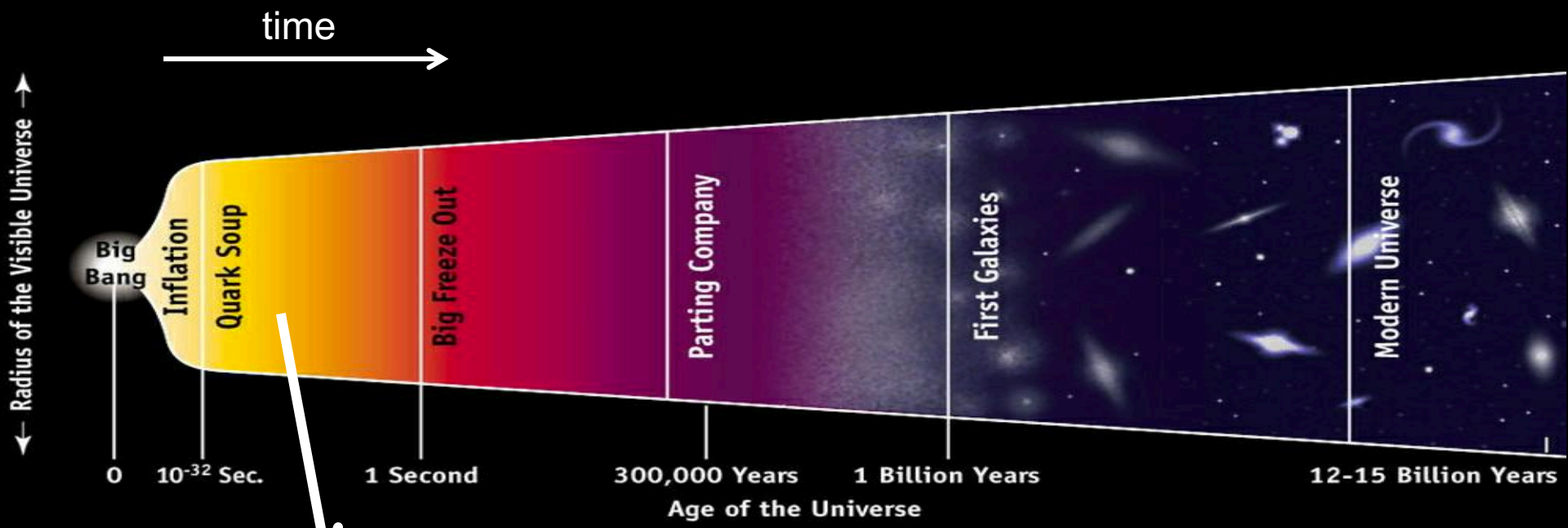
Utrecht University

The inner workings of the Quark Gluon Plasma

Marta Verweij
Utrecht University

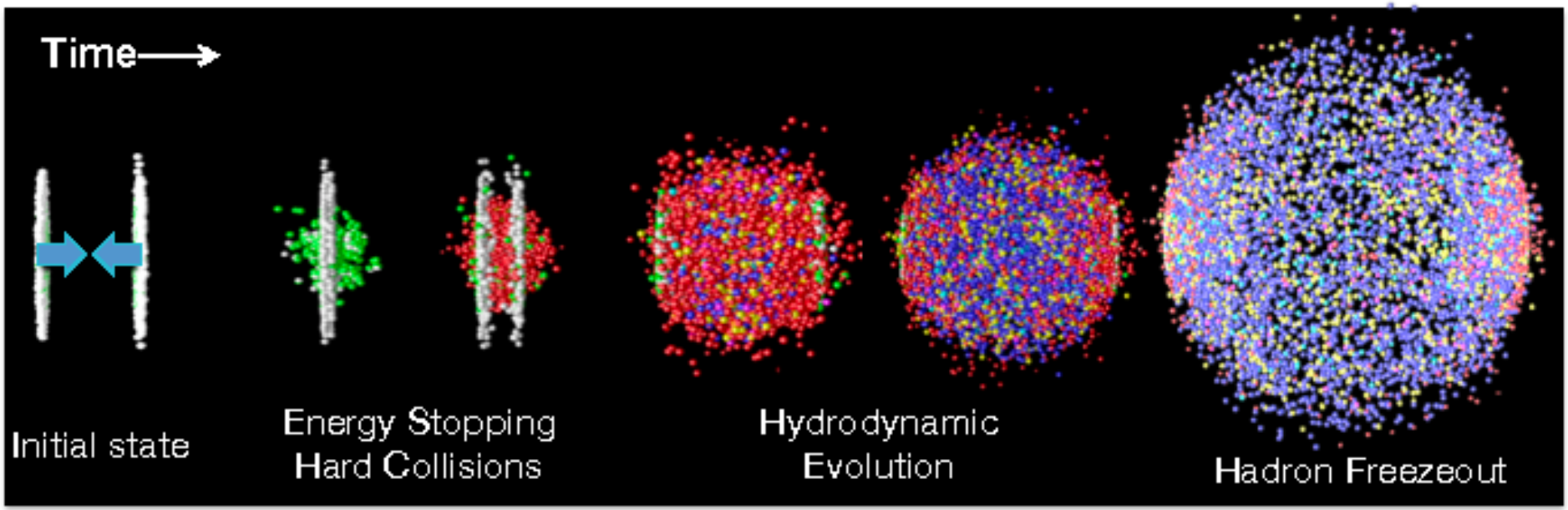
NNV Meeting
November 5, 2021

Big bang



Such quark-gluon soup can be created in the lab: heavy ion collision
→ Constrain fundamental properties of hottest matter
+ how it emerges from fundamental theory (strong interaction)

Smashing heavy ions

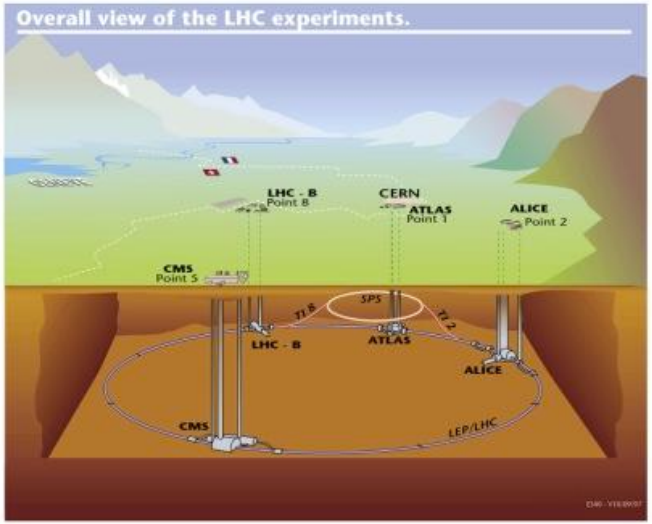


Heavy ion colliders

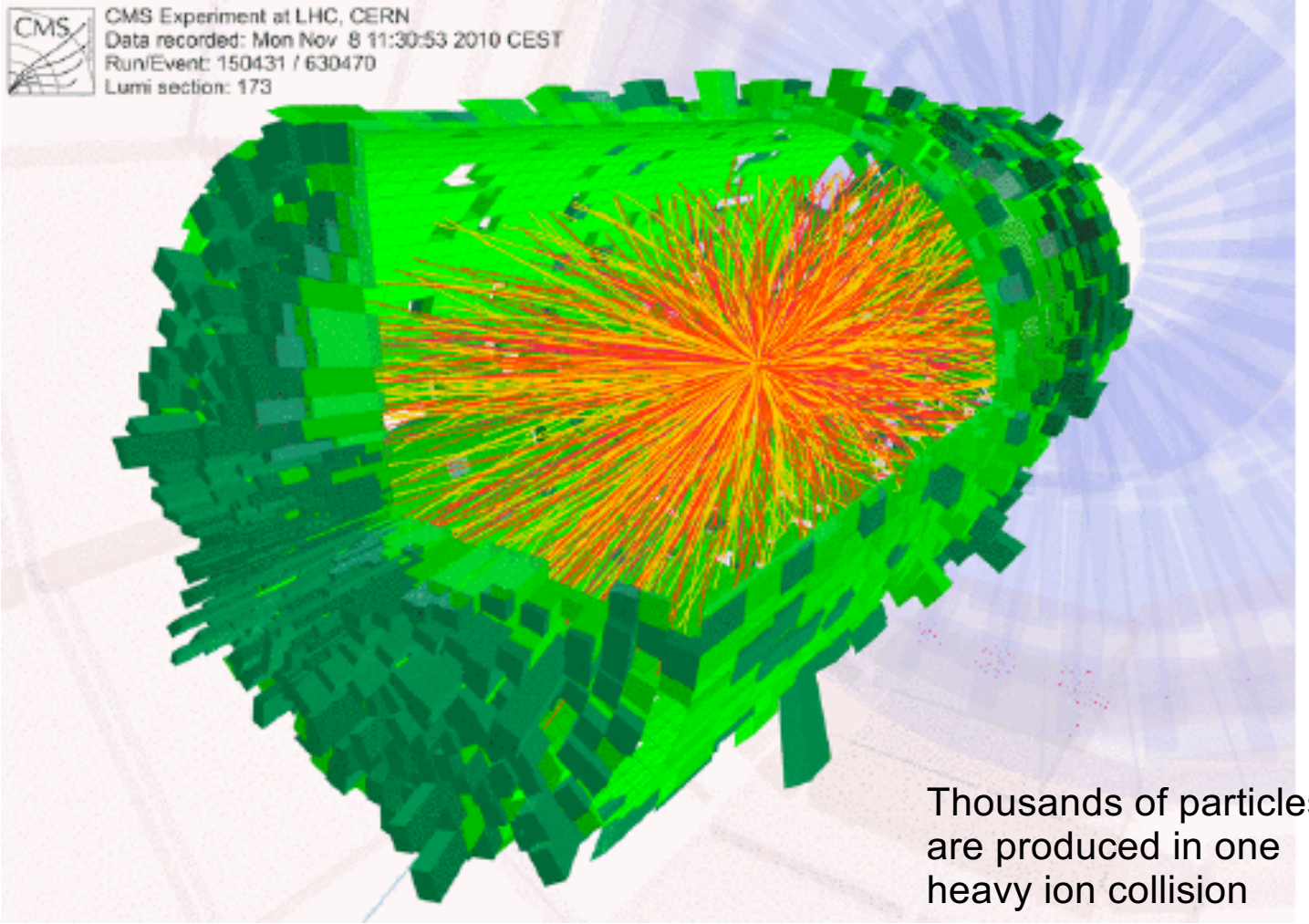
Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Laboratory
Au+Au $\sqrt{s_{NN}}$ = 200 GeV

