Heavy Ion Overview

PHENOEXP 2026

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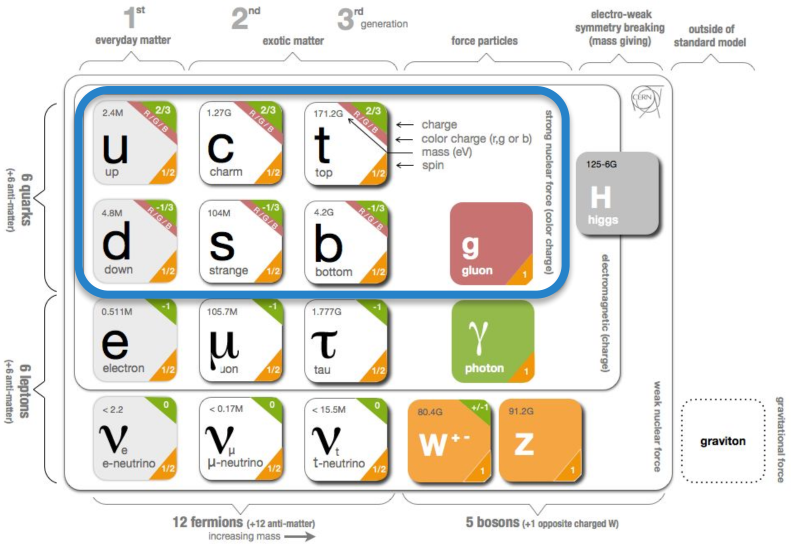
Disclaimer

- General introduction for a broad audience
  - What is the scope, motivation, and importance of this area of research?
- Very biased view from an experimentalist who is a member of an LHC collaboration
- Focused on a few aspects of the field and some recent results to clarify the picture that heavy ion collisions bring us about the QCD matter

Some of QCD's open issues

- The nature of confinement
- Understanding the structure of hadrons
- Accurate measurements of QCD phenomena are essential for the search for Physics beyond the Standard Model
- **What are the emerging properties of QCD in systems with many constituents?**
    - **A kind of "QCD Condensed Matter"**



What are the emerging properties of QCD?

- **In the beginning:**

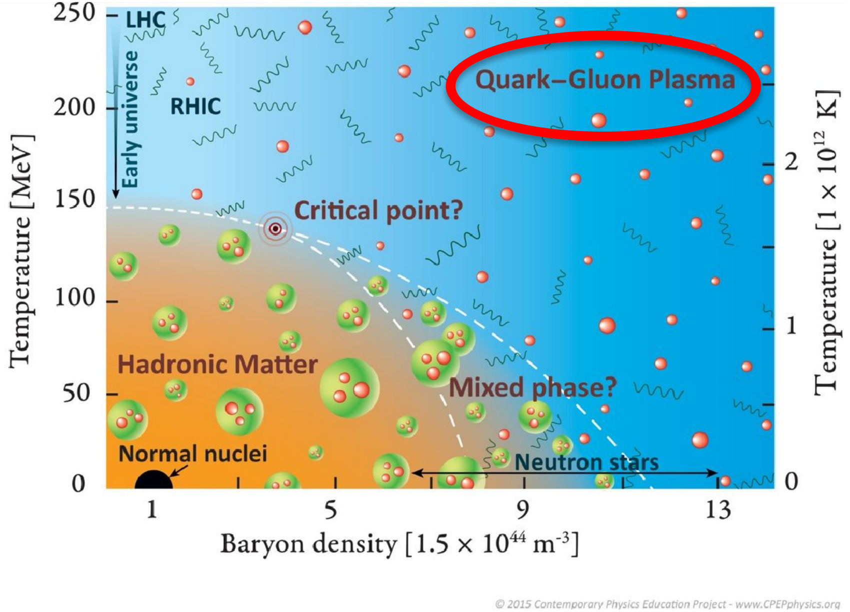
- *Superdense Matter: Neutrons or Asymptotically Free Quarks?*, J.C. Collins and M.J. Perry, Phys. Rev. Lett. 34, 1353 (1975).
  - *"We suggest that matter at such high densities is a quark soup."*

- *Quantum Chromodynamics and the Theory of Superdense Matter*, E. V. Shuryak, *Phys. Rep. 61, 71 (1980)*
  - *"Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD (or quark-gluon) plasma."*

What are the emerging properties of QCD?

- Characterization of the phase diagram of matter governed by strong interaction (QCD)

- In particular, the so-called Quark-Gluon Plasma, a natural consequence of QCD at high temperatures and densities



Quark-Gluon Plasma (QGP)

- *"A locally thermally equilibrated state of matter in which quarks and gluons are **deconfined** from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes."*

  (STAR Collaboration's Critical Assessment of the Evidence from RHIC Collisions - 2005)

- *"It is the simplest form of complex matter that we know of, ..., most directly connected to the fundamental laws that govern all matter in the universe."*

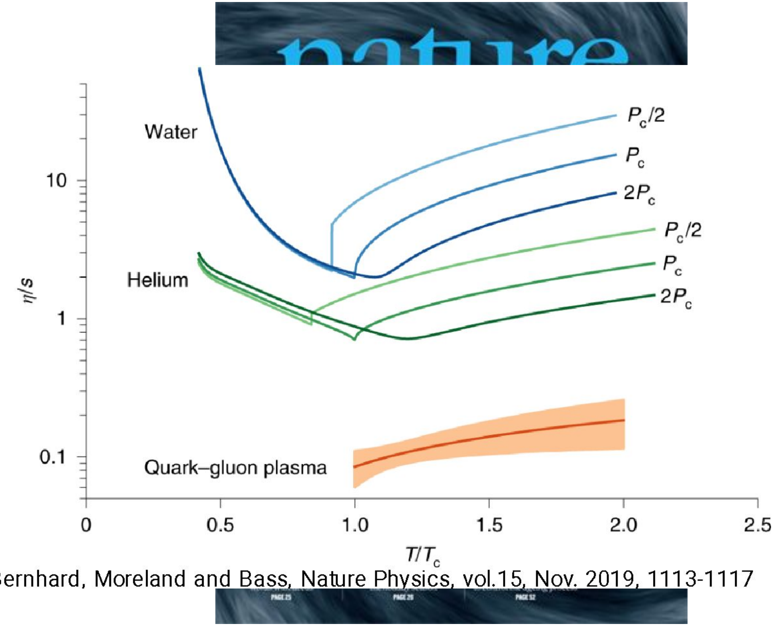
  (W. Busza, K. Rajagopal and W. van der Schee, Ann. Rev. Nucl. Part. Sci. 2018. 68:1–49)

Quark-Gluon Plasma (QGP)

- Amazing properties have already been observed

- Despite the asymptotic freedom, QGP behaves like a fluid of minimal viscosity, being called "the perfect fluid"

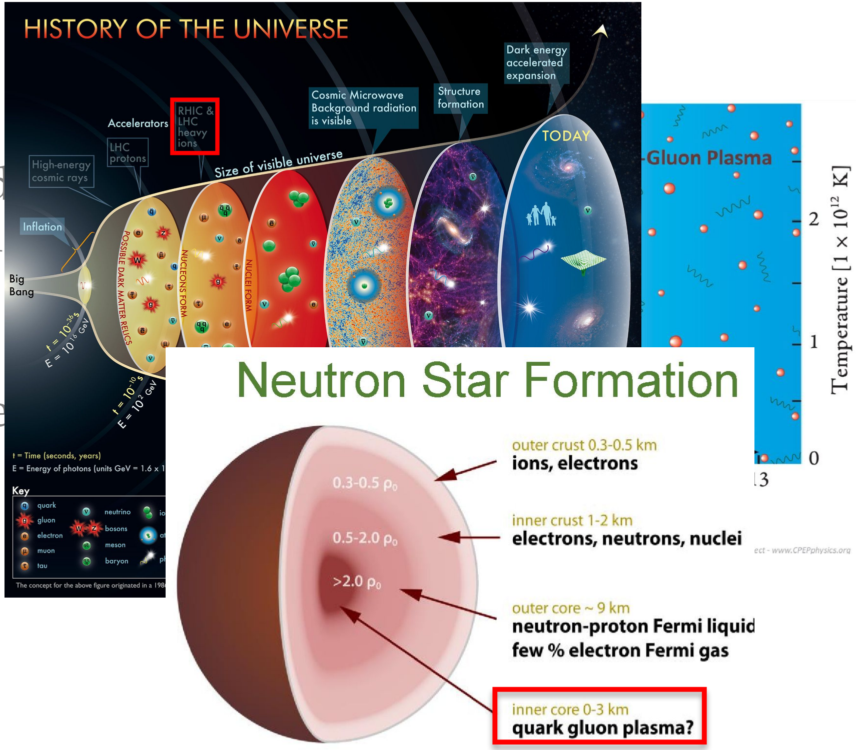
- Extreme behavior in terms of angular momentum leading to extremes of vorticity



Bernhard, Moreland and Bass, Nature Physics, vol.15, Nov. 2019, 1113-1117

Why study QGP?

