Jets in Higgs Searches

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Jets play many roles in Higgs searches:

They may come from Higgs decay ($H \to b\bar{b}$)

They may help distinguish different Higgs-production mechanisms (VBF v. gluon-fusion)

They may help distinguish signal from background, e.g. jet bins in $H \to WW$ v. $t\bar{t} \to WWb\bar{b}$

Two main topics in this talk:

How well can we predict radiation/absence of jets in Higgs production?

What's the status of jet substructure tools?
[potentially relevant for $H \to b\bar{b}$]

0-jet bin
important for $gg \to H \to WW$

- 0-jet requirement suppresses $t\bar{t} \to WWb\bar{b}$ bkgd by $\sim$ factor 100
- To extract couplings, must know fraction of $gg \to H$ that survives veto

  i.e. has no significant ISR radiation
- But jet veto scale $\sim 25 - 30$ GeV $\ll m_H \longrightarrow$ large logarithms

  $$1 - 6\frac{\alpha_s}{\pi}\ln^2 M_H/p_{t,veto} + \dots$$

  cause problems for fixed-order perturbation theory

What are genuine uncertainties in fixed-order calculations?

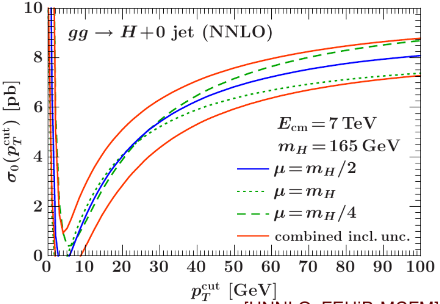
Total cross section series: $\sigma_{\text{tot}} \simeq \sigma_{\text{LO}}(1 + 10\alpha_s + 36\alpha_s^2 + \cdots)$
Vetoed cross section series: $\sigma_{\text{veto}} \simeq \sigma_{\text{LO}}(1 + 4\alpha_s + 8\alpha_s^2 + \cdots)$

Better-looking perturbative series gives spuriously low scale uncertainties

Stewart–Tackmann '11: write $\sigma_{\text{veto@NNLO}} = \sigma_{\text{tot@NNLO}} - \sigma_{\text{1-jet@NLO}}$
Treat uncertainties in total and 1-jet as uncorrelated.

New procedure. Is it overly conservative? Just right?

Higgs + 0 Jets



[HNNLO, FEHiP, MCFM]

Stewart & Tackmann '11

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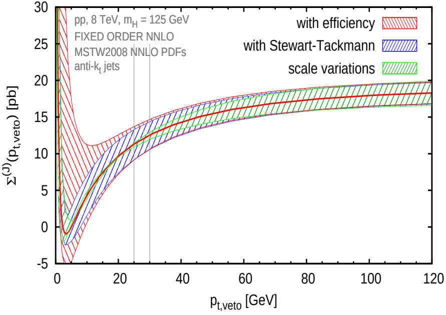


Banfi et al '12

Alternative view: two physical effects

- large K-factor in σ_{tot}
- Sudakov suppression (veto efficiency $= \epsilon = \sigma_{\text{veto}}/\sigma_{\text{tot}}$)

Treat veto efficiency and total cross-section uncertainties as uncorrelated.

Summing logs $\alpha_s^n \ln^{2n} m_H/p_{t,\text{veto}}$ had been perceived as a tough task for anything involving a standard pp jet algorithm, e.g. anti-k_t.

But answer was actually knowable at NLL (at least) since 2003, because jet-veto rate within scope of CAESAR

Computer Automated Expert Semi-Analytical Resummer
Banfi, GPS & Zanderighi '03–'05

NLL answer was remarkably simple: pure Sudakov form factor (no jets = no radiation)

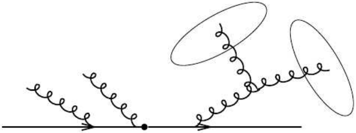
$$\text{veto efficiency } \epsilon(p_t) = \exp\left[\underbrace{L g_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \cdots\right] \qquad L \equiv \ln \frac{m_H}{p_t}$$

resummation functions g_1 and g_2 ≡
those inside Fourier Transform of Higgs p_t resum^n
Banfi, GPS & Zanderighi '12

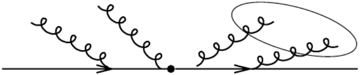
Resummation at NNLL

Story is almost the same at NNLL, i.e. pure Sudakov, plus quasi fixed-order correction

any number of emissions plus
1 gluon splits into two jets

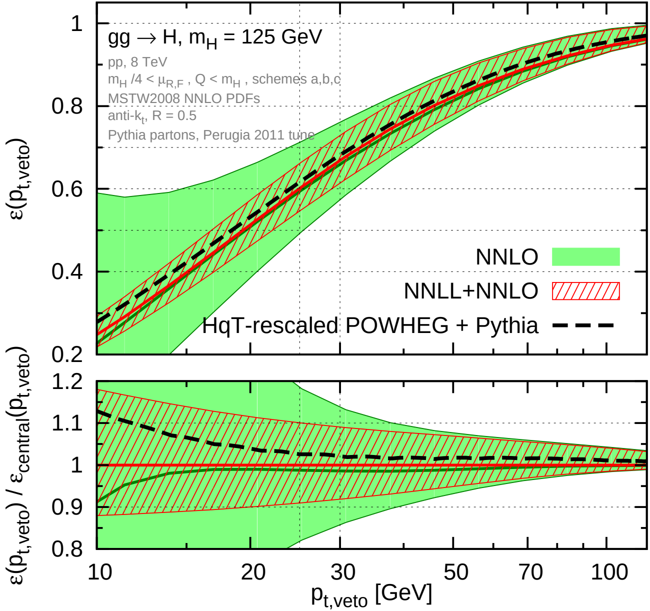


any number of emissions plus
2 gluons clustered into one jet



$$\epsilon(p_t) = \Big(1 + \underbrace{\alpha_s^2(p_{t,\text{veto}})L}_{\text{NNLL}}\Big)\, e^{\left[\underbrace{Lg_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{g_3(\alpha_s L)}_{\text{NNLL}} + \cdots\right]}$$

NNLL structure understood independently by
Banfi, GPS & Zanderighi + Monni (BMSZ) '12; Becher & Neubert '12
Full calculation: BMSZ '12; proposed structure beyond NNLL: BN '12
struct. beyond NNLL disputed by Tackmann, Walsh & Zuberi '12
Results build on Higgs p_t resum^n of Bozzi et al '03-, Becher & Neubert '10



