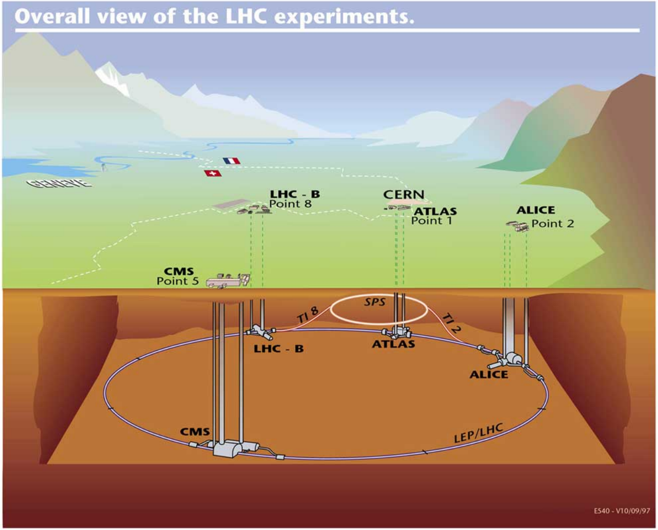
INSTITUTO DE FÍSICA CORPUSCULAR
Centro mixto U. de València (Estudi General) - CSIC

Top physics and resonances

Miguel Villaplana

Thanks to the ATLAS group at IFIC for their help in preparing these slides.

LHC


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

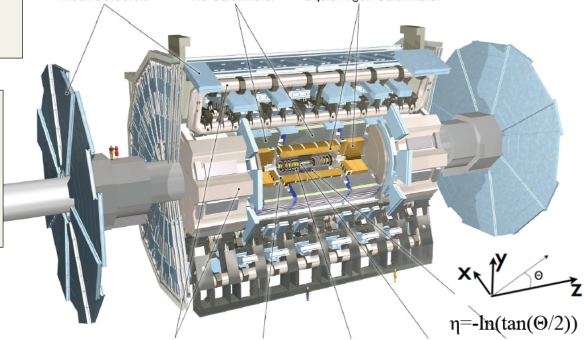
The ATLAS detector

Detector overview

The Inner Detector provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at $\eta = 0$. Coverage: $|\eta| < 2.5$ (2.0 for TRT)
Resolution goal: $\sigma_{pT}/p_T = 0.05\%\, p_T \oplus 1\%$

EM Calorimeter: ($|\eta|<4.9$) Pb-LAr accordion structure provides e/γ trigger, identification, measurement **$\sigma/E \sim 10\%\sqrt{E}$**
Hadronic (Tile): provides trigger, jet measurement, E_T^{miss}
$\sigma/E \sim 50\%\sqrt{E} \oplus 0.03$. ($|\eta|<1.7$)

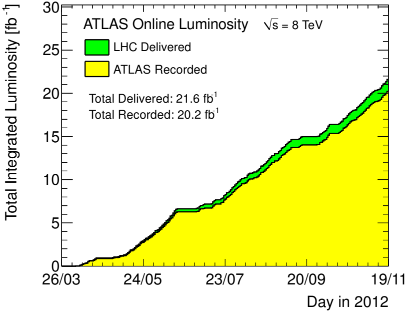
Muon spectrometer: high precision tracking and trigger chambers. $|\eta|$ coverage up to 2.7. Magnetic field produced by 3x8 air-core toroids.

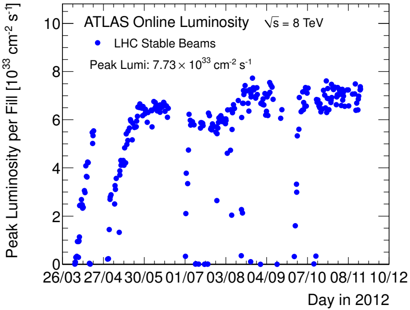


Kirill Prokofiev

LHC Status

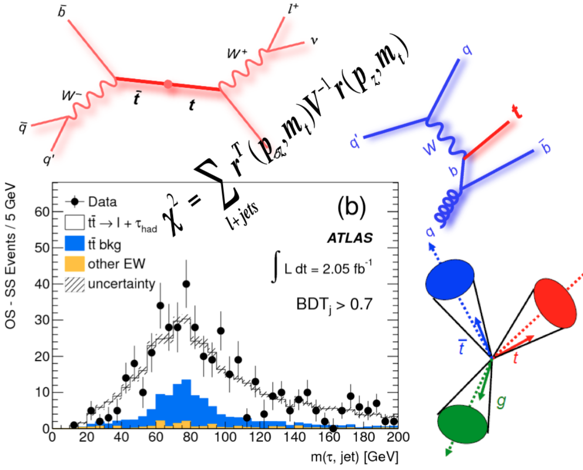
LHC and ATLAS performance far beyond expectation





more than $20 fb^{-1}$ to play with!

