Time-domain Jet Substructure & Boosted Object Tagging

Matthew Klimek
Cornell University
Korea University

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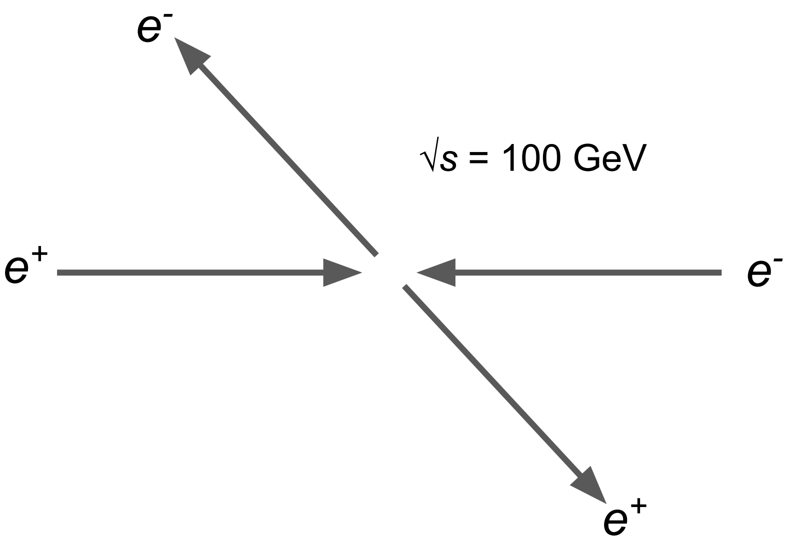
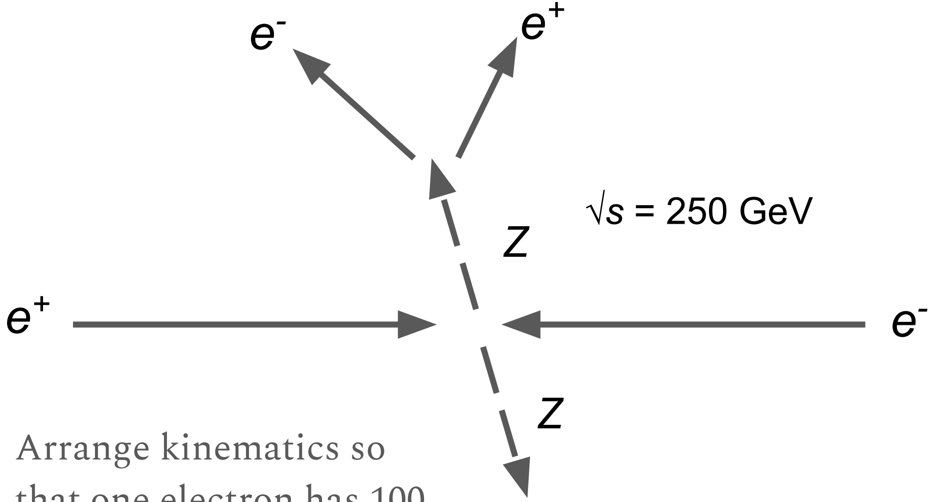
Future Colliders Workshop –
KAIST

$e^+e^- \rightarrow e^+e^-$ scattering



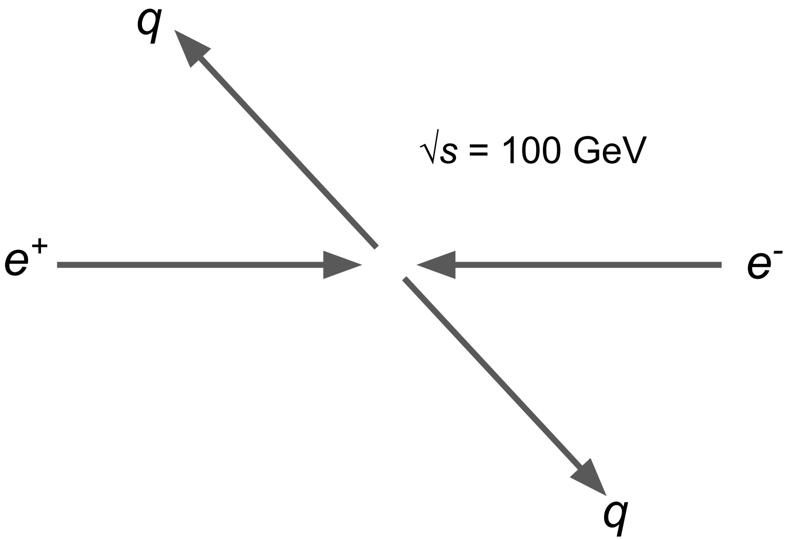
$e^+e^- \rightarrow$ leptonic ZZ production



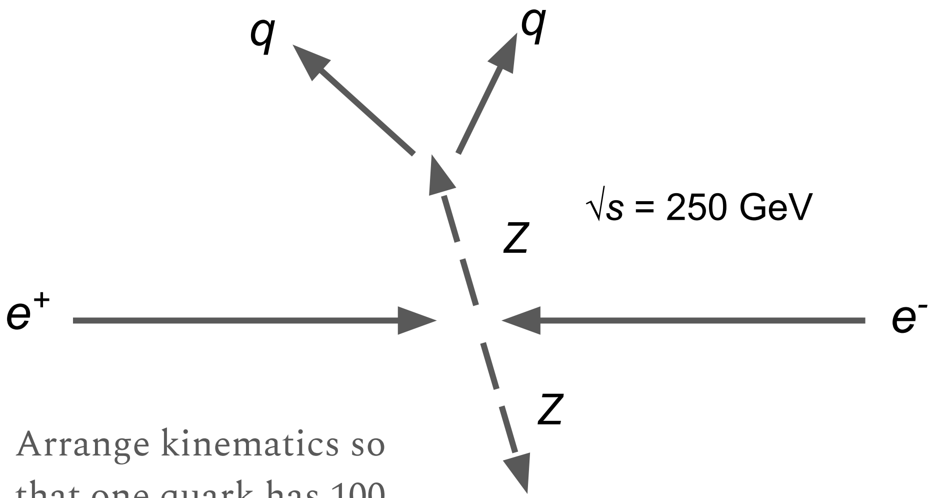
Arrange kinematics so that one electron has 100 GeV in lab frame

What is the difference between these electrons?

$e^+e^- \rightarrow qq$ dijet



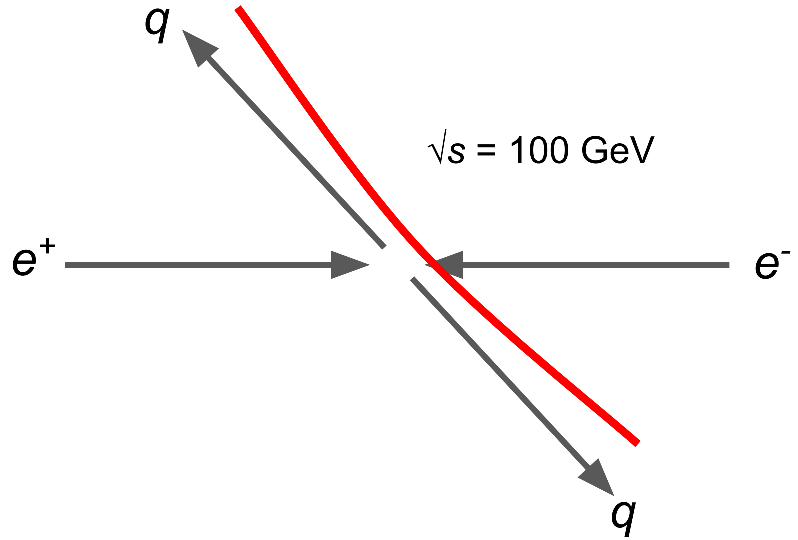
$e^+e^- \rightarrow$ hadronic ZZ production



Arrange kinematics so that one quark has 100 GeV in lab frame

What is the difference between these *quarks*?