NNLL+NNLO compared to NNLO and POWHEG+Pythia

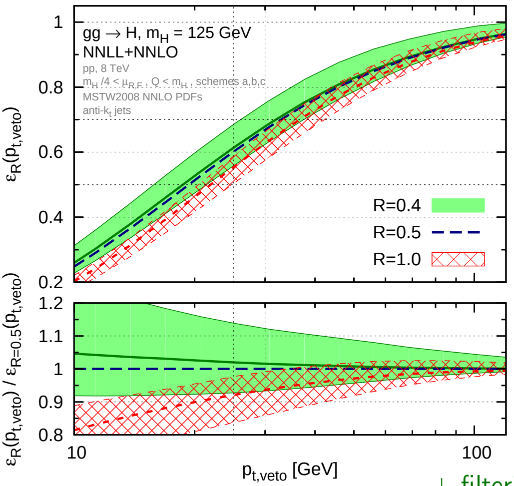
good agreement!

NNLL reduces uncertainties from $\sim 15\% \to \sim 9\%$

[0-jet / $\geq$ 1-jet correlations available too]

public code at

http://jetvheto.hepforge.org



There are all-order terms like $\alpha_s^{n+1} L \ln^n \frac{1}{R}$.

If R is too small these become large.

In practice, choosing $R \sim 1$ reduces uncertainties

Should we resum $\ln R$ terms?
Tackmann, Walsh & Zuberi '12

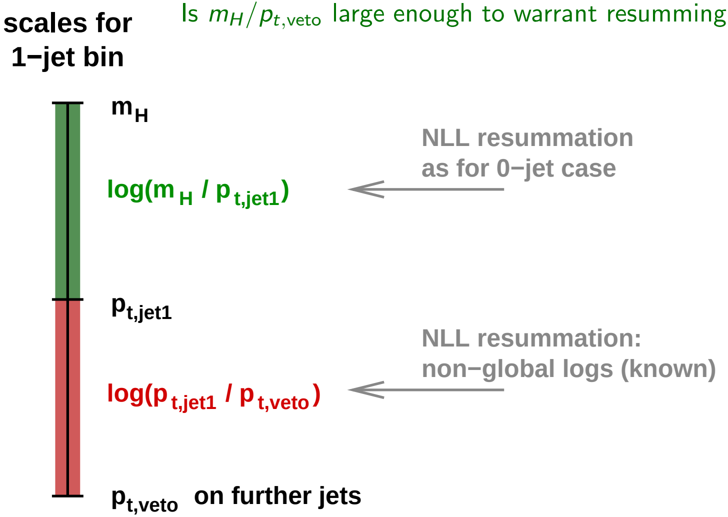
Should experiments switch to larger R for utmost accuracy?

+ filtering to control UE/pileup dependence

(exactly) 1-jet bin

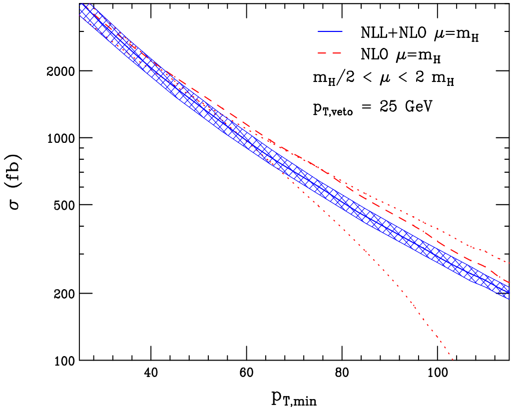
NLL is within easy reach for (exclusive) 1-jet bin

"easy" means no conceptual issues or new ingredients;
assembling known ingredients correctly still involves (tedious) work
Is $m_H/p_{t,\text{veto}}$ large enough to warrant resumming two sets of logs?



Liu & Petriello '12

exclusive 1-jet rate v. $p_{t,min}$ for jet 1



- Resums just $\ln p_{t,jet1}/p_{t,\text{veto}}$
- "poor-man's NLL" rather full NLL

  $\alpha_s^n L^{2n} + \alpha_s^n L^{2n-1}$ instead of

  $\exp(\alpha_s^n L^{n+1} + \alpha_s^n L^n)$

  no non-global logs

  e.g. full NNLL+NNLO

  $\sim$ poor-man's N^{4}LL
- A first step towards understanding 1-jet bin

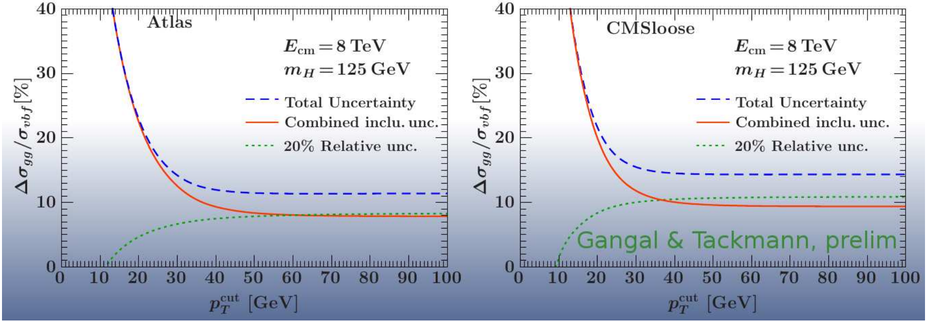
gluon fusion as “background” to VBF 2-jet selection

[NB: see also the NLO MC talk, with much recent progress from aMC@NLO, POWHEG and Sherpa]

Does a 3rd-jet veto help disentangle VBF and gluon-fusion?

Normal wisdom says use of a jet veto reduces gluon-fusion "background".

But (at least in fixed order), it may increase uncertainty on how much gluon-fusion you have.



Preliminary conclusion shown by Gangal & Tackmann: a 3rd (central?) jet veto does not help.

Really? An artefact of ST? (Uncertainty never lower than for inclusive selection)

Would conclusion change with different prescription, resummation?

