Title: New Results in Jet Substructure

Date: Oct 23, 2012 01:00 PM

URL: http://pirsa.org/12100128

Abstract: We present new results on the performance of jet substructure techniques and their use in distinguishing the signatures of new boosted massive particles from the QCD background. Advanced approaches to jet reconstruction using jet grooming algorithms such as filtering, trimming, and pruning are compared. Measurements of the jet invariant mass for each jet algorithm are compared both at the particle level to multiple Monte Carlo event generators and at the detector level for several configurations of the jet grooming algorithms. The performance of these strategies and improvements in search sensitivity for new boosted hadronic particles are compared. Recent results using these techniques for both boosted RPV gluinos and top quark pairs from new particles are presented. The result is a comprehensive foundation for the use of substructure algorithms in the search for new physics at the LHC

Jets, Substructure, and Boosted Object Searches

Using new approaches to search for new physics in ATLAS

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Perimeter Institute for Theoretical Physics

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THE UNIVERSITY OF CHICAGO

23 October, 2012

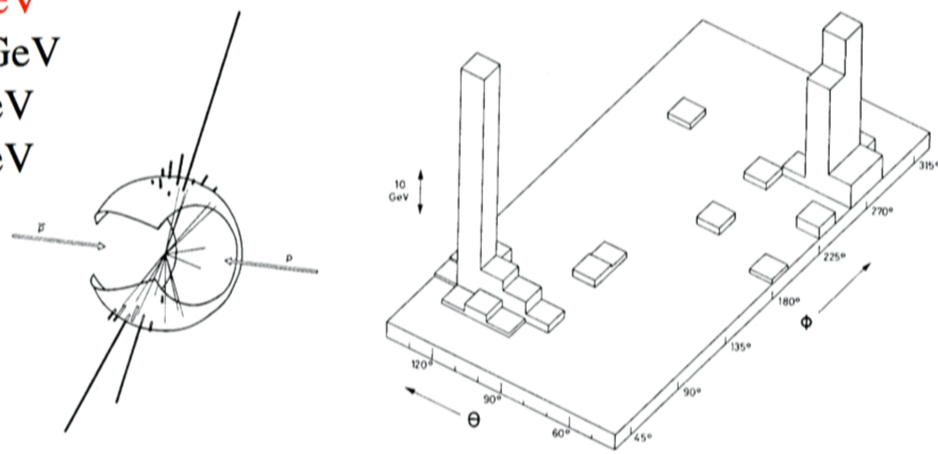
Roadmap

1. Introduction
2. The ATLAS detector
3. Quark gluon tagging and inclusive jet measurements of substructure
4. Boosted hadronic object tagging in data
5. New physics searches with substructure
6. Summary and Conclusions

Evidence for jet production at CERN's UA2 (1982)

First observation at a hadron-hadron collider

$\sqrt{s} = 540$ GeV
$m_{1,2} = 140$ GeV
$p_{T,1} = 60$ GeV
$p_{T,2} = 57$ GeV



(a) (b)

Fig. 4

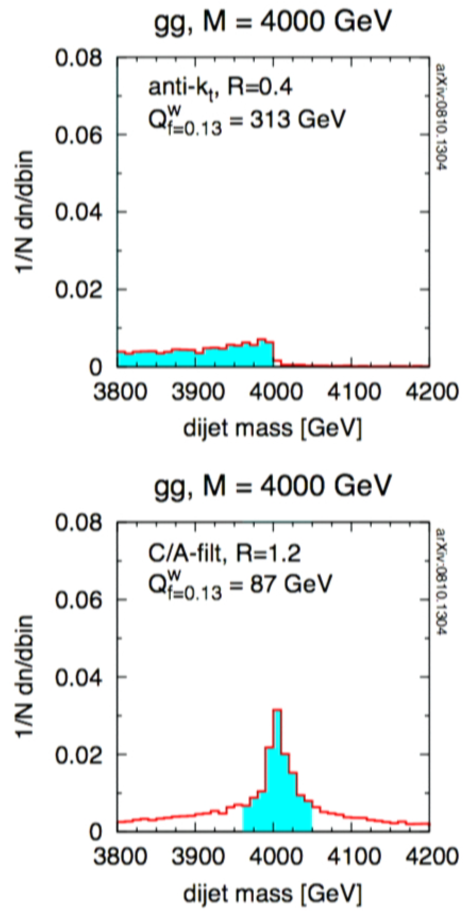
Figure 4 shows the configuration of the event with the largest value of ΣE_T, 127 GeV. It exhibits striking features : energy is concentrated within two small regions separated in azimuth by $\Delta\phi \simeq 180^\circ$ and towards which several collimated tracks are observed to point. In addition the transverse energies of the two clusters are approximately equal (57 and 60 GeV).

Impact of the jet definition on the di-jet mass resolution

- Dramatic difference depending on jet algorithm and size
- Jet "grooming" may be important
  - Dynamic modification of the jet algorithm in a theoretically well-defined manner
  - *Examples:* Trimming, filtering, pruning
- Ability to discover a new resonance may be compromised by our preconceived notions

→ ***Flexibility in jet definition is important.***

Gavin Salam:



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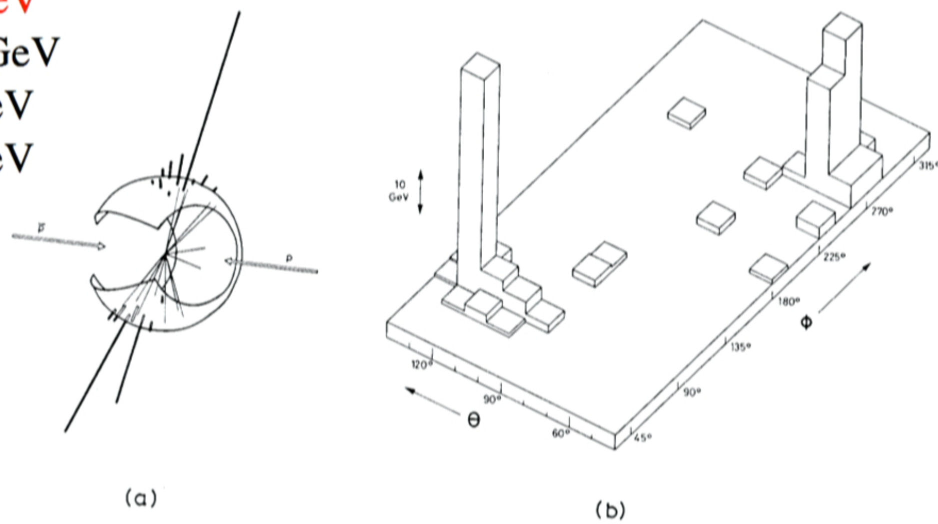

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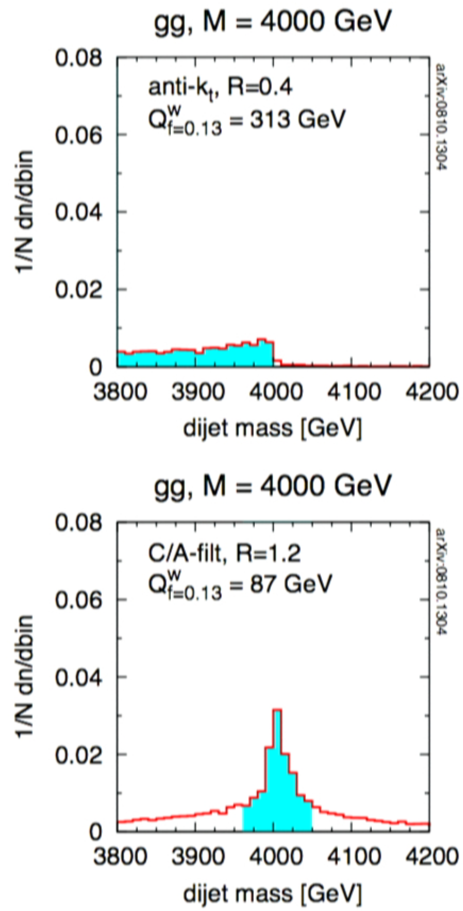
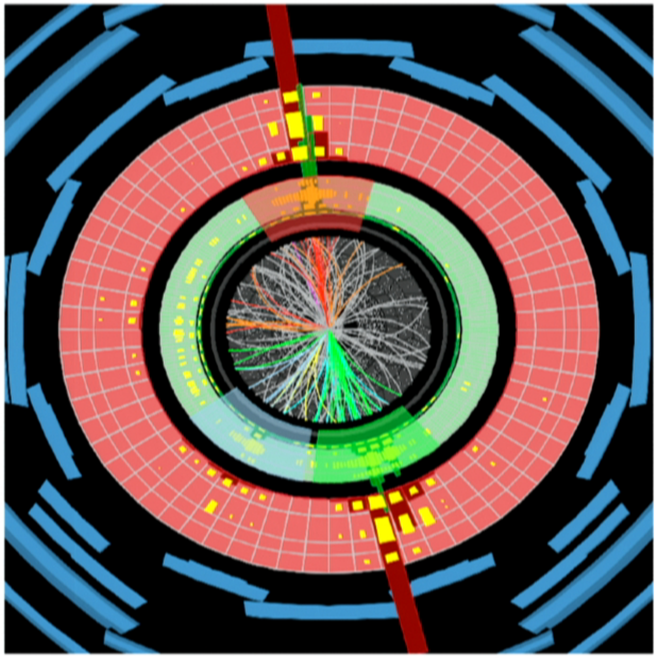
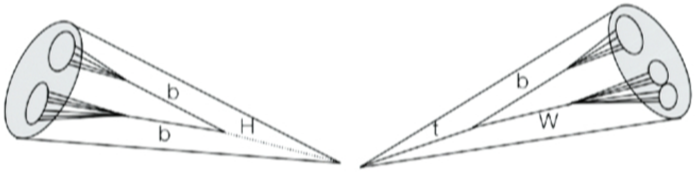


Relevance and motivation for jet substructure at the LHC

The structure of the jet itself begs for much **more** than just a simple 4-vector description.

- Develop understanding of the wide-angle emissions that give rise to jet mass (NLO, but *LO in the jet mass*!)
- Study the interplay of the parton shower with the matrix element description
- Provide a foundation on which to predict the backgrounds to new physics searches
- Assess tools for predicting the shapes and structure of jets formed from boosted massive particle decays to quarks and gluons



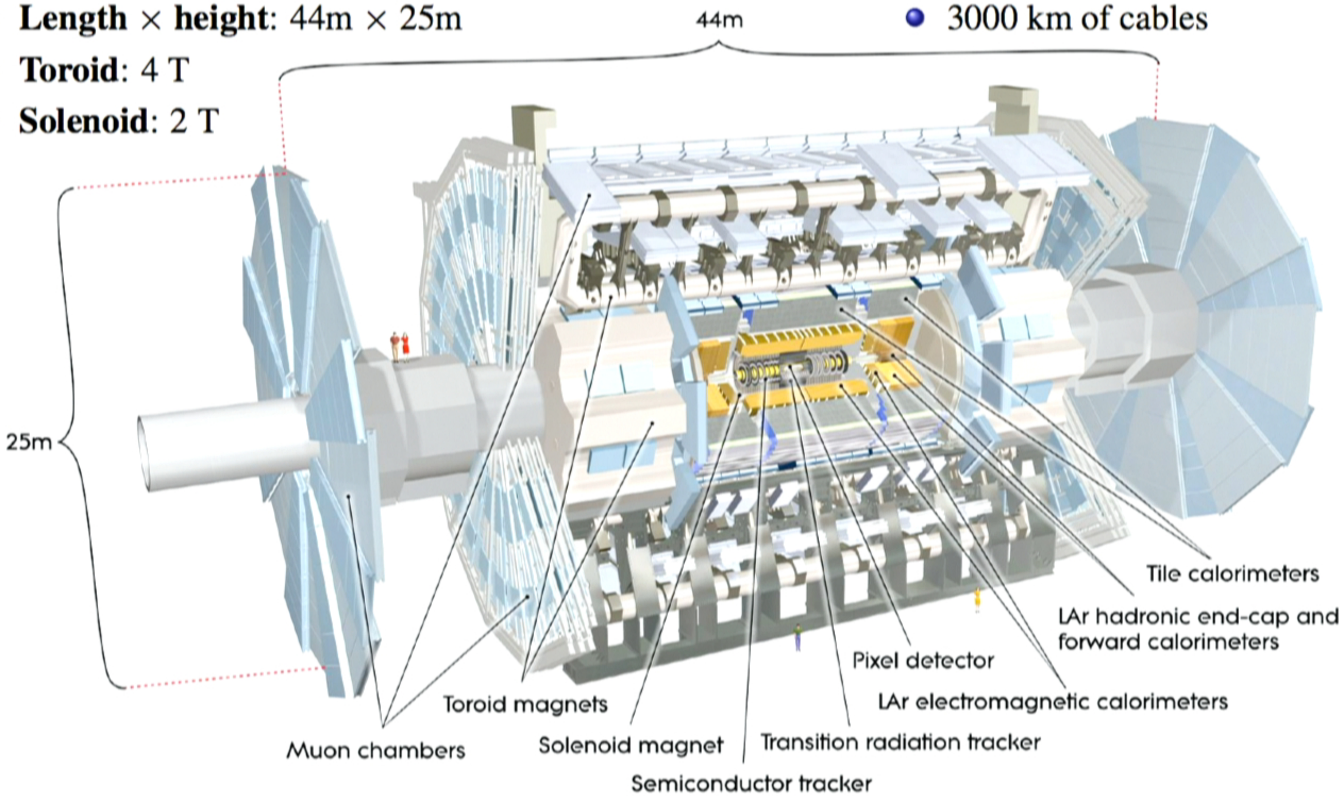


How much do these jets look like they have hard substructure?

The ATLAS detector at the LHC

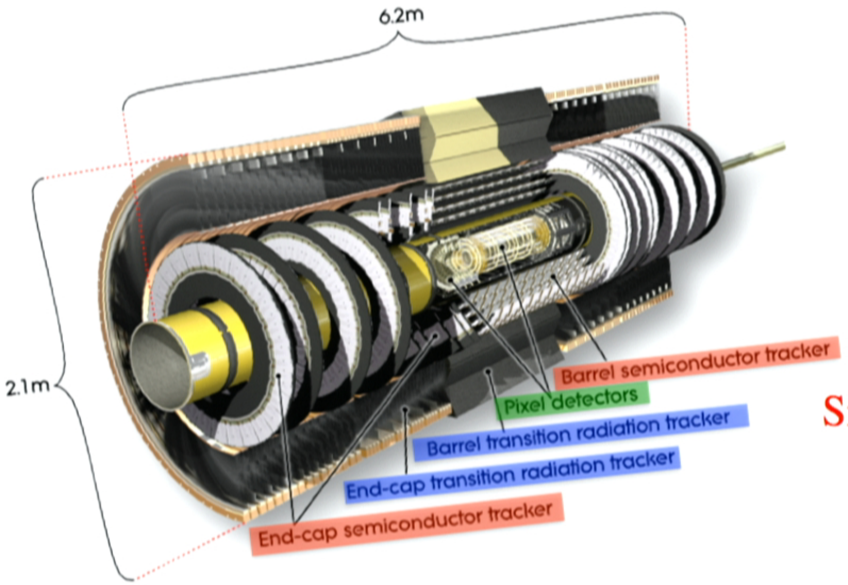
- **Weight**: 7000 tons
- **Length** × **height**: 44m × 25m
- **Toroid**: 4 T
- **Solenoid**: 2 T

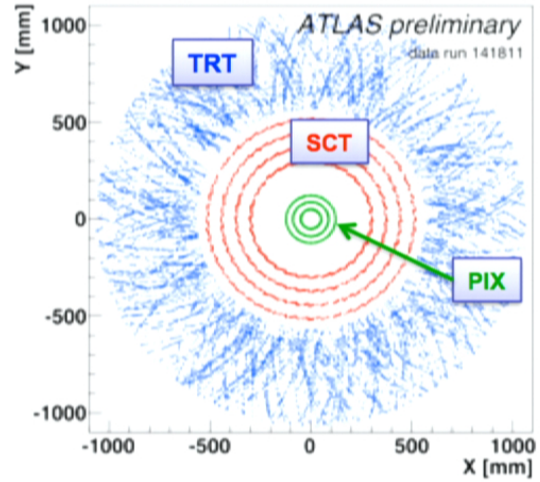
- 100,000,000 electronic channels
- 3000 km of cables



But the whole is more than just the sum of its parts...

