Superboosted Jets

Gilad Perez

Weizmann Inst.

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

Super-resolution workshop

Plan

- What are jets?
- What are "boosted" jets ? Why are they challenging (jet substructure)?
- Future collider: the challenge of searching for new physics with superboosted jets.

(60-80% of the problem can be resolved semi-conventionally but I won't discuss it - just attempt to explain the issue, more in Sanmay's talk)

Jets & New Physics

- ”Jets” in cosmic rays described in: Edwards et al., Phil. Mag. (1957)
- Looking for new physics in “energetic” jets has a long tradition:

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No. 4077 December 20, 1947 NATURE

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER
AND
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Physical Laboratories, University, Manchester

AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe that one of the forked tracks, shown in Fig. 1 (tracks *a* and *b*), represents the spontaneous transformation in the gas of the chamber of a new type of uncharged elementary particle into lighter charged particles, and that the other, shown in Fig. 2 (tracks *a* and *b*), represents similarly the transformation of a new type of charged particle into two light particles, one of which is charged and the other uncharged.

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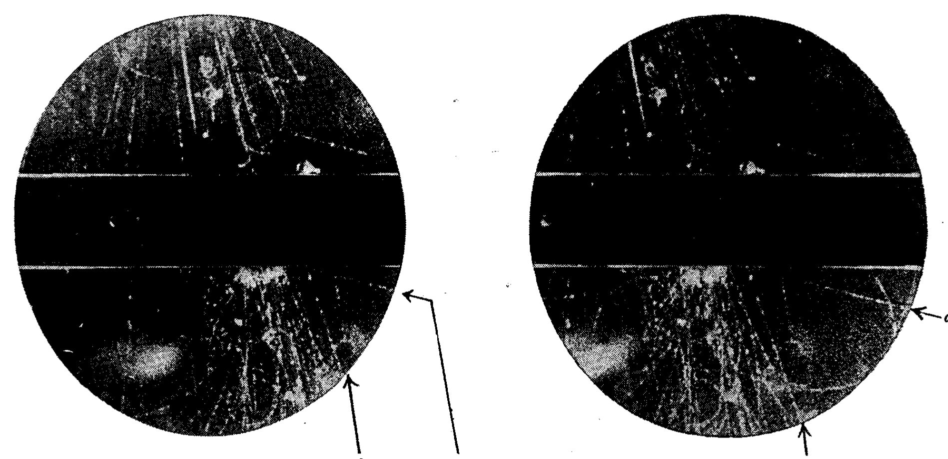

Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

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1953 Rep. Prog. Phys. 16 364

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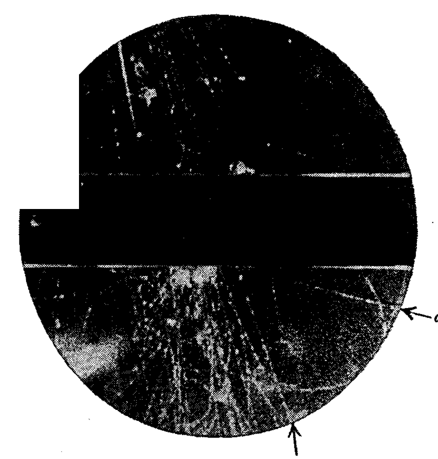
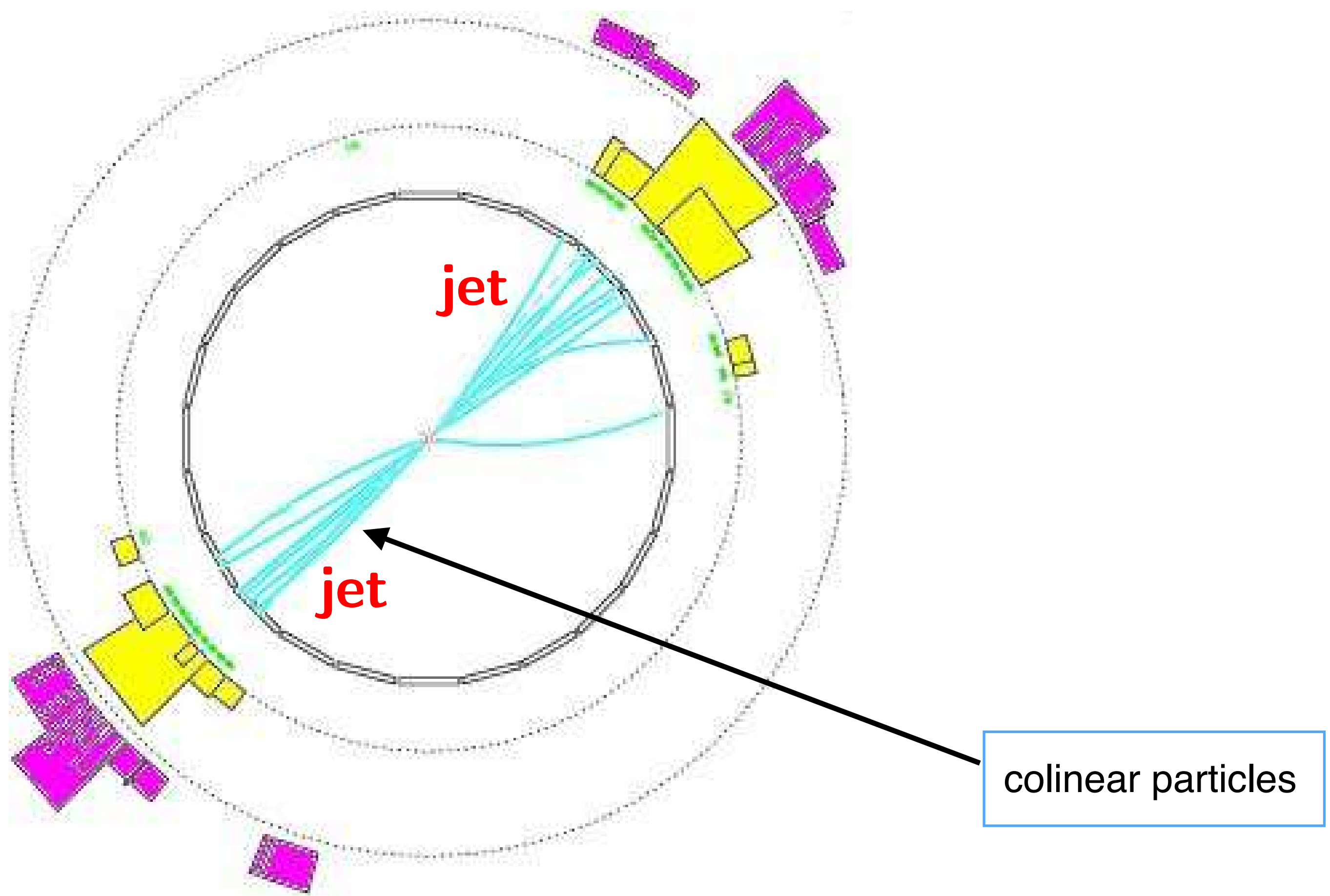


Fig. 1. Stereoscopic photographs showing an unusual fork (a b) in the gas. The direction of the magnetic field is such that a positive particle coming downwards is deviated in an anticlockwise direction

What are jets ?

- Jets: spray of particles (stable hadrons, pions, protons, neutrons) roughly moving in same directions.

