Searches for new physics using heavy flavour in ATLAS

Marcel Vos (IFIC Valencia), for the ATLAS collaboration

Working Group on the Interplay between Collider and Flavour Physics

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ATLAS flavour tagging
Some signatures of new physics with heavy flavour
An “early” analysis
Tools for exotic signatures

Heavy flavour?

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

An experimentalist's view: 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

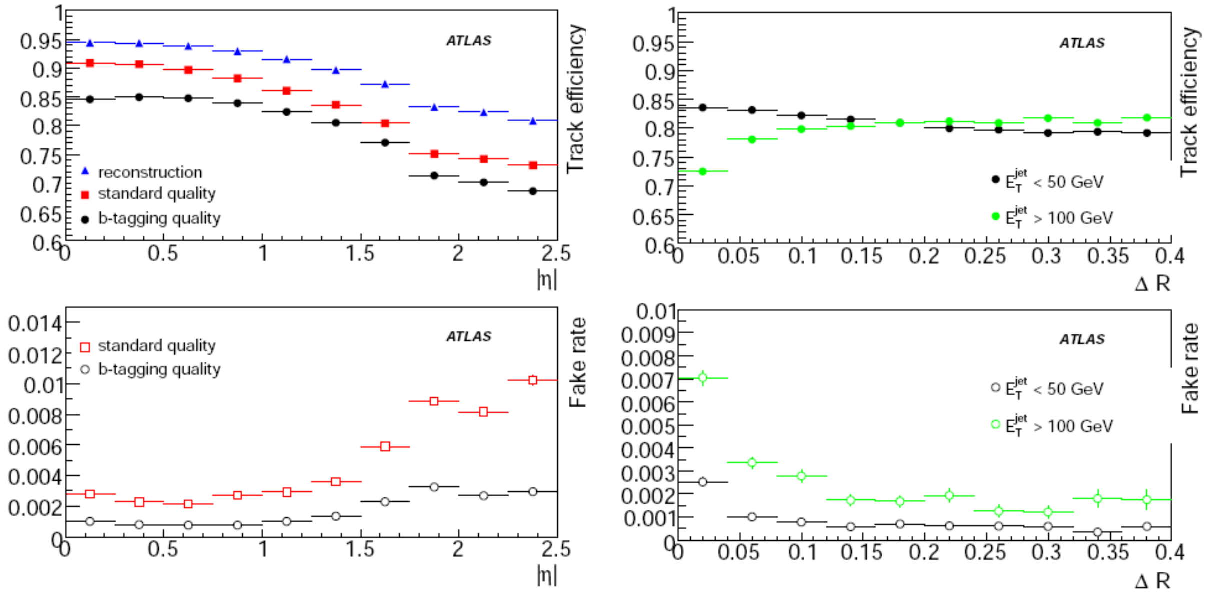
Each fermion has it's own unique (dis) advantages.

All quarks both benefit AND suffer from strong coupling. Large production cross-section for new physics, but an even larger Standard Model background

Bottom and top quarks can be identified efficiently
Top is the only quark that produces isolated leptons.

When I say "new physics with heavy flavour", read "new physics coupling to bottom and top quarks".

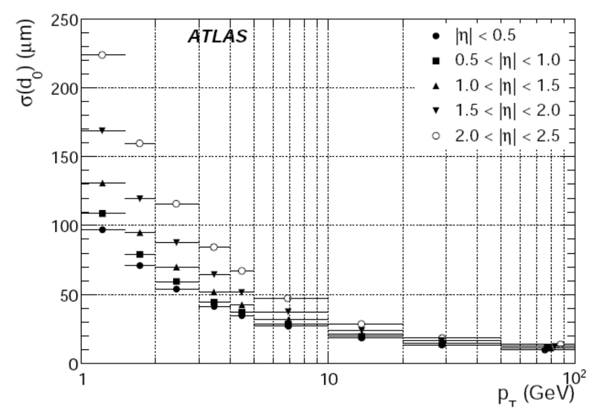
ATLAS flavour tagging



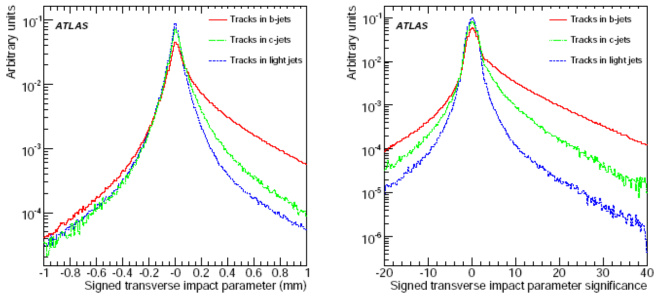
Efficient and clean tracking even inside moderate p_T jets

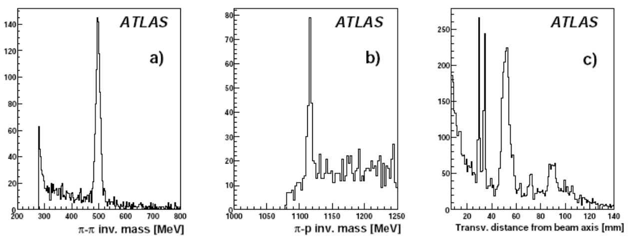
Over the last decade the ATLAS collaboration developed a set of sophisticated tools: tracking. For a complete (1800 pages) overview: Expected performance of the ATLAS experiment, CERN-OPEN-2008-020

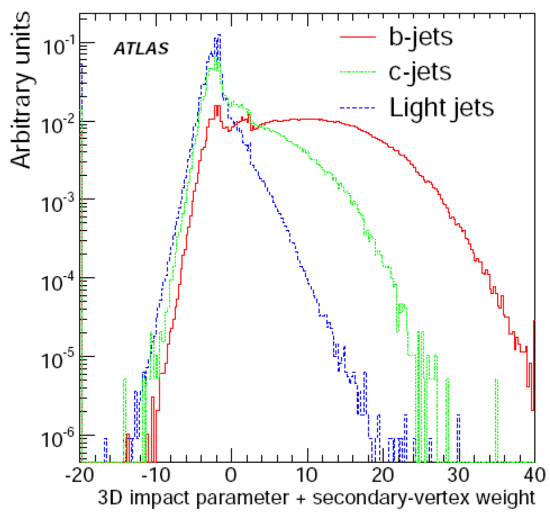
Precise determination of impact parameter



ATLAS flavour tagging







Selection:

