Heavy-ion collision experiment
（Lecture 2）

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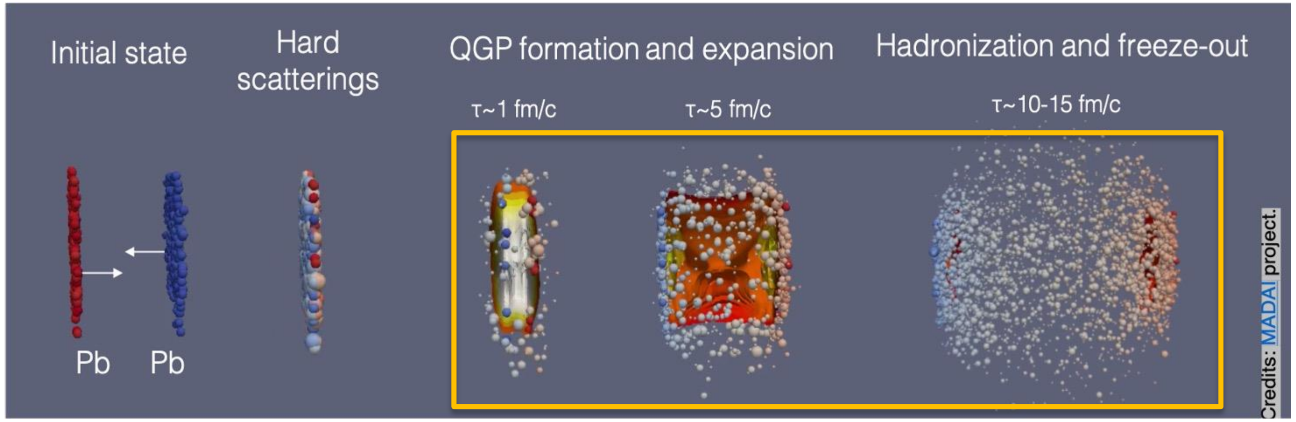
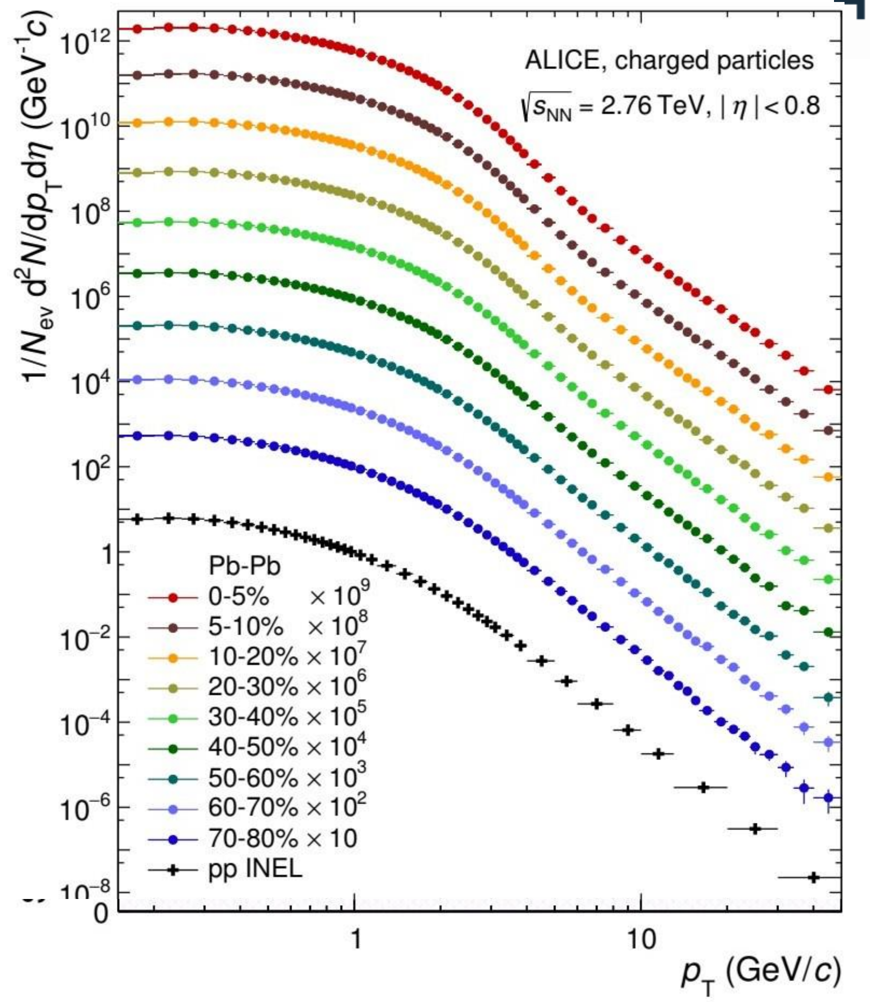
1. Introduction to relativistic heavy-ion collisions
2. Particle yields and statistical model
3. Hard probes of QGP: jets
4. Hard probes of QGP: heavy-flavors
5. Quarkonia
6. Highlights from small systems
7. Summary and outlook

2. Particle yields and statistical model

Bulk particle production





The bulk of particles is **soft** and composed by **light flavour** hadrons that are produced when the QGP hadronises.

The p_T and azimuthal distributions of hadrons carry information about the **collective evolution** of the system and its thermodynamical properties.

Goal: determine the thermodynamical and transport properties of the QGP

Particle spectra

Low p_T (< 2 GeV/c)

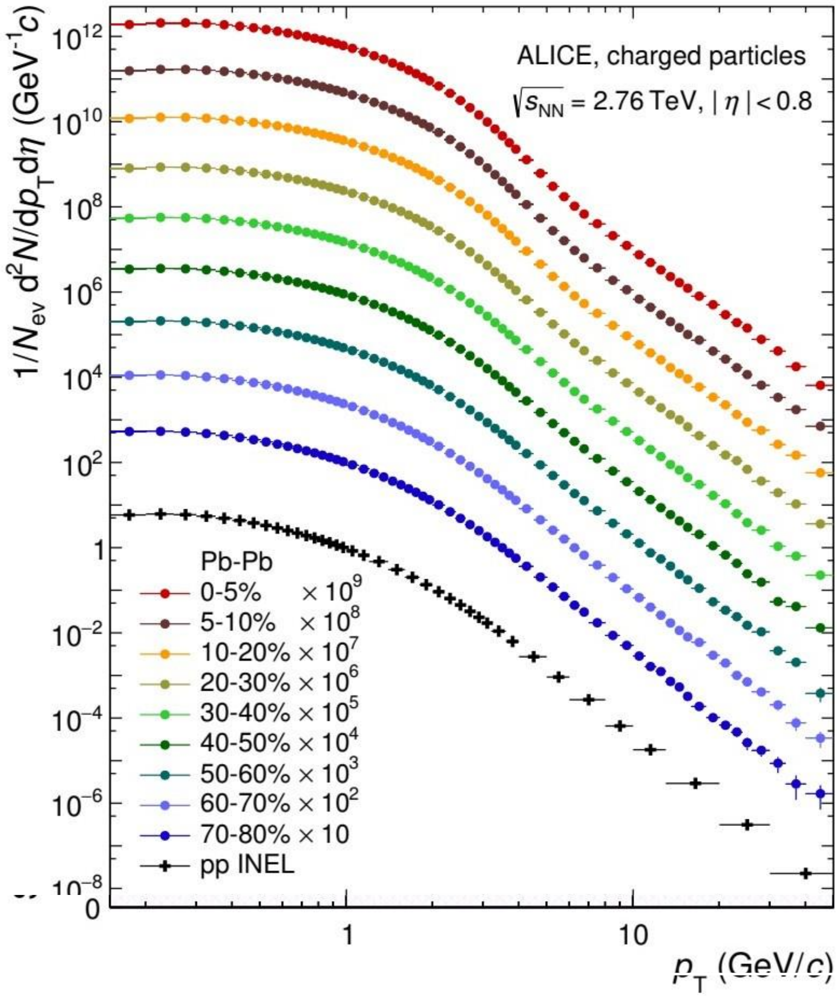
- Particle spectra are described by a Boltzmann distribution → "thermal", ~ exp(-1/k_BT)
- "Bulk" dominated by light flavor particles
- Non-perturbative QCD regime

High p_T (> 8-10 GeV/c)

- Particle spectra described by a power law
- Dominated by parton fragmentation (jets)
- Perturbative QCD regime

Mid p_T (2 to 8 GeV/c)

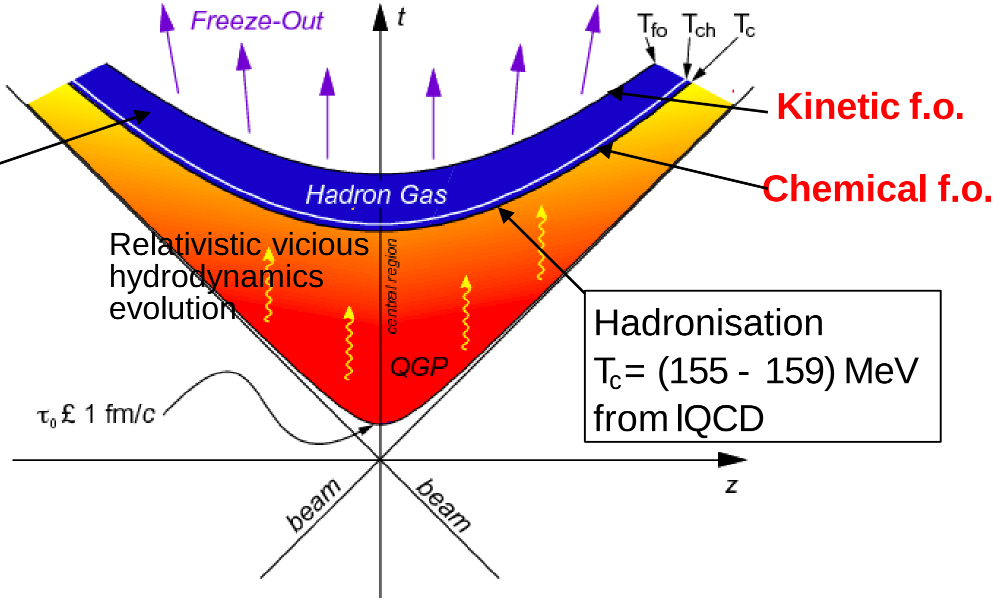
- Interplay of parton fragmentation and recombination of partons from QGP



越是中心碰撞，粒子产额越高，说明中心碰撞存积能量越多

Chemical freez-out and Hadron-gas phase

After hadronisation, the system is a hot (T< 155 MeV) and dense gas of hadrons and resonances.



