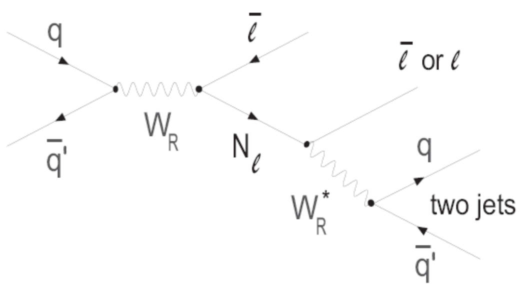
SM tt is the dominant background for LRSM important also for lepto-quarks

Vector-boson scattering:

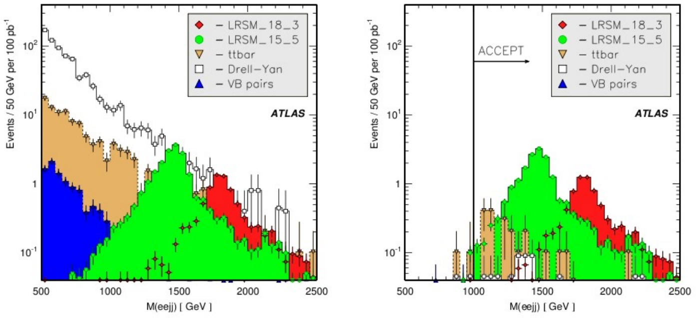
SM tt and tW events are an important background

Black holes:

SM tt among important backgrounds



Exotics/di-lepton+jets studies (Stroehmer, Savinov)



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

How well will we know this corner of phase space?

Top as a signal

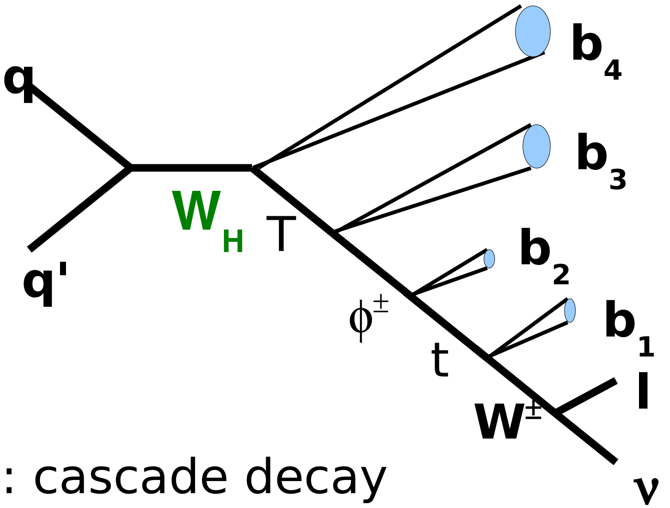
Wishful thinking?: Will the top quark be the messenger by which Beyond The Standard Model physics reveals itself? It's the heaviest know particle (some will claim it's mass is tantalizingly close to the Higgs boson mass)

More pragmatic: there are 12 known fermions. Some are indistinguishable experimentally or leave no signal in the detector. effectively we are left with have 7 potential signatures:

$\mu^{\pm}$, $e^{\pm}$, $\tau^{\pm}$, E_t^{miss}, uds(g), b/c and top

The top quarks has it's own unique (dis) advantages.
The only quark (strong coupling!) that produces isolated leptons
Anyway, we cannot afford to ignore any of them.

There are certainly plenty of models, where top quarks play a special role

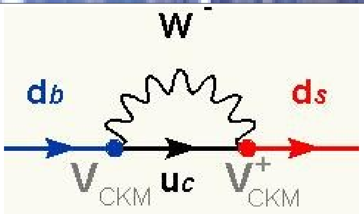


LR Twin Higgs model: cascade decay

$W_H \rightarrow Tb \rightarrow \phi^{\pm}bb \rightarrow t+3b \rightarrow bb + l + E_t^{miss}$

Searches for rare decays

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



Standard Model: the Wtb coupling is purely left-handed at the tree level and its strength governed by **V_{tb} ~ 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}
- new radiative contributions

Flavor Changing Neutral Current (FCNC) are strongly suppressed in the SM by the Glawhow-Iliopoulos-Maiani (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
$t \to uZ$	8×10^{-7}	1.1×10^{-4}	x	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	x	2×10^{-6}	1×10^{-6}
$t \to uZ$	3.7×10^{-14}	1.5×10^{-7}	x	8×10^{-5}	2×10^{-4}
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim10^{-7}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim10^{-6}$	2×10^{-6}	1×10^{-6}
$t \to cZ$	4.6×10^{-12}	1.5×10^{-7}	$\sim10^{-4}$	8×10^{-5}	2×10^{-4}

Are these extremely small branching ratios accessible experimentally?

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

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Searches for rare FCNC decays

channel	$tt \rightarrow bWq\gamma$	$tt \rightarrow bWqg$	$tt \rightarrow bWqZ$
Pre-selection	Exactly 1 ℓ ($p_T > 25$ GeV)	Exactly 1 ℓ ($p_T > 25$ GeV)	Exactly 3 ℓ ($p_T > 25$ GeV)
	≥ 2 jets ($p_T > 20$ GeV)	3 jets ($p_T > 40,20,20$ GeV)	≥ 2 jets ($p_T > 30,20$ GeV)
	Exactly 1 γ ($p_T > 25$ GeV)	No γ ($p_T > 25$ GeV)	No γ ($p_T > 25$ GeV)
	missing $E_T > 20$ GeV	missing $E_T > 20$ GeV	missing $E_T > 20$ GeV
Final selection	$p_T(\gamma) > 75$ GeV	$E_{vis} > 300$ GeV	2 ℓ (same flavour, opposite sign)
		$p_T(g) > 75$ GeV	
		$m_{qg} > 125$ GeV	
		$m_{qg} < 200$ GeV	
Trigger	e25i, mu20i or g60	e25i or mu20i	e25i or mu20i

Selection strategy for the three channels

Number of events after $L=1fb^{-1}$ and fraction of signal events

	e	μ	l
$tt \rightarrow bWq\gamma$			
Total	$(4.4 \pm 0.6) \times 102$	$(2.2 \pm 0.6) \times 10^2$	$(6.5 \pm 0.7) \times 10^2$
Signal (%)	3.6 ± 0.2	4.1 ± 0.2	7.6 ± 0.2
$tt \rightarrow bWqg$			
Total	$(11.0 \pm 0.3) \times 10^3$	$(8.3 \pm 0.2) \times 10^3$	$(19.3 \pm 0.4) \times 10^3$
Signal (%)	1.3 ± 0.1	1.5 ± 0.1	2.9 ± 0.1
$tt \rightarrow bWqZ$			
Total	$(0.3 \pm 0.6) \times 102$	$(0.1 \pm 0.6) \times 10^2$	$(1.3 \pm 0.6) \times 10^2$
Signal (%)	1.4 ± 0.2	2.5 ± 0.2	7.6 ± 0.2

Searches for rare FCNC decays

Current experimental limits on the branching ratio of rare top decays

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

We haven't gotten very close, so far. But, the LHC is the first top factory!

