Jet sub-structure

Physics case: boosted objects as a probe for BSM
Interplay with detector: requirements on calorimeter

Jornadas sobre la participación Española en futuros colisionadres

Universidad de Granada, 16th of May

Based largely on a contribution to the "TeraScale meeting on

emerging opportunities at the Linear Collider", University of Oregon, USA

Marcel Vos (IFIC Valencia)

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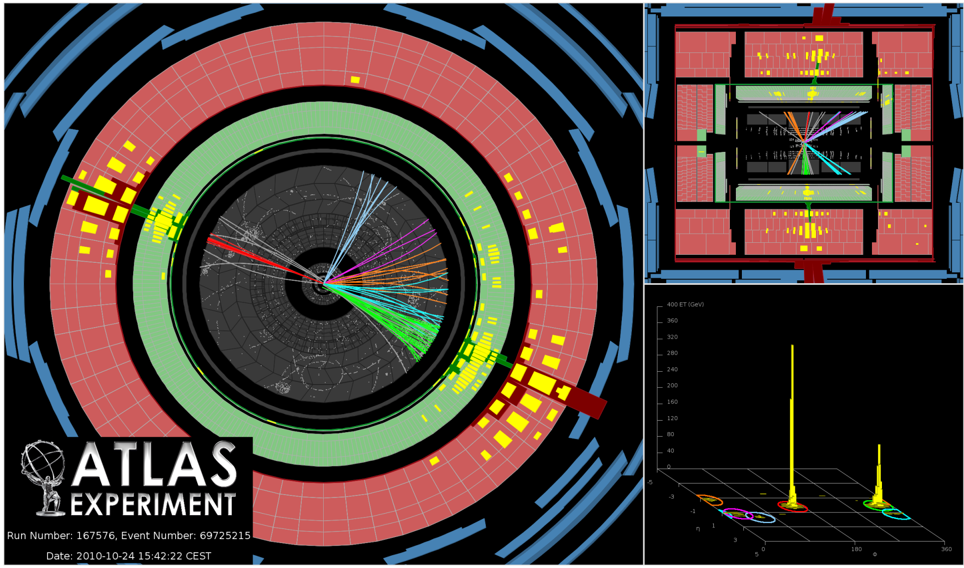
Today's menu:

Boosted objects



Detectors!

Fat jet, according to Colin G.

Fat jets

Boosted objects: a probe of beyond the standard model physics

Report of the hadronic working group of the BOOST2010 workshop, held at Oxford University, from the 22^{nd} to the 25^{th} of June, 2010.

The participants of BOOST2010:
A. Abdesselam[1], E. Bergeaas Kuutmann[2], U. Bitenc[3], G. Brooijmans[4], J. Butterworth[5], P. Bruckman de Renstrom[6], D. Buarque Franzosi[7], R. Buckingham[1], B. Chapleau[8], M. Dasgupta[9], A. Davison[5], J. Dolen[10], S. Ellis[11], F. Fassi[12], J. Ferrando[1], M.T. Frandsen[1], J. Frost[13], T. Gadfort[14], N. Glover[15], A. Haas[16], E. Halkiadakis[17], K. Hamilton[18], C. Hays[1], C. Hill[19], J. Jackson[20], C. Issever[1], M. Karagoz[1], A. Katz[21], L. Kreczko[22], D. Krohn[23], A. Lewis[1], S. Livermore[1], P. Loch[24], P. Maksimovic[25], J. March-Russell[26], A. Martin[27], N. McCubbin[20], D. Newbold[22], J. Ott[28], G. Perez[29], A. Policchio[11], S. Rappoccio[25], A.R. Raklev[30,31], P. Richardson[15], G.P. Salam[23,32,33], F. Sannino[34], J. Santiago[35], A. Schwartzman[16], C. Shepherd-Themistocleous[20], P. Sinervo[36], J. Sjoelin[37], M. Son[38], M. Spannowsky[39], E. Strauss[16], M. Takeuchi[40], J. Tseng[1], B. Tweedie[25,41], C. Vermillion[11,42,43], J. Voigt[28], M. Vos[44], J. Wacker[16], J. Wagner-Kuhr[28], and M.G. Wilson[16]

✔ **Hadronic WG**

M. Spannowsky UO, theory),

M.V. (IFIC Valencia, experiment)

✔ Strongly focussed on jet sub-structure (= QCD for BSM)

✔ Continued regular meetings

✔ WG Report collects participants' contributions

✔ Today's talk largely based on this document

✔ Further workshops (Oregon/Boston Jet workshops), LHCC QCD/BSM session

report submitted to EPJC (arXiv:1012.5412 [hep-ph])

BOOST2011 at Princeton next week

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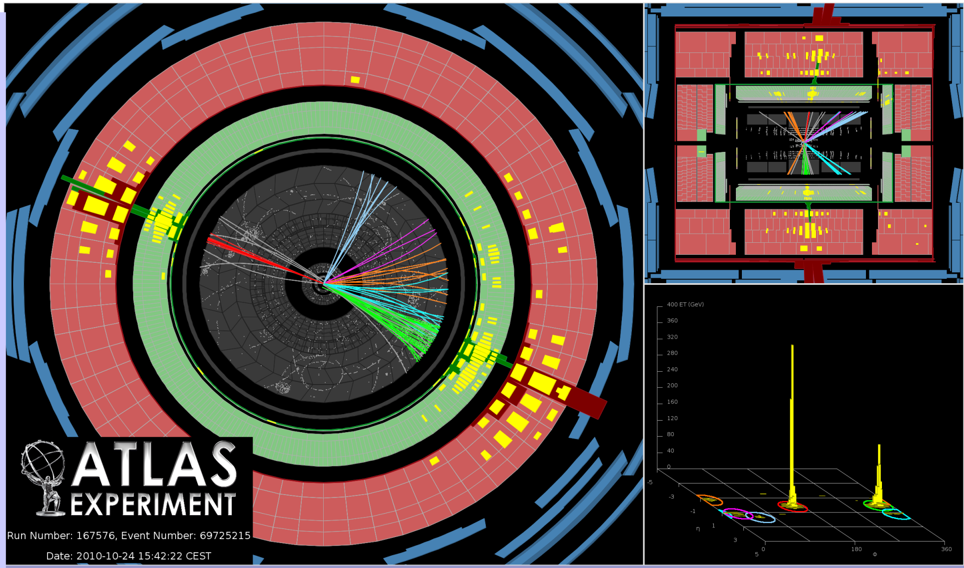
Boosted objects: motivation

- **BSM motivation to look for boosted objects:**
  - Something heavy (e.g. Z’) decays to something lighter (t,W/Z,H,. . .)
  - A new light particle (H, χ^0, . . .) is more easily isolated from background when boosted, for example because combinatorics are less of an issue
  - Cascade decay of exotic objects leads to signatures like lepton jets
- **As $\sqrt{s}_{LHC} >> m_{EW}$ boosted t, W, Z from SM production are actually rather common at the LHC. This remains true for top, and at 7 TeV.**
  - ➔ 17 % of pp $\rightarrow$ tt events has at least one top quark with $p_T > m_t$
  - ➔ That's 1000 events/expt today, ten thousands next year (MC@NLO with CTEQ6.6)

The highest mass central dijet event and the highest-pT jet collected by the end of October 2010: two central high-pT jets have an invariant mass of 2.6 TeV.

* 1st jet: pT = 1.3 TeV, η = 0.2, φ = 2.8
* 2nd jet: pT = 1.2 TeV, η = 0.0, φ = -0.5
* Missing ET = 42 GeV, φ = 1.5
* Sum ET = 2.2 TeV

Jet momenta are calibrated according to the "EM+JES" scheme.

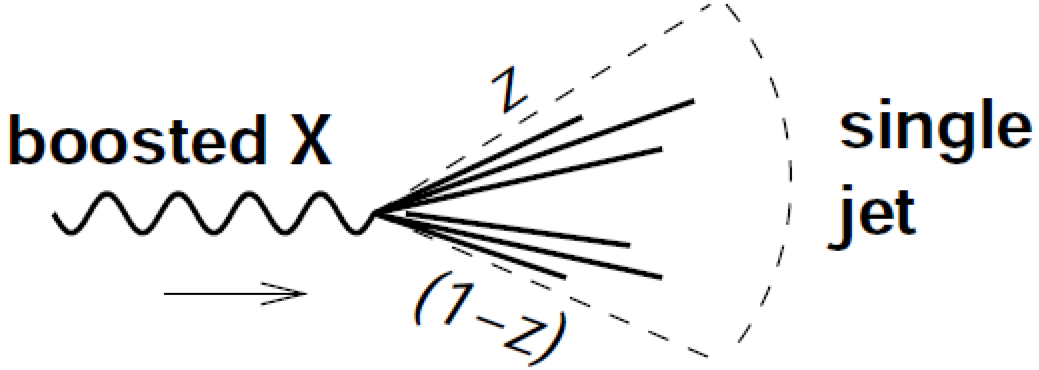


Boosted objects: introduction

- **Boosted topologies require special attention** when boost causes standard algorithms to fail due to overlapping/merging decay products.
- **Invert the logic:** rather than reconstructing the pieces and putting the puzzle back together, reconstruct the composite object and decompose it. Decouple momentum measurement from the study of the lowest-level structure.
- **Rule of thumb** for maximum jet size to resolve both partons in a two-body decay:

$$R < 2m_X/p_T^X \qquad (X \to q\bar{q})$$

$$R < 0.4 \qquad (W^{\pm} \to q\bar{q}\text{, with } p_T^W = 400\text{ GeV})$$



Boosted objects: LC intermezzo

- ✔ Objects with a mass O(100 GeV) will receive a moderate boost at a 500 GeV ILC
  - ➔ To "catch" W-bosons as single jets need R=1
- ✔ Boosted objects will be important at the 1 TeV ILC upgrade (DBD!!)
  - ➔ the maximum R according to our rule of thumb goes down to 0.5
- ✔ Good performance for boosted objects will be absolutely vital at CLIC
  - ➔ No chance to resolve decays of TeV W and Z bosons and top quarks

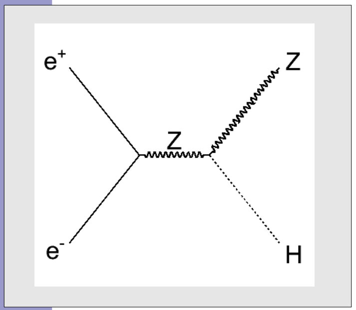
Especially for forward region, see next two slides and:

Forward tracking at the next e+ e- collider. Part I. The Physics case.

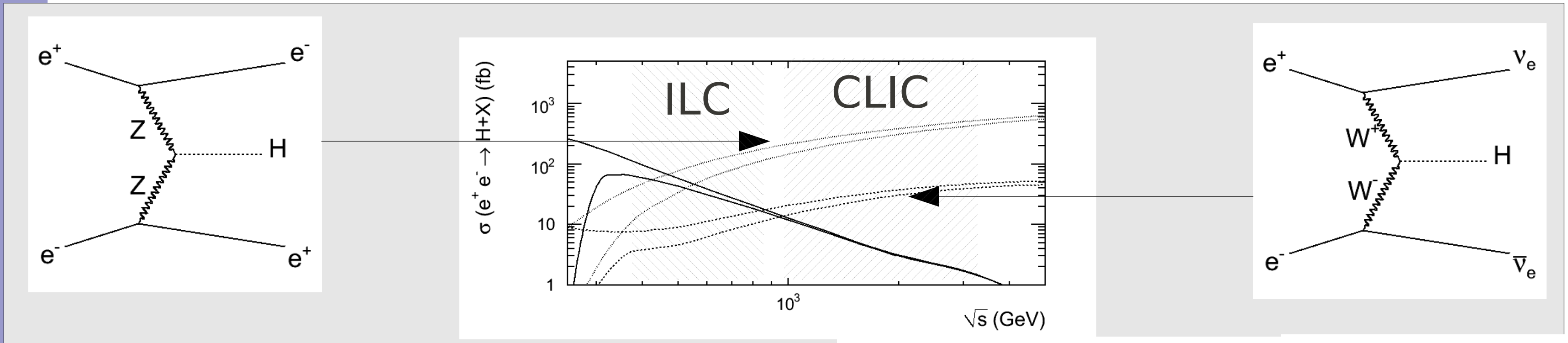
J. Fuster, S. Heinemeyer, C. Lacasta, C. Marinas, A. Ruiz Jimeno, M. Vos,

JINST 4 P08002,2009, arXiv:0905.2038 [hep-ex]

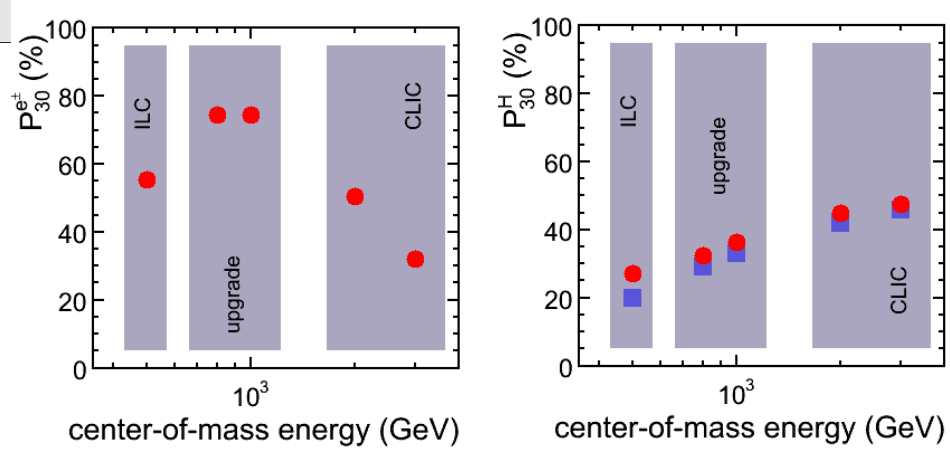
Higgs production



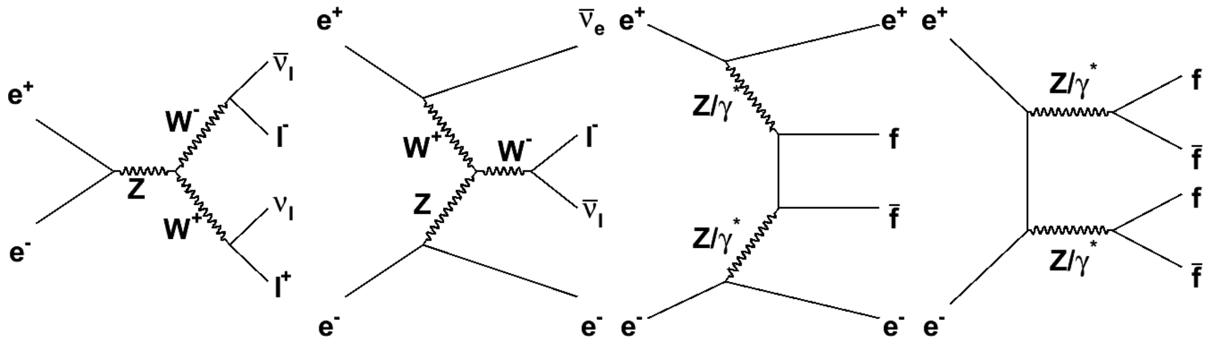
- Higgs-strahlung is the dominant Higgs production process for a low-mass at small √s
- Recoil-mass reconstruction is the tracking benchmark analysis par excellence
- A very central signature



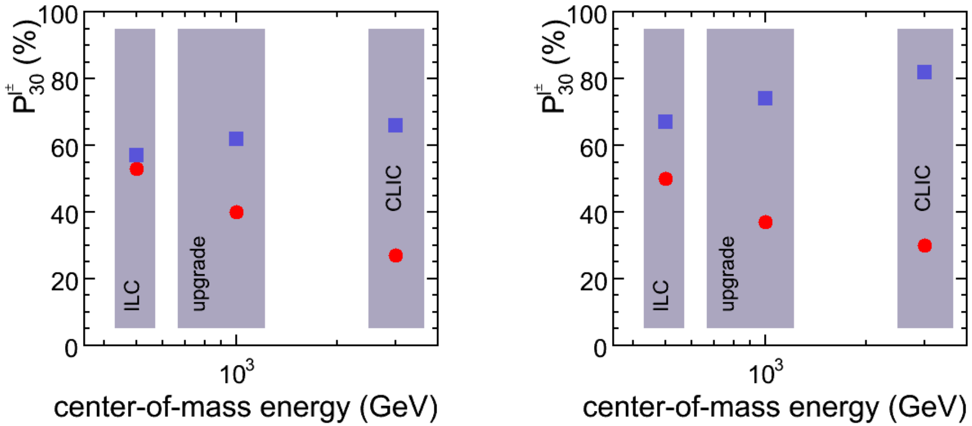
Vector boson fusion processes are much more interesting at CLIC
ZZH can be reconstructed using the recoil-mass analysis on extremely forward electrons



Di-boson production

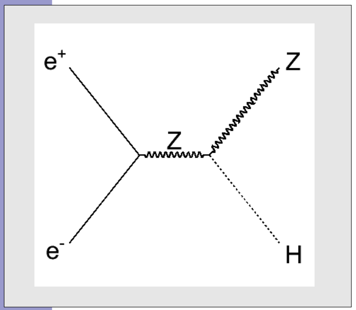


The last example: di-boson production.