Chemical freeze-out

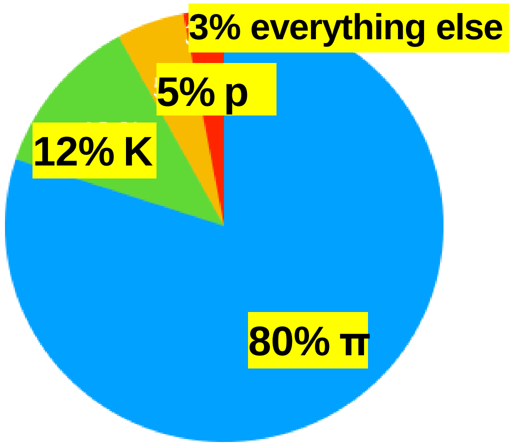
- Inelastic collisions stop
- Relative particle abundances are fixed

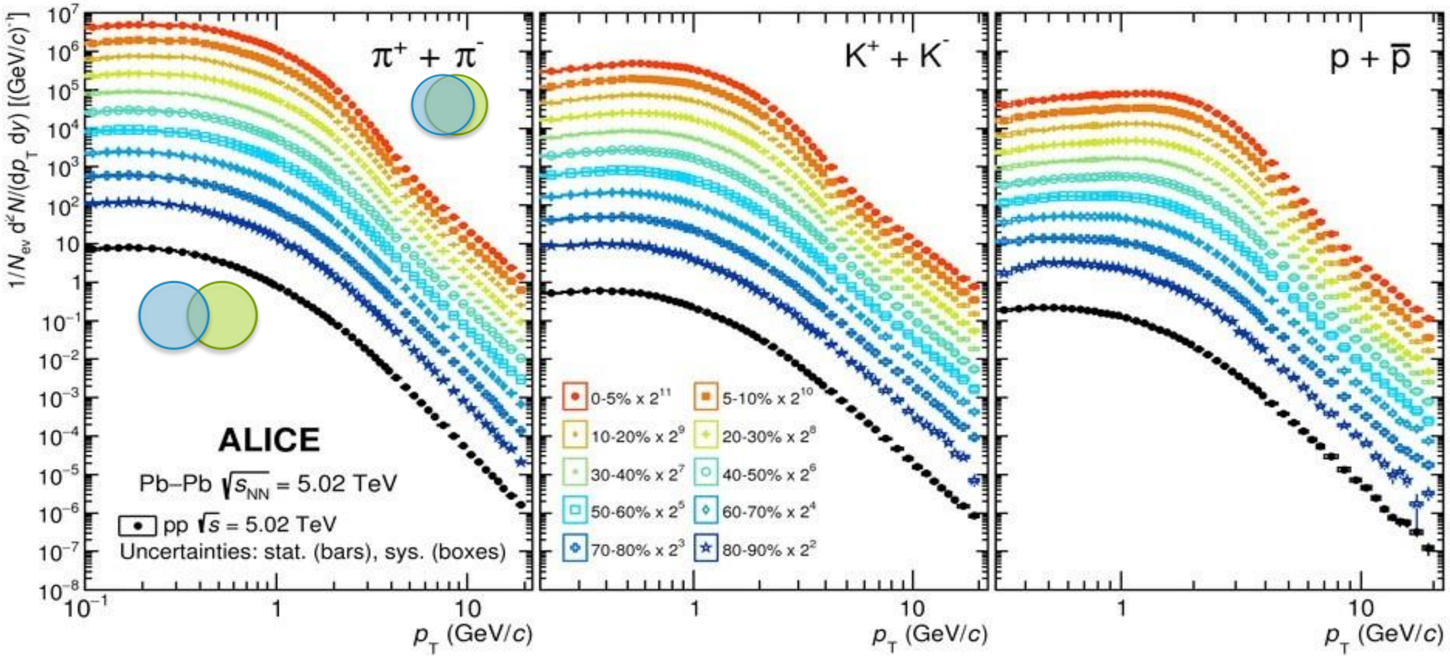
Kinetic freeze-out

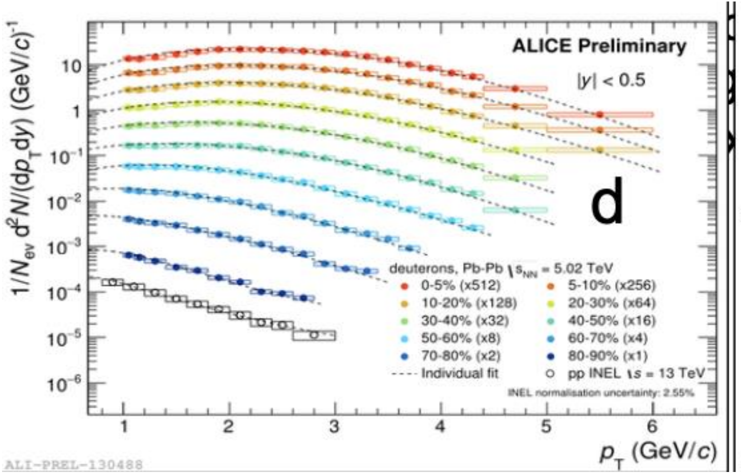
- (pseudo)elastic collisions stop
- Momentum distributions are fixed

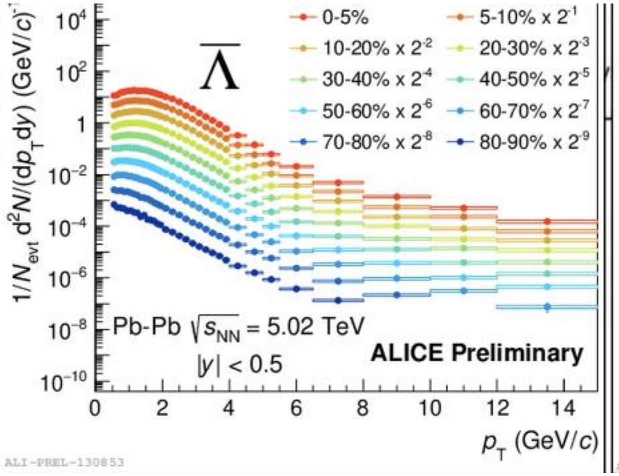
→ Fit abundance of identified hadrons: probe chemical equilibrium at **chemical freeze-out**
→ Fit shape of p_T spectra: probe final hadron kinematics at **kinetic freeze-out**

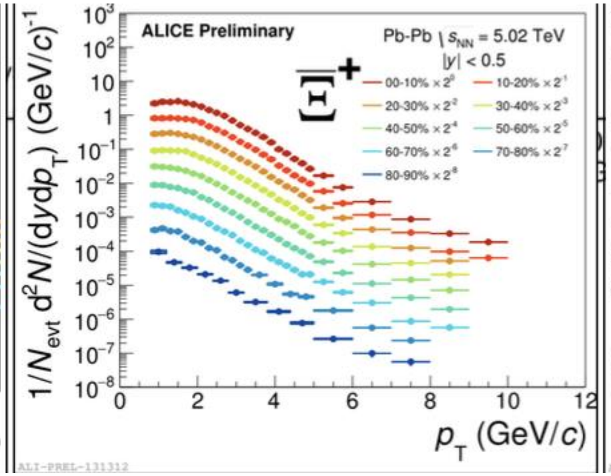
Identified particle production

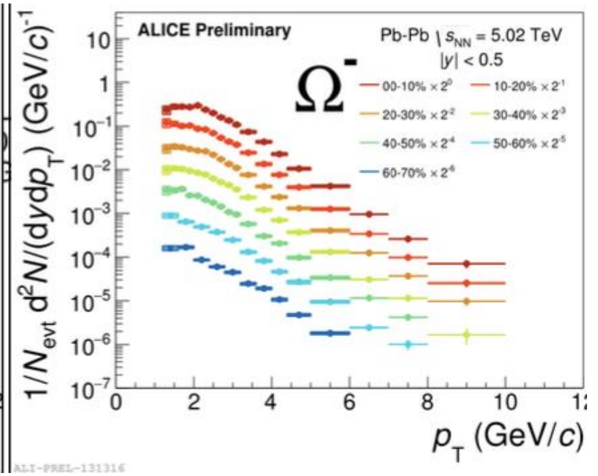












Statistical hadronisation model

It models an ideal relativistic gas of hadrons and resonances in **chemical equilibrium** (as the result of the hadronization of a QGP in thermodynamical equilibrium)

Particle abundances are obtained from the partition function of a Grand Canonical (GC) ensemble

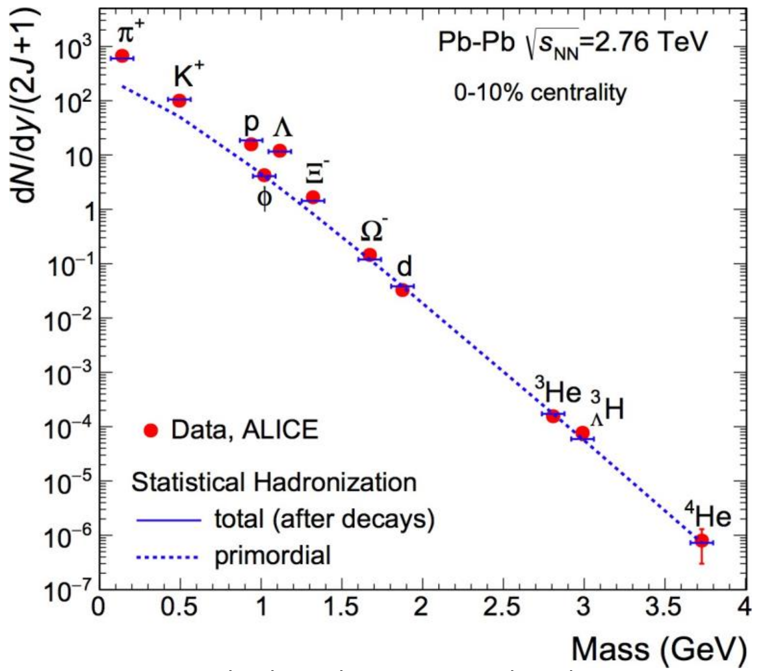
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i-\mu_i)/T] \pm 1}$$

where chemical potential for quantum numbers are constrained with conservation laws.

