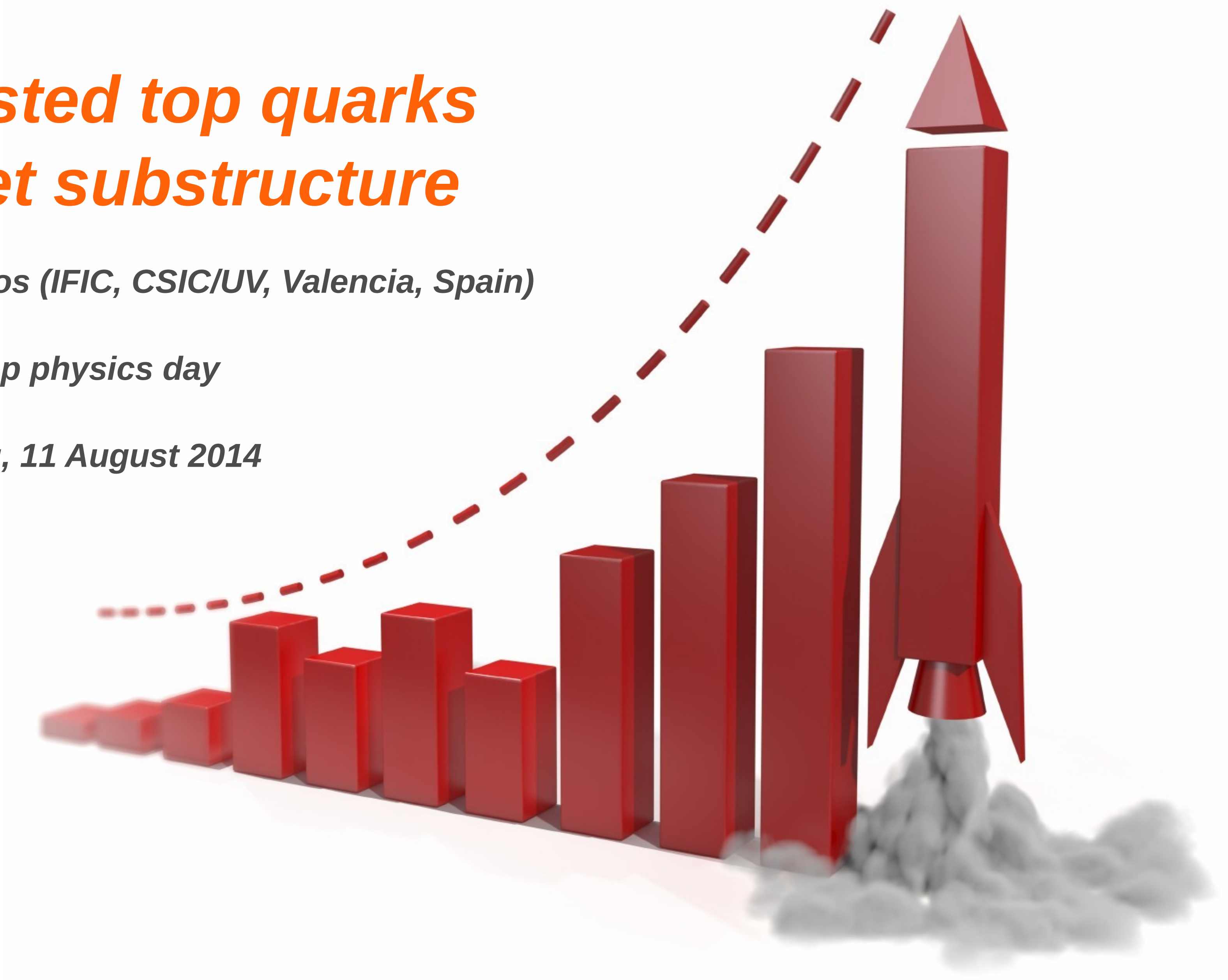
Boosted top quarks & jet substructure

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

MIAPP top physics day

Garching, 11 August 2014



The “boosted production” threshold

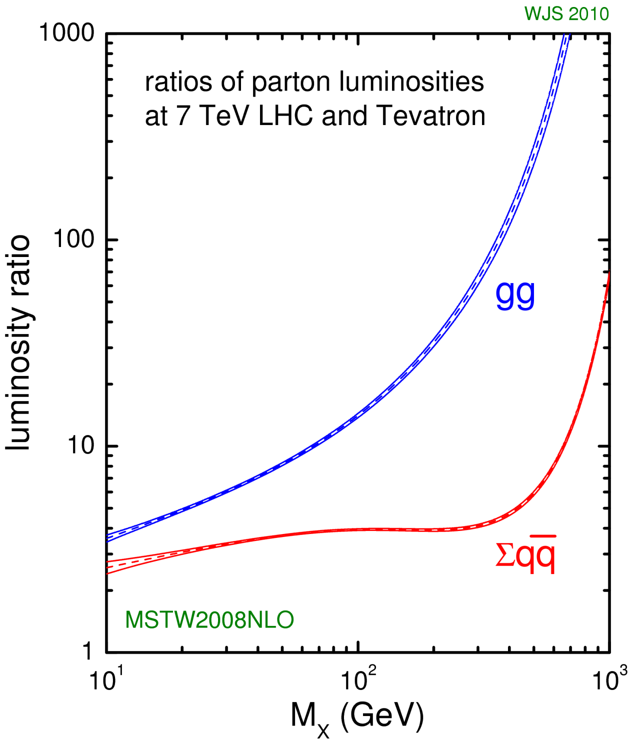
LHC: $\sqrt{s} >> E_{EW}$

Even the heaviest SM particles often acquire $p_T >> m$
→ abundant production of “boosted objects”

LHC8: A top factory, the world's first sample of boosted top quarks

Expected number of tt events in three different kinematical regimes	***Tevatron run II*** *10 fb-1 @ 1.96 TeV*	***LHC 2012*** *20 fb-1 @ 8 TeV*
Inclusive tt production	**57.000**	**2.600.000**
Boosted production: M_{tt} > 1 TeV	**25**	**30.000**
Highly boosted: M_{tt} > 2 TeV	**0**	**300**

Tevatron: sufficient parton luminosity to discover the top quark, ~ no boosted production



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

Eur.Phys.J. C74 (2014) 2792

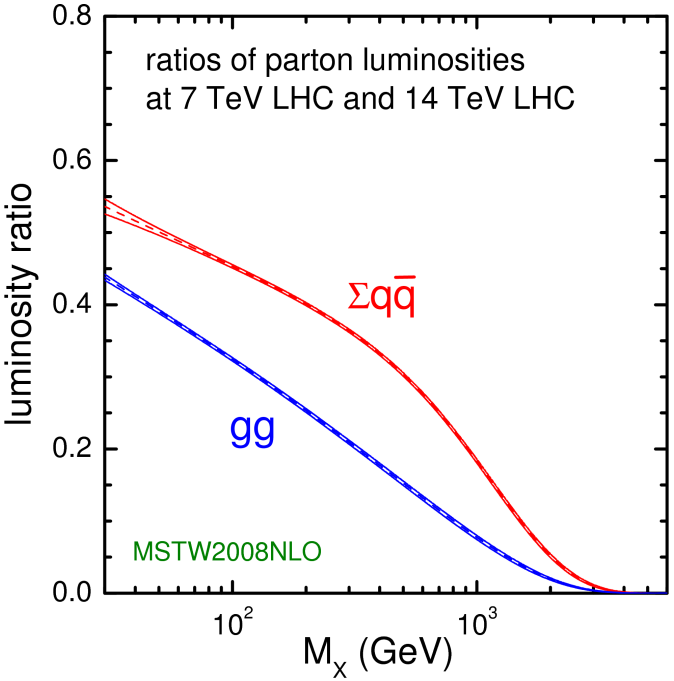
Results obtained with MCFM, arXiv:1204.1513 [hep-ph] & MSTW2008NLO PDFs

The “boosted production” threshold

The next stage of LHC operation (LHC14 from ~April 2015) will produce millions of boosted top quarks and the first events with very high boost

Expected number of tt events in three different kinematical regimes	***LHC 2012*** ***20 fb^{-1} @ 8 TeV***	***LHC design*** ***300 fb^{-1} @ 13 TeV***
Inclusive tt production	**2.600.000**	**155.000.000**
Boosted production: M_{tt} > 1 TeV	**30.000**	**3.000.000**
Highly boosted: M_{tt} > 2 TeV	**300**	**47.000**

Millions of boosted top quarks, 50.000 extremely boosted events



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Boosted top quarks

As the top quark p_T increases, the opening angle between W and b decreases

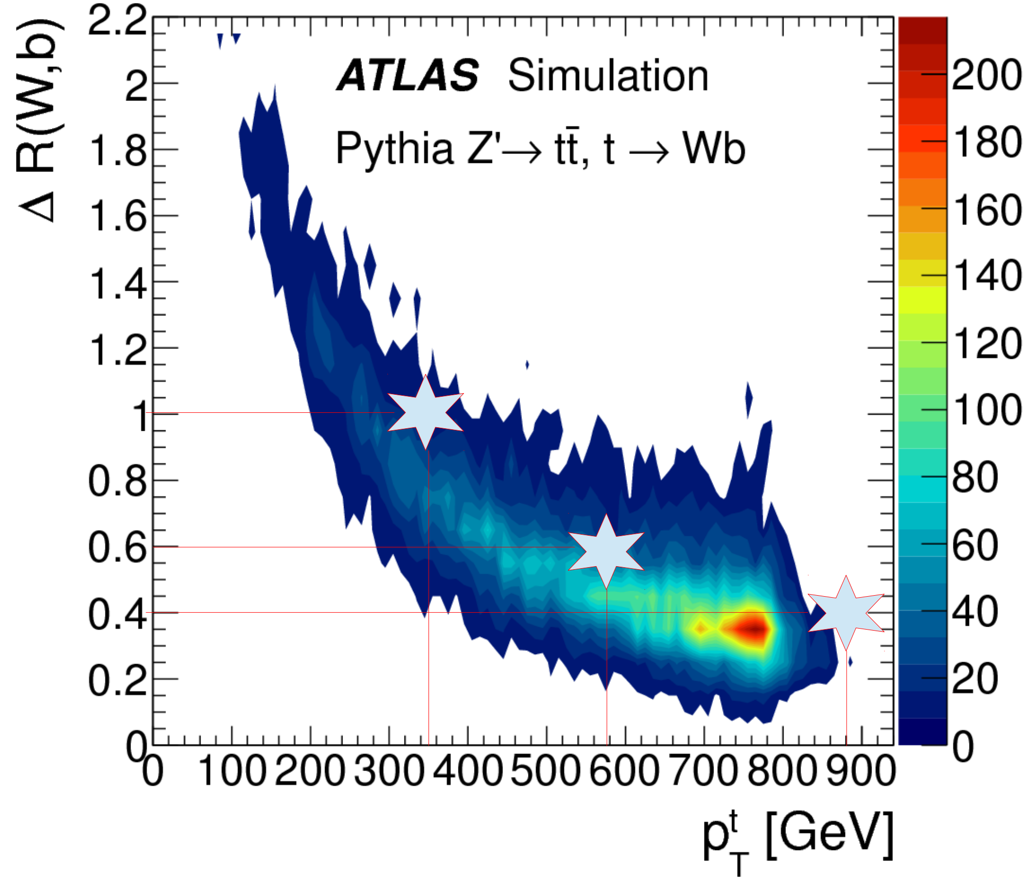
For very high p_T the decay topology is so collimated that individual partons are not resolved with R = 0.4

