Heavy Ion Physics

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17th Hadron Collider Physics Summer School
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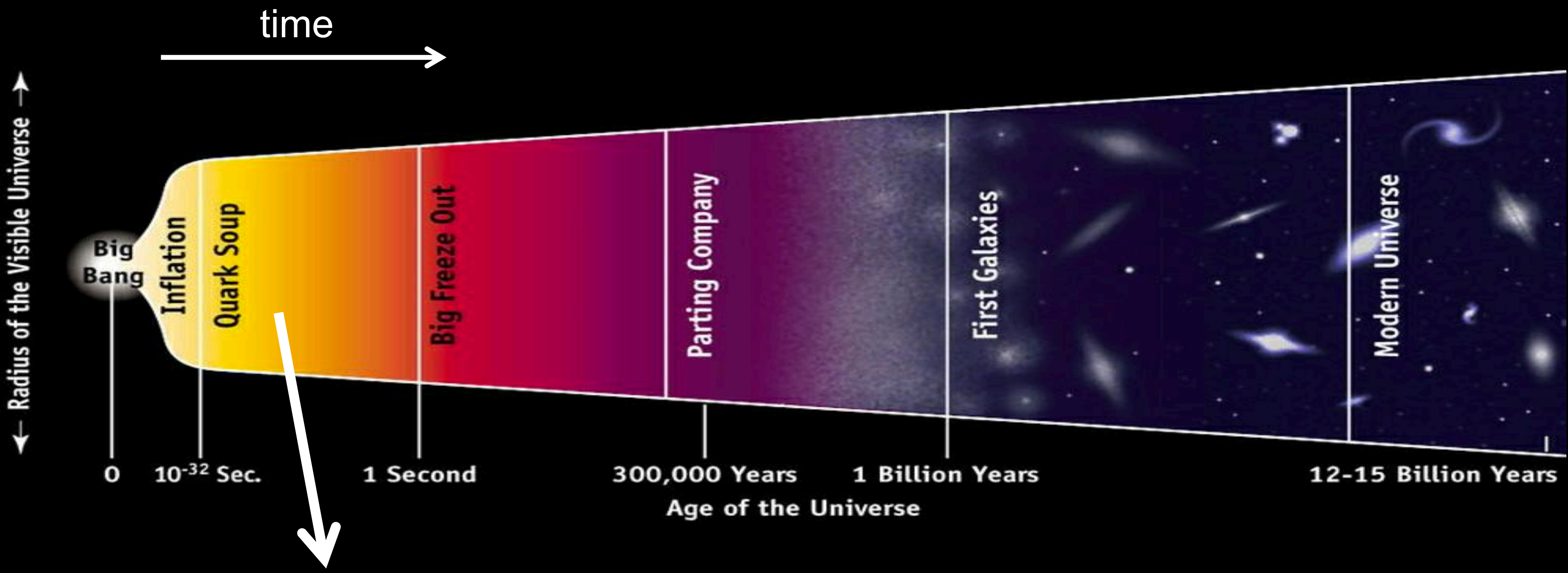
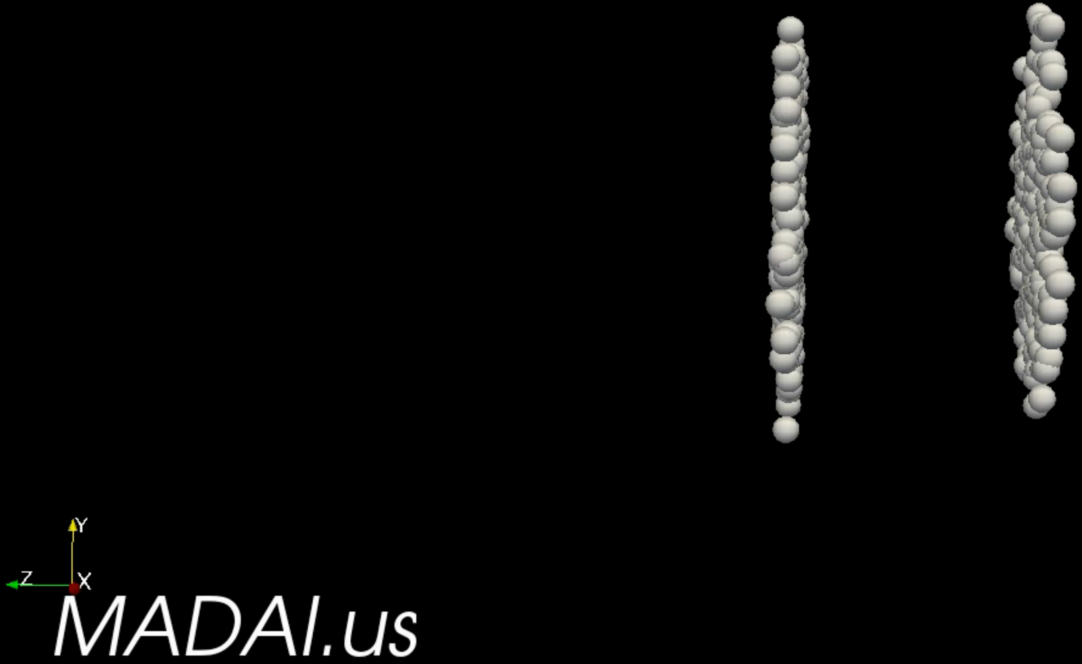
Big bang

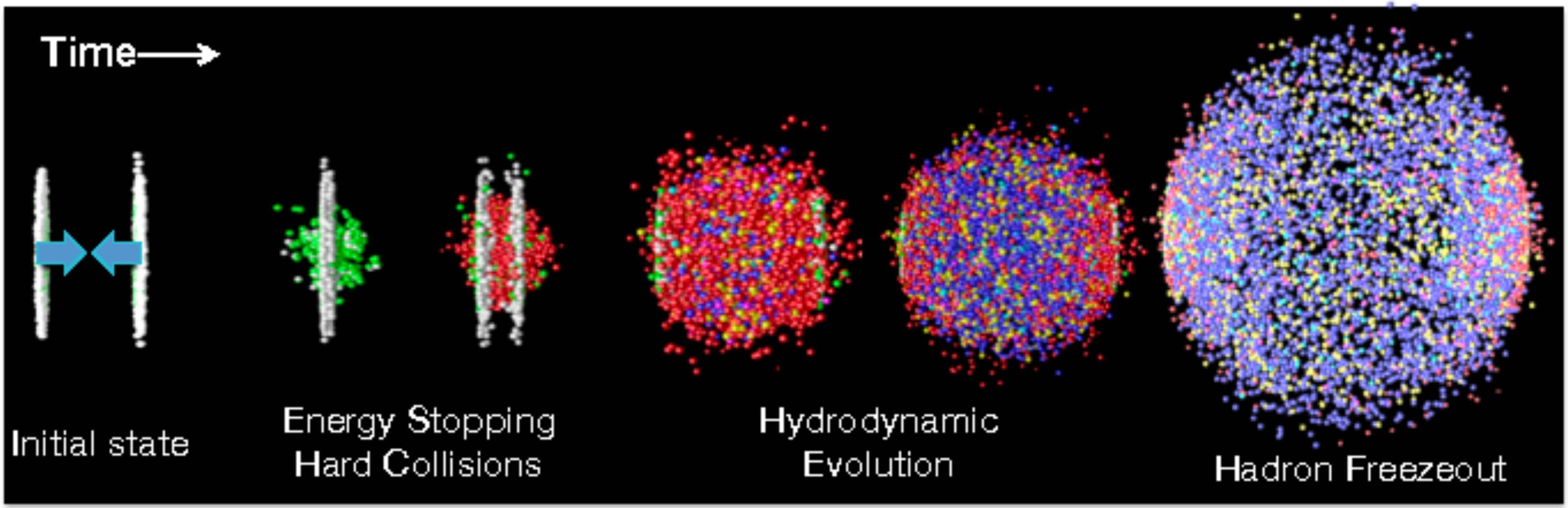


Such quark-gluon soup can be created in the lab: heavy-ion collision
→ Constrain fundamental properties of hottest matter
+ how it emerges from fundamental theory (strong interaction)

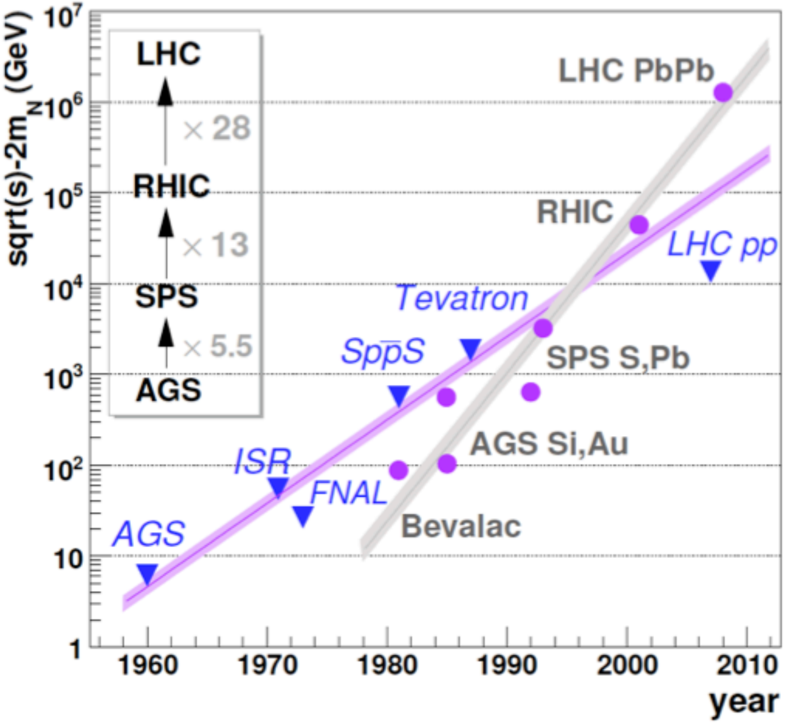
link

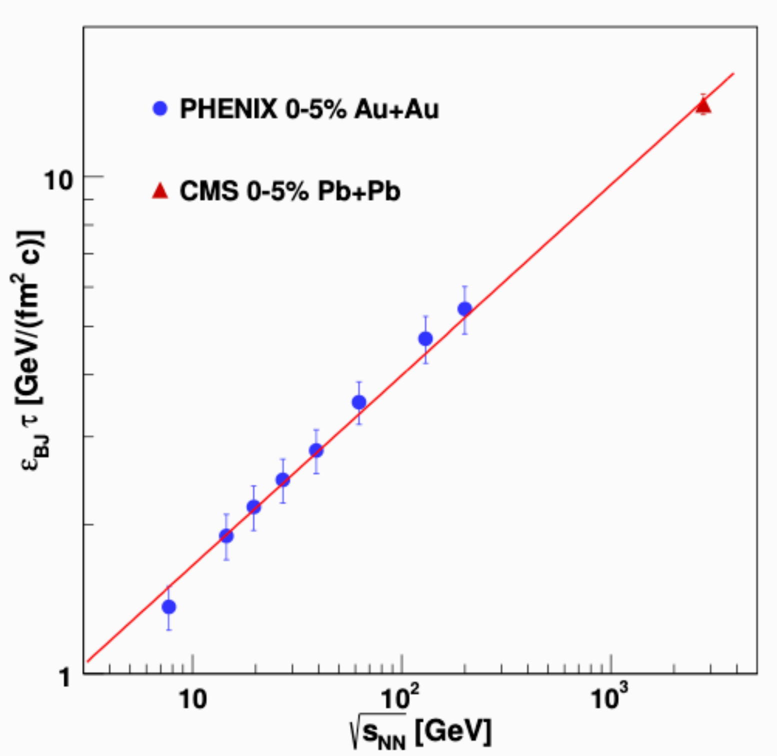


Smashing heavy ions



Heavy-ion colliders





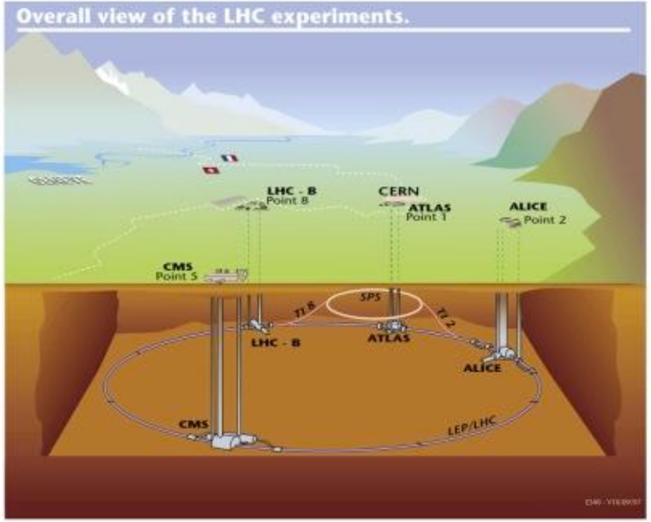
Matter created in heavy-ion collisions has 3-30 times larger energy density than the energy density inside the nucleon

Heavy-ion colliders

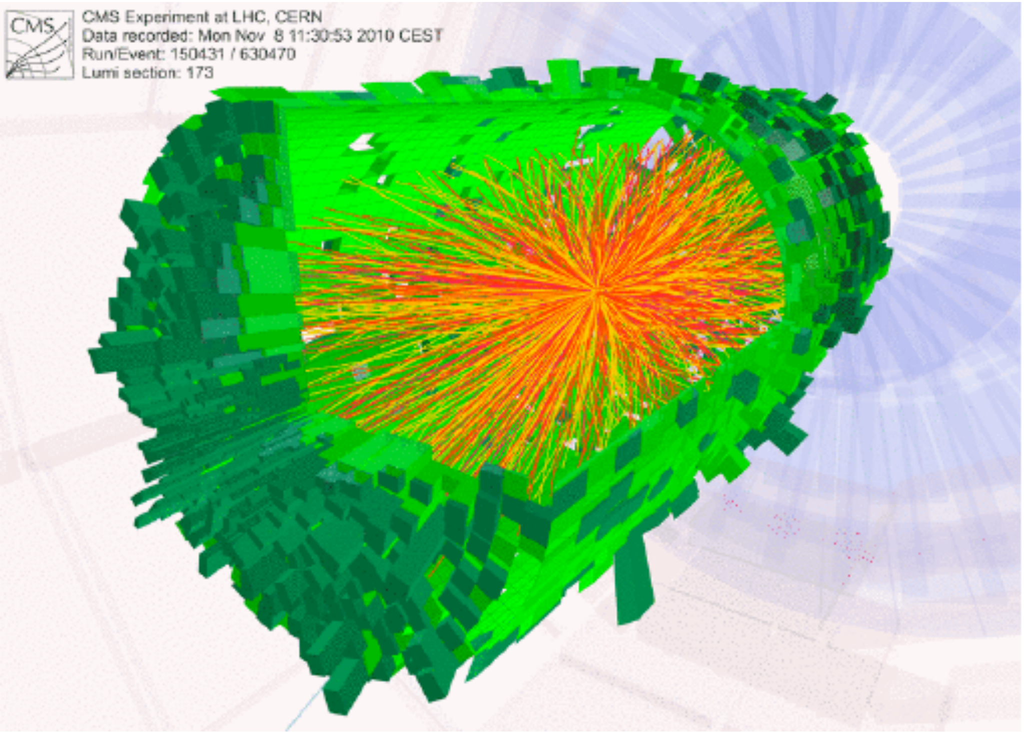
Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Laboratory
Au+Au $\sqrt{s_{NN}}$ = 200 GeV

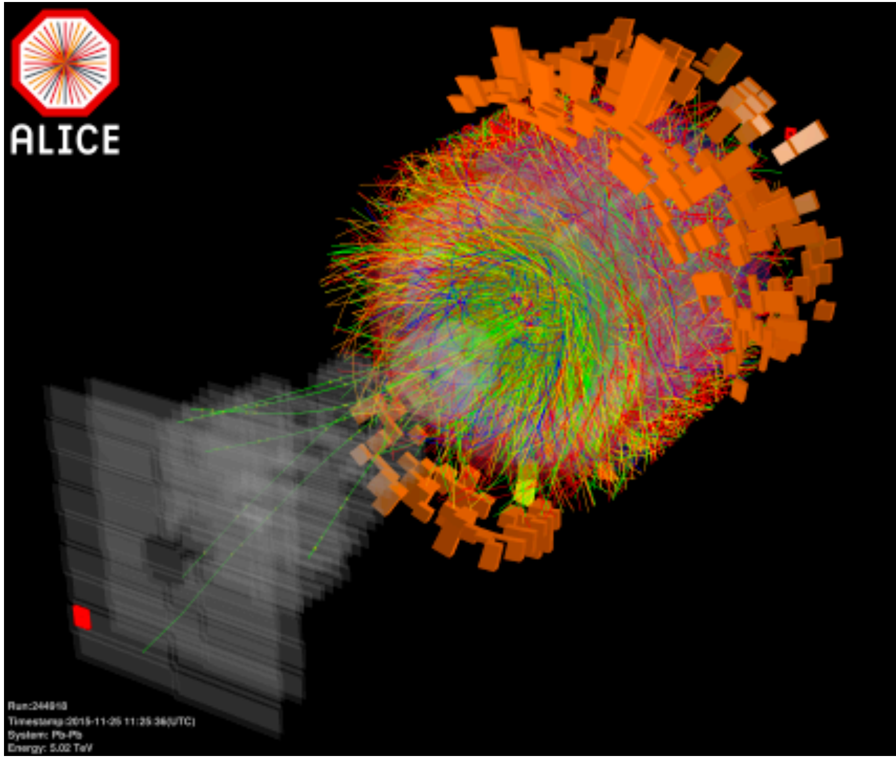
First run: 2000
STAR, PHENIX, PHOBOS, BRAHMS
2023: new detector sPHENIX