$e^+e^- \rightarrow qq$ dijet



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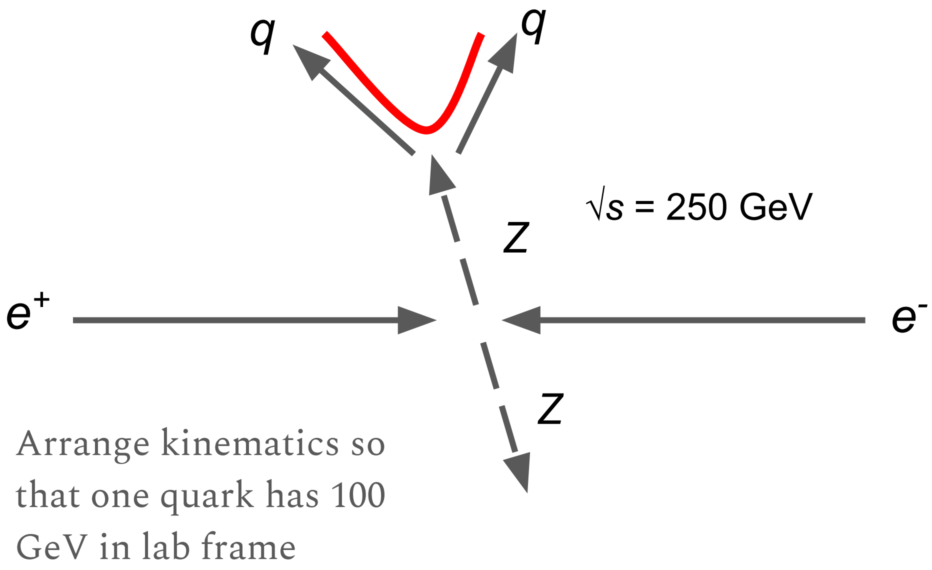

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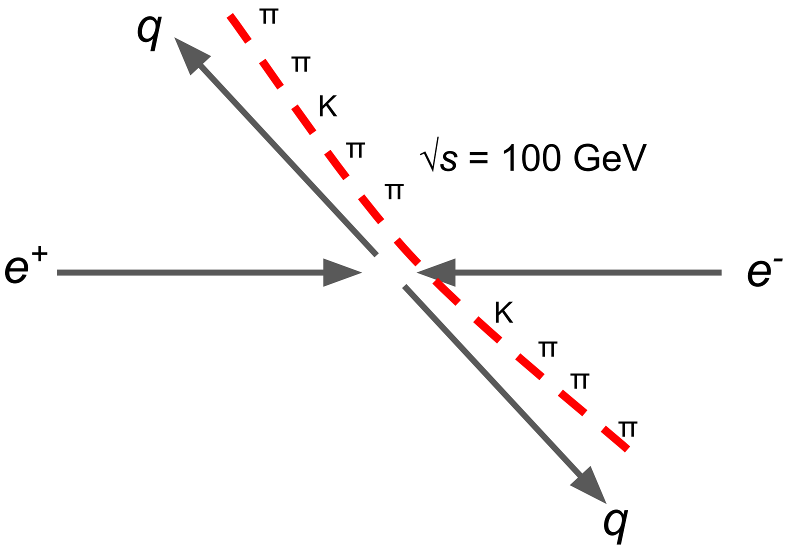

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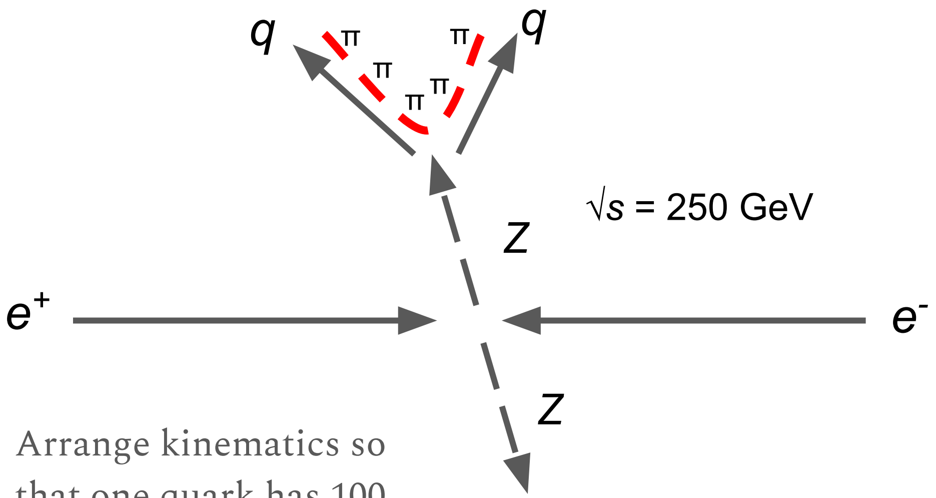


Arrange kinematics so that one quark has 100 GeV in lab frame

What is the difference between these *quarks*?

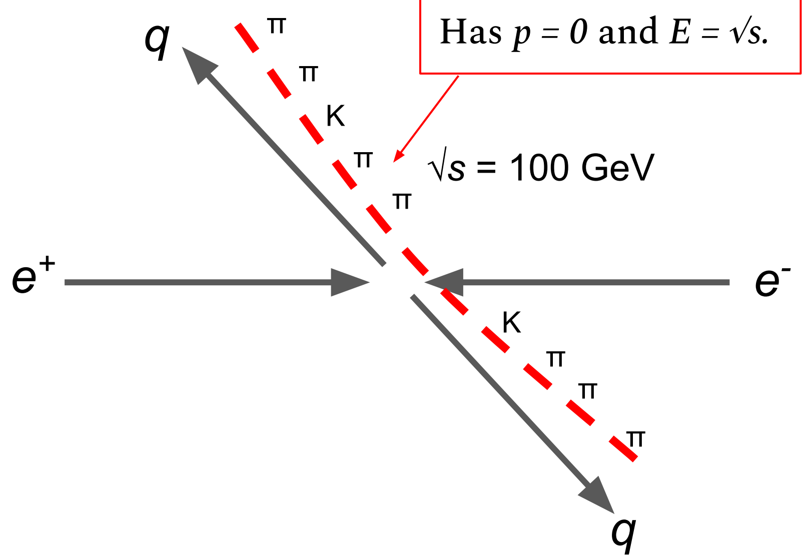
The *quarks* are *not* directly observable.

The (fragmentation products of) the color *string are* observable.

$e^+e^- \rightarrow qq$ dijet

Spans the event.

