Smashing Atoms to Rewind the Universe

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NITheCS
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Theoretical and Computational Sciences

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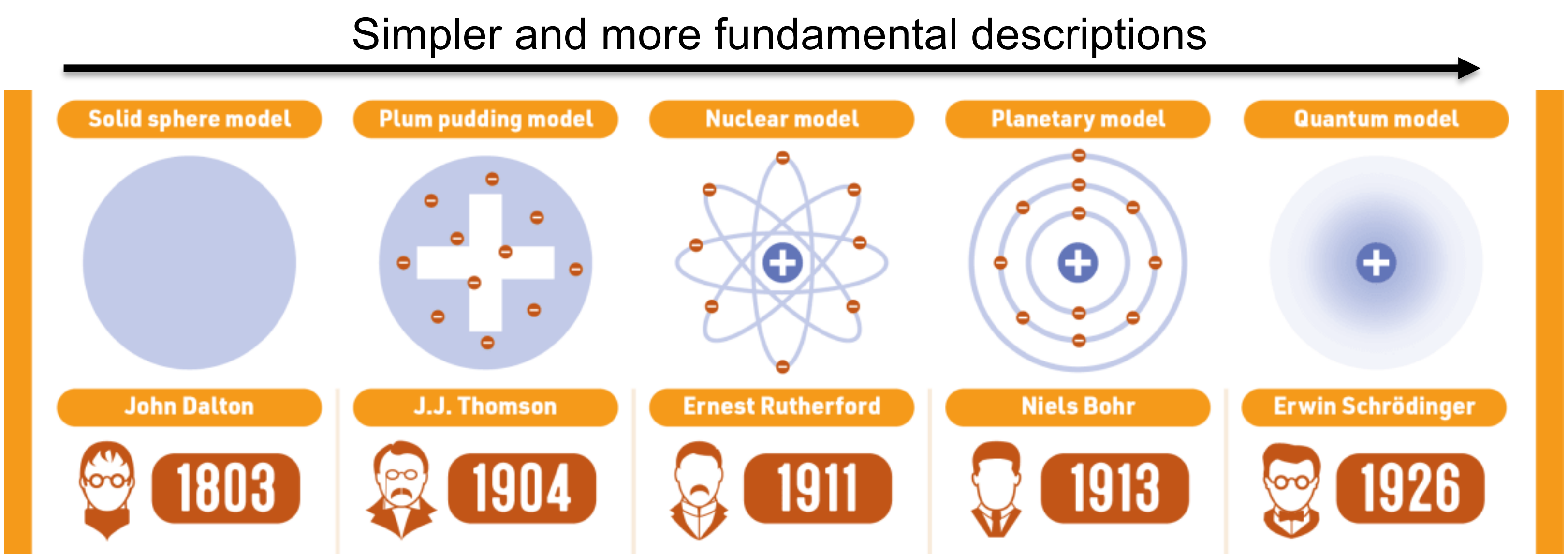
CERN

NRF National Research Foundation

Introduction

Philosophy of Physics

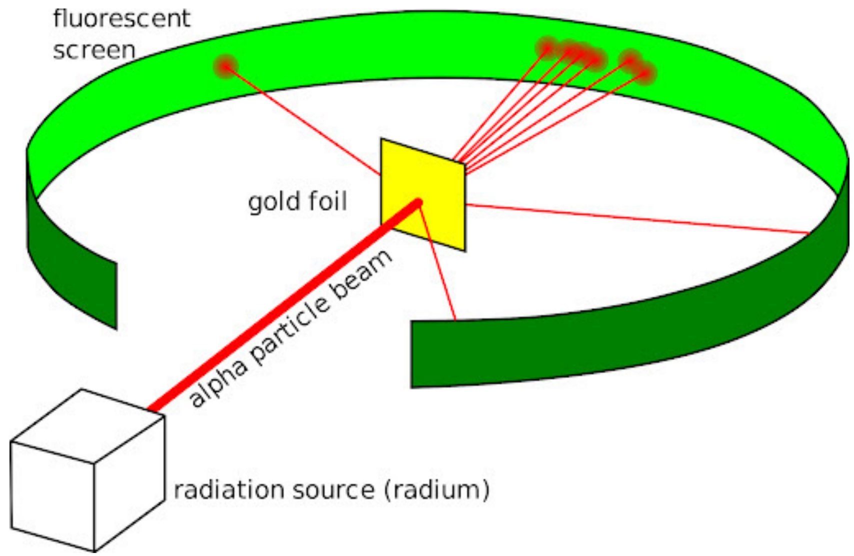
- **Physics follows the reductionist philosophy to understand the universe**
  - **Things are understood in terms of simpler constituents**



Source: https://www.compoundchem.com/2016/10/13/atomicmodels/

Studying the Small

- **In order to reach more fundamental descriptions, one must understand objects at smaller scales**
- **de Broglie tell us:** $\lambda = \frac{h}{p} \Rightarrow$ **small scales are probed by high energies**

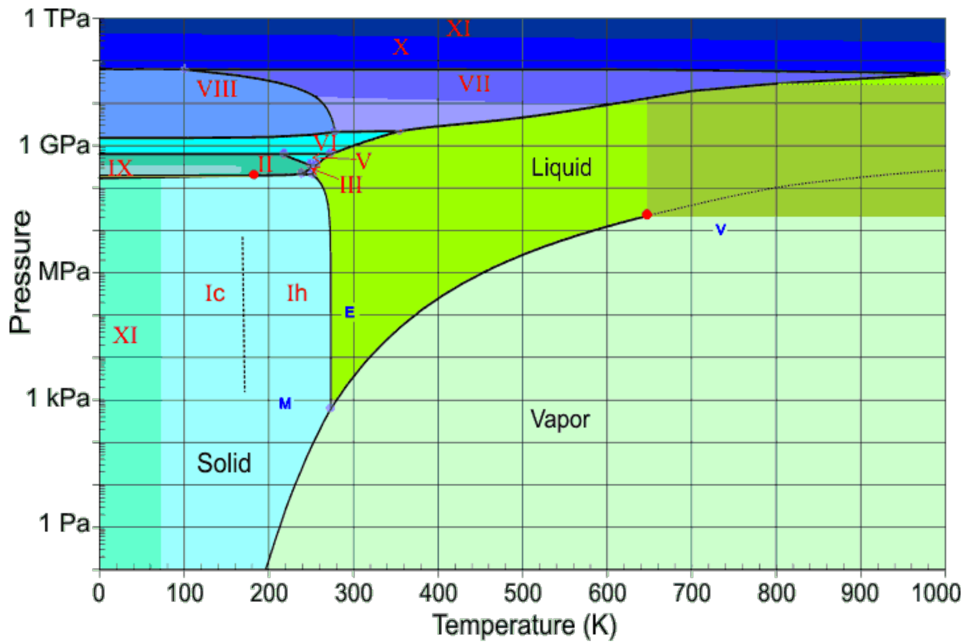


Rutherford gold foil experiment

Source: https://www.compoundchem.com/2016/10/13/atomicmodels/

Studying the Many

- **Understanding the small does not tell us everything!**
  - **SM lagrangian ⇒ … ⇒ tables, chairs, people, etc. is not an easy calculation**
- **Therefore understanding *collective* behaviour is interesting and important work**



Back to the Small: Zoom in on the Nucleus

- Nuclei are made up of protons and neutrons
- p + n are made up of quarks and gluons
- Under normal circumstances, quarks and gluons are confined to colour-neutral objects (like protons and neutrons) by the *strong force*

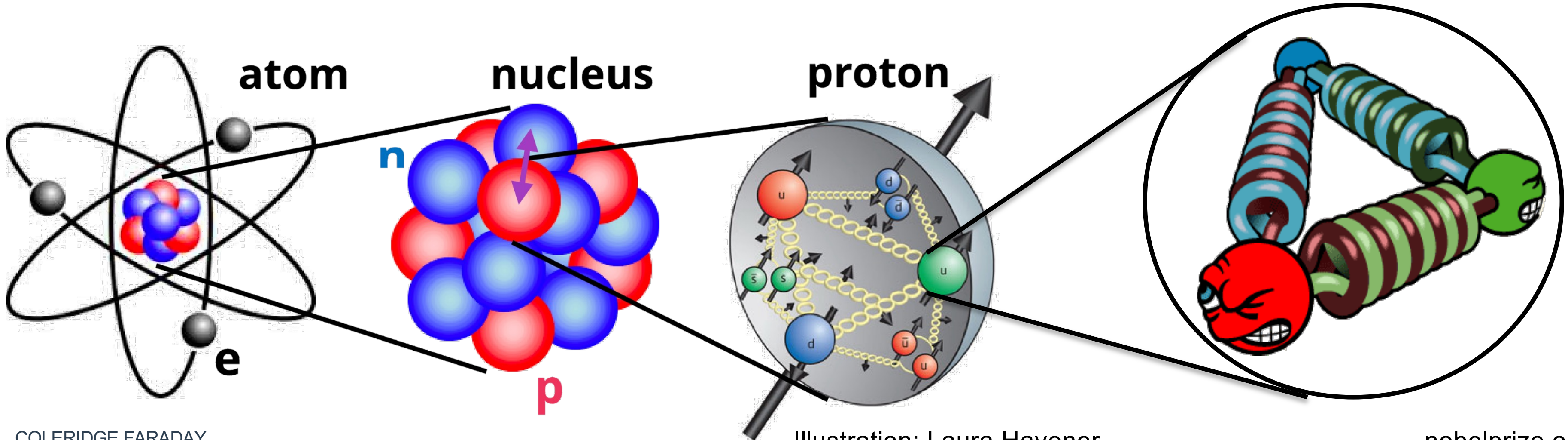
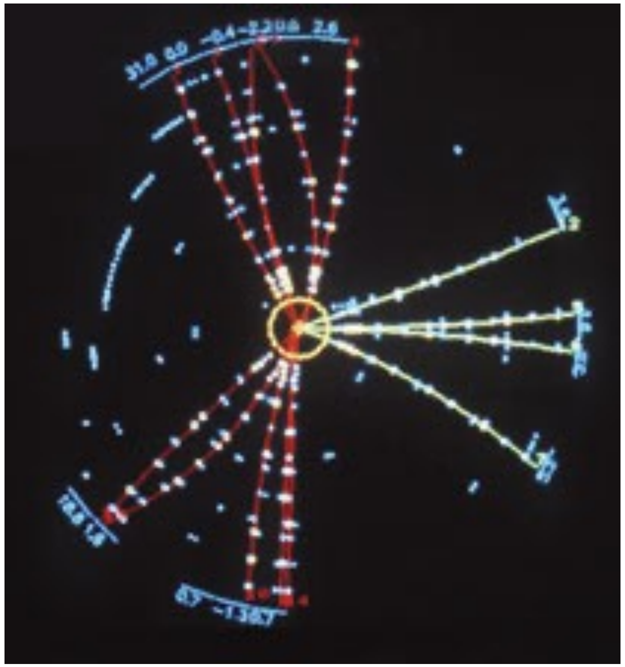


Illustration: Laura Havener

nobelprize.org

Strong Force

- Described by quantum chromodynamics (QCD)
- Extremely complicated, even today
  - 9 years' of Nobel Prizes
  - Clay $1M Prize: prove there exists mass gap

