Time-domain Jet Substructure & Boosted Object Tagging

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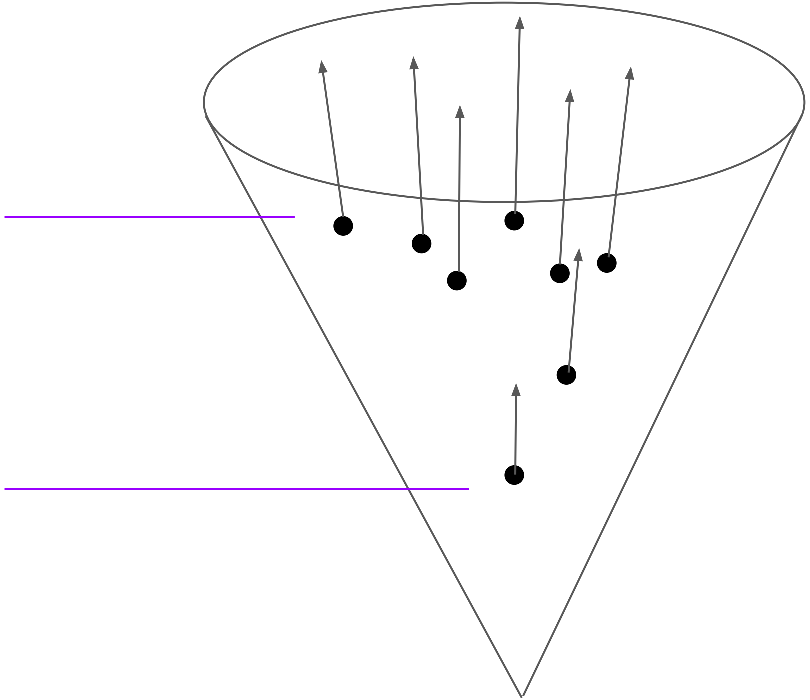
Jets are special

Among physics objects observed at particle colliders, jets are special:

They are <u>collections</u> of particles.

Trivial consequence:

If jet particles have different velocities, they arrive at the detector over some finite time span.



How long does a jet last?

Estimate:

- E_j – **Jet energy ~ 100 GeV**
- n – **Number of hadrons in jet ~ 10**
- m_p – **proton mass ~ 1 GeV**
- R – **distance to detector ~ 1 m**

Typical Lorentz boost of a jet hadron:

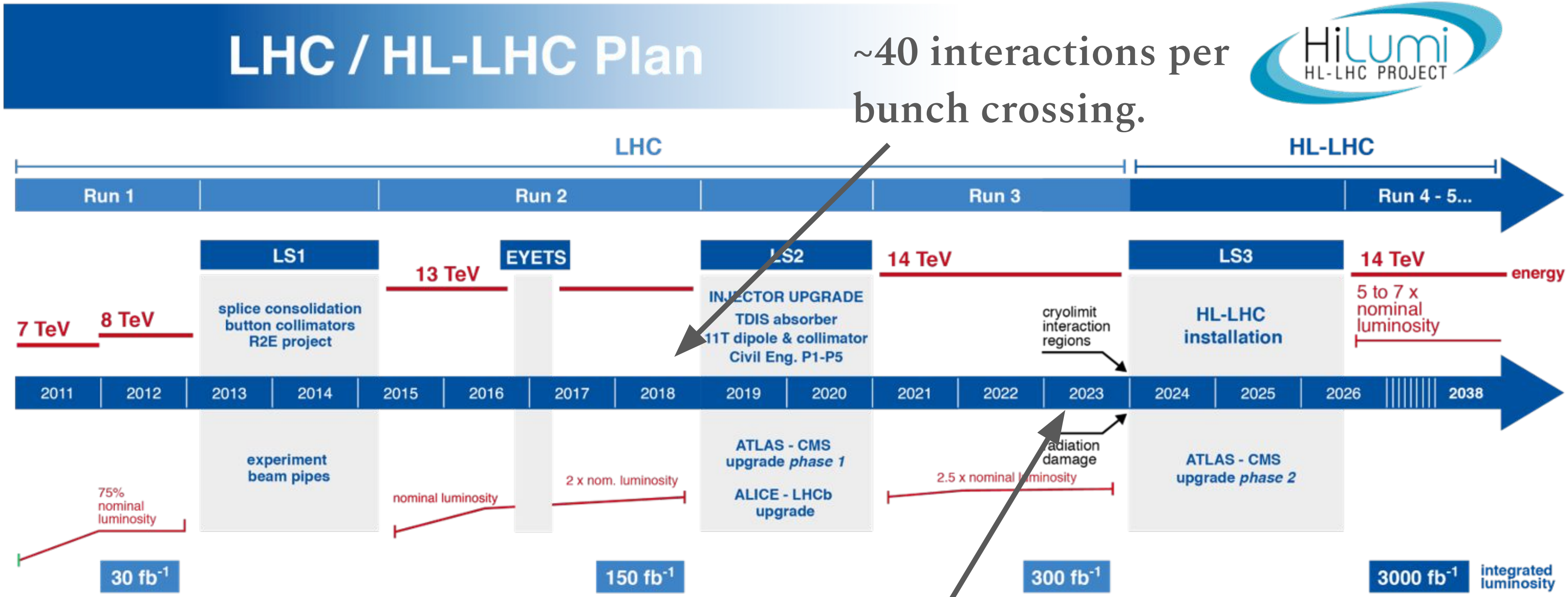
$$\gamma = \frac{E}{m} \sim \frac{E_j}{nm_p}$$

Arrival time spread:

$$\delta t \sim R\delta v \sim R\gamma^{-2}$$

For typical values of these quantities, we find δt ~ 30 ps.

Current calorimeter based timing is limited to ~150 ps, and only for particles with energy >50 GeV.



~40 interactions per bunch crossing.

Protons per bunch up by ~2x, interactions/crossing up by ~4x.

<u>140 – 200 per crossing</u> → New techniques for pileup mitigation

In this document, we show that the ability to reconstruct the timing of most of the final state particles provides further discrimination of the interaction vertices in the same 25 ns bunch crossing beyond spatial tracking algorithms. A timing resolution of about 30 ps offsets the performance degradation due to event pileup experienced in several observables, recovering the track purity of vertices of current LHC conditions. Global event timing can be achieved by upgrading CMS with a timing detector sensitive to minimum ionizing particles (MIPs) between the tracker and the electromagnetic calorimeters. This **additional MIP Timing Detector** will be specialized to provide timing for the individual tracks crossing it, while photon and hadron

