Theory of Fat Jets and Jet Substructure

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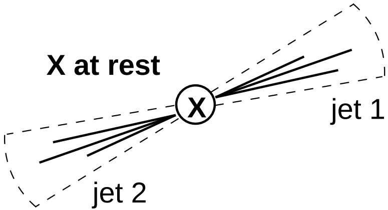
Higgs Hunting 2012
Orsay, France, 18–20 July 2012

Boosted massive particles → fat jets

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



Boosted massive particles $\to$ fat jets

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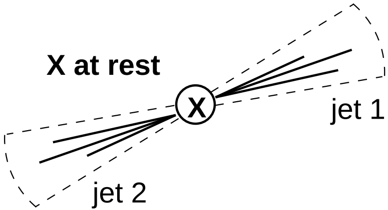
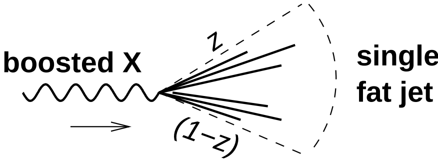


High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



Happens for $p_t \gtrsim 2m/R$

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

As LHC explores far above EW scale, such configurations become of interest

Motivation #1

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

or $H \to 2a \to 4g$: Chen, Nojiri & Sreethawong '10 + Falkowski et al '10

Motivation #2

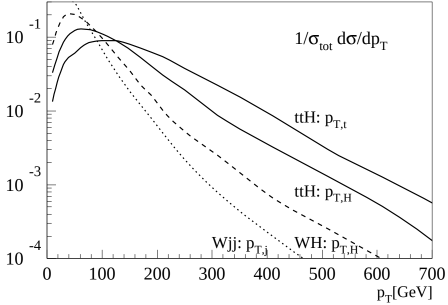
Hadronic decays of new EW-scale particles may be *easier* to see at high p_t

e.g. 125 GeV Higgs with 60% BR for $H \to b\bar{b}$ decay

v. 0.2% for $\gamma\gamma$ and 2.6% for ZZ

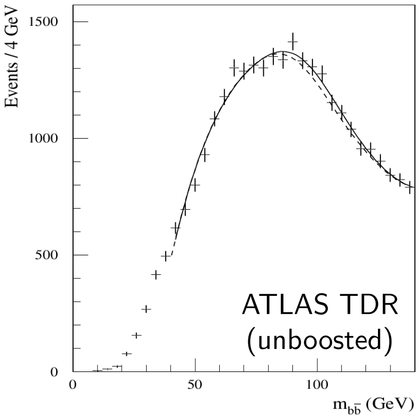
Specifically for VH and $t\bar{t}H$:

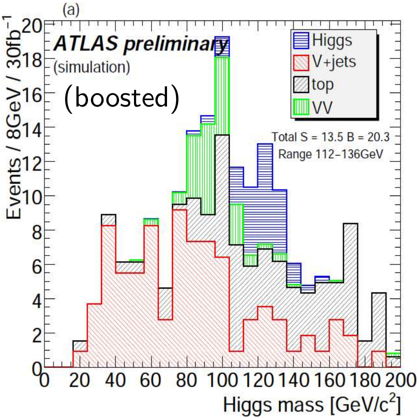
- Some relevant fraction produced at high p_t ($\sqrt{s_{\text{LHC}}} \gg m_{\text{EW}}$)
- Backgrounds often fall faster than signal at high p_t
- Jet combinatorics are easier at high p_t — cleaner events
- Easier to organise cuts so as not to sculpt backgrounds