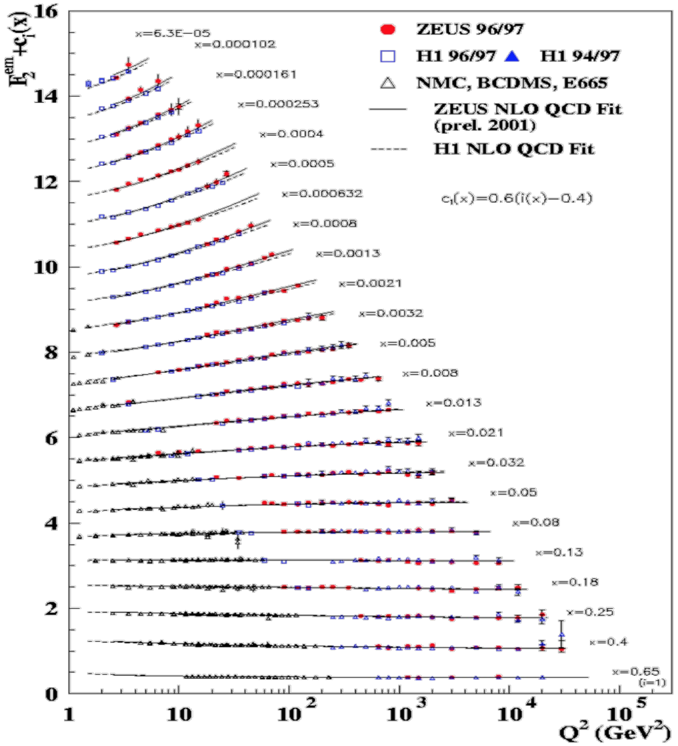


Three-jet events used to discover the gluon

Source: CERN, https://home.cern/news/news/physics/four-decades-gluons

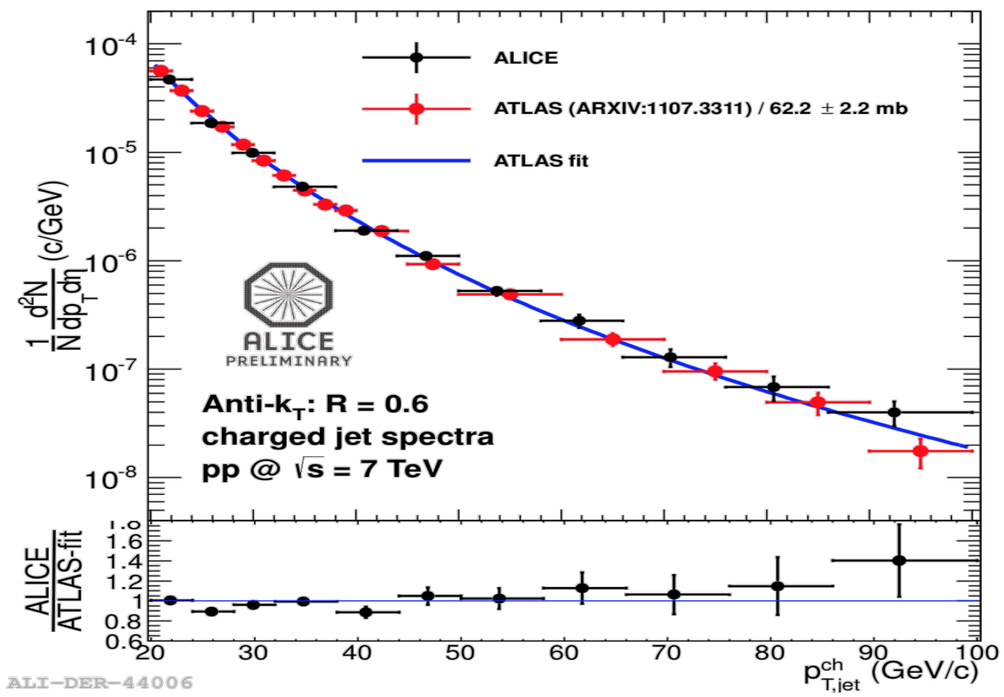
Much of QCD Particle Physics Understood

- e+p Collisions



C. A. García Canal, R. Sassot; *AIP Conf. Proc.* 30 August 2000; 531 (1): 199–246. https://doi.org/10.1063/1.1315039

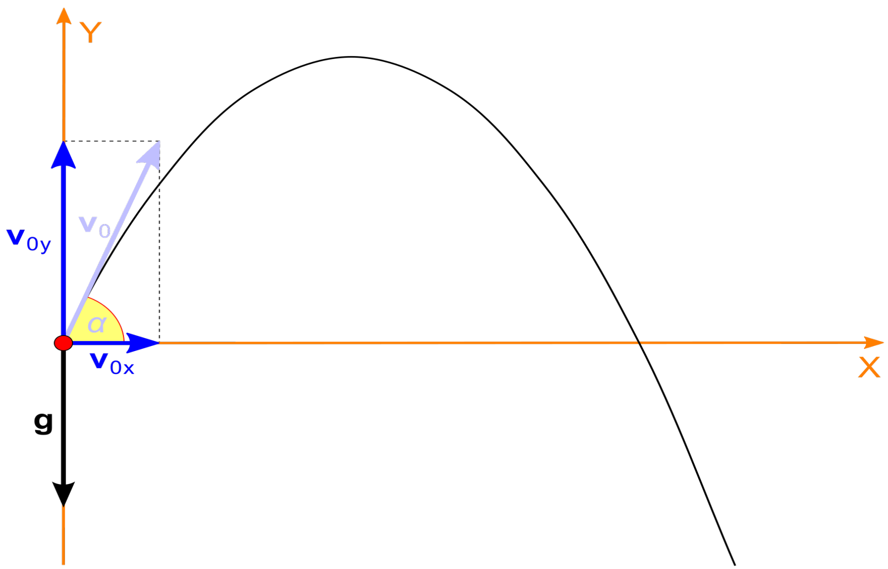
- p+p Collisions

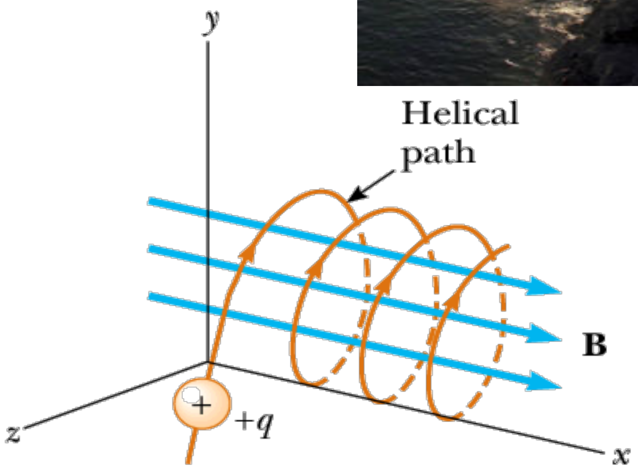


Michal Vajzer, arxiv: 1311.0148

Physics of the Small

- Much of physics is ***particle*** physics
  - – What is the motion of a single object?





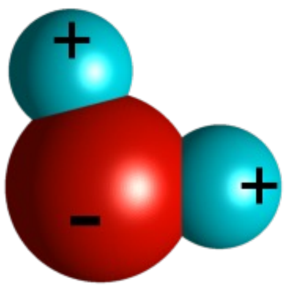
Back to the Many: H20

- How does Maxwell equations + quantum mechanics lead to, e.g., water?

One H_20 is very boring

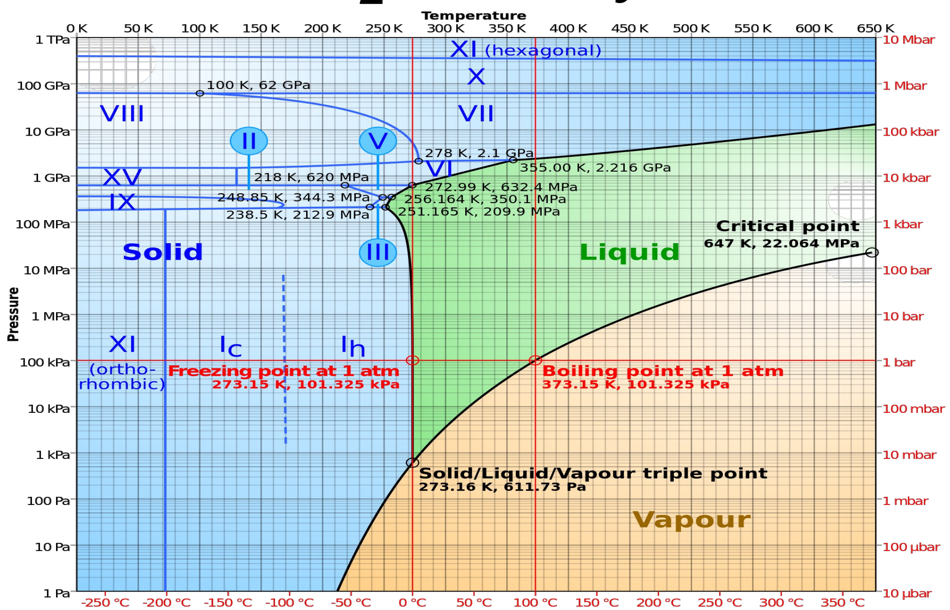
Vibrates, rotates

Extremely well understood



http://howyourbrainworks.net/content/neutral-polar-and-electrically-charged-particles

Lots of H_20 is *very* interesting



http://en.wikipedia.org/wiki/Phase_diagram

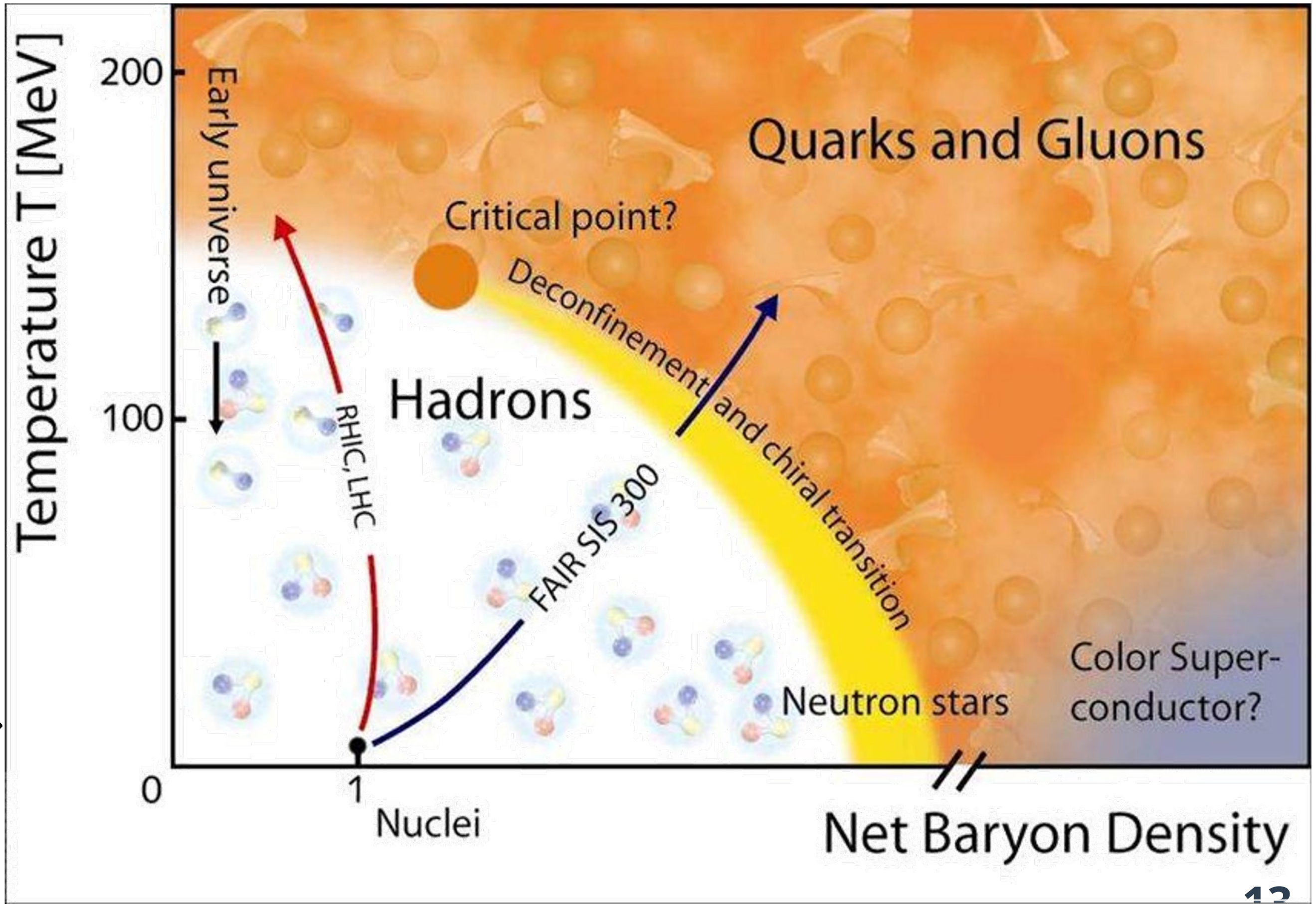
Emergent Phenomena

- Many particles together can have ***collective*** behavior, not directly understandable from understanding a single object
  - Pressure, temperature, compressibility, waves

What are we Studying?

- We want to understand the multi-particles dynamics of quarks and gluons
  - Both the *small* and the *many*
  - Study the phase diagram of nuclear matter

- Lots of question marks ⇒ lots of work to be done!



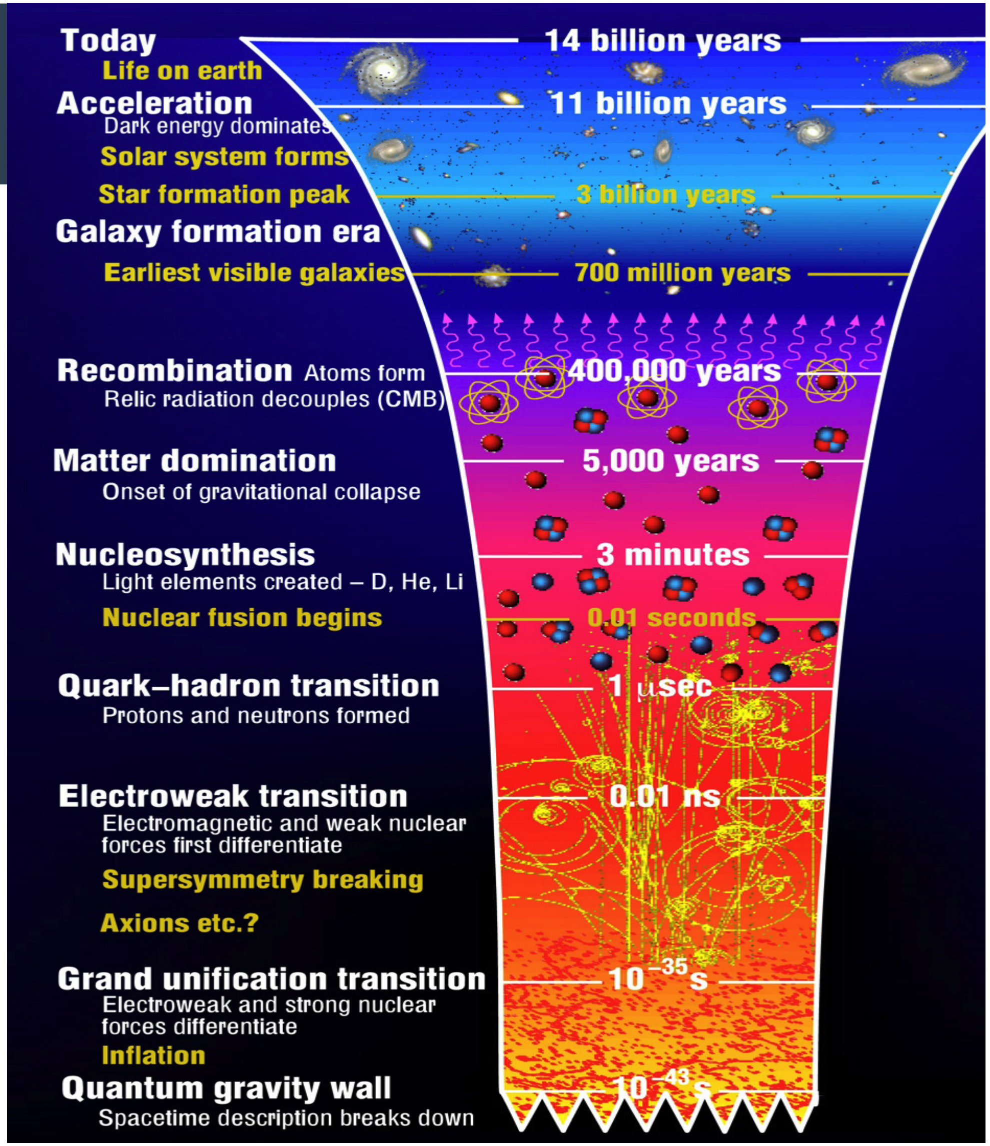

Motivation

WHY? Basic Curiosity

- Desire to know:
  - What are the unchanging physical laws of the matter that surrounds us?

