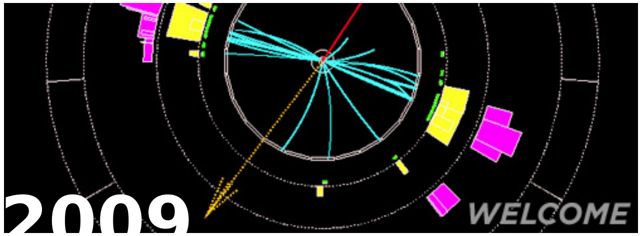
Summary of Boost2010

Boosted objects: a probe of BSM physics

BOOST2011
Princeton, NJ, USA
May 22-26, 2011

Marcel Vos (IFIC Valencia)

Boost workshops



Giving New Physics a Boost

Thursday and Friday, July 9-10, 2009

SLAC National Accelerator Laboratory

+ U. Washingtop, january 2010
+ Manchester, November 2010
+ Boston, january 2011
+ Oregon, february 2011
+ LPCC, CERN, february 2011

A very busy agenda. Coordinate schedule to ensure optimum frequency and alternation US/EU?

Boost2012: Europe (Valencia)

Boost2010

The aim of the workshop is to **boost** collaboration between theory and experimentalists to develop tools & techniques that **boost** the BSM physics potential of the Tevatron and LHC experiments

- ✓ A bit over 50 attendants, good mix between theory and experiment, experience and enthousiasm
- ✓ Great venue

- ✓ Excellent organization by the local committee:

A. Carslaw (IT support), J. Ferrando, S. Geddes (Secretariat), C. Issever, M. Karagoz (Chair), J. March-Russell, A. Sherstnev

Boosted objects: motivation

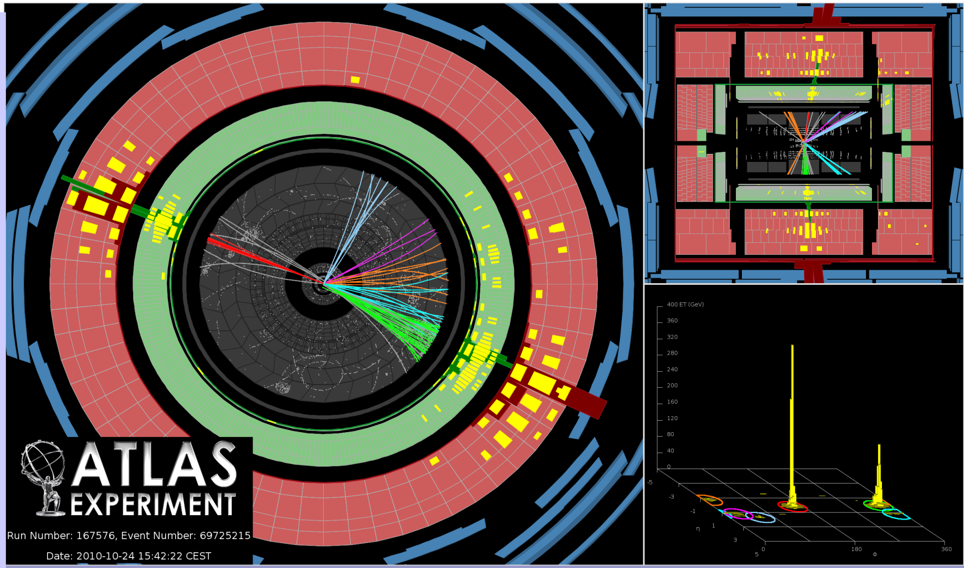
- **BSM motivation to look for boosted objects:**
  - Something heavy (e.g. Z’) decays to something lighter (t,W/Z,H,. . .)
  - A new light particle (H, χ^0, . . .) is more easily isolated from background when boosted, for example because combinatorics are less of an issue
  - Cascade decay of exotic 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

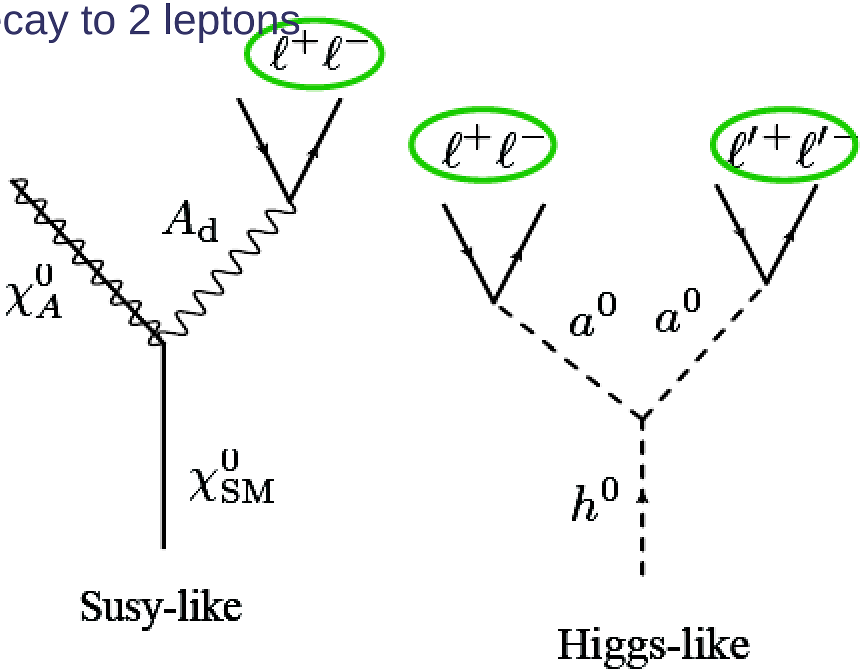
Jet momenta are calibrated according to the "EM+JES" scheme.