The polar angle distribution of electrons is extremely peaked in forward direction

Higgs production



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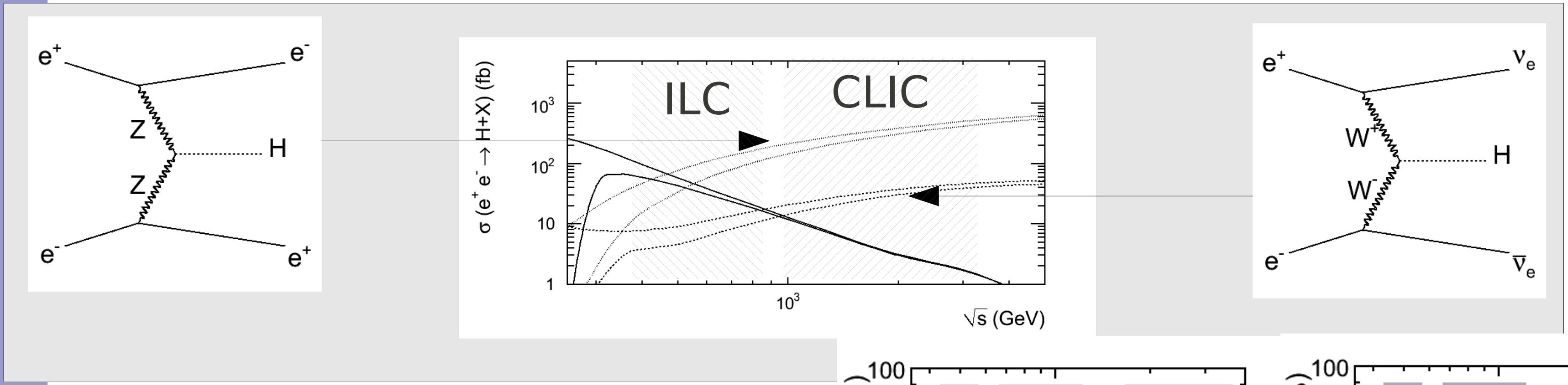

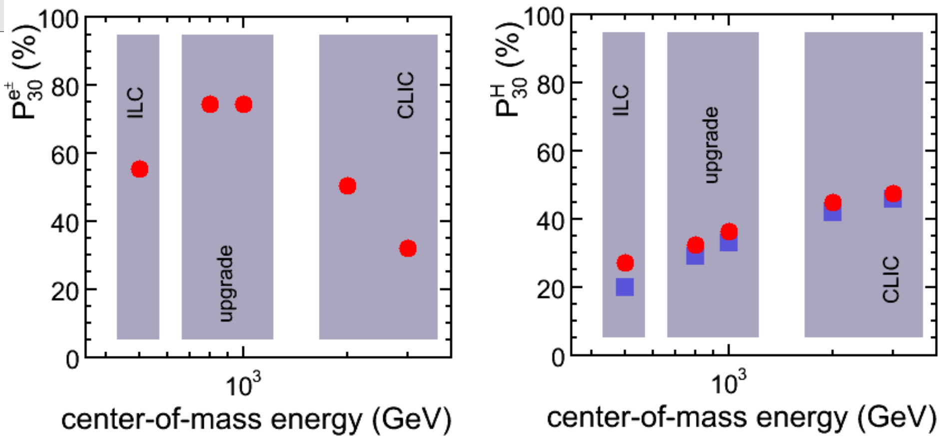

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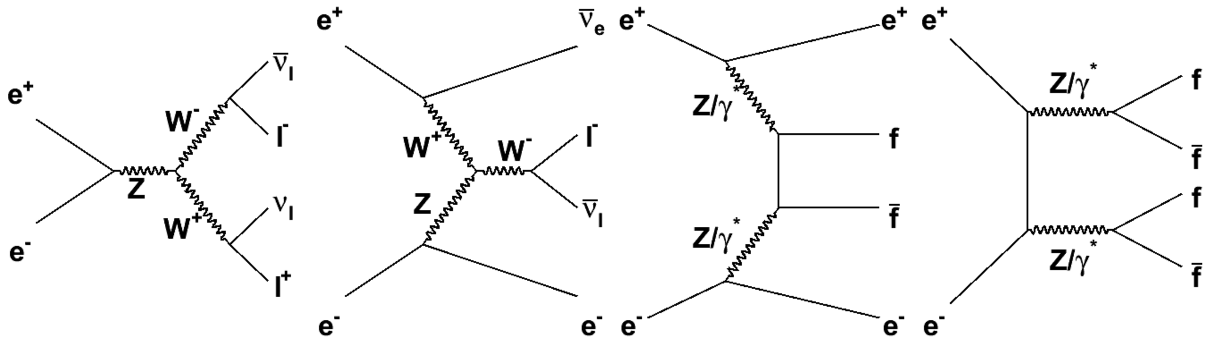
Di-boson production



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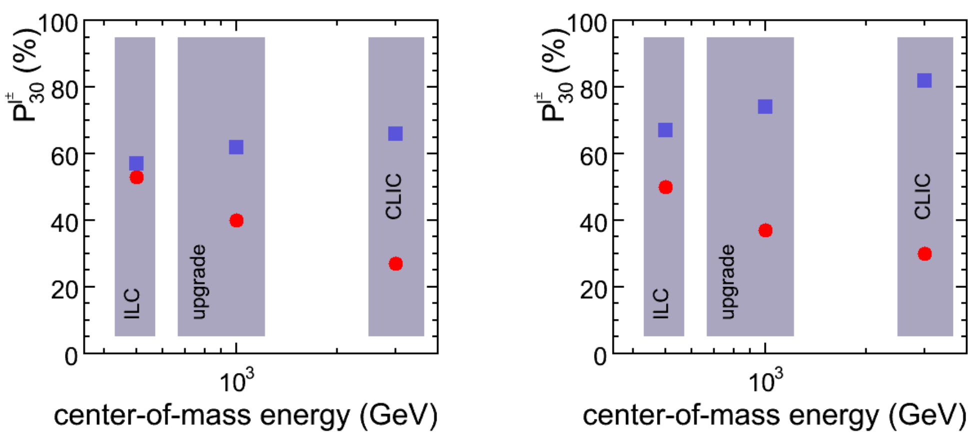
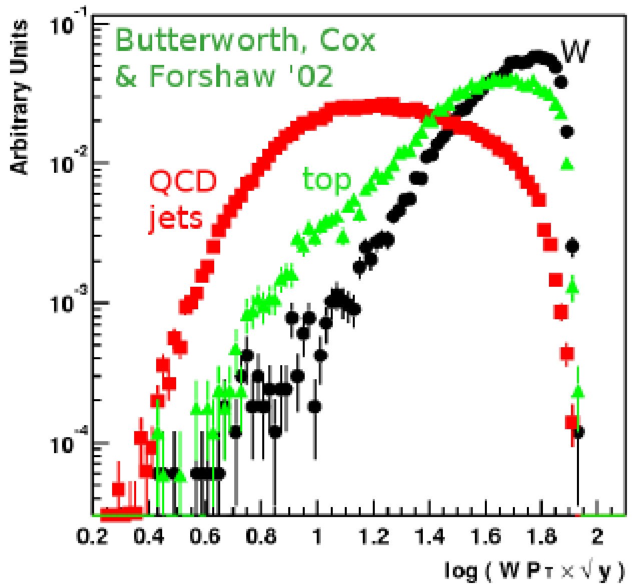


The polar angle distribution of electrons is extremely peaked in forward direction

Boosted objects: from prehistory to modern day

Change of paradigm for reconstruction of highly collimated N-body decays: rather than trying to resolve nearby objects, catch all objects from decay in a single fat jet. Then, to remove backgrounds that were controlled by jet multiplicity, isolated leptons, etc., identify (tag) the object as composite.



1994: Seymour paper

2002: first exploration of jet substructure as a BSM tool

2006: Y-splitter implemented in ATLAS software

The potential of this paradigm has been amply demonstrated:

✔ Boosted W

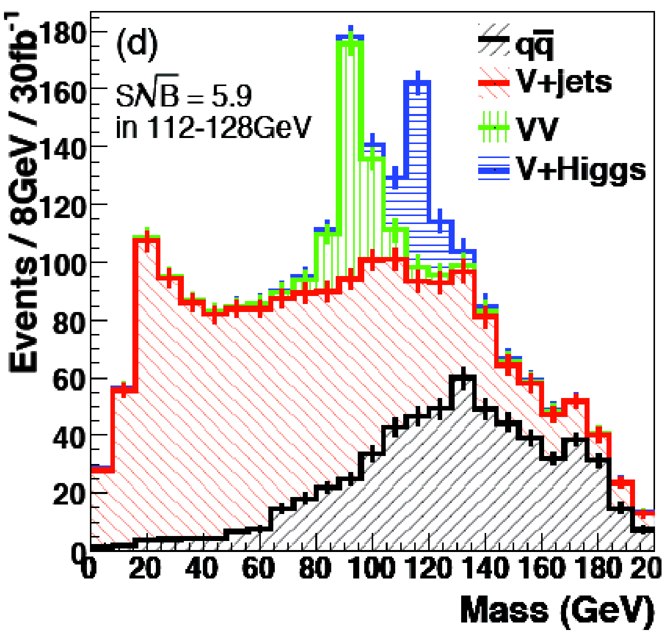
➔ Vector boson scattering, Butterworth, Cox and Forshaw, Phys. Rev. D65:096014 (2002)

"A new method for identifying hadronically decaying W bosons is introduced, which we expect to be useful more generally in the identification of hadronically decaying massive particles which have energy large compared to their mass"

➔ See also paper by Cui, Han, Schwartz paper, arXiv:1012.2077[hep-ph]

✔ Boosted Higgs, in particular light H → bb

- WH, 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"
- ZH, Soper, Spannowsksy, JHEP 1008:029 (2010)
- ttH, Plehn, Salam, Spannowsky, Phys. Rev. Lett. 104 (2010)



Full-simulation by experiments:

Boosted W: CERN-OPEN-2008-020, arXiv:0901:0512 [hep-ex], pages 262 and pages 1769)

Boosted Higgs: ATL-PHYS-PUB-2009-088, CERN-THESIS-2010-027

Tools & Technniques: reconstruction

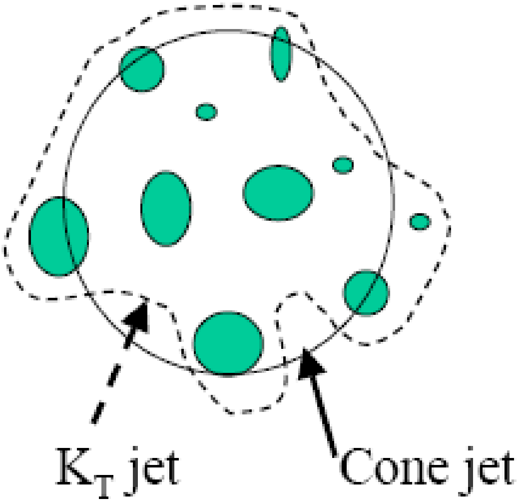
"clustering" jet algorithms use a distance or metr

$$d_{ij} = \min(p_{Ti}^{2p}, p_{Tj}^{2p}) * \Delta R_{ij}^2/R^2)$$

p=0 → Cambridge Aachen (C/A)

p=1 → k_T

p=-1 → anti-k_T



Default jet algorithm for ATLAS/CMS is anti-k_T (R=0.4, 0.6, or 0.5, 0.7)

- Infra-red safe and with nearly circular footprint

Rerun jet algorithms on jet components to reveal jet substructure

- k_T yields clustering that is intrinsically ordered in p_T scale → easy to identify relevant events
- C/A clustering sequence is ordered by angle → intuitive
- Anti-k_T not used extensively for substructure analysis

See also: Butterworth @ Machester workshop:

http://agenda.hep.manchester.ac.uk/getFile.py/access?contribId=9&sessionId=2&resId=0&materialId=slides&confId=1961

Ultimately, we want the metric that provides the most robust clustering of clusters/tracks/particles in an intrinsically busy environment

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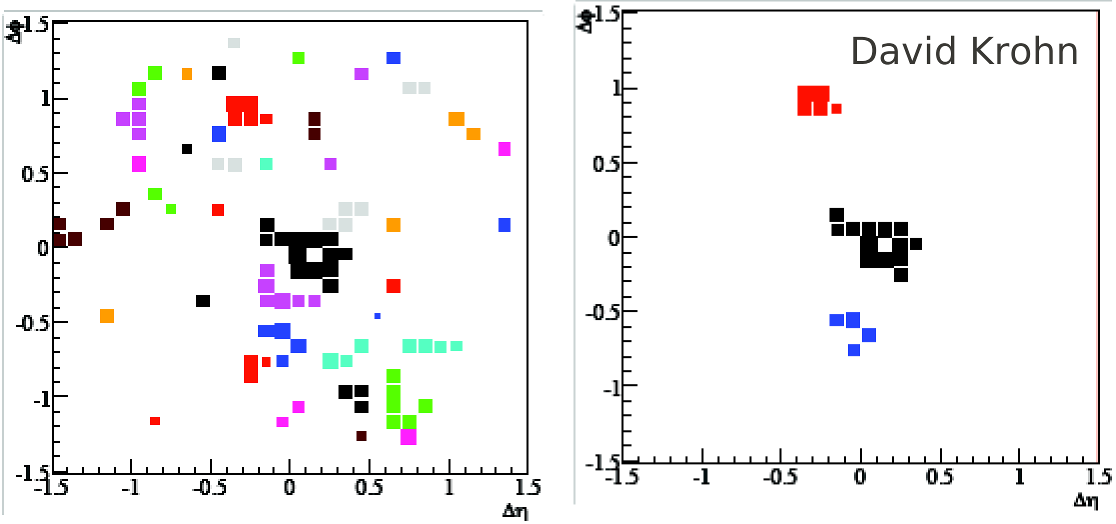
Tools and Techniques: grooming

Jet substructure is often hidden:

- ✔ **Soft emissions inside the jet**
- ✔ **Underlying event**
- ✔ **Pile-up***



*Pile-up is identified and (partially) corrected for by associating jets or clusters to tracks and vertices

***Jet grooming techniques* to remove the "softest" parts (at large angle) 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:** as you build up the jet, if the two subjets about to be recombined have $R > R_{prune}$ and min(pt1, pt2) $< \varepsilon_{prune} (p_{T1} + p_{T2})$, discard the softer one. Ellis, Vermilion & Walsh '09

Boost2010 ignored the variable R option

Tools & Techniques: Benchmark Samples

- ✔ Many groups, many great ideas, many promising results, but … not easy to compare performance in a meaningful way
- ✔ Benchmark: created events for QCD inclusive jets and SM tt production
- ✔ Pythia and Herwig, several tunes for UE, several options for parton shower. Their use here does not imply we claim that these samples are any more “true” than others. Recent LHC work has rendered them obsolete, as expected.
- ✔ Samples provided on two “mirror” sites:
  - ➔ http://www.lpthe.jussieu.fr/esalam/projects/boost2010-events/
  - ➔ http://tev4.phys.washington.edu/TeraScale/boost2010/

HERWIG is used in conjunction with JIMMY that takes care of the underlying event generation. For this study we rely on a tune from ATLAS [ATLPHYS-PUB-2010-002]

PYTHIA 6.4, with a number of tunes for the UE description: DW, DWT and Perugia0. The parton shower model of the DW and DWT samples is Q2-ordered. Both yield identical results for the underlying event at the Tevatron. However, the two tunes extrapolate differently to the LHC, where DWT leads to a more active underlying event. The Perugia tune [Peter Zeiler Skands. Tuning Monte Carlo Generators: The Perugia Tunes. 2010.] uses a pT -ordered parton shower.