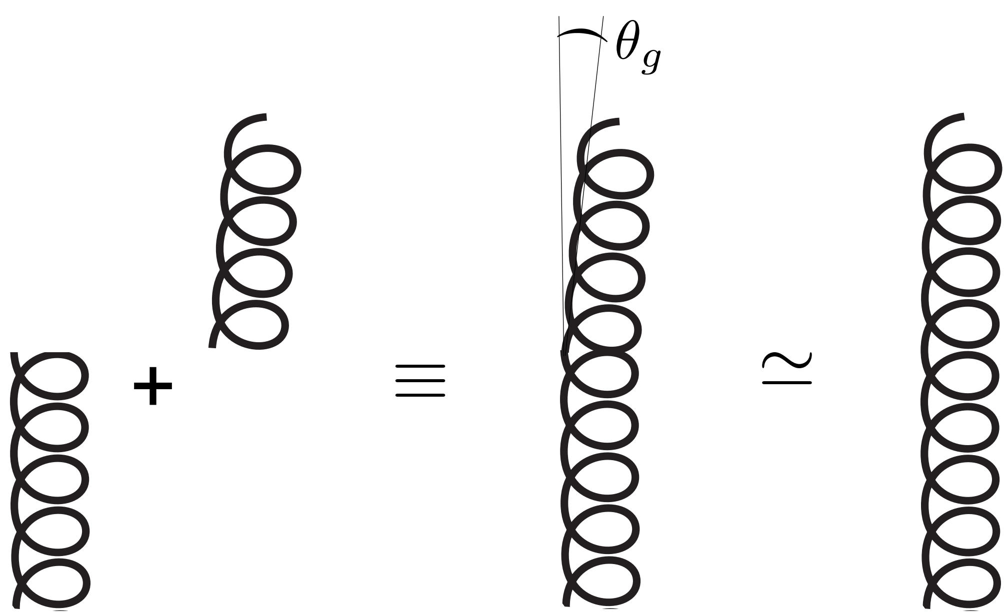


Why jets are unavoidable in QCD ?

(QCD=quantum-chromodynamics, the theory of the strong force)

- Quarks (matter constituents) & gluons (QCD-force mediators) are the basic members of the QCD family => cause jets to appear.

- States with one or two gluons of $E/2$ on top of each others are identical; probability to emit a colinear gluon diverges => colinear singularities:

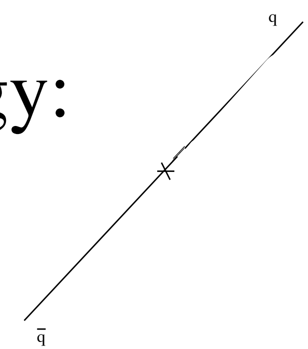


$$\Rightarrow \Gamma(\theta_g) \propto d\theta_g/\theta_g$$

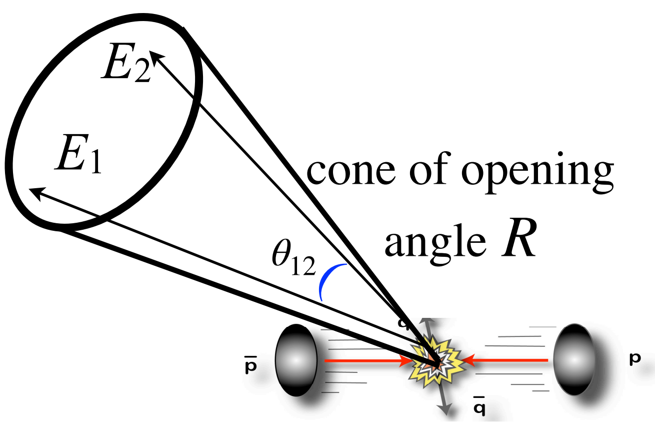
jet mass & jet substructure QCD story

- So: if you produce a fundamental quark/gluon it would always interpolate a *narrow* jet (radiate spray of colinear particles, hadrons)

narrow: its mass << original energy:



- Jet mass definition (say for 2-particles jet): $m_j^2 \sim E_1 E_2 \, \theta_{12}^2$



Measuring jet mass requires looking inside the jet = *jet substructure*

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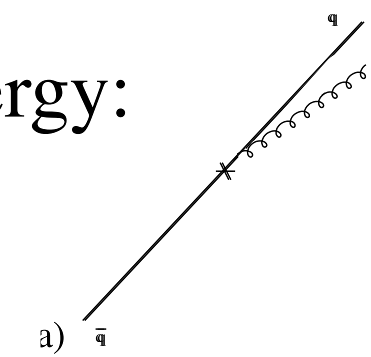

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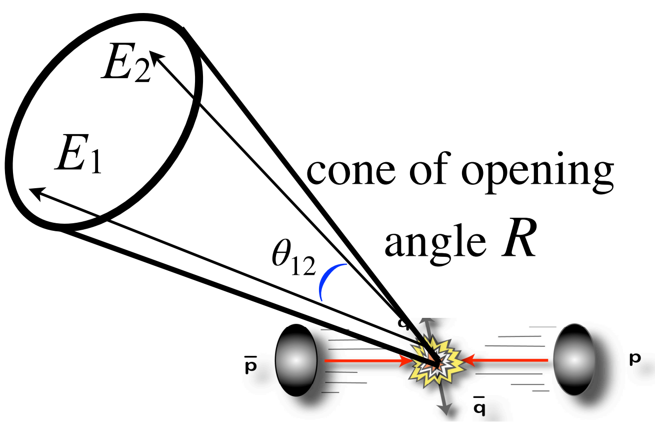

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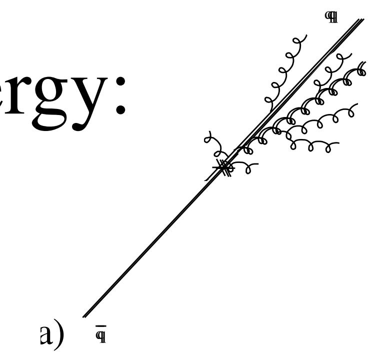

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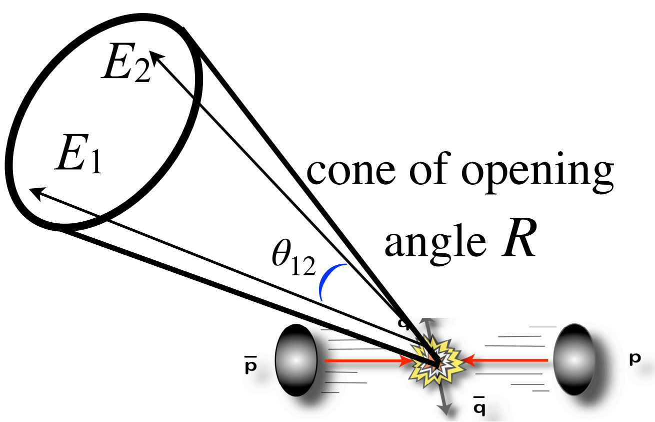

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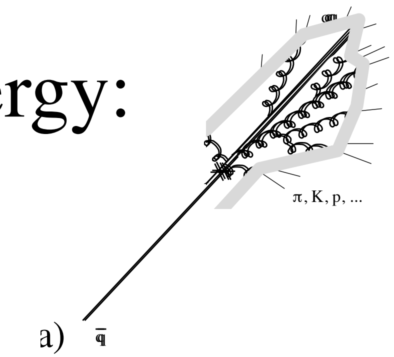
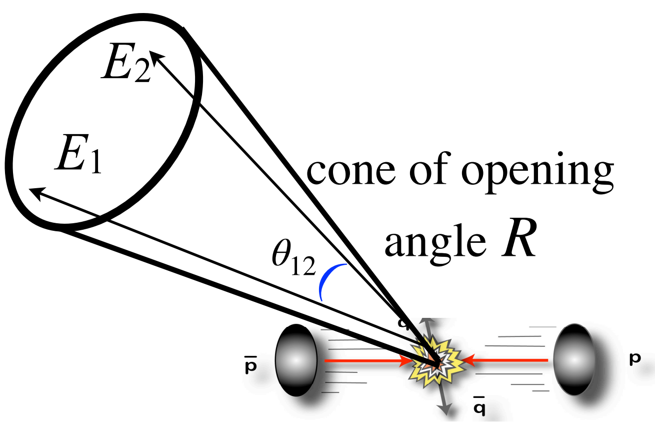


$$m_J^2 \ll E_J^2 R^2$$

- Jet mass definition (say for 2-particles jet): $m_j^2 \sim E_1 E_2\, \theta_{12}^2$