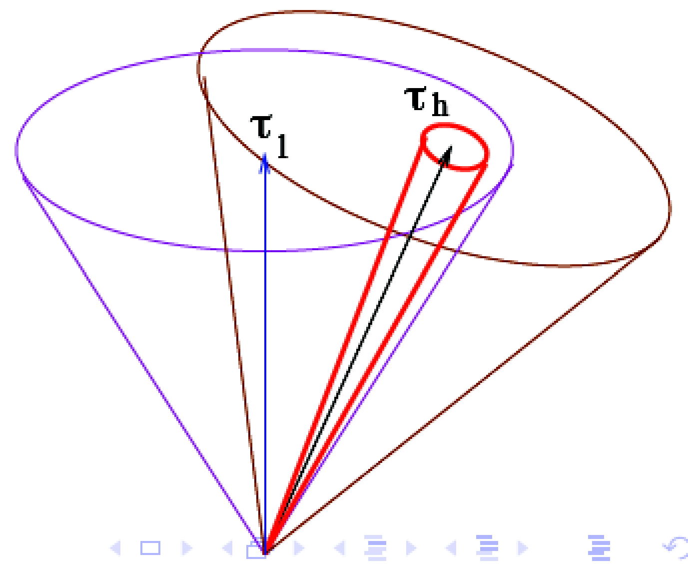
One slide on leptonic WG

- ✓ **Leptonic WG led by Chris Hill and Jay Wacker**
- ✓ With apologies to the people involved in this WG, I'll only devote just one slide here

D0 and CDF have performed searches based on a combination of signatures including lepton jets that form in the decay chain: heavy object → 2 light neutral objects (dark photons, a_0), that in turn decay to 2 leptons



Z' → Zh → $f^+f^-\tau^+\tau^-$ Katz, Son, Tweedie, arXiv:1011.4523



Define di-τ object to avoid loosing both non-isolated τ decays

Hadronic WG

- ✓ Hadronic WG led by Michael Spannowsky U. Oregon, theory), M.V. (IFIC Valencia, experiment)
- ✓ Stronly focussed on jet sub-structure

(= QCD for BSM)

Fat jet, according to Colin G.

- ✓ Continued regular meetings after the workshop
- ✓ WG Report contains contributions by a good fraction of participants
- ✓ Today's talk largely based on this useful document

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]

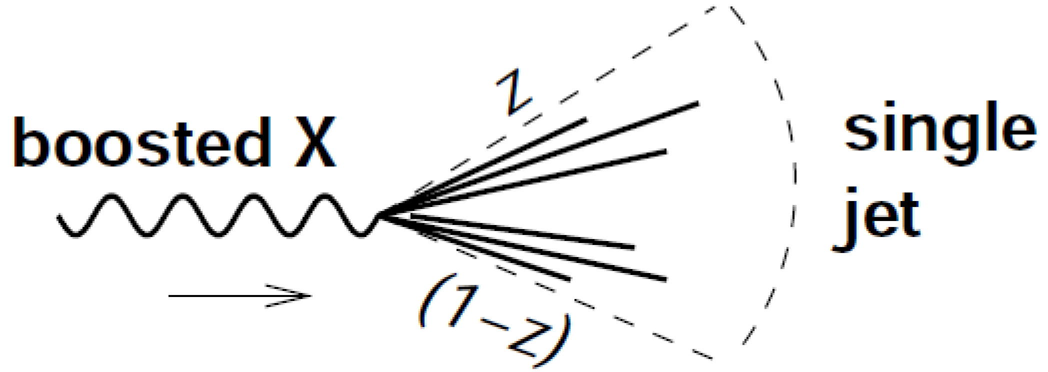
report accepted by EPJC (arXiv:1012.5412 [hep-ph])

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

$$R < 2m_X/p_T^X \qquad (X \to qq)$$

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



Michael H. Seymour. Searches for new particles using cone and cluster jet algorithms: A Comparative study. Z. Phys., C62:127–138, 1994.

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"

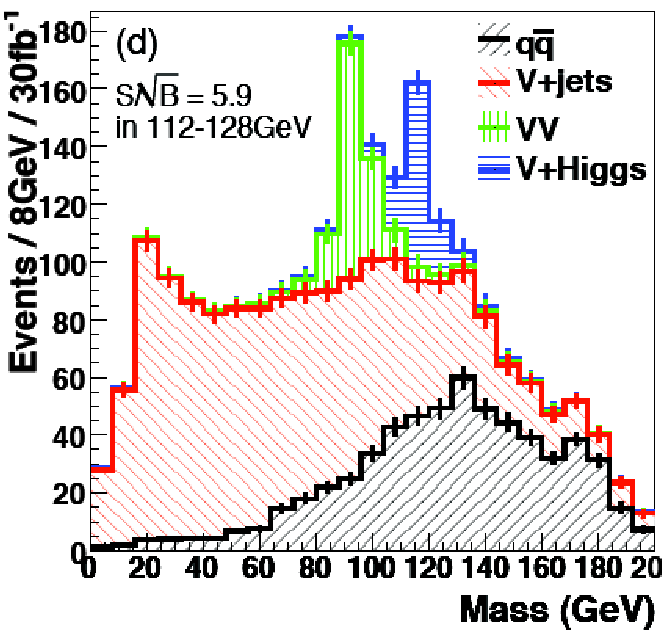
➔ See also paper by Cui, Han, Schwartz paper, arXiv:1012.2077[hep-ph]