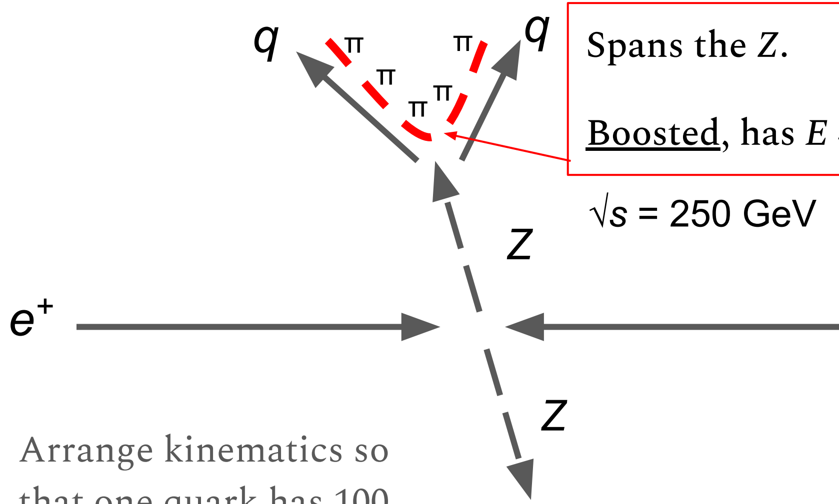
Has $p = 0$ and $E = \sqrt{s}$.



$e^+e^- \rightarrow$ hadronic ZZ production

Spans the Z.

Boosted, has $E = m_Z$.



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Of the various objects reconstructed at the LHC, jets are special in that they are collections of particles.

Trivial observation:

Unless all jet constituents have the same velocity, they will arrive spread over some finite time.

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Typical Lorentz boost of a jet hadron:

$$\gamma = \frac{E}{m} \sim \frac{E_j}{n\Lambda_{\rm QCD}}$$

Jet energy E_j and multiplicity n

Typical deviation of hadron velocity from 1:

$$1 - v \sim \gamma^{-2} \sim \left(\frac{E_j}{n\Lambda_{\rm QCD}}\right)^{-2}$$

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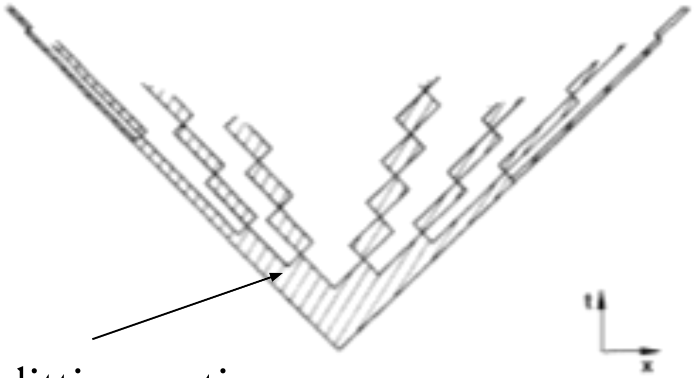
For meter-scale detectors, $n \sim 10$, $E \sim 100$ GeV, typical time-of-flight differences among jet hadrons:

$$\Delta t \sim R\Delta v \sim 10^{-8}\left(\frac{10 \times 1\ \mathrm{GeV}}{100\ \mathrm{GeV}}\right)^2 \mathrm{s} \sim 100\ \mathrm{ps}$$

What is the velocity profile of a jet?

Any jet hadrons which are not ultra-relativistic have their velocities set by the non-perturbative physics of hadronization.

Cannot calculate from QCD but can be successfully treated phenomenologically, e.g. Lund string model



String splitting vertices are space-like separated

1+1-d phase space is flat in *rapidity*

$$d^2k\ \delta(k^2 - m^2) = \frac{dk}{2E} = \frac{1}{2}dy$$

$$k = m \sinh y \quad E = m \cosh y$$

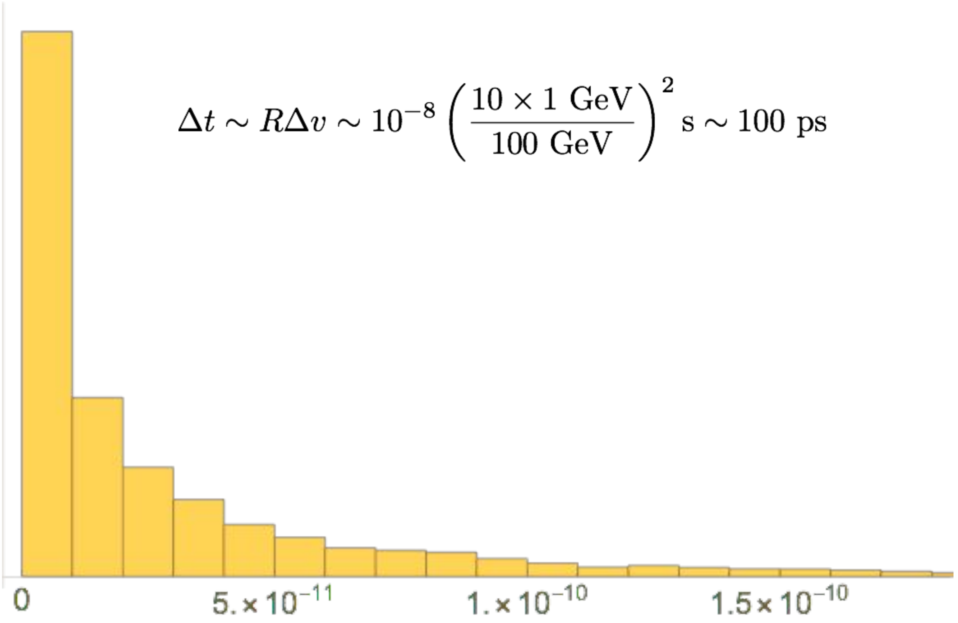
PYTHIA MC

Since v = tanh y, a flat distribution in rapidity gives a sharp peak towards v=1.

String model is the basis for PYTHIA hadronization.

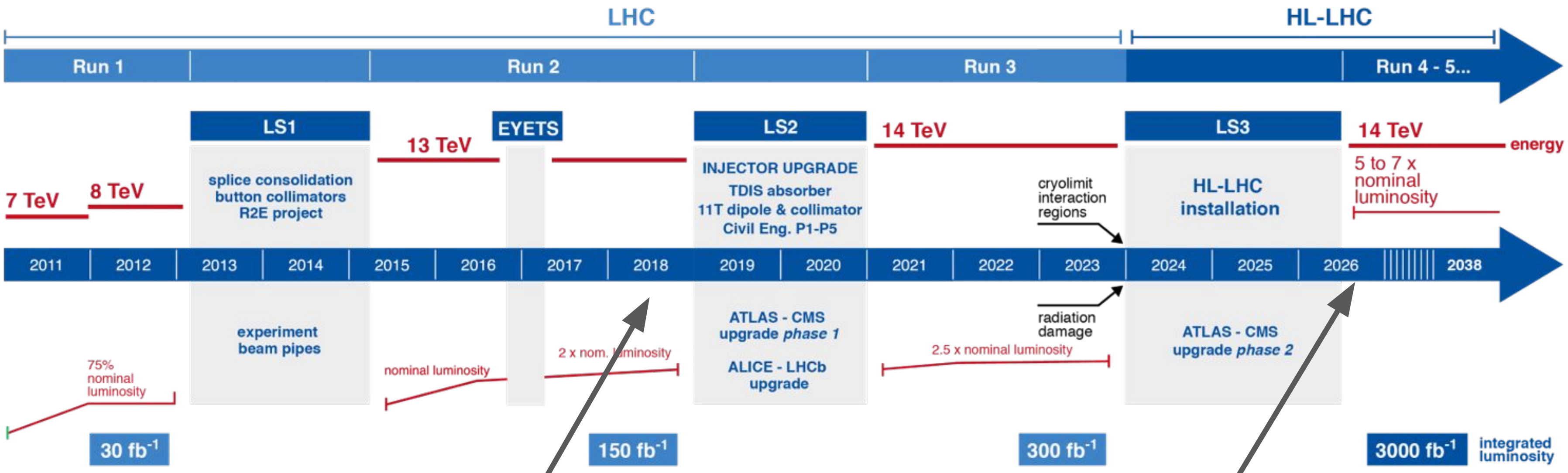
PYTHIA MC of 100 GeV quark jets.