CMS Timing Detector Technical Proposal LHCC-P-009

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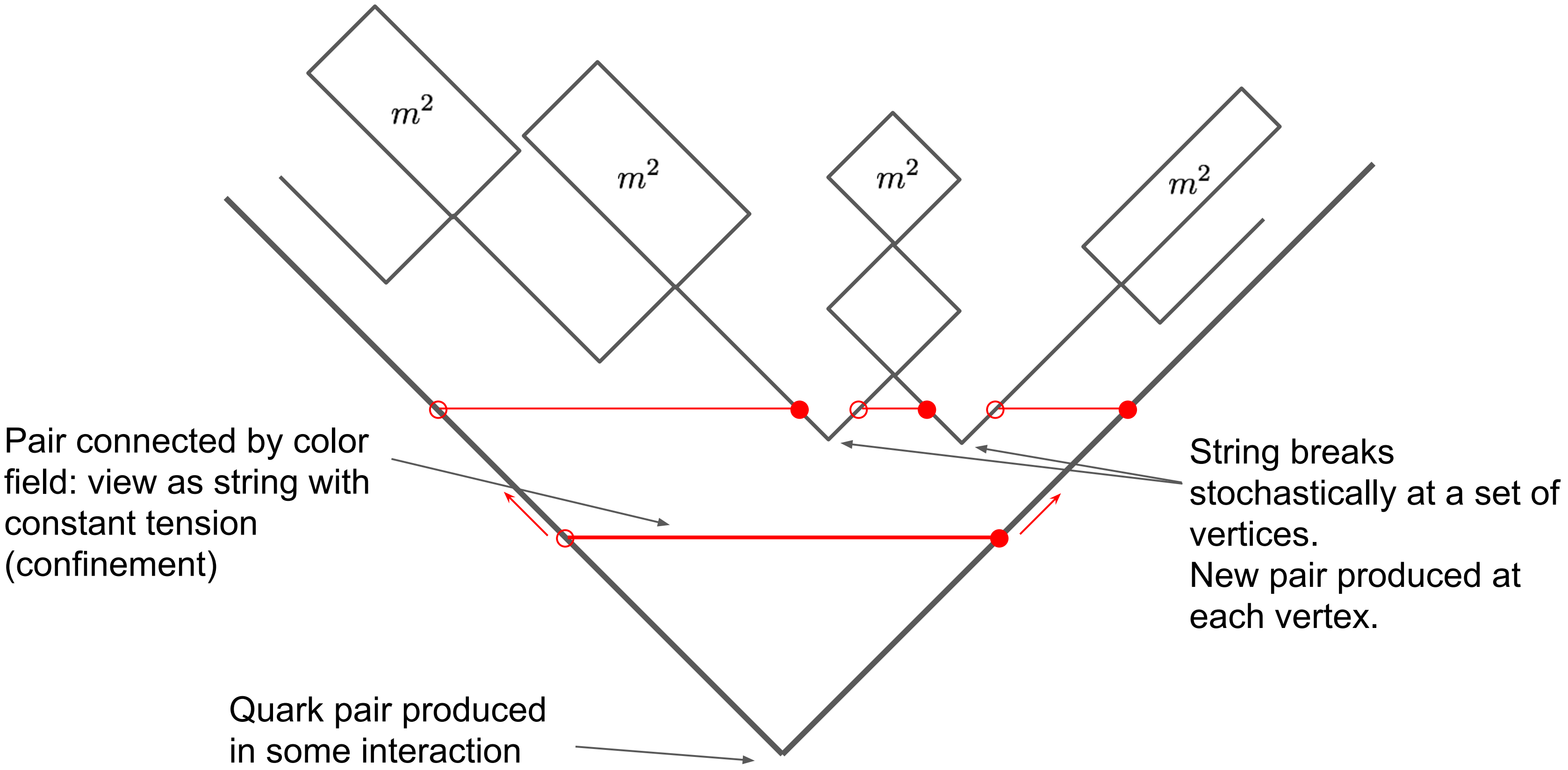
However: hadronization is a non-perturbative phenomenon.
→ We don't know how to calculate from first principles.

We have to use phenomenological models.
(But they are very successful to date)

Lund string model

(PYTHIA hadronization model)

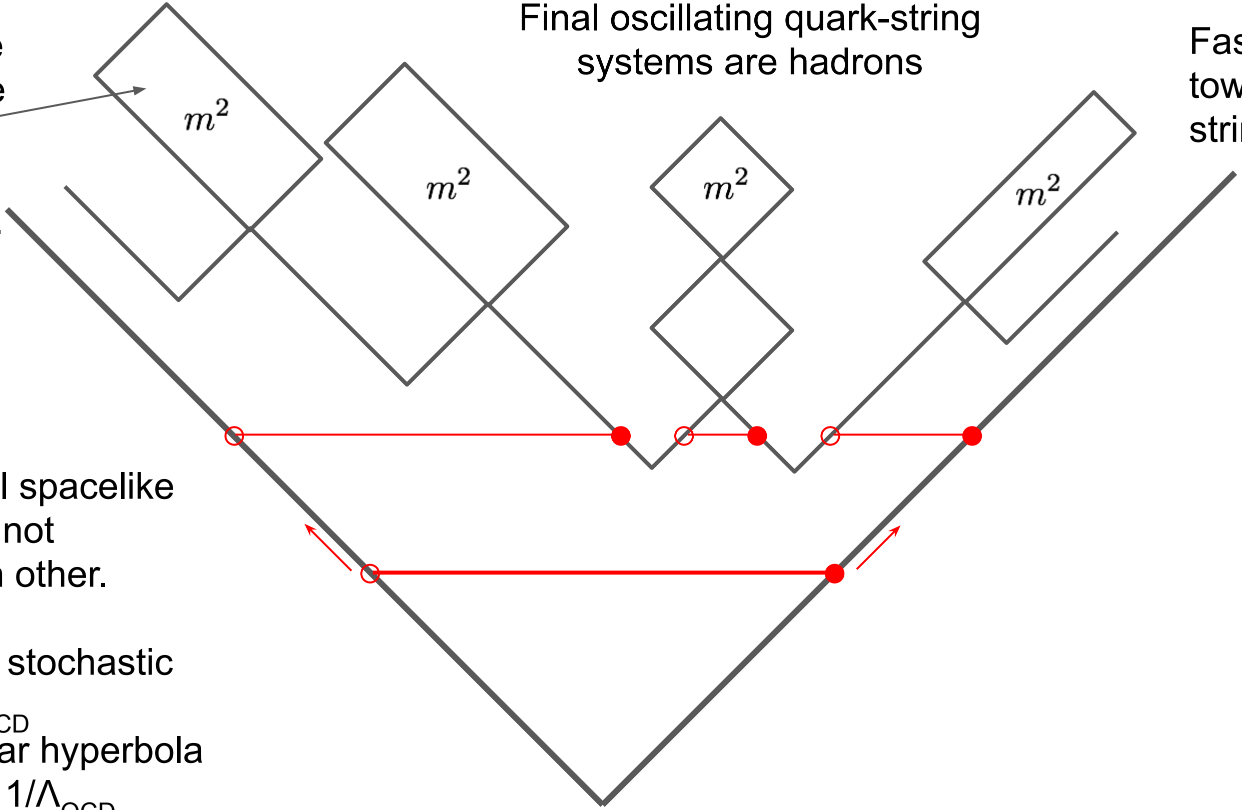


Lund string model

Area covered by one period is equal to the squared mass.
→ Constraint on neighboring vertices.

