Superboosted Jets

(Challenges and opportunities for jet substructure in the superboosted regime)

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Bressler, Flacke, Kats, Lee & GP (15)

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Prologue: on the future of energy frontier

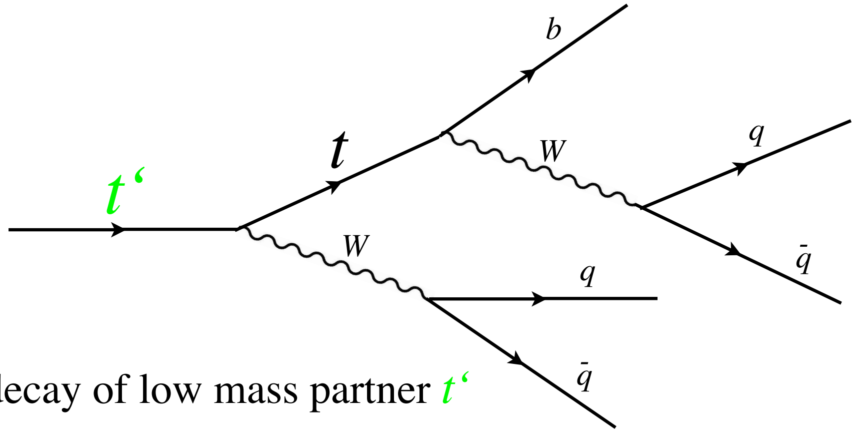
- Energy frontier @ colliders => looking for standard model (SM) particles with large momenta.

- Searches @ energy frontier => many cases final states involve SM heavy particles, $t/W/Z/h$, with very large momenta.

A (trivial) example

- The challenge of searching for heavy resonance top-partners:

As $m_{t'} \gg m_{t,W,Z,h}$ outgoing tops/EW are ultra-relativistic, their products collimate => t,W,Z,h-jets.

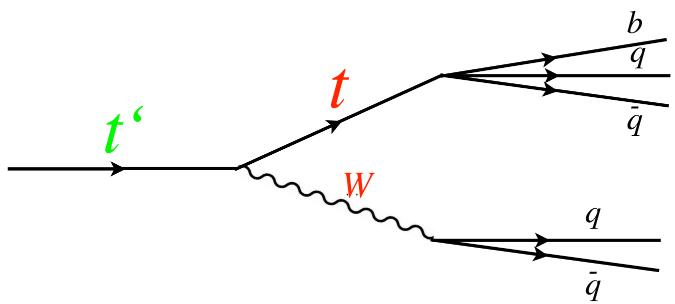


decay of low mass partner t'

Boosted tops/EW bosons: $m_{t'} \gg m_{t,W,Z,h}$

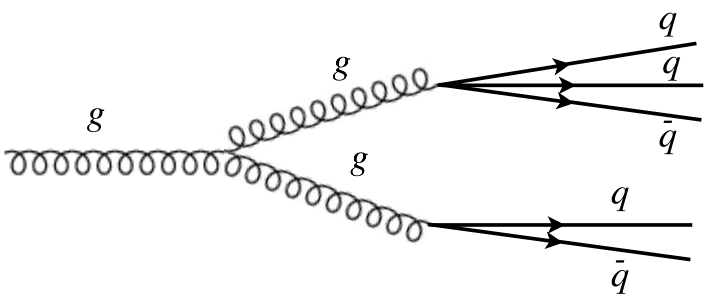
- The challenge of searching for heavy resonance top-partners:

As $m_{t'} \gg m_{t,W,Z,h}$ outgoing tops/EW are ultra-relativistic, their products collimate => t,W,Z,h-jets.



decay of heavy partner t'

Similar to ordinary 2-jet QCD process hard to observe



Bottom-up: direct tests of naturalness

- So far only tested directly to O(1:10^1).
  What is required to establish tuning of $> 1:10^3$?

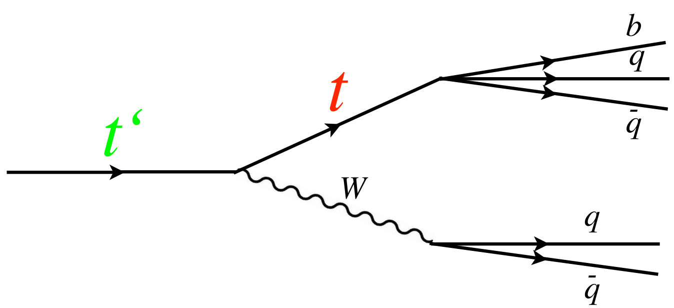
  $m_{t'}, f > O(10)$ TeV

  $m_{Z'} > O(50)$ TeV

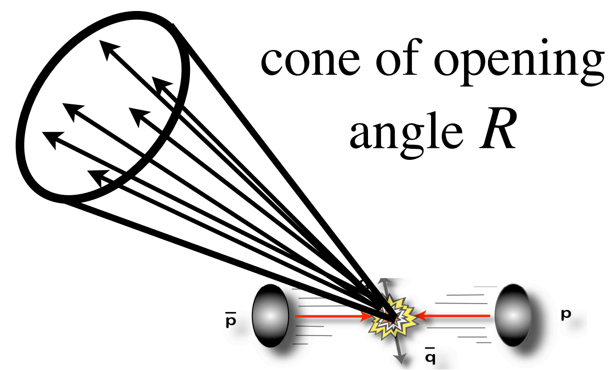
- Heavy new states => large boost for SM ones.
  So what?