$$\Delta t \sim R\Delta v \sim 10^{-8} \left(\frac{10 \times 1 \text{ GeV}}{100 \text{ GeV}}\right)^2 \text{s} \sim 100 \text{ ps}$$



Delay in arrival time of jet hadrons at 1 m (ps)

LHC / HL-LHC Plan

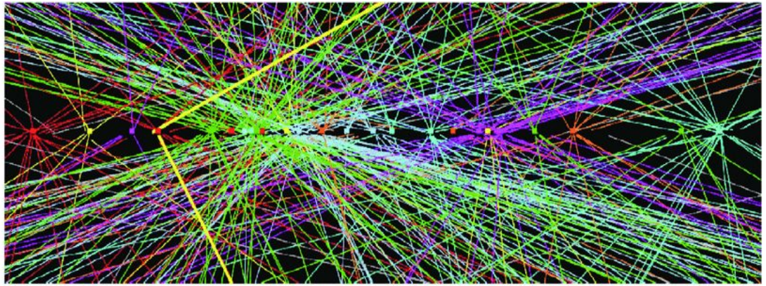


~40 interactions per bunch crossing.

Protons per bunch up by ~2x

→ interactions/crossing up by ~4x.

140 – 200 per crossing.



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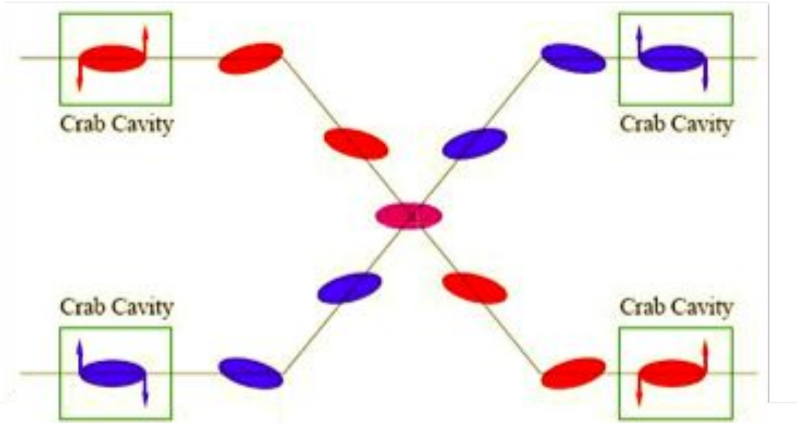


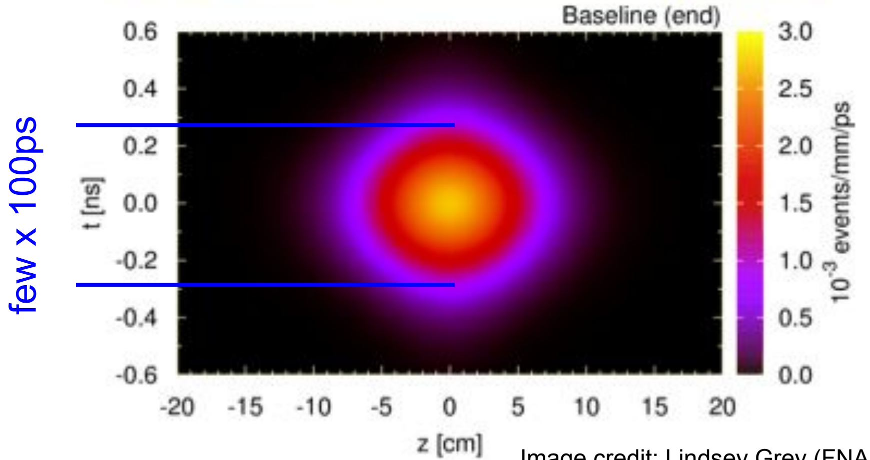
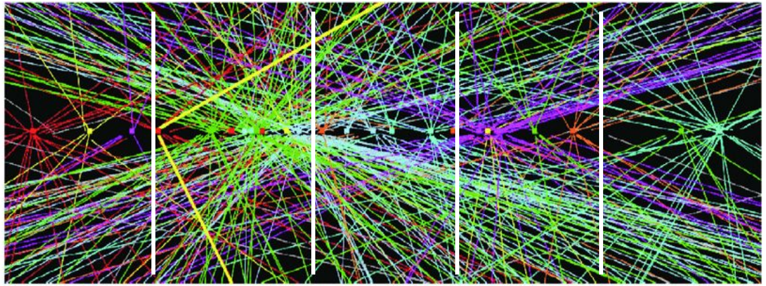


Image credit: Lindsey Grey (FNAL)



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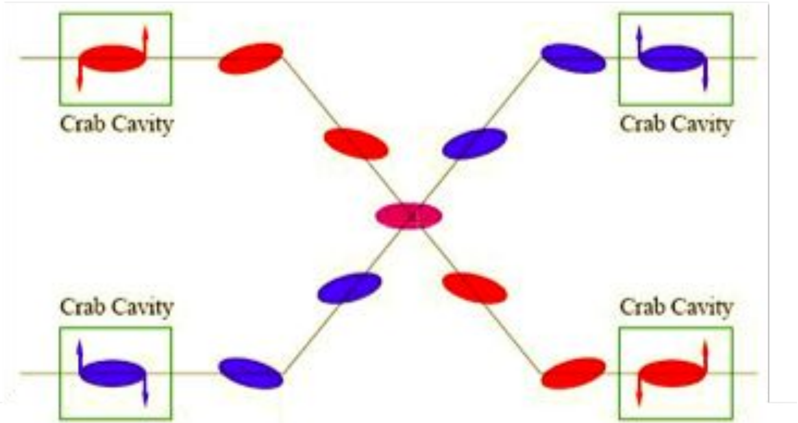
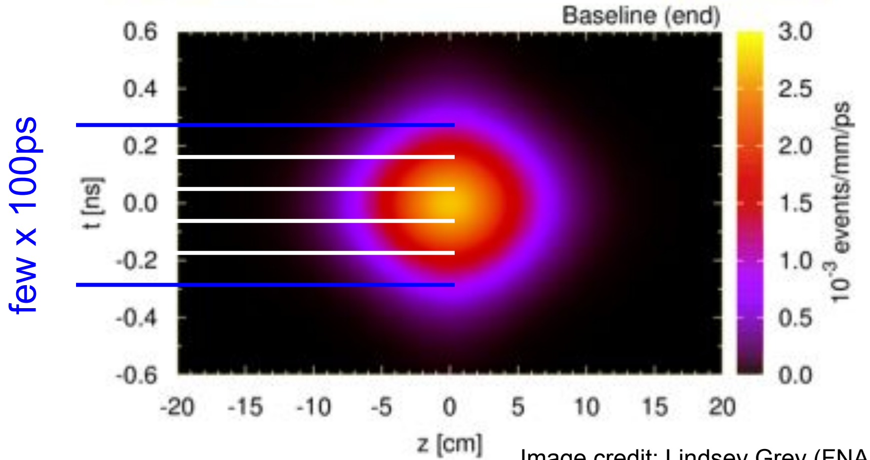
If you could slice the bunch crossing into *n* snapshots, pileup would be reduced by a factor of ~*n*.

LHC upgrades for HL phase:

30ps timing resolution.

Reduces pileup to current levels.





