Summary of Jet Substructure Measurements and their usefulness in Heavy Ion Collisions

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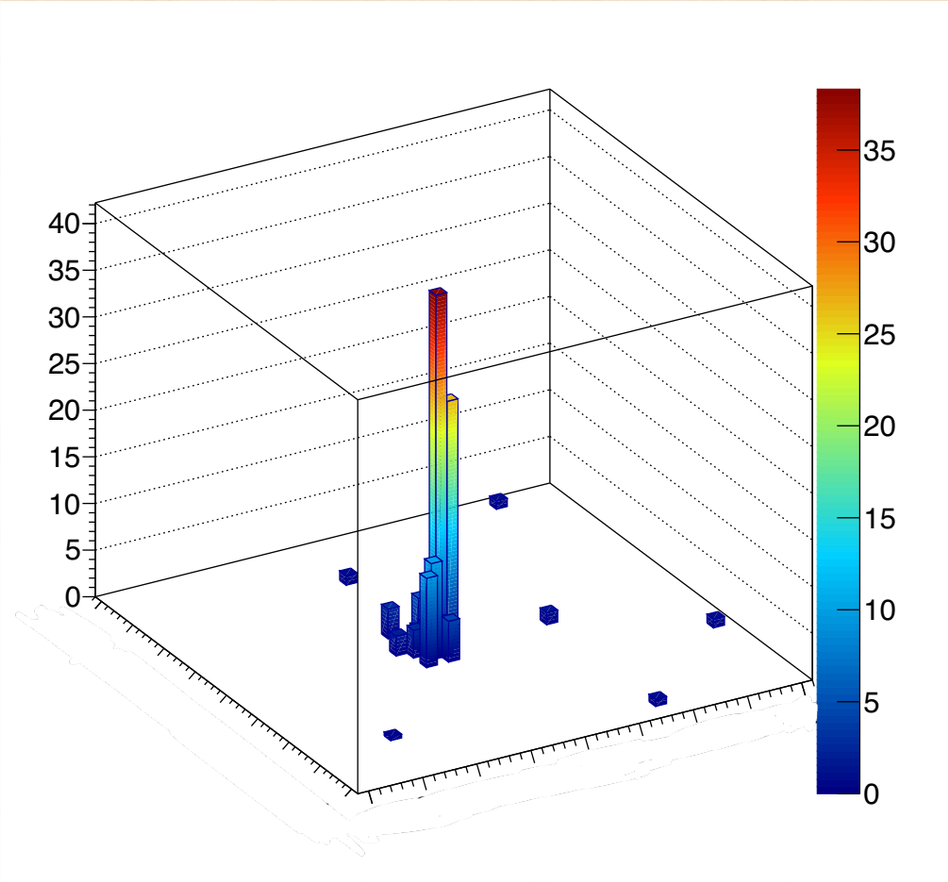
RHIC & AGC Annual Users Meeting, June 4, 2019

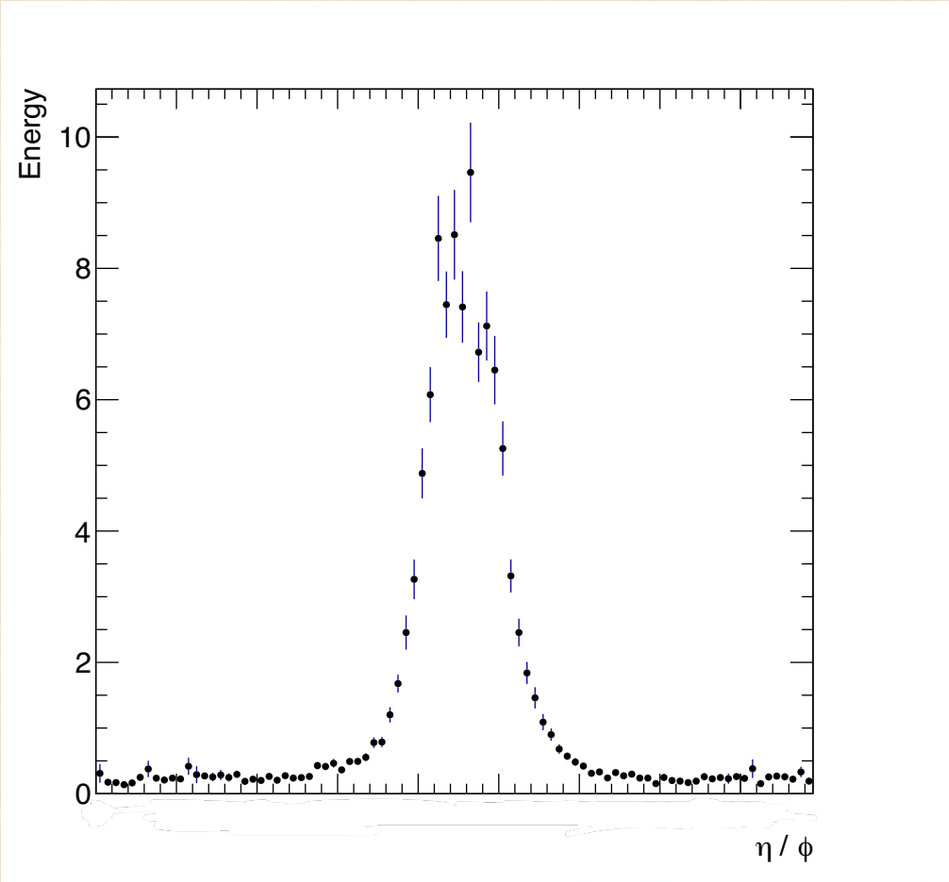
The MIT group's work is supported by US DOE-NP

Experimental Jets

Experimentally…

A jet is a cluster of energy defined by an algorithm



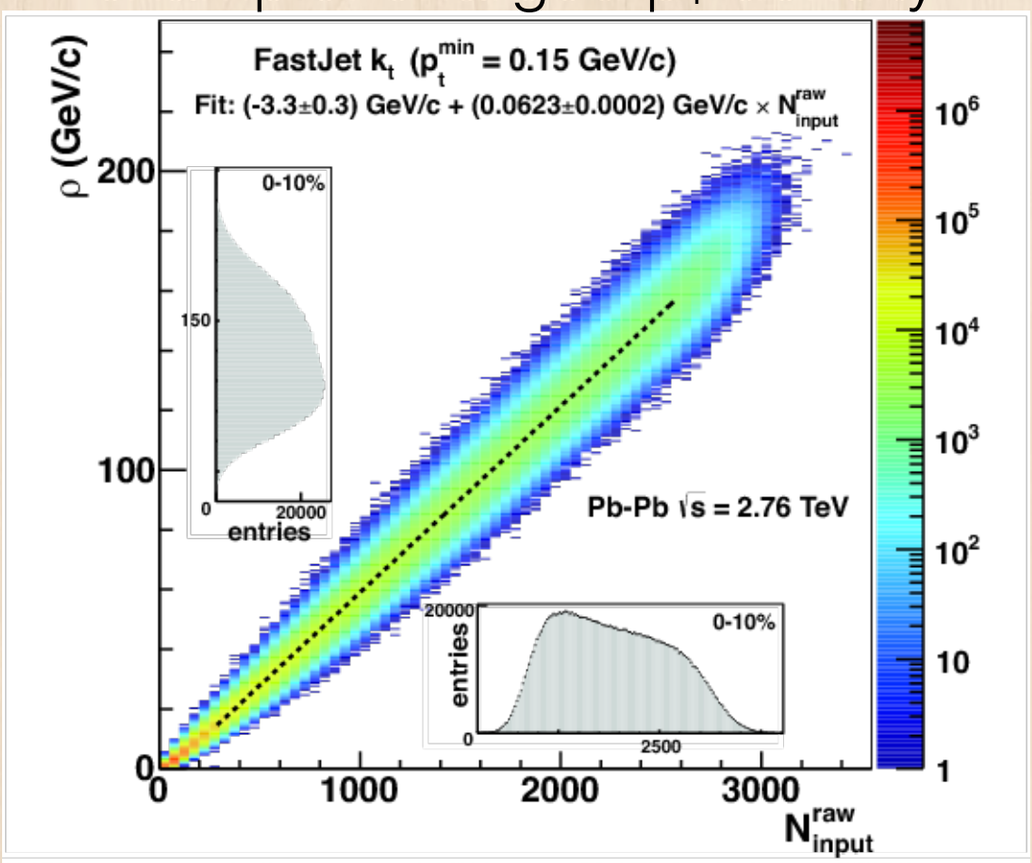


for example: sequential clustering

Background subtraction

In heavy ion collisions jets are sitting on top of huge energy from the hot QCD medium

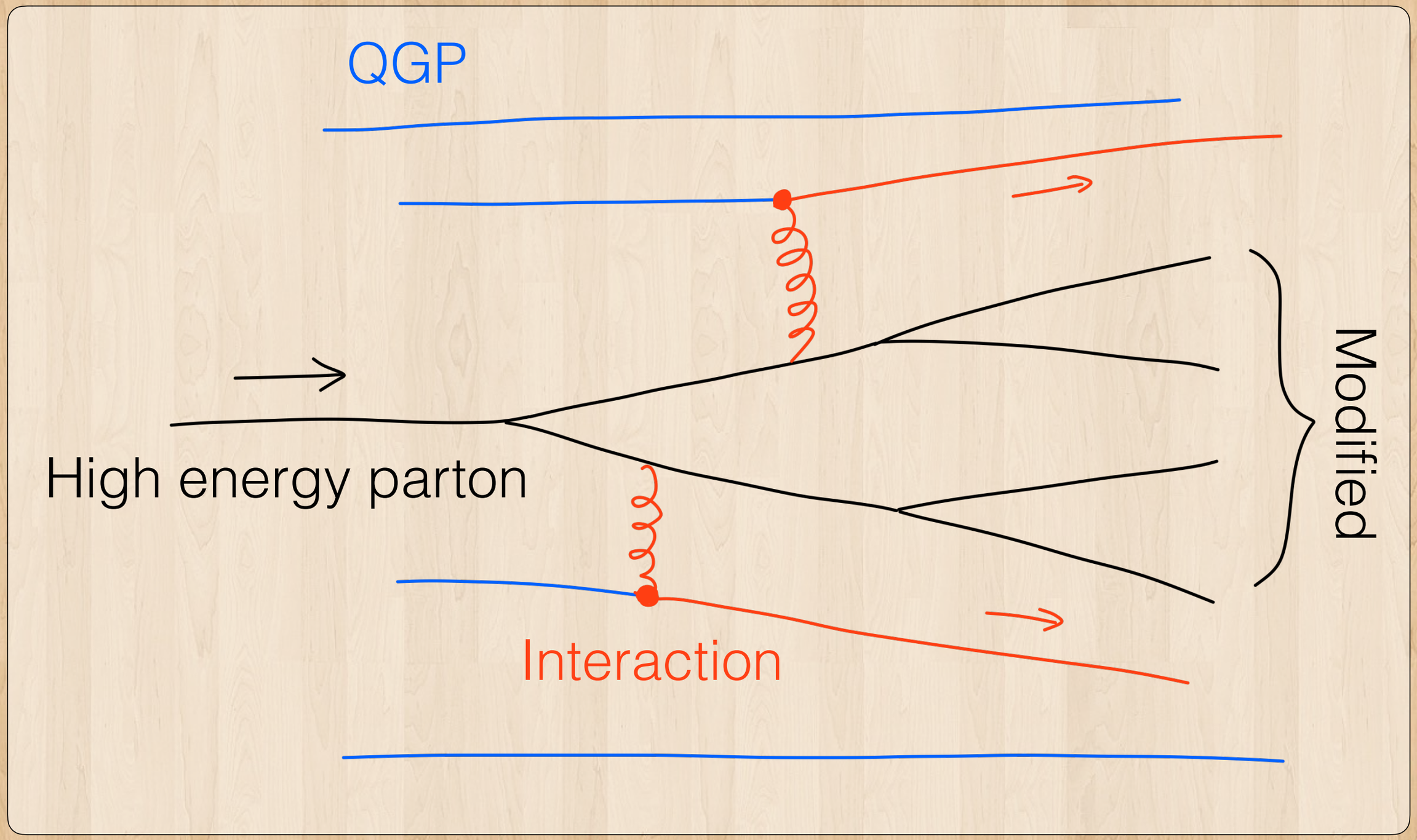
example: charged p_T density



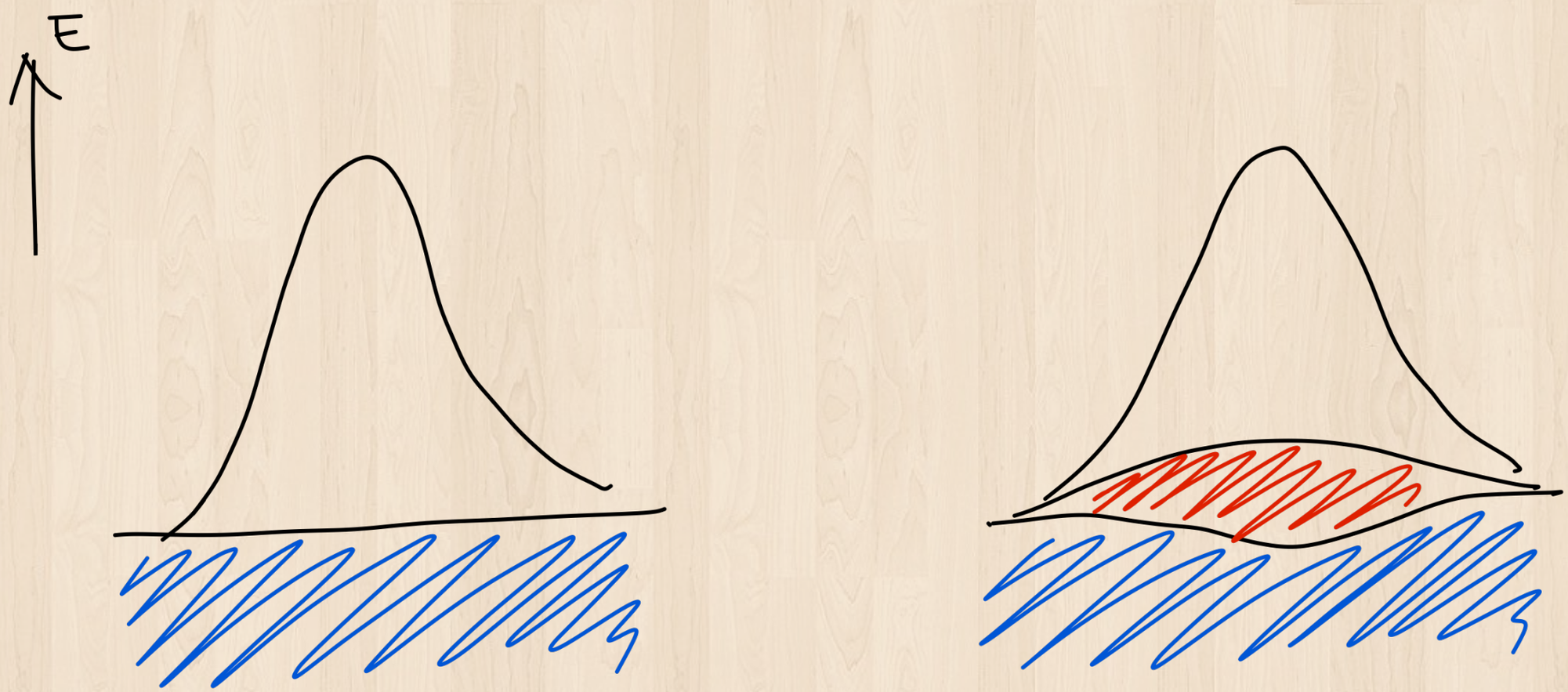
Experiments perform "background" subtraction to remove the expected contribution from the QCD medium

?

Rough parton picture



Averaged picture

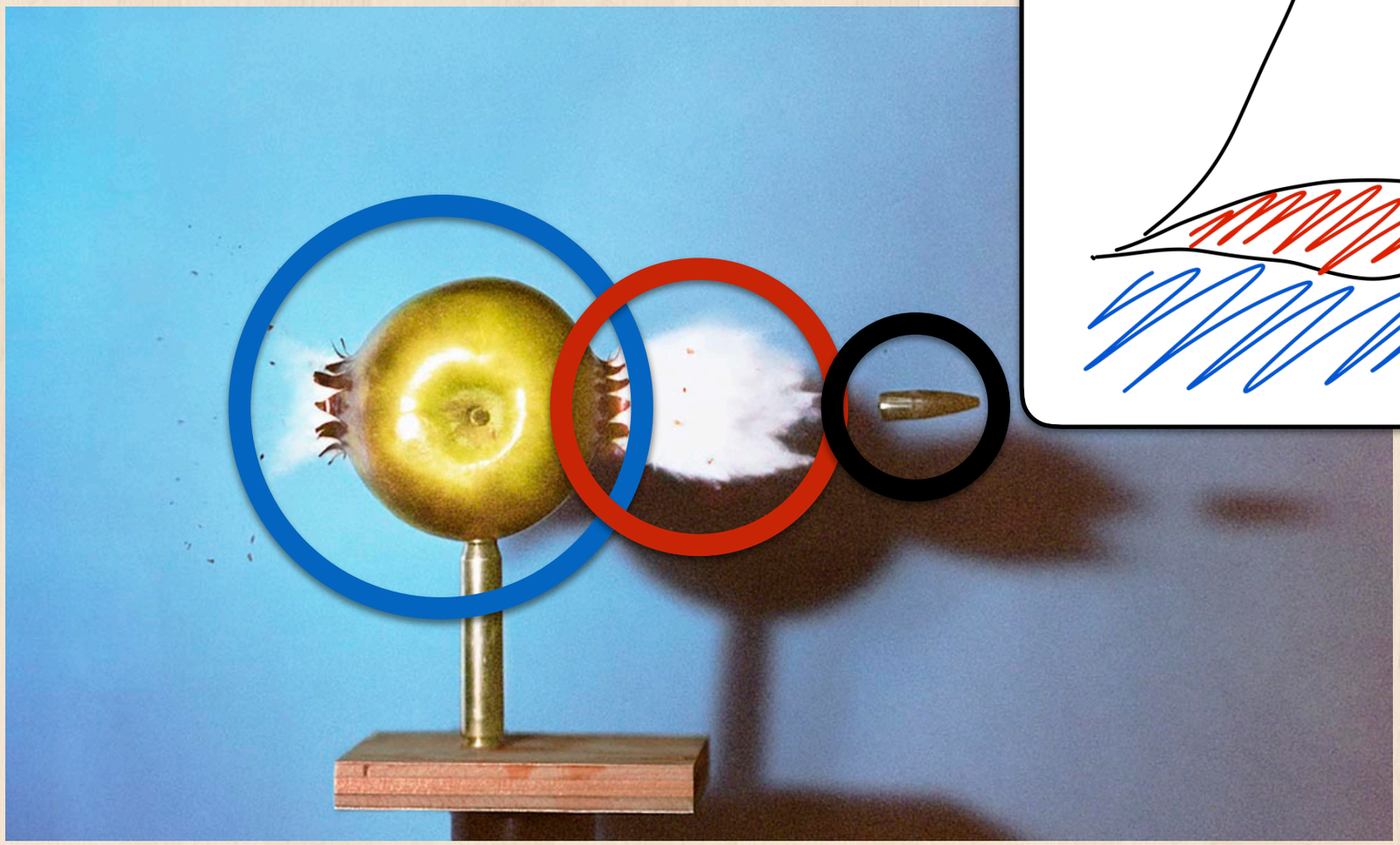


No interaction

With interaction (*)