First run: 2000
STAR, PHENIX, PHOBOS, BRAHMS
~2023: new detector sPHENIX

Large Hadron Collider (LHC)
CERN
Pb+Pb $\sqrt{s_{NN}}$ = 5020 GeV



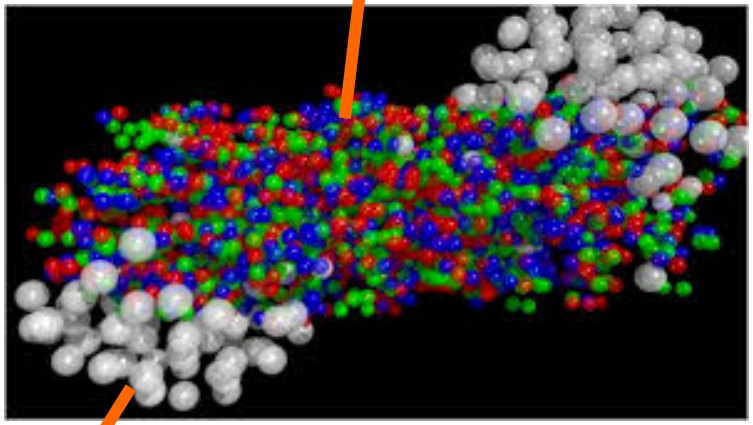
First run: 2010
ALICE, ATLAS, CMS, LHCb



Thousands of particles are produced in one heavy ion collision

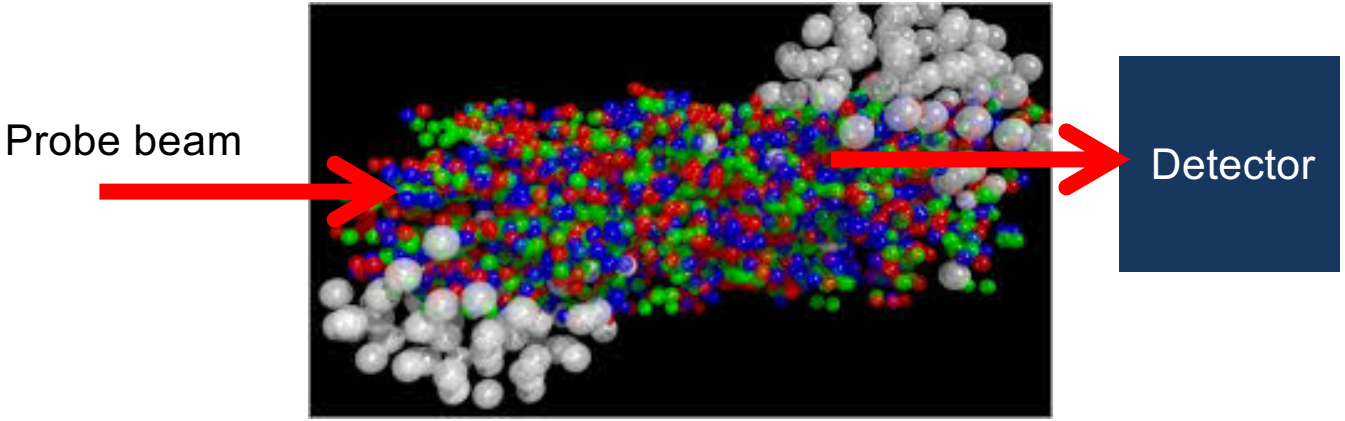
Probing the QGP

Participants forming hot matter: mixture of quarks and gluons (QGP)
Result of the part of the nuclei that do collide

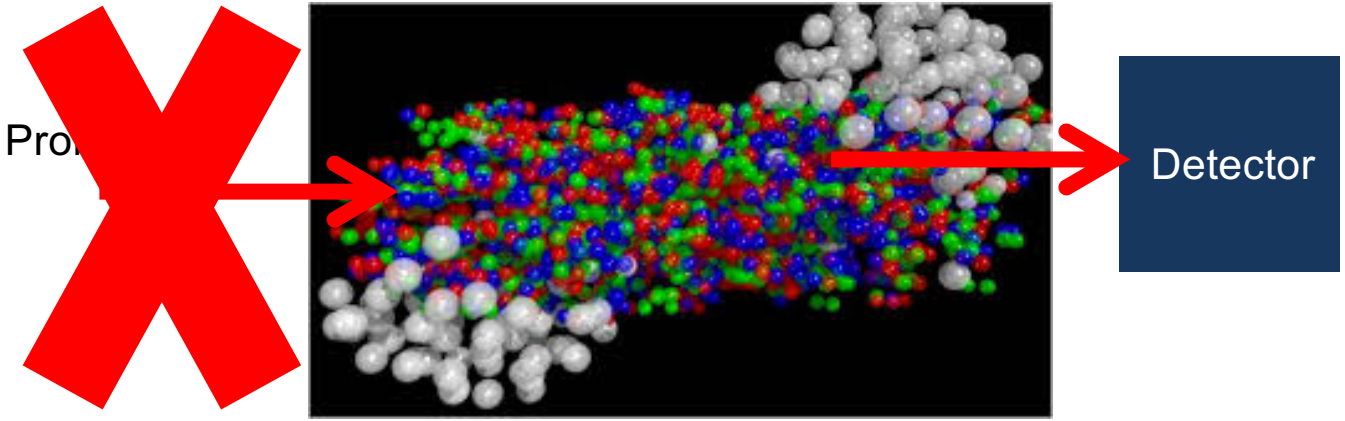


Spectators
Part of the nuclei that do not collide

Probing the QGP



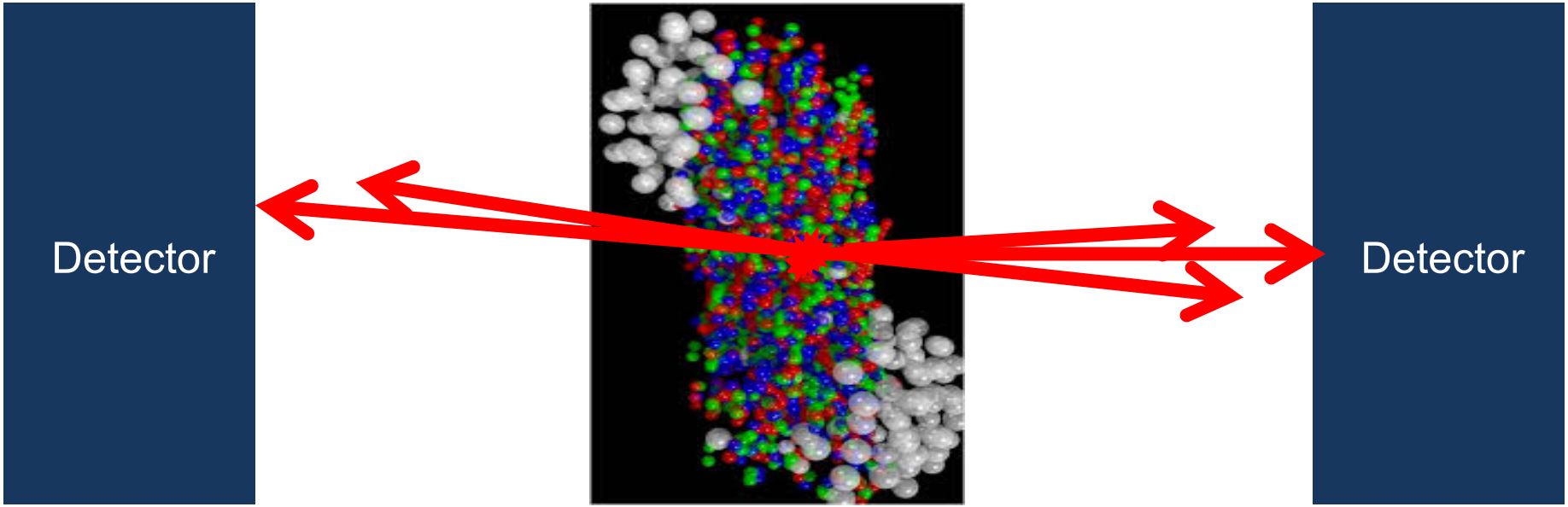
Probing the QGP



Lifetime of QGP too short (~10^{-23} sec.) to probe it with an external beam

Instead: use self-generated probes
→ Quarks and gluons created in a hard scattering