The ATLAS tracking system





Transition Radiation Drift Tubes (TRT)

- 73 barrel straws, 2x160 end-cap disks
- $\sigma_r \sim 130\mu$m, particle ID
- 350k channels

Silicon Strips (SCT)

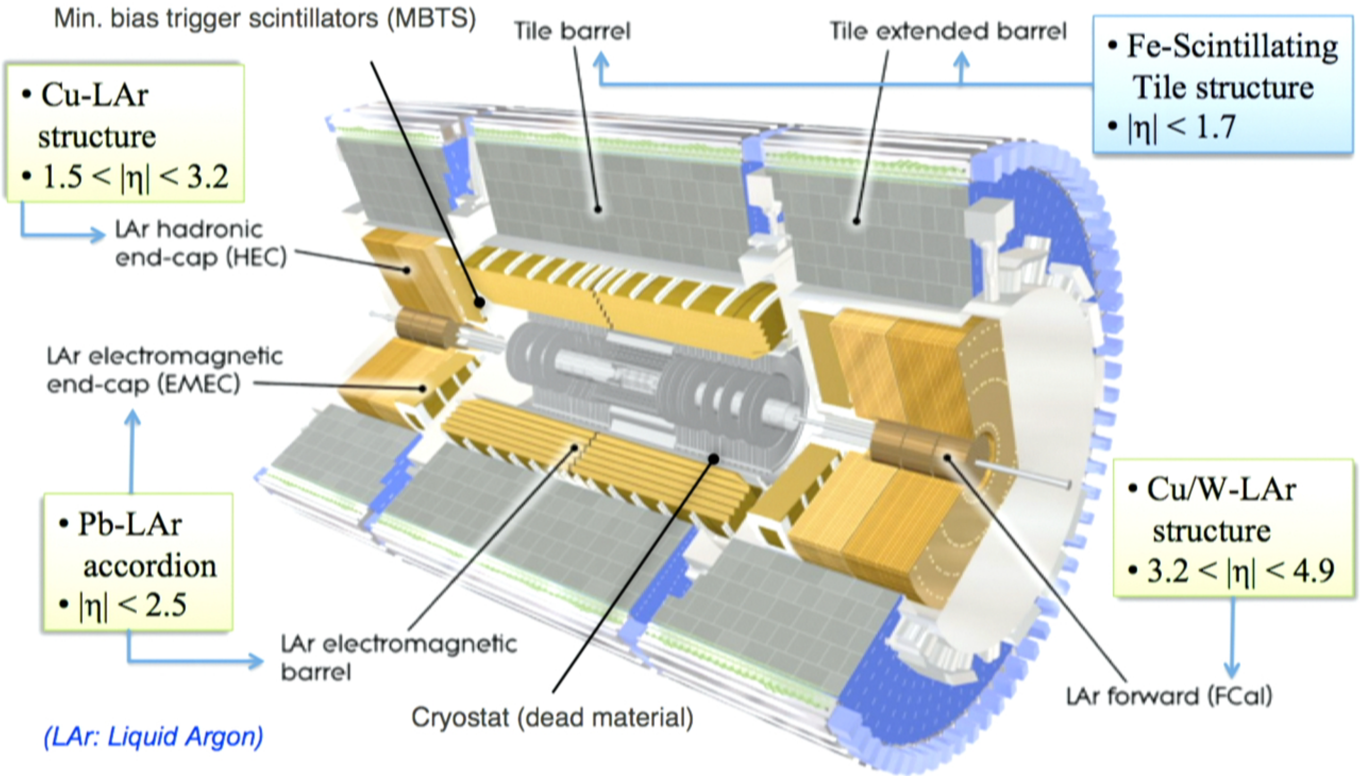
- 4 barrel layers, 2x9 end-cap disks
- $\sigma_{r\phi} \sim 17\mu$m, $\sigma_z \sim 580\mu$m
- 6.3M channels

Silicon Pixels (PIX)

- 3 barrel layers, 2x3 end-cap disks
- $\sigma_{r\phi} \sim 10\mu$m, $\sigma_z \sim 115\mu$m
- 80M channels

Excellent position resolution, tracking efficiency, vertexing performance.

The ATLAS calorimeter systems



Well known technologies with fast readout and high granularity.

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3. ***Quark gluon tagging and inclusive jet measurements of substructure***
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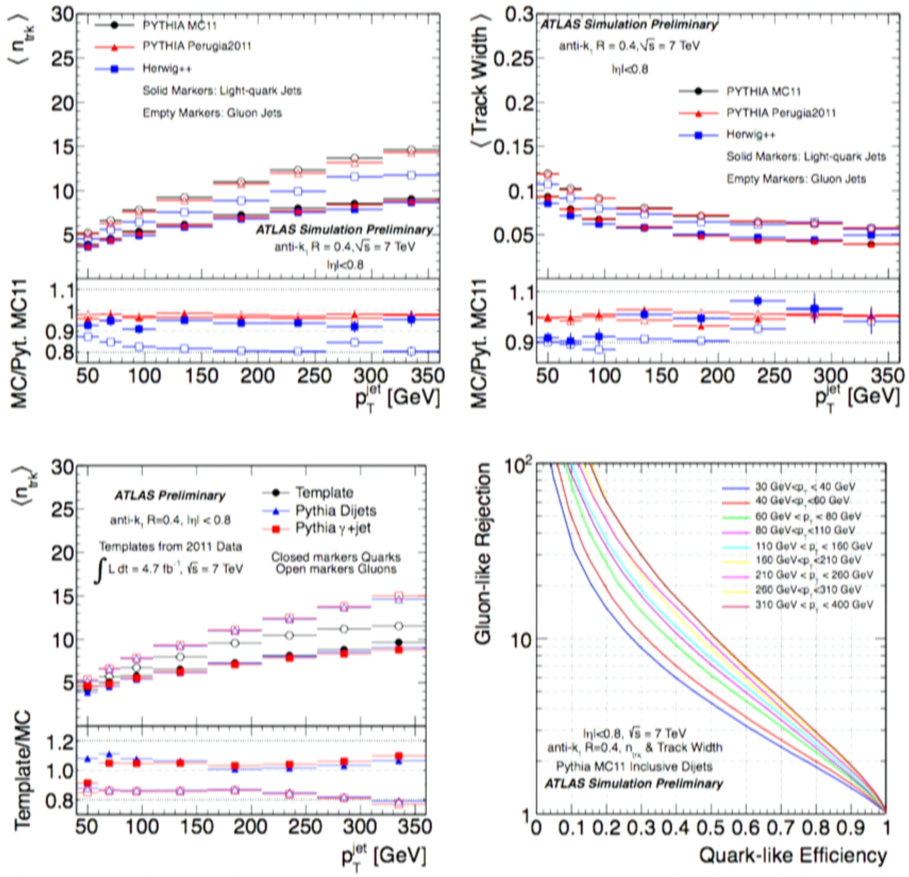
Quark vs. gluon tagging

ATLAS-CONF-2011-053 and additional ATLAS studies

- Use jet properties to distinguish **quark-like** from **gluon-like jets**
  - N_{track} and width (first moment of radial p_{T} distribution)
  - Schwartz and Gallichio (arXiv:1106.3076)
- HERWIG++ 2.5.2 gluon jet properties signif. different from PYTHIA, seems to agree with data

▸ More on Quarks vs. Gluons

- Applications in **Higgs, SUSY, Exotics, and SM** (*Lauren, Antonio, and Bjoern already exploring these*)



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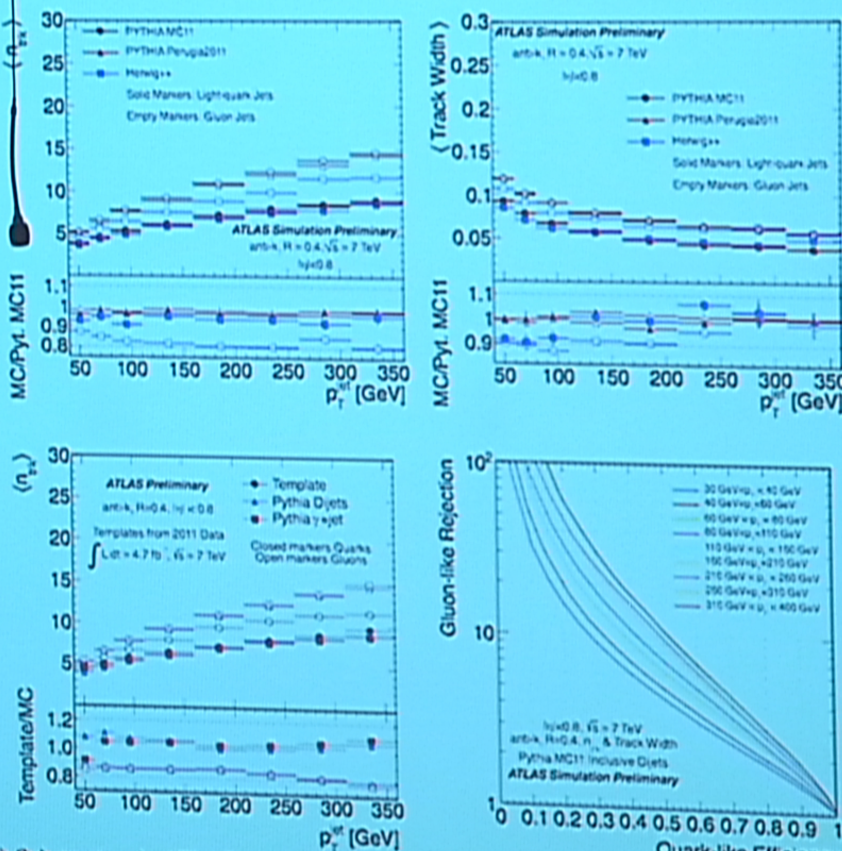

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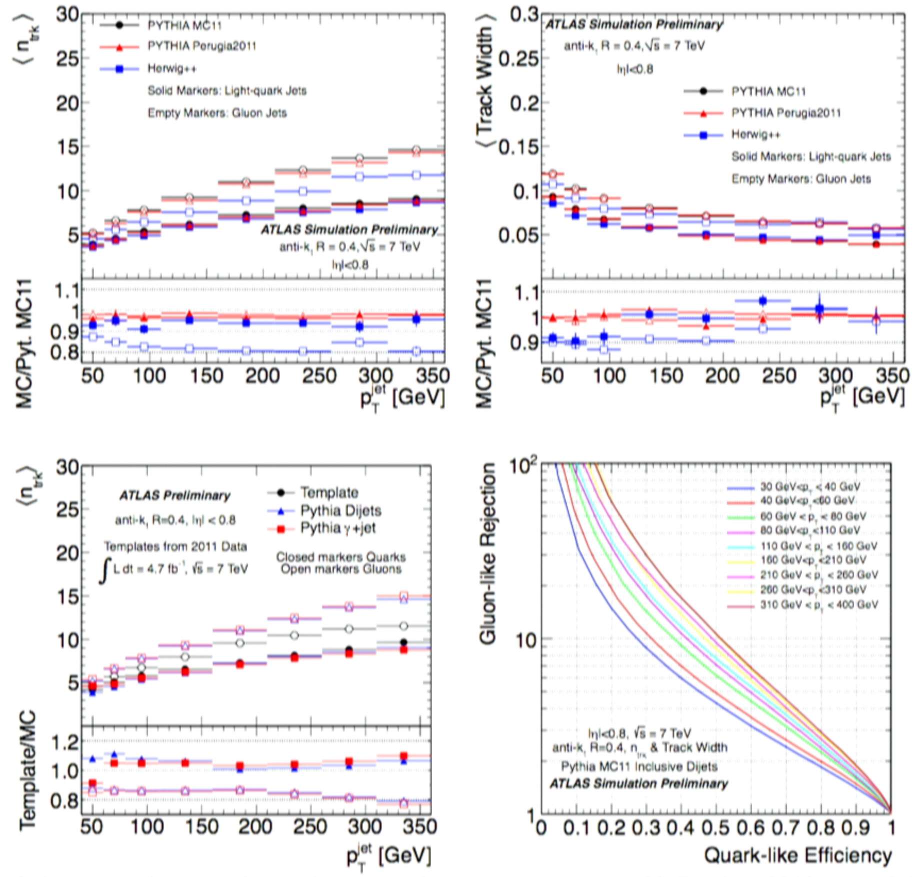
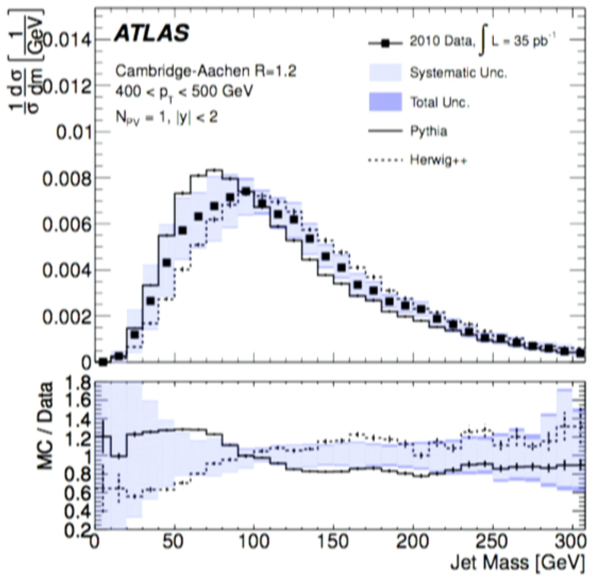


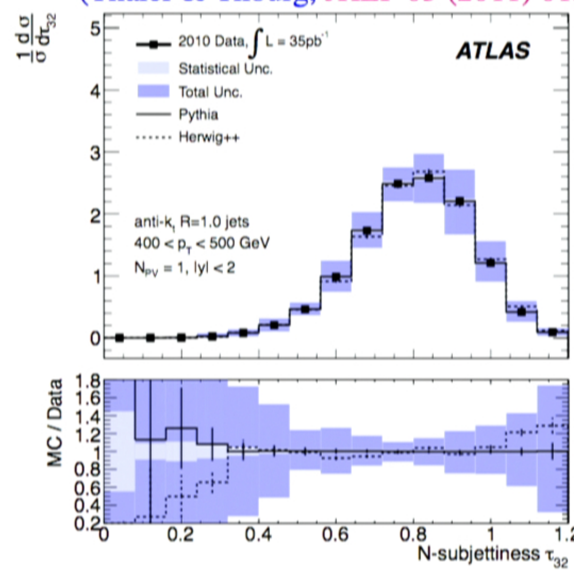
First measurements of "fat" jet substructure (35 pb^{-1})

Using the anti-k_t, $R = 1.0$ and C/A, $R = 1.2$ "fat" jet algorithms (arXiv:1203.4606)

(Thaler & Tilburg, JHEP 03 (2011) 015)



C/A, $R = 1.2$ mass (35 pb^{-1})



anti-k_t, $R = 1.0$ τ_N (35 pb^{-1})

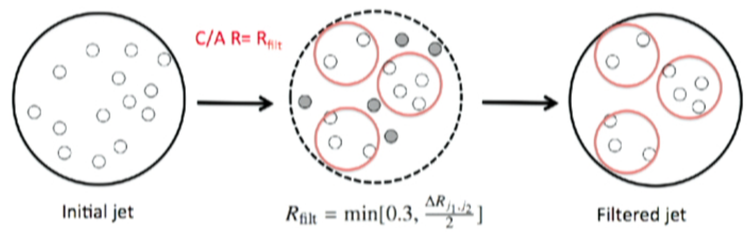
- Jet mass is unfolded to the particle level to correct for detector effects.
- PYTHIA under(over)estimates number of jets with large (small) jet mass
- **"3-body-like"** measure: ***N*-subjettiness, τ_N** (Thaler & Tilburg)

More measurements from 2010

Jet "grooming" algorithms in active use in ATLAS

An attempt to remove uncorrelated soft, wide-angle radiation without significantly affecting hard, massive splittings within parton shower or, more importantly, heavy particle decays $\rightarrow$ *Improve mass resolution & S/B, reduce sensitivity to UE/pile-up.*