Measuring jet mass requires looking inside the jet = *jet substructure*

So far have learned that:

1. When we produce an energetic quark or gluon it generates a collimated spray of particles, roughly denoted as a jet.

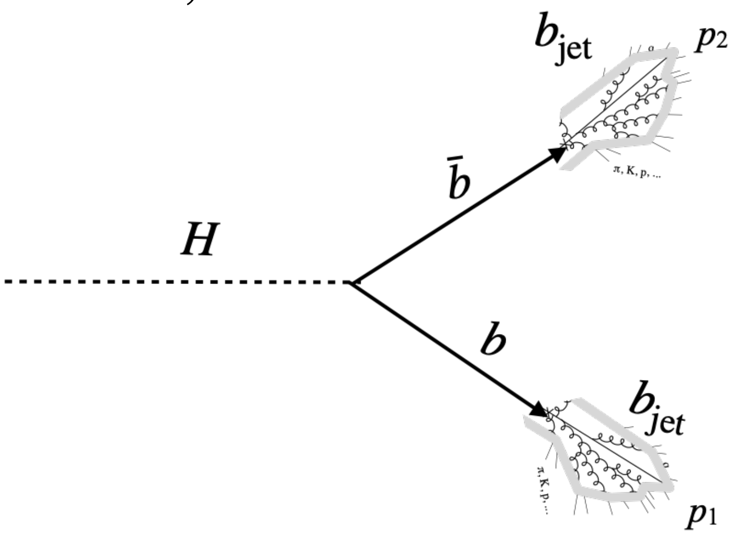
2. To measure the jet mass we need to look inside the jet; Jet mass => jet substructure info.

Why do we care? New physics searches

In colliders, energy frontier, we use jet mass (substructure) to search for new particles, where QCD events => main background.

(Pseudo realistic) Ex. how to search for new massive particles

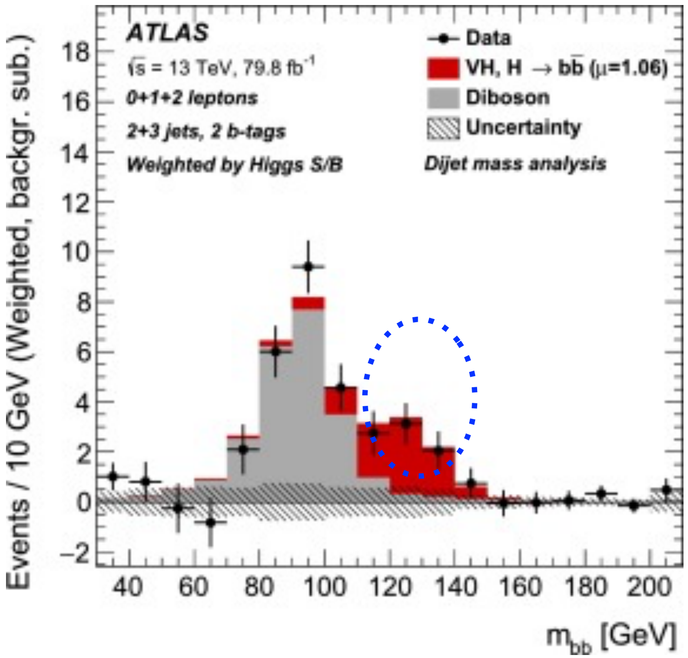
- Is the Higgs behind the mass of all particles? For instance *b-quarks?* To answer, need to observe the decay of the Higgs to 2-b's, $H \to \bar{b}b$!

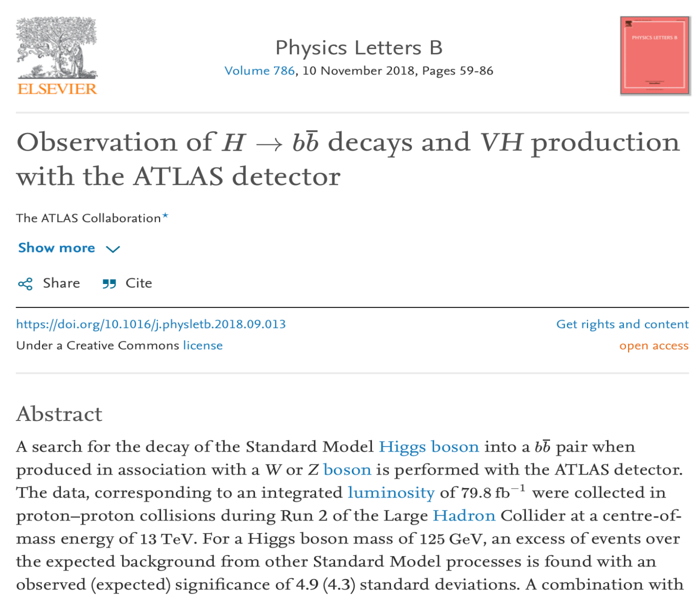


$$m_H^2 \simeq m_{b\bar{b}}^2 \simeq E_1E_2(1-\cos\theta_{12}) \sim (125\text{GeV})^2$$

the b's are not colinear, θ_{12} is not small

(If H is at rest then $\theta_{12} = \pi$)





ELSEVIER
Physics Letters B
Volume 786, 10 November 2018, Pages 59-86

Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector

The ATLAS Collaboration*

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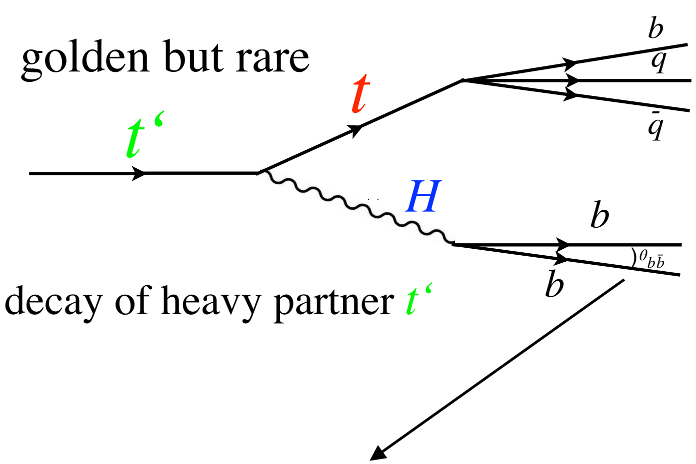
Abstract

A search for the decay of the Standard Model Higgs boson into a $b\bar{b}$ pair when produced in association with a W or Z boson is performed with the ATLAS detector. The data, corresponding to an integrated luminosity of 79.8 fb^{-1} were collected in proton–proton collisions during Run 2 of the Large Hadron Collider at a centre-of-mass energy of 13 TeV. For a Higgs boson mass of 125 GeV, an excess of events over the expected background from other Standard Model processes is found with an observed (expected) significance of 4.9 (4.3) standard deviations. A combination with

Future: searching for new heavy particles

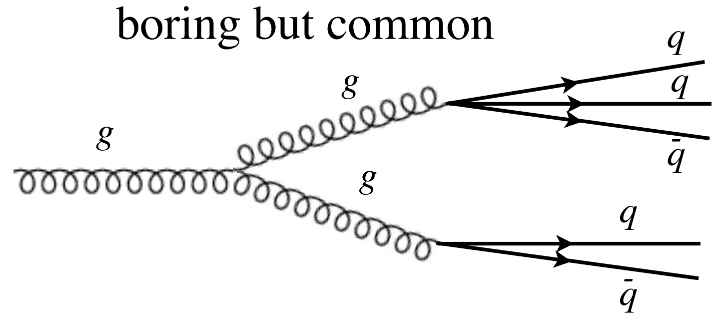
- We have solid motivation to think that there is an ultra massive particle *t'* that decay to *H* and other massive particles.