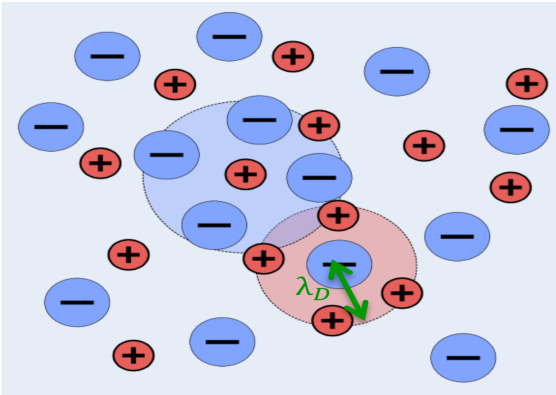
WHY? Early Universe

- Turn up the heat, turn back the clock
- Physics of a **trillion degrees**
  - Physics a **micro-second after the Big Bang**
- **400 thousand years before the CMB!**
  - **Only way to understand the universe in the first 400 thousand years**

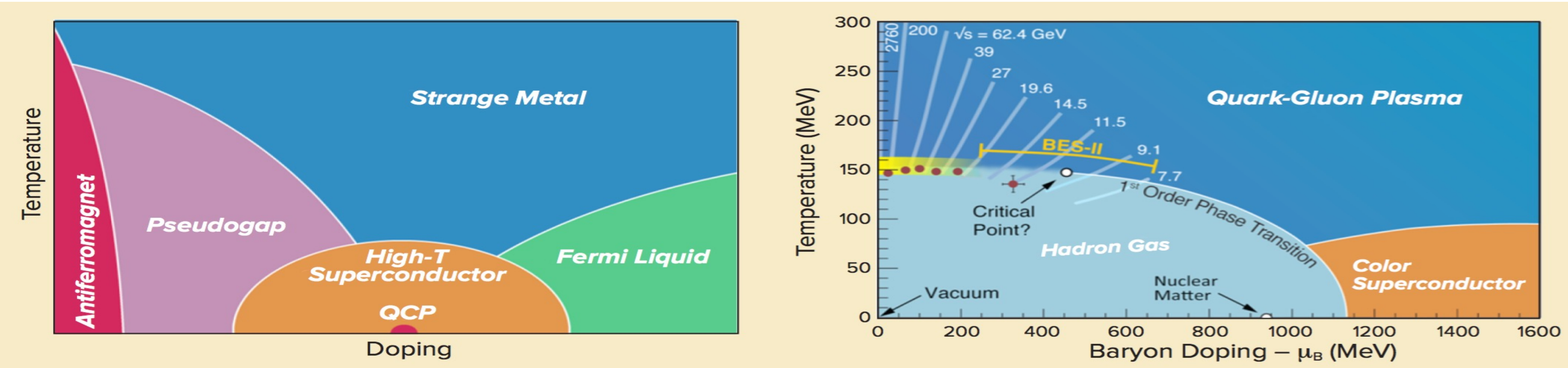


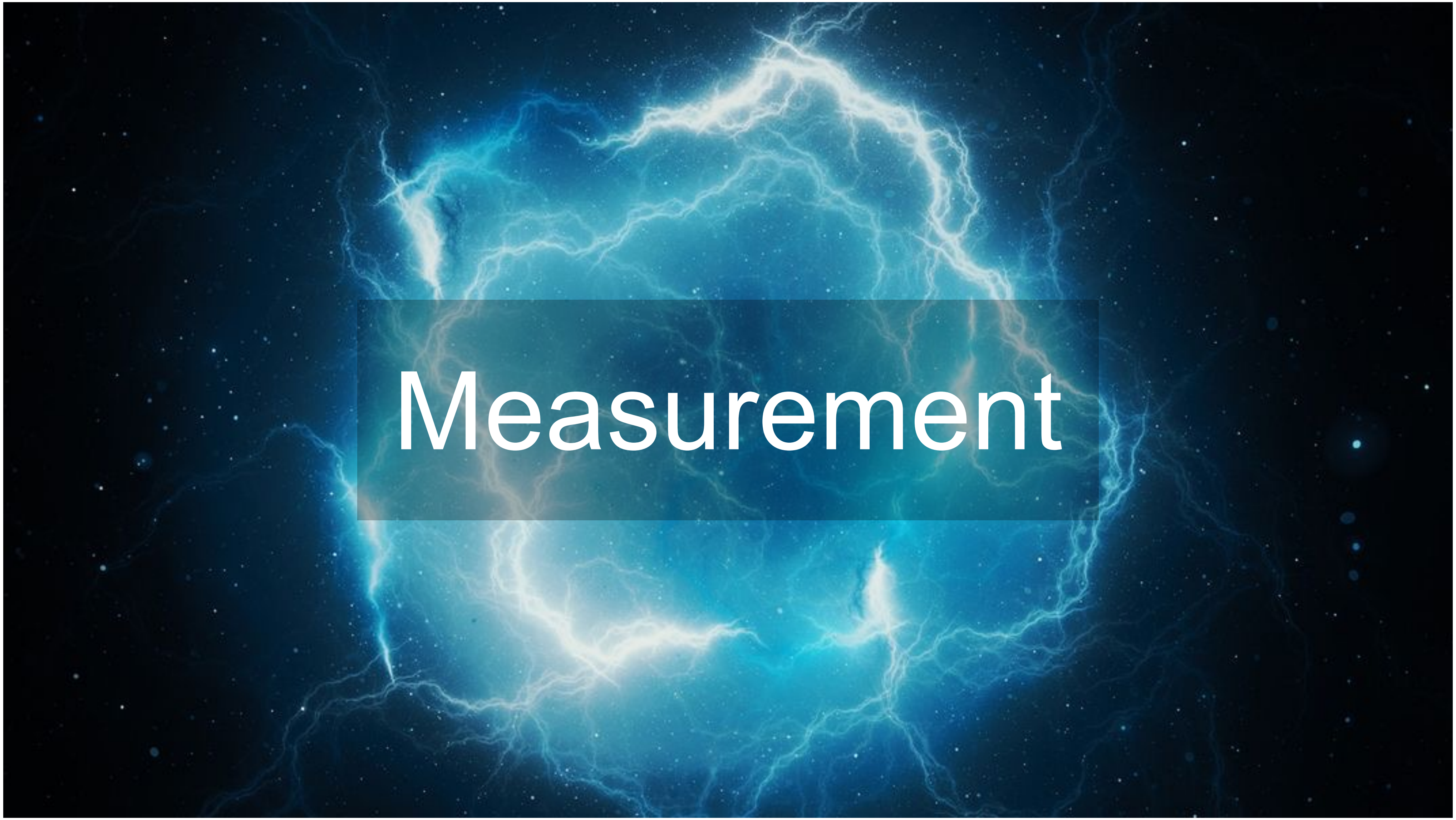
WHY? Connections to Plasma/CM

- Does quark-gluon plasma organize itself like a weakly-coupled gas?
- Or more like a strongly-coupled fluid?



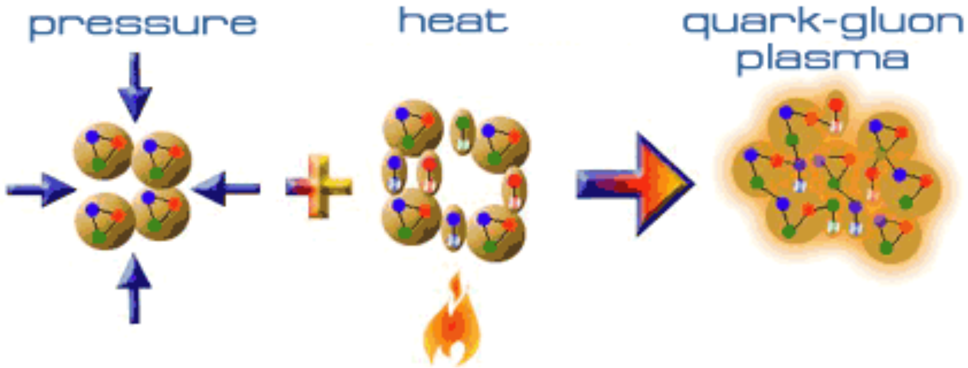
Debye screening

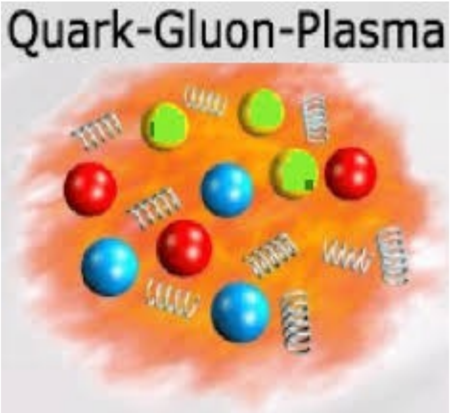



Measurement

The Quark Gluon Plasma

- Hadrons overlap
- Quarks roam freely in the medium (*deconfinement*)
- Temperatures of a trillion degrees
- Lasts only 10^{-23}seconds

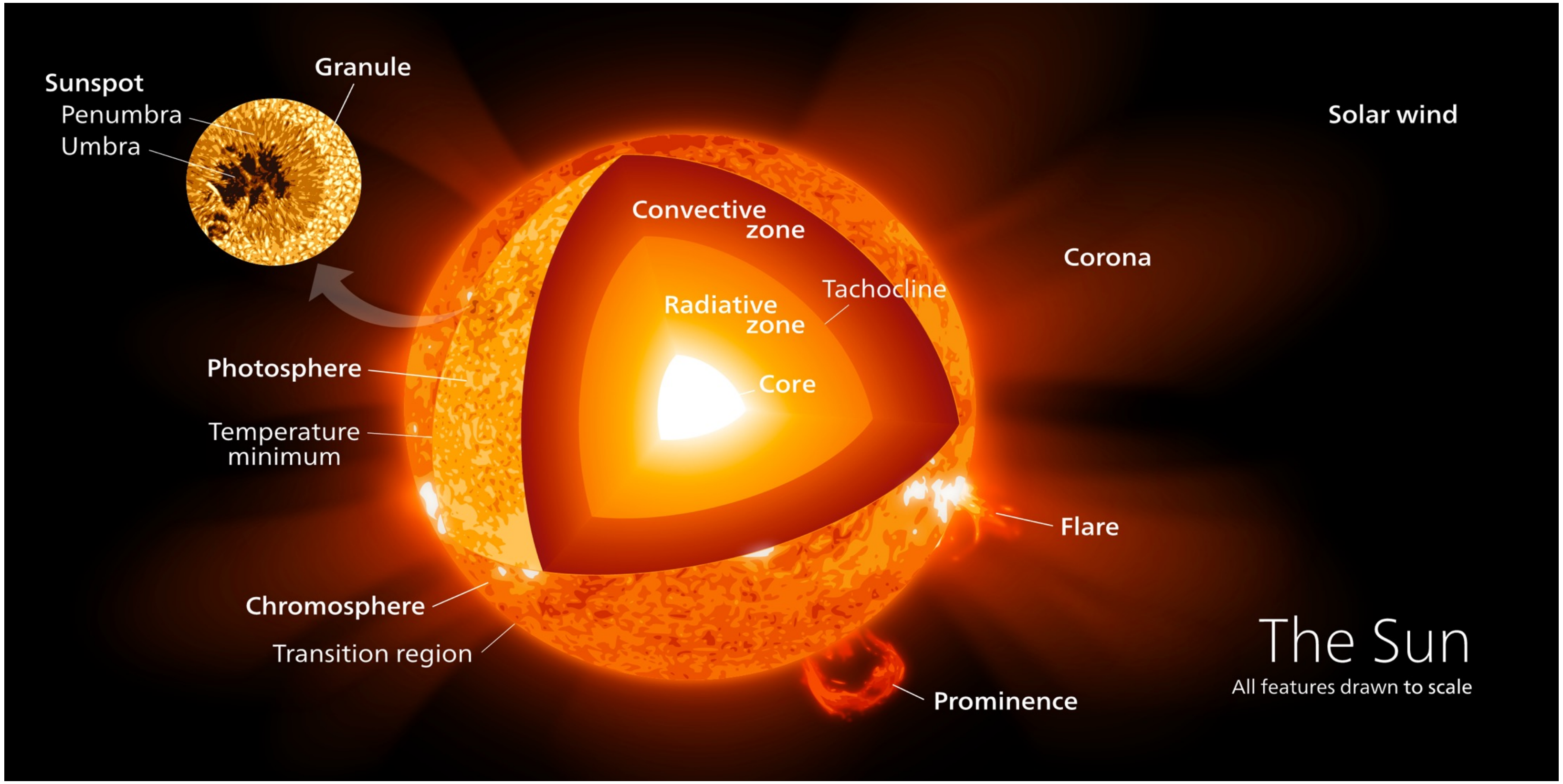




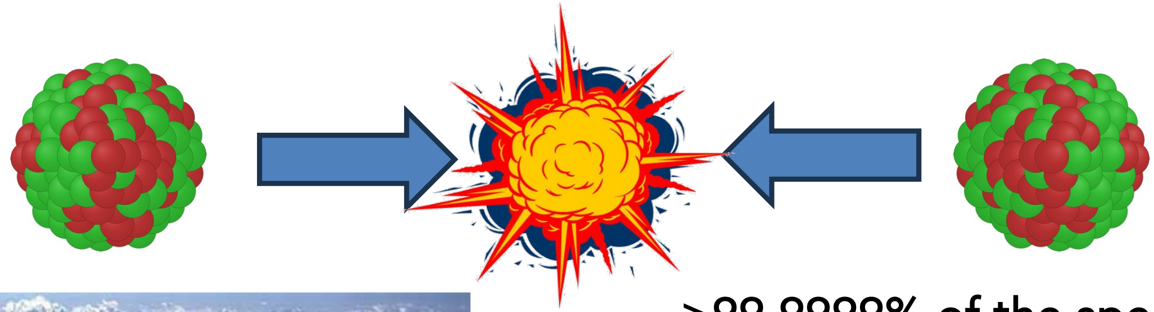
https://www.researchgate.net/figure/Illustration-of-quark-gluon-plasma-QGP-comprising-several-red-green-blue-RGB_fig12_280969662

How hot is a trillion degrees?