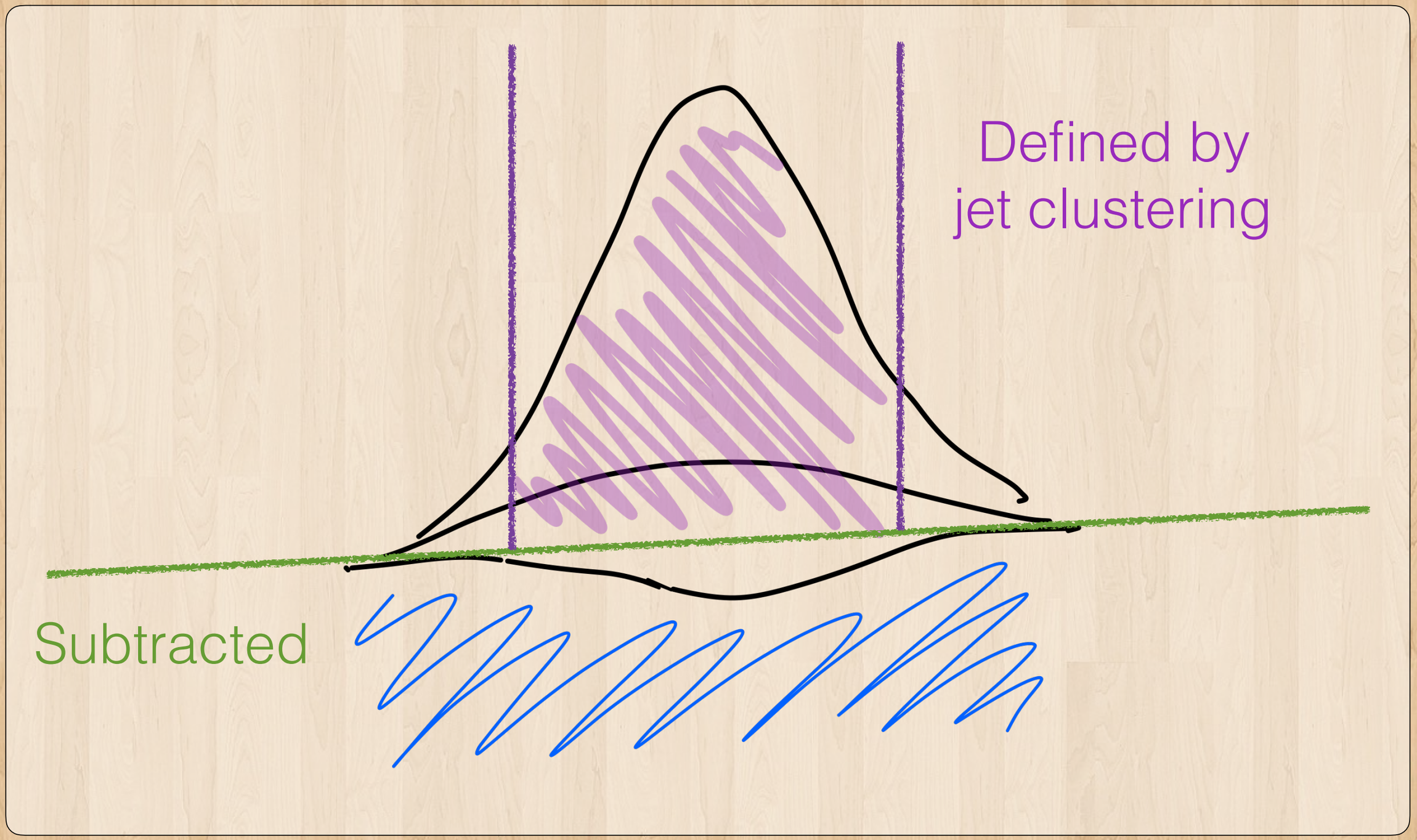
* most likely not to scale

Bullet through apple



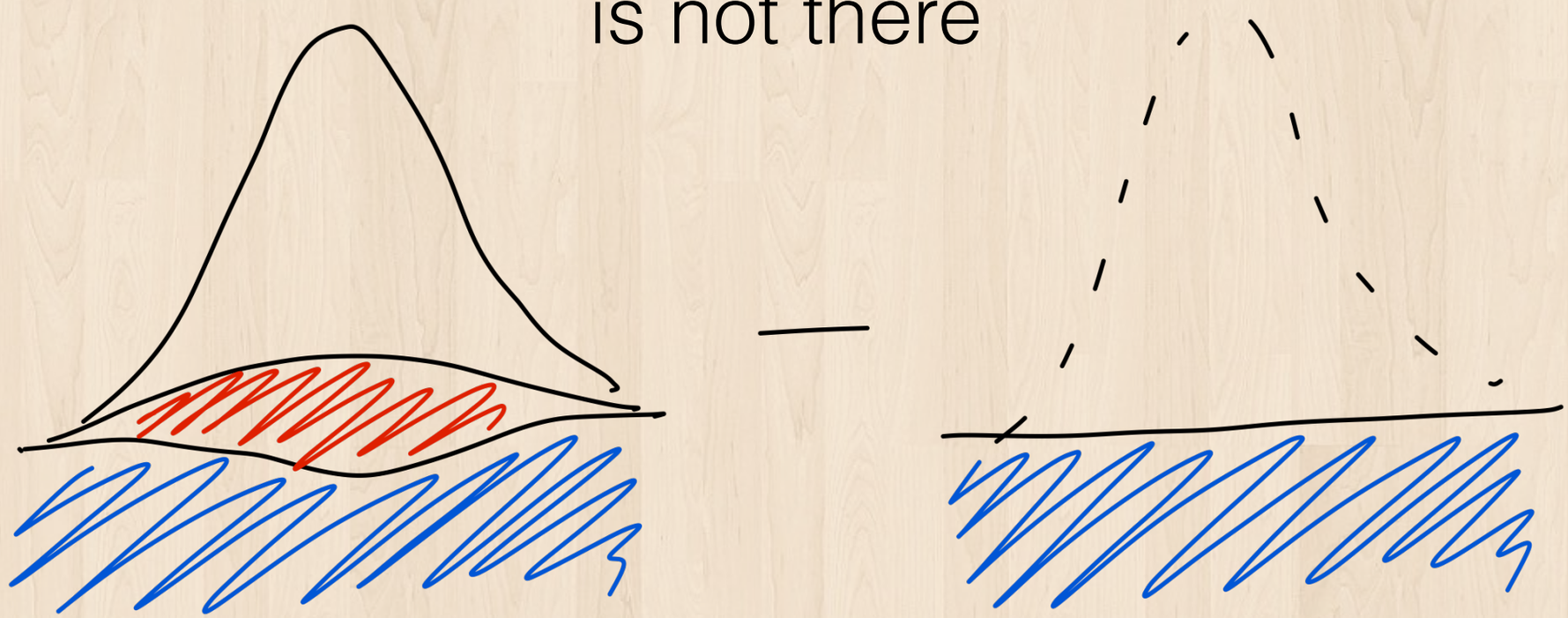
Source: Harold Edgerton, MIT

What do we measure



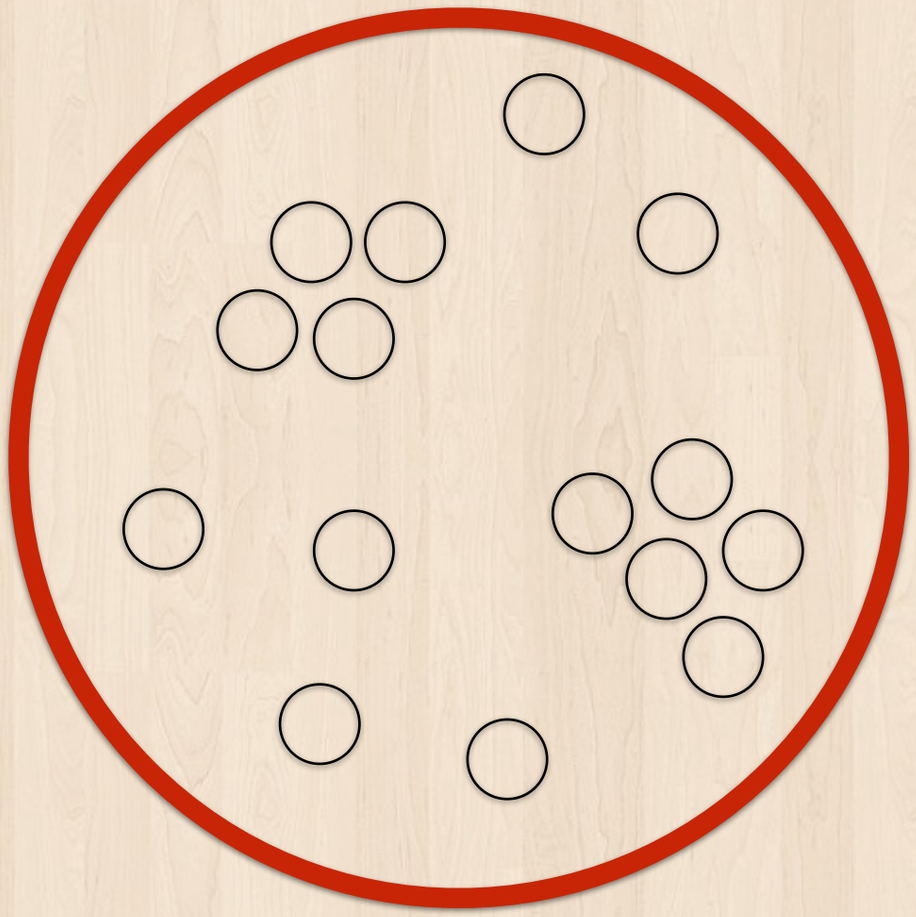
"expected contribution"

An experimental (subtracted) jet in heavy ion collision is a cluster of energy, defined by a clustering algorithm, that is above the expected contribution from the QGP, in the case where the jet is not there

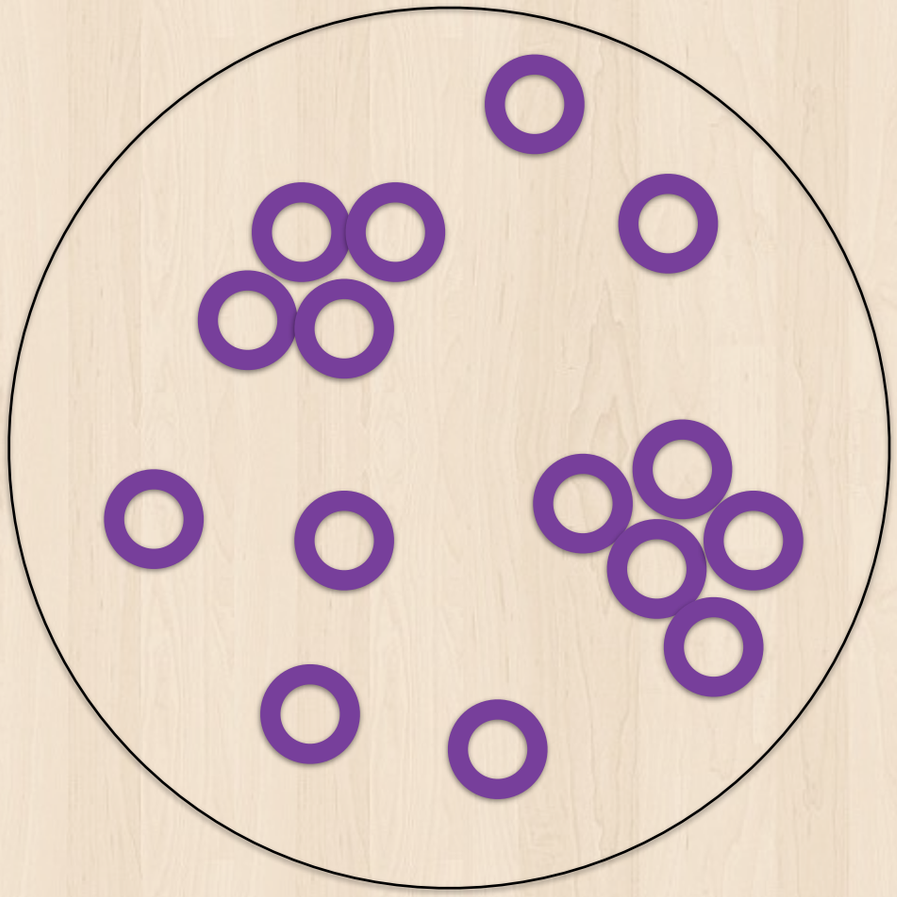


Level of Details

Level of Detail

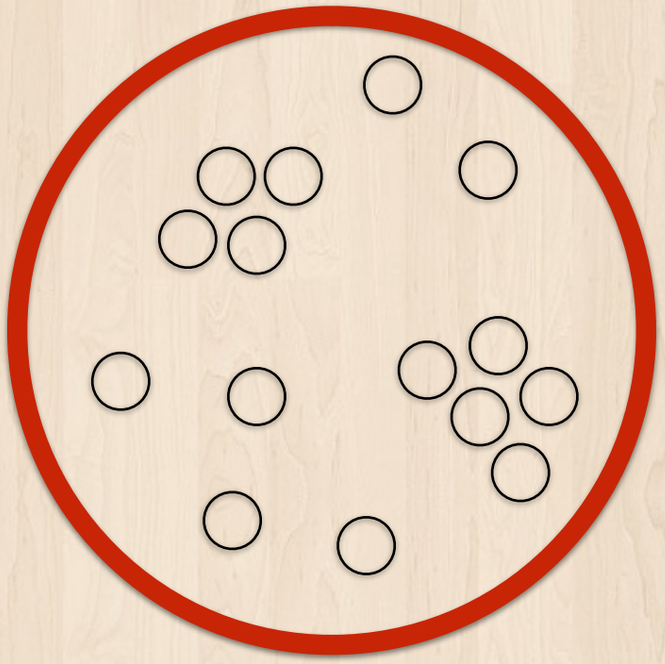


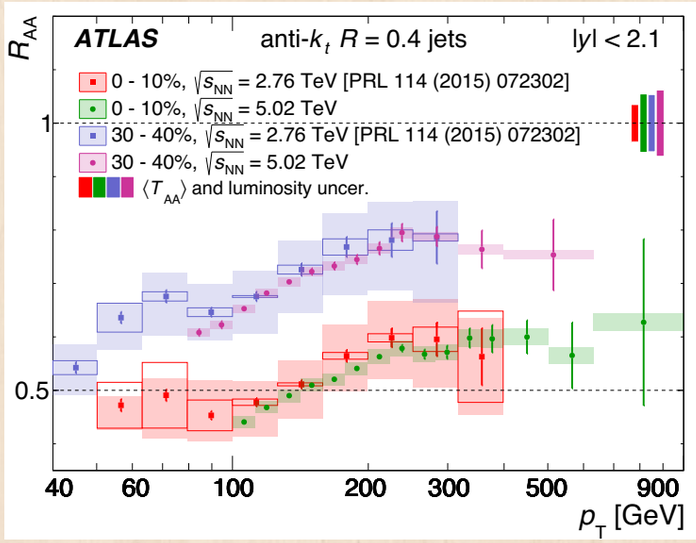
Full Jet

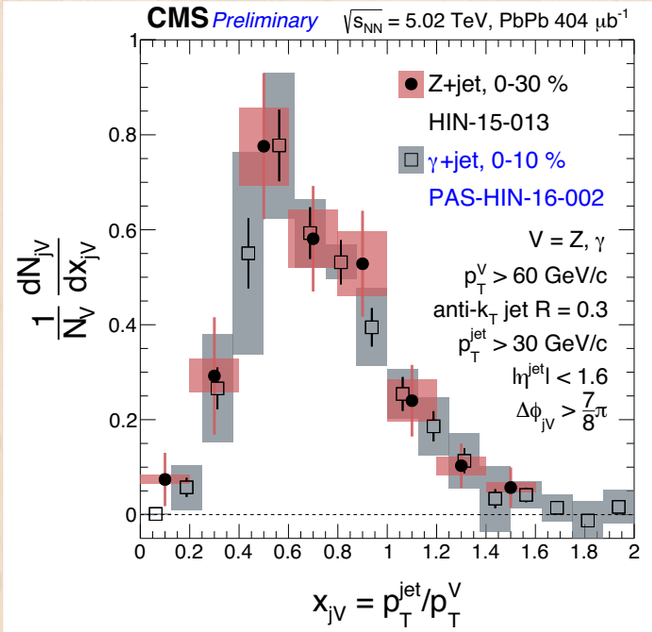


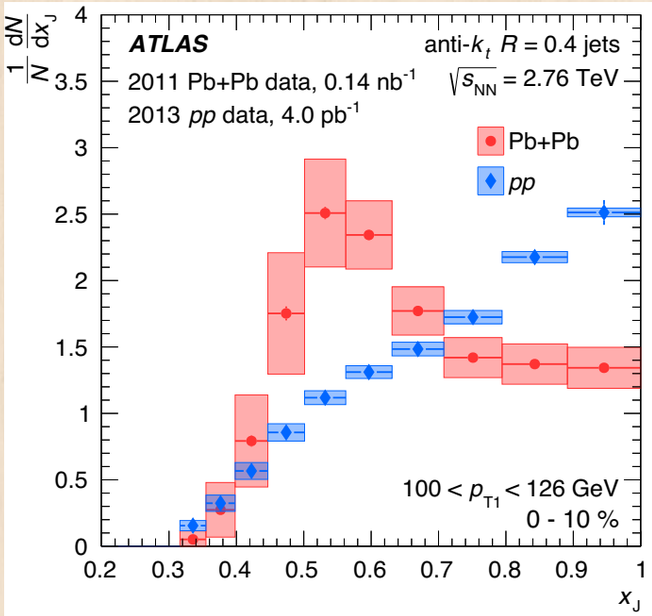
Constituents

Full Jet









Treat jet as a whole

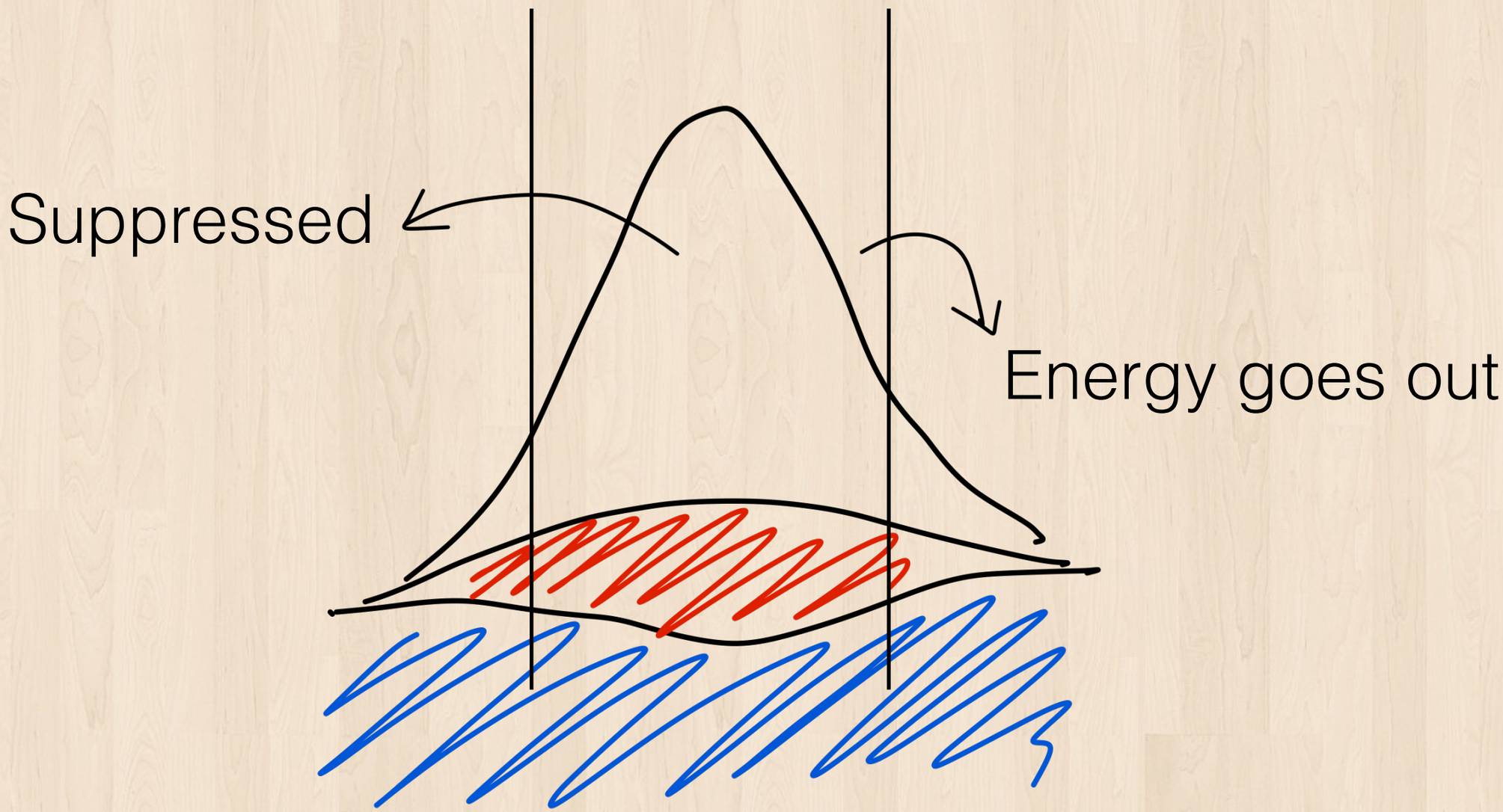
Jets are suppressed

Jets lose energy

See Nima's talk for more details

PLB 790 (2019) 108
PLB 774 (2017) 379, PRL 119 (2017)082301

Jet modification



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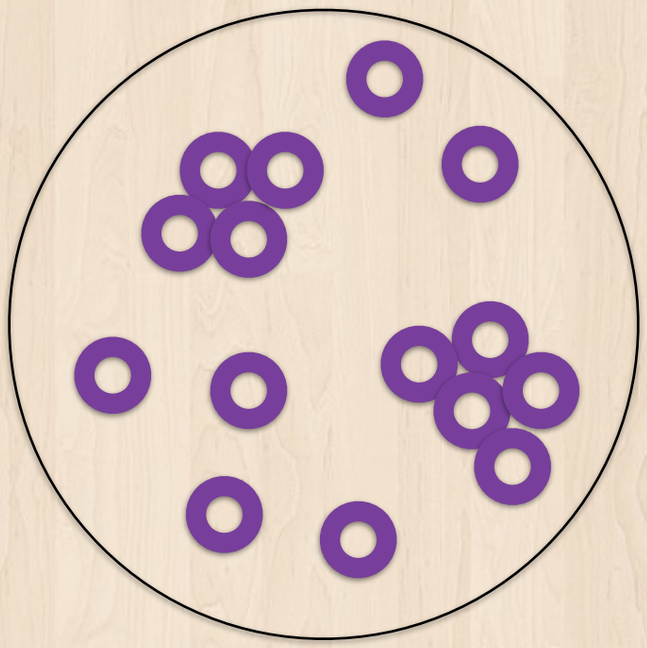
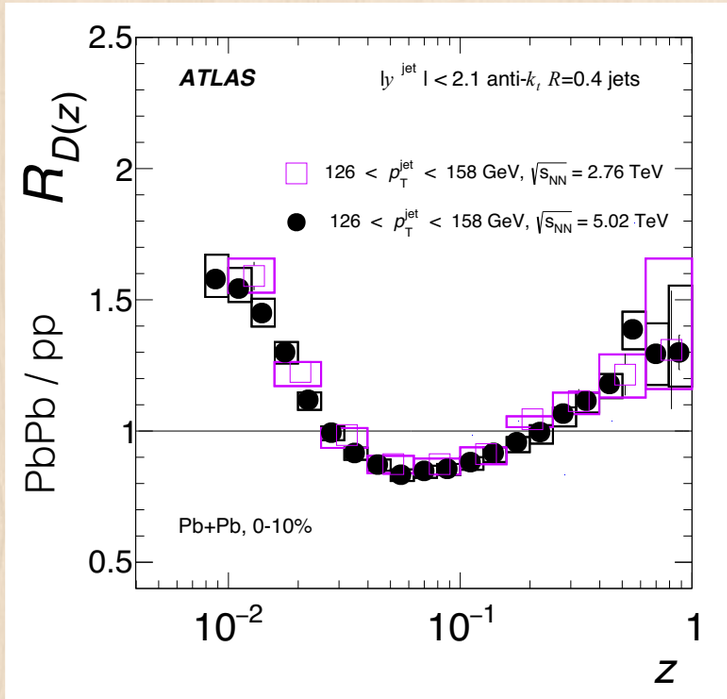
Constituents