To disentangle the impact of the parton shower and that of the underlying event, we generated an additional set of samples with the UE generation switched off.

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Results: grooming

Pythia: $500 < p_T < 600$ GeV
Anti k_T (R=1.0) particle-level

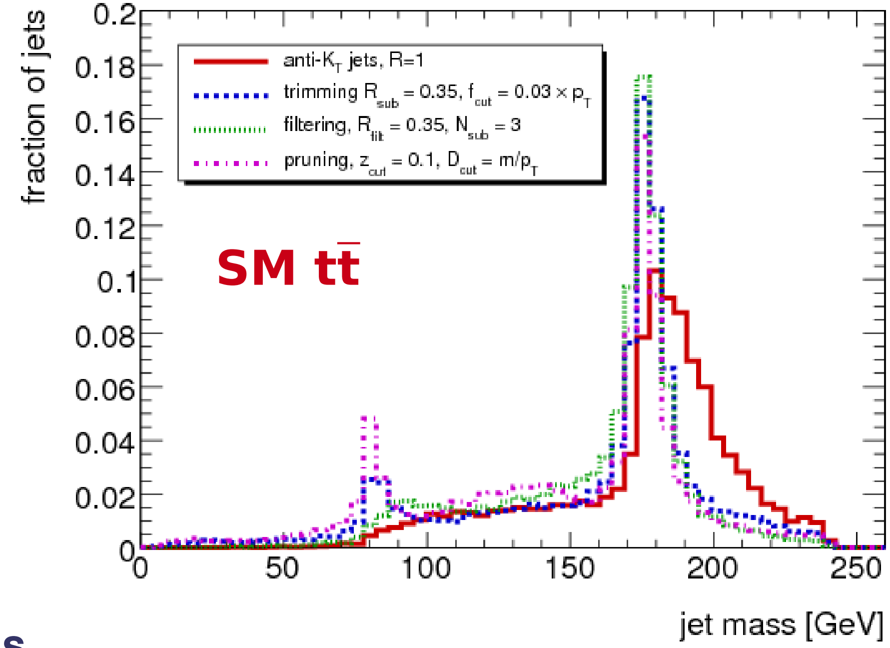
Results on common samples, with common definitions. Algorithm "optimization" performed by authors or under close supervision.

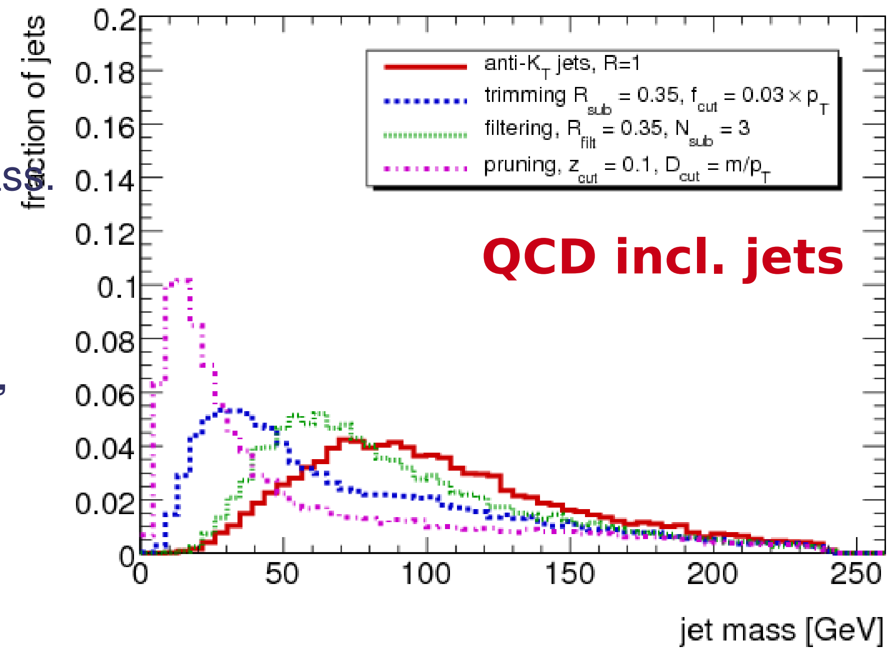
Results confirm that grooming indeed cleans up the jet, removing soft contamination

- ✔ Mass resolution for "fat" jet mass spectrum significantly improved.
- ✔ Inclusive QCD jets migrate to smaller jet mass. Effect at high mass is limited (dominated by real, hard emissions)

Different groomers have a similar impact on the number of events in the "signal window"

- ✔ With these parameters, pruning is most aggressive

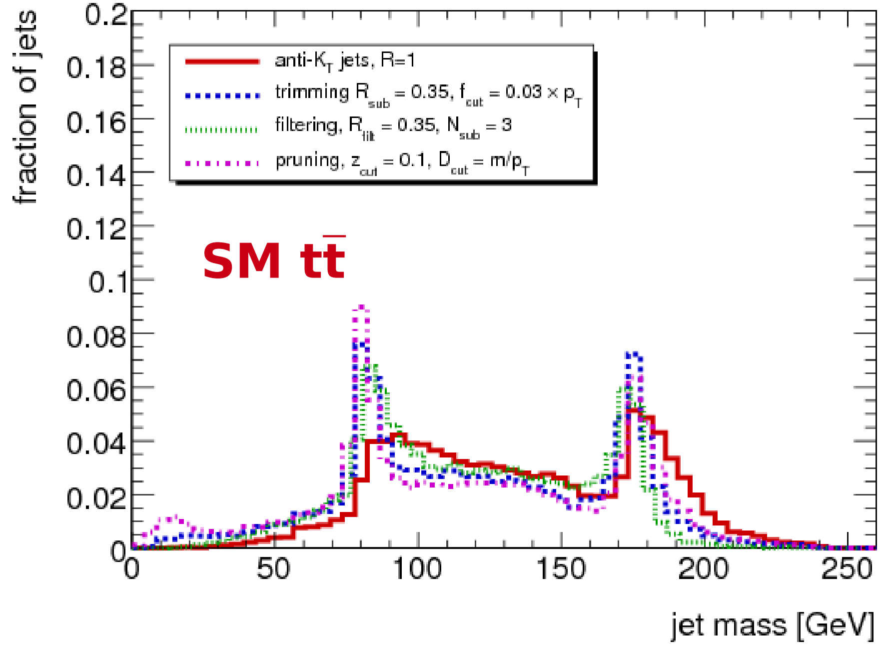


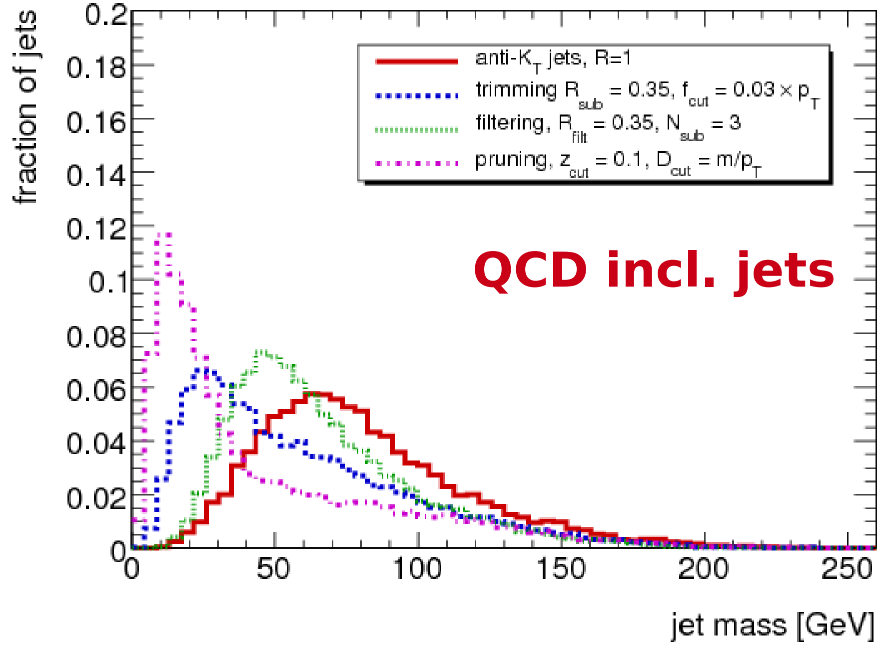


Results: grooming

Pythia: $300 < p_T < 400$ GeV
Anti k_T (R=1.0) particle-level

- ✔ Same as previous slide, but with more moderate boost
- ✔ Grooming forces events into narrow top mass peak (good!) or into the W mass peak (not so good!)
- ✔

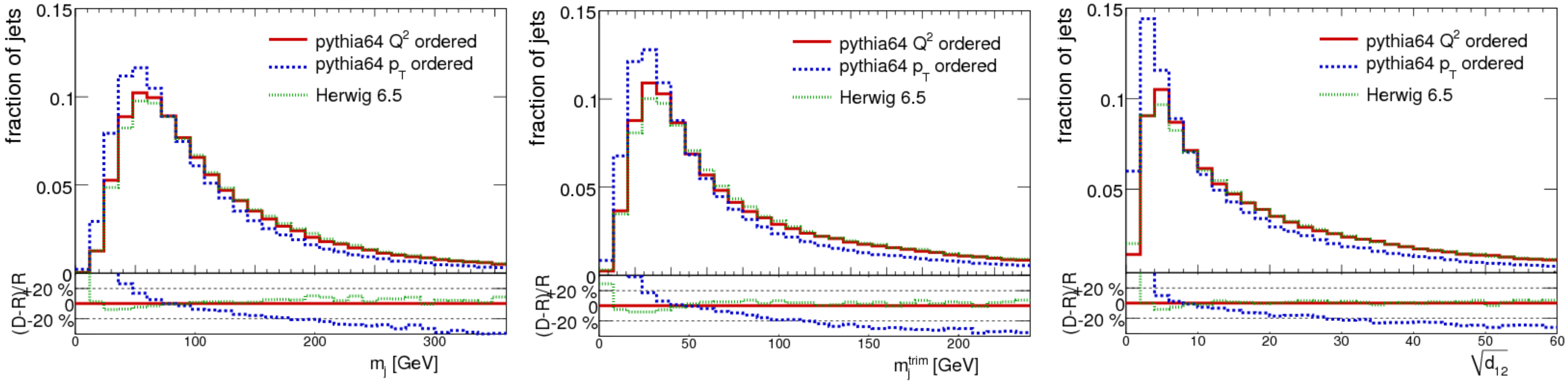




Results: generator uncertainties

Compare different PS models...

... with UE switched off to isolate effects of parton shower.



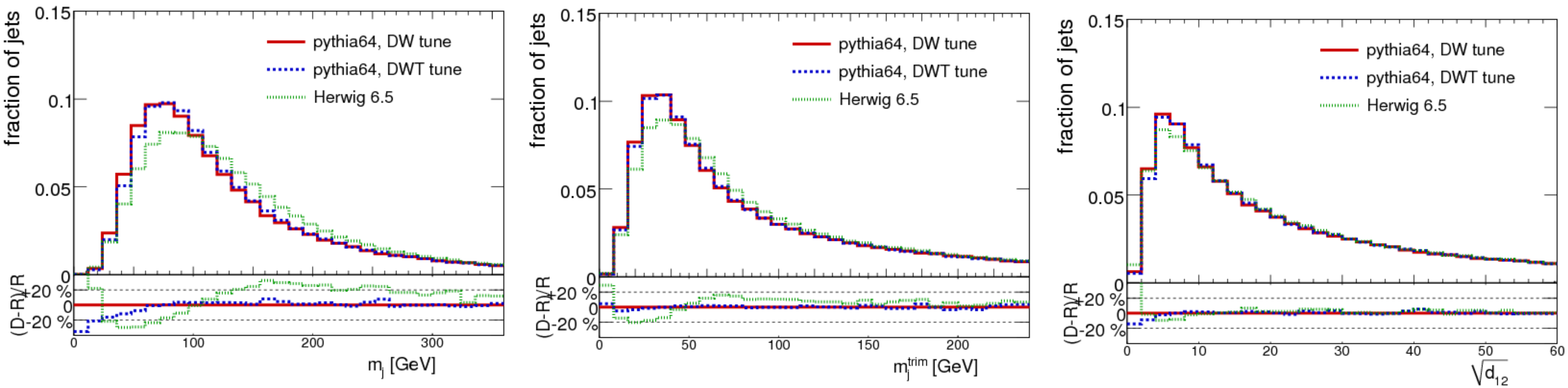
Pythia's p_T-ordered showers (perugia) are clearly "softer", while Pythia Q^2 and Herwig are similar

>> 20 % effect in shape confirms benchmark samples are useful.

All observables "suffer" in a similar way. As might be expected, grooming does not help (this is not what it's for)

Results: generator uncertainties

Underlying Event (~ soft contamination of jet substructure).



Herwig/Jimmy is much “harder” than Pythia DW/DWT (see also ATLAS jet shapes paper)

Invariant mass of R=1 jets is very strongly affected even for jets with 200 < pT < 1500 GeV.

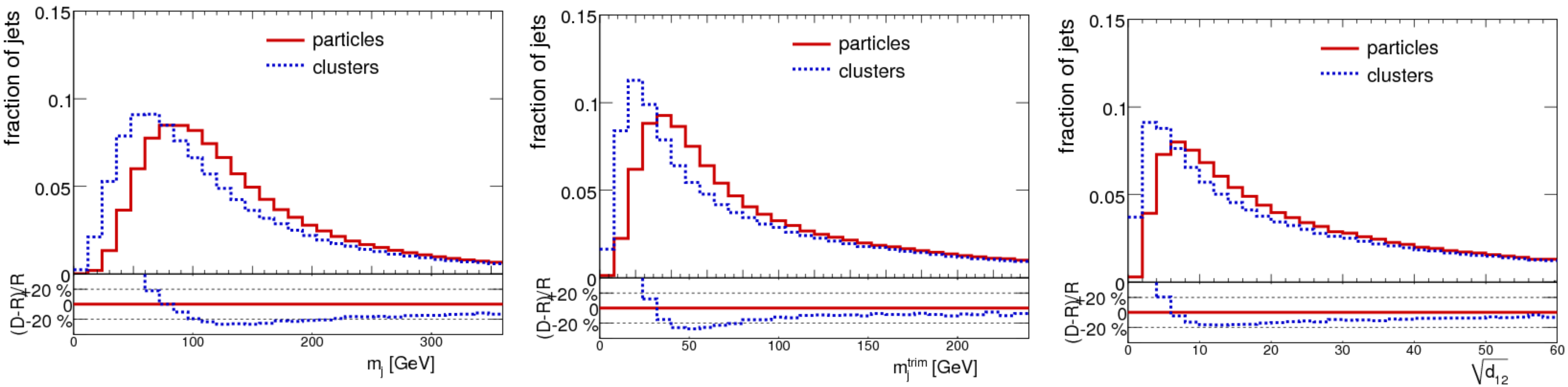
Trimmed mass is less sensitive to “contamination” than raw mass (pile-up!)

Also observables that concentrate on “hard” splits are more robust.

> 20 % effect in shape confirms benchmark samples are needed.