Related dijet resummations: Forshaw, Seymour & collaborators

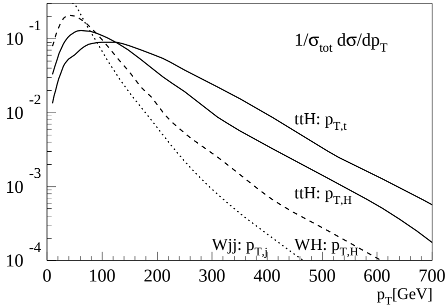
Jets from [boosted] Higgs decays

Seeing the $\sim 58\%$ BR of $H \to b\bar{b}$ in VH and $t\bar{t}H$

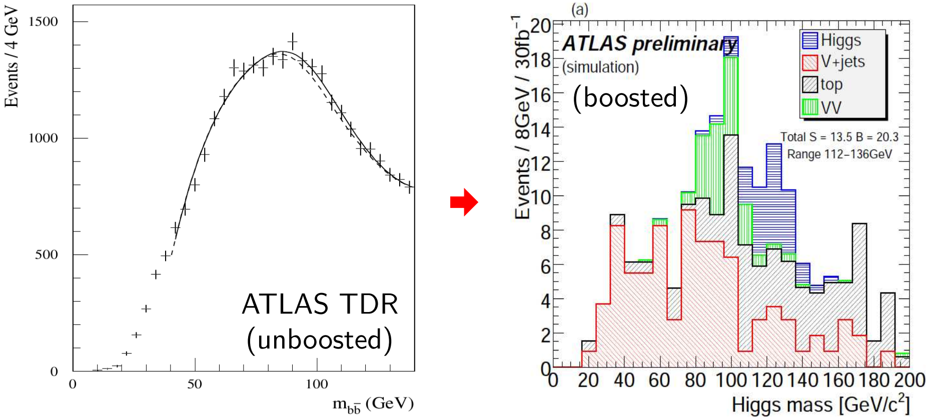
Hadronic decays of new EW-scale particles may be *easier* to see at high p_t

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

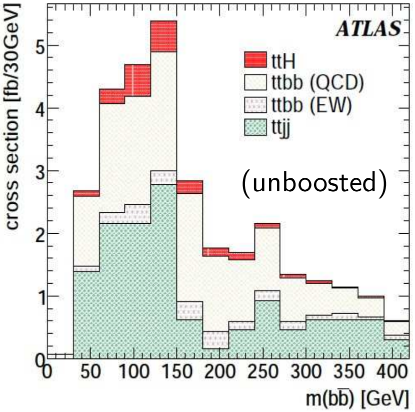


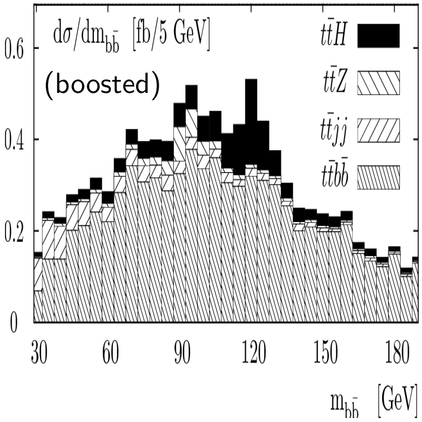
Search for main decay of light Higgs boson in W/Z+H, $H \to b\bar{b}$



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

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

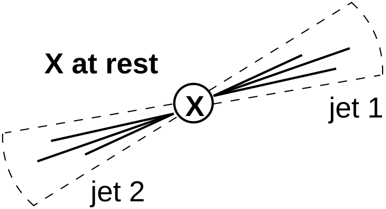




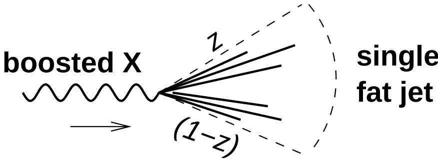
restricting search to $p_{t,H} > 200$ GeV, $p_{t,t\to\text{hadrons}} > 200$ GeV, one leptonic top

Plehn, GPS & Spannowsky '09

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



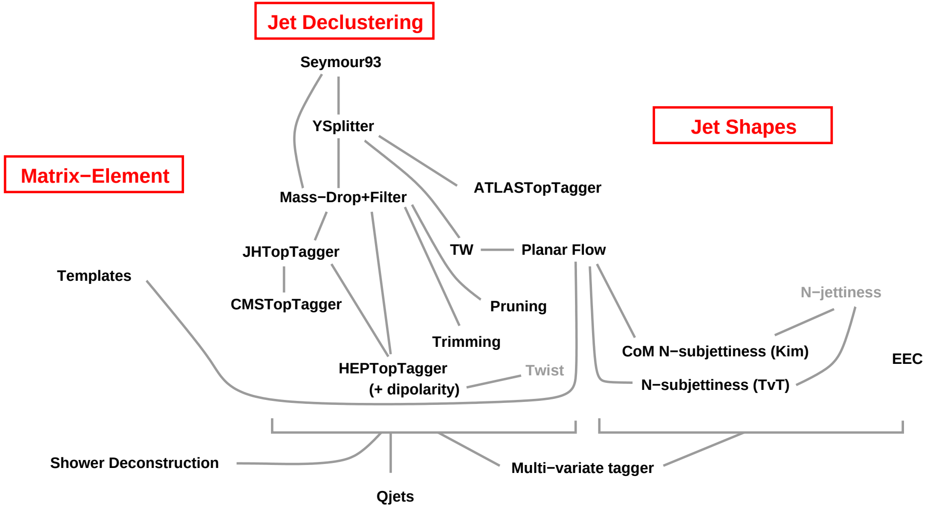
High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



Happens for $p_t \gtrsim 2m/R$

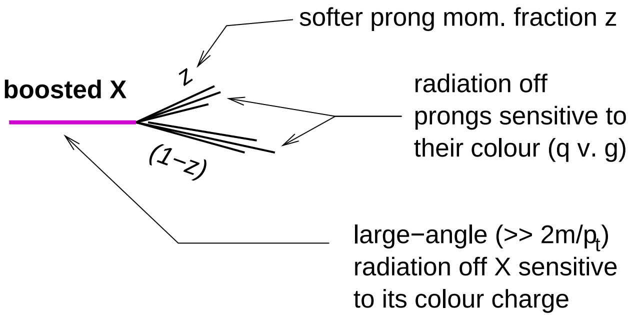
$p_t \gtrsim 320$ GeV for $m = m_W$, $R = 0.5$

Some taggers and jet-substructure observables



apologies for omitted taggers, arguable links, etc.