Characteristic scale of jets? opening angle?

As $m_{t'} \gg m_{t/W/Z/h}$ outgoing objects are ultra-relativistic, their products collimate => $t/W/Z/h$ jets.



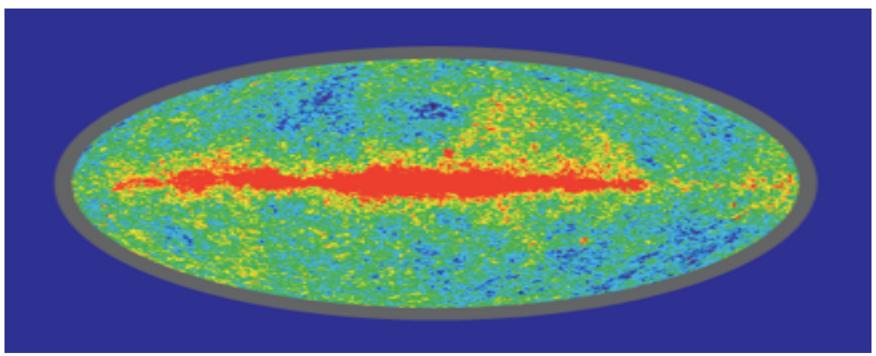
decay of heavy partner t'

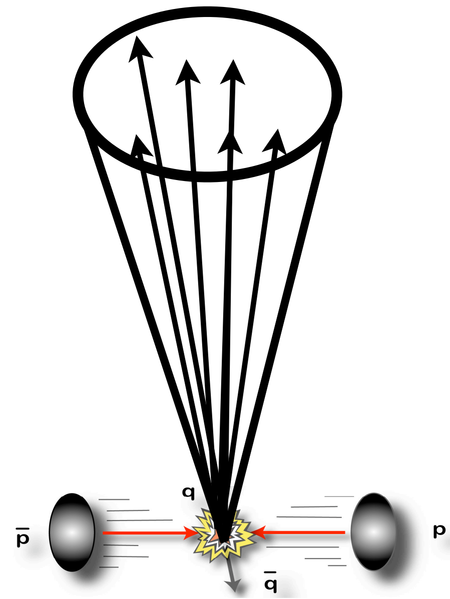


$$\delta R \sim \frac{2m_X}{E_{J_X}}$$

The opening angle of 10 TeV $t/W/Z/h$ is O(1%)

Can we survive doing more of the same?
(using known jet substructure tools)





Outline

- Hadronic shower size, the superboosted regime.

- Implications for neutraless jet substructure.

- (2) Opportunities: flavor dependence E mismatches; when $W/Z/h$ become the new τ.

- Outlook.

Hadronic shower size

- Simplicity: focus below on color neutral $W/Z/h$ - jets. (boost invariant)

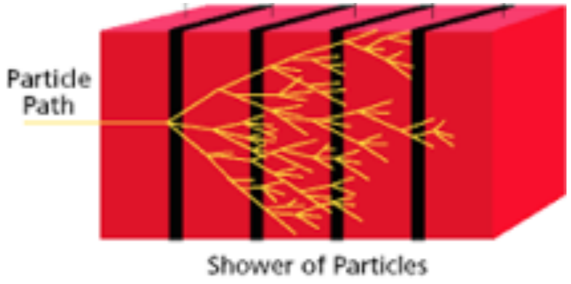
- Hadronicaly decaying $W/Z/h$ - jets produce energetic hadrons:

  For W jet with $p_T \sim 3$ (10) TeV -

  2 leading hadrons energies = 1.2 (2.7), 0.7 (1.5) TeV;

  2 leading "stable"-neutrals energies = 0.6 (1.3), 0.2 (0.5) TeV.

- Hadronic calorimeter is built to contain all hadrons produced.



Pheno' of hadronic shower size

- Long. & trans. size of average/fluctuation shower sizes is:

$$L_{95\%} \approx (6.2 + 0.8\ln(E/100\ \mathrm{GeV}))\,\lambda_A\,; \quad T_{95\%} \approx \lambda_A$$

$L_{95\%}$ / $T_{95\%}$: depth/breadth within 95% of hadronic cascade-E deposited.

λ_A: nuclear interaction length.

$\lambda_A \approx$ 10,11,15,17,17,40 cm for tungsten, uranium, copper, iron, lead & aluminum;

(with typical lengths, in ATLAS , CMS & future cal [CALICE] being 20–30 cm)

Leroy & Rancoita (00); Fabjan & Gianotti (03); Akchurin & Wigmans (08); CALICE Col., Adloff et al. (13)

Finite resolution

(typical lengths, in ATLAS , CMS & future cal [CALICE] being 20–30 cm)

- Smaller scales cannot be resolved in the hadronic cal. (HCAL)!