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i$$

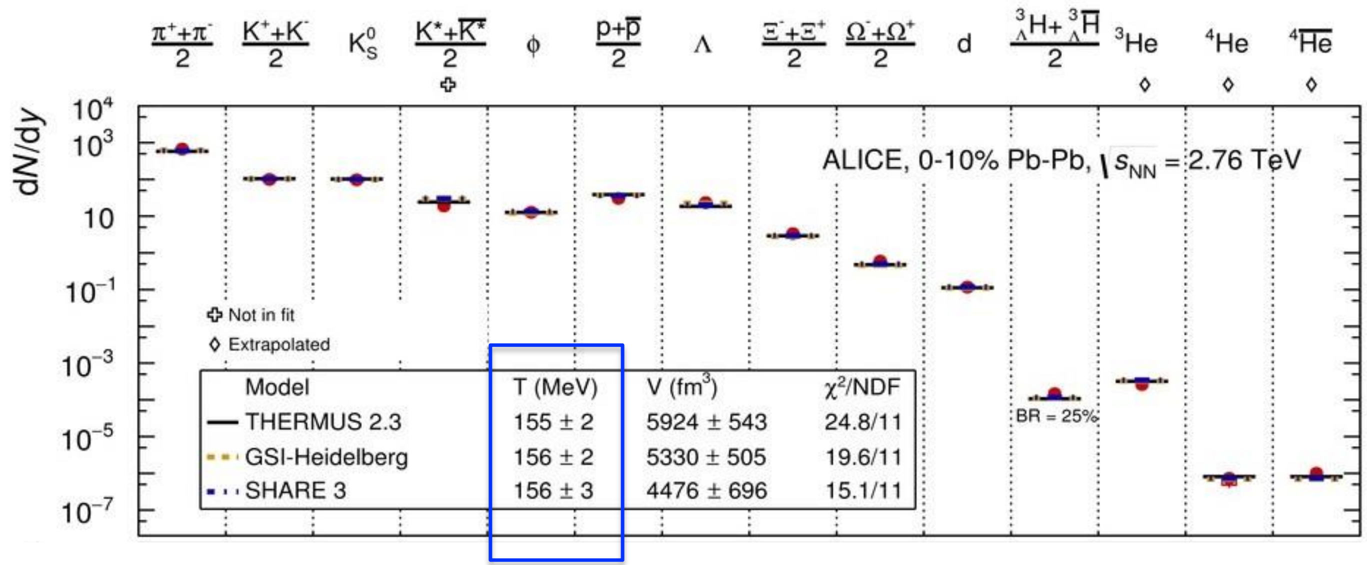
- ❑ Predict yields (see right figure) at a given temperature
- ❑ Fit measured particle yields (or ratios) to extract μ_B, T_{ch}, V.

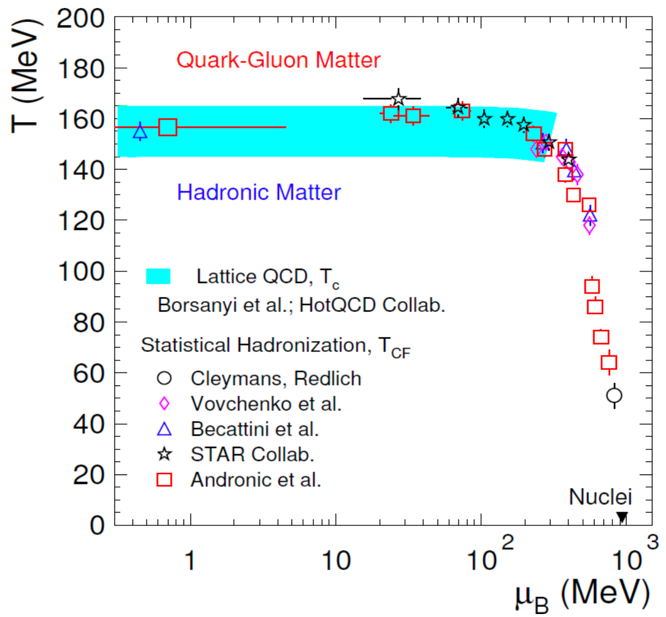
(2J+1)-spin degeneracy factor



A. Andronic et al., Nature 561, (2018)321-330

Chemical freeze-out temperature





Production of (most) light-flavour hadrons (and anti-nuclei) is described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out** temperature, ***T_{ch}* ≈ 156 MeV**

→ Approaches the critical temperature roof from lattice QCD: **limiting temperature** for hadrons!

→ the success of the model in fitting yields over 10 orders of magnitude supports the picture of a system in **local thermodynamical equilibrium**

Summary (Particle Yields & Statistical Model)

- After chemical freeze-out particle composition is fixed
- More than 16 species of hadrons measured at LHC
- Statistical model allows extraction of freeze-out temperature and baryochemical potential
- At high $\sqrt{s_{NN}}$ chemical freeze-out temperature close to phase transition temperature

Statistical models describe hadron production from $\sqrt{s_{NN}}$ = 2 to 5040 GeV

→

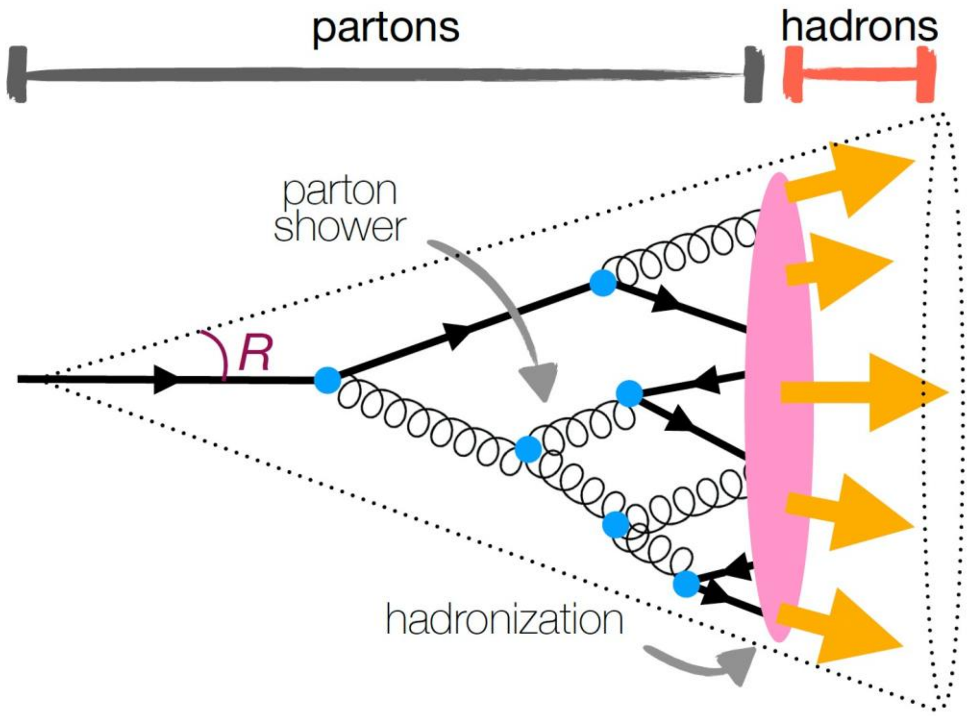
Matter created in HI collisions is in local thermal equilibrium

3. Hard probes of QGP: jets

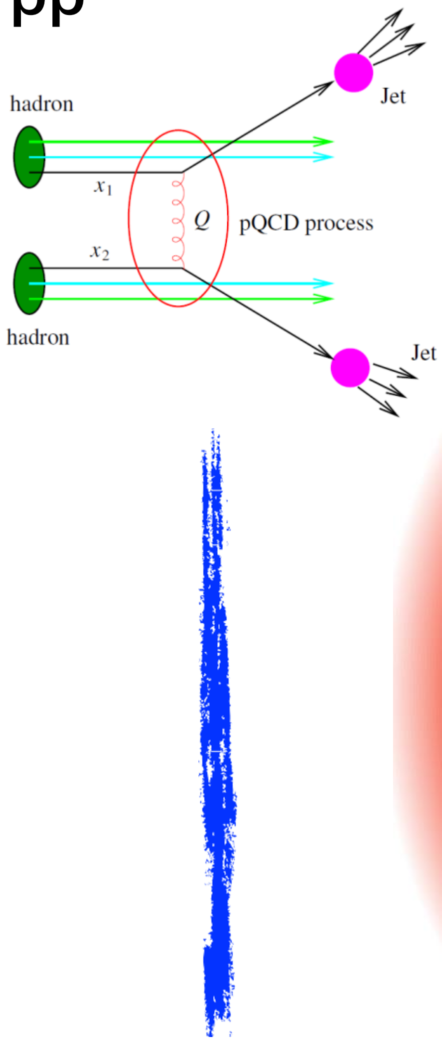
Probing QGP with jets

Vacuum fragmentation (pp collisions)

Collimated sprays of hadrons resulting from fragmentation and subsequent hadronization of "high-energy" partons (quarks&gluons)