good (low fake rate) tracks

reliable (precise IP) tracks

Assign category: shared hits

Clean: remove V0s

Calculate impact parameter significance

significance = d_0/σ

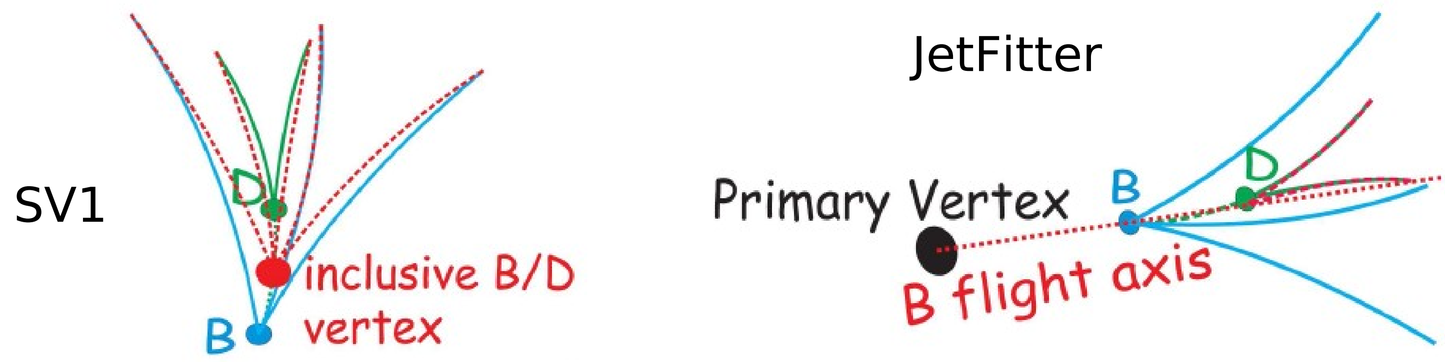
Determine likelihood

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

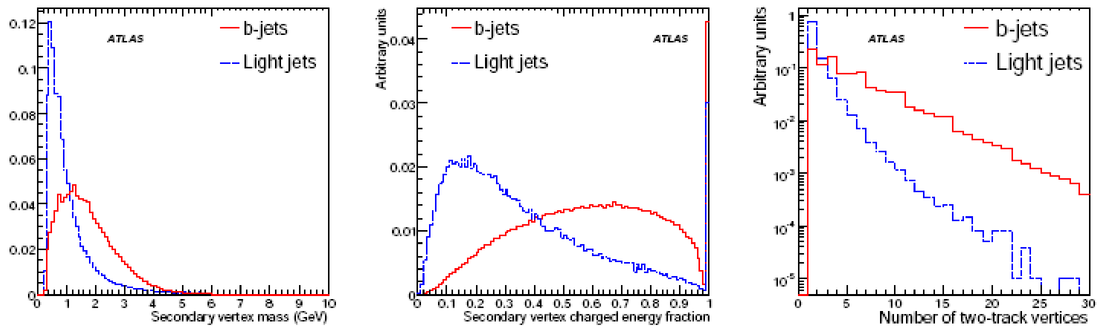
Construct jet likelihood

Sum 3D impact parameter log(likelihood) of all (good) tracks in the jet

ATLAS flavour tagging: SV



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



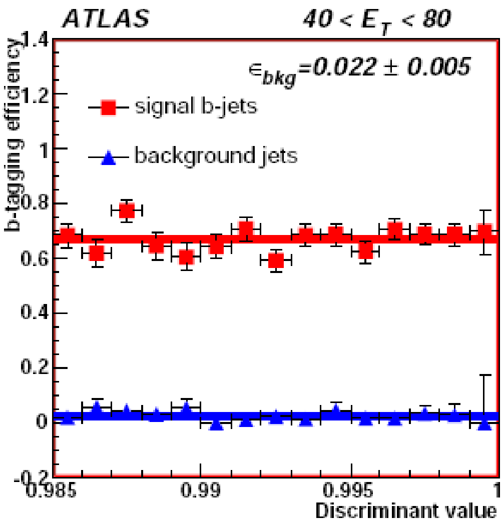
	JetProb	IP2D	IP3D	IP3D+SV1	IP3D + JetFitter
E_b = 50 %	83 ± 1	116 ± 2	190 ± 3	458 ± 13	555 ± 17
E_b = 60 %	30 ± 0	42 ± 0	59 ± 1	117 ± 2	134 ± 2

Light jet rejection ($R_u = 1/\varepsilon_u$) for two values of the b-tag efficiency
five life-time based algorithms, in order of increasing "sophistication"

ATLAS start-up

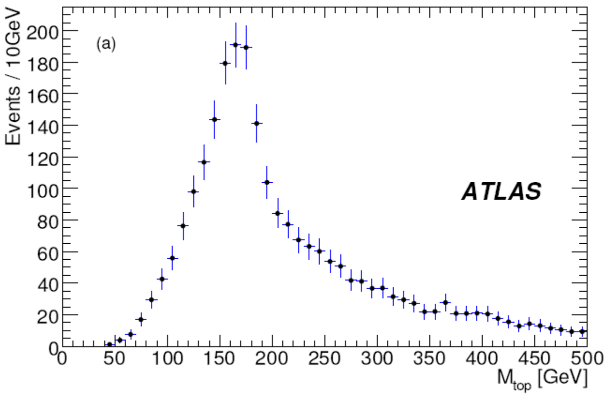
Start-up:

- understand tracking (material, alignment, errors)
- understand impact of alignment, detector imperfections, MC
- back to basic: simple taggers that require little calibration (track counting, rather than likelihoods, BDT and NN)
- measure (and optimize) performance on data
  counting method (5% for 100 pb^{-1}, global)
  select b-jet sample in tt (10% for 100 pb^{-1}, p_T, η dependence)



Top cross-section analysis without b-tagging!

Mass distribution of 3-jet top-candidates in a sample of 100 pb^{-1} (selection aimed at semi-leptonic events)



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:

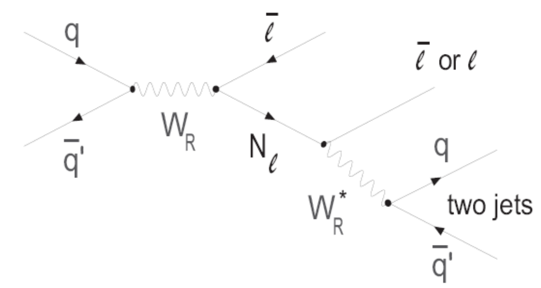
SM tt is the dominant background for LRSM important also for lepto-quarks

Vector-boson scattering:

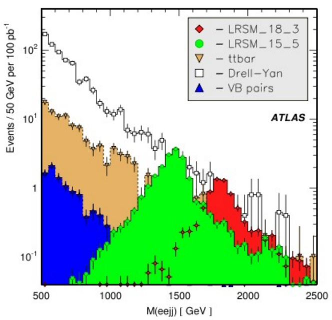
SM tt and tW events are an important background

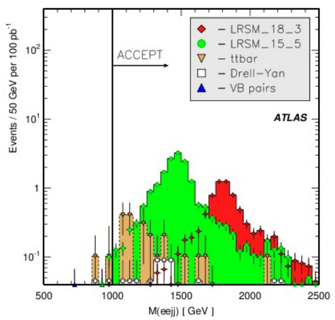
Black holes:

SM tt among important backgrounds



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

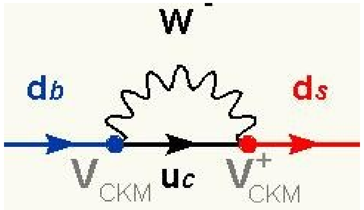




Event selection reduces SM tt sample to a tiny fraction with extraordinary properties (Etmiss, #jets, p_T of final state objects)

Searches for rare top decays

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



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} 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
$t \to uZ$	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?

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

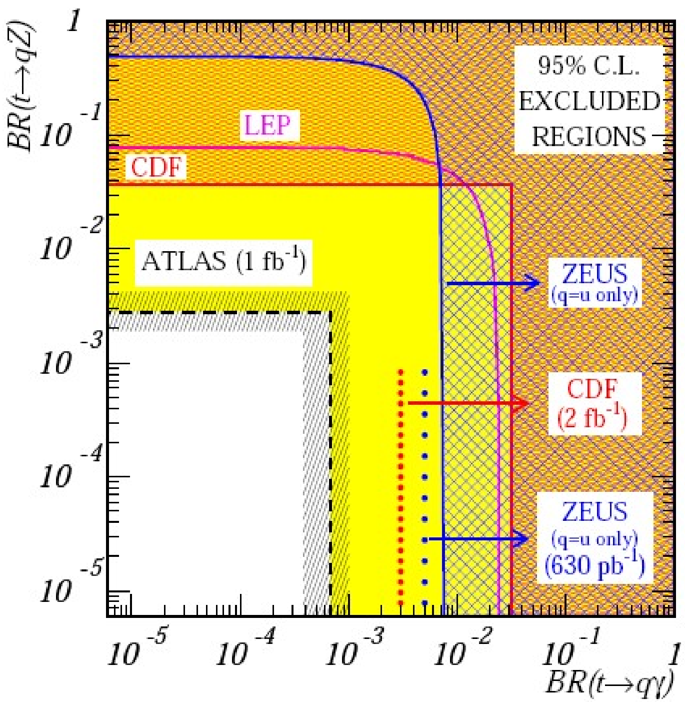
	LEP	HERA	Tevatron
BR ($t \to qZ$)	7.8%	49%	3.7%
BR ($t \to q\gamma$)	2.4%	0.75%	3.2%
BR ($t \to qg$)	17.0%	13%	0.1-1%