As $m_{t'} \gg m_H$ outgoing Higgs is ultra-relativistic, its decay products collimate => *H*-jets.



$$\theta_{b\bar{b}} \sim m_H / m_{t'} \ll 1$$

Similar to ordinary 2-jet QCD process hard to observe



Jet substructure analysis required to separate signal from QCD background!

How difficult of a problem is it ?
Hadronic shower size

- The opening angle of boosted Higgs decay product,

$\theta_{b\bar{b}} \sim m_H/m_{t'}$, for $m_{t'} \sim$ 10000 GeV is of O(2%).

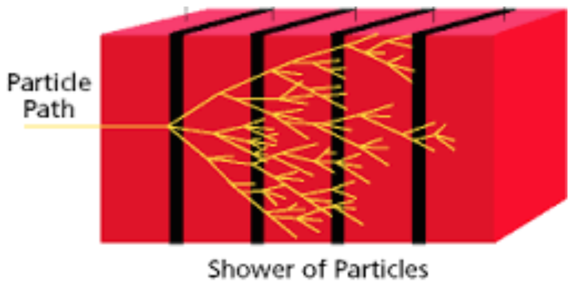
- Hadronicaly decaying *H* - jets produce energetic hadrons:

For *H* jet with *E*~ 10000 GeV -

2 leading hadrons energies = 1200 (2700), 700 (15000) GeV;

2 leading “stable”-neutrals energies = 600 (1300), 200 (500) GeV.

- 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:

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

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

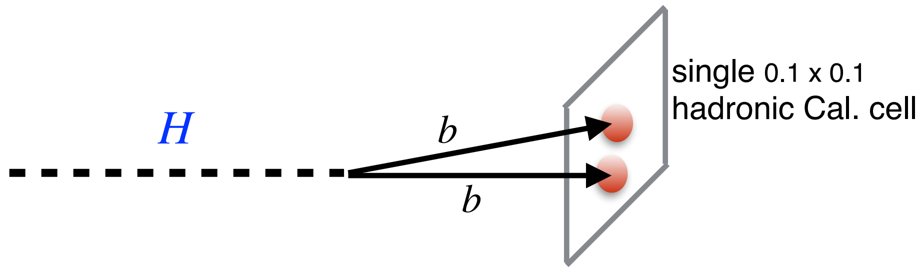
Hadronic calorimeter (HCAL)

The superboosted regime

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

$$\theta_{\rm superboost} \sim \frac{2m_H}{E_H} \lesssim \theta_{\rm had} \sim 0.1$$

$$E_H > 2500\,\mathrm{GeV}$$



Conclusions

♦ Search for heavy new particles => boosted Higgs, with hadronic final states that are collimated.

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

········· More in Sanmay's talk ·········

♦ Some information can be recovered by "tracker" + electromagnetic calorimeter.

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

Neutraless jet substructure

- Superboosted jet substructure, who cares?

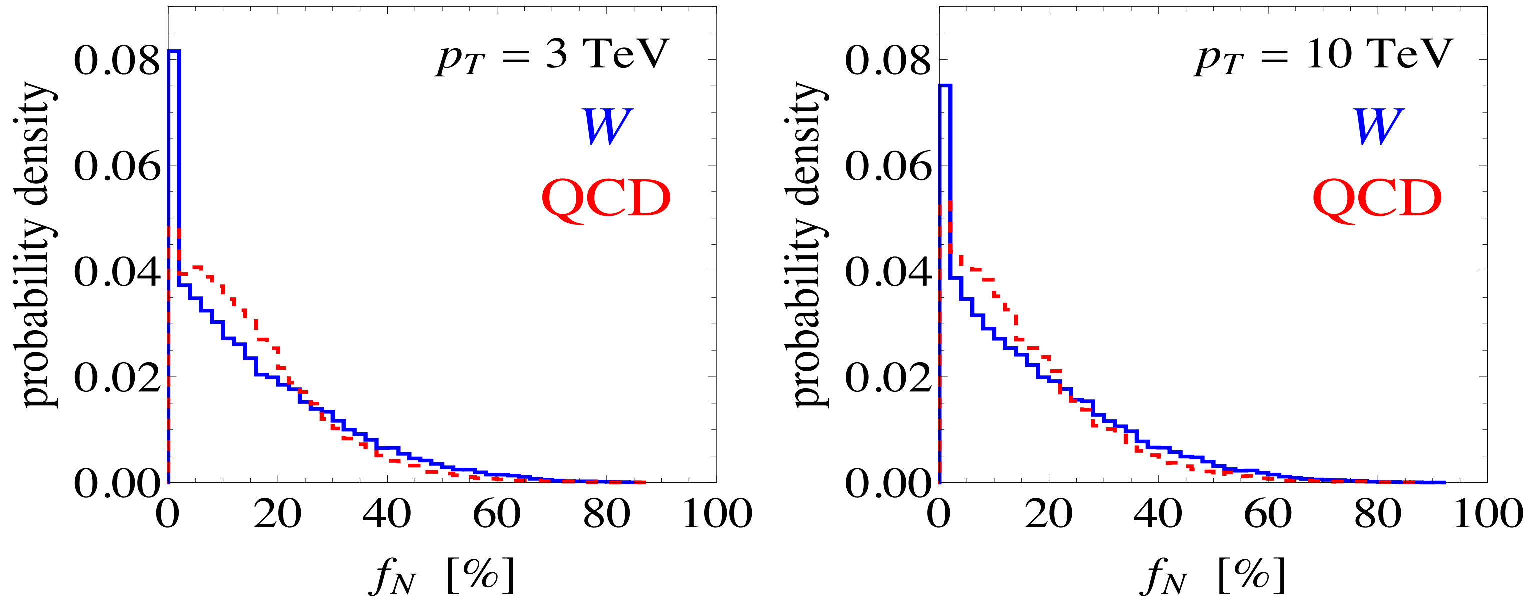
Can probe jet inner energy deposition via tracker + EM Cal.

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 $K_{L,S}, n$ ... is inaccessible.

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



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

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:

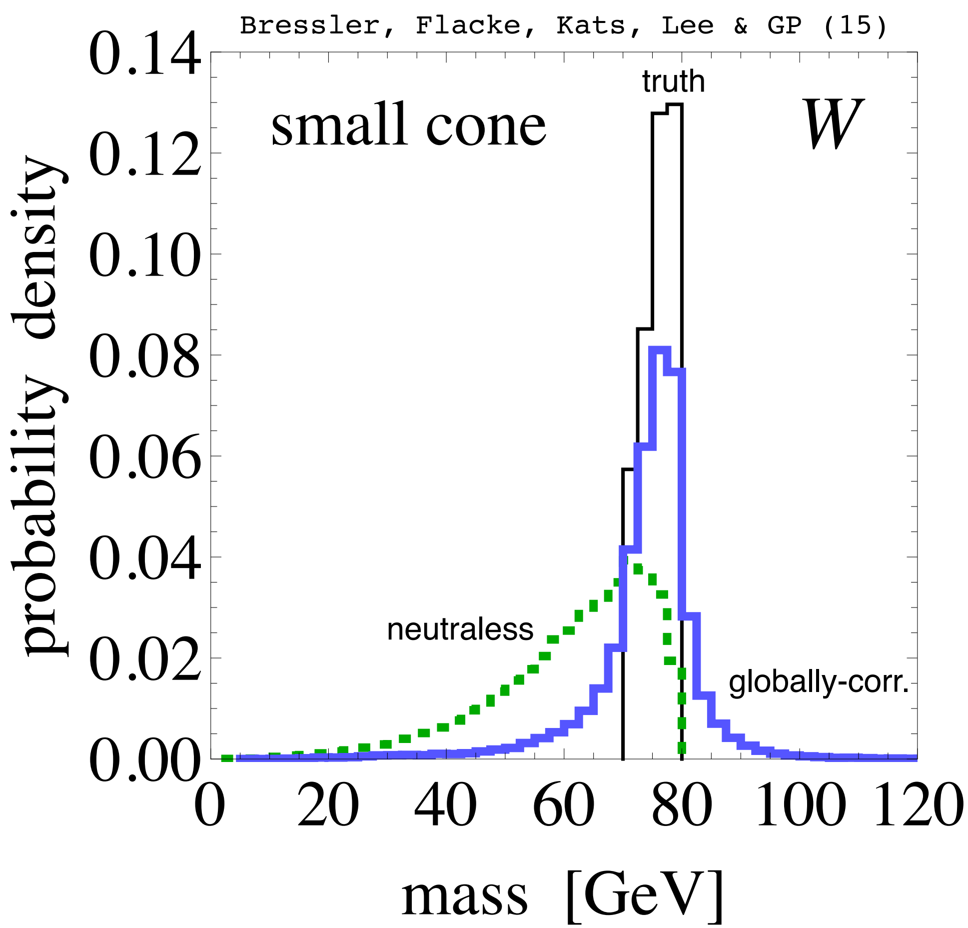
$$m_{12}^2 = E_1 E_2 \theta_{12}^2 , \quad z = E_2/E_{12} \leq \tfrac{1}{2}.$$