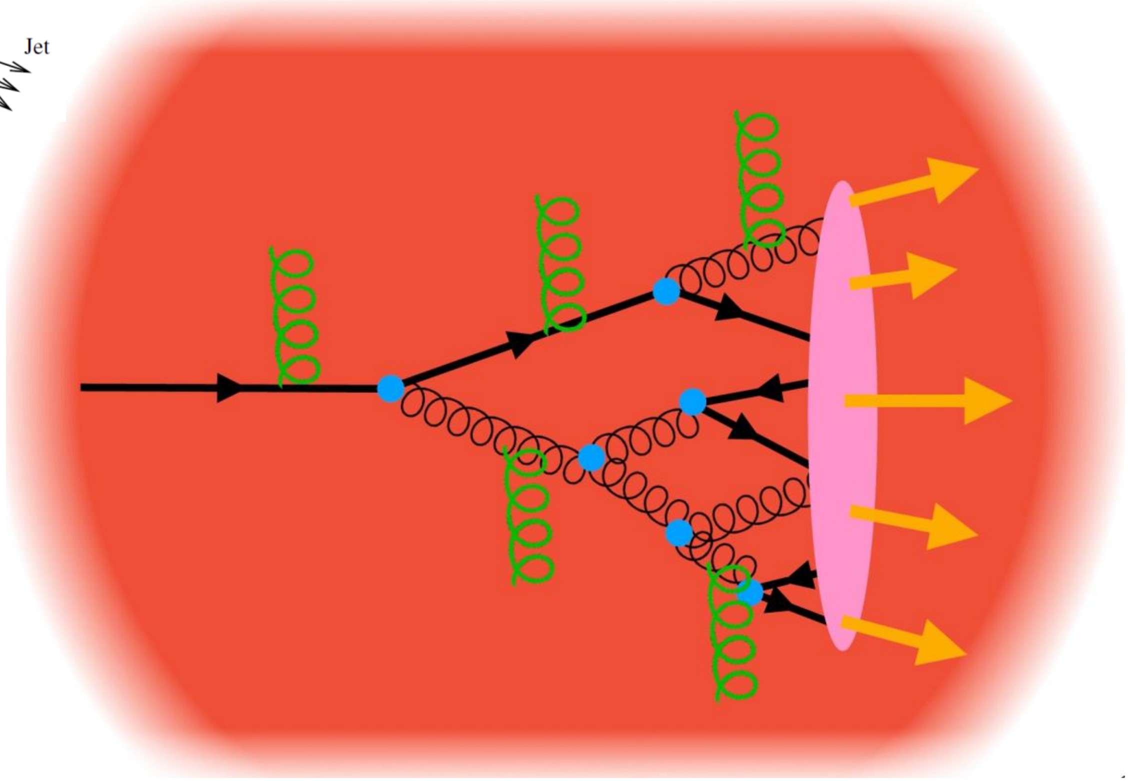


pp



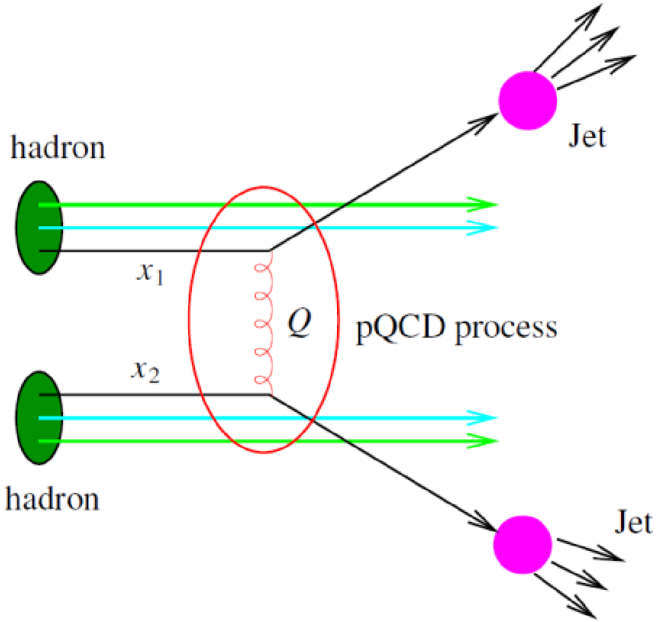
In-medium fragmentation (Pb-Pb collisions)

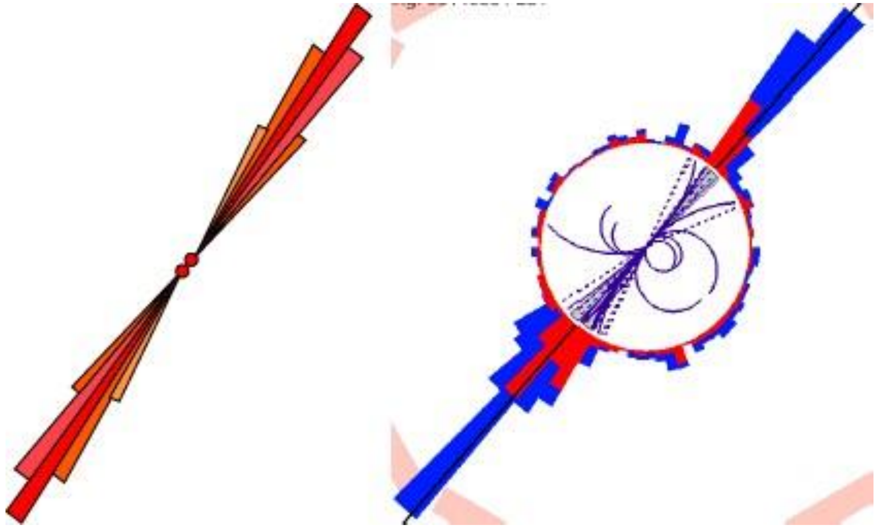
Quenching→parton lose energy through medium-induced gluon radiations and collisions with medium constituents