Results: detector uncertainties

Simple "theorist's" detector with pessimistic granularity ($\Delta\eta \times \Delta\phi$ = 0.1 x 0.1), energy threshold (1 GeV)



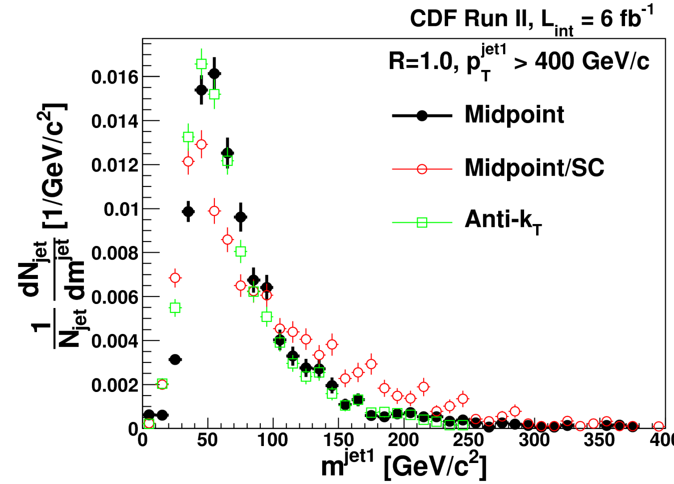
All observables receive large corrections in clustering. Detector response must be modeled precisely in MC to avoid large uncertainties on the calibration that takes the detector response back to "particle-level"

This model is not very satisfactory. Propagate a more realistic detector model to theorists and experimentalists designing substructure analyses → **will get back to this point!**

Experimental work

From the introduction of the hadronic WG report: "We hope that this report may be an incentive for further work and in particular for studies into the substructure of highly energetic jets in the earliest LHC data."

Experiments need to deploy new techniques and “commission” jet substructure tools. So far, no published results using filtered C/A1.2 jets. A section discusses “history”, offering guidance found in Hera and Tevatron studies.



S. Chekanov et al. Measurement of subjet multiplicities in neutral current deep inelastic scattering at HERA and determination of s. Phys. Lett. B, 558:41, 2003.

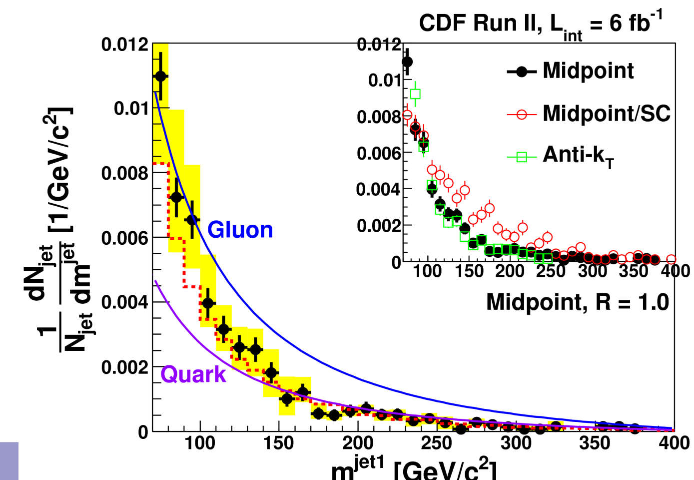
S. Chekanov et al. Substructure dependence of jet cross sections at HERA and determination of s. Nucl. Phys. B, 700:3, 2004.

S. Chekanov et al. Subjet Distributions in Deep Inelastic Scattering at HERA. Eur. Phys. J, 63:527, 2009.

V.M. Abazov et al. Subjet multiplicity of gluon and quark jets reconstructed with the kT algorithm in p¯p collisions. Phys. Rev. D, 65:052008, 2002.

D. Acosta et al. Study of Jet Shapes in Inclusive Jet Production in p¯p Collisions at ps = 1.96 TeV. Phys. Rev. D71:112002, 2005.

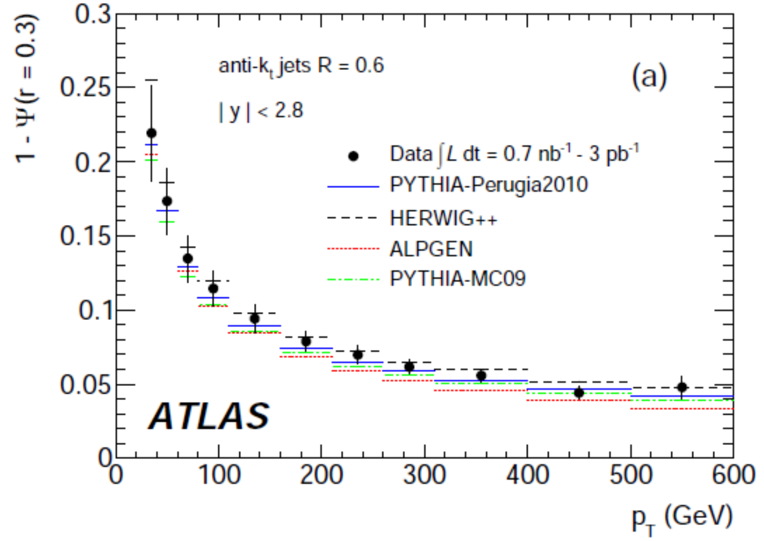
T. Aaltonen et al. The Substructure of High Transverse Momentum Jets Observed by CDF II. CDF Note, 10199, 2010.



Experimental work: outlook

Much has been learnt from the LHC. ATLAS and CMS have published jet shapes papers.

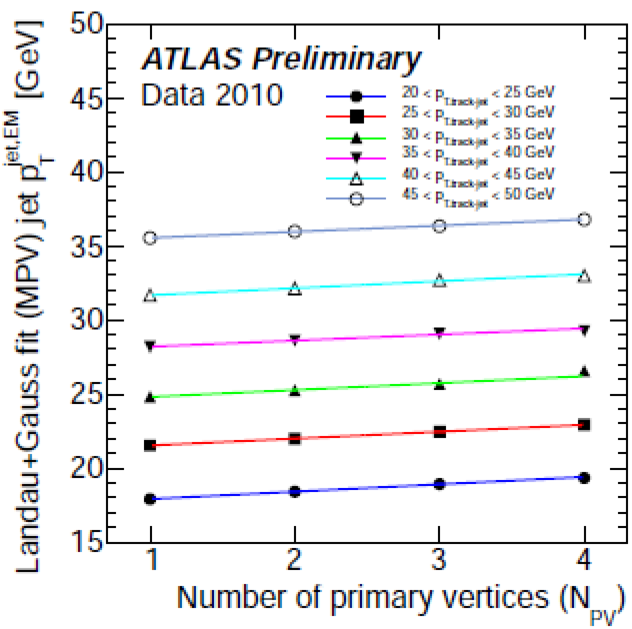
Study of Jet Shapes in Inclusive Jet Production in pp Collisions at $\sqrt{s}$ = 7 TeV using the ATLAS Detector, Phys Rev. D arXiv:1101.0070 [hep-ex],
The CMS collaboration, Jet Transverse Structure and Momentum Distribution in pp Collisions at 7 TeV, QCD-10-014-PAS, july 2010, 10 nb^{-1}, 20 < p_T < 100 GeV



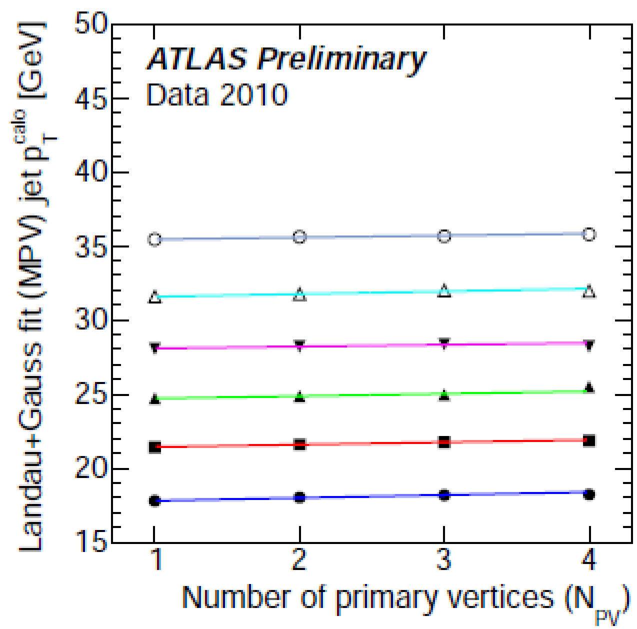
Results feeding back into tunes, strategies to deal with pile-up under development, calibrations improving. Make sure non-standard jet algorithms and observables are not forgotten (i.e. ATLAS boosted objects group, jet substructure paper)

Commissioning on data

- ATLAS has a "boosted objects" group
  - ➔ Initiated in Exotics group
  - ➔ Followed by people in Top group since the start
  - ➔ Merged with effort in Higgs group
  - ➔ Preparing a jet substructure note/paper for Standard Model group
- Effort on understanding substructure of jets with 300 < p_T < 700 GeV recorded in 2010



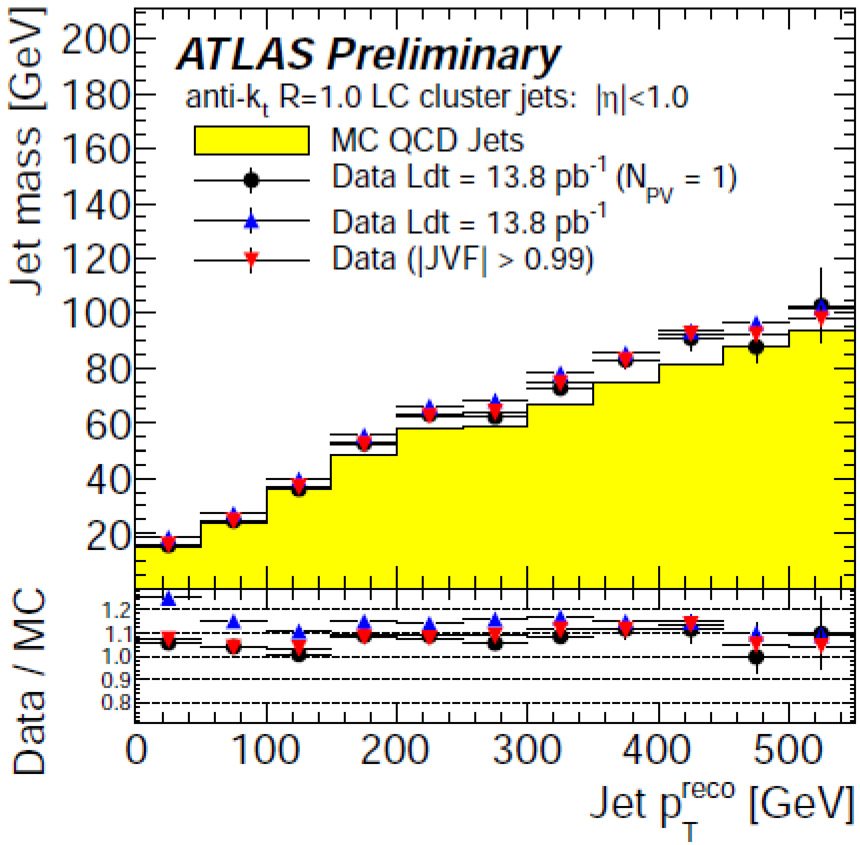
Topo-cluster jet p_T^{EM} vs N_{PV} (MPV from fit)



Jet-level closure test (MPV from fit)

Commissioning jet substructure

- ✔ Large jets rather sensitive to pile-up
- ✔ Invariant mass is VERY sensitive to pile-up
- ✔ Even in early days (2-3 vertices)
- ✔ Even in 500 GeV jets

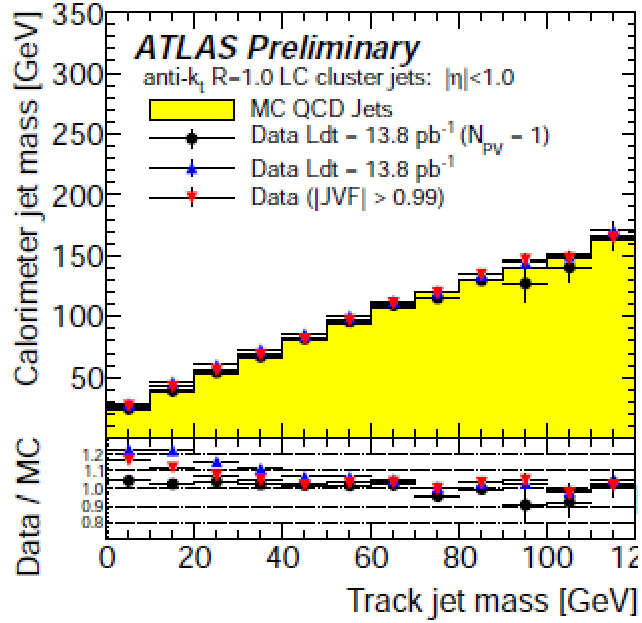


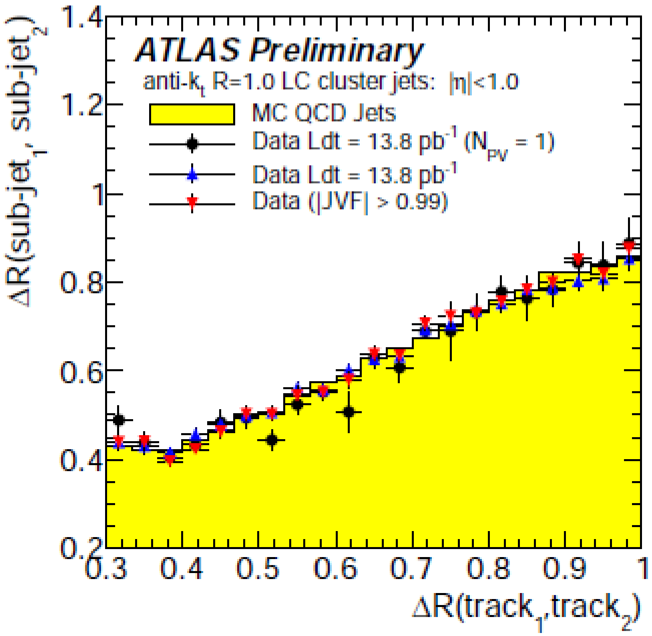
anti-k_t, $R = 1.0$, $p_{T,1} > 250$ GeV, $|\eta| < 1$