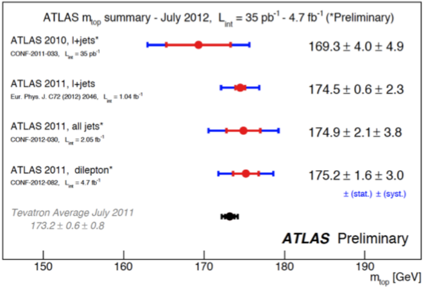
ATLAS top physics analysis at IFIC

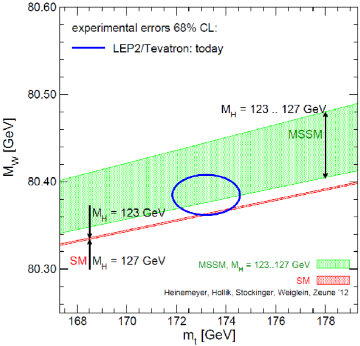


- Top mass measurements
- Single top
- $t\bar{t} \longrightarrow l + \tau_{had}$
- $t\bar{t}$ resonance searches

Top quark mass measurements

- The top quark was discovered by CDF & D0 Collaborations in 1995.
- The top quark mass is a fundamental parameter of the SM.
- It has large contributions to radiative corrections.
- The world average mass is $173.18 \pm 0.56(stat.) \pm 0.75(syst.)$ as measured by CDF & D0.

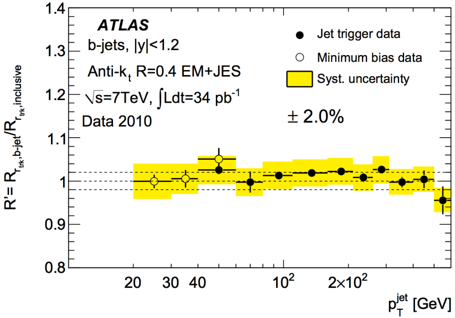




- Precise top mass measurements are fundamental.
  - Consistency checks of SM
  - High sensitivity to BSM physics

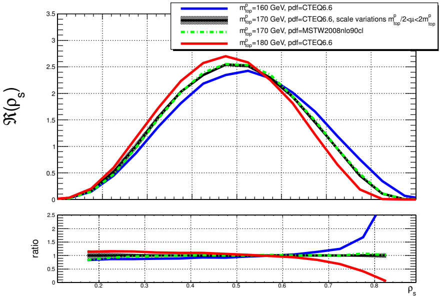
Top quark mass measurements

- IFIC has contributed to the top mass measurement in the l+jets channel.
- One of the most important contributions has been done on the systematics study, specially in the reduction of the b-jet energy scale uncertainty.
- IFIC is currently working in an alternative kinematic fit for the top mass measurement



A new observable to measure the top quark mass

Based on normalized differential $t\bar{t}$ + 1 jet distributions

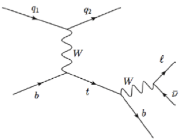


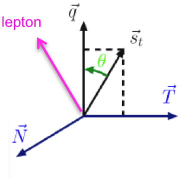
- Why $t\bar{t}$ + 1 jet ?
  Top quark mass dependence through:
  - Threshold effects
  - Cone effects
- Why differential ?
  - Inclusive quantities show limited sensitivity to top's mass
    $\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \approx 5\frac{\Delta m_t}{m_t}$
  - Differential distributions enhance sensitivity
- Why normalized distribution ?
  - Many theoretical and experimental dependences cancel

- The observable is defined at NLO in a defined mass scheme (pole mass)
- The observable is sensitive to the top quark mass
- Theoretical uncertainties are estimated to be below 600 MeV

