Boosted Objects Theory Review

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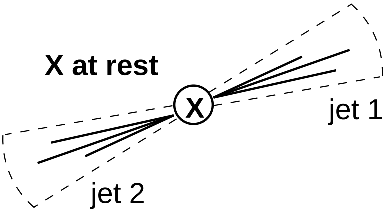
Implications of LHC for TeV-scale Physics
[WG1: Prospects for LHC searches in 2011/12: boosted Higgs, WBF, etc.]

CERN, 30 August 2011

Boosted massive particles, e.g.: EW bosons

Normal analyses: two quarks from $X \to q\bar{q}$ reconstructed as two jets



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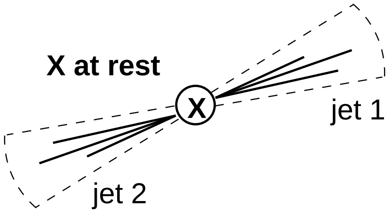
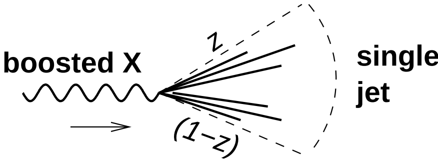


High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



Happens for $p_t \gtrsim 2m/R$

$p_t \gtrsim 320$ GeV for $m = m_W$, $R = 0.5$

As LHC starts to explore far above EW scale, such configurations become of interest

Two motivations

New heavy particles can decay to boosted W, Z, H, top, χ^0 (RPV); WW scattering at high p_t

- leptonic decays easily tagged, but rare and/or have MET
- hadronic decays more common and fully reconstructible

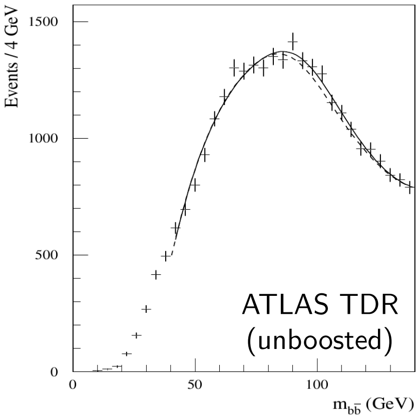
not especially Higgs oriented, except e.g.
SUSY cascades → Higgs: Butterworth, Ellis & Raklev '07
Kribs, Martin, Roy & Spannowsky '09, '10

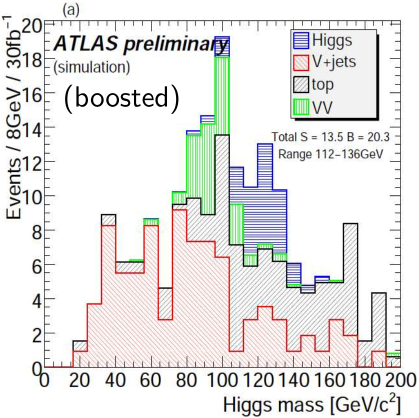
New EW-scale particles may be *easier* to discover at high p_t

- e.g. light Higgs with predominantly $H \to b\bar{b}$ decay, in VH and $t\bar{t}H$
- Some relevant fraction produced at high p_t ($\sqrt{s_{\text{LHC}}} \gg m_{\text{EW}}$)
- Backgrounds often fall faster than signal at high p_t
- Jet combinatorics are easier at high p_t — cleaner events
- Easier to organise cuts so as not to sculpt backgrounds

Example improvement from boosted regime

Search for main decay of light Higgs boson in W/Z+H, $H \to b\bar{b}$



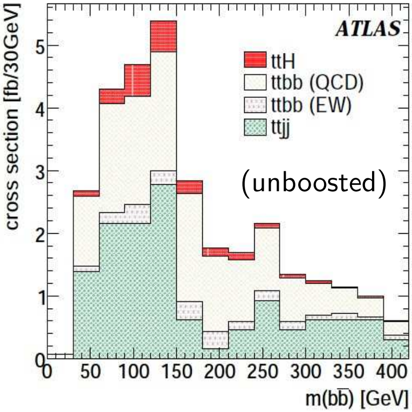


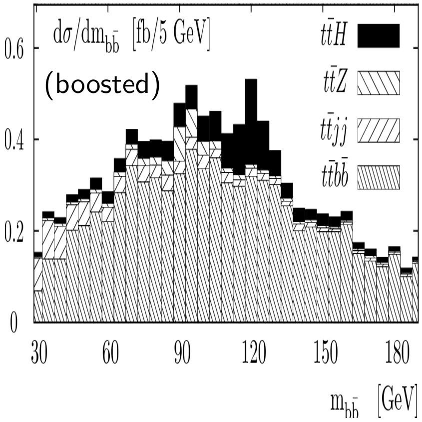
restricting search to $p_{tH} > 200$ GeV