Final oscillating quark-string systems are hadrons

Fastest hadrons towards edges of string



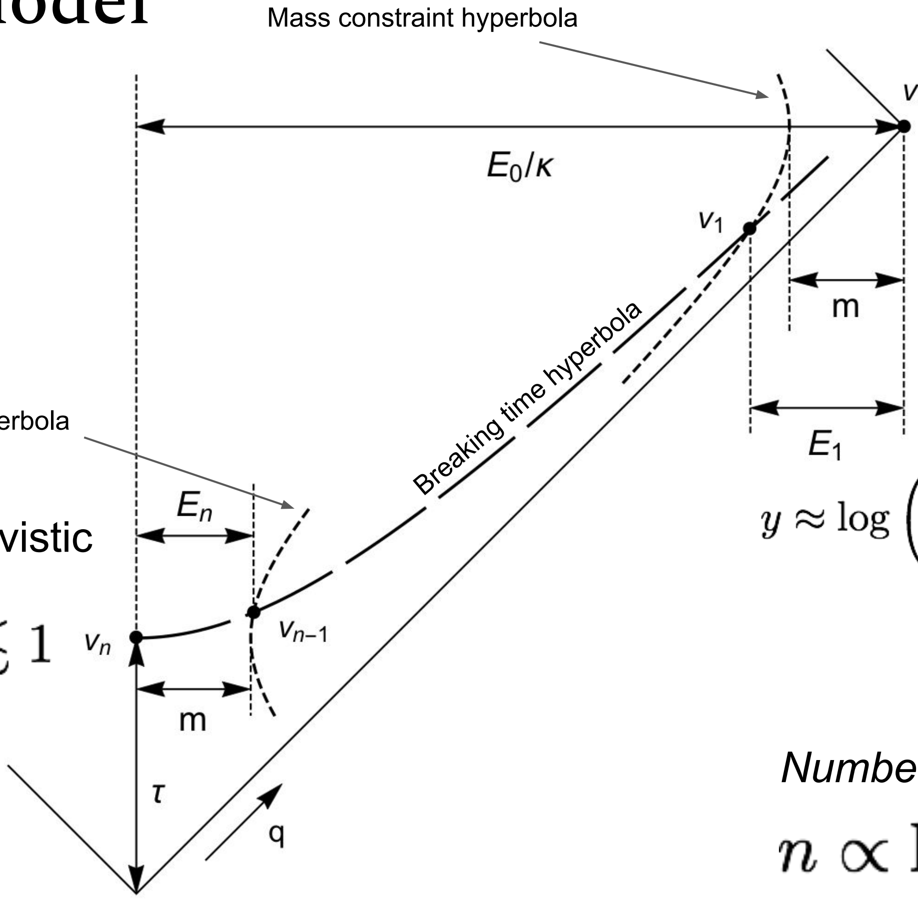
Vertices are all spacelike separated, do not influence each other.

Time scale for stochastic breaking ~ Λ_{QCD}
→ Vertices near hyperbola of proper time $1/\Lambda_{QCD}$

Lund string model

Outer hadron

Central hadron



E > m → relativistic

$$y \approx \log\left(\frac{2E_0 m}{m^2 + \kappa^2\tau^2}\right) \sim 5-6$$

E ~ m → non-relativistic

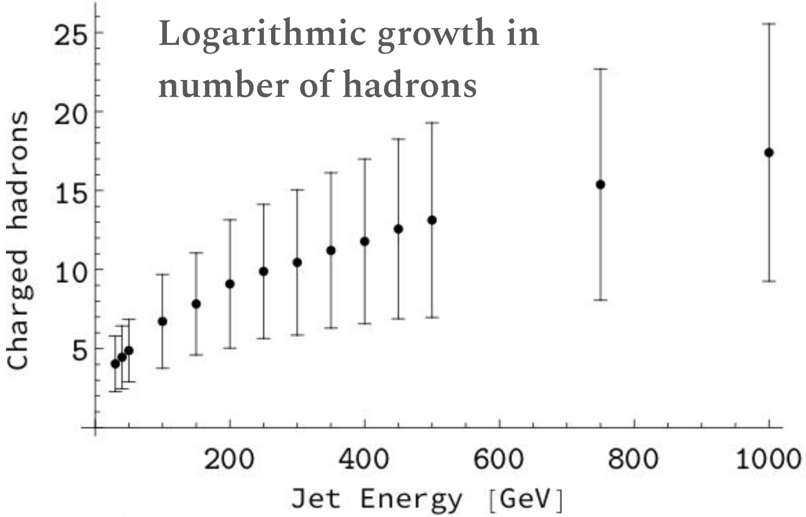
$$y \sim \mathcal{O}(m^2/\kappa^2\tau^2) \lesssim 1$$

Number of hadrons

$$n \propto \log E_0/\kappa\tau$$

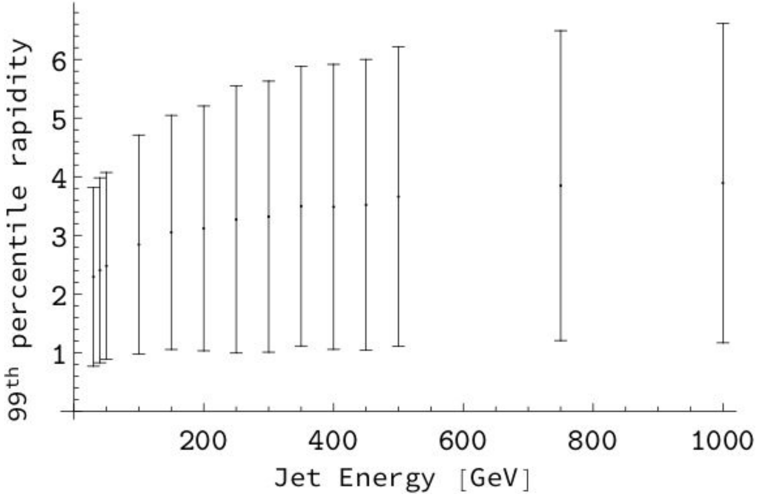
Verify general predictions in PYTHIA dijet events.

Latest tune to LHC data.