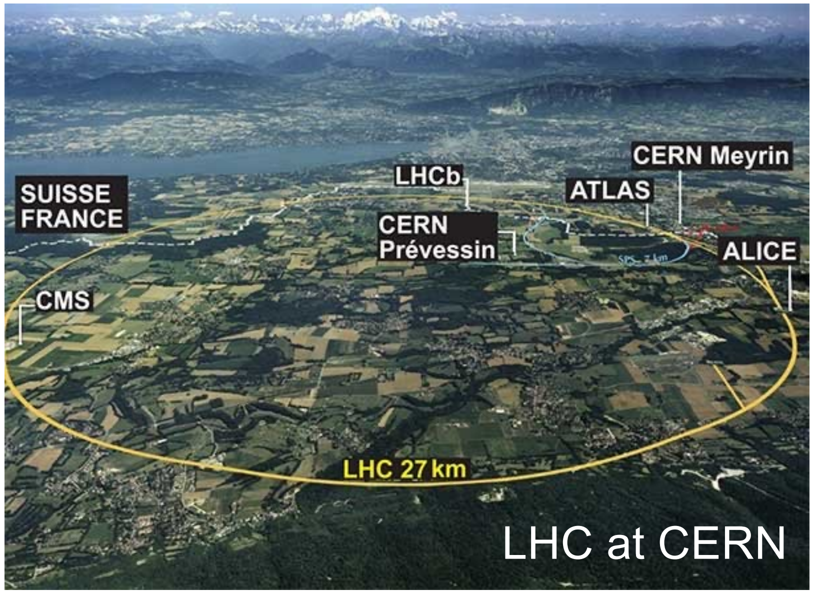
- 100,000x hotter than the center of the sun

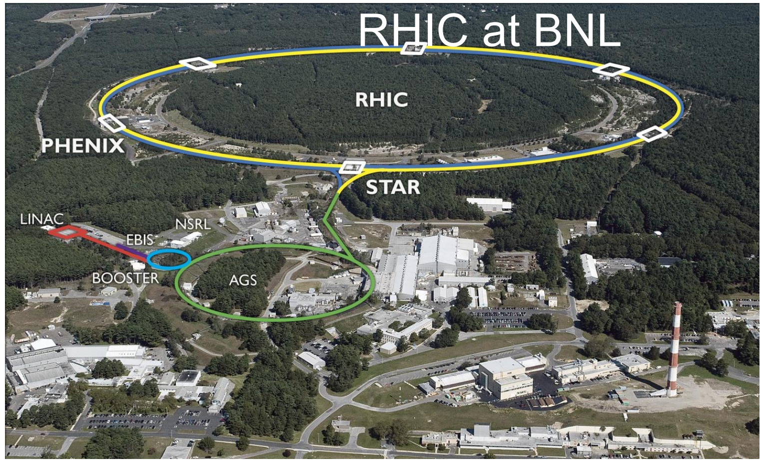


Large-hadron colliders

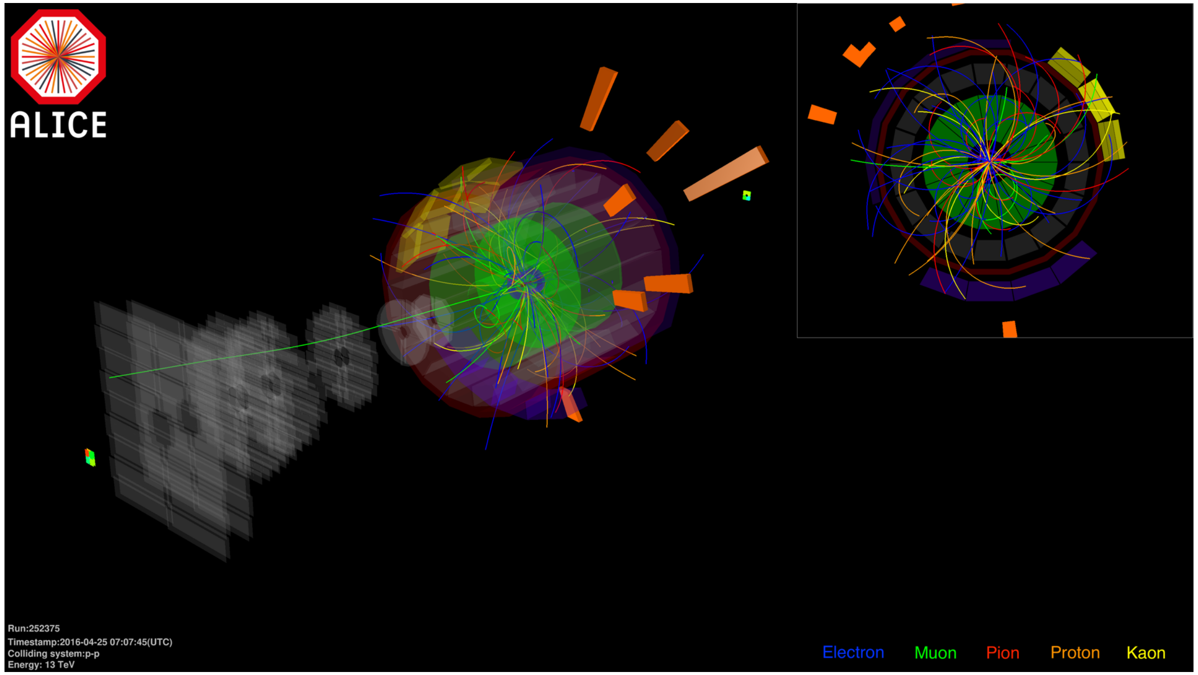


>99.9999% of the speed of light





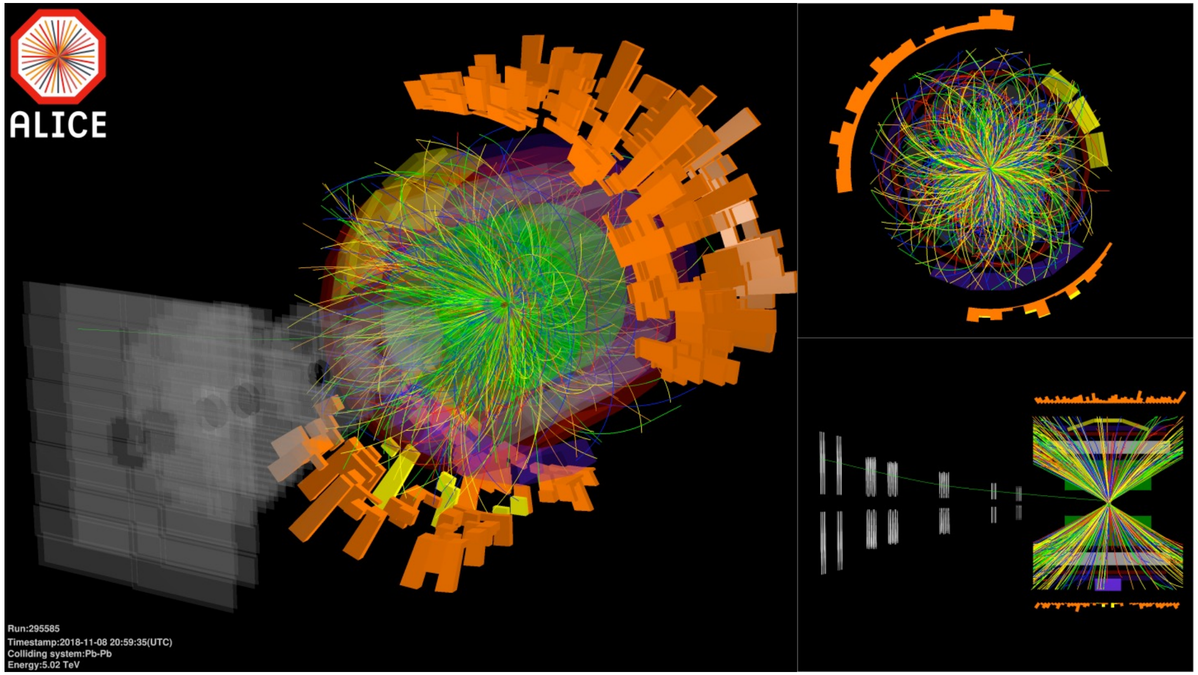
p + p collisions



Source: CERN, https://cds.cern.ch/record/2149032

- **Teaches us about the standard model**
- **Potential way to find beyond the standard model (BSM) physics**
- **Used as a baseline for understanding heavy-ion collisions**

Heavy-ion collisions: what we see



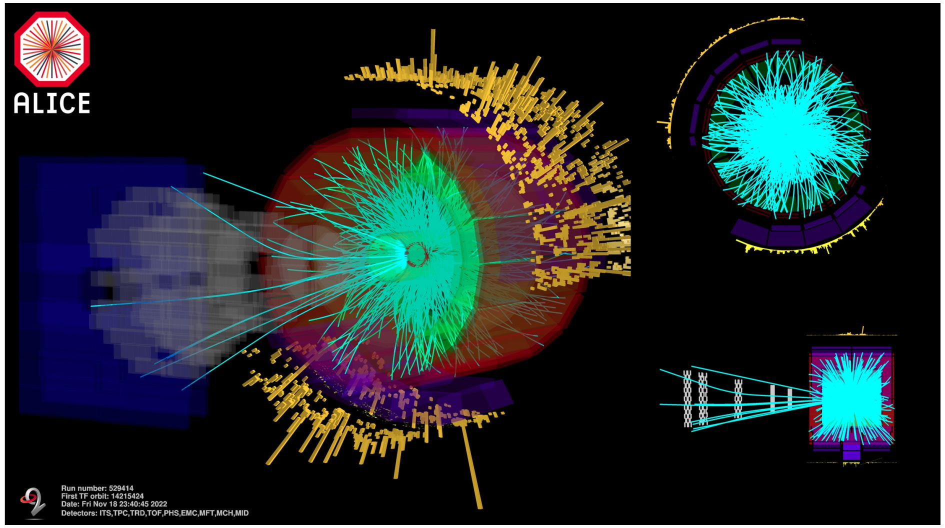
Source: CERN, https://home.cern/news/news/accelerators/time-lead-collisions-lhc

- **Many, many more particles**
- **Information from the collision is encoded in the properties of the final state particles**
- **Observables must be constructed which are sensitive to various properties of the state of matter formed in the collision**

Measuring the Quark Gluon Plasma

QGP in heavy-ion collisions lasts for only $\simeq$ **10^{-23} s!** $\rightarrow$ difficult to probe

Experiment



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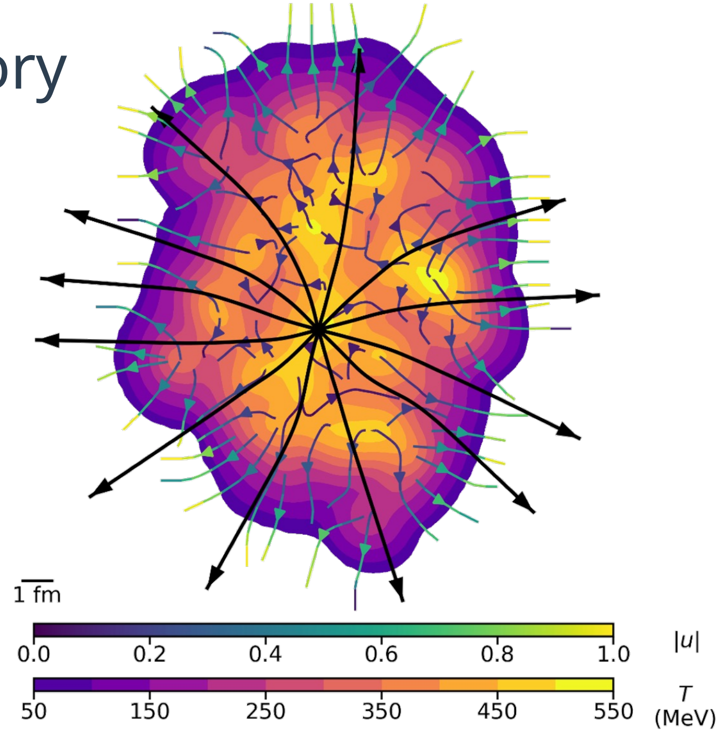
Theory

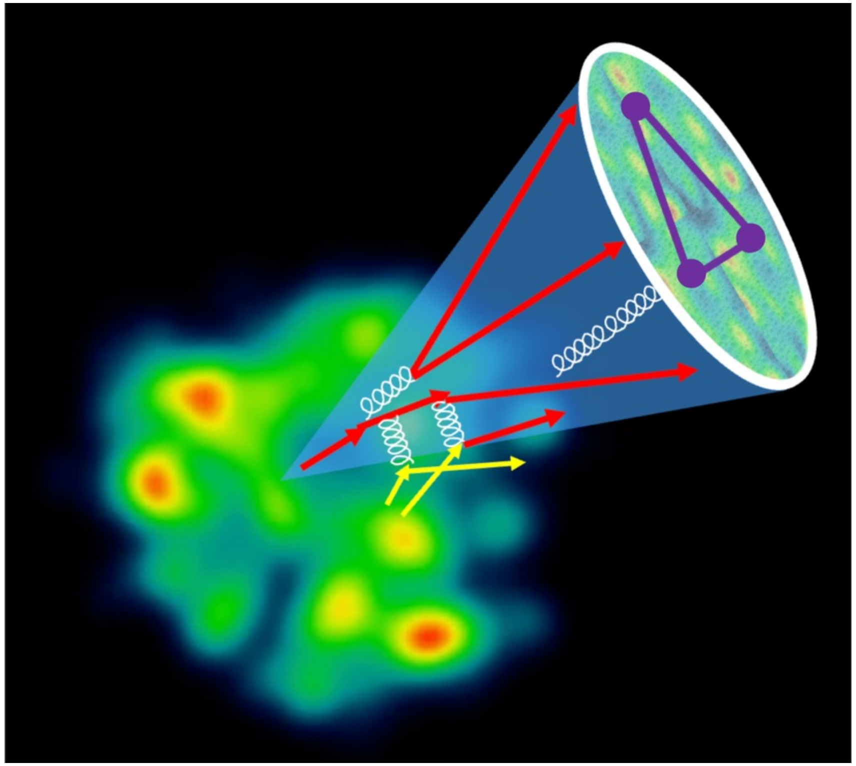


Source: CERN

J. Bahder, H. Rahman, M. D. Sievert, and I. Vitev, arxiv: 2412.05474

How do we know a QGP is formed?