- For any given detector exists minimal angular scale:

$$\theta_{\mathrm{had}} \approx \frac{d_{\mathrm{had}}}{r_{\mathrm{HCAL}}} \approx 0.1 \times \frac{\lambda_{\mathrm{HCAL}}}{20\,\mathrm{cm}} \times \frac{2\,\mathrm{m}}{r_{\mathrm{HCAL}}}$$

(muon-cal+magnets => hard to imagine r_{HCAL} > 1-2 meters)

The superboosted regime

♦ Superboosted jets: ultra energetic jets where perturbative substructure cannot be probed within the HCAL:

$$\delta R_{\rm superboost} \sim \frac{2m_{W,Z,H,t}}{p_T} \lesssim \theta_{\rm had} \sim 0.1$$

$$p_T{}^{W,Z,H,t}_{\rm superboosted} \gtrsim 1.6, 1.8, 2.5, 3.4\,{\rm TeV}$$

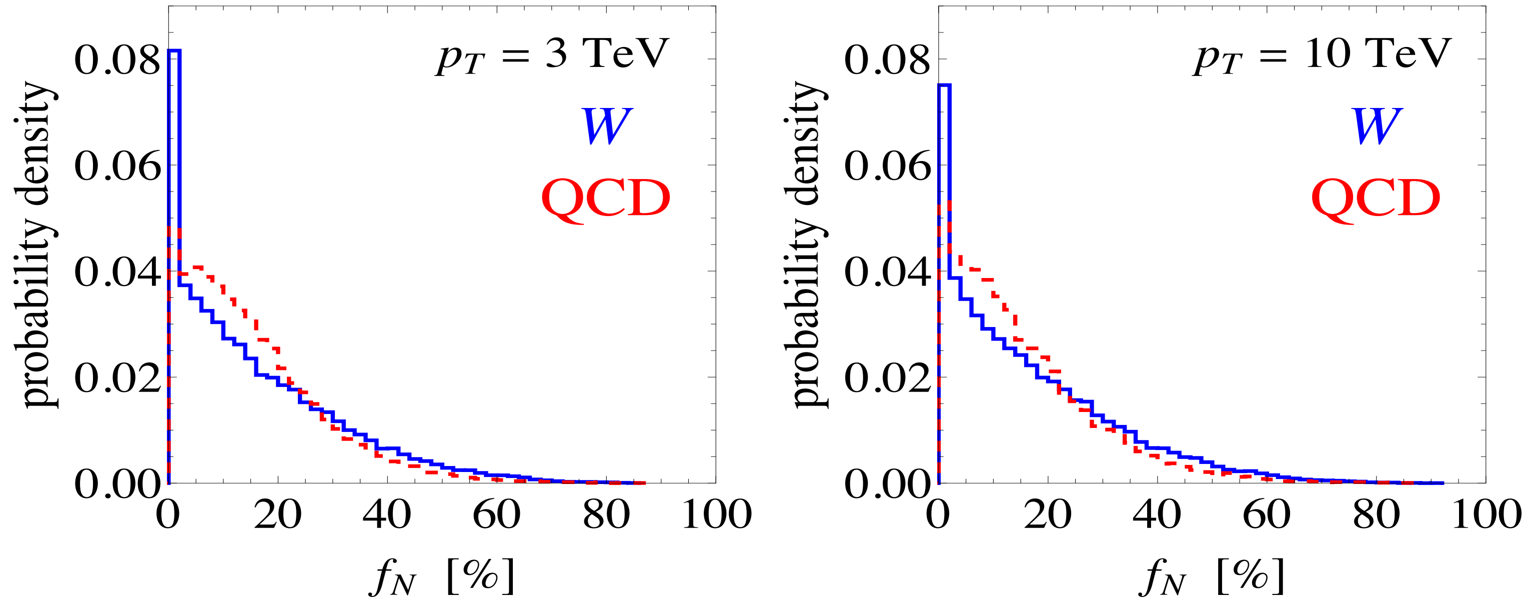
Neutraless jet substructure

- Superboosted jet substructure, who cares?
  Can probe jet inner energy deposition via tracker + EM Cal.

  Katz, Son & Tweedie (10); Son, Spethmann & Tweedie (12); Schaetzel & Spannowsky; Chang, Procura, Thaler & Waalewijn x2 (13); Larkoski, Maltoni & Selvaggi; Spannowsky & Stoll (15)

- Neutral-“stable” hadrons not visible to tracker + EM Cal.
  Separate momenta of $K_{L,S}, n \ldots$ is inaccessible.

  Bressler, Flacke, Kats, Lee & GP (15)



Stable neutrals, Ave & RMS *E*-fraction [%]: $\langle f_N^{W,\mathrm{QCD}} \rangle_{pT=3\,(10)\,\mathrm{TeV}} = 16, 15\,(17, 15)\,,\ \delta f_N^{W,\mathrm{QCD}} = 15, 13\,(15, 13)\,.$

Neutraless jet substructure

Bressler, Flacke, Kats, Lee & GP (15)

mean (RMS) *E*-fraction of stable particles [%] : $\langle f_N^{W,\mathrm{QCD}} \rangle = 16, 15\,(17, 15)\,,\ \delta f_N^{W,\mathrm{QCD}} = 15, 13\,(15, 13)\,.$

⇓

- Tracker+ECAL capture roughly 85% ± 15% of actual jet energy.
- Subjet-neutrals fluctuate indep': $R_{\mathrm{subjet}} = (3/4)\, m_W/p_T$, 40% larger.
- Who cares? Let's correct the jet globally.