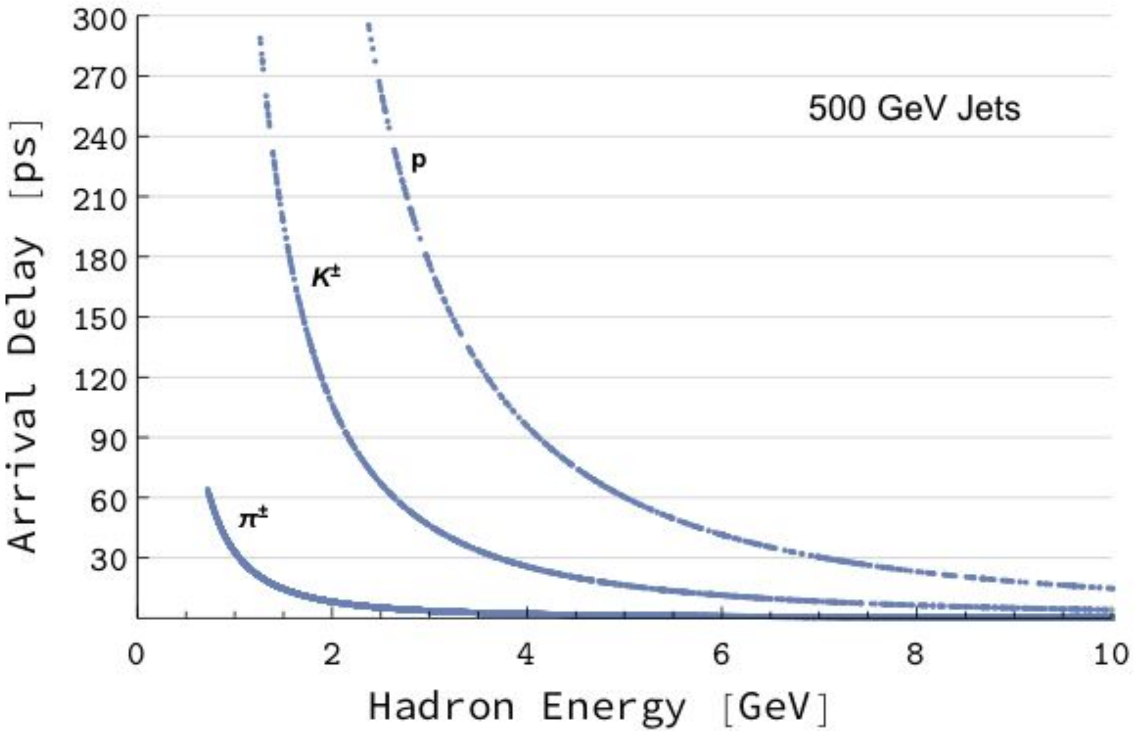
Logarithmic growth in maximum rapidity, always relativistic

Minimum rapidity approximately constant, O(1)



In terms of arrival time delay vs. light travel time

Graph units are the nominal CMS detector time resolution.



Summary up to now

1. Jets have an intrinsic velocity spread.
   Time of flight to detector → time spread.
2. Next generation detectors will resolve this.
3. This effect is directly related to hadronization.
4. On general grounds, our understanding of hadronization confirms observable effects.
5. Testing this is a direct and novel test of hadronization.

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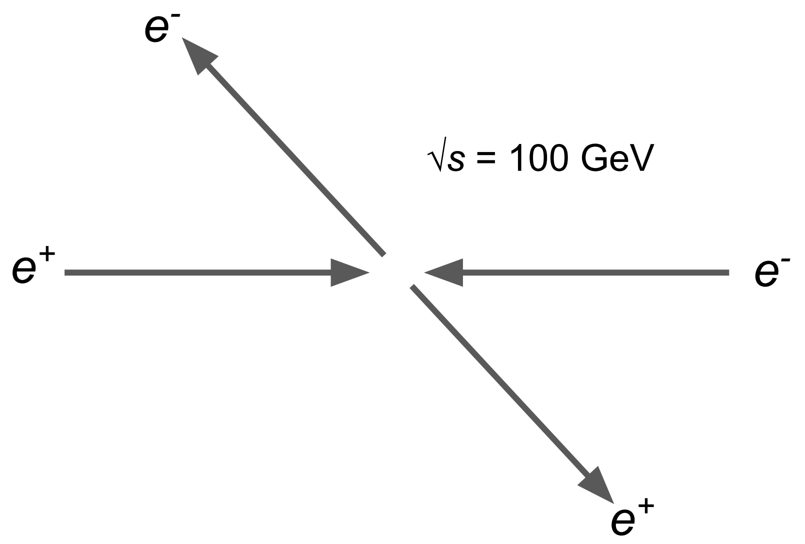
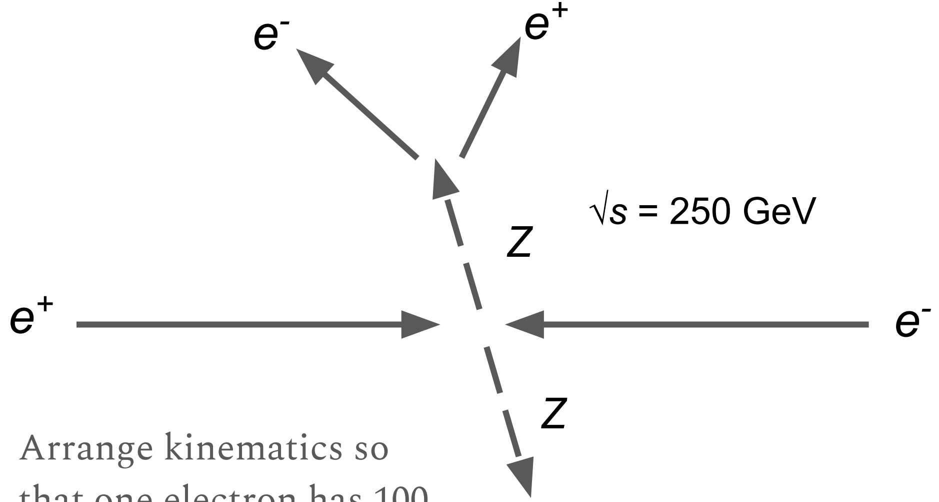
Next: Beyond direct observation, can this new data be used as a tool in any other way?

Proposal: Boosted object tagging

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



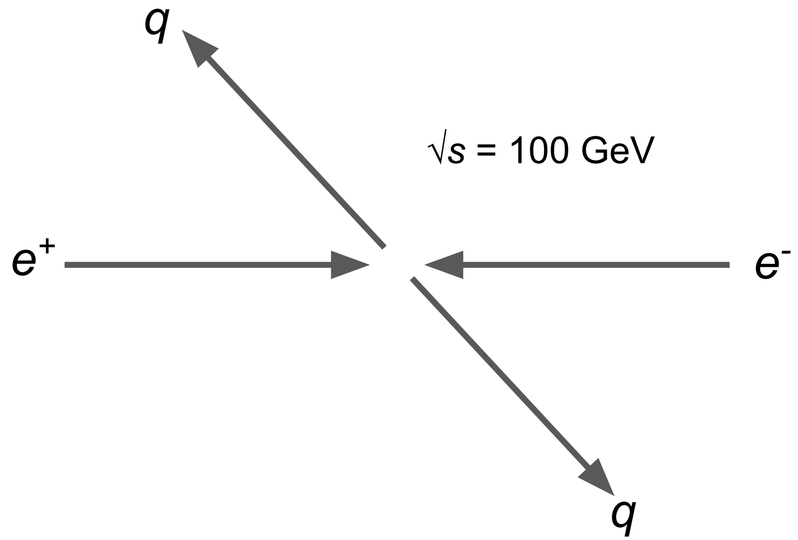
$e^+e^- \rightarrow$ leptonic ZZ production