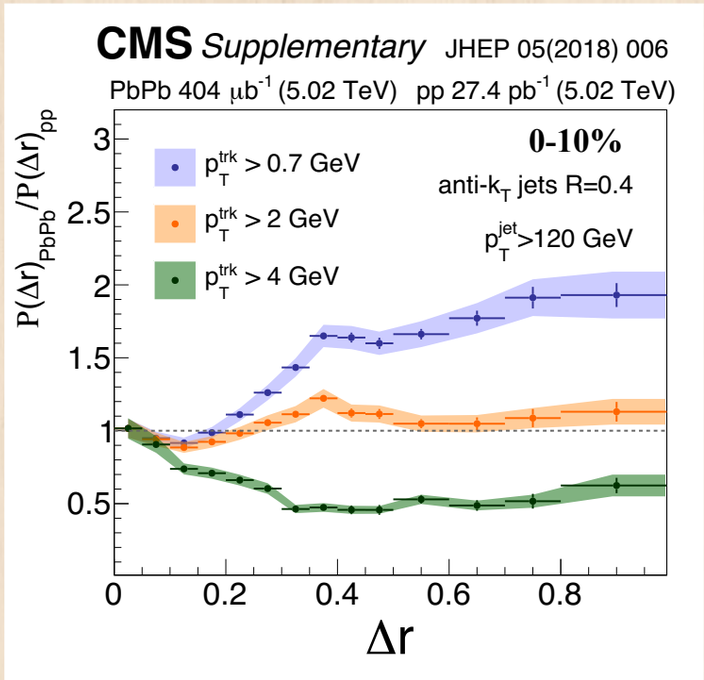


Look at the
particles of the jet



z = fraction of PT
carried by track

Relative suppression of
moderate energy tracks
and enhancement of
low energy tracks



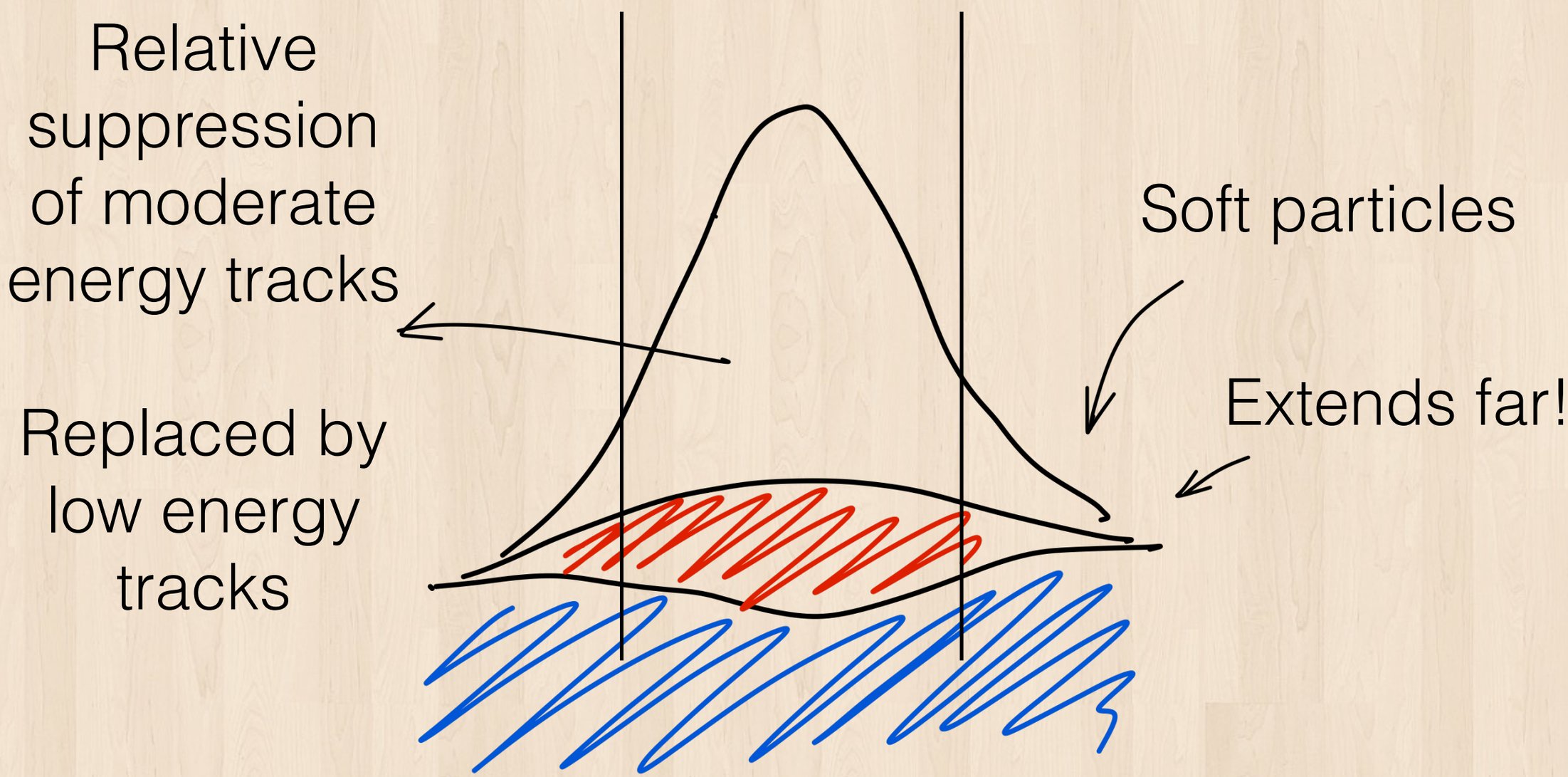
Radial jet shape: momentum as a function of radius

Energy extend to large angle
Carried by low-energy particles

See Nima's talk for more details

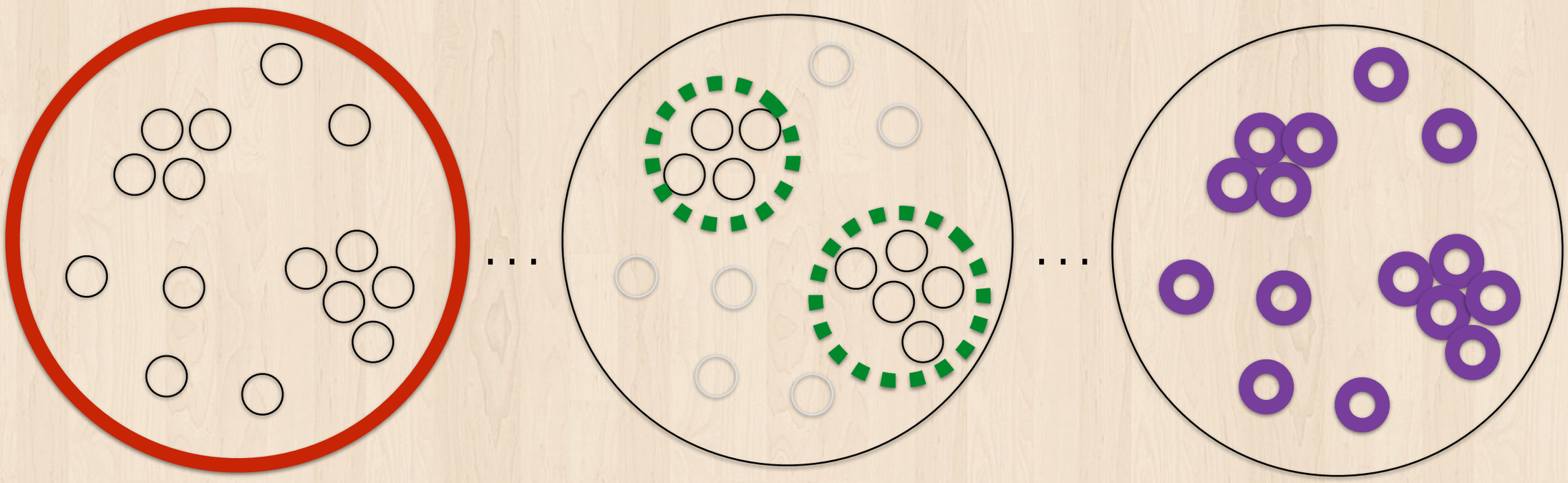
PRC 98 (2018) 024908, JHEP 05 (2018) 006

Jet modification



See Nima's talk for more details

Level of details



In addition to the two views, one can also look at intermediate structure to probe jet-medium interactions

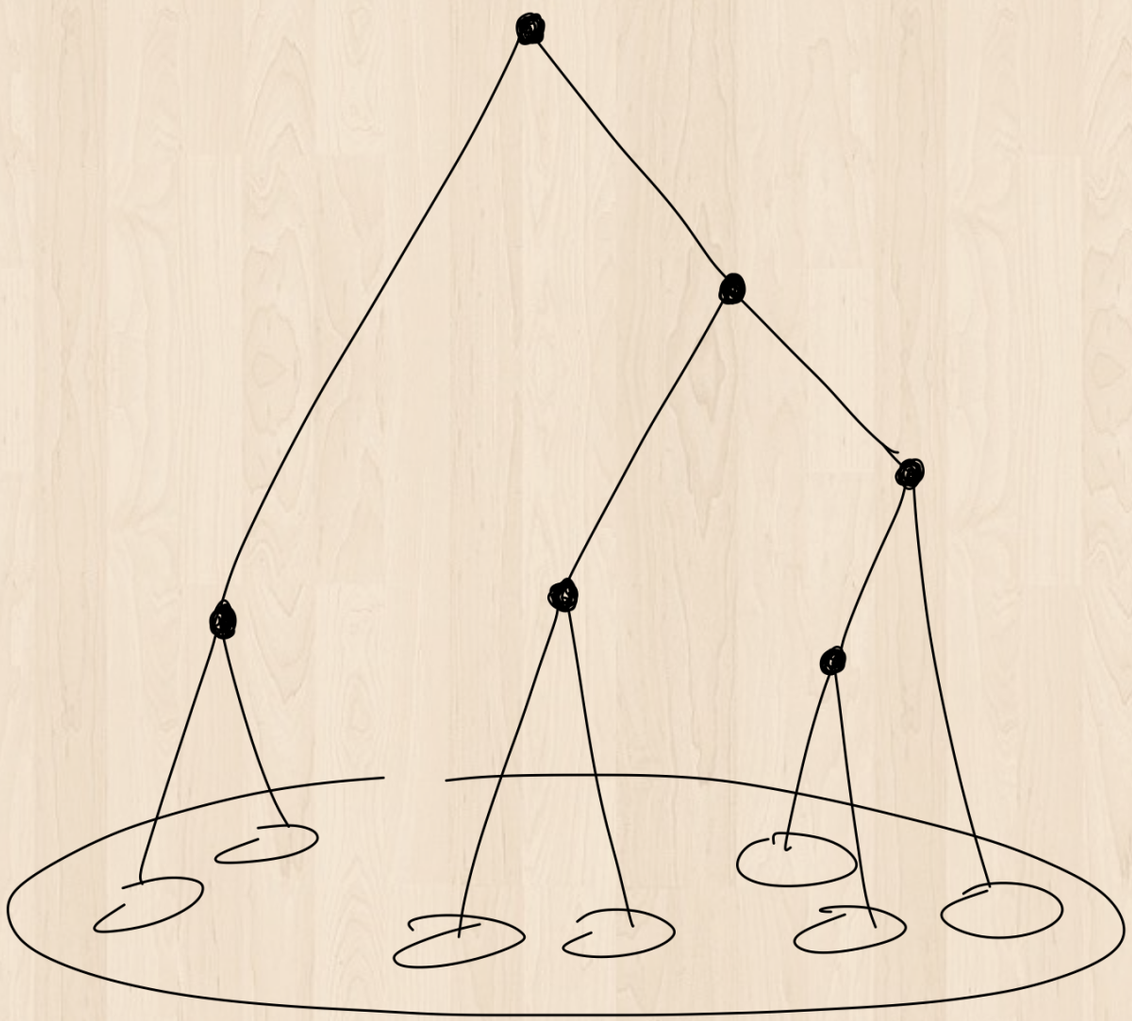
Observables

Summary observables	Identify structures
N-subjettiness	Cluster with smaller radius
Inclusive jet mass	Grooming (mMDT, soft drop, …)
…	…

Some selected results*

* not complete; maybe biased

Jet declustering



Recluster constituents with recombination algortihms (C/A, anti-k_T, ...)

Trace the tree down and examine each pair of branches

Soft drop condition:

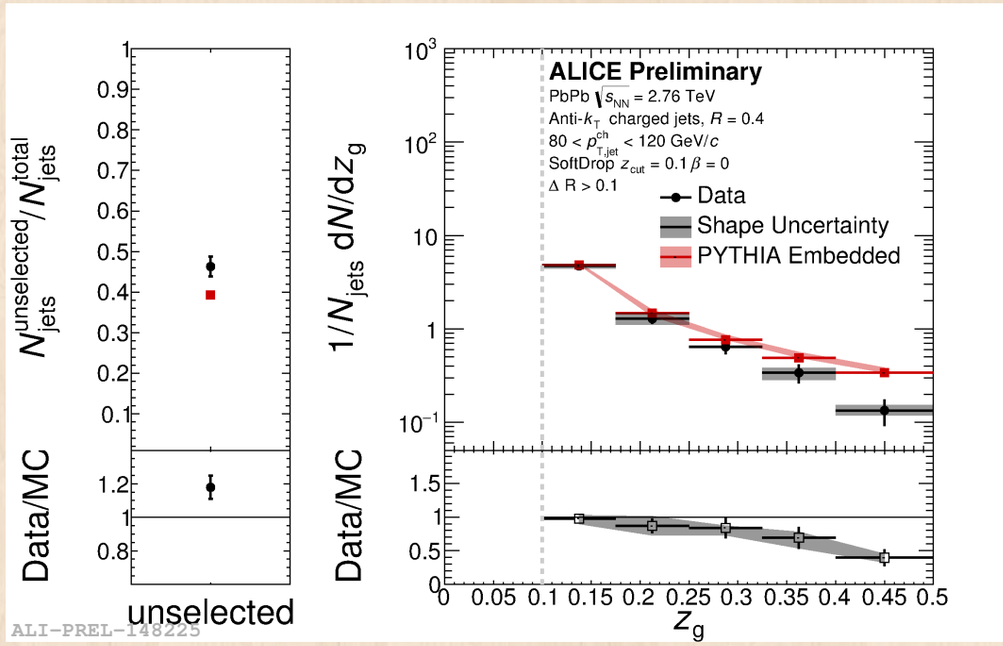
$$z_g \equiv \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{\text{cut}}\,\theta^{\beta}$$

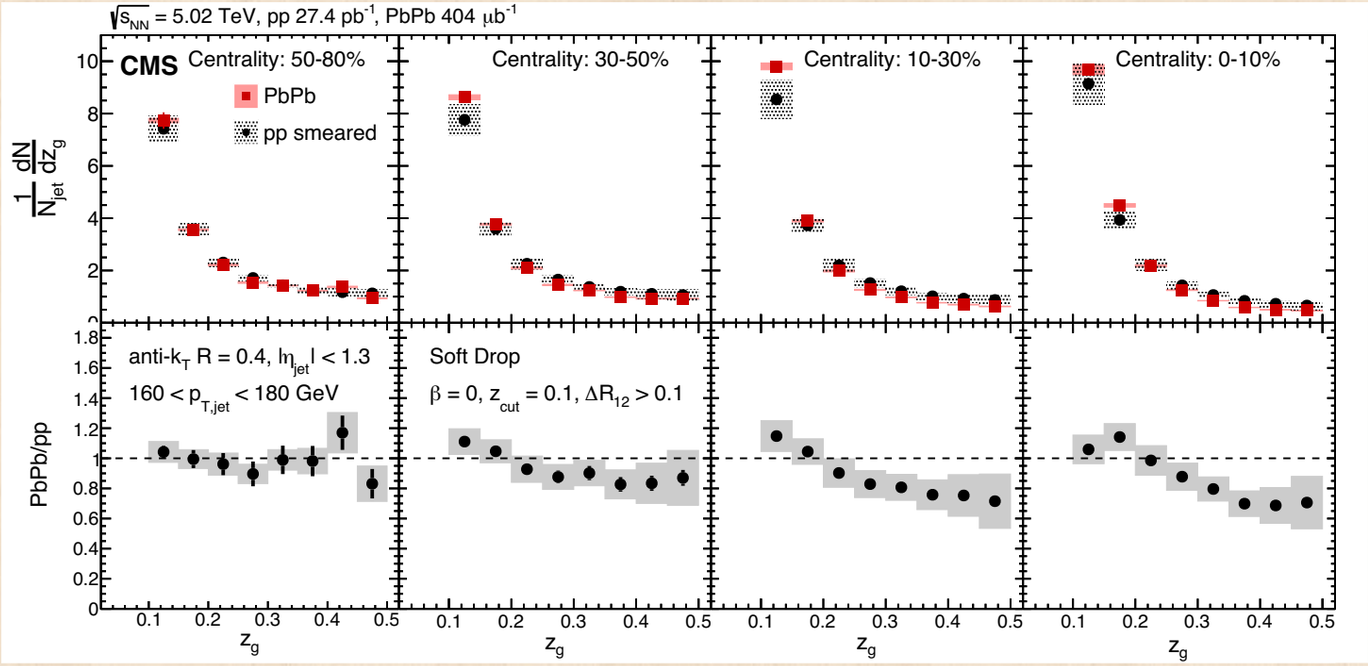
arXiv 1402.2657

Groomed z_g

LHC

Groom with soft drop algorithm —> calculate momentum sharing between the two subjets