- Essential for understanding strong interaction
- What are the properties of QGP and is the relationship between them an fundamental interaction of QCD?
- Laboratory for the primordial matte the Universe
- and high-density stars

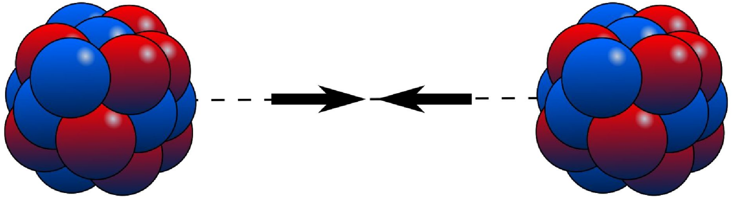


What can we learn about QGP?

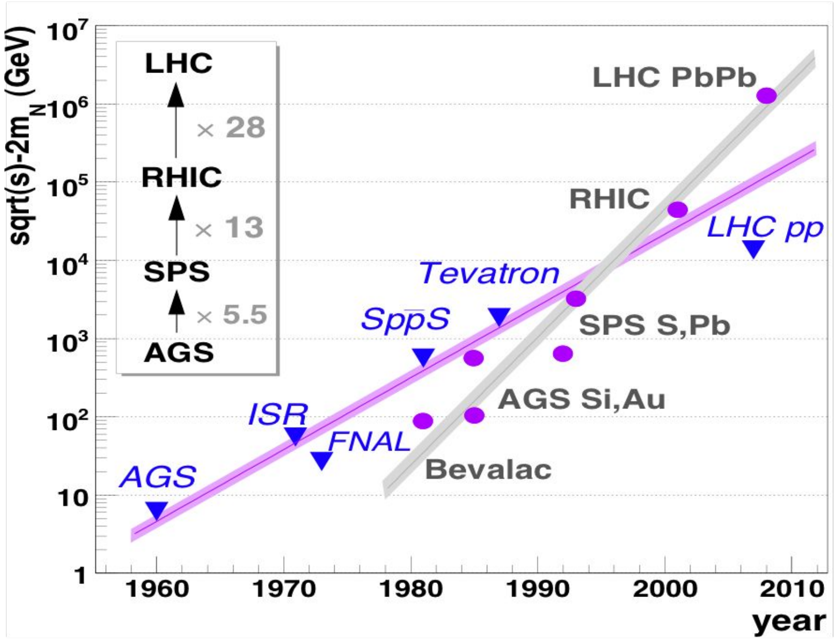
- What are the thermodynamic and global properties of QGP?
- What are its hydrodynamic and transport properties?
- How does QGP affect hadron formation?
- How does QGP affect the propagation of energetic partons and respond to the excitation caused by these particles?
- How does the non-confinement of the QGP affect strong interactions?
- Can QGP lead to the discovery of new effects of QCD?
- What are the limits of the formation of the QGP?
- Can QGP help elucidate the nature of hadron-hadron interactions?
- Can the QGP study elucidate specific aspects of the relationship between perturbative QCD and the strong interaction at longer distances?

How to study the QGP experimentally?

- Collisions between heavy ions at relativistic energies



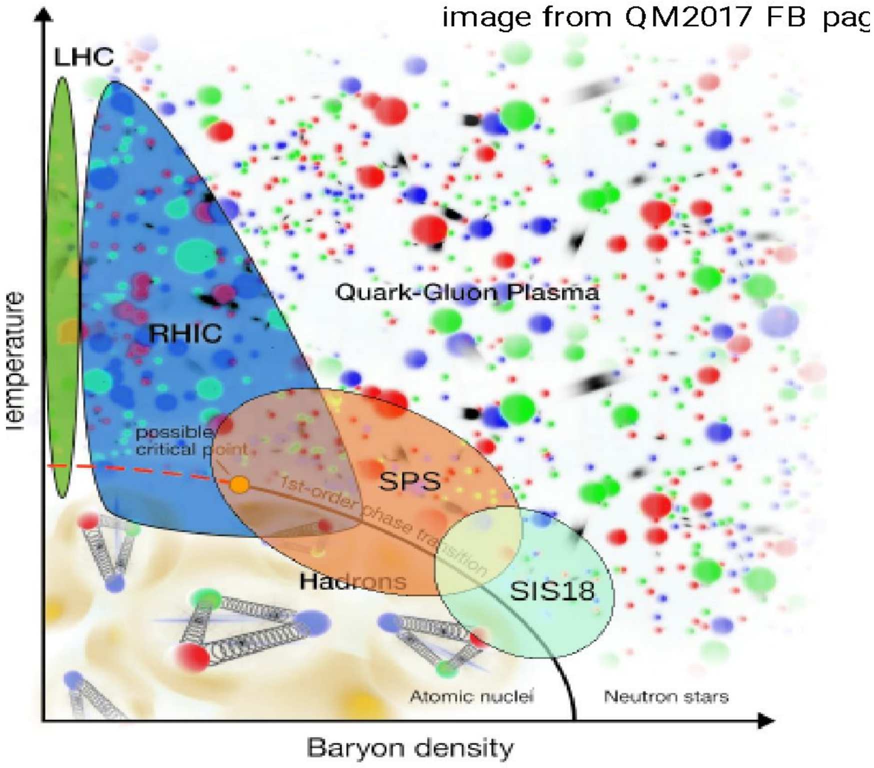
- Several heavy ion accelerators built over the years



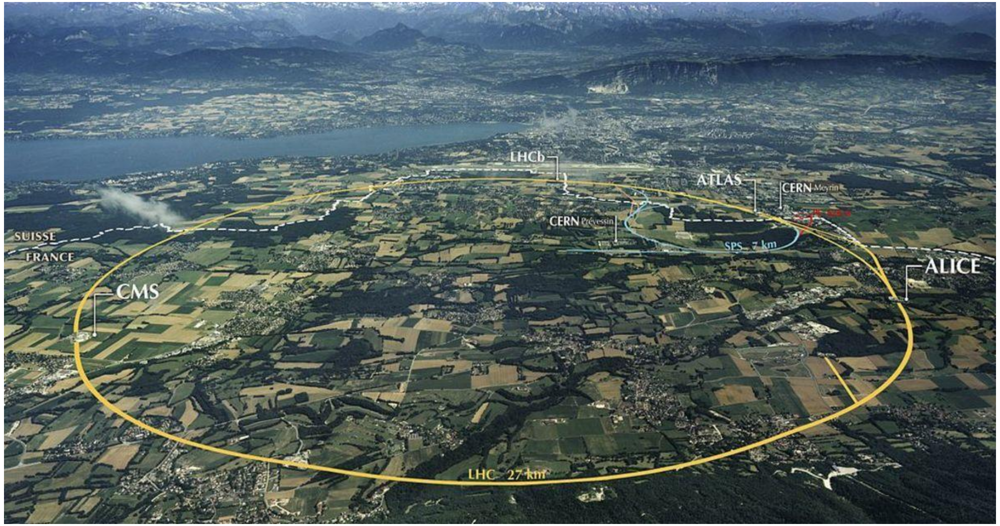
Nuclear matter phase diagram

- Currently, a few accelerators around the globe in full operation
  - SIS18 – GSI
  - SPS – CERN
  - RHIC – BNL
  - LHC – CERN