Probing the Quark Gluon Plasma



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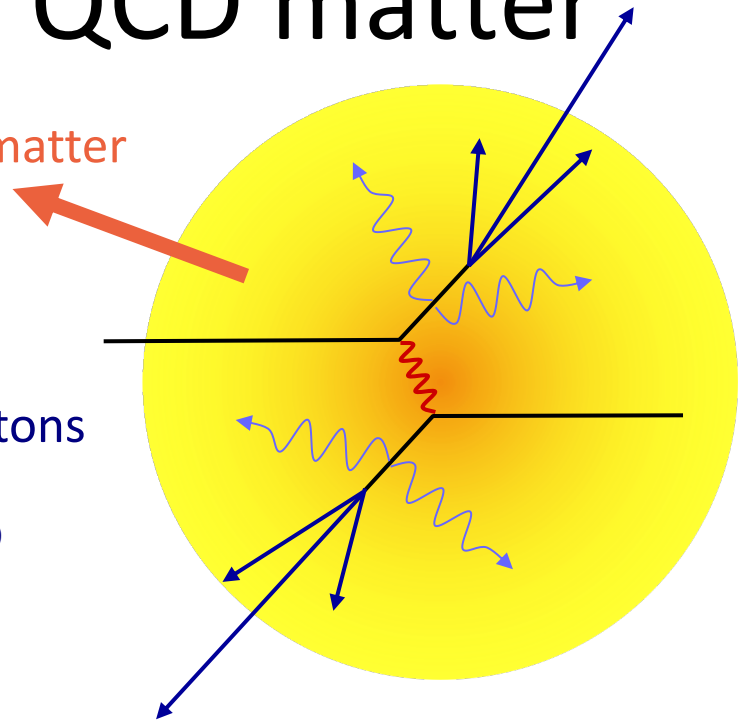
→ Quarks and gluons created in a hard scattering

Hard Probes in QCD matter

Heavy-ion collisions produce dense QCD matter
→ dominated by soft partons
p_T~100-300 MeV



Hard scatterings produce high energy partons

- Initial state production known from pQCD
- Parton loses energy due to interaction with medium
  → **medium-induced gluon radiation**

Use hard partons to explore QCD matter

Hard Probes in QCD matter

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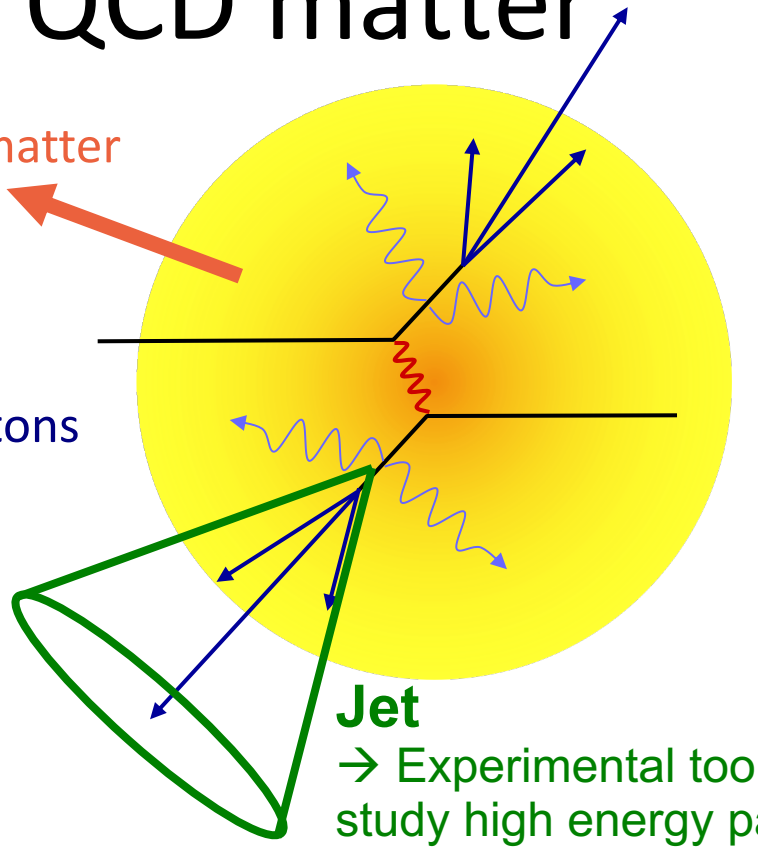


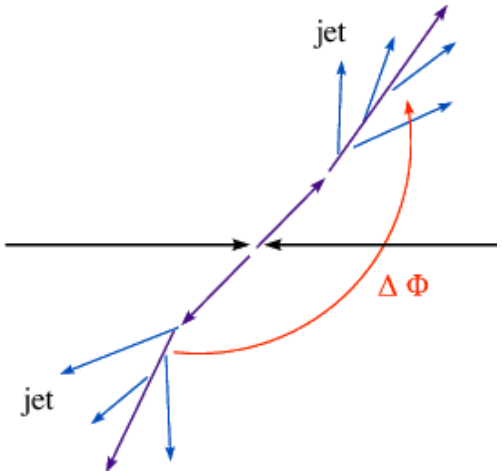
Jet
→ Experimental tool to study high energy partons

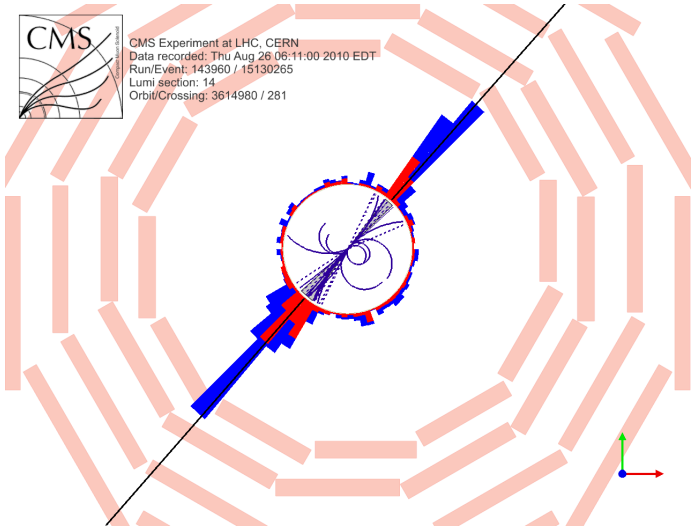
Use hard partons to explore QCD matter

What is a jet?

The manifestation of quarks and gluons in a particle detector

Observed as a collimated spray of high momentum particles

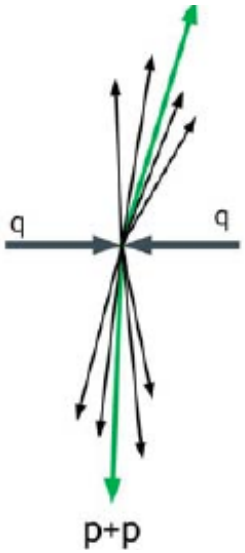




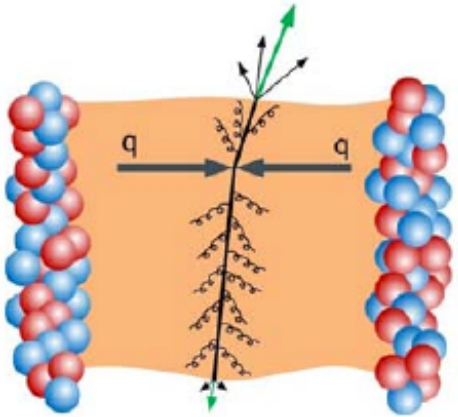
In experiment and theory particles are clustered into a cone → jet