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



First run: 2010
ALICE, ATLAS, CMS, LHCb

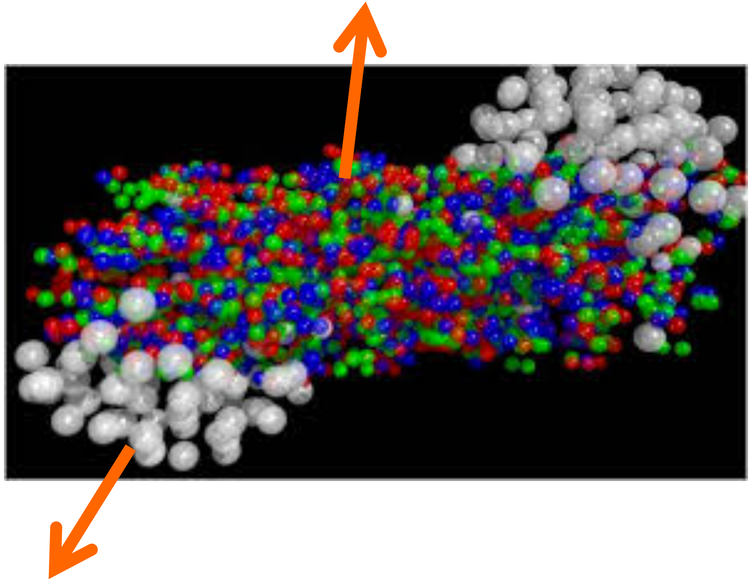




Thousands of particles are produced in one heavy-ion collision

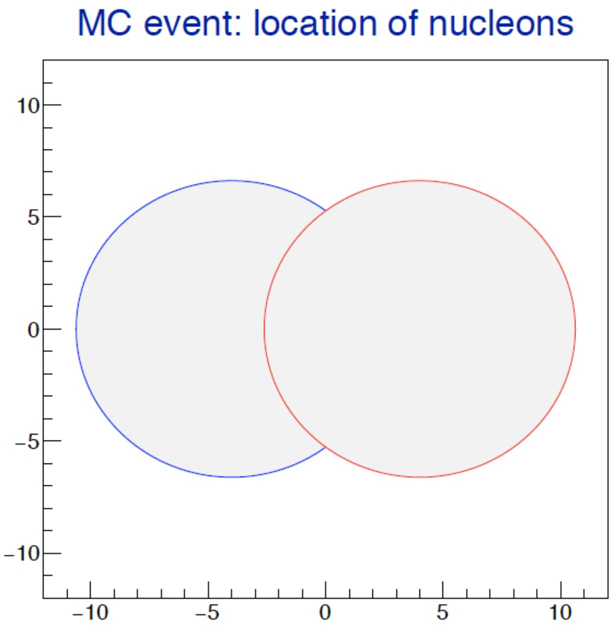
Probing the QGP

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

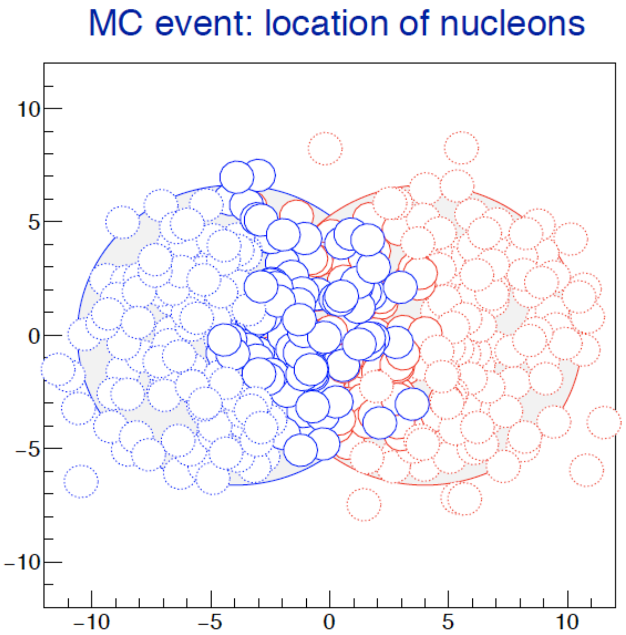


Spectators
Part of the nuclei that do not collide

Azimuthal anisotropy

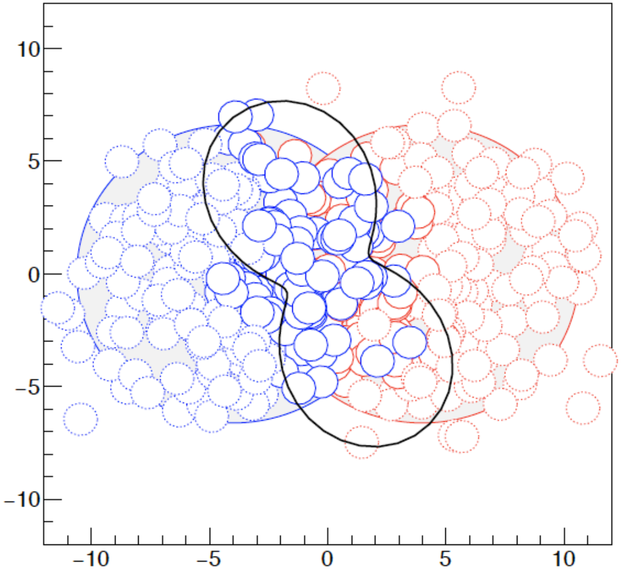


Azimuthal anisotropy



Azimuthal anisotropy

MC event: location of nucleons



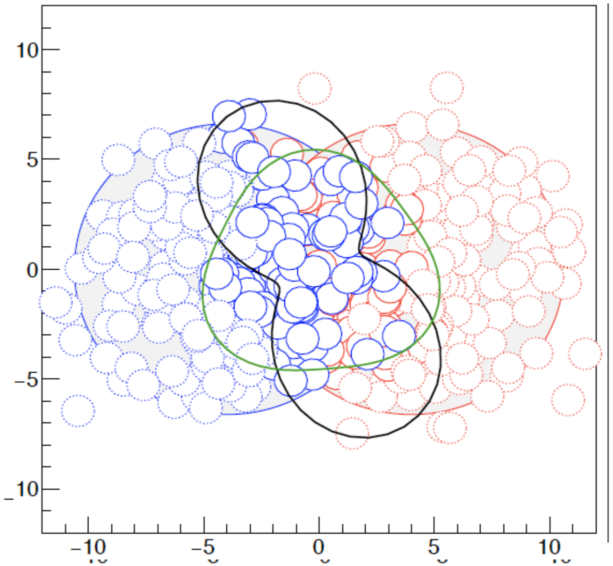
n=2

Characterise shape by angular moments:

$$\varepsilon_n = \frac{\sum r^2(\cos^2 n\varphi + \sin^2 n\varphi)}{\sum r^2}$$

Azimuthal anisotropy

MC event: location of nucleons



n=2

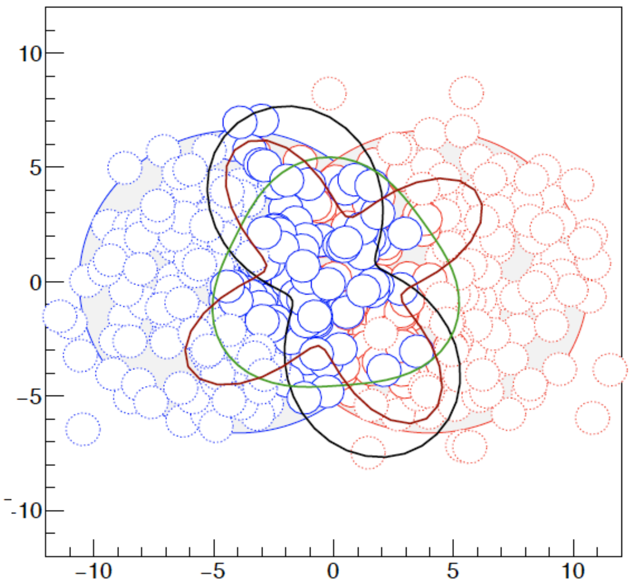
n=3

Characterise shape by angular moments:

$$\varepsilon_n = \frac{\sum r^2 (\cos^2 n\varphi + \sin^2 n\varphi)}{\sum r^2}$$

Azimuthal anisotropy

MC event: location of nucleons



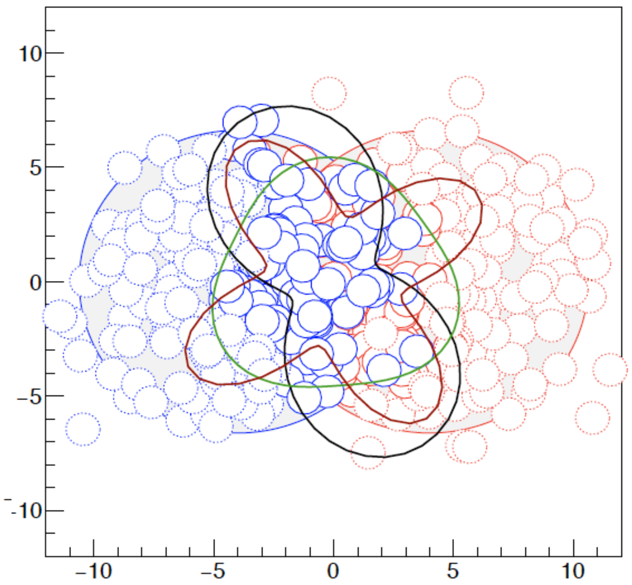
n=2
n=3
n=4

Characterise shape by angular moments:

$$\varepsilon_n = \frac{\sum r^2(\cos^2 n\varphi + \sin^2 n\varphi)}{\sum r^2}$$

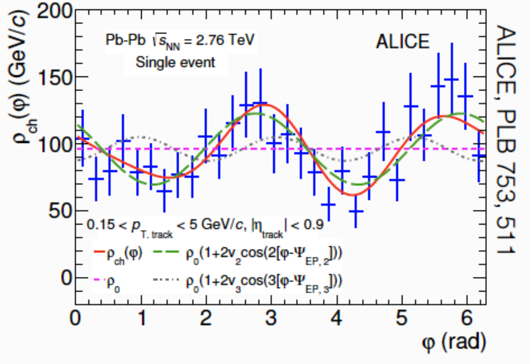
Azimuthal anisotropy

MC event: location of nucleons



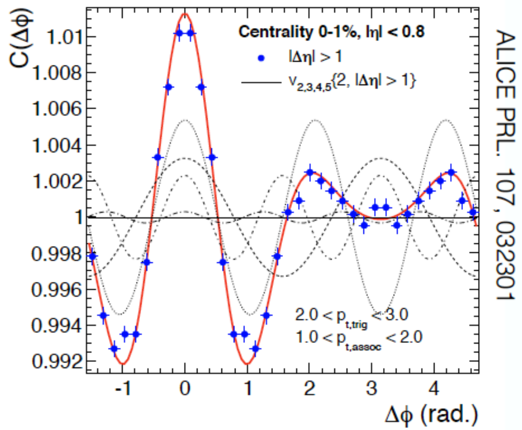
$$\nabla p = \rho \frac{d\vec{v}}{dt}$$

Azimuthal distribution single event



ALICE, PLB 753, 511

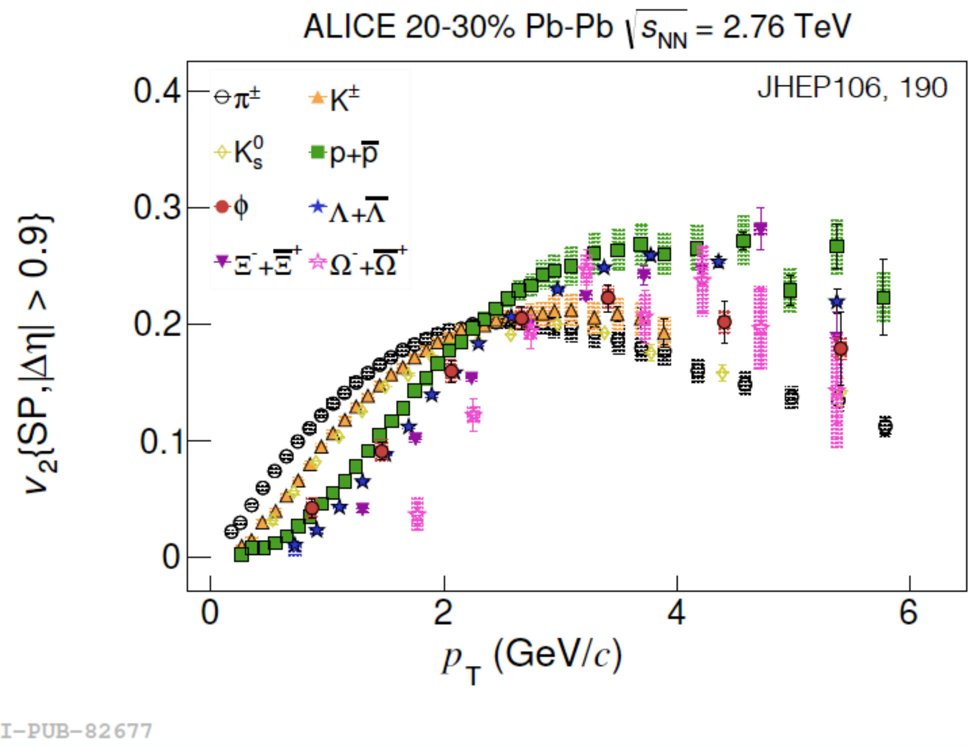
Sum over many events

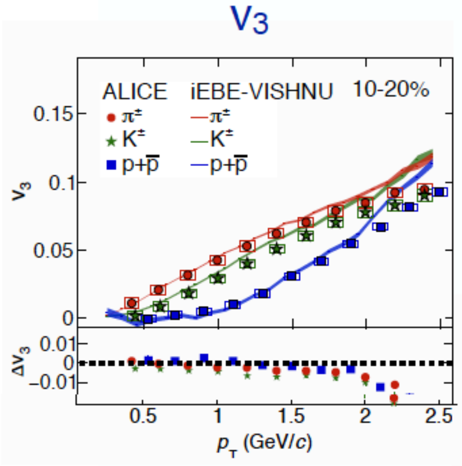


ALICE PRL. 107, 032301

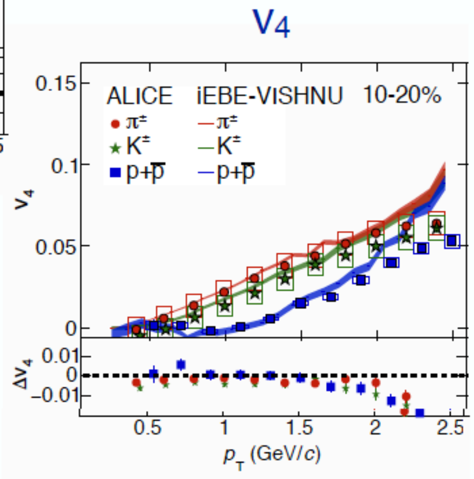
Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n by pressure gradients, flow of the Quark Gluon Plasma

Anisotropic flow: experimental results





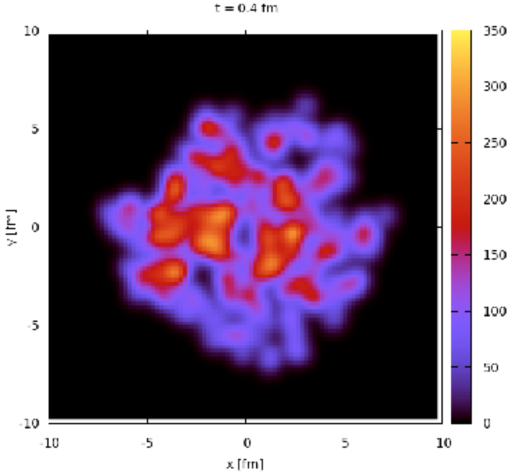
arXiv:1606.06057



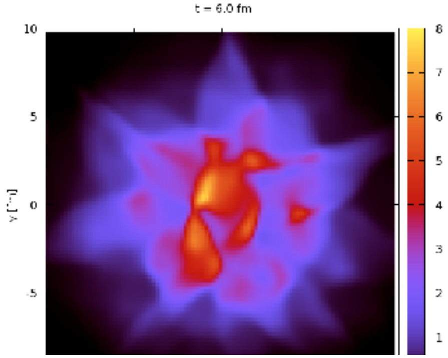
Mass-dependence of v2 → flow velocity, $p = \gamma m \beta$

Shear viscosity and dissipation

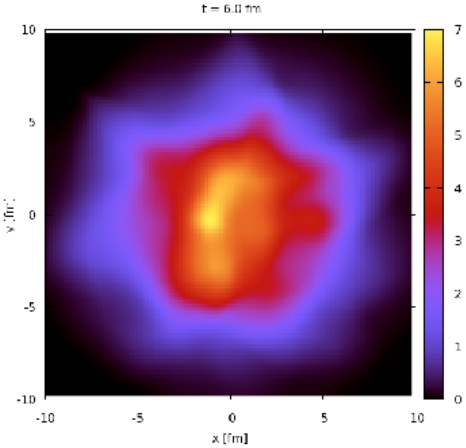
Initial state



$\frac{\eta}{s} = 0$



$\frac{\eta}{s} = 0.16$

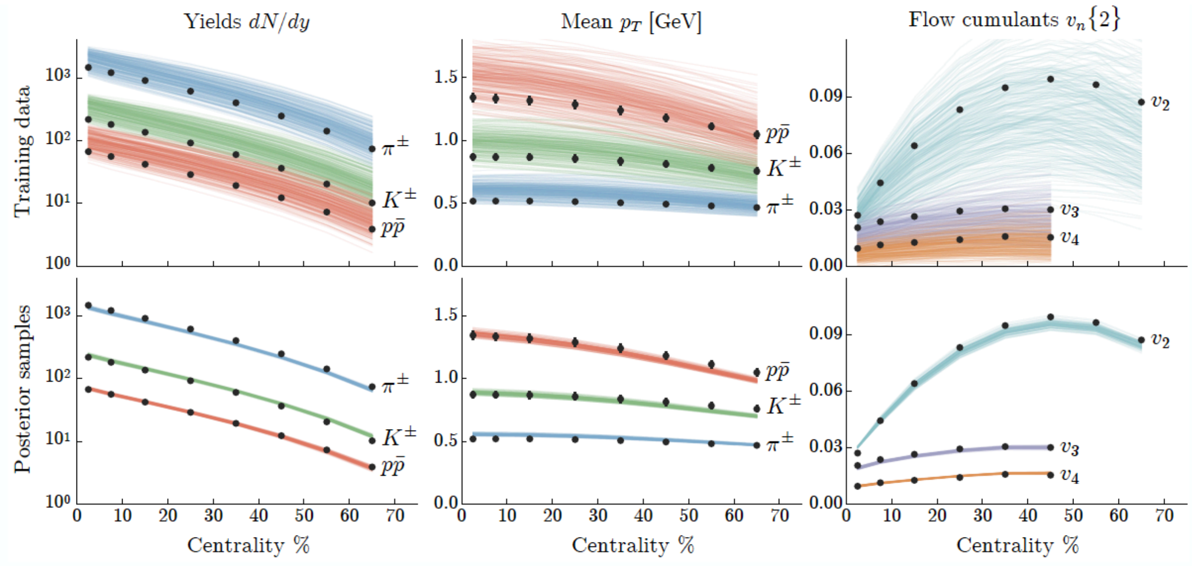


Lumpiness of initial state is visible in final state but depends on shear viscosity η

$$\frac{d\epsilon}{d\tau} = -\frac{\epsilon + p_s}{\tau}\left(1 - \frac{4}{3\tau T}\frac{\eta}{s} - \frac{1}{\tau T}\frac{\zeta}{s}\right)$$