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: $m_{12,\text{corr}} = \dfrac{\sum_i E_i}{\sum_i \left(1 - f_N^i\right) E_i}\, m_{12,\not{N}}\,,$



As expected, fluct. size, not reduced:

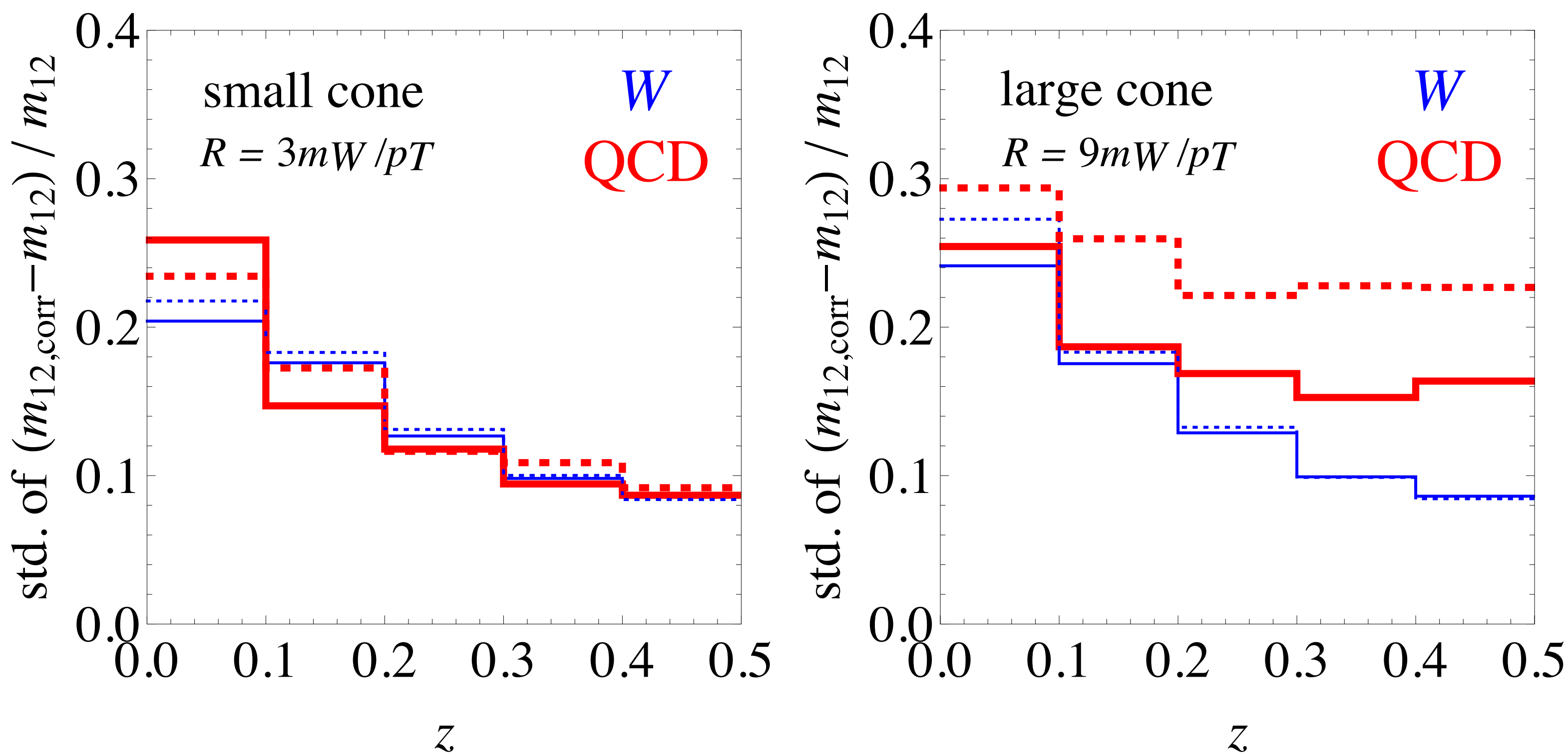
$$\left(\frac{\delta m}{m}\right)^{\text{corr.}}_{\text{RMS}} \sim 15\%$$

(*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)



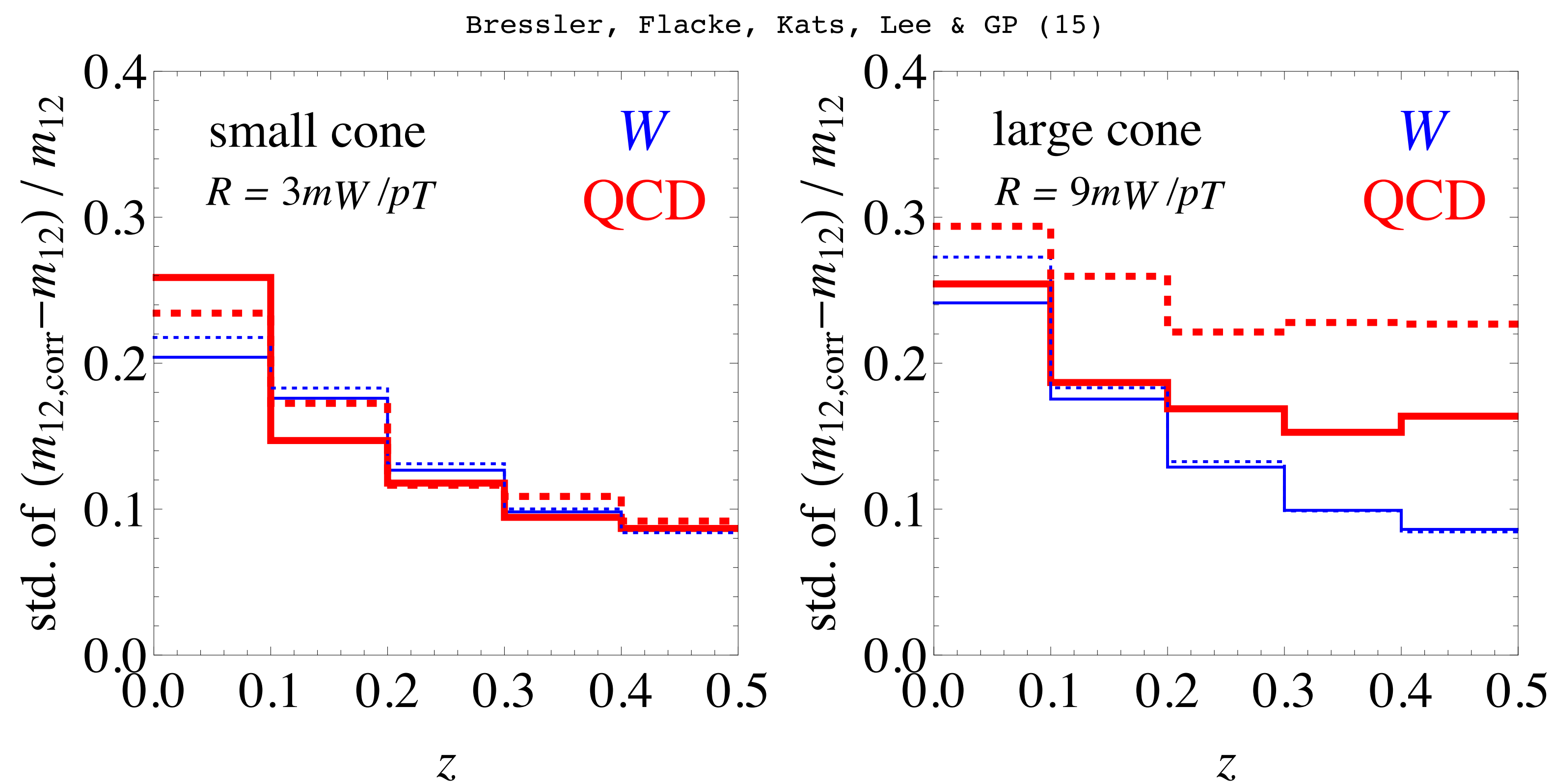
jet mass (truth mass = 75 ± 5 GeV), jet pT = 3 TeV (solid) , 10 TeV (dotted).