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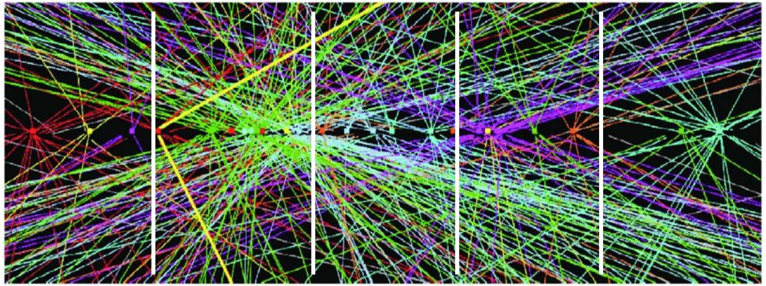

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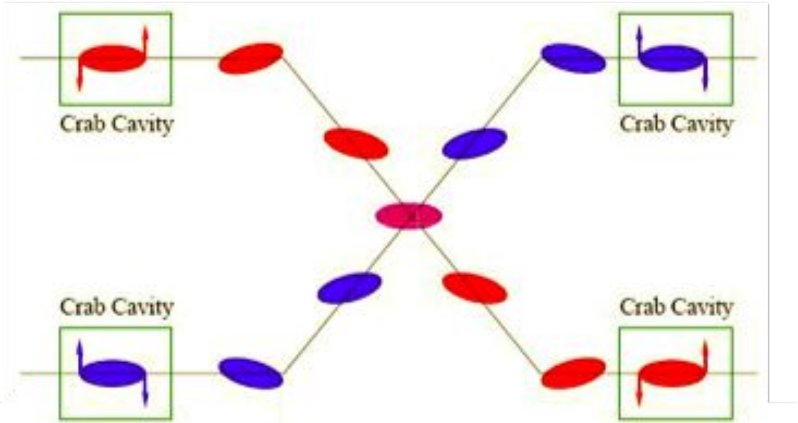

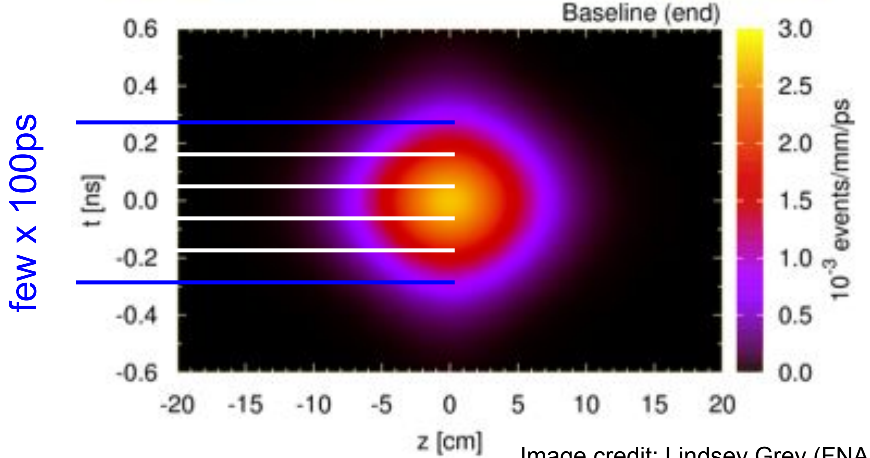

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Current and future detector technology will routinely resolve the time structure of jets.

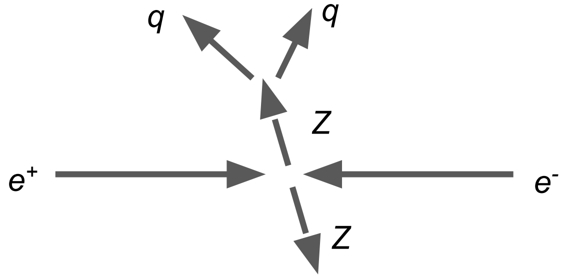
Test case: Discriminating $ZZ \to$ jets from QCD (1 TeV)

Lepton collider

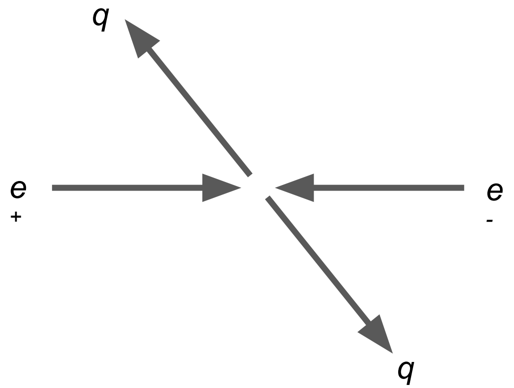
- **Hard process $\sqrt{s}$ fixed**
- **No underlying event, etc., to contaminate time profile**
- **Color strings do not connect to initial state**

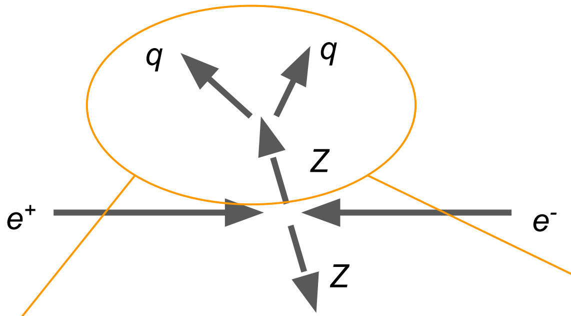
Proxy for heavy diboson resonance.
In that case, *Z*s are fairly central so that kinematics are similar to the lepton collider case.

Signal:
***ZZ* to quarks**

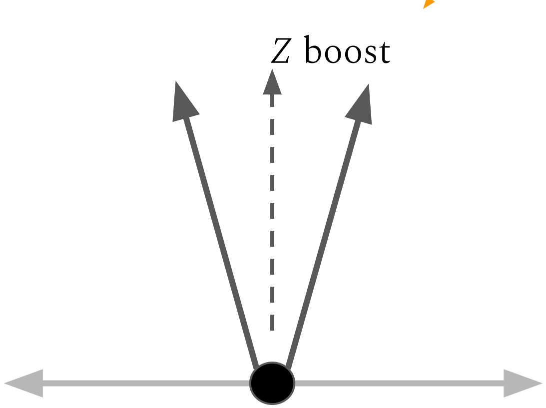


Background:
≤4 jets

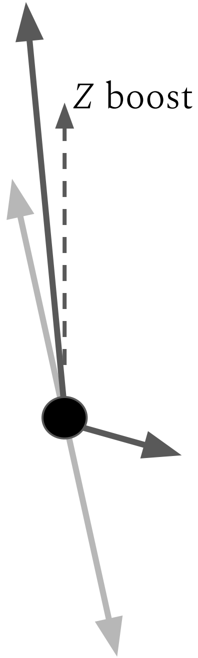


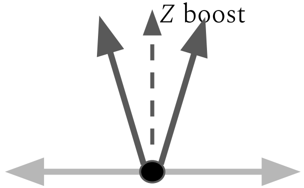


- ➢ Two roughly symmetrical jets
- ➢ Small opening angle
- ➢ Classic 2-prong object



- ➢ One hard narrow jet carrying most of *Z*'s energy
- ➢ One very soft, broadened jet – may fail reconstruction
- ➢ Hadrons from backwards jet may be pushed into forward jet's cone