Global fit

Experimental input: single particle yields, mean p_T, flow



J. E. Bernhard et al,
arXiv: 1605.03954

Explore large parameter space: test reliability of the modelling

Model: initial anisotropies + medium response

Global fit

J. E. Bernhard et al,
arXiv: 1605.03954

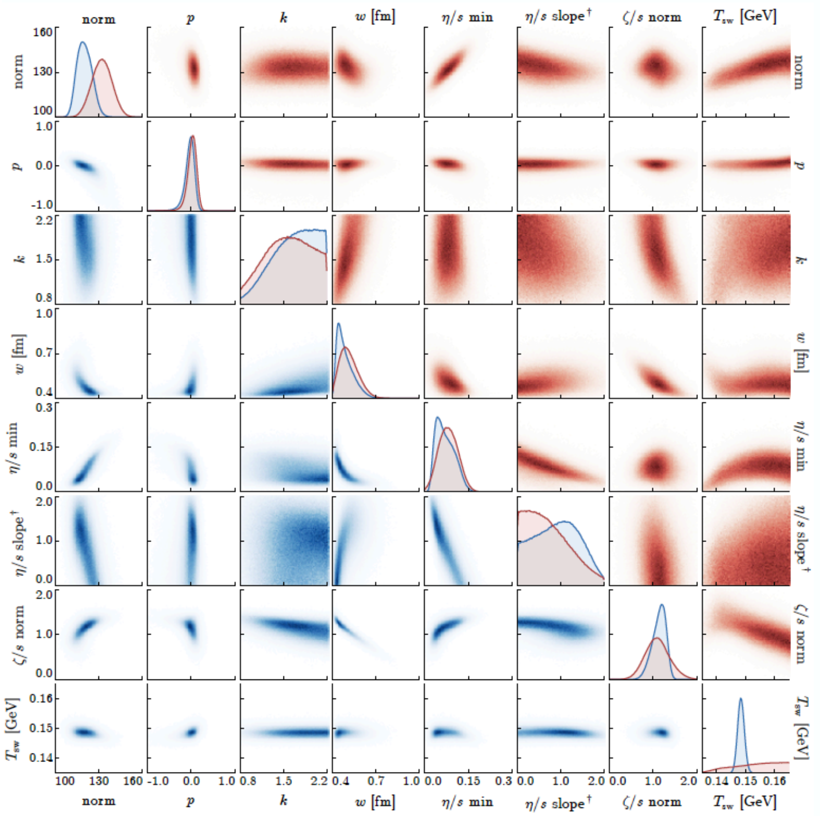
Model: initial state + hydrodynamics

$$\begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} \text{Response} \\ \\ \\ \end{pmatrix} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}$$

ε_n : initial spatial anisotropies from initial state model

v_n : observed final state momentum anisotropy

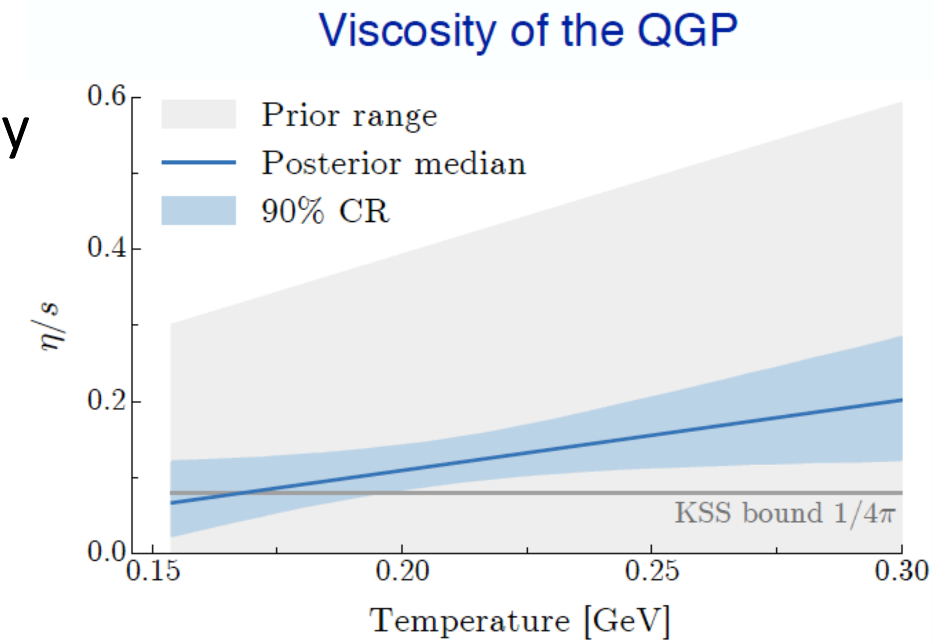
Response: modeled by hydrodynamic evolution



Global fit: result

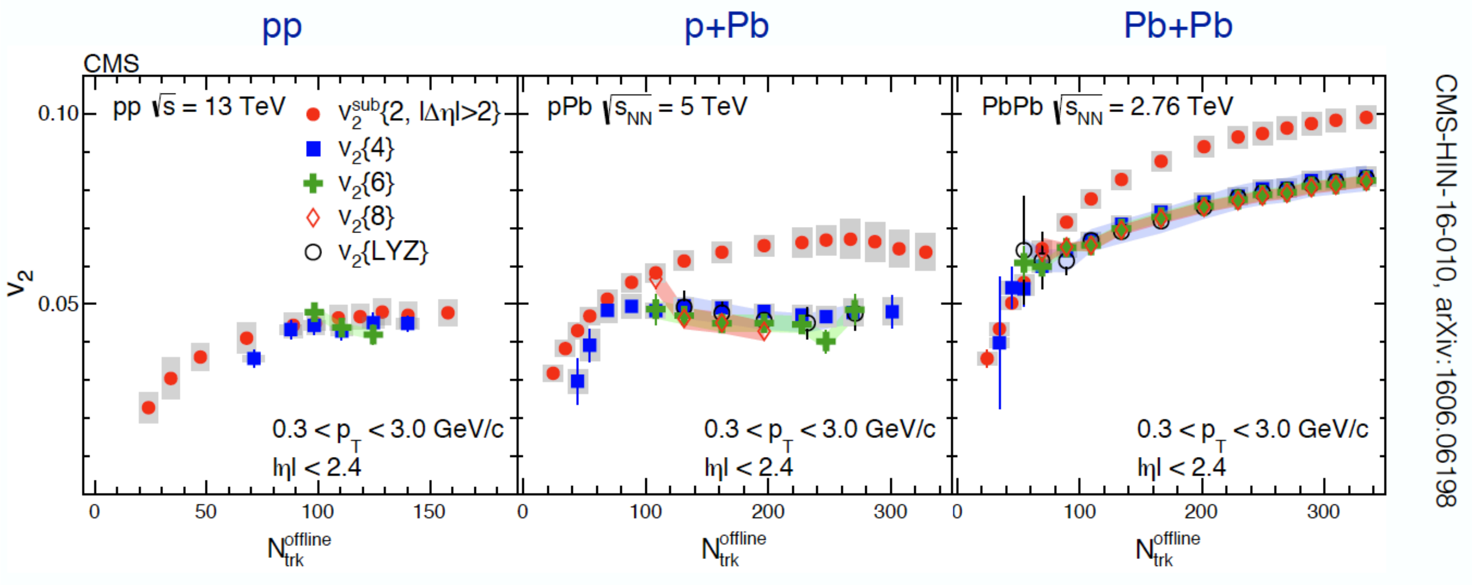
Fit constrains initial state geometry and transport properties at the same time

Viscosity close to lower bound



Collectivity in small systems

In smaller systems than QGP created in Pb-Pb collisions, collective behavior of particles is also observed. Unexpected!



Why are these smaller systems behaving like a fluid?

Is there enough time to thermalize?

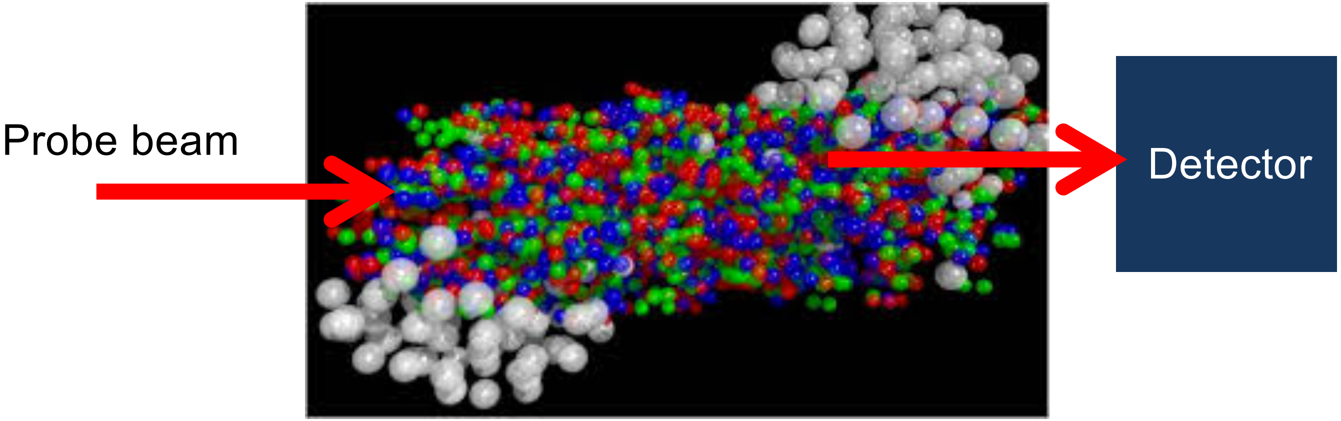
Limits on hydrodynamic behavior

Expect: at least a few collisions for each parton to reach thermal equilibrium and apply hydrodynamics

- System size larger than mean free path ($R > \lambda$)
  Would not expect azimuthal asymmetries in pp and p-Pb
  → Turns out not to be true: asymmetries also generated for $R < \lambda$

- Thermalization time: $\tau > \frac{\lambda}{\nu}$
  Fit to data: $\tau \approx 0.1 - 1$ fm/c
  → Also too strict: (viscous) hydro describes non-thermal systems

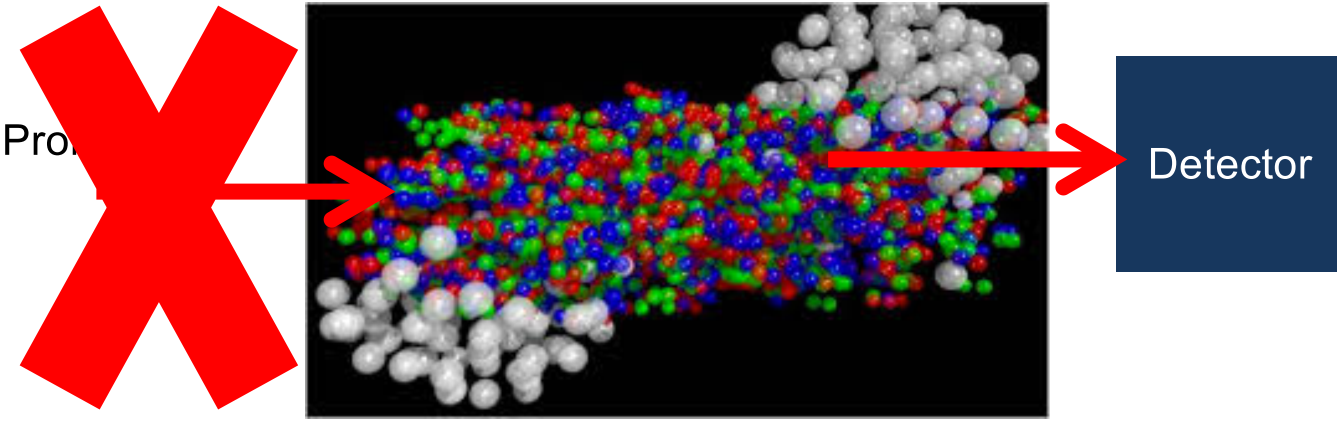
Probing the QGP



Probe beam

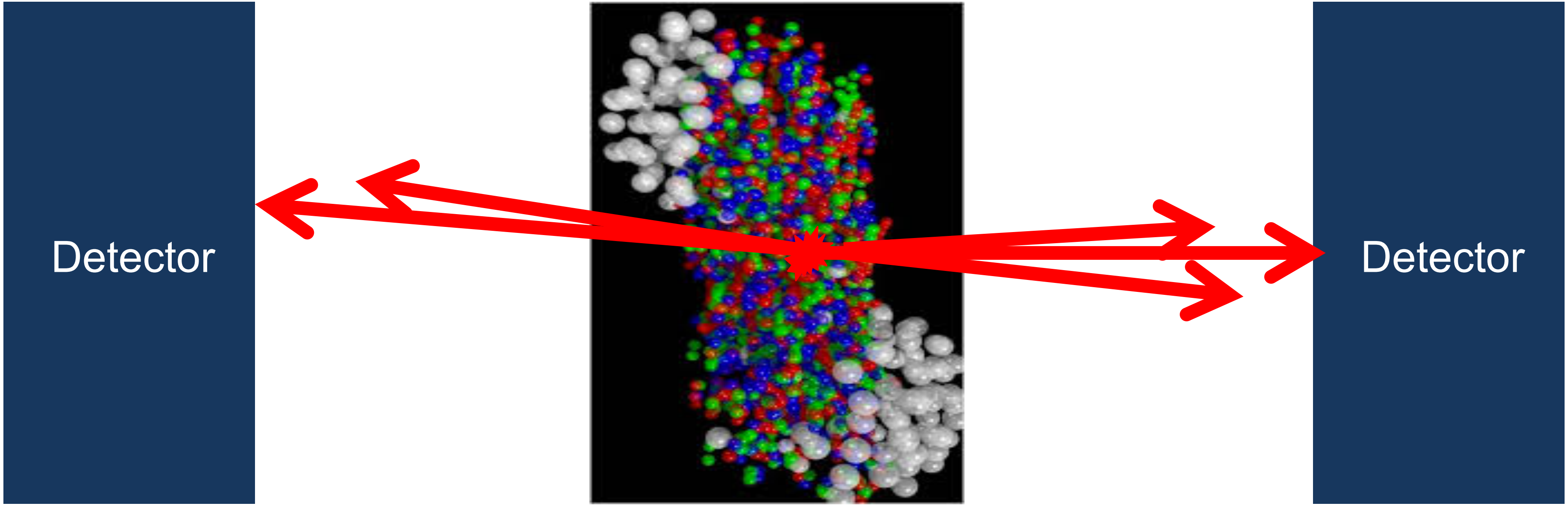
Detector

Probing the QGP



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

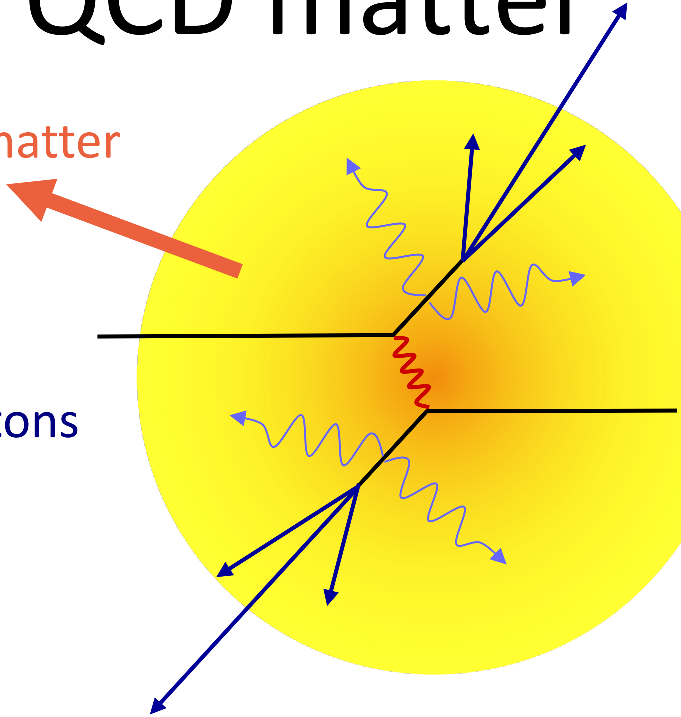
Probing the Quark Gluon Plasma



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

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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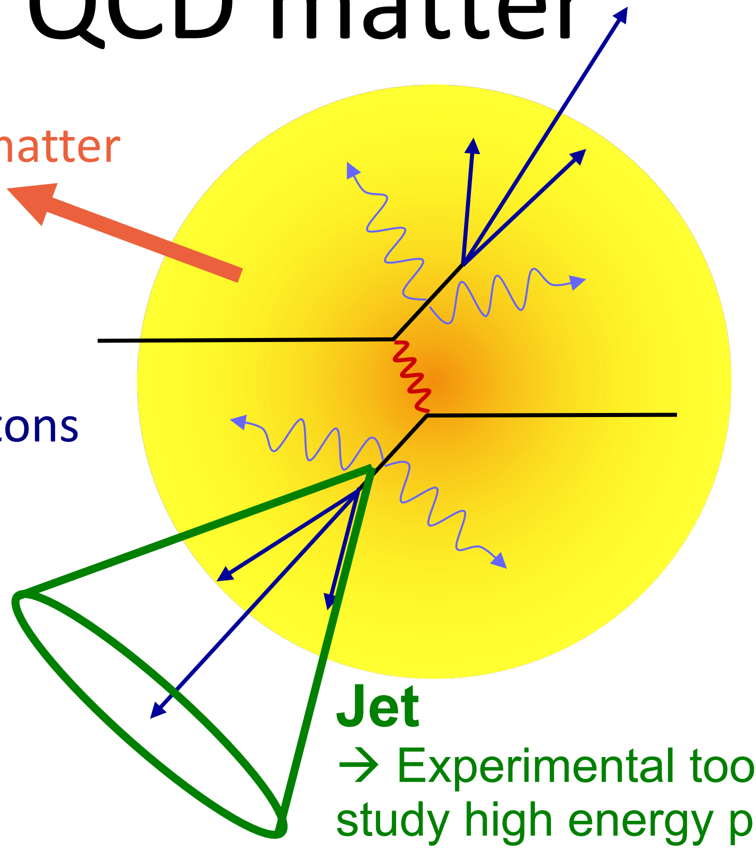


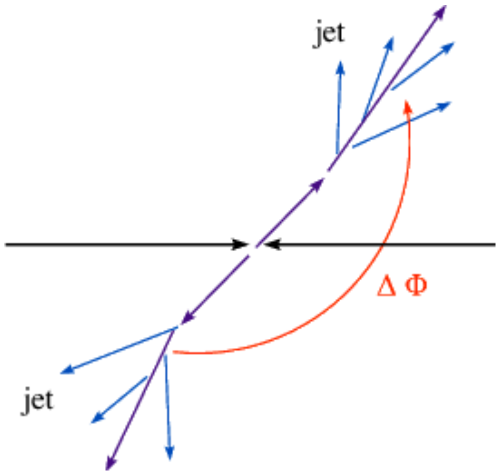
Jet
→ Experimental tool to study high energy partons

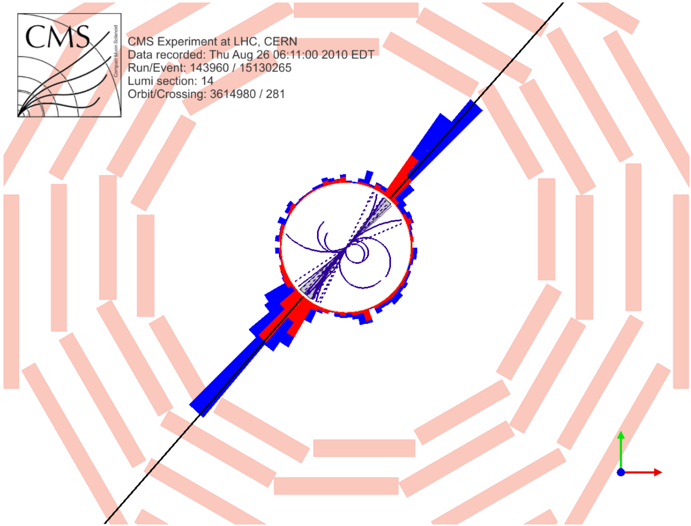
Use hard partons to explore QCD matter

What is a jet?