- Different energy regimes probe different regions of the phase diagram



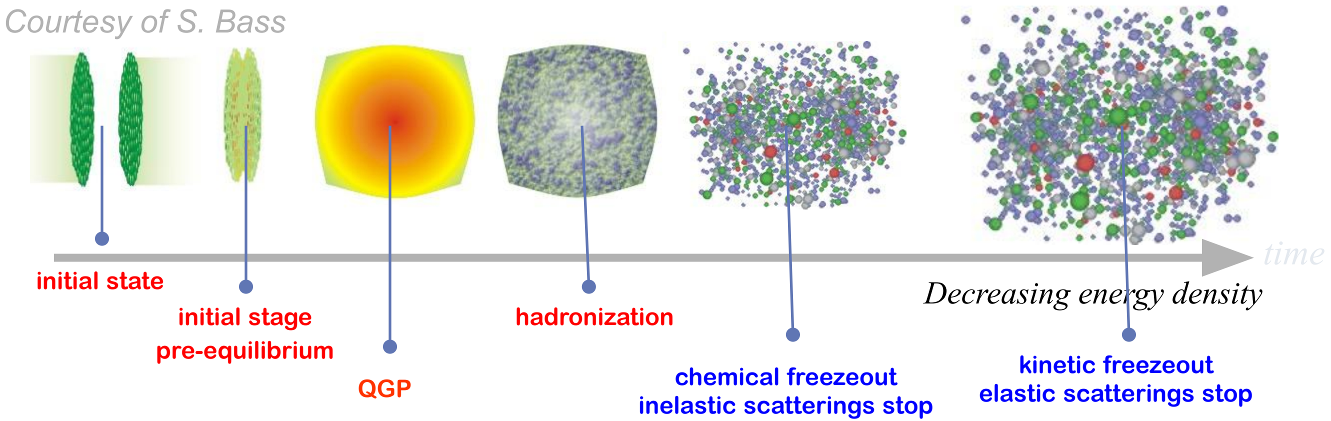
Large Hadron Collider



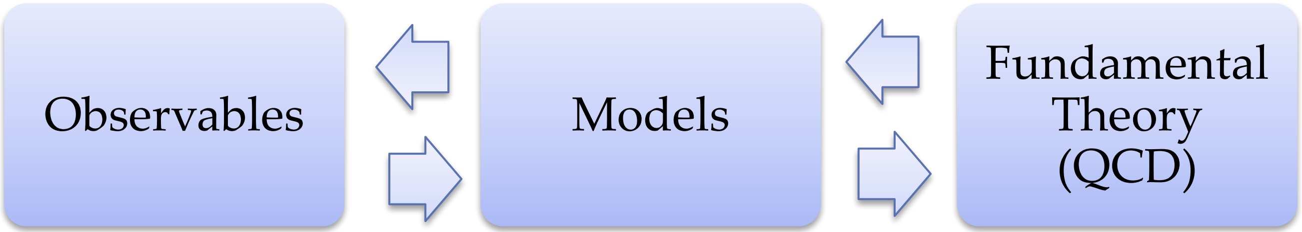
- Highest energies ever achieved ($\sqrt{s_{NN}}$ in TeV)
  - pp (0.9, 2.36, 2.76, 5.02, 7, 8, 13), p-Pb (5.02, 8.16), Xe-Xe (5.44), Pb-Pb (2.76, 5.02)
  - **New light ions: O-O and Ne-Ne (5.36)**

Relativistic heavy-ion collisions

- Describe the dynamics of relativistic heavy-ion collisions
  - Access to fundamental QCD processes.
- Schematic description of collision time evolution:

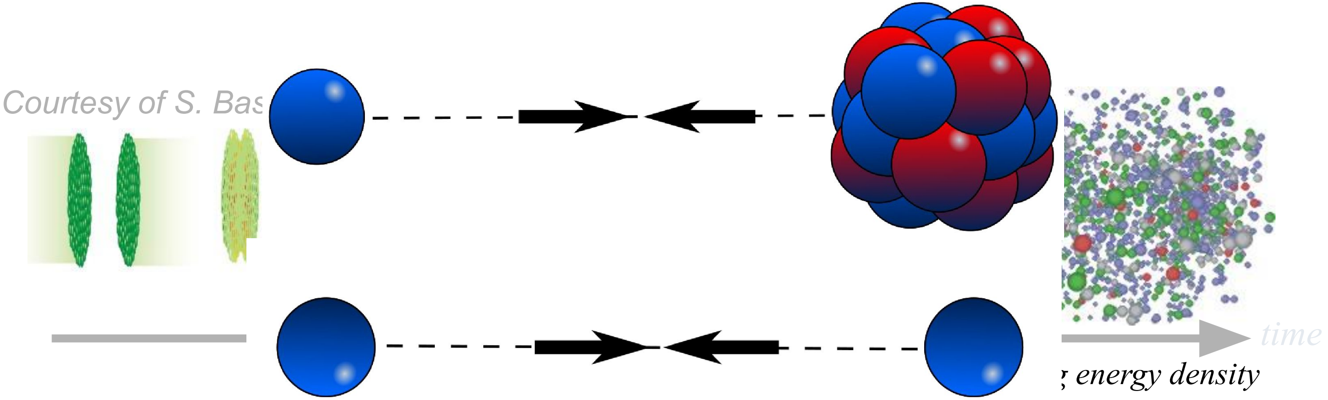


Relativistic heavy-ion collisions



- Collisions between heavy ions are quite complex processes, with many phenomena occurring simultaneously
- Therefore, models are needed to consider all these phenomena and describe the observables
- The hypotheses and considerations of these models should connect to QCD, seeking to bring insights into fundamental aspects of nature

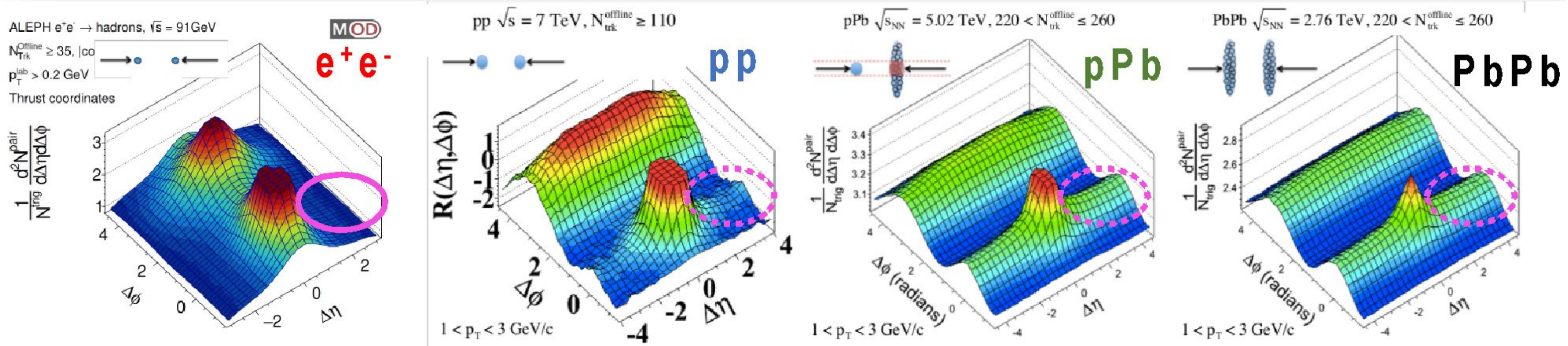
Relativistic heavy-ion collisions



- Macroscopic (long wavelength) characterization of QGP
  - Global (bulk) observables of the freeze-out state
- Microscopic (short wavelength or quasi-particle) characterization of QGP
  - High-energy probes (Hard Probes)
- In both cases, comparison with more elementary collisions, p-p and p-Pb types, is essential.

Not so simple...

- An interesting phenomenon was observed for the first time at the LHC: correlations between particles in more elementary collisions similar to those observed in nucleus-nucleus collisions!



Badea et al., arXiv:1906.00489

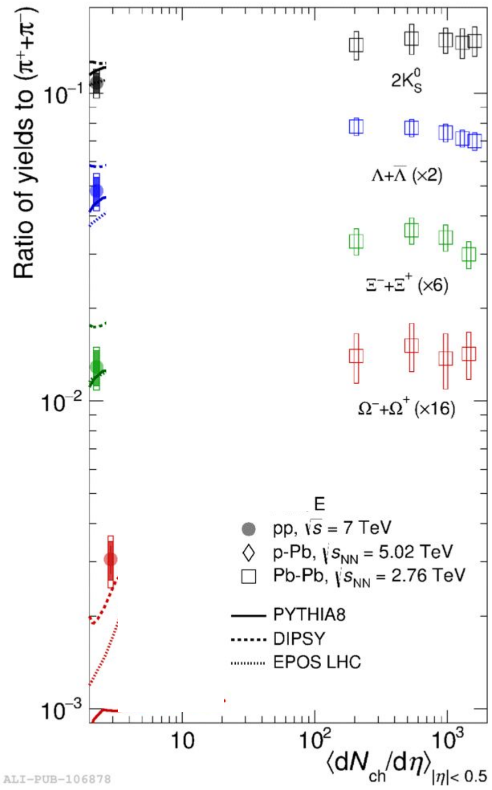
CMS, JHEP09 (2010) 091

CMS, PLB 724 (2013) 213

Not so simple...

