Subjet algorithm and N-subjettiness for identifying fat jets.

Ji-Hun Kim

Department of Physics, Seoul National University, Korea

21 July 2011

Based on : JHK, PRD 83:011502(R),2011.

Outline

Hadron jets

Jet algorithms.

- Colored partons radiate : produce collimated hadrons.
- Jet algorithms are for grouping them.
- Inclusive kT, Cambridge/Aachen, Anti-kT, and SISCone, ...
- They have a free parameter, 'a jet radius' R_{jet}.

Hadron jets

Jet algorithms.

- Colored partons radiate : produce collimated hadrons.
- Jet algorithms are for grouping them.
- Inclusive kT, Cambridge/Aachen, Anti-kT, and SISCone, ...
- They have a free parameter, 'a jet radius' R_{jet}.

R_{jet} : a jet radius.

- Larger R_{jet} : good for capturing the radiations.
- Smaller R_{jet} : good for reducing effects of UE and pileup.
- Optimal jet radius, Jets with Variable R : to optimize R_{jet}.

Usually, QCD backgrounds are huge.

Why Study Boosted Objects?

Example : $pp \to H + W/Z \to b\bar{b} + leptons$

- $t\bar{t} \to\to b\bar{b} + W^+ + W^-$: one of main backgrounds.
- Hard, collimated $b\bar{b}$ and leptons of an opposite direction : boosted Higgs can produce it, but $t\bar{t}$ is unlikely.
- Geometric shape of fat jet signals are highly constrained, and backgrounds are much smaller than ordinary cases.
- $b\bar{b}$ forms a single jet : a fat jet.

- Jet substructure techniques(Filtering, trimming, pruning, ...) for tagging the boosted particles : set R_{jet} large, and then remove some of soft particles to reject radiations from UE, pileup.
- Next question : what given fat jets originate from?

Fat jets from Higgs vs gluons.

Boosted H

- $b\bar{b}$ forms a color singlet.
- Fewer radiation
- Narrow two b subjets.

QCD jets are likely to give

- $b\bar{b}$ forms a color octet.
- More radiations.
- Broad two b subjets.

Strategy for finding boosted Higgs

- Looking for fat jets
- which have two narrow, hard b-subjets
- and no more hard subjets.
- In their rest frame, fat jets from Higgs decaying to two narrow b-jets.

For selecting fat jets with N subjets, N-subjettiness is introduced.

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.
- Momentum of rest frame subjet, $q_k^\mu = E_{jet}(1, \hat{n}_{jet})$.

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.
- Momentum of rest frame subjet, $q_k^\mu = E_{jet}(1, \hat{n}_{jet})$.
- Each constituent particle is assigned to the nearest subjet.

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.
- Momentum of rest frame subjet, $q_k^\mu = E_{jet}(1, \hat{n}_{jet})$.
- Each constituent particle is assigned to the nearest subjet.

- N infinitely narrow subjets $\Rightarrow \tau_N^{rest} \to 0$.

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.
- Momentum of rest frame subjet, $q_k^\mu = E_{jet}(1, \hat{n}_{jet})$.
- Each constituent particle is assigned to the nearest subjet.

- N infinitely narrow subjets $\Rightarrow \tau_N^{rest} \to 0$.
- Broader subjets $\Rightarrow \tau_N^{rest} \uparrow$.

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.
- Momentum of rest frame subjet, $q_k^\mu = E_{jet}(1, \hat{n}_{jet})$.
- Each constituent particle is assigned to the nearest subjet.

- N infinitely narrow subjets $\Rightarrow \tau_N^{rest} \to 0$.
- Broader subjets $\Rightarrow \tau_N^{rest} \uparrow$.
- Additional subjets $\Rightarrow \tau_N^{rest} \uparrow$.

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.
- Momentum of rest frame subjet, $q_k^\mu = E_{jet}(1, \hat{n}_{jet})$.
- Each constituent particle is assigned to the nearest subjet.

- N infinitely narrow subjets $\Rightarrow \tau_N^{rest} \to 0$.
- Broader subjets $\Rightarrow \tau_N^{rest} \uparrow$.
- Additional subjets $\Rightarrow \tau_N^{rest} \uparrow$.

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.
- Momentum of rest frame subjet, $q_k^\mu = E_{jet}(1, \hat{n}_{jet})$.
- Each constituent particle is assigned to the nearest subjet.

- N infinitely narrow subjets $\Rightarrow \tau_N^{rest} \to 0$.
- Broader subjets $\Rightarrow \tau_N^{rest} \uparrow$.
- Additional subjets $\Rightarrow \tau_N^{rest} \uparrow$.

Boosted H/W/Z jets : smaller τ_2^{rest}

N-subjettiness, τ_N^{rest} : Definition

A variation of 'N-jettiness', a global event shape introduced by Iain W. Stewart, Frank J. Tackmann, Wouter J. Waalewijn, PRL.105:092002,2010.

$$M_{jet}^2 \equiv (p_\mu^{jet})^2$$

$$\tau_N^{rest} \equiv \frac{2}{M_{jet}^2} \sum_{i \in J} \min\left(p_i \cdot q_1 , p_i \cdot q_2, \ldots, p_i \cdot q_N \right)$$

- Momentum of constituent particle, i.
- Momentum of rest frame subjet, $q_k^\mu = E_{jet}(1, \hat{n}_{jet})$.
- Each constituent particle is assigned to the nearest subjet.