Commissioning jet substructure

Isolate instrumental effects by comparing track jets and calorimeter jets

- ✔ Physics drops out
- ✔ Track jets are insensitive to pile-up

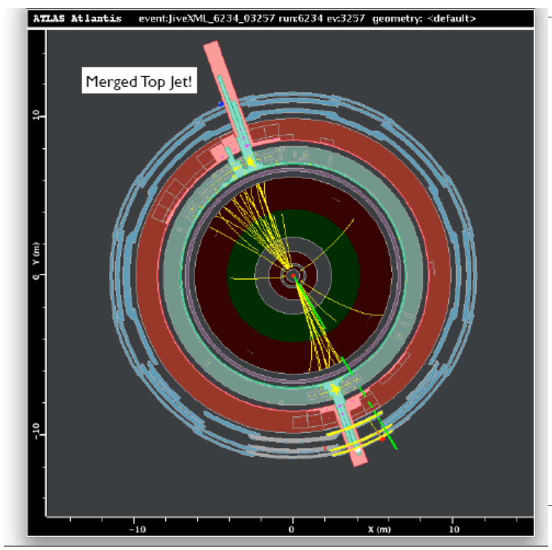


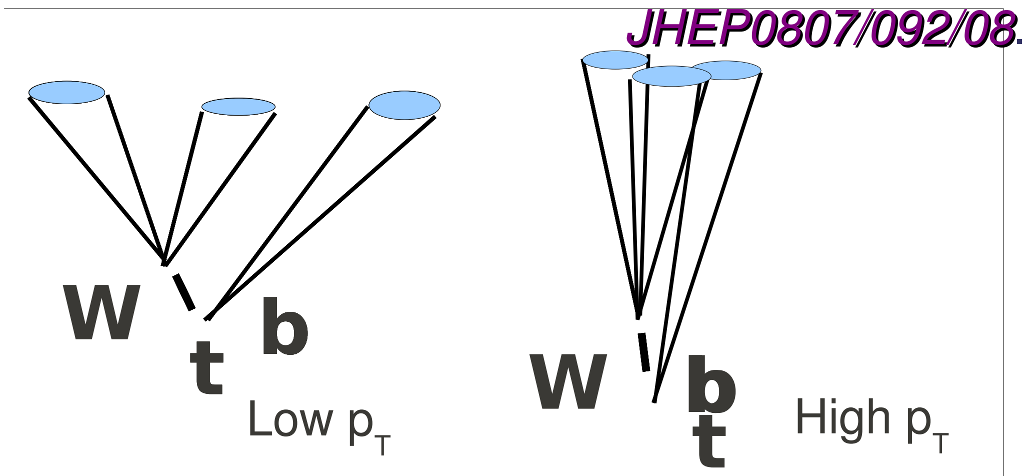


Focus is on jet mass,

but other observables are not forgotten

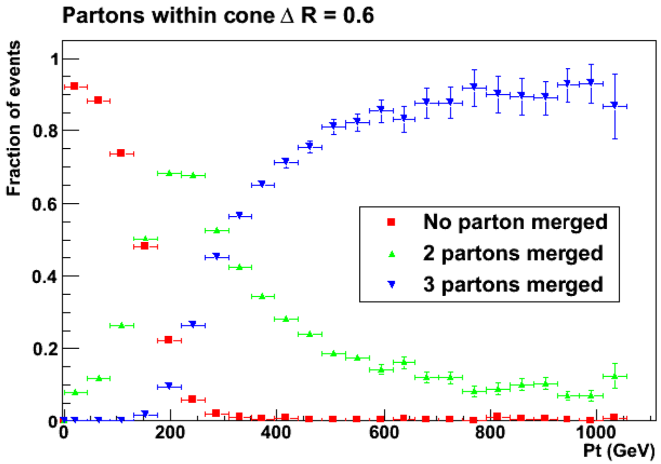
Example: boosted tops





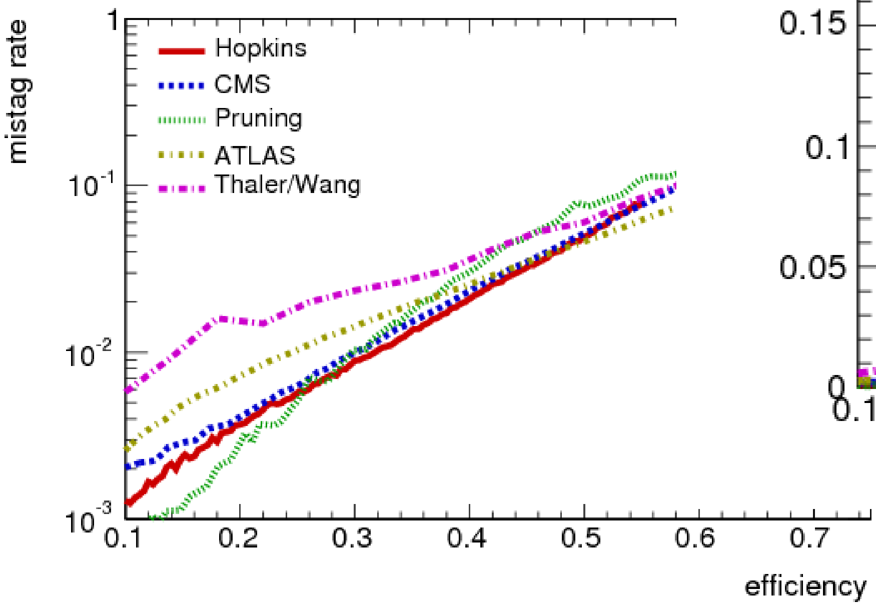
Classical “resolved” algorithms run into problems for highly boosted tops:

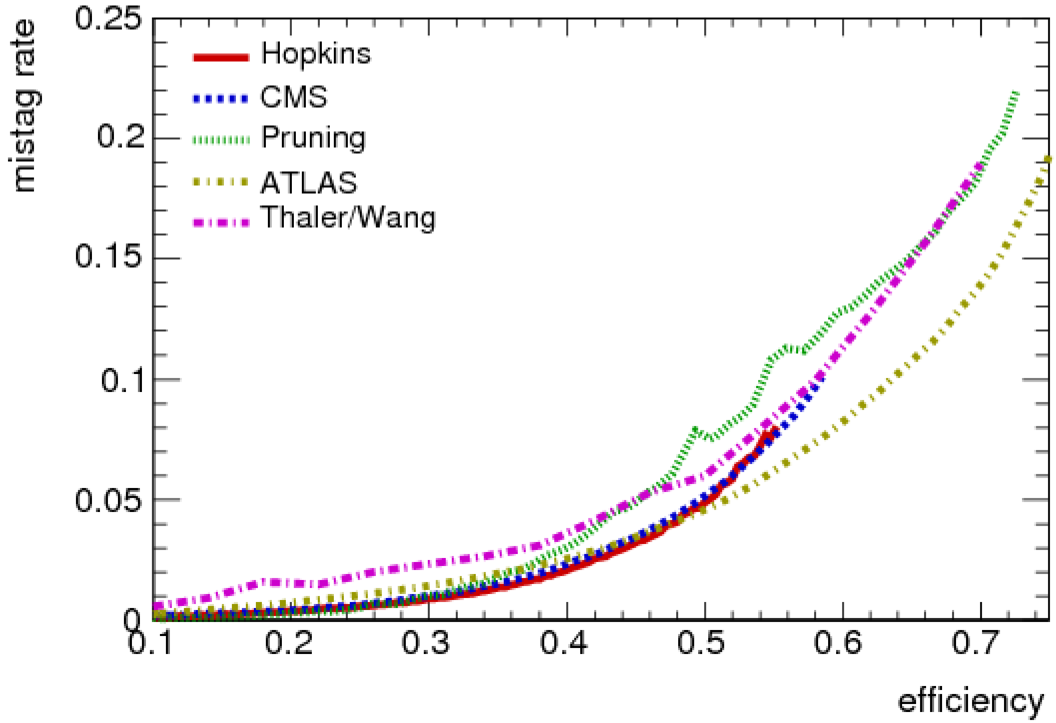
- **Partons not resolved by jet algorithms**
- **isolation of leptons (incl. trigger)**
- E_T^{miss} resolution in events with TeV jets
- tracking performance in jets (b-tagging)
- control samples (jet calibration, b-tag)



➔ B. Lillie, L. Randall, and LTW, hep-ph/0701166
➔ L. Almeida, S. Lee, G. Perez, I. Sung, J. Virzi, arXiv:0810.0934
➔ Kaplan, Rehermann, Schwartz, Tweedie, Phys. Rev. Lett 101:142001 (2008)
➔ Thaler and Wang, JHEP 07:092 (2008)
➔ Plehn, Spannowsky, Takeuchi, Zerwas,

Top-tagging III





Comparison of hadronic top-tagging performance: ε_{QCD} vs ε_{top}

- ➔ Factor 6 @ 70%
- ➔ Factor 50 @ 50 %
- ➔ Factor 300 @ 30 %

For $200 < p_T < 800$ GeV

- ✔ Groomed taggers (Hopkins/CMS/Pruning) provide best performance for $\varepsilon < 50$ %
- ✔ Ungroomed taggers (Thaler & Wang/ATLAS) provide better performance for $\varepsilon \sim 70$ %
- ✔ Choice depends on analysis, in particular lepton + jets final state vs. fully hadronic event

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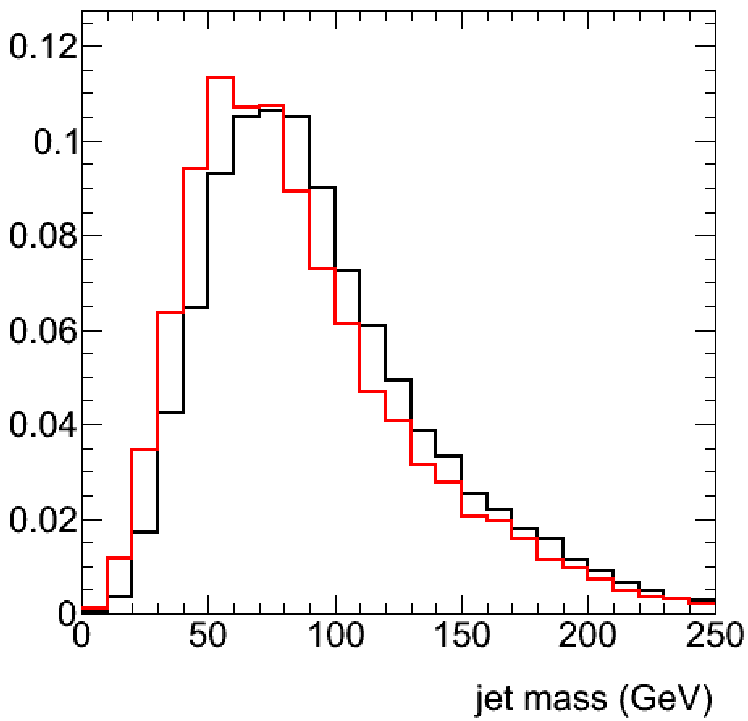
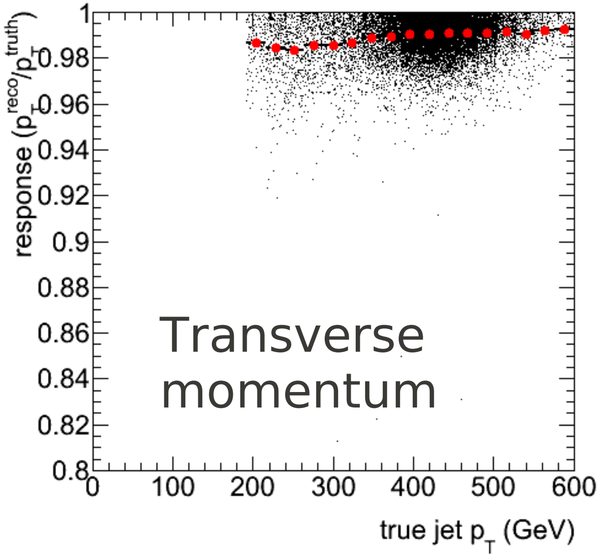
Interplay jet substructure and detector

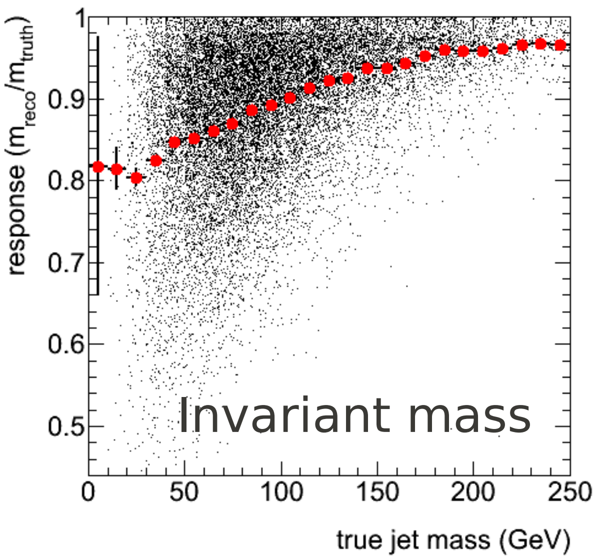
- ✔ Preliminary ATLAS results on inclusive jet sample confirm the naïve expectation that the detector has considerable effect on the small-scale (DR < 0.3) substructure of jets
  - ➔ Not approved yet (expect to approve results for BOOST2011)
  - ➔ ATLAS calorimetry ≠ ILC/CLIC calorimetry
- ✔ In the remainder of this talk I'll discuss the interplay of detector and jet substructure using a toy model
  - ➔ Building on work by Chris Vermillion and Steve Ellis
  - ➔ Hope to bring this to maturity in the next months, with detector experts (P. Loch, M. Thomson)
  - ➔ A stress test for jet substructure tools (definitely not a competitor for full simulation)
  - ➔ If successful provide this as a FastJet tool

Simple detector effects

Threshold: particles with E < 1 GeV are simply discarded







- ✔ Transverse momentum measurement relatively stable
  - ➔ Response hardly affected: average ~ 99 %
  - ➔ Resolution effect small: RMS < 1 %
- ✔ Strong impact on jet invariant mass measurement
  - ➔ Mass response drops by 10s of % for low mass jets
  - ➔ Resolution 6 % overall

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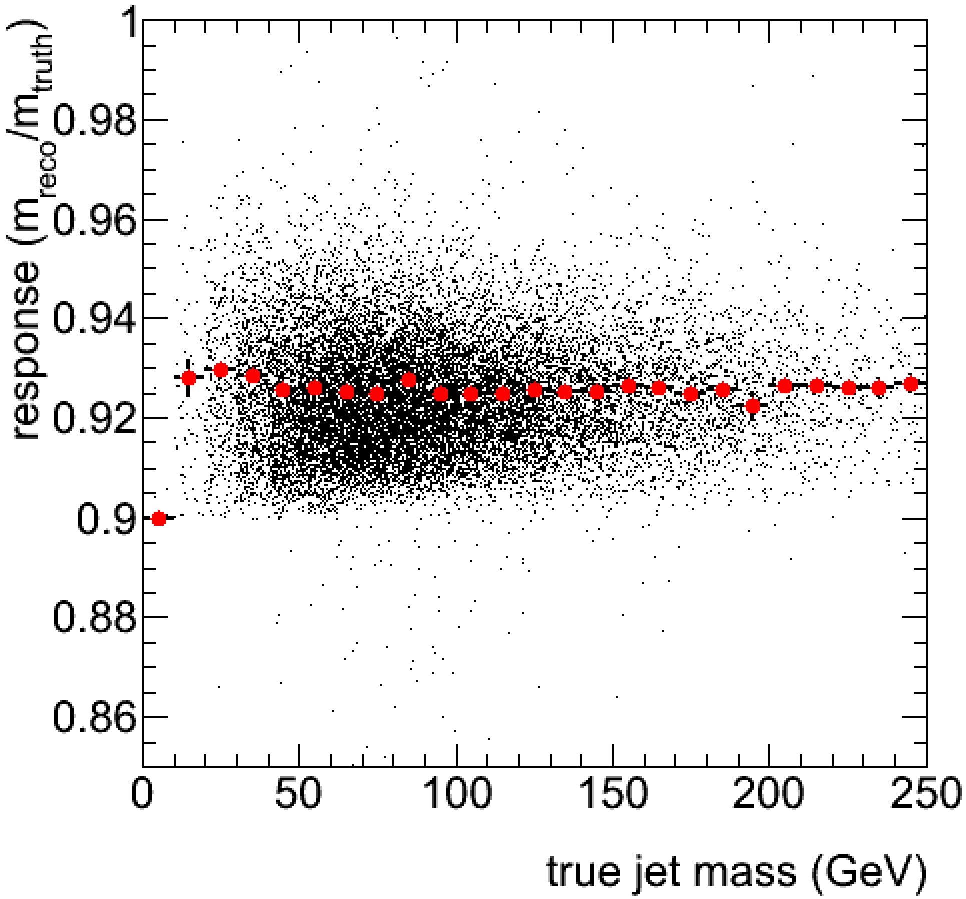
Simple detector effects