✓ 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

The potential of this paradigm has been amply demonstrated

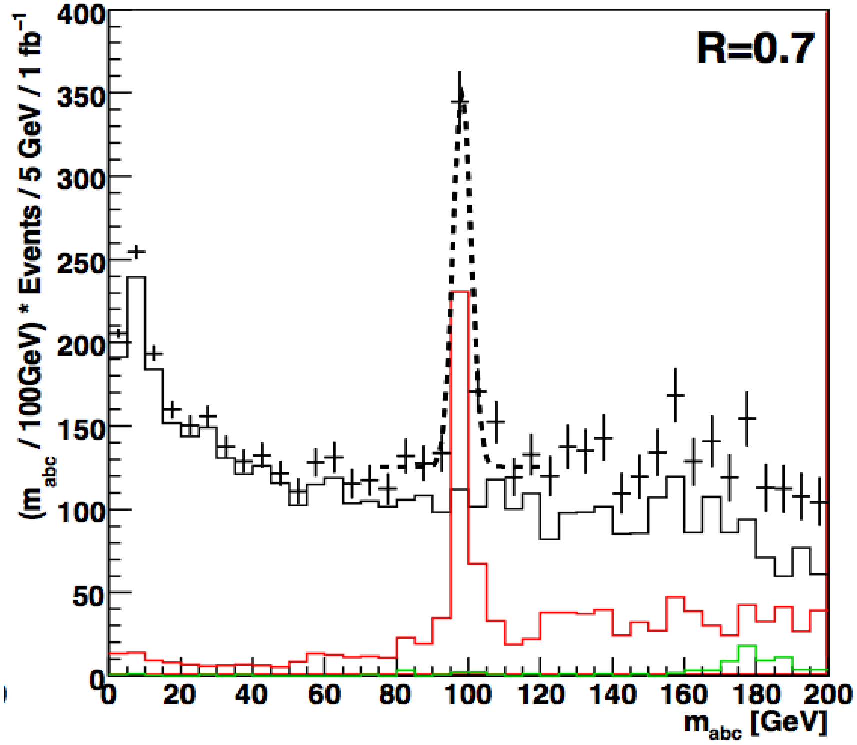
✓ **Boosted BSM particles**

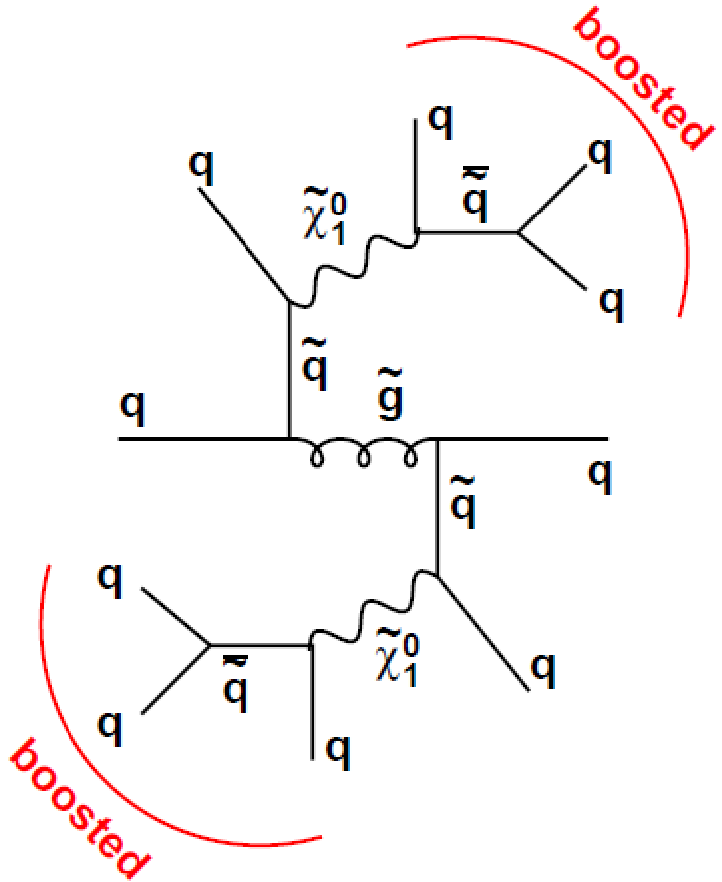
SUSY cascade decays with V->qq, Butterworth, Ellis, Raklev, hep-ph/0702150

RPV SUSY decays, Butterworth, Ellis, Raklev, Salam, Phys. Rev. Lett. 103:241803 (2009)

Confirmed in full simulation:

ATL-PHYS-PUB-2009-076





Boosted objects: phenomenology

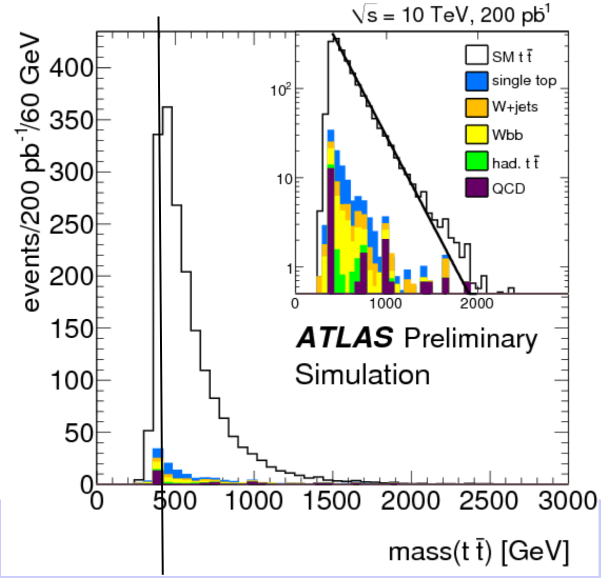
- ✓ **Boosted top**
  - ➔ B. Lillie, L. Randall, and LTW, hep-ph/0701166
  - ➔ L. Almeida, S. Lee, G. Perez, I. Sung, J. Virzi, arXiv:0810.0934
  - ➔ Kaplan, Rehermann, Schwartz, Tweedie, Phys. Rev. Lett 101:142001 (2008)
  - ➔ Thaler and Wang, JHEP 07:092 (2008)
  - ➔ Plehn, Spannowsky, Takeuchi, Zerwas,JHEP 1010:078,2010.

- ✓ **Very different situation:**
  - ➔ It's typically the parent we're after
  - ➔ Pair-produced: use lepton+jets signature
  - ➔ Three body decay

- ✓ **Large gain in reconstruction efficiency:**

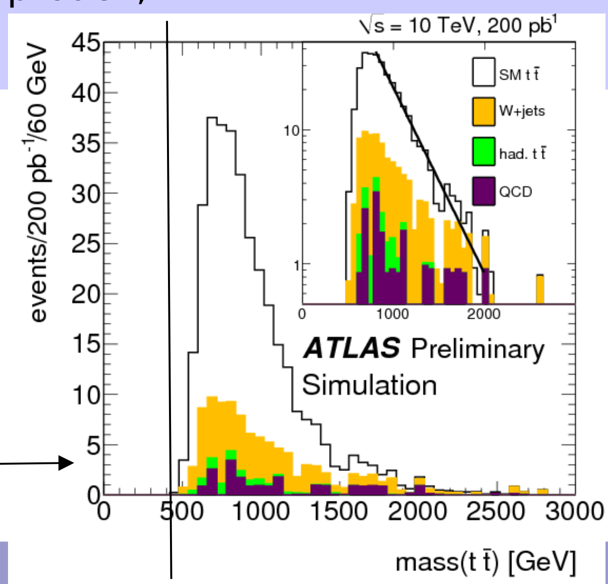
  Factor 2 wrt "full reconstruction" at m_{tt} = 1 TeV

2 x m_t



Modified "resolved" reconstruction

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



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

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Since then: phenomenology

More use-cases to be explored at BOOST2011:

- SUSY, squarks, stops
- SUSY, Higgses
- polarization and asymmetry
- ...