Study ATLAS reach for: $tt \to bl\nu qX$, where X = g or $\gamma/Z \to \ell\ell$ with $\ell = e^{\pm}, \mu^{\pm}$

Consider large set of backgrounds:

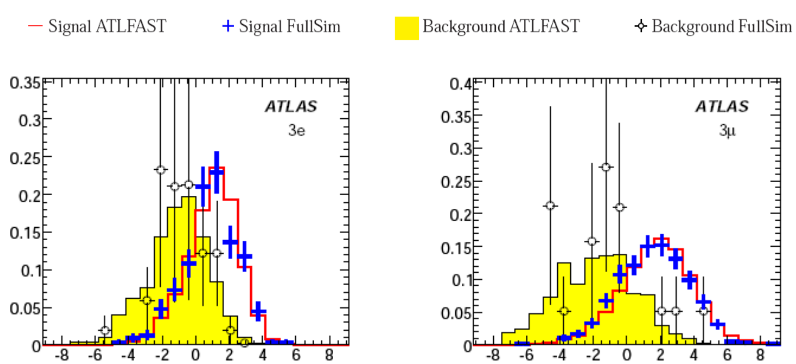
SM tt (fully hadronic, semi-leptonic and leptonic, MC@NLO), W+jets, Wbb+jets, Wcc+jets (ALPGEN), Drell-Yan: $Z \to e^+e^-$, $Z \to \mu^+\mu^-$, $Z \to \tau^+\tau^-$ (PYTHIA), Di-boson: WW, ZZ, WZ (HERWIG)

$$\chi^2 = (m_{l\nu ja} - m_t)^2/\sigma_t^2 + (m_t - m_t)^2/\sigma_t^2 + (m_{l\nu} - m_W)^2/\sigma_W^2 + (m_{lblc} - m_Z)^2/\sigma_Z^2$$

σ_t = 14 GeV, σ_W = 10 GeV , σ_Z = 3 GeV

$tt \to bWqZ$: likelihood based on

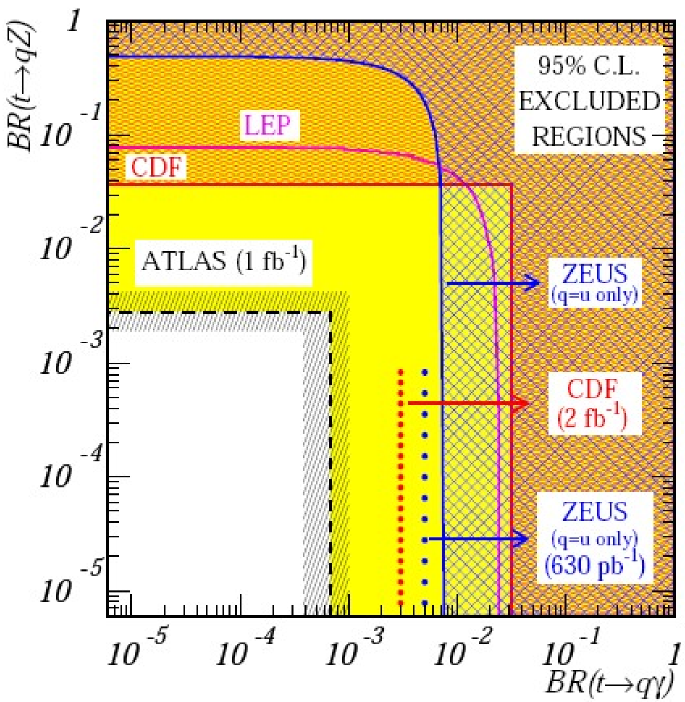
- the mass of the top quark with FCNC decay (m_t^{FCNC})
- the minimum invariant mass of the 3 combinations of two leptons (m_{ll}^{min}),
- the reconstructed mass of the Z and the the b-quark (m_{bZ}),
- the reconstructed mass of the two quarks (m_{qb})
- the transverse momentum of the light quark (p_T^q)



Rare FCNC top decays

Derive 95 % CL limits using the modified fequentist likelihood method (A.L. Read, Modified frequentist analysis of search results (The Cls Method), 2000, CERN Report 2000-005)

Convert limits into limits on branching ratios using SM tt cross-section



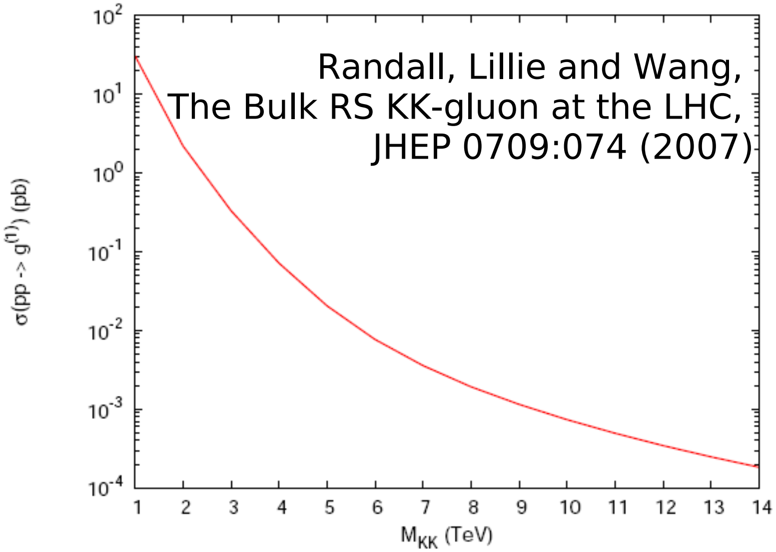
	-1s	Expected	1σ
tt → bWqγ			
e	4.3×10^{-3}	1.1×10^{-3}	1.9×10^{-3}
m	4.5×10^{-4}	8.3×10^{-4}	1.3×10^{-3}
l	3.8×10^{-4}	6.8×10^{-4}	1.0×10^{-3}
tt → bWqg			
e	1.3×10^{-2}	2.1×10^{-2}	3.0×10^{-2}
m	1.0×10^{-2}	1.7×10^{-2}	2.4×10^{-2}
l	7.2×10^{-3}	1.2×10^{-2}	1.8×10^{-2}
tt → bWqZ			
e	5.5×10^{-3}	9.4×10^{-3}	1.4×10^{-2}
m	2.4×10^{-3}	4.2×10^{-3}	6.4×10^{-3}
l	1.9×10^{-3}	2.8×10^{-3}	4.3×10^{-3}

+/- 1 σ includes statistical error and systematic effect of jet energy calibration, luminosity, top quark mass, background cross-section, ISR/FSR, Pile-up, Generator, χ^2