- **Mass-drop Filtering:** (BDRS, PRL 2008)
  - Go to filtering results



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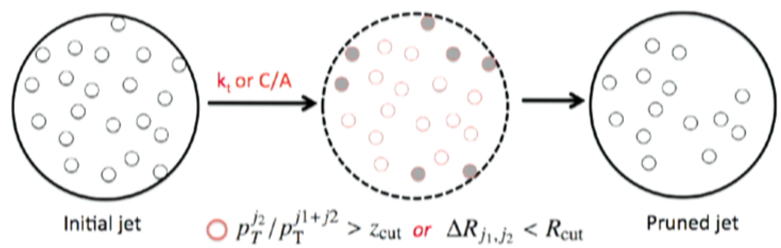

- **Trimming:** (Krohn, Thaler, & Wang, JHEP 2010)
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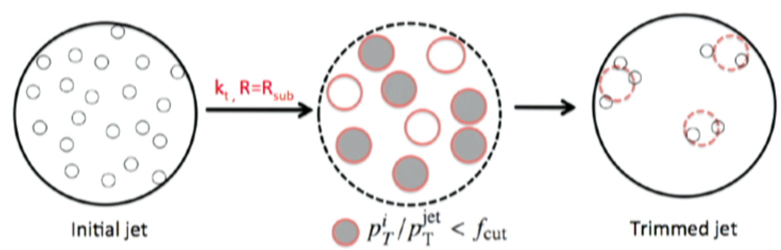
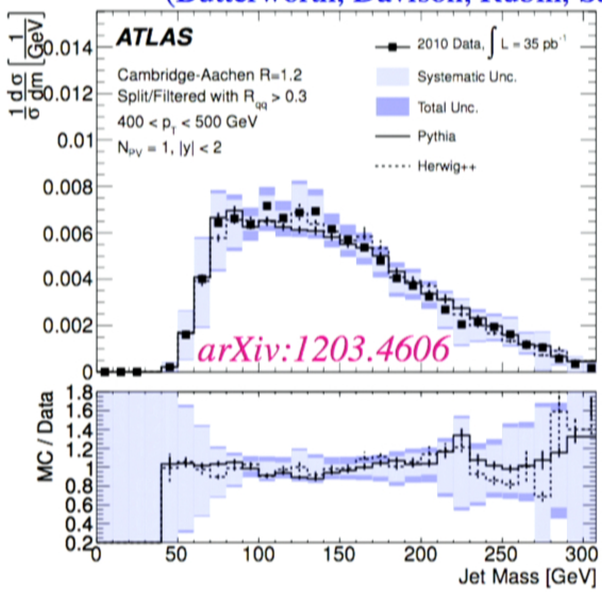


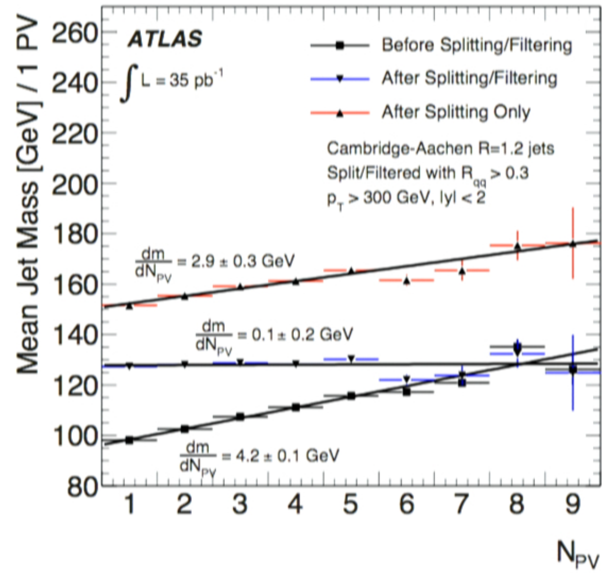
First measurements of split/filtered jet mass (35 pb^{-1}*)*

By applying the jet filtering algorithm (necessary for mass resolution in boosted Higgs, $H \to b\bar{b}$), generator differences are reduced and impact of pile-up is removed.

(Butterworth, Davison, Rubin, Salam - BDRS, PRL 100, 242001 (2008))



C/A, $R = 1.2$ (filtered) mass (35 pb^{-1})



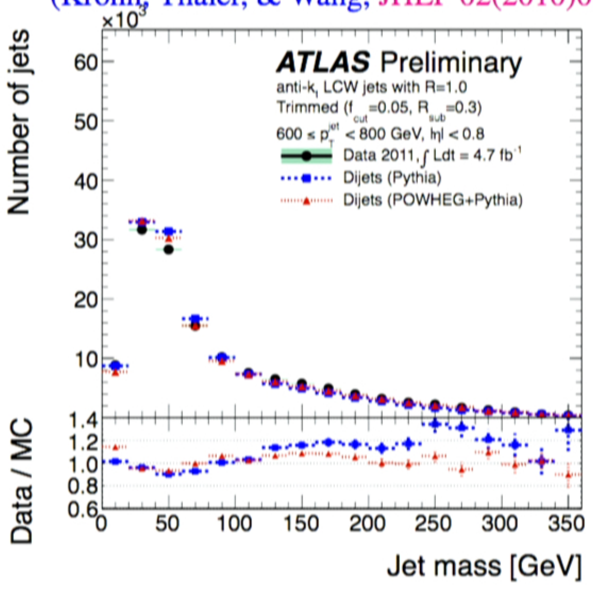
Impact of pile-up on mass w/ & w/o filtering

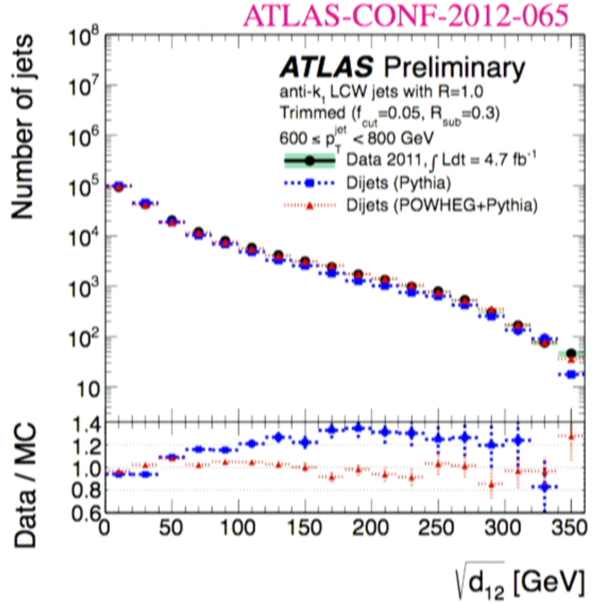
- World's first measurement of split/filtered jet mass. Agreement among MC is good after filtering → *soft components reduced / removed.*

Comparisons of "fat" jet substructure with 5 fb^{-1} *(I)*

"Ungroomed" and trimmed jet mass: PYTHIA *vs. POWHEG*+PYTHIA

(Krohn, Thaler, & Wang, JHEP 02(2010)084)   ATLAS-CONF-2012-065





anti-k_t, $R = 1.0$ mass (600-800 GeV, trimmed)   anti-k_t, $R = 1.0$ $\sqrt{d_{12}}$ (600-800 GeV, trimmed)

- 10%-15% improvements in jet mass description with NLO, up to 25% for $\sqrt{d_{12}}$
- PYTHIA 6.425 tends to underestimate underestimate hard, wide-angle emission
- POWHEG+PYTHIA 6.425 is accurate to few %, even at large M^{jet}.

Jet "grooming" algorithms in active use in ATLAS

An attempt to remove uncorrelated soft, wide-angle radiation without significantly affecting hard, massive splittings within parton shower or, more importantly, heavy particle decays → Improve mass resolution & S/B, reduce sensitivity to UE/pile-up.

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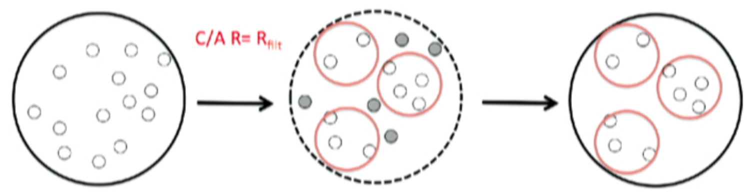

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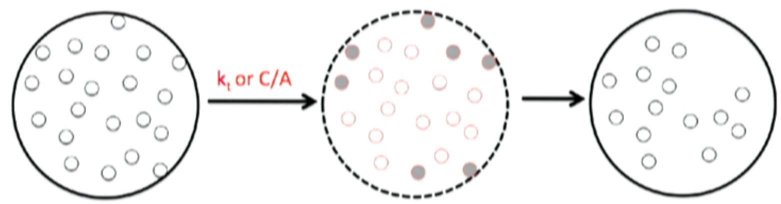

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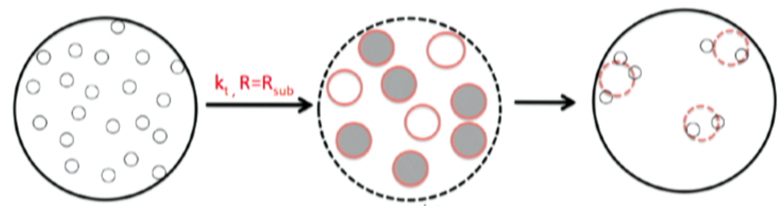

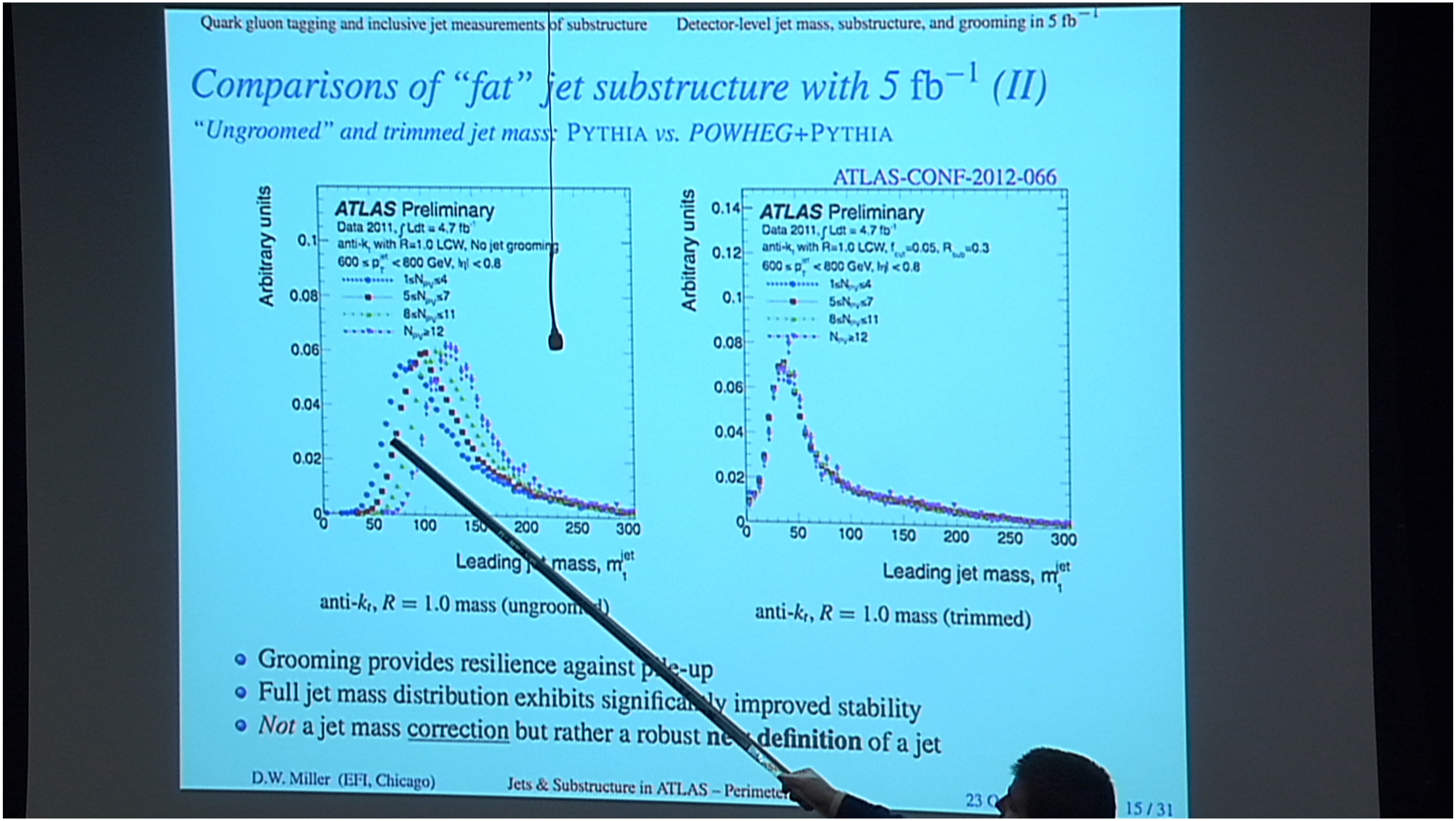
Quark gluon tagging and inclusive jet measurements of substructure
Detector-level jet mass, substructure, and grooming in 5 fb⁻¹
Comparisons of "fat" jet substructure with 5 fb⁻¹ (II)
"Ungroomed" and trimmed jet mass: PYTHIA vs. POWHEG+PYTHIA
ATLAS-CONF-2012-066
ATLAS Preliminary
Data 2011, ∫ Ldt = 4.7 fb⁻¹
600 ≤ p_T^jet < 800 GeV, |η| < 0.8
Arbitrary units
Leading jet mass, m_1^jet
anti-kt, R = 1.0 mass (trimmed)
anti-kt with R=1.0 LCW, f_cut=0.05, R_sub=0.3
Grooming provides resilience against
Full jet mass distribution exhibits signific
improved stability
Not a jet mass correction but rather a robust
definition of a jet
D.W. Miller (EFI, Chicago)
Jets & Substructure in ATLAS – Perimete
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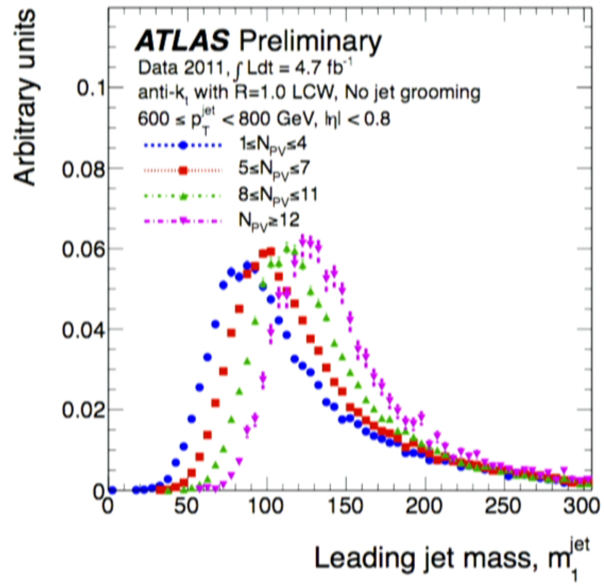
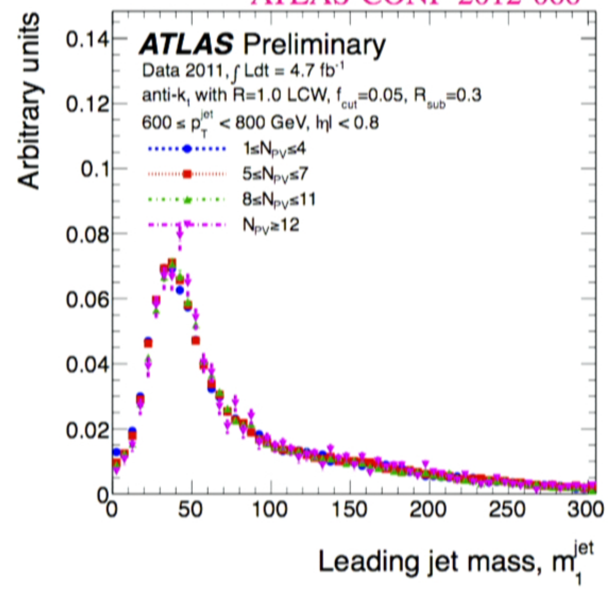
Comparisons of "fat" jet substructure with 5 fb^{-1} *(II)*