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Tools & Technniques: reconstruction

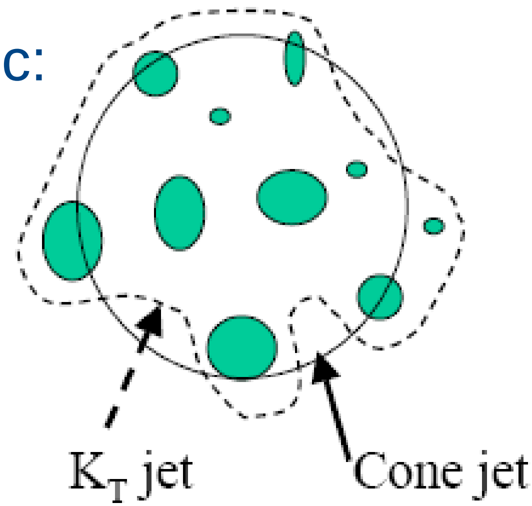
"clustering" jet algorithms use a distance or metric:

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

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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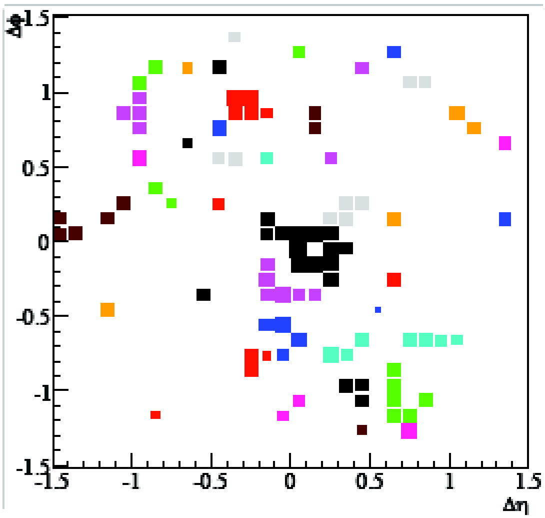
Tools and Techniques: grooming

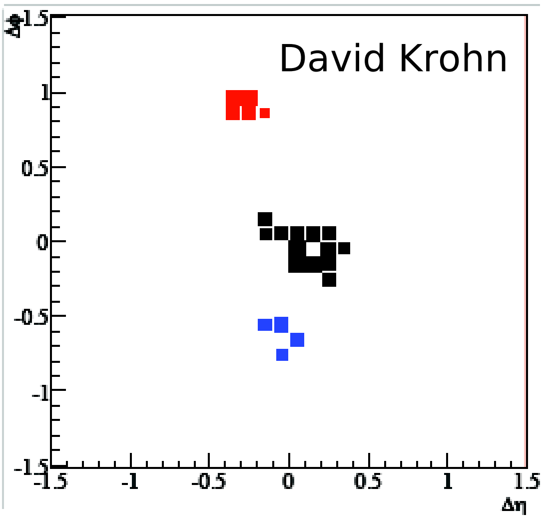
Jet substructure is often hidden:

✓**Soft emissions inside the jet**

✓**Underlying event**

✓**Pile-up* (identified by associating jets/clusters to tracks/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

Now, after seeing with our own eyes what pile-up can do to jet, is a good time to convince your experiment to support these

Revisit/reoptimize based on experience on data

Boost2010 report 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/

Proposal: extend the benchmark set:

- incorporate more up-to-date tunes (comparing ATLAS and CMS' favorites tunes for several generators?)
- include ME-PS matched samples (ALPGEN?)
- provide minimum-bias events, enabling pile-up studies
- provide benchmark detector (cf Peter Loch's tutorial)

(*) 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

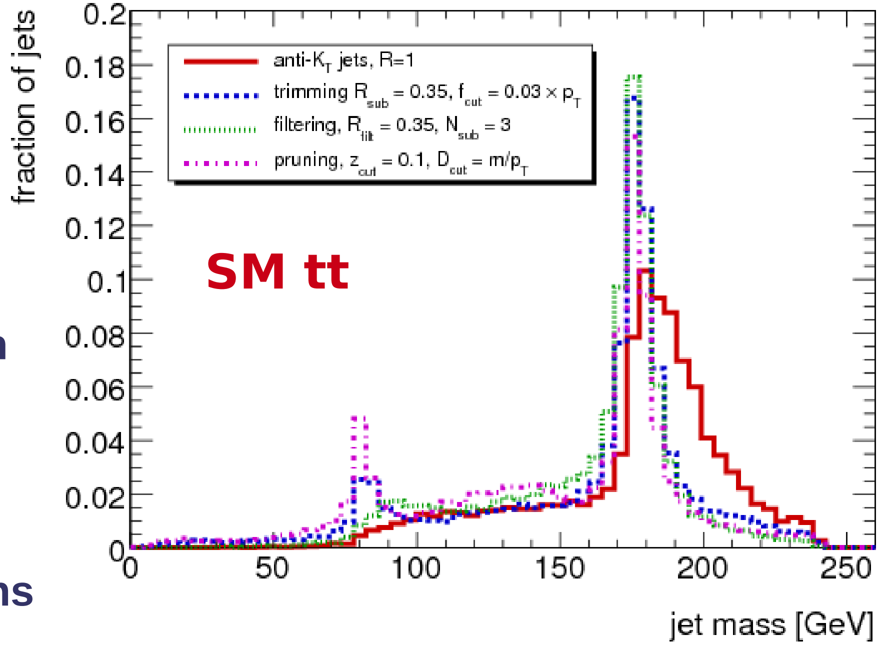
Results on common samples, with common definitions. Algorithm "optimization" performed by authors or under close supervision.