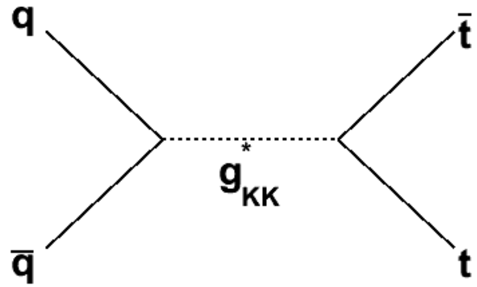
An example of a signal

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 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 TeV @ 10 TeV

but, by the same token:

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

Large branching fraction into tt

Basic RS scenario: 92.6 %

Fast simulation study into ATLAS potential of heavy gluon searches, March, Ros, Salvachua, PHYS-PUB-2006-002

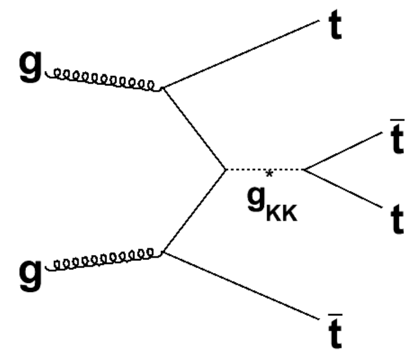
An example of a signal

Remember: it's just one example of a signal...

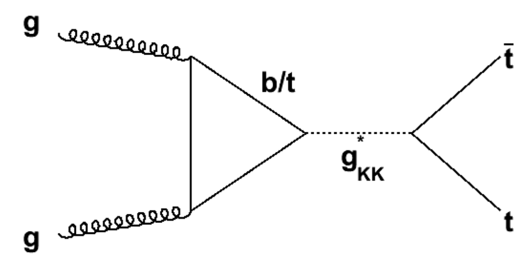
The other gauge bosons are not considered

Higher-order process are less dependent on couplings to light quarks

Many possible choices for parameters



Scenario	g^q	$g_L^b = g_L^t$	g_R^b	g_R^t	$\Sigma(g^*_{KK} \to qq)$	$\Sigma(g^*_{KK} \to bb)$	$\Sigma(g^*_{KK} \to tt)$	$\Gamma g^*/Mg^*$
Basic RS	-٠.٢	١	-٠.٢	٤	١.٧%	٥.٧%	٩٢.٦%	٠.١٥٣
$kr_{IR} = 5$	-٠.٤	-٠.٢	-٠.٤	٠.٦	٦٨.١%	١٠.٦%	٢١.٣%	٠.٠١٦
$Kr_{IR} = 20$	-٠.٨	-٠.٦	-٠.٨	-٠.٢	٧٨.٥%	١٥.٣%	٦.١%	٠.٠٥٤
SO(٥), N=٠	-٠.٢	٢.٧٦	-٠.٢	٠.٠٧	٢.٠%	٤٩.١%	٤٨.٩%	٠.١٣٠
SO(٥), N=١	-٠.٢	٢.٧٦	-٠.٢	٠.٠٧	٠.٧%	١٦.٠%	١٥.٩%	٠.٤٠٠
E_1	-٠.٢	١.٣٤	٠.٥٥	٤.٩	١.١%	٧.٤%	٩١.٤%	٠.٢٣٥
E_2	-٠.٢	١.٣٤	٣.٠٤	٤.٩	٠.٩%	٢٩.٧%	٦٩.٤%	٠.٣١٠
E_3	-٠.٢	١.٣٤	٠.٥٥	٣.٢٥	٢.٢%	١٤.٢%	٨٣.٦%	٠.١٢٣
E_4	-٠.٢	١.٣٤	٣.٠٤	٣.٢٥	١.٣%	٤٦.٦%	٥٢.١%	٠.١٩٨



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)

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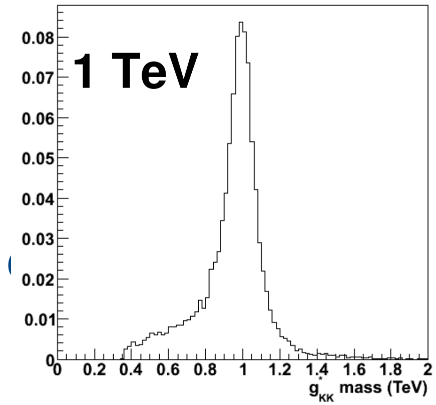
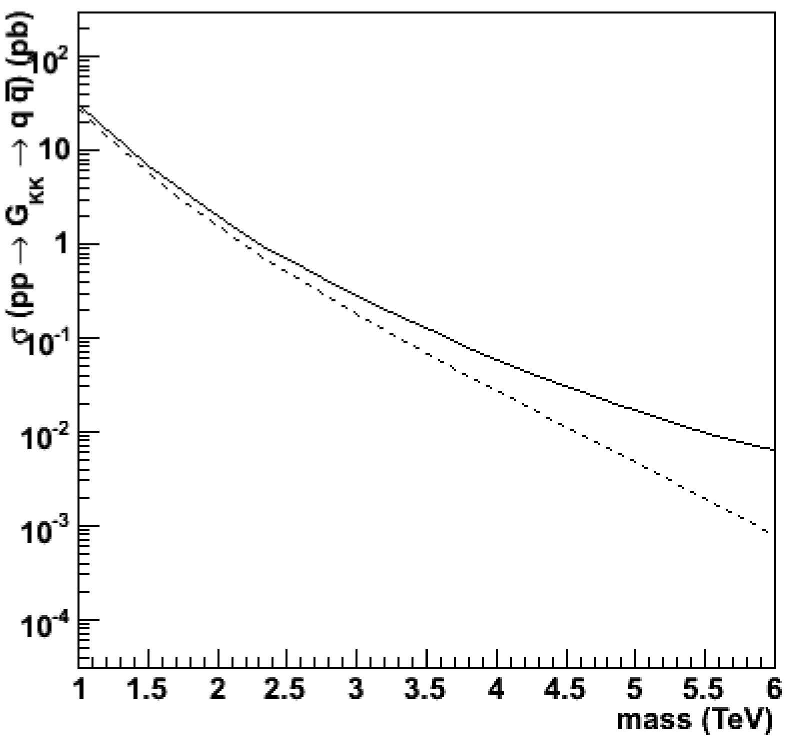
Generate some events

MadGraph/MadEvent (Maltoni/Stelzer, hep-ph/0208156)
TopBSM model (R. Frederix and F. Maltoni, 0712.2355)
with some modifications (thanks to R. Frederix)

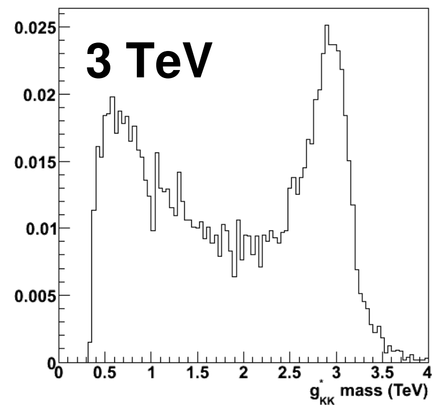
Full Matrix Element calculation of pp → g* → tt → bb lν

g* is represented by a generic colour octet labelled o1





Mass distribution:
Convolution of broad Breit-Wigner and luminosity function



MadGraph:

cross-section @ 14 TeV (solid line)

within nominal mass ± 30 % (dashed line)

Tevatron searches

Important program at the Tevatron ~ 20 papers since 2000.