Rule of thumb for a 2-body decay:

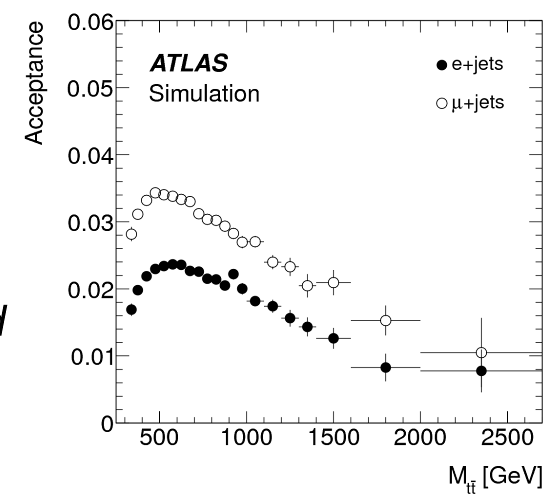
$$R < \frac{2m_X}{p_T}$$

For top, assuming $p_T^W = p_T^t/2$

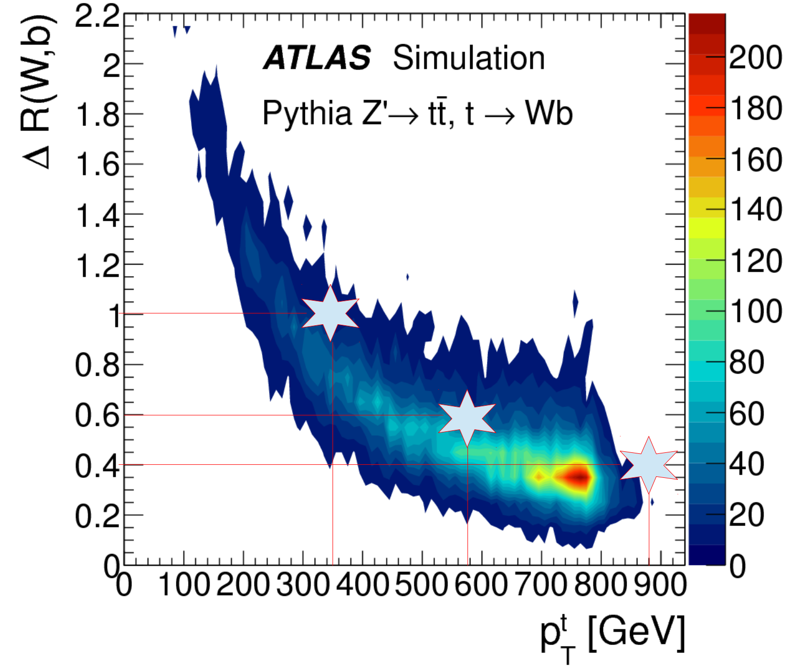
$$R < \frac{2m_t}{p_T^t} \quad \text{and} \quad R < \frac{4m_W}{p_T^t}$$



Classical algorithms are not adequate for boosted top quarks. See e.g. arXiv:1207.5644



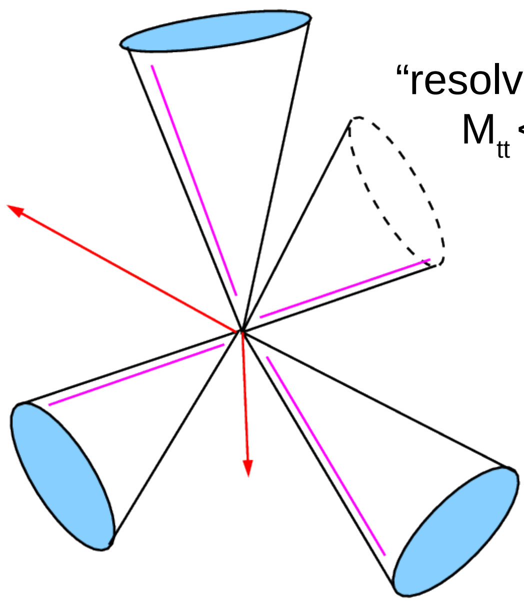
Boosted top quarks



For very high p_T the decay topology is so collimated that individual partons are not resolved with R = 0.4

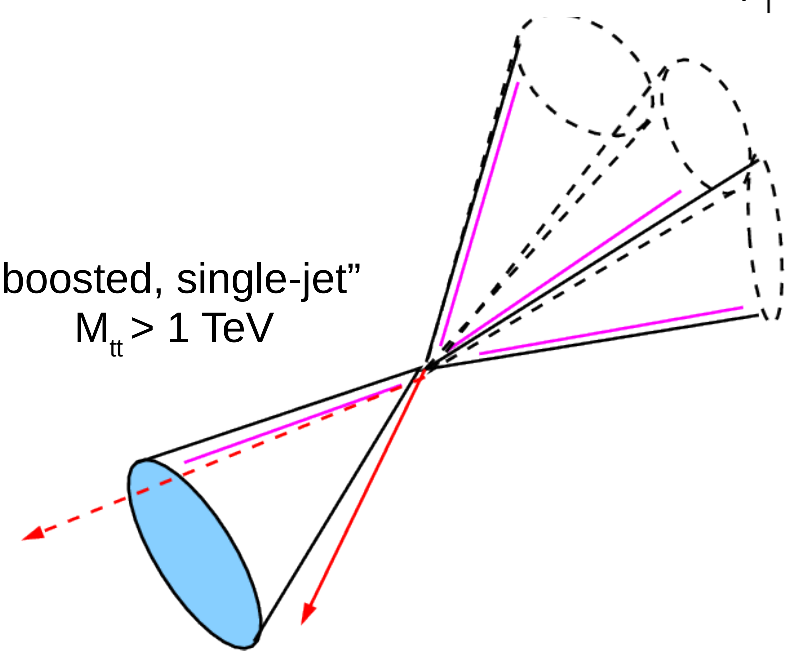
Reconstruct **"boosted object"** as a single R~1 **"fat"** jet.

M. Seymour, Z. Phys C62 (1994) 127-138



"resolved, at rest"
$M_{tt} < 1$ TeV

"boosted, single-jet"
$M_{tt} > 1$ TeV



Top tagging:
Kaplan, Rehermann, Schwartz, Tweedie, PRL101,

Boosted top and top-tagging literature

Early phenomenology papers:

Lillie, Randall, Wang, hep-ph/0701166,

Almeida, Lee, Perez, Sung, Virzi, arXiv:0810.0934,

New Physics at the LHC, Les Houches 2007

New sources of boosted tops:

Plehn, Spannowsky, Takeuchi, arXiv:1102.0557 [hep-ph]

Perelstein, Spray, arXiv:1106.2171 [hep-ph]

Berger et al., arXiv:1111.6594 [hep-ph]

More sophisticated techniques/taggers:

Plehn, Spannowsky, Takeuchi, arXiv:1111.5034 [hep-ph]

Soper, Spannowsky, arXiv:1102.3480 [hep-ph]

Barger, Huang, arXiv:1110.2214 [hep-ph]

Thaler, van Tilburg, arXiv:1102.3480 [hep-ph]

arXiv:1011.2268 [hep-ph]

Reherman, Tweedie, arXiv:1007.2221 [hep-ph]

Kaplan, Rehermann, Schwartz, Tweedie, PRL101
HepTopTagger arXiv:1006.2833
Template top-tagging arXiv:1112.1957 [hep-ph]
Q-jets arXiv:1201.1914 [hep-ph]
Shower deconstruction arXiv:1102.3480

Early experimental work

CMS-PAS-JME-09-001, CMS-PAS-EXO-09-002, CMS-PAS-EXO-09-08, CMS-PAS-TOP-09-009, ATLAS-PHYS-CONF-2008-008/016, ATL-PHYS-PUB-2010-008

Find good reviews in: Plehn & Spannowsky (J. Phys. G39), Schaetzel (arXiv:1403.5176), BOOST reports

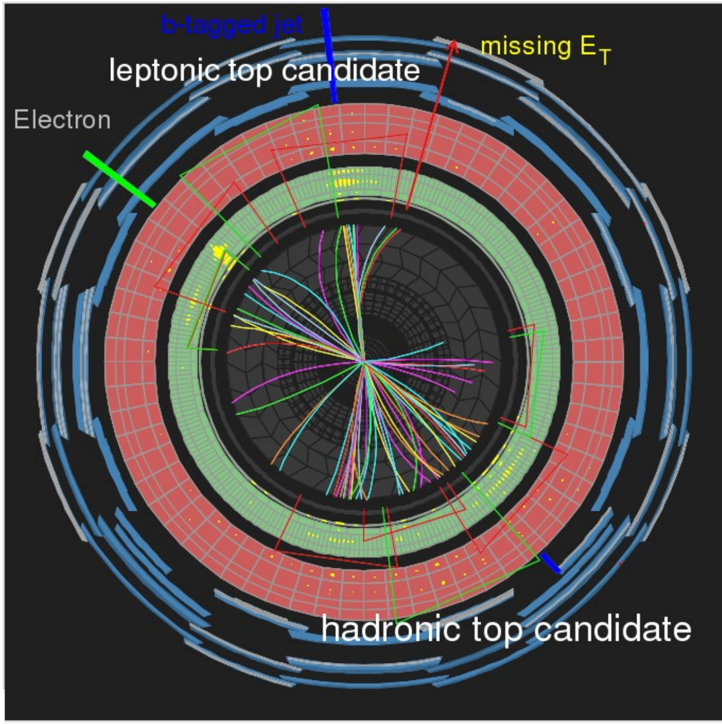
Jet substructure

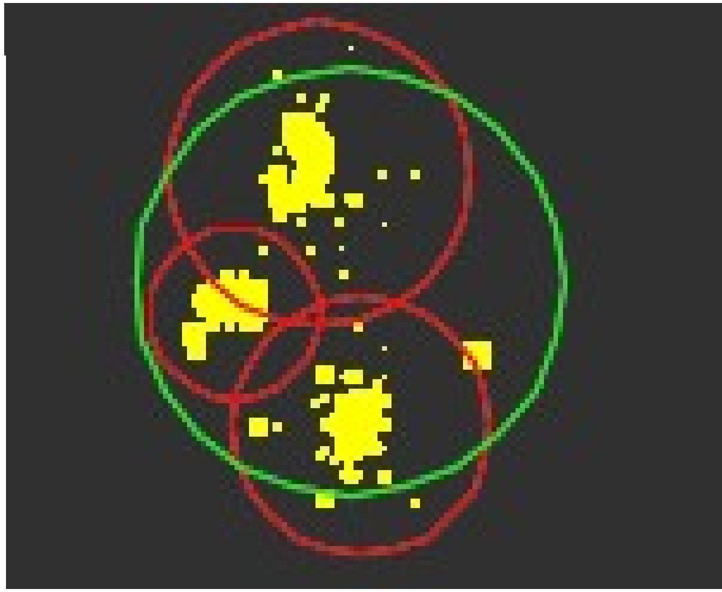
Distinguish boosted objects from background through an analysis of the jet substructure