Wtb vertex in the t-channel single top quark decay

- For un-polarized top quark decays, the only meaningful direction in the top quark rest frame is the one of the W boson (and b quark) momentum.
- For polarized top quark decays further spin directions may be considered:





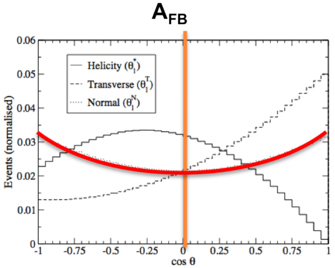
Transverse and normal directions

$\vec{q}$ → W mom in t rest frame
$\vec{s}_t$ → top spin

$$\vec{N} = \vec{s}_t \times \vec{q}$$
$$\vec{T} = \vec{q} \times \vec{N}$$

meaningful for polarised t decays
(e.g. in single top production)

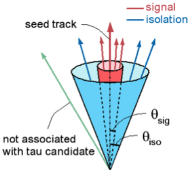
- θ^* ⟶ Angle btw. lepton (in W rest frame) w.r.t. W boson (in top rest frame)
- θ^N ⟶ Angle btw. lepton (in W rest frame) w.r.t. N
- θ^T ⟶ Angle btw. lepton (in W rest frame) w.r.t. T



- **First goal:** measure the forward-backward asymmetry in the normal direction since it is very sensitive to complex phase g_R : $A^N_{FB} \simeq 0.64\ P\ Im(g_R)$
- **Challenging measurement:**
  - Dominated by W+jets and top pairs backgrounds
  - A^N_{FB} needs to be corrected to parton level (acceptance and resolution effects) -unfolding method-

τ leptons in top quark decays

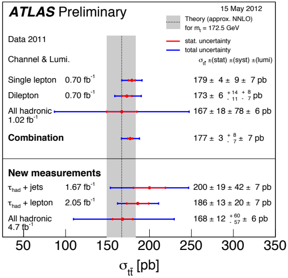
- Unlike electrons and muons, τ leptons decay mostly hadronically into jets
- τ jets are characterized by low multiplicity and high collimation
- Identify τ jets from light quarks is the main challenge in τ related analysis



- Contribution to Top Cross section measurements in the $\tau + \textit{lepton}$ channel:
  - $\sigma_{t\bar{t}} = 186 \pm 13(\textit{stat.}) \pm 20(\textit{syst.}) \pm 7(\textit{lumi.})\textit{pb}$
  - arXiv:1205.2067v1, CERN-PH-EP-2012-102, Phys. Lett. B 717 (2012) 89-108

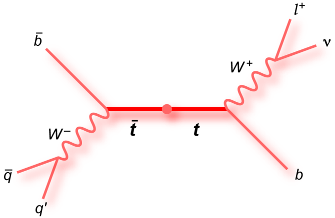
- Main background to SM Higgs searches
  - $t\bar{t}H \rightarrow t\bar{t}\tau\tau(100 - 150GeV)$
  - $q\bar{q}H \rightarrow q\bar{q}\tau\tau$
  - $H^{\pm} \rightarrow \tau\nu$
- Search for new physics: measured values of R > 1 would be indication of the presence of new physics not included in the SM

$$R = \frac{t \rightarrow \tau\nu_{\tau}b}{t \rightarrow l\nu_{l}b}(l = e, \mu)$$



BSM searches with top quarks. Resonances

- The heaviest known particle benefits from strong coupling and plays a special role in many extensions of the Standard Model.
- Only bottom and top quarks can be identified efficiently.
- Top is the only quark that produces isolated leptons and can be easily distinguished from anti-quarks. (charge asymmetries, same-sign top signature)



Testing a few benchmarks for $t\bar{t}$ resonances

Leptophobic topcolor Z'

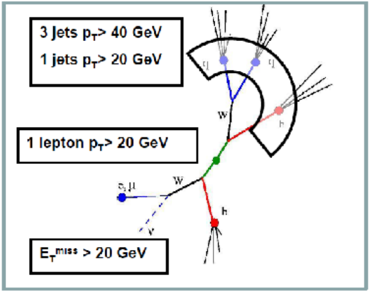
- spin 1, color singlet
- narrow resonance (width $\sim$ 1% of mass)