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

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

QCD jet mass & the Sudakov peak

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



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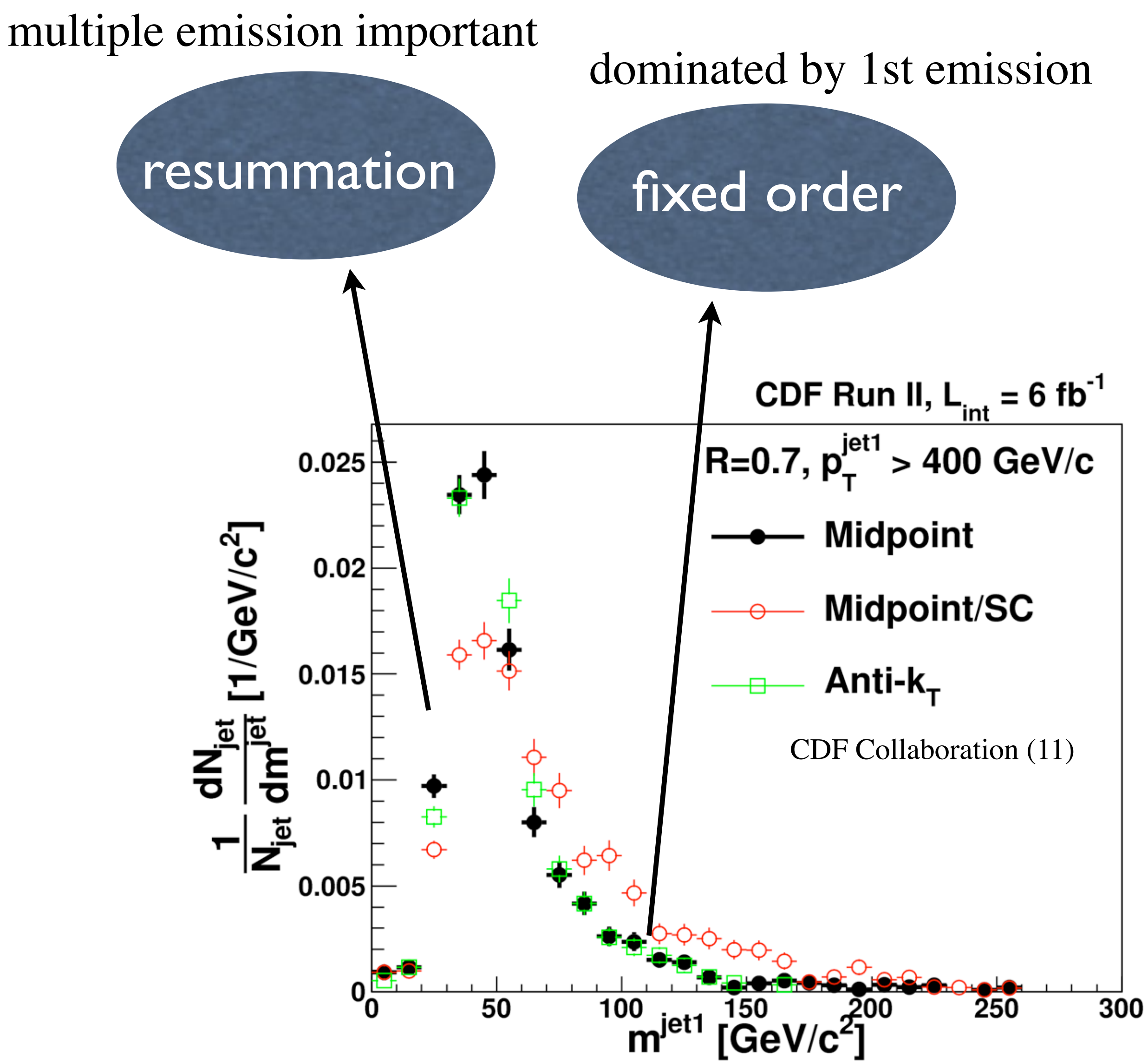
Structure of QCD jet mass

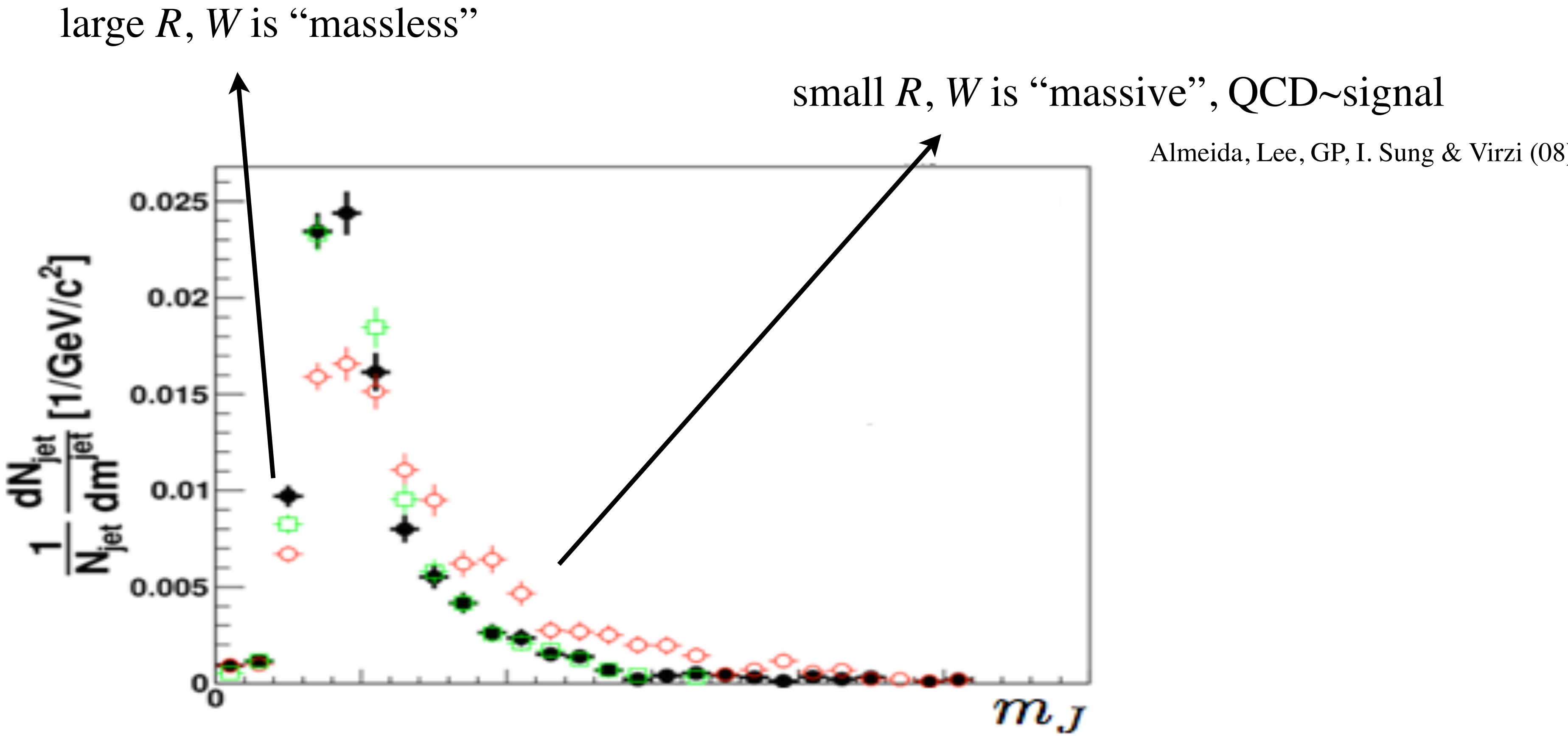
♦ Why background fluctuation in red depend strongly on *R* ?