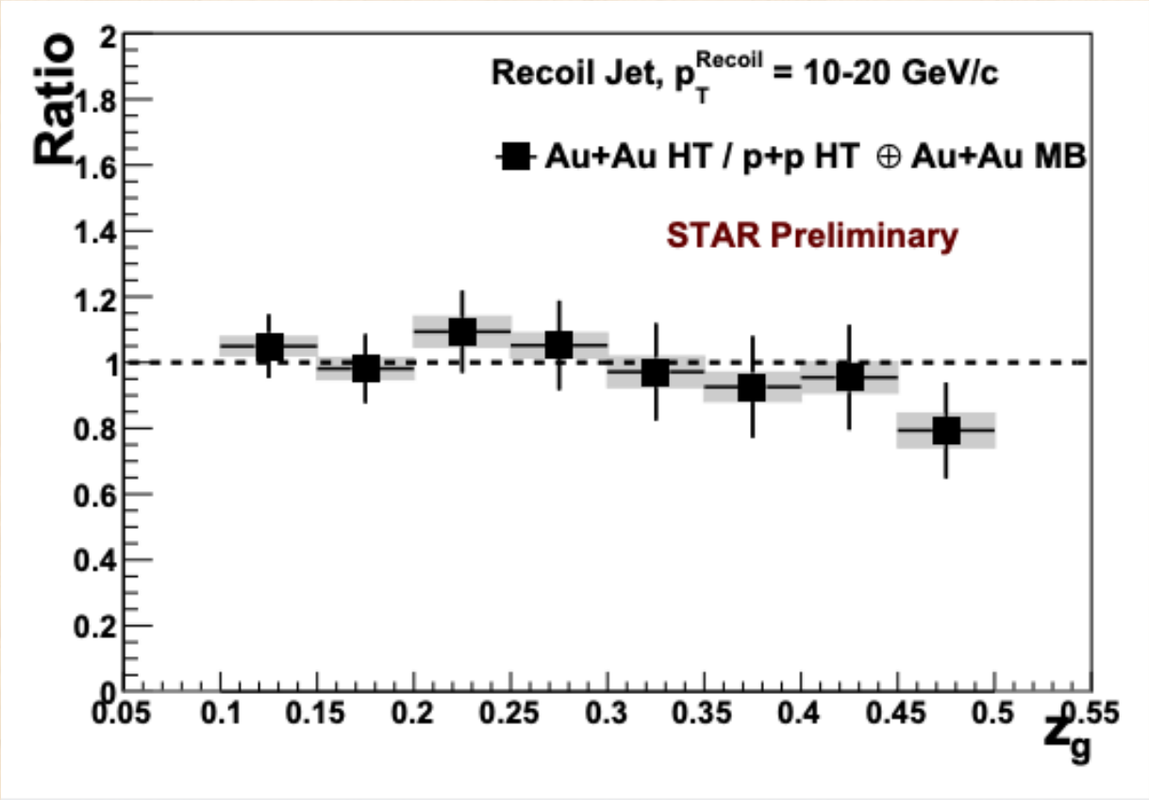


More <u>imbalanced subjets</u> in central collisions

PRL 120 (2018) 142302, Nucl. phys. A 982 (2019) 587

Groomed z_g

RHIC



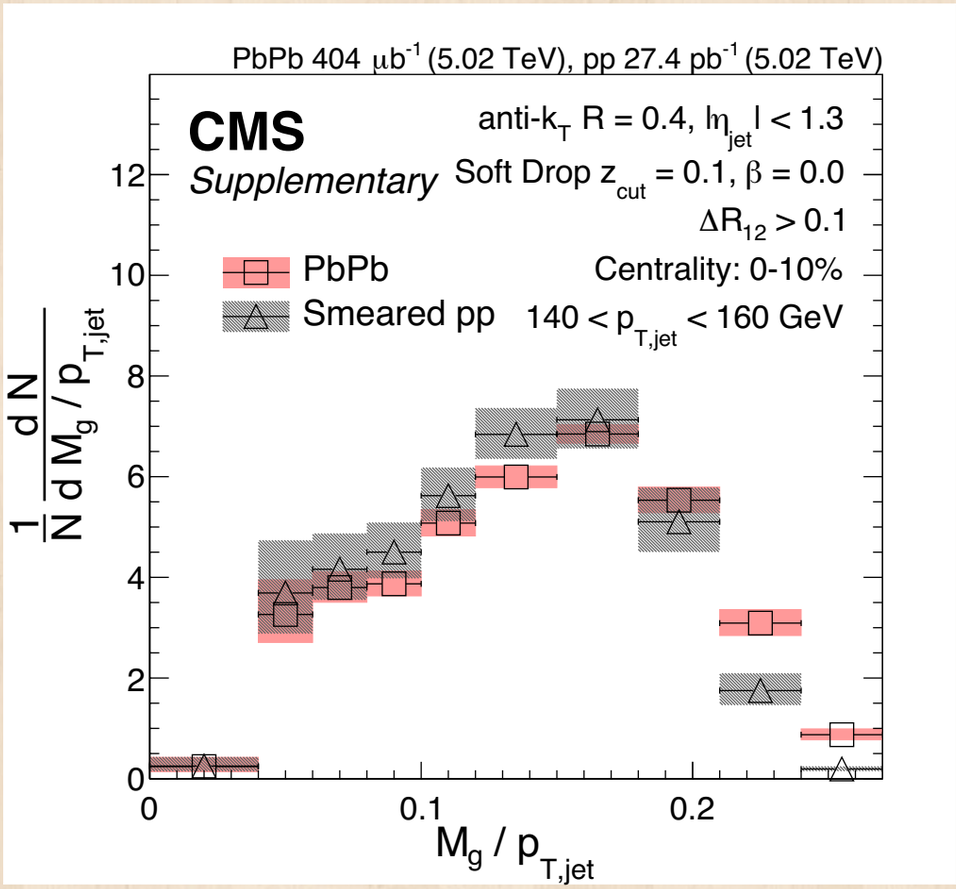
The same thing, however, is <u>not</u> observed in RHIC

Jet energy is very different: formation time difference?

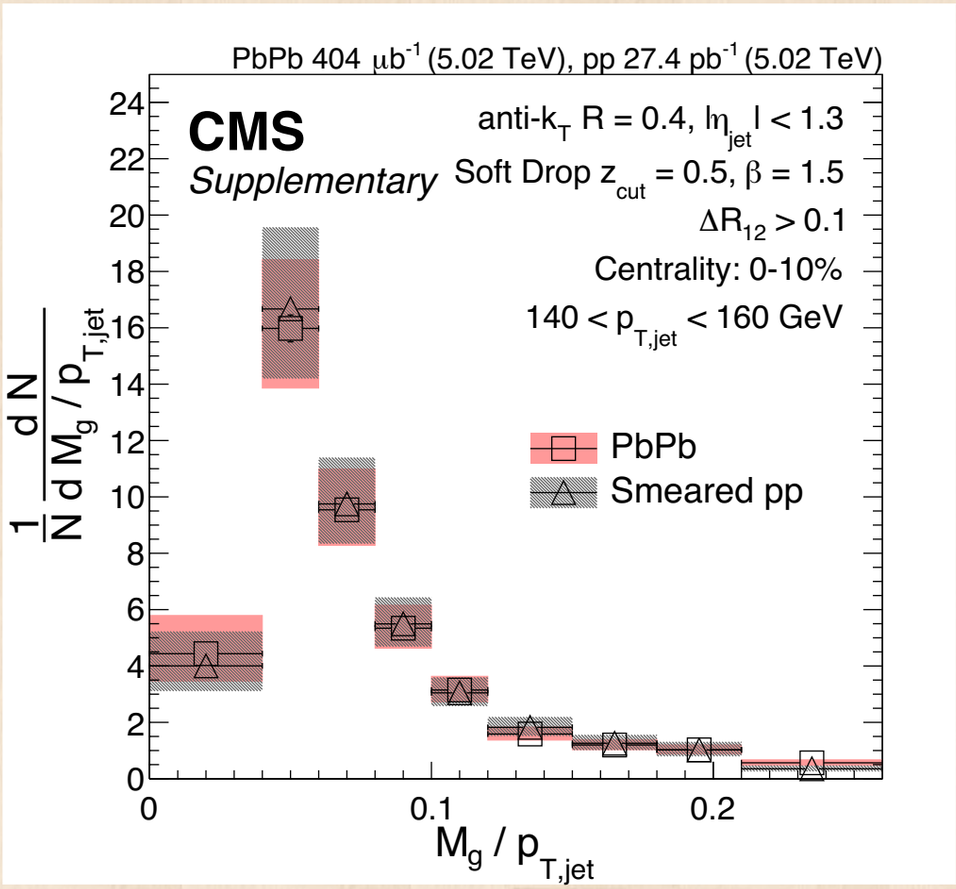
arXiv 1703.10933

Groomed mass

Classic grooming



"Jet core" grooming



Some sign of jet mass enhancement
Core of the jet not modified

JHEP 10 (2018) 161

Full jet mass

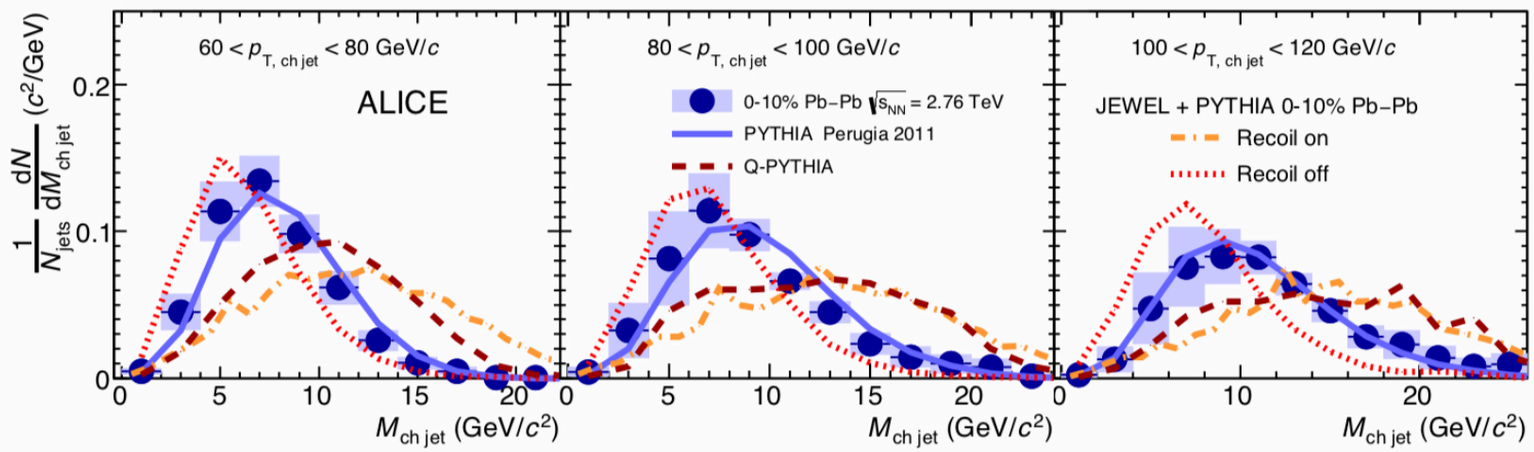
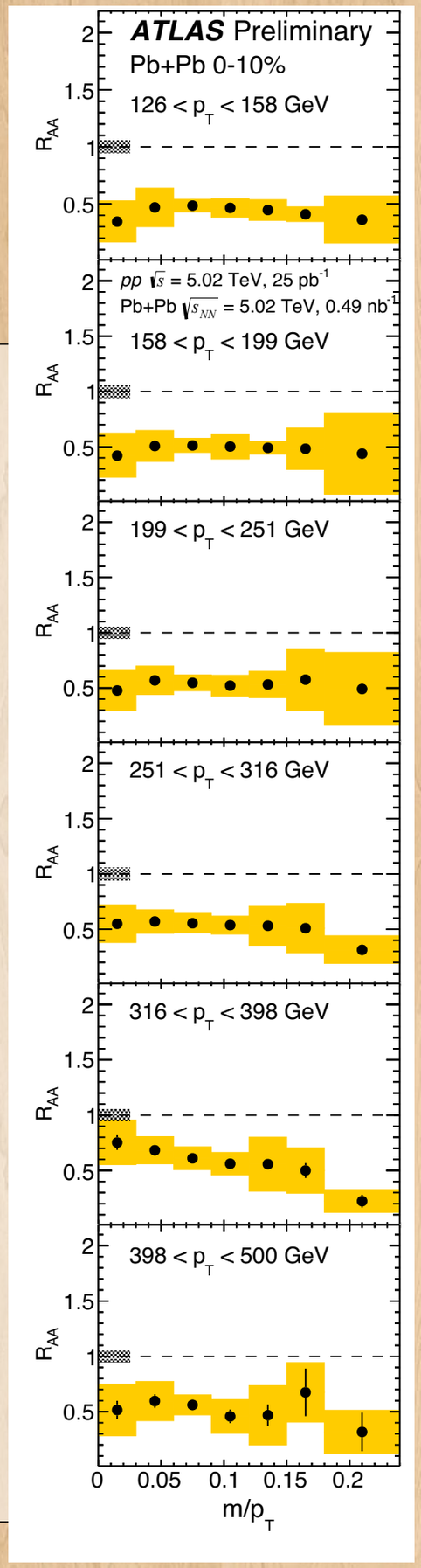


Fig. 10: Fully-corrected jet mass distribution for anti-k_T jets with $R = 0.4$ in the 10% most central Pb–Pb collisions compared to PYTHIA with tune Perugia 2011 and predictions from the jet quenching event generators (JEWEL and Q-PYTHIA). Statistical uncertainties are not shown for the model calculations.

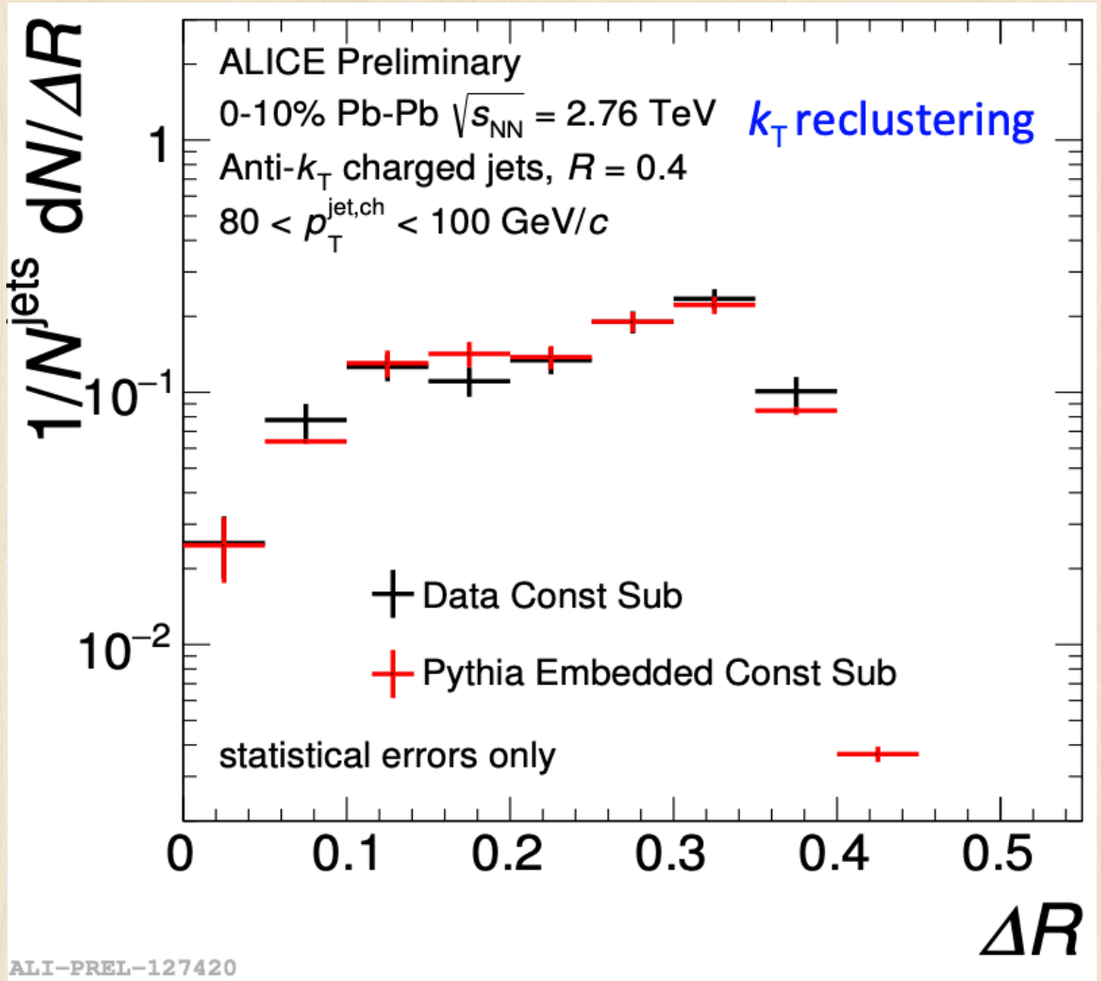


With subtraction, but no grooming
More contribution from soft particles

No big change in shape: PbPb vs pp

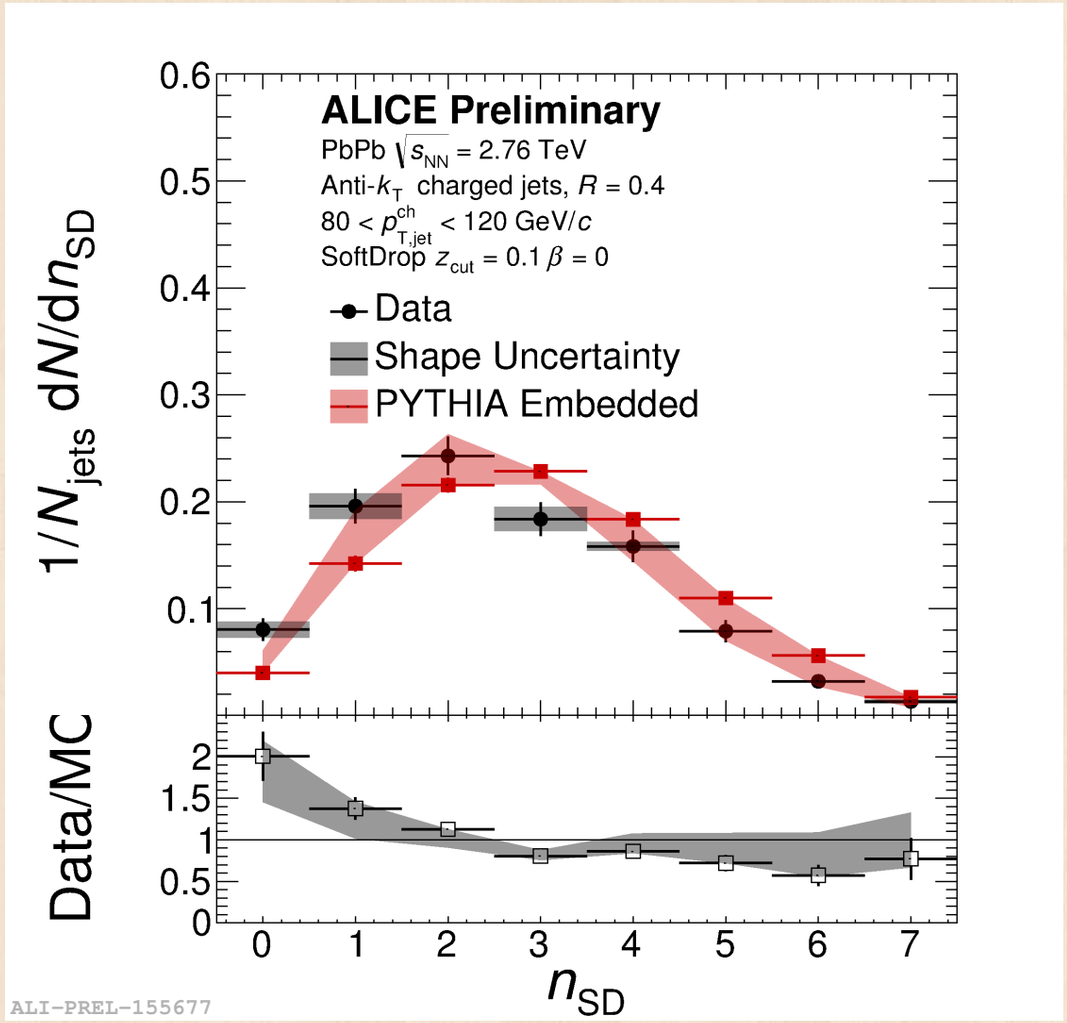
PLB 776 (2018) 249, ATLAS CONF 2018-014

Subjet opening angle



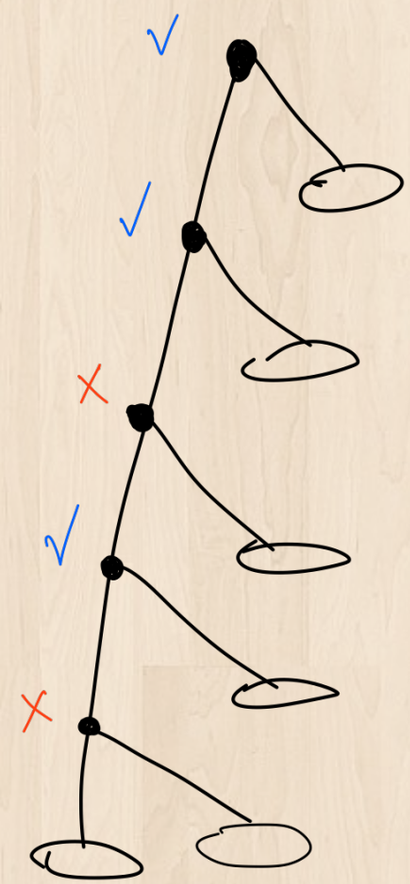
No modification is observed — the presence of large "background" clouds interpretation