"Ungroomed" and trimmed jet mass: PYTHIA *vs. POWHEG+*PYTHIA

ATLAS-CONF-2012-066



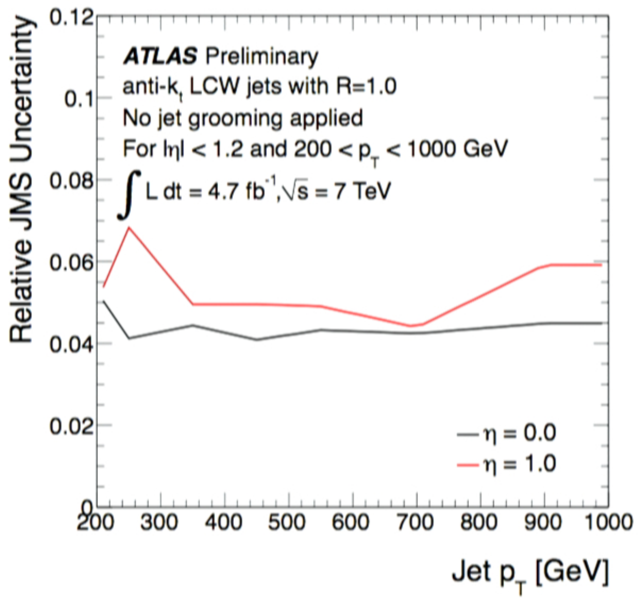
anti-k_t, $R = 1.0$ mass (ungroomed)

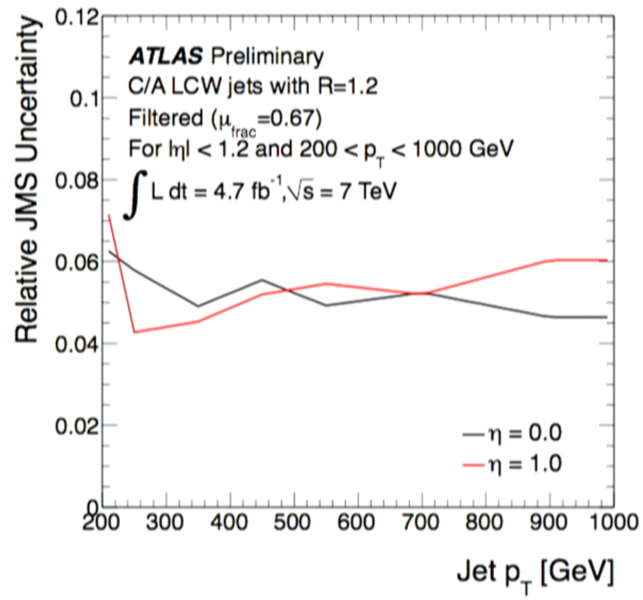


anti-k_t, $R = 1.0$ mass (trimmed)

- Grooming provides resilience against pile-up
- Full jet mass distribution exhibits significantly improved stability
- *Not* a jet mass correction but rather a robust **new definition** of a jet

Preliminary mass scale uncertainties using tracking



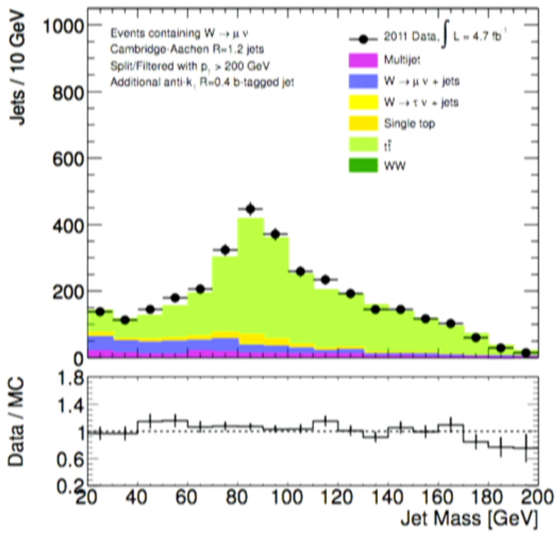


- Preliminary mass scale uncertainties for large-*R* jets: **approximately 5-6%**

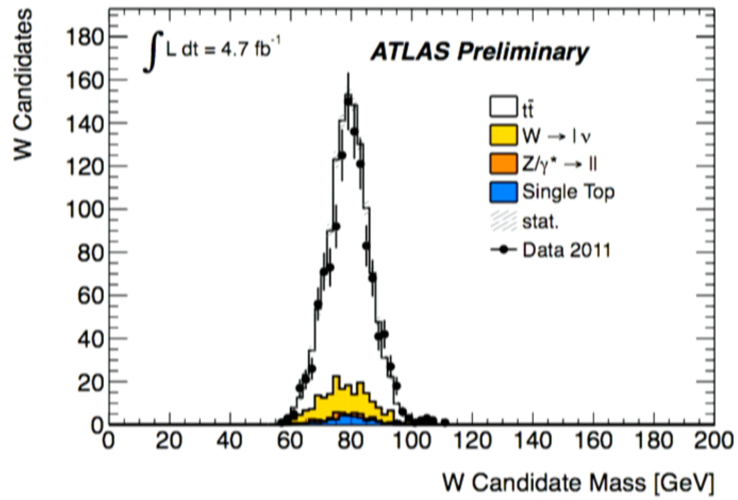
▸ More details on track jet systematics

Using hadronic W decays as a standard candle

Adam Davison (UCL) & Gregor Kasieczka (Heidelberg)



Direct filtered C/A W+jets



HEPTopTagger + $t\bar{t}$ selection

- Direct filtered C/A W+jets: W+1 jet, $\Delta\phi(W, \text{jet}) > 1.8$, $p_T^{\text{jet}} > 200$ GeV
- Focus on muon channel only, use filtered C/A jets and trimmed jets
- For HEPTopTagger: use a full $t\bar{t}$ semi-leptonic muon-channel selection
- *Preliminary preliminary expected uncertainty: **2-3%!***

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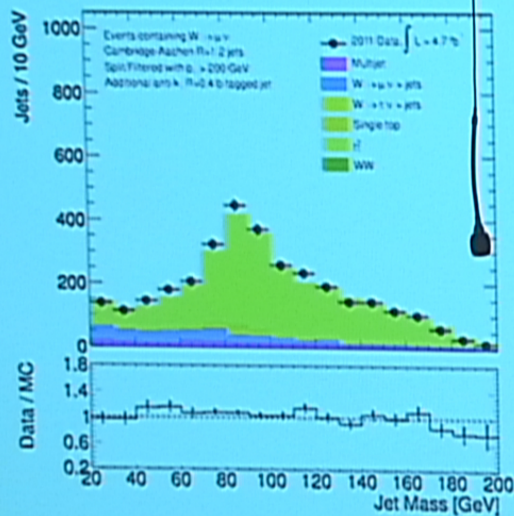

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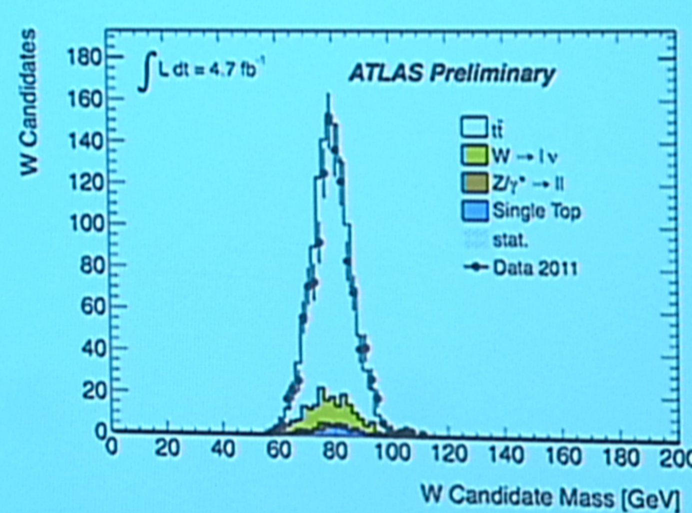

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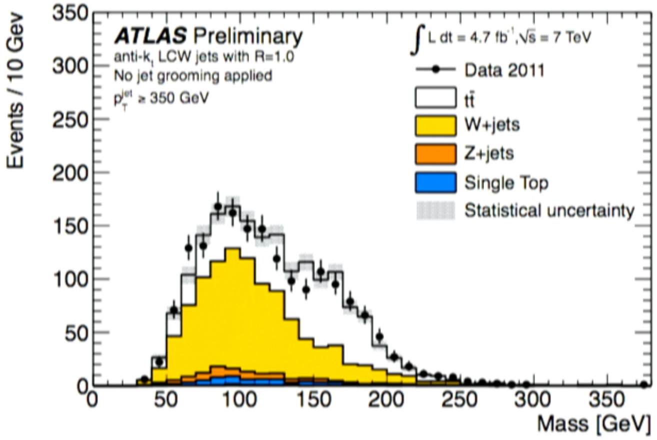
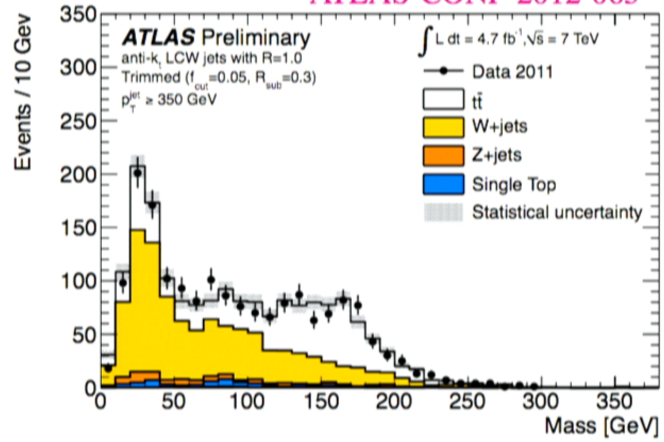
Commissioning boosted object tools with SM top quarks (I)

Enriched sample of boosted tops using semi-leptonic (μ) selection and high-p_T fat jets

ATLAS-CONF-2012-065



anti-k_t, $R = 1.0$, ungroomed



anti-k_t, $R = 1.0$, trimmed

- Significant increase in the purity of the top mass peak between $120 < M^{\text{jet}} < 200$ GeV
- Narrower top mass peak after trimming that is well described by the data
- Rate of boosted tops is well-predicted by MC@NLO top MC
  - *implicit limits from this plot alone*

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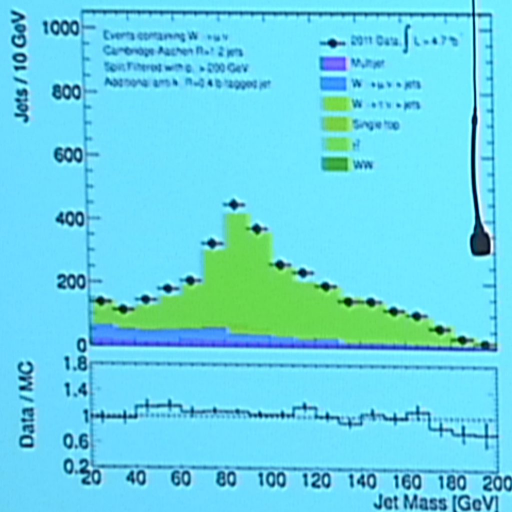
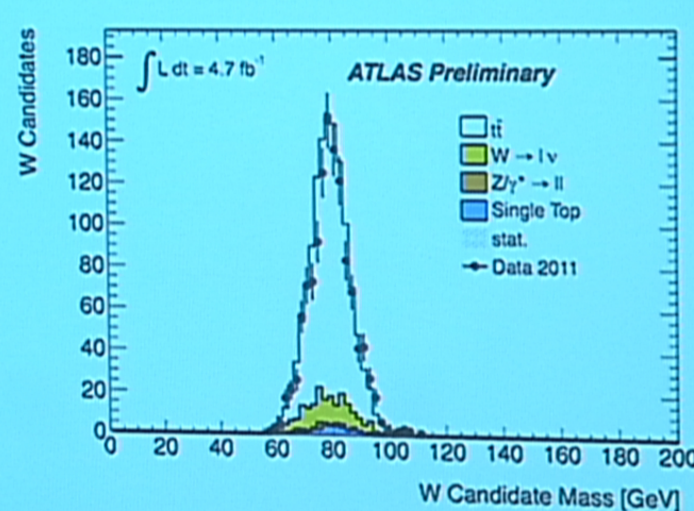


Direct filtered C/A W+jets



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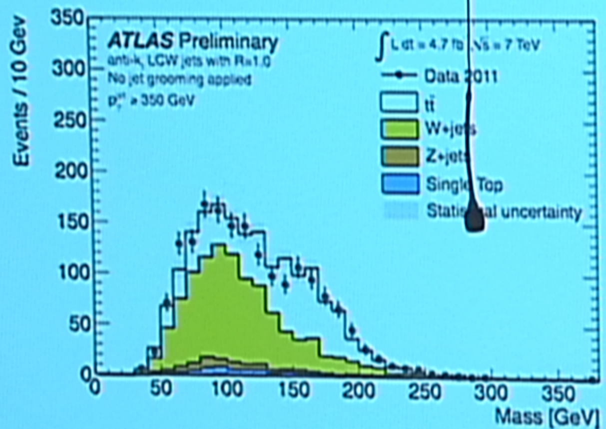

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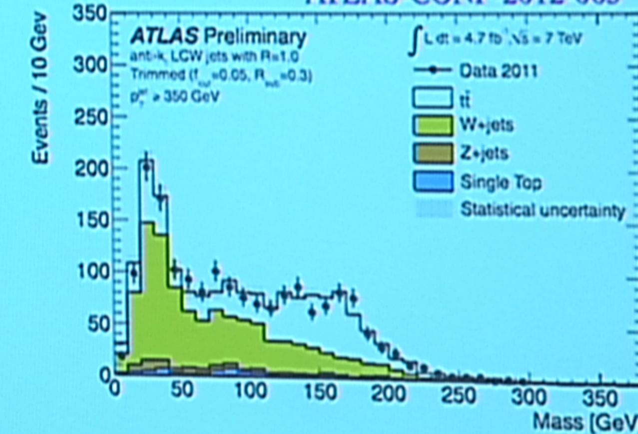

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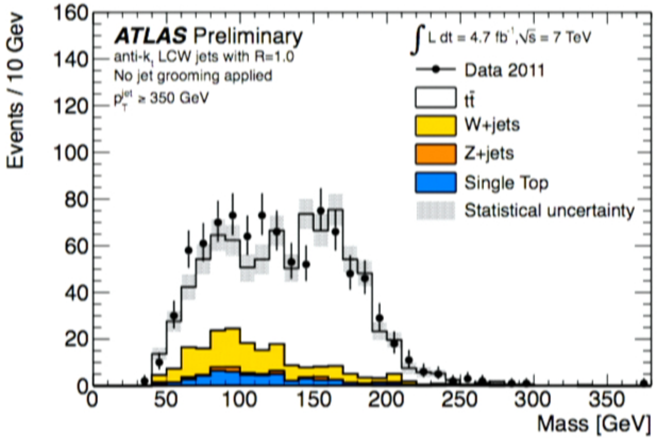
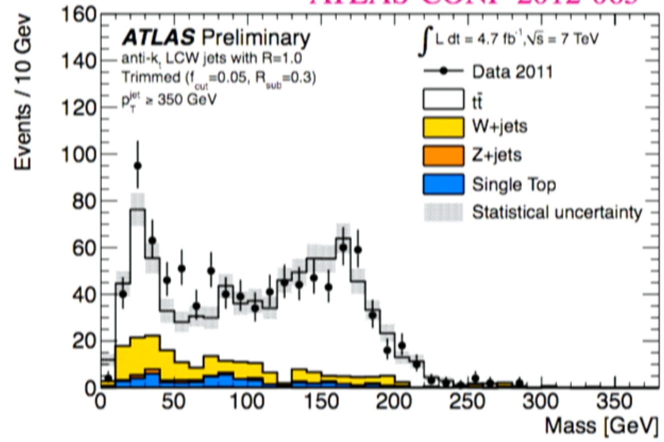
Commissioning boosted object tools with SM top quarks (I)

Enriched sample of boosted tops using semi-leptonic (μ) selection and high-p_T fat jets