Jet production in medium

The experimentalist perspective*



proton-proton (pp) collision
No QGP created

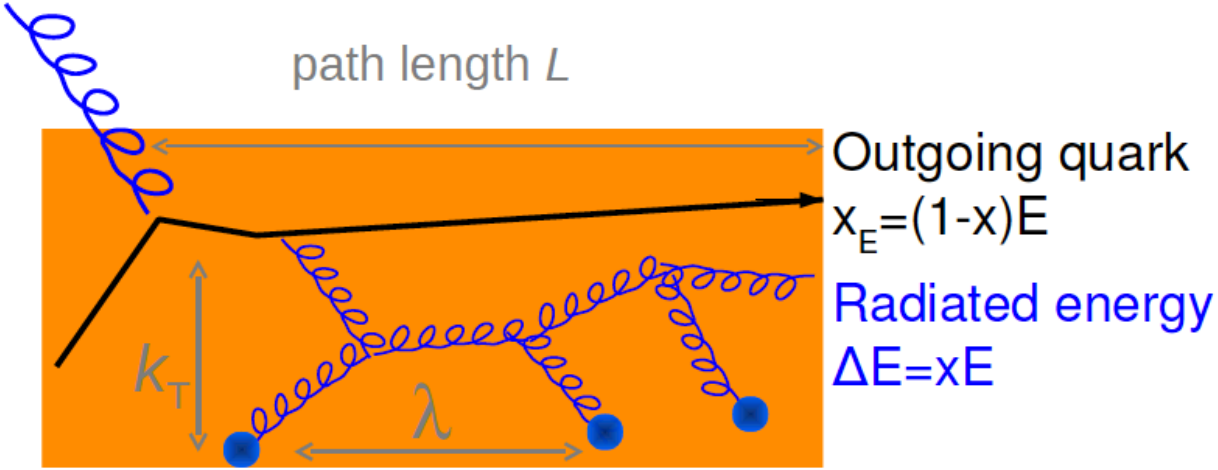


Heavy-ion collision
QGP created
→ additional gluon radiation
wrt pp collisions

* according to an experimentalist (me)

Schematic picture of energy loss mechanism

in hot dense matter

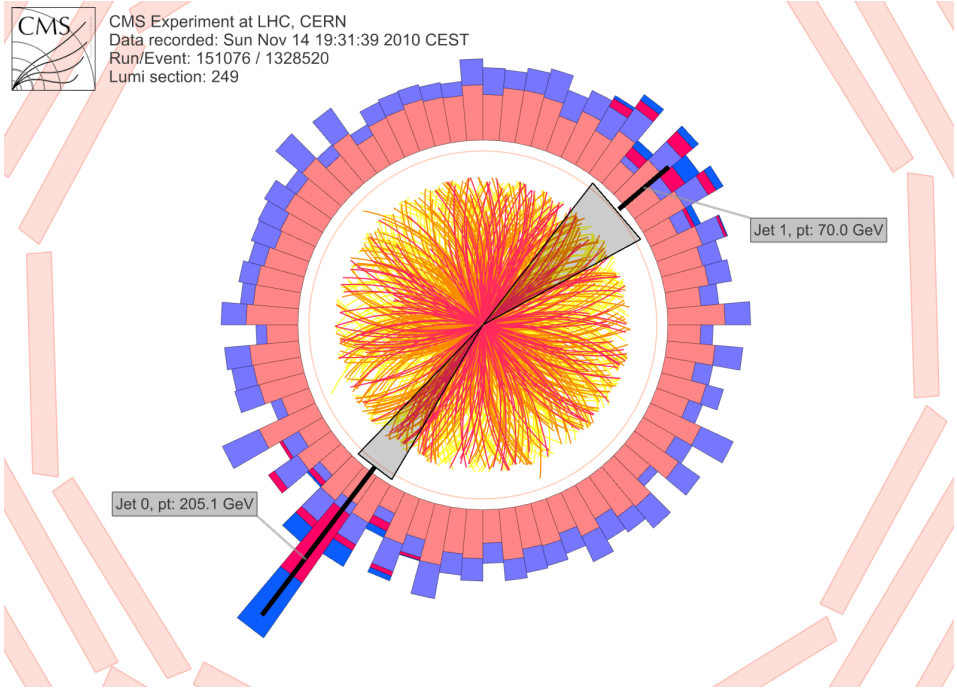


- Energy loss due to gluon bremsstrahlung in a hot dense medium

Find the jets in heavy-ion collisions

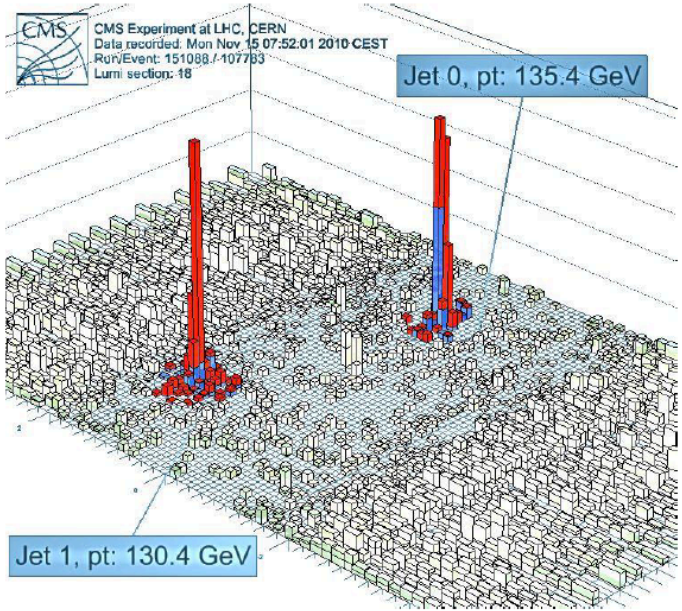
Jets are not so easy to find in a heavy-ion collision

→ Need sophisticated tools for background subtraction

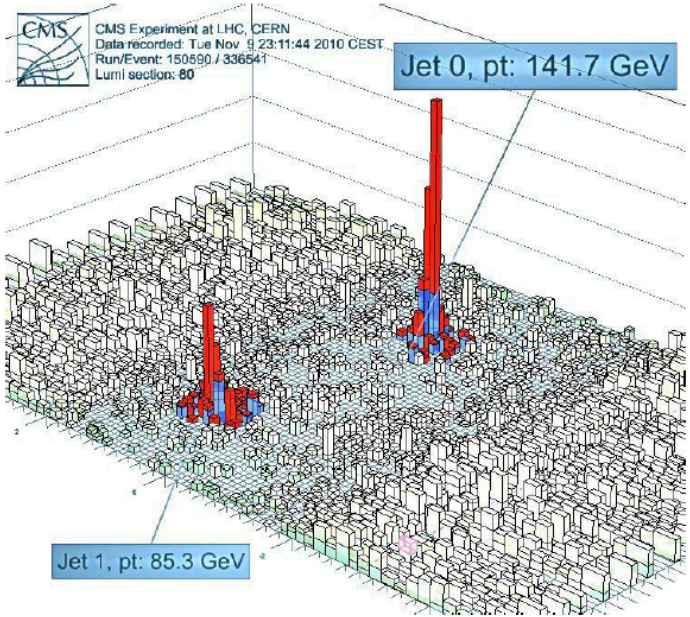


Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)



Balanced Energy



Unbalanced Energy

Dijets in PbPb

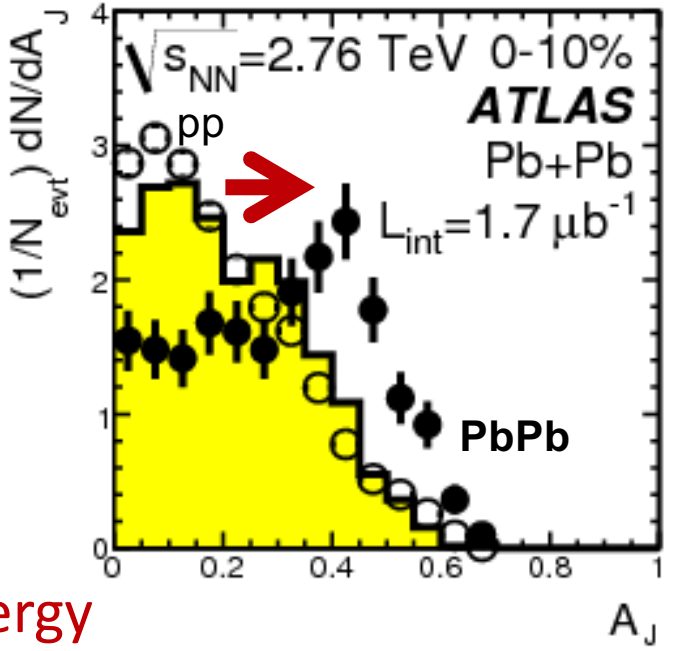
First direct observation of jet quenching (Dec. 2010 LHC)