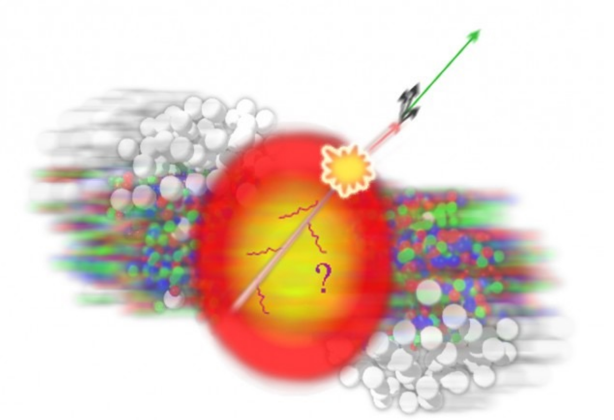
- Look for *signatures* of QGP formation
- How does the QGP effect the properties (momentum, particle number, angular direction, etc.) of detected particles



Signatures of the QGP

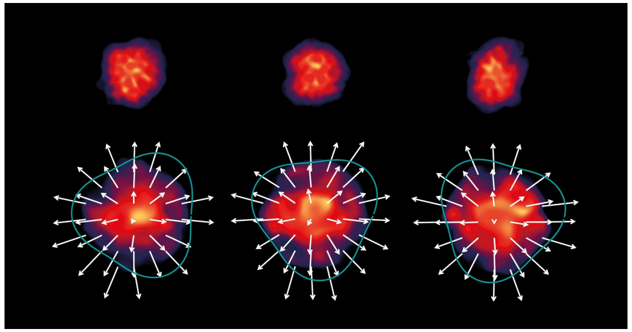
Jet Quenching

Particles lose energy through interactions in the QGP



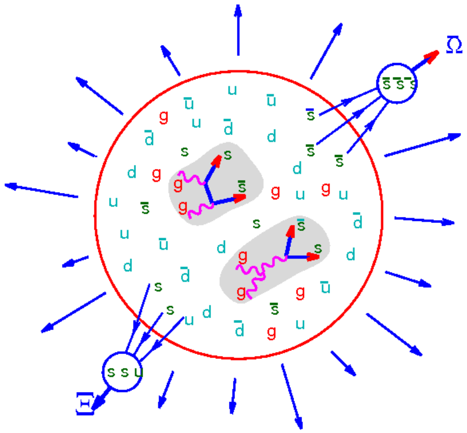
Collective Flow

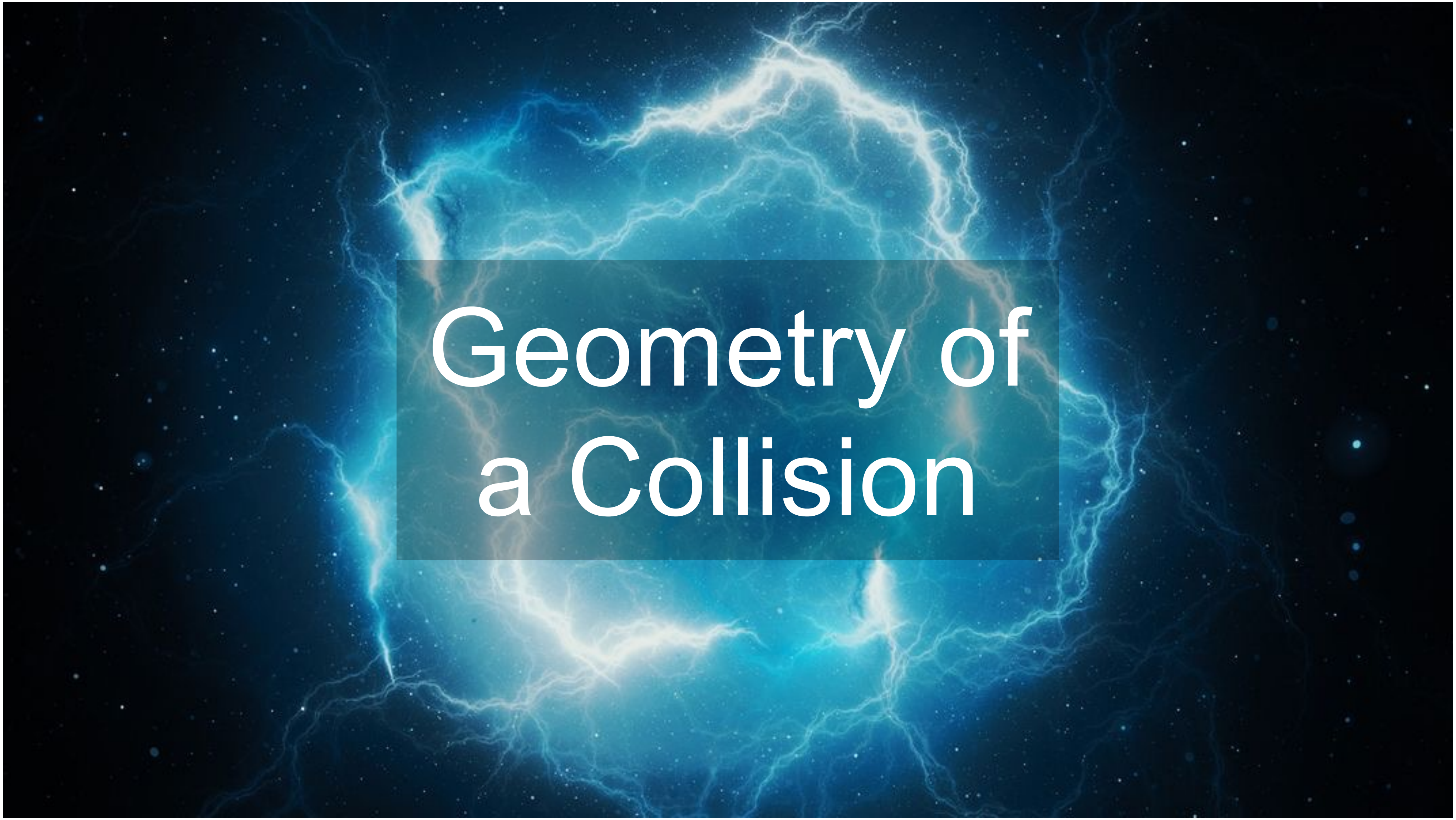
Pressure gradients change the distribution of particles



Strangeness Enhancement

Thermal equilibration leads to higher mass quarks (strange quarks) being produced

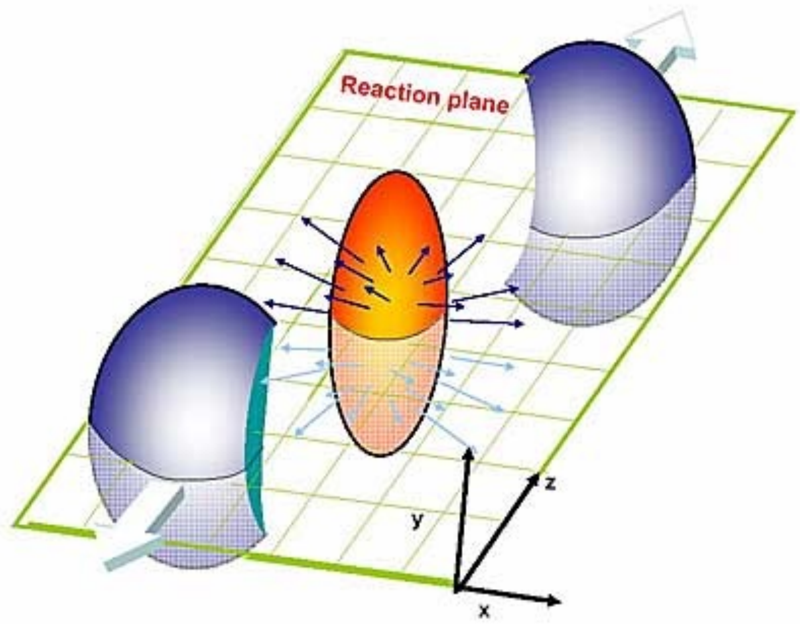



Geometry of
a Collision

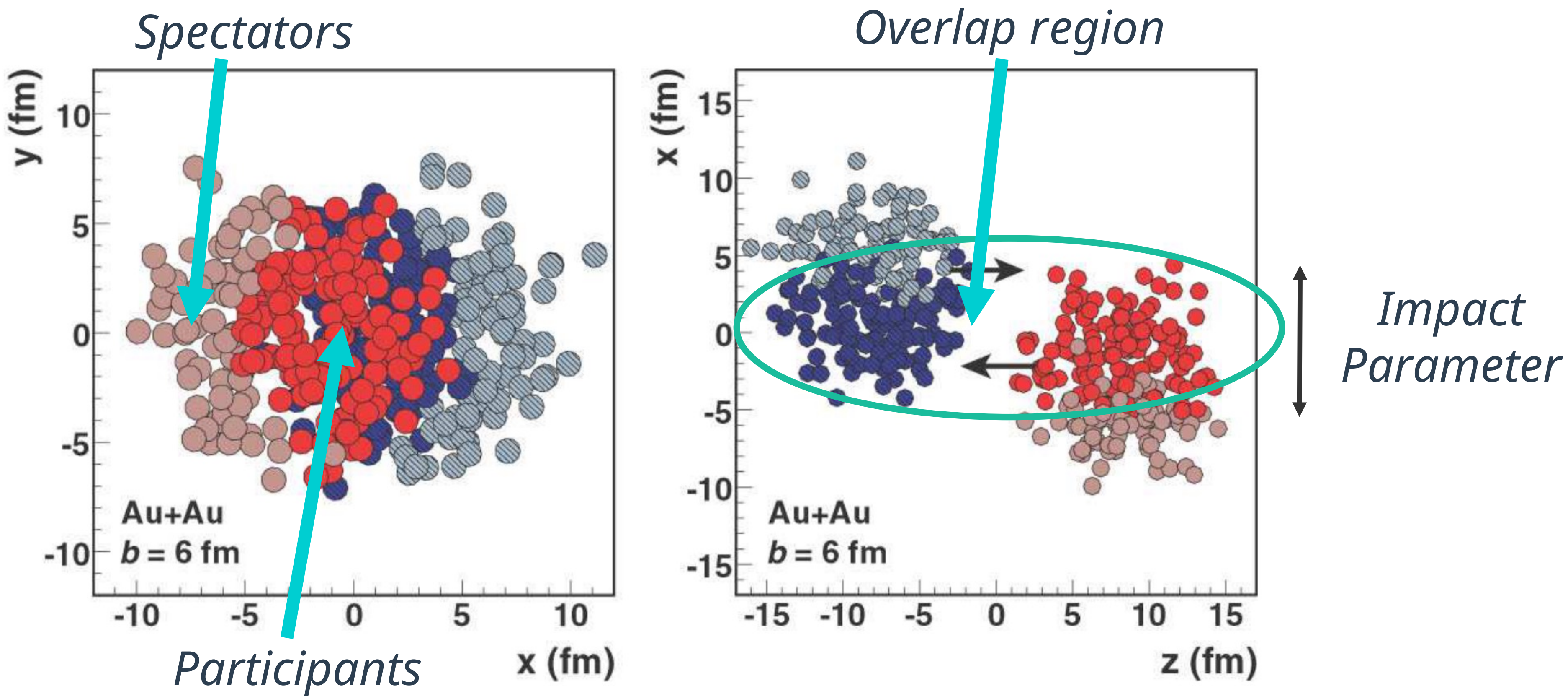
The Glauber Model

The *Glauber Model* is used to understand **geometrical aspects** of a heavy-ion collision

- Assumes
  - Nucleons are **distributed independently** in the nucleus
  - Nucleons interact with other nucleons, but are **undeflected**

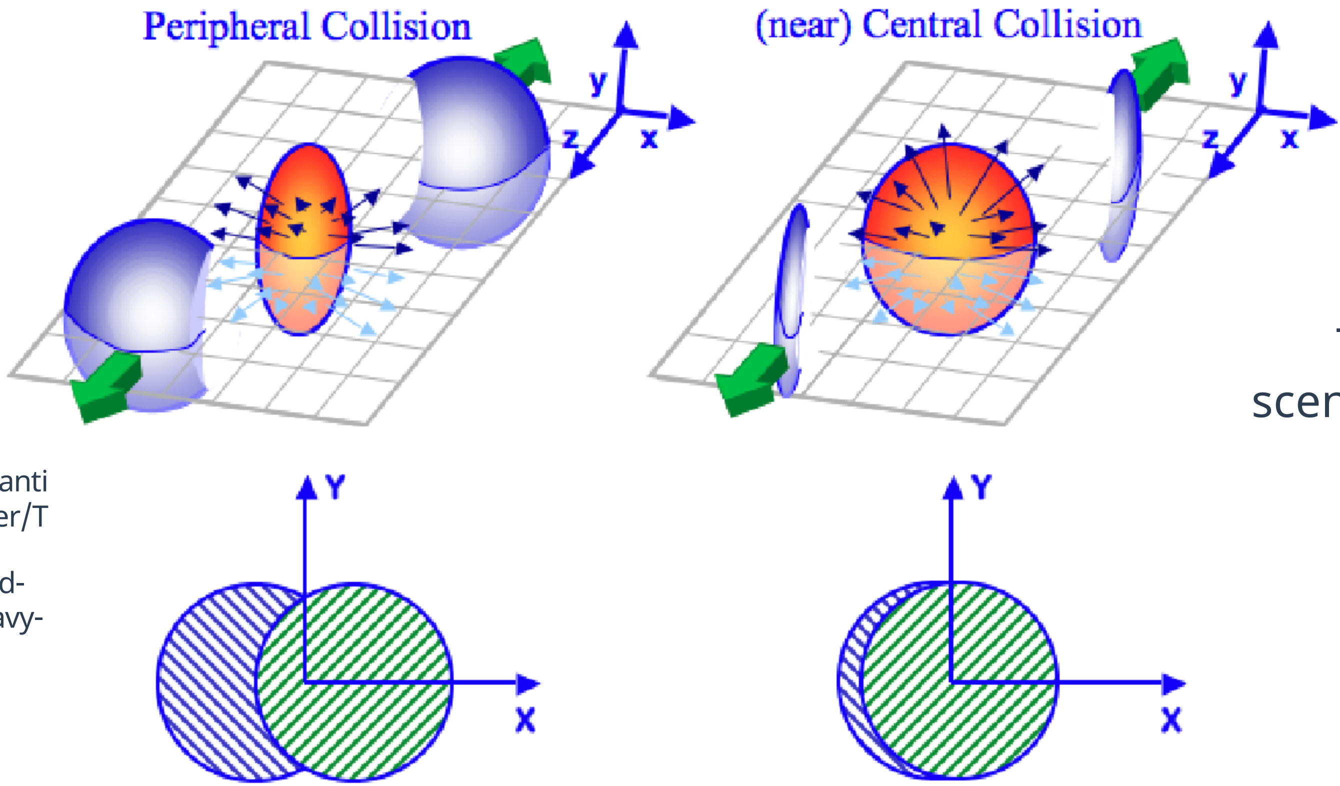


The Glauber Model continued



Glauber model implications

Q: How to know what *type of collision* occurred?