The manifestation of quarks and gluons in a particle detector

Observed as a collimated spray of high momentum particles

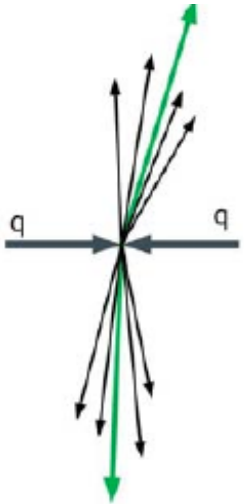




In experiment and theory particles are clustered into a cone → jet

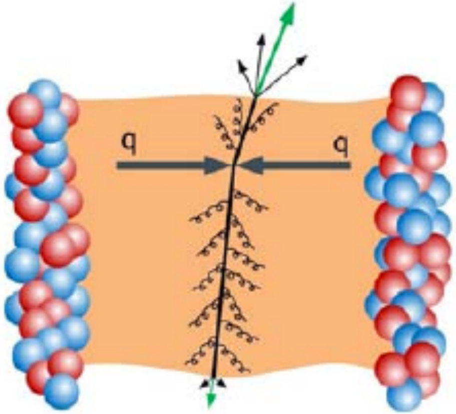
Jet production in medium

The experimentalist perspective*



p+p

proton-proton (pp) collision
No QGP created

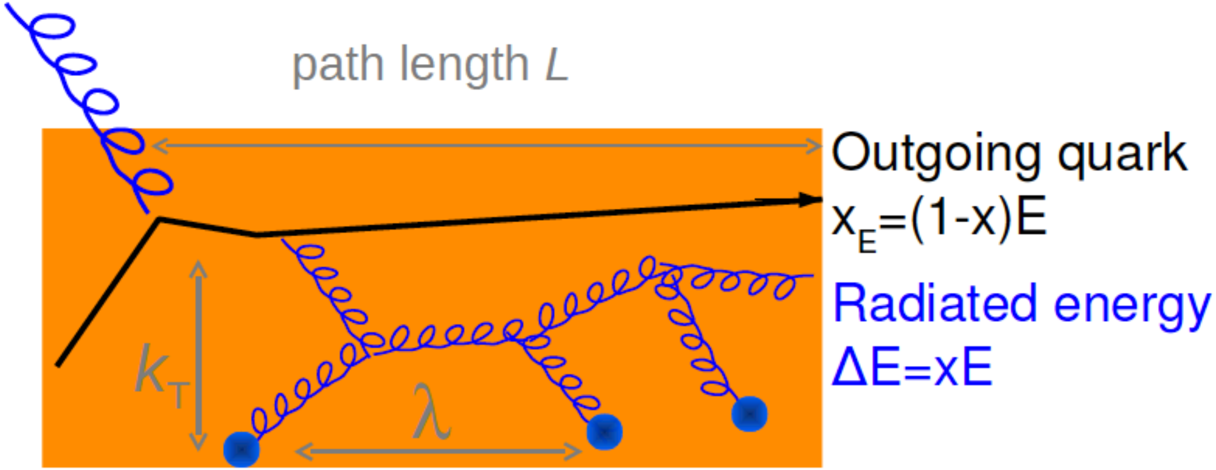


Heavy-ion collision
QGP created
→ additional gluon radiation
wrt pp collisions

* according to an experimentalist (me)

Schematic picture of energy loss mechanism

in hot dense matter

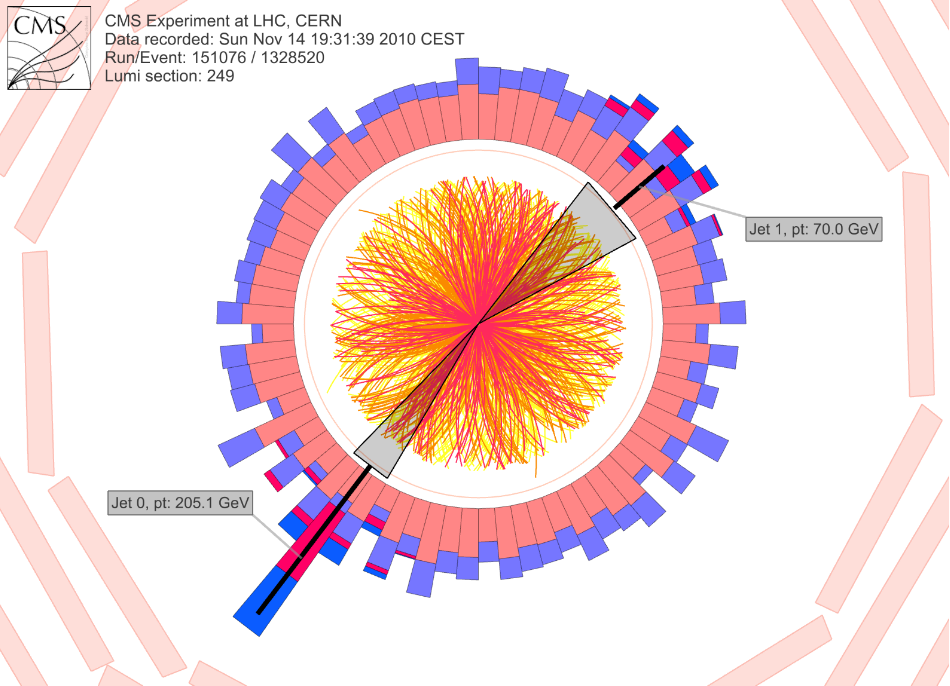


- Energy loss due to gluon bremsstrahlung in a hot dense medium

Find the jets in heavy-ion collisions

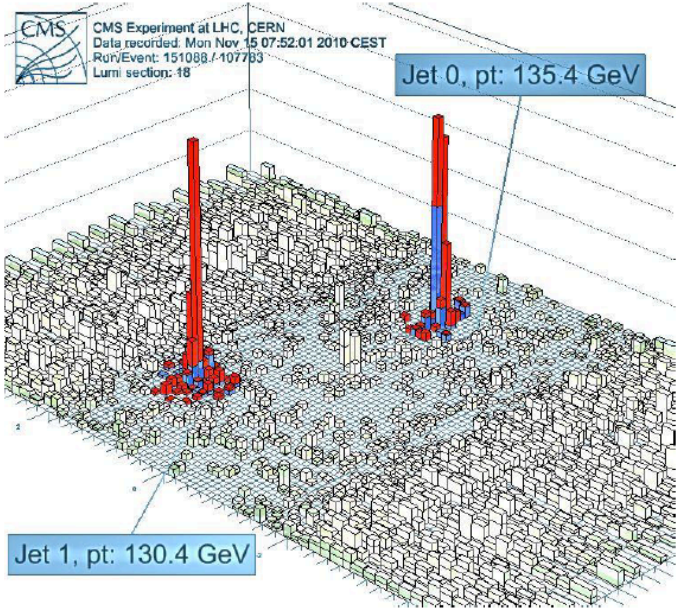
Jets are not so easy to find in a heavy-ion collision

→ Need sophisticated tools for background subtraction

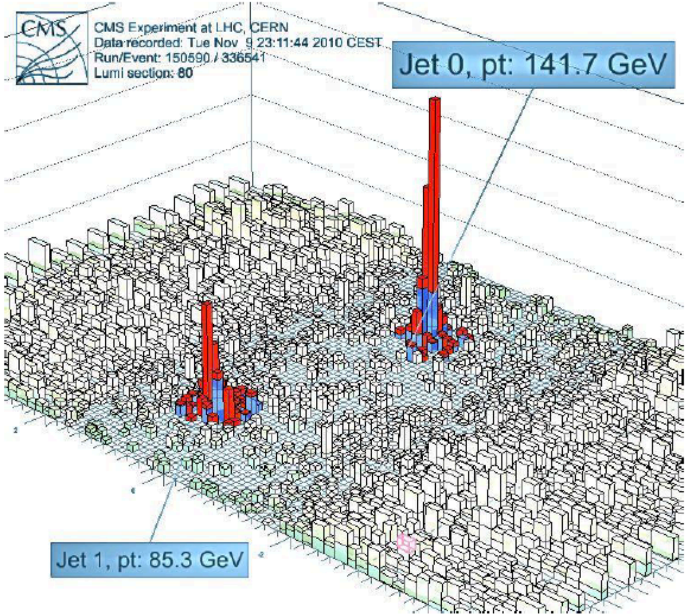


Dijets in PbPb

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



Balanced
Energy



Unbalanced
Energy

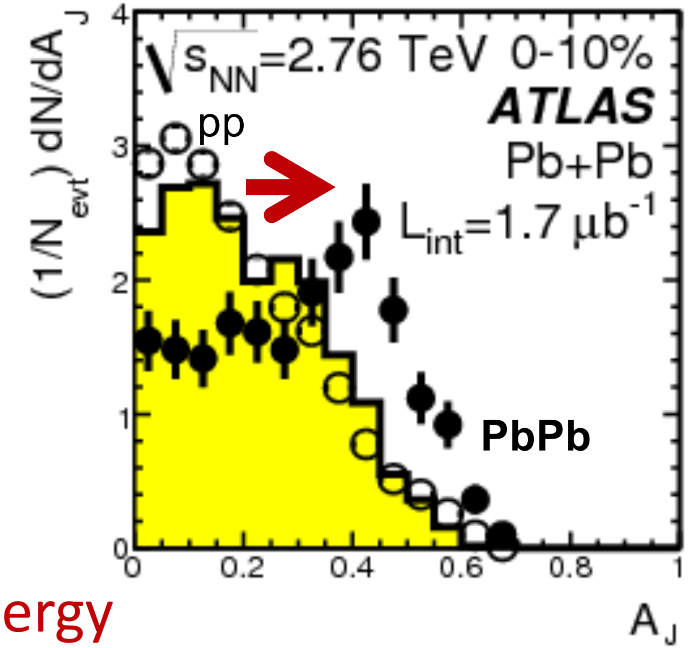
Dijets in PbPb

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



balanced *unbalanced*

Dijets in PbPb are less balanced in energy

Phys.Rev.Lett.105:252303,2010

Dijets in PbPb

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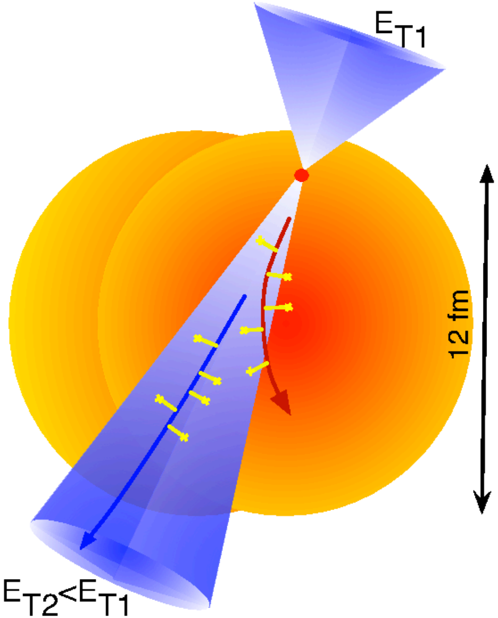
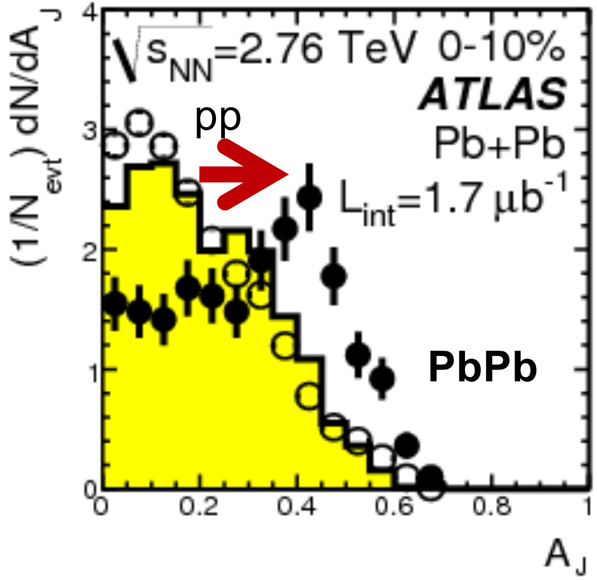
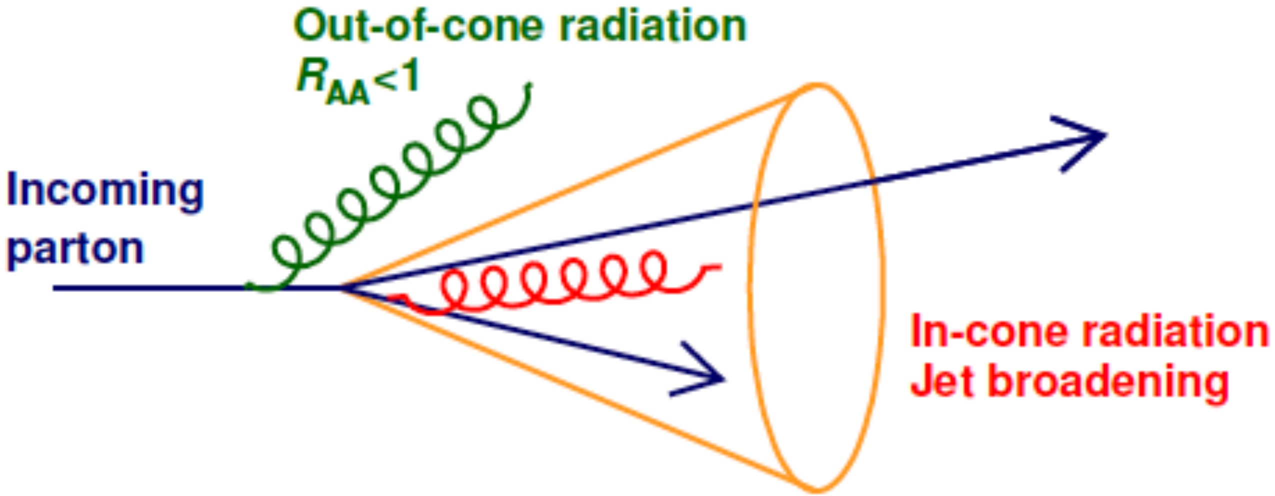




Phys.Rev.Lett.105:252303,2010

Jets in heavy-ion collisions

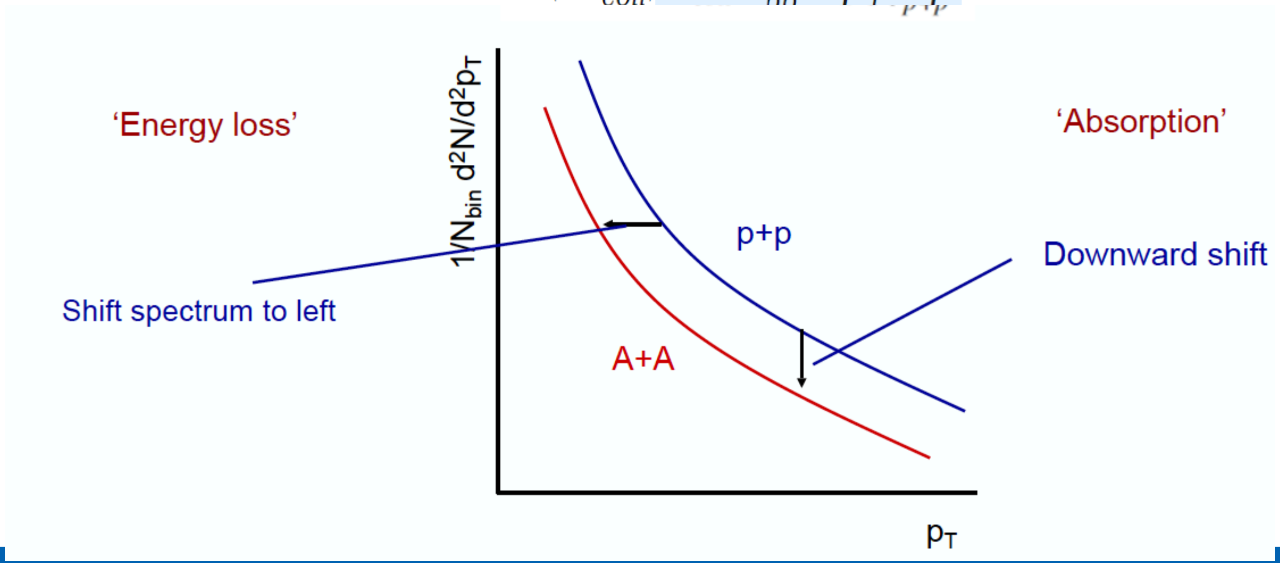
Due to interactions of the partons with the medium, the jet is modified relative to the jets we see in proton-proton collisions
→ Jet Quenching



Nuclear modification factor R_{AA}

Nuclear modification is measured by taking ratio between measured yield PbPb and pp collisions

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_T d\eta}{d^2 \sigma_{pp} / dp_T d\eta}$$



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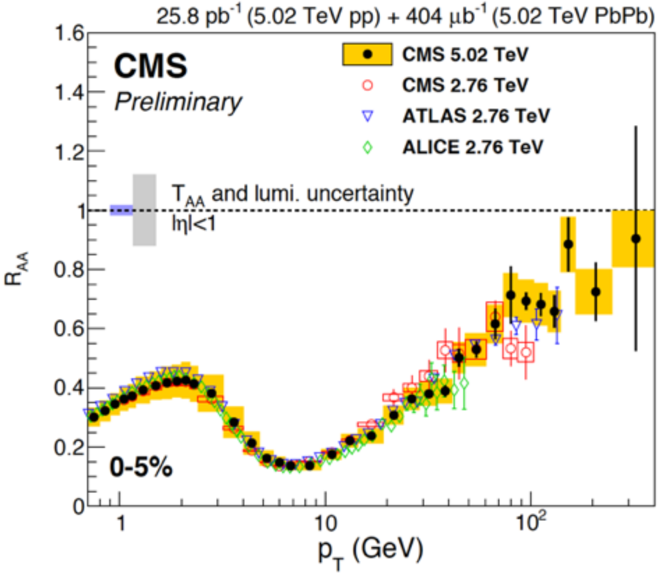


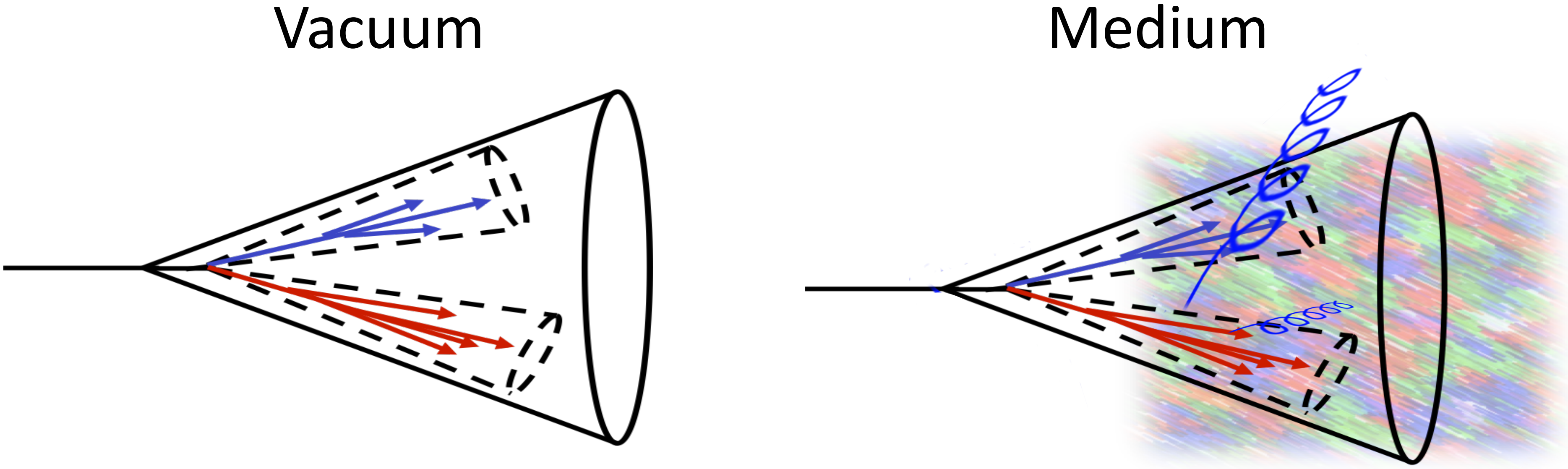
High p_T hadron production is suppressed by a factor 2-6

The shape of the distribution is very different from pp

→ Low p_T: Radial flow

→ High p_T: Jet quenching

Parton showers

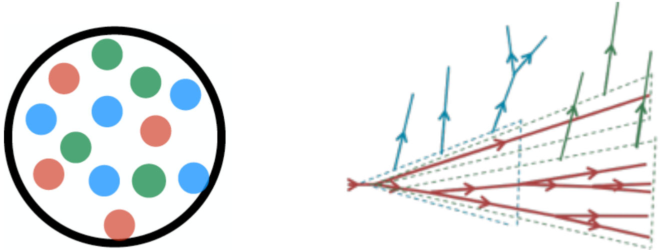


What happens to the parton shower in a hot QCD medium?
And what does that tell us about this medium?