ATLAS-CONF-2012-065



anti-k_t, $R = 1.0$, ungroomed



anti-k_t, $R = 1.0$, trimmed

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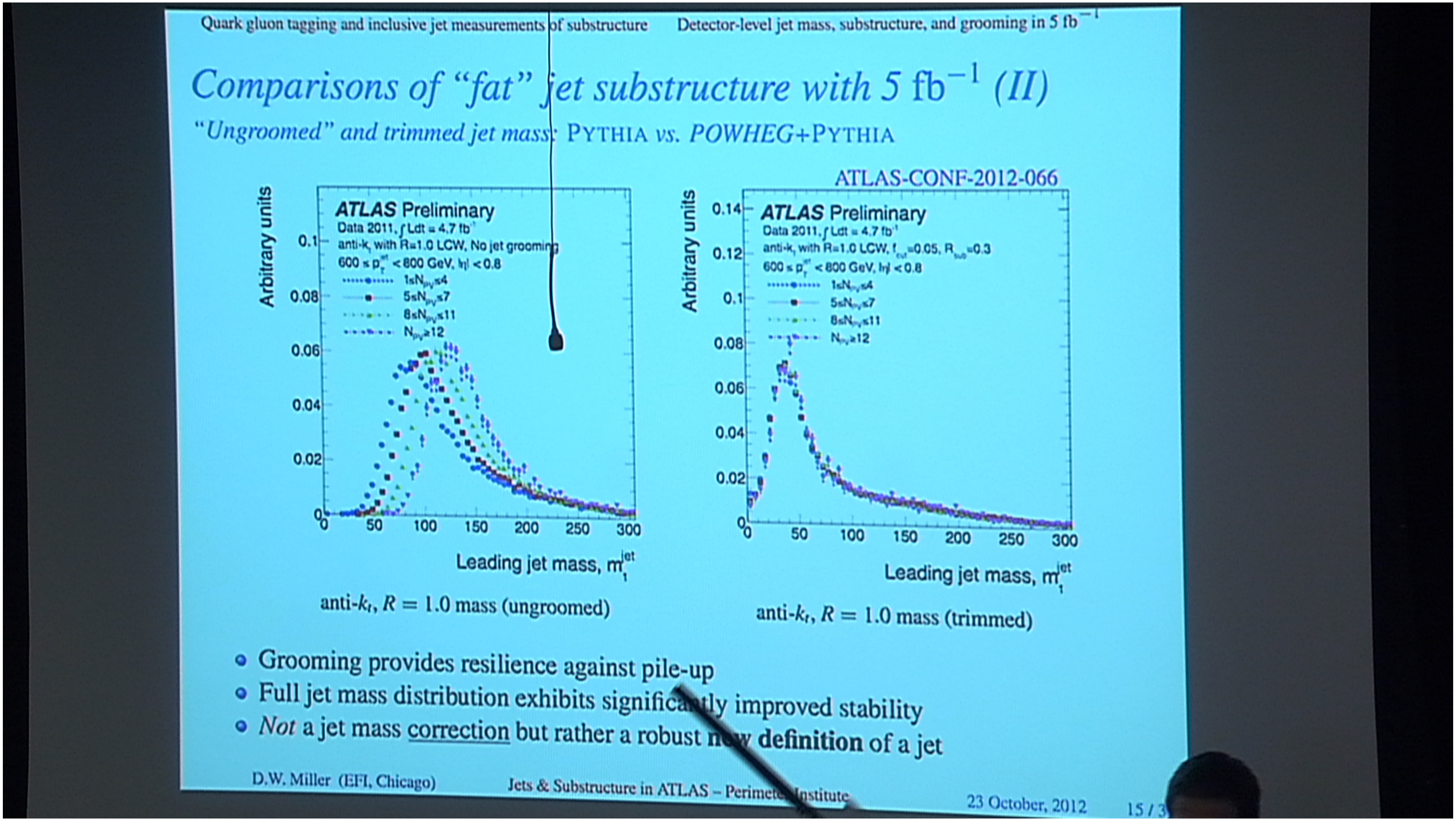
Quark gluon tagging and inclusive jet measurements of substructure
Detector-level jet mass, substructure, and grooming in 5 fb⁻¹
Comparisons of "fat" jet substructure with 5 fb⁻¹ (II)
"Ungroomed" and trimmed jet mass: PYTHIA vs. POWHEG+PYTHIA
ATLAS-CONF-2012-066
ATLAS Preliminary
Data 2011, ∫ Ldt = 4.7 fb⁻¹
anti-kt with R=1.0 LCW, No jet grooming
600 ≤ pT jet < 800 GeV, |η| < 0.8
1≤Npv≤4
5≤Npv≤7
8≤Npv≤11
Npv≥12
Arbitrary units
Leading jet mass, m1 jet
anti-kt, R = 1.0 mass (ungroomed)
ATLAS Preliminary
Data 2011, ∫ Ldt = 4.7 fb⁻¹
anti-kt with R=1.0 LCW, fcut=0.05, Rsub=0.3
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Grooming provides resilience against pile-up
Full jet mass distribution exhibits significantly improved stability
Not a jet mass correction but rather a robust new definition of a jet
D.W. Miller (EFI, Chicago)
Jets & Substructure in ATLAS – Perimeter Institute
23 October, 2012
15 / 3

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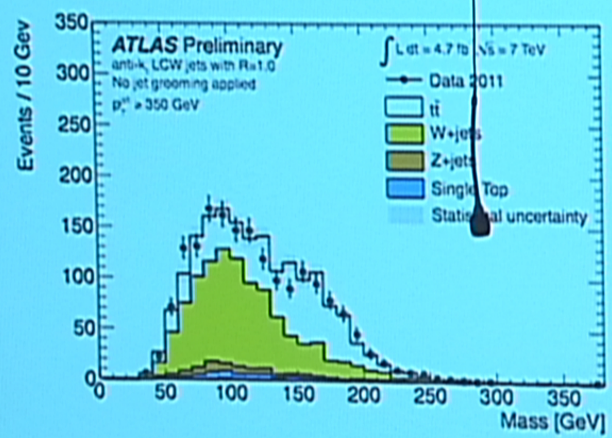
ATLAS-CONF-2012-065



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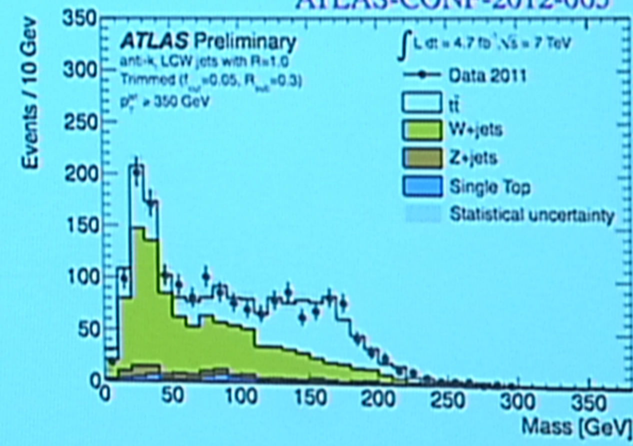

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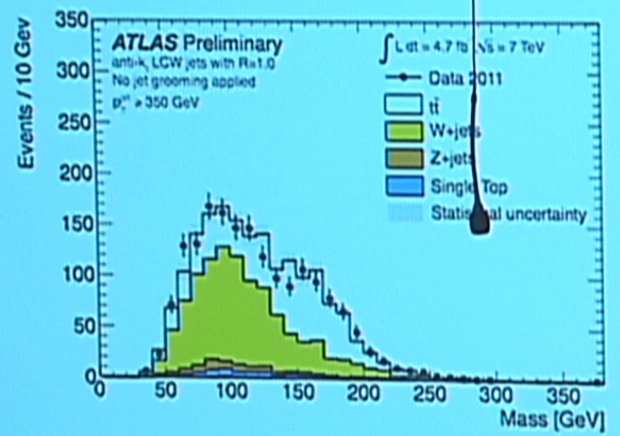

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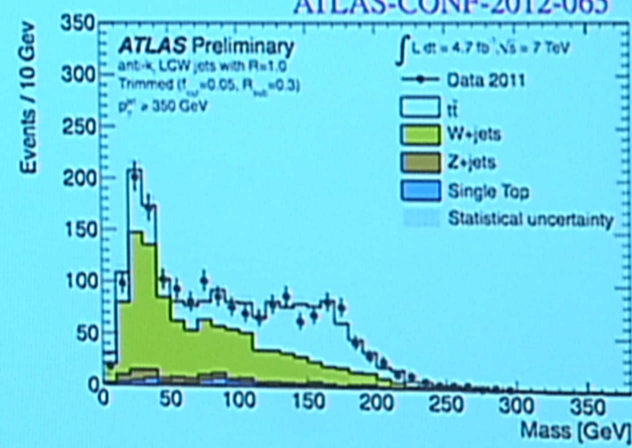

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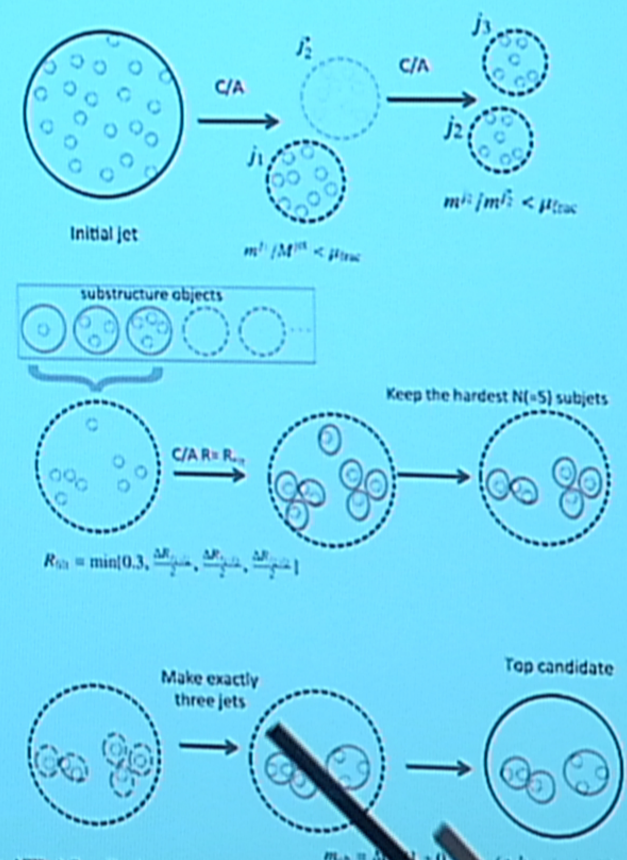
Complex tagging algorithms using substructure

HEPTopTagger: Plehn, Salam, Spannowksy, PRL 104, 111801 (2010) and Plehn, Spannowsky, Takeuchi, Zerwas JHEP 10(2010)078

Combine generic substructure tools like mass drop and properties of the decay products like the helicity angle of the *W* and create a tagger:

1. Cluster fat jet and apply mass-drop
2. Find subjets and keep N hardest
3. Recluster into 3 objects (for top tagging)



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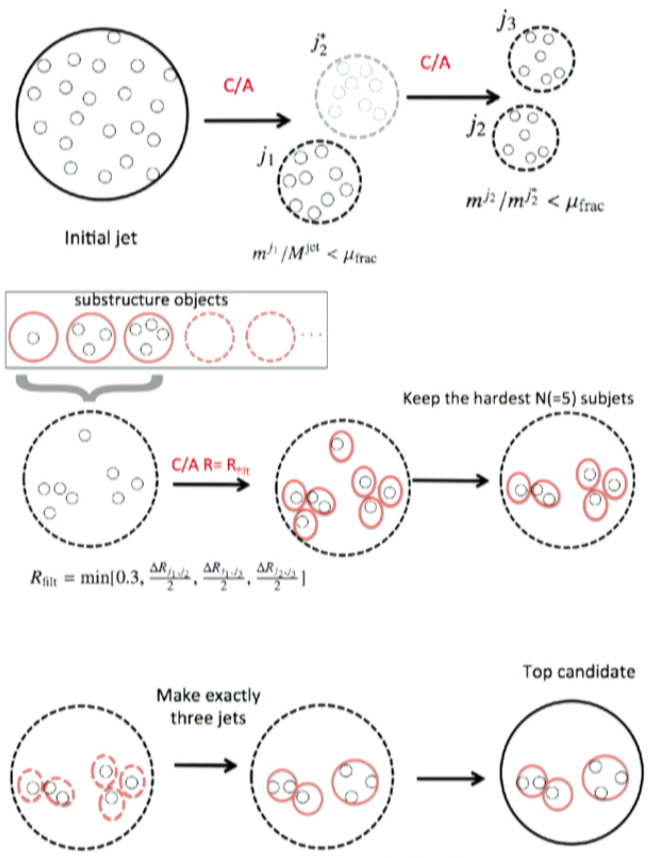

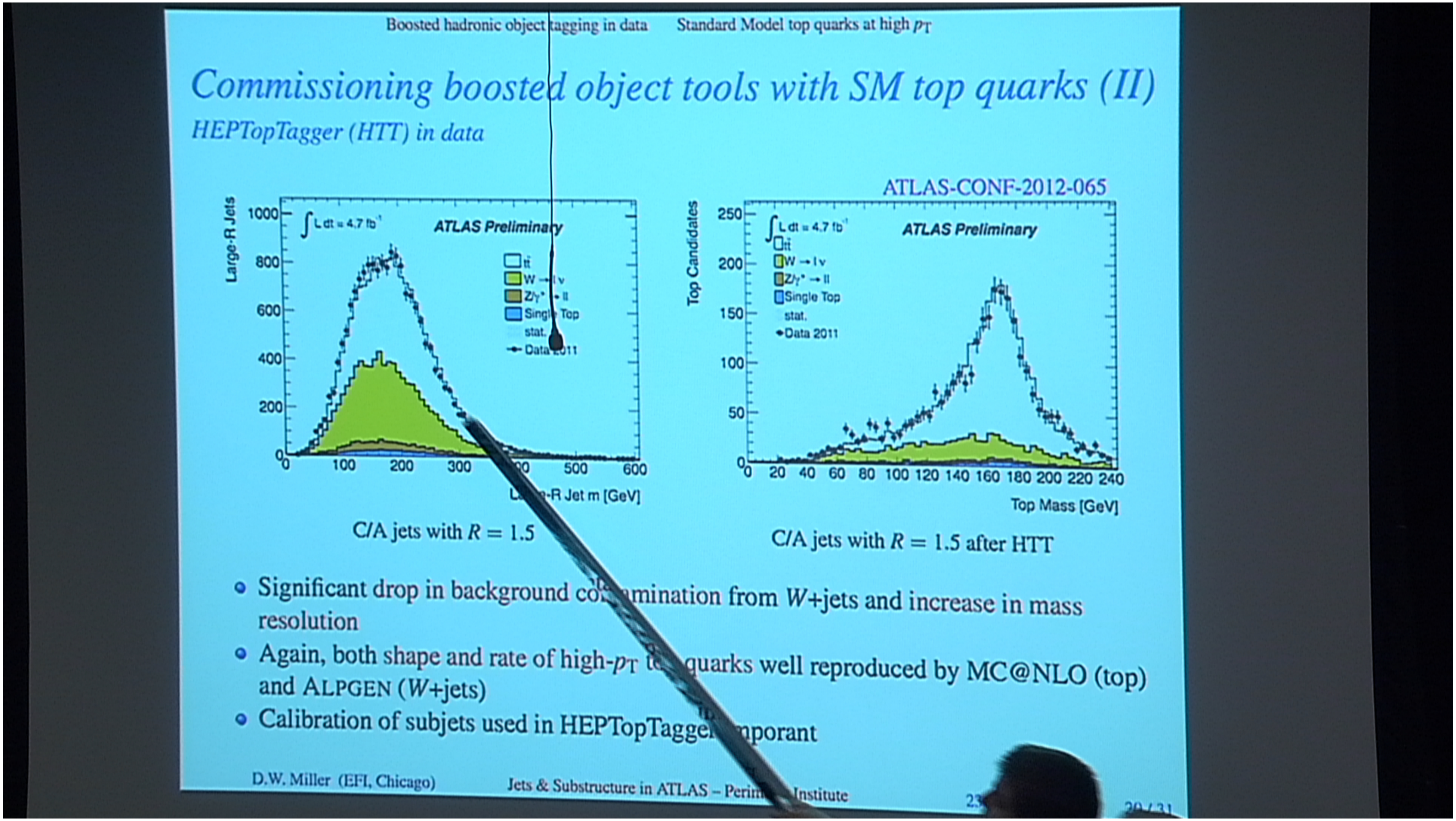
Boosted hadronic object tagging in data
Standard Model top quarks at high p_T
Commissioning boosted object tools with SM top quarks (II)
HEPTopTagger (HTT) in data
ATLAS-CONF-2012-065
ATLAS Preliminary
Large-R Jets
Large-R Jet m [GeV]
C/A jets with $R = 1.5$
ATLAS Preliminary
Top Candidates
Top Mass [GeV]
C/A jets with $R = 1.5$ after HTT
Significant drop in background contamination from W+jets and increase in mass resolution
and ALPGEN (W+jets)
D.W. Miller (EFI, Chicago)