ALICE, Nature Phys. 13, (2017) 535

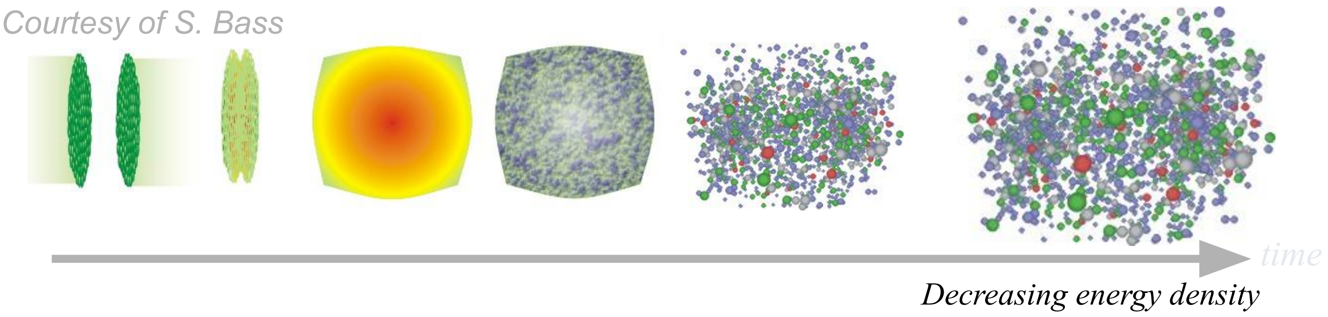
- Strangeness Enhancement in Pb-Pb collisions was always seen as a QGP signature
- Strangeness Enhancement in pp data, where no QGP is expected
- Strangeness increases with multiplicity following a universal trend
- Paradigm shift in heavy-ion physics



Small Systems

- First O-O and Ne-Ne run in LHC for 9 days in July 2025 at a colliding energy of 5.36 TeV per nucleon
- Why collide light ions?
  - Bridge from small to large systems
  - QGP formation in smaller systems? → Onset of deconfinement
  - Sharper control of initial-state geometry of ion-ion collisions → Investigate Cold Nuclear Matter effects

Relativistic heavy-ion collisions



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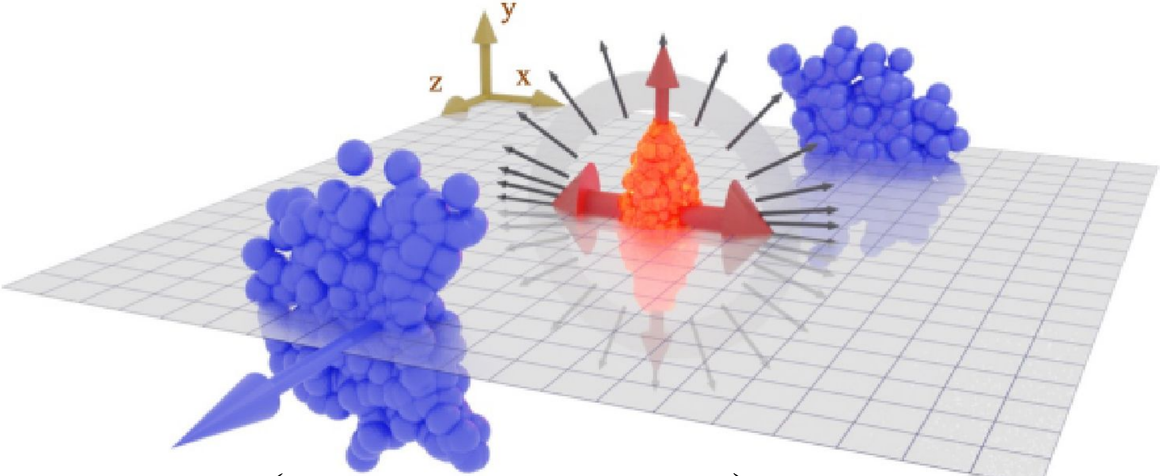
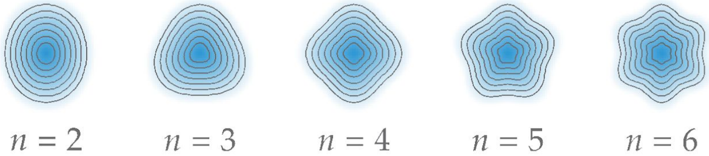
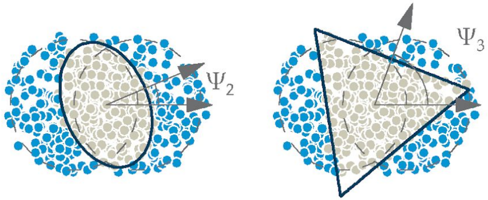
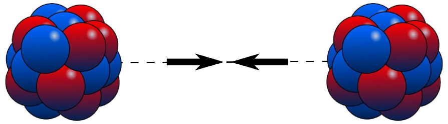
Elliptic Flow



$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\Psi_r\right)\right)\right)$$