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

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

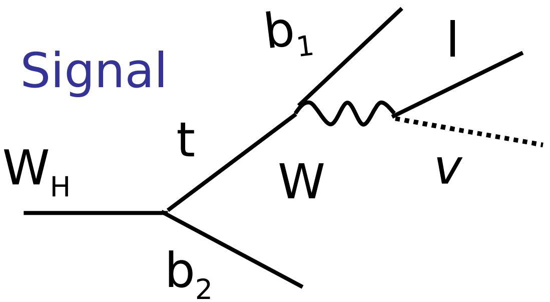


	-1s	Expected	1σ
tt → bWqγ			
e	4.3 x 10^{-3}	1.1 x 10^{-3}	1.9 x 10^{-3}
m	4.5 x 10^{-4}	8.3 x 10^{-4}	1.3 x 10^{-3}
l	3.8 x 10^{-4}	6.8 x 10^{-4}	1.0 x 10^{-3}
tt → bWqg			
e	1.3 x 10^{-2}	2.1 x 10^{-2}	3.0 x 10^{-2}
m	1.0 x 10^{-2}	1.7 x 10^{-2}	2.4 x 10^{-2}
l	7.2 x 10^{-3}	1.2 x 10^{-2}	1.8 x 10^{-2}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

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

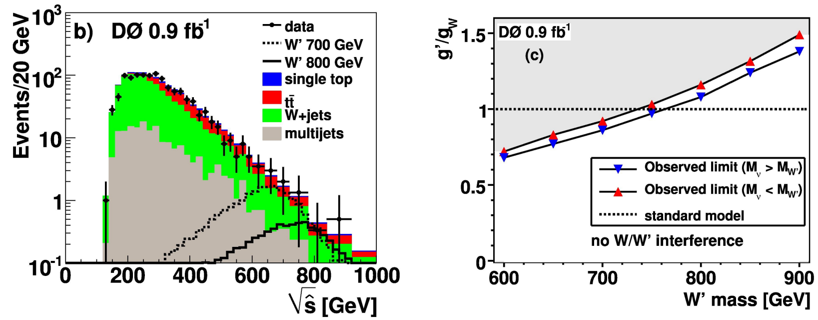
Signal



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

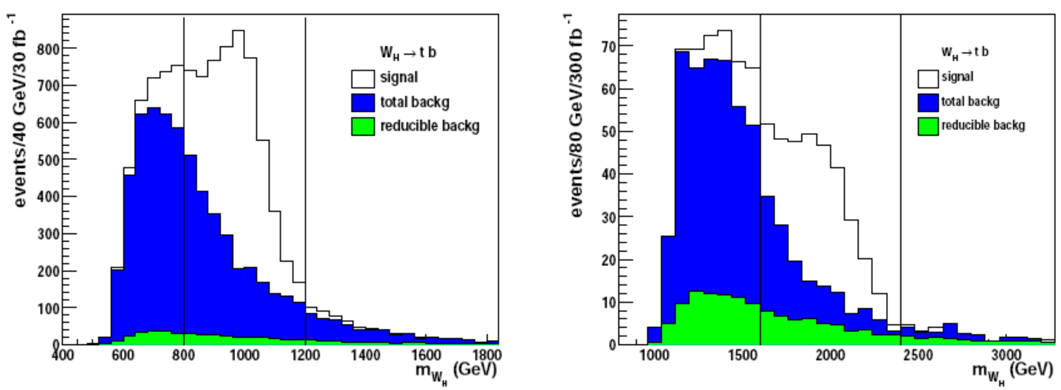


ATLAS fast simulation
Littlest Higgs $W_H \to tb$

discovery up to 2.5 TeV

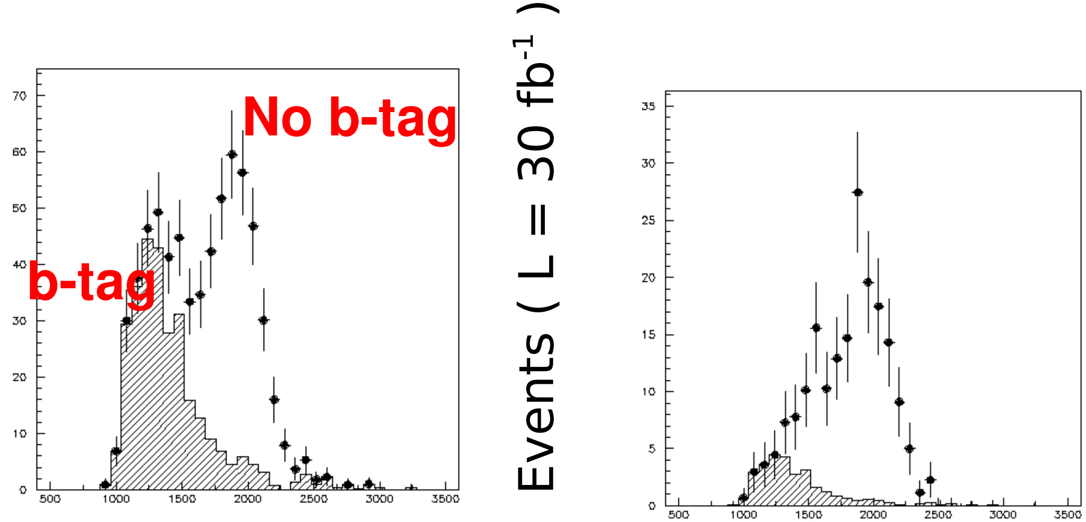
(cot θ = 1, PHYS-PUB-2006-003)

ZH -> tt and ZH -> bb more difficult

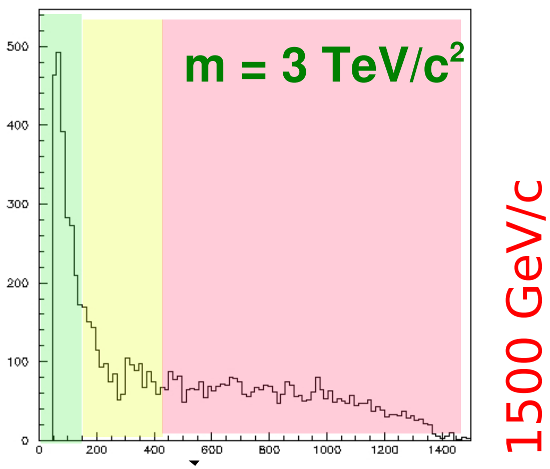


Full simulation study within more challenging LR Twin Higgs model (PHYS-PUB-2008-004)

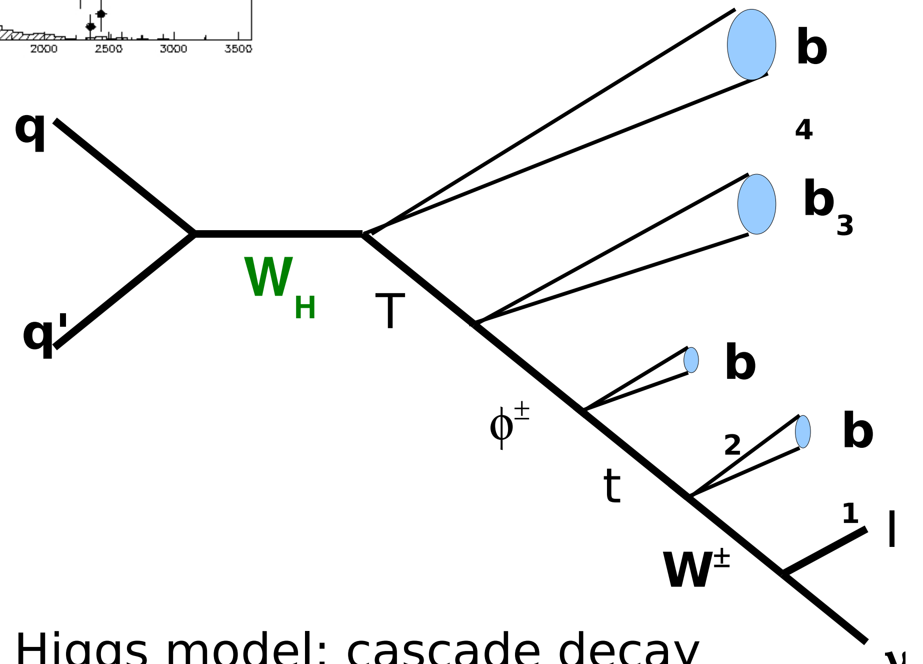
Now, for something a bit more complex: tbbb