Number of accepted branches



Smaller amount of accepted branches in PbPb

Repeatedly apply soft drop algorithm on the stronger branch



Nucl. phys. A 982 (2019) 587

N-subjettiness

Measures how N-pronged the jet is

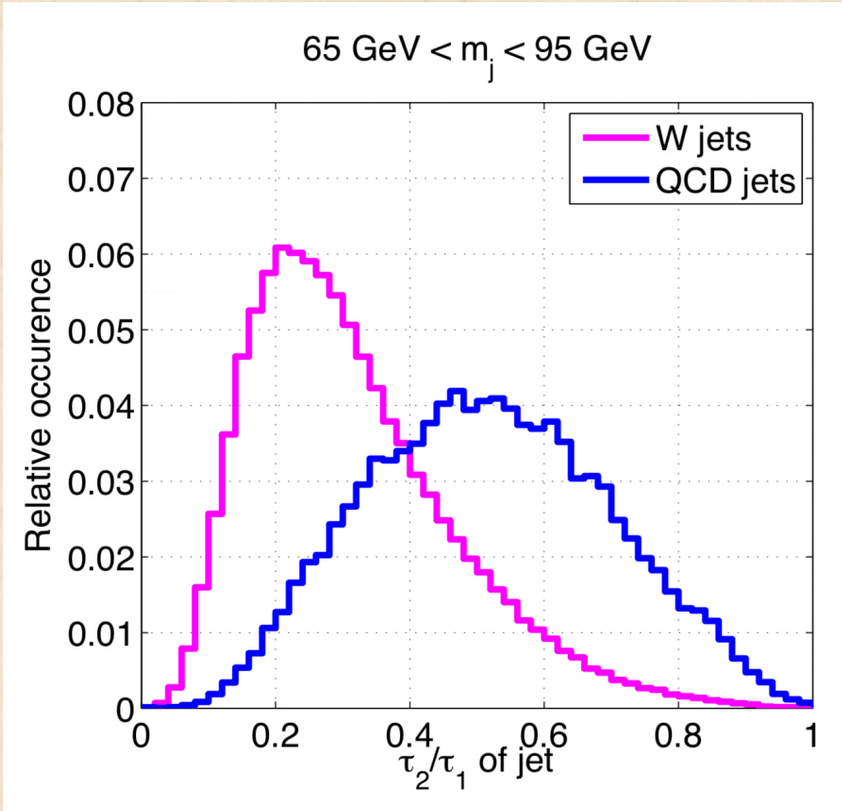
$$\tau_N = \frac{1}{\sum_k p_{T,k} R_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \ldots, \Delta R_{N,k}\}$$

Subjet: 1 - N, tracks: 1 - k

$\tau_N \to 0$: jet has N or fewer cores

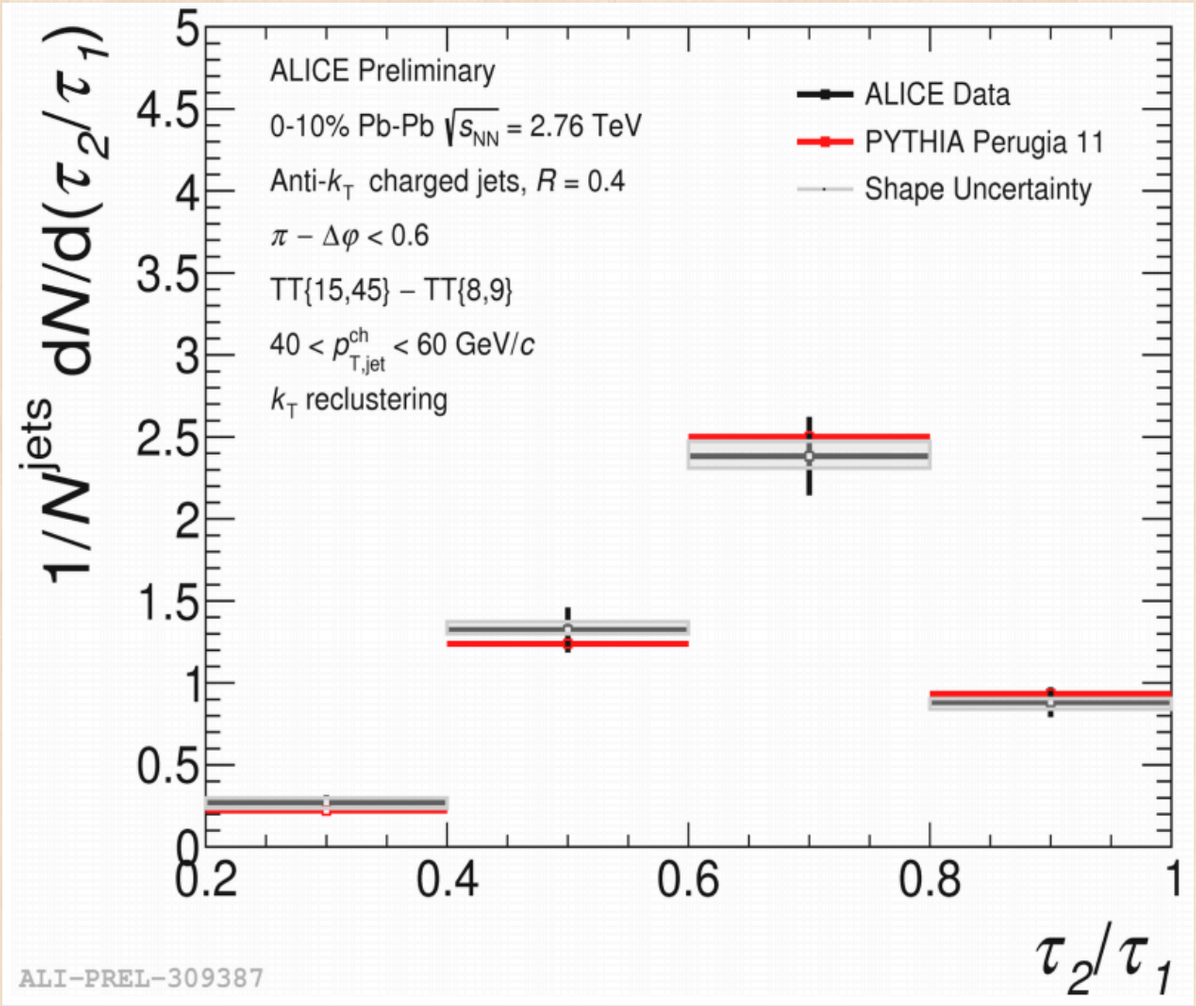
$\tau_N \to 1$: jet has > N cores

$\tau_2/\tau_1 \to 0$: two-pronged



arXiv 1011.2268

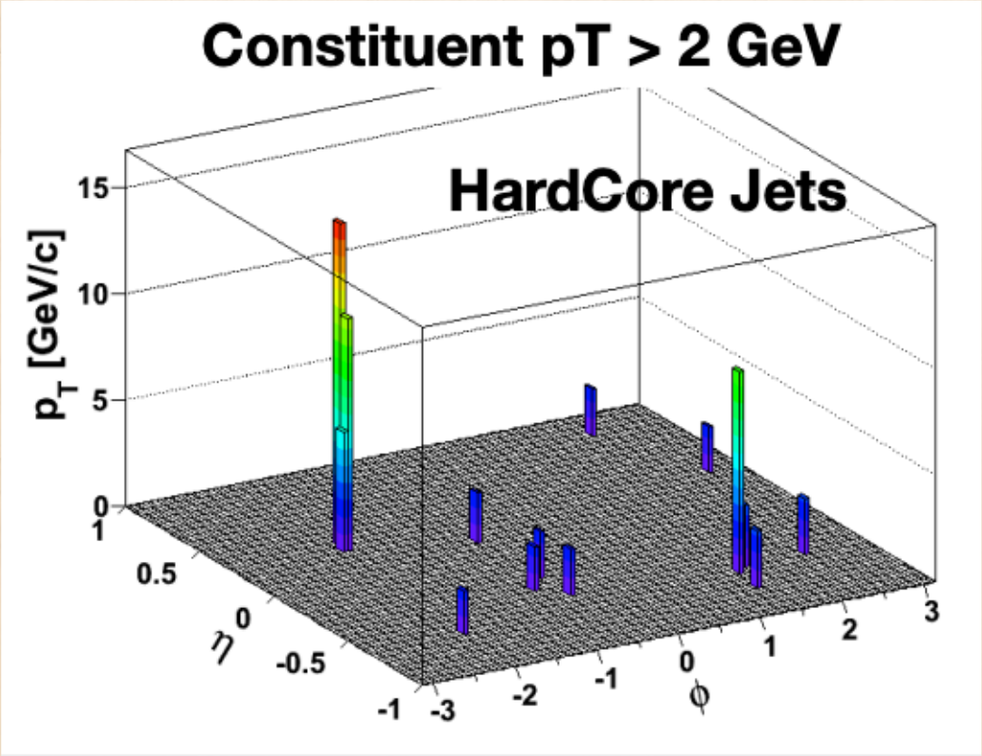
N-subjettiness

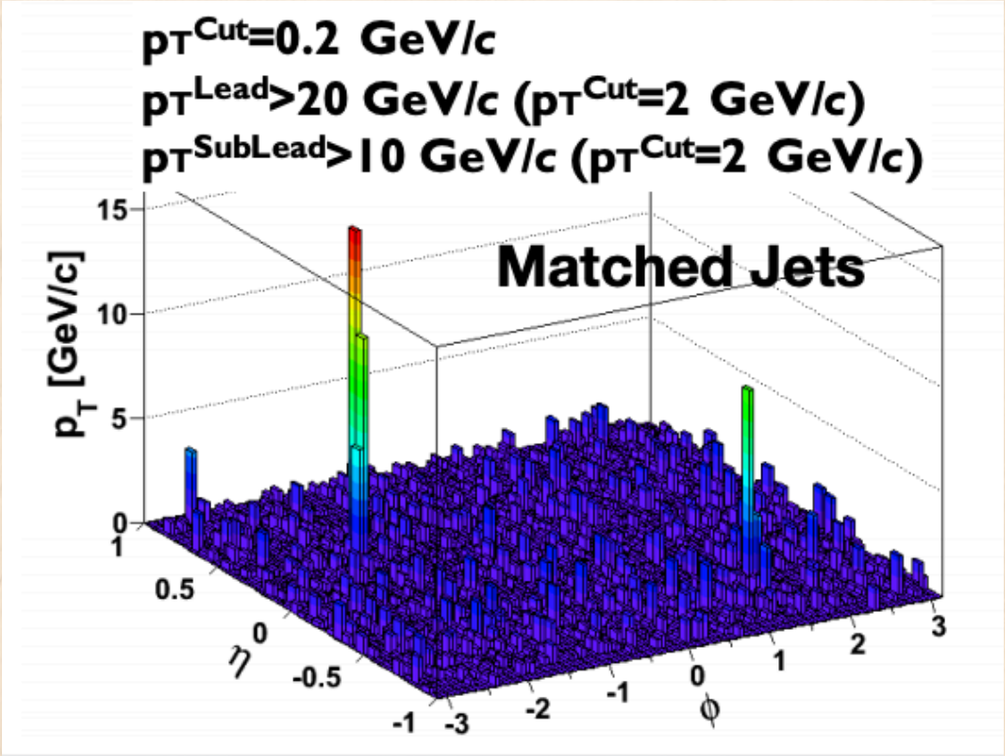


Very similar between PbPb and pp expectations
—> core of the jet behave very similar

Hard core jets at STAR

Identify population of jets using a hard cut on the constituent: “Hard core” jets



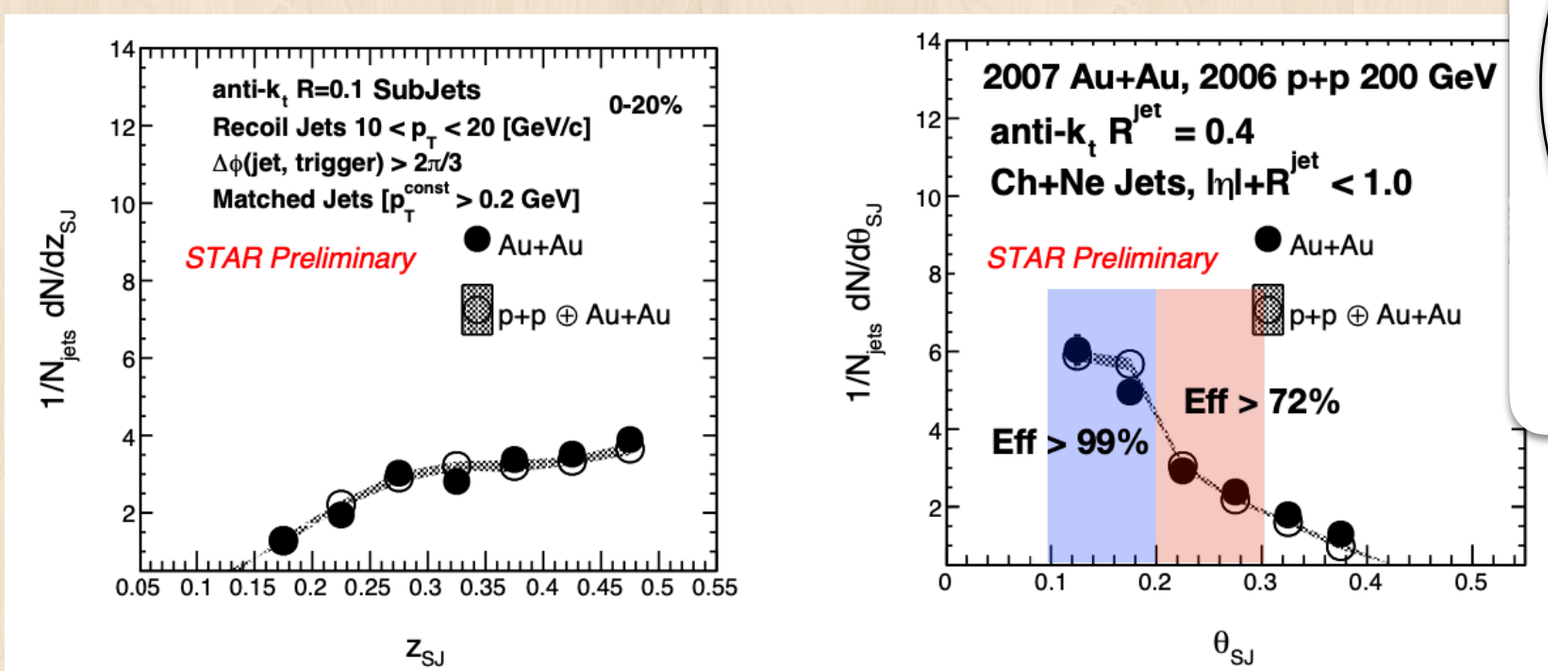


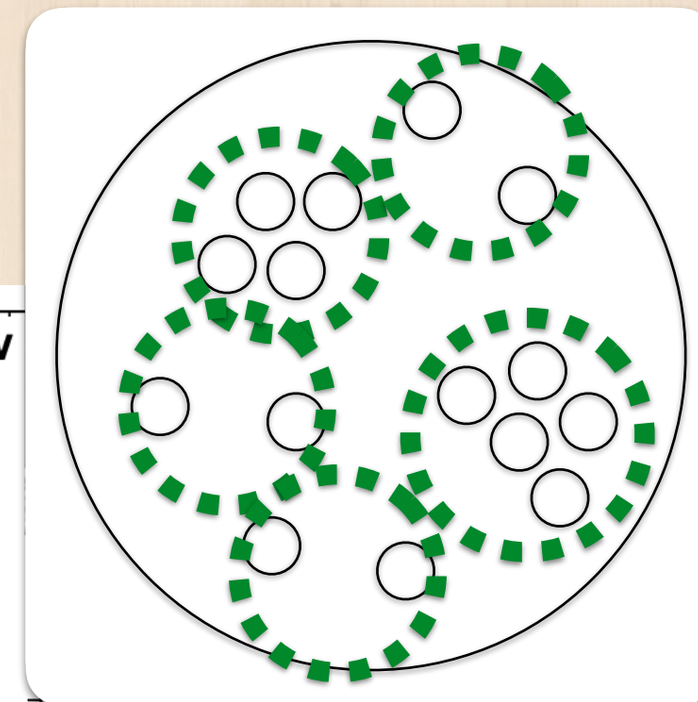
Match the hard core jets with jets clustered with everything: “matched” jets = full jet with hard core

Subjet clustering

Cluster constituents with R = 0.1

More robust against “background”



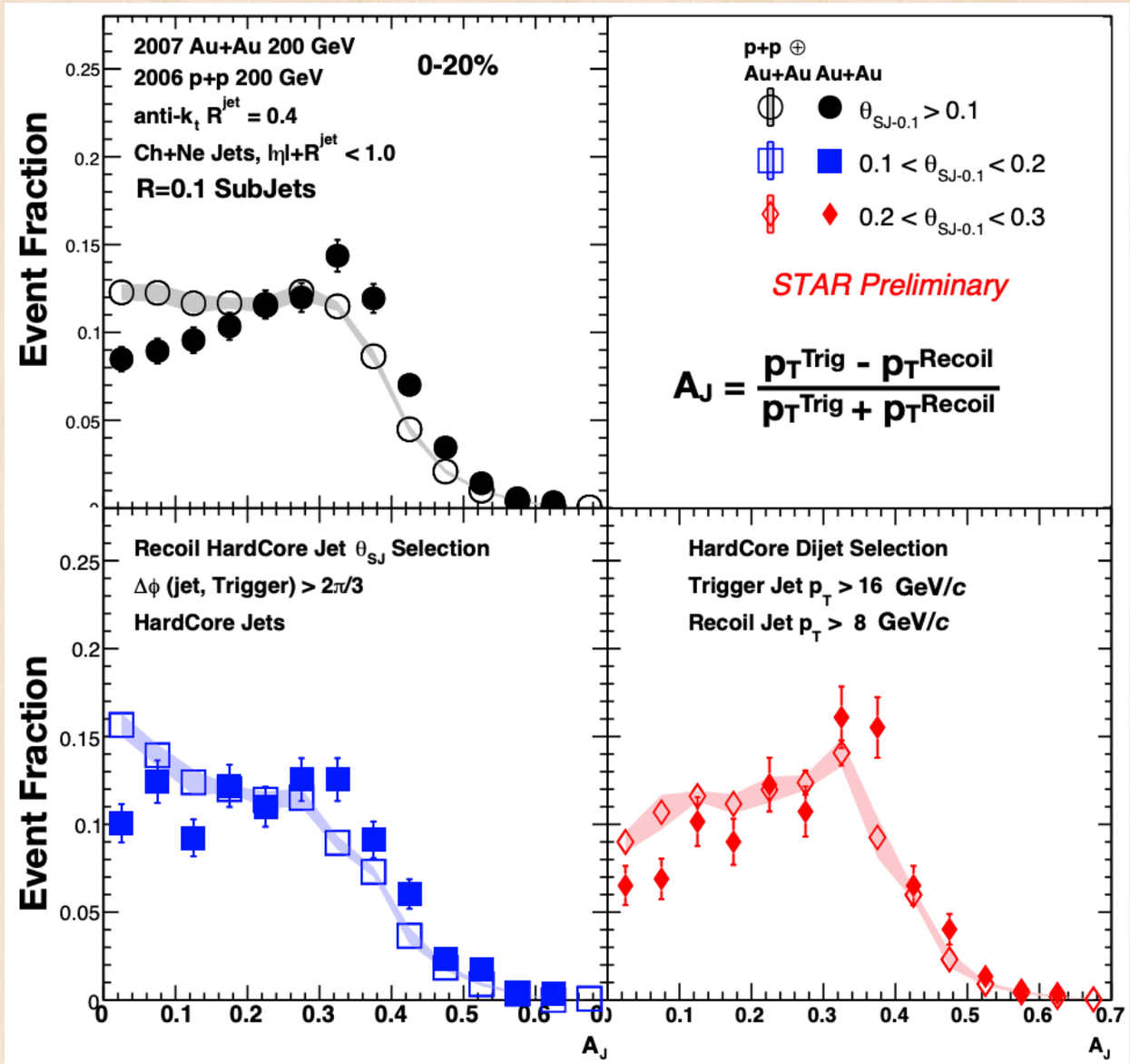


No significant difference in shape is observed

Using angle as classification

Some imbalance is observed for all opening angle classes …if we look at the hard core of the jets

