Title: boosted top: lessons learnt

Date: Feb 21, 2013 10:00 AM

URL: http://pirsa.org/13020141

Abstract: I briefly summarize the potential of the LHC to produce boosted objects and that of the experiments to recognize them as such analyzing jet substructure. Then, I consider boosted top quarks in some detail, the boosted object that has probably been most extensively studied. I evaluate ATLAS ttbar resonance searches to understand how and why dedicated algorithms outperform more classical techniques. Finally, I discuss a number of analyses where boosted techniques are likely to make a difference

Boosted top: lessons learnt

Marcel Vos (IFIC, CSIC/UV, Valencia, Spain)

Applications of Jet Substructure to New Physics Searches

Thanks to the organizers for the kind invitation

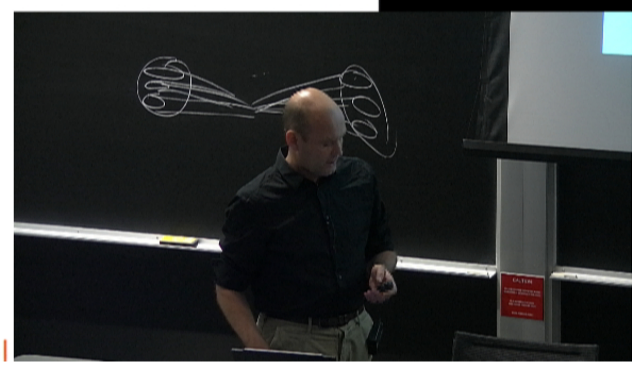
Apologies for the incomplete and biased inventory

Outline

A very quick introduction

Early searches with boosted top quarks - post-mortem
- Does it work?
- Why does it work?
- Can it work better?

What should we be boosting next?



Introduction

If you are looking for a good introduction to boosted objects and jet substructure, this presentation is probably not what you want. I suggest instead:

Classics:

M. Seymour. Z. Phys., C62:127–138, 1994.

BDRS, Butterworth, Davison, Rubin, Salam, Phys. Rev. Lett. 100:242001 (2008)

Reviews:

BOOST2010 report

BOOST2011 report

BOOST2012 report hopefully out soon

Gavin Salam's Towards Jetography

Plehn & Spannowsky's top-tagging review

A more extensive discussion of where we stand with boosted top quarks:

M.V., CERN TH seminar – 15/06/2012

M.V., NIKHEF Colloquium – 09/11/2012

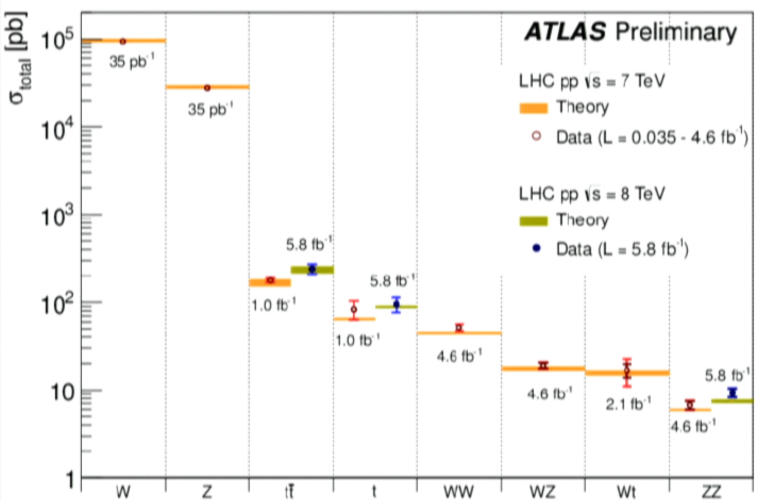
Welcome to the TeraScale!

With the LHC we enter a new kinematic regime

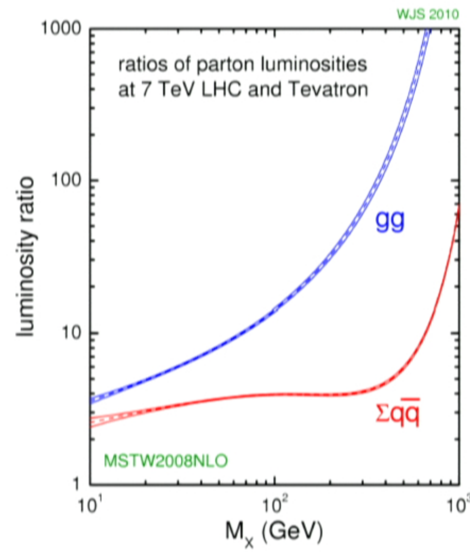
Parton luminosity at 1 TeV is 2-4 orders of magnitude higher at the 7 TeV LHC than at the Tevatron

A search with 315 nb^{-1} can be competitive. The first 7 TeV paper: Phys.Rev.Lett. 105 (2010) 161801

2010: 35/pb
2011: 5/fb
2012: over 20/fb



Characterizing pb-level processes



After a nice little pause:
12-13 TeV
HiLumi LHC
VLHC

marcel.vos@ific.uv.es

Boosted objects form "fat" jets

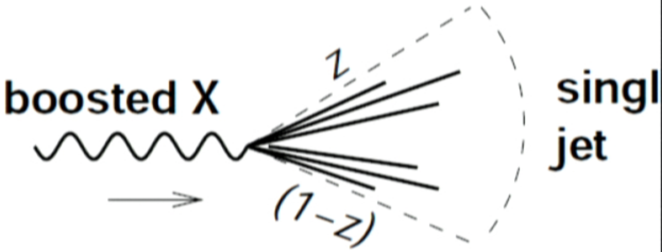
At the LHC "heavy" particles like W, Z and top are produced abundantly with $p_T >> m$

Rule of thumb for maximum jet size to resolve both partons in a two-body decay:

$R < 2m_X/p_T^X$

R = 0.4 corresponds to W with 400 GeV

Reconstruct **"boosted object"** as a single jet. Figure out it was indeed a **"fat jet"** by analyzing substructure



***M. Seymour**. Searches for new particles using cone and cluster jet algorithms: A Comparative study. Z. Phys., C62:127-138, 1994.*

Butterworth, Cox and Forshaw, Phys. Rev. D65:096014 (2002)

"A new method for identifying hadronically decaying W bosons is introduced, which we expect to be useful more generally [...]"

Boosted objects: great promise

Boosted Higgs (light Higgs → bb)
Butterworth, Davison, Rubin, Salam, Phys. Rev. Lett. 100:242001 (2008)

" We conclude that subjet techniques have the potential to transform the high-pT WH, ZH (H → bb) channel into one of the best channels for discovery of a low mass Standard Model Higgs at the LHC"

The "boosted" threshold

Numbers obtained with MCFM
J. M. Campbell and R. K. Ellis,
arXiv:1204.1513 [hep-ph]
MSTW2008NLO PDFs

A top factory, our first sample of boosted top quarks

Expected number of events	*Tevatron run II* *10 fb^{-1} @ 1.96 TeV*	*LHC 2012* *20 fb^{-1} @ 8 TeV*	*LHC design* *300 fb^{-1} @ 13 TeV*	*Very LHC* *300 fb^{-1} @ 33 TeV*
Inclusive tt production	**57.000**	**2.600.000**	**155.000.000**	**1.000.000.000**
Boosted production: M_{tt} > 1 TeV	**25**	**30.000**	**3.000.000**	**46.000.000**
Highly boosted: M_{tt} > 2 TeV	**0**	**300**	**47.000**	**2.300.000**

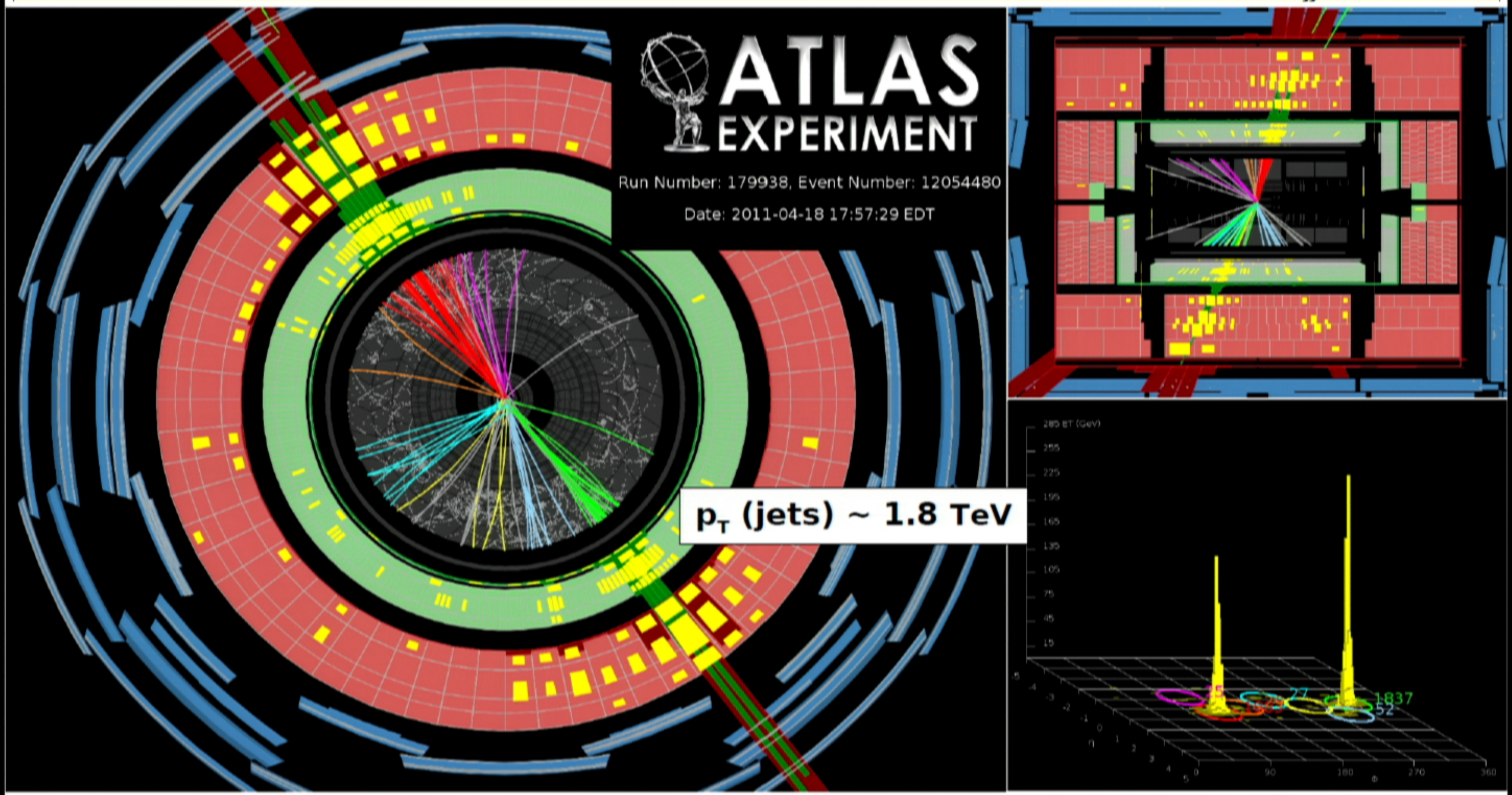
Enough to discover the top quark, no boosted production

Millions of boosted top quarks, 50.000 extremely boosted events

M.V., Boosting sensitivity to new physics, CERN Courier, Oct 2012

Jets!