Kaluza-Klein gluon, g_{KK}, in Randall-Sundrum models

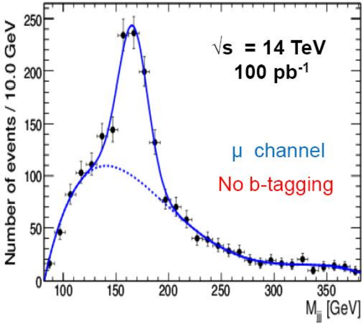
- spin 1, color octect
- wide resonance (width $\sim$ 10% of mass)

Top reconstruction basics

- Top reconstruction algorithms are well-established at the Tevatron. The same "resolved" approach forms the back-bone of the ATLAS preparation for top physics.
- Find isolated lepton.
- Find 4 jets.
- Reconstruct neutrino using lepton, E_T^{miss} and W-mass constraint
- (Optional) Tag b-jets.
- Piece it all together again, selecting the right combination.



tt -> Wb Wb -> ℓνb qqb

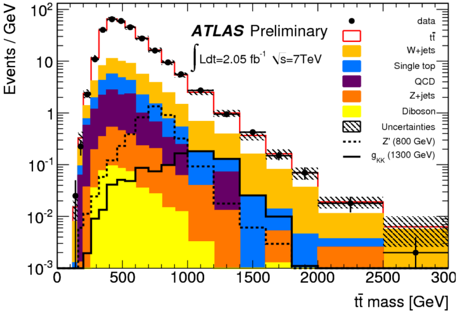


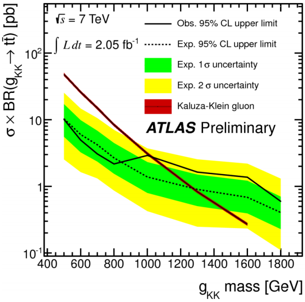
three jet mass

$t\bar{t}$ resonances: $2fb^{-1}$, resolved reconstruction

Eur.Phys.J. C72 (2012) 2083

Selection: lepton + 1 b-tagged jet + 3 jets



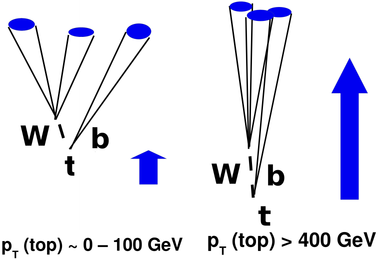


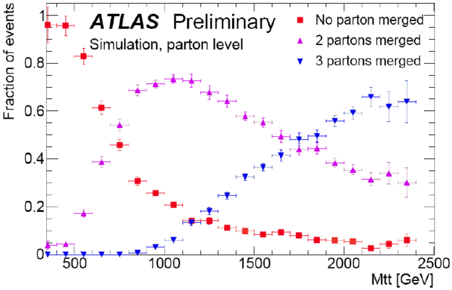
Excluded mass range:

- $500GeV < m(Z') < 860GeV$
- $500GeV < m(g_{KK}) < 1025GeV$

As the exclussion limits go further up the importance of being able to populate the high mass tail of the $t\bar{t}$ mass distribution becomes clear

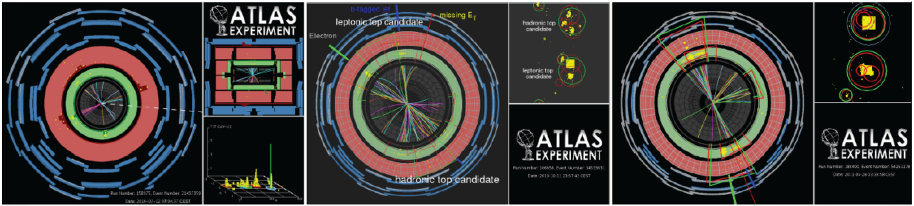
Prospects for reconstruction of boosted top quarks





- Classical “resolved”, algorithms run into problems for highly boosted tops
- For a ΔR of 0.6 the decay products can be resolved individually up to 700 GeV and a “fat” mono-jet is formed starting approximately at 1 TeV.