Direction and size of modification is not too different

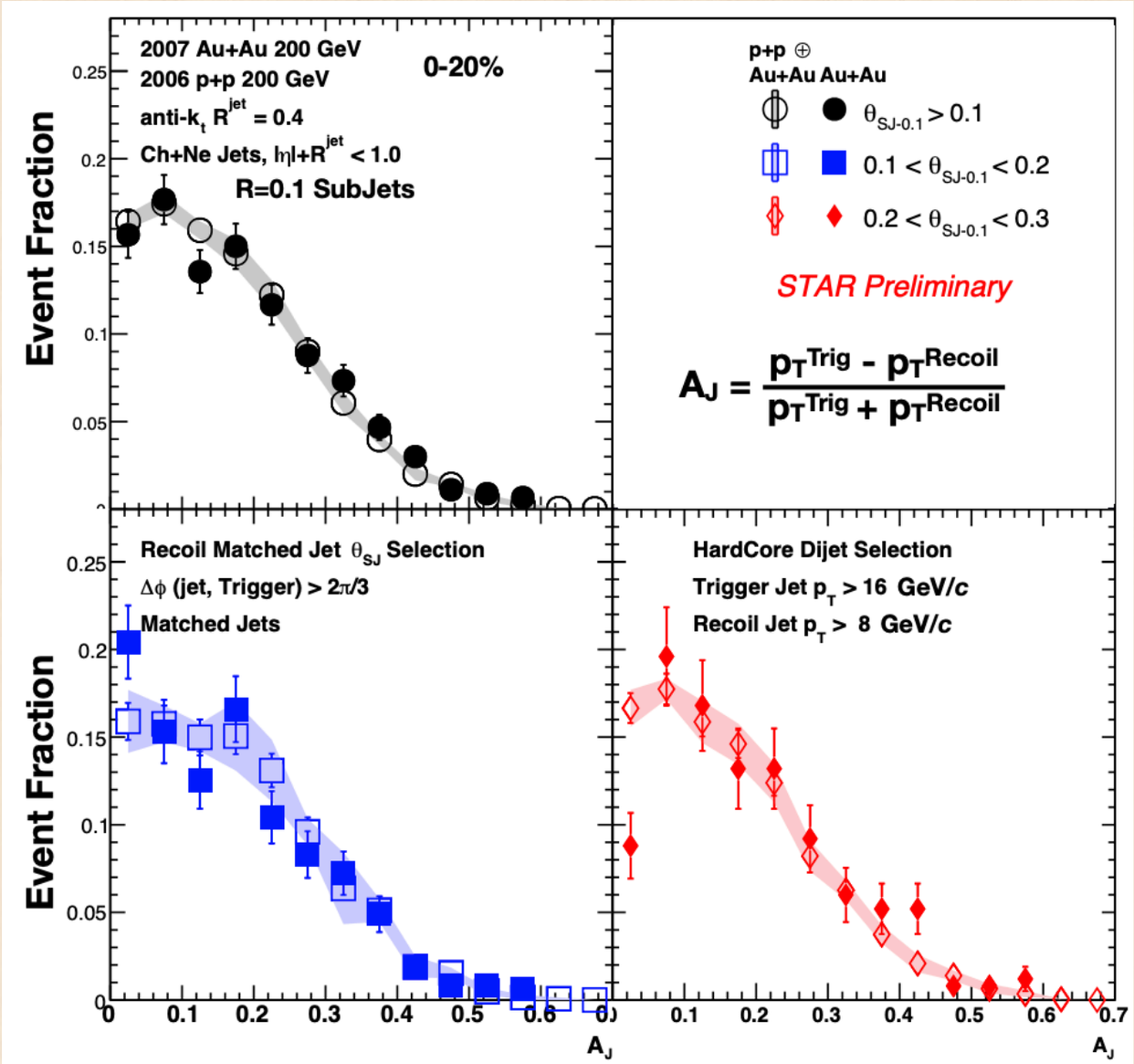


Using angle as classification

When we include back all the soft energies, balance is restored

This is independent of the subjet opening angle classes

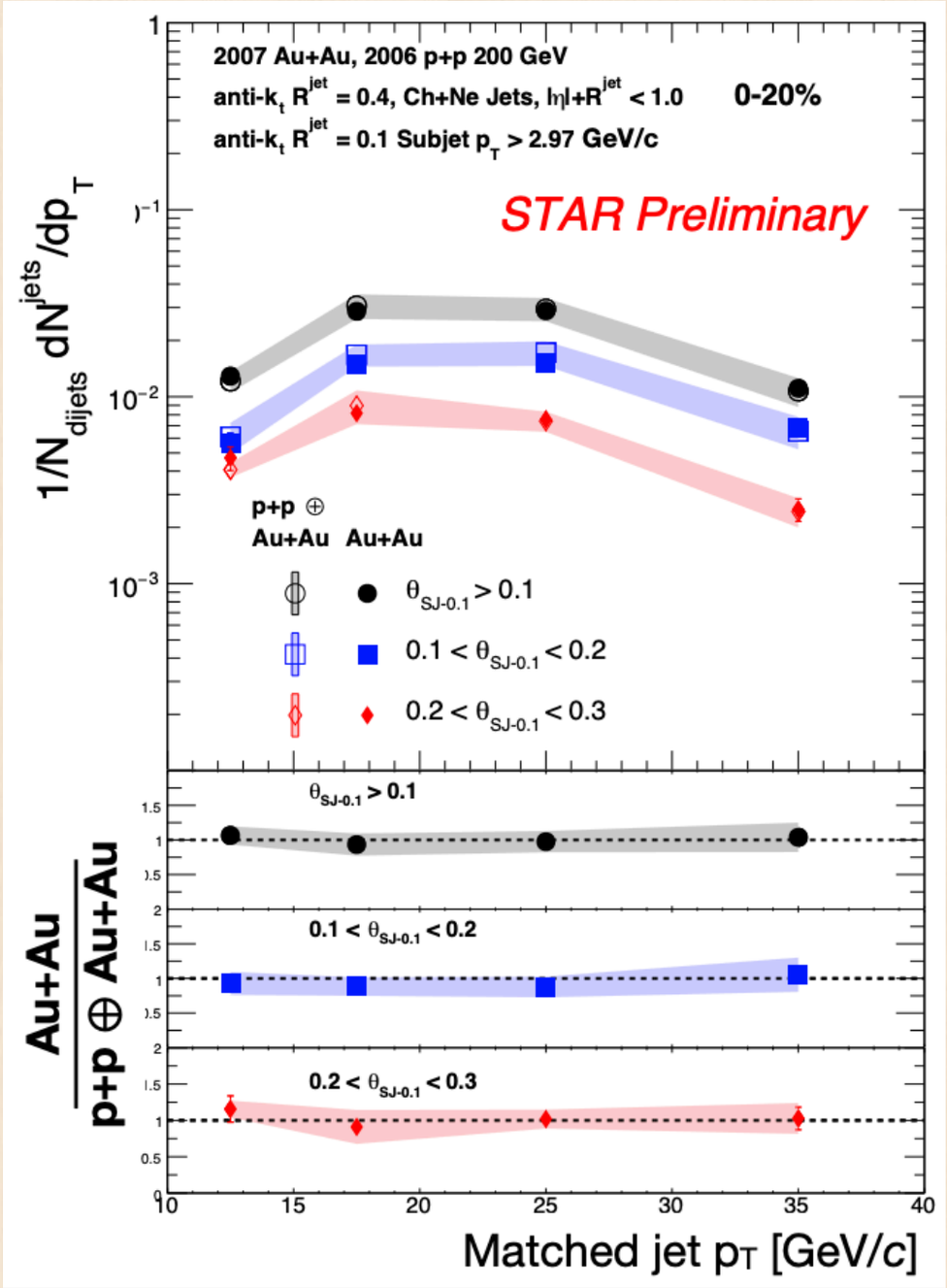
R = 0.4 seems to be able to recover all the energy



Using angle as classification

Yield of the recoil matched jet normalized per di-jet

No significant differences for all opening angle classes between AuAu and embedded pp

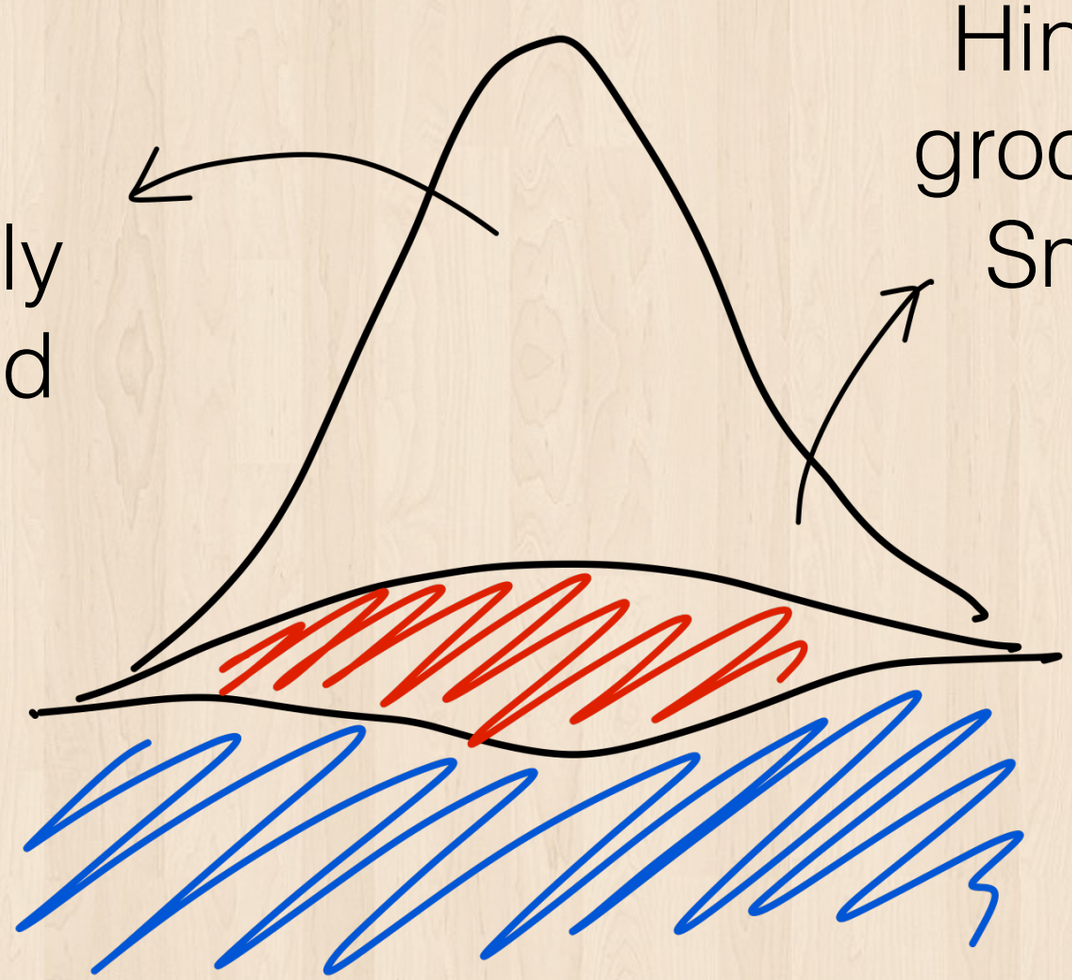


What have we learned

LHC

Core:
not really
modified

Imbalanced subjet
Hint of larger
groomed mass
Smaller n_{SD}



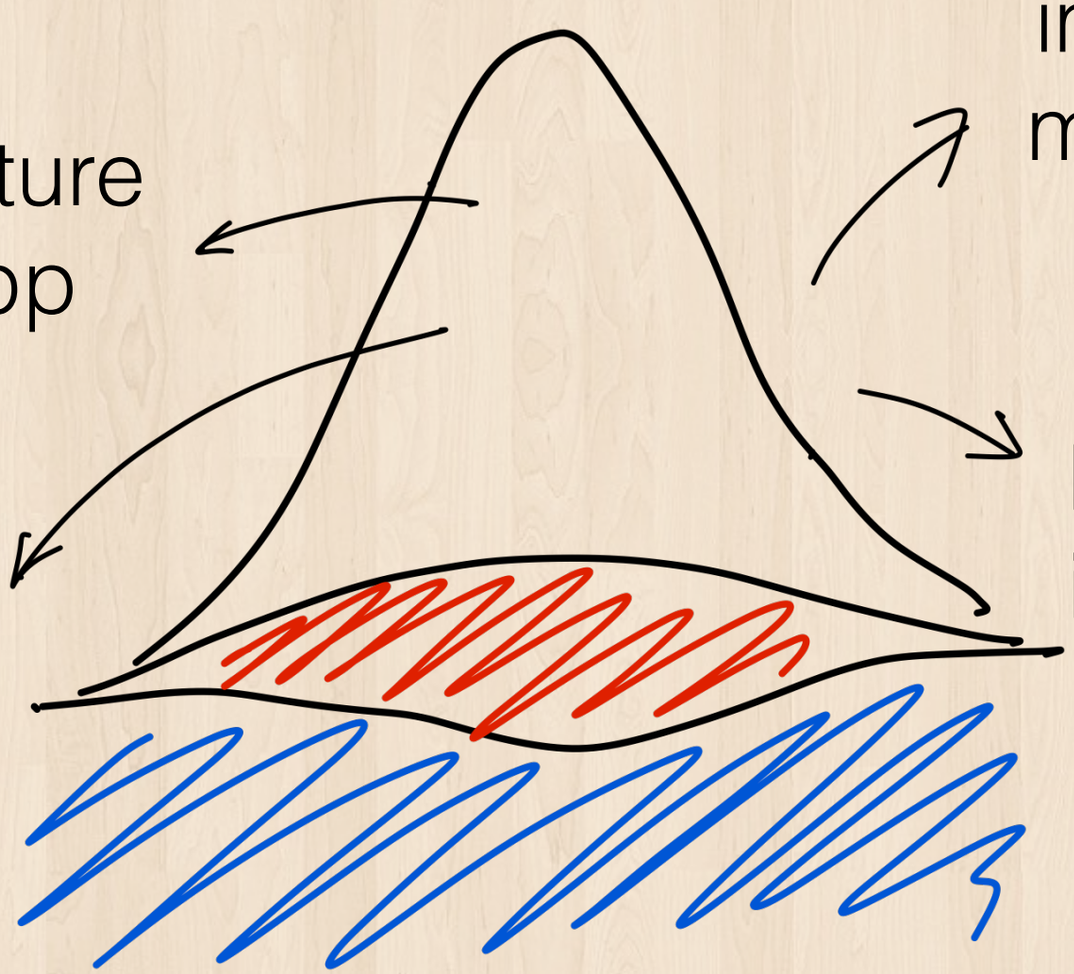
Overall: no significant modification to mass

What have we learned

RHIC

Hard structure
AuAu ~ pp

No significant imbalance for matched hard core jets



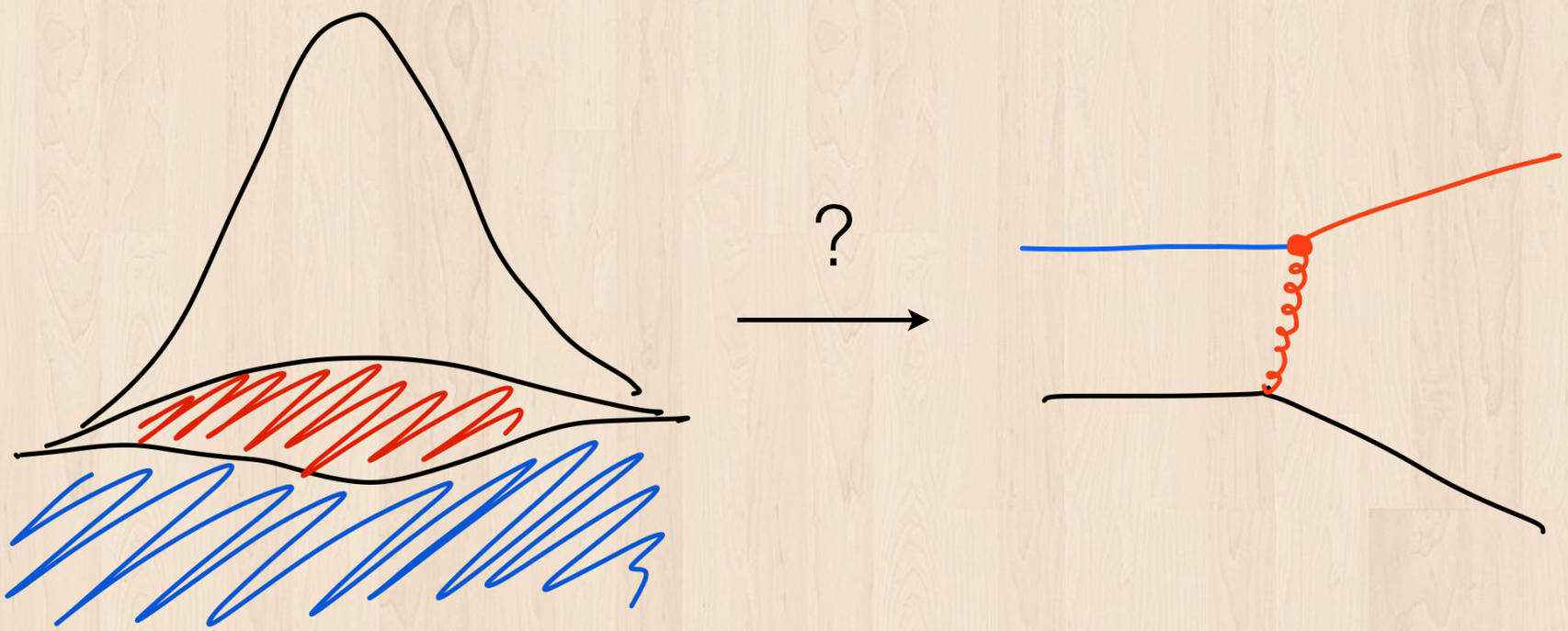
Imbalanced dijet with hard core only

No significant imbalance for groomed recoil jets either

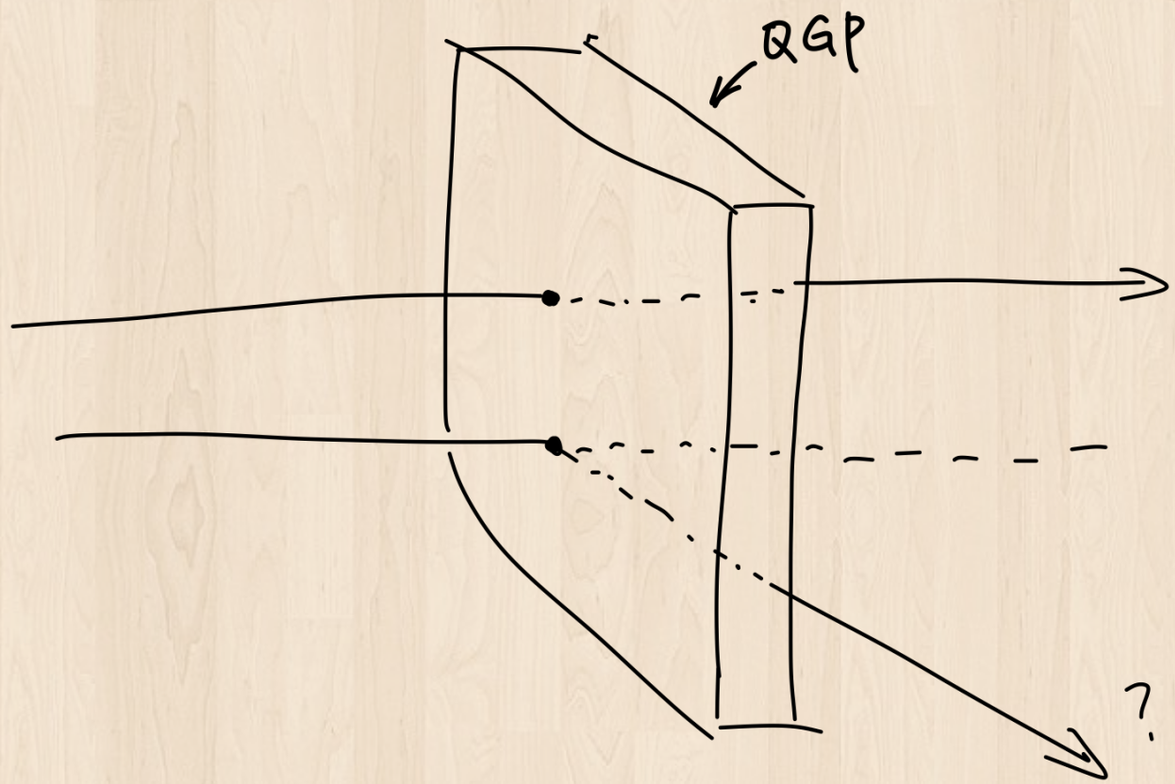
Looking Forward

The big question

How do we learn about parton-medium interaction from substructure observables?