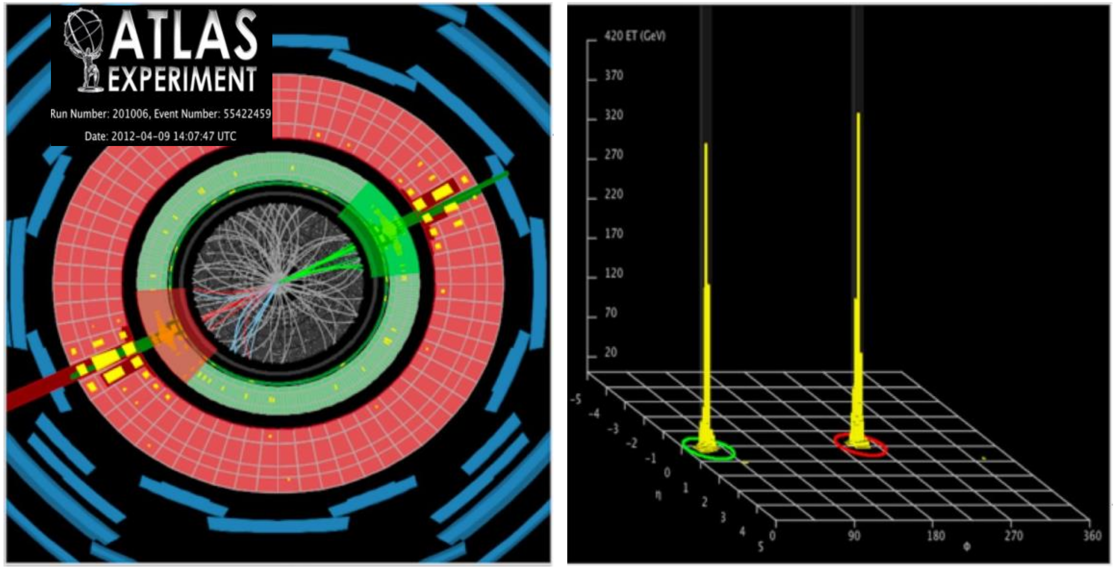


Jets in pp collisions

pp

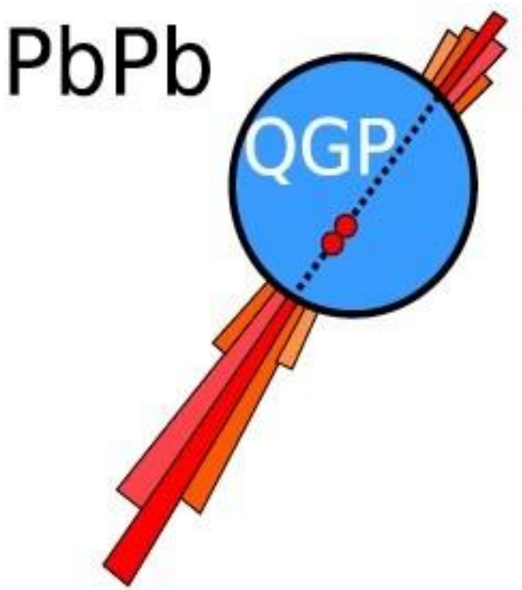


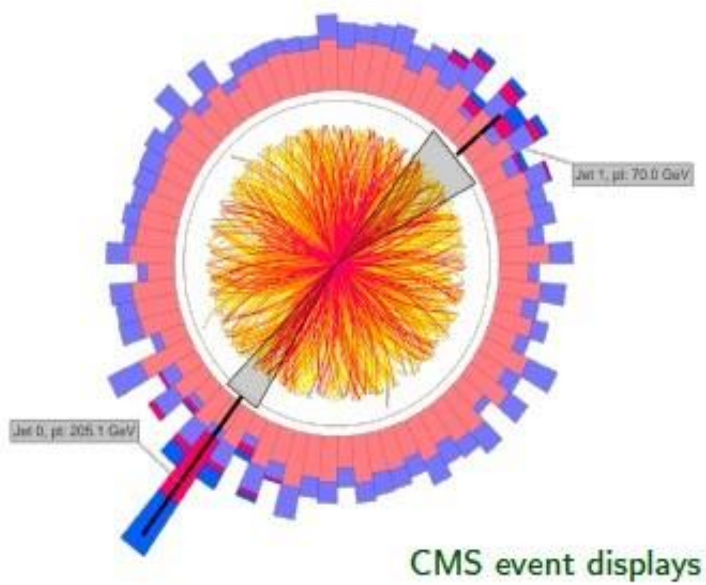


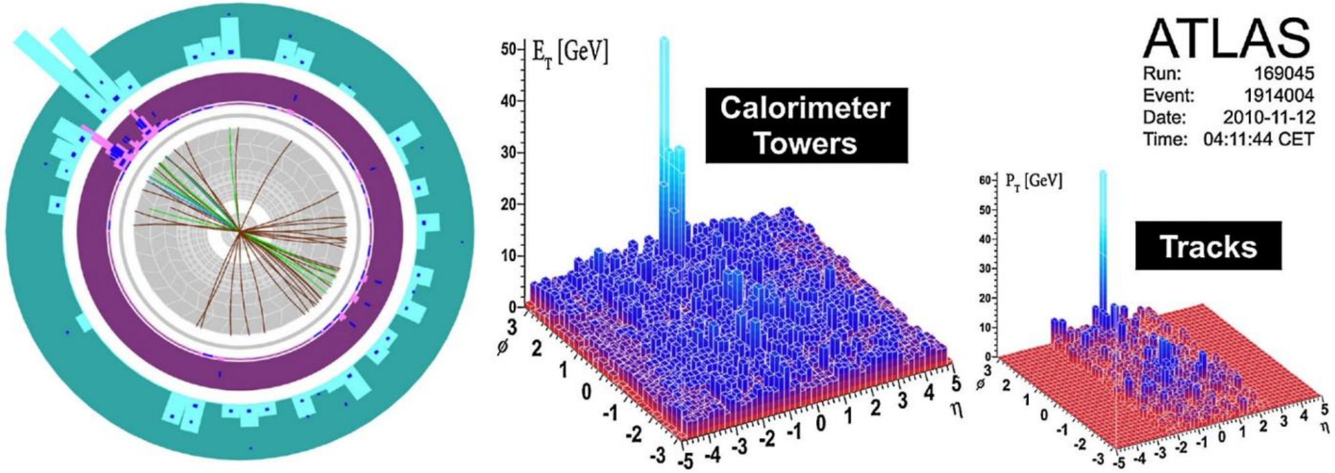


ATLAS, pp collision event display

Jets in Pb-Pb collisions

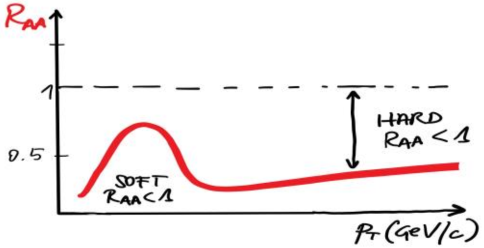






Nuclear modification factor: R_{AA}

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

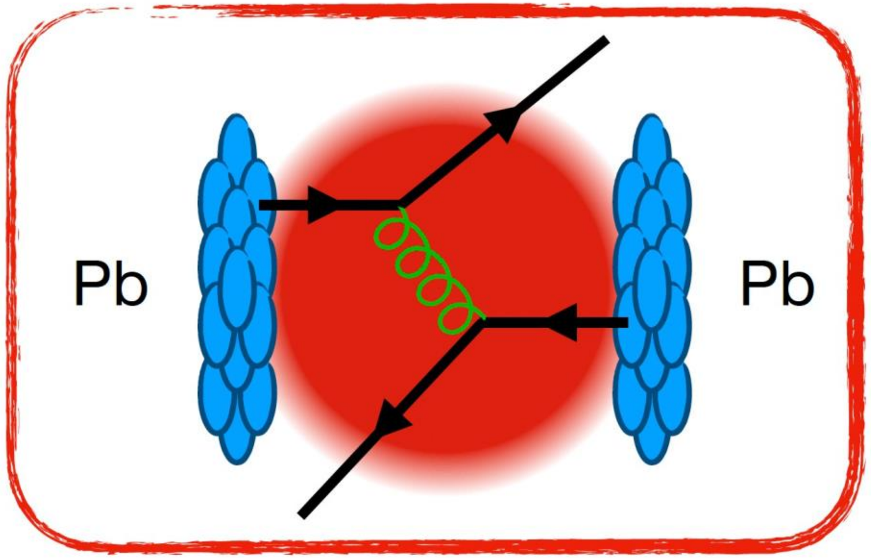


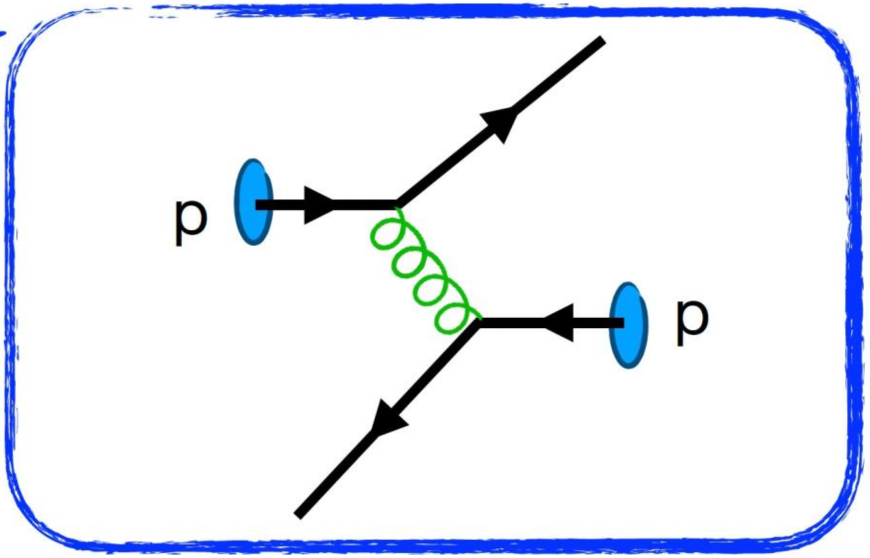
Parton energy loss in QGP

$R_{AA} > 1 \rightarrow$ enhancement

$R_{AA} = 1 \rightarrow$ no medium modification

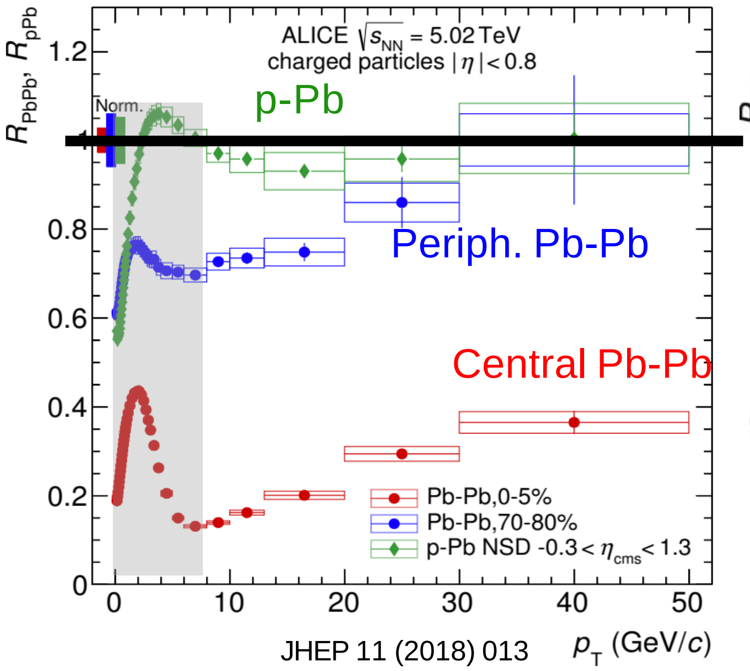
$R_{AA} < 1 \rightarrow$ supression





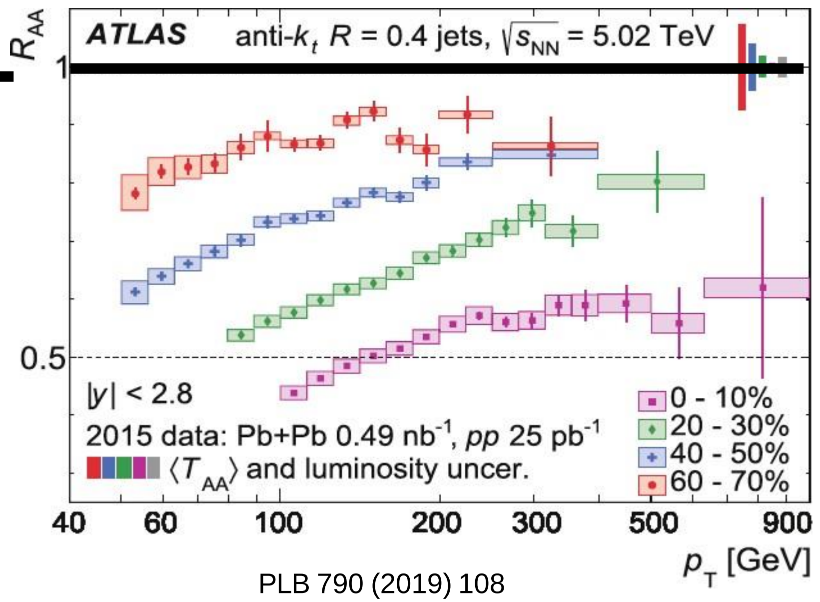
Evidence of parton energy loss in QGP

Charged particles



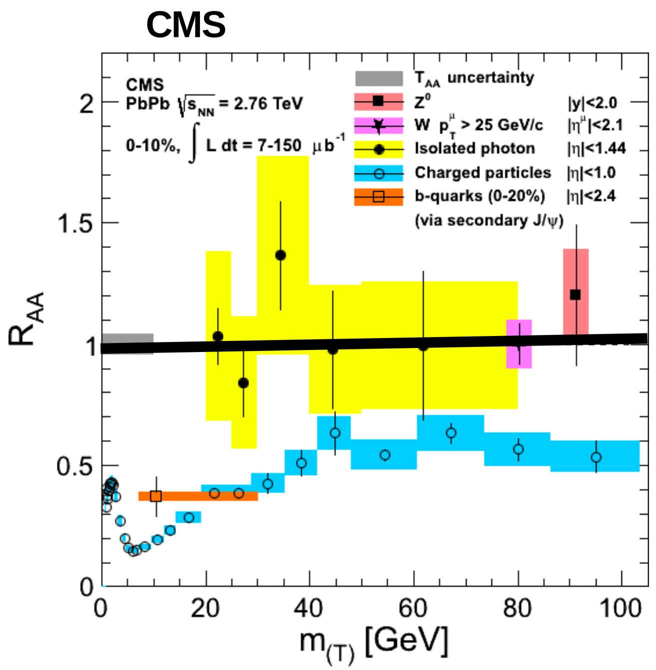
JHEP 11 (2018) 013

Inclusive jets



PLB 790 (2019) 108

EW bosons



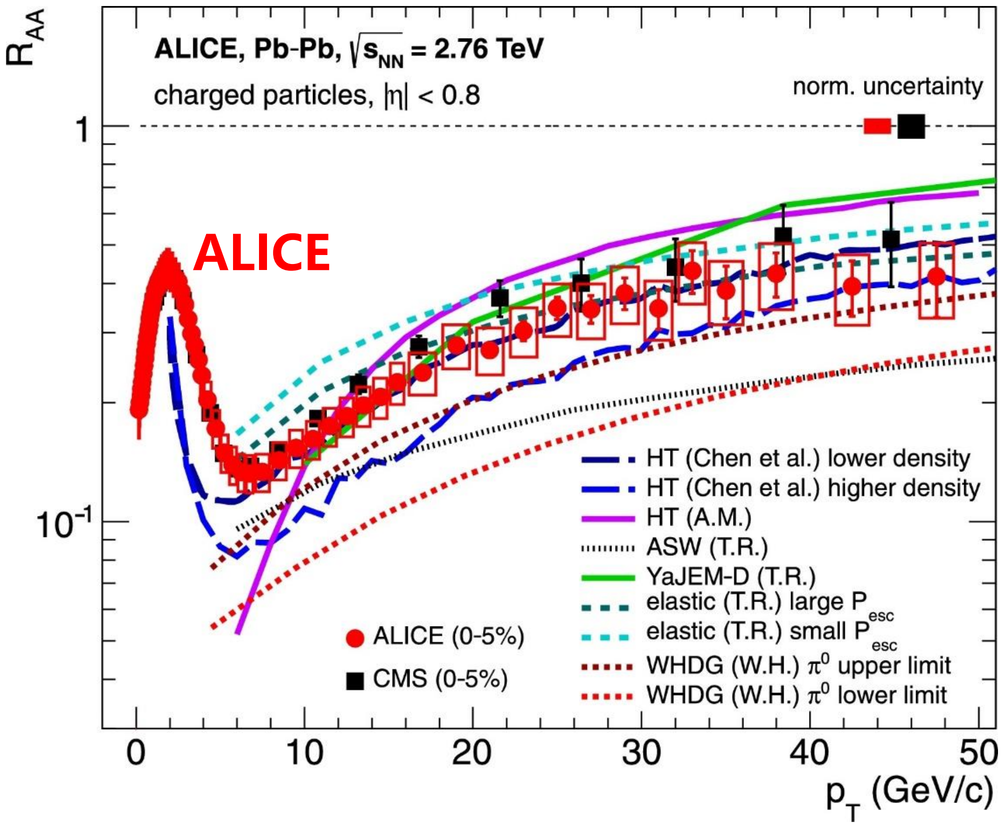
- A strong suppression of high-p_T hadrons and jets is observed in central Pb-Pb collisions.
- No suppression observed in p-Pb collisions, nor for the color-less Z bosons and photons.