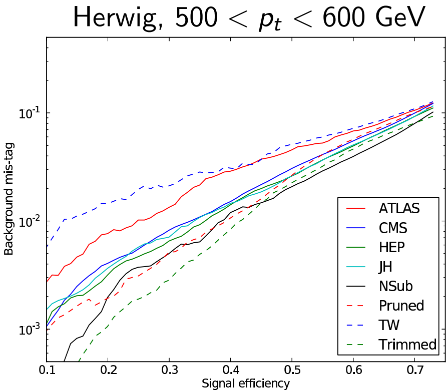
[NB: many of the tools available in FastJet & SpartyJet]

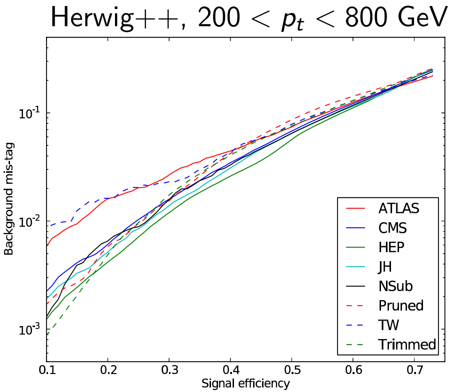


	$g_{\to gg(g)}$	$q_{\to qg(g)}$	$g_{\to b\bar{b}}$	$H_{\to b\bar{b}}$	$t_{\to qq\bar{q}}$
softer prong z	soft	soft	hard	hard	hard
prong colour factors	$2\times C_A$	$C_F + C_A$	$2\times C_F$	$2\times C_F$	$3\times C_F$
system colour factor	C_A	C_F	C_A	0	C_F

Background-like — Signal-like

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

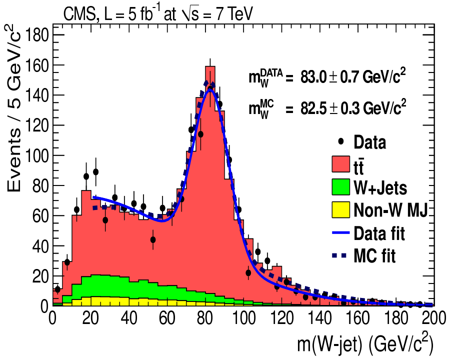




From the extensive "Boost 2011" report, which reviewed taggers discussed software, determined performance on MC, etc.

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

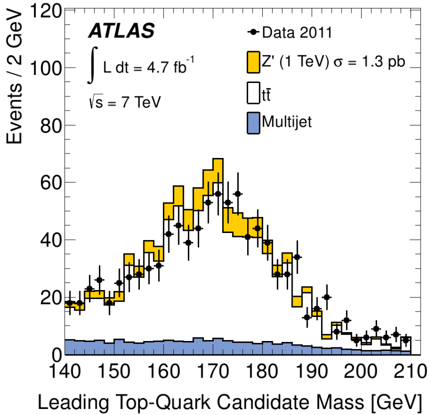
W's in a single jet



with Pruning + Mass Drop requirement

NB: combined in IR unsafe way...

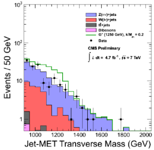
tops in a single jet



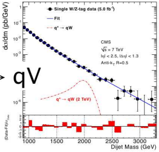
with HEPTopTagger

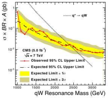
Some BSM searches with jet-substructure techniques

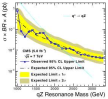
$X \to ZZ \to 2\nu 2q$

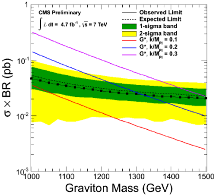


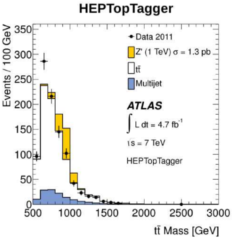
$X \to qV$

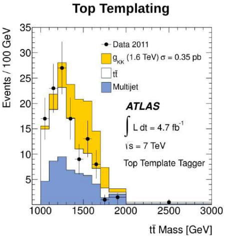




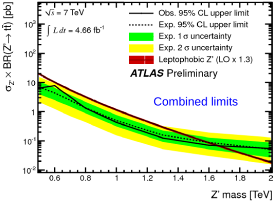






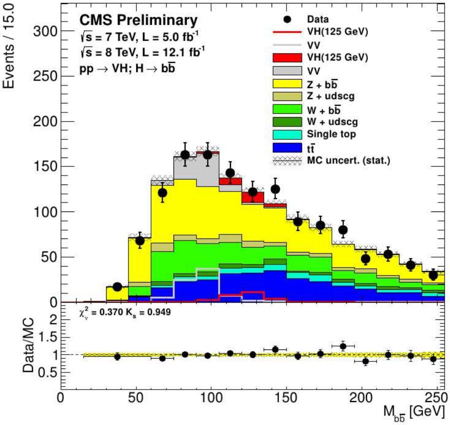


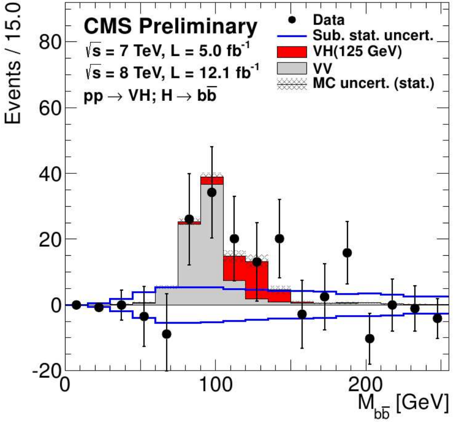
ATLAS-CONF-2012-136

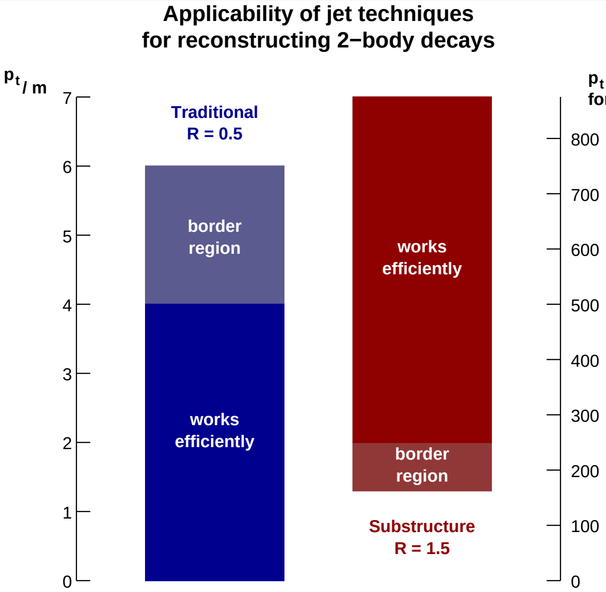


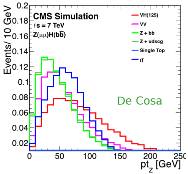
A range of techniques being used for varied BSM scenarios