Jet energy asymmetry

$$A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$

In pp: used to calibrate jets

In PbPb: physics signal



Phys.Rev.Lett.105:252303,2010

Dijets in PbPb are less balanced in energy

balanced *unbalanced*

Dijets in PbPb

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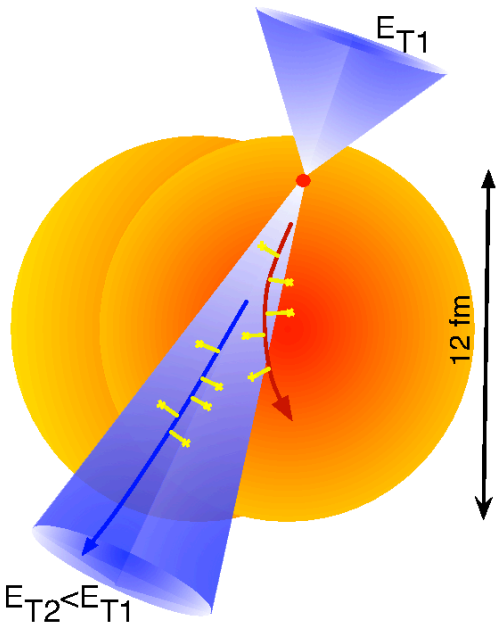

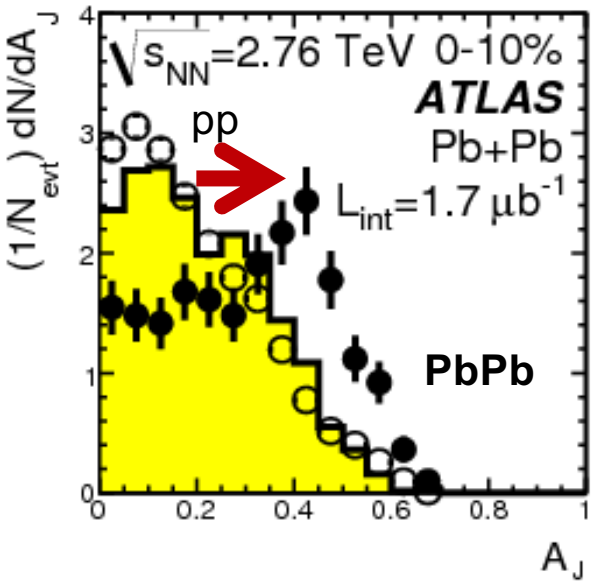

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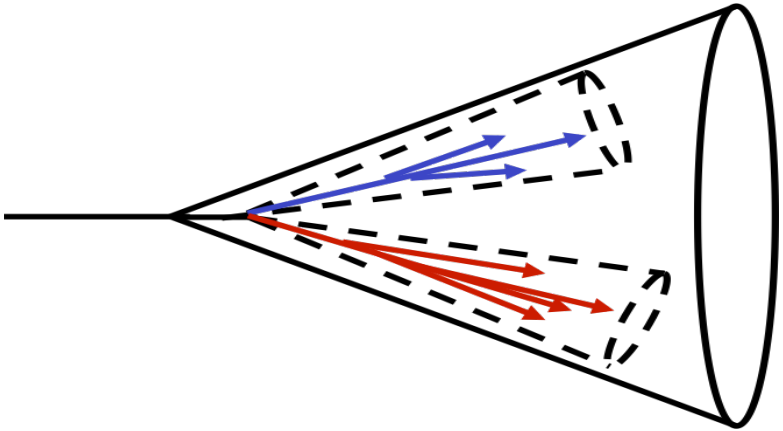
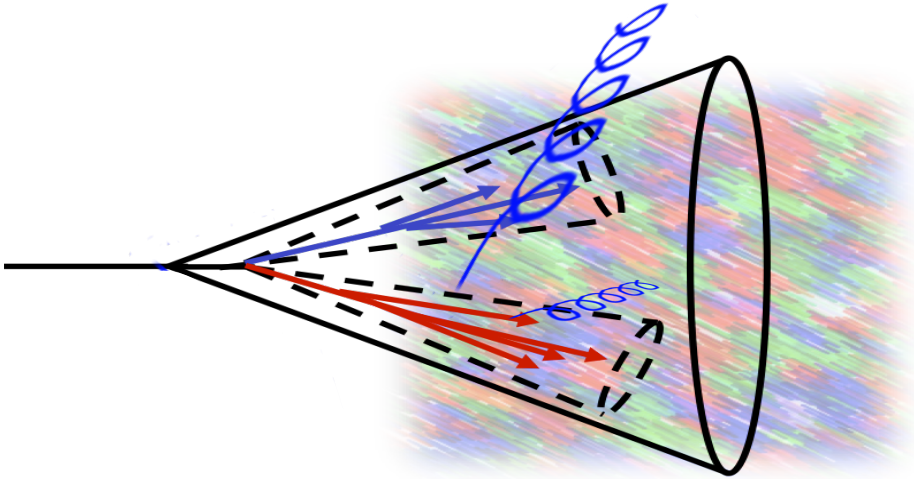
Parton showers

Vacuum



Medium

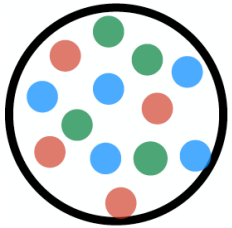


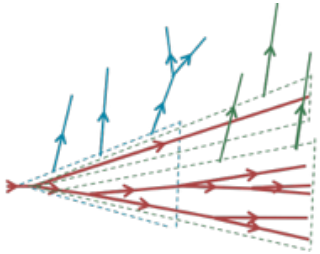
What happens to the parton shower in a hot QCD medium?

Probing the Quark Gluon Plasma

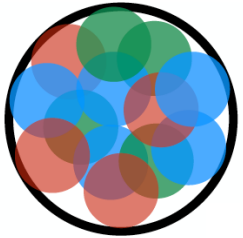
Two descriptions for parton interaction with QGP:

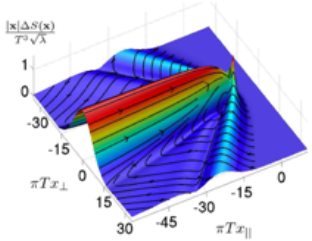
- Weak coupling (pQCD)
  medium-induced radiation





- Strong coupling (AdS/CFT)
  energy damped into the medium





How to disentangle?
Study the various stages of jet formation

Probing the Quark Gluon Plasma

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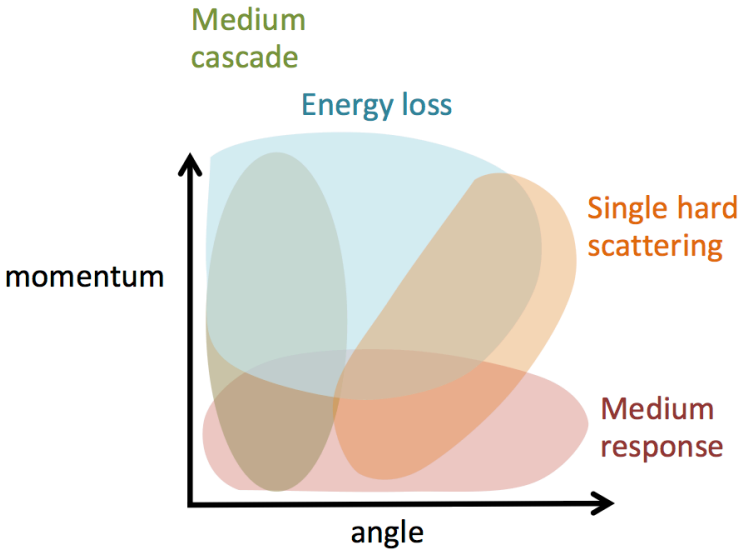


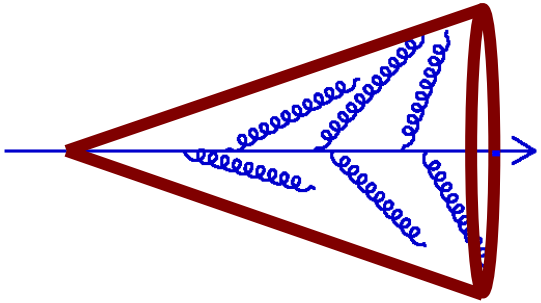
How to disentangle?

Study the various stages of jet formation

What is jet substructure?