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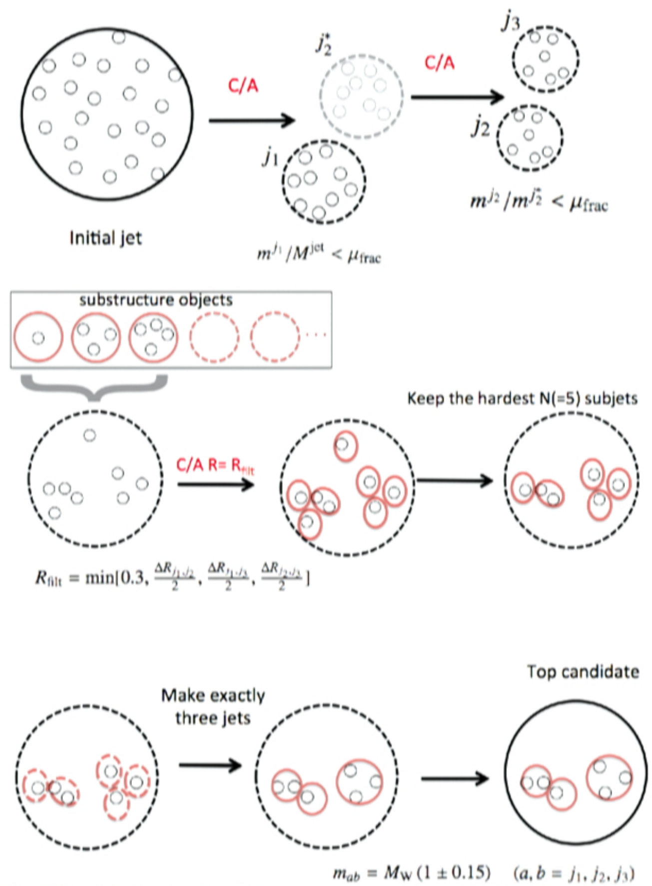

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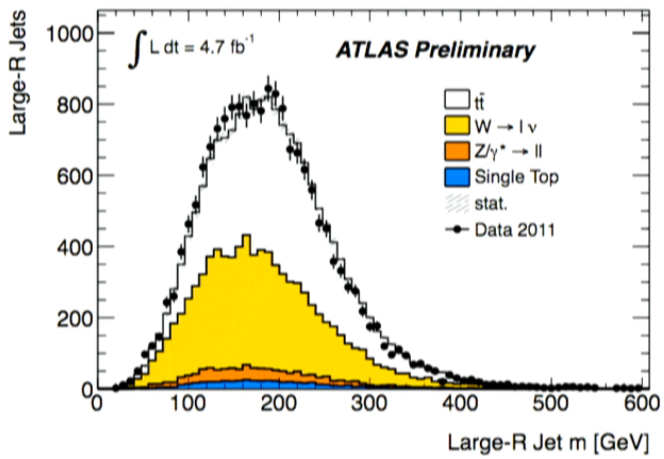
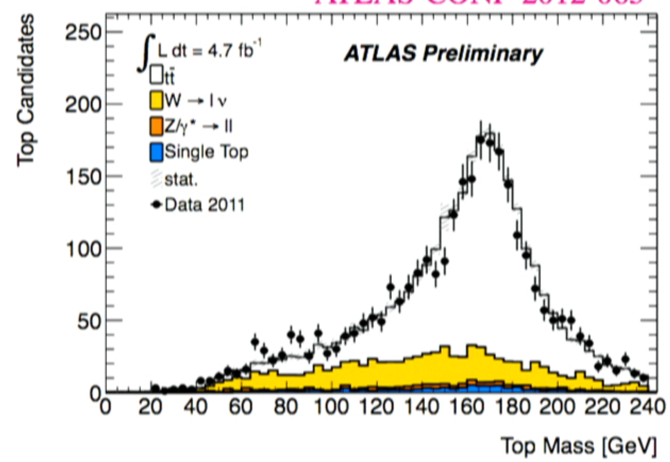
ATLAS-CONF-2012-065

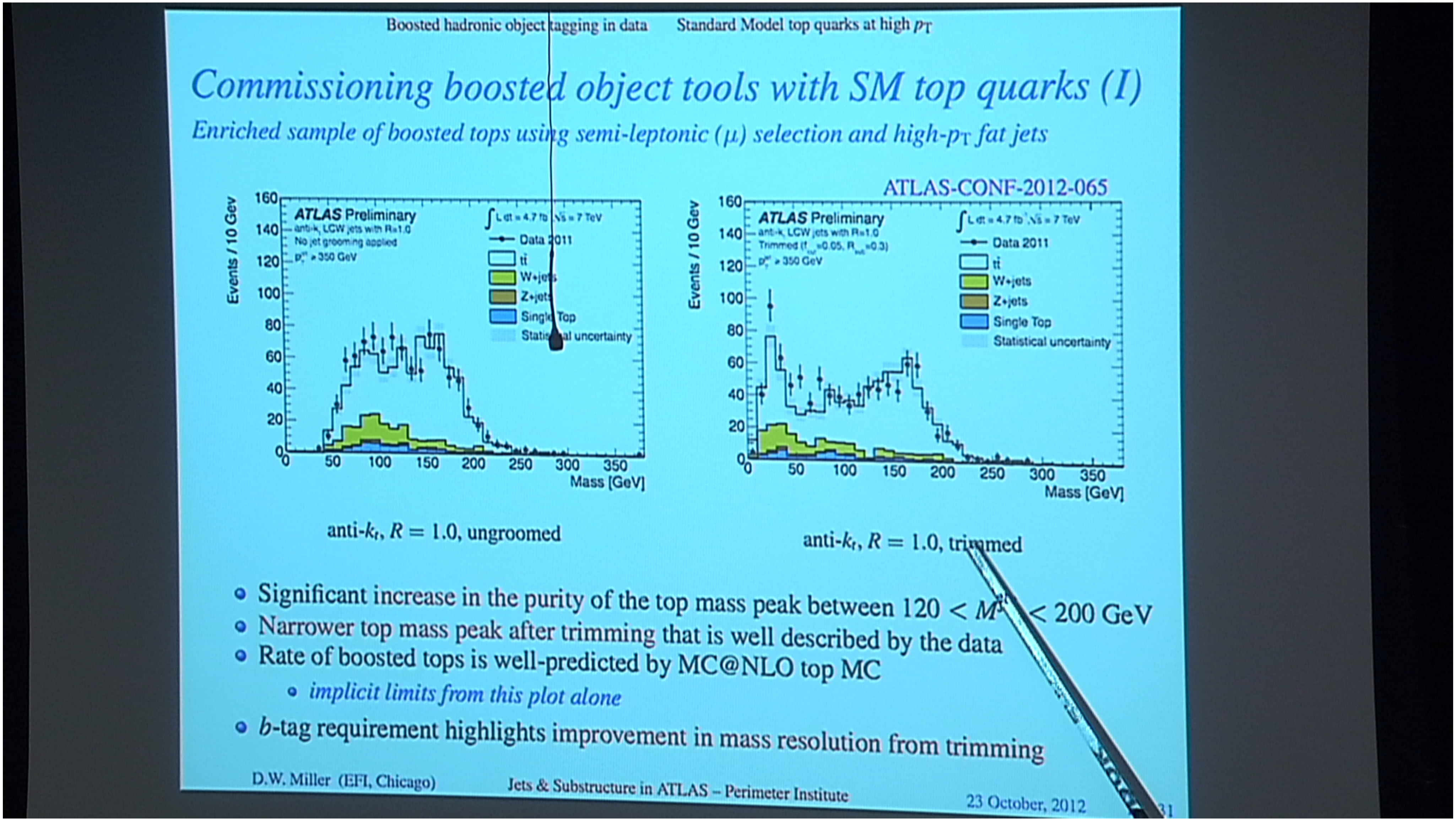


C/A jets with $R = 1.5$



C/A jets with $R = 1.5$ after HTT

- Significant drop in background contamination from W+jets and increase in mass resolution
- Again, both shape and rate of high-p_T top quarks well reproduced by MC@NLO (top) and ALPGEN (W+jets)
- Calibration of subjets used in HEPTopTagger imporant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ATLAS-CONF-2012-065
ATLAS Preliminary
Events / 10 Gev
Data 2011
$t\bar{t}$
W+jets
Z+jets
Single Top
Statistical uncertainty
Mass [GeV]
anti-k_t, $R = 1.0$, ungroomed
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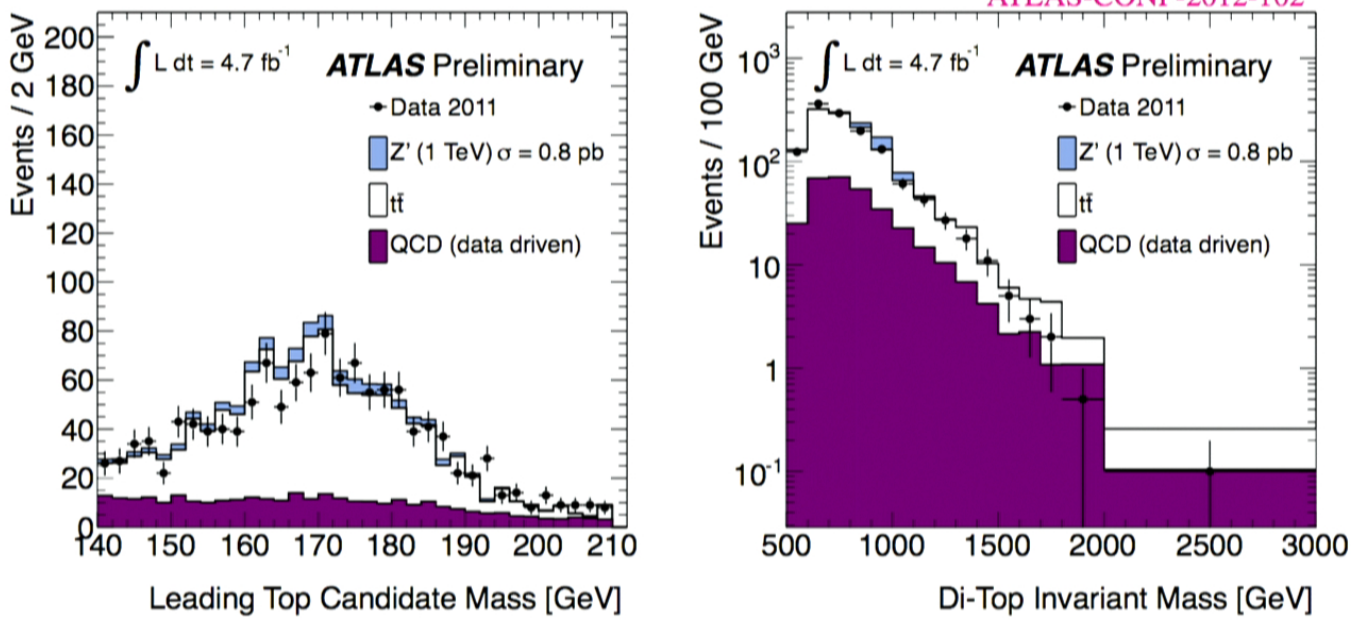
Jets & Substructure in ATLAS – Perimeter Institute
23 October, 2012

Search for all-hadronic $t\bar{t}$ resonances using HEPTopTagger

ATLAS-CONF-2012-102

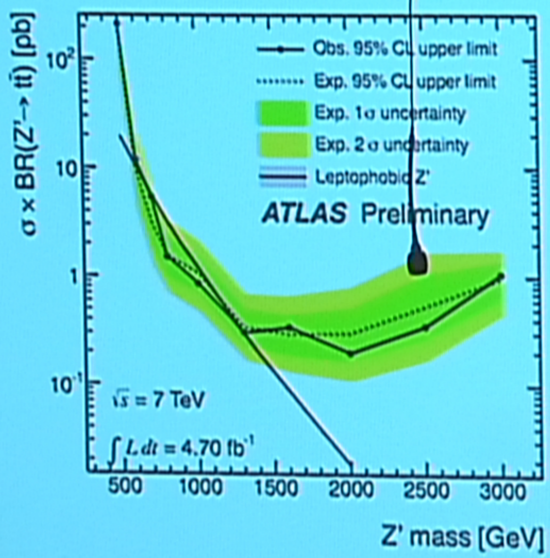


C/A jets with $R = 1.5$ C/A jets with $R = 1.5$ after HTT

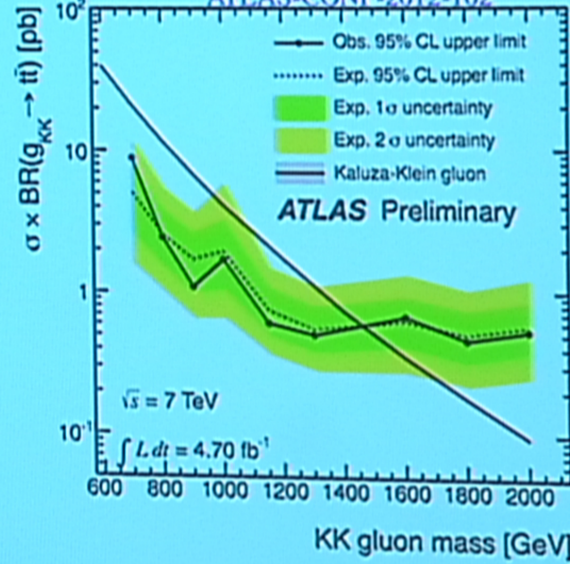
- Put HEPTopTagger to use in search for $Z' \to t\bar{t}$
- Reconstruct top mass peak to demonstrate a consistent and well-understood final state
- Search in the $t\bar{t}$ invariant mass spectrum for signs of new physics.

Search for all-hadronic $t\bar{t}$ resonances using HEPTopTagger

ATLAS-CONF-2012-102



$Z' \to t\bar{t}$



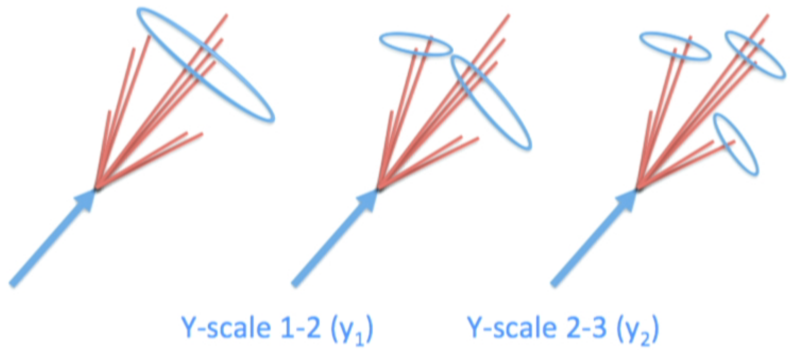
$g_{KK} \to t\bar{t}$

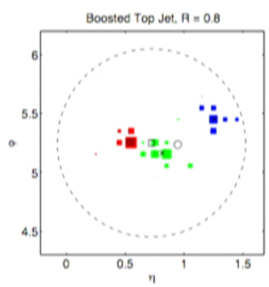
- Expected and observed limits on the $\sigma \times$BR vs. the $m_{t\bar{t}}$ for (left) $Z' \to t\bar{t}$ and (right) Kaluza-Klein gluon $g_{KK} \to t\bar{t}$
- Largest uncertainties: b-tagging efficiency, $t\bar{t}$ normalization, the jet energy scale
- Upcoming combination with a 2nd approach for even higher-p_T sensitivity

Boosted RPV signatures via jet substructure

Concept: Focus on the high-p_T tail of the $\tilde{g}$ spectrum and utilize jet substructure to reduce the QCD background and combinatorial issues.