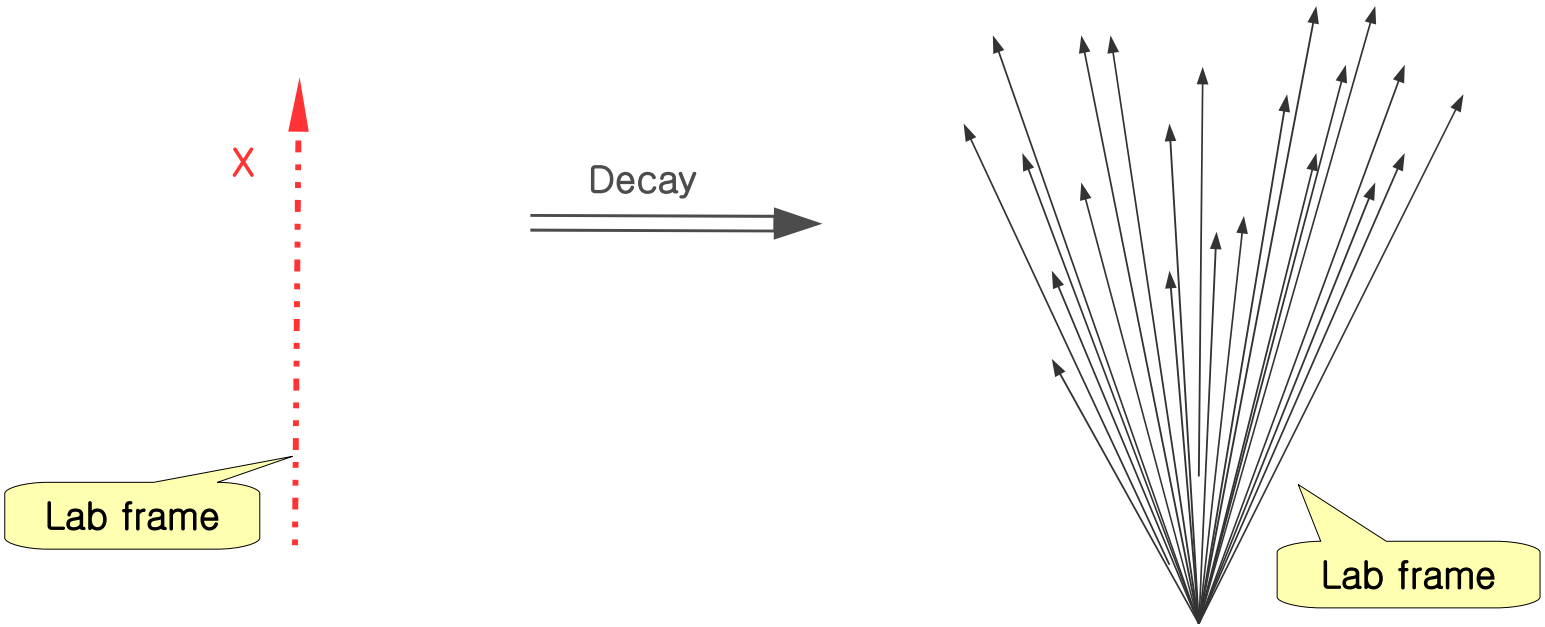
- N infinitely narrow subjets $\Rightarrow \tau_N^{rest} \to 0$.
- Broader subjets $\Rightarrow \tau_N^{rest} \uparrow$.
- Additional subjets $\Rightarrow \tau_N^{rest} \uparrow$.

Boosted H/W/Z jets : smaller τ_2^{rest} $\Longleftrightarrow$ QCD jets : larger τ_2^{rest}.

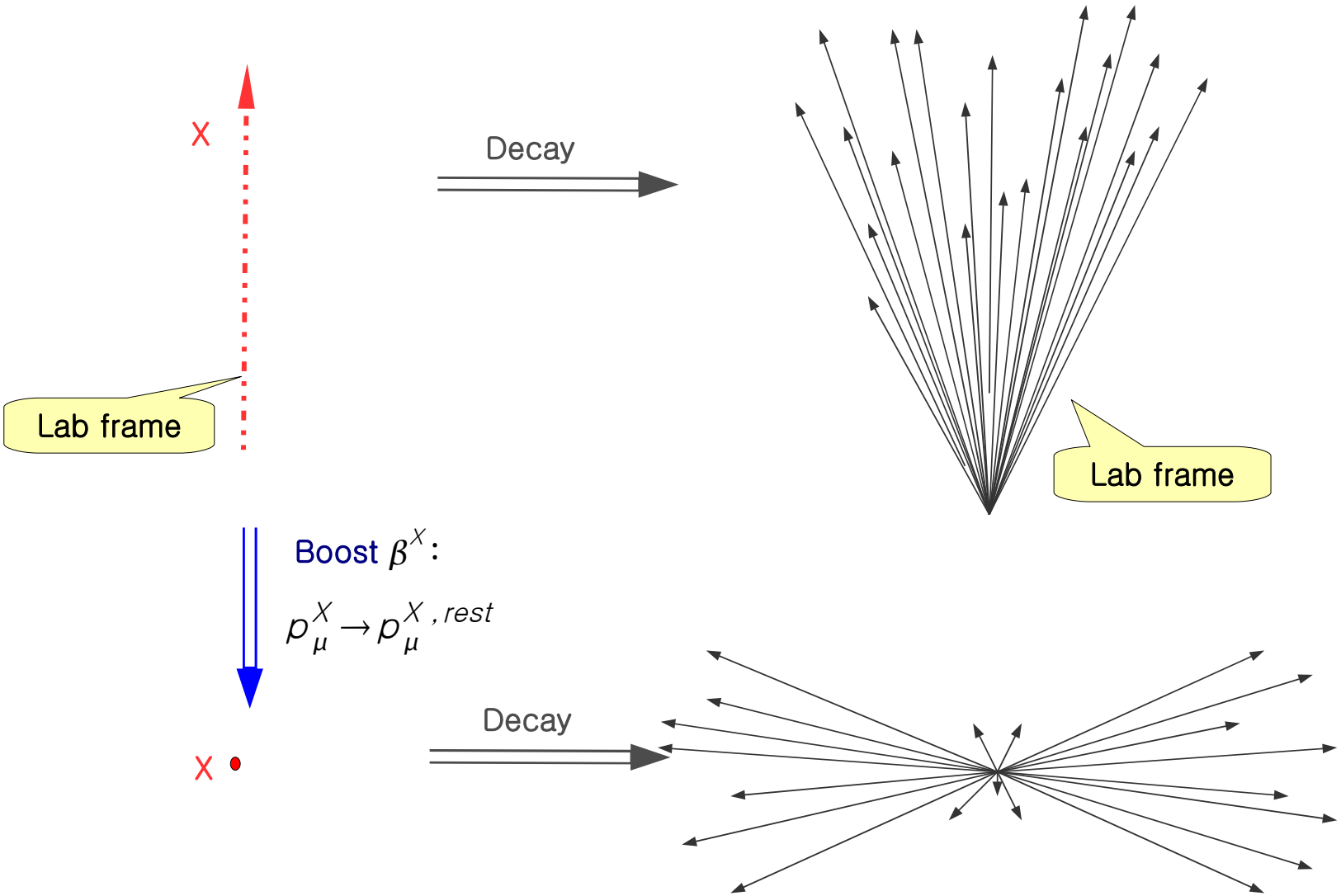
Needs of the subjet definitions.