Dynamics of particles inside the jet

Two scales: angular + momentum space



Fragmentation Functions

Single hadron

Classic Jet Shapes

All hadrons

Groomed Observables

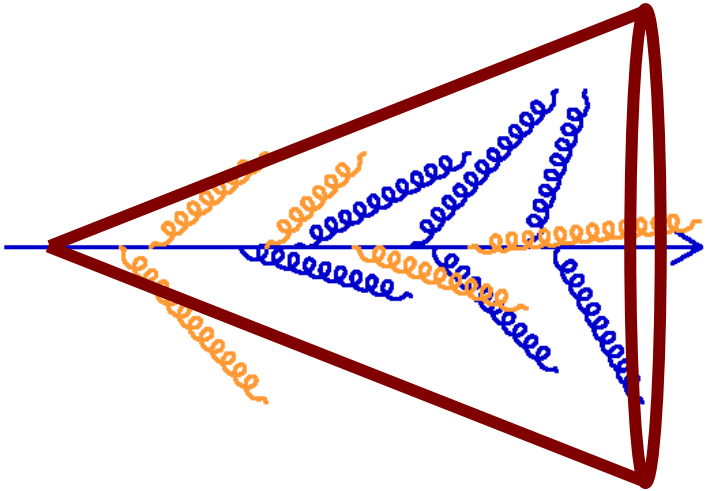
Subset of hadrons

Sketches by J. Thaler

Why jet substructure?

Structure of quenched jet different from unquenched?

- How is the parton shower modified?
- What is the exact mechanism modifying the shower?
- Can we relate shower modifications to medium properties?



The complication

In experiment we see the end of the parton shower.

A convolution of many effects. Multi-scale problem

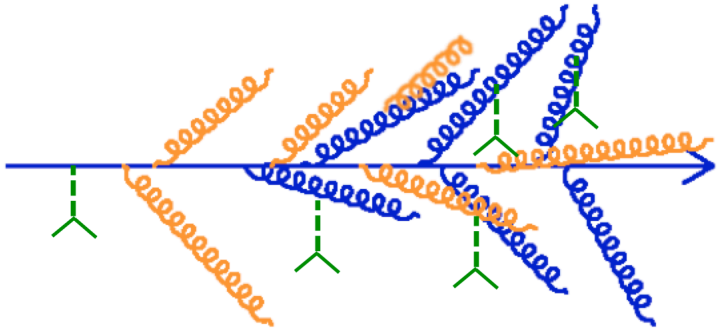
Decorrelation of radiated gluons

All partons in shower ‘see’ medium

Role of coherence

Medium response

…

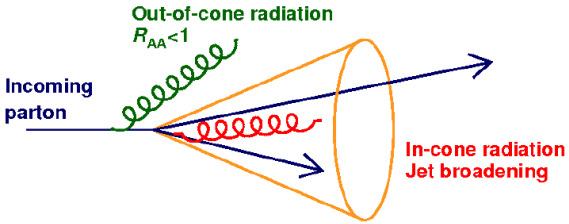


…

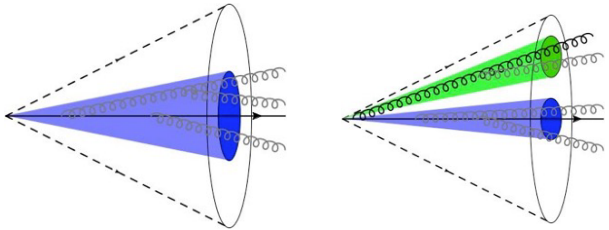
Each jet observable has different sensitivity

Jet modification in hot QCD medium

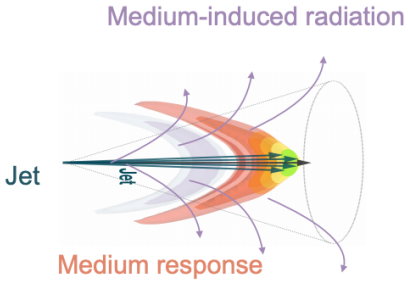
Medium-induced energy loss



Coherence effects



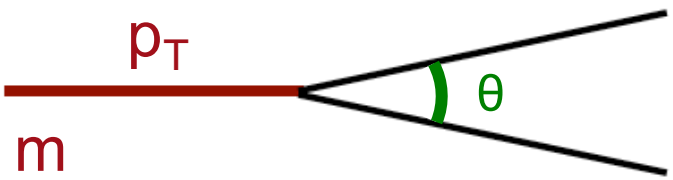
Medium recoil



Hard splitting as probe of medium

Idea: let a high p_T parton that splits into two other partons (antenna) propagate through the medium

Then study the influence of the medium on the antenna



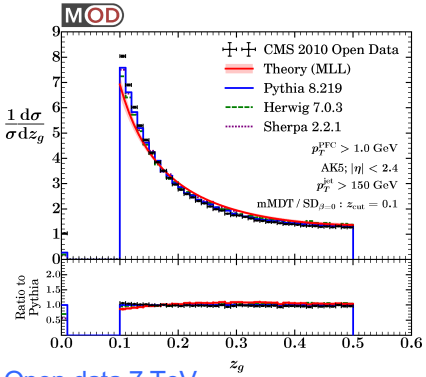
$$p_{T,1} = (1-z_{split})p_T$$

$$p_{T,2} = z_{split}\, p_T$$

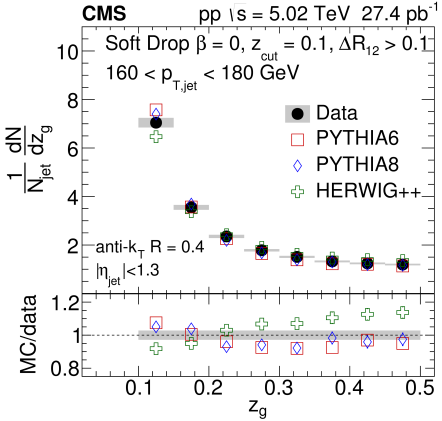
Two relevant scales:

- Opening angle between the two branches: θ
- Momentum balance between the two branches: z_{split}

Jet splitting function

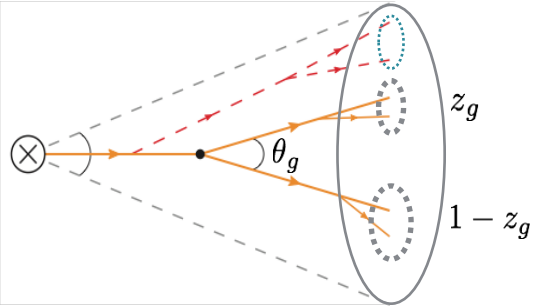


CMS Open data 7 TeV
Larkoski, Marzani, Thaler, Tripathee, Xue
PRL 119 (2017), 132003
Phys.Rev. D96 (2017), 074003



CMS 5 TeV, PRL 120 (2018), 142302

Robust observable: Momentum fraction carried by the subleading branch of first hard splitting



$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

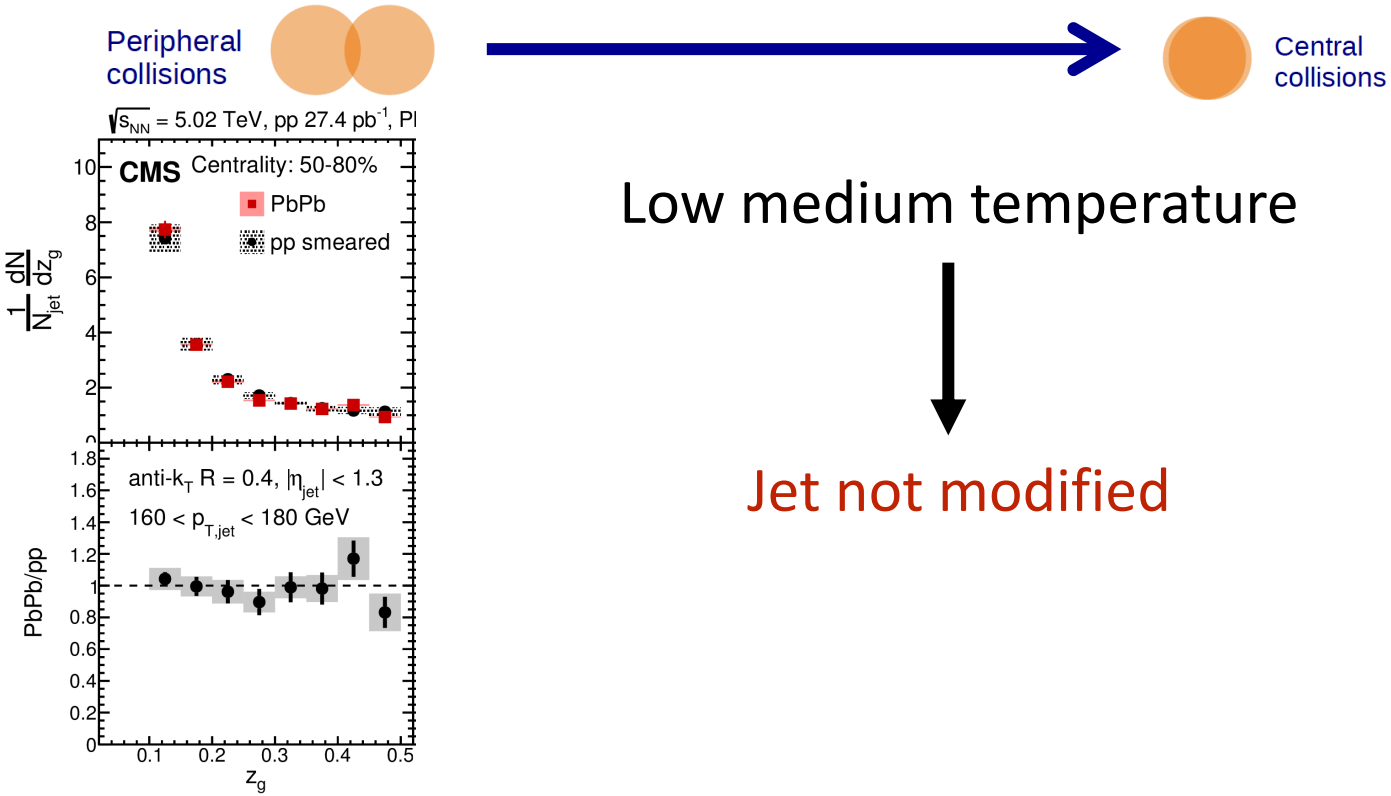
With groomed jets: soft large angle radiation removed to define the hardest splitting