→ Jet quenching is explained as **parton energy loss in a strongly interacting plasma**

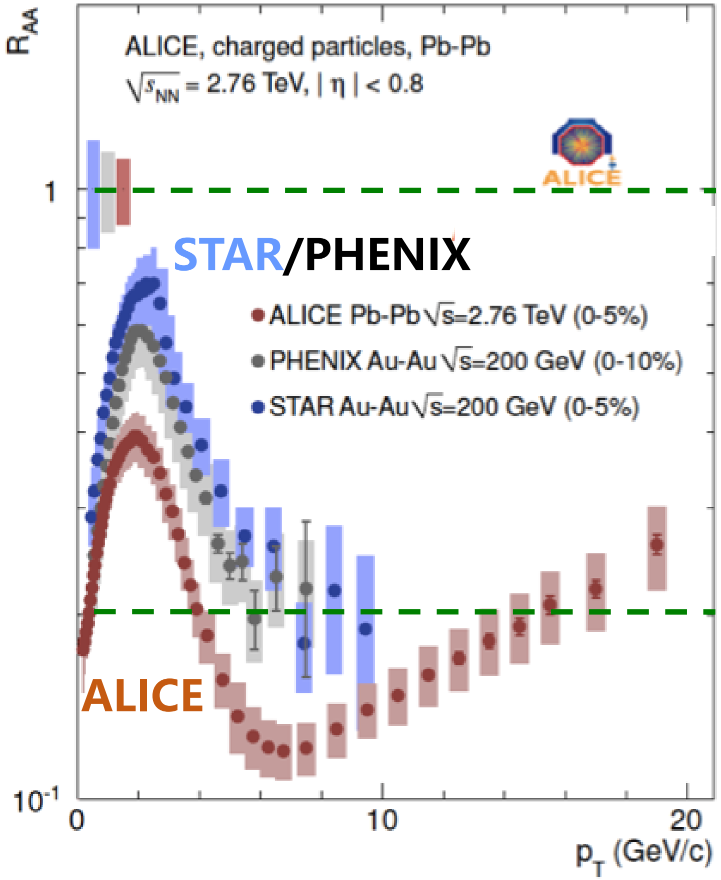
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

核修正因子R_{AA}压低的能区比较

ALICE, PLB 720 (2013) 52



PHENIX: PRC69, 034910(04) STAR: PRL91, 172302(03)

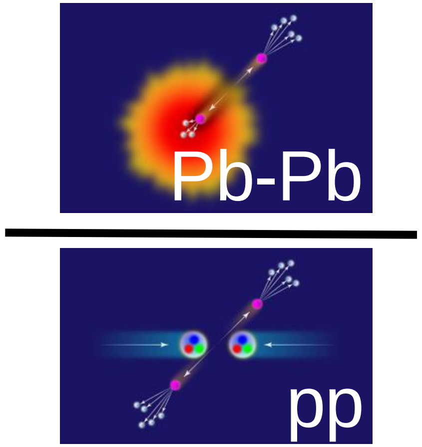


- 在RHIC和LHC两种能区，R_AA 均遭受强烈压低：QGP物质形成，给出诱导部分子辐射能量损失的证据
- 碰撞能量越高，压低越强

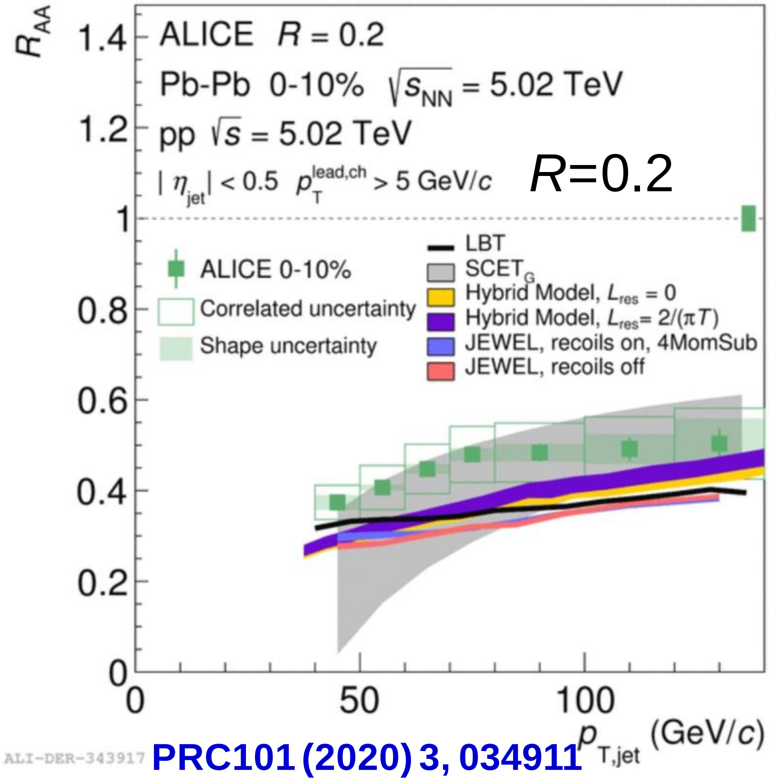
➢ 在更高碰撞能量下，生成的QGP物质温度更高，系统更热，能量密度更高，物质更稠密

Jet quenching masurements

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$

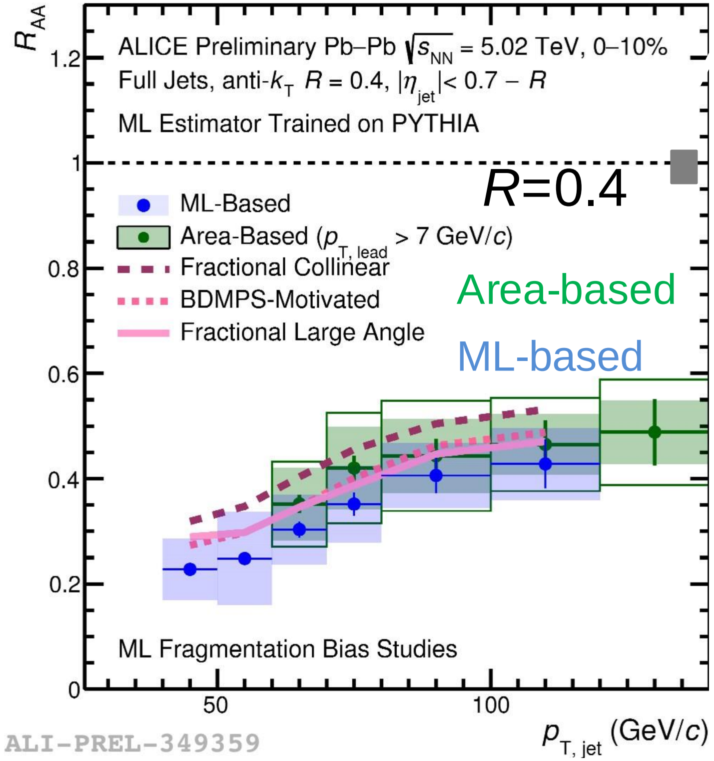


with area-based background subtraction

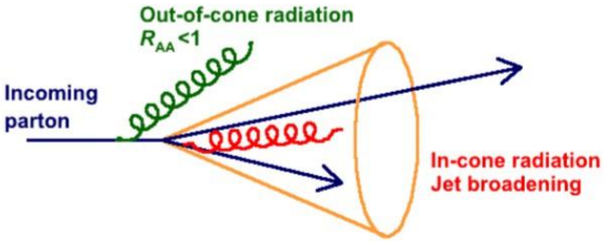


PRC101 (2020) 3, 034911

Exploring ML background subtraction



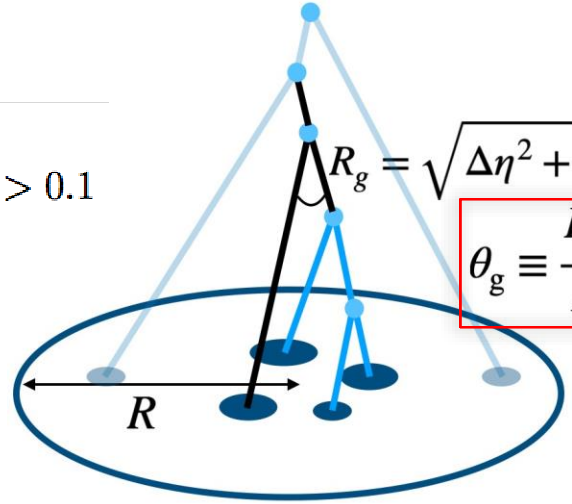
- Large reduction (factor 3-4) of jet yields, down to 40 GeV/*c*
- Lost energy is not recovered within the jet "cone" up to R= 0.4→ large angle QGP-induced gluon emission