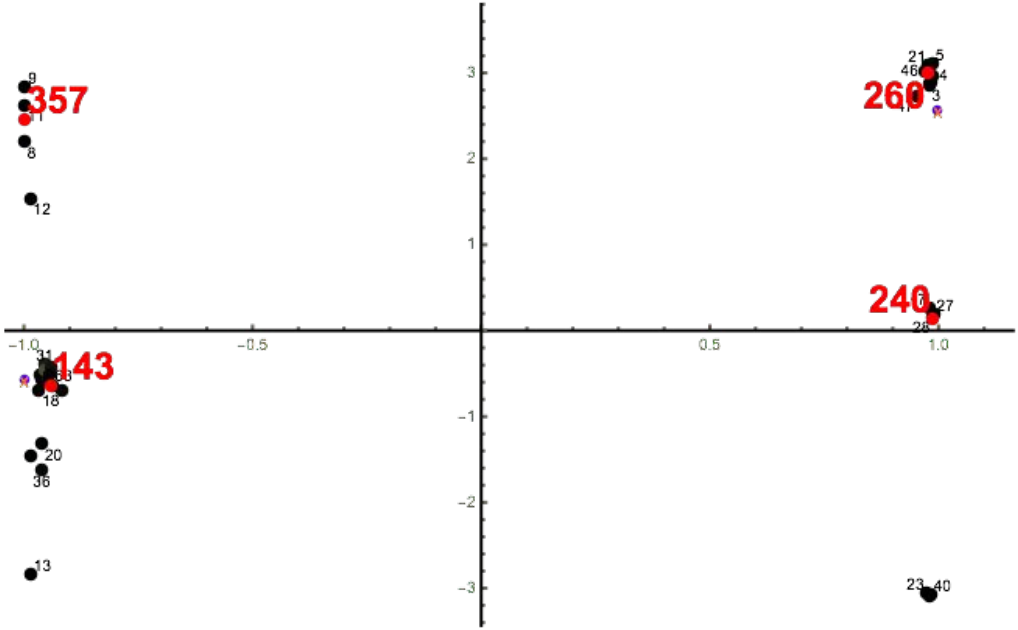




This kind of boosted ZZ event should be recognized by jet substructure

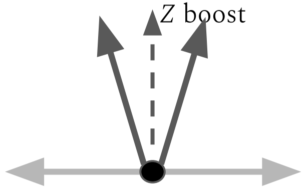
Mass drop:

- Cluster jet using CA algorithm
- Sequentially undo clustering. At each step ask:
    - Is most massive prong much lighter than the total?
    - Is splitting symmetric?
- If yes, call it a boosted object.
- If no, take most massive prong and continue.



ZZ signal event

Both jets tagged as boosted object with masses (90.1, 91.9) GeV.



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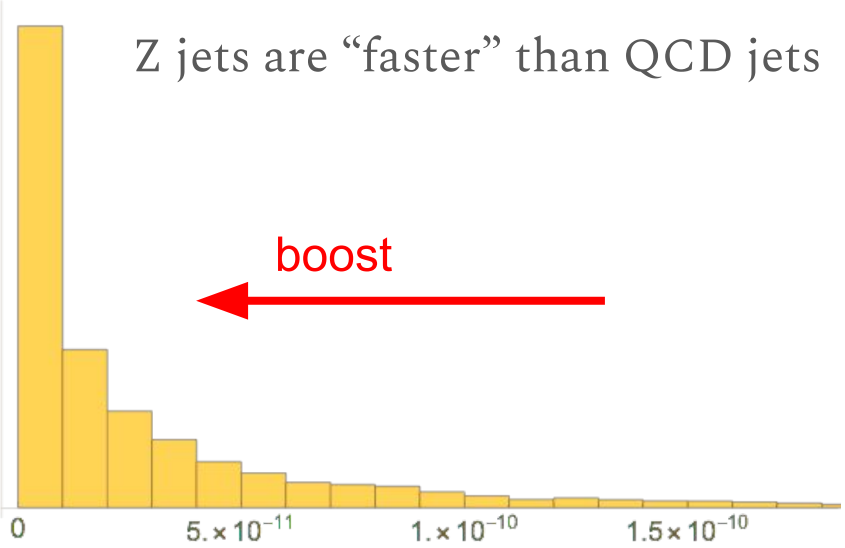
QCD dijet event.

One jet fails Mass Drop; other is accidentally tagged with mass 90.1 GeV.

But there is a meaningful sense in which the Z jets are boosted relative to a QCD jet of the same energy.

The natural time profile will be compressed by the boost.

Z jets are “faster” than QCD jets



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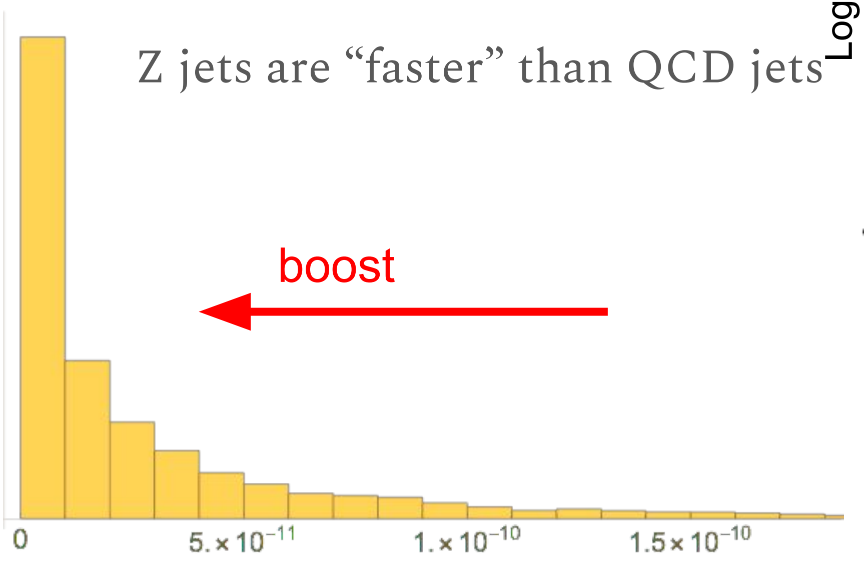
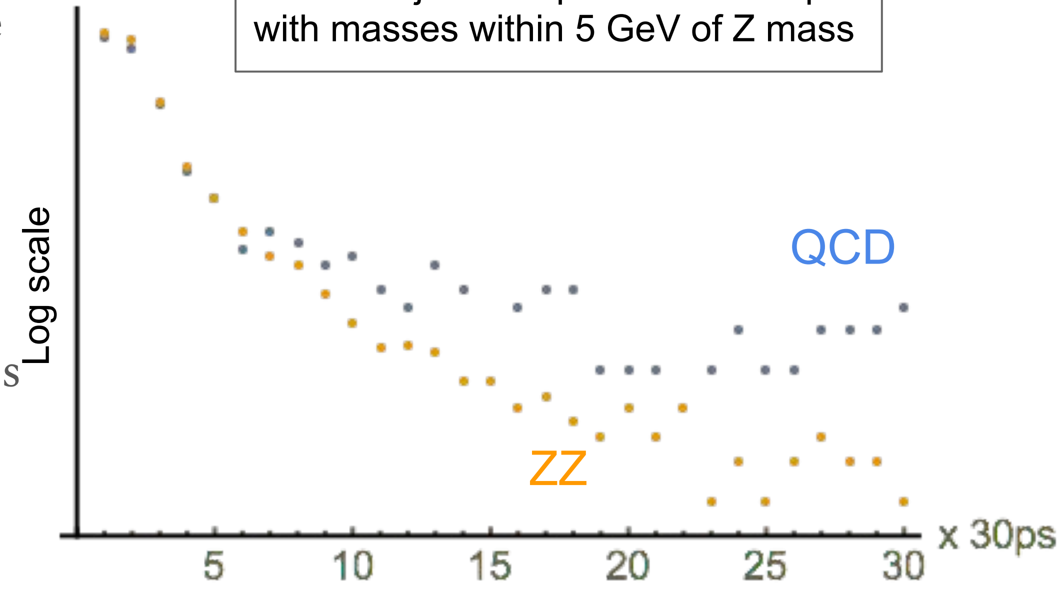
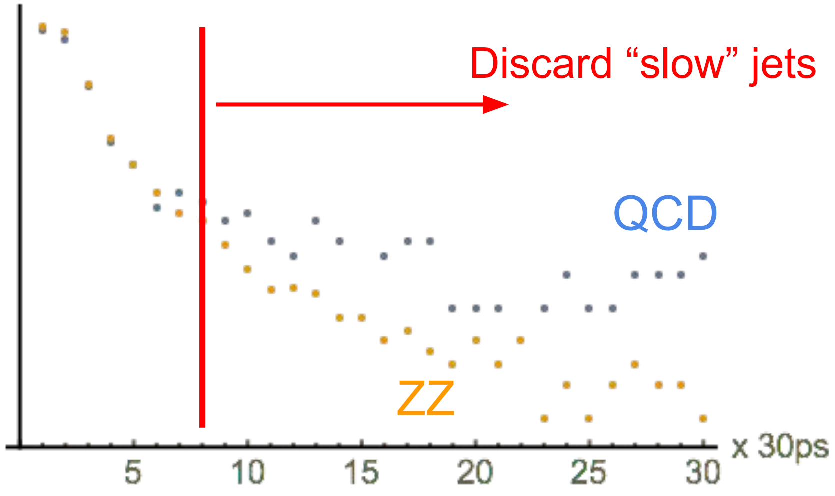