- Weak dependence on α_s
- Weak dependence on jet p_T
- In vacuum: Altarelli-Parisi Splitting Function

$$d\sigma^{vac}_{DGLAP} \sim \frac{\alpha_s}{z}$$

PRL 120 (2018), 142302

Jet splitting function

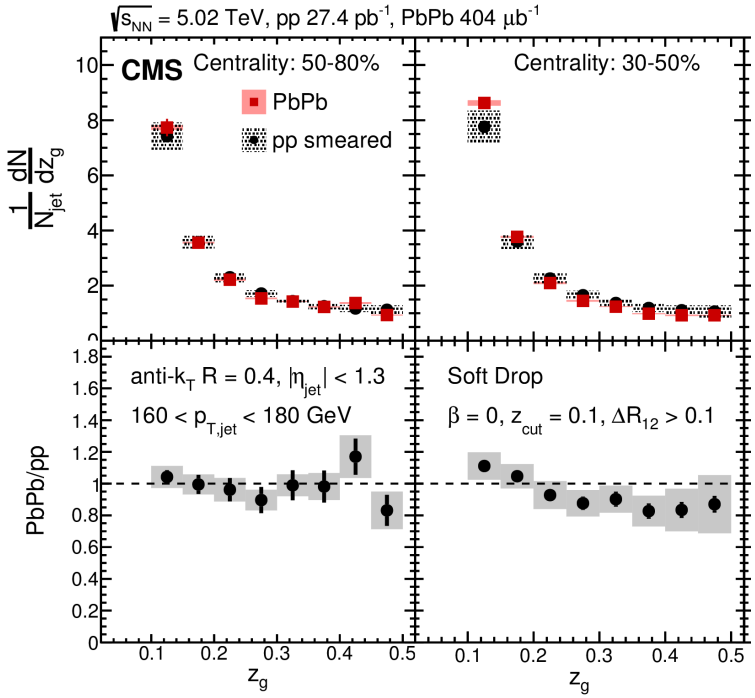


Low medium temperature

Jet not modified

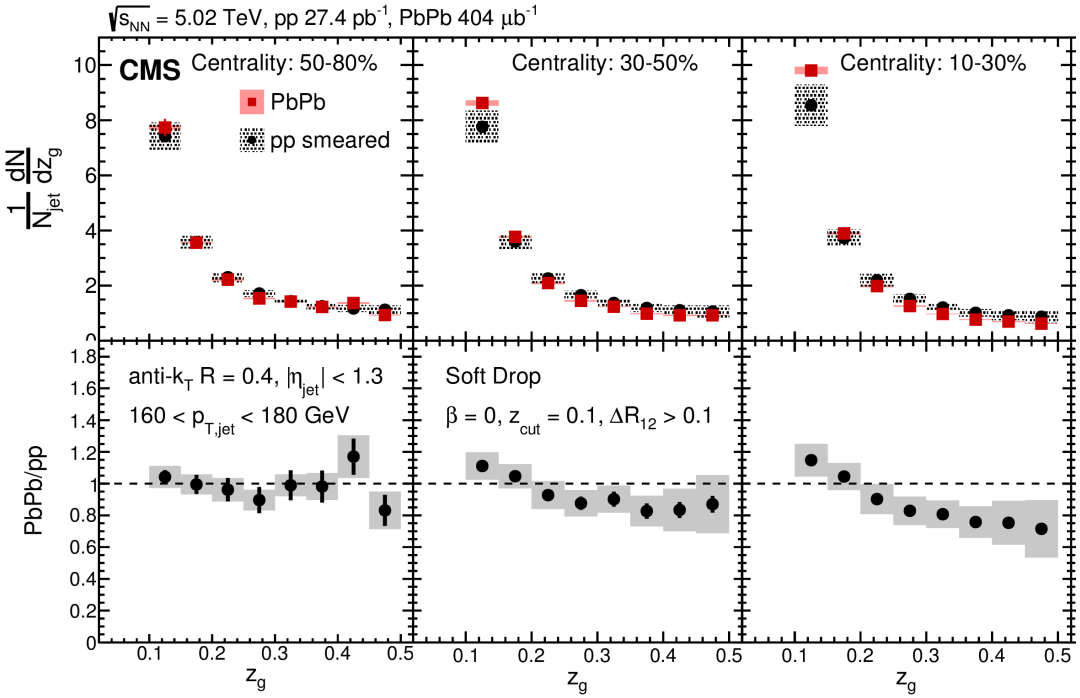
PRL 120 (2018), 142302

Jet splitting function



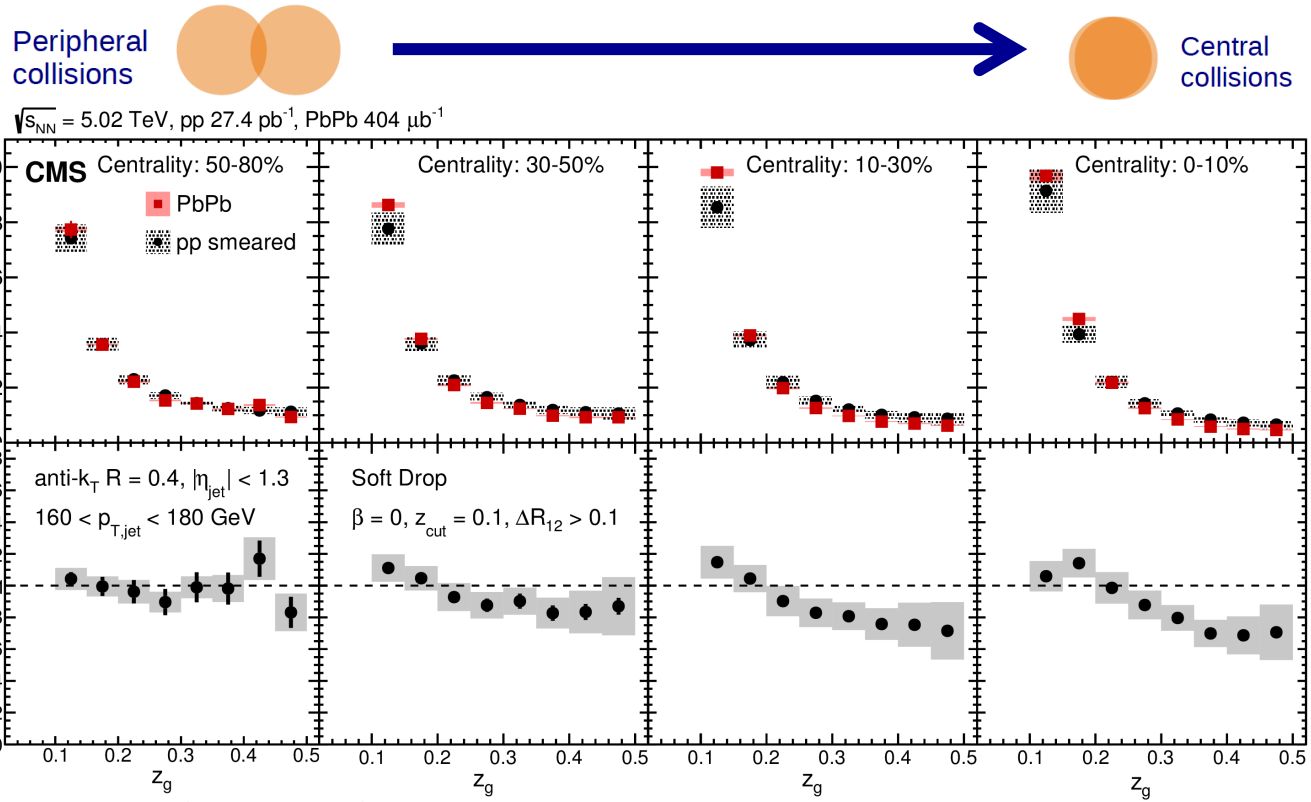
PRL 120 (2018), 142302

Jet splitting function



PRL 120 (2018), 142302

Jet splitting function



Strong modification of subjet balance observed in central PbPb collisions

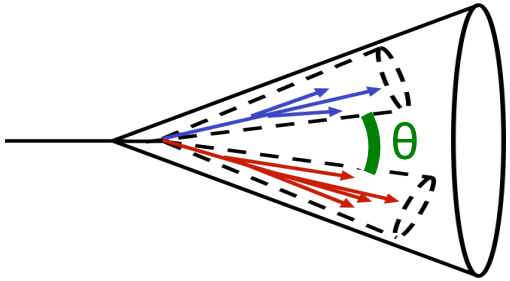
Branching more imbalanced in hotter medium