Hadronic top jet:

$$m_j \sim m_t$$

(jet contains complete hadronic top decay, *Images: first boosted top candidates, ATLAS-CONF-2011-073,* m_j = 197 GeV)

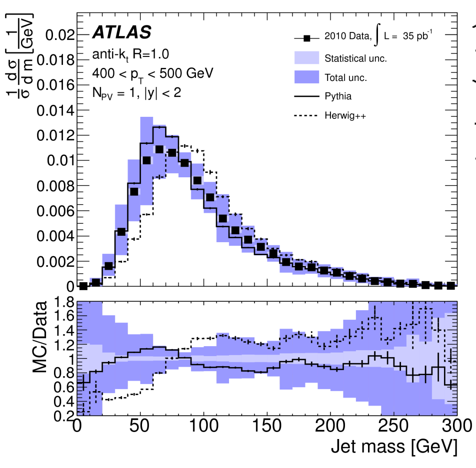


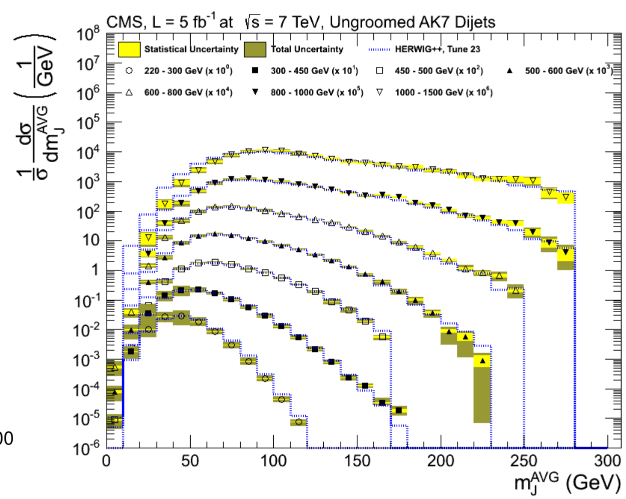


Light-quark and gluon jets:

$$m_j \mu\ \alpha_s p_T R$$

(peaks at approx. 70 GeV for p_T = 500 GeV)





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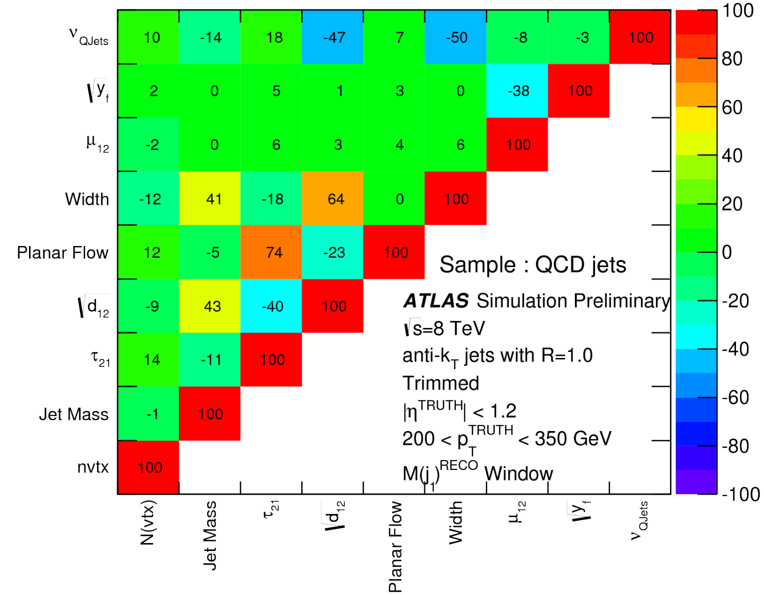
Other jet substructure observables?



Often correlated, combine with care

ATL-PHYS-PUB-2014-004

Splitting scale: $\sqrt{d_{ij}} = min(p_{Ti}, p_{Tj}) \times \Delta R_{ij}$

Butterworth, Cox, Forshaw, PRD65

Momentum balance: $\sqrt{y} = \sqrt{d_{ij}} / m_{ij}$

BDRS, PRL100

Mass drop: $\mu_{ij} = \frac{max(m_i, m_j)}{m_{ij}}$

BDRS, PRL100

Jet width: $w = \frac{\Sigma_i \Delta R_{iJ} \, p_{Ti}}{\Sigma_i p_{Ti}}$

N-subjettiness: $\tau_N = \frac{\Sigma_k p_{Tk} (min(\Delta R_{1k}, \Delta R_{2k}, ... \Delta R_{Nk}))^{\beta}}{\Sigma_k p_T R_0^{\beta}}$ *Thaler, van Tilburg, JHEP03*

More sophisticated:
+ inject "physics", shower deconstruction *(Soper & Spannowsky)*, templates *(Perez et al.)*
+ quantify uncertainty inherent in the decision making process, e.g. volatility *(Krohn et al.)*

Jet substructure performance

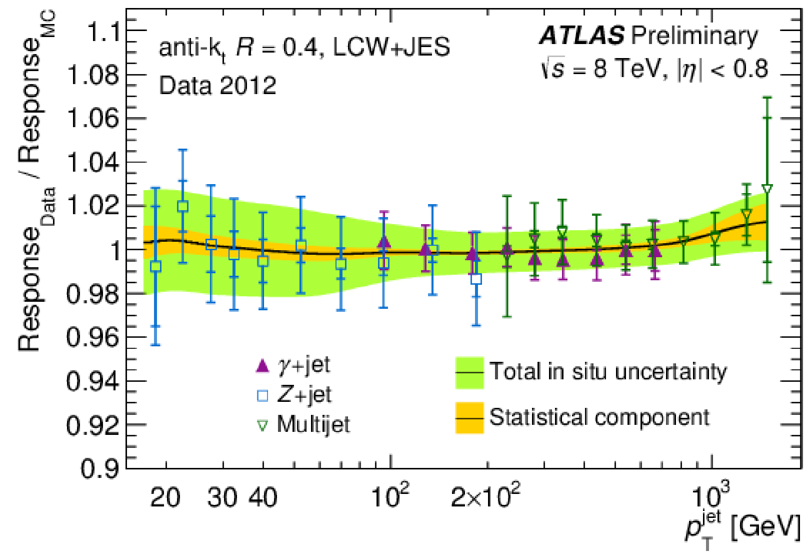
ATLAS and CMS reach %-level jet energy scale uncertainty for some jets

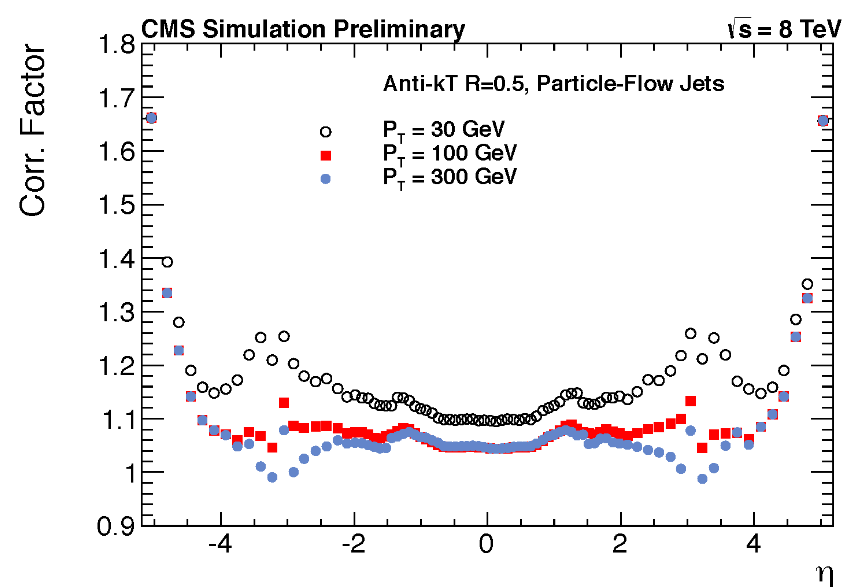
Jet substructure is rather sensitive to the subtleties of the detector response

	position	threshold	energy
	$\delta\phi \times \delta\eta = 0.1 \times 0.1$ grid	$p_T > 1$ GeV	smear by 50% $/\sqrt{E}$
p_T^{reco} / p_T^{true}	1.1%	0.5%	2.5%
$\frac{m^{reco}}{m^{true}}$	3.5%	9%	4%

Impact on p_T and mass resolution for QCD multi-jets with 400 < p_T < 500 GeV of a discrete $\eta \times \phi$ grid, a p_T threshold and energy smearing.

Ideally: bring jet constituents (close) to the particle-scale (CMS → particle flow objects, ATLAS → micro-jets)





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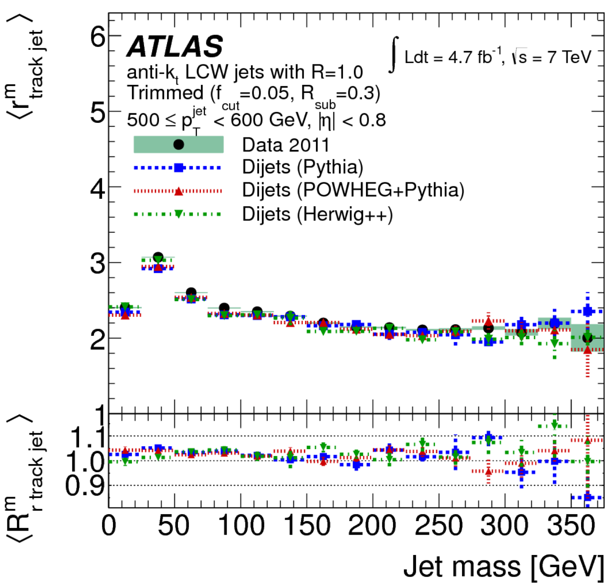
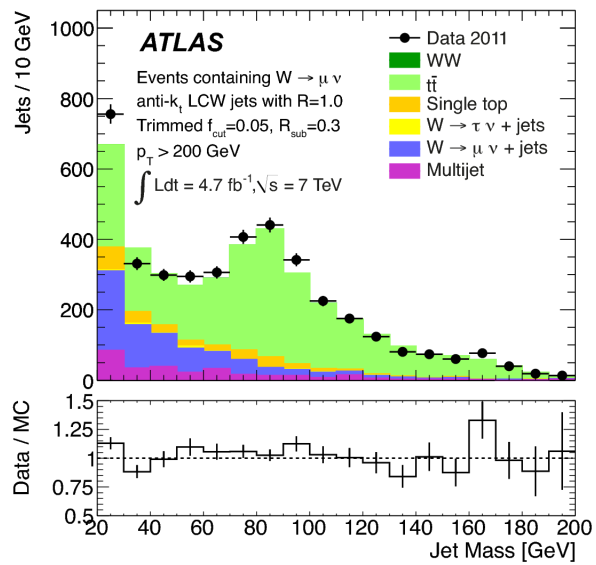
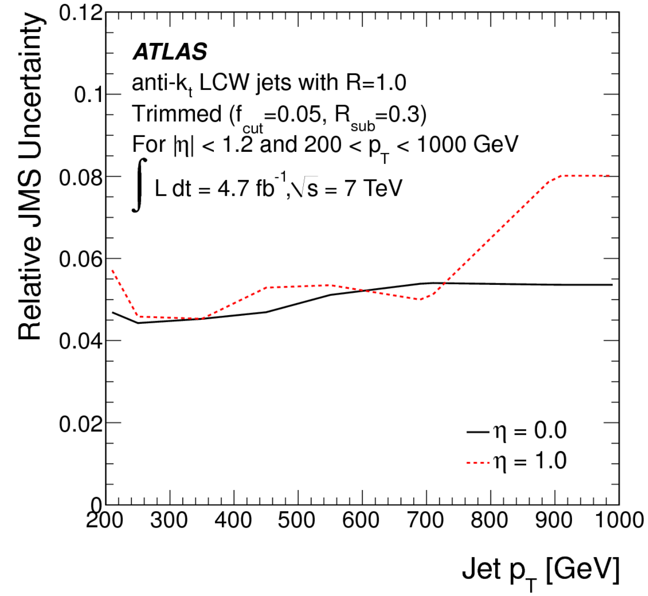
Large-R jet and substructure performance