Jet substructure in Pb-Pb collisions

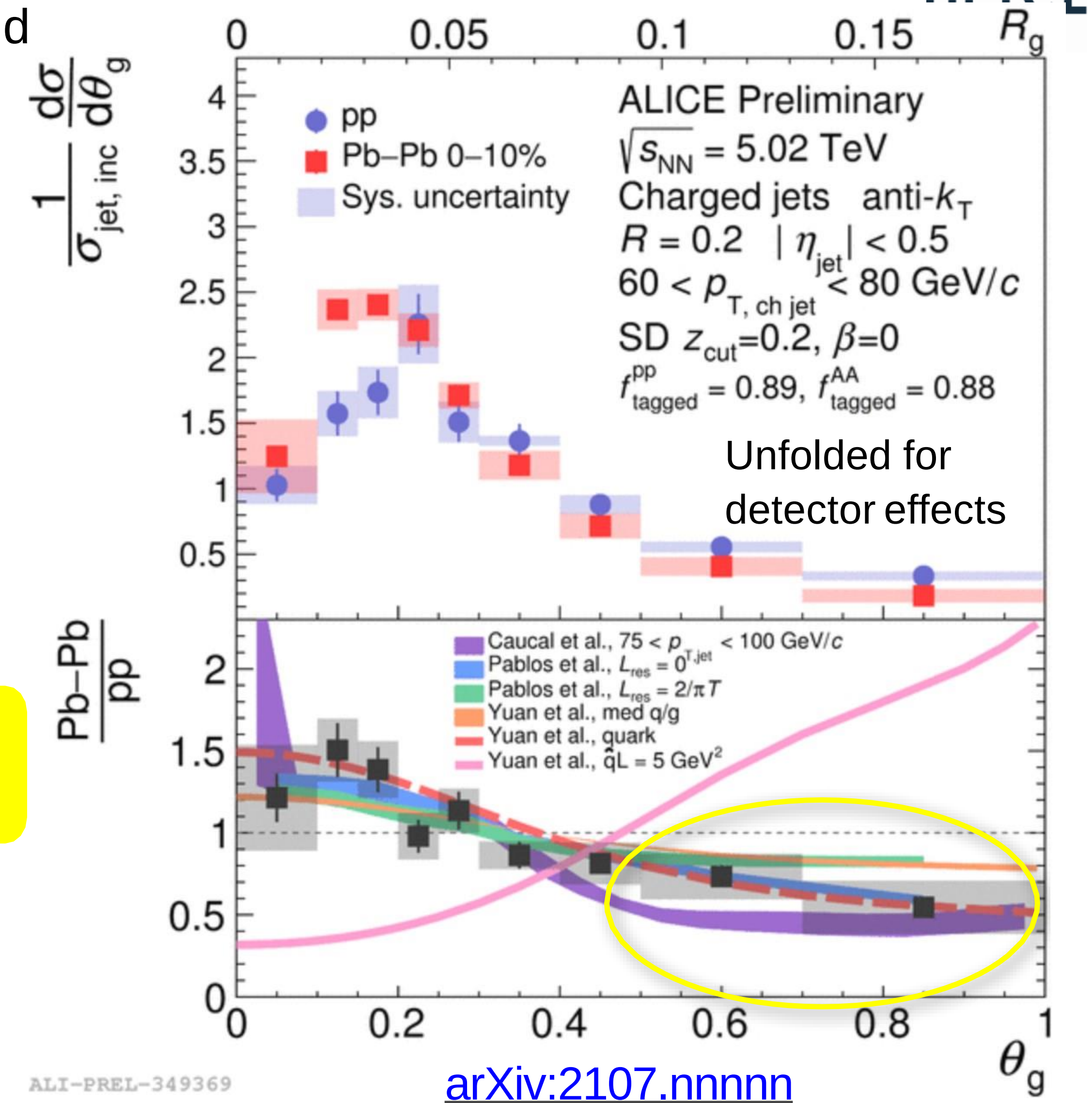
- Understand evolution of parton-medium interactions and energy redistribution by exploring substructure of jet
  - —By soft drop (SD) grooming to find first hard splitting

$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \qquad z_g > 0.1$$



$$R_g = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

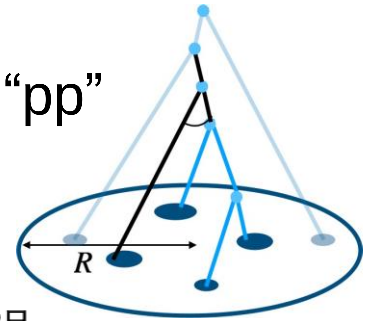
$$\theta_g \equiv \frac{R_g}{R}$$



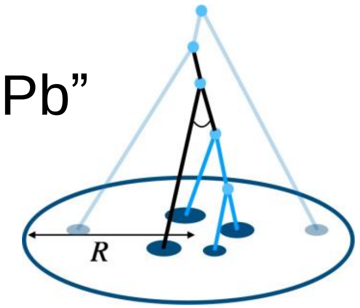
arXiv:2107.nnnnn

> ➢ First evidence: Jet core is more collimated in Pb-Pb than in pp

Cartoon: "pp"

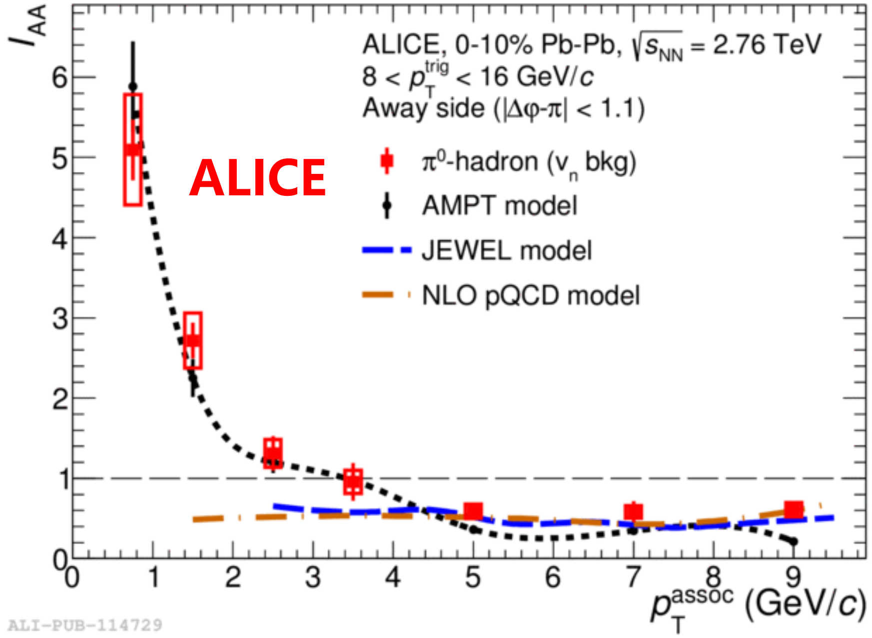


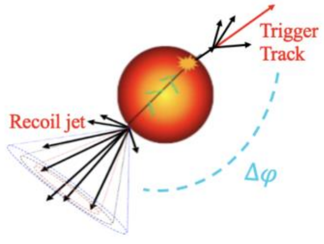
"Pb-Pb"

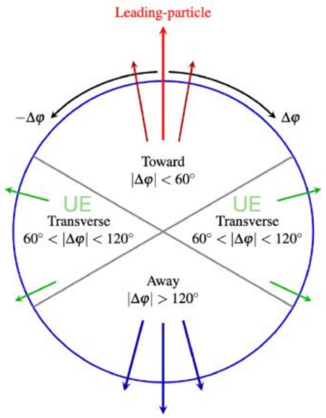


夸克物质输运性质与喷注结构

Phys. Lett. B763 (2016) 238
Phys. Lett. B776 (2018) 249
Phys. Lett. B746 (2015) 1
JHEP 03 (2014) 013

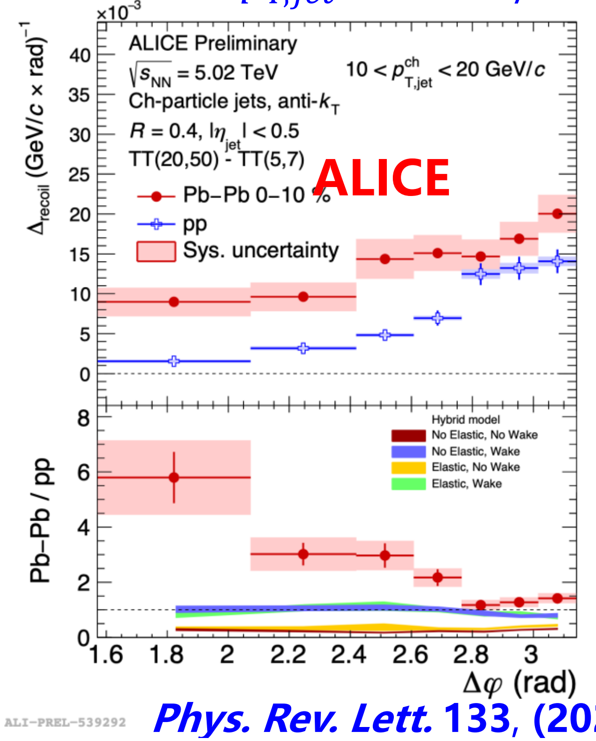






R=0.4, 0−10%

$10 < p_{T,jet} < 20 GeV/c$



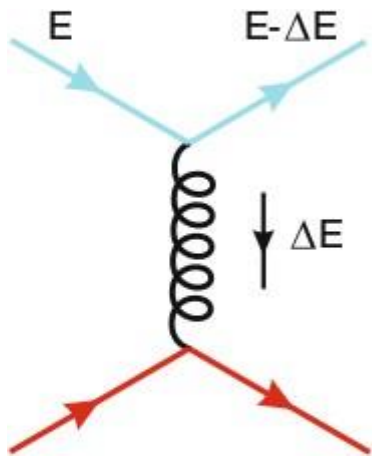
Phys. Rev. Lett. 133, (2024)022301

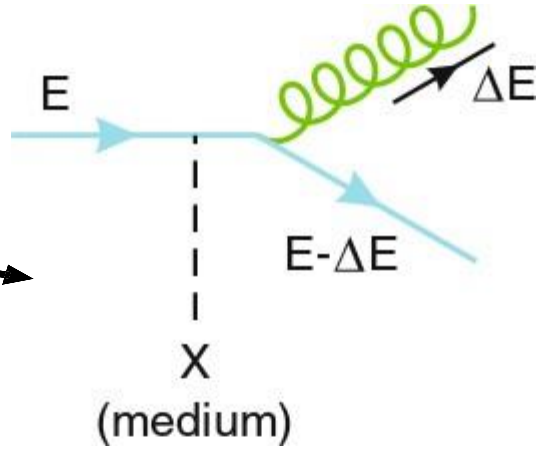
- 在低横动量区间观测到介质诱导喷注相互作用，引起核修正因子显著升高现象，被认为是介质激发效应；
- 首次实现低横动量、大锥角的喷注测量，明显观测到喷注轴的展宽效应和喷注能量在介质中的再分布的证据