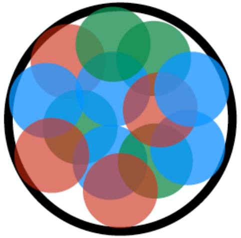
Probing the Quark Gluon Plasma

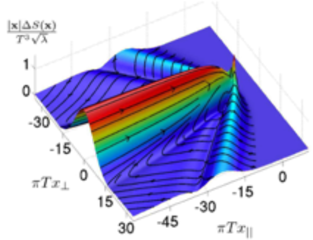
Two descriptions for parton interaction with QGP:

- 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

Two descriptions for parton interaction with QGP:

- Weak coupling (pQCD)
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- Strong coupling (AdS/CFT)
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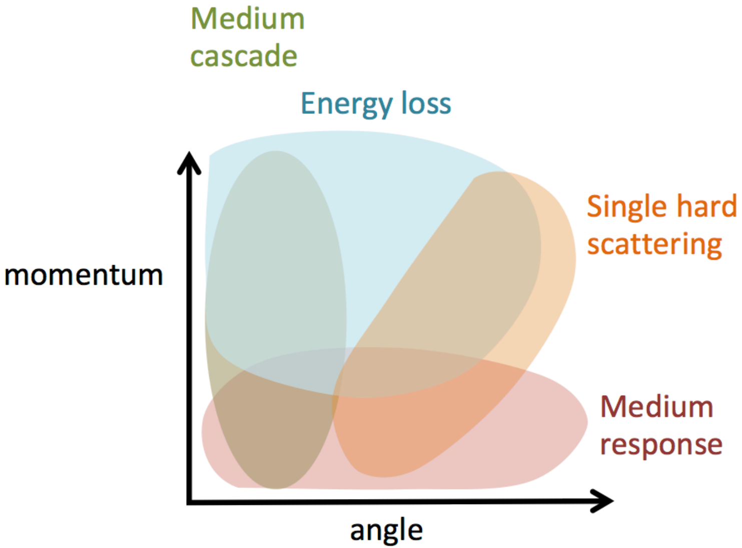
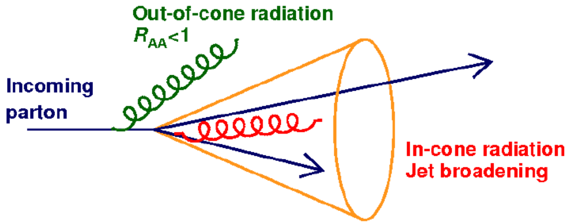
How to disentangle?

Study the various stages of jet formation

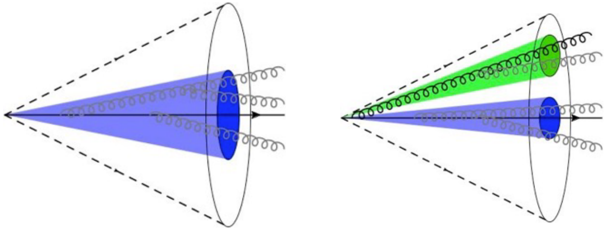


Jet modification in hot QCD medium

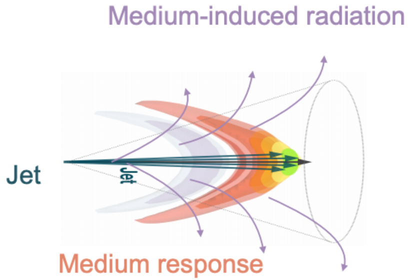
Medium-induced energy loss



Coherence effects



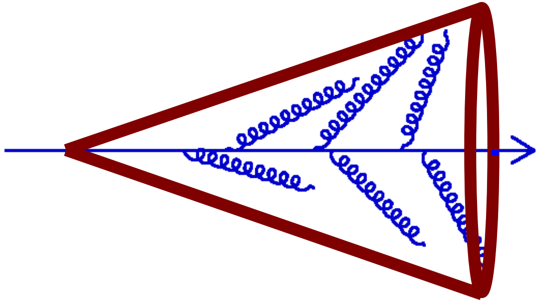
Medium recoil



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

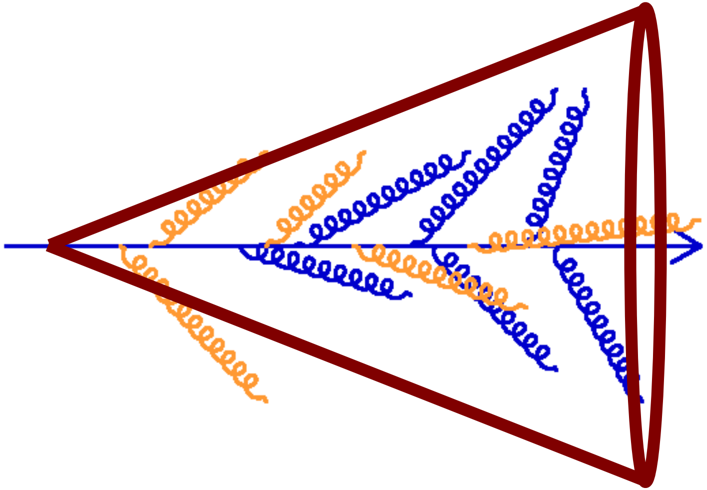
Subset of hadrons

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

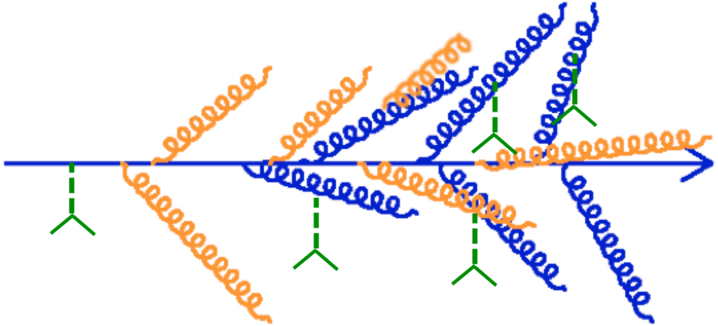
All partons in shower ‘see’ medium

Role of coherence

Medium response

…

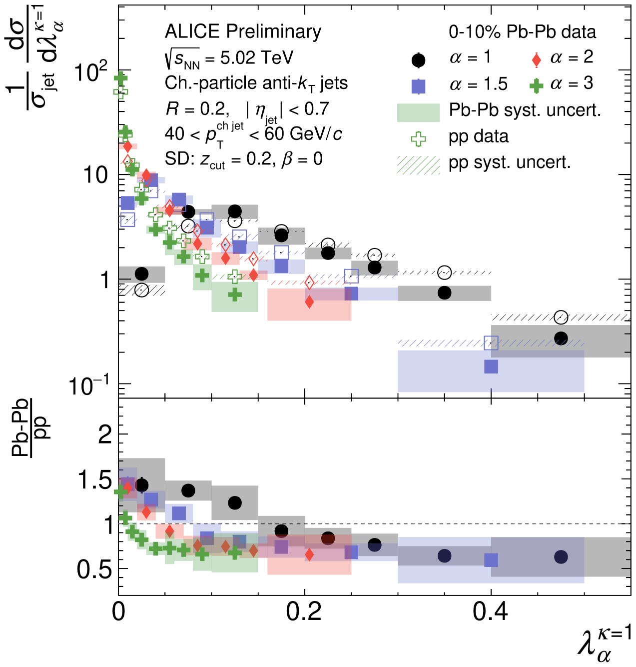
…

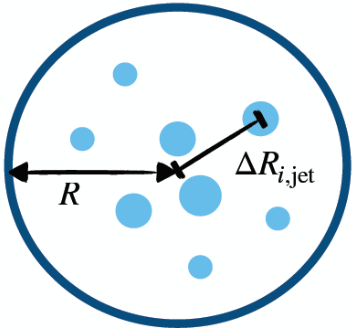


Each jet observable has different sensitivity

Jet angularities vs models

Small jets: R=0.2





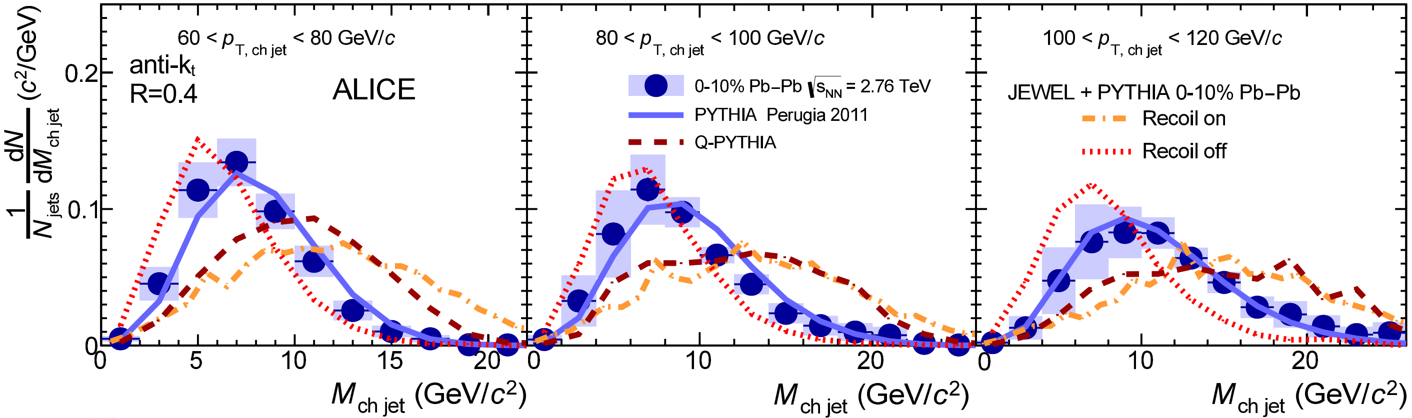
$$\lambda_\alpha \equiv \sum_{i \in \mathrm{jet}} z_i \theta_i^\alpha$$

$$z_i \equiv \frac{p_{T,i}}{p_{T,\mathrm{jet}}} \qquad \theta_i \equiv \frac{\Delta R_{i,\mathrm{jet}}}{R}$$

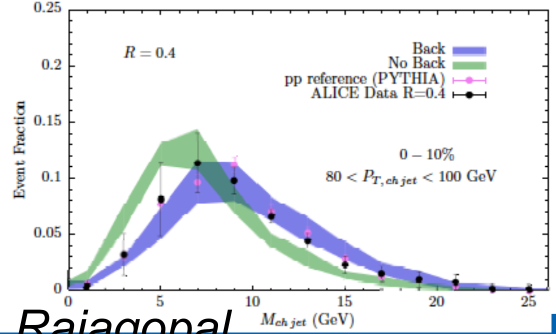
Selected jets are narrower in Pb-Pb collisions
For small jets, medium response small effect

Jet mass

Small mass: collimated jet, small number of constituents. Low virtuality
Large mass: broad jet, large number of constituents. High virtuality



arXiv:1702.00804



K. Rajagopal

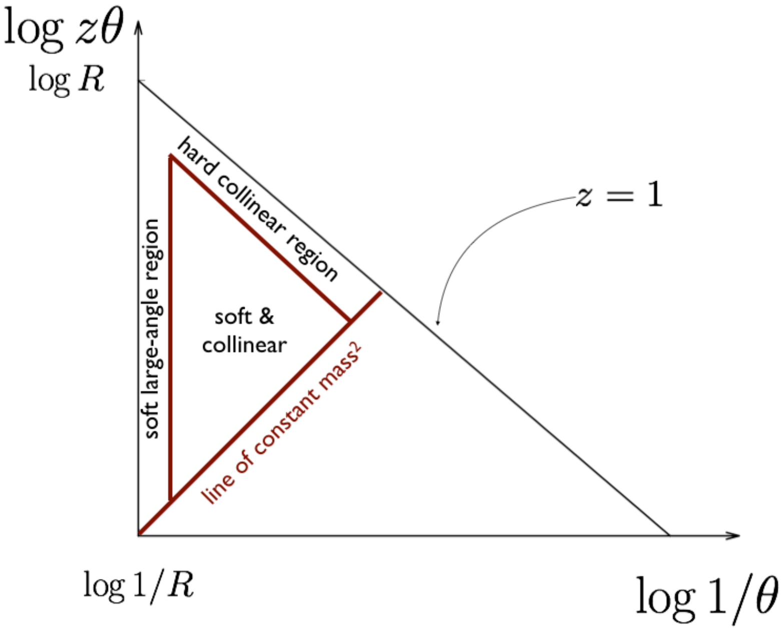
Data looks like PYTHIA
No modification?

Competing effects from energy loss and medium response in JEWEL and Hybrid model.

The Lund diagram

Just a plane to depict parton splittings

$k_\perp / E \sim z\theta$

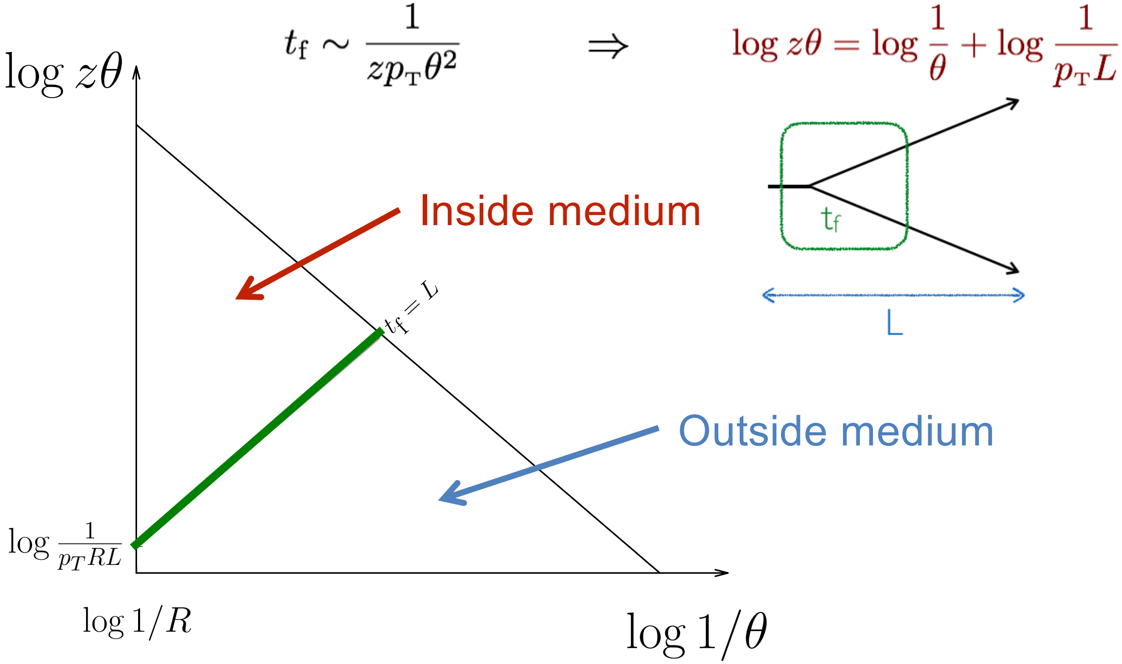


Triangle uniformly filled for a vacuum parton shower at LO

B. Andersson, G. Gustafson, L. Lönnblad and U. Pettersson, Z. Phys. C 43 (1989) 625
F. Dreyer, G. Salam, G. Soyez arXiv:1807.04758