Global vs. local jet corrections

♦ Can apply rescaling to correct for the missing neutral component based on total jet-E, measured in the HCAL.

JES: $\sigma(E_J)/E_J \approx 1.0/E_J/\mathrm{GeV} \oplus 0.05$, for E_J 50 GeV associated fluctuations < 15%.

♦ As neutral component fluctuate indep' not expected to work.

Consider a simple ex., jet mass, in the 2-prong approximation:

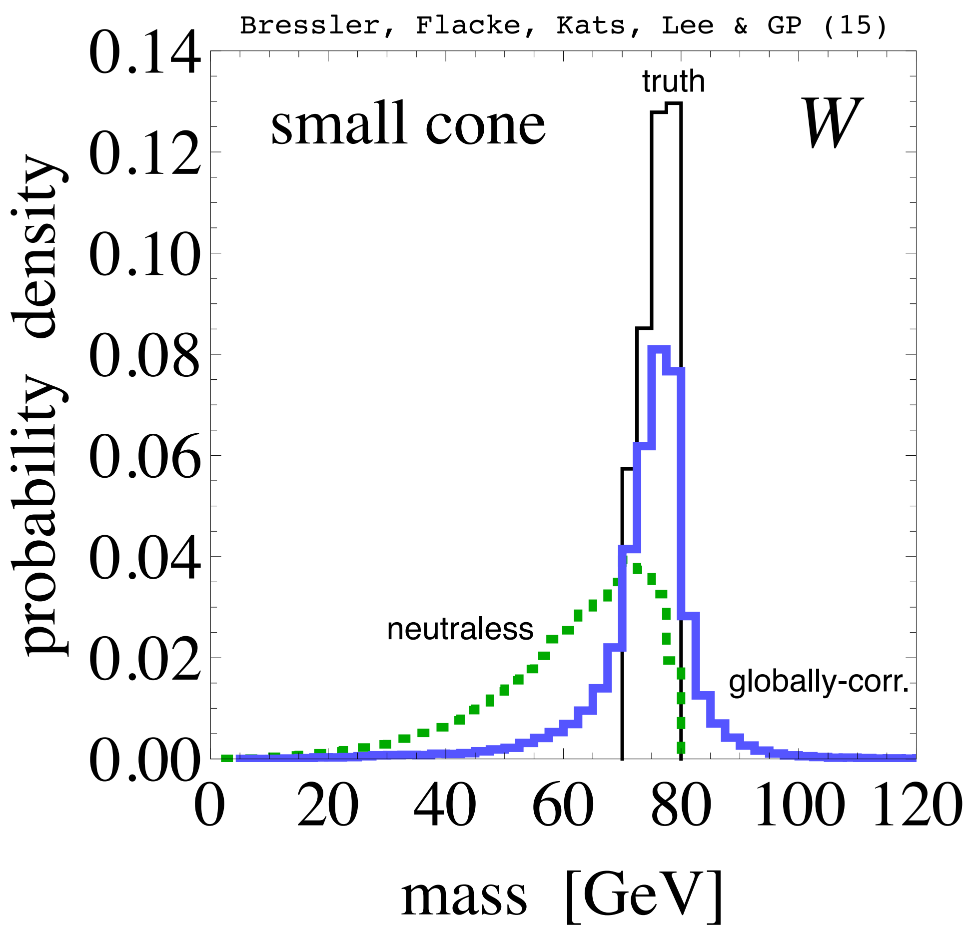
$$m_{12}^2 = E_1 E_2 \theta_{12}^2 \,, \quad z = E_2/E_{12} \leq \tfrac{1}{2}.$$

Without the HCAL: $m_{12,\not{N}}^2 = (1 - f_N^1)(1 - f_N^2)\, m_{12}^2$

$\not{N}$ = omitted neutrals; f_N^i = neutral fraction within ith subjet.

Global vs. local & the jet mass

- Global correction: $m_{12,\mathrm{corr}} = \frac{\sum_i E_i}{\sum_i \left(1 - f_N^i\right) E_i}\, m_{12,\not{N}}\,,$



As expected, fluct. size, not reduced:

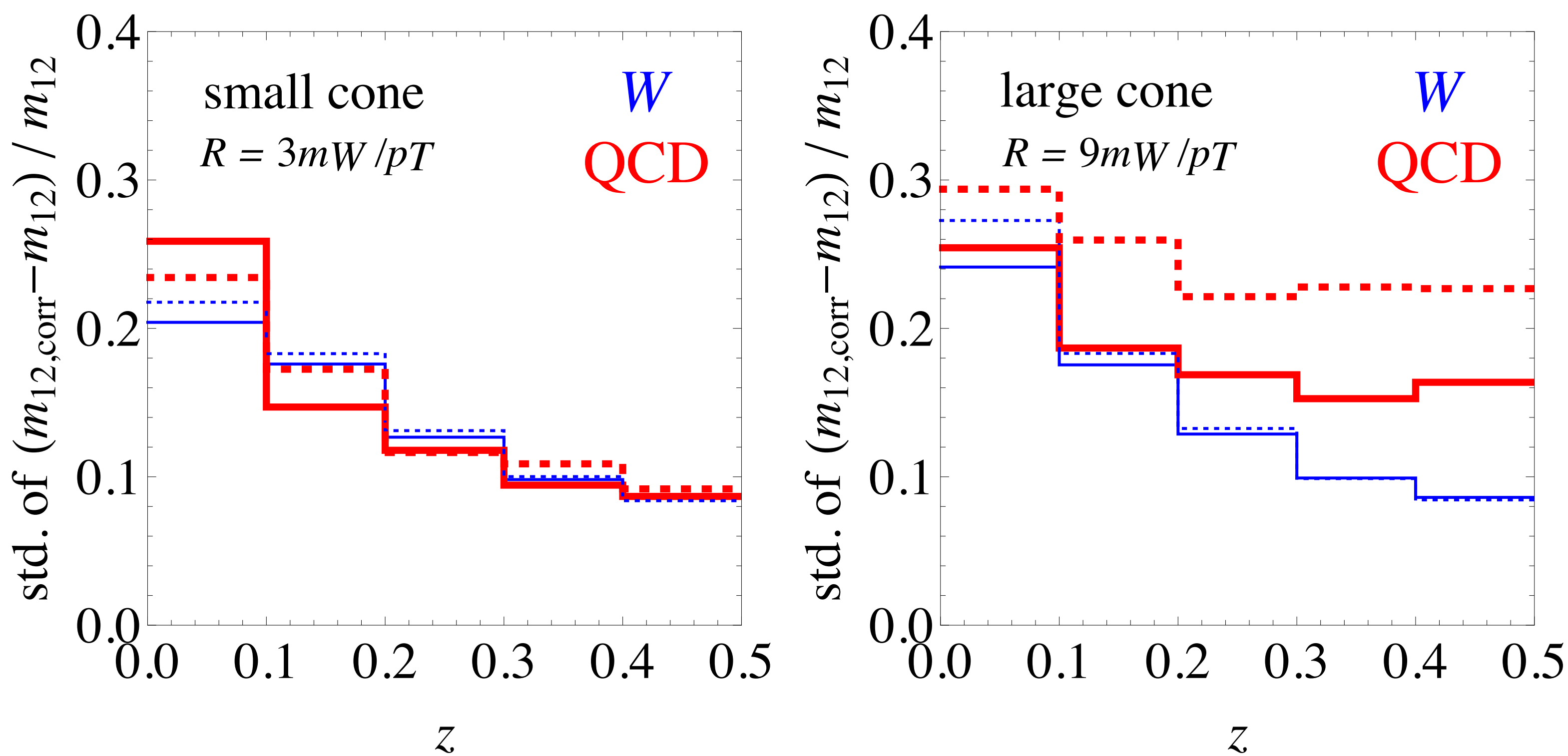
$$\left(\frac{\delta m}{m}\right)^{\mathrm{corr.}}_{\mathrm{RMS}} \sim 15\%$$

(*cf.* ATLAS 2TeV-*Z'* anomaly takes 9%)

Jet mass error due to subjet fluctuations

- Understand analytically, first focus on blue curves for signal:

Bressler, Flacke, Kats, Lee & GP (15)