Large angle



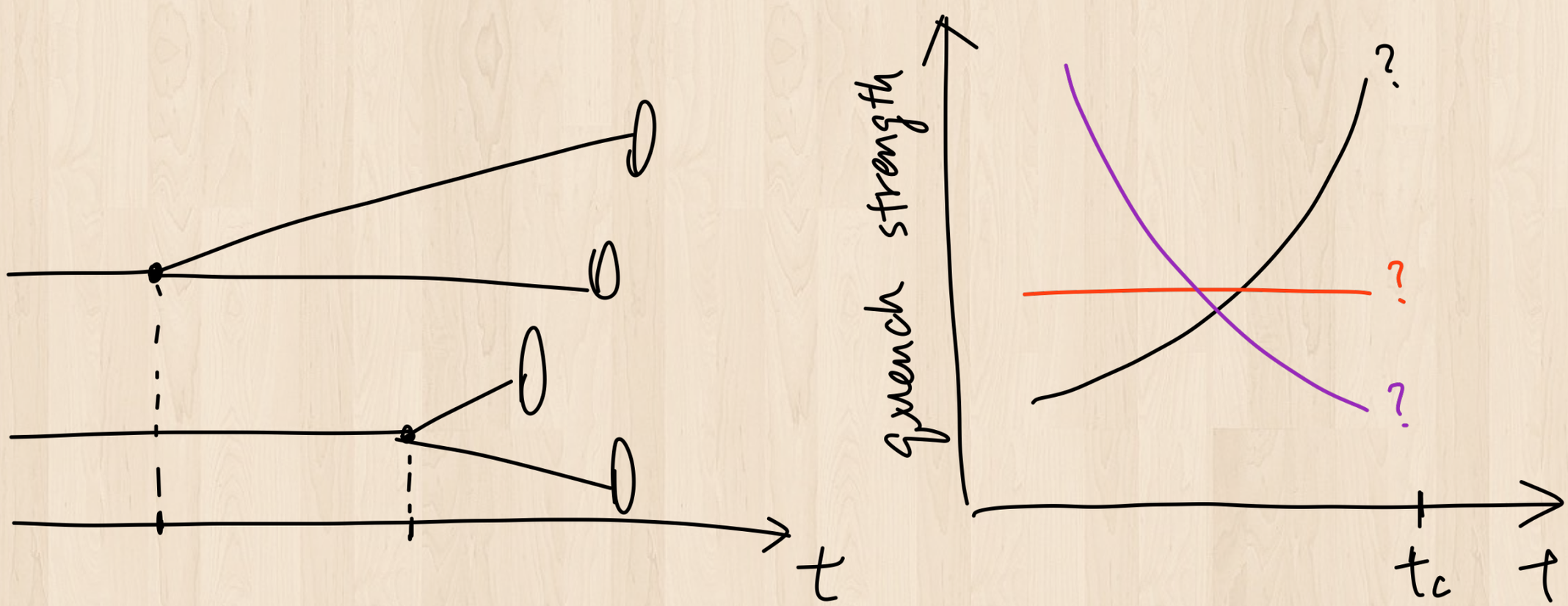
Large angle hard radiation?

Energy of jet extends to large angle
--> substructure of large radius jets

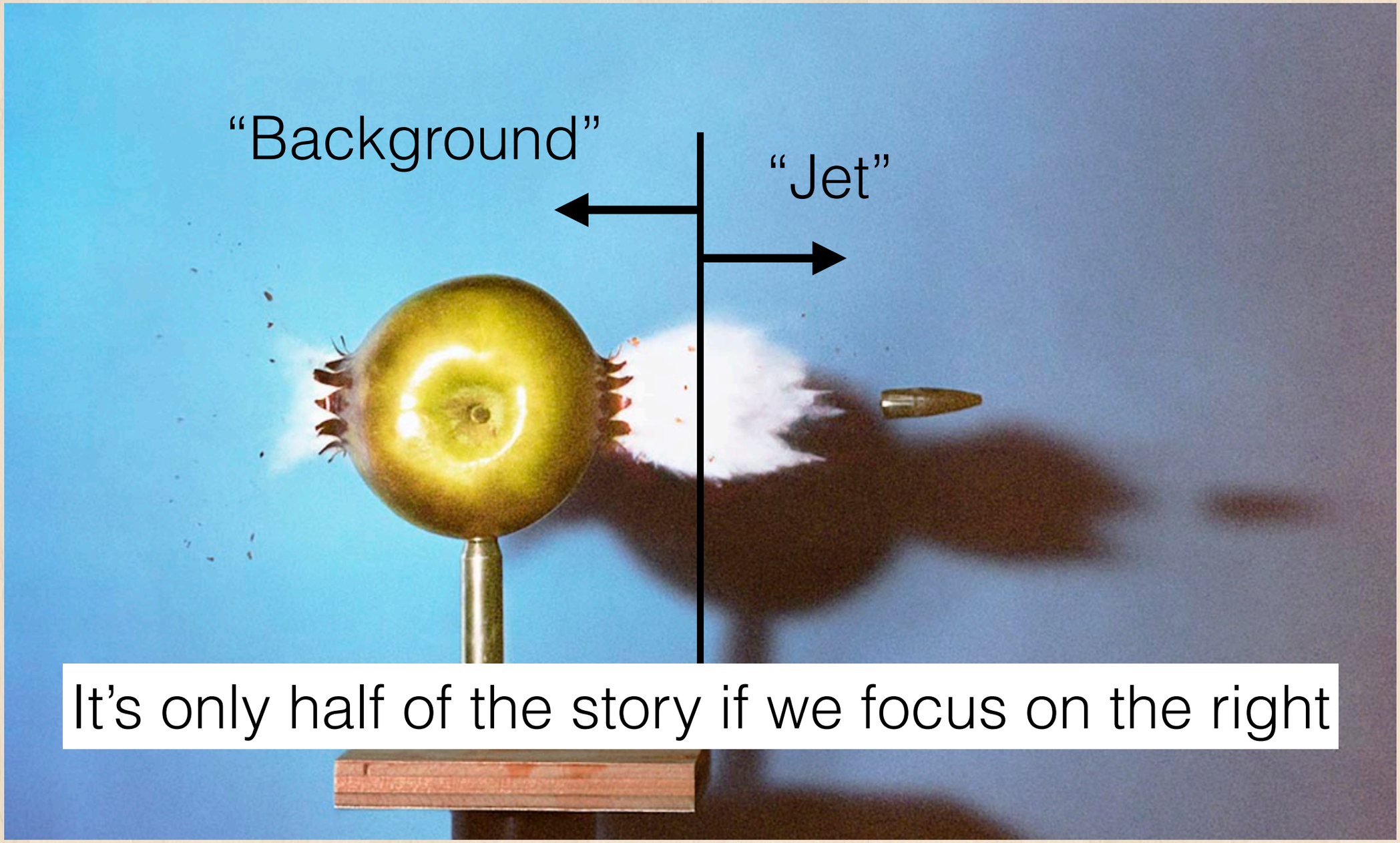
"Time axis"

Formation time: harder splittings form earlier
Can we use this to probe different time inside QGP?

What other handles do we have?



The Apple


“Background”
“Jet”
It’s only half of the story if we focus on the right

Systematic observables

- Is there a set of observables that
  - Forms a (over?) complete basis
  - Each item gives us some new piece of information
  - Brings out physics in a natural way (to humans)
- Then we just go and measure them one by one

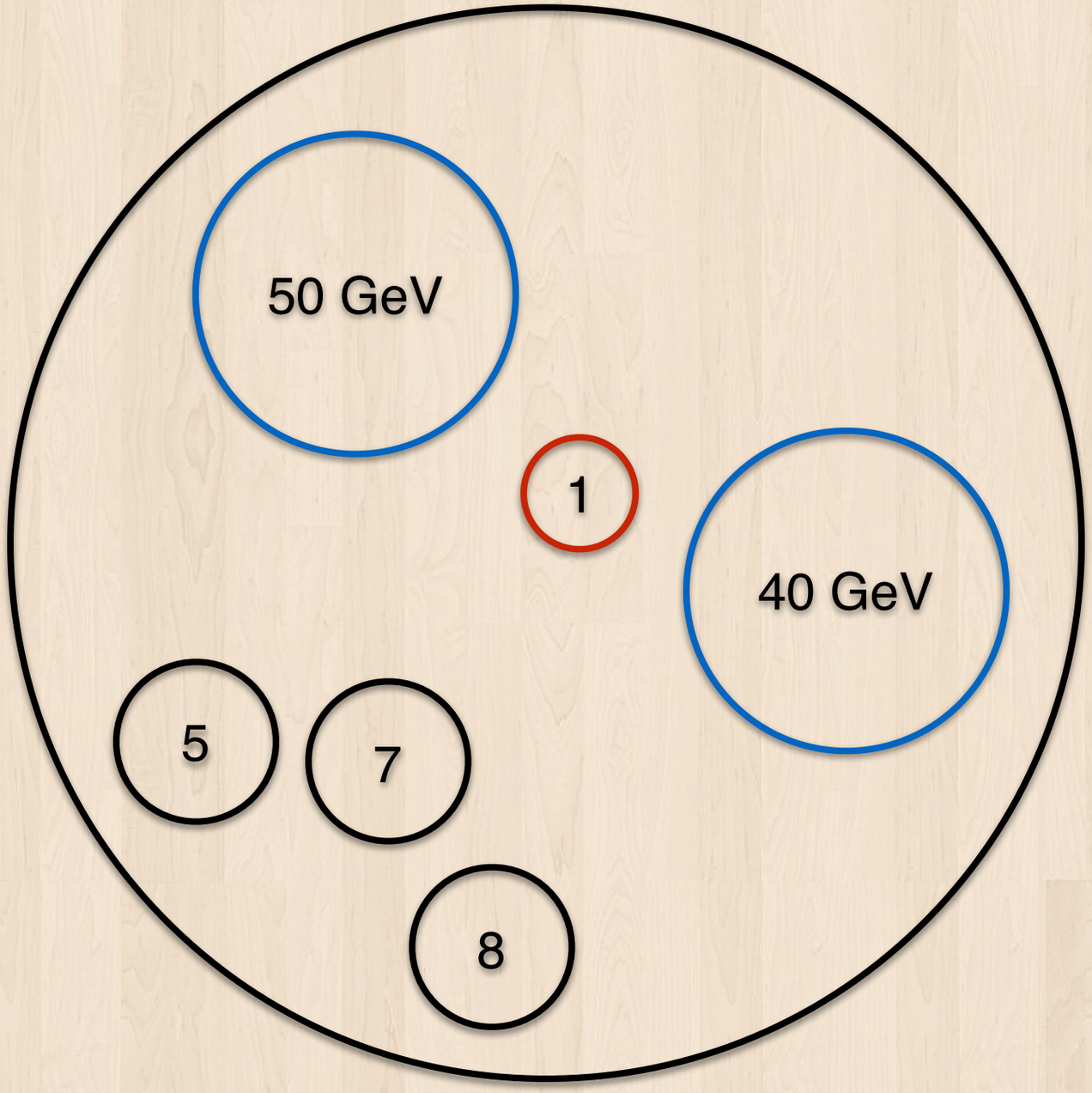
Summary

Summary

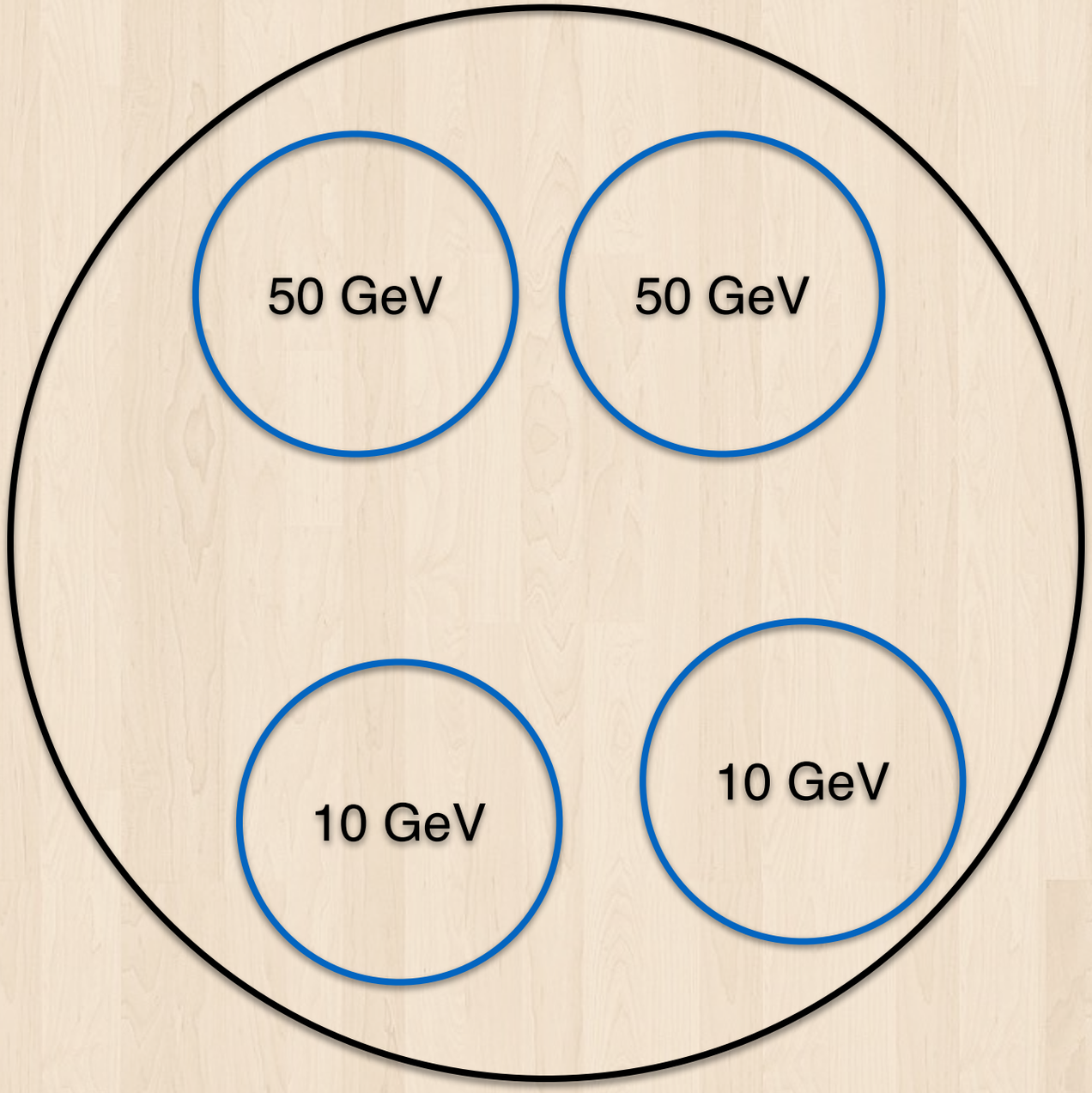
- Substructure observables open up many possibilities to probe the interaction between high energy partons and the hot QCD medium
  - Complements other jet measurements
- With the large dataset at LHC and RHIC, looking forward to many exciting results in the next few years!