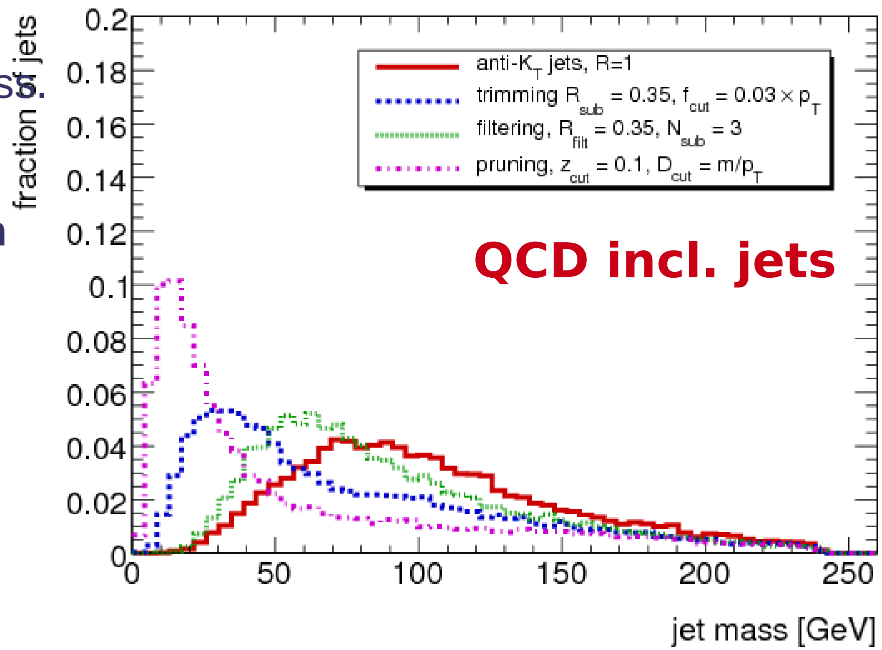
Results confirm that grooming indeed cleans up the jet, removing soft contamination

- ✓ 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

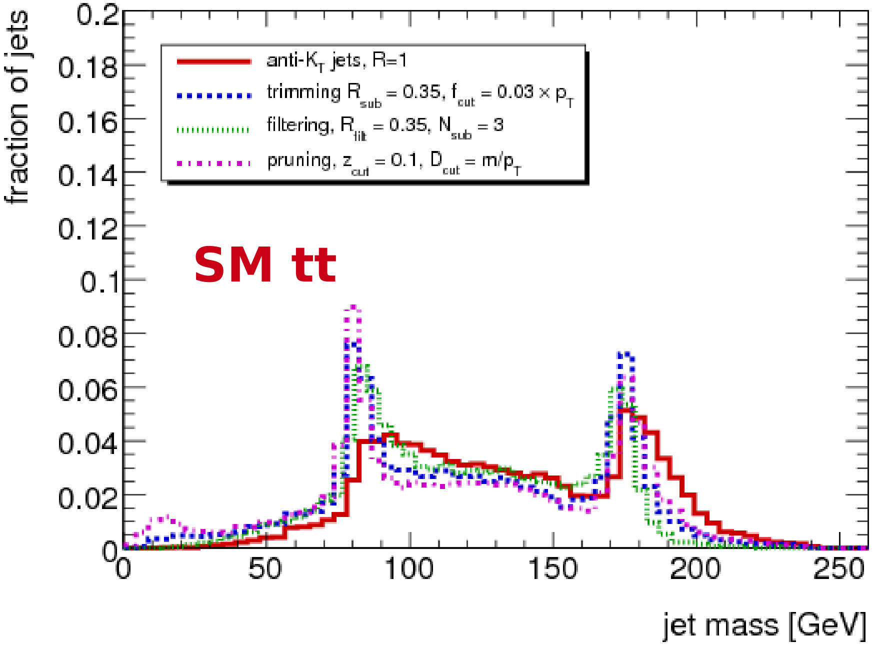


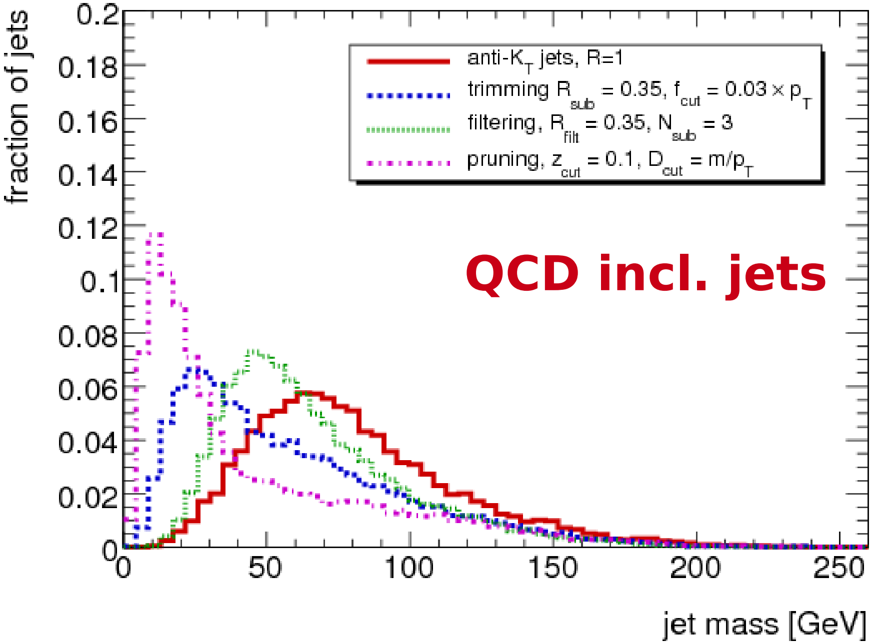


Results: grooming

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 ma peak (good!) or into the W mass peak (not s good!)