Example improvement from boosted regime

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

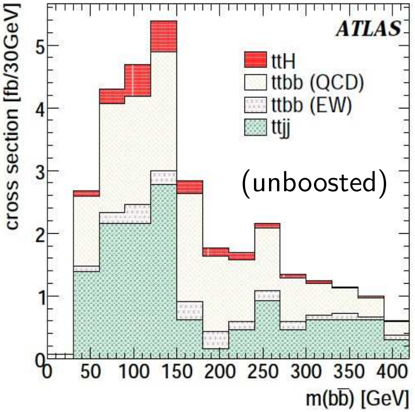


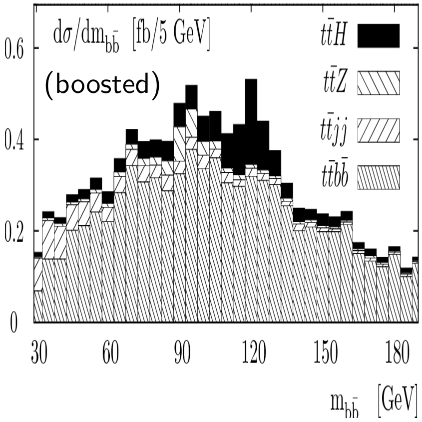


restricting search to $p_{tH} > 200$ GeV,
using the method from Butterworth, Davison, Rubin & GPS '08

Example improvement from boosted regime

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





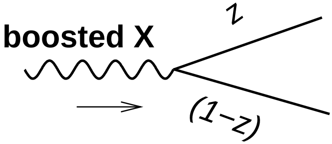
restricting search to $p_{t,H} > 200$ GeV, $p_{t,t\to\text{hadrons}} > 200$ GeV, one leptonic top

Plehn, GPS & Spannowsky '09

Key element #1
Leading Order Structure

QCD principle: soft divergence

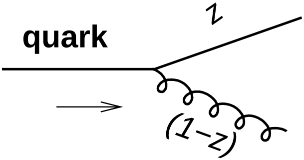
Signal



Splitting probability for Higgs:

$$P(z) \propto 1$$

Background



Splitting probability for quark:

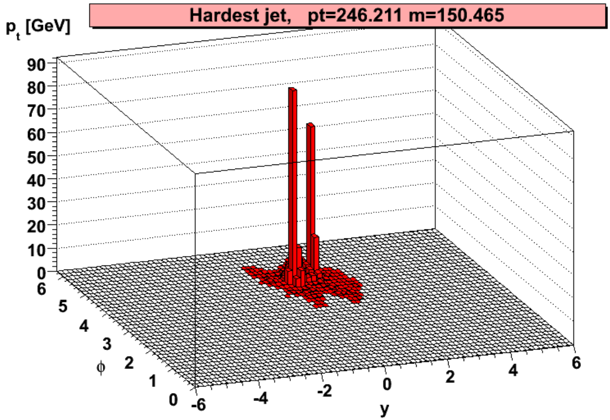
$$P(z) \propto \frac{1+z^2}{1-z}$$

$1/(1-z)$ 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)

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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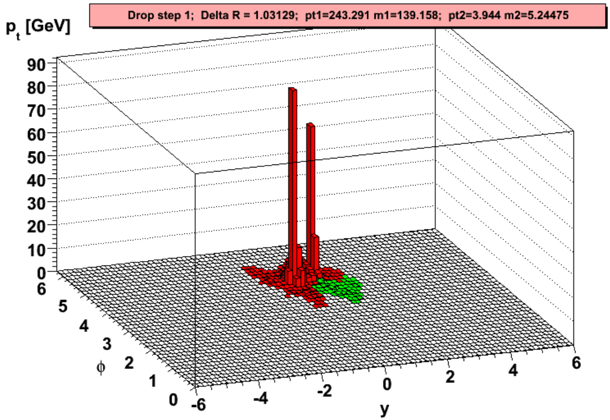

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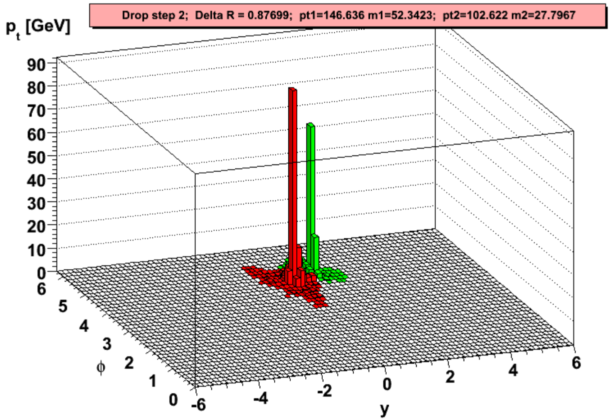