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:



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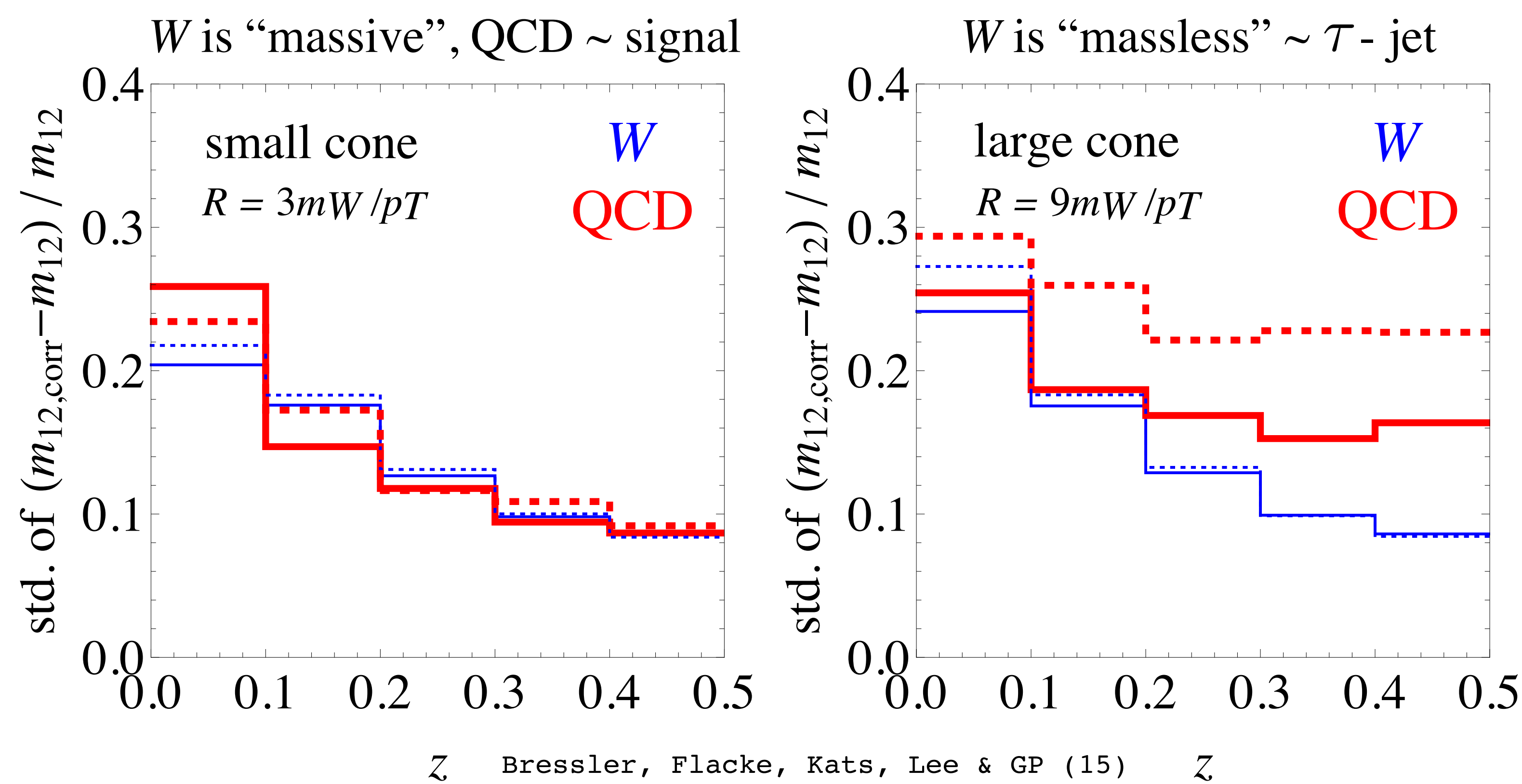

Bressler, Flacke, Kats, Lee & GP (15)

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

- 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

Why are they common in QCD (strong interaction)? (*soft*-collinear singularities)

- A state with extra 0-energy gluon is unchanged; probability to emit a soft gluon diverges => *soft* singularities. $(E \gg m_{\text{hadron}} \sim \Lambda_{\text{QCD}})$

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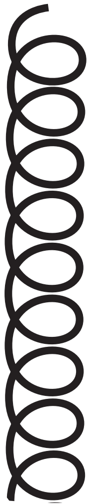

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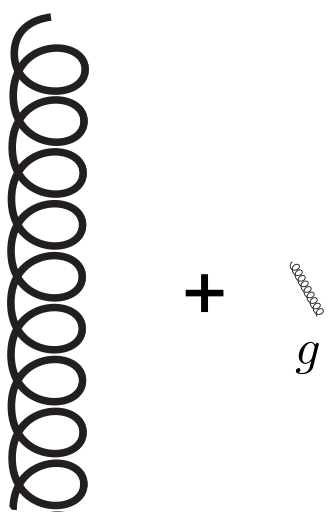

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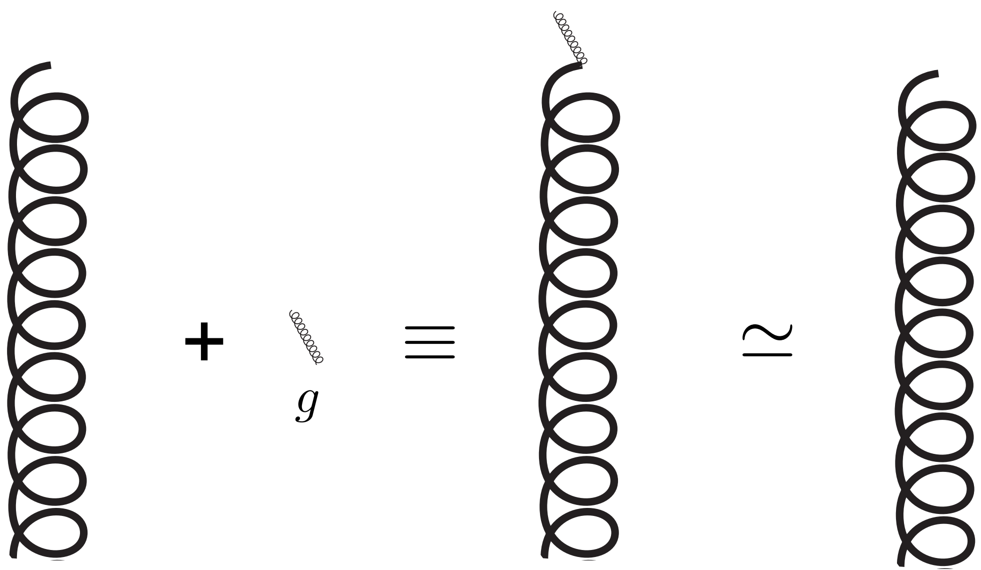