- To find fat jets which have N subjets : we need to define subjets.
- ATLAS, CMS use the anti-k_T jet algorithm :
  want a subjet definition is applicable to cone-like jet algorithms.
- Re-clustering the constituents of a jet with smaller radius :
  behave badly if some of subjets overlap.
- Defining subjets of a color dipole system :
  just re-clustering the constituents particles in the rest frame of the color dipole.

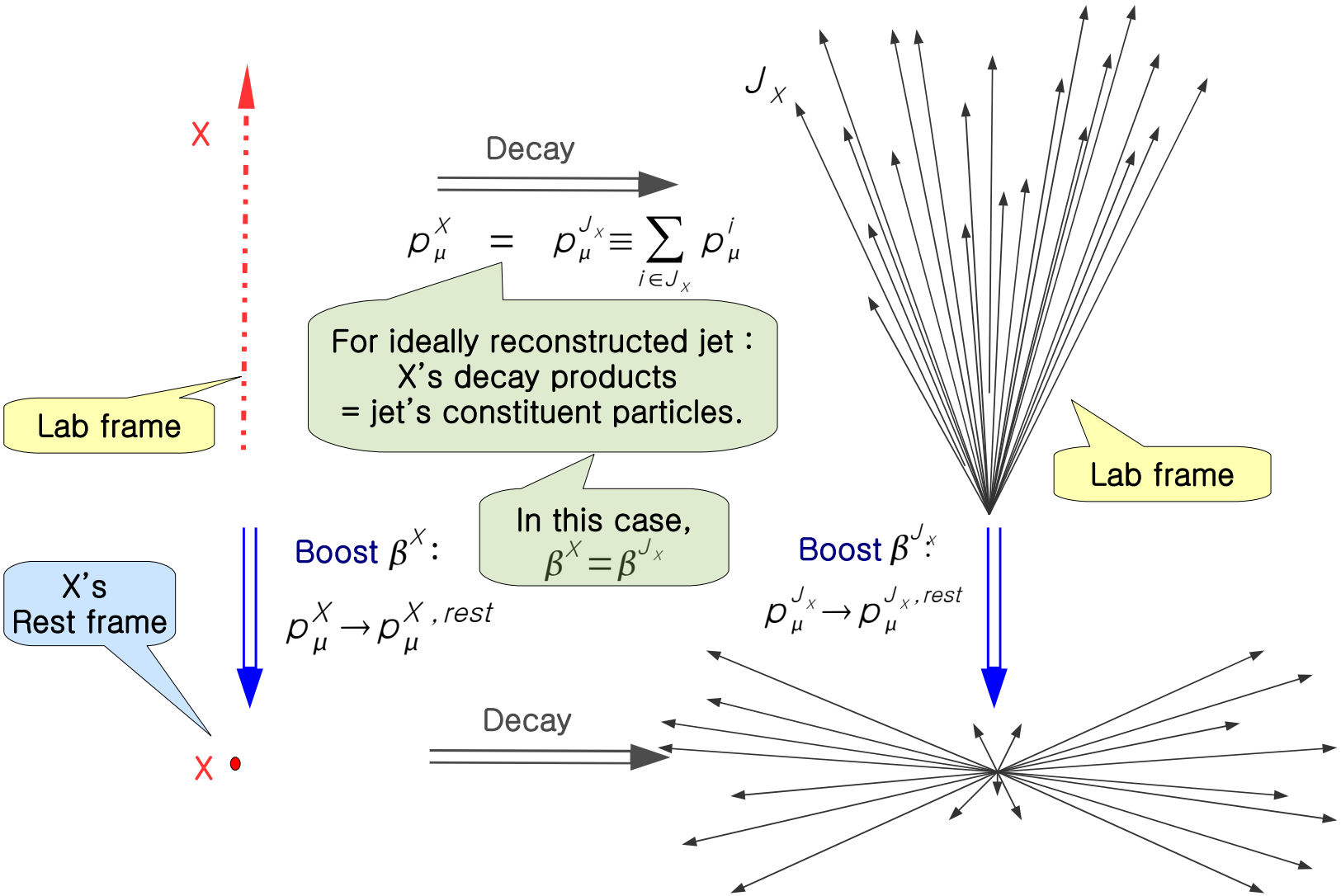
Boosted color singlet particle in the jet rest frame.



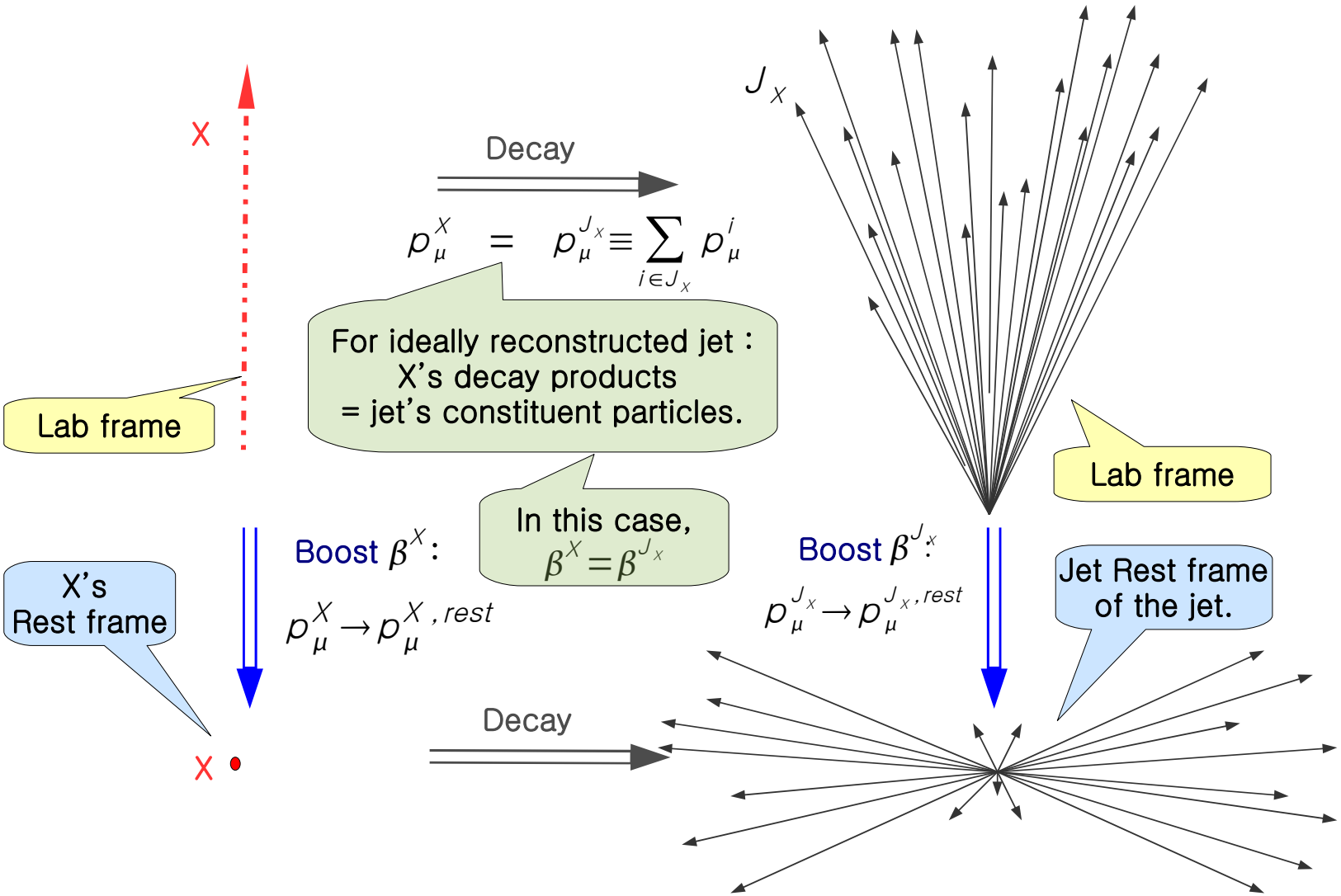
Boosted color singlet particle in the jet rest frame.