Use in-situ methods (track/calo, data/MC double ratio, W-mass constraint) to constrain jet mass response or large jets, JHEP09 (2013) 076

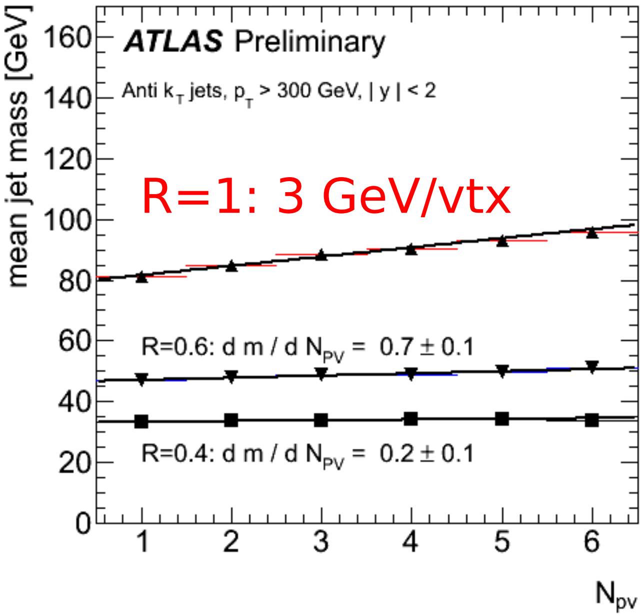
Recent progress: use γ+jets for energy response + topology systematic

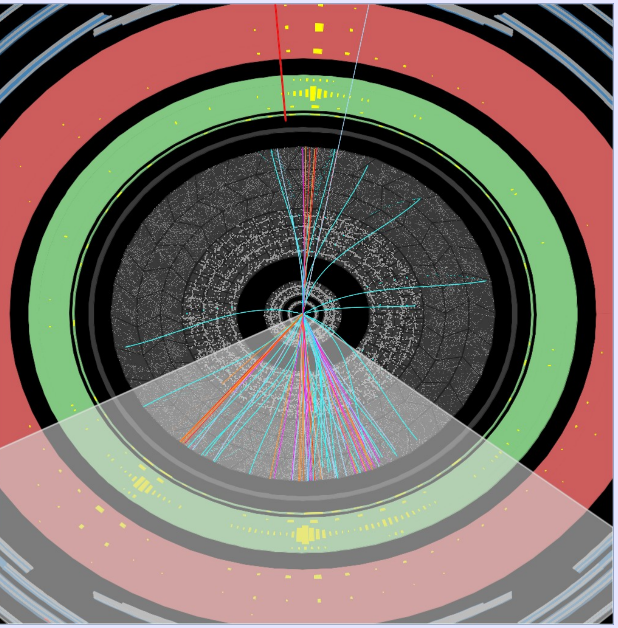
Detector response

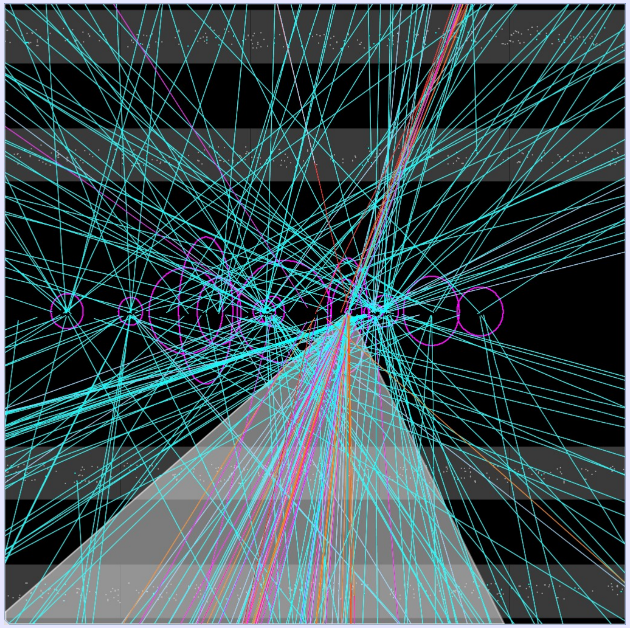
Can we measure jet substructure precisely and reliably?

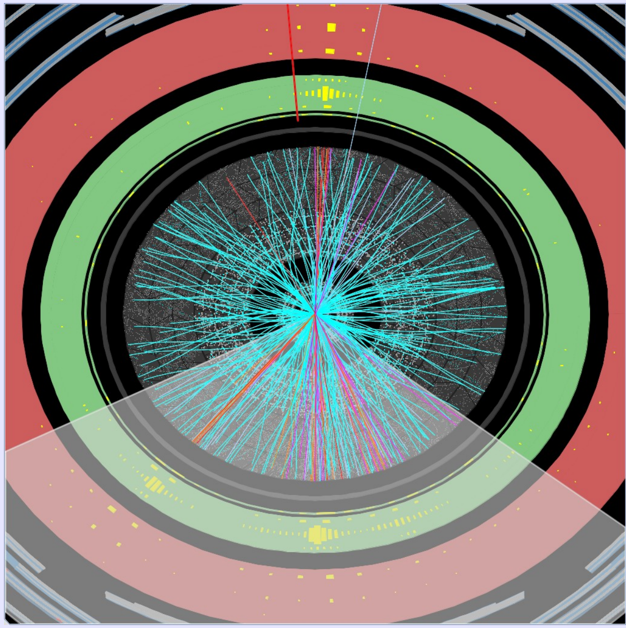
Under the pile-up conditions of the HL-HLC?

2010: few events/crossing
2011: ~12 events/crossing
2012: up to ~25 events/crossing
HL-LHC: up to 200 events/crossing









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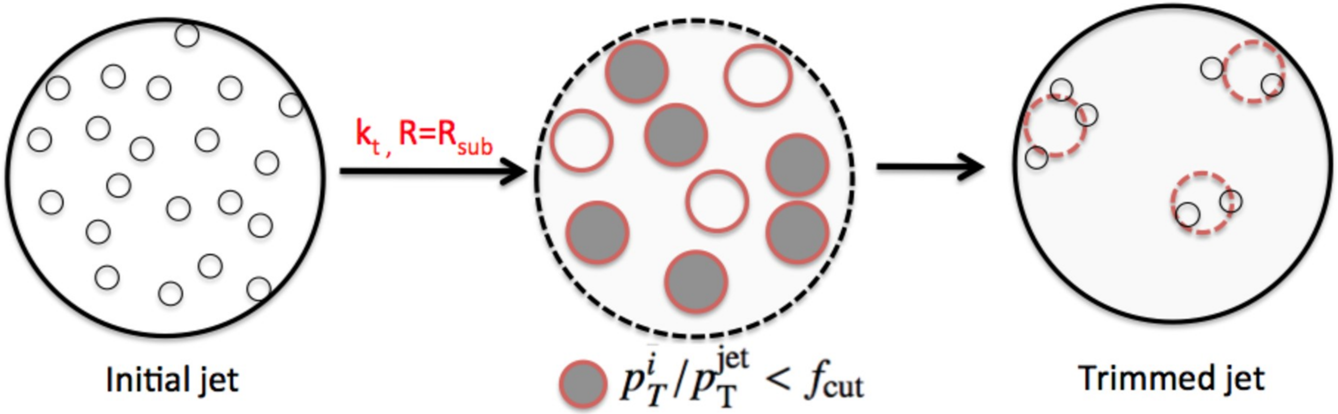
Tools and Techniques: jet grooming



Jet substructure is often hidden by "soft stuff"

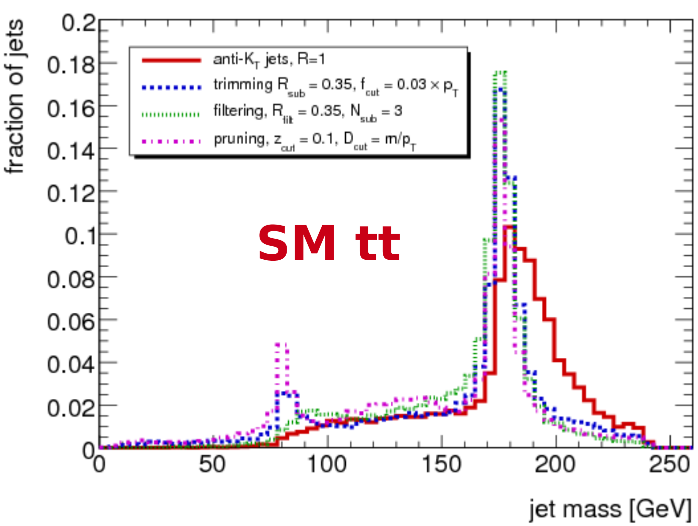
(pile-up, underlying event and soft radiation from the jet itself).