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



P_T spectrum of b-jets



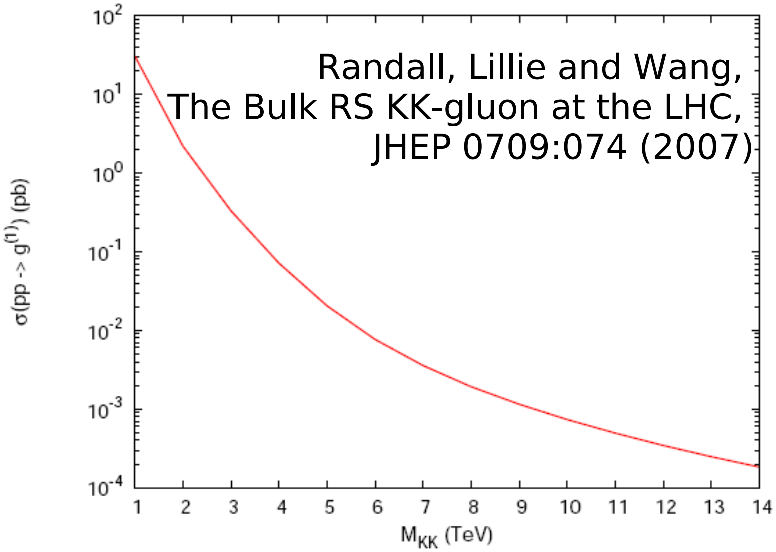
LR Twin Higgs model: cascade decay

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

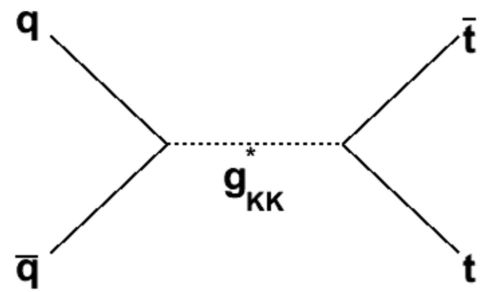
And more spectacular

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 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...

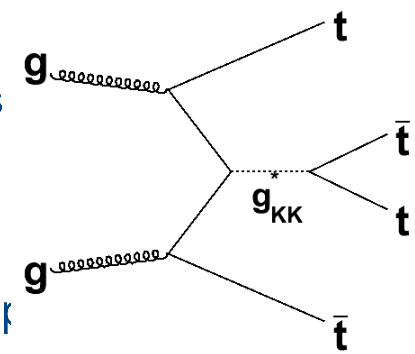
The other gauge bosons are not considered

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

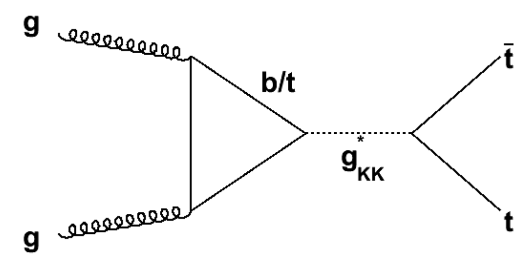
Many possible choices for parameters

Four tops!

(see also: top compositeness,
Lillie, Shu, Tait; Kumar, Tait, Vega-Morales; Javi Serra, this workshop



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	-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)

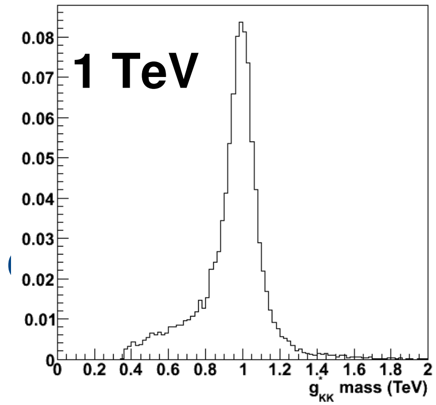
A^b_{FB} inspired: A. Djouadi, G. Moreau, and R.K. Singh, Nucl. Phys. B 797 (2008)

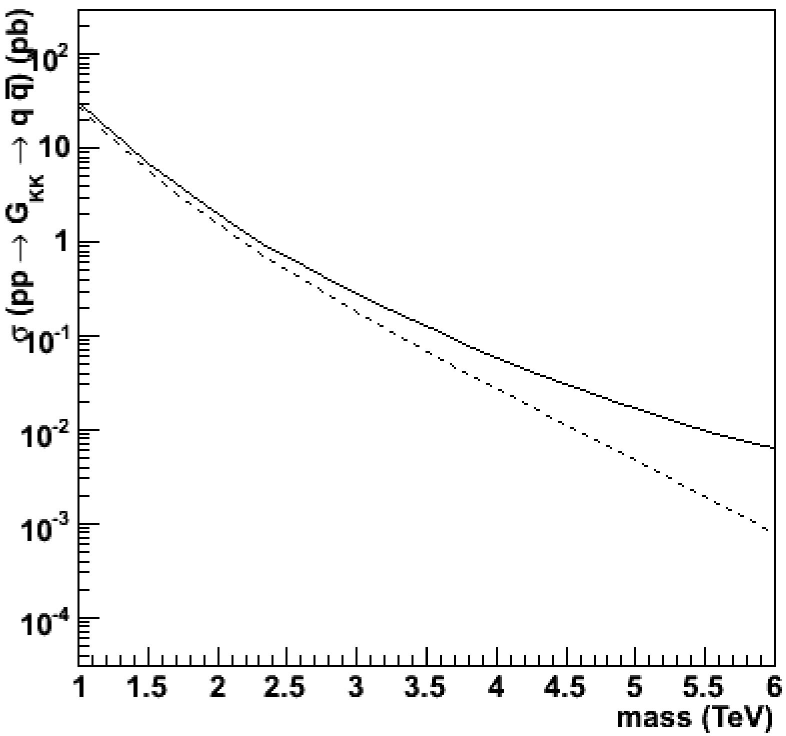
Generate some events

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

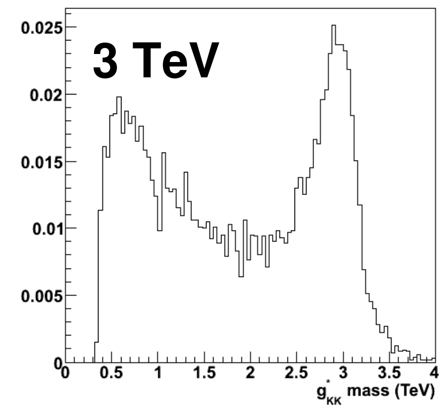
Full Matrix Element calculation of pp → g* → tt → bb lν