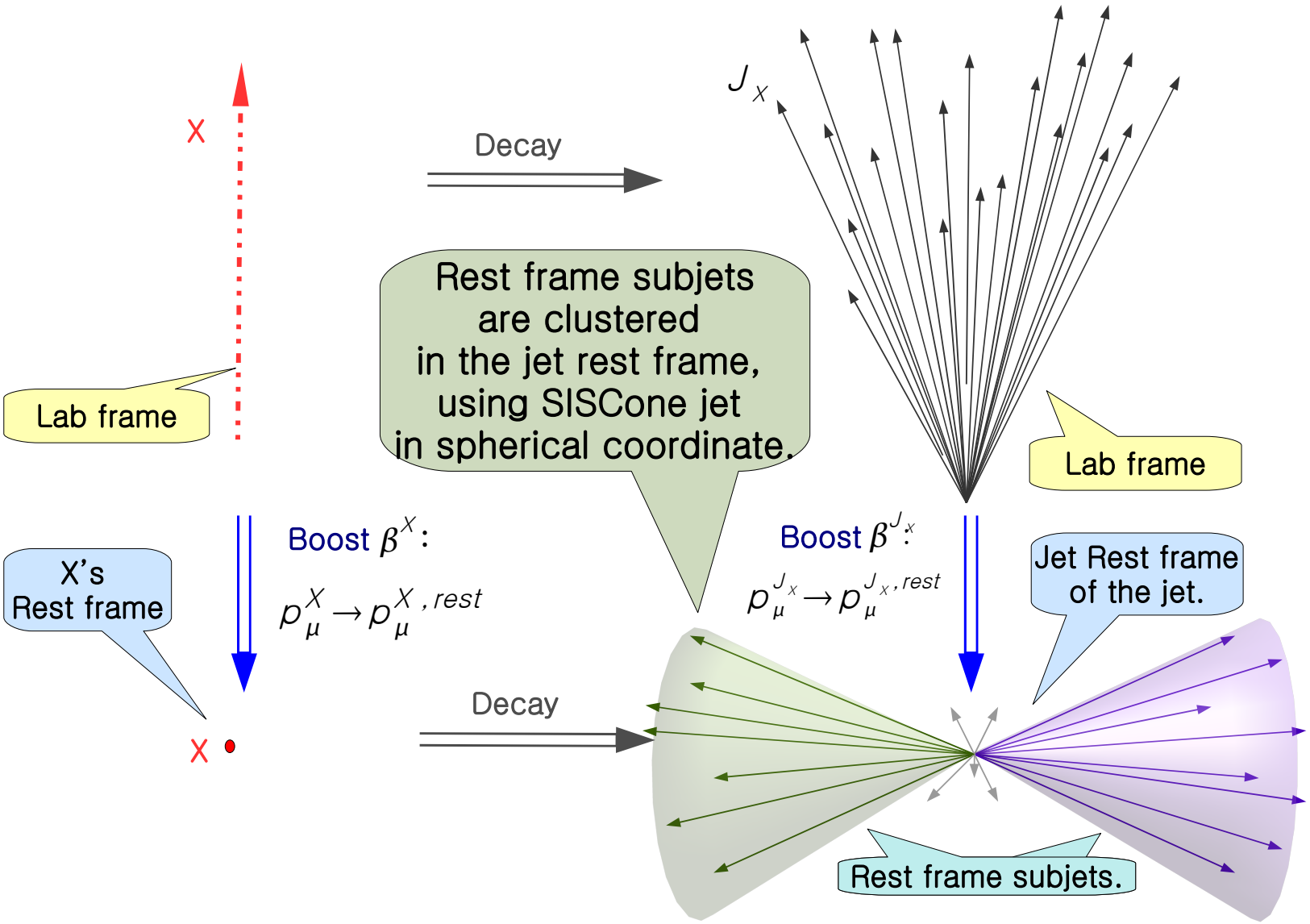
Boosted color singlet particle in the jet rest frame.