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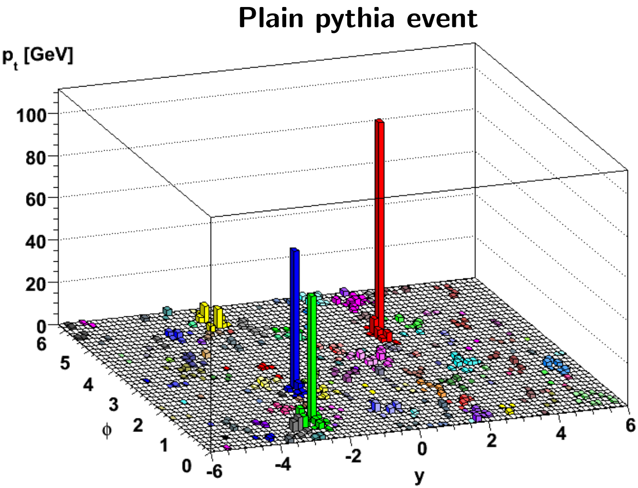
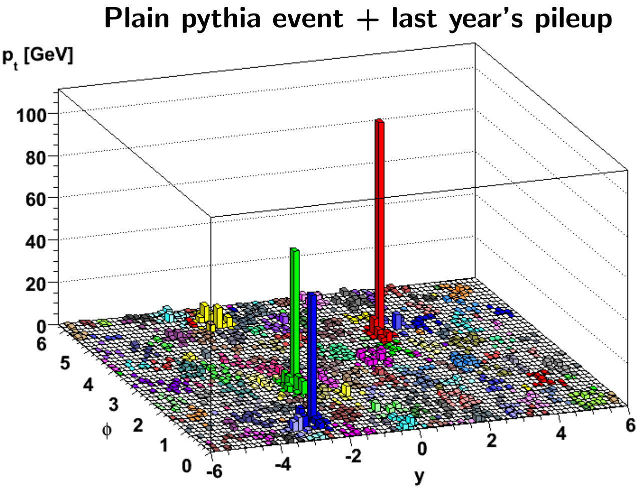
Noise reduction

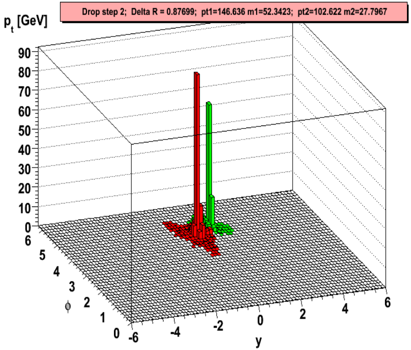
Noise & different kinds of event



Noise & different kinds of event



Noise removal from jets — a boosted top example



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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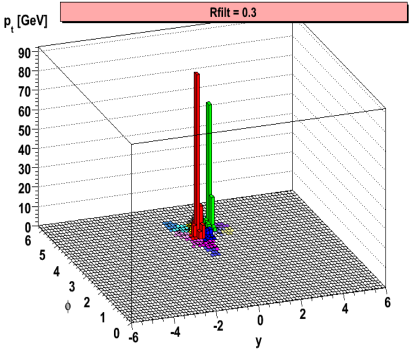

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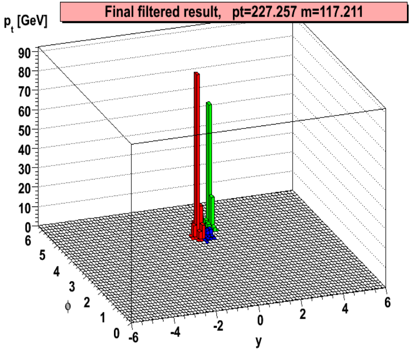