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

– – · within nominal mass ± 30 %

Tevatron searches

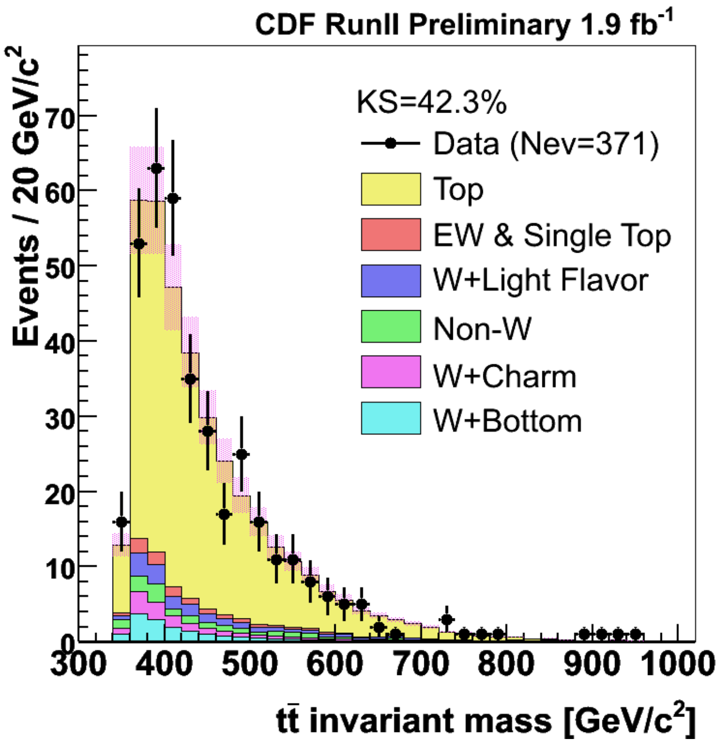
Important program at the Tevatron ~ 20 papers since 2000.

(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

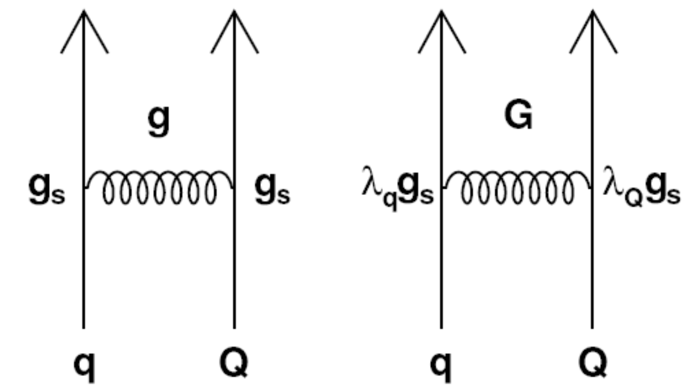


Tevatron

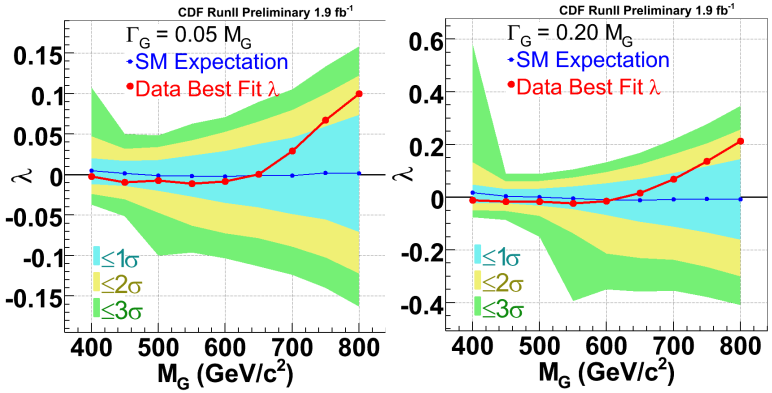
No significant deviations from the Standard Model predictions observed

At the Tevatron experimental upper limits were 84 set at 95%C.L. for the $\sigma(p\bar{p}\to Z')\times BR(Z'\to t\bar{t})$ 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)

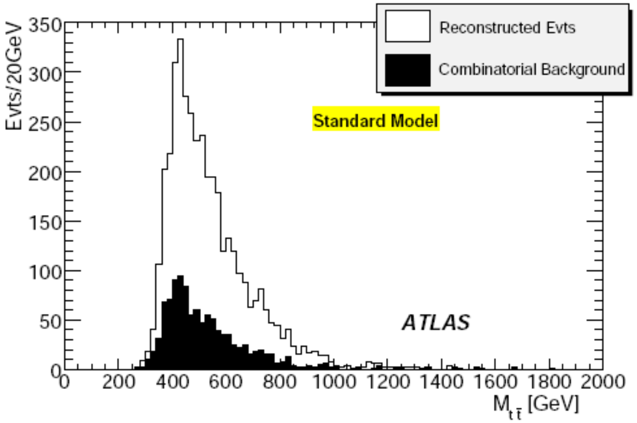
Standard event selection:

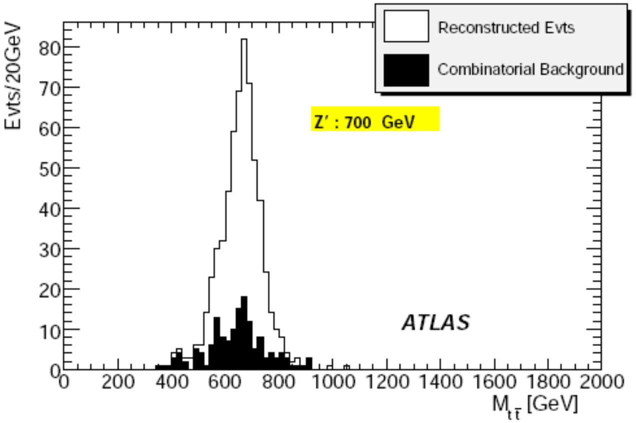
- exactly one isolated electron (muon),
- $|\eta| < 2.5$ and $p_T > 25$ GeV ($p_T > 20$ GeV)
- at least four jets with $|\eta| < 2.5$ and $p_T > 30$ GeV
- at least 2 jets tagged as b-jets
- $E_t^{miss} > 20$ GeV

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

NB: Different approaches may yield interesting results: ATLAS has recently explored an **alternative for very early tt resonance searches using the di-lepton channel**
Results are not publicly available yet $\Rightarrow$ concentrate on the semi-leptonic analyses

ATLAS tt resonance searches



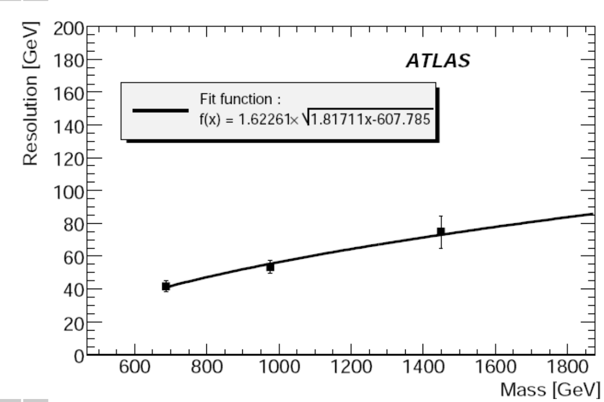


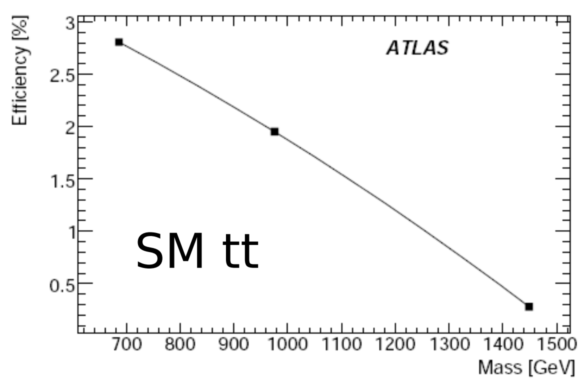
Hadronic W ⇒ the jet combination with the smallest DR separation
Hadronic top ⇒ add the nearest b-jet
Leptonic W ⇒ use W-mass constraint and lepton momentum and E_T^{miss} measurement constraint to solve for p_z^{ν}. (two solutions)

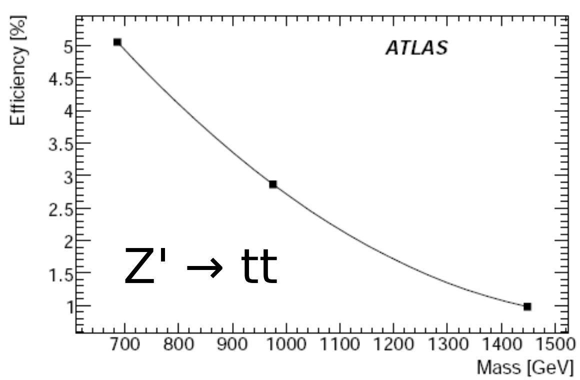
Leptonic top ⇒ Combine with remaining b-jet. Choose the neutrino solution that gives the leptonic top mass closest to the average mass of the hadronic top.