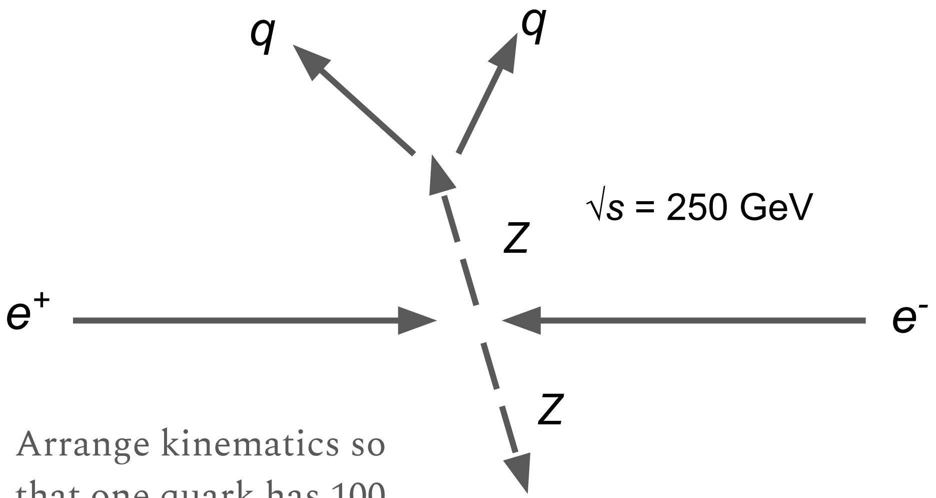
Arrange kinematics so that one electron has 100 GeV in lab frame

What is the difference between these electrons?

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



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



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

What is the difference between these *quarks*?

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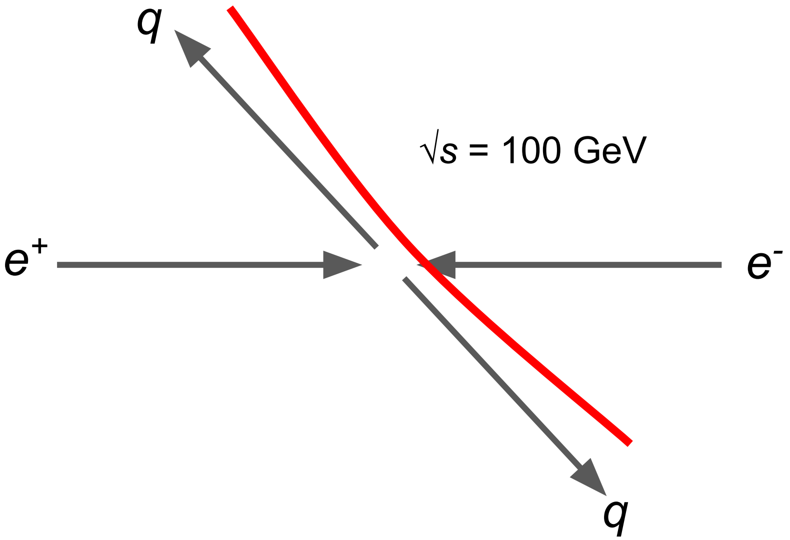

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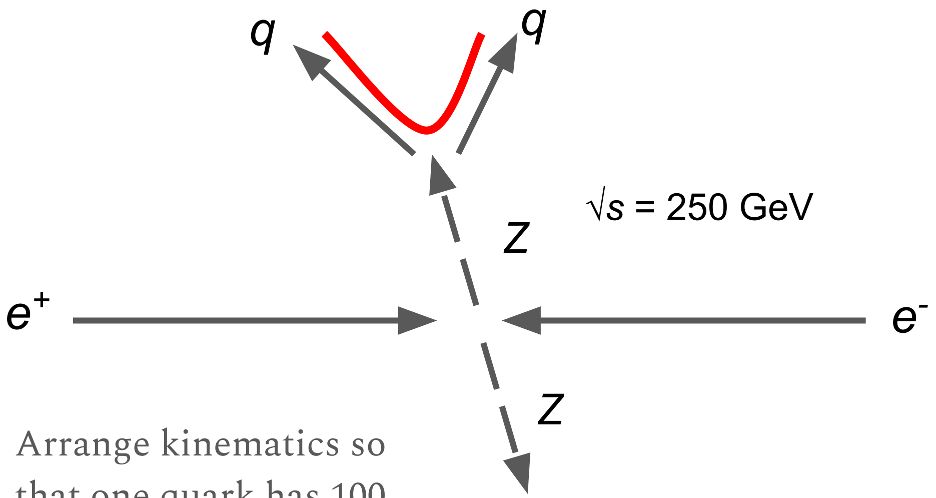

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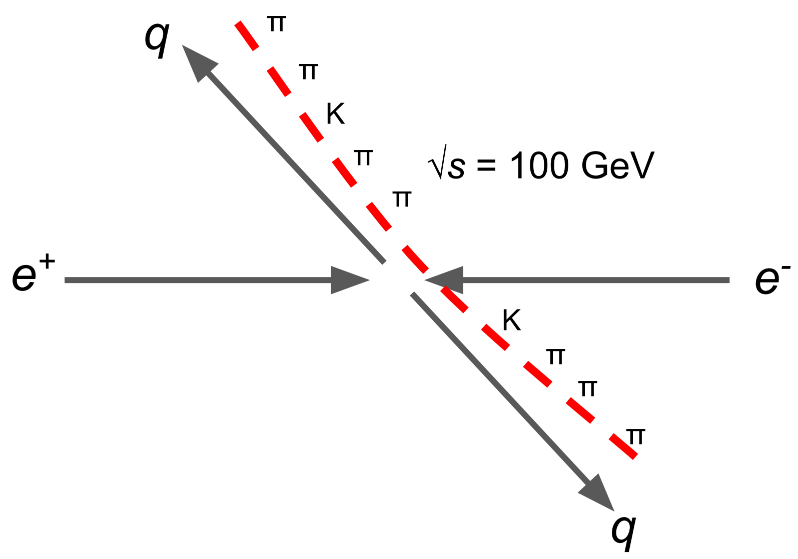

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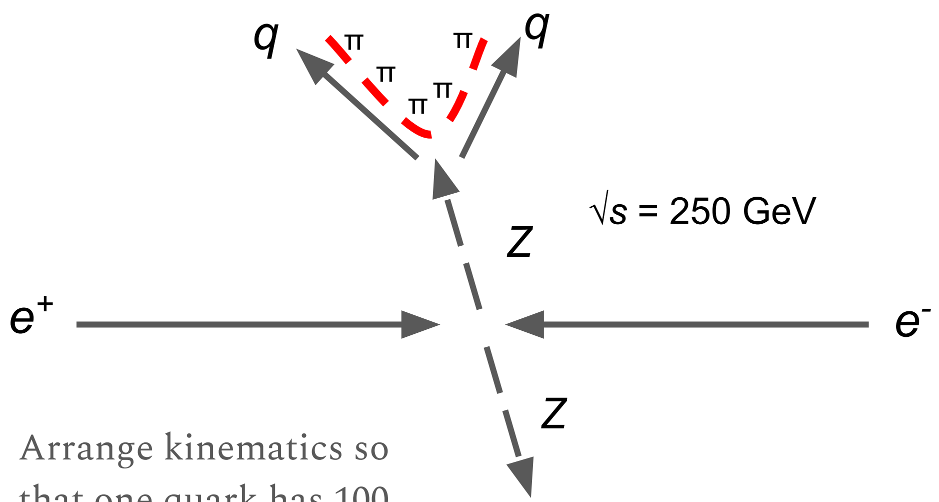

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The *quarks* are *not* directly observable.