(narrow) tt resonances

D0, FERMILAB-PUB-08-097E, arXiv:0804.3664

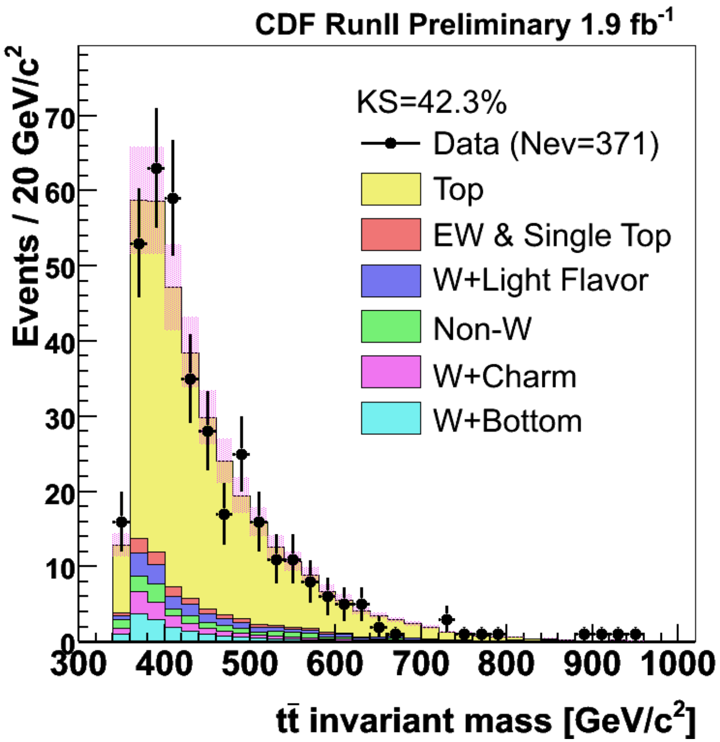
CDF, Phys.Rev.Lett.85 (2000), arXiv:0710.5335v1

W'→ tb search @ D0:

Phys.Rev.Lett.100 (2008) 21180

Few tt events at large invariant mass (CDF totals 347 evts. In 1 fb^{-1}).

Heaviest observed tt pair: ~950 GeV

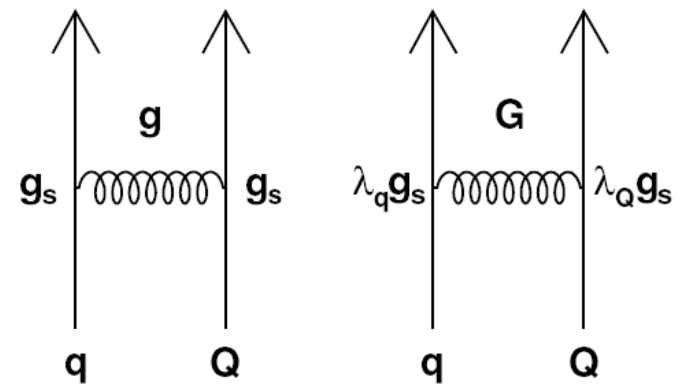


Tevatron

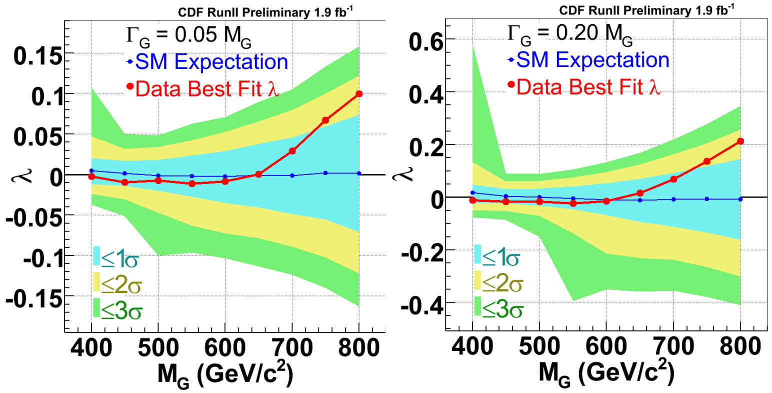
No significant deviations from the Standard Model predictions observed

At the Tevatron experimental upper limits were 84 set at 95%C.L. for the $\sigma(p\bar{p}\rightarrow Z')\times BR(Z'\rightarrow t\bar{t})$ and Z' masses above 450 GeV and below 900 GeV. A topcolor leptophobic Z' is ruled out below 720 GeV and the cross section of any narrow Z' decaying to a $t\bar{t}$ is less than 0.64 pb at 95%C.L., for Z' masses above 700 GeV (ATLAS CSC book)

Exclusion limits are primarily limited by the Tevatron center-of-mass energy



CDF note 9164: massive gluon search in 1.9 fb^{-1}: data compatible with SM within 1.7 σ



The standard approach:

Thorougly exercised on full simulation since 2006 (ATL-PHYS-PUB-2006-033). Well-known strengths and weaknesses.
Intended primarily for early physics (relatively light resonances)

Concentrate on semi-leptonic events (e, μ)

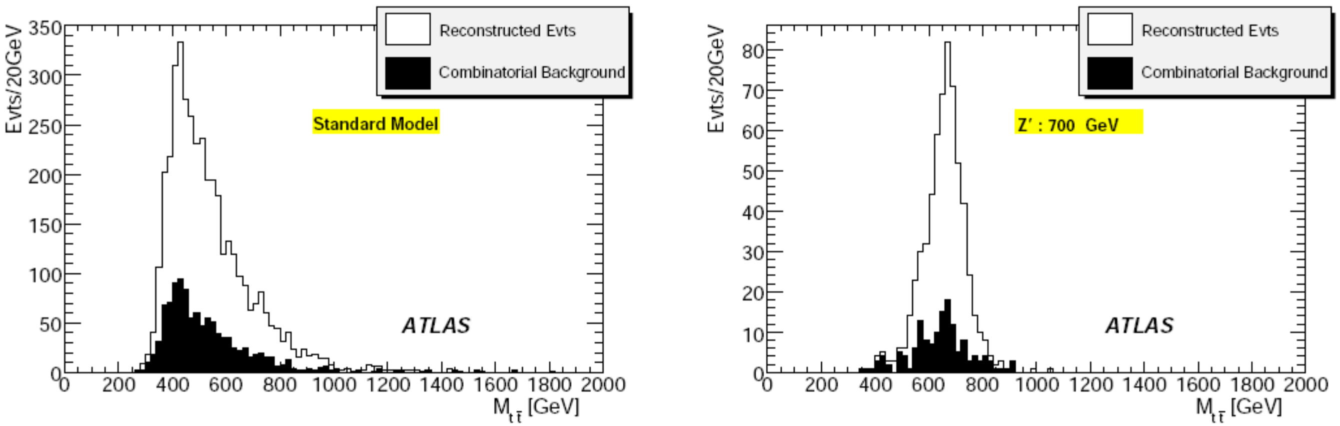
Standard event selection:

- 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
- $E_t^{miss} > 20$ GeV

After this, it's between us and the Standard Model tt background

NB: Different approaches may yield interesting results: a group of people in ATLAS (H. Gray, B. Heineman, E. Hughes, A. Korn, M. Scherzer) has explored an **alternative for very early tt resonance searches using the di-lepton channel**
Results are not publicly available yet ⇒ concentrate on the semi-leptonic analyses

ATLAS tt resonance searches

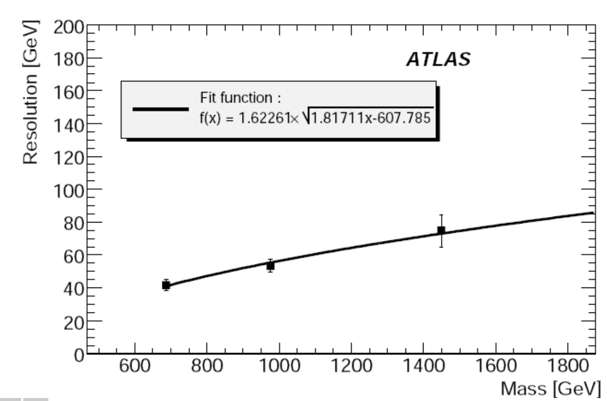


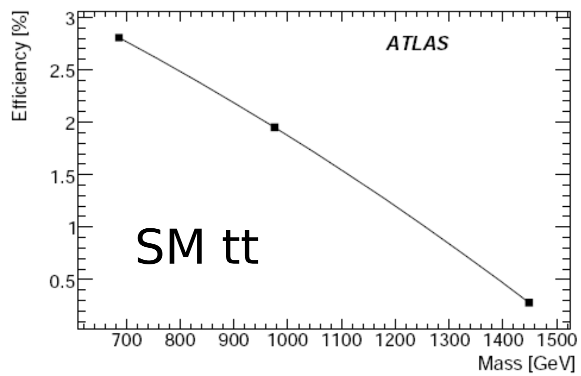
Hadronic W ⇒ the jet combination with the smallest DR separation
Hadronic top ⇒ add the nearest b-jet
Leptonic W ⇒ use W-mass constraint and lepton momentum and E_T^{miss} measurement constraint to solve for p_z^{ν}. (two solutions)

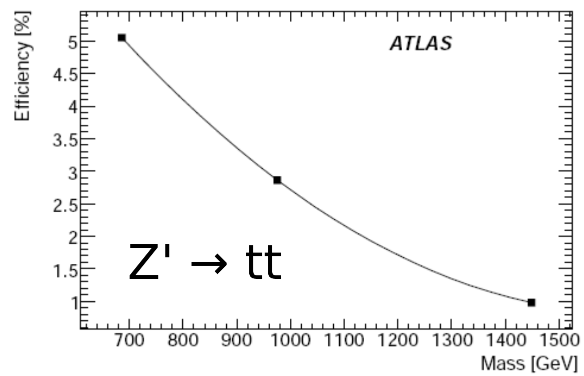
Leptonic top ⇒ Combine with remaining b-jet. Choose the neutrino solution that gives the leptonic top mass closest to the average mass of the hadronic top.

Fancier approaches (like the kinematic fit used by D0, or the matrix element based method of CDF) remain to be explored

ATLAS tt resonance searches







Resonance mass resolution increases from ~40 GeV to slightly less than 80 GeV over mass range from 700 to 1500 GeV.

A sharp efficiency drop towards larger resonance mass (known since long. Confirmed by recent studies by Pallin/Cogneras and Lessard/Lefebvre):

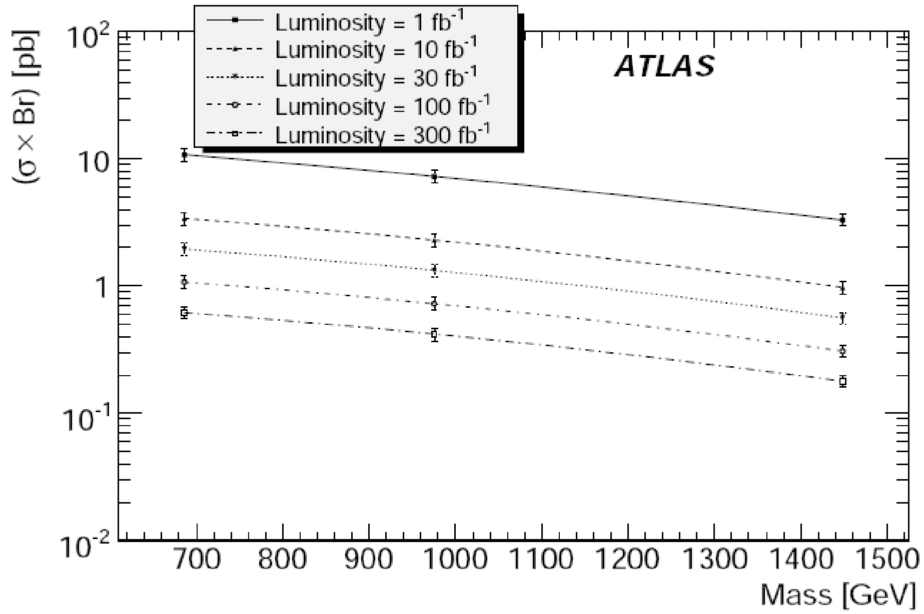
5 % @ 700 GeV

< 1 % @ 1500 GeV

A detailed analysis reveals that (a) several selection criteria lead to increasing inefficiency as the resonance mass is raised (electron trigger (e25i), muon isolation, jet selection) and (b) for many events at large resonance mass there is no one-to-one matching of partons to jets (several partons point to the same jet)