ATLAS and CMS $H \to b\bar{b}$ are high-p_t, but 2-jet based





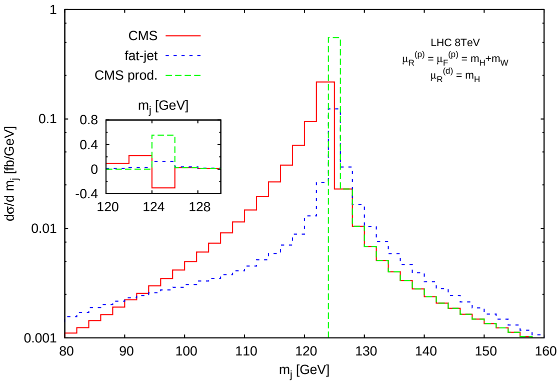




NB: in overlap region, substructure techniques may sculpt less, help with combinatorics, improve resolution etc.

Suitable tricks with traditional methods can (maybe) make them behave like substructure techniques.

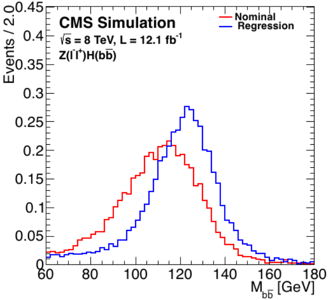
WH@NLO in production and decay: fat-jet and CMS 2-jet analyses



Banfi & Cancino '12

fat-jet: better mass resol^n
2-jet: larger σ (lower p_t)

CMS: $m_{b\bar{b}}$ regression improves resolution too



What physics does it exploit? Does it have interplay with jet vetoes?

Impact on prospects for accurate theoretical prodictions?

Other calculations in or applicable to boosted regime

- WH at NNLO — Ferrera, Grazzini & Tramontano '11
- $H \to b\bar{b}$ decay at NNLO — Anastasiou et al '11
- subjettiness τ_{21} @ N^{3}LL for 2-body decays — Feige et al '12
- jet mass distributions — Dasgupta et al '12, Chien et al '12, Stewart et al '12
- NLL p_t resummation for WH system — Dawson et at '12
- Arguments about resummability of various substructure observables — Walsh & Zuberi '12
- New pileup subtraction techniques for shapes [and IR unsafety of τ_{32} unless also have τ_{12} cut] — Soyez et al '12

Expect yet more to appear in near future!

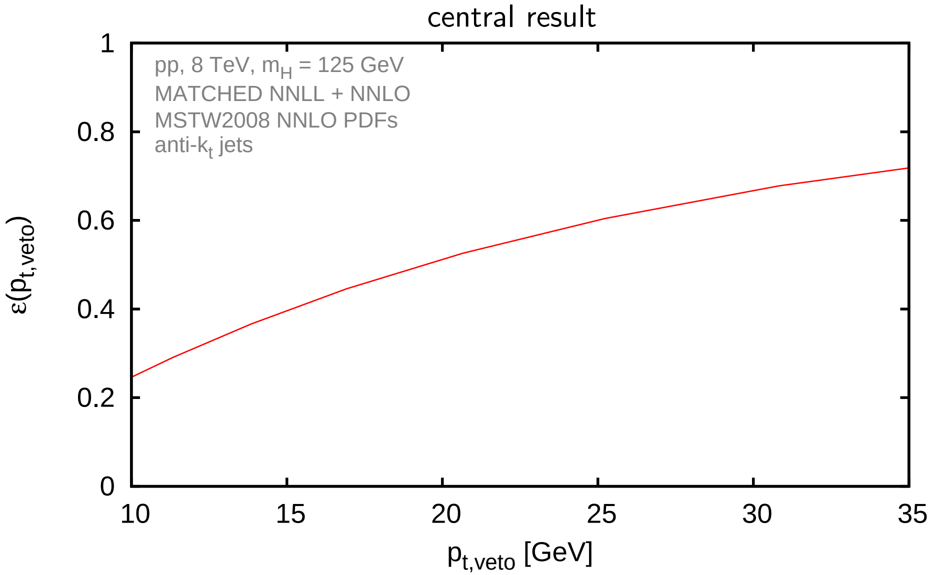
Significant progress in analytical calculations with jets:
NNLL resummation is now possible for jet vetoes
Should help open road to various other results

Fat jets are going mainstream
Many theoretical ideas for how to use jet substructure
Increasing range of exp. validation and use in searches
Calculations following too

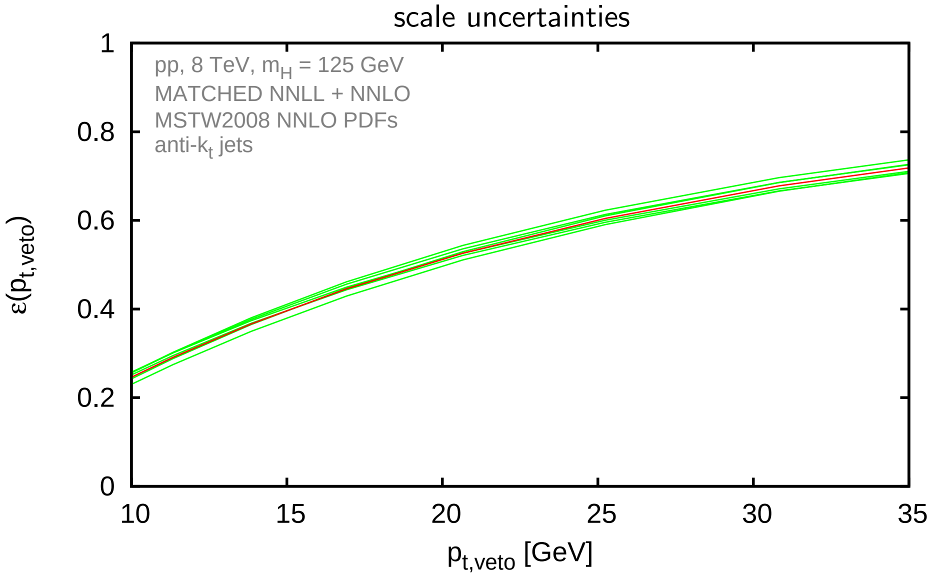
Boost exploited in $H \to b\bar{b}$ searches, but not yet fat jets
We still need understanding of tradeoffs,
also with view to 14 TeV running?