using the method from Butterworth, Davison, Rubin & GPS '08

Example improvement from boosted regime

Search for main decay of light Higgs boson in $t\bar{t}$+H, H → $b\bar{b}$





restricting search to $p_{t,H} > 200$ GeV, $p_{t,t\to\text{hadrons}} > 200$ GeV, one leptonic top

Plehn, GPS & Spannowsky '09

Key ingredients

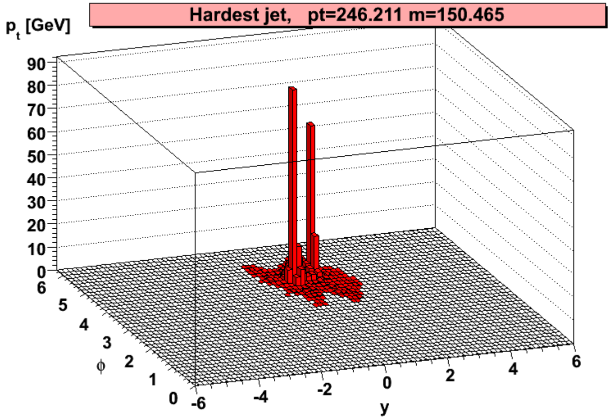
- Resolving the underlying $1 \to 2$ splitting and using its characteristic kinematics to help reject background [Leading-order Structure]
- Protecting jet-mass resolution from the mess of underlying event and pileup [Non-perturbative structure]
- Exploiting different colour structures of signal and background and resulting different energy flows [Higher-order structure]

A highly active field, here just cover a handful of the main considerations

See also Boost 2010 writeup, recent Boost 2011 conference and tomorrow's WG3 session

Leading Order Structure

Common idea: undo jet clustering & cut



First proposed for W's by Seymour '93

Refined by Butterworth, Cox & Forshaw '02

Refined more + showed how to use it to find $H \to b\bar{b}$ at LHC, Butterworth, Davison, Rubin & GPS '08

Later in '08: extended to top quarks by ATLAS; Thaler & Wang; Kaplan, Rehermann, Schwartz & Tweedie [Johns Hopkins top tagger].

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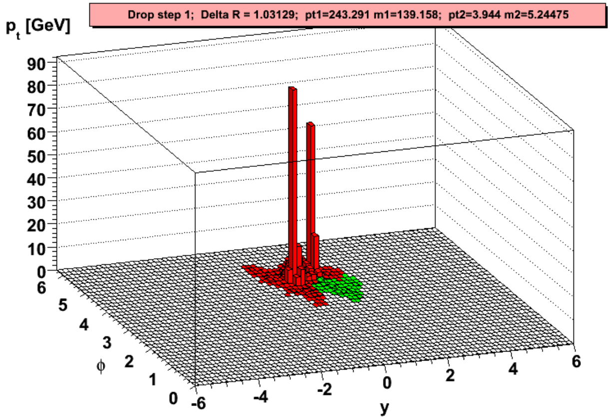

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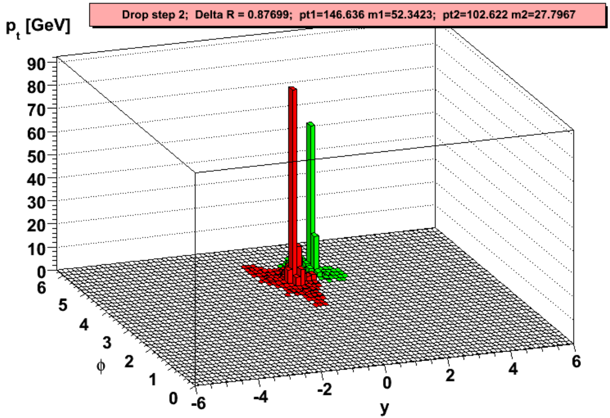