- 6-jet signature $\rightarrow$ 2-heavy-jet signature + calculable discriminants



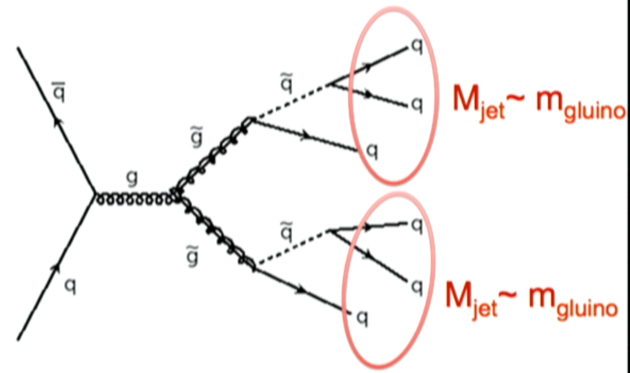


$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min_A \{\Delta R_{A,k}\}$$

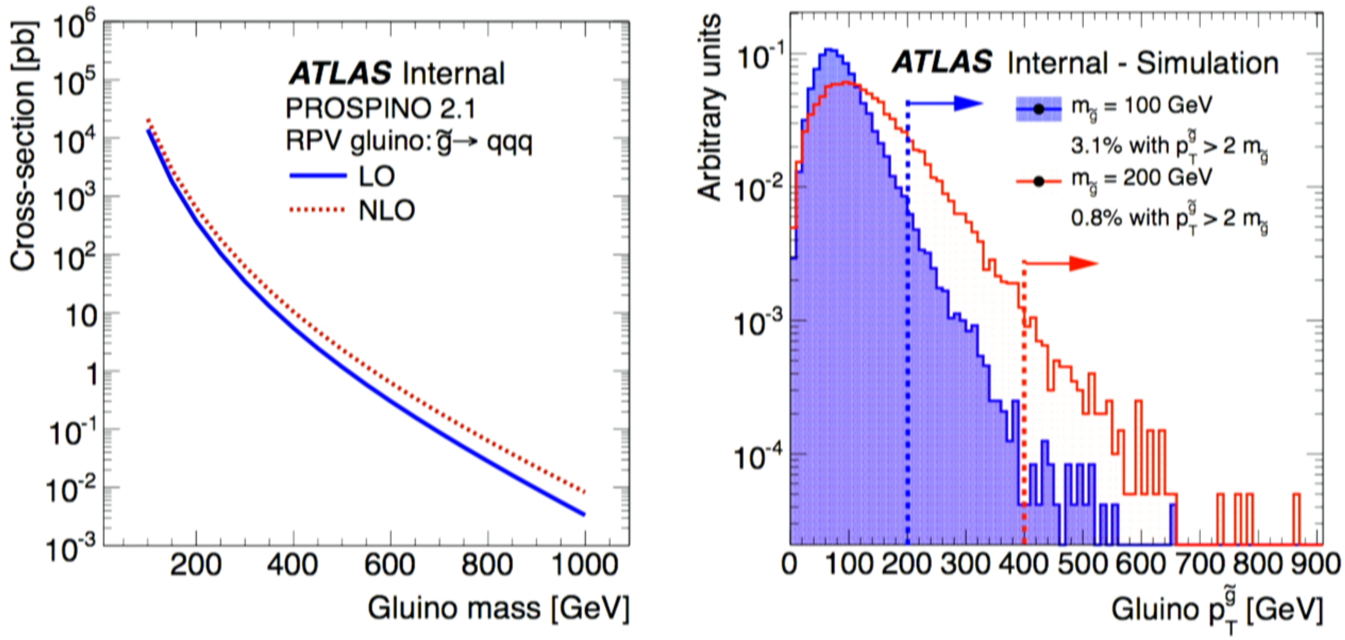
Sum over constituents

Minimize distance to candidate subjet axes

Later: Minimize τ_N over all possible subjet axes, becomes a true jet shape



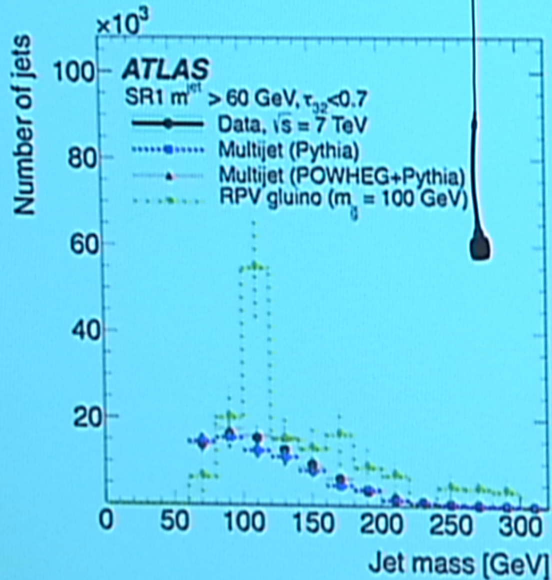
Boosted RPV signal kinematics

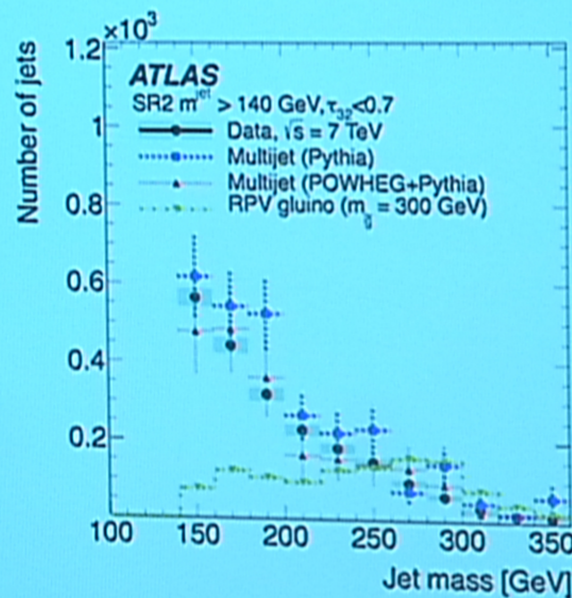


(Left) Gluino production cross-section calculated in PROSPINO 2.1 as a function of $m_{\tilde{g}}$. (Right) Gluino transverse momentum ($p_{\mathrm{T}}^{\tilde{g}}$) spectrum for two low-mass gluino models.

Boosted gluino mass distributions

arXiv:1210.4813





- Hard selection on the p_T of the leading jet: $p_T > 200$ GeV (350 GeV) for $m_{\tilde{g}} = 100$ GeV (300 GeV)
- Incomplete "merging" of gluino decay products in latter case, but still good discrimination (peak at $M^{jet} \approx 275$ GeV)

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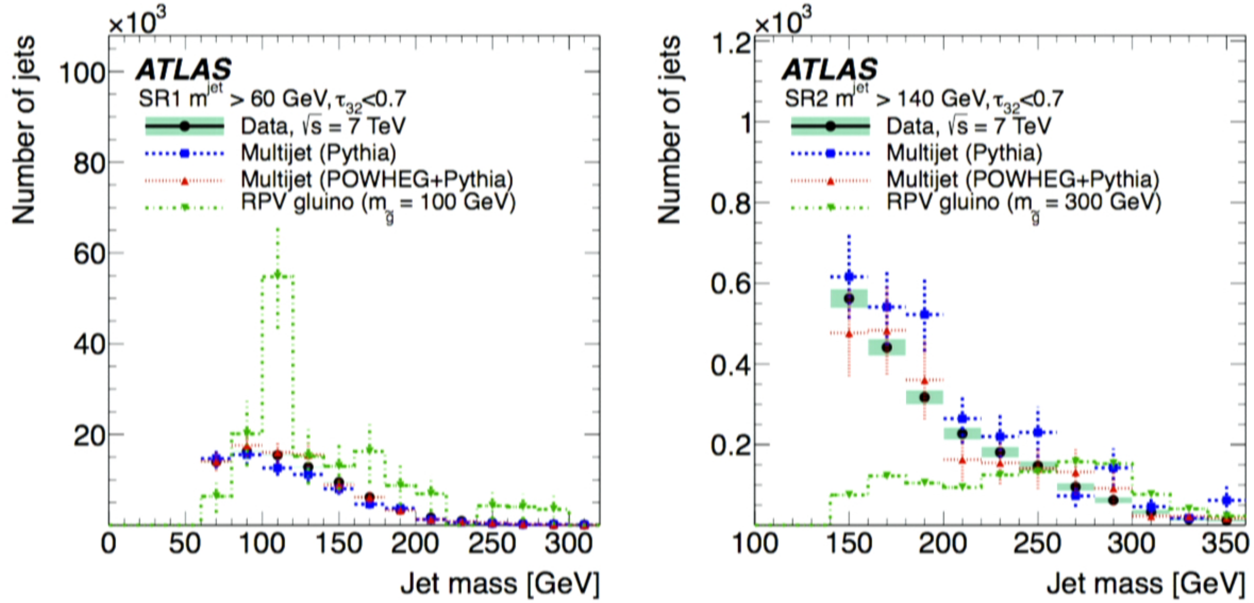

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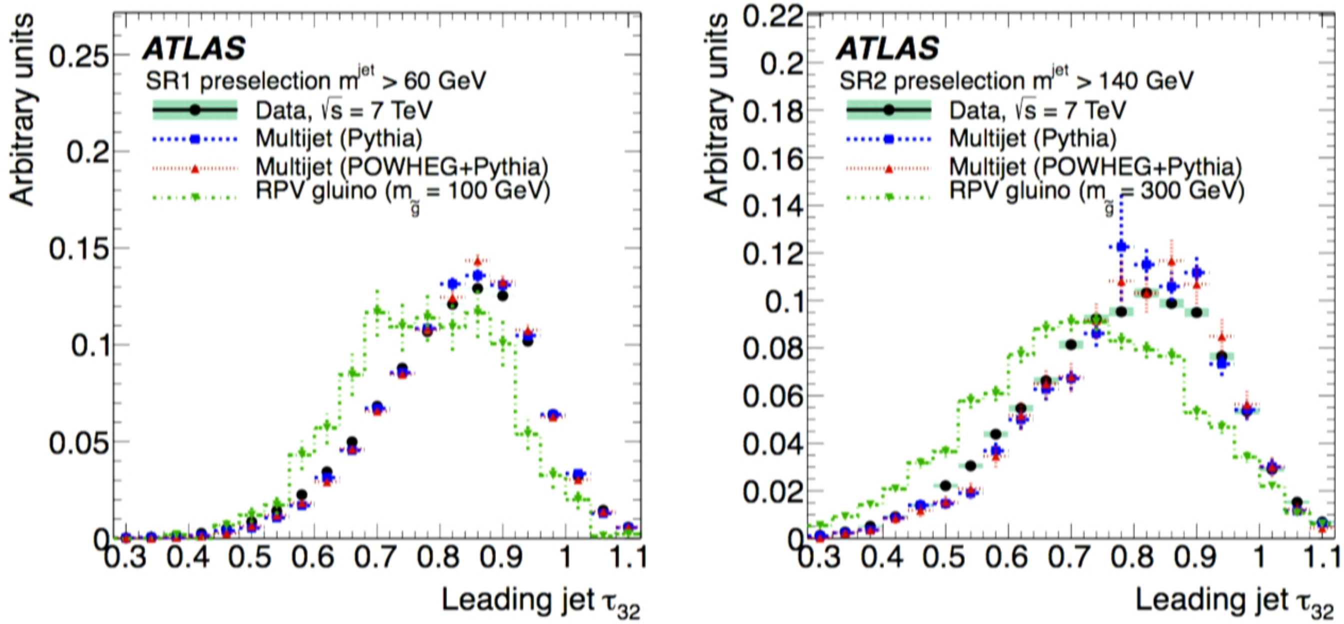
Background discrimination using τ_{32}

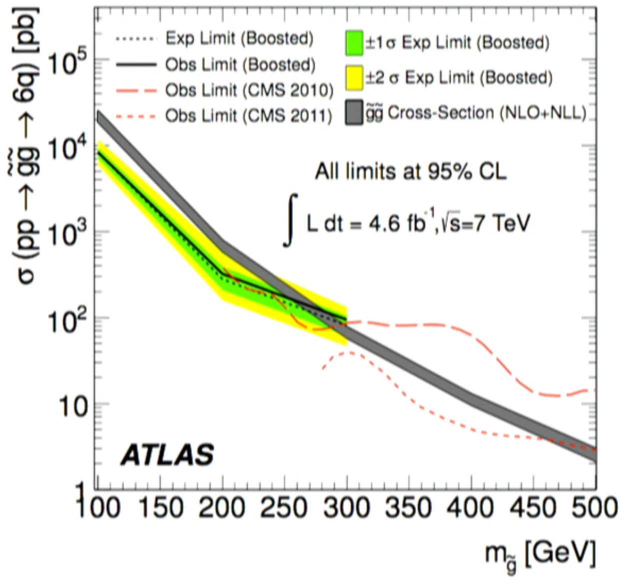
arXiv:1210.4813



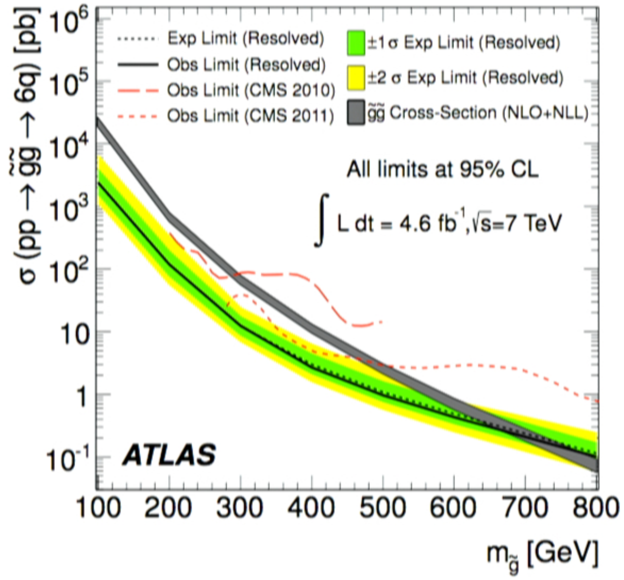
- τ_{32} provides an increase in S/B by a factor of two
  - Signal efficiency drops by $\times 2.5$, background efficiency drops by $\times 5$
- Final optimization yields $\varepsilon = 12\%$ and $f_{\text{mis-tag}} = 1.5\%$, as compared to leading jet p_{T} and trigger requirements alone

RPV gluino limits: resolved & boosted approaches

arXiv:1210.4813



Boosted limits (jet mass and substructre)



Resolved limits (jet counting)

- Both analyses exclude top-mass region (non-trivial!)
- Resolved analysis extends reach to exclude up to $m_{\tilde{g}} > 666$ GeV
- Lack of extensive optimization of boosted analysis hurts final limits...do better for 8 TeV!