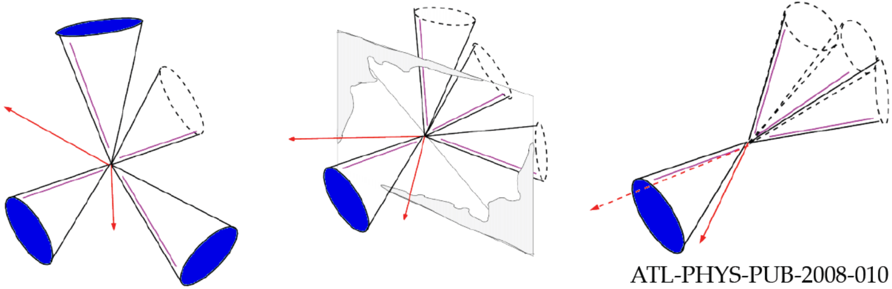
$t\bar{t}$ reconstruction: Three regimes



At rest: Mtt<500 GeV

Transition region: 500GeV<Mtt<700GeV

Mono-jet: Mtt>700GeV



ATL-PHYS-PUB-2008-010

BSM searches with boosted top quarks

Timeline

2009 MC studies on $t\bar{t}$ resonance searches show that boosted techniques can improve sensibility even at 7TeV and with first ATLAS data

"Prospects for top anti-top resonance searches using early ATLAS data" (ATL-PHYS-PUB-2010-008, Jul, 2010)

2010 Commissioning of substructure observables on first ATLAS data and first BSM physics searches

"Jet mass and substructure of inclusive jets in $\sqrt{s}$ = 7 TeV pp collisions with the ATLAS experiment" (JHEP 1205 (2012) 128)

2011 BSM searches using boosted tops on ATLAS 2011 data improve established limits to date

"A search for resonances in lepton+jets $t\bar{t}$ events with highly boosted top quarks in 2 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV." (JHEP 1209 (2012) 041)

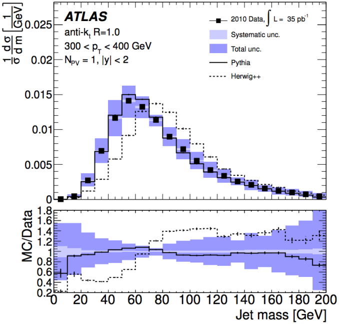
2012 New results on $5fb^{-1}$ of ATLAS data push the limits on some BSM models further up

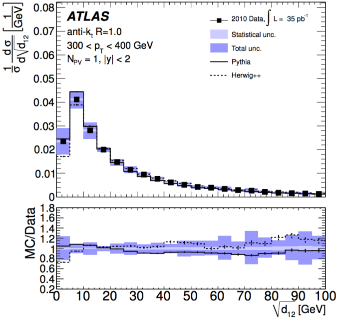
"A search for ttbar resonances in the lepton plus jets final state using 5 fb-1 of pp collisions at sqrt(s)=7 TeV", ATL-CONF-2012-136, to be submitted to: Phys. Rev. D

Boosted jet techniques

- ATLAS jet finding default is anti-k_T (R=0.4 or 0.6)
- For a parent with m and p_T, merging starts showing at $R > \frac{2m}{p_T}$.
- Use jet mass and jet substructure to resolve merging.
- Rerun jet algorithms (k_T) on jet components to reveal jet substructure.

$$\sqrt{d_{ij}} = min(p_T^i, p_T^j) \times \Delta R_{i,j}$$

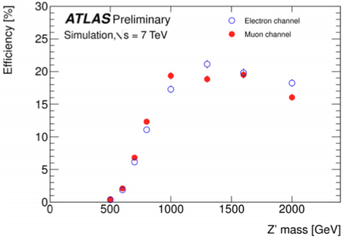


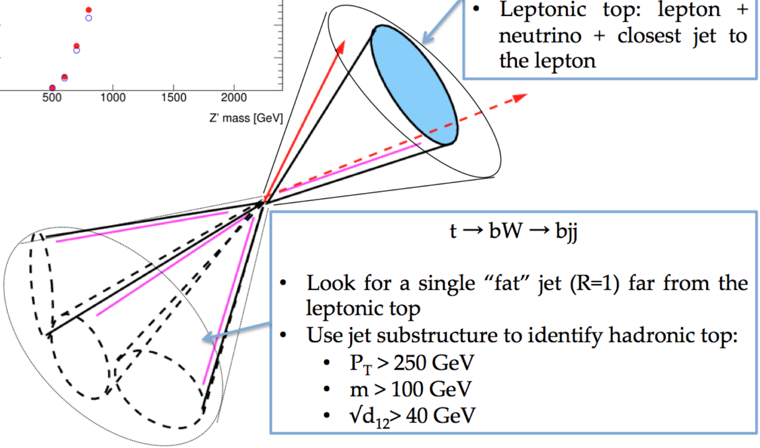


Complete inventory of existing literature appears in proceedings of
BOOST2010: EPJC 2011 71:1661
BOOST2011: J. Phys. G. Part. Phys. 39 063001