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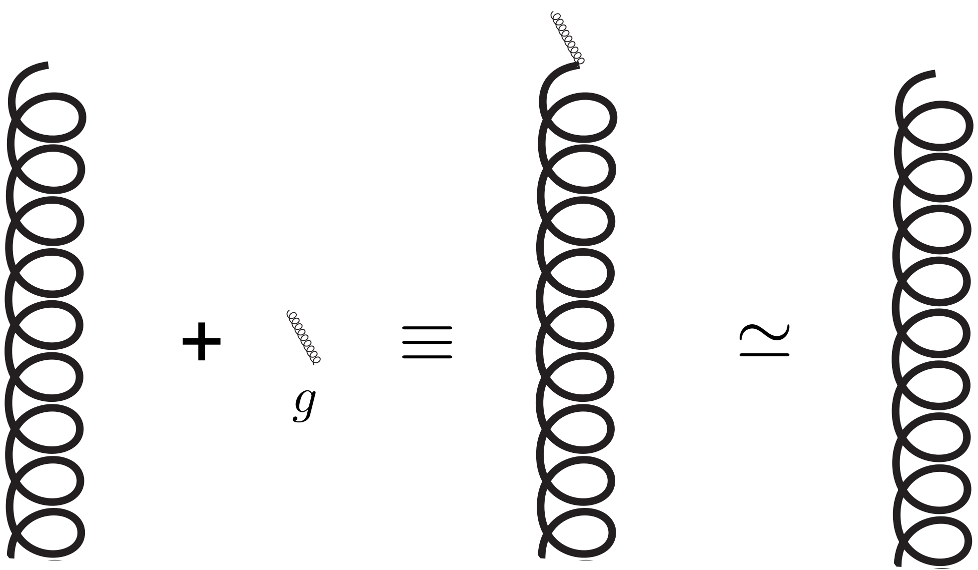
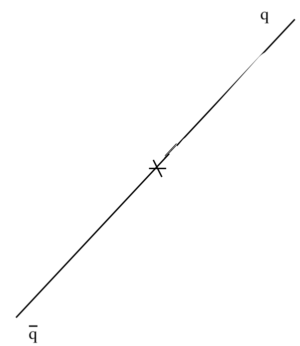


$$\Rightarrow \Gamma(E_g) \propto dE_g/E_g$$

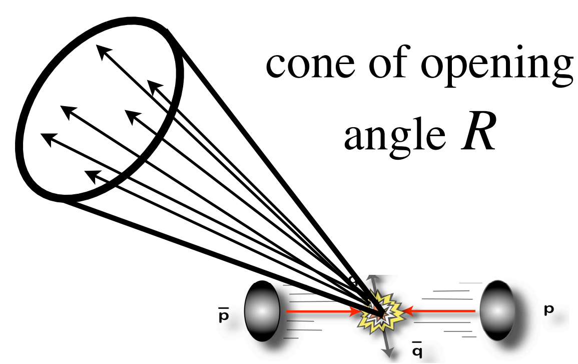
jet mass & jet substructure QCD story

- QCD: soft collinear singularities => narrow jets are “light”.



- Jet mass definition:

$$m_J^2 = (\sum_{i\in R} P_i)^2, \quad Pi^2 = 0\,, \ \text{for} \quad E_J \gg m_J \gg \Lambda_{\text{QCD}}\,.$$



jet mass & jet substructure QCD story

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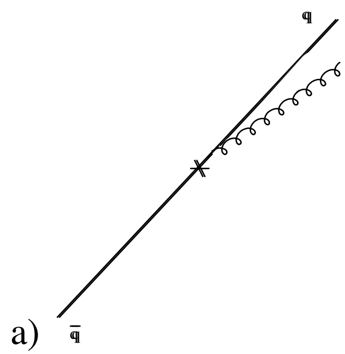

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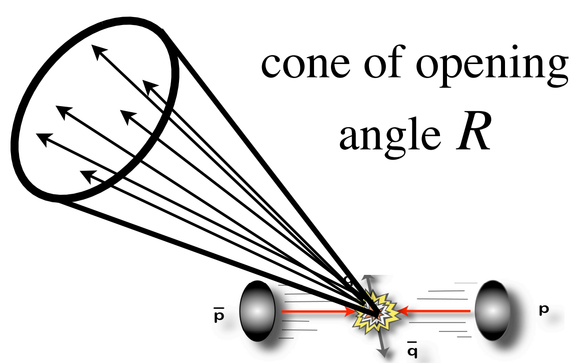

jet mass & jet substructure QCD story

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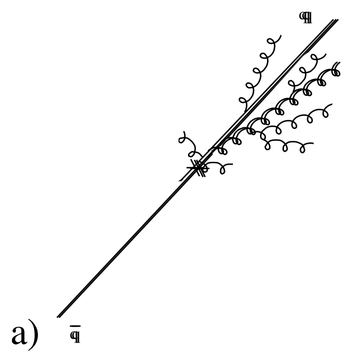

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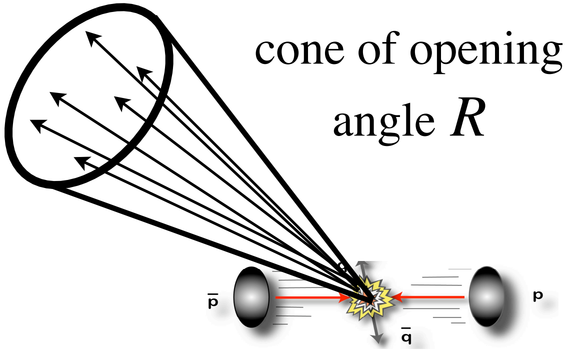

jet mass & jet substructure QCD story

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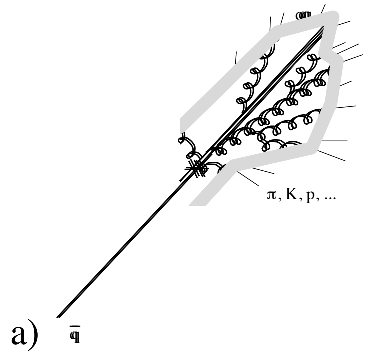
$$m_J^2 \ll E_J^2 R^2$$



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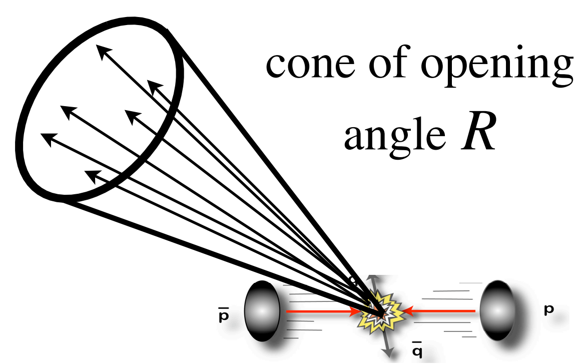

How difficult of a problem is it ?
Hadronic shower size

- The opening angle of boosted Higgs decay product,

$\theta_{b\bar{b}} \sim m_H / m_{t'}$, for $m_{t'} \sim$ 10000 GeV is of O(1%).

- 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.