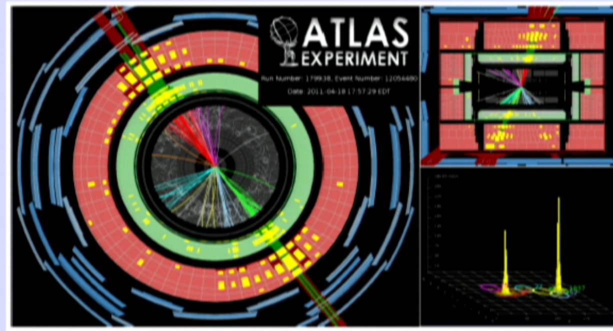
One of the most spectacular dijet events recorded by ATLAS: M_{jj} ~ 4 TeV

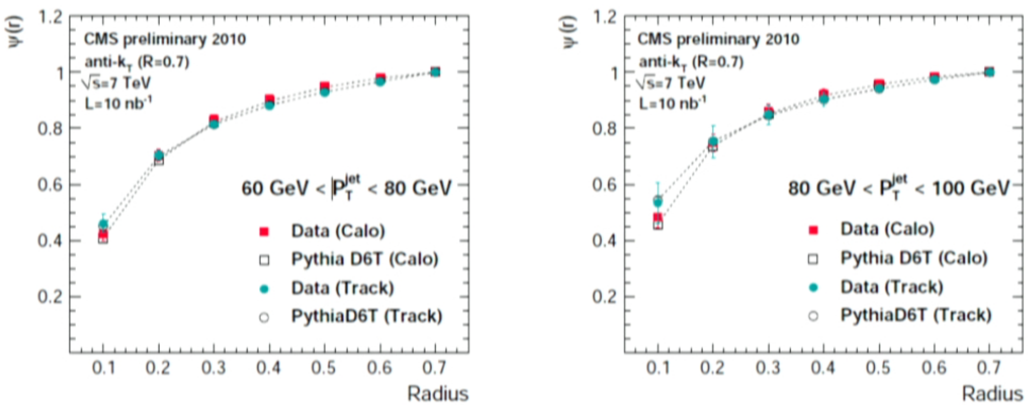


There is more to a jet than a four-vector

Jet substructure

Jet shapes

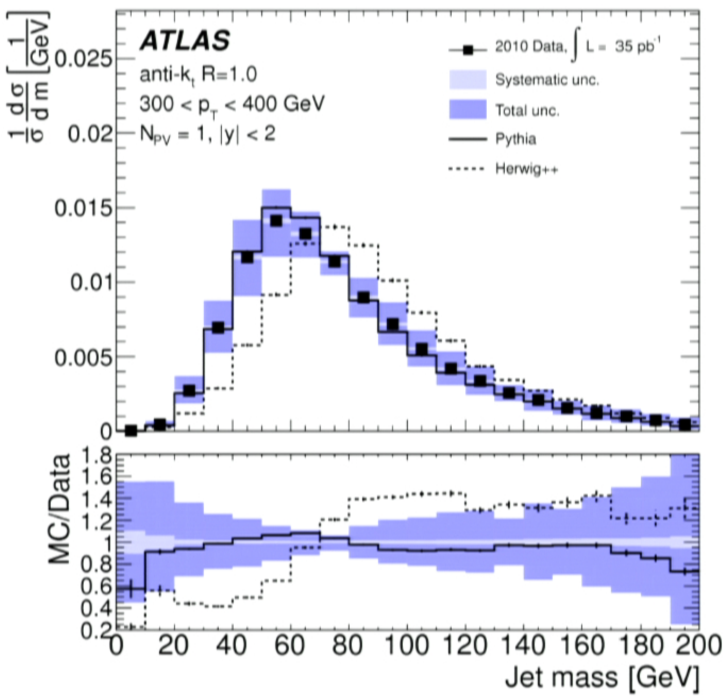


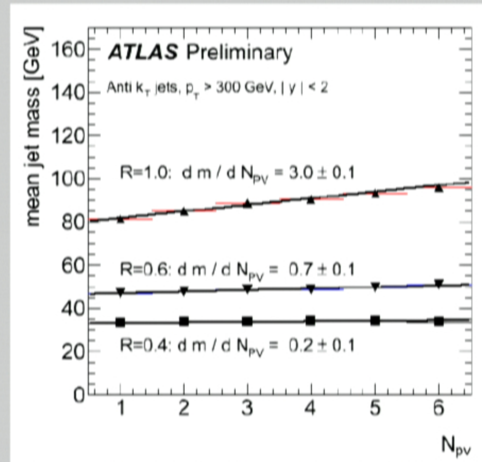


QCD-10-14-PAS: Measure how energy is distributed inside the jet
Detailed comparison to MC... see ATL-PHYS-PUB-2011-010

Some dedicated measurements

Measurement of Jet Mass and Substructure for Inclusive Jets in √s = 7 TeV pp Collisions with the ATLAS Experiment, JHEP 1205 (2012) 128

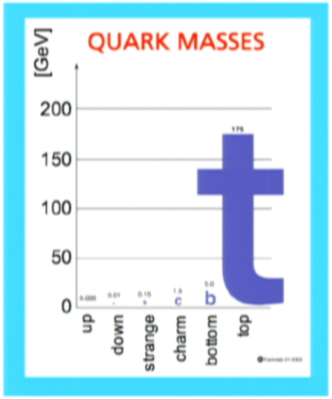




Confirm the impact of pile-up

Fully corrected measurements of jet mass, k_t splitting scales and n-subjettiness available on HEPDATA

Parton Shower is adequate
Detector response is under control
Pile-up confirmed to be a problem



The top quark - motivation

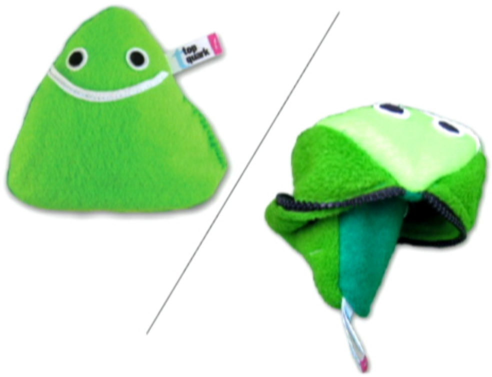
Mass hierarchy

We don't know why the SM fermion have the masses they have. The top quark has a mass of ~173 GeV. What does that number come from? In the SM it's the result of the Yukawa coupling of the top quark to the Higgs boson. But what does the number come from? We have been worrying about this for 45 years and we haven't made any progress!

Steve Weinberg, public lecture UTA, 24/10/2012

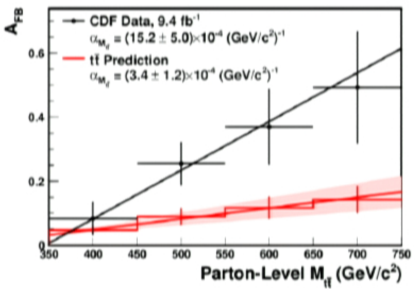
Compositeness

observable	*L compositeness [TeV]*
L (eeee)	*O(10) (LEP)*
L (eeqq)	*O(10) (LEP)*
L (qqqq)	*5.6 (CMS)*
$e^* \rightarrow e\ \gamma$	*1 (CMS)*
$q^* \rightarrow q\ g$	*2.5 TeV (CMS)*
Top...	*?*



Experimental hints?

Papers with the word "Evidence" in the title
Phys.ReV.D83 (2011) 112003



The top quark: experimental perspective

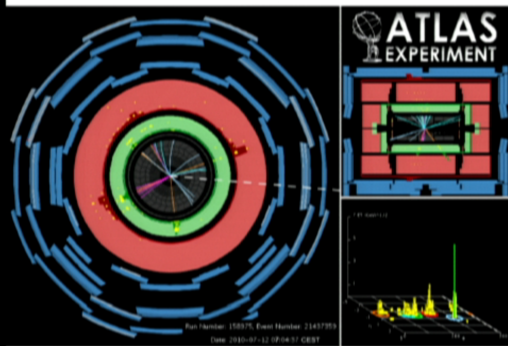
Top is a quark that we CAN study very well

A *nude* quark, we can easily isolate its signature from that of other quarks and gluons, we can distinguish top and anti-top quarks, we can study top quark polarization

For the purpose of this workshop …

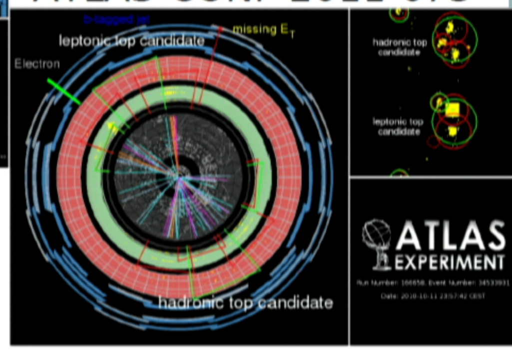
top is probably the best studied boosted system. Resonance searches using classical and dedicated methods have gone through a few cycles already.

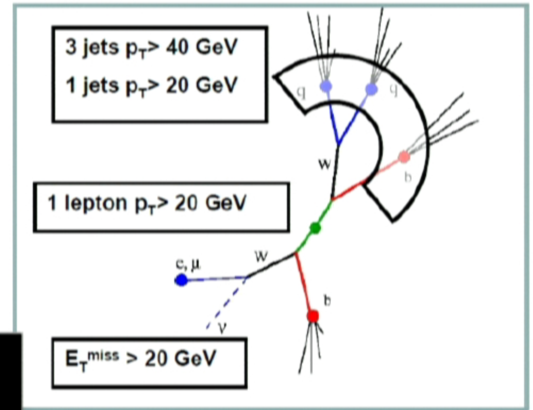
Boosted top quarks (I)



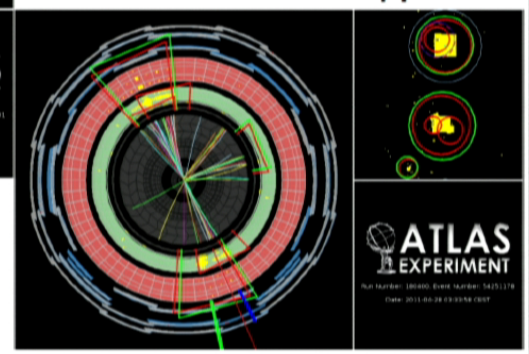
Early "l+jets" candidate
ATLAS-CONF-2010-063

First boosted top quark
Mtt ~ 800 GeV
ATLAS-CONF-2011-073

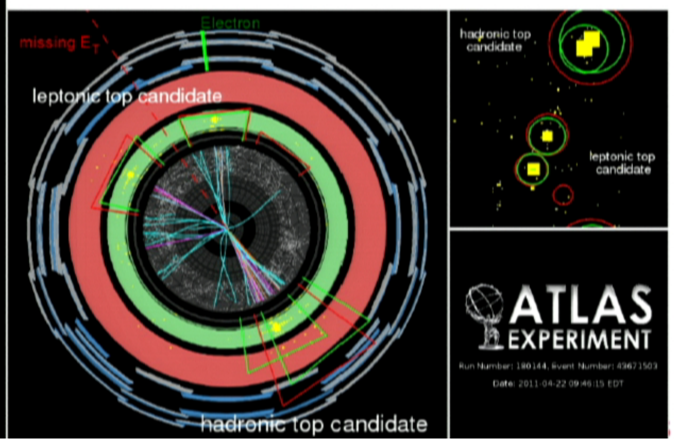




tt -> Wb Wb -> ℓνb qqb



m_{tt} > 1 TeV
ATLAS-CONF-2011-083

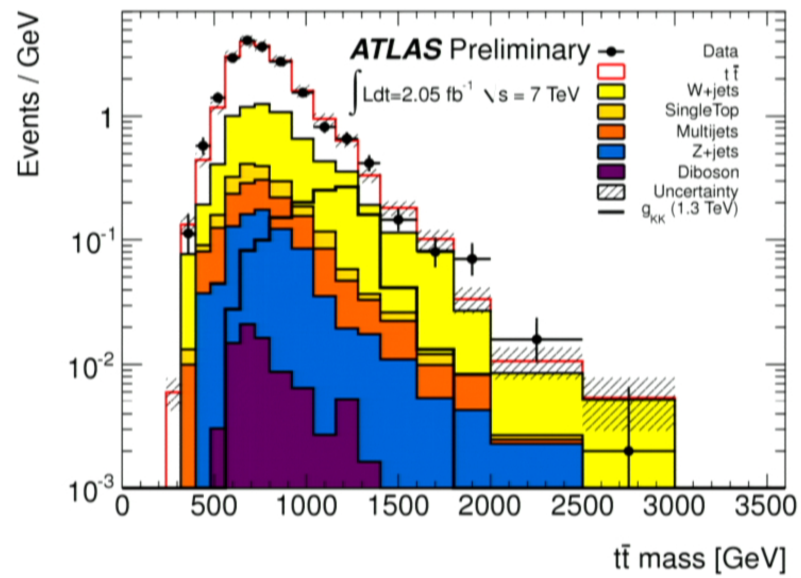


M_{tt} ~ 2.5 TeV
arXiv:1207.2409

A graphical account of the same argument, with real events

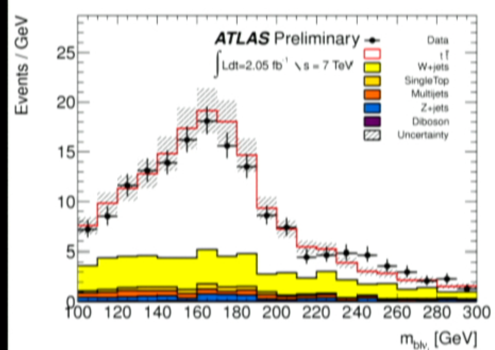
tt resonances: boosted (lepton + jets)

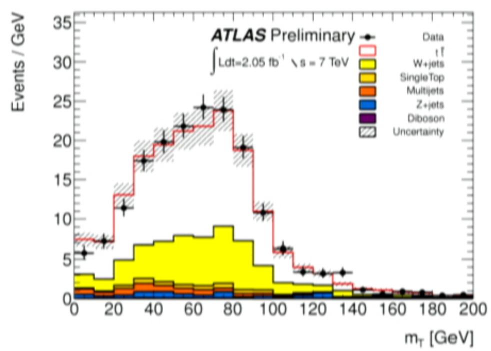
tt mass spectrum combining electron+jets and muon+jets channels compared to a SM template from data and MC