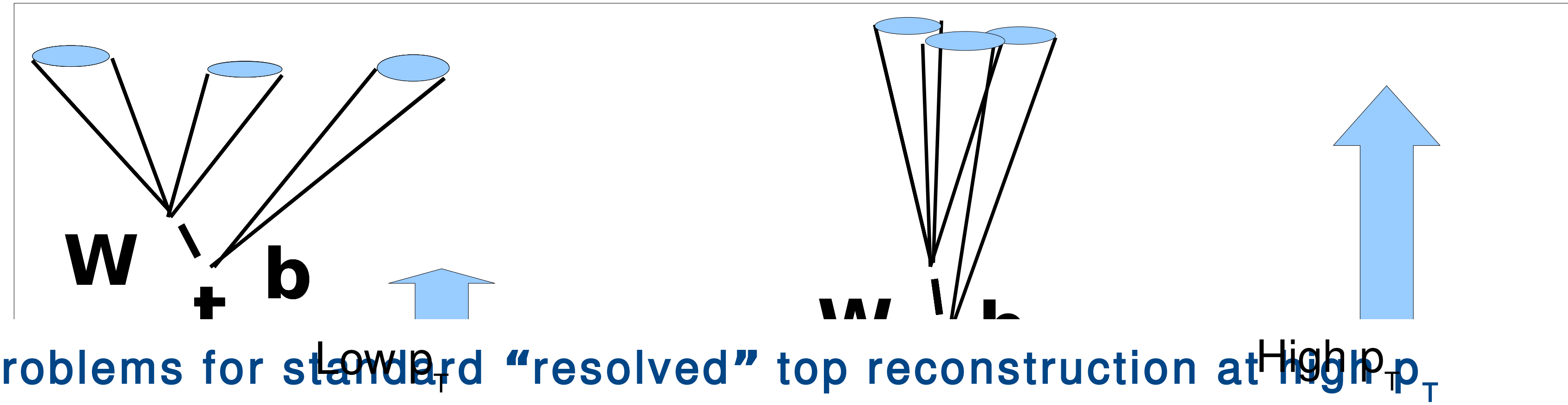
ATLAS tt resonances searches

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



Is this sensitivity sufficient to discover typical narrow resonances or rule out those models?
Where can we gain? Mass resolution, efficiency?

Reconstruction of high p_T tops

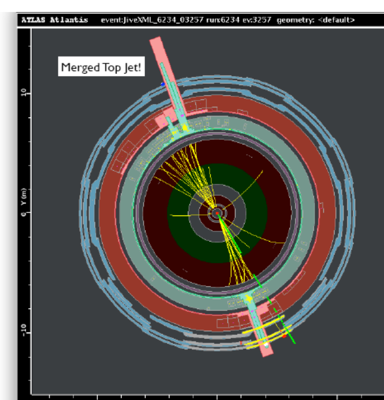


Problems for standard "resolved" top reconstruction at high p_T

- 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)

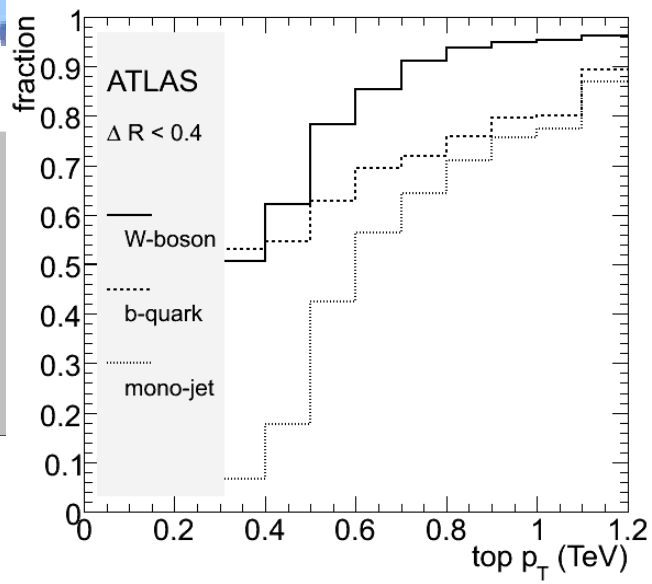
jets from hadronically decaying top are not resolved by jet reconstruction algorithms

In a nut shell: do not attemp to resolve the hadronic decay of the W and the corresponding b-quark.
Just tag the "blob" as stemming from a top quark.
(just want to measure the three-momentum of the top quark to get to the resonance mass)



The alternative?

(Hadronic) Top mono-jet : probability that a single reconstructed jet contains both quarks from W and the corresponding b-quark (within $\Delta R < 0.4$)
ATL-PHYS-CONF-2008-016



But: low-multiplicity backgrounds that are negligible in resolved approach (i.e. di-jet events) can become dangerous. Need to identify (tag) these top (mono-) jets!

Many authors have discussed this issue in the last few years:
K. Agashe et al.,LHC Signals from Warped Extra Dimensions, Phys. Rev. D77) 2008) 015003, hep-ph/0612015
Randall, Lillie and Wang, The Bulk RS KK-gluon at the LHC, JHEP 0709:074 (2007)
Kaplan et al., Top-tagging: a method for identifying boosted hadronic tops, arXiv:0806.0848

The high p_T alternative

G. Brooijmans, High p_T Hadronic Top Quark Identification Part 1 : **Jet Mass and Ysplitter**

ATL-PHYS-CONF-2008-008; ATL-COM-PHYS-2008-001

(see talk by G. Brooijmans in this workshop)

M. Vos, High p_T Hadronic Top Quark Identification Part 1 : **the life-time signature**

ATL-PHYS-CONF-2008-016 ;ATL-COM-PHYS-2008-050

ATLAS NOTE

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High p^T Hadronic Top Quark Identification
Part I: Jet Mass and YSplitter

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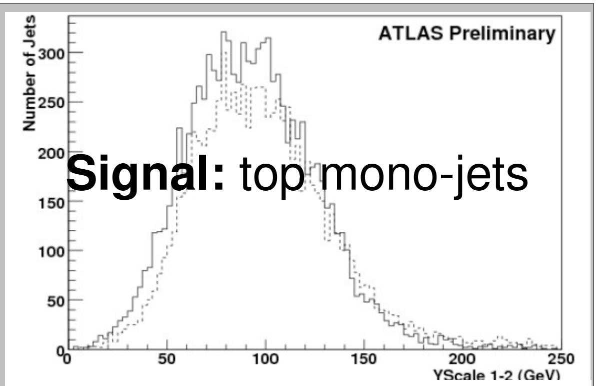
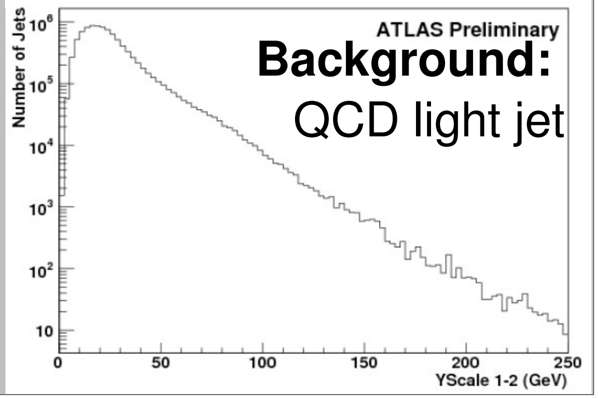
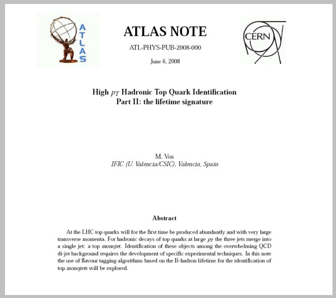
Abstract

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 decay hadronically, producing a set of collimated jets. This interesting new experimental phenomenology requires the development and tuning of new tools, since the usual reconstruction methods would simply reconstruct a single jet. This note describes the application of the YSplitter algorithm in conjunction with the jet mass to identify high transverse momentum top quarks decaying hadronically.