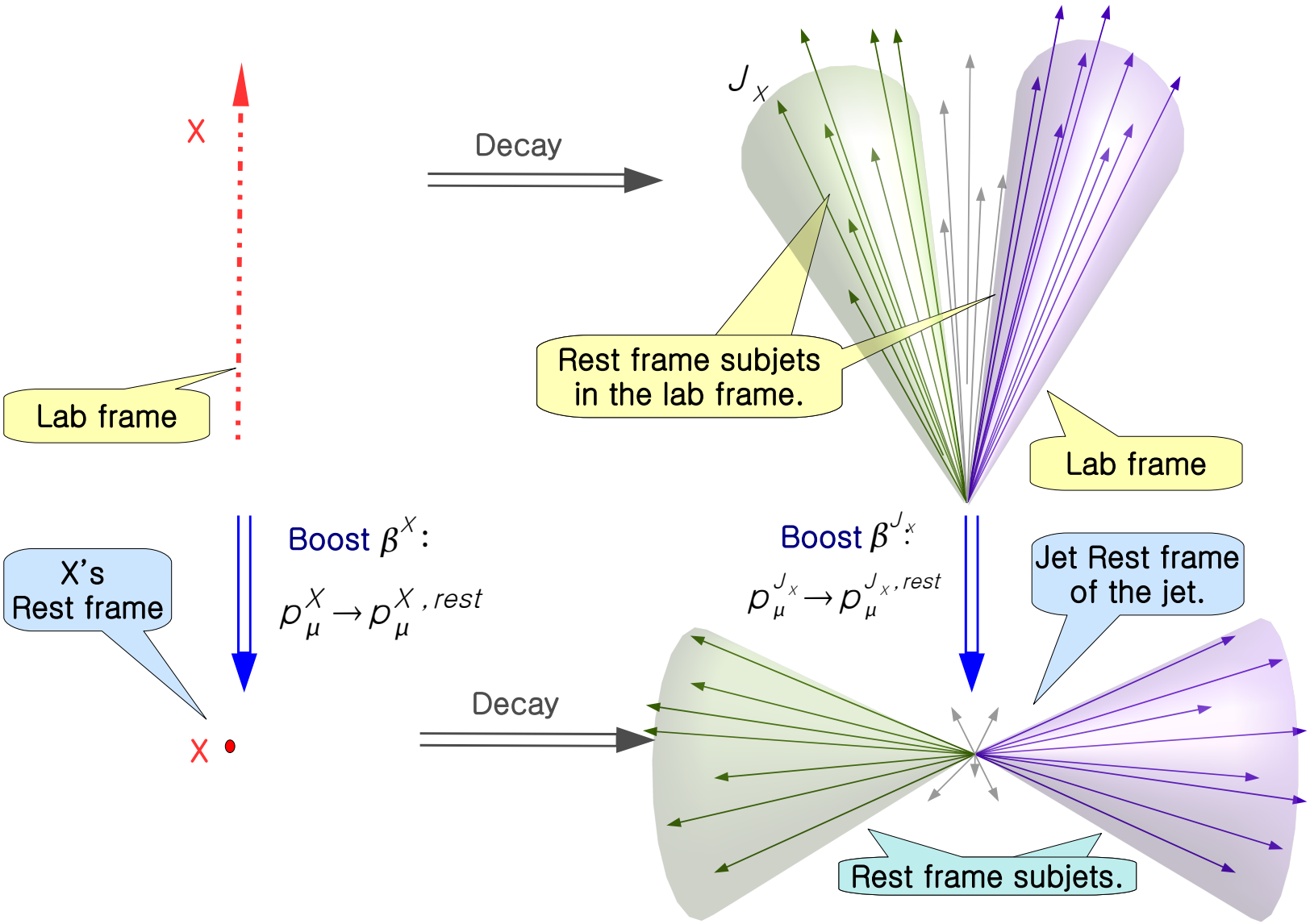
Boosted color singlet particle in the jet rest frame.



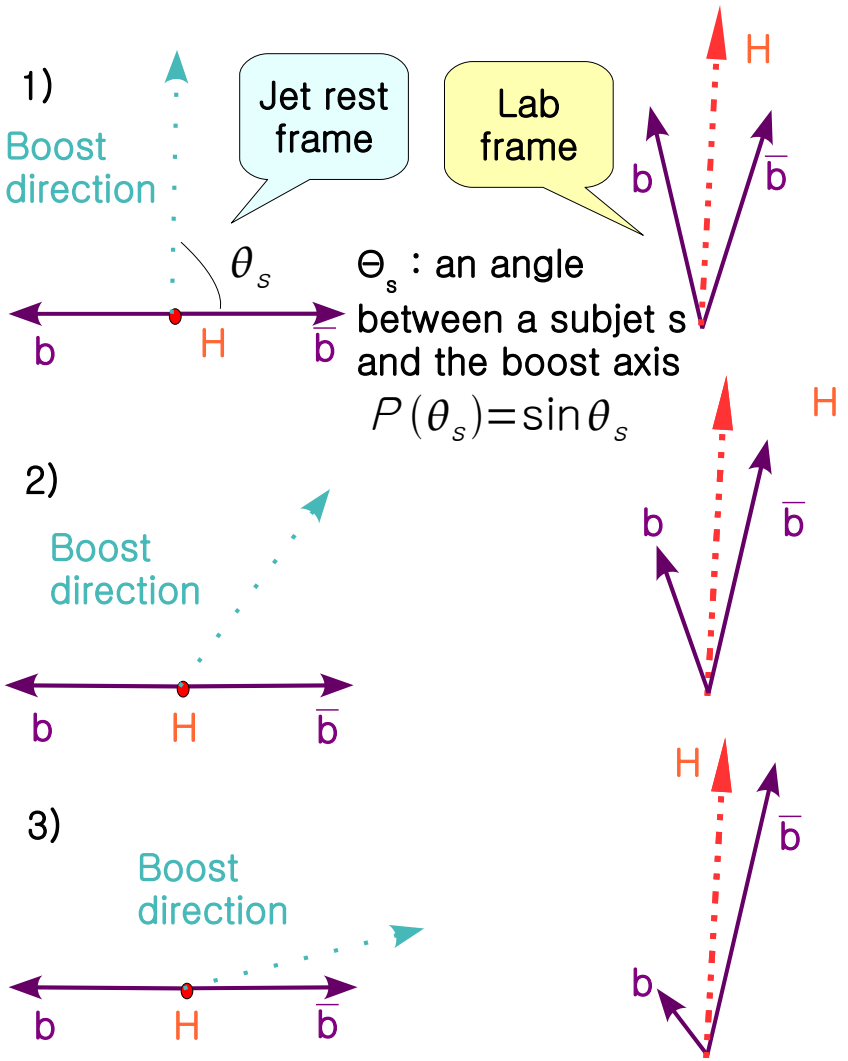
Boosted color singlet particle in the jet rest frame.



Boosted color singlet particle in the jet rest frame.



Rest frame subjet : Higgs jet case.