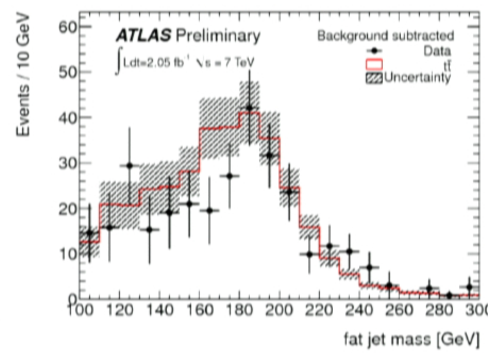


Very good agreement, unfortunately
Largest excess ~ 1.4 σ

Mass peaks at the right places







tt resonances: 2/fb summary

Observed limits

Leptophobic Z': m < 1.2 TeV

KK gluon: m < 1.5 TeV

Expected limit @ 600 GeV

ATLAS Classical: 6.0 pb

ATLAS Boosted: 10.4 pb

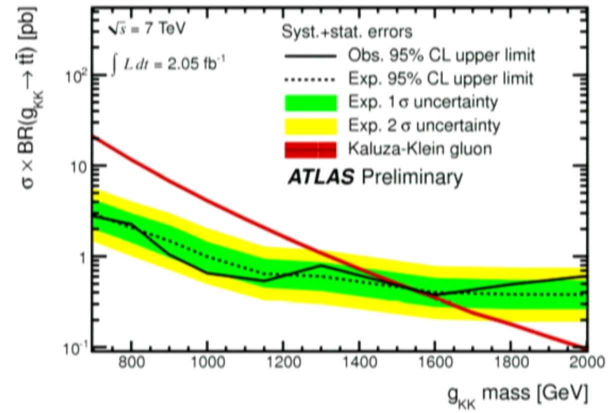
Expected limit @ 1.6 TeV

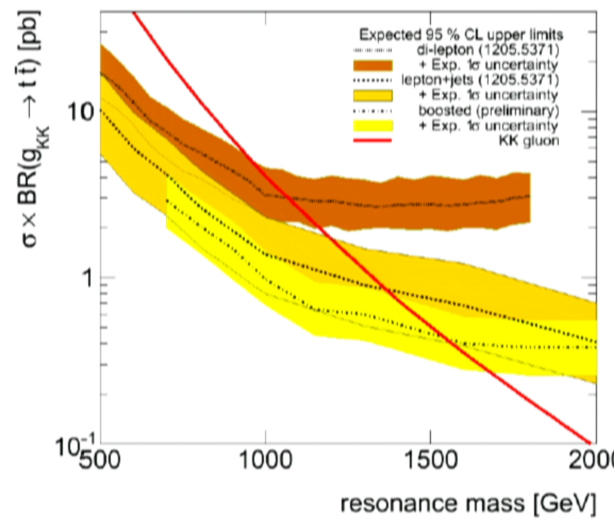
ATLAS Classical: 0.46 pb

ATLAS Boosted: 0.22 pb

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

Many things can be improved...





tt resonances: 2/fb summary

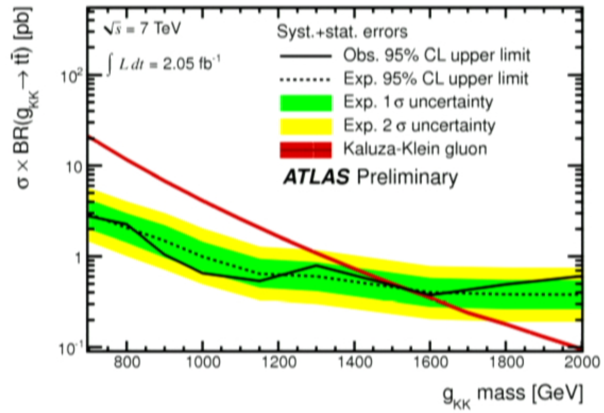
Observed limits
Leptophobic Z': m < 1.2 TeV
KK gluon: m < 1.5 TeV

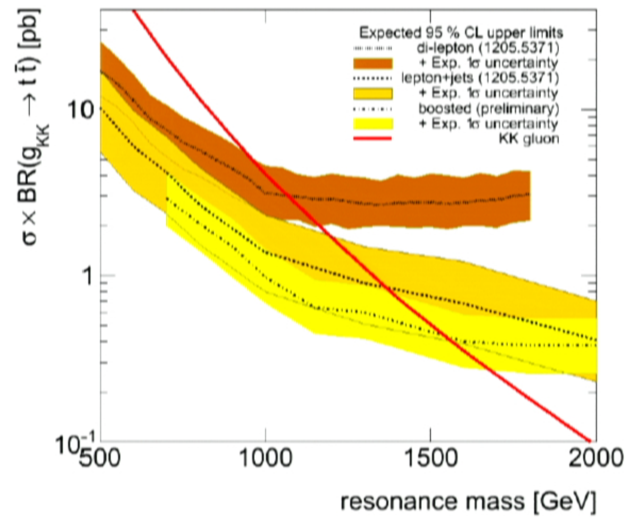
Expected limit @ 600 GeV
ATLAS Classical: 6.0 pb
ATLAS Boosted: 10.4 pb

Expected limit @ 1.6 TeV
ATLAS Classical: 0.46 pb
ATLAS Boosted: 0.22 pb

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

Many things can be improved...



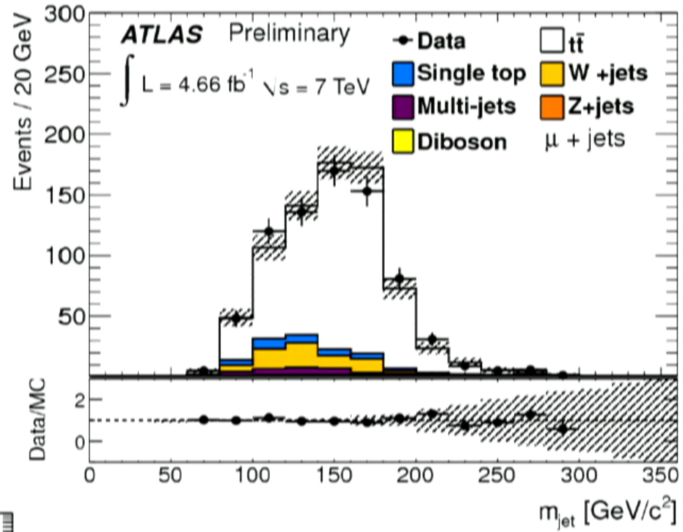


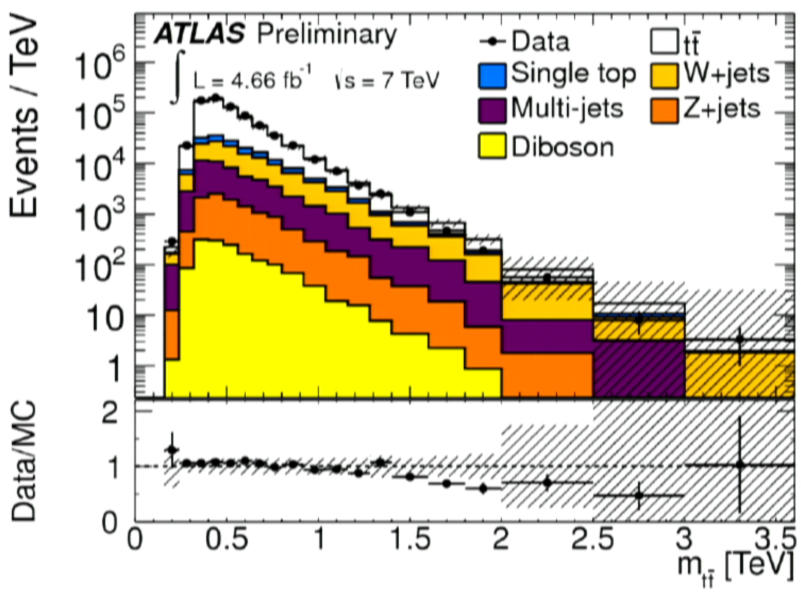
marcel.vos@ific.uv.es

$t\bar{t}$ resonances – lepton + jets

Lepton+jets search with full (4.7/fb) 7 TeV data ATLAS-CONF-2012-136 includes:

- B-tagging
- Mini-isolation (Reherman, Tweedie, 2011)
- Combination of resolved and boosted limits



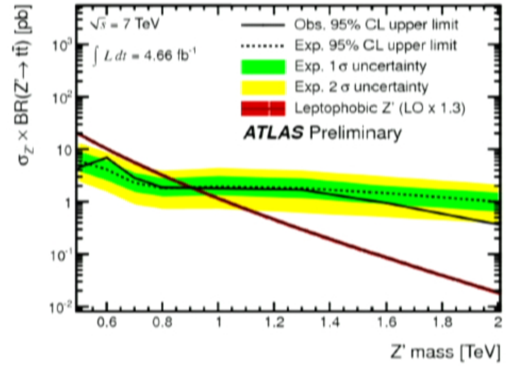


Broad top mass peak
Correctly modeled!

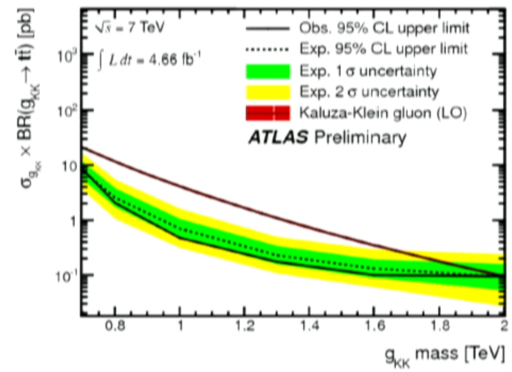
Great overall $t\bar{t}$ purity,
tails still problematic

Update for boosted (lepton+jets)

“Resolved” selection

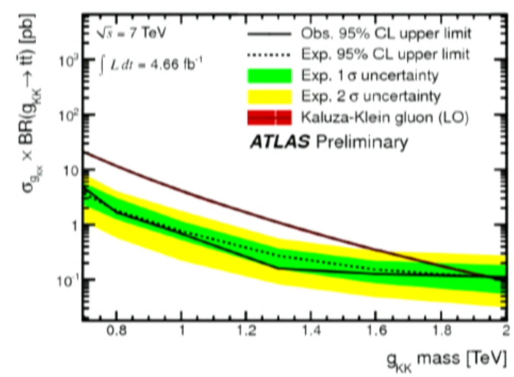


“Boosted” selection

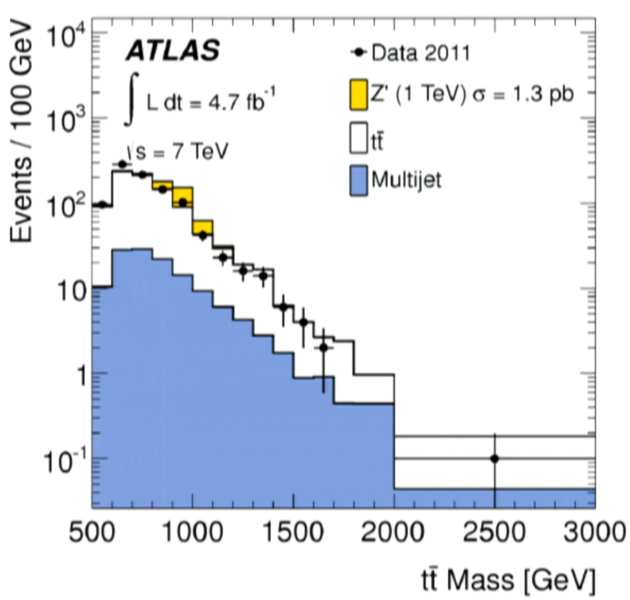


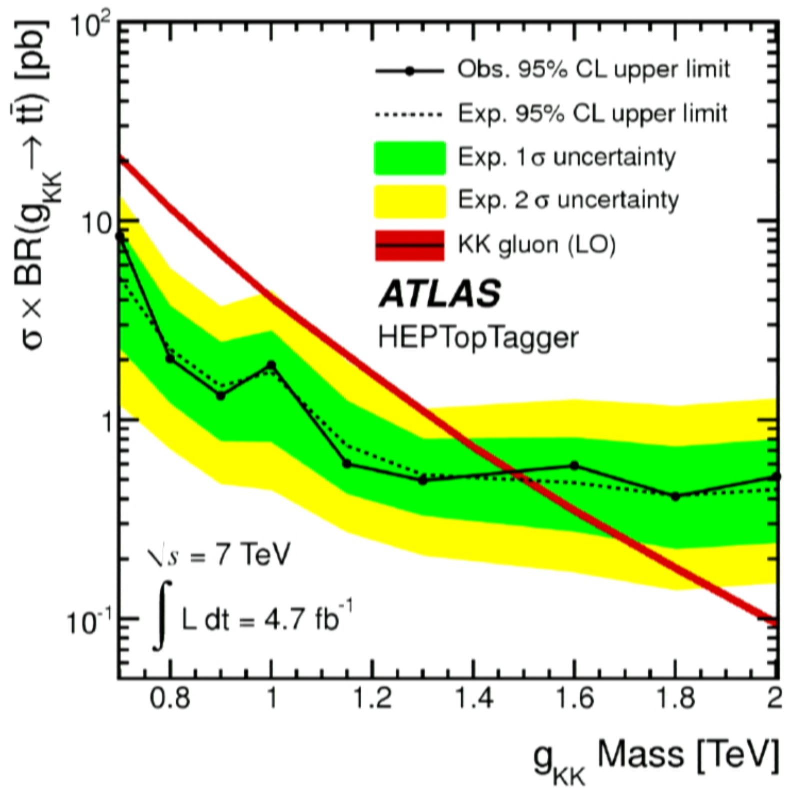
Orthogonal data sets, if event satisfies both selections, prefer boosted