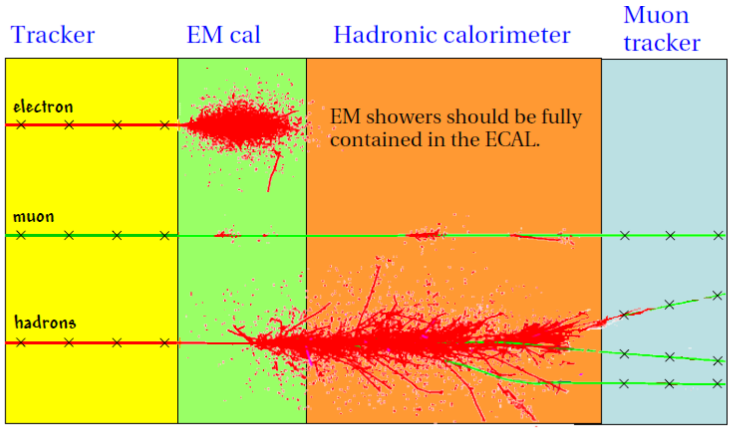
Hadronic scale off by 10 %

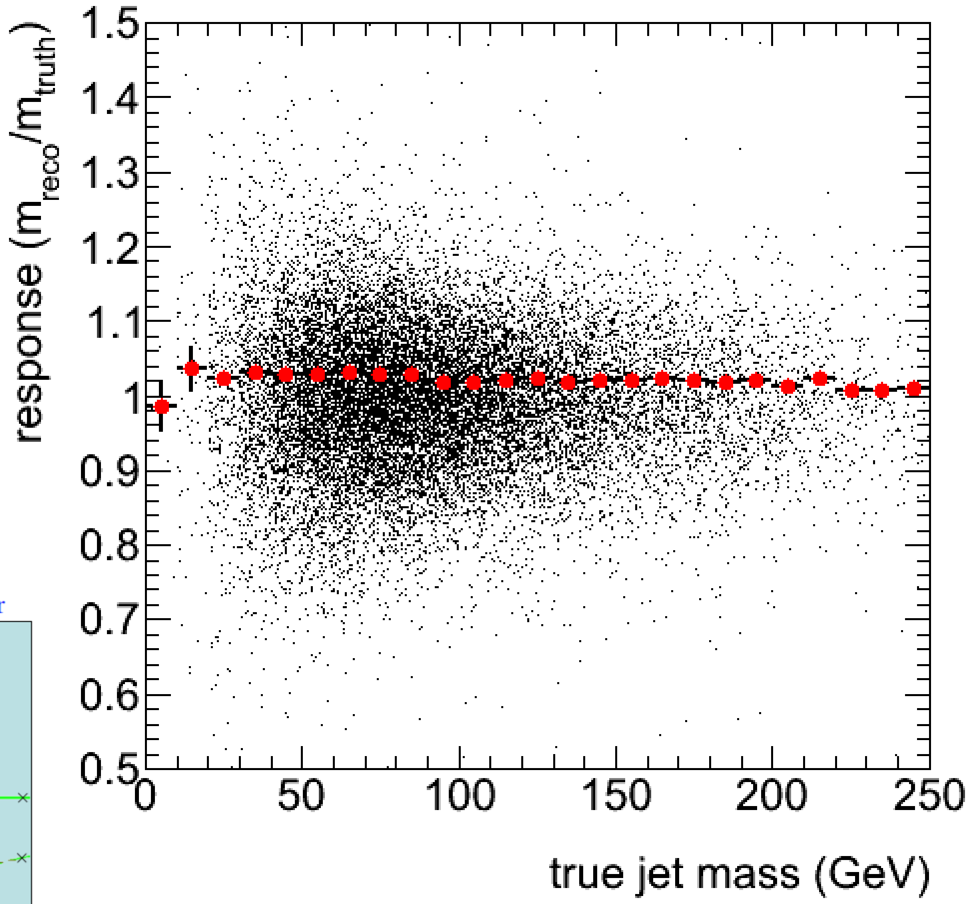
- ✔ difference between QGSP and QGSP_BERT
- ✔ Overall effect on scale is compensate
  even by blind calibration
- ✔ Calibration that distinguishes EM/hadronic scales needed to remov
  residual resolution effect



Simple detector effects

- ✔ Resolution
- ✔ Hadronic;: 50%/sqrt(E) + 3 %
- ✔ EM: 20 %/sqrt(E) + 1 %



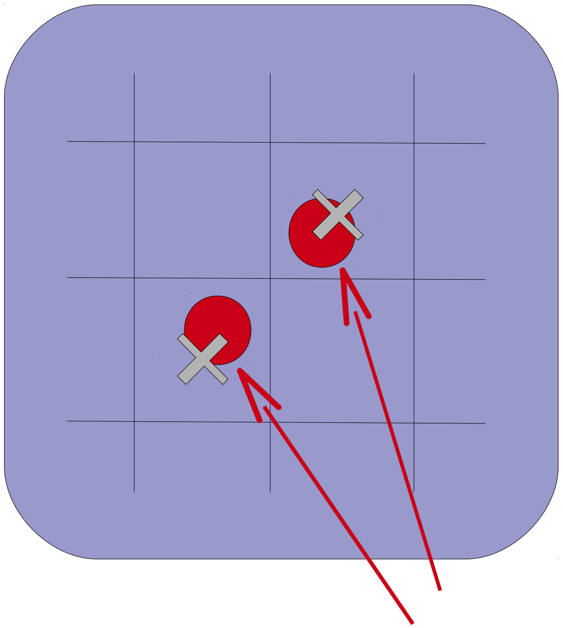


Mass destruction

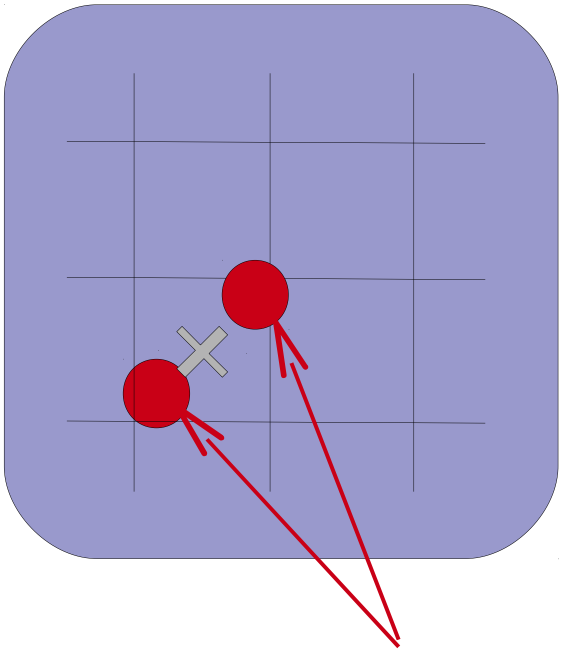
A toy clustering model. Shoot two 50 GeV pions with $\Delta R = 0.1$.

Cluster on a $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ grid

Compare $m_{\pi\pi}$ (= 5 GeV) with "measured" mass



Two clusters. Invariant mass ~correct

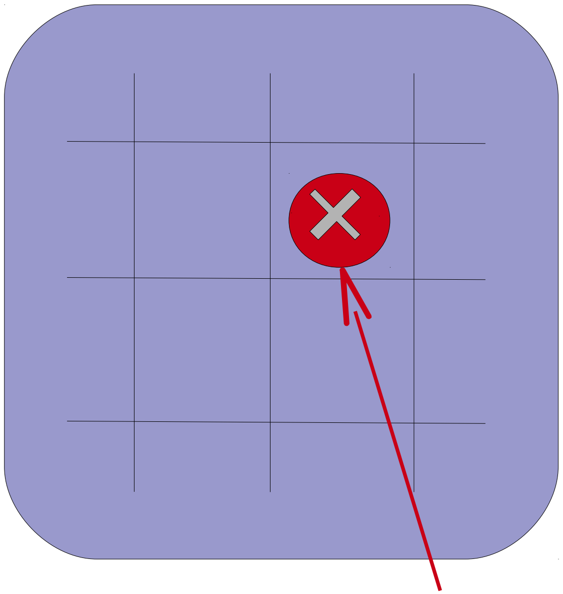


One mass-less cluster

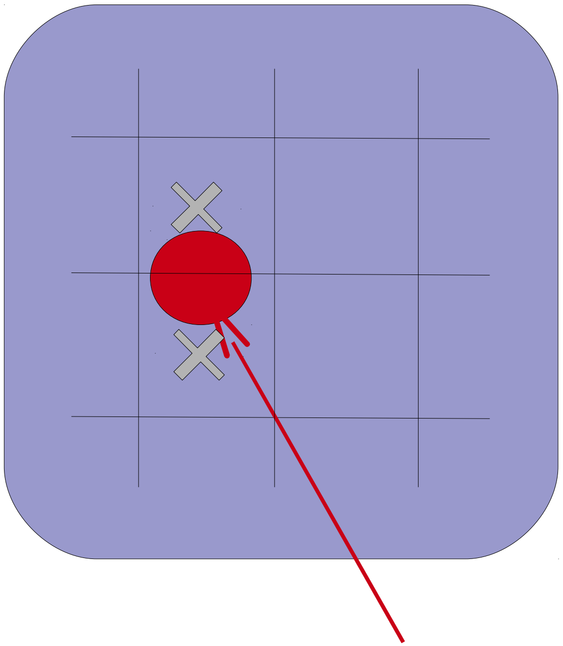
Mass generation

A toy clustering model. Shoot a single 100 GeV pionCluster on a $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ grid

Compare $m_{\pi\pi}$ (~ 0 GeV) with “measured” mass



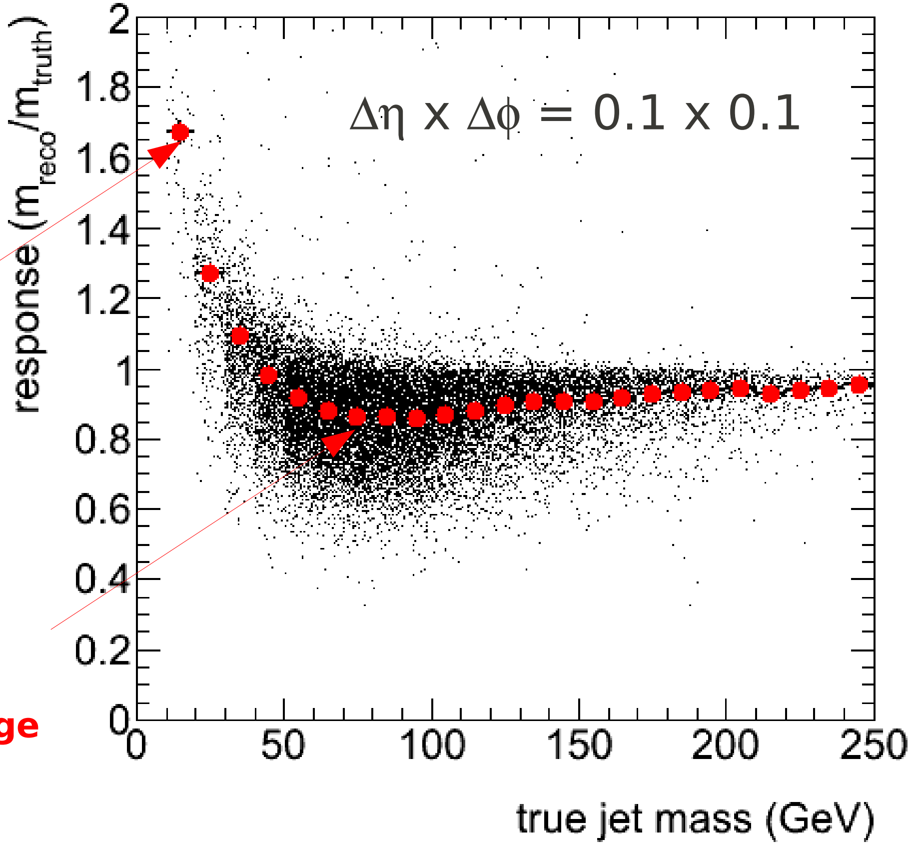
One cluster. Invariant mass = 0



Two clusters
Invariant mass ~ 5 GeV

Impact of detector granularity on response

These and the following slides:
Herwig di-jet samples for 7 TeV LHC.
400 < pT < 500 GeV



Rise due to particles torn apart in clustering → promotion of low-mass jets

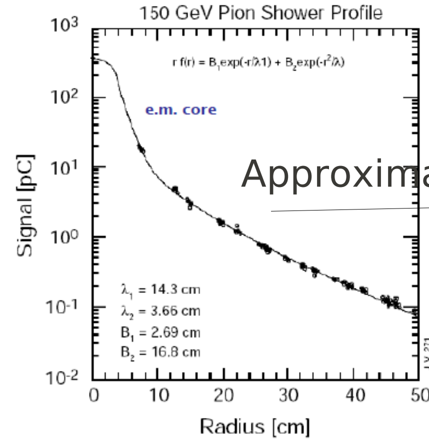
Dip due to merged particles
→ underestimate intermediate mass range

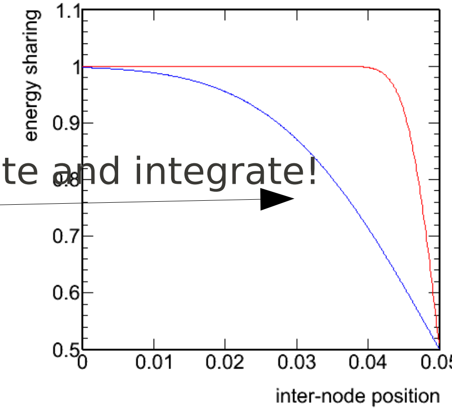
Trivial detector model leads to non-trivial and sizeable effects

- Substructure is removed by clustering massive systems into a mass-less object
- Significant fake substructure is created by splitting mass-less objects (tearing them apart)

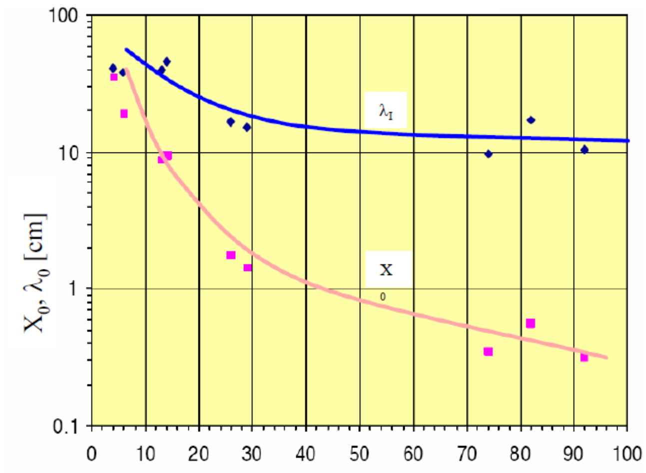
Granularity - Caveat

Assumptions on shower shape lead to strong differences in the observed response

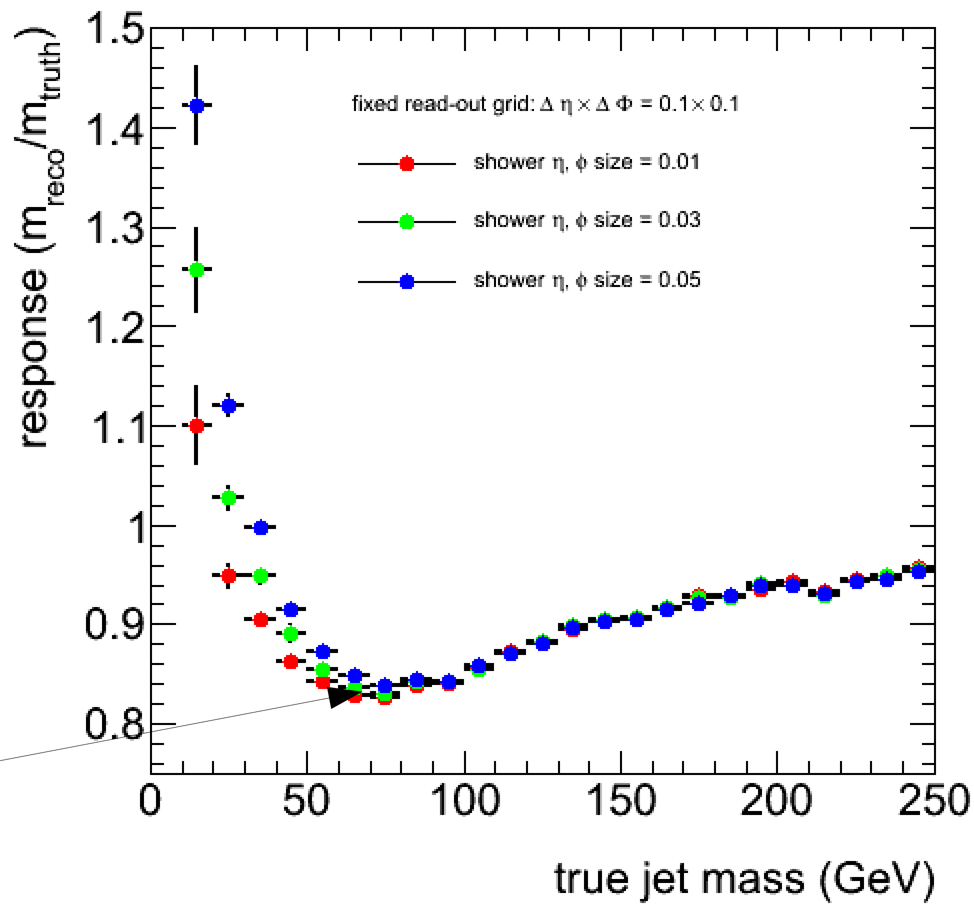




Approximate and integrate!