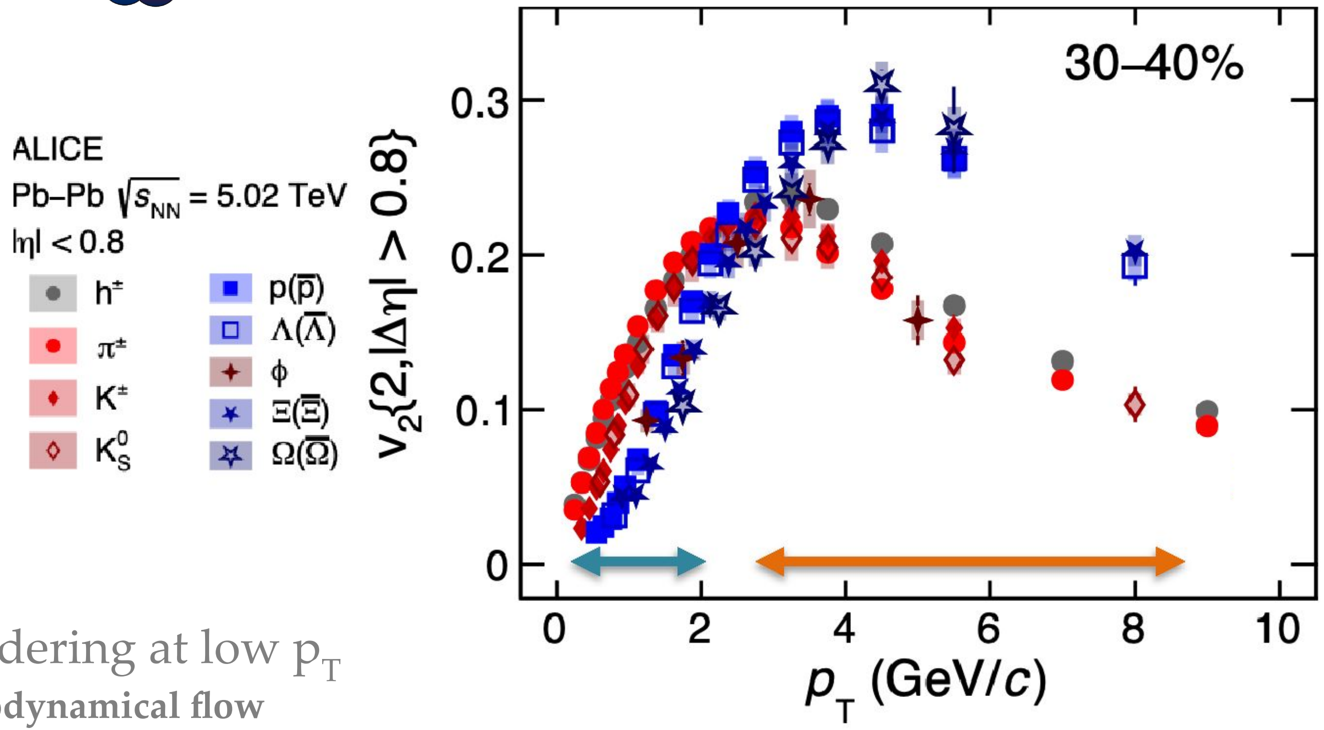




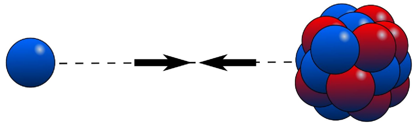


Elliptic Flow

arxiv:2206.04587

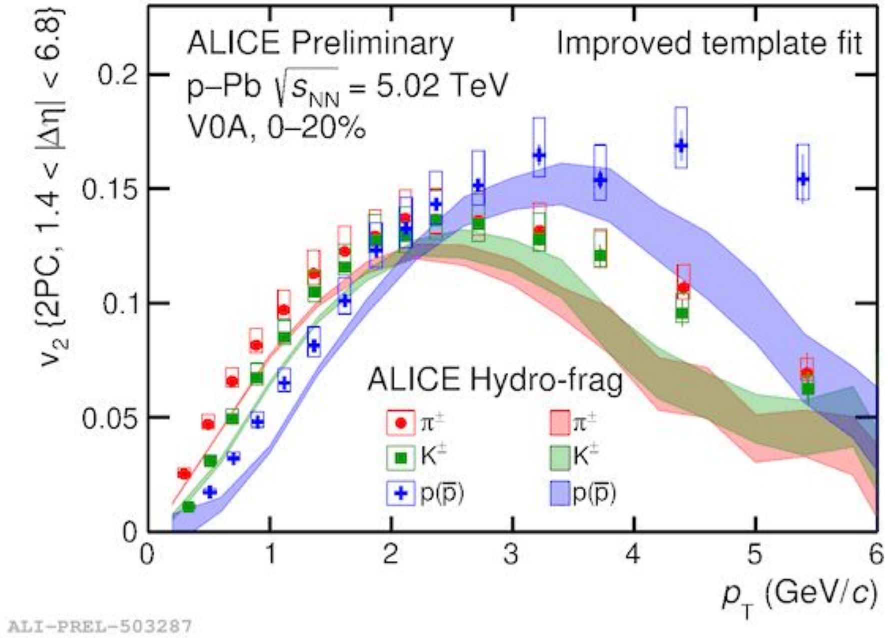


- Mass ordering at low p_T
  - **Hydrodynamical flow**
- Baryon vs. meson grouping at higher p_T
  - **Quark-level flow and recombination**

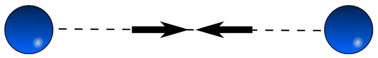


Elliptic Flow

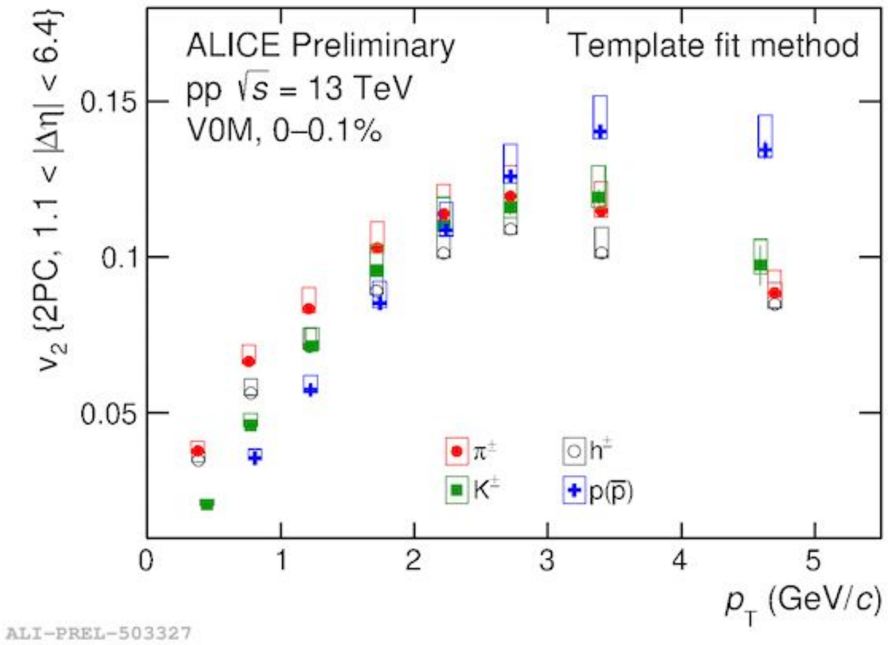
Hydro-frag: Phys. Rev. Lett. 125, 072301 (2020)



- Model comparison for p-Pb results indicates quark-level flow and recombination as well



Elliptic Flow



- Model comparison for p-Pb results indicates quark-level flow and recombination as well
- Baryon vs. meson grouping at higher p_T in high-multiplicity pp

Elliptic Flow – Light Ions

PRC 113 (2026) 045205

- Significant collective flow observed in O–O and Ne–Ne collisions
- Flow magnitude follows the initial collision geometry
- Measurements are well described by models incorporating QGP evolution
- Provides evidence for collective QCD dynamics in smaller collision systems
- Collective behavior persists down to light-ion collisions, offering new constraints on the onset of QGP formation.

arXiv 2510.02580

Elliptic Flow – Light Ions

- Low p_T: scaling with particle mass due to hydrodynamic expansion of the system
- Intermediate p_T: grouping of mesons and baryons → Hadronisation via quark recombination (coalescence)

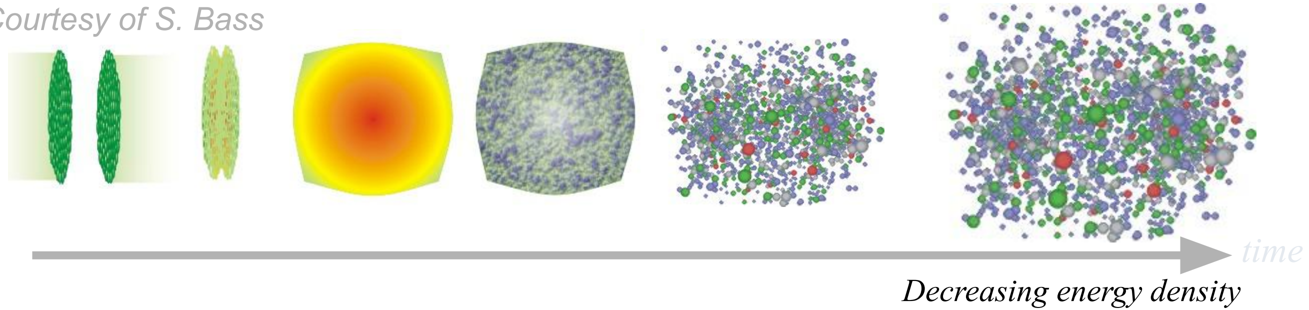
Elliptic Flow– Light Ions

- Different anisotropy of the initial geometry is expected to be transferred to the momentum space of final-state particles
- Larger elliptic flow is expected in Ne-Ne collisions

ATLAS: PRC 113 (2026) 045205

Relativistic heavy-ion collisions

Courtesy of S. Bass



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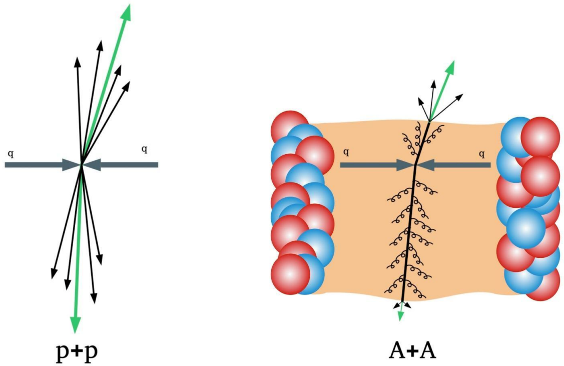
- In both cases, comparison with more elementary collisions, p-p and p-Pb types, is essential.

Nuclear Modification Factor

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

$$\langle N_{coll} \rangle = \langle T_{AA} \rangle \cdot \sigma_{pp}^{INEL}$$

- Simple observable of medium interaction



Nuclear Modification Factor

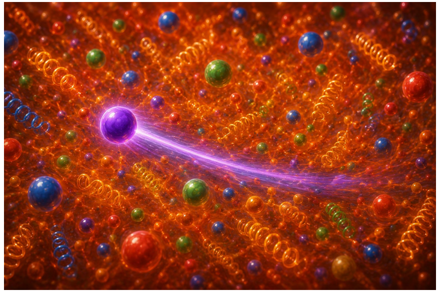
- p-Pb collisions: $R_{pPb} = 1$
  - No extended QGP medium created, no energy loss
- Pb-Pb and Xe-Xe collisions: $R_{AA} < 1$
  - Partons lose energy via interaction with QGP constituents → collisional and gluon radiation
- How does it look in intermediate systems (light ions)?
  - **Partonic energy loss observed in OO collisions**

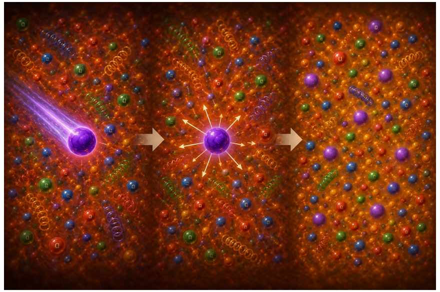
Nuclear Modification Factor

- In the ratio R_{OO}/R^2_{pO}, effects due to nuclear modification of parton distribution functions (cold nuclear matter effects) cancel
- Significant deviation from the QGP baseline
- Compatible with models implementing energy loss in QGP