$t\bar{t}$ resonances: $2fb^{-1}$, boosted reconstruction

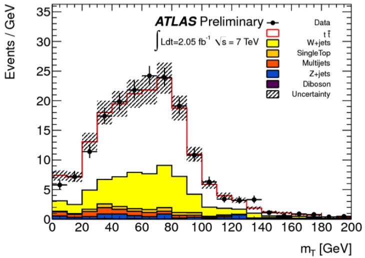
JHEP 1209 (2012) 041

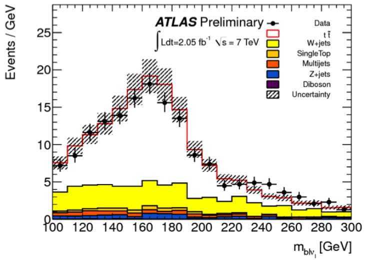




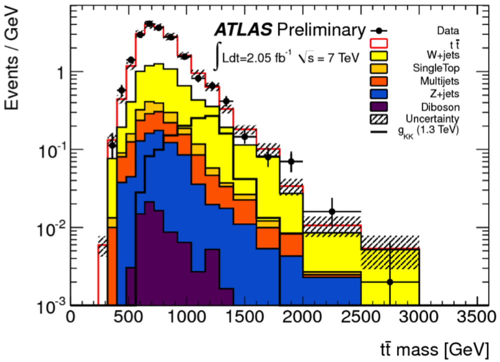
$t\bar{t}$ resonances: $2 fb^{-1}$, boosted reconstruction

Mass peaks at the right places



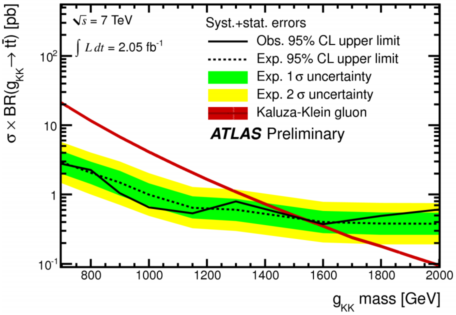


$M_{t\bar{t}}$ spectrum combining electron+jets and muon+jets channels is in very good agreement with a SM template



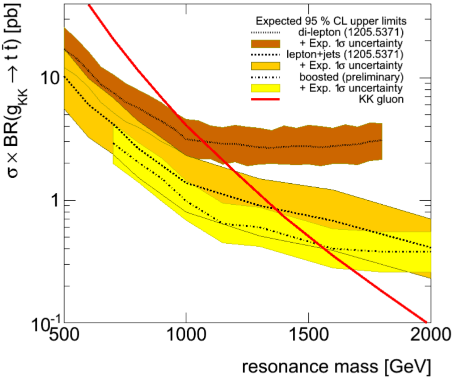
$t\bar{t}$ resonances: $2fb^{-1}$, boosted reconstruction

- 30 sources of systematic uncertainty on yield and shape of background and signal (complete list of systematics in backup slides)
- Jet energy and mass scale (5-7%) have the largest impact on the sensitivity
- Pile-up has a big impact on jet mass resolution, but is fairly well modeled
- Large uncertainty on background yield ($t\bar{t}$ normalization, ISR/FSR) does not necessarily lead to a large impact on the exclusion limit for resonances



- Leptophobic Z': $m(Z') < 1.2\,TeV$
- KK gluon: $m(g_{KK}) < 1.5\,TeV$

$t\bar{t}$ resonances: $2fb^{-1}$, summary



- Expected limit @ 600 GeV
  - Resolved: 6.0 pb
  - Boosted: 10.4 pb
- Expected limit @ 1.6 TeV
  - Resolved: 0.46 pb
  - Boosted: 0.22 pb

Classical and boosted algorithms have complementary low and high mass sensitivity.