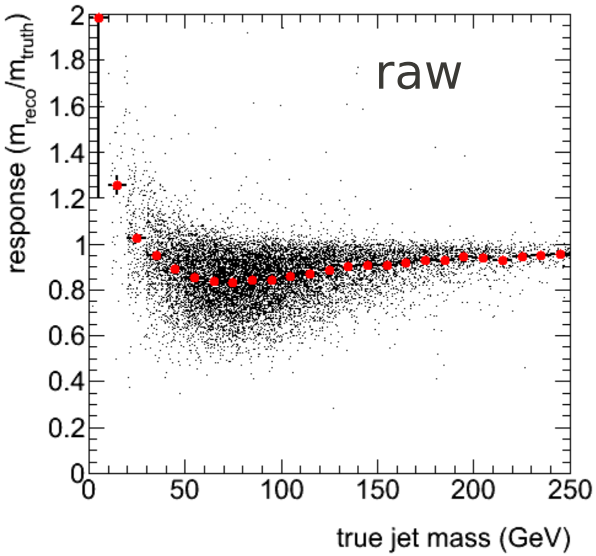


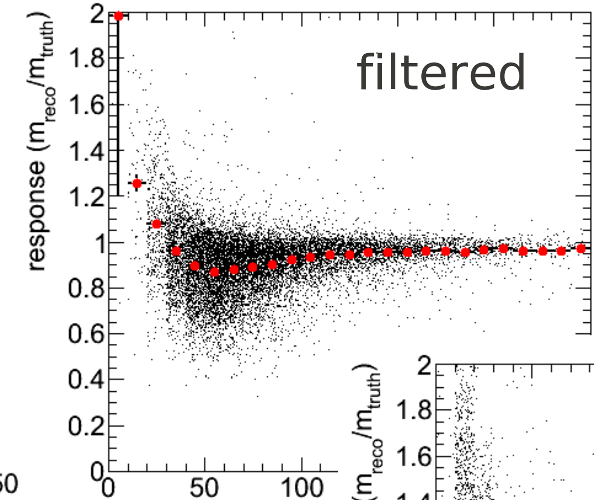
Real shower size depends on material and detector size



Dip +/- constant

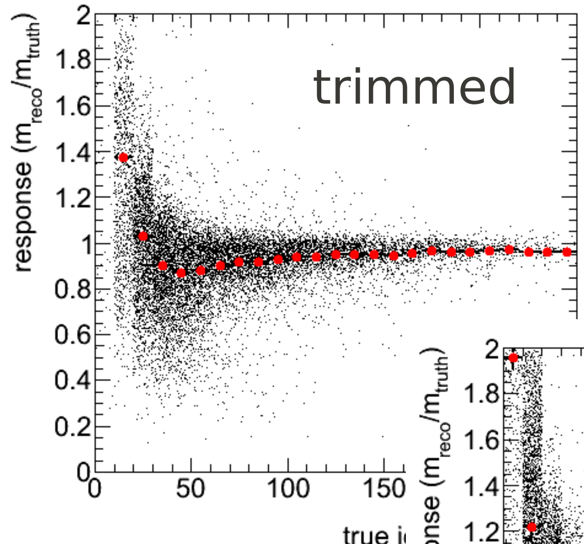
Grooming

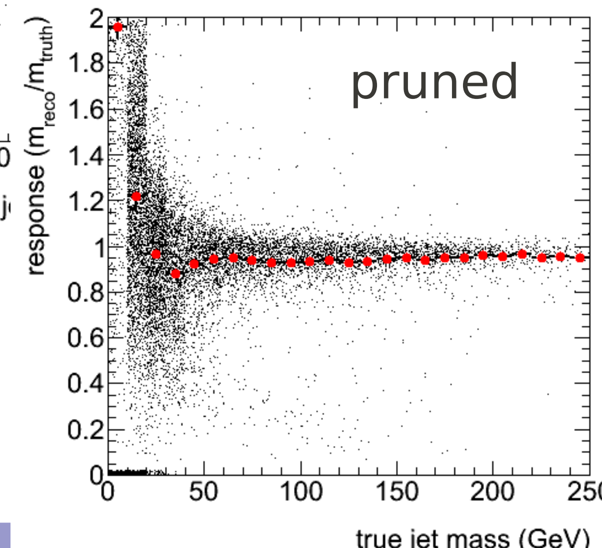




$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

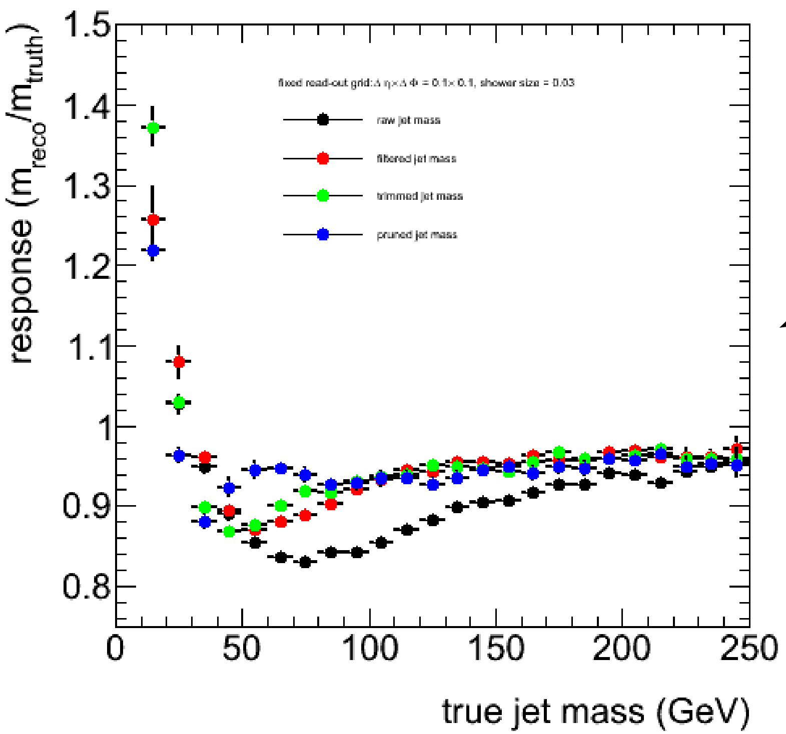
shower size = 0.03





Try different grooming methods: in this setup pruning is known to act most aggressively, followed by trimming

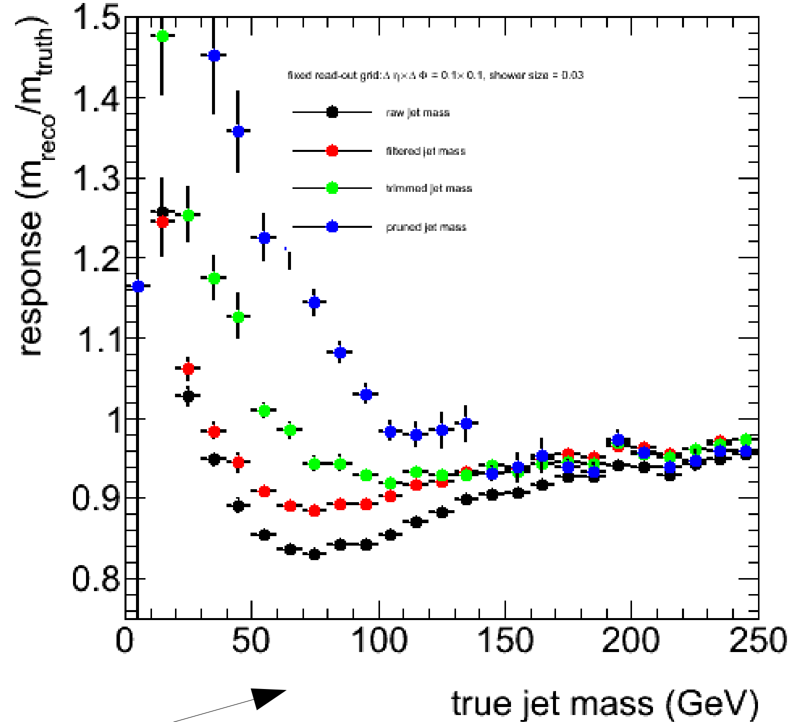
Grooming



$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
shower size = 0.03

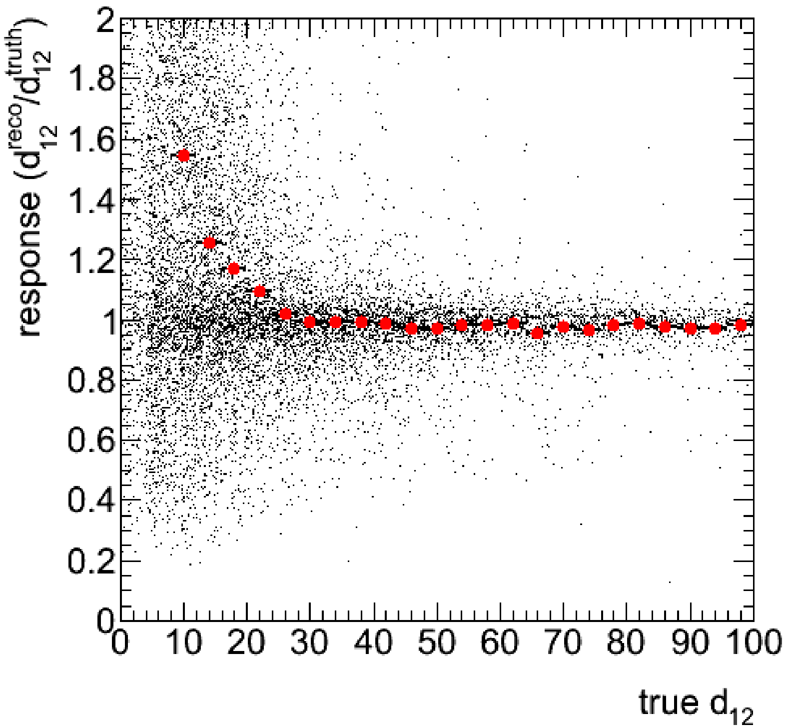
Denominator = groomed jet mass

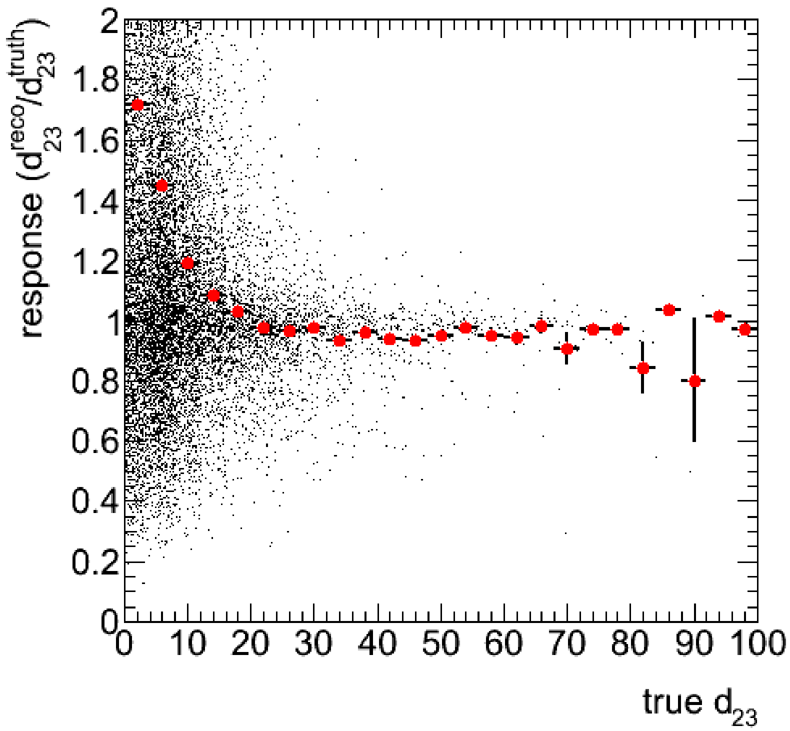
Grooming moves the response problems to lower true (groomed) mass!



Denominator = raw jet mass

Other substructure observables





✔ Splitting scales are very sensitive to limited granularity, especially for jets with little substructure

Now to highly granular calorimetry

Transvserse read-out granularity increased by order(s) of magnitude

+ very finely segmented ongitudinally!

However, shower size comparable*

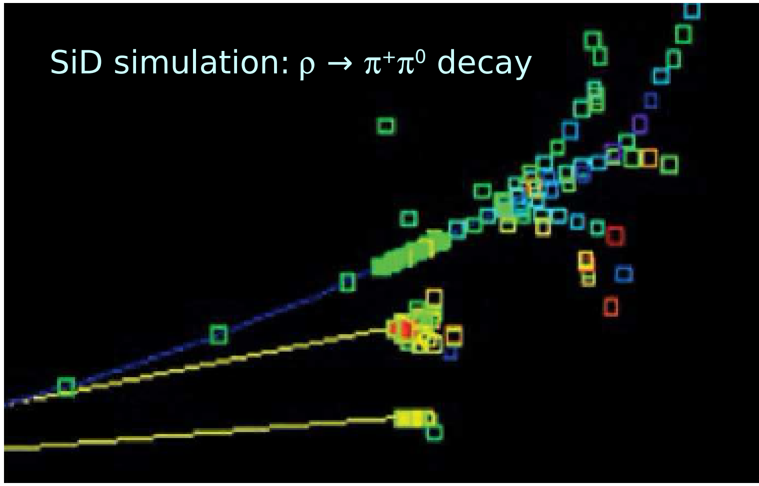
Spatial resolution on isolated particle:.

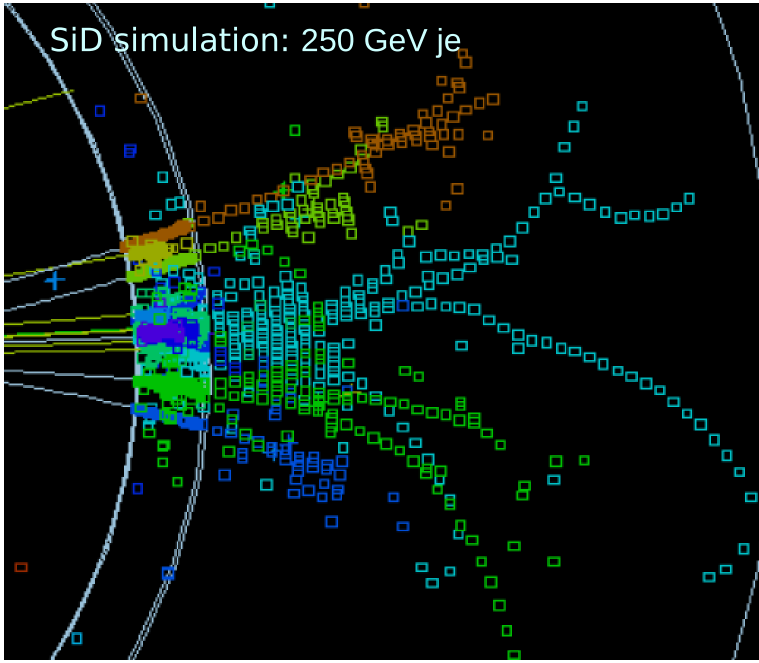
- ➔Assume: σ/sqrt(N_samples) → perfect

Two-particle resolution (minimal separation to cleanly disentangle two hadronic showers

- ➔Naively: σ

(*) remember Tungsten yields factor 2. larger detectors are not a very cost-effective way of dealing with this