In or outside the medium

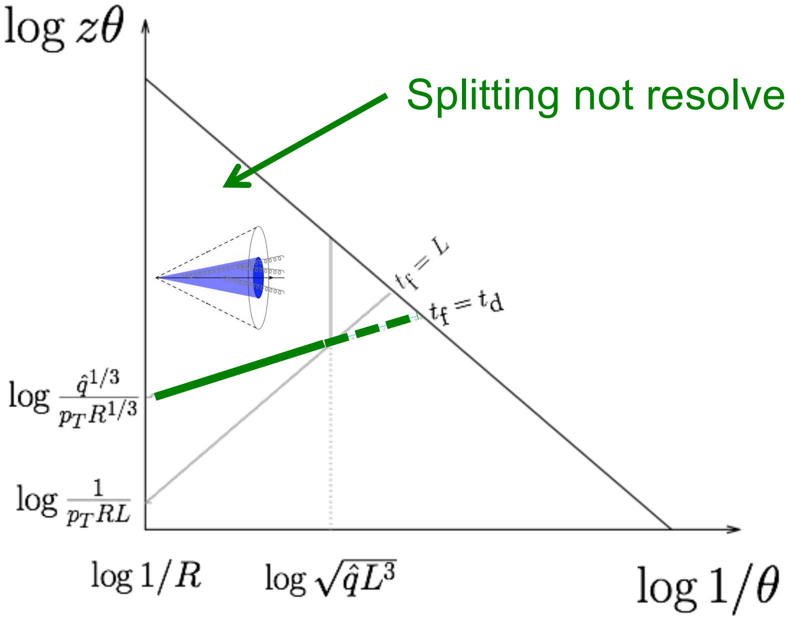
A splitting can either occur inside or outside the medium
→ depends on the formation time of the splitting



$$t_{\mathrm{f}} \sim \frac{1}{z p_{\mathrm{T}} \theta^2} \quad \Rightarrow \quad \log z\theta = \log \frac{1}{\theta} + \log \frac{1}{p_{\mathrm{T}} L}$$

arXiv:1808.03689

Coherent or incoherent splitting



Splitting not resolved by medium

Formation time: $t_{\rm f} \sim \dfrac{1}{z p_{\rm T} \theta^2}$

Decoherence time: $t_{\rm d} \sim \dfrac{1}{(\hat{q}\theta^2)^{1/3}}$

$$\log z\theta = \frac{1}{3}\log\frac{1}{\theta} + \log\frac{\hat{q}^{1/3}}{p_{\rm T}}\,,$$

arXiv:1808.03689

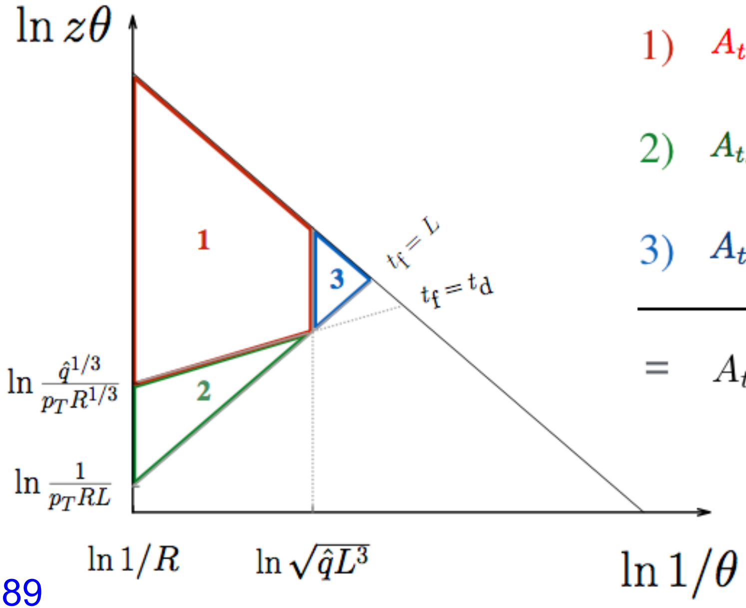
Phase space in medium

3 regions for a splitting happening in medium

1) vacuum-like splitting inside medium that will be quenched

2) medium-induced splitting → not uniform in Lund plane

3) unresolved splitting



1) $A_{t_f<t_d<L} = \frac{1}{2}\ln\frac{R^2}{\theta_c^2}\left(\ln\frac{p_T}{\omega_c}+\frac{1}{3}\ln\frac{R^2}{\theta_c^2}\right)$

2) $A_{t_d<t_f<L} = \frac{1}{12}\ln^2\frac{R^2}{\theta_c^2}$

3) $A_{t_f<L<t_d} = \frac{1}{4}\ln^2\frac{p_T}{\omega_c}$

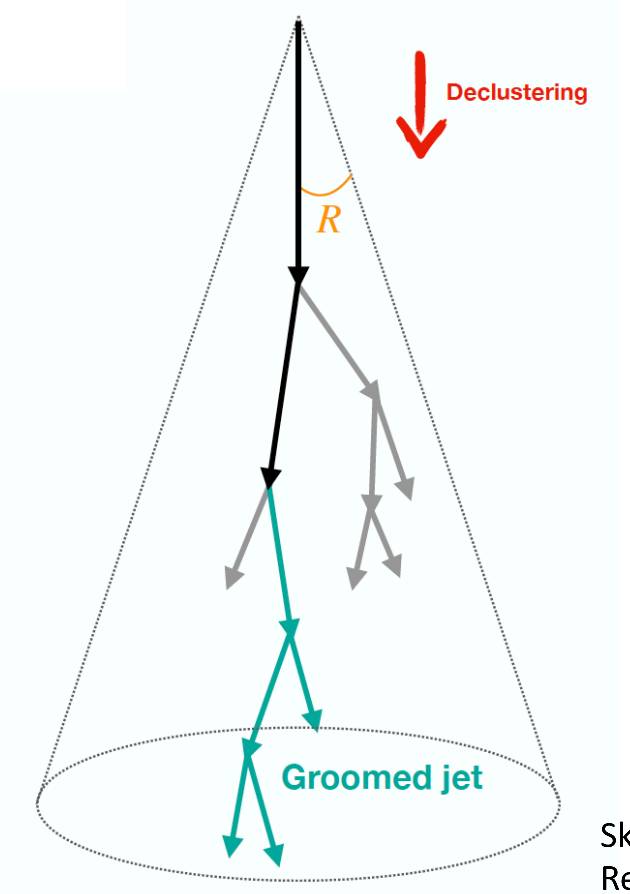
$= \quad A_{t_f<L} = \frac{1}{4}\ln^2 p_T R^2 L$

arXiv:1808.03689

Access to splittings in experiment

Order constituents in the jet

Walk back in history to identify splittings of interest



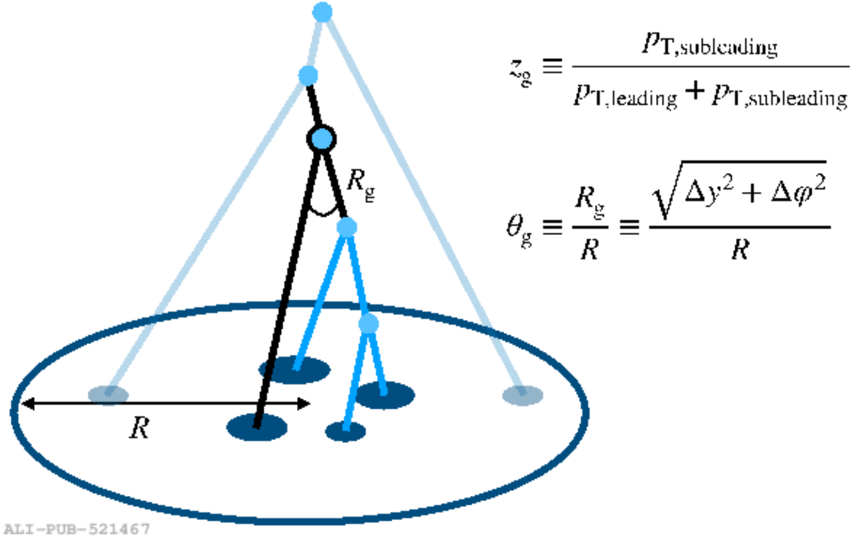
Sketch by Rey Torres

Access to splittings in experiment

Order constituents in the jet

Walk back in history to identify
splittings of interest

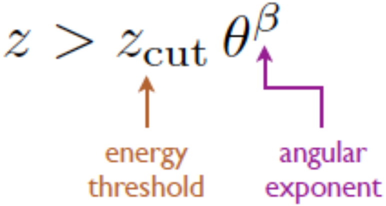
Define your observable
- can be one specific splitting;
- but also multiple in one jet;



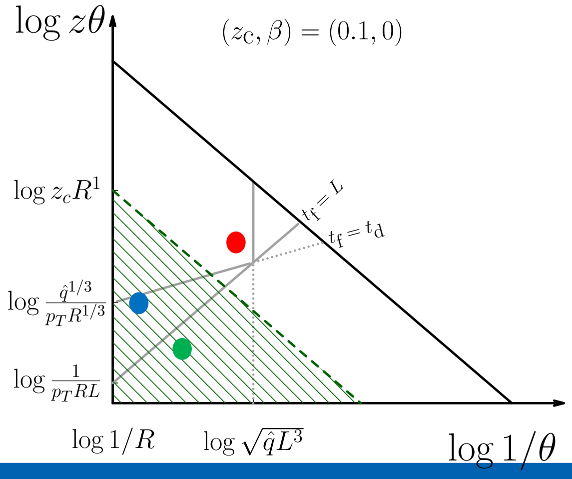
ALI-PUB-521467

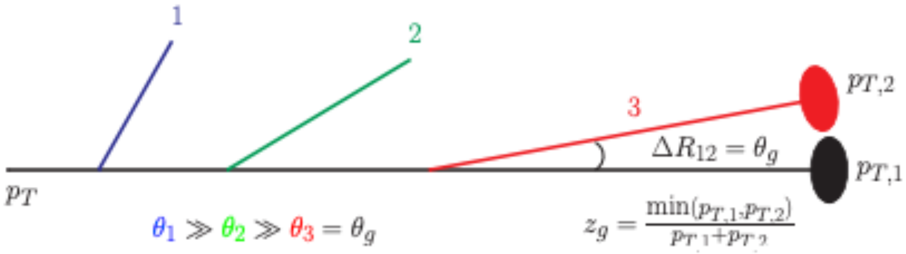
Lund plane and grooming

Grooming selects on momentum fraction and angle of branches in angular ordered tree



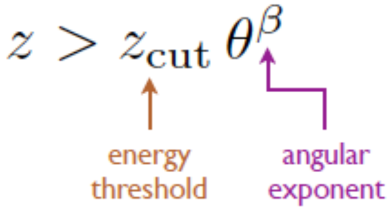
$z_{\mathrm{cut}} = 0.1$ and $\beta = 0$





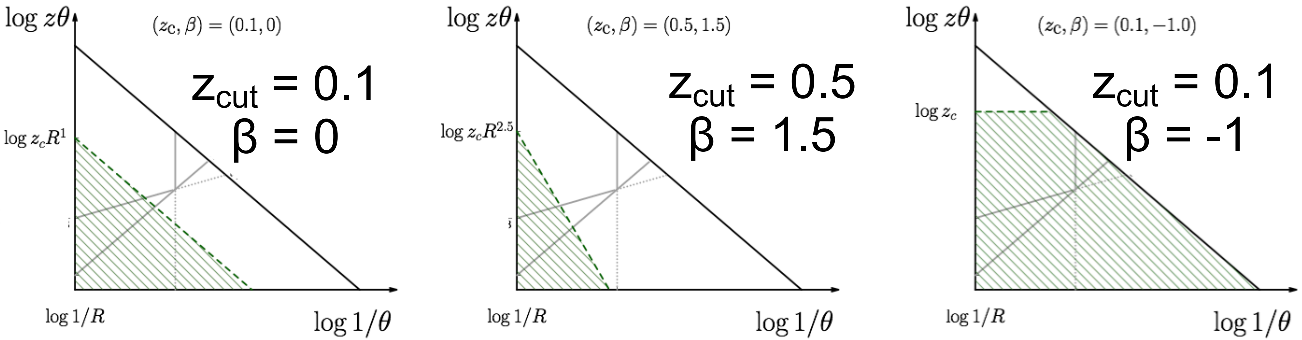
Lund and grooming

Grooming selects on momentum fraction and angle of branches in angular ordered tree



$z > z_{\text{cut}}\,\theta^{\beta}$

[Shaded region is excluded.]



cuts only on the energy sharing fraction

stronger grooming at large angle

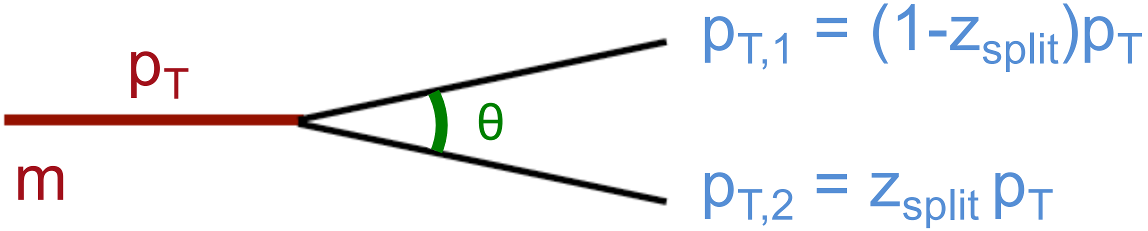
only hard radiation remains

Varying the grooming condition allows to select different regions of radiation phase space

Hard splitting as probe of medium

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

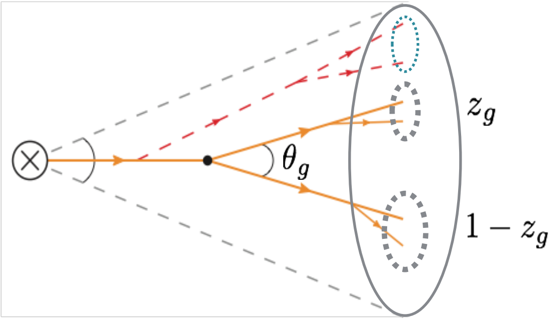
Then study the influence of the medium on the antenna

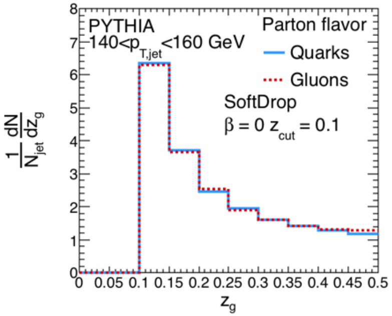


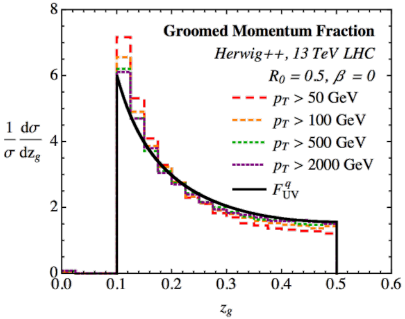
Splitting probability in vacuum:

$$\mathrm{d}\mathcal{P}_{\mathrm{vac}} = 2\frac{\alpha_s C_R}{\pi}\,\mathrm{d}\log z\theta\,\mathrm{d}\log\frac{1}{\theta}$$

Shared momentum fraction







JHEP 1405 (2014) 146

No flavor dependence

Weak jet p_T dependence

In vacuum: Altarelli-Parisi splitting function

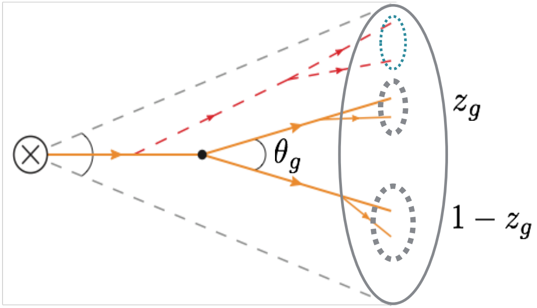
Observable:
Momentum balance between the two subjets as defined by grooming procedure

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

Momentum fraction carried by the subleading branch

Jet splitting function

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

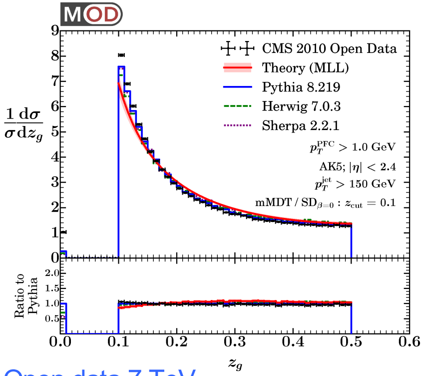


$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}.$$

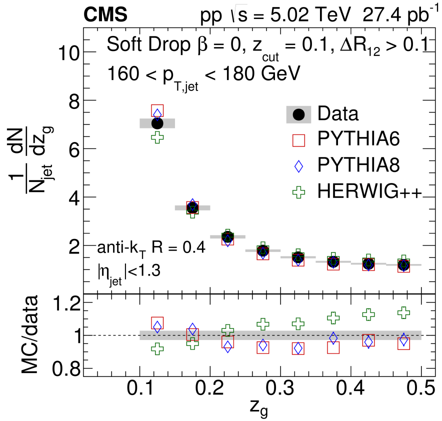
With groomed jets: soft large angle radiation removed to define the hardest splitting

$$\frac{1}{N_{\text{jets}}}\frac{dN_i}{dz_g} \propto \overbrace{\bar{P}_i(z_g)}^{\text{measure splitting function !}} \sim \frac{1}{z_g}$$

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



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



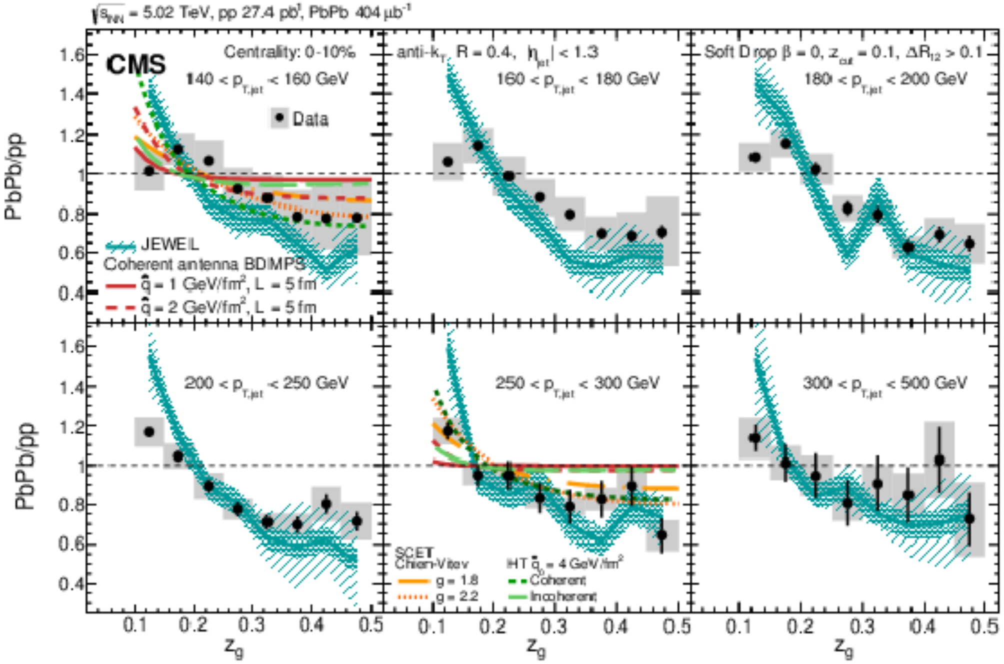
CMS 5 TeV, PRL 120 (2018), 142302

Splitting fraction

Data suggests:

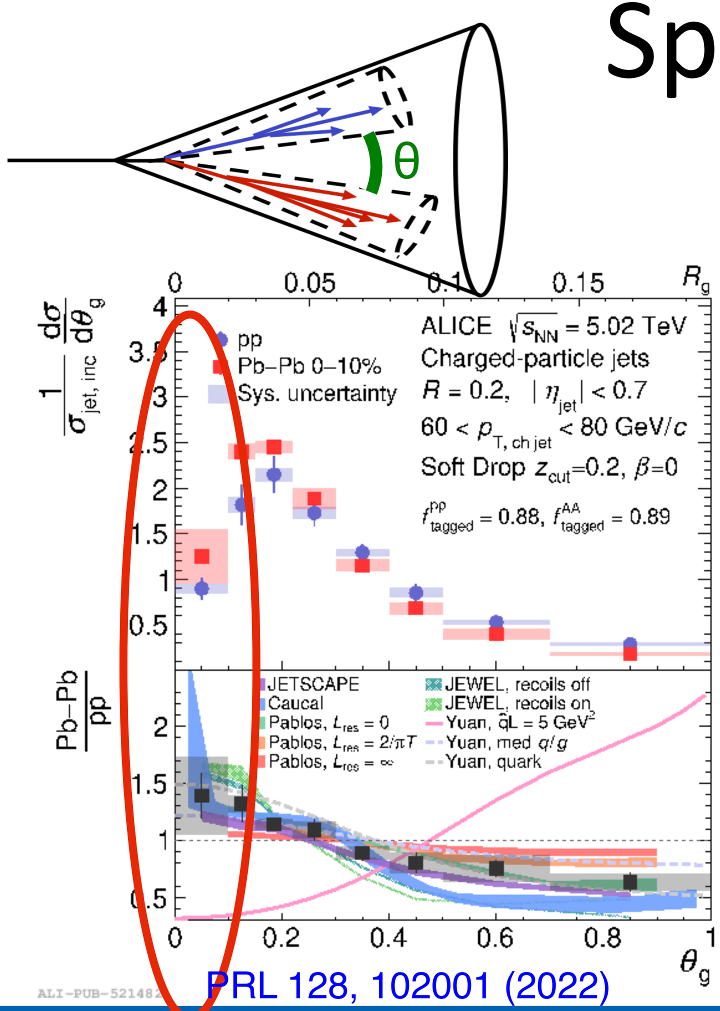
Splittings in quenched jets
are a bit less balanced

Models capture the trend
but different physics
mechanisms responsible



[Phys. Rev. Lett. 120 (2018) 142302]

Splitting angle

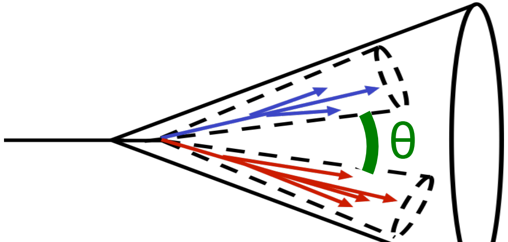


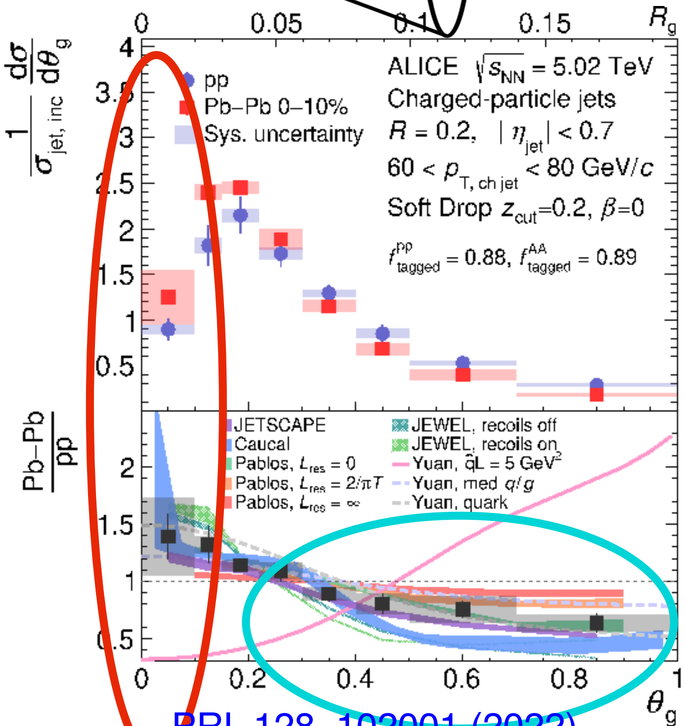
PRL 128, 102001 (2022)

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

→less suppression observed in data

Splitting angle

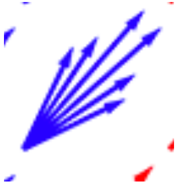




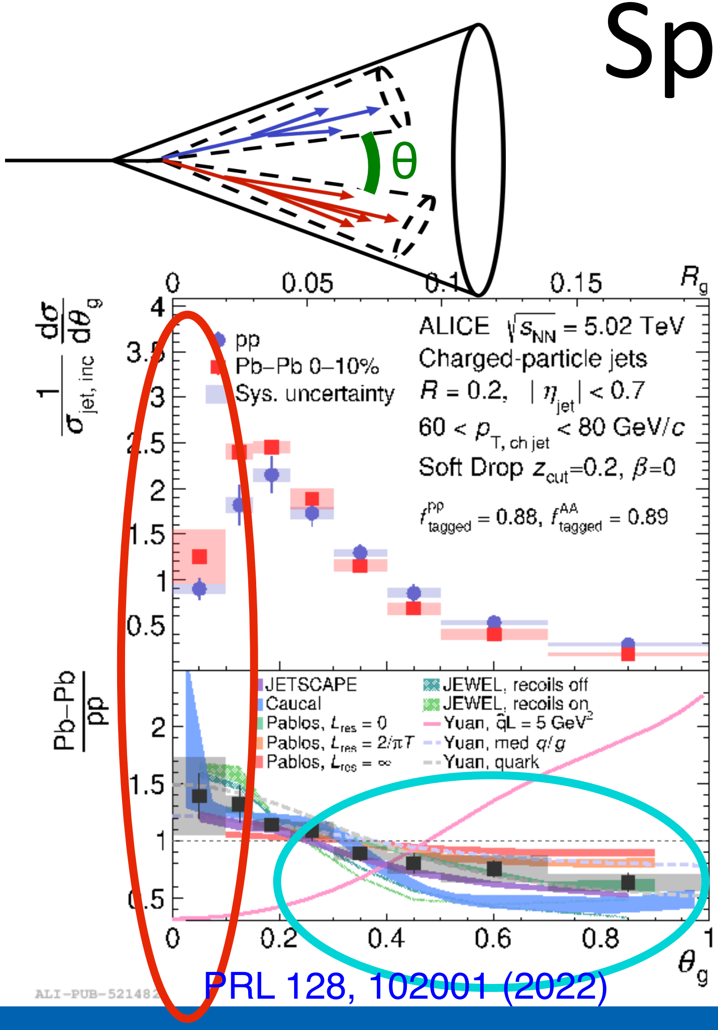
PRL 128, 102001 (2022)

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

Large θ_g : more suppressed

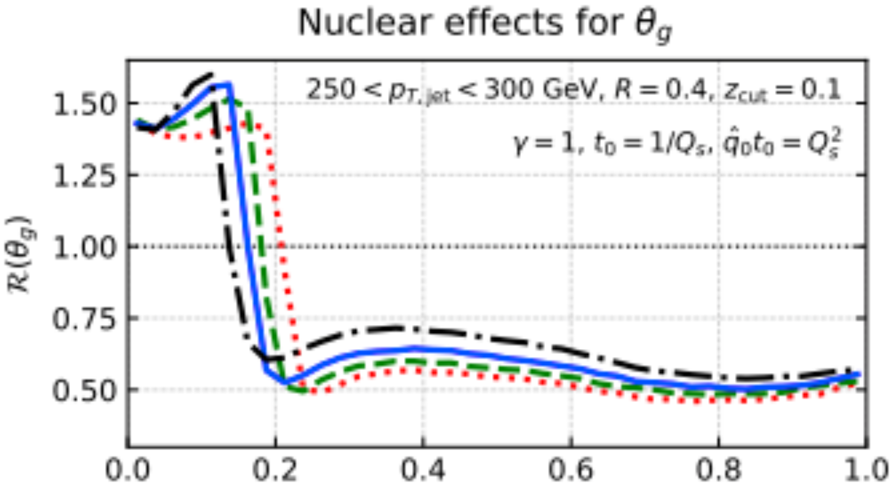


Splitting angle



PRL 128, 102001 (2022)

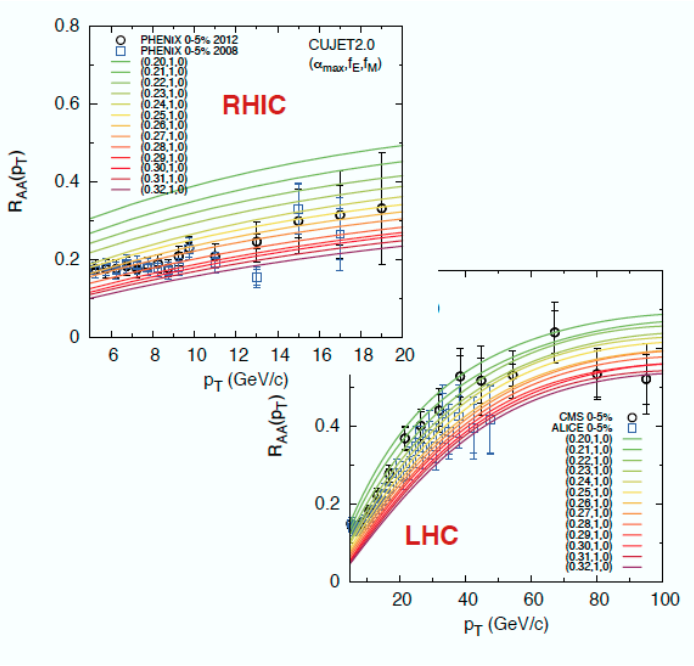
Caucal, Iancu, Soyez, 1907.04866 & 2012.01457

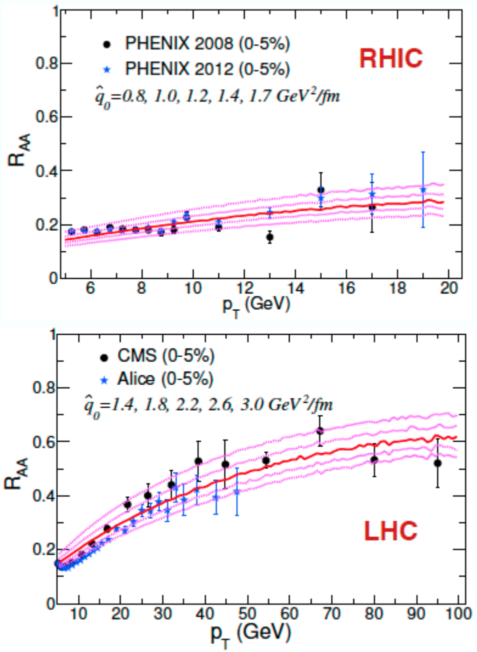


Jets with $\theta_g \geq \theta_c$ are suppressed while jets with $\theta_g \leq \theta_c$ are relatively enhanced.

Is ALICE seeing the critical angle?
Or is this due to the number of emitters?
Or a selection bias?

Extraction of transport coefficient





Burke et al, JET Collaboration, arXiv:1312.5003

Systematic comparison of energy loss models with selected set of data

Medium modelled by Hydrodynamics (2+1D, 3+1D)

p_T dependence matches reasonably well

Extraction of transport coefficient

RHIC: $\sqrt{s_{NN}} = 200$ GeV

$$\hat{q} = 1.2 \pm 0.3\ GeV^2/fm$$

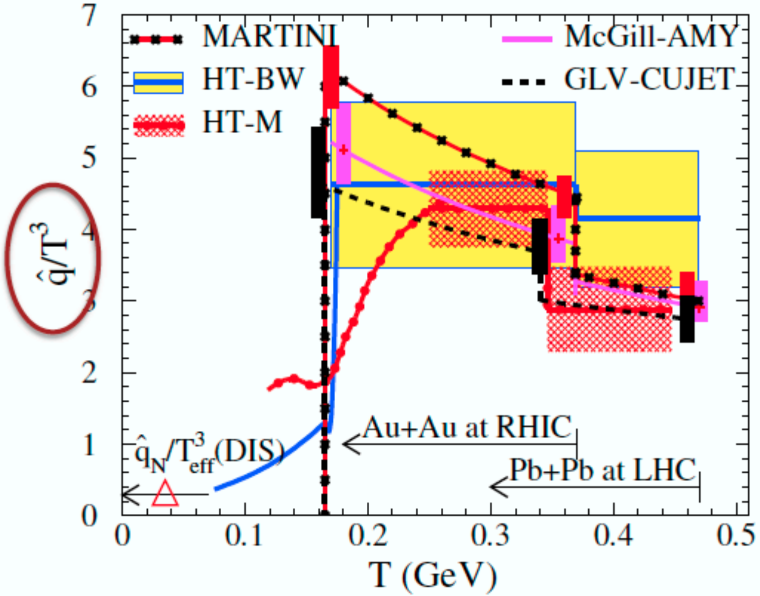
($T_i = 370$ MeV)

LHC: $\sqrt{s_{NN}} = 2760$ GeV

$$\hat{q} = 1.9 \pm 0.7\ GeV^2/fm$$

($T_i = 470$ MeV)

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$



Burke et al, JET Collaboration, arXiv:1312.5003

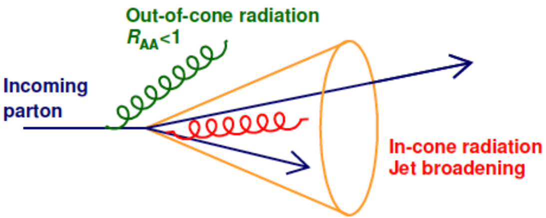
$\hat{q}$ values from different models consistent

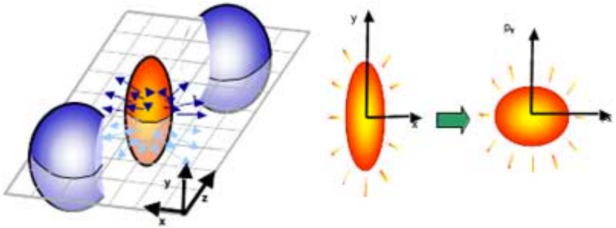
Summary

Heavy ion collisions are used to study hot nuclear matter

Self-generated probes
(this talk)

Soft QGP fragments
(low p_T hadrons)





Jet quenching

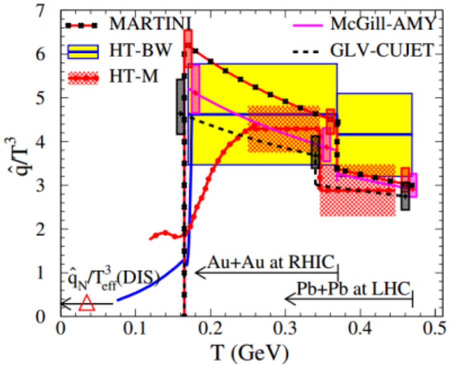
Elliptic flow: collective behaviour

Both type of measurement in agreement with very dense system + small mean free path

Summary

Heavy ion collisions are used to study hot nuclear matter

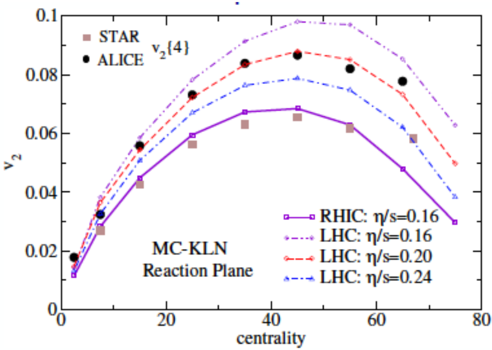
Self-generated probes (this talk)



JET Collaboration, PRC 90, 014909 (2014)

Jet quenching

Soft QGP fragments (low p_T hadrons)

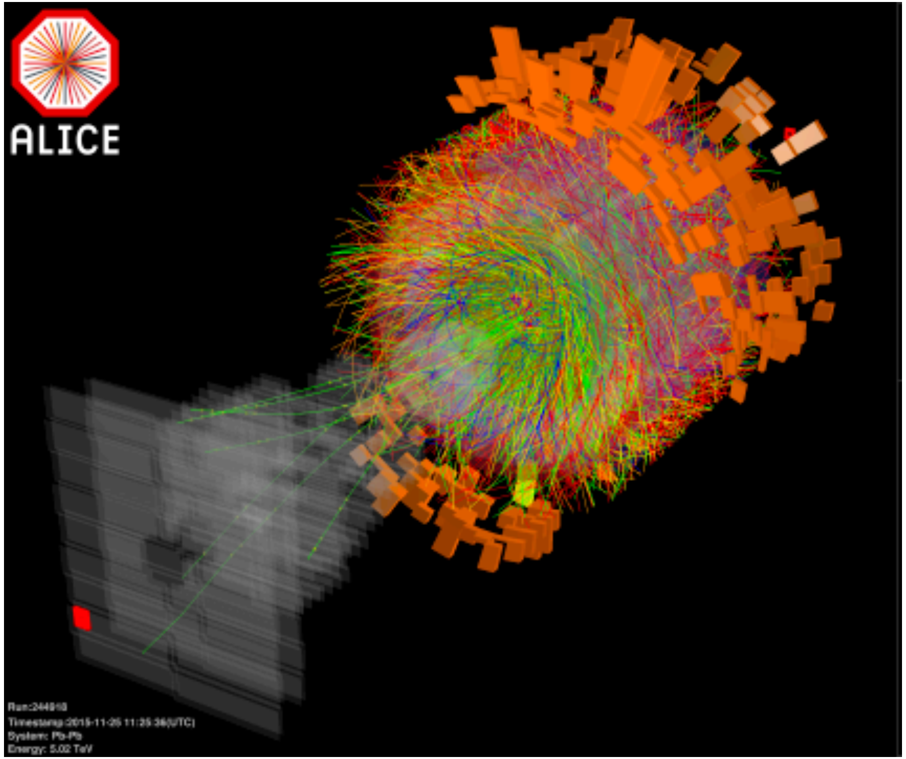


H. Song et al, PRC83, 054912

Elliptic flow: collective behaviour

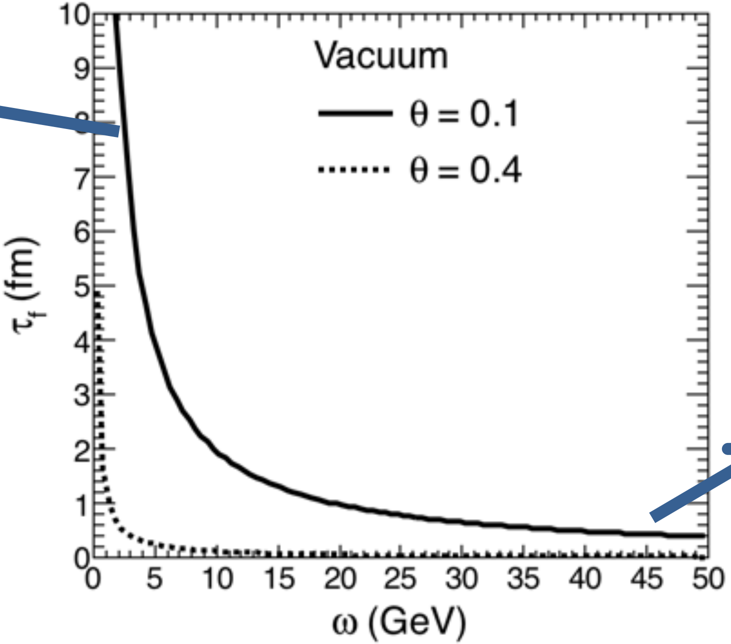
Both type of measurement in agreement with very dense system + small mean free path