Most probable &
⇒ Likely to be reconstructed properly

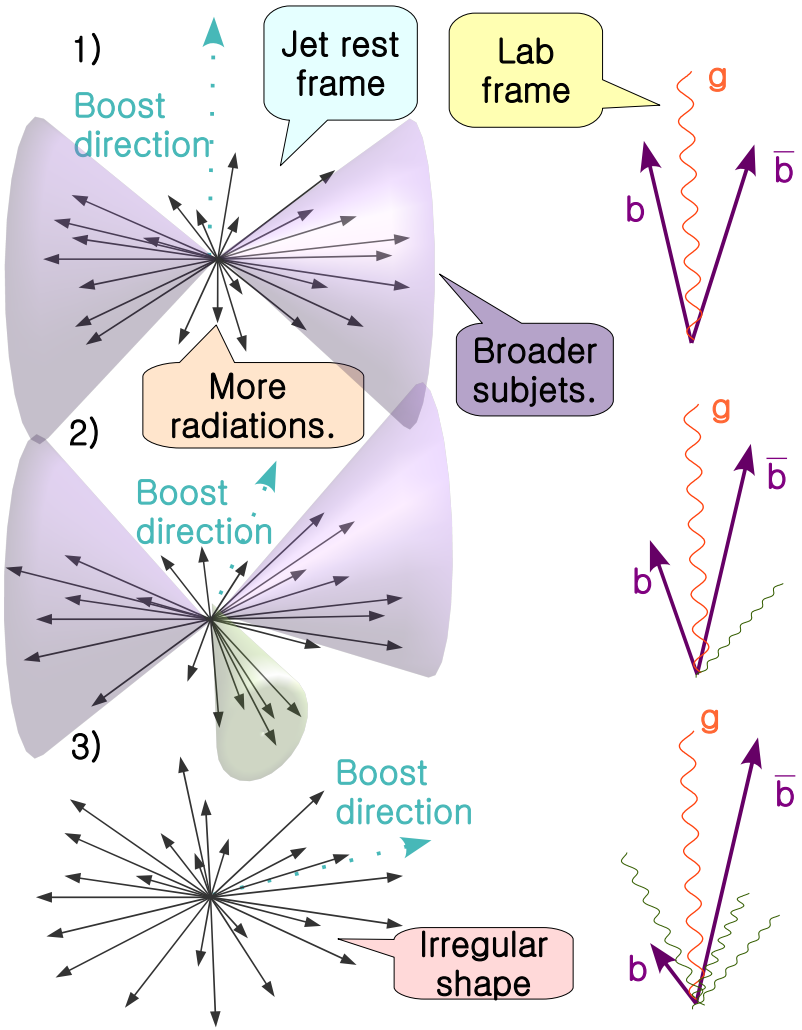
Less probable &
⇒ Less likely to be reconstructed properly

Least probable &
⇒ Unlikely to be reconstructed properly

The jet rest frame : QCD jet case

Colored partons hadronize

$\Rightarrow$ causes their shape in the jet rest frame more irregular. Moreover,



Corresponds to
hard gluon splitting &
$\Rightarrow$ no more hard radiation.
Least probable.

Less hard gluon splitting &
$\Rightarrow$ additional radiation.
More probable.

Soft gluon splitting &
$\Rightarrow$ additional radiations.
Most probable.

Difference between fat jets and QCD jets.

Boosted H / W / Z jets are likely to give

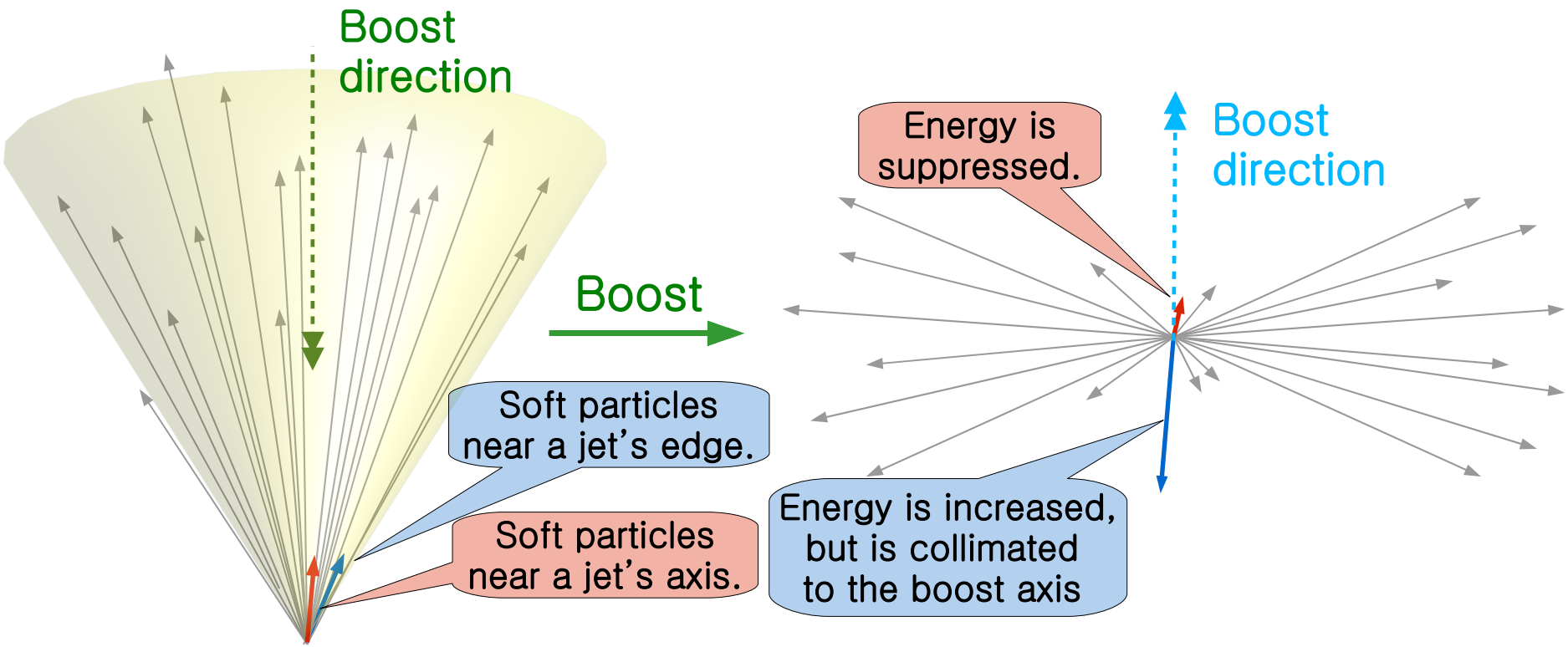
- Two energetic subjets
- Narrower subjets.
- $\theta_s \sim \pi/2$.
- Smaller τ_2.