Many improvements still to be made:

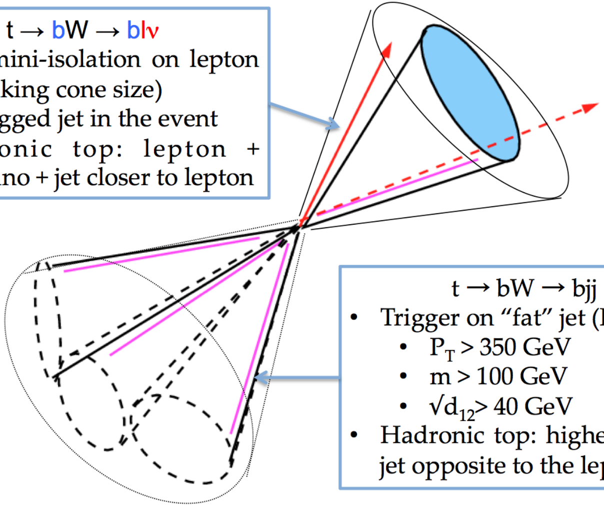
- Combine two approaches
- Lepton selection
- Better W+jets rejection

$t\bar{t}$ resonances: $4.66 fb^{-1}$ dataset

ATL-CONF-2012-136

$t \rightarrow bW \rightarrow bl\nu$

- Use mini-isolation on lepton (shrinking cone size)
- 1 b-tagged jet in the event
- Leptonic top: lepton + neutrino + jet closer to lepton



$t \rightarrow bW \rightarrow bjj$

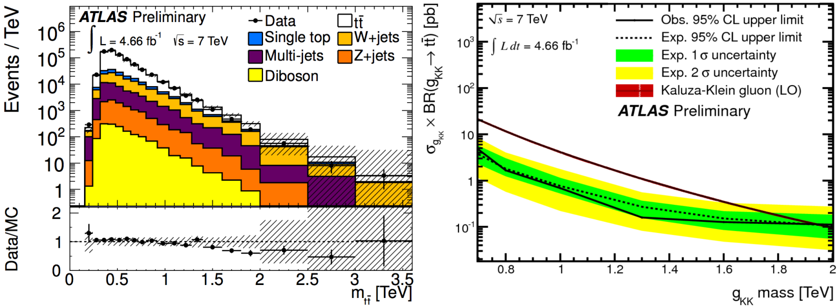
- Trigger on "fat" jet (R=1)
  - $P_T > 350$ GeV
  - $m > 100$ GeV
  - $\sqrt{d_{12}} > 40$ GeV
- Hadronic top: highest P_T fat jet opposite to the lepton

$t\bar{t}$ resonances: $4.66 fb^{-1}$ dataset

ATL-CONF-2012-136

Resolved and boosted selections combined

Orthogonal data sets, if event satisfies both selections, prefer boosted



- Systematics from W+jets shape & normalization diminished w.r.t previous analysis
- Jet energy scale impact on the sensitivity still high.
- B-tagging systematics high as well.
- Full table of systematics in backup

$t\bar{t}$ resonances: summary

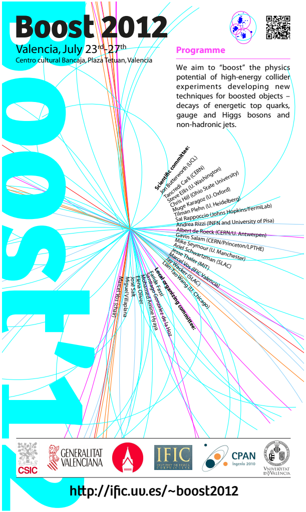
Final state	lepton+jets	boosted l+jets	combined l+jets
Preprint/publication	EPJC72	JHEP1209	2012-136
Data set	2 fb^{-1}	2 fb^{-1}	4.7 fb^{-1}
Z' limits [TeV]	0.55 - 0.88	0.6 - 1.15	0.7 – 1.7
g_{KK} limits [TeV]	0.5 - 1.13	0.6 - 1.5	0.7 – 1.9

More specialized algorithms allow us to achieve better sensitivity and to get the most out of the data!