Thank you


ALICE
Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

z_g – formation times

Vacuum formation time of gluons with certain energy



Low energy gluons are emitted late

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

High energy gluons are emitted early

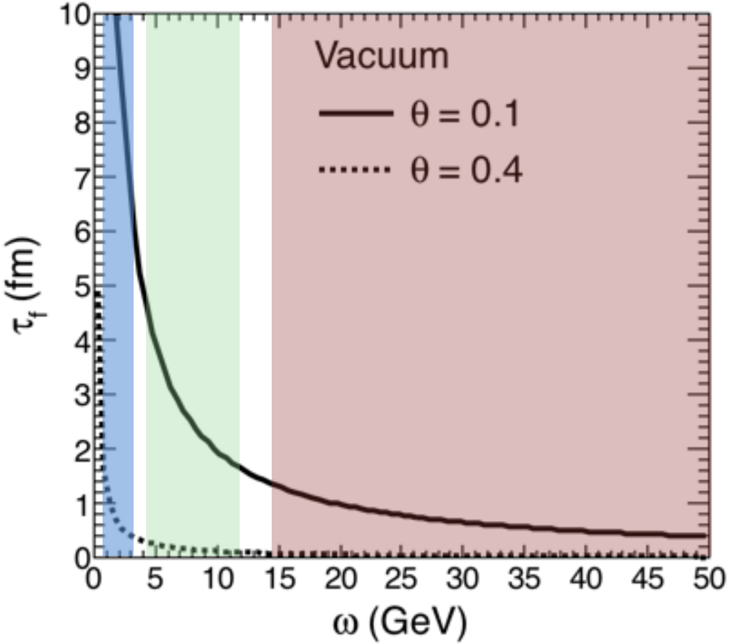
Large angle radiation first, small angle later

→ A lot of the vacuum radiation is created too late to see the medium

z_g – RHIC vs LHC

Vacuum formation time of gluons with certain energy

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$



Phase space covered for z_g=0.1

🟦 STAR

🟩 ALICE

🟥 CMS

Different experiments probing very different formation times. No overlap

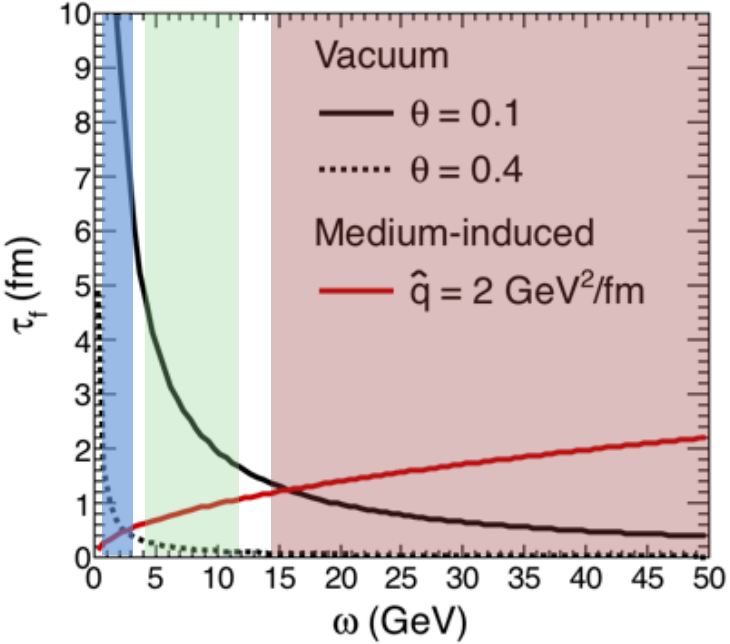
z_g – RHIC vs LHC

Vacuum and medium formation times

Hard medium-induced radiation happens late in the shower

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$



Phase space covered for z_g=0.1

STAR

ALICE

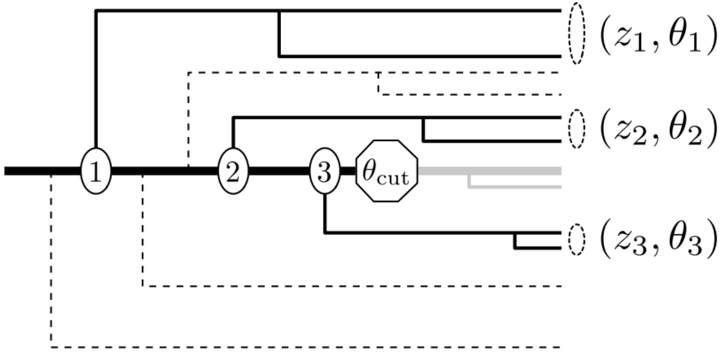
CMS

Lund plane in collision events

Measure Lund diagram in data or Monte Carlo event generator:
Use **iterative declustering technique** to unwind the angular ordered tree retrieving information about all parton splittings
→ probe of QCD branching history

Iterative SoftDrop:

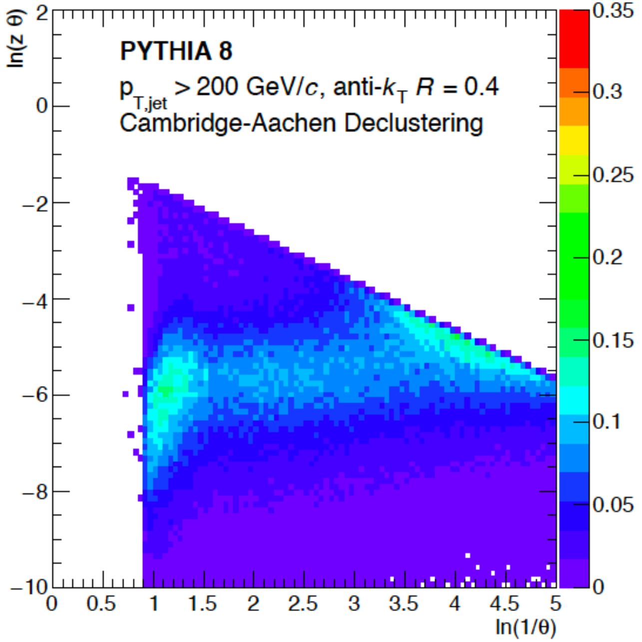
- Look at multiple branches satisfying grooming criterium
- Follow the leading subjet
- Branches you will find will automatically have smaller angle and p_T



arXiv:1704.06266

Lund plane in MC

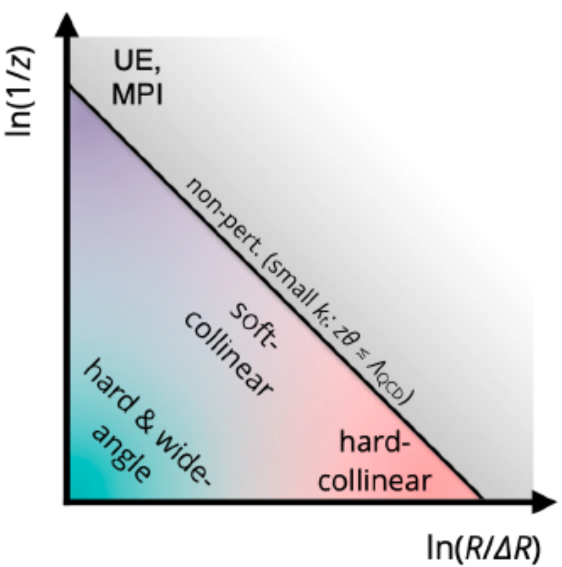
Measure Lund diagram in data or Monte Carlo event generator:
Use **iterative declustering technique** to unwind the angular ordered tree retrieving information about all parton splittings
→ probe of QCD branching history



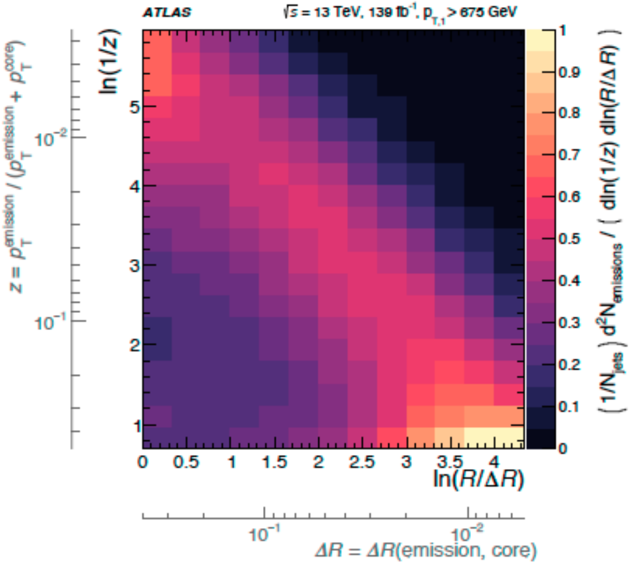
More radiation for larger k_T due to running coupling

+ some distortion from underlying event uncorrelated to jet

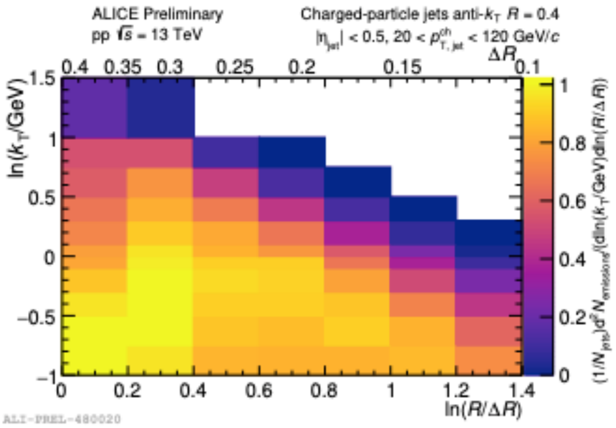
Vacuum Lund Plane



ATLAS, PRL 124 (2020) 22, 222002



ALICE-PUBLIC-2021-002



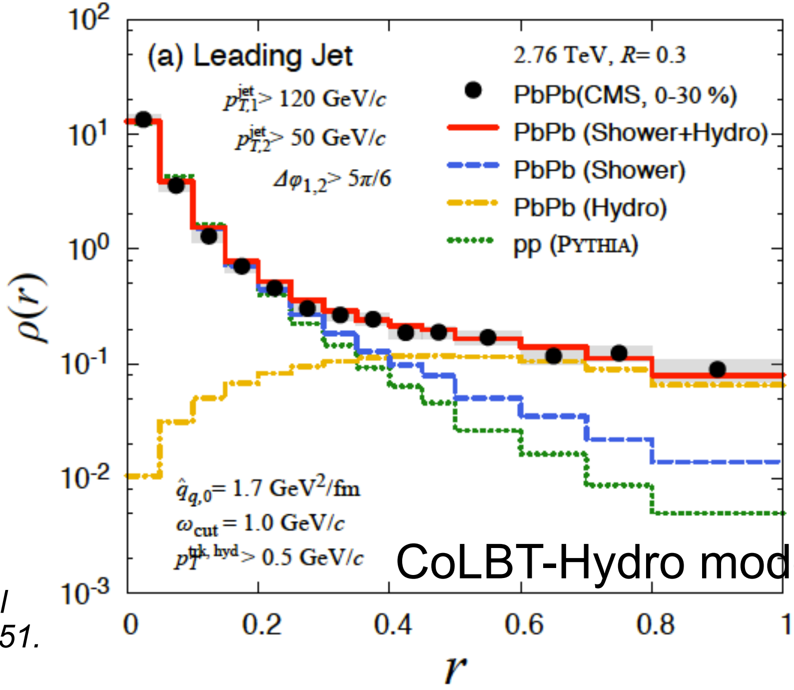
Running of α_s sculpts the plane

Medium response

Medium excitation | wake | jet-correlated medium

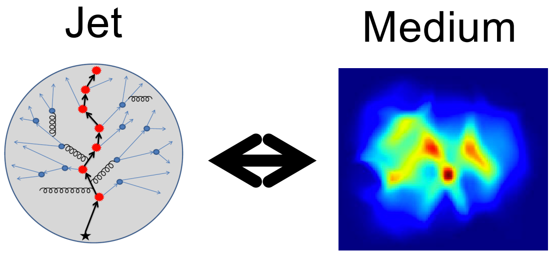
== a bit of the medium becomes part of the jet

→ Causing excess of soft particles at large angle



CoLBT-Hydro model

Tachibana et. al arXiv:1701.07951.



Quenched parton shower + medium excitation

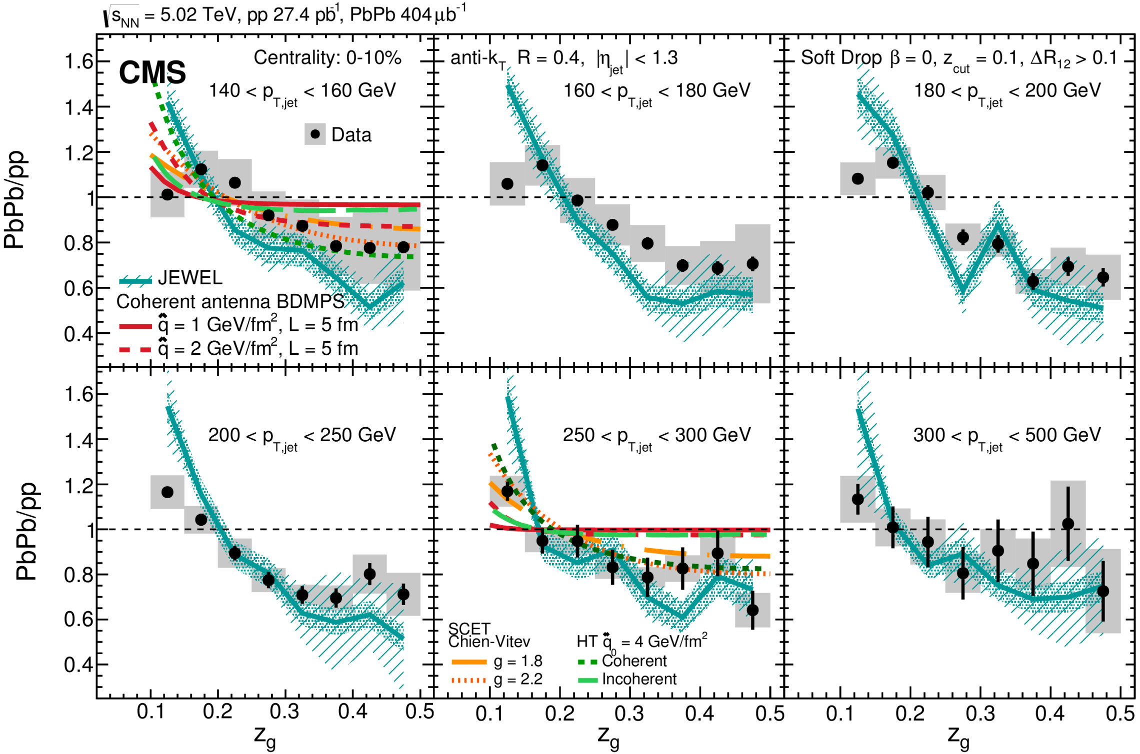
Quenched parton shower

Vacuum parton shower

Medium response needed to explain large angle measurements

Jet p_T dependence

Modification gets slightly weaker when increasing jet p_T



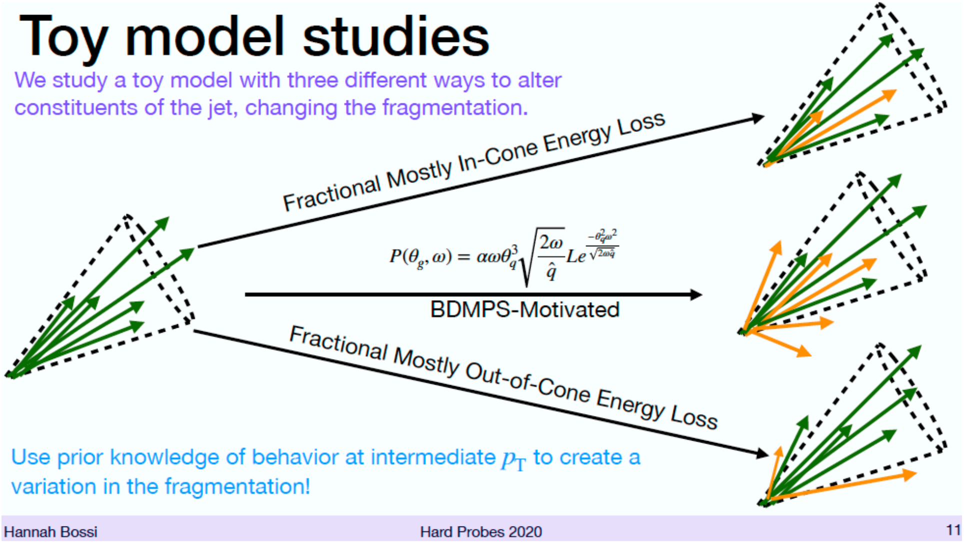
PRL 120 (2018) 142302

Due to normalization, cannot distinguish between increase at low z_g or suppression at high z_g

Machine Learning Biases

Machine learning used to improve p_T resolution

But how sensitive is the training to the fragmentation model?



Toy model studies

We study a toy model with three different ways to alter constituents of the jet, changing the fragmentation.

Fractional Mostly In-Cone Energy Loss

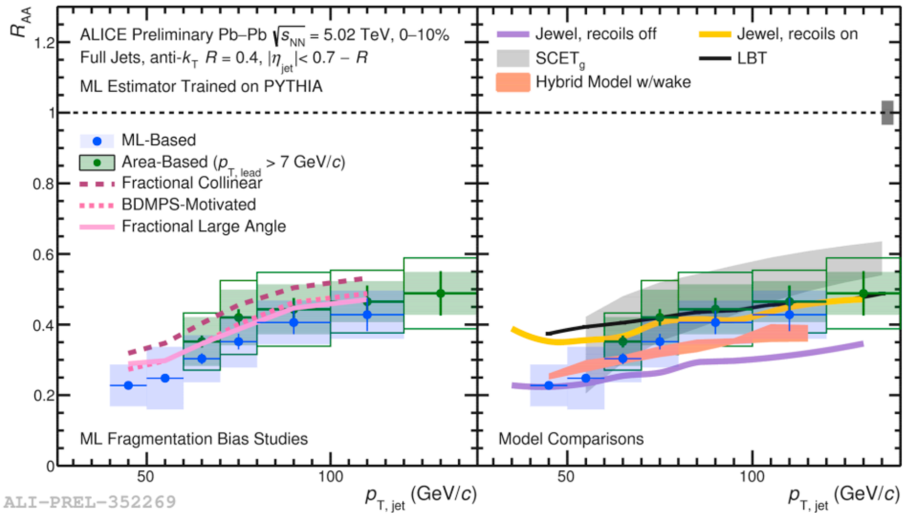
$$P(\theta_g, \omega) = \alpha\omega\theta_q^3\sqrt{\frac{2\omega}{\hat{q}}}Le^{\frac{-\theta_q^2\omega^2}{\sqrt{2\omega\hat{q}}}}$$

BDMPS-Motivated

Fractional Mostly Out-of-Cone Energy Loss

Use prior knowledge of behavior at intermediate p_T to create a variation in the fragmentation!

Hannah Bossi Hard Probes 2020 11



Effects of up to 40% are observed

Future: need method less dependent on model and/or constrain FF