Since then: tools & techniques

Many new ideas to be adopted by experiments:

- Tagging different signatures:
  - gluons
  - ISR
- Multivariate methods
- Substructure observables:
  - (tau_) n-subjettiness
  - template method
  - dipolarity,....
- boosted SCET

- event-by-event pile-up measurement & correction

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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

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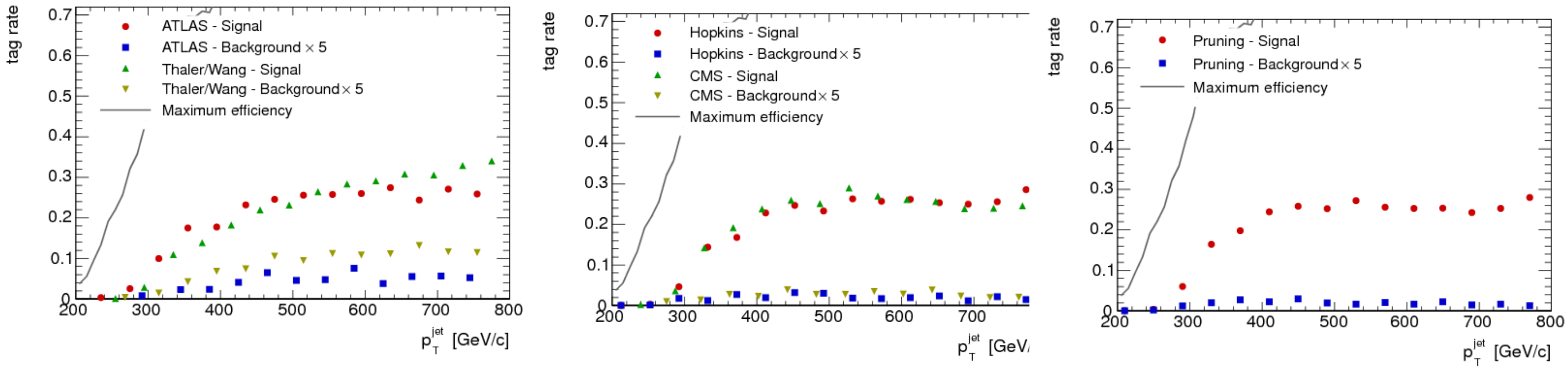
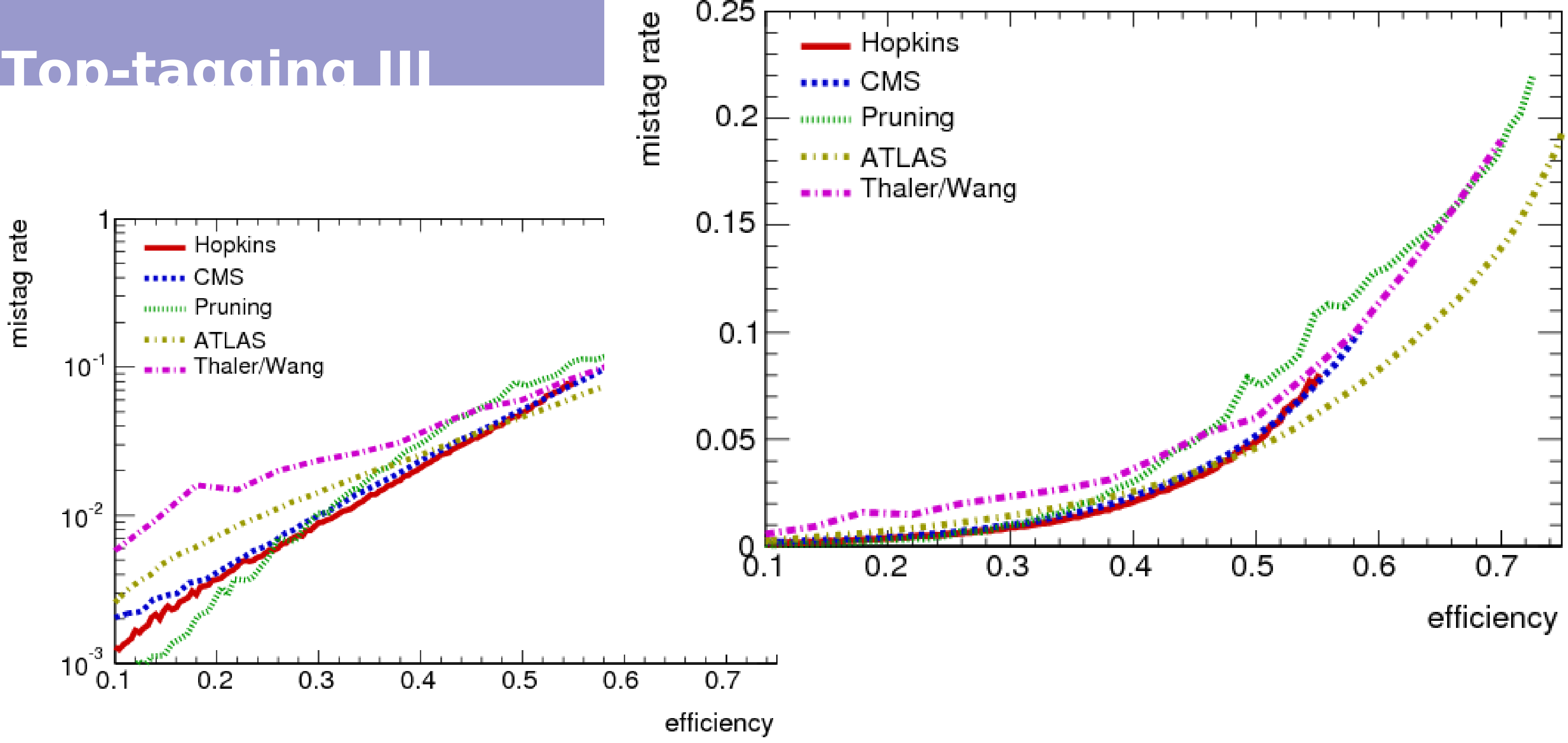
Top tagging II