Grooming reduces the effective jet area

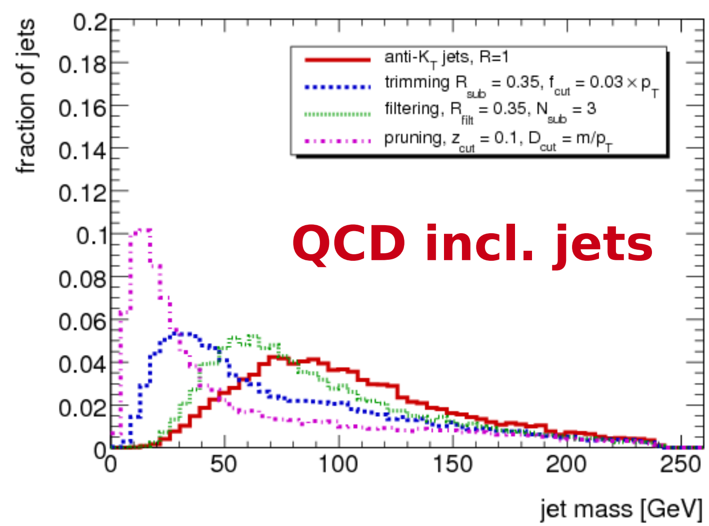
(substructure resolution, background rejection, and pile-up resilience)

Three flavours: *mass-drop filtering (BDRS '08), trimming (Krohn, Thaler, Wang '09)*

pruning (Ellis, Vermillion, Walsh '09)



BOOST2010 report EPJC73



Tools and Techniques: jet grooming (II)

A theoretical comparison: Dasgupta, Fregoso, Marzani, Salam, JHEP1309

✓**Filtering:** break jet into subjets on angular scale R_{filt} , require mass drop and asymmetry, take n_{filt} hardest subjets

Butterworth, Davison, Rubin & Salam ’08

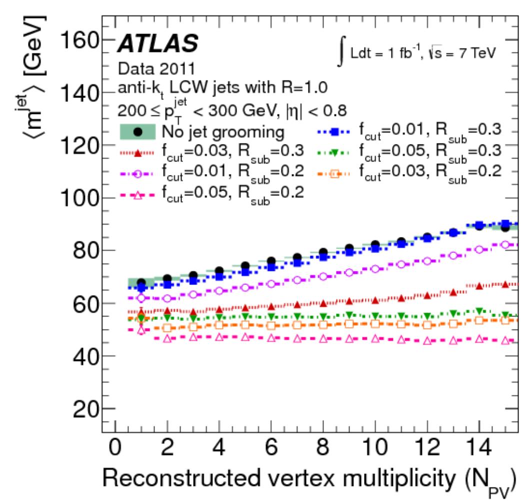
✓**Trimming:** break jet into subjets on angular scale R_{trim}, take all subjets with $p_{T,sub} > \varepsilon_{trim} p_{T,jjet}$

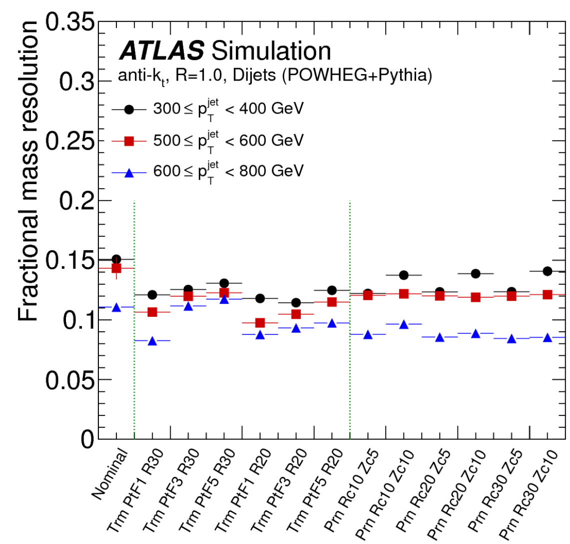
Krohn, Thaler & Wang ’09

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

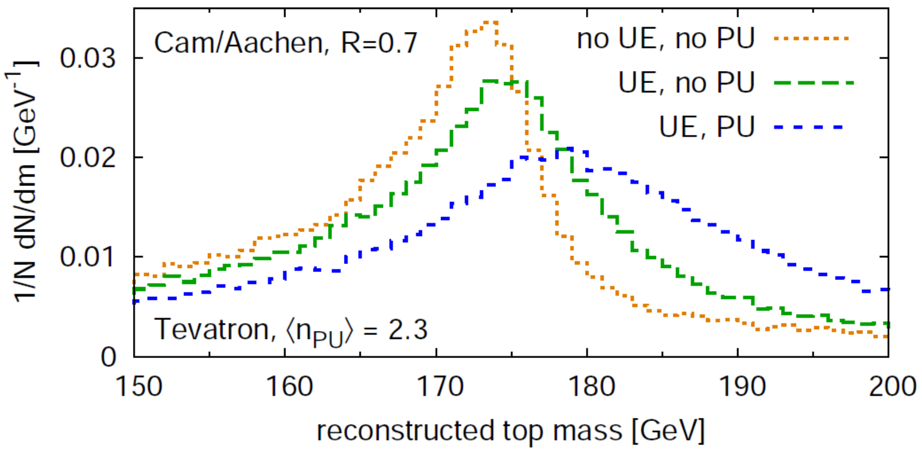
Ellis, Vermilion & Walsh ’09

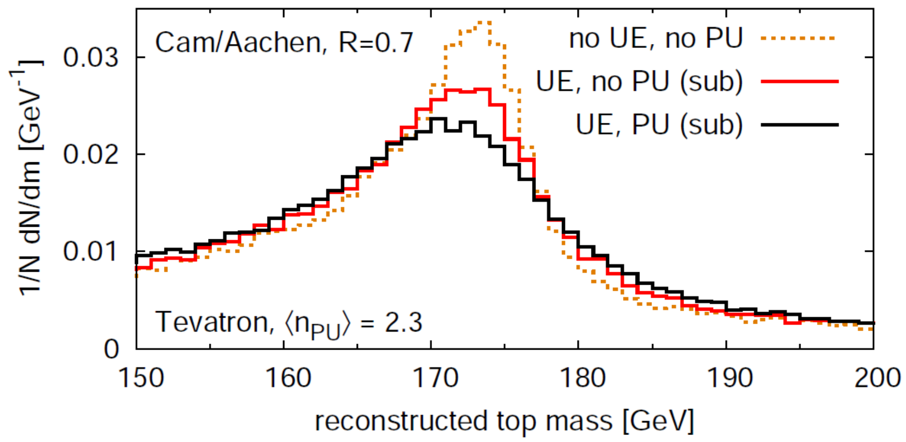
A detailed experimental comparison: *ATLAS large-R jet paper, JHEP1309*





Pile-up correction





Simulation (2008!) by Salam, Cacciari, Soyez

Jet area: shoot infinitely soft “ghost” particles at the jet and register area where they are clustered into the jet

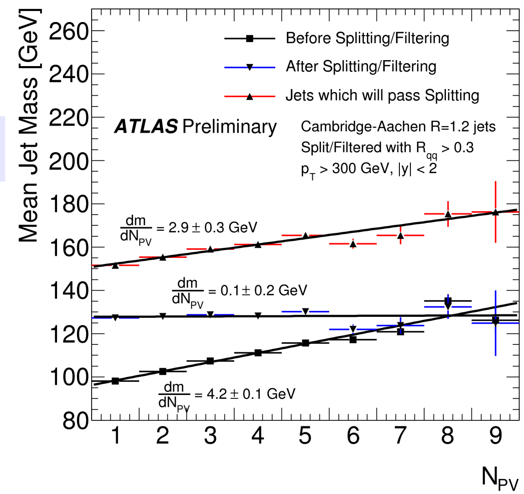
Pile-up density: determine the level of pile-up activity on an event-by-event basis as the median of the

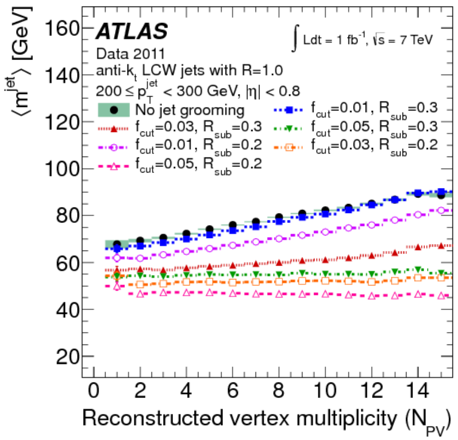
Subtract density x area

Jet area subtraction restores mass scale and the shape

Jet substructure and pile-up

First LHC data (2010): filtered jet mass flat up to 9 pile-up events for R=1.2

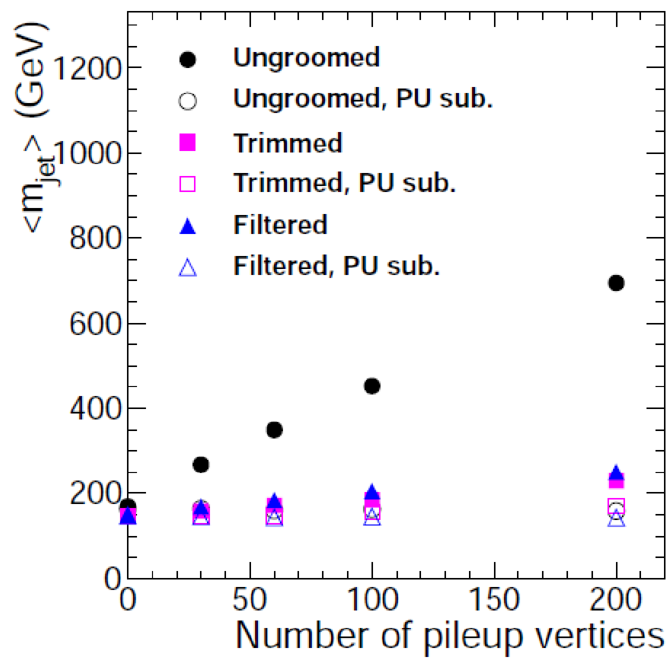


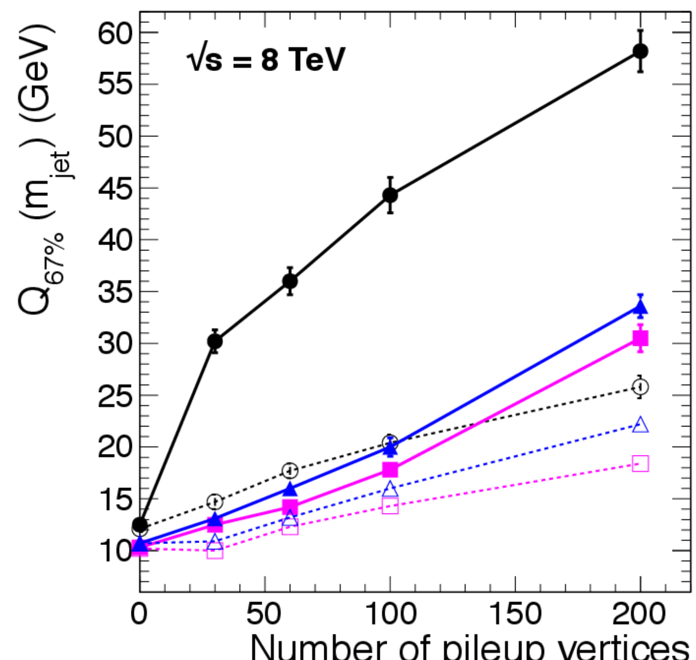


LHC 7 TeV: average trimmed jet mass flat up to 14 pile-up events for R=1.0

Simulation: jet mass scale for boosted top quarks with up to 200 pile-up vertices. Combination of grooming and pile-up subtraction restores the scale and mitigates impact on resolution