Energy Loss in the QGP

- QGP: high density of quarks and gluons / color sources
- Traversing quark / gluon feels color fields
- Collisional energy loss
  - Elastic scatterings
  - Dominates at low momentum
- Radiative energy loss
  - Inelastic scatterings
  - Dominates at high momentum
  - Gluon bremsstrahlung

$$\Delta E = \Delta E_{coll} + \Delta E_{rad}$$



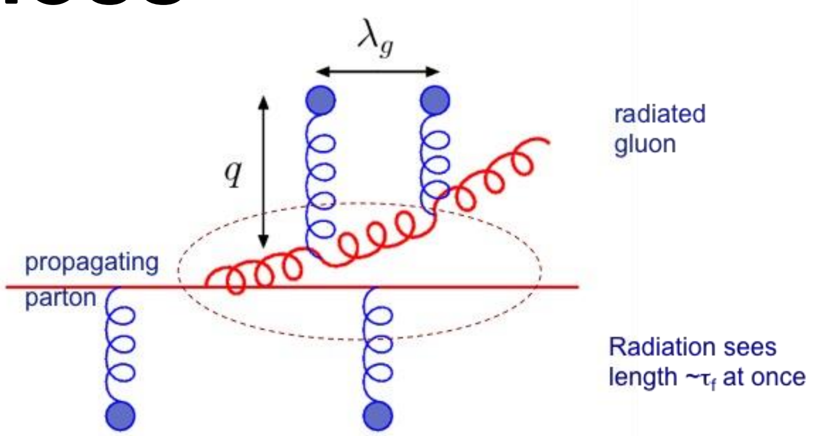


Lect. Notes Phys. 785,285 (2010)

Radiative energy loss

In the BDMPS (*Baier-Dokshitzer-Mueller-Peigné-Schiff*) approach, the energy loss depends on

- the **color-charge** via the Casimir factors C_r
  - $C_r = 3$ for gluon interactions
  - $C_r = 4/3$ for quark interactions
- the **strong coupling**
- the **path length** *L*
- the **transport coefficient** $\hat{q}$ ("q-hat")
  - gives an estimate of the "strength" of the jet quenching
  - is <u>not directly measurable</u> → from data through model(s)



$$\frac{dE}{dx} = -C_r \alpha_s \hat{q} L^2$$

$$\hat{q} = \frac{\mu^2}{\lambda}$$

Average transverse momentum transfer

Mean free path

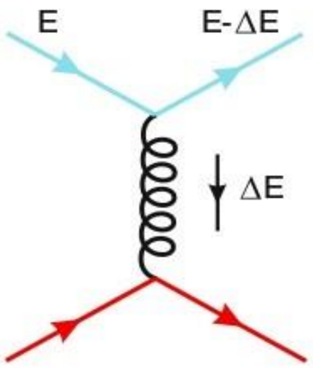
$$\lambda \propto \frac{1}{\rho}$$

Density

Baier-Dokshitzer-Mueller-Peigné-Schiff, Nucl. Phys. B. 483 (1997) 291

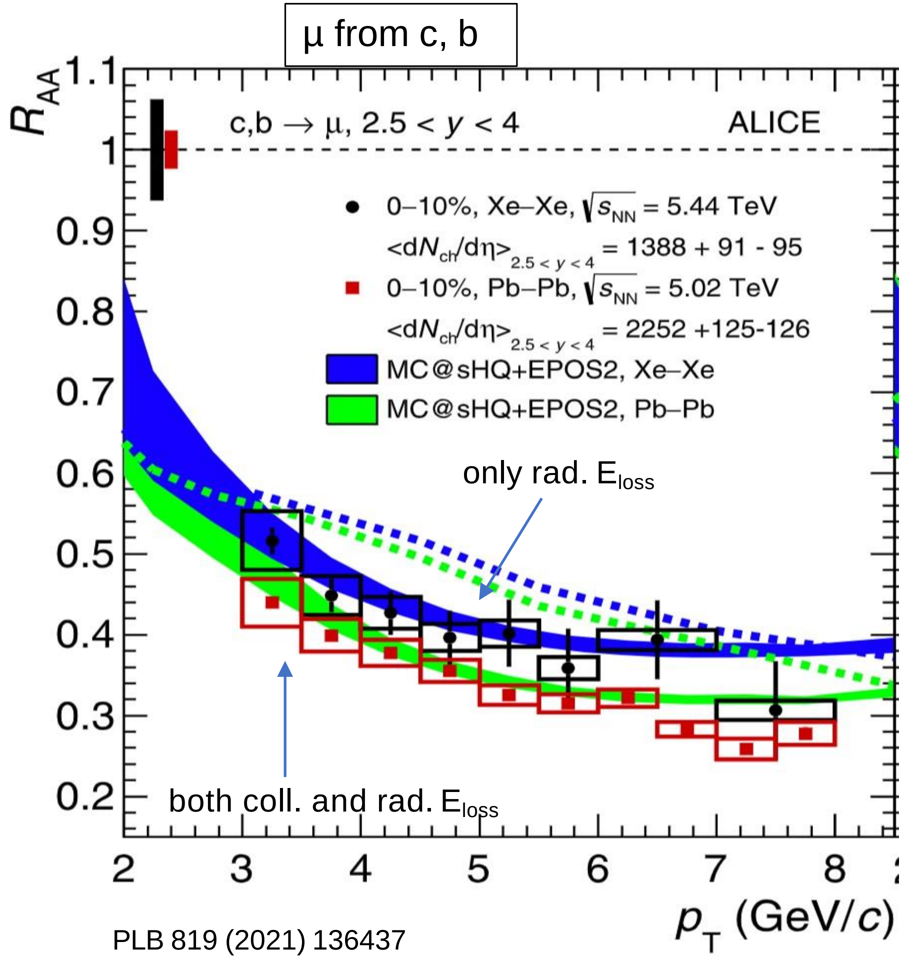
Collisional energy loss

It depends on
- **path length** through the medium, L (linearly)
- **parton type**
  - – For light quarks $$\Delta E_{q,g} \sim \alpha_S C_R \mu^2 L \ln \frac{ET}{\mu^2}$$
  - – For heavy quarks $$+ \alpha_s^2 T^2 C_R \mu^2 L \ln \frac{ET}{M^2}$$



- **temperature** of the medium, T
- **mass** of the heavy quark M
- **average transverse momentum transfer μ** in the medium

→ Data are well described by models （MC@sHQ+EPOS2） that include both collisional and radiative E_{loss} , but PHSD model including nuclear PDF modification and collisional energy loss cann't (see dot lines).



PLB 819 (2021) 136437

Jet transport coefficient $\hat{q}$

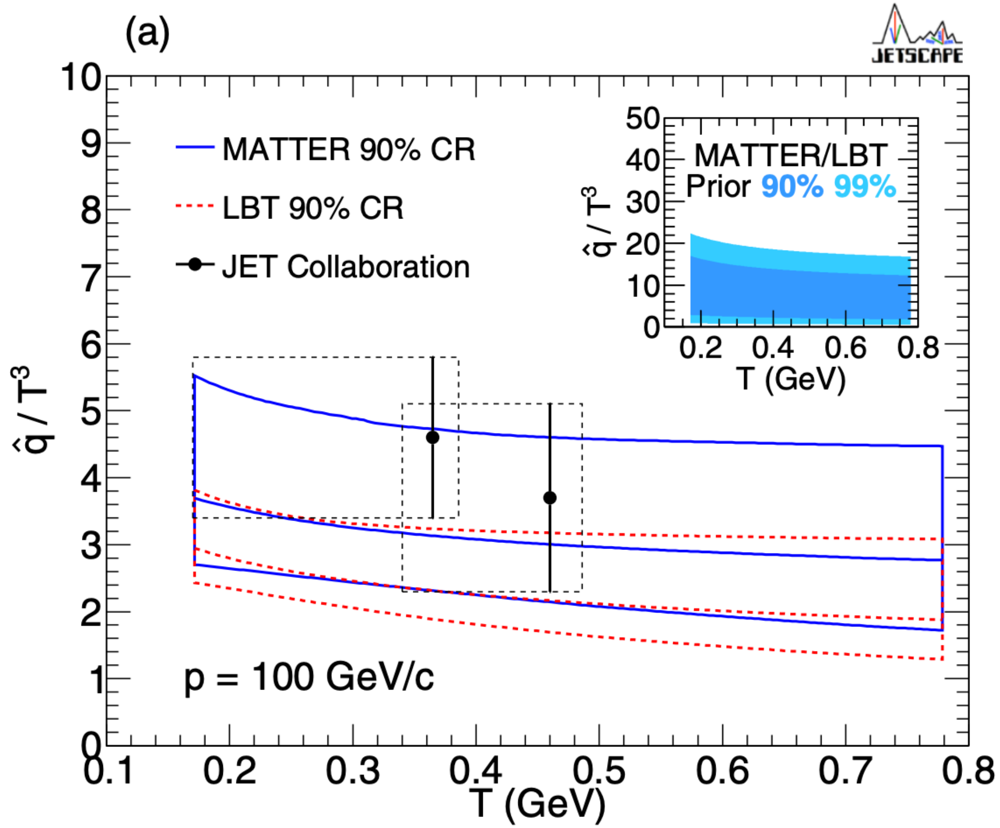
A recent combined analysis of the RHIC and the LHC data on jet quenching (inclusive hadron R_{AA}) allowed to extract a value for the $\hat{q}$ parameter

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

For a **quark jet** with E = 10 GeV

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \text{ at } \ \begin{matrix} \mathrm{T{=}370\ MeV} \\ \mathrm{T{=}470\ MeV} \end{matrix}$$

→ Still large uncertainties, but important step **towards a quantitative characterisation** of the QGP.



S. Cao et al., PRC 104, 024905 (2021)

In-medium jets: main questions

Related to the properties of the medium

- Density of the medium and transport properties
- Nature of the scattering centers
- Distribution of the radiated energy
- …

Related to the energy loss mechanism

- Path length dependence
- Broadening effects
- Microscopic mechanism for energy loss
  → Study the **shape and structure of jets** for insight into the details of jet modification mechanisms due to interactions with the plasma
- Flavour dependence
  → **measure charm and beauty R_{AA}**