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

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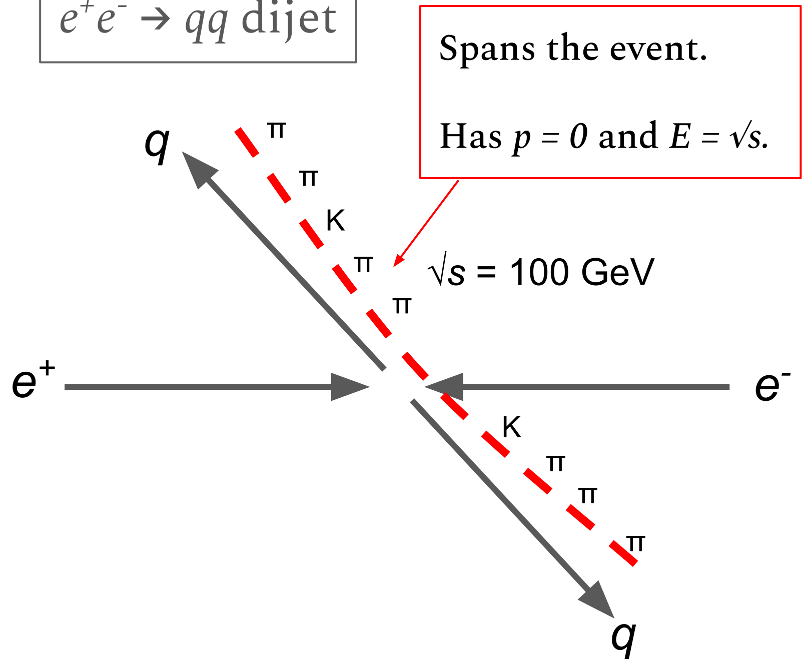

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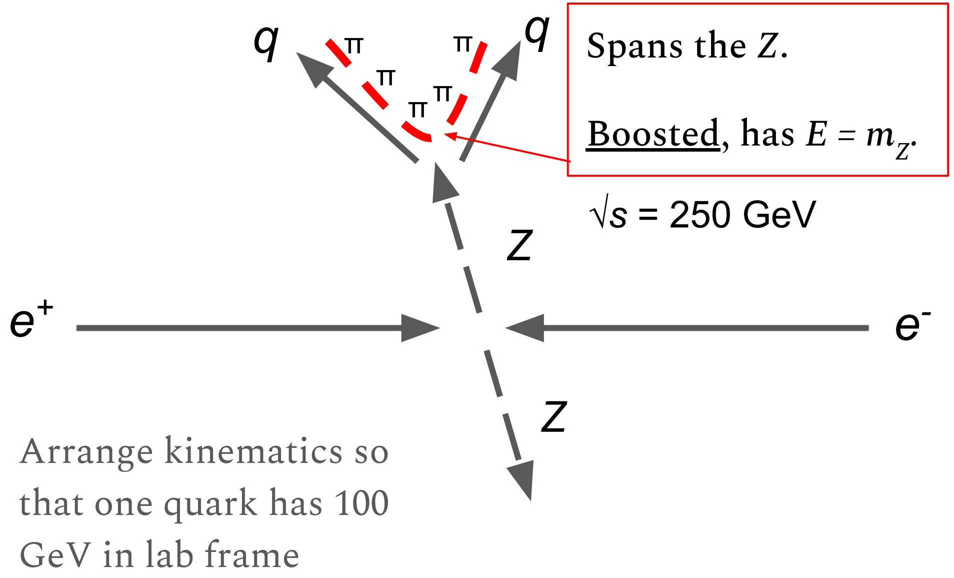

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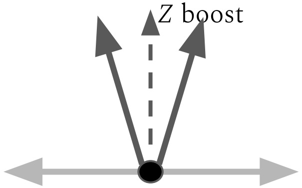
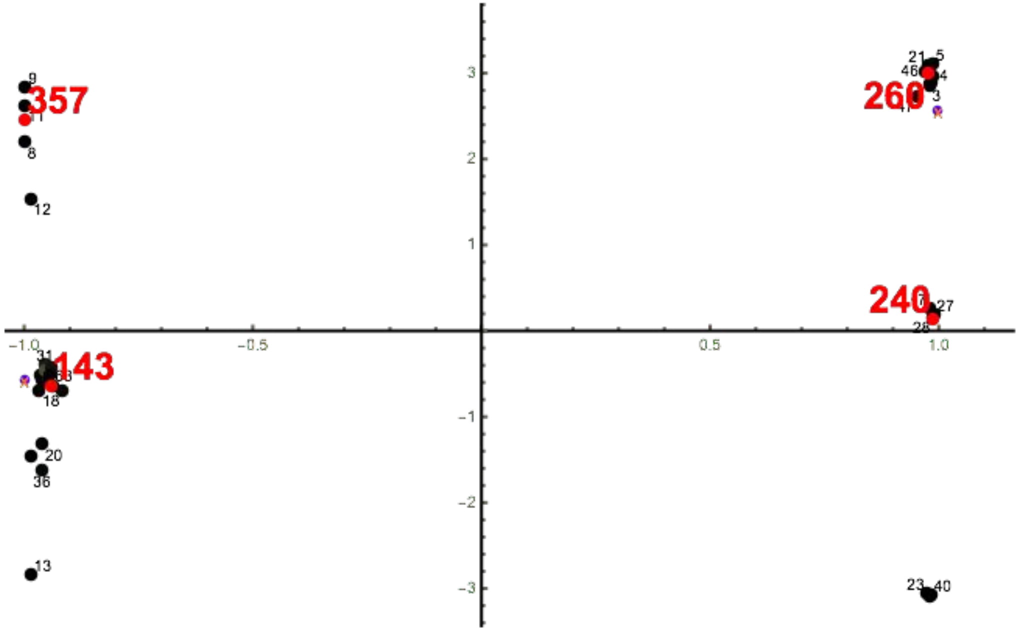
Many spatial jet substructure techniques have been developed to identify such boosted jets



This kind of boosted ZZ event should be recognized by these techniques.