Heavy flavor

- Heavy quarks produced at the early stages of the collision and survive the QGP lifetime
  - Production time $\tau_p \sim 1/m_Q \sim 0.05 - 0.15$ fm/c
- Energy loss in the QGP (high p_T)
  - Heavy quarks are expected to lose less energy than light quarks and gluons
  - Medium density and size
- Probe thermalization in the QGP (low p_T)
  - Medium transport properties
- Measurement channels:
  - **c, b → e**
  - **c, b → μ**
  - **$D^0 \rightarrow K\,\pi$ ($c\tau \sim 122.9$ μm)**
  - **$D^+ \rightarrow K\,\pi\,\pi$ ($c\tau \sim 311.8$ μm)**
  - **$D^{*+} \rightarrow D^0\,\pi$**
  - **$D_s^+ \rightarrow K\,K\,\pi$ ($c\tau \sim 149.9$ μm)**





Heavy flavor: Nuclear modification factor

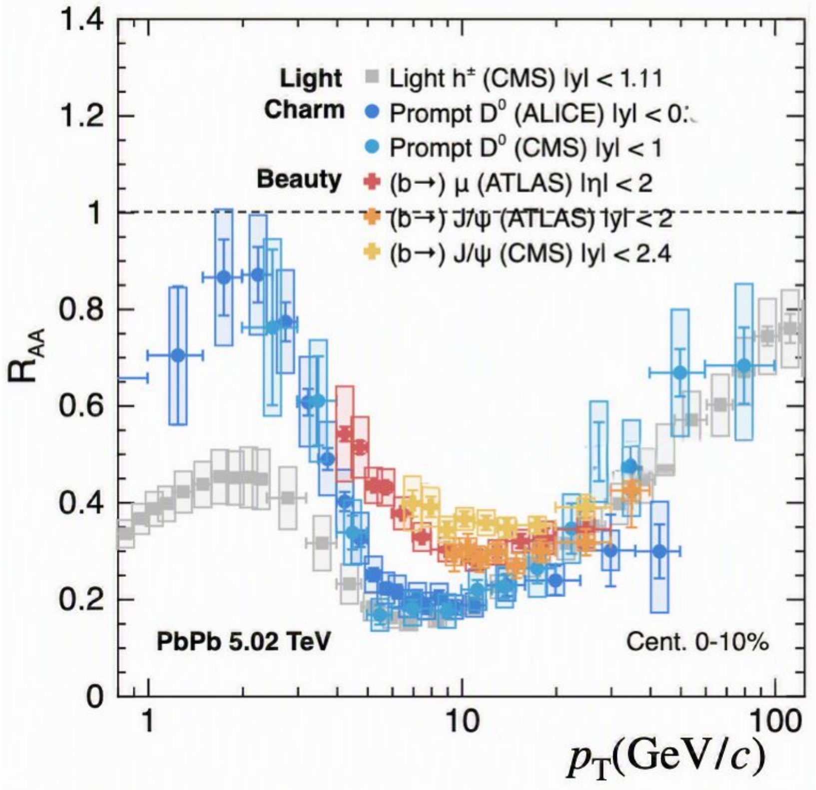
https://boundino.github.io/hinHFplot/

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

$$\langle N_{coll}\rangle = \langle T_{AA}\rangle \cdot \sigma_{pp}^{INEL}$$

- Significant suppression of D-mesons
- **Prompt D^0 and non-prompt heavy quark open/quarkonia**
  - **Quarks c** (prompt) and **b** (non-prompt) energy loss
  - Consistent with expectation ("dead cone" effect)

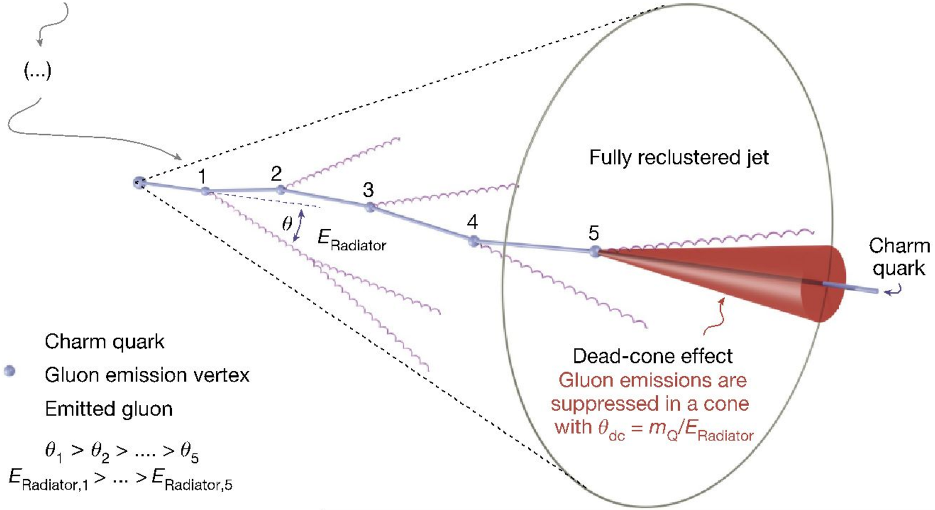
    $\Delta E_b < \Delta E_c$ since $m_b > m_c$

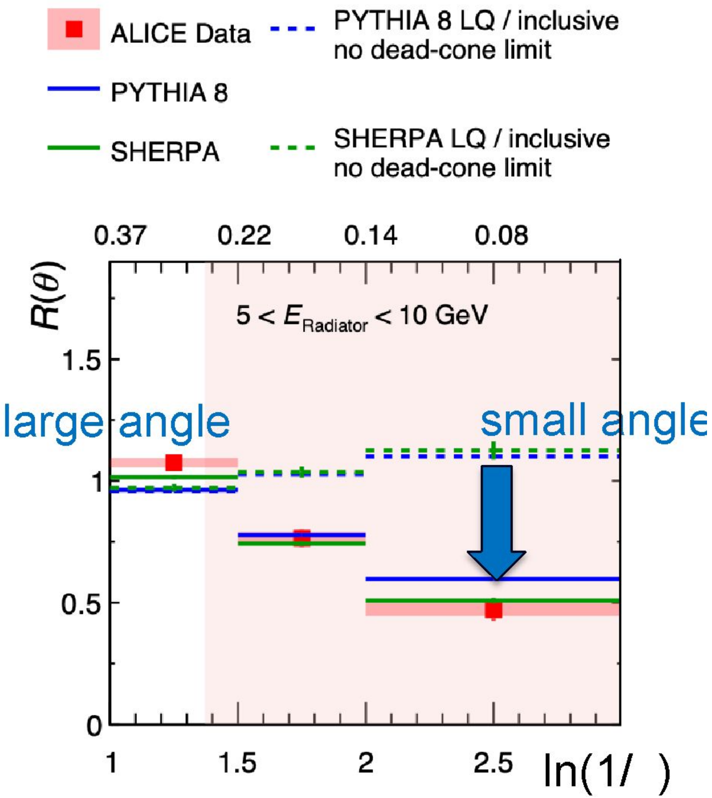


Heavy Flavor: Dead-Cone Effect in pp

Nature 605 (2022) 7910, 440

- Reduction of gluon radiation from heavy quarks at small angles





- The observable:

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}},E_{\mathrm{Radiator}}}$$

Heavy flavor – R_{AA} in Light Ions

- D-meson R_{Ne-Ne}/R_{OO} ratio expected to be flat as a function of p_T in the case of no energy loss
- p_T-dependent suppression in case of energy loss, due to the slightly larger size of Ne compared to O nuclei
  - **Measurement compatible with energy loss scenario**

Heavy flavor - Elliptic Flow

- Charm quarks are produced in initial hard scatterings, before the QGP is formed
- Their interaction with the QGP leads to thermalization and collective flow
- At low (p_T), charm-hadron (v_2) follows the expected mass hierarchy
- At intermediate (p_T), baryon–meson splitting points to charm-quark flow and recombination during hadronization
- **Charm quarks interact strongly enough with the QGP to acquire its collective motion.**