Boosted RPV signatures via jet substructure

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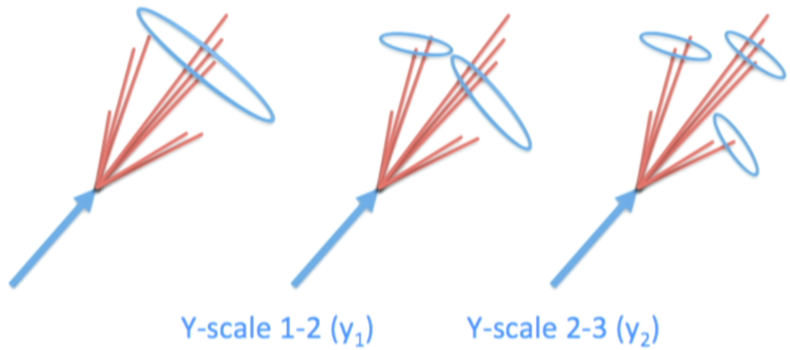

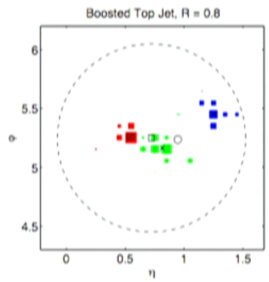

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Sum over constituents

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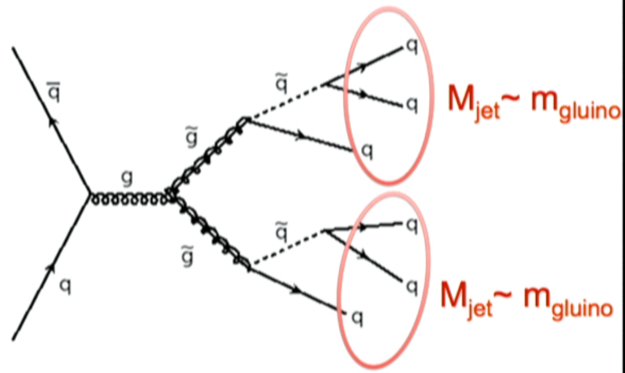
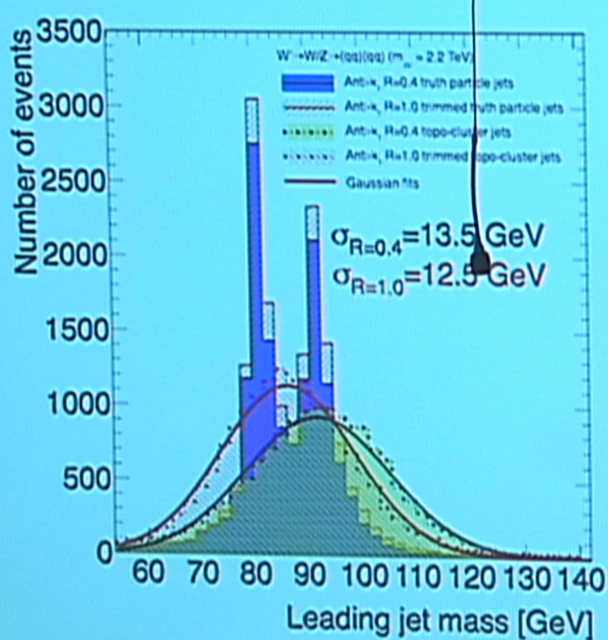
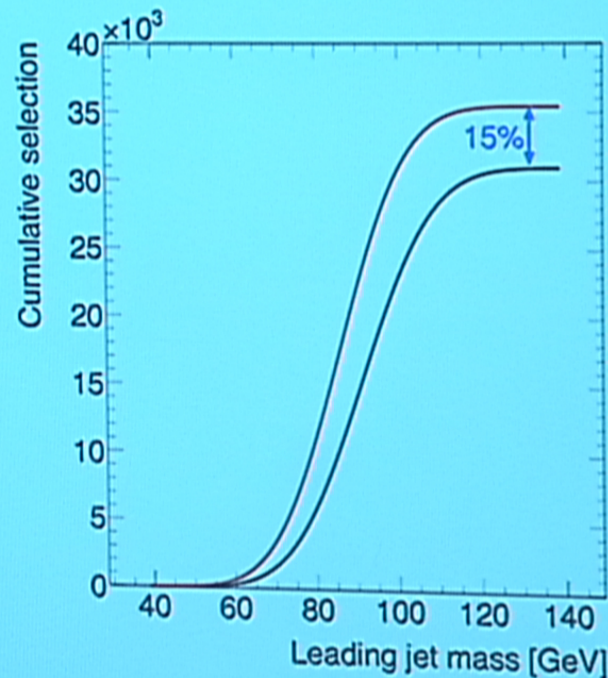


One of the holy grails of calorimetery: hadronic W vs. Z





- Can these techniques help us attain discrimination between hadronic *W*'s and *Z*'s?
- Might this impact the strategy for new calorimeters?

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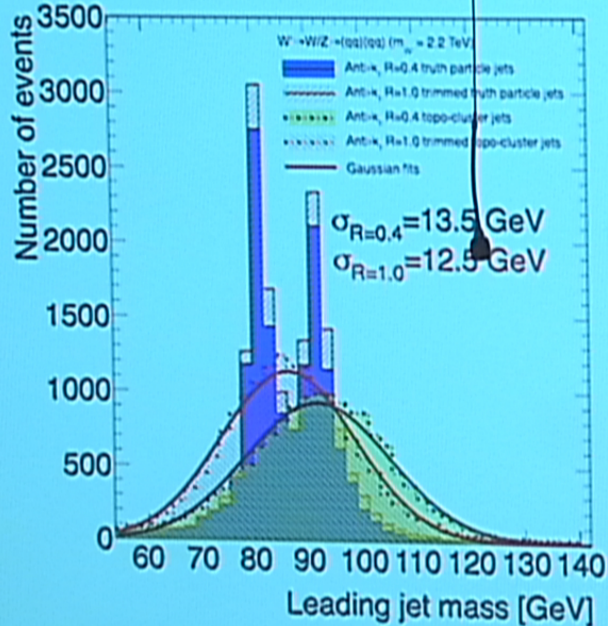

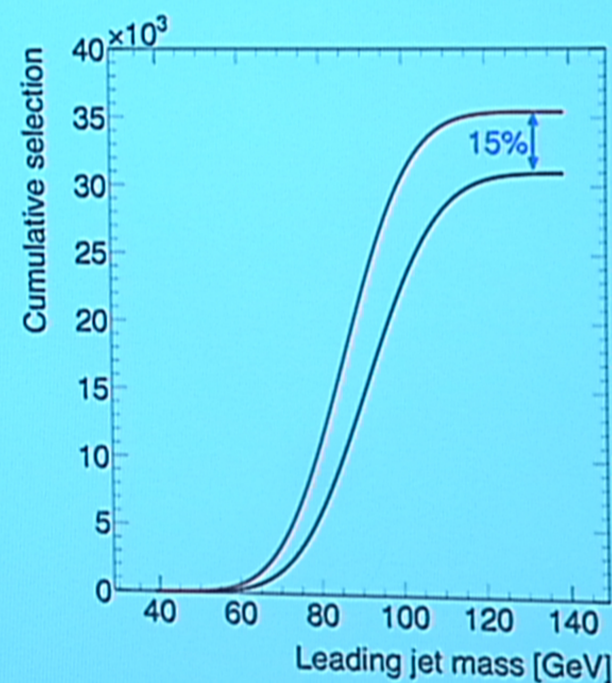

- Can these techniques help us attain discrimination between hadronic W's and Z's?
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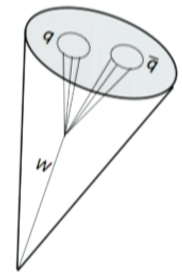
Putting the substructure toolbox in ATLAS to work

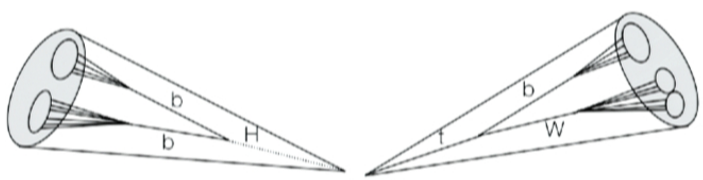
Aim: *Exploit internal jet structure in order to understand QCD better and search for new physics.*

Measurements and searches that aim to benefit from substructure-based analysis, including examples that use "fat" jets and grooming techniques.

- Jet mass and splitting scale measurements (SM QCD)
- High p_T W bosons and top quarks (SM EW / Exotics)
- Boosted Higgs channels for light mass discovery (Higgs)
- HRPV gluino or neutralino decays: $\tilde{g}/\tilde{\chi}^0 \rightarrow qqq$ (SUSY)
- Heavy particle (e.g. Z') decays to boosted top quarks (Exotics)



<u>Goal:</u> study these objects and algorithms within the JetEtMiss Group to develop strategies, calibrations, and understand systematic issues.



ATLAS NOTE

ATLAS-CONF-2012-065

June 26, 2012

Performanc ... **with the**

Extensive work on uncertainties, tagging techniques, S/B, and more! (link)

Abstract

This paper presents the application of techniques to study jet substructure. The performance of modified jet algorithms for a variety of jet types and event topologies is investigated. Properties of jets subjected to the mass-drop filtering, trimming and pruning algorithms are found to have a reduced sensitivity to multiple proton-proton interactions and exhibit improved stability at high luminosity. Monte Carlo studies of the signal-background discrimination with jet grooming in new physics searches based on jet invariant mass and jet substructure properties are also presented. The application of jet trimming is shown to improve the robustness of large-R jet measurements, reduce sensitivity to the superfluous effects due to the intense environment of the high luminosity LHC, and improve the physics potential of searches for heavy boosted objects. The analyses presented in this note use the full 2011 ATLAS dataset, corresponding to an integrated luminosity of $4.7 \pm 0.2\ \text{fb}^{-1}$.

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ATLAS NOTE

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June

Performance of large-*R* jets and je
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ATLAS NOTE

ATLAS-CONF-2012-066

June 26, 2012

Studies of the impact and mitigation of pile-up on large radius and groomed jets in ATLAS at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

Abstract

Large radius jets provide one avenue towards efficient reconstruction of massive boosted objects whose decay products are sufficiently collimated so as to make standard reconstruction techniques impractical. The potentially adverse impact of additional proton-proton interactions on such large jets is assessed for a variety of jet types and hadronic final state topologies. The mitigation of these effects via jet grooming algorithms such as trimming, pruning, and filtering is then studied for high transverse momentum jets at $\sqrt{s} = 7$ TeV using an integrated luminosity of 4.7 fb^{-1} collected with the ATLAS detector. A total of 29 jet algorithms and grooming configuration combinations are studied. The application of jet trimming and filtering significantly improves the robustness of large-*R* jets and reduces their sensitivity to the intense environment of the high-luminosity LHC. The consequence is an overall improvement in the physics potential of searches for heavy boosted objects.

ATLAS NOTE

ATLAS-C

June

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full 2011 ATLAS dataset, corresponding to

ATLAS NOTE

ATLAS-CONF-2012-066

June 26, 2012

Studies of the impact and mitigation of pile-up on large radius and groomed jets in ATLAS at $\sqrt{s}$ = 7 TeV

Dedicated study of pile-up effects on mass and jet properties with and without grooming (link)

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teractions on such large jets is assessed for a variety of jet types and hadronic final state topologies. The mitigation of these effects via jet grooming algorithms such as trimming, pruning, and filtering is then studied for high transverse momentum jets at $\sqrt{s}$ = 7 TeV using an integrated luminosity of 4.7 fb^{-1} collected with the ATLAS detector. A total of 29 jet algorithms and grooming configuration combinations are studied. The application of jet trimming and filtering significantly improves the robustness of large-R jets and reduces their sensitivity to the intense environment of the high-luminosity LHC. The consequence is an overall improvement in the physics potential of searches for heavy boosted objects.

ATLAS NOTE

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Performance of large-R jets and je
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JETM-2012-XXX

Version: 0.0

To be submitted to: JHEP(?)

Corresponding editor(s)

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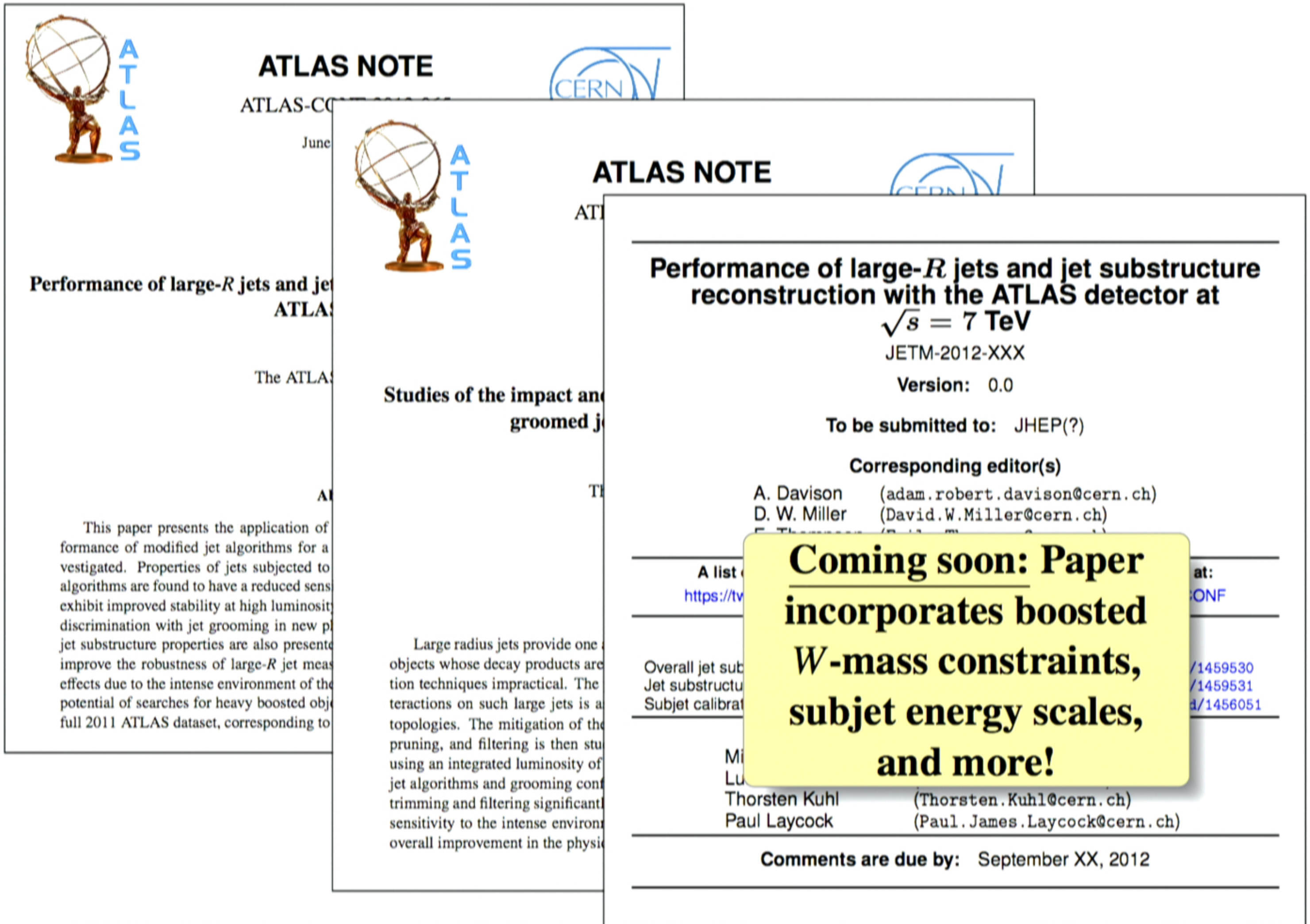
A list of supporting internal notes and their authors can be found at:
https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/LargeRGroomingCONF

Supporting internal notes

Overall jet substructure performance	http://cdsweb.cern.ch/record/1459530
Jet substructure and grooming with pile-up	http://cdsweb.cern.ch/record/1459531
Subjet calibration and systematics	https://cdsweb.cern.ch/record/1456051

Editorial Board

Comments are due by: September XX, 2012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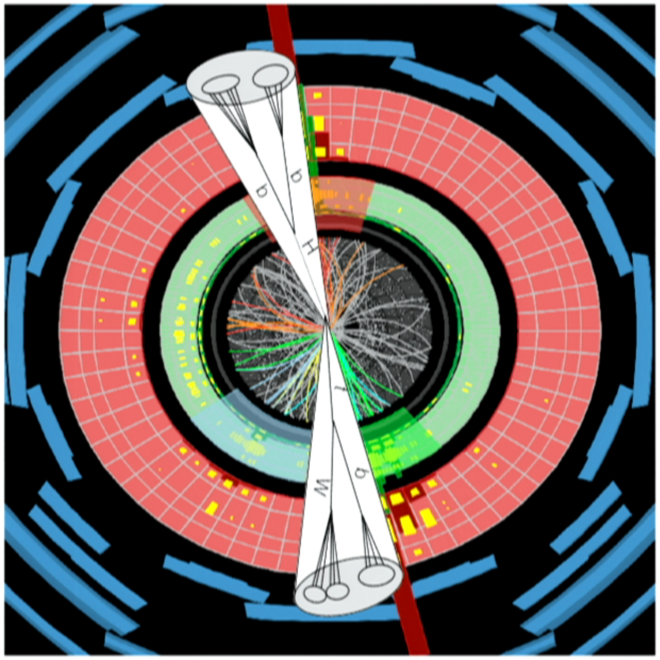
Comments are due by: September XX, 2012
Coming soon: Paper incorporates boosted W-mass constraints, subjet energy scales, and more!

Summary and conclusions

ATLAS has a robust and broad effort devoted to understanding and treating jets as much **more** than just a fixed 4-vector surrogate for a parton.

Summary

- Fully unfolded Standard Model jet mass measurements with a variety of algorithms, including grooming
- Comprehensive detector-level benchmarks and "analysis-ready" syst. unc. for many additional configurations
- many searches employing these techniques, some of which are not possible without them!



2014?

Conclusions

- **ATLAS is leveraging advances in detector technology and theoretical foundations to investigate the limits of the energy frontier**