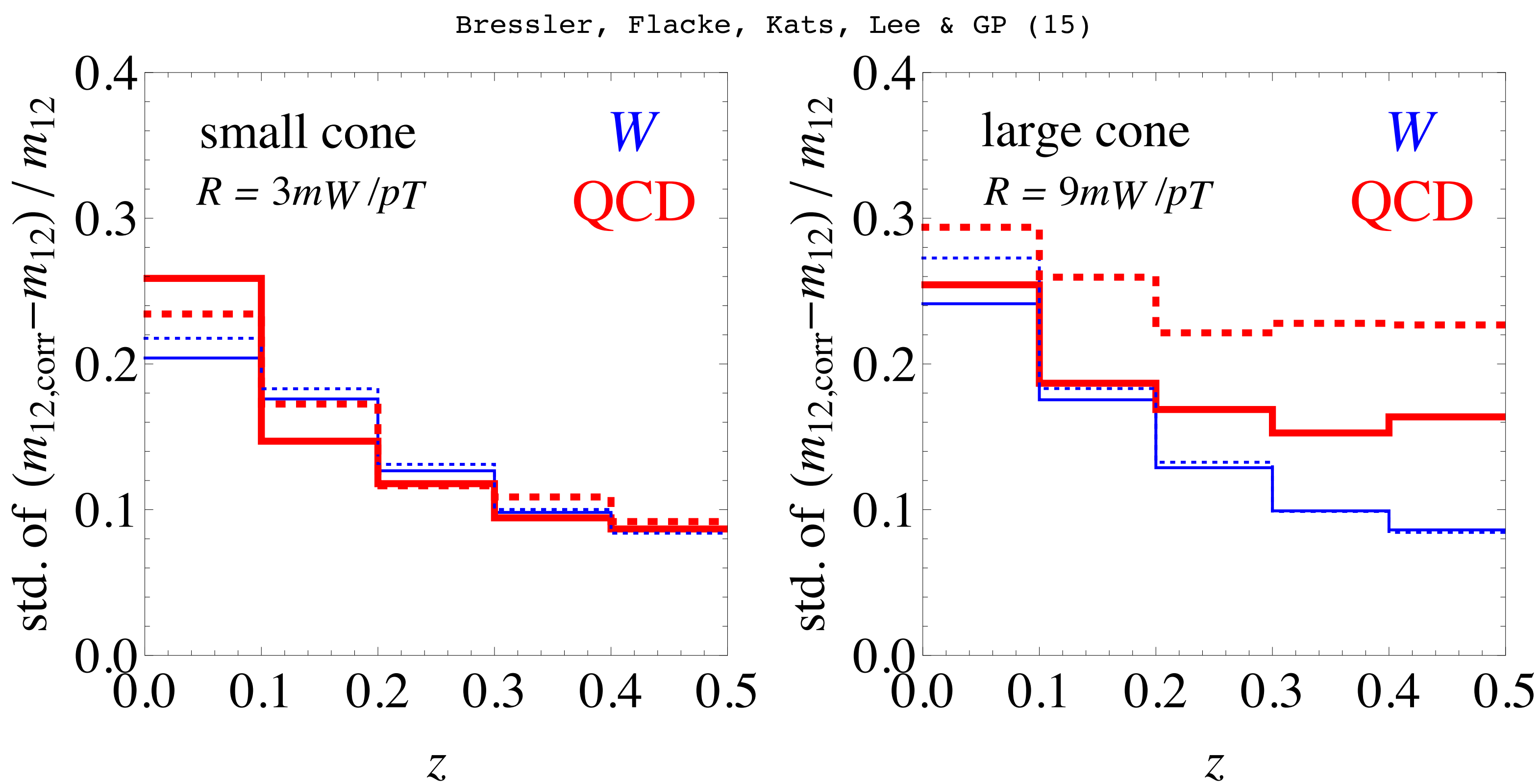
jet mass (truth mass = 75 ± 5 GeV), jet pT = 3 TeV (solid) , 10 TeV (dotted).

$$\left(\delta\left(\frac{m_{12,\mathrm{corr}} - m_{12}}{m_{12}}\right)\right)^2 \simeq 2\left(\frac{1}{2} - z\right)^2 (\delta f_N^{1,2})^2 + \langle y\rangle^2 (\delta f_N^{3+})^2 + \ \ldots$$

$$y \equiv \left(\sum_i E_i - E_1 - E_2\right) / \sum_i E_i, \quad f_N^{3+} \equiv \sum f_N^i E_i / \sum E_i,$$

QCD jet mass & the Sudakov peak

- Why background fluctuations, in red, depend strongly on R ?



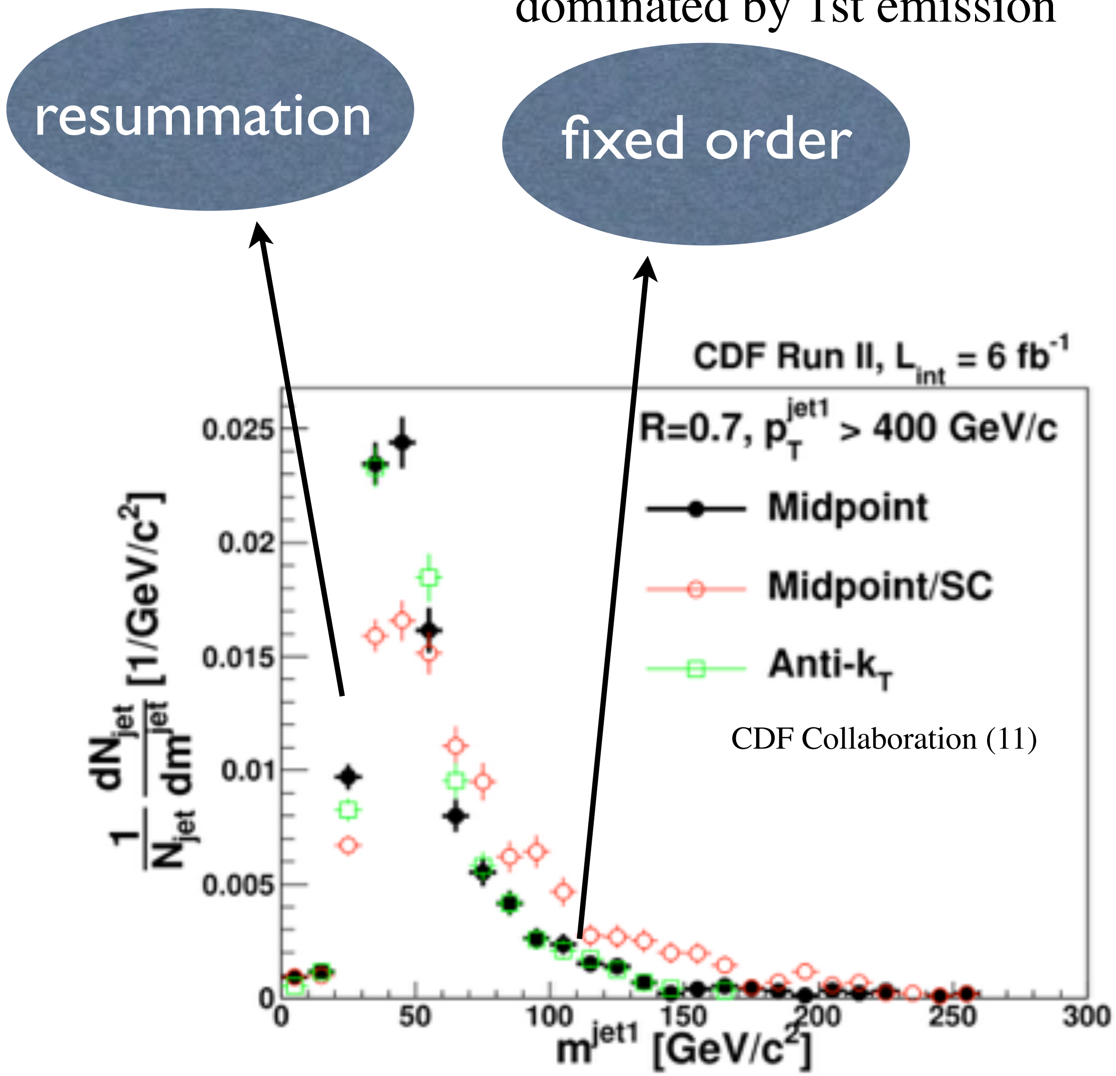
jet mass (truth mass = 75 ± 5 GeV), jet pT = 3 TeV (solid) , 10 TeV (dotted).