ATLAS NOTE

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

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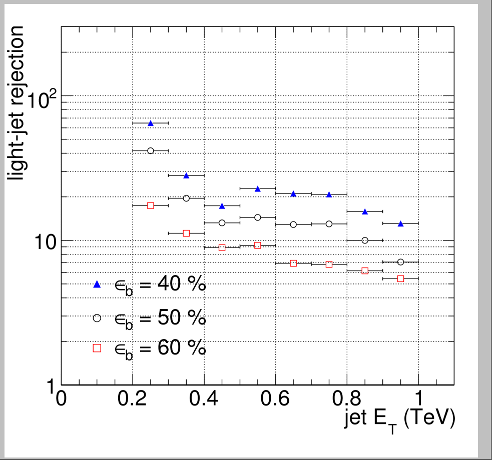
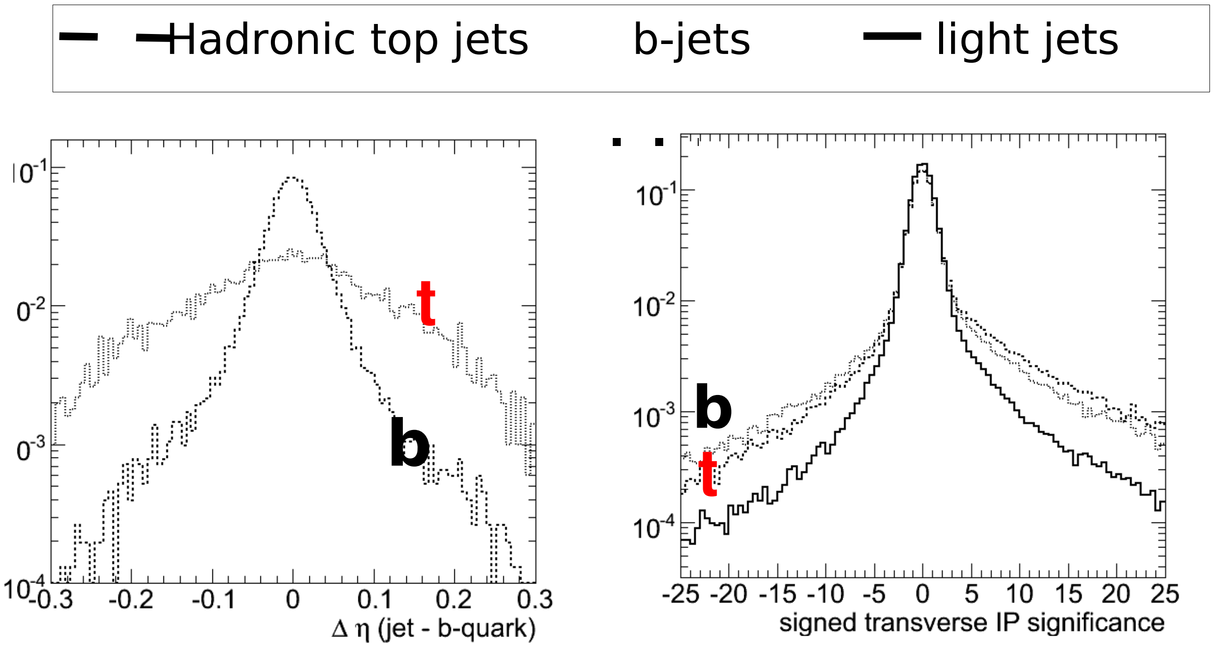
Abstract

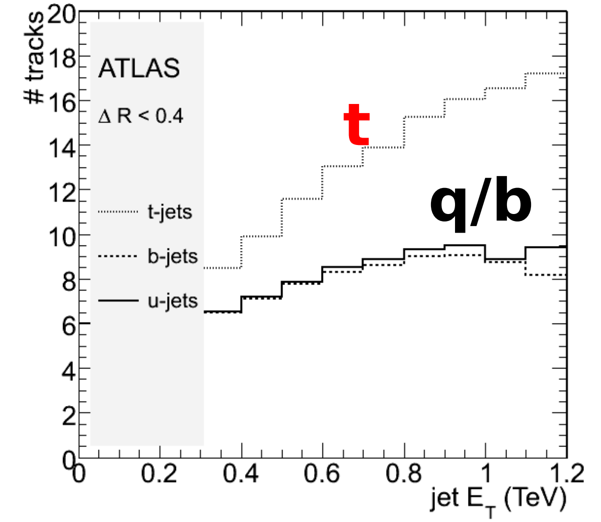
At the LHC top quarks will for the first time be produced abundantly and with very large transverse momenta. For hadronic decays of top quarks at large p_T the three jets merge into a single jet: a top *monojet*. Identification of these objects among the overwhelming QCD di-jet background requires the development of specific experimental techniques. In this note the use of flavour tagging algorithms based on the B-hadron lifetime for the identification of top *monojets* will be explored.