The BOOST Conference Series

Bring together world-leading theorists and experimentalists in order to enhance the potential of the LHC for the decay topologies that form when highly boosted heavy particles decay

- SLAC (2009) and Oxford (2010) focused on Monte Carlo studies (Eur. Phys. J. C 71 1661)
- Princeton (2011), (J. Phys. G. Part. Phys. 39 063001)
  - First measurements on LHC data of jet substructure
  - Candidate events for the world's first boosted top quarks
- Boost2012 - Valencia, July 2012
  - Invariant mass of energetic jets prediction
  - New techniques to deal with pile-up
  - *Higgs* $\longrightarrow b\bar{b}$
  - BSM searches from ATLAS and CMS
- Boost2012 report will be submitted to Eur. Phys. J.
- Several media picked up Boost2012.
  - RTVE, The Guardian, CERN Courier, ABC, . . .
  - More detailed information at CPAN webpage
    http://www.i-cpan.es/detalleNoticia.php?id=260
- Next stop Arizona, August 2013



Summary

- The 7-8 TeV LHC is a “boosted object” factory. Their role in the physics program will grow in future operation at larger energy.
- A lot of effort was invested to understand jet substructure - the physics modeling, the detector response and pile-up - and provide the uncertainties that searches need
- The first analyses that use these techniques have pushed up the limits on the benchmark models used (m(Z’)<1.7 TeV and m(g_{KK})<1.9 TeV) demonstrating that dedicated algorithms for these special topologies indeed enhance the LHC physics potential.
- Now it is time to extend the usage of boosted techniques: $\frac{d\sigma}{dM}$, charge asymmetries, ttH, . . .

BACK UP

Systematics ($2fb^{-1}$, boosted reconstruction)

JHEP 1209 (2012) 041

Systematic effect	Impact on yield [%] background	Impact on yield [%] Z'1.3 TeV	Impact on sensitivity [%]
Luminosity	2.5	3.7	0.4
PDF uncertainty	3.1	1.0	0.2
$t\bar{t}$ normalization	4.9	—	0.7
$t\bar{t}$ ISR, FSR	6.3	—	0.7
$t\bar{t}$ fragmentation & parton shower	3.4	—	0.9
$t\bar{t}$ generator dependence	2.8	—	2.2
$W+$ jets normalization	4.3	—	1.4
$W+$ jets shape	*norm.*	—	0.1
Multijets normalization	2.1	—	0.2
Multijets shape	*norm.*	—	1.1
$Z+$ jets normalization	2.0	—	0.5
Jet energy and mass scale	6.7	2.0	5.2
Jet energy and mass resolution	4.7	4.0	1.2
Electron ID and reconstruction	1.1	1.3	1.0
Muon ID and reconstruction	2.2	2.1	4.8

Systematic uncertainties and their impact on the sensitivity. In the first two columns the relative impact (in percent) is shown on the total expected background yield and on the number of selected signal events (a Z' with m = 1.3 TeV). The third column lists the relative variation for this benchmark of the expected limit on the production cross section times branching fraction if the corresponding systematic effect is ignored.

Systematics ($4.7 fb^{-1}$)

ATL-CONF-2012-136

Impact on Systematic effect	*Resolved selection* yield [%] total bgr.	*Resolved selection* yield [%] Z'	*Boosted selection* yield [%] total bgr.	*Boosted selection* yield [%] Z'
ISR/FSR	0.3	–	5.9	–
PDF	3.5	–	7.9	–
$t\bar{t}$ normalization	8.0	–	9.0	–
EW Sudakov	1.9	–	4.2	–
$t\bar{t}$ higher order QCD corr.	1.2	–	9.0	–
W + heavy flavor	1.3	–	1.2	–
Multi-jets norm, e+jets	2.6	–	0.6	–
Multi-jets norm, μ+jets	1.0	–	1.1	–
Parton shower	0.2	–	7.3	–
JES, anti-k_t $R = 0.4$ jets	7.8	2.9	0.5	0.5
JES, anti-k_t $R = 1.0$ jets	0.2	4.8	17.0	2.8
b-tag efficiency	3.8	7.7	6.0	3.5
c-tag efficiency	1.2	0.6	0.1	2.5
Mistag rate	1.0	0.3	0.7	0.1

Average impact of the dominant systematic effects on the total background yield and on the estimated yield of a Z' with m = 1.6 TeV. The shift is given in percent of the nominal values