Select all jets that pass Mass Drop with masses within 5 GeV of Z mass



Arrival delay of latest (detectable) charged hadron



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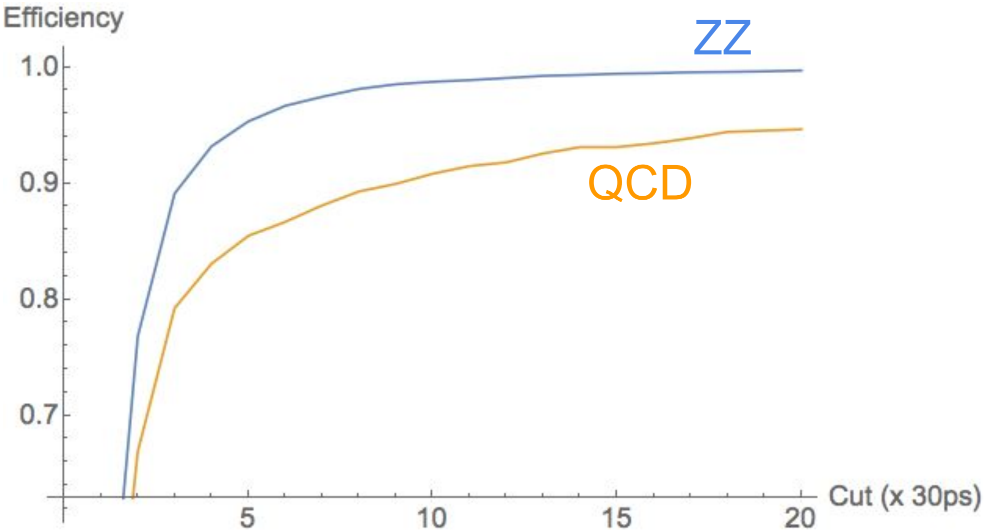
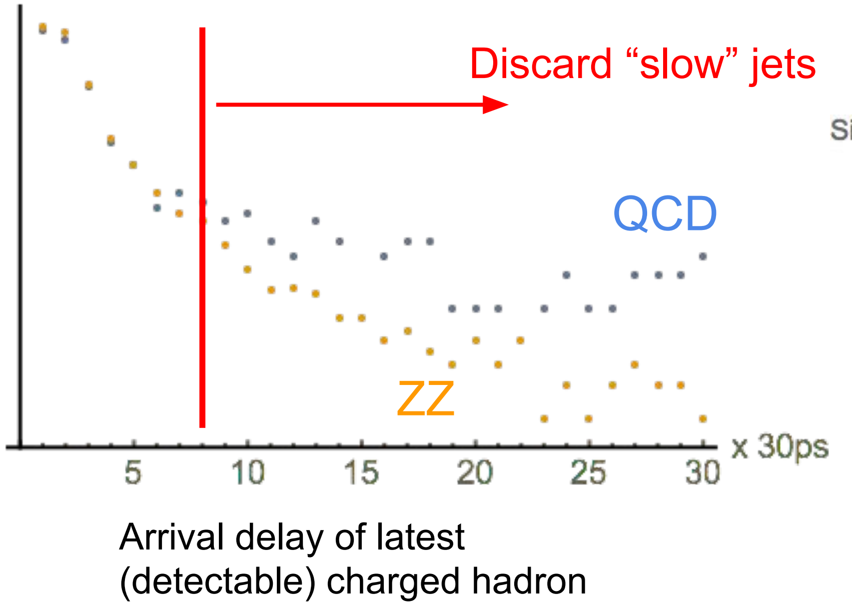
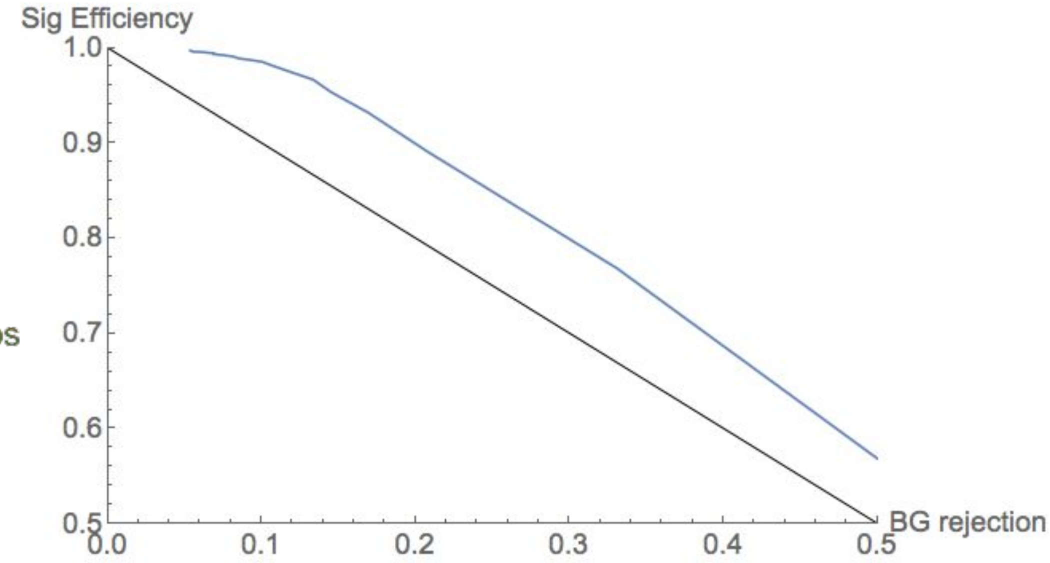


This simple cut alone can reduce the efficiency for fake Z-mass QCD jets vs. true boosted Z jets by about 10%.