- ✓ **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**

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 ε < 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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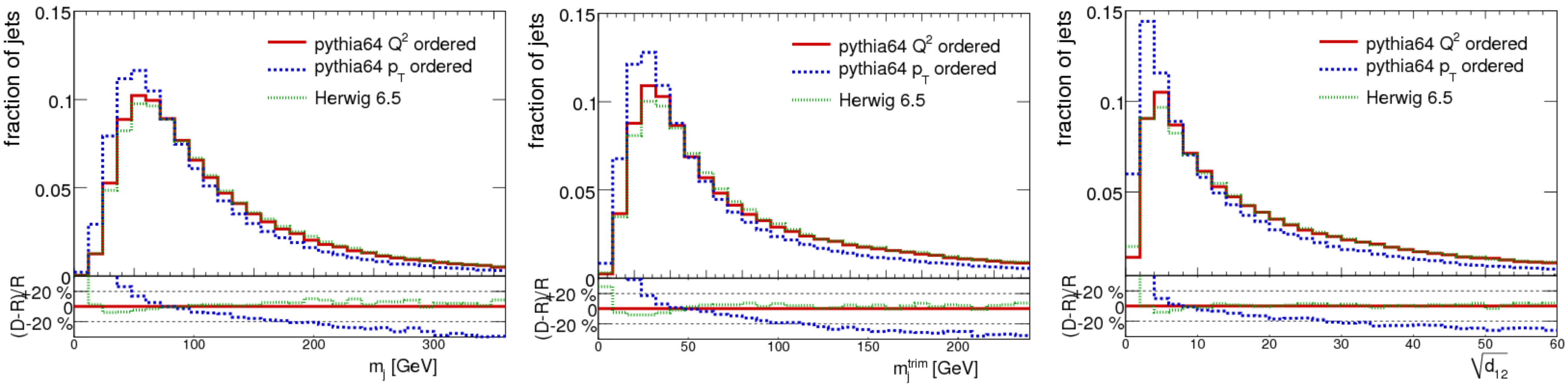
Results: generator uncertainties

Compare different PS models...

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

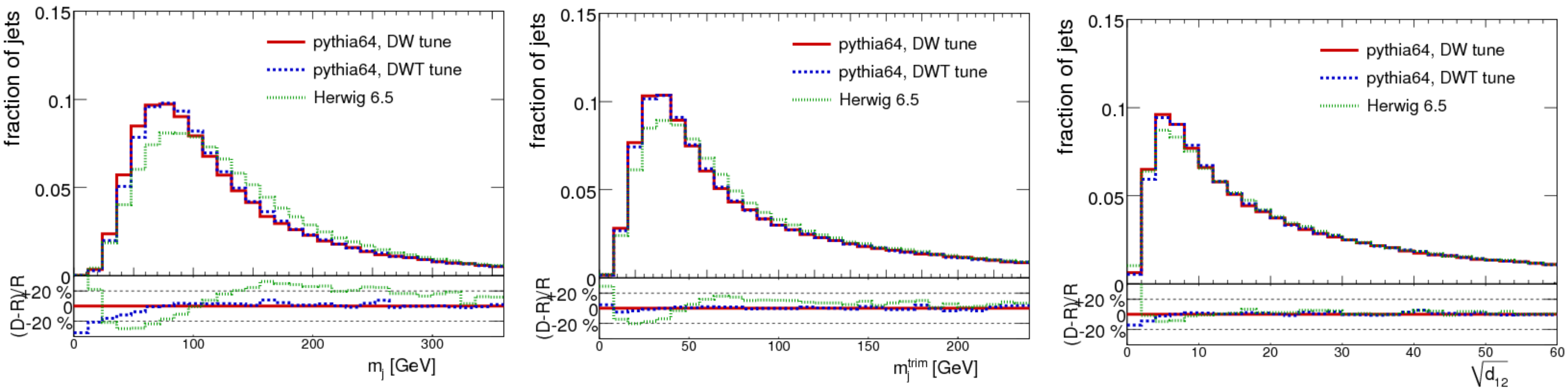


Pythia's p_T-ordered showers (perugia) are clearly "softer", while Pythia Q^2 and Herwig are similar

>> 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)

Underlying Event (~ soft contamination of jet substructure).



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

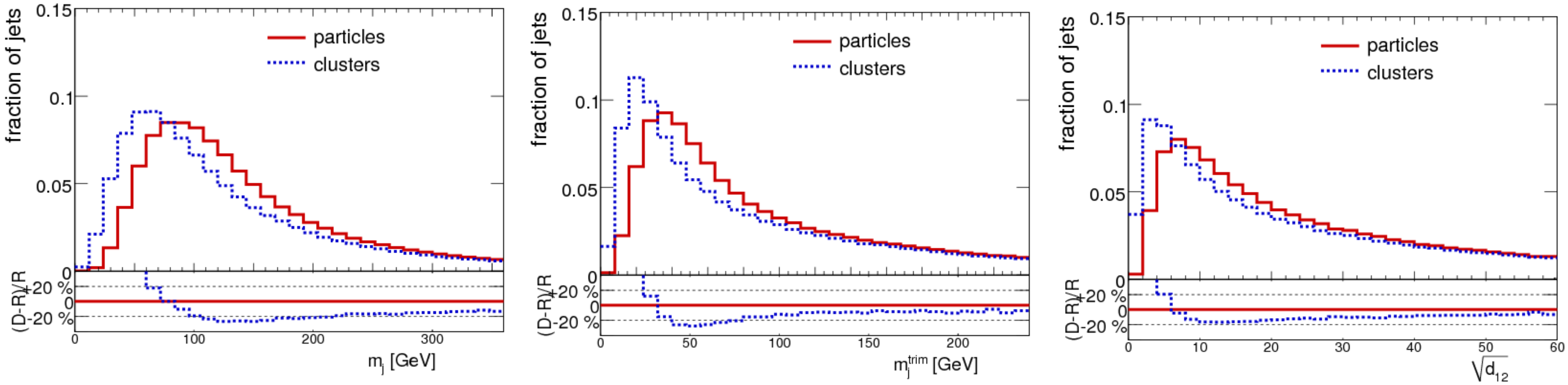
Invariant mass of R=1 jets is very strongly affected even for jets with 200 < pT < 1500 GeV.

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.

Simple “theorist's” detector with pessimistic granularity ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$) and optimistic resolution (perfect)



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.

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 in the WG report 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.