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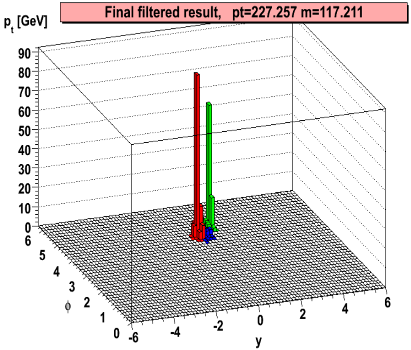

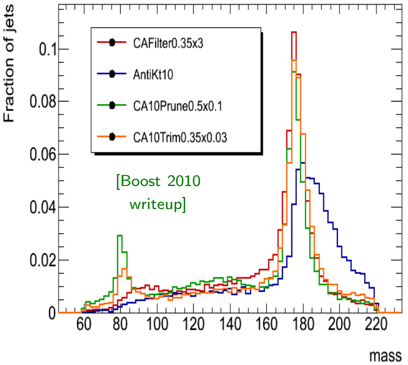

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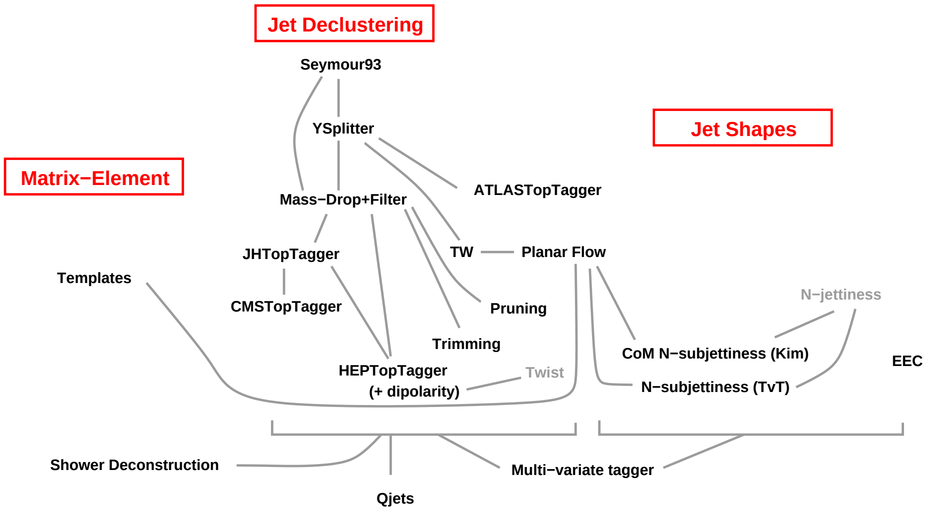
Overview of methods

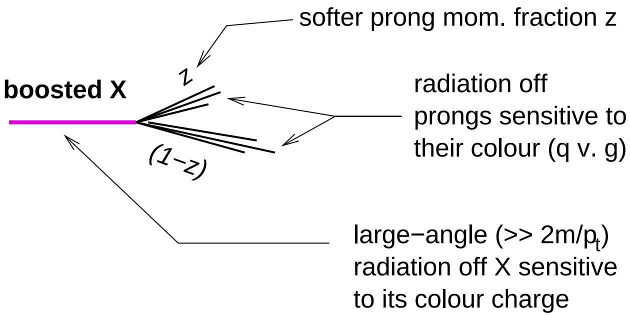
Some taggers and jet-substructure observables



apologies for omitted taggers, arguable links, etc.