EXTRAS

Different uncertainty contributions at NNLO + NNLL



Different uncertainty contributions at NNLO + NNLL



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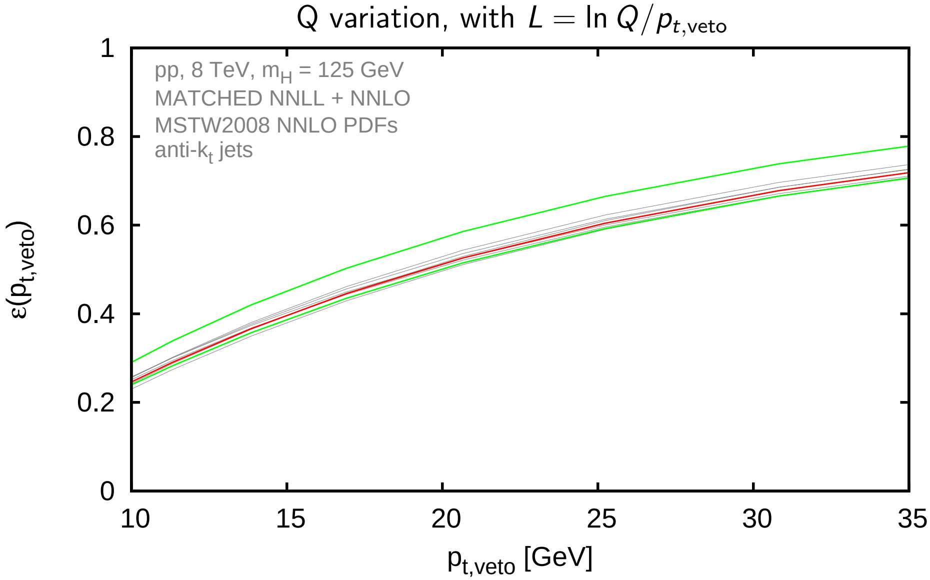

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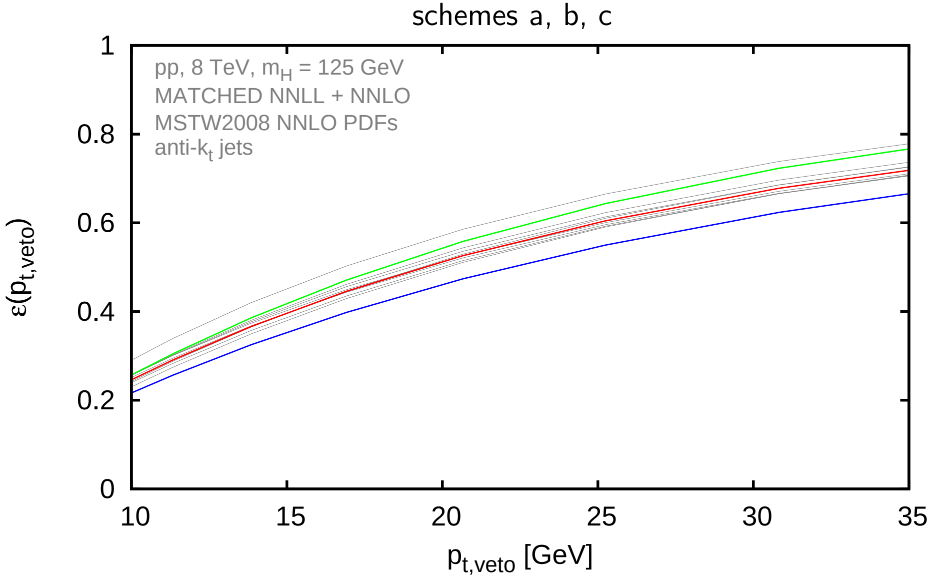
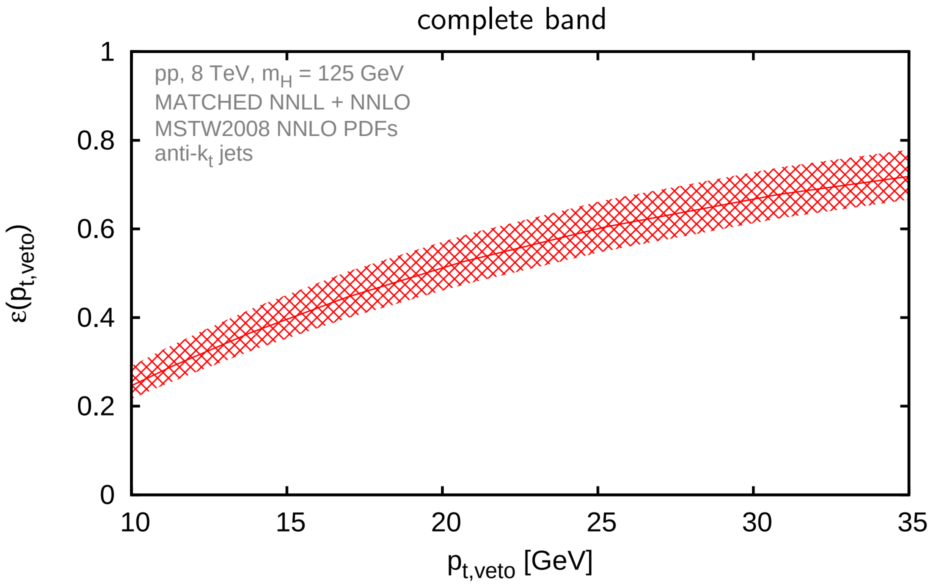


Different uncertainty contributions at NNLO + NNLL



There are two widely-used definitions of "NLL", "NNLL", etc.:

[+ minor variants]

- "poor-man's": $\Sigma = \sum_n \underbrace{\alpha_s^n L^{2n}}_{\text{LL}} + \underbrace{\alpha_s^n L^{2n-1}}_{\text{NLL}} + \underbrace{\alpha_s^n L^{2n-2}}_{\text{NNLL}} + \cdots$

  for $L \sim 1/\sqrt{\alpha_s}$, N^{p}LL uncertainty is $\mathcal{O}\left(\alpha_s^{(p+1)/2}\right)$