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):

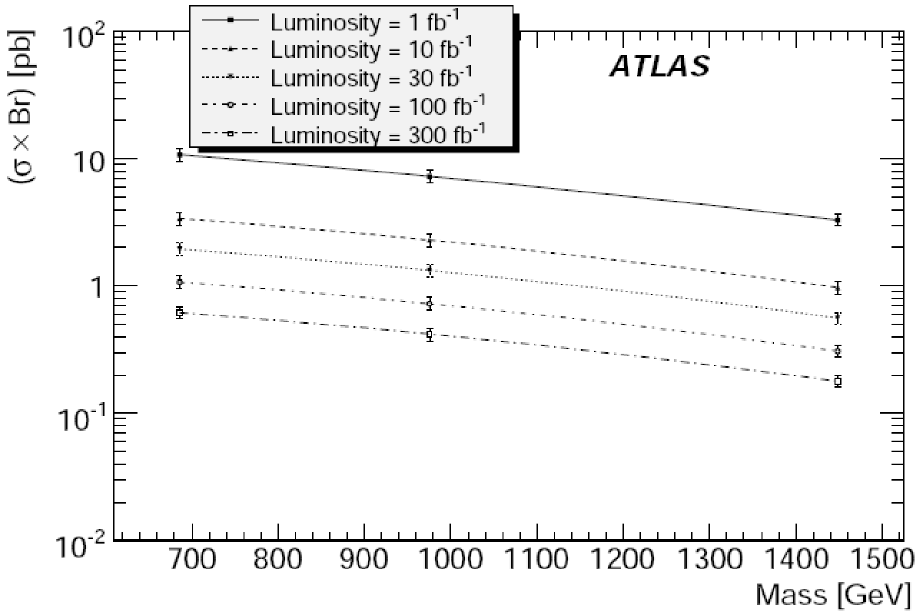
5 % @ 700 GeV

< 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)

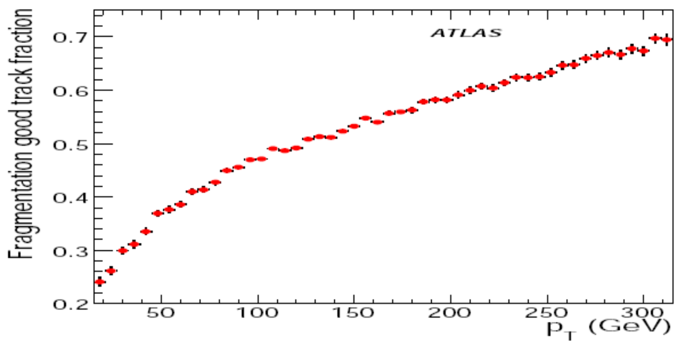
ATLAS tt resonances searches

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



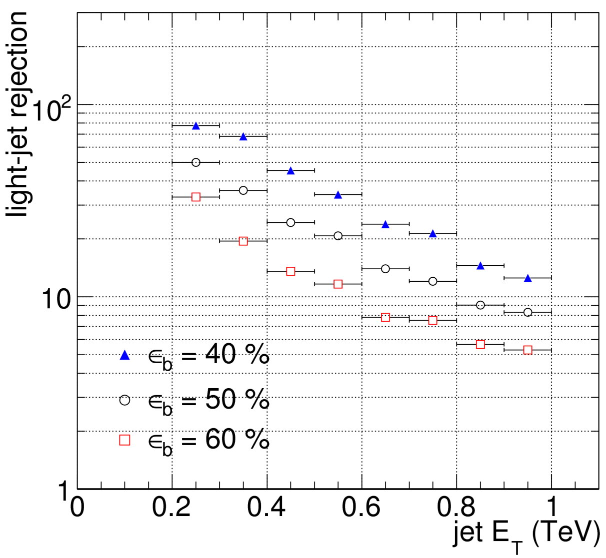
Is this sensitivity sufficient to discover typical narrow resonances or rule out those models?
Where can we gain? Mass resolution, efficiency?

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)

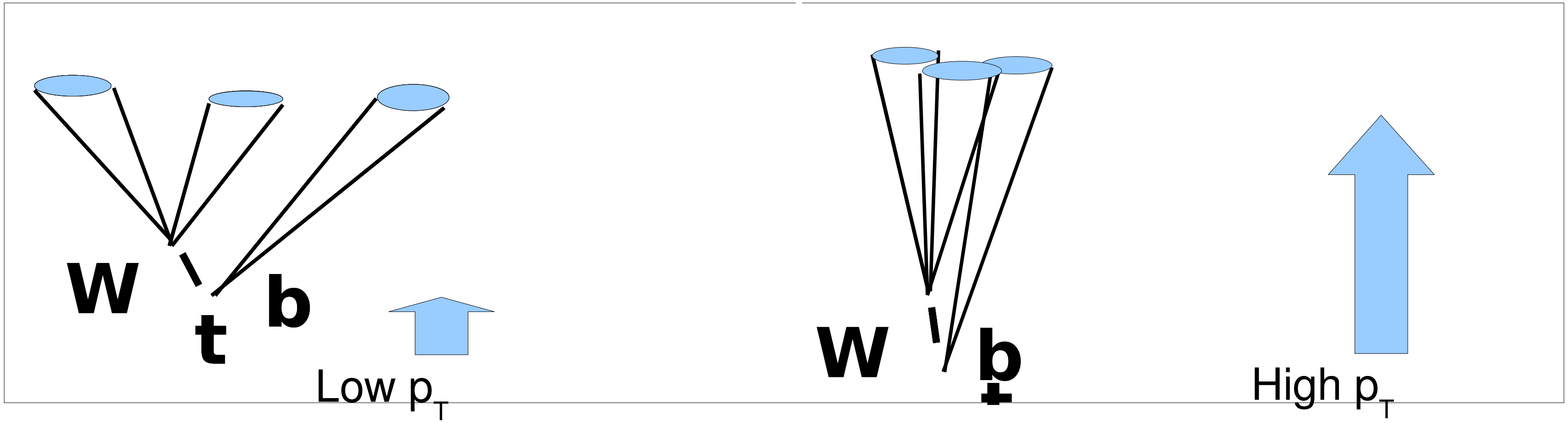


	R_B > 2.9 (%)	R_B > 5.1 (%)
E_T > 100 GeV	12.2	3.9
E_T > 200 GeV	21.1	7.9

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

Flavour tagging performance suffers

Reconstruction of high p_T tops

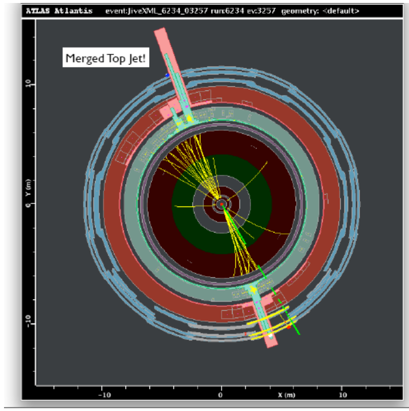


Problems for standard "resolved" top reconstruction at high p_T

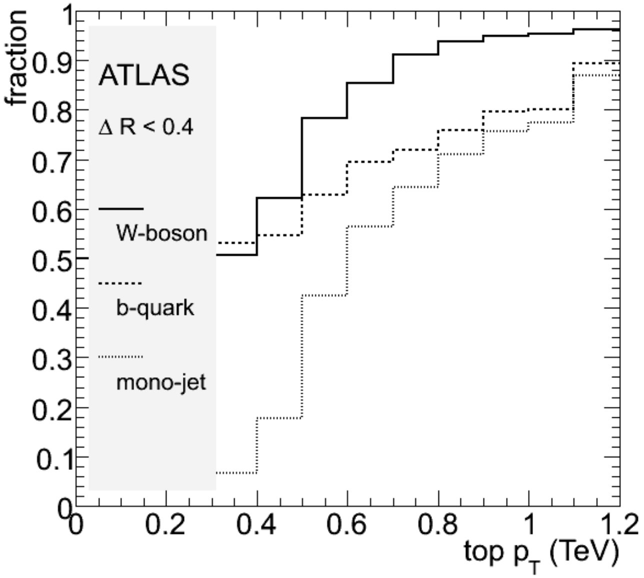
- isolation of leptons (trigger)
- E_T^{miss} resolution in events with TeV jets
- tracking performance in jets (b-tagging)
- control samples (jet calibration, b-tag)