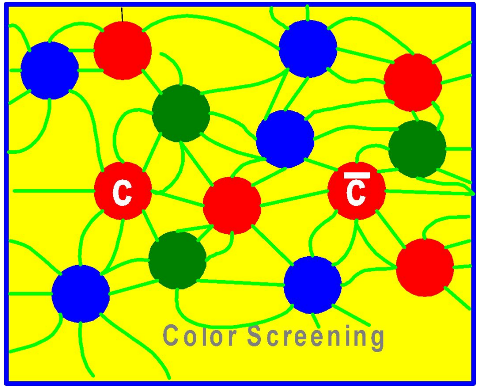
Quarkonia

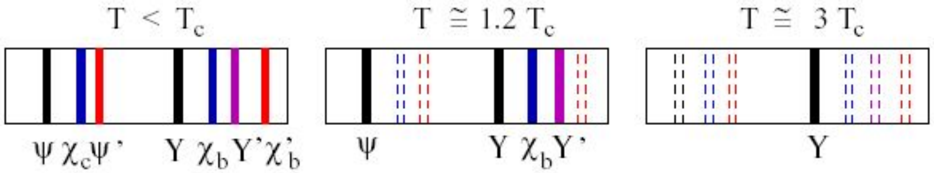
- Quarkonium suppression via color screening: probe of deconfinement

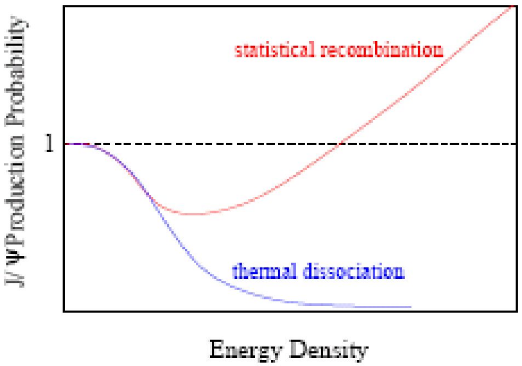
  (Matsui and Satz, PLB 178 (1986) 416)
- Sequential suppression of the quarkonium states

  (Digal, Petreczky, Satz, PRD 64 (2001) 0940150)
- Enhancement via (re)generation of quarkonia, due to the large heavy-quark multiplicity

  (Andronic, Braun-Munzinger, Redlich, Stachel, PLB 571(2003) 36)

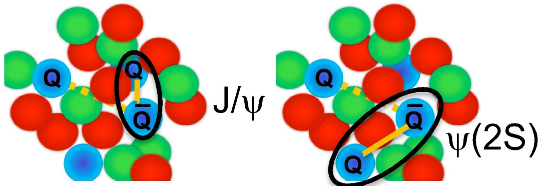




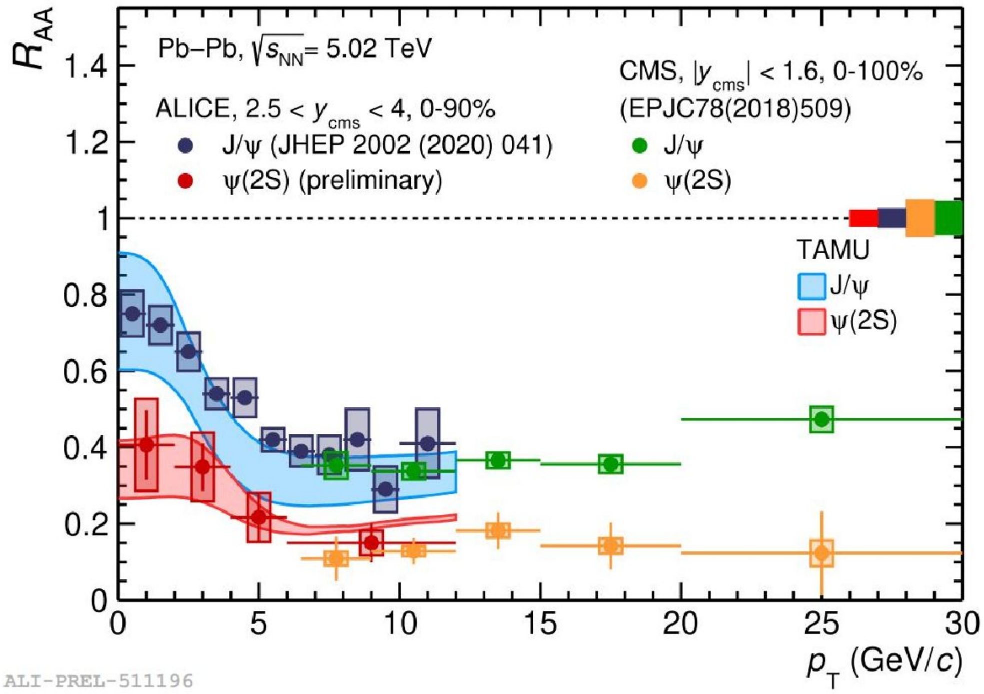


Quarkonia: Nuclear modification factor

- Enhancement in R_{AA} of charmonium for low p_T
  - **Indicates the occurrence of the regeneration process**
- ψ(2S) more suppressed than J/ψ
  - **Lower binding energy!**



TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158



Quarkonia – R_{AA} in Light Ions

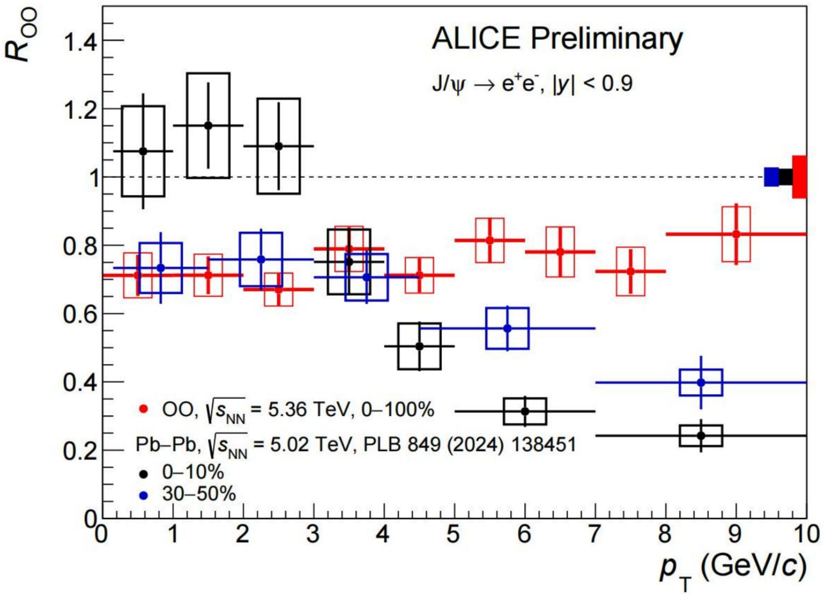
- Nuclear Modification Factor for J/ψ in O-O for mid and forward rapidity

- Suppression in the full p_T range and no rapidity dependence is observed

- Data are in agreement with transport model including both hot and cold nuclear matter effects (J. ZHAO ET AL., PNP 114 (2020) 10380)

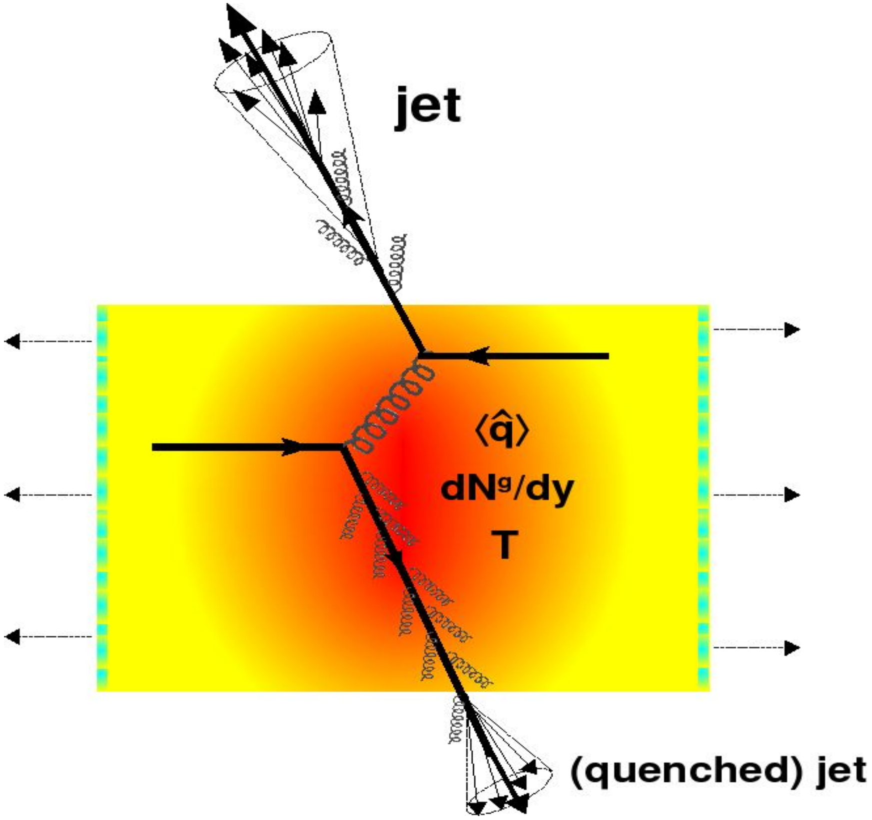
Quarkonia – R_{AA} in Light Ions

- J/ψ suppression is observed in both Pb–Pb and O–O collisions
- The suppression is stronger in Pb–Pb for higher p_T, reflecting the larger and longer-lived QGP medium
- The observation of suppression in O–O indicates that medium effects persist in light-ion collisions
- No clear low-p_T regeneration enhancement is observed in the present O-O measurements