Combined limit



tt resonances: boosted fully hadronic



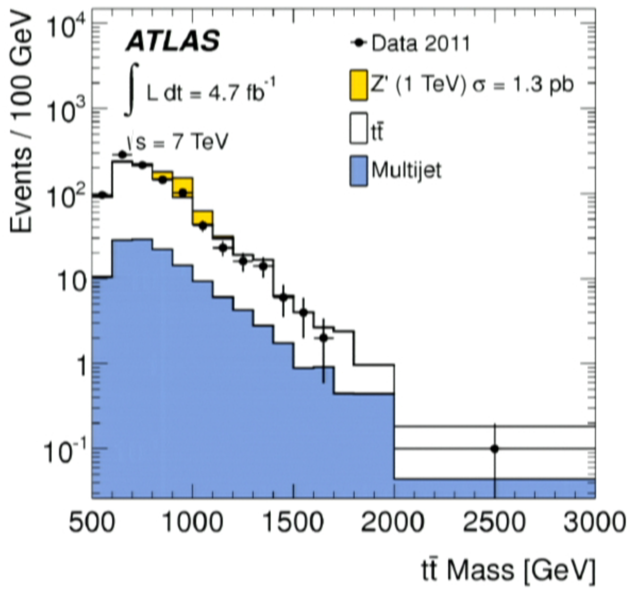


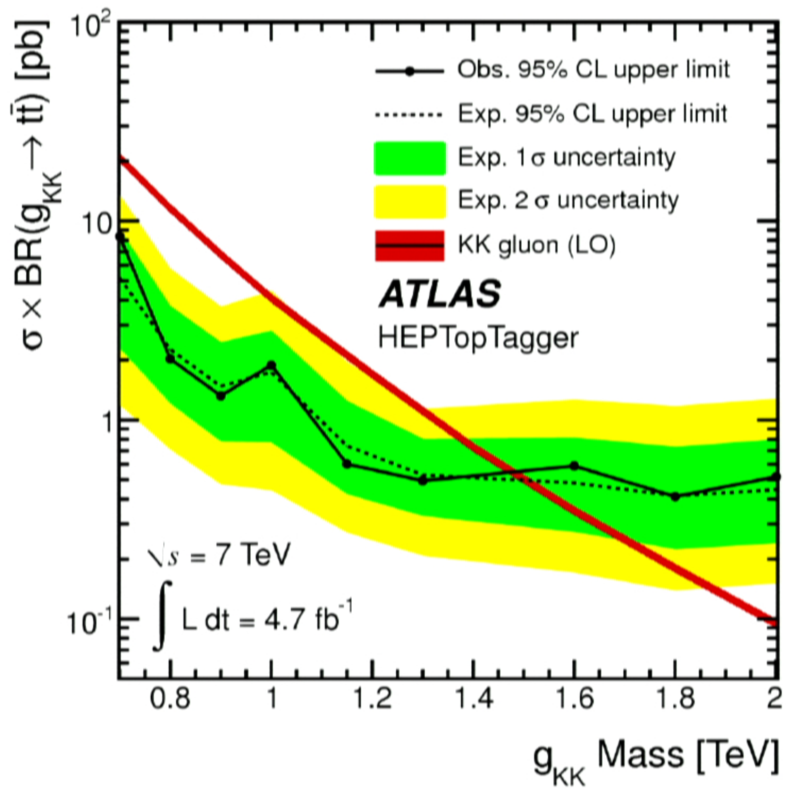
Sophisticated jet substructure based top-tagging required to reduce multi-jets background in searches in fully hadronic final state

First ATLAS study uses HEPTopTagger and Template top tagging

→ JHEP1301 (2013) 116

tt resonances: boosted fully hadronic





Sophisticated jet substructure based top-tagging required to reduce multi-jets background in searches in fully hadronic final state

First ATLAS study uses HEPTopTagger and Template top tagging
→ JHEP1301 (2013) 116

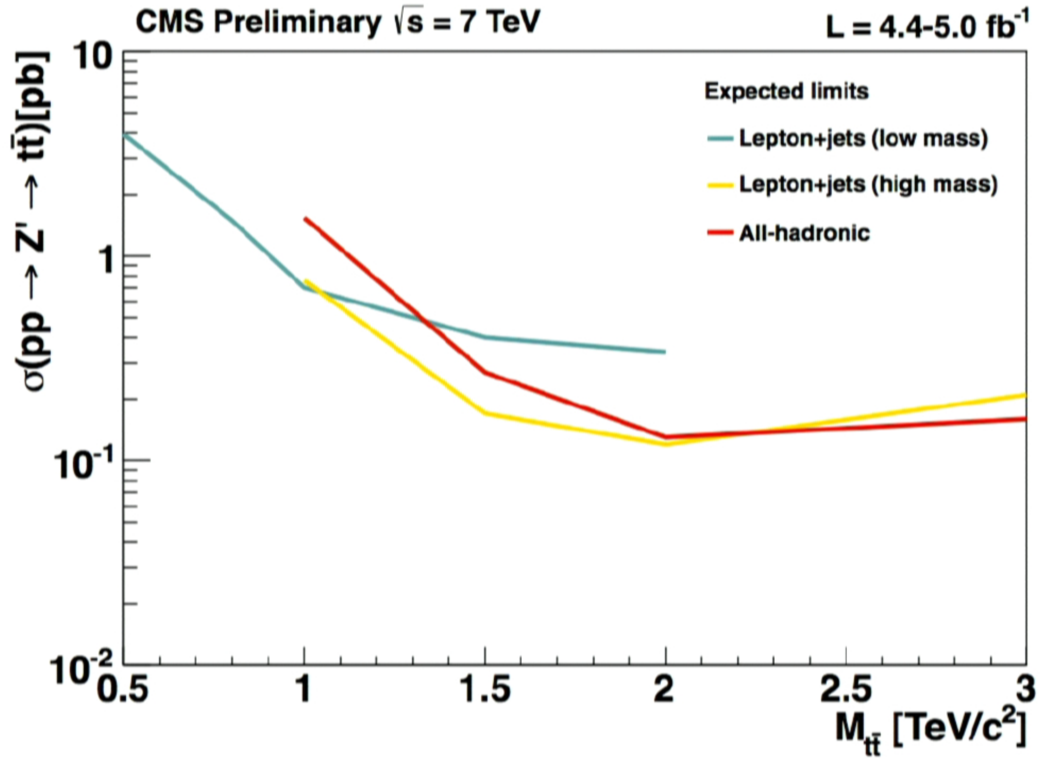
ATLAS resonance searches – executive summary

Final state	di-lepton	lepton+jets	boosted l+jets	Boosted fully had	combined l+jets
Preprint/publication	EPJC72	EPJC72	JHEP1209	2012-102	2012-136
Data set	2 fb^{-1}	2 fb^{-1}	2 fb^{-1}	4.7 fb^{-1}	4.7 fb^{-1}
Z' limits [TeV]	-	0.55 - 0.88	0.6 - 1.15	0.7 – 1.3	0.7 – 1.7
g_{KK} limits [TeV]	0.5 - 1.08	0.5 - 1.13	0.6 - 1.5	0.7 – 1.5	0.7 – 1.9

Better (more specialized) algorithms allows us to achieve better sensitivity on the same data set!

marcel.vos@ific.uv.es

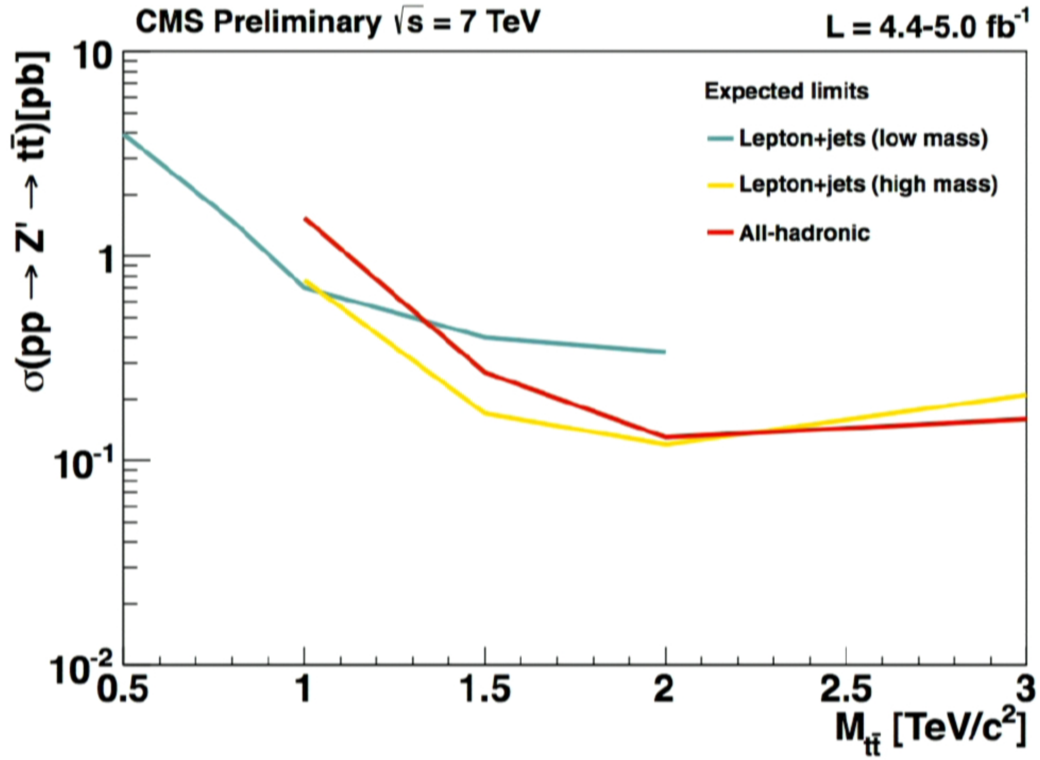
And CMS?



Same story here!

(not discussing the relative sensitivities of ATLAS and CMS today)

And CMS?

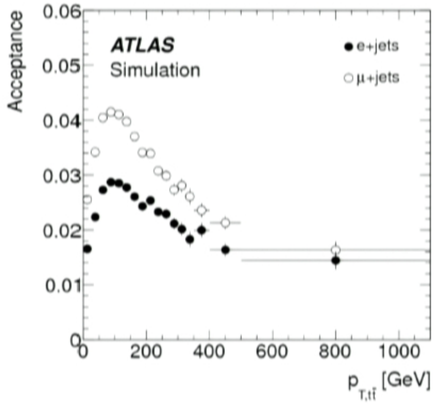


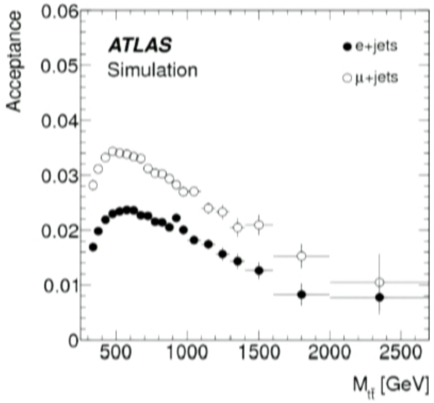
Same story here!

(not discussing the relative sensitivities of ATLAS and CMS today)

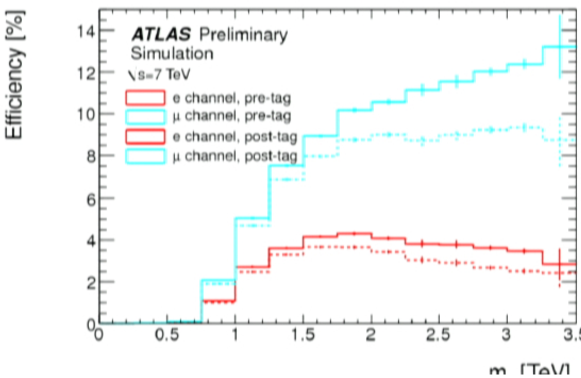
Boosted top quarks

Classical algorithms have good acceptance for top quarks at rest, but are not adequate for boosted top quarks : see ATLAS differential tt x-sec measurement: arXiv:1207.5644



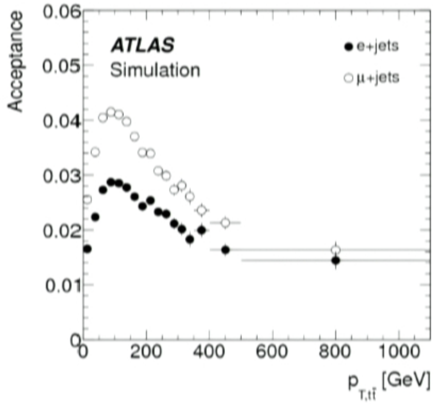


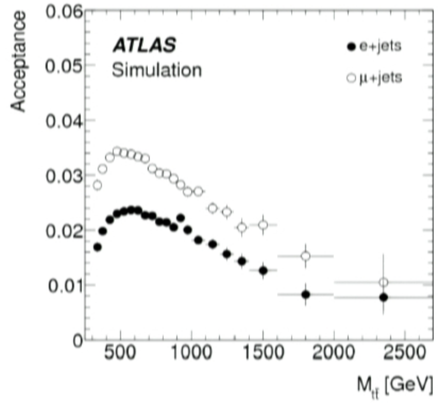
Signal acceptance is important …



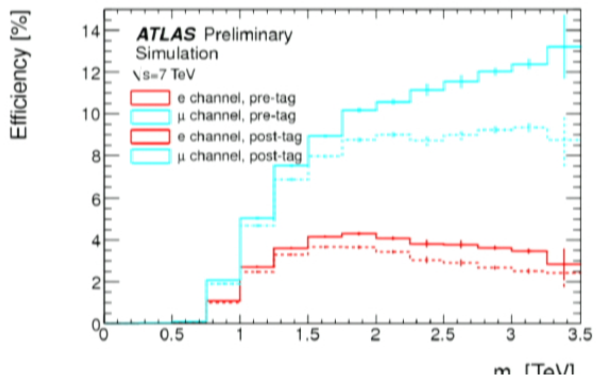
Boosted top quarks

Classical algorithms have good acceptance for top quarks at rest, but are not adequate for boosted top quarks : see ATLAS differential tt x-sec measurement: arXiv:1207.5644