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

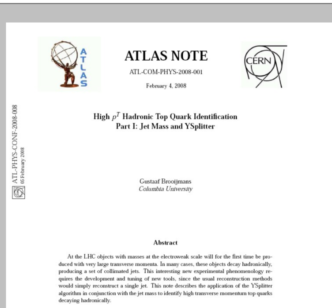
The high p_T alternative

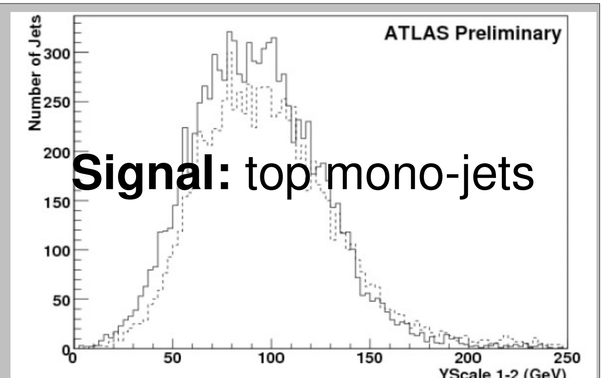
G. Brooijmans, High p_T Hadronic Top Quark Identification Part 1 : **Jet Mass and Ysplitter**

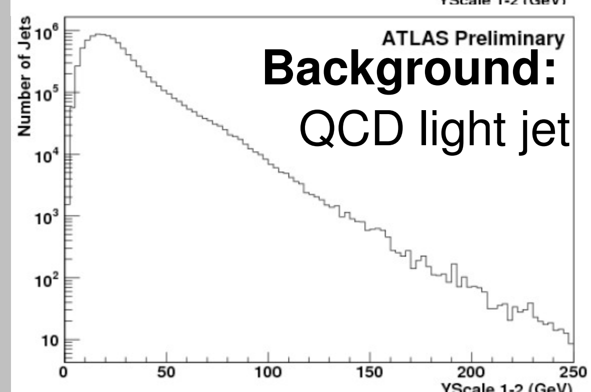
ATL-PHYS-CONF-2008-008; ATL-COM-PHYS-2008-001

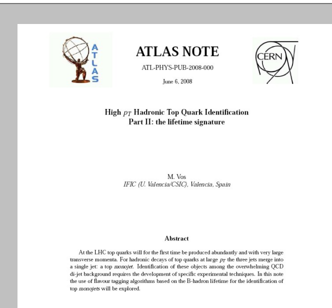
M. Vos, High p_T Hadronic Top Quark Identification Part 1 : **the life-time signature**

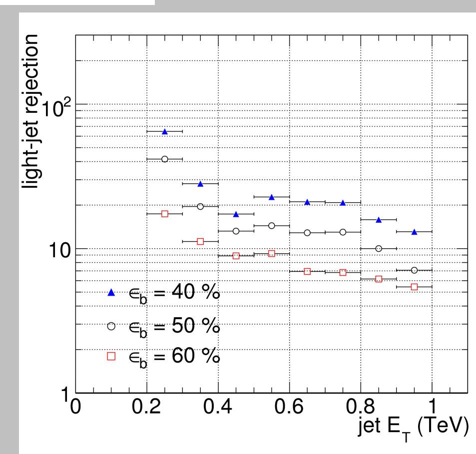
ATL-PHYS-CONF-2008-016 ;ATL-COM-PHYS-2008-050