Jets

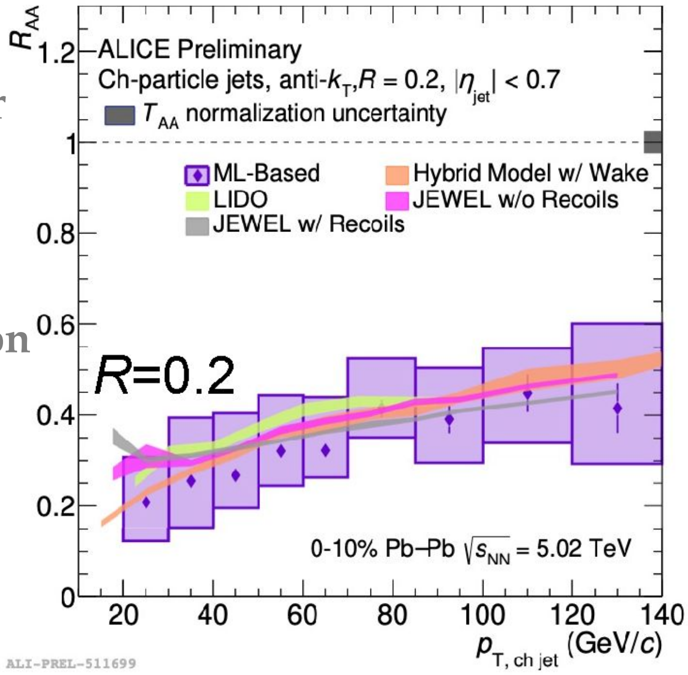
- Hard scattering of partons during the collision
- Excellent probe of the medium properties due to energy loss
- The strategy is to look for jet modifications (quenching)

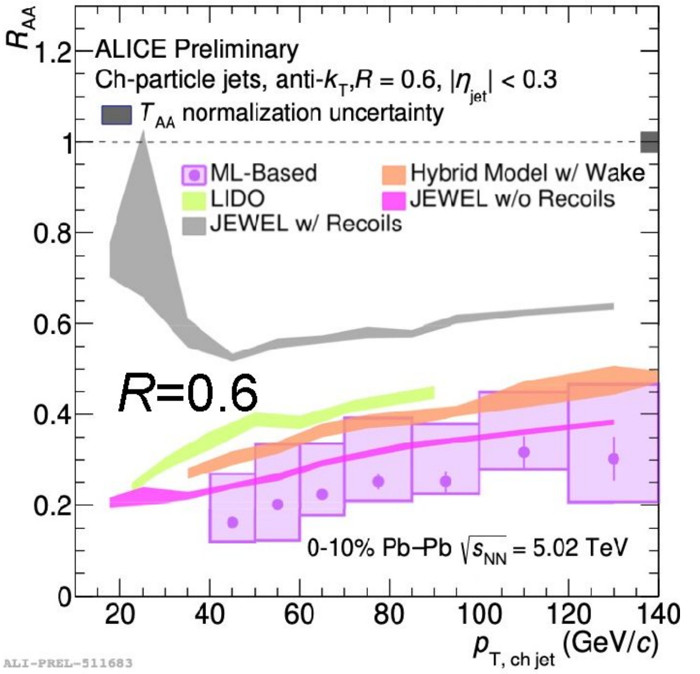


D. d'Enterria, arXiv:0902.2011

Jets: Nuclear modification factor

- Big challenge: background subtraction
  - Push to low p_T and large R
- Measurements extended to lower jet p_T and large R using Machine Learning (ML)
  - **Improvements on background subtraction and systematics**





JEWEL: JHEP 1707 (2017) 141
Hybrid Model: Phys. Rev. Lett. 124, 052301
LIDO: JHEP 05 (2021) 041

Jets – R_{AA} in Light Ions

- Suppression hierarchy:

- R_{pPb}: no suppression

- R_{AA}: clear suppression

- R_{OO}: intermediate values indicating suppression but less than in Pb-Pb

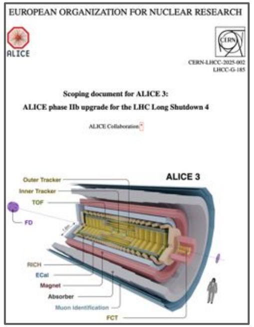
Jets - Elliptic Flow in Light Ions

- Jet v_2 probes the path-length dependence of parton energy loss
- In O–O collisions, the measured v_2 is compatible with zero
- Current precision does not yet allow a significant anisotropy to be established

The Future: ALICE 3

- A compact detector system
- A high-resolution vertex detector delivering precise pointing across a wid acceptance
- Strong particle identification spanning muons, electrons, and hadrons
- Superconducting Magnet
- Fast read-out paired with online processing (24 MHz in pp and >100 khZ in Pb-Pb)

LoI: CERN-LHCC-2022-009

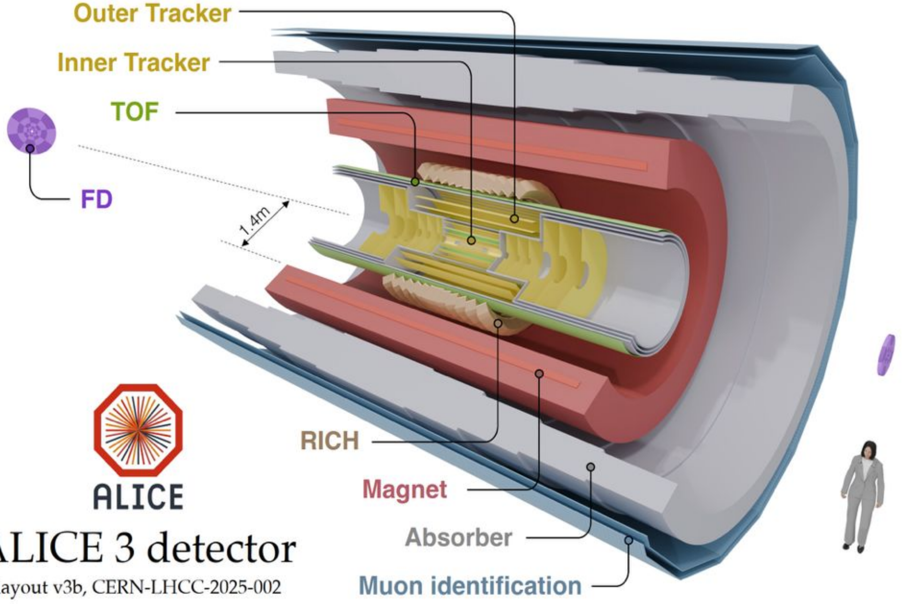

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-LHCC-2025-002
LHCC-G-185

Scoping document for ALICE 3:
ALICE phase IIb upgrade for the LHC Long Shutdown 4

ALICE Collaboration

SD: CERN-LHCC-2025-002



ALICE 3 detector
layout v3b, CERN-LHCC-2025-002

Summary

- Relativistic heavy-ion collisions provide a unique laboratory to study QCD matter under extreme conditions
- A broad range of measurements shows collective behavior and strong interactions with the medium
- Results from small to large systems challenge a simple picture of QGP formation and help constrain its limits
- Heavy flavor and quarkonia probe the interaction, transport, and hadronization of heavy quarks in the medium
- Jets and high-pT probes reveal energy loss and modifications of parton propagation
- Recent light-ion results provide new opportunities to study the onset of collective and medium effects
- The next generation of measurements will move from observation to precision characterization of QGP properties
- **We are moving toward a quantitative understanding of how QCD interactions generate the emergent properties of strongly interacting matter.**

Thank you!

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