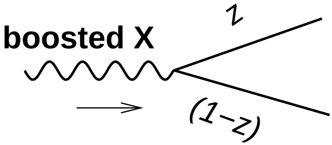
- "full": $\Sigma = \exp\left[\sum_n \underbrace{\alpha_s^n L^{n+1}}_{\text{LL}} + \underbrace{\alpha_s^n L^{n}}_{\text{NLL}} + \underbrace{\alpha_s^n L^{n-1}}_{\text{NNLL}} + \cdots\right]$

  for $L \sim 1/\alpha_s$, N^{p}LL uncertainty is $\mathcal{O}\left(\alpha_s^p\right)$

As an example, "full" NNLL (+ NNLO) $\sim$ poor-man's N^{4}LL

QCD principle: soft divergence

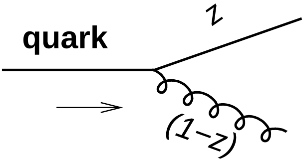
Signal



Splitting probability for Higgs:

$$P(z) \propto 1$$

Background



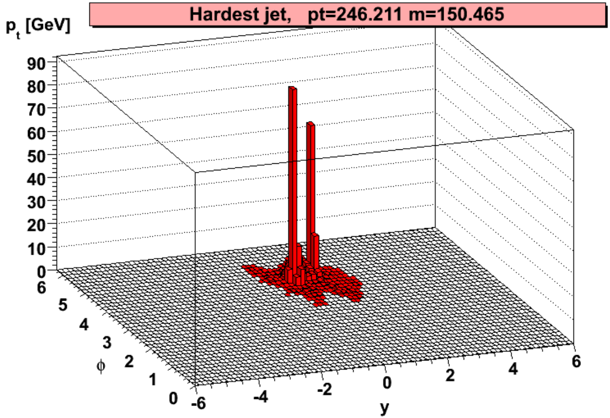
Splitting probability for quark:

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

$1/(1-z)$ 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)

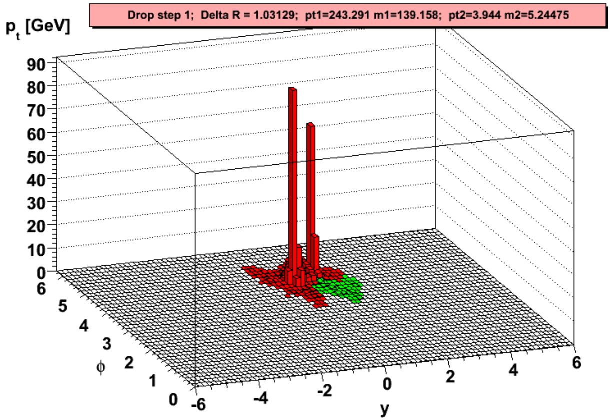


First proposed for W's by Seymour '93

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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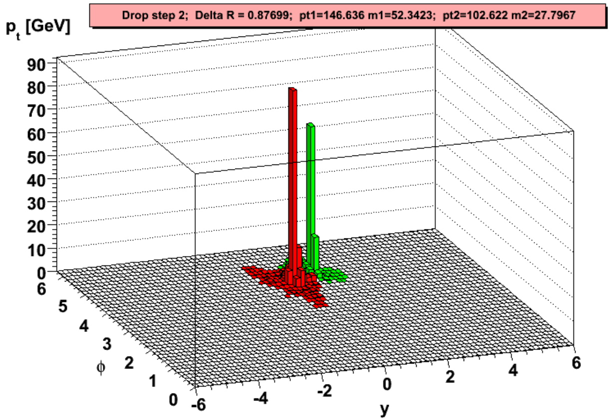

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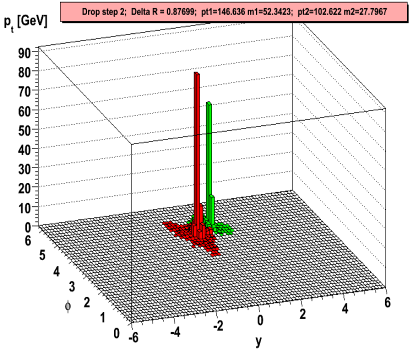
Noise removal from jets — a boosted top example



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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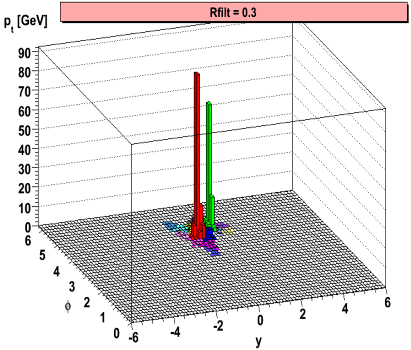

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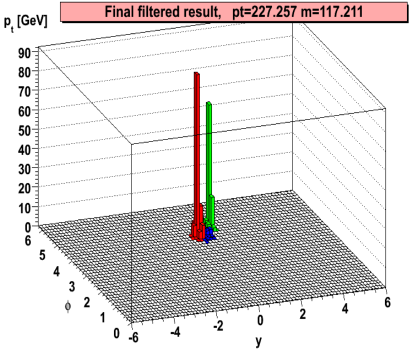

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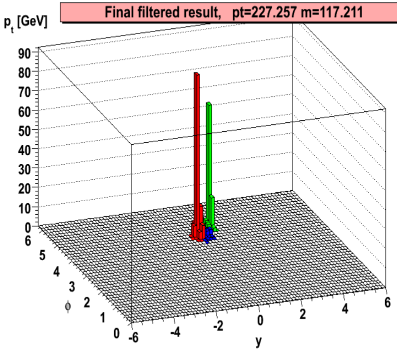

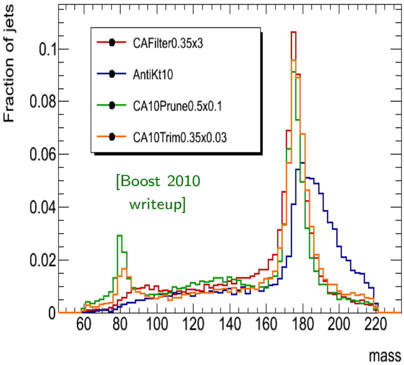

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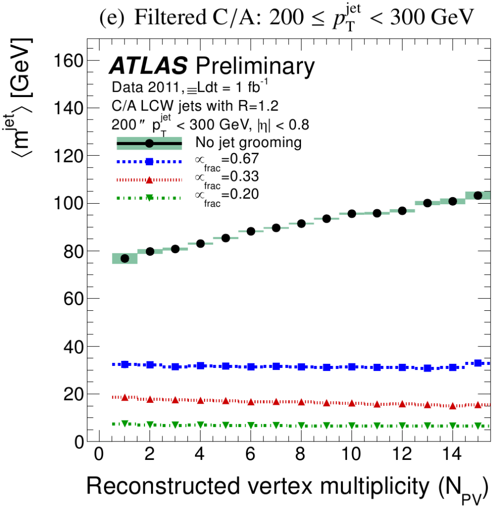