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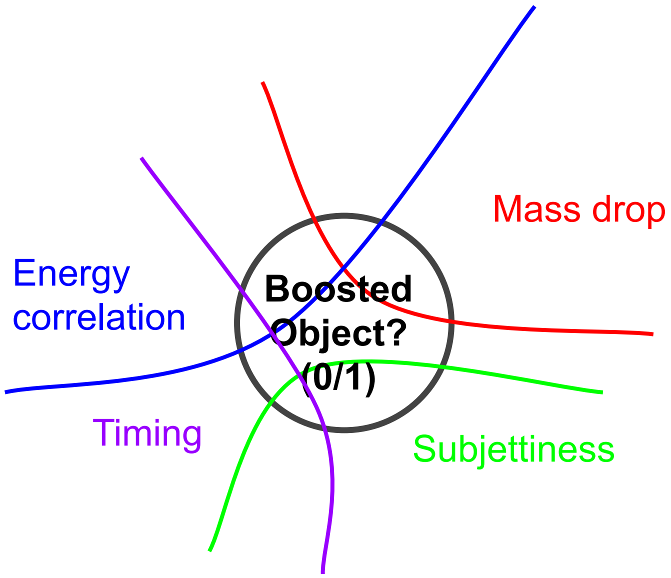
Natural question:

"The velocity is just one way to describe the kinematic data. Aren't you just saying the QCD jets have more soft particles? The tracker already measures momenta well. Can't I do this measurement another way?"

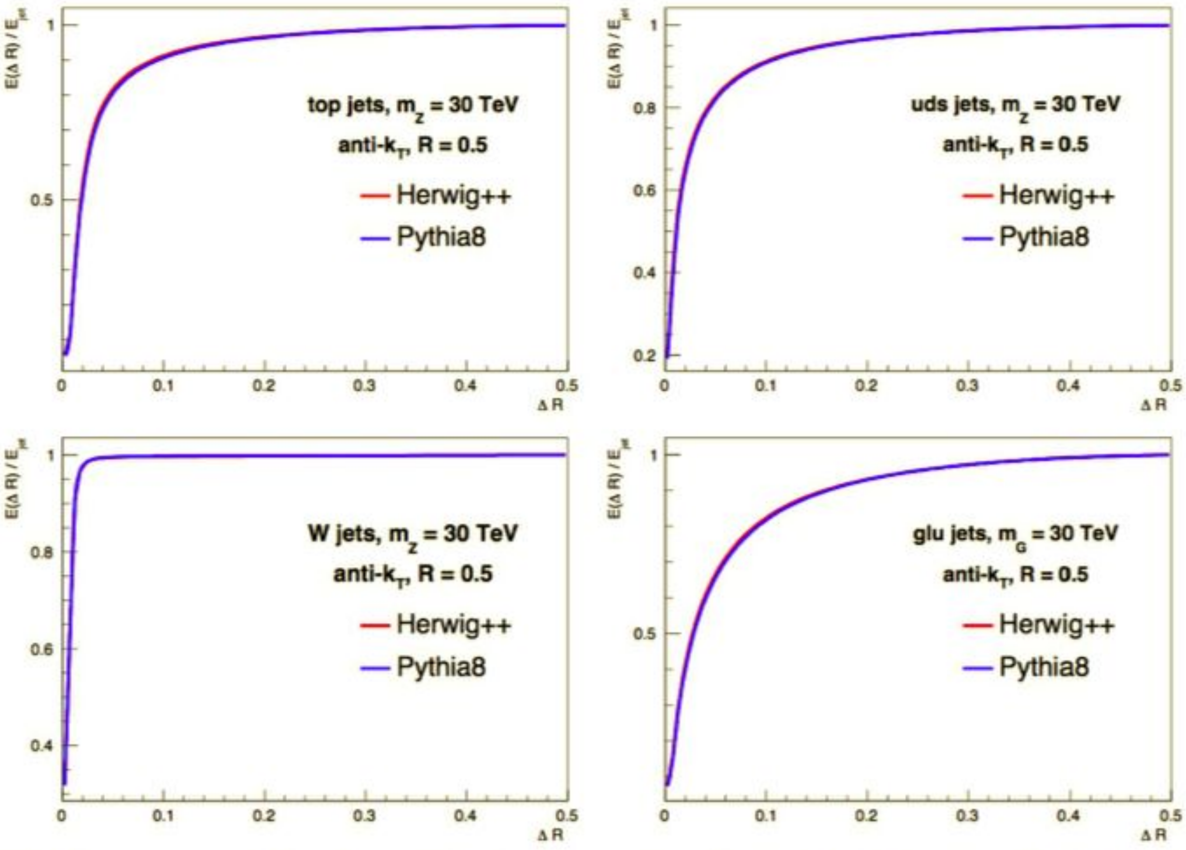
Answer: (1)

Yes! All jet-substructure tests are trying to extract the answer to a binary yes/no question from very complex data that includes much more information.



Jets' energy shape: $E(r<R) / E_{jet}$
(⇒ calorimeter granularity, tracker)

From M. Mangano in yesterday's QCD session



Natural question:

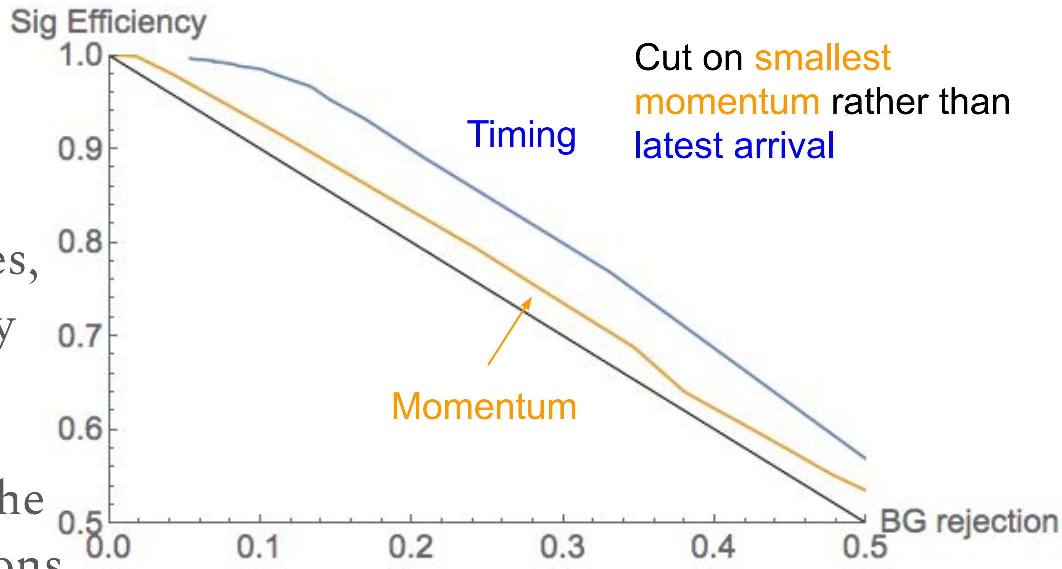
“The velocity is just one way to describe the kinematic data. Aren’t you just saying the QCD jets have more soft particles? The tracker already measures momenta well. Can’t I do this measurement another way?”

Answer: (2)

No, not exactly...

Boosts act naturally on velocities, *e.g.* boosts do not change the velocity ordering of a set of particles.

The effect on *momenta* depends on the masses, which vary amount jet hadrons



Conclusions

- Timing detectors being installed for the HL-LHC, and available for all future colliders, will probe the time scales over which jets arrive.
- Because jets encode additional information about the event because they are formed from the fragmentation of strings that span different parts of the process.
- This information may be used for distinguishing boosted objects from QCD fakes.