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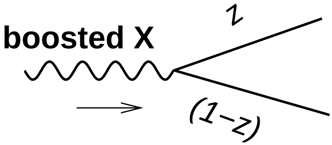
Beginning of a wave of intense activity, motivating $\sim$ 6 dedicated workshops in 3 years

QCD principle: soft divergence

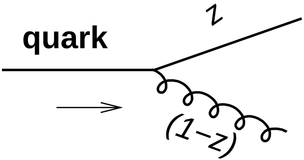
Signal



Splitting probability for Higgs:

$$P(z) \propto 1$$

Background



Splitting probability for quark:

$$P(z) \propto \frac{1+z^2}{1-z}$$

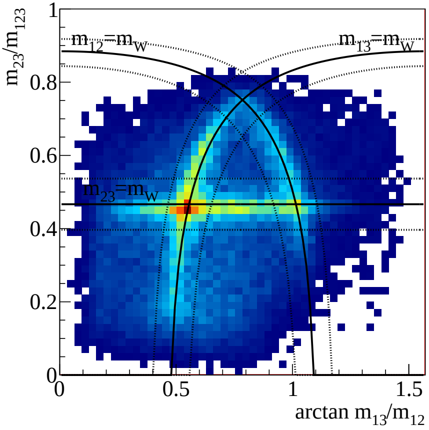
$1/(1-z)$ divergence enhances background

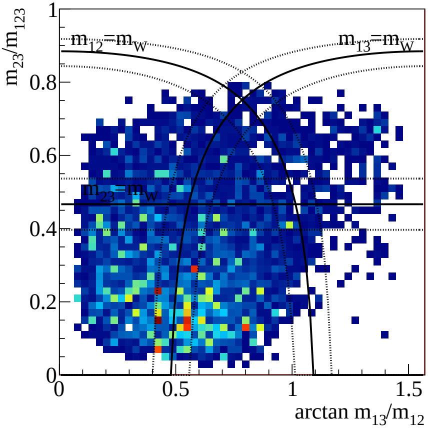
Remove divergence in bkdg with cut on z
Can choose cut analytically so as to maximise $S/\sqrt{B}$

Originally: cut on opening angle (Seymour '93)
or k_t-distance (Butterworth, Cox & Forshaw '02)

$t \to bjj$ decays — multiple kinematic variables

Top signal **QCD background**



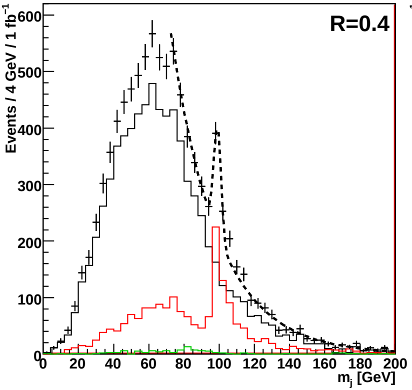


Using Dalitz-like plots to pull out the W **without using *b* tagging**

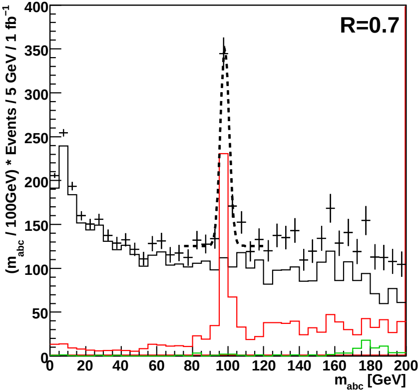
Plehn, Spannowsky, Takeuchi & Zerwas '10

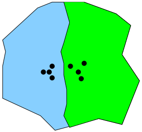
Different jet algs, different bkgd shaping

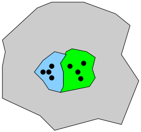
k_t algorithm



Cambridge/Aachen alg.



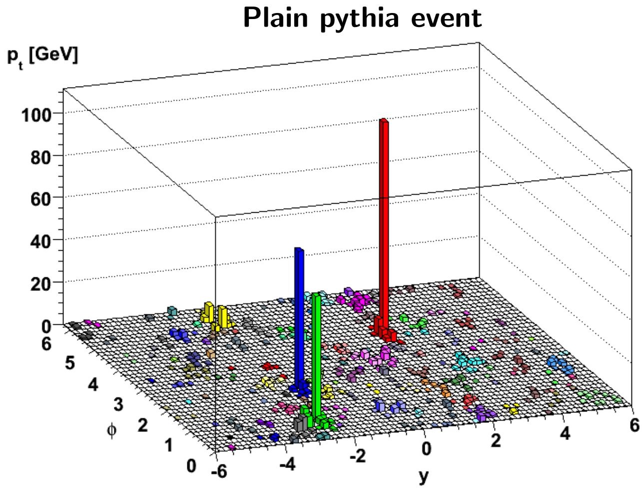




[RPV χ^0 search BERS '09]