[NB: many of the tools available in FastJet & SpartyJet]

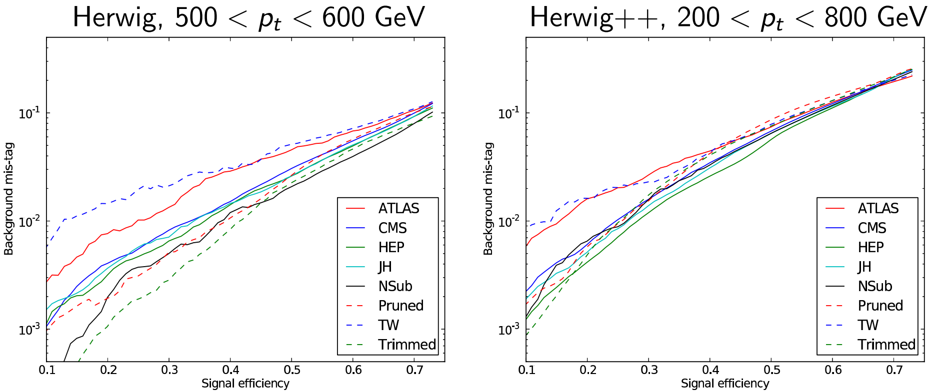
Handles for distinguishing signal v. background



	$g_{\to gg(g)}$	$q_{\to qg(g)}$	$g_{\to b\bar{b}}$	$H_{\to b\bar{b}}$	$t_{\to qq\bar{q}}$
softer prong z	soft	soft	hard	hard	hard
prong colour factors	$2\times C_A$	$C_F + C_A$	$2\times C_F$	$2\times C_F$	$3\times C_F$
system colour factor	C_A	C_F	C_A	0	C_F

Background-like ⟶ Signal-like

Comparing top taggers: QCD fakes rate v. signal eff.

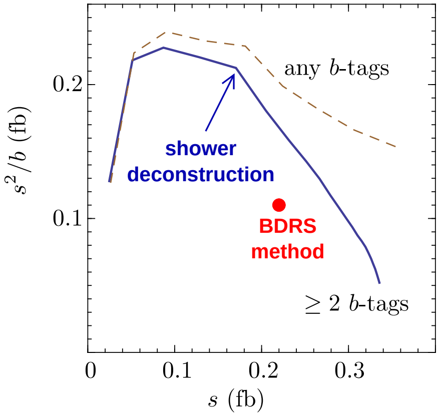


From the extensive "Boost 2011" report, which reviewed taggers discussed software, determined performance on MC, etc.

Bottom line: some taggers clearly better than others.
But many taggers behave similarly & details depend on analysis (+ MC choice)

Shower deconstruction for ZH

Matrix-element method on steroids



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

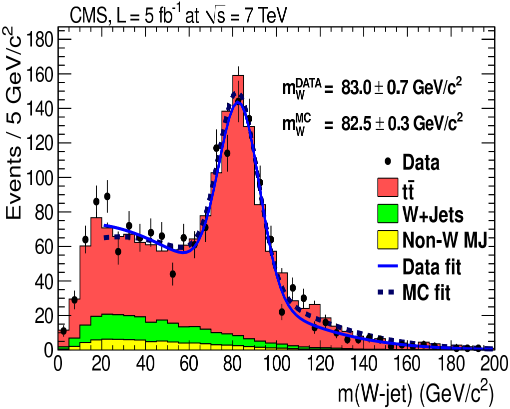
Break event into many mini-jets; use Monte-Carlo type Sudakovs and splitting functions to get estimate of multi-parton matrix element for S & B hypotheses.

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

Soper & Spannowsky '11

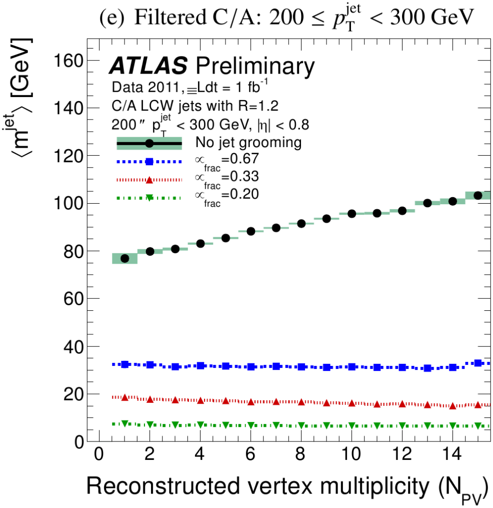
cf. also multivariate (BDT) type methods from Cui & Schwartz '10

Experimental validation
(two brief examples)



CMS single-jet W mass peak in events with a lepton and separate b-tagged jet.