Backup slides ahead

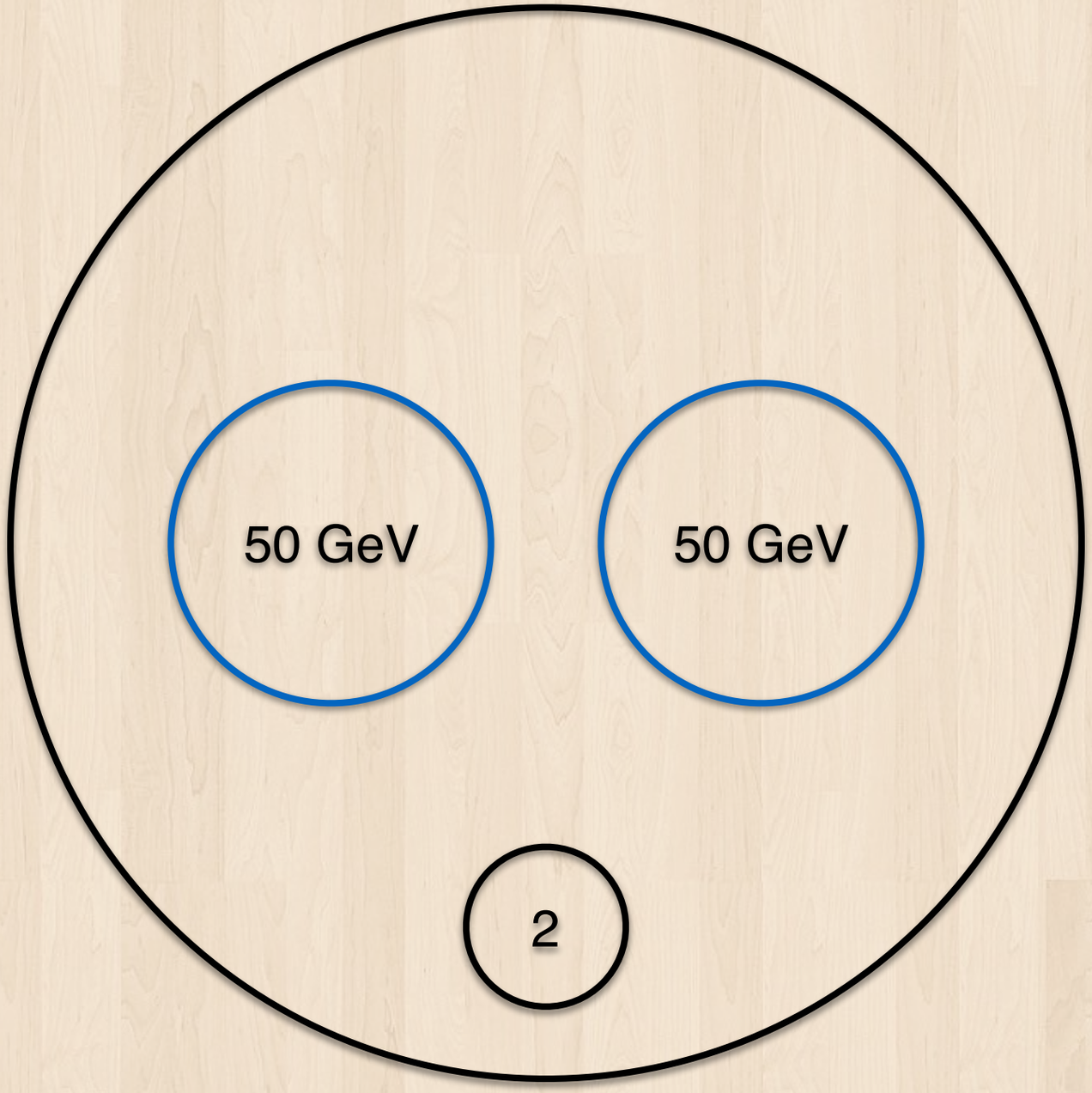
Jet #1



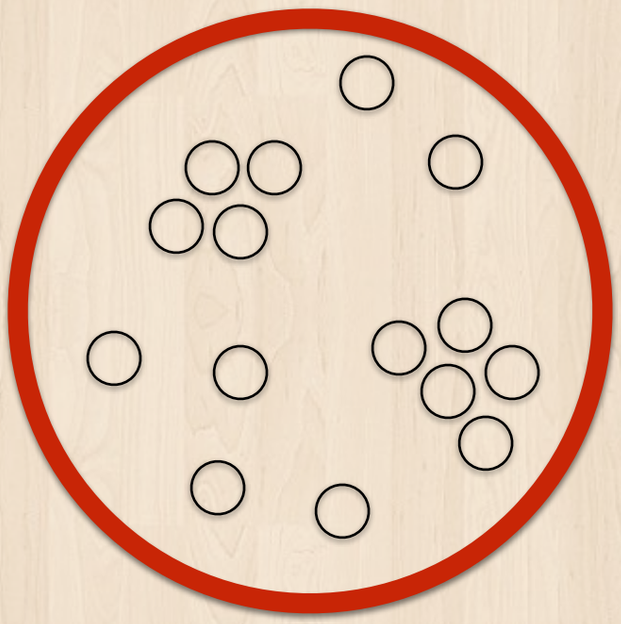
Jet #2



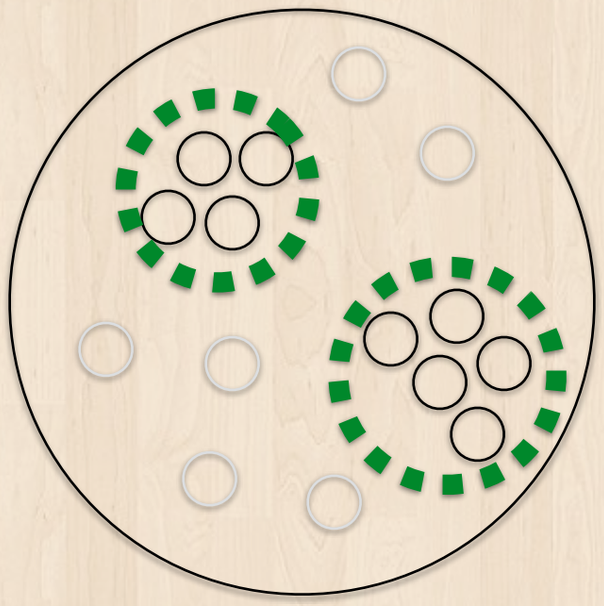
Jet #3



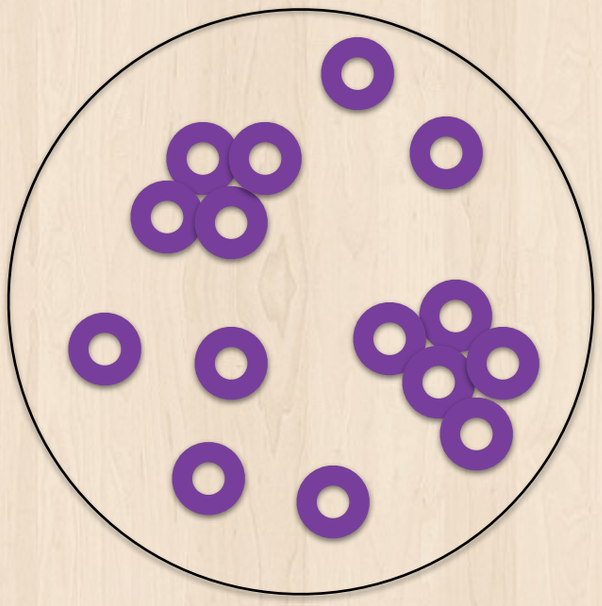
Level of detail



Full jet

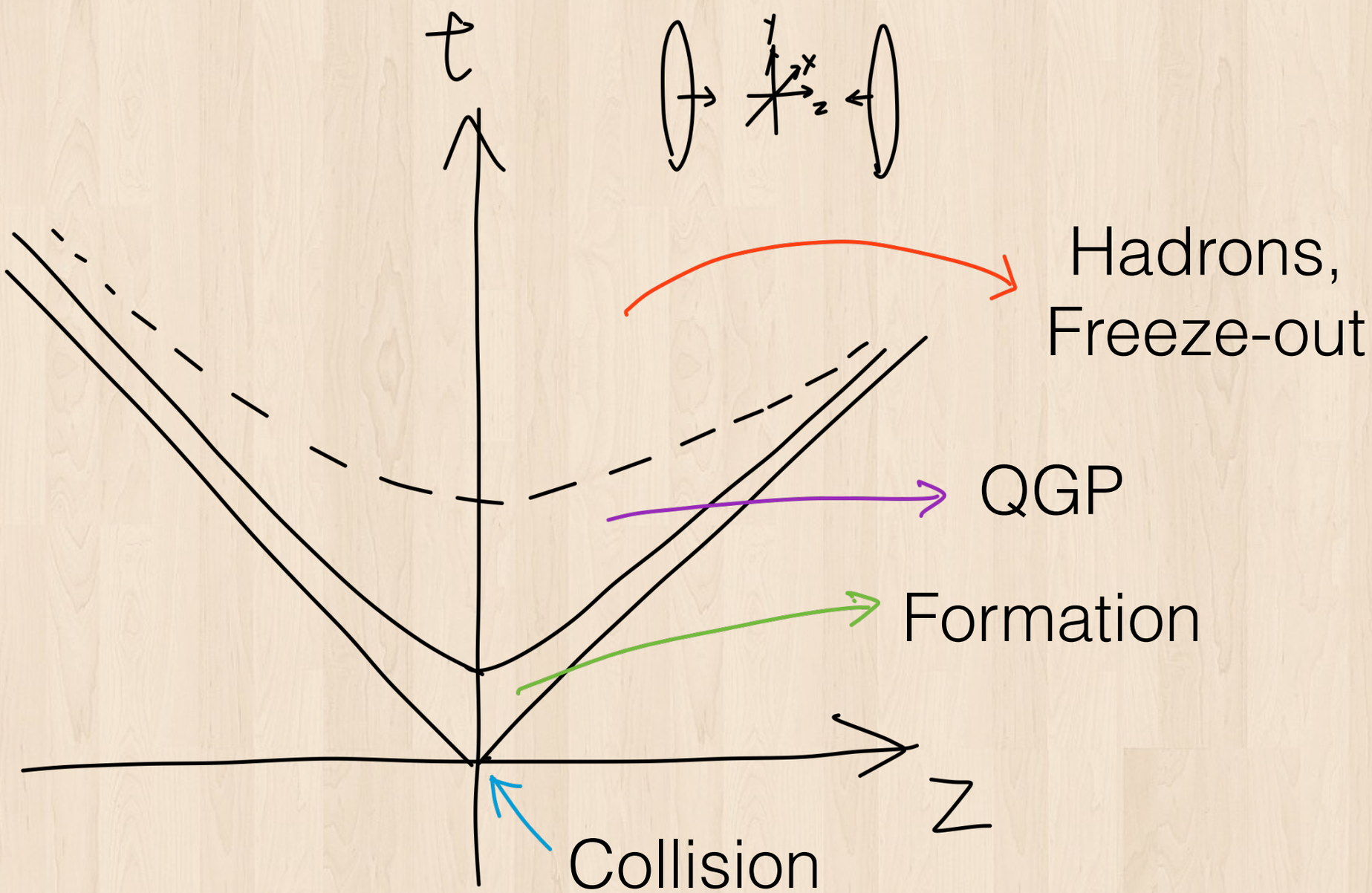


Large structure

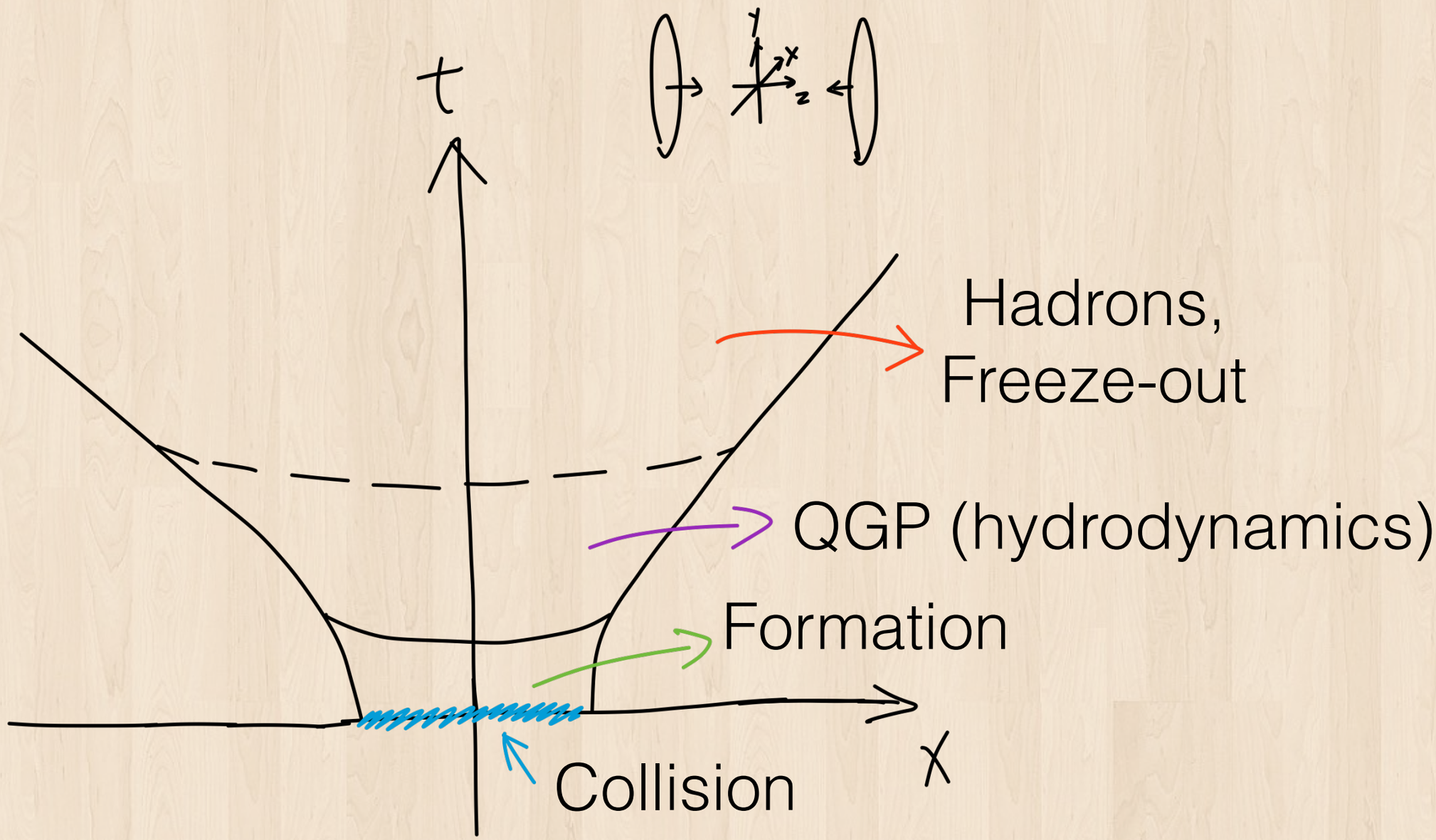


Constituent

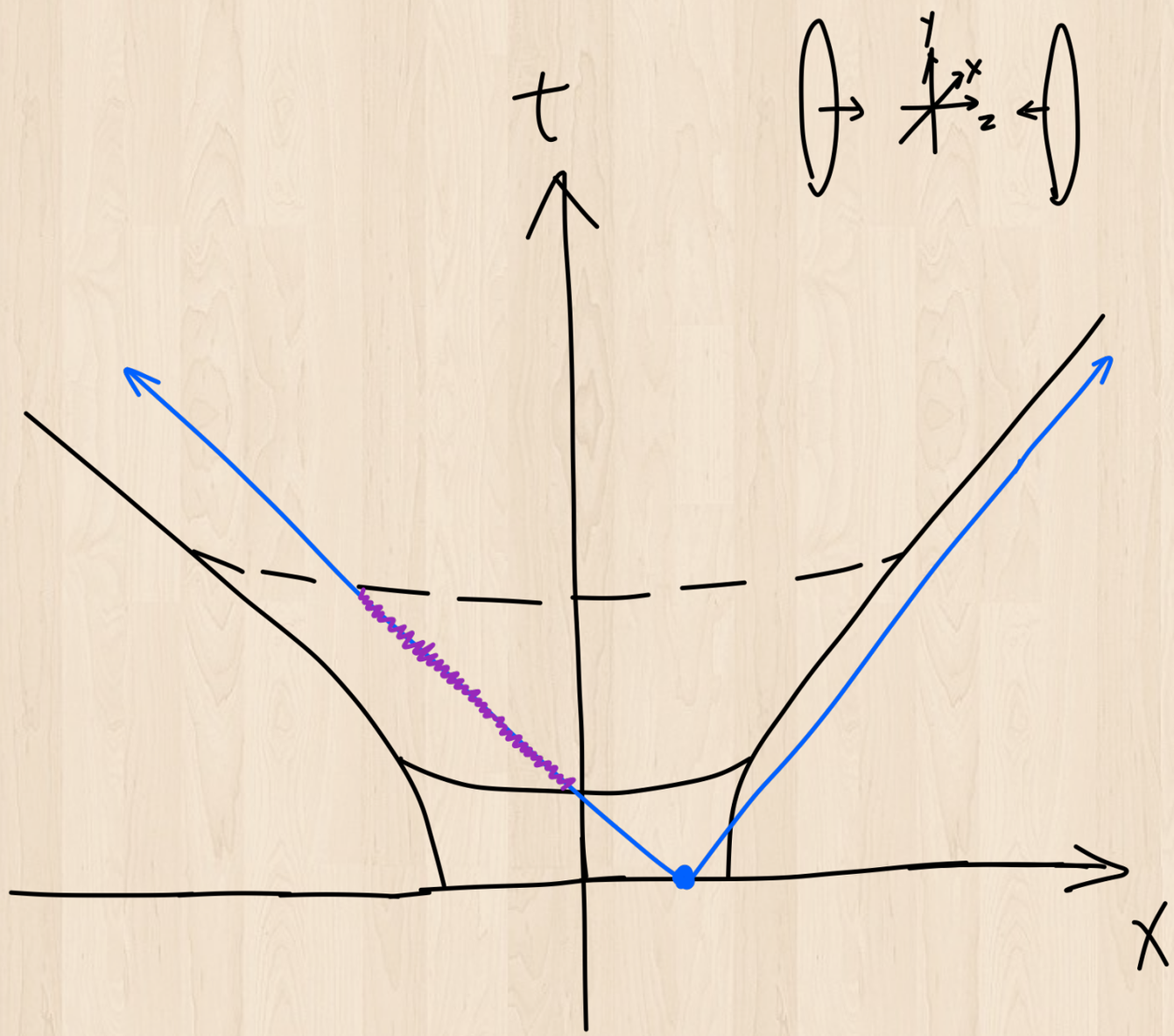
Time evolution



Time evolution (bulk)



Jets in Heavy Ion

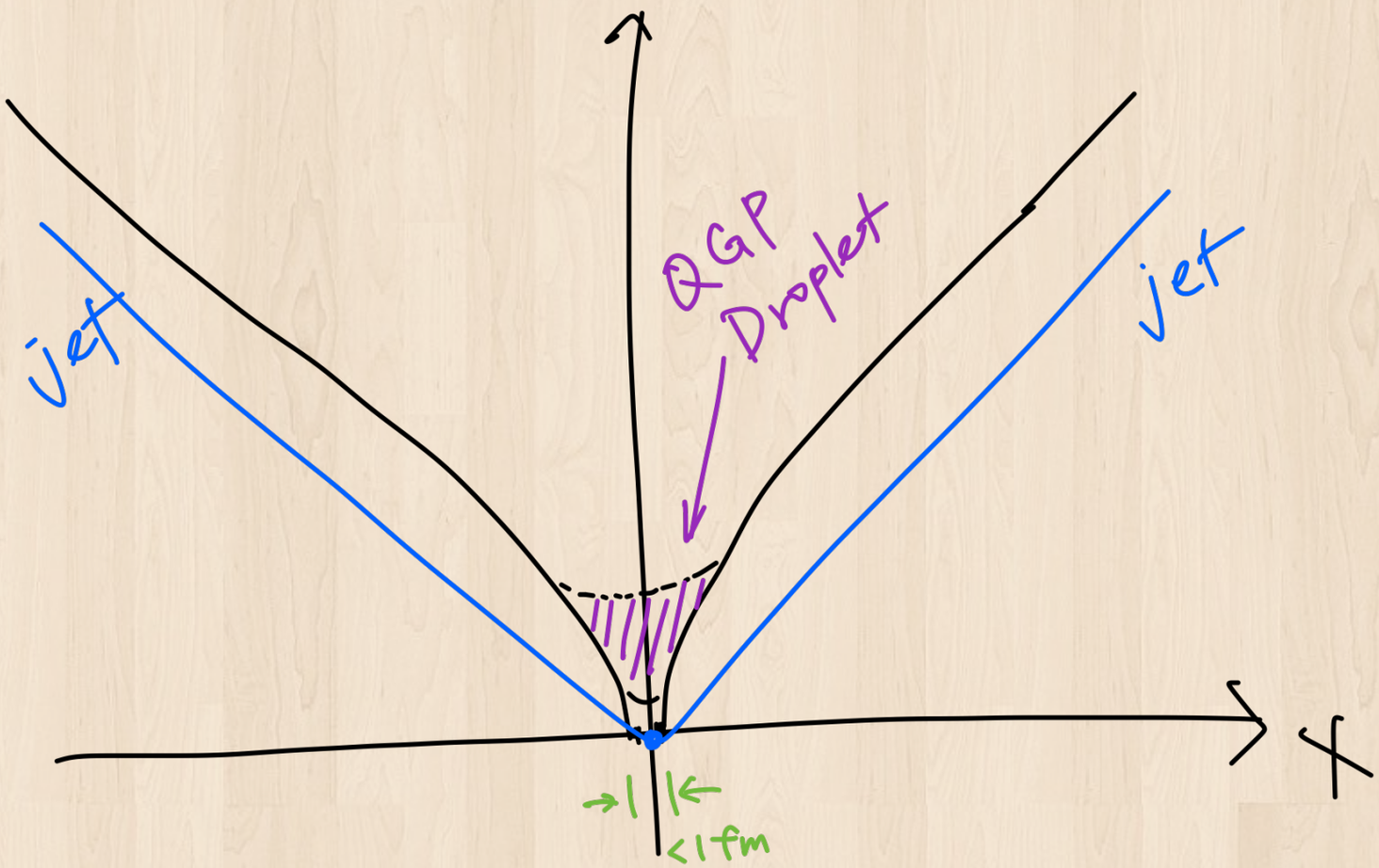


Partons interact with the QGP!

Geometry is important

What happens?

Small system?

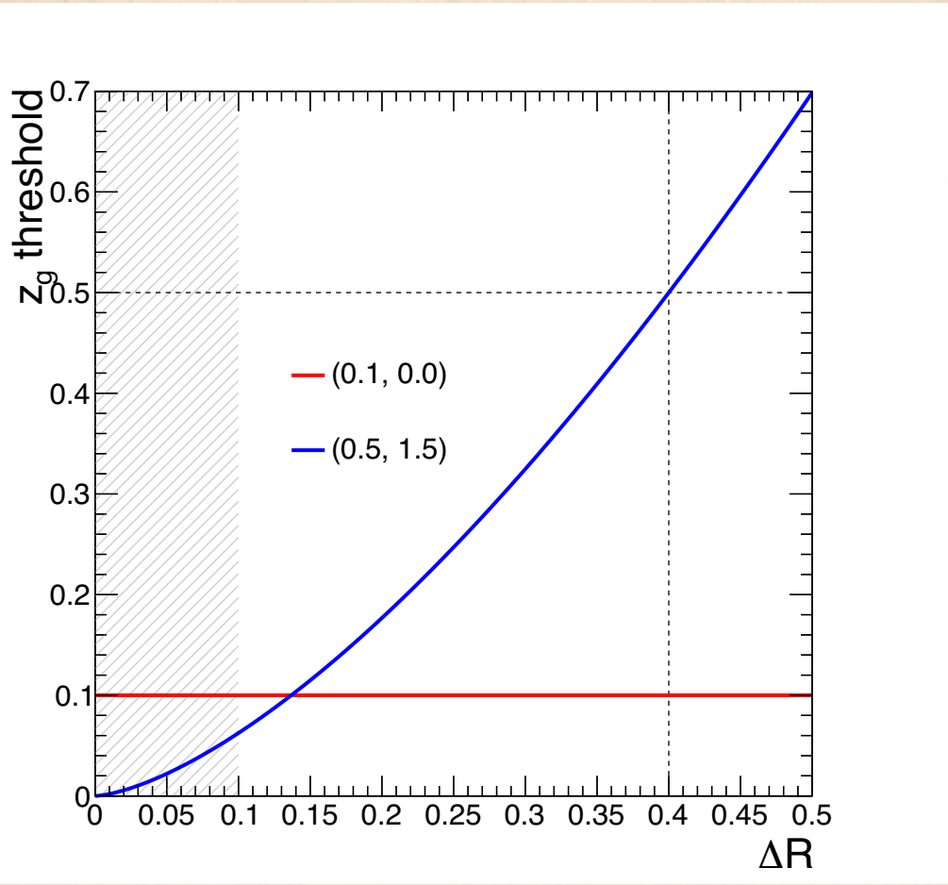


Grooming Profiles

Two grooming settings considered
(z_{cut}, β) = (0.1, 0.0), (0.5, 1.5)

flat

good theoretical properties



core of the jet

less sensitive to large angle soft radiation