The lifetime signature

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

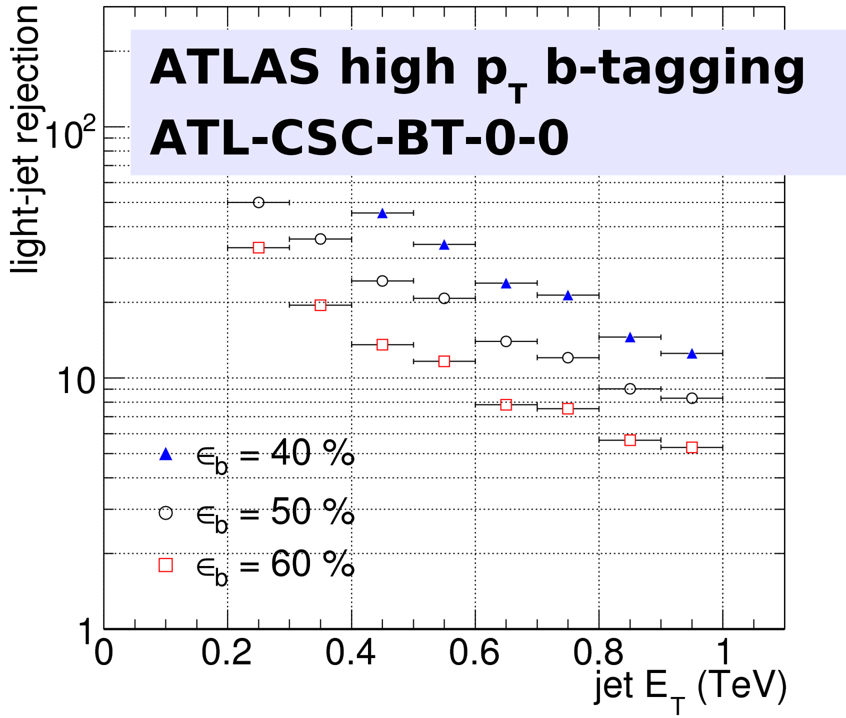


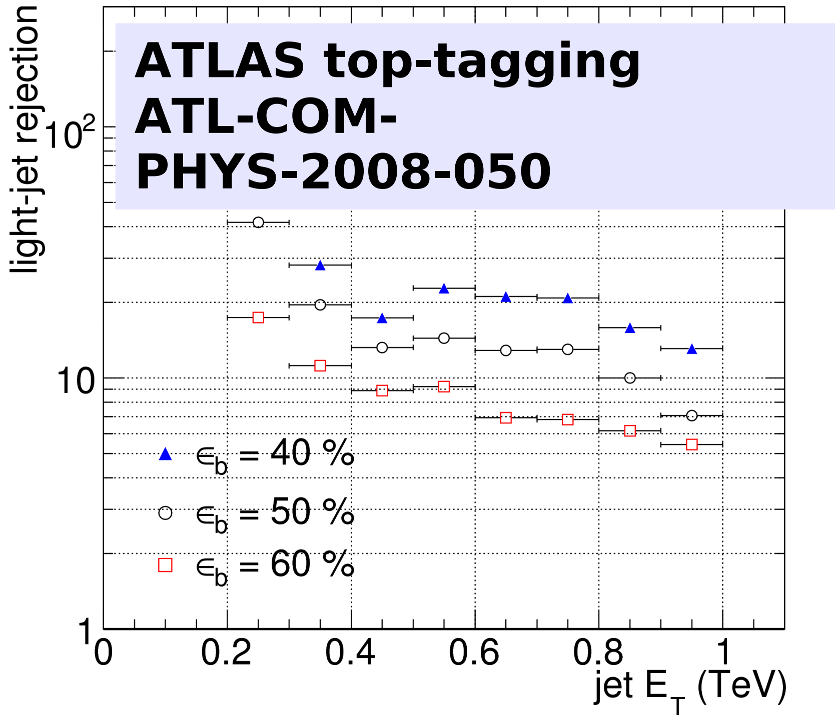


What about top-jets. Does the "noise" from close-by W-decay affect the tagging performance?

- 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

The lifetime signature

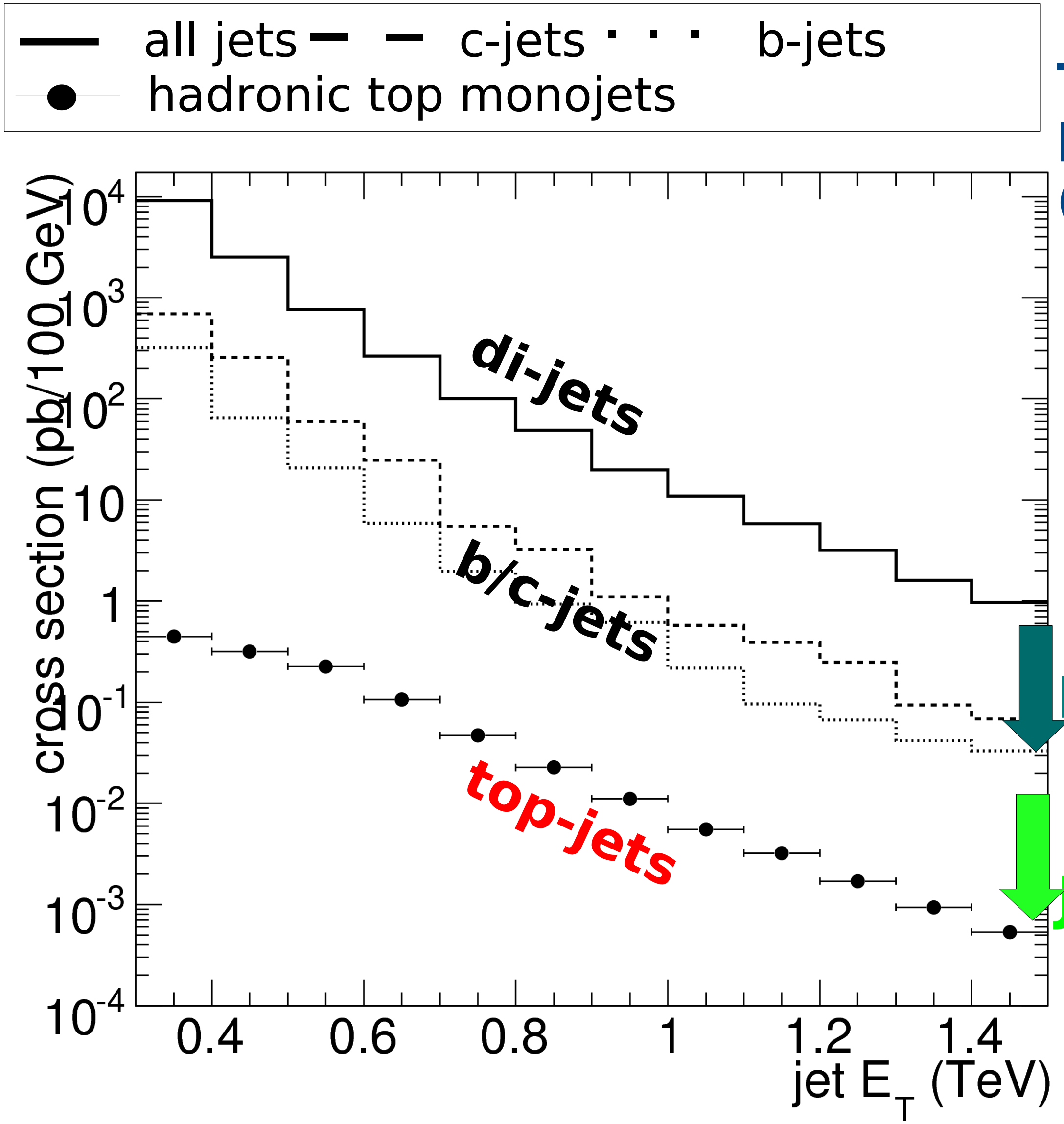




High p_T b-tagging can yield significant rejection of light jets

The performance of high p_T "top-tagging" is further degraded by "noise" from superposed W (distorts jet direction, dilutes lifetime signature)

The alternative



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

Lifetime signature

Jet substructure

ATLAS tt resonance searches - conclusions

Events with top quarks are **the most dangerous background** for many BSM physics searches **and one of the most exciting places to look for signal**. Explore exotic corners of tt phase space (large tt invariant mass, top p_T, E_t^{miss}, multiplicity, sum of jet E_T)

Rare decays: improve existing limits significantly

tt resonance searches:

High p_T top ≠ Low p_T top.

Standard “resolved” approach deemed adequate for early searches of relatively light resonances,

Several handles to distinguish high p_T top jets (up to several TeV) have been developed

Reconstruction efficiency and resonance mass resolution must be improved over full mass range: bridge the gap between the two p_T ranges.