Uses pruning (+ mass-drop condition on split jet)



ATLAS validation showing average MD-F (BDRS) jet mass as robust against pileup.

Trimming, with suitable parameters, is also robust.

NB: Pileup now 2× higher
Could get 4× worse?

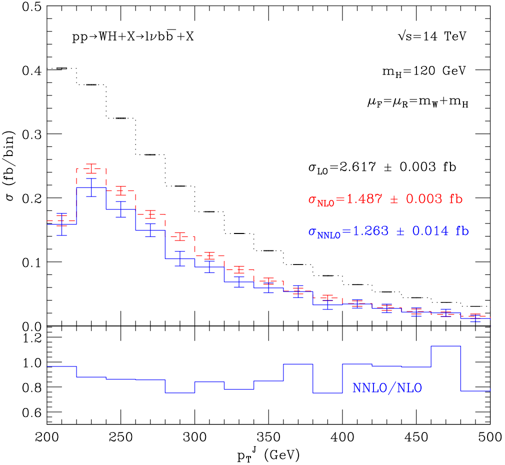
Further improvements maybe needed (and possible)

Calculations

(Just those for VH & for single-jet properties)

Fully differential WH @ NNLO

Ferrera, Grazzini & Tramontano '11



WH production with $H \to b\bar{b}$

Fat-jet pt distribution at

LO

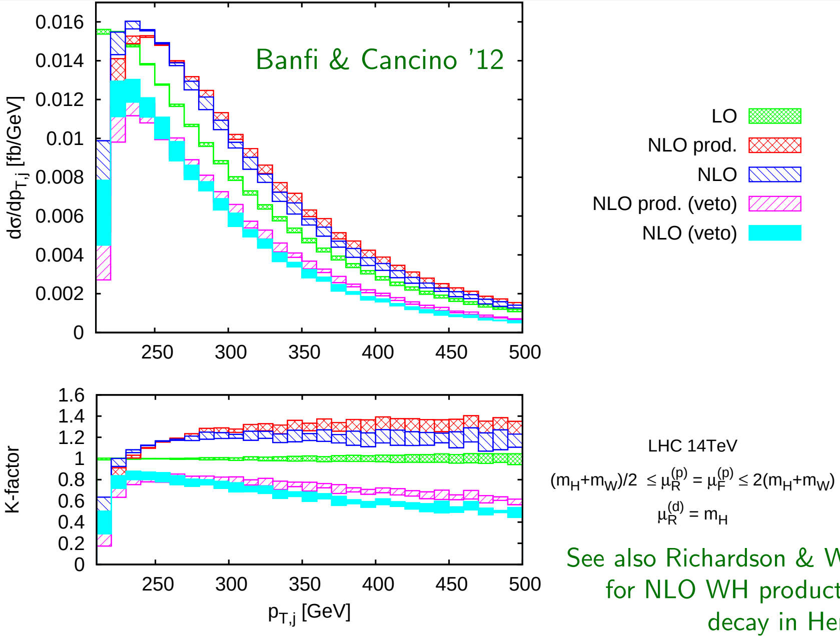
NLO

NNLO

shows good stability from NLO to NNLO

it's the top-killing jet veto that causes the K-factor to be < 1

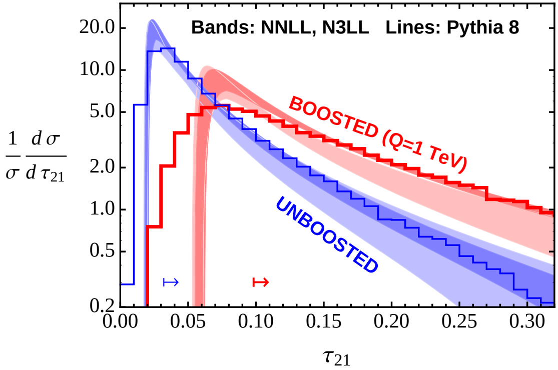
WH @ NLO in production and decays



See also Richardson & Winn '12 for NLO WH production and decay in Herwig++

Resummed subjettiness for boosted Z (just decay)