Noise reduction

Noise & different kinds of event



The problem of noise and contamination is common to low-lumi pp running, high-lumi LHC pp running, and even heavy-ion running

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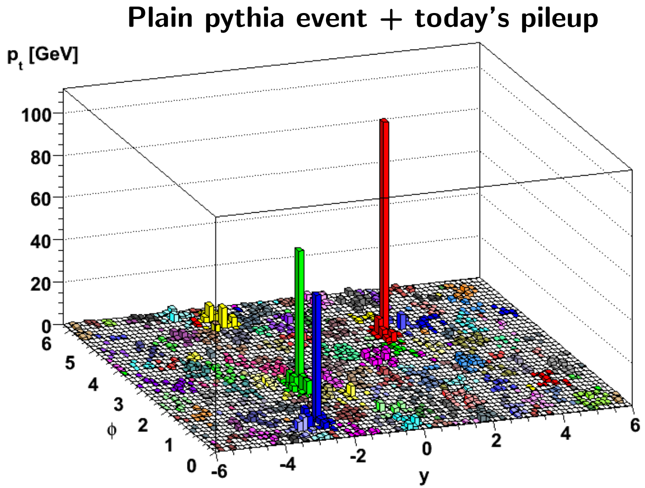

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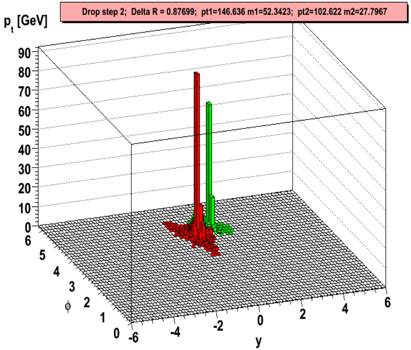
Noise removal from jets



Key idea:

- Look at jet on smaller angular scale
- Discard its softer parts

- Filtering — Butterworth et al '08
- Pruning — Ellis, Vermillion and Walsh '09
- Trimming — Krohn, Thaler & Wang '09

[With earlier methods by Seymour '93 and Kodolova et al '07; also Soper & Spannowsky '10, '11]

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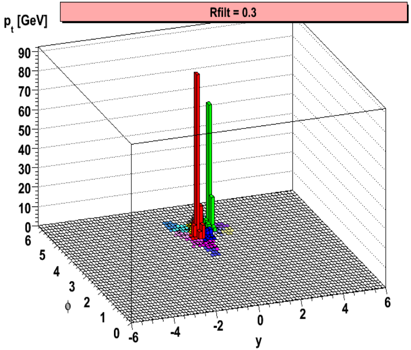

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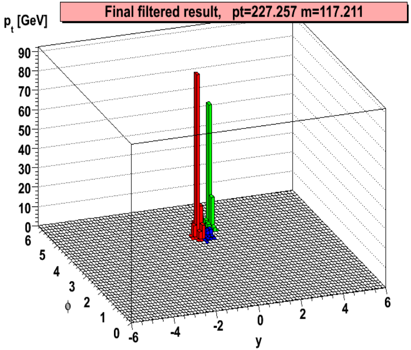

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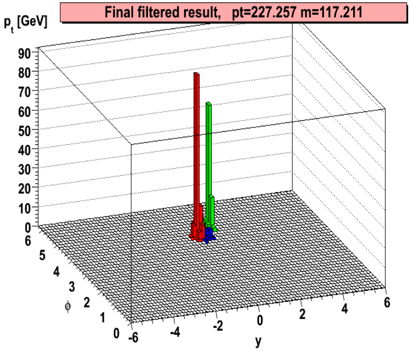