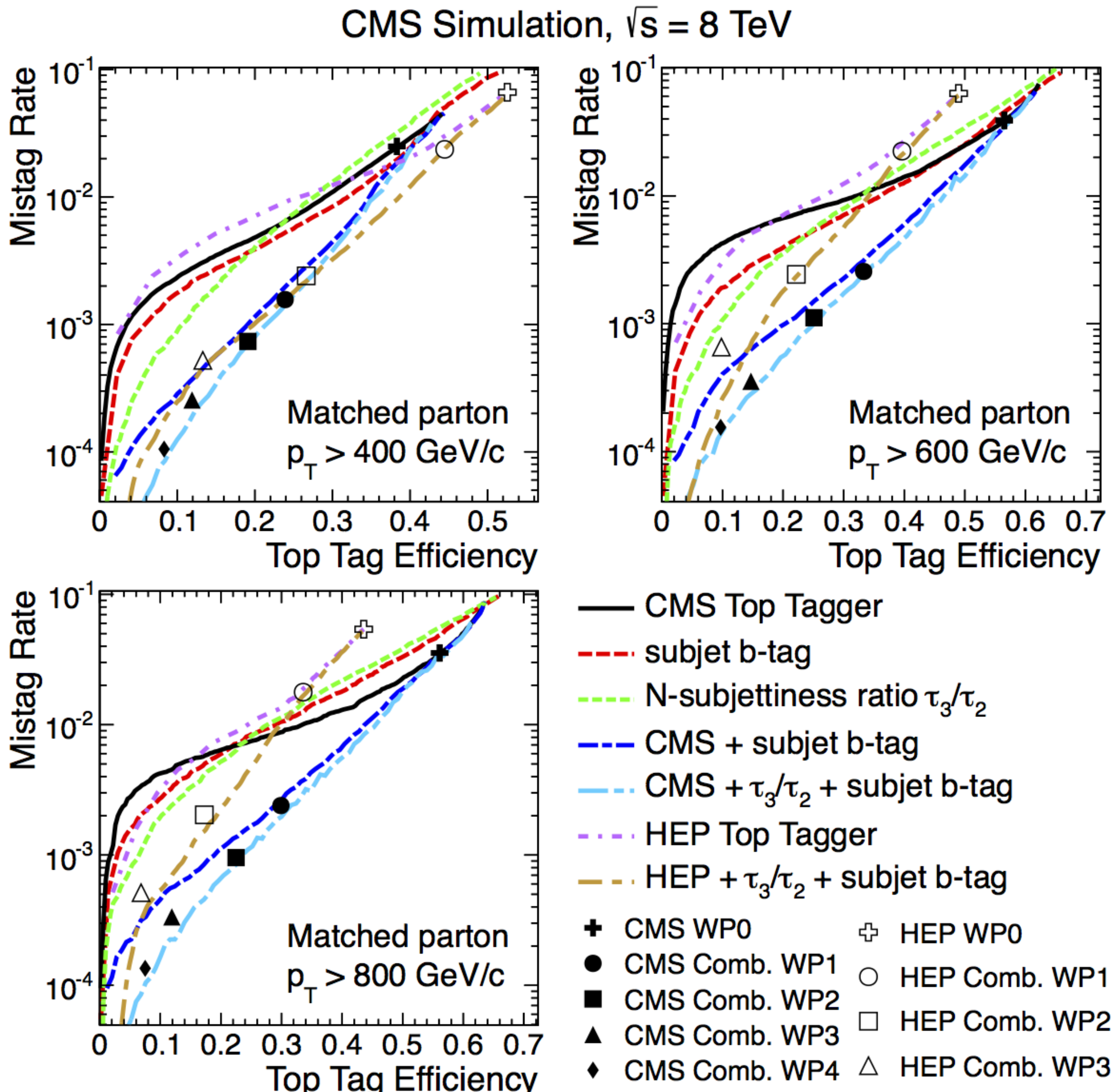
Jet substructure analysis will work for foreseeable future
BOOST2012 report, EPJC74 (2014)





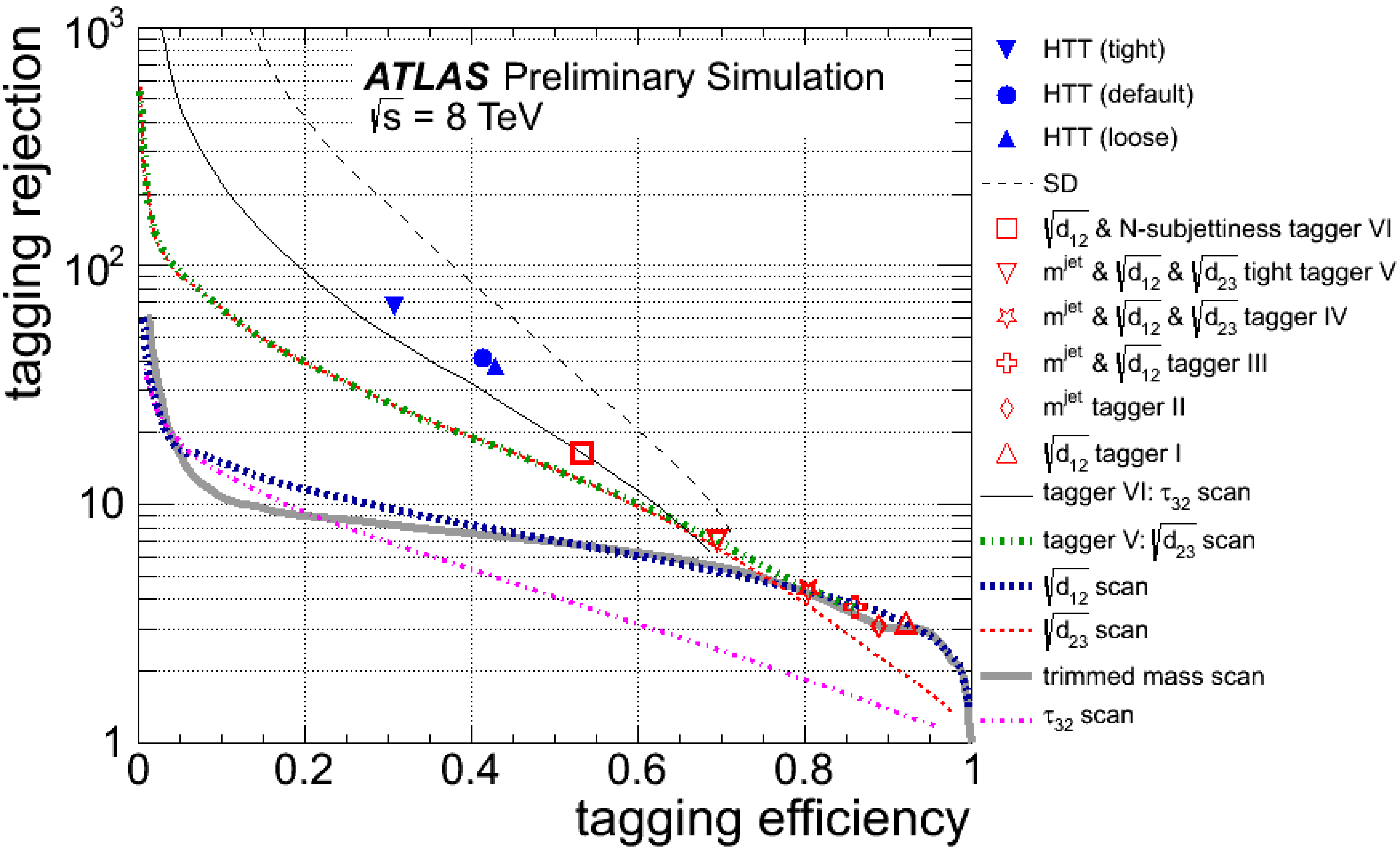
CMS top-tagging

CMS-JME-13-007



ATLAS Top-tagging

ATLAS top-tagging note
ATLAS-CONF-2013-084 +
shower deconstruction
ATLAS-CONF-2014-003



Performance on a Z' → tt sample (m=1.75 TeV)

So, is everything done, then?

Where we stand:

Resolved regime has solutions since 1990s

Cope with the boosted regime ~now

Primitive combinations

The next challenge:
very high boost in the 13 TeV operation

– R=1/1.2 is too large
– Detector granularity is marginal

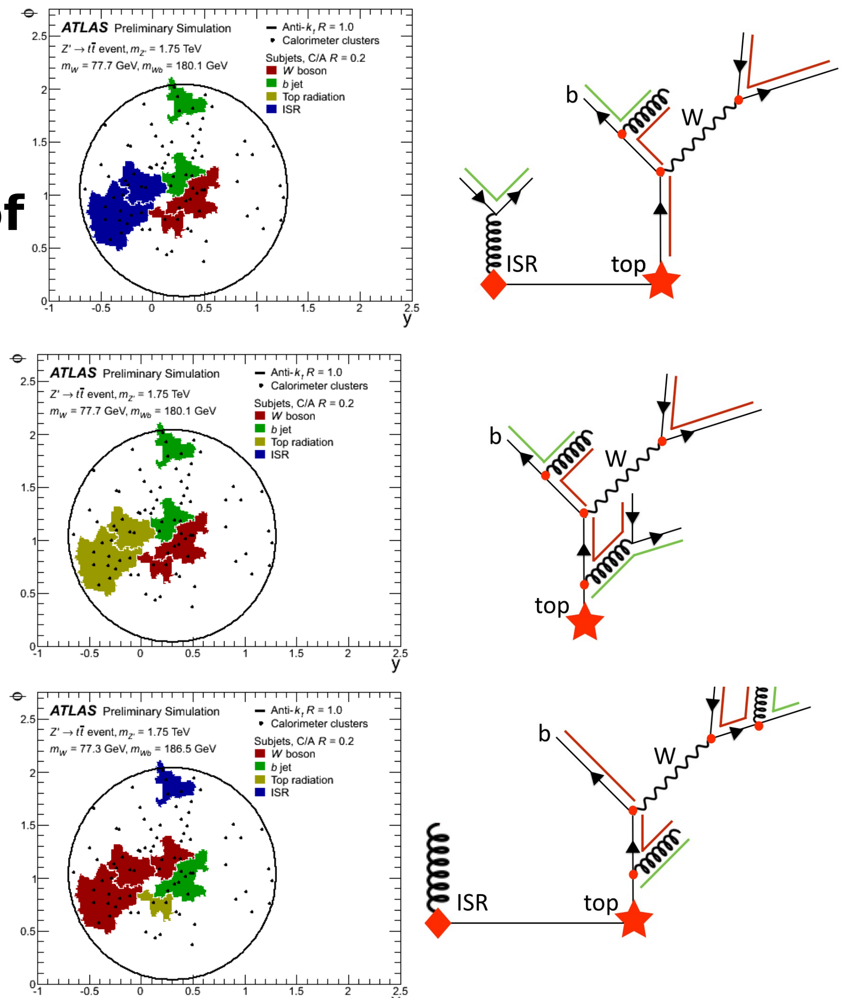
Solutions for a seamless connection of boosted and highly boosted regimes:

- combination of orthogonal signal regions

- scale-invariant tagging
  (Gouzevitch et al., JHEP1307)

- variable-R jet reconstruction
  (Krohn, Thaler, Wang, JHEP0906)

- inject more detailed knowledge of physics
  (template overlap and shower deconstruction, the subject of Dave Soper's contribution)



Images: shower deconstruction, ATLAS-CONF-2014-003

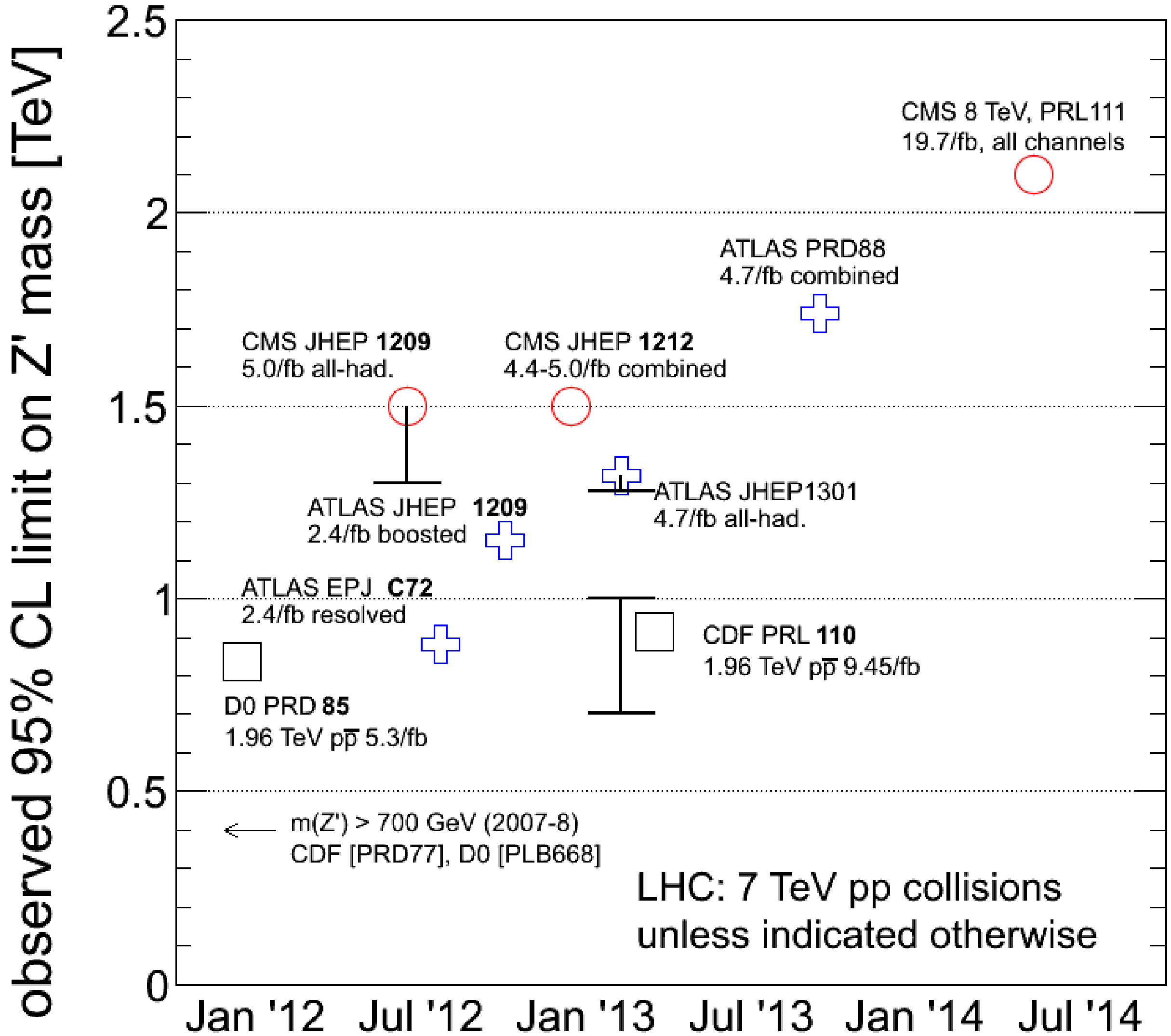
$t\bar{t}$ resonance summary

First "boosted" analysis by ATLAS and CMS in JHEP 1209

Mass reach greatly enhanced

The "resolved" analysis offers complementary low-mass sensitivity

Recent analyses combine both (even if maybe not as well as they could)



W' → tb

Search for W' → tb → bbqq

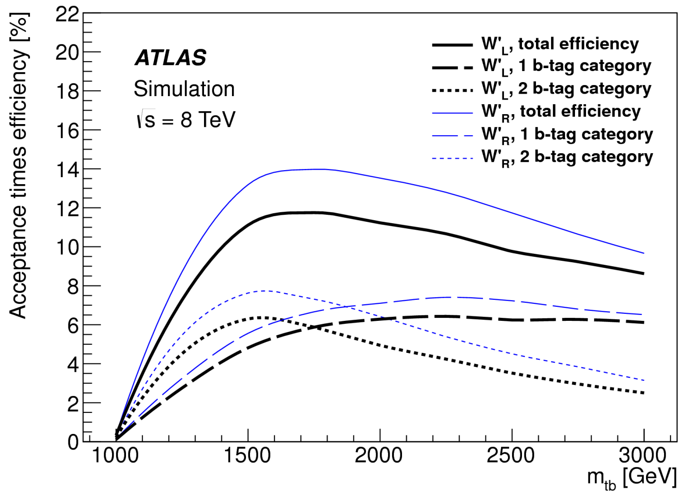
Complete 2012 data set

arXiv:1408.0886 since last week

BR (bbqq) = 3 x BR(bb e/m n)

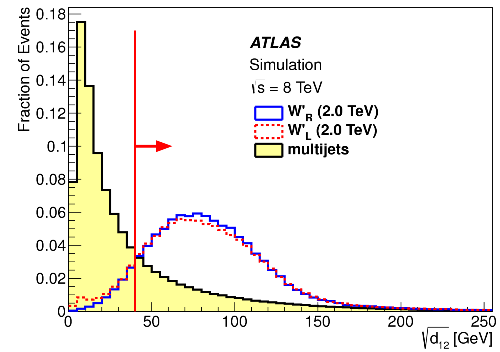
Senstive to right-handed W' with only hadronic decays

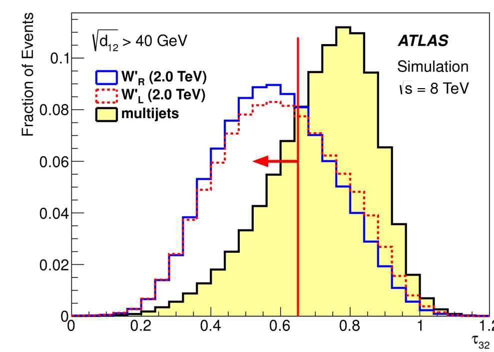
Deal with large multi-jet background using b-tag and top-tag

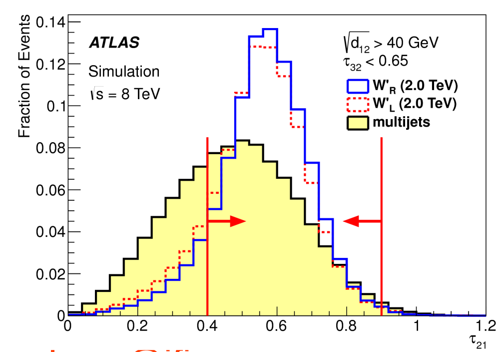


R=1 anti-k_t jet for hadronic top + b-tagged jet

Mass-less top-tagger based on splitting scale and n-subjettiness







Max. deviation 1.4 s, limits on new states with SM coupling:

m(W') > 1.68 TeV (left-handed)

> 1.76 TeV (right-handed)

Preliminary CMS result (B2G-12-009) has considerably tighter limits!

More on searches in Duc Bao Ta's contribution this afternoon

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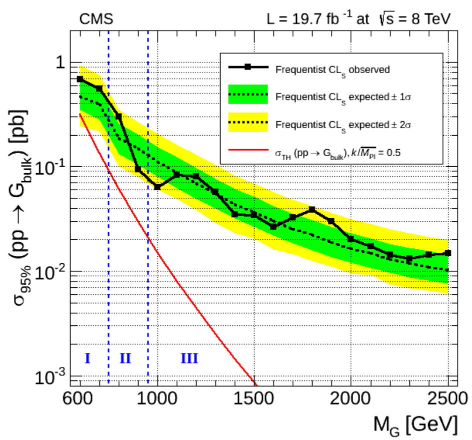
Boosted W,Z

First envisaged application: vector boson scattering cross section

Butterworth, Cox, Forshaw, Phys. Rev. D65 (2002)

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



A lot of recent performance work in the experiments

CMS-PAS-JME-13-006

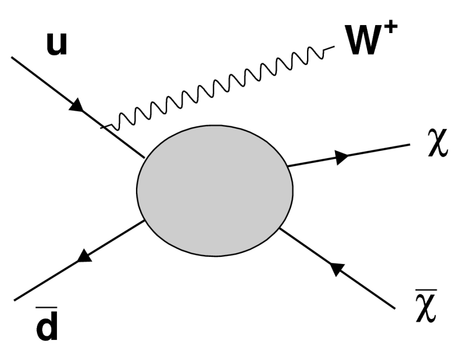
ATL-PHYS-PUB-2014-004

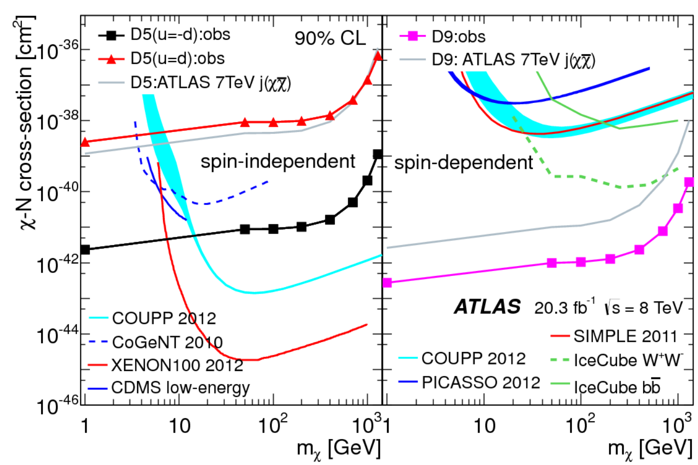
CMS X → VV and X → Vj search

Fully hadronic (arXiv:1405.1994)

ll,lv + j (arXiv:1405.3447)