These two scenarios are very different!

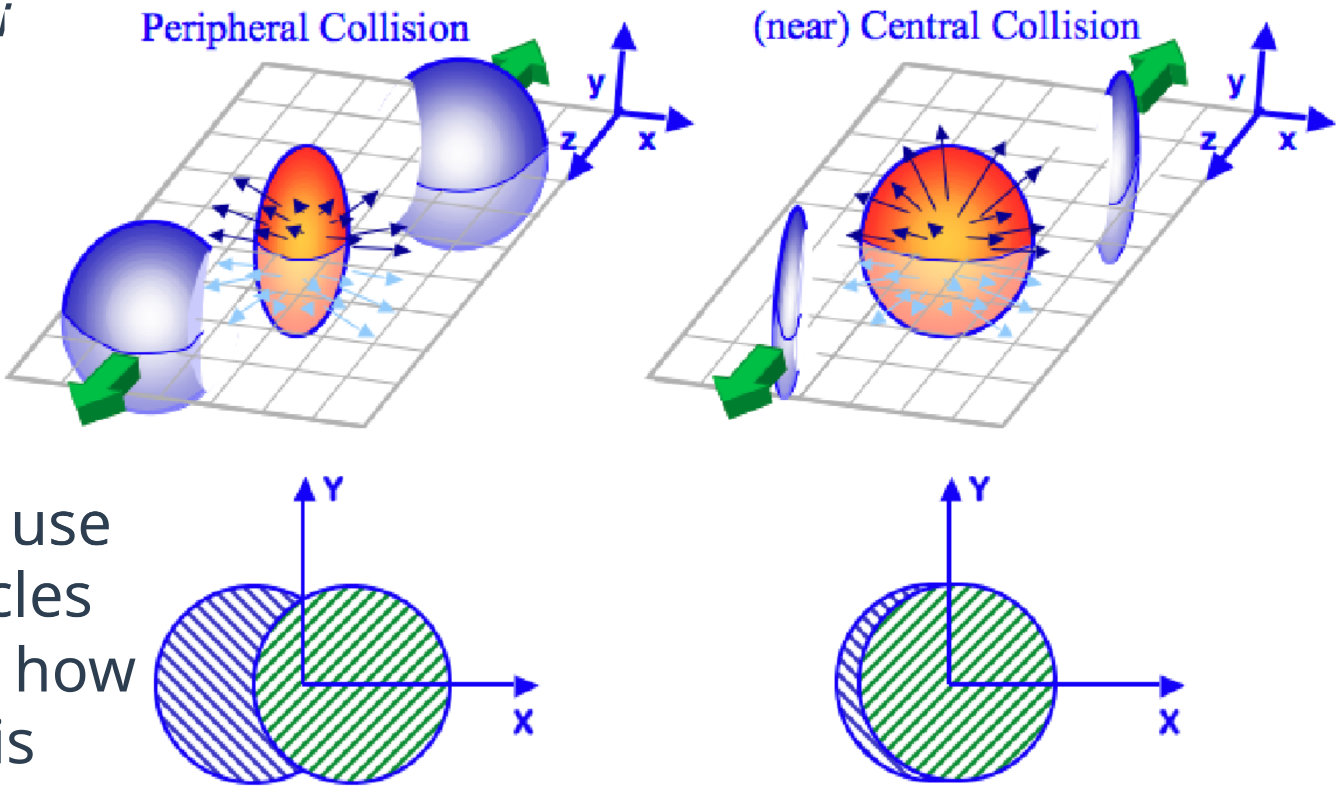
https://www.semanticscholar.org/paper/Two-Particle-Correlations-And-The-Ridge-In-Heavy-Moschelli

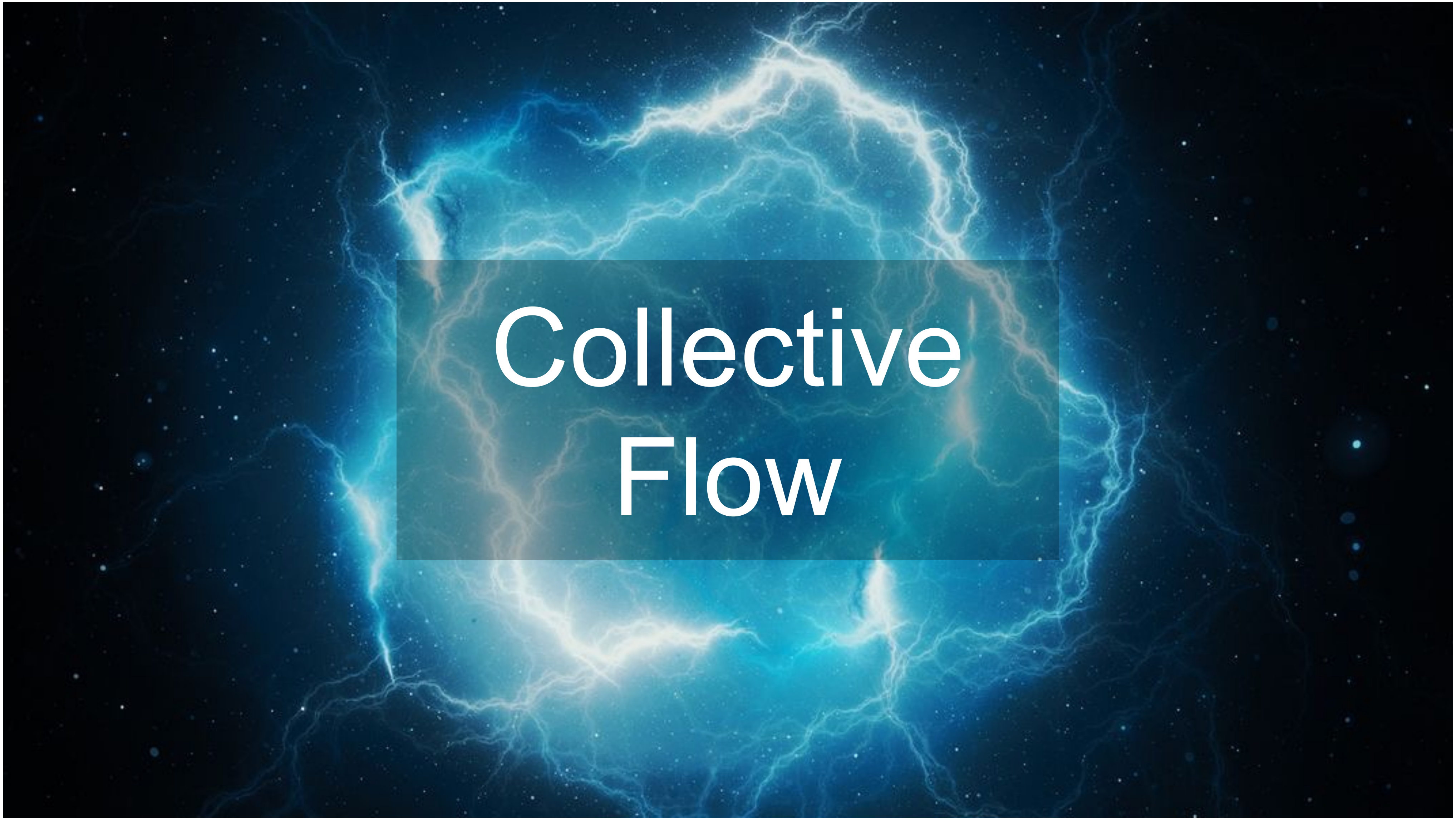
Centrality

One talks about how *central* a collision is

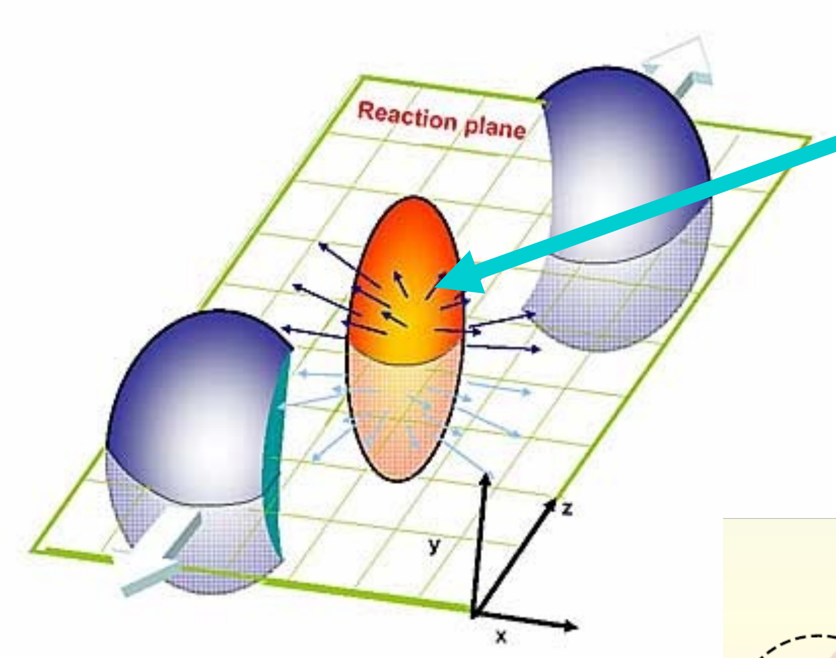
The more the two nuclei overlap, the more central

Experimentalists can use the number of particles produced to work out how central a collision is