Signal acceptance is important …

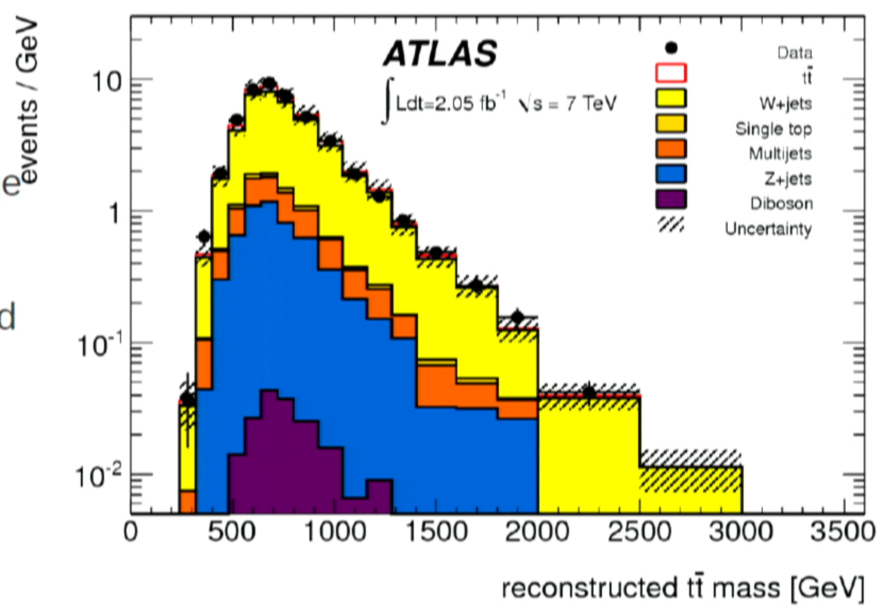


Why does this work?

... as is (data-driven) control over the backgrounds

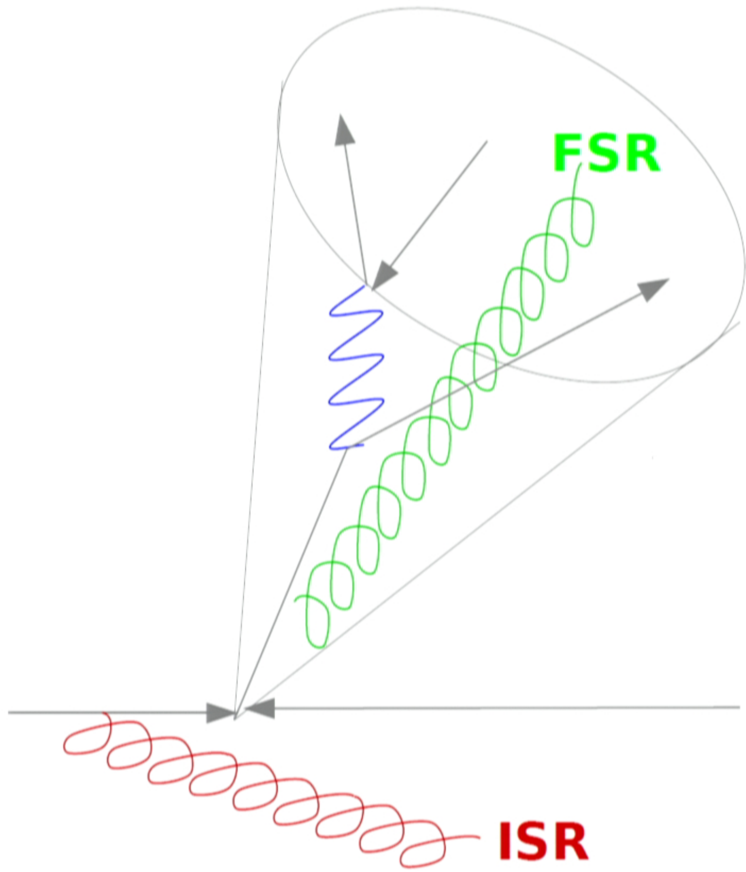
W+jets enriched control region after normalization using charge asymmetry method

No factors 2 due to Ws radiated off jets...



marcel.vos@ific.uv.es

Improving: mass resolution



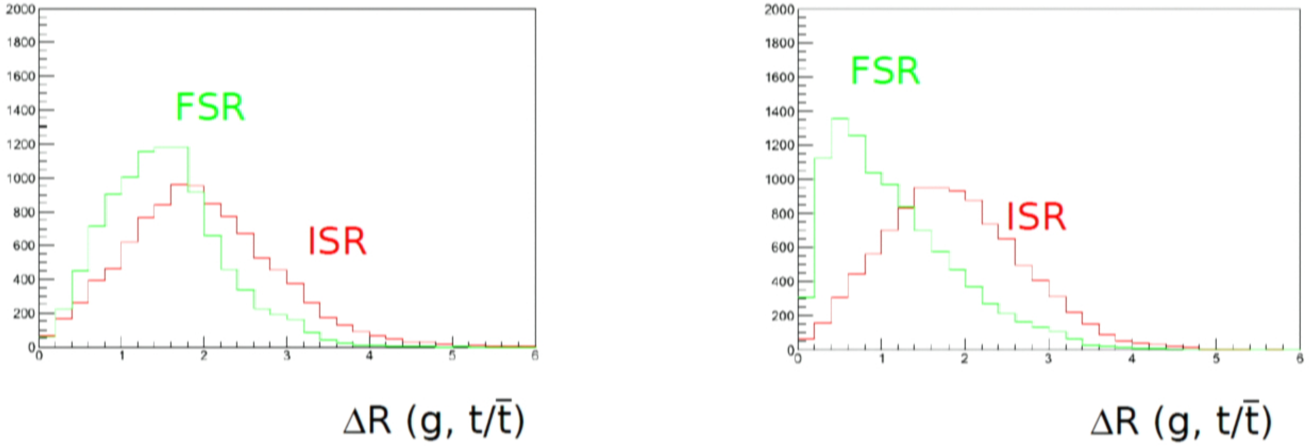
We need to include FSR to get the correct resonance mass

But we should not add ISR jets!

marcel.vos@ific.uv.es

ISR/FSR

MadGraph pp → $t\bar{t}$+g



Resonance mass = 500 GeV

Resonance mass = 2 TeV

For sufficiently boosted top quarks, the FSR seems to stay close enough

marcel.vos@ific.uv.es

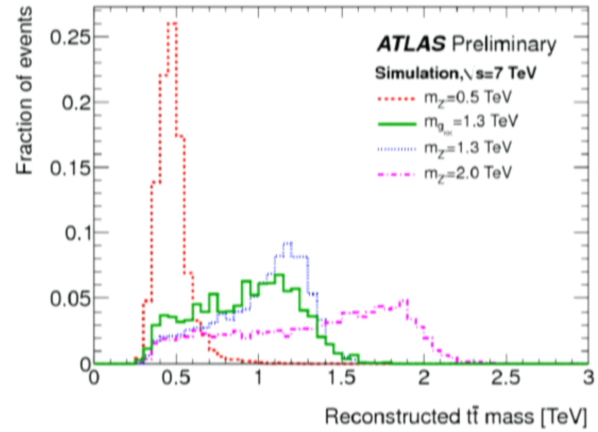
Improving mass resolution

Both algorithms do more or less equally well on the core resolution, but the tails are different!

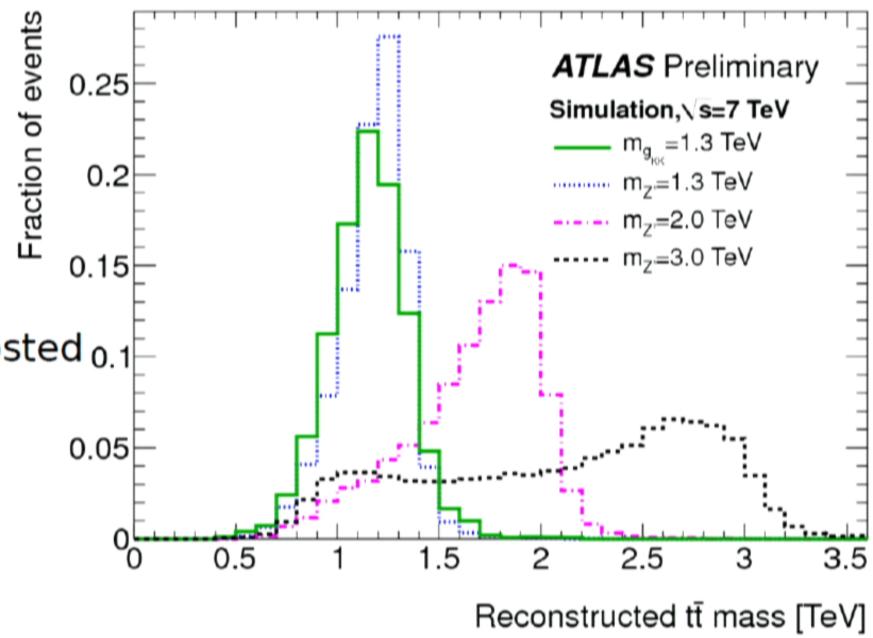
Boosted algorithm tends to underestimate mass
→ slight acceptance loss

Resolved algorithm tends to promote low-mass events into the tails
→ dangerous migration

Resolved

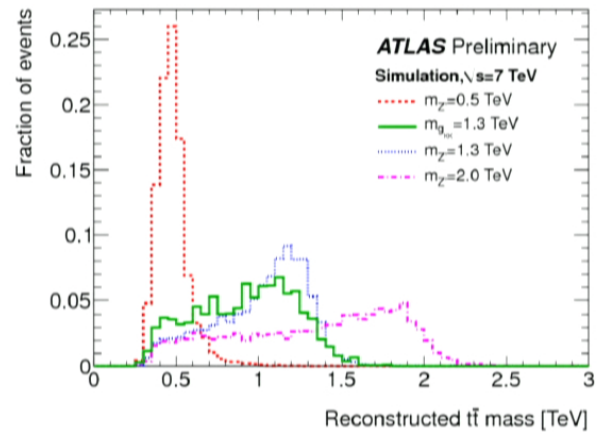


Boosted



Improving mass resolution

Resolved

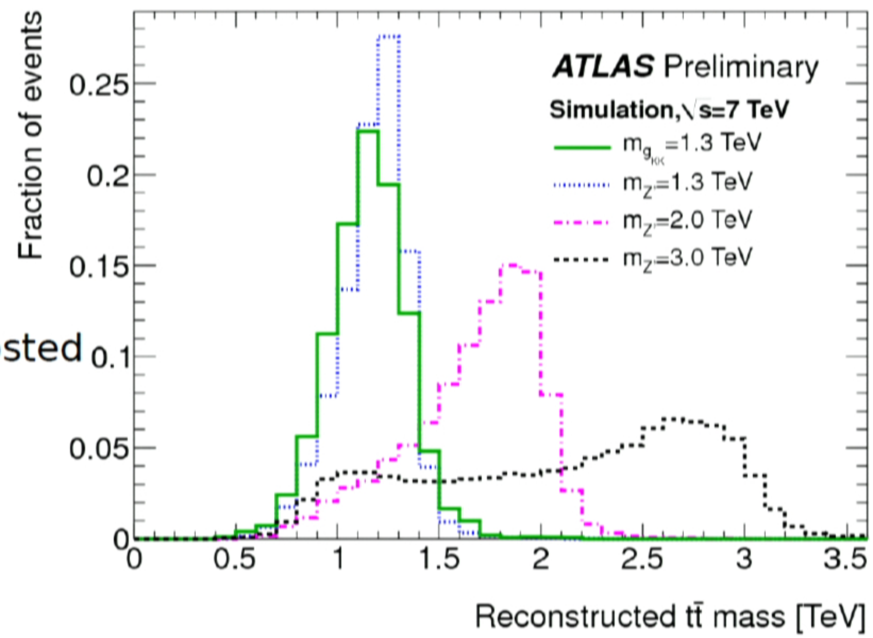


Both algorithms do more or less equally well on the core resolution, but the tails are different!