ATLAS mono-V search

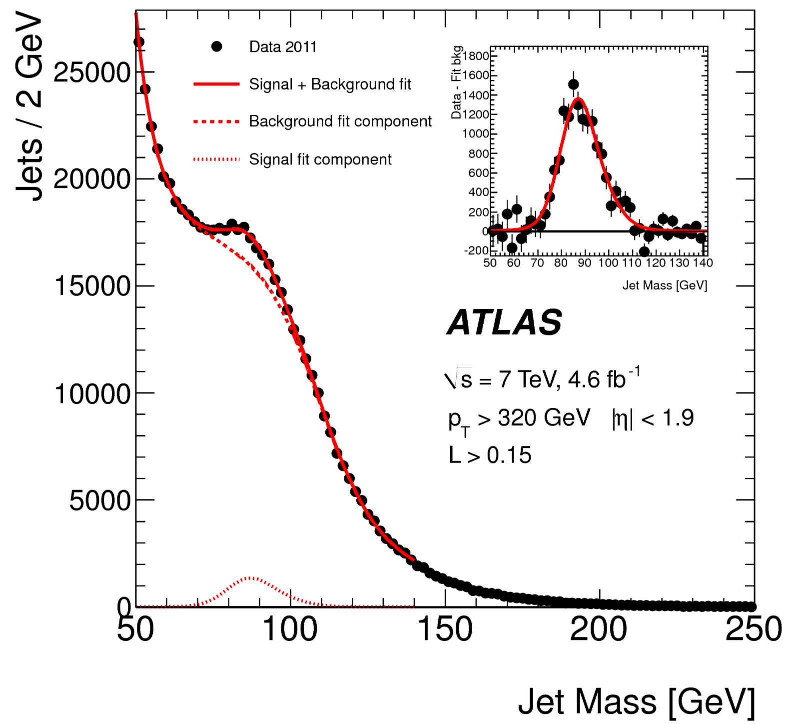




SM measurements of boosted production rate

Measurement of SM production of boosted objects

ATLAS: high p_T W-boson production, arXiv:1407.0800
σ = 8.5 +/- 1.7 pb (p_T > 320, $|\eta|$ < 1.9)



Further scrutiny of inclusive top quark pair production rate limited by theory uncertainty

After first exploration, characterize differential distributions of top quark p_T, $t\bar{t}$ mass, charge asymmetry, as precisely as possible

Can theorists compute a precise differential cross section for pseudo-tops, if their definition involves jet grooming?

Boosted Higgs

Motivation to look for boosted objects:

- A new light particle (H, χ^0, . . .) is more easily isolated from background when boosted, for example because combinatorics are less of an issue
- Or, the measurement of a corner of phase space yields conplementary sensitivity

Boosted Higgs (W/Z + light Higgs → $b\bar{b}$)

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

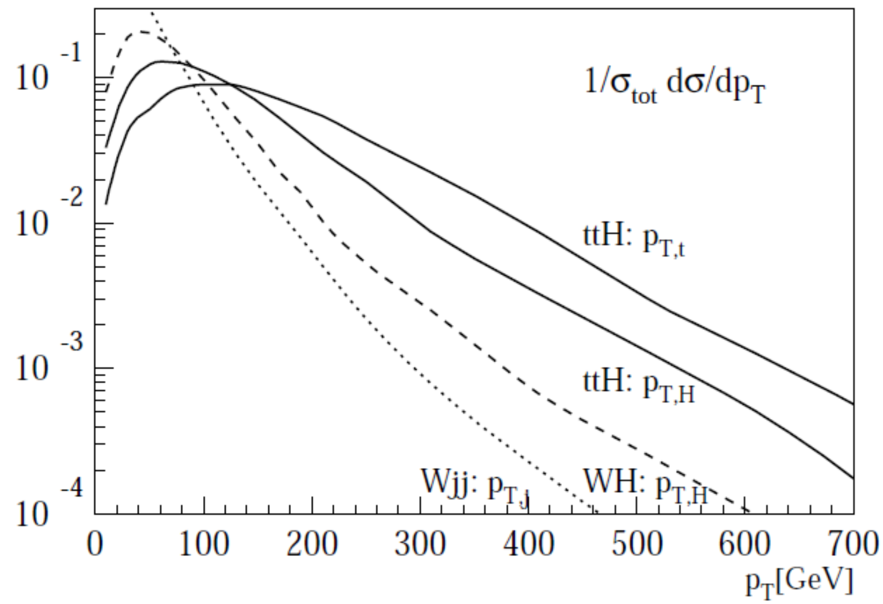
" We conclude that subjet techniques have the potential to transform the high-pT WH,ZH (H → bb) channel into one of the best channels for discovery of a low mass Standard Model Higgs at the LHC"

ZH, Soper, Spannowsksy, JHEP 1008:029 (2010)

gg → H, Grojean et al., JHEP1405

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

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

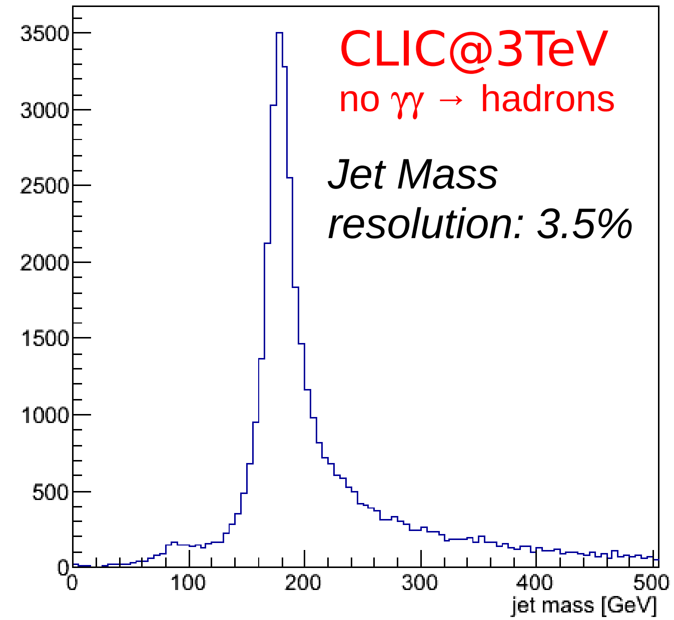


A good shot at measuring the top and bottom Yukawa coupling

The longer-term future of boost

Future e^+e^- machines:

Any machine: new ideas on jet reconstruction
Ultra-granular detectors: benchmark ultimate particle-flow performance
ILC or CLIC at 1-3 TeV: a small (few 100k events), but easy-to-control sample of (nearly) mono-chromatic boosted top quarks



Future hadron colliders:

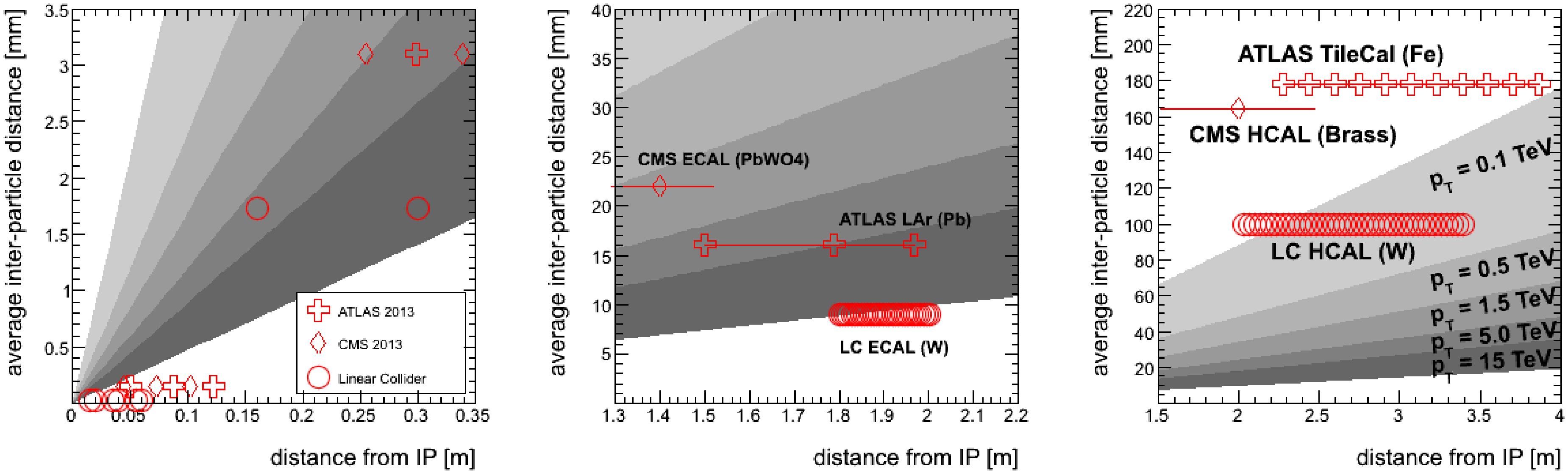
Expected number of boosted tt events in three different kinematical regimes	**LHC design** (2015 – ...) **300 fb-1 @ 13 TeV**	**HE-LHC** (>2030) **3000 fb^{-1} @ 33 TeV**	**VHE-LHC** (>2030) **3000 fb^{-1} @ 100 TeV**
Boosted production: Mtt > 1 TeV	3.000.000	46.000.000	820.000.000
Highly boosted: Mtt > 2 TeV	47.000	23.000.000	450.000.000
Extremely boosted: Mtt > 5 TeV	30	150.000	9.500.000

So much boost we don't know how to deal with it!

Future colliders & detectors

A 150 x 150 μm^2 pixel at r = 4.4cm → $\Delta\phi/\Delta\eta \sim 0.003$
A 10 cm x 80 μm μ-strip at r = 50 cm → $\Delta\phi/\Delta\eta \sim 0.006$
An ECAL crystal at r = 1.4 m → $\Delta\phi/\Delta\eta \sim 0.015$
A tile in HCAL at r = 1.5 m → $\Delta\phi/\Delta\eta \sim 0.1$

A jet may cover 5000 pixels/layer, 1000 ECAL crystals, but only HCAL 50 tiles



Preliminary: typical inter-particle distance vs. distance from IP

Superposed feature size, Moliere radius and interaction length of current experiments (and concepts)

BOOST: the workshop series

The workshop series:

+ events at Boston, CERN LHCC, Manchester, Oregon, Seattle, SLAC

SLAC 2009

Oxford 2010, *Eur. Phys. J. C71 (2011) 1661*

Princeton 2011, *J.Phys.G G39 (2012) 063001*

Valencia 2012, *Eur. Phys. J. C74 (2014) 2792*

Arizona, August 2013, *report underway*

UC London, August 2014

BOOST2014 is the sixth of a series of successful joint theory/experiment workshops which bring together the world leading experts from theory and the Tevatron and LHC experiments to discuss the latest progress and develop new approaches on the reconstruction and use of boosted decay topologies as search tools for new physics. This year, the workshop is hosted by the UCL HEP Group at the heart of London.

Conclusions

The LHC is a “boosted object” factory.

A lot of effort was invested to understand jet substructure: physics modeling, detector response and pile-up

Mature and complete tool-box now available

The first searches with these techniques indeed enhance the LHC physics potential

Measurements of boosted object production rates are starting to appear

Much more “boost” expected in the 2015 run of the LHC

+

= ...