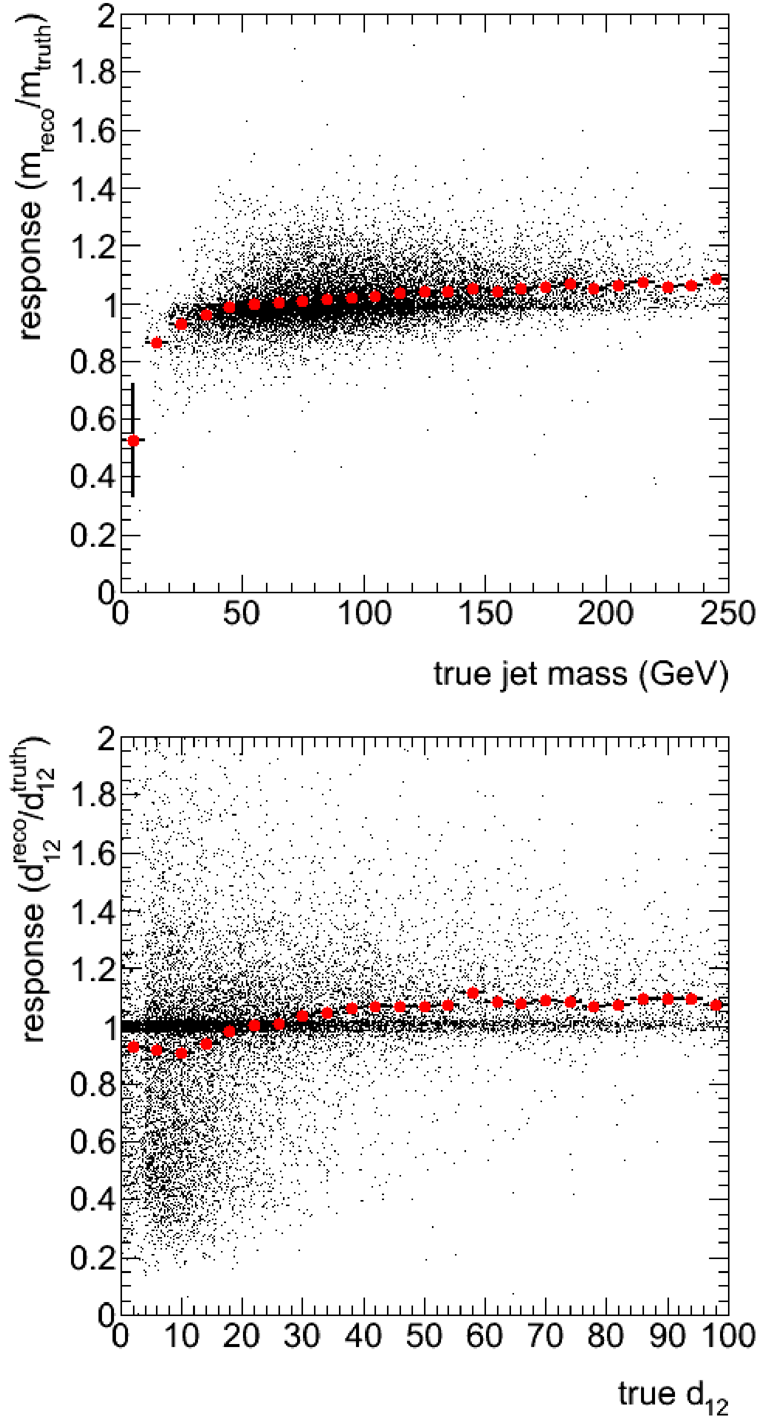


Highly granular calorimetry

- ✔ Hadronic energy deposits within $\Delta R < 0.1$ are merged into a single mass-less cluster
- ✔ Even with shower size of 0.1.. the response is extremely flat...
- ✔ Granularity term to resolution is smaller
- ✔ And nasty promotion of low-mass jets is gone!

- ✔ Validate this maybe-too-optimistic view with Pandora on full simulation

- ✔ Note I haven't used particle flow; the track information can be used to restore the mass of the merged clusters!!



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Summary

- ✔ Jet substructure is opening yet another door to BSM physics at the LHC
- ✔ ATLAS is commissioning, first searches using substructure soon

- ✔ Expect a very important role also at a TeV linear collider. If there is more to a jet than just a momentum vector, then there must also be more to detector requirements than just energy resolution. Exploring jet substructure as a driver for detector requirements:
  - ➔ Read-out granularity is clearly a dominant player in mass (sub-structure) response of the current generation of calorimeters
  - ➔ The increase instrumentation density of the next generation of calorimeters will allow real jetography
- ✔ One emerging opportunity I'd like to explore: understand jet substructure performance in an LC detector in detail
  - ➔ Detector parameters like size and material (tungsten vs. stainless steel)
  - ➔ Real physics scenario to measure “real” gain, beyond simple performance plots

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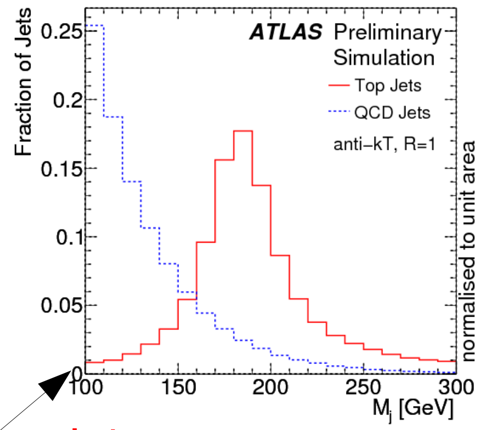
Example: boosted tops

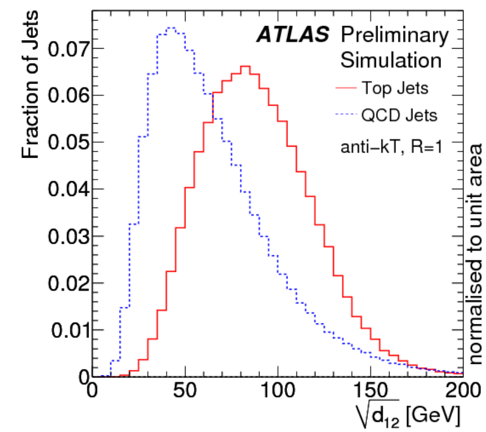
Start
Anti-k_T with R=1.0

Axis cut off at m=100 GeV



Jet mass: invariant mass of all components

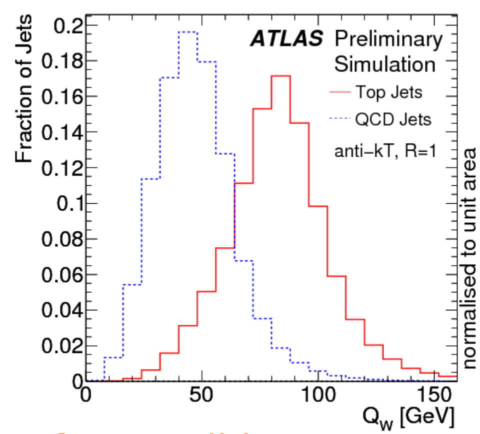
Re-run jet algorithm
(or unwind clustering sequence)



Splitting scales

(ATL-PHYS-PUB-2010-008)

Use sub-jet information to calculate further observables



Mass of W-candidate

...?

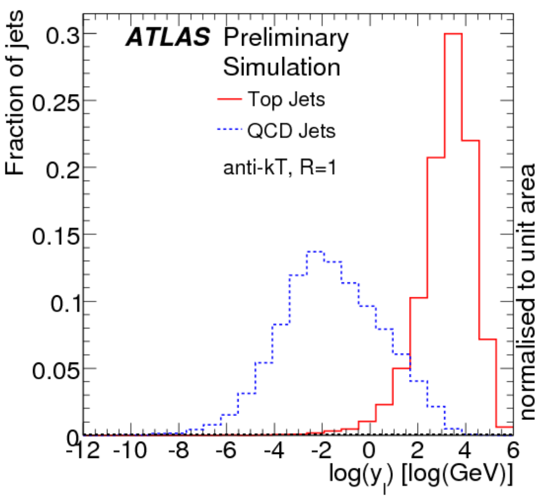
Refined direction for b-tagging, N-subjettiness, templates....

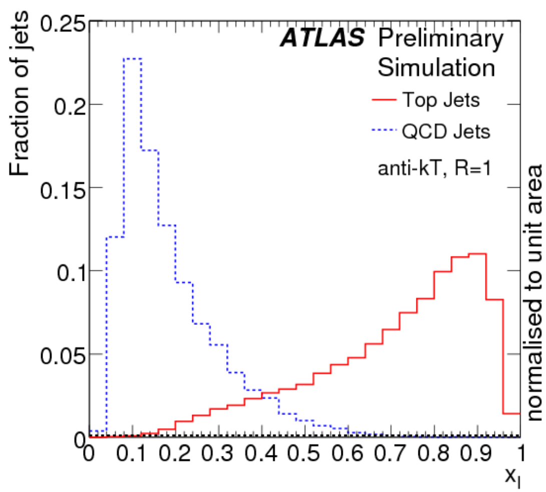
Embedded lepton

For moderate p_T (700 GeV < resonance mass < 2 TeV) the lepton from W-decay in ttbar events is typically "embedded":

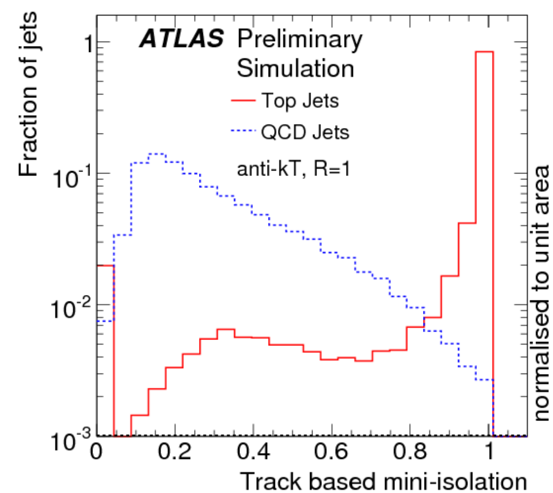
- ➔ contained in the fat top jet (isolation likely to fail)
- ➔ usually found in the jet periphery (efficient reconstruction can be achieved)

If traditional isolation is discarded, leptons from bottom and charm decay become a dangerous background





Energy sharing between jet and lepton (Thaler & Wang)



Mini-isolation (B. Tweedie): energy sum in dynamically shrinking cone around the lepton

(ATL-PHYS-PUB-2010-008)

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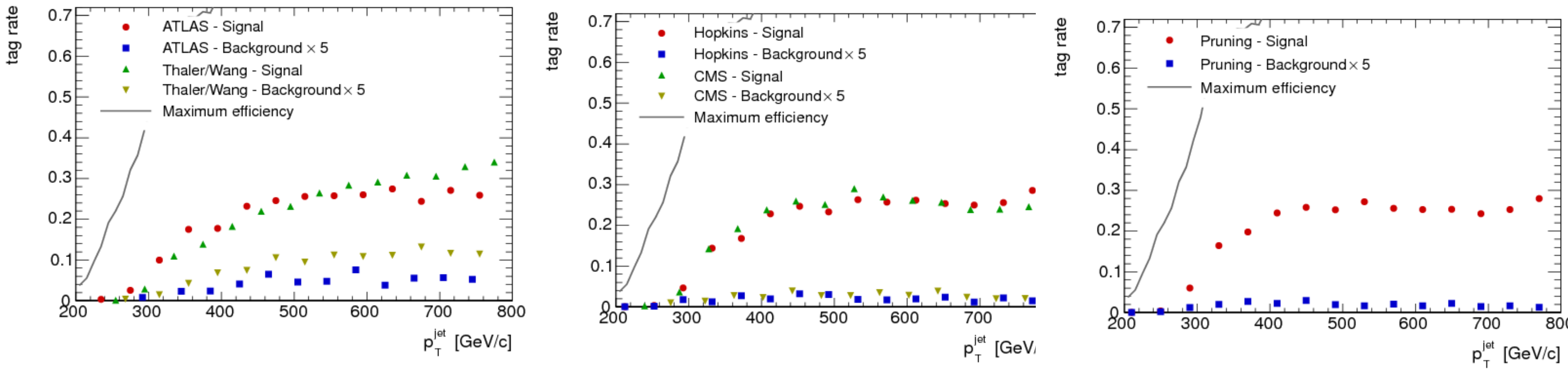
Top-tagging I

Configure (with the authors) a number of popular taggers for optimal performance at given target efficiency

	20 % efficiency point	50 % efficiency point
Hopkins	$\delta_p = 0.1$, $\delta_r = 0.19$ $170 < m_{top} < 195$ GeV $\cos\theta_h < 0.675$, $75 < m_W < 95$ GeV	$\delta_p = 0.04$, $\delta_r = 0.19$ $160 < m_{top} < 265$ GeV $\cos\theta_h < 0.95$, $60 < m_W < 120$ GeV
CMS	$170 < m_{jet} < 195$ GeV $m_{min} > 75$ GeV	$164 < m_{jet} < 299$ GeV $m_{min} > 42.5$ GeV
pruning	$z_{cut} = 0.1$, $D_{cut} / (2m/p_T) = 0.2$ $150 < m_{top} < 190$ GeV $68 < m_W < 88$ GeV	$z_{cut} = 0.05$, $D_{cut} / (2m/p_T) = 0.1$ $120 < m_{top} < 228$ GeV $28 < m_W < 128$ GeV
ATLAS	N/A	N/A
Thaler/Wang	$0.249 < z_{cell} < 0.664$ $183 < m_{jet} < 234$ GeV $m_W > 68$ GeV	$0.05 < z_{cell} < 0.51$ $162 < m_{jet} < 265$ GeV $m_W > 59$ GeV

Top tagging II



- **Top-tagging efficiency and mis-tag rate versus jet p_T**
- **Overall efficiency 200 < p_T < 800 GeV is 20 %**
- **Distinct turn-on between 300 and 400 GeV (caused by failure of lower p_T tops to merge into a proper mono-jet)**
- **Flat otherwise**

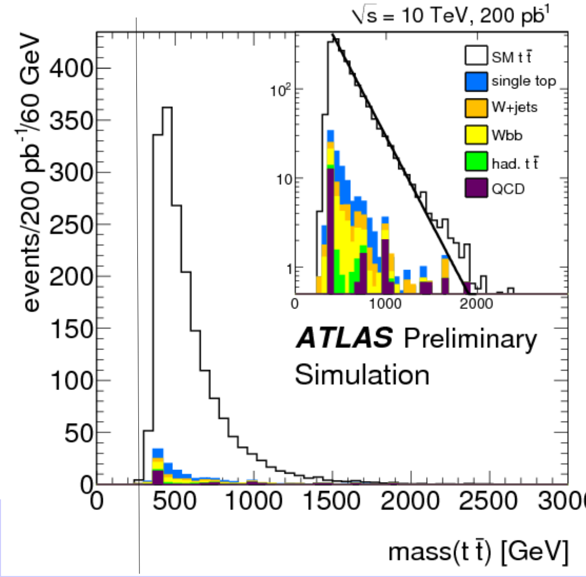
Boosted tops

Boosted top algorithm is definitely competitive for resonance searches

- ✔ As expected for a resonance mass of 2,3 TeV
- ✔ Resolved algorithms adapted to perform better for high mass
- ✔ Still, performance comparable at 1 TeV

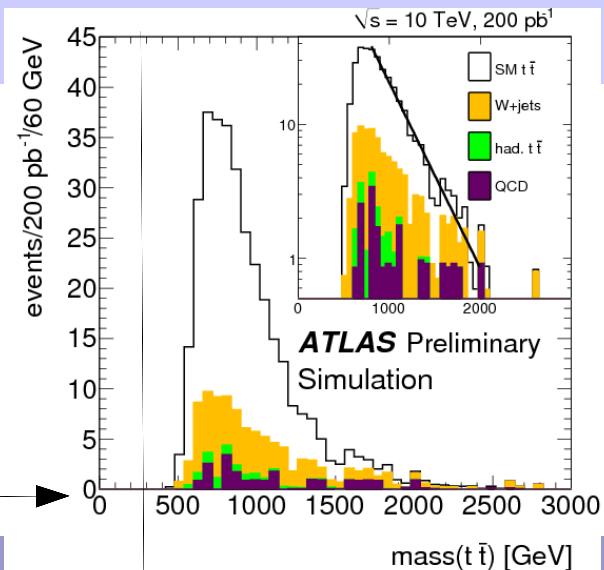
With a combination of both types of algorithms we can make our way through the "transition region"

2 x m_t



Modified "resolved" reconstruction

"Mono-jet" approach, anti-k_T, R=1



Resolved result ~ now

Mono-jet result in summer

Other clients: t' (u_4) search (see Shufang's talk)

W' → tb (under discussion)

Rather spectacular ATLAS/CMS effort in 2008/2009:

CMS-PAS-JME-09-001, CMS-PAS-EXO-09-002, CMS-PAS-EXO-09-08, CMS-PAS-TOP-09-009,

ATL-PHYS-PUB-2009-081, ATL-PHYS-PUB-2010-008