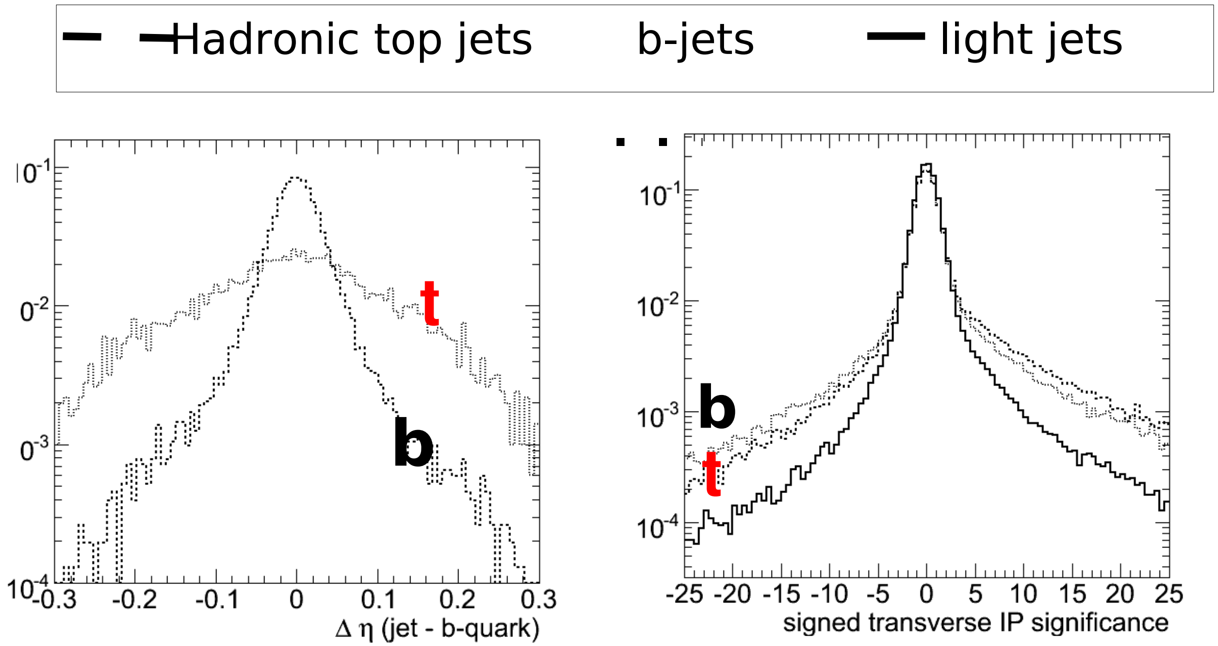






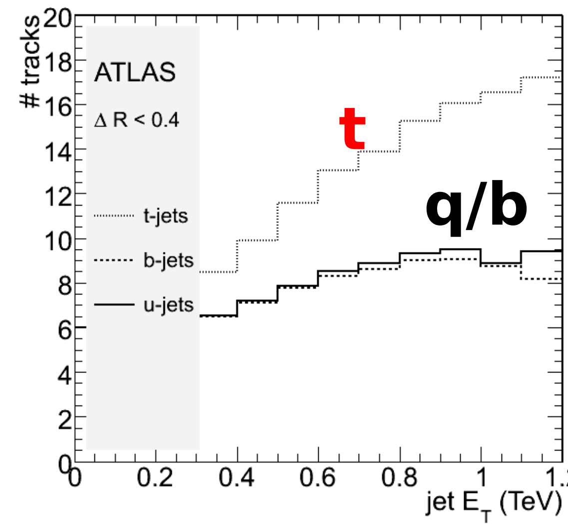
The lifetime signature

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

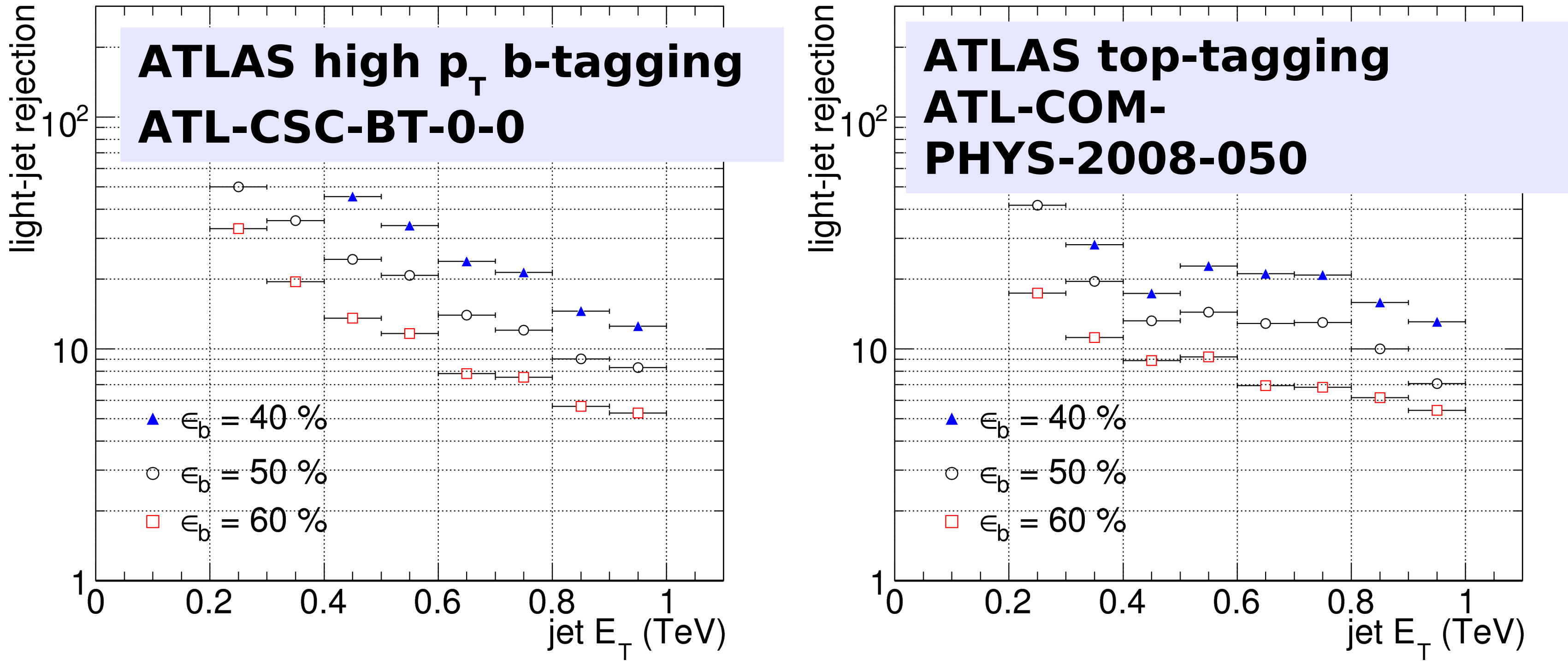


What about top-jets. Does the "noise" from close-by W-decay affect the tagging performance?

- 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



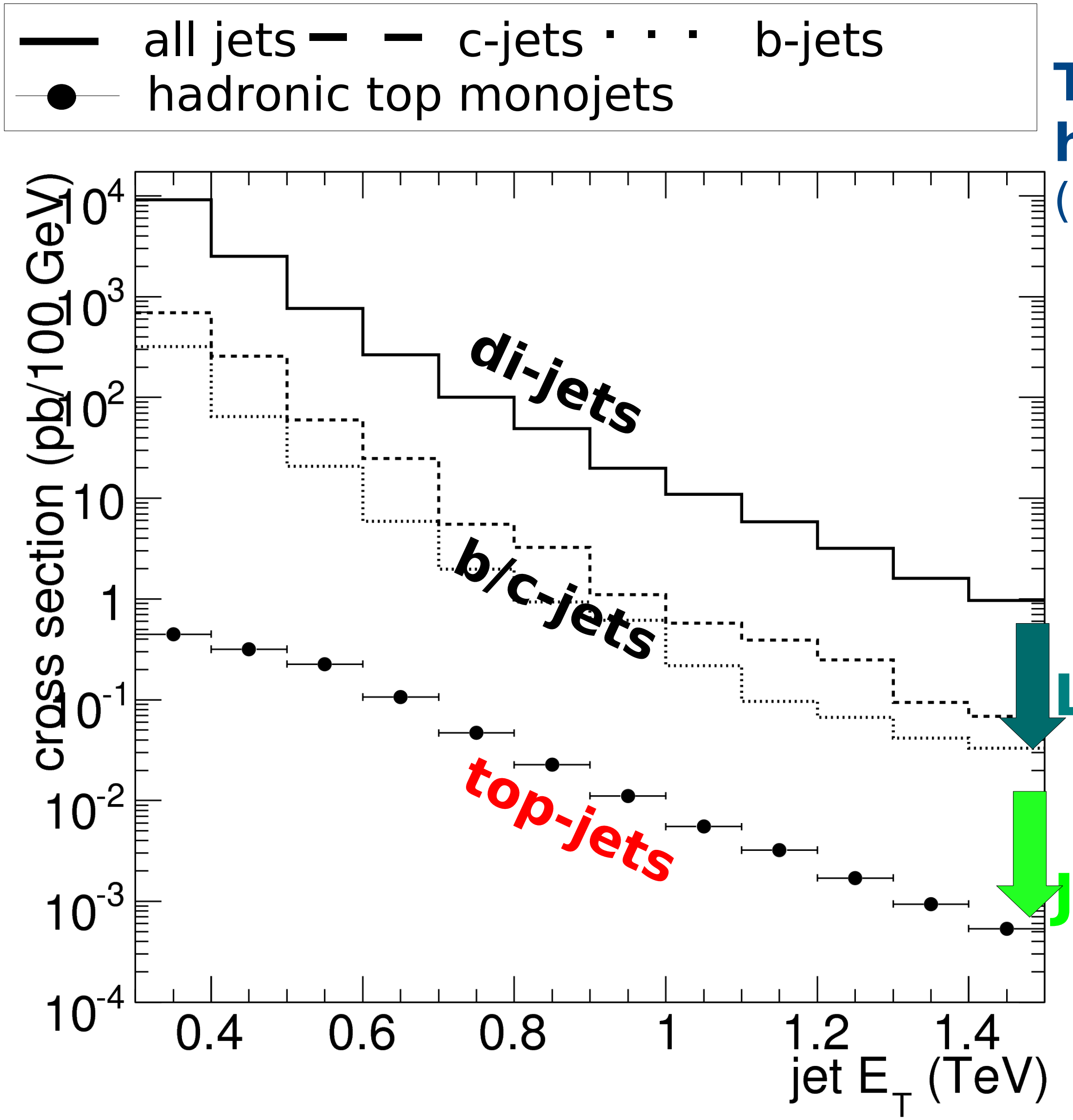
The lifetime signature



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

Exotic searches with heavy flavour in ATLAS

Heavy quarks may be abundantly produced through new physics processes AND can be discriminated from main QCD background: ATLAS flavour tagging tools

Rare decays: improve existing limits significantly

Discovery of W'->tb and W'->tbbb feasible in little Higgs/twin Higgs models

$d\sigma/dM_{tt}$ and searches for (strongly interacting) tt resonance: early physics

And then on to many related.

Dedicated effort required for high p_T b- and top identification