QCD jets are likely to give

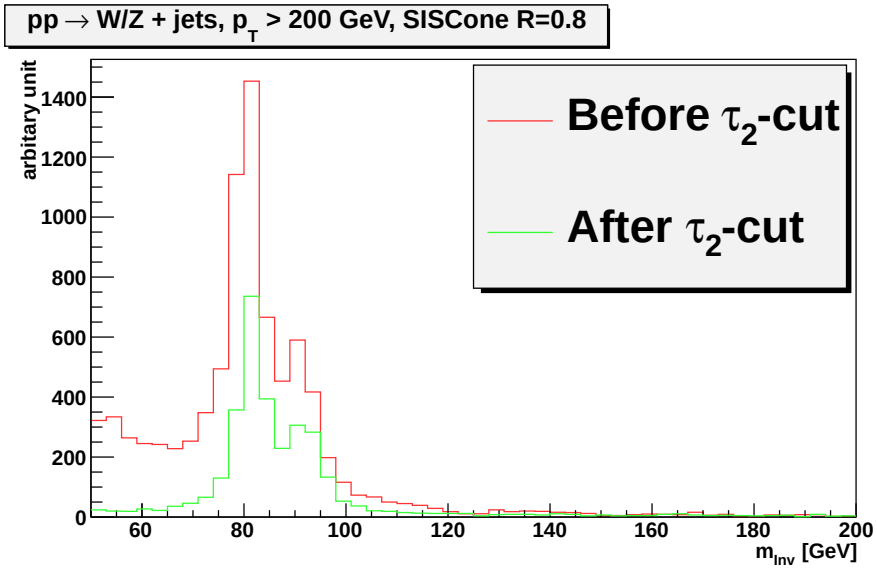
- Several subjets.
- Broader subjets.
- $\theta_s \sim 0$, or π.
- Larger τ_2.

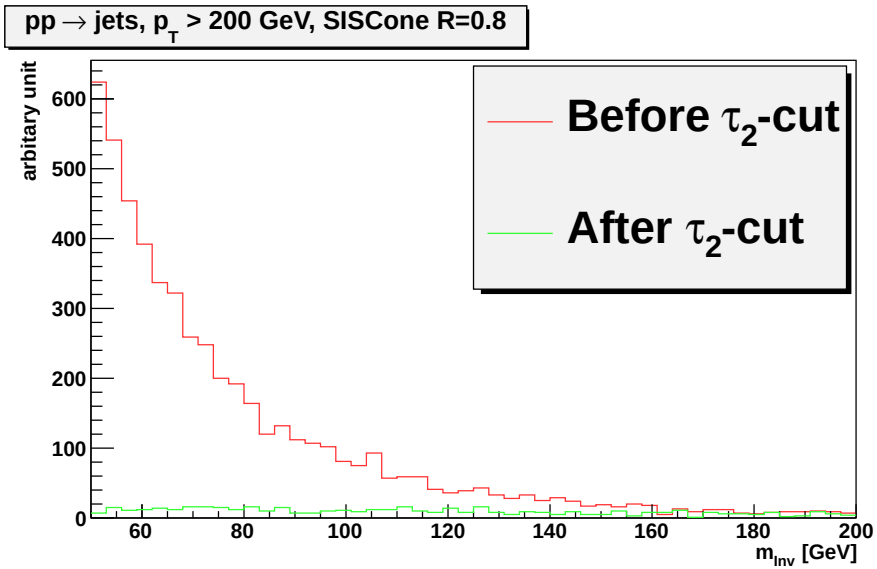
Effects of underlying event(UE) and plieup on N-subjettiness.

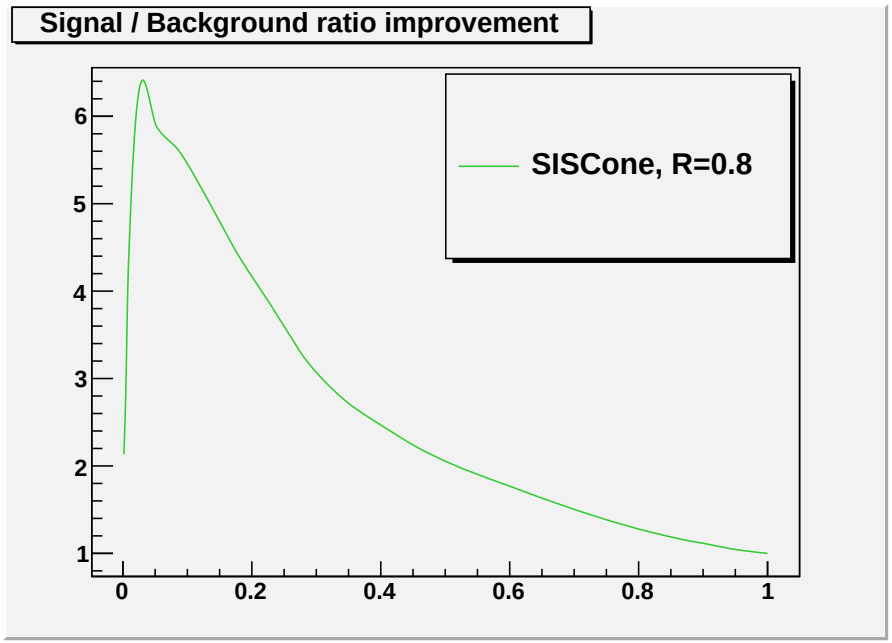
- UE, Pileup : Affects τ_N^j via jet mass, subjets.
- $\tau_N^j \propto m_{jet}^{-2}$: 10% $\uparrow$ of m_{jet} $\Rightarrow$ 20% $\downarrow$ of τ_N^{rest}.
- Note that, very soft particles can change τ_N^{rest} only a little bit : τ_N^{rest} is infra red safe.