Boosted algorithm tends to underestimate mass
→ slight acceptance loss

Resolved algorithm tends to promote low-mass events into the tails
→ dangerous migration

Boosted



How can we improve these searches

30 sources of systematic uncertainty on yield and shape of background and signal

Jet energy and mass scale (5-7%) dominates boosted analysis

Parton shower & b-tagging also important

Impact on Systematic effect	*Resolved selection* yield [%] total bgr.	Z'	*Boosted selection* yield [%] total bgr.	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

*Impact depends on signal model considered. Large uncertainty on background yield ($t\bar{t}$) → small impact on the exclusion limit for narrow resonances

Tools and Techniques: grooming (II)

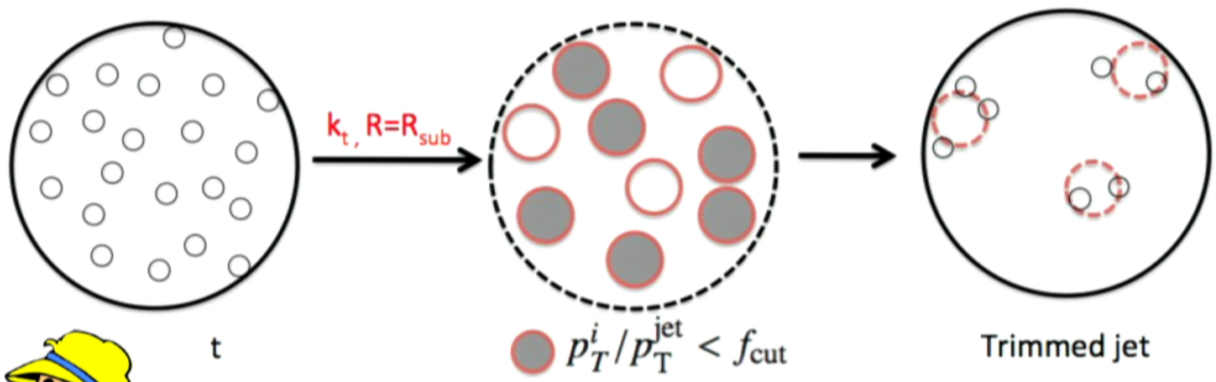
Jet grooming techniques **to remove the "softest" part of the jet:**

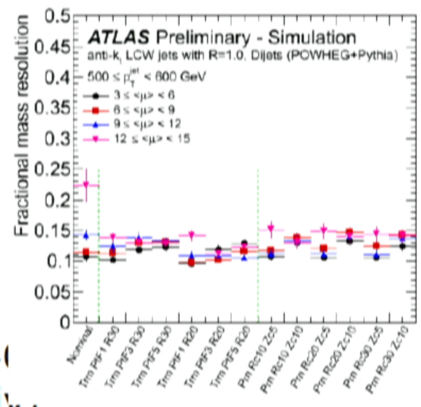
✓**Filtering:** break jet into subjets on angular scale R_{filt}, take n_{filt} hardest subjets
Butterworth, Davison, Rubin & Salam '08

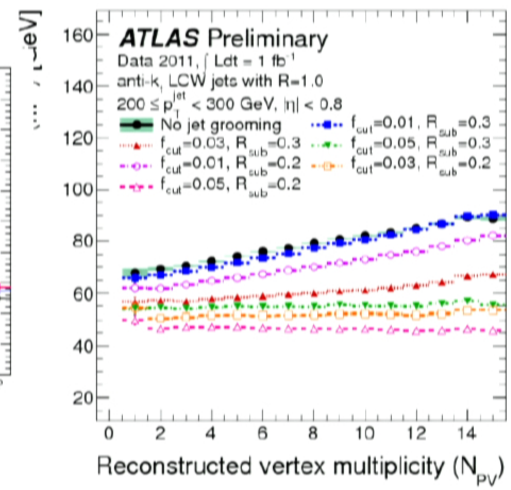
✓**Trimming:** break jet into subjets on angular scale R_{trim}, take all subjets with $p_{T,sub} > \varepsilon_{trim} p_{T,jjet}$
Krohn, Thaler & Wang '09

✓**Pruning:** building up the jet, if the two subjets about to be recombined have $R > R_{prune}$ and $\min(p_{T1}, p_{T2}) < \varepsilon_{prune} (p_{T1} + p_{T2})$, discard the softer one.
Ellis, Vermilion & Walsh '09

Trim!





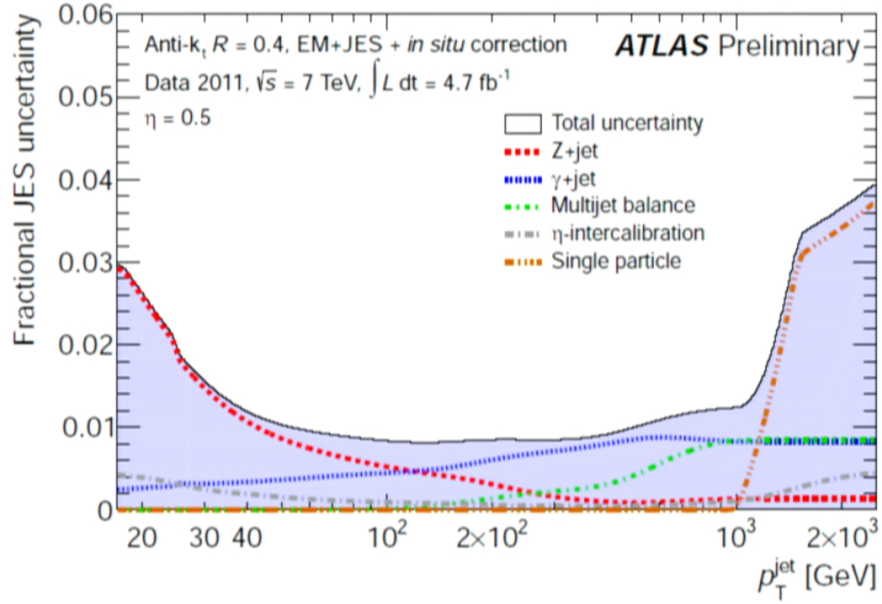


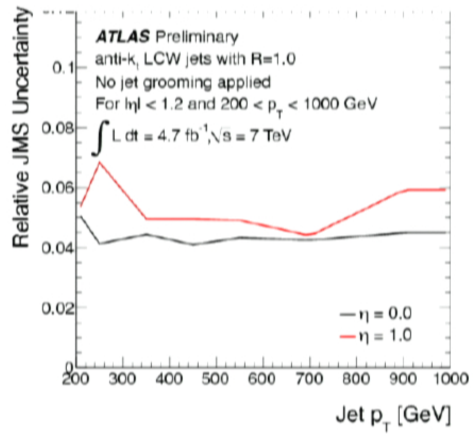
Performance of large-R jets…ATLAS-CONF-2012-(
(keep an eye on the arXiv)

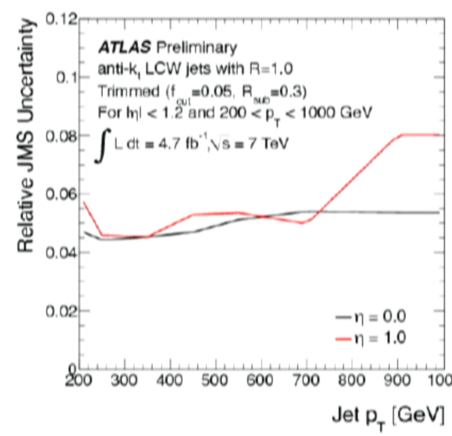
Jet Mass Scale??

Jet mass scale uncertainty does not yet want to descend to the level of the jet energy scale energy...

Is this because the MC is really not to be trusted to better than 5% for jet mass (even after grooming)
Or are we simply not yet able to constrain the mass scale (using ratios of calorimeter and track jets) as well as the energy scale?







marcel.vos@ific.uv.es

Jet Mass Scale??

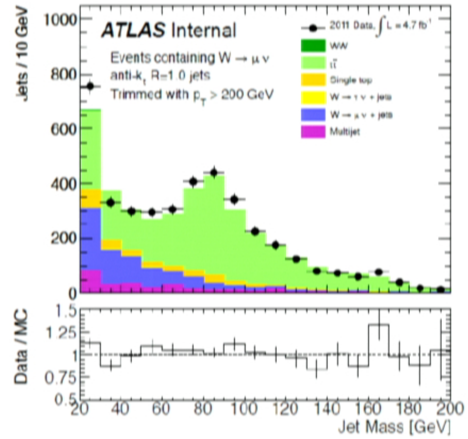
Boosted W in tt decays

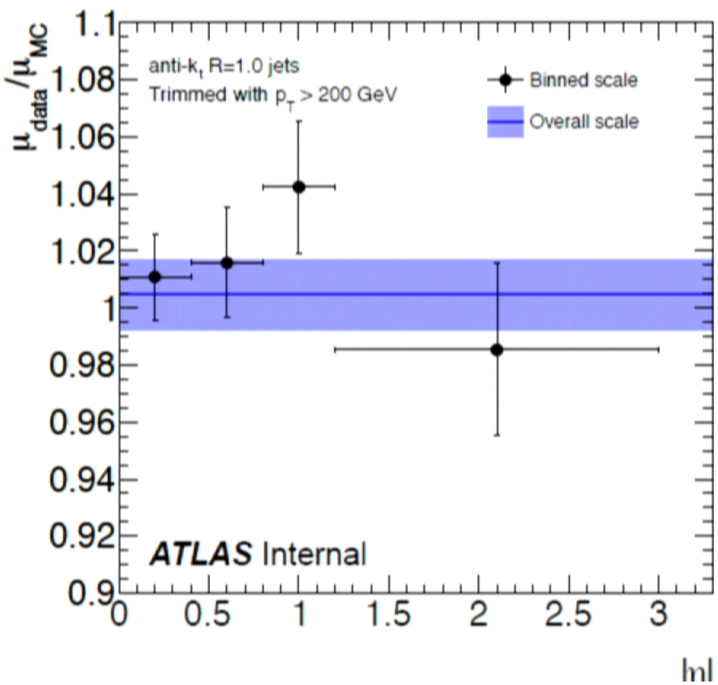
Better handle: includes the uncertainty due to the presence of a real boosted object

More precise handle: overall scale estimated to couple of %.

Result is compatible with 1!
MC is not doing too badly!

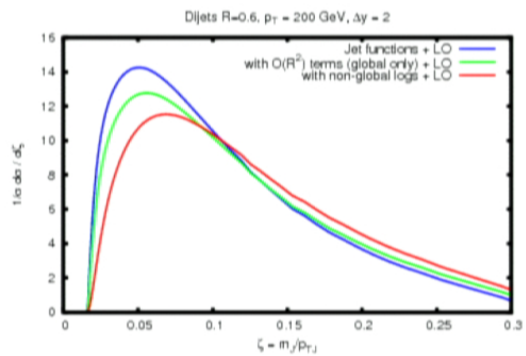
Ask Adam, David and Emily

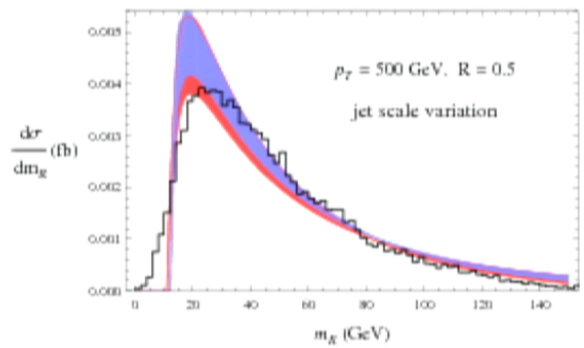




Theory input

Can we understand jet substructure?





Still some way to go before a meaningful comparison with data is possible

Push QCD calculations into new areas: brave attempts to describe the structure of jets with first-order QCD calculation

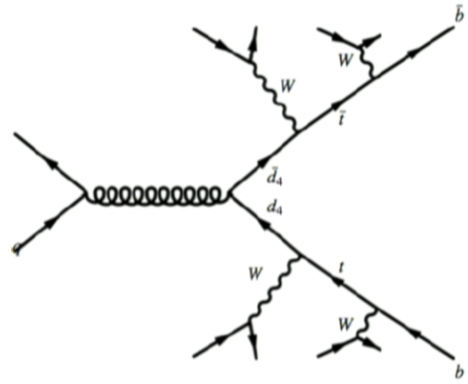
pQCD: M. Dasgupta, K. Khelifa-Kerfa, S. Marzani, M. Spannowsky, JHEP 1210 (2012) 126

SCET: I. Feige, M. Schwartz, I. Stewart, J. Thaler, Phys. Rev. Lett. 109 (2012) 092001

Y.T. Chien, R. Kelley, M. Schwartz, H.X. Zhu, arXiv:1208.0010

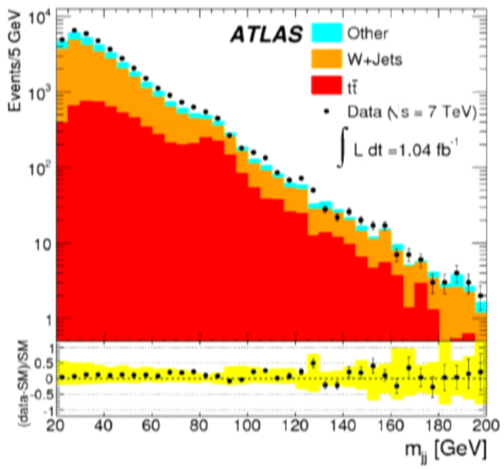
T. Jouttenus, I. Stewart, F. Tackmann, W. Walewijn,

b' → Wt

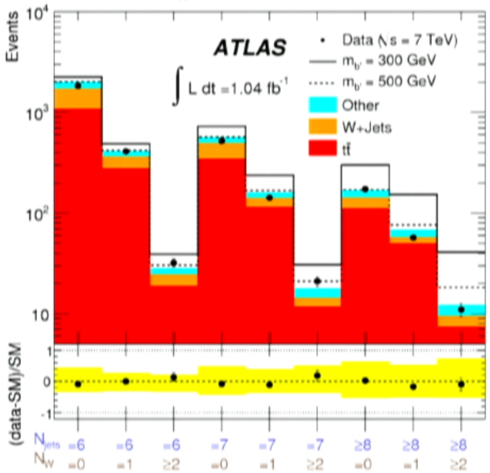


“Boosted objects without substructure”
(ATLAS b' search in arXiv:1202.6540)
Signal: tt pair + 2 boosted W bosons