Structure of QCD jet mass

- Why background fluctuation in red depend strongly on R ?

multiple emission important

dominated by 1st emission



Location of peak is hard to calculate but depends on R & pT;

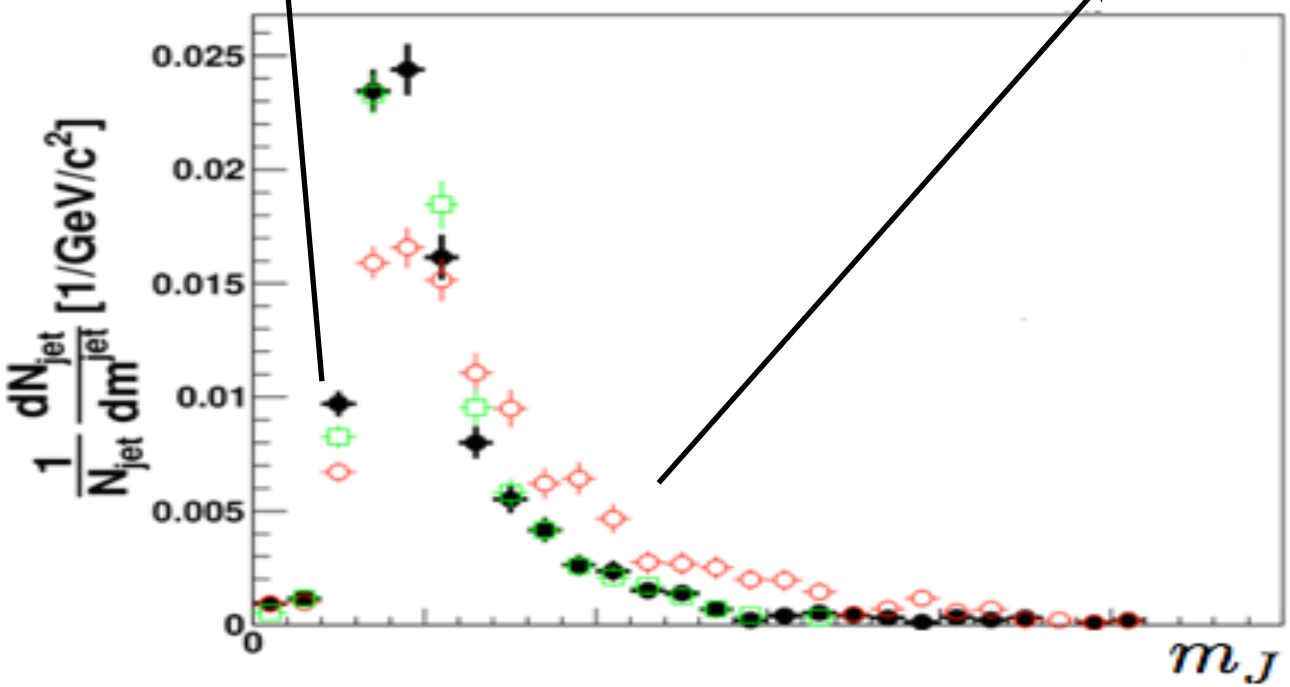
Structure of QCD jet mass

♦ Changing *R* moves the W mass relative to the peak:

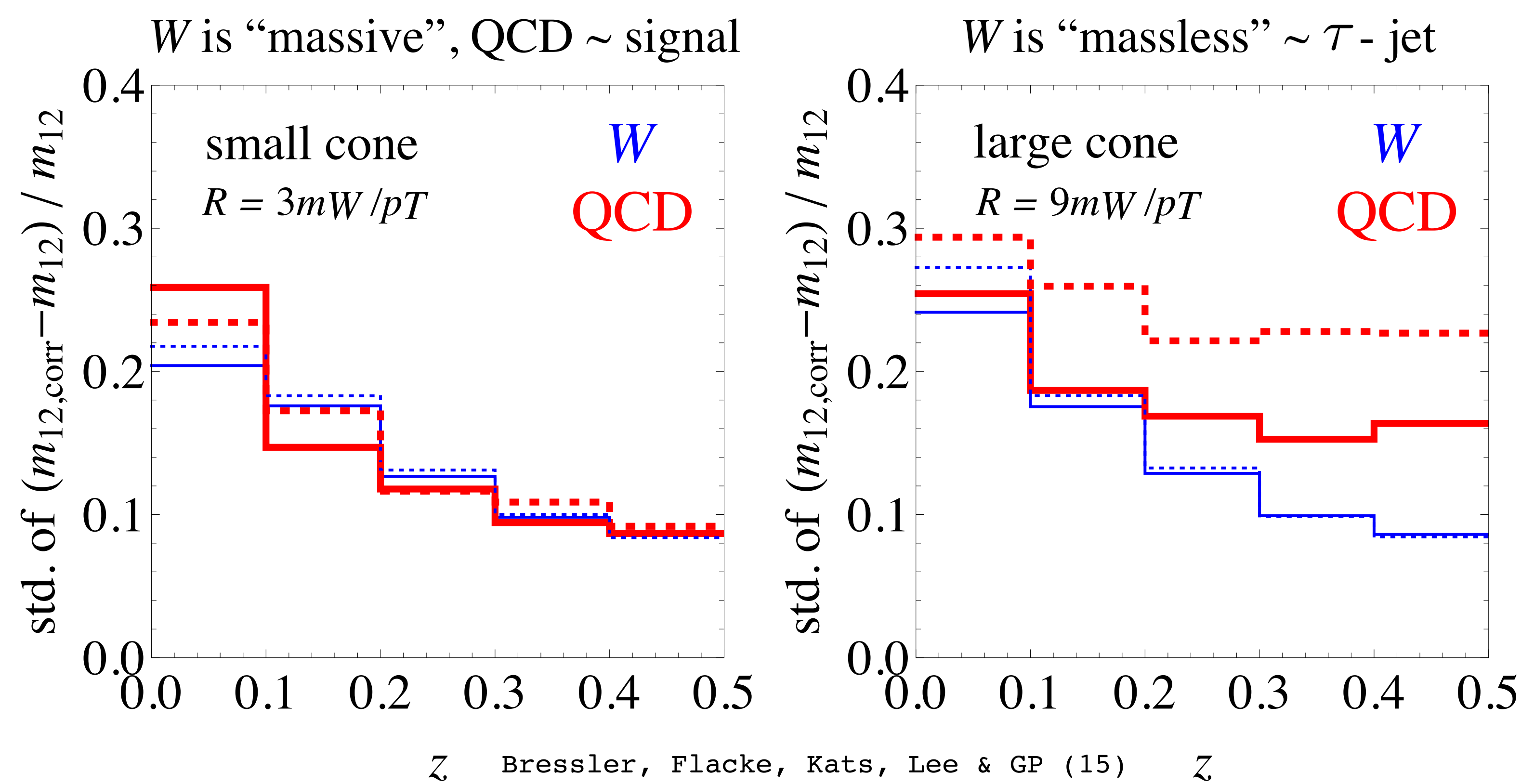
large *R*, *W* is “massless”

small *R*, *W* is “massive”, QCD~signal

Almeida, Lee, GP, I. Sung & Virzi (08)



QCD jet mass & the Sudakov peak



Bressler, Flacke, Kats, Lee & GP (15)

jet mass (truth mass = 75 ± 5 GeV), jet pT = 3 TeV (solid) , 10 TeV (dotted).

Different region of superboosted jets => different behaviour of BG, new type of substructure.

Flavor dependent neutraless fraction

- Fragmentation fractions for *g/u/d* is different than the others. Especially when comparing the neutrals: $(m_\pi \ll m_N)$

$$\langle f_N^{W\to c\bar{s},\; W\to u\bar{d}/QCD} \rangle = 21, 14, \quad \delta f_N^{W\to c\bar{s},\; W\to u\bar{d}/QCD} = 16, 14$$

- New handle: $\left(\frac{W(cs) - jet}{W(ud), QCD - jet} \right)_{\text{corr.ratio}} \sim 1.5$

- Can be calibrated using boosted top events.

Conclusions

♦ Finite hadronic shower size implies that jet substructure of very energetic jet is inaccessible via HCAL = superboosted regime.

♦ Fluct.: O(15%) information carried by “stable” neutrals is lost. Dependence on how asymmetric are the jet subcomponents.

♦ Opportunities:
(i) when *W*/*Z*/*h* are lighter than Sudakov peak new type of substructure phys. emerges.
(ii) flavor dependence of neutral component => potential new “tagger”.

Backups