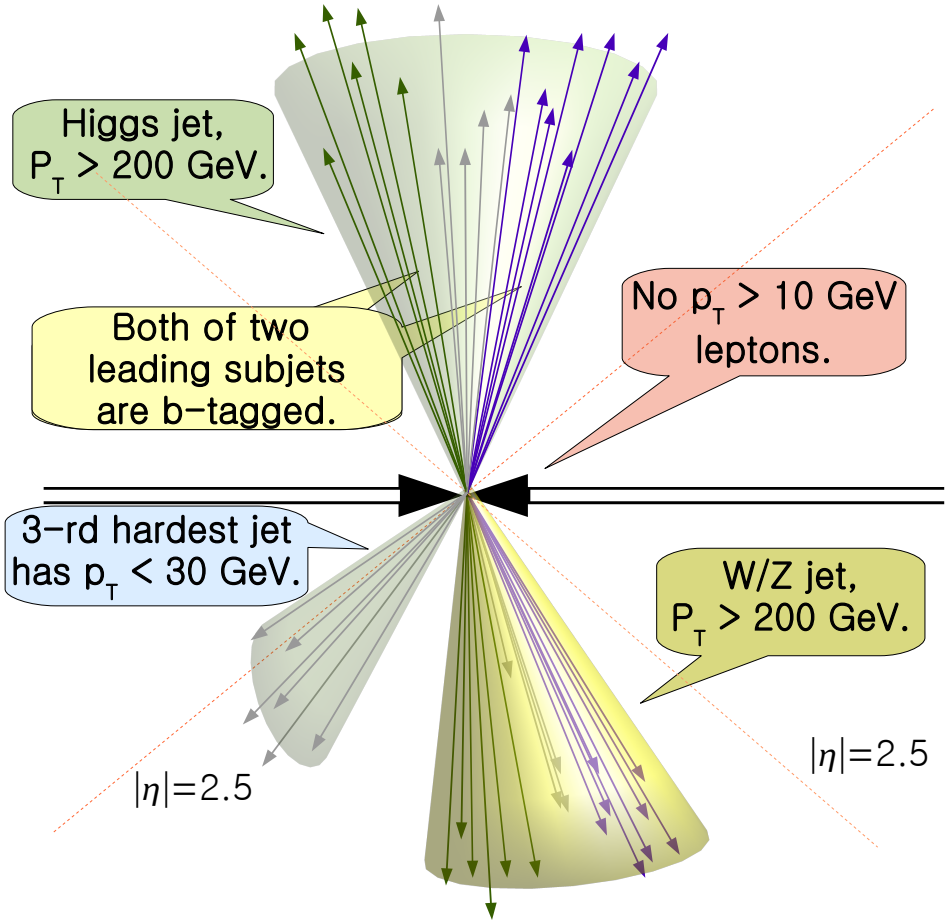
Before and after τ_2^{rest}-cut : $W/Z + jets$ case @ 7TeV LHC.







Higgs searches via $pp \to H + W/Z$ @14TeV collision .



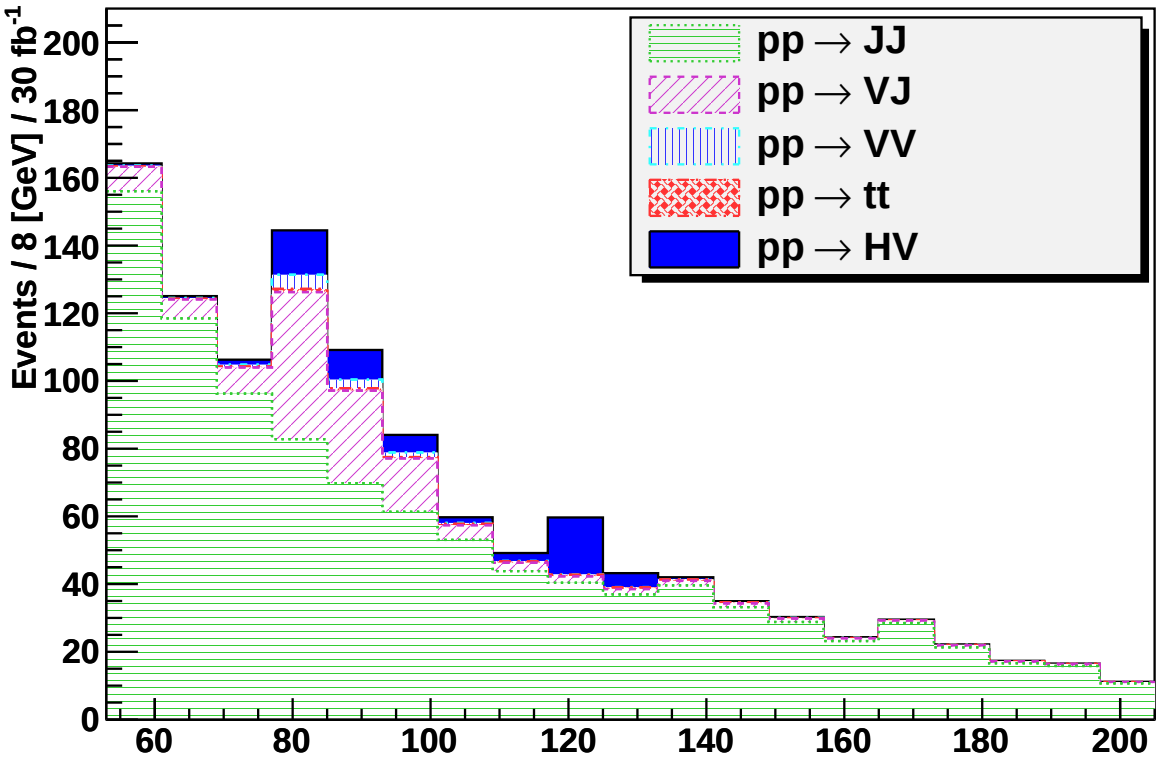
Both of two leading jets are required to satisfy :

- $\tau_2^{rest} < 0.08$ cut.
- $\cos\theta_s < 0.8$ cut.

And two leading subjets of the Higgs candidate jets are required to be b-tagged.

The results

PYTHIA 6.4.23 + ATLAS MC09 parameter tune.
Jet clustering : SISCone jet, R = 0.8, f = 0.75 (f = overlab threshold).
Subjet clustering : SISCone jet in spherical coordinate, R = 0.7, f = 0.75.



- $30\mathrm{fb}^{-1}$ of LHC 14 TeV,
- With a jet mass resolution $\pm 10\mathrm{GeV}$:
  $S/B \sim 30/200$ and
  $S/\sqrt{B} \sim 2\sigma$.

Summary

- Rest frame subjet algorithm provides a subjet definition for any jet algorithm including SISCone, Anti-k_T jet algorithm.
- N-subjettiness : for selecting boosted particles decaying to N partons.
- τ_2^{rest} cut, $\cos\theta_s$ cut identify boosted H / W / Z jets.
- The scheme will be improved further to increase the significance : work in progress.
- LHC @7TeV : smaller σ, but fewer UE, pileup.
- τ_3 can be used for boosted top tagging : work in progress.
- Fastjet plug-in for N-subjettiness will be released soon.