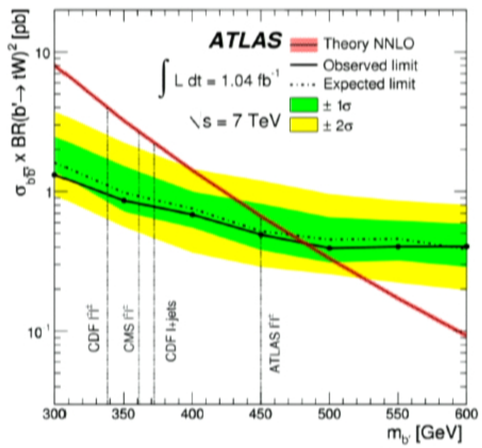
Combine two R=0.4 jets in a ΔR < 1 cone



Count the Ws (pairs with $70 < m_{jj} < 100$ GeV

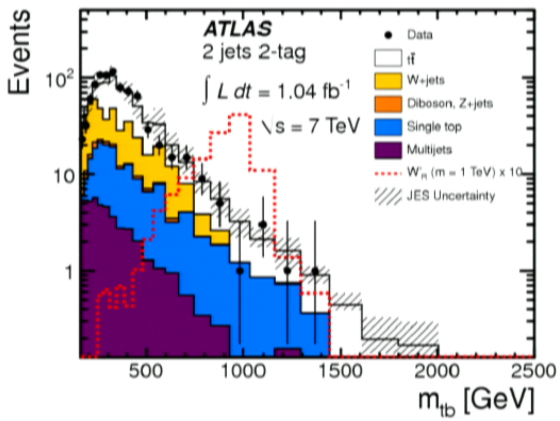


Exclusion at 95 % CL m(b') < 480 GeV

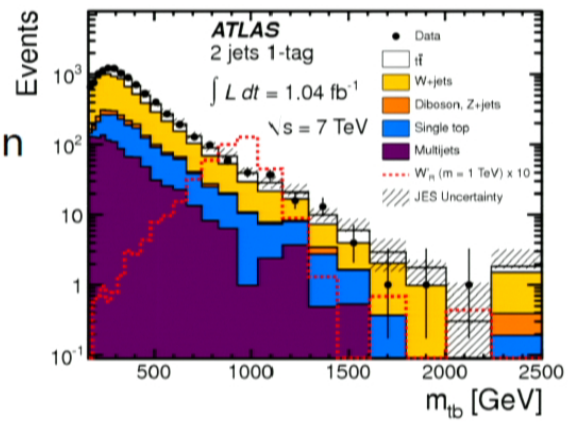


Search for tb resonances in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detect

Analyses to be boosted: W' → tb

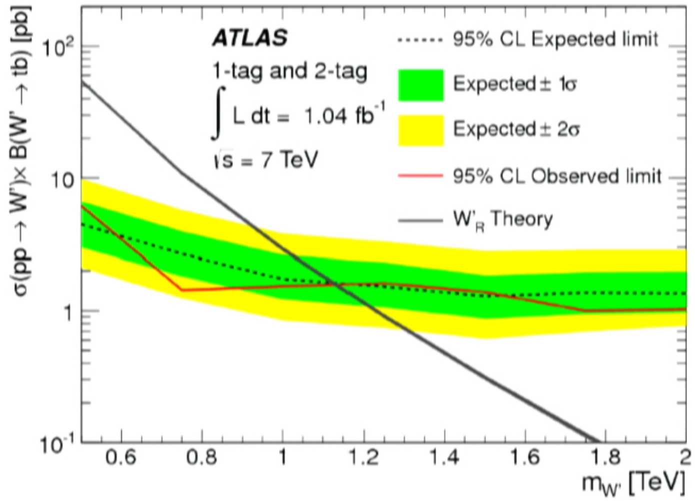


Single and double tagged signal region

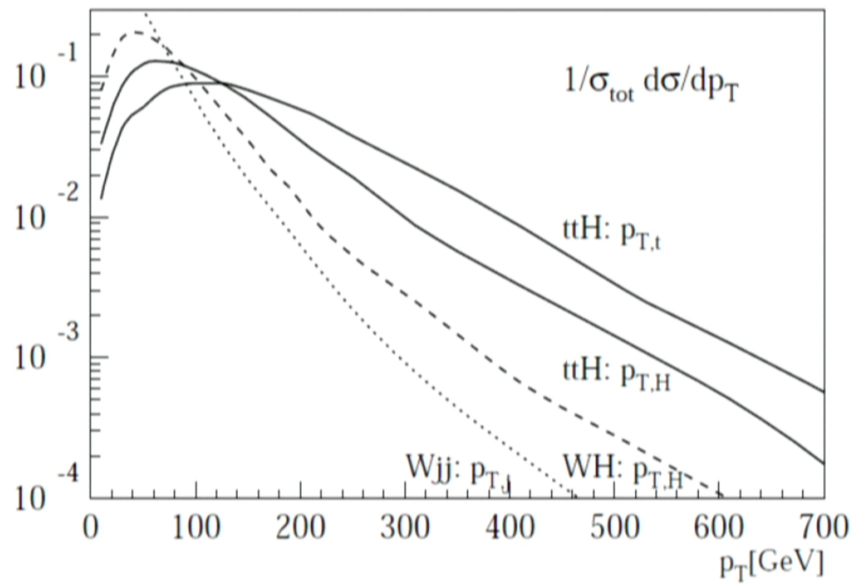


Selection similar to single top (but less stringent)

Can benefit from alternative isolation for leptons from boosted top decay developed for tt resonance searches



$t\bar{t}H$



A signal that's actually there!

Due to poor $b\bar{b}$ mass resolution and large combinatorics this is something in between a counting experiment and a resonance search

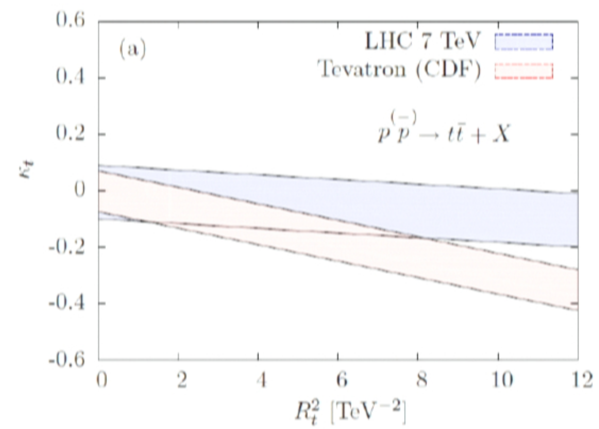
Hardly any events have highly boosted top, anti-top and Higgs, but moderate boost helps work out assignment of energy deposits to t and H candidates

"Combinatorial backgrounds are not a problem,and we find a multitude of distributions distinguishing between signal and continuum background."

Plehn, Salam, Spannowsky, Phys.Rev.Lett. 104 (2010) 111801

Constraints on top quark structure

C. Englert, A. Freitas, M. Spira and P. Zerwas, arXiv:1210.2570 [hep-ph]



Constraining the top chromo-magnetic moment using gg → tt

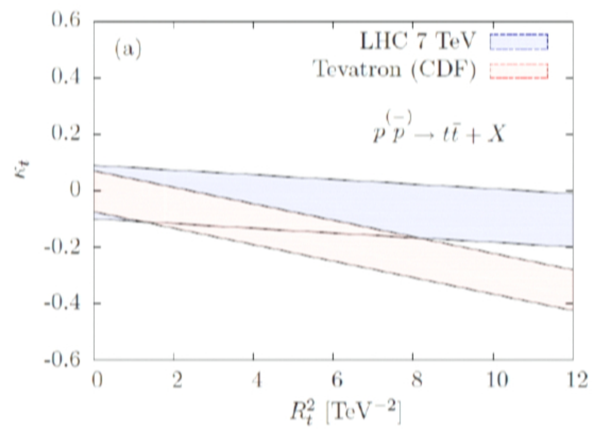
	R_t [TeV^{-1}] / [10^{-16} cm]	$\lvert k_t \rvert$
Tevatron + LHC @ 7 TeV	2.9 / 0.57	0.17
Tevatron + LHC @ 14 TeV	2.1 / 0.41	0.07
LHC @ 14 TeV + boosted top	0.7 / 0.14	0.05

See also: Degrande, Gerard, Grojean, Maltoni, Servant, Phys.Lett. B703 (2011) 306-309

Combined x-sec measurement: ATLAS-CONF-2012-134
Differential x-sec measurement: arXiv:1207.5644

Constraints on top quark structure

C. Englert, A. Freitas, M. Spira and P. Zerwas, arXiv:1210.2570 [hep-ph]



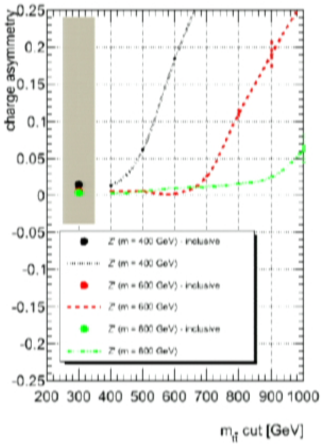
Constraining the top chromo-magnetic moment using gg → tt

	R_t [TeV^{-1}] / [10^{-16} cm]	$\|k_t\|$
Tevatron + LHC @ 7 TeV	2.9 / 0.57	0.17
Tevatron + LHC @ 14 TeV	2.1 / 0.41	0.07
LHC @ 14 TeV + boosted top	0.7 / 0.14	0.05

See also: Degrande, Gerard, Grojean, Maltoni, Servant, Phys.Lett. B703 (2011) 306-309

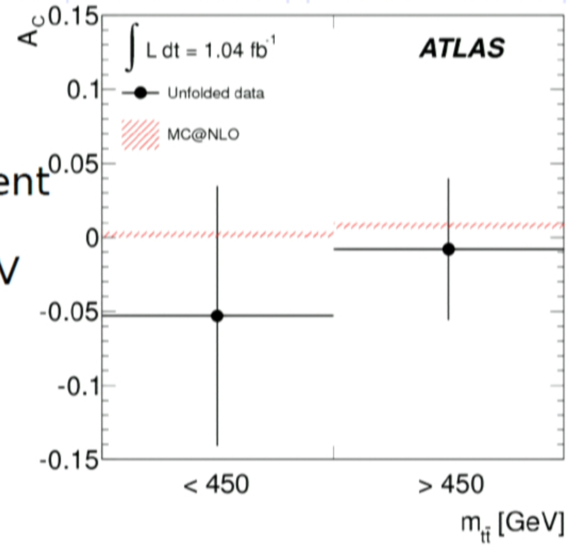
Combined x-sec measurement: ATLAS-CONF-2012-134
Differential x-sec measurement: arXiv:1207.5644

Charge asymmetry

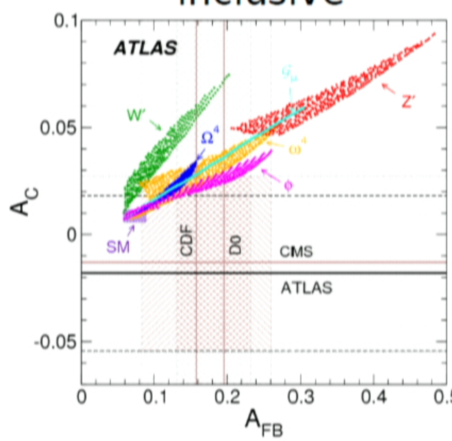


A_C vs. mass for Z' model
(V. Sanchez, A. Hyaya)

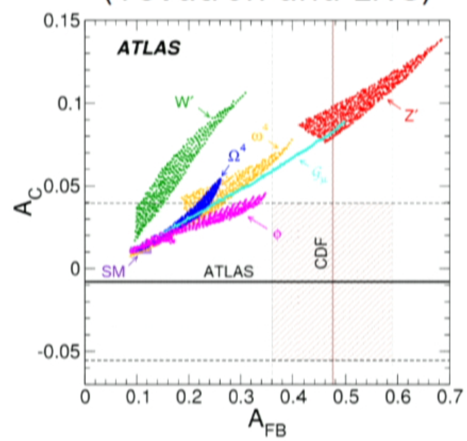
Inclusive measurement
and two mass bins
<450 GeV, >450 GeV



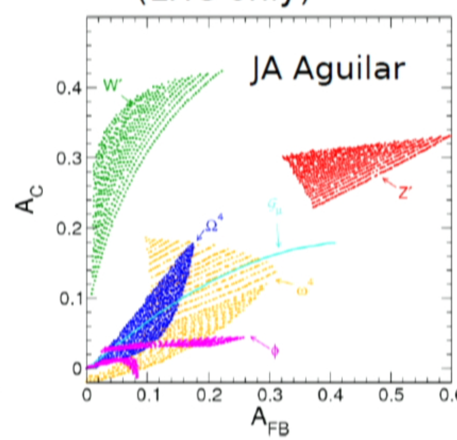
Impact on model zoo
inclusive



m_{tt} > 450 GeV
(Tevatron and LHC)