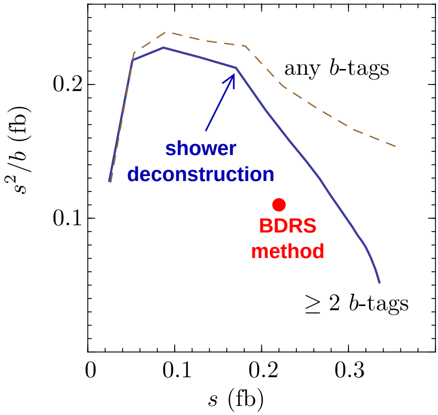
ATLAS validation showing average MD-F (BDRS) jet mass as robust against pileup.

Trimming, with suitable parameters, is also robust.

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

Further improvements maybe needed (and possible)

Matrix-element method on steroids



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

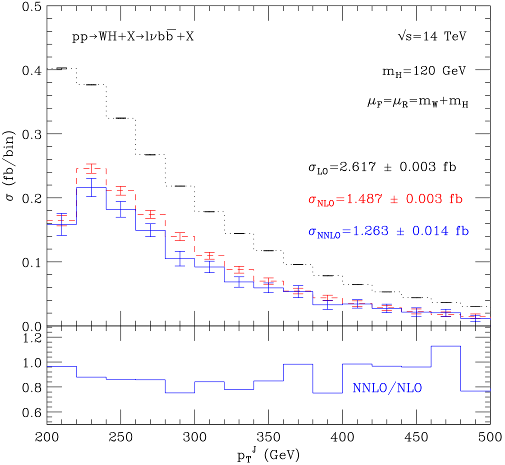
Break event into many mini-jets; use Monte-Carlo type Sudakovs and splitting functions to get estimate of multi-parton matrix element for S & B hypotheses.

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

Soper & Spannowsky '11

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

Ferrera, Grazzini & Tramontano '11



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

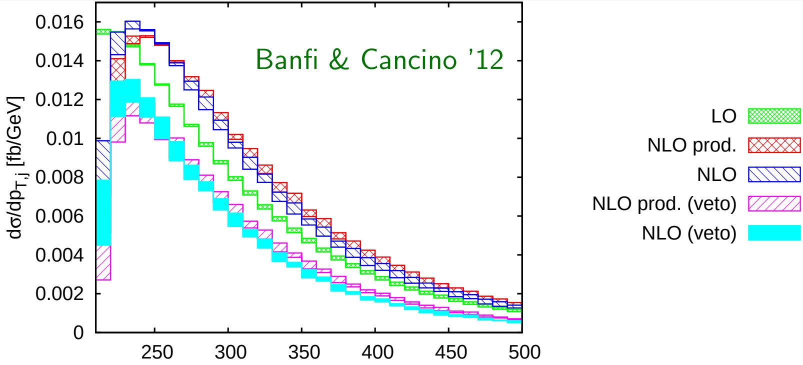
Fat-jet pt distribution at

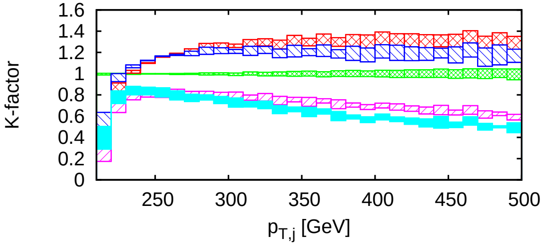
LO
NLO
NNLO

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





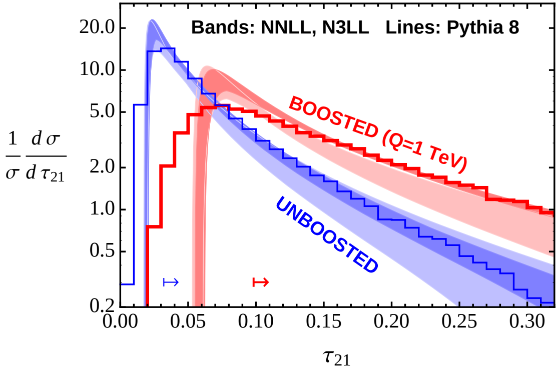
LHC 14TeV

$(m_H+m_W)/2 \le \mu_R^{(p)} = \mu_F^{(p)} \le 2(m_H+m_W)$

$\mu_R^{(d)} = m_H$

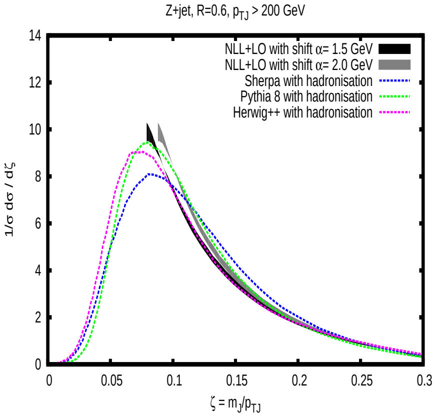
See also Richardson & Winn '12 for NLO WH production and decay in Herwig++

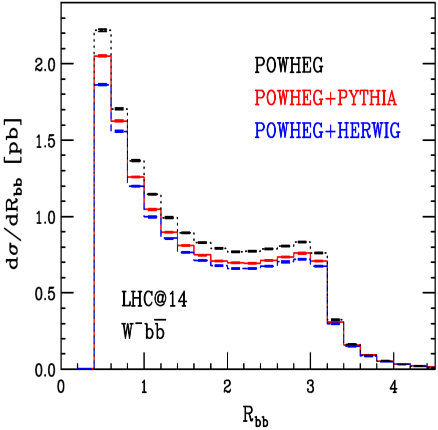
Distribution of τ_{21} subjettiness ratio



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)





NLL+LO jet mass calculation
Dasgupta et al '12

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