Example: Mass drop

Does a high mass jet split into two low mass sub-jets?



ZZ signal event

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

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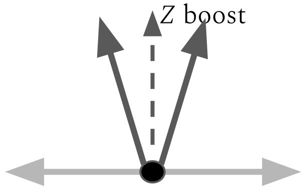

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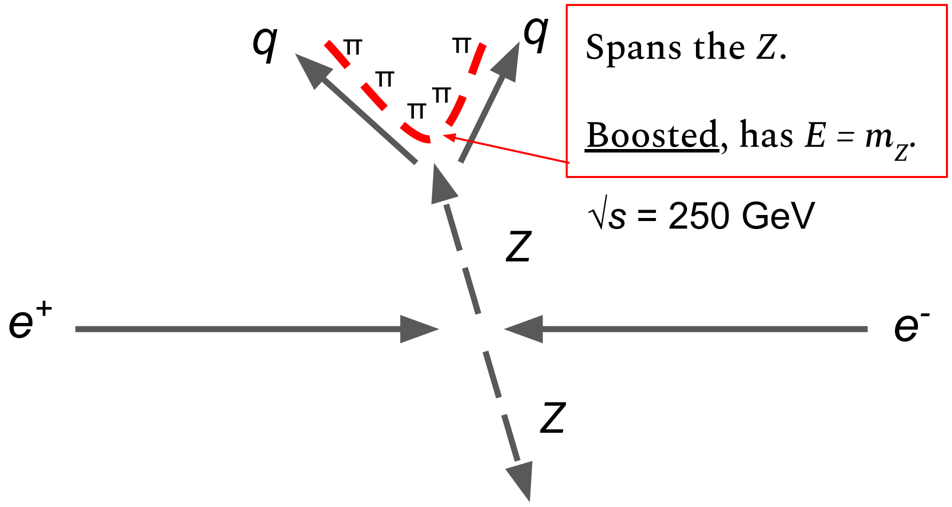
QCD dijet event.

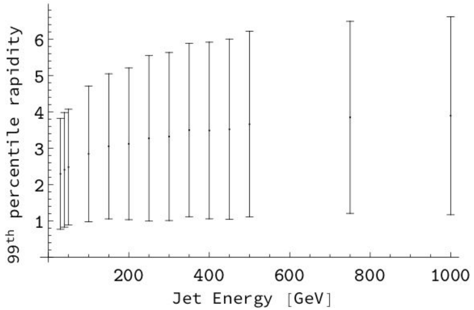
One jet fails Mass Drop; other is accidentally tagged with mass 90.1 GeV.

What is a boosted jet?



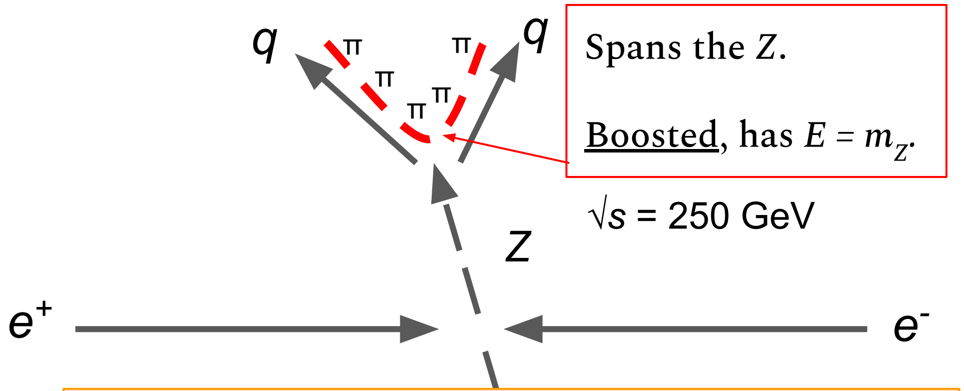
String model predictions were made in the rest frame of the string (quark/antiquark system)

In this frame there were generically slow hadrons.



If the whole string is boosted, they may no longer be slow.

What is a boosted jet?



IDEA: A non-boosted jet should have some slow hadrons… A boosted jet may not…

So…

Cut on arrival time of latest observable hadron in jet.

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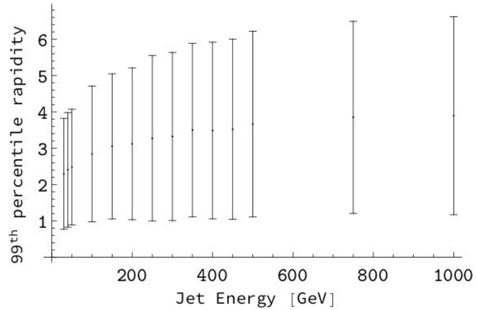

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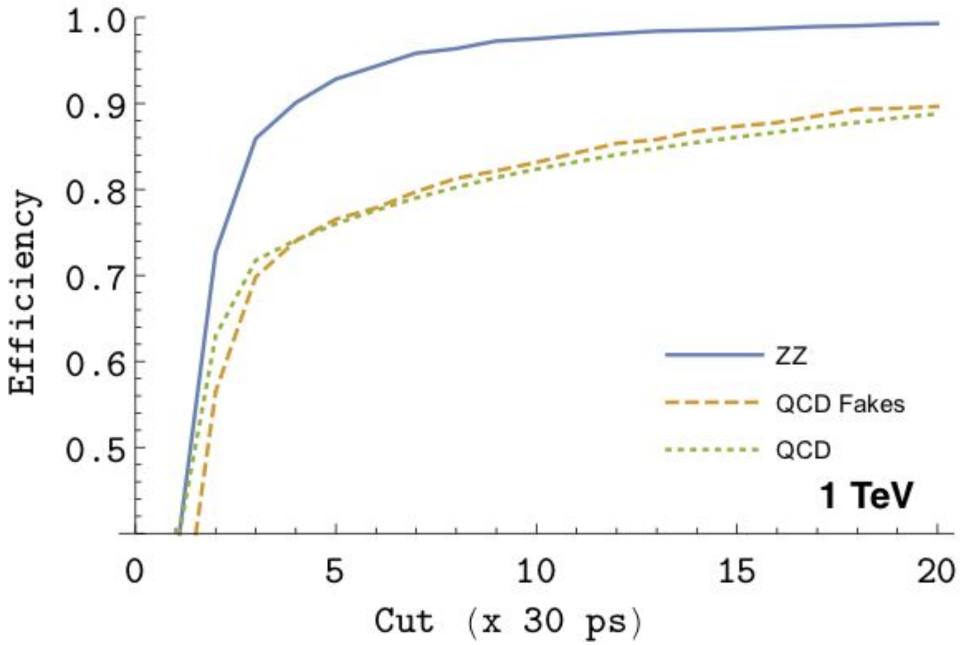
Results: selection efficiencies

Efficiency is very high for true Z jets, lower for QCD jets.

→ enriches samples with QCD backgrounds.