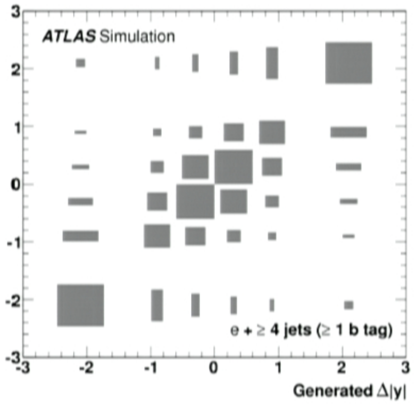


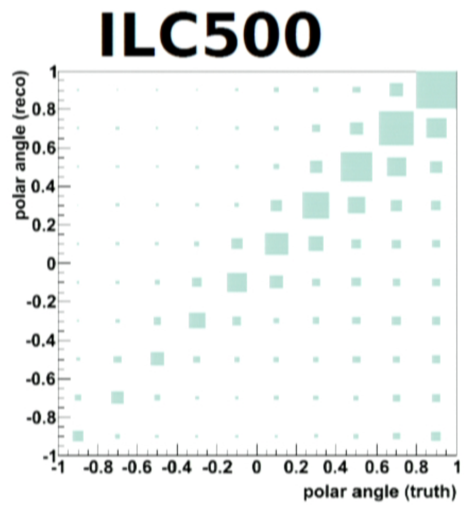
M_{tt} > 800 GeV
(LHC only)

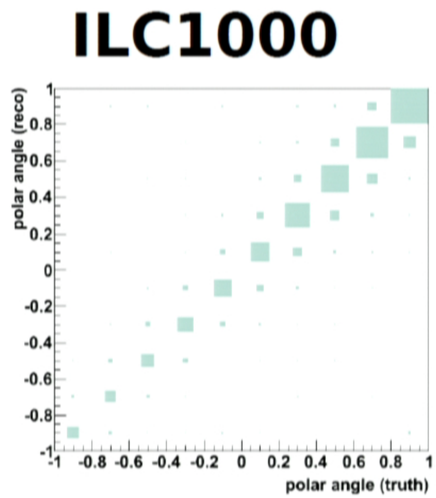


Charge asymmetry

If we select high mass and reconstruct them with adequate tools, we moreover get rid of the strong migration in the reconstructed top direction







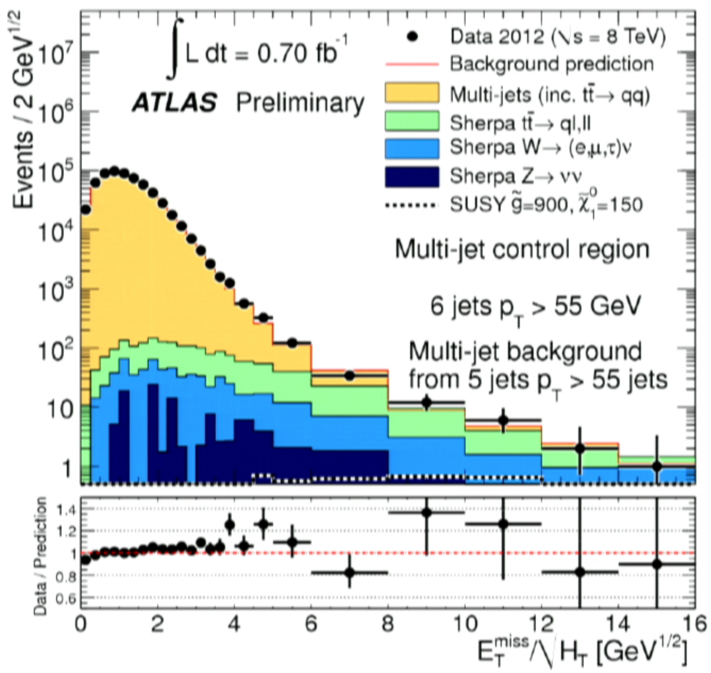
N. Garcia, E. Ros, MV, DESY ILC Forum 2012

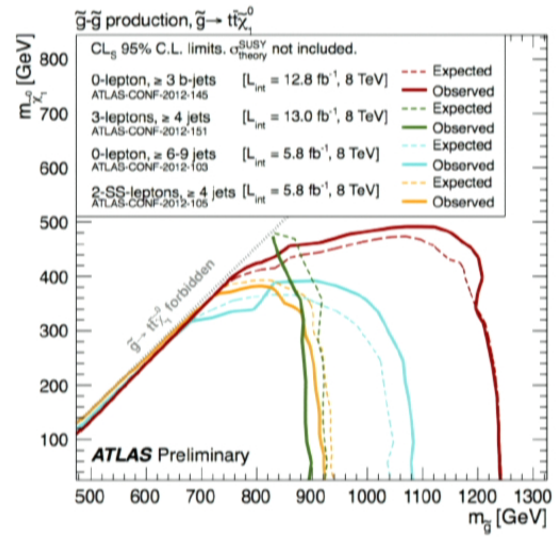
For another way of avoiding dilution of the asymmetry (boost along z), see:
Boosting the t tbar charge asymmetry. JA Aguilar, A Juste, F Rubbo, PLB707 (2012)

ATLAS multi-jet SUSY search

Sensitive to anything that produces high multiplicity

ATLAS-CONF-2012-103





Interpreted in a number of SUSY scenarios

Surprisingly good control over momentum imbalance in QCD multi-jet events...

Etmiss resolution dominated by stochastic term jet energy measurement

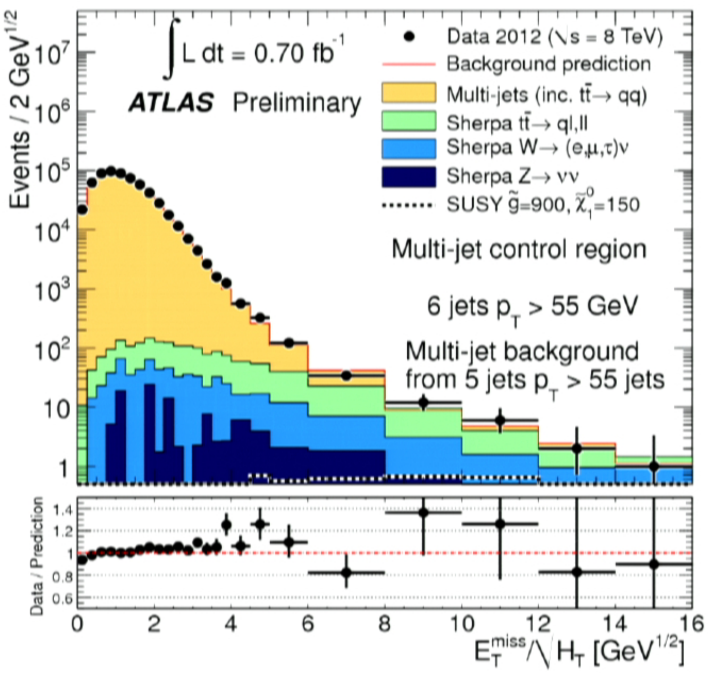
→ scales with H_T and is independent of N_j

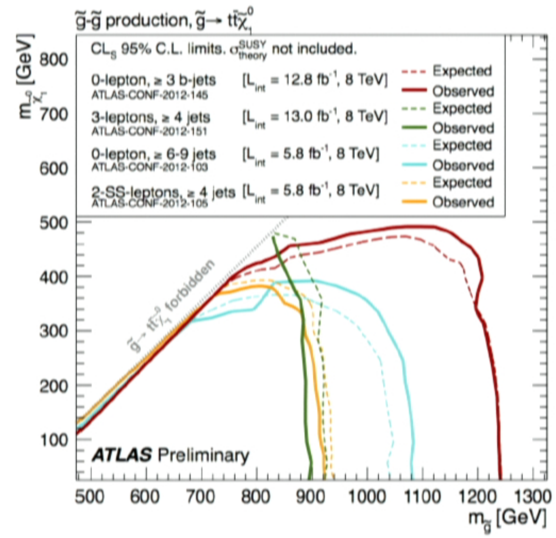
→ transfer template from signal-free region to signal region

ATLAS multi-jet SUSY search

Sensitive to anything that produces high multiplicity

ATLAS-CONF-2012-103





Interpreted in a number of SUSY scenarios

Surprisingly good control over momentum imbalance in QCD multi-jet events...

Etmiss resolution dominated by stochastic term jet energy measurement

→ scales with H_T and is independent of N_j

→ transfer template from signal-free region to signal region

Learning to count

Learning How to Count: A High Multiplicity Search for the LHC

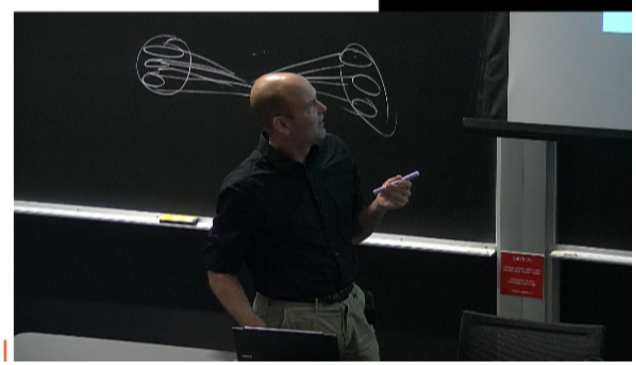
Can we predict jet mass in the same way?
Combining jets from signal-free di-jet events
into a more complex topology...
Can we even get rid of Etmiss altogether?

If you paid attention during Jay's talk you should know the answers...

marcel.vos@ific.uv.es

Missing

Could one perform a search on the (shape of the) jet mass spectrum for inclusive jet production?



Perspective

We've proven that boosted techniques help gain sensitivity

Continue to improve our tools

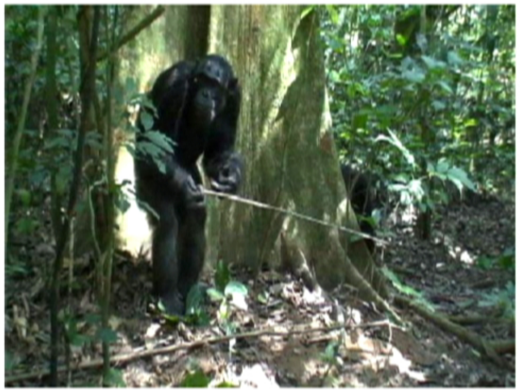
Set of searches steadily growing

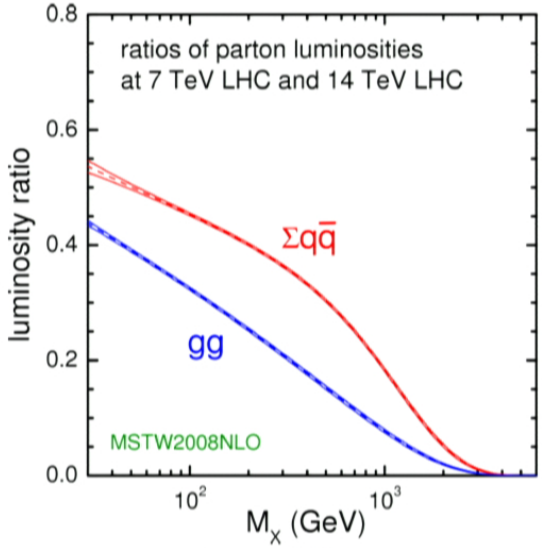
Perform first measurements of the boosted object production rate

Find the Higgs boson (or whatever it is) using substructure techniques

Fully hadronic final states

Get ready for 13-14 TeV





marcel.vos@ific.uv.es

Perspective

We've proven that boosted techniques help gain sensitivity

Continue to improve our tools

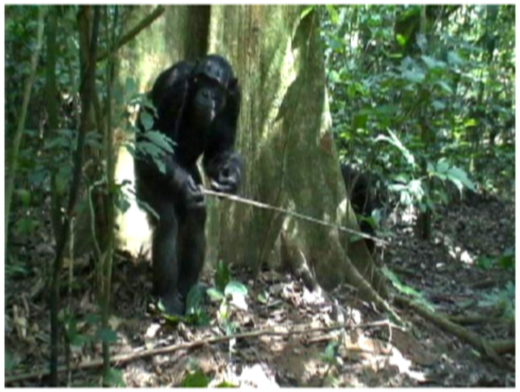
Set of searches steadily growing

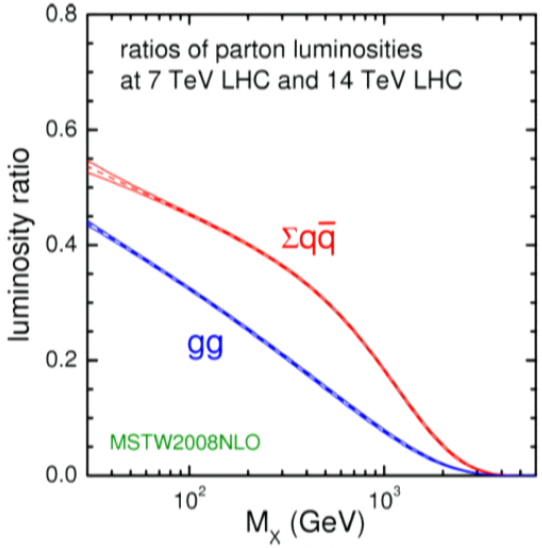
Perform first measurements of the boosted object production rate

Find the Higgs boson (or whatever it is) using substructure techniques

Fully hadronic final states

Get ready for 13-14 TeV





marcel.vos@ific.uv.es