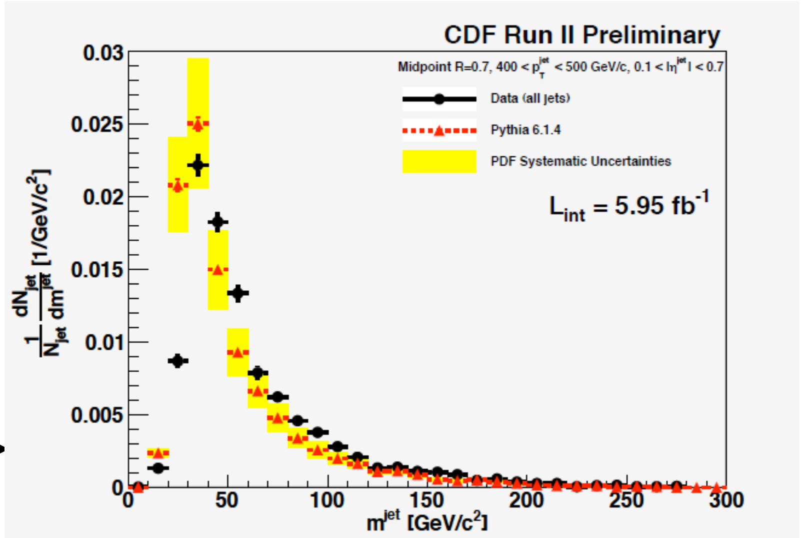
S. Chekanov et al. Substructure dependence of jet cross sections at HERA and determination of s. Nucl. Phys. B, 700:3, 2004.

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

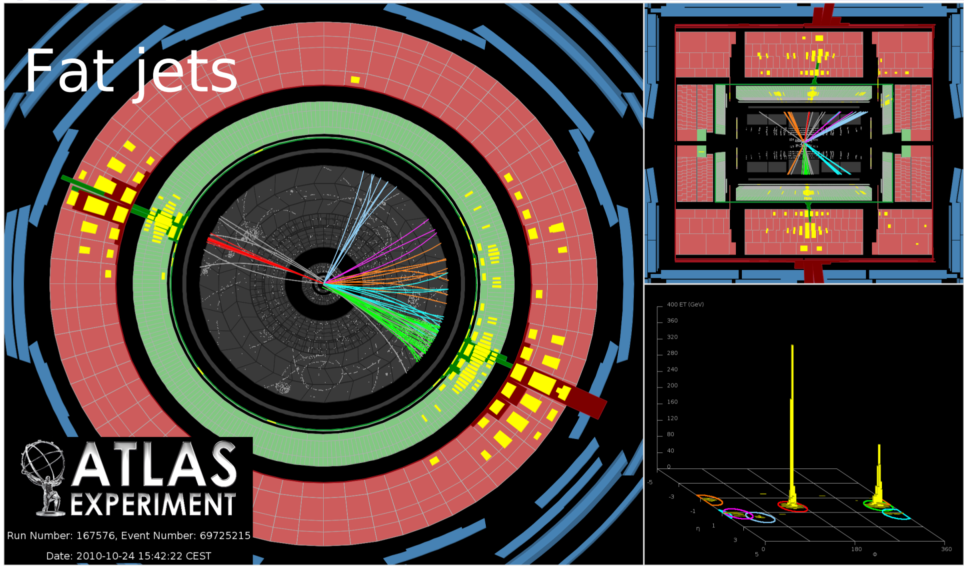
V.M. Abazov et al. Subjet multiplicity of gluon and quark jets reconstructed with the kT algorithm in p¯p collisions. Phys. Rev. D, 65:052008, 2002.

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.



Since then: LHC data... lots of it!



ATLAS and CMS have published jet shapes papers.

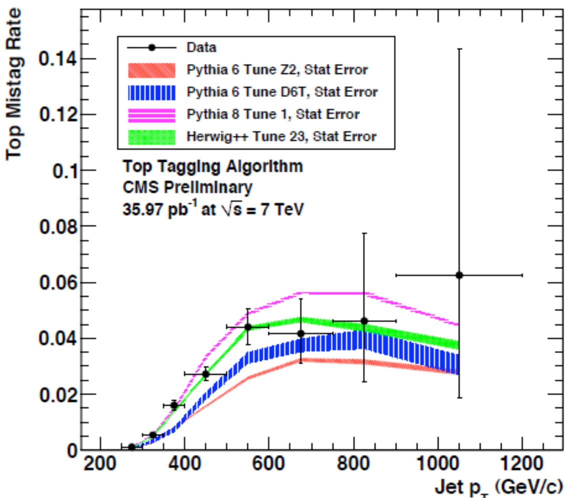
Study of Jet Shapes in Inclusive Jet Production in pp Collisions at √s = 7 TeV using the ATLAS Detector, Phys Rev. D arXiv:1101.0070 [hep-ex], 3 pb^{-1}, $30 < p_T < 600$ GeV

The CMS collaboration, Jet Transverse Structure and Momentum Distribution in pp Collisions at 7 TeV, QCD-10-014-PAS, 10 nb^{-1}, $20 < p_T < 100$ GeV

The world's heaviest known particle has been produced with sufficient momentum for it to become a "boosted object"

Detailed understanding of what's needed for succesful deployment of sub-structure techniques in LHC searches in terms of:

- MC choice & tunes
- calibrations & systematics, mis-tag rate measurements
- strategies to deal with pile-up



jet substructure in pp collisions at 7 TeV in CMS, Boston jet workshop

BOOST2011: searches for boosted objects

Lepton jets:

- Steady flow of results to BOOST conferences since BOOST09
- Established technique
- results from CDF, ATLAS and CMS to be presented this week

Boosted hadronic objects:

- A lot of commissioning work in Tevatron and LHC
- Background studies & control samples of “boosted objects”
  → CMS mis-tagging measurement
  → ATLAS jet substructure measurement
- The boosted era begins now: many searches in the making

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Conclusion

- ✓ The BOOST series continues to improve communication between experimenters and theorists
- ✓ The review sections and bibliography of the BOOST2010 report + some new result hopefully cement collaboration further
- ✓ Happy to see so much is obsolete already

- ✓ Now, on to BOOST2011. Looking forward to hear about all that has been done since Oxfordt.