QCD Fakes: QCD jets that Mass Drop resolves *as having Z mass.*



$$t_{\text{last}} < t_{\text{cut}}$$

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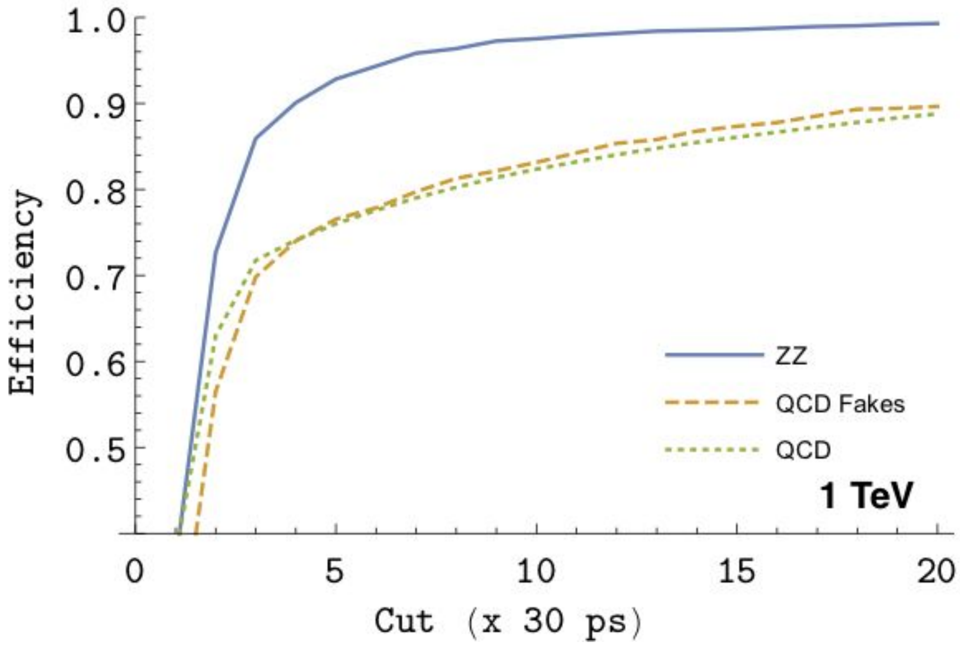
<u>QCD Fakes</u>: QCD jets that Mass Drop resolves *as having Z mass.*

The time cut is just as effective against fake QCD Z jets as any other kind of QCD jet.

The time cut is using new information that is missed by traditional spatial substructure taggers.



$$t_{\text{last}} < t_{\text{cut}}$$

Natural questions:

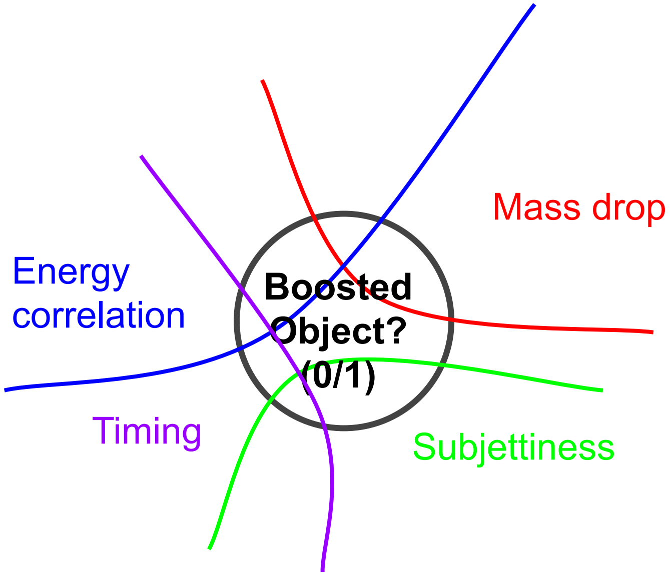
“The velocity is just one way to describe the kinematic data. Aren’t you just saying the QCD jets have more soft particles?

The tracker already measures momenta well. Can’t I do this measurement another way?

Low mass string produce fewer hadrons. Why don’t you just cut on hadron multiplicity?”

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.



Answer: (2)

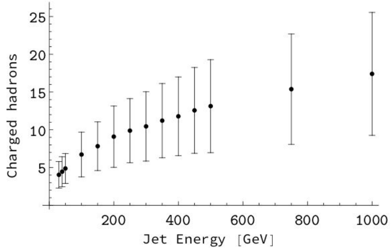
No, not exactly...

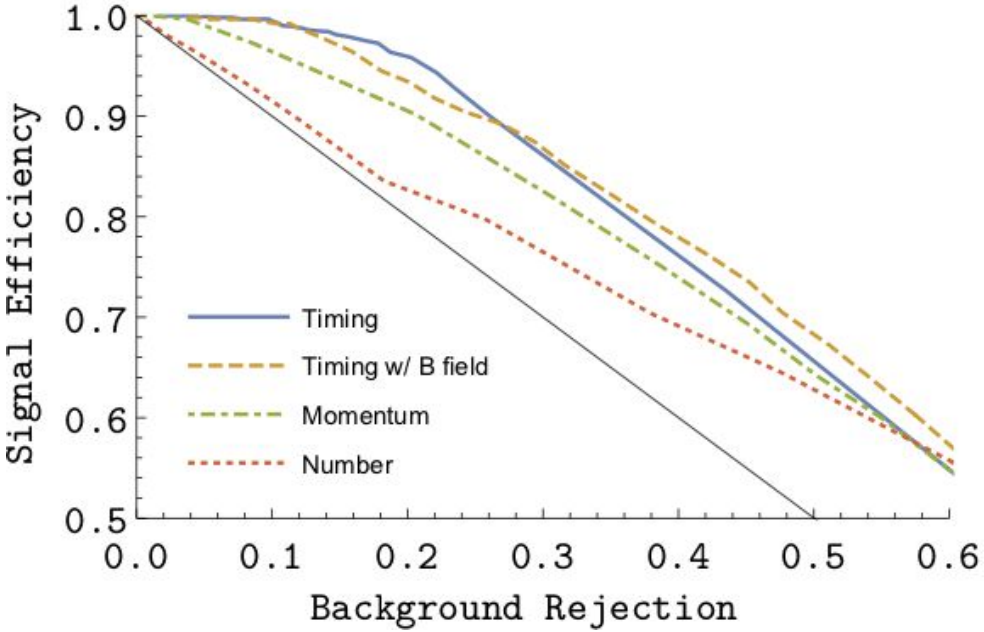
Re: Momenta

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

Re: Hadron multiplicity

The scatter is very large





Timing does best.

Conclusions

- Timing detectors being installed for the HL-LHC, and available for future colliders, will probe the time scales over which jets arrive.
- Observation of the time/velocity spectrum is a probe of hadronization.
- Jets encode additional information about the event because they represent strings that connect different parts of the process.
- This information can be used for distinguishing boosted objects from QCD fakes in a novel way.