Collective
Flow

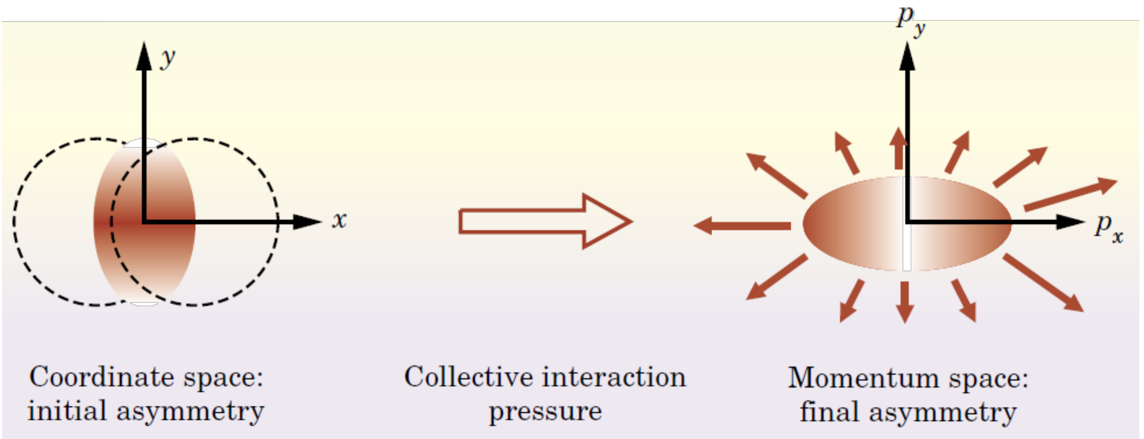
Collective Flow



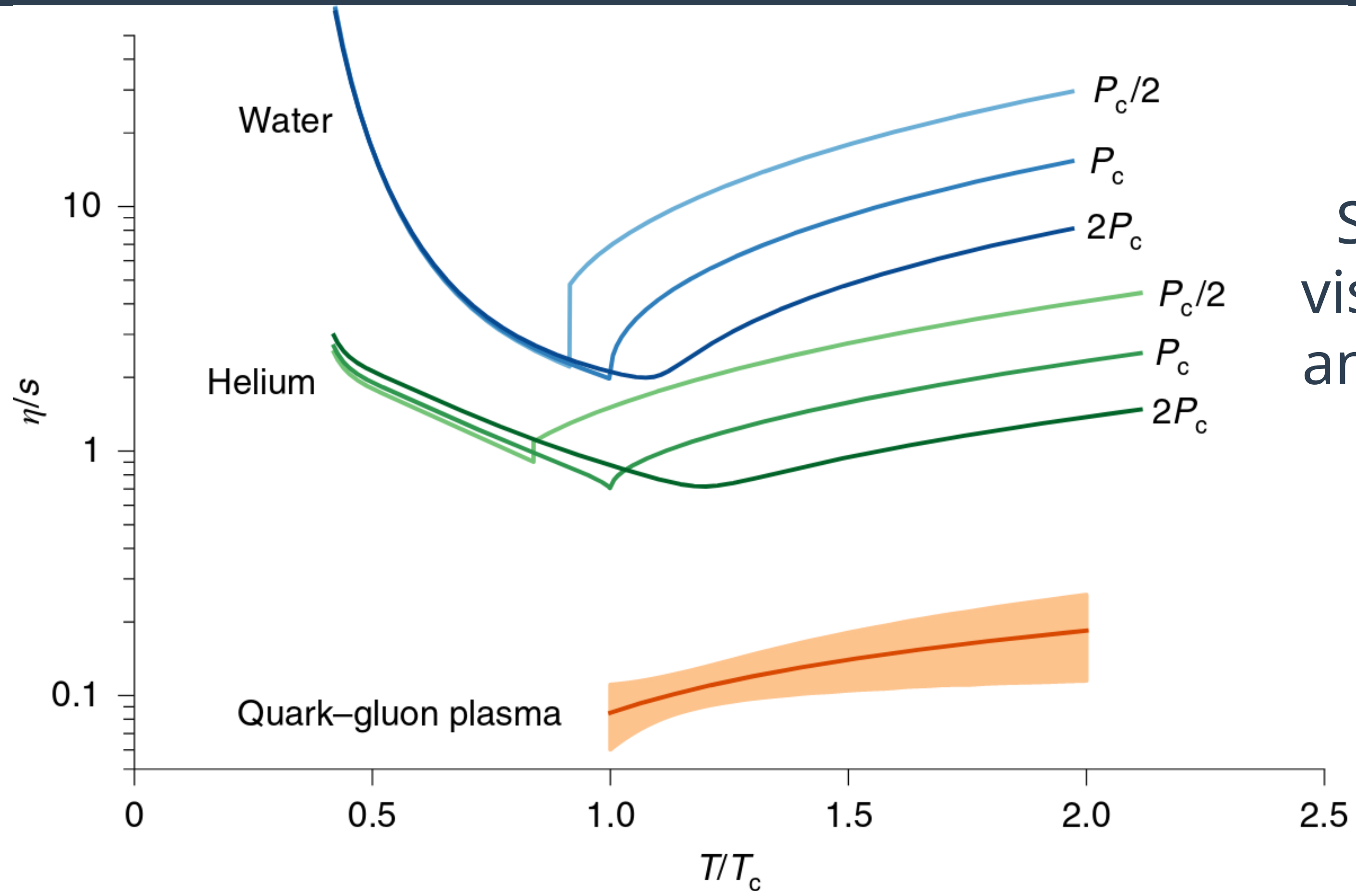
Non-symmetrical shape initially

$\Longrightarrow$

Non-symmetric final state in momentum space, due to pressure gradients



Creation of the Most Perfect Fluid



Smallest viscosity of any known fluid!

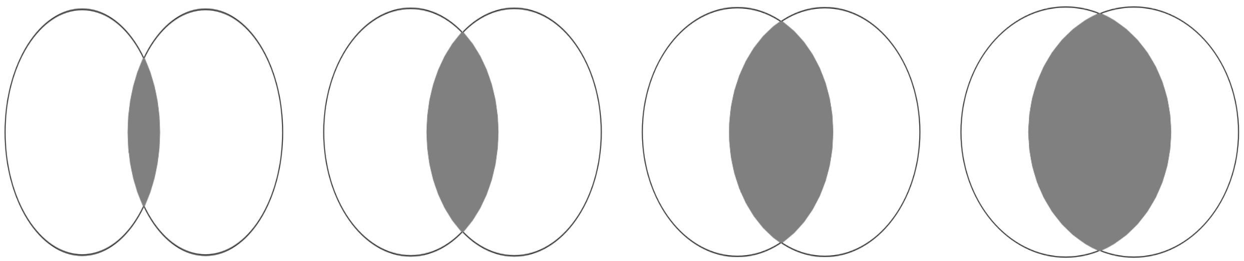
Elliptic flow – v_2

- The v_2 captures the *ellipticity* of the collision

- v_2 is the Fourier coefficient of $\cos(2\varphi)$

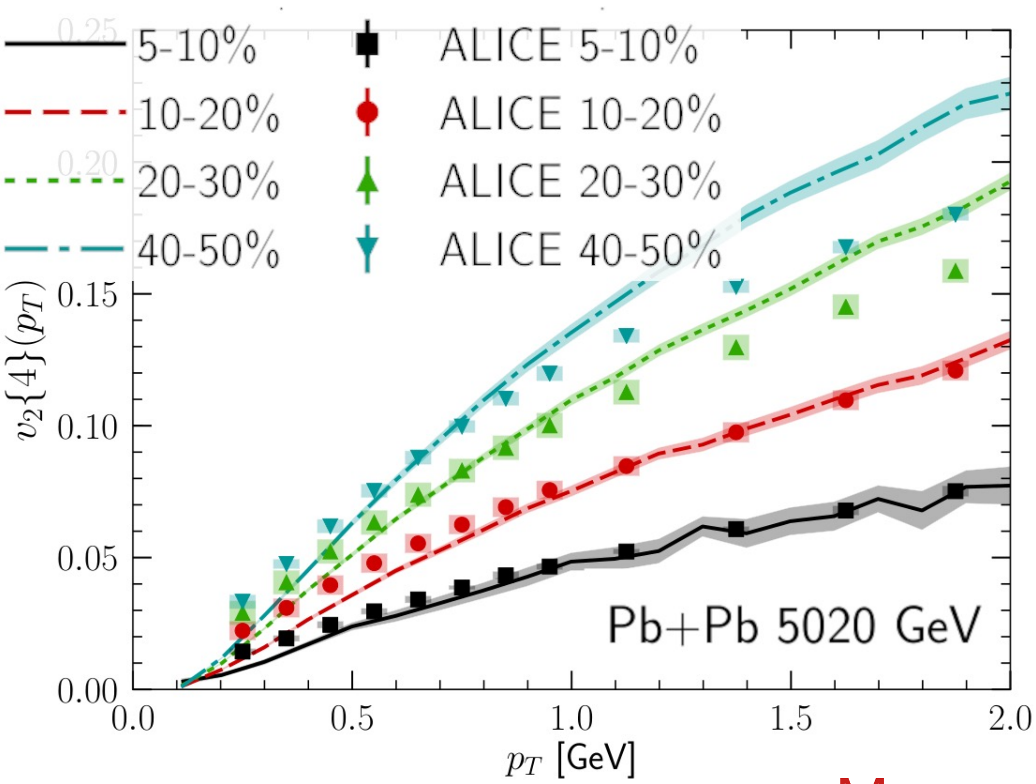
Very elliptic

Less elliptic

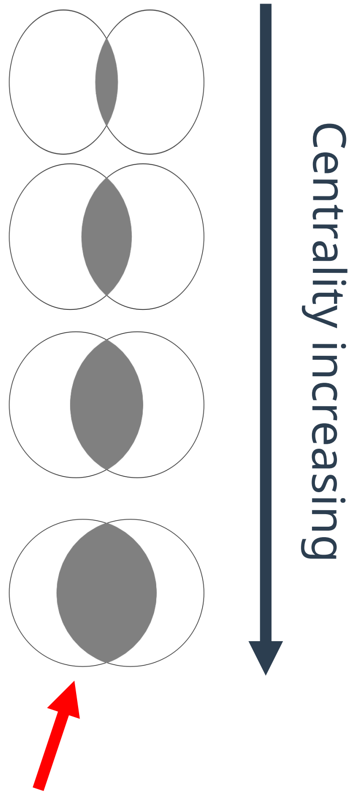


Quantitative Comparison to Data

Hydrodynamics models describe data



Schenke et al., Phys. Rev. C 102 (2020) 044905



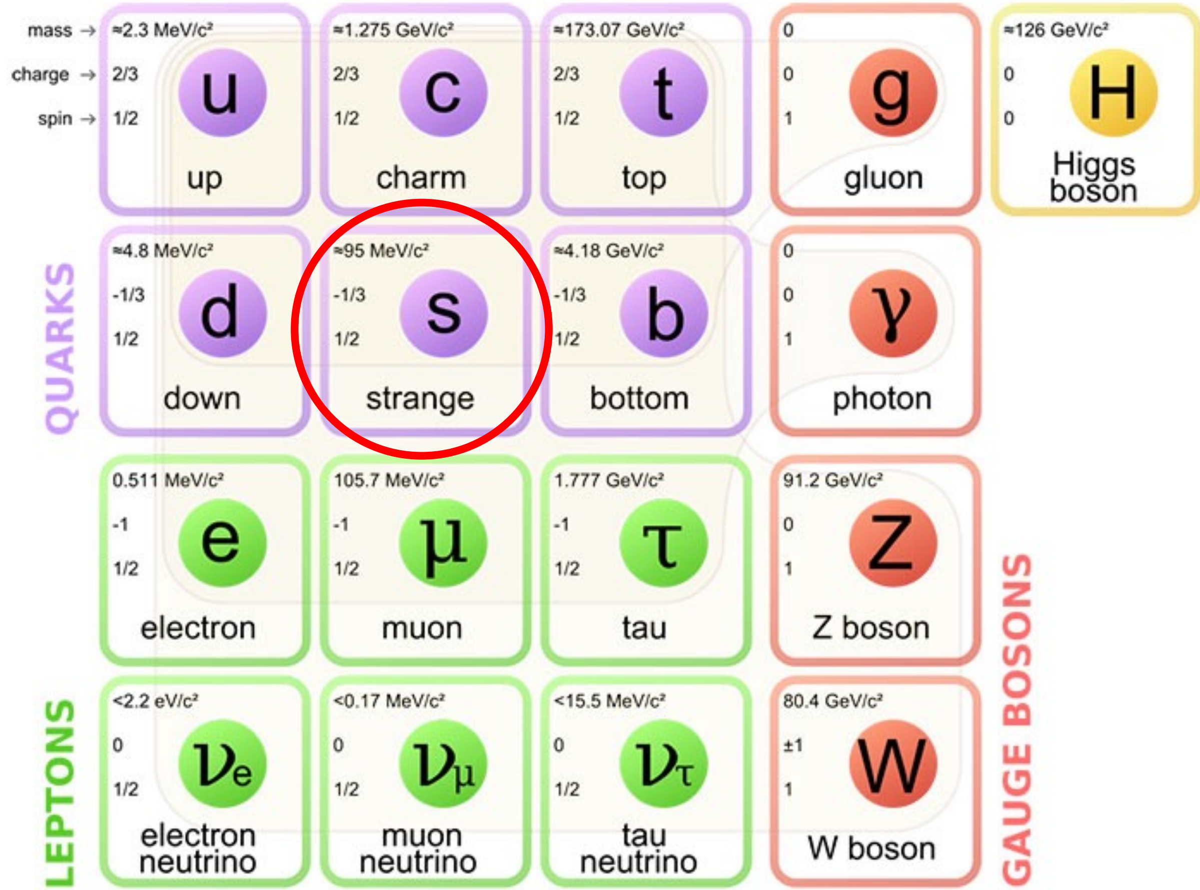
More elliptic, more flow


Strangeness
Enhancement

Strangeness enhancement

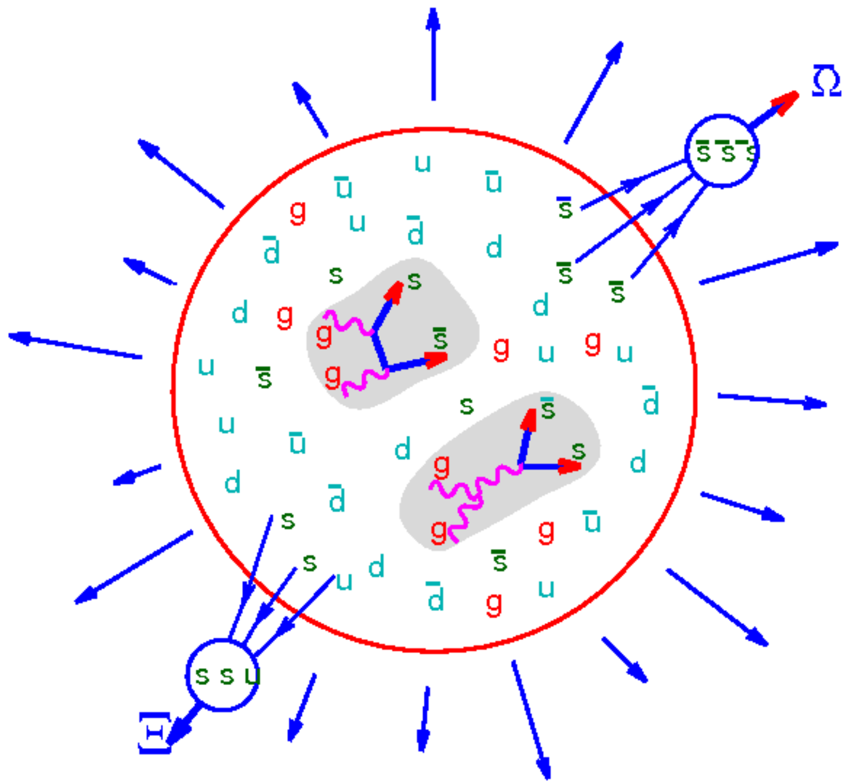
There are more strange quarks produced in a QGP

Protons and neutrons made from ups and downs => no strange before the collision



Why is there extra strange?