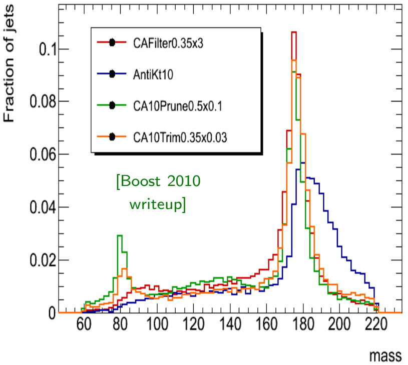

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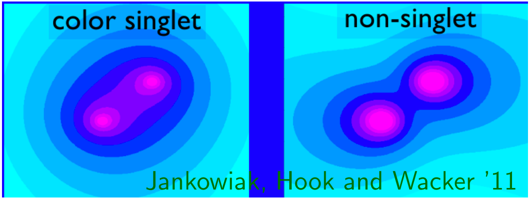
Radiation beyond leading order

Exploiting energy-flow beyond LO structure

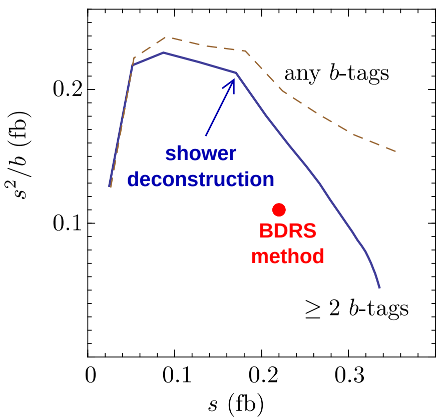


Background (e.g. $g \to gg$) and signal (e.g. $W \to q\bar{q}$) often have different colour structure $\to$ **different radiation patterns**.

- Pull (non-boosted context) — Gallicchio & Schwartz '10
- N-subjettiness — Jihun Kim '10; Thaler & Van Tilburg '10
- "Buried Higgs" light singlets — Falkowski et al '10; Chen et al '10
- Boosted decision trees — Cui & Schwartz '10
- Dipolarity, applied to HEPTopTagger — Jankowiak, Hook and Wacker '11
- Jet deconstruction — Soper & Spannowsky '11
- Template method beyond LO — Almeida et al '11; cf. talk tomorrow by Gilad Perez
- ...

Shower deconstruction for ZH

Matrix-element method on steroids



For each event estimate the probability that event is signal-like or background like.

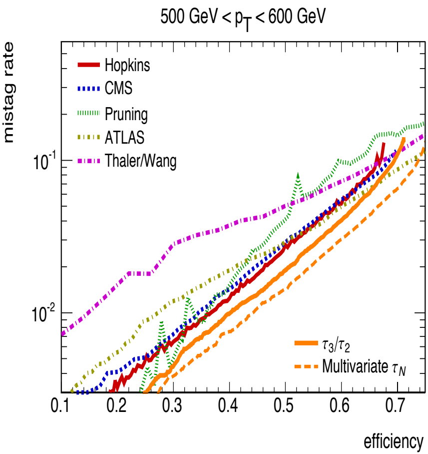
Break event into many mini-jets; use Monte-Carlo type Sudakovs and splitting functions to get estimate of multi-parton matrix element for S & B hypotheses.

Intelligently combines full info about LO splitting, radiation, b-tags, etc.

Soper & Spannowsky '11

cf. also multivariate (BDT) type methods from Cui & Schwartz '10

Jet shape variables (here for top tagging)



Thaler & van Tilburg '11
cf. also J.-H. Kim '10 for Higgs

Early proposals include planar flow (3- v. 2-body structure of top decay) Thaler & Wang '08 Almeida et al '08

Recent try: N-subjettiness. Break jet into subjets $1, \ldots, N$

$$\tau_N = \frac{1}{p_{t,jet}} \sum_i p_{ti} \min(R_{i1}, \ldots, R_{iN})$$

N-pronged decay: cut on mass &

$$\frac{\tau_N}{\tau_{N-1}}$$

Combines constraints on LO structure (energy sharing among prongs) and higher-order rad^n (from quarks in signal v. gluons in bkgd)

Concluding remarks

High-p_t regime offers new perspectives on both BSM and Higgs searches.

For LHC7 and O(1–2fb^{-1}) luminosity, boosted techniques start to play role. For Higgs they're only at the very beginning. [See next talk!]

For Higgs, we're in a borderline region where boosted and traditional multi-jet techniques overlap; lessons about value of boosting the Higgs hold also in traditional analyses.

Meanwhile, much theory work going on to pull maximum information out of fat jets, with $20 - 100\%$ improvements obtained relative to earlier studies.