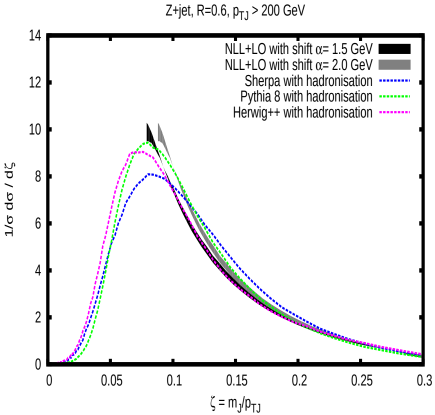
Distribution of τ_{21} subjettiness ratio



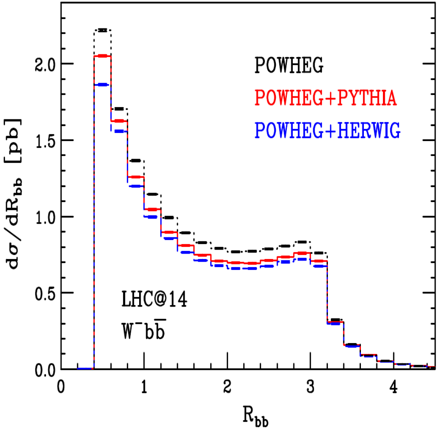
Feige, Schwartz, Stewart & Thaler '12 (adapted)

Precise resummed calculations for thrust $e^+e^- \to Z \to q\bar{q}$ can be carried over to hadronic boosted Z τ_{21} subjettiness ratio (because it's basically the same observable)

Calculations of backgrounds

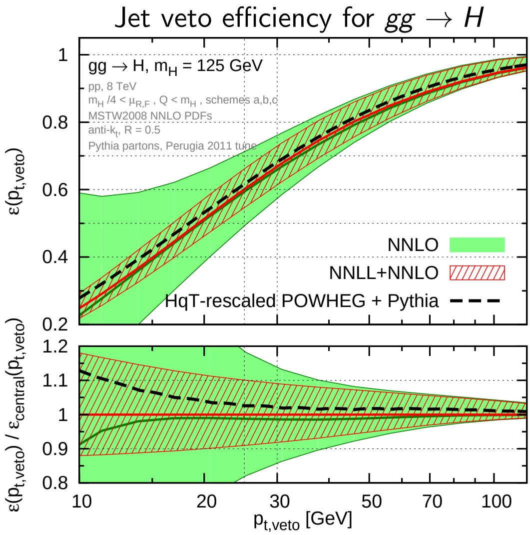


NLL+LO jet mass calculation
Dasgupta et al '12



$Wb\bar{b}$ background in POWHEG
Oleari & Reina '11

Long term aim? Concordance of different tools



Banfi, Monni, GPS & Zanderighi '12

cf. also Becher & Neubert '12

Illustrate with an example from standard $gg \to H$: jet veto efficiency, where various tools agree well:

pure NNLO

NNLL+NNLO jet-veto resummation

POWHEG reweighted with HqT NNLL+NNLO

Outlook

Outlook

The next two talks will probably not show fat jet $H \to b\bar{b}$ searches!

(a) they do use the boosted Higgs idea (i.e. high p_t), but lumi so far insufficiect to go to p_t's where fat-jet methods perform well.

(b) at intermediate p_t's "traditional" jet analyses can be adapted to mimic fat-jet searches.

Recent experimental validation has provided maturity needed for fat-jet methods to come "on-line" as higher luminosities are delivered to ATLAS and CMS.

Advanced theory tools not always as mature as for $gg \to H$, but developing rapidly.