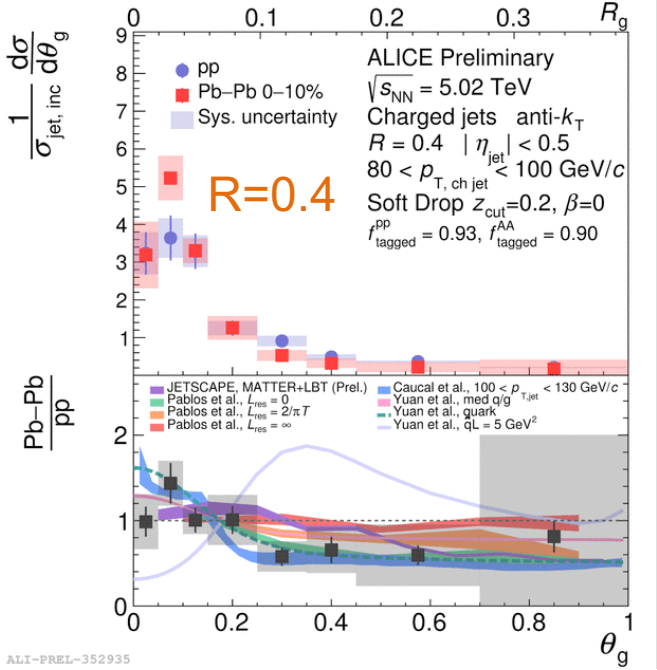
Does the inner structure of the jet look the same with and without medium?

No!

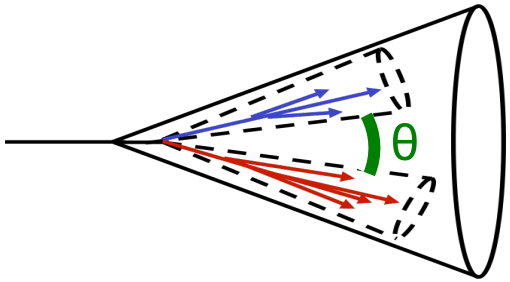
→ With theoretically well-controlled observables we can constrain the properties of the QGP

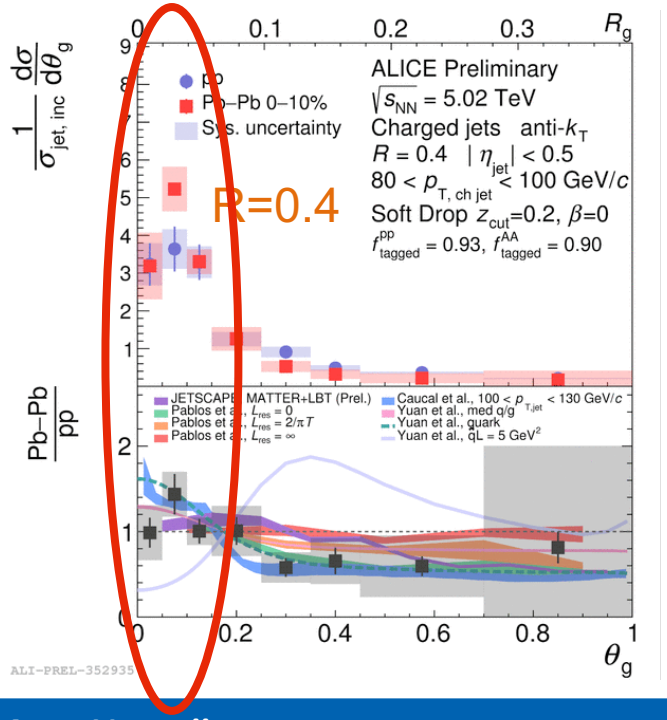
Splitting angle





Splitting angle

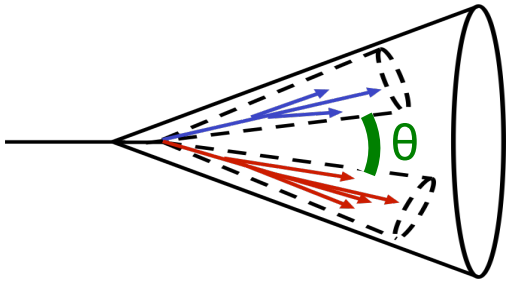


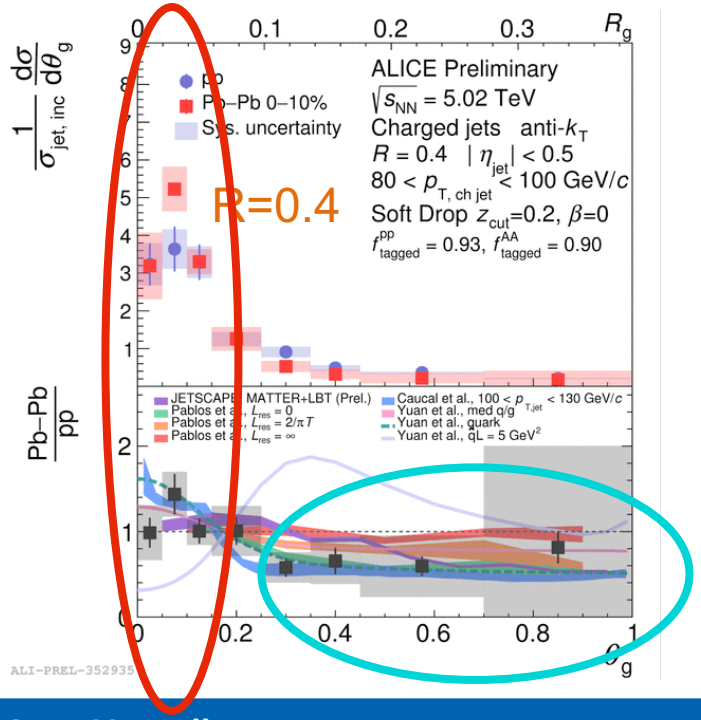


Small θ_g: less vacuum-like emitters from which energy can be radiated

→ less suppression observed in data

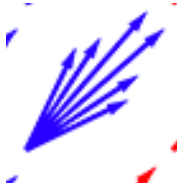
Splitting angle





Small θ_g: less vacuum-like emitters from which energy can be radiated
→ less suppression observed in data

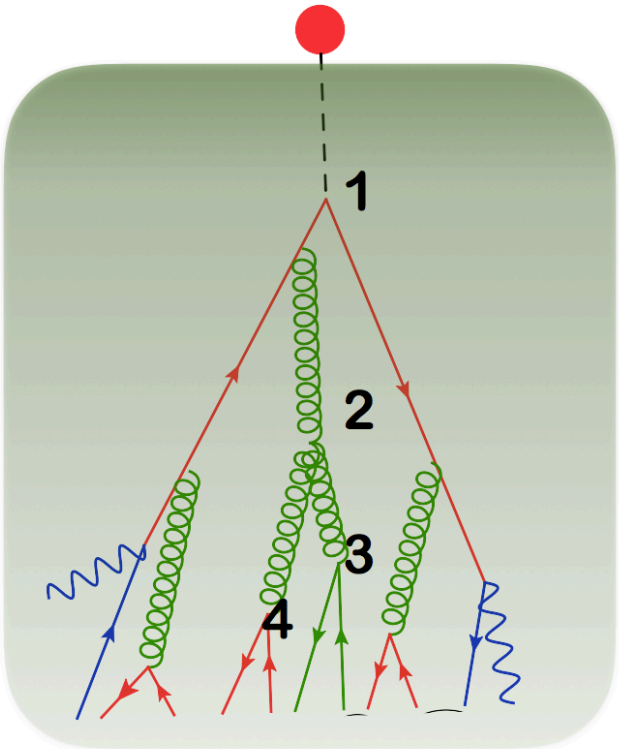
Large θ_g : more suppressed



Formation time in regular jets

Explore space-time structure of QGP by ordering parton shower in formation time

$$\tau_{form} = \frac{1}{z(1-z)E\theta^2}$$



No measurement yet

… but might be important step towards opening the black box → input to EoS

Summary

A lot of progress on understanding in-medium parton shower

→ This leads to more accurate extraction of QGP properties (transport coefficient $\hat{q}$, (de)coherence angle θ_c, …)

But there are open questions

- Role of medium response? Resolution scale of QGP? Quasi-particles?

Exciting times ahead with new data runs at RHIC and LHC

Thank you