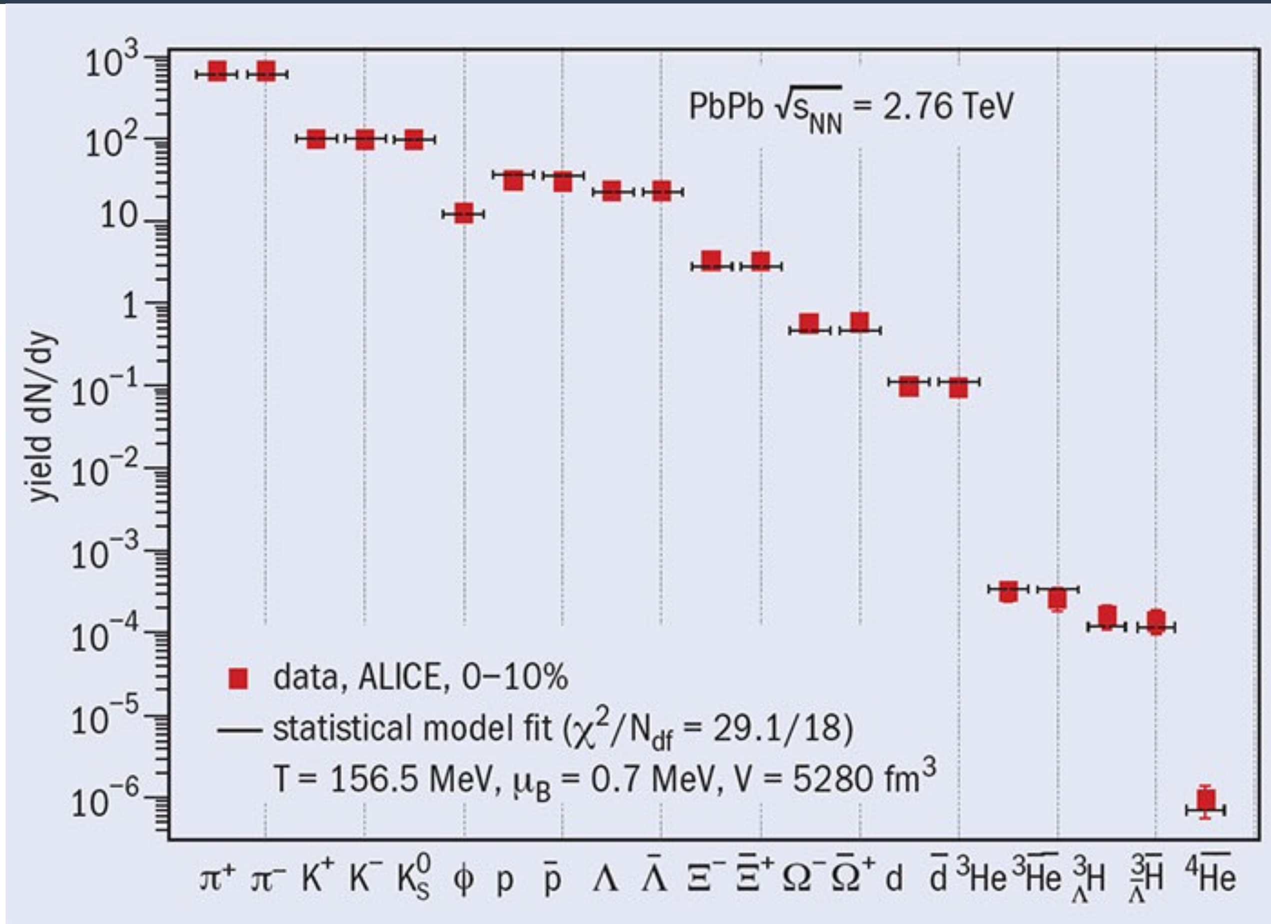
- Strange quark mass ~ 100 MeV ~ temperature of Quark Gluon Plasma
- **Extra energy from the temperature** allows strange quarks to be produced thermally



Detailed Model Comparison

Present day:

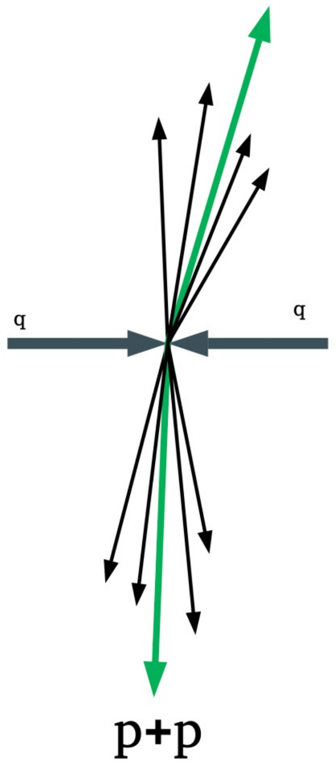
- Statistical models can reproduce *all* numbers of various particles
- Shows that particles are produced thermally at a single freeze-out temperature $T \simeq 0.15$

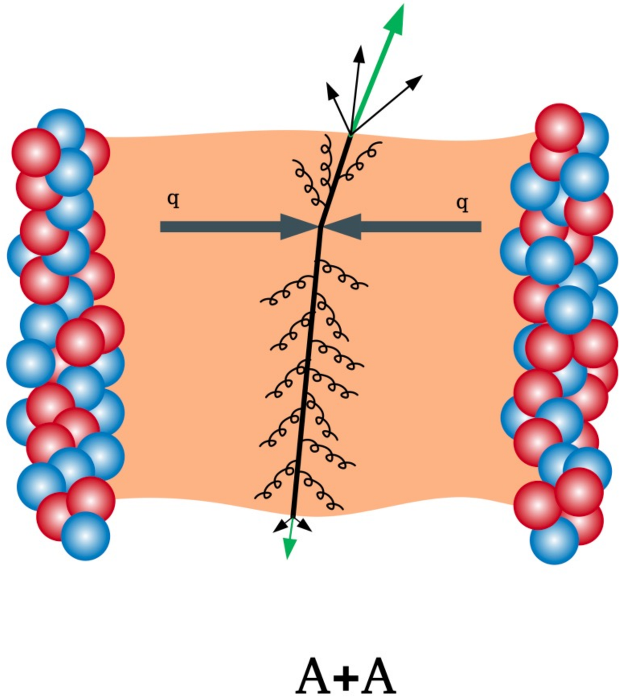



Jet Quenching

Energy loss

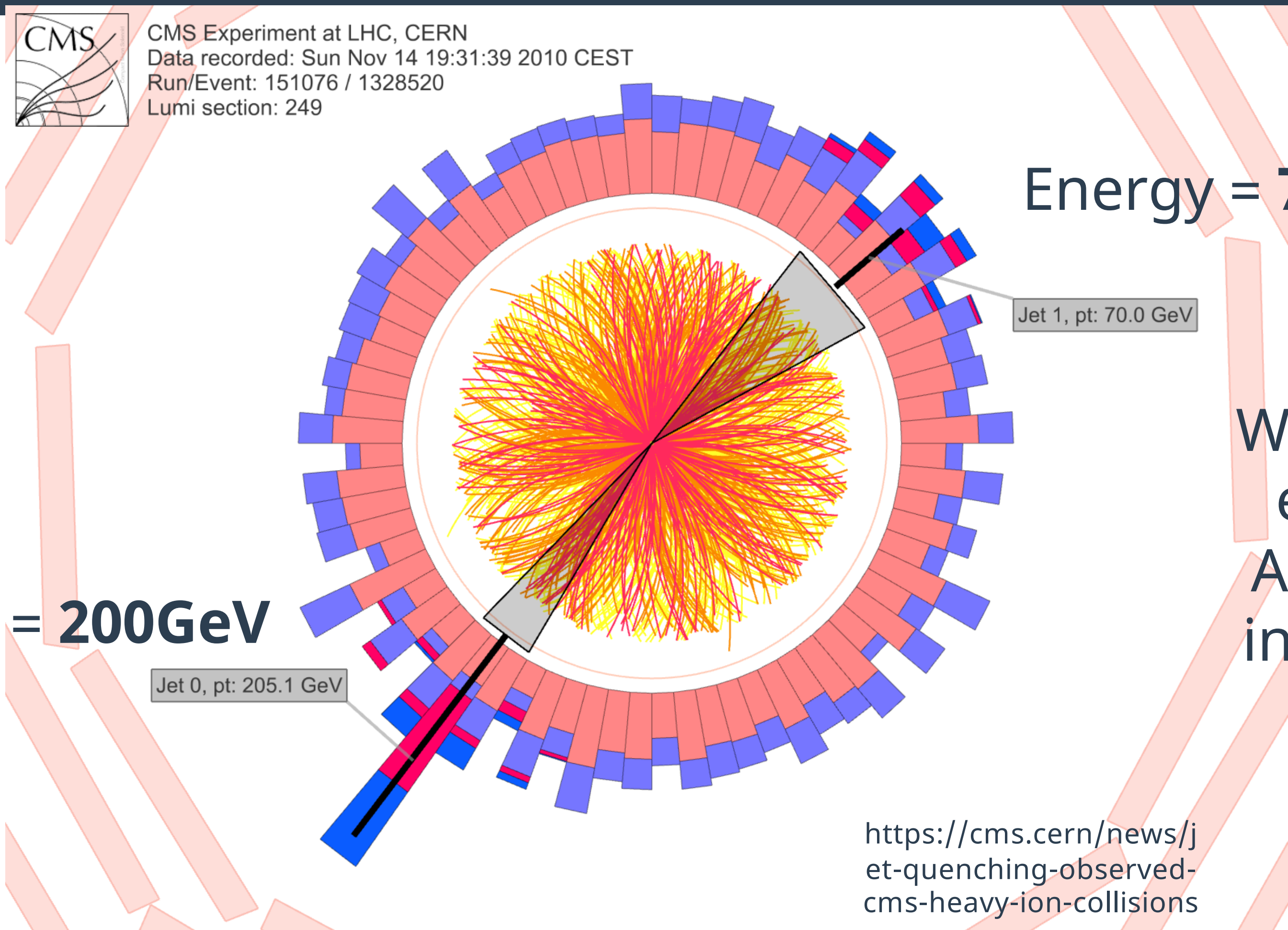
- As quarks and gluons move through the plasma, they lose energy





https://atlas.cern/Updates/Feature/Heavy-Ion-Physics

Seeing energy loss



Energy = **70GeV**

Energy = **200GeV**

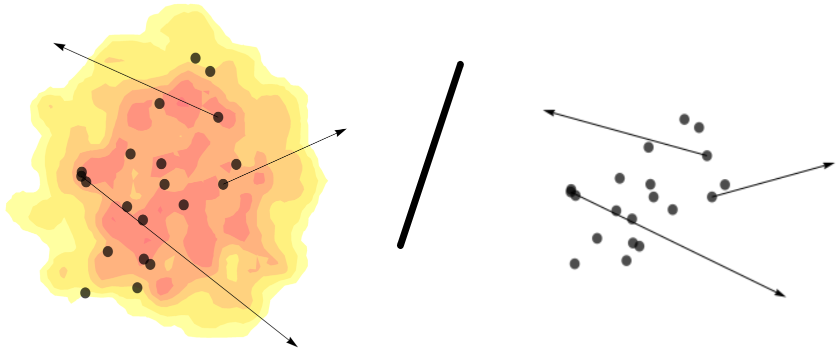
Where did the energy go?
A: Dissipated into the QGP!

https://cms.cern/news/jet-quenching-observed-cms-heavy-ion-collisions

Nuclear Modification Factor

Again, we need to go *quantitative*

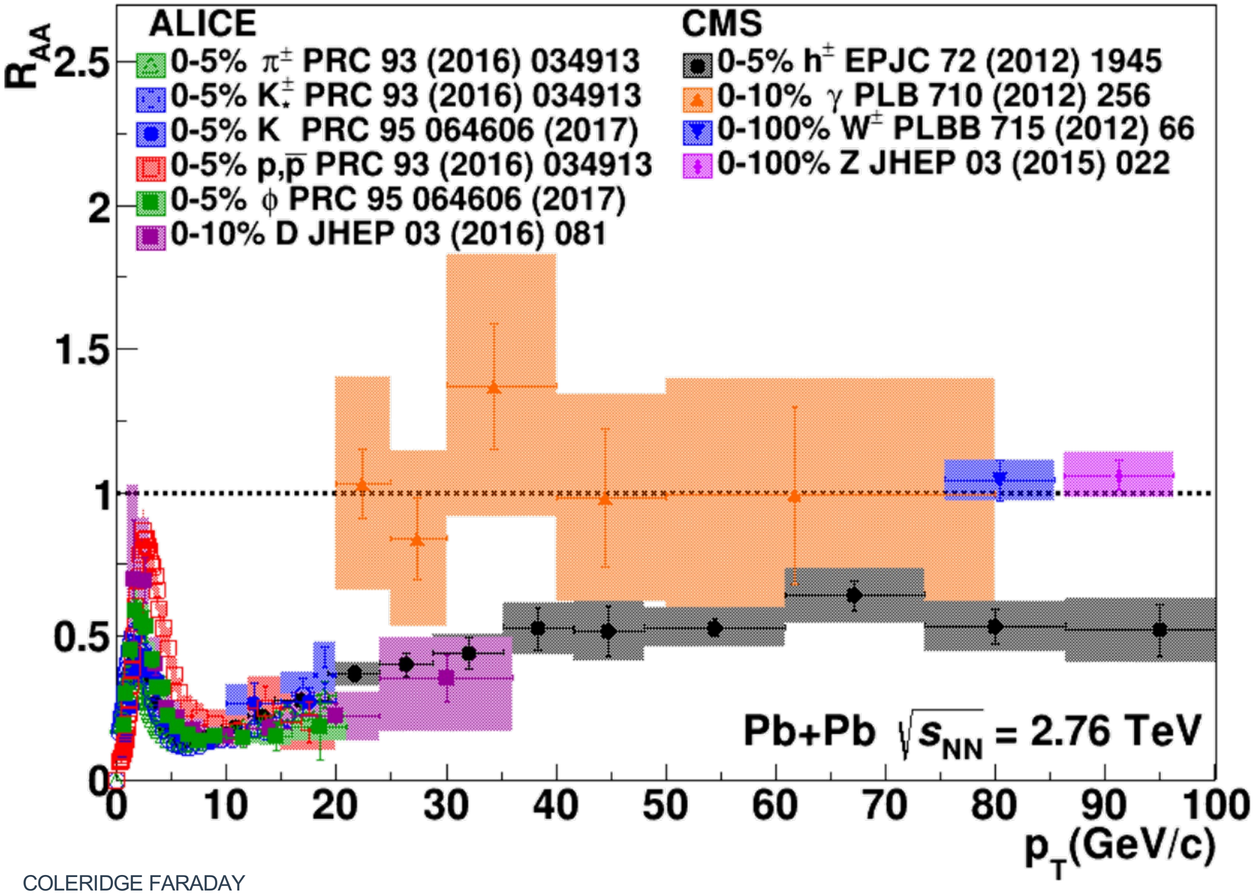
$$R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} =$$



Glauber model is back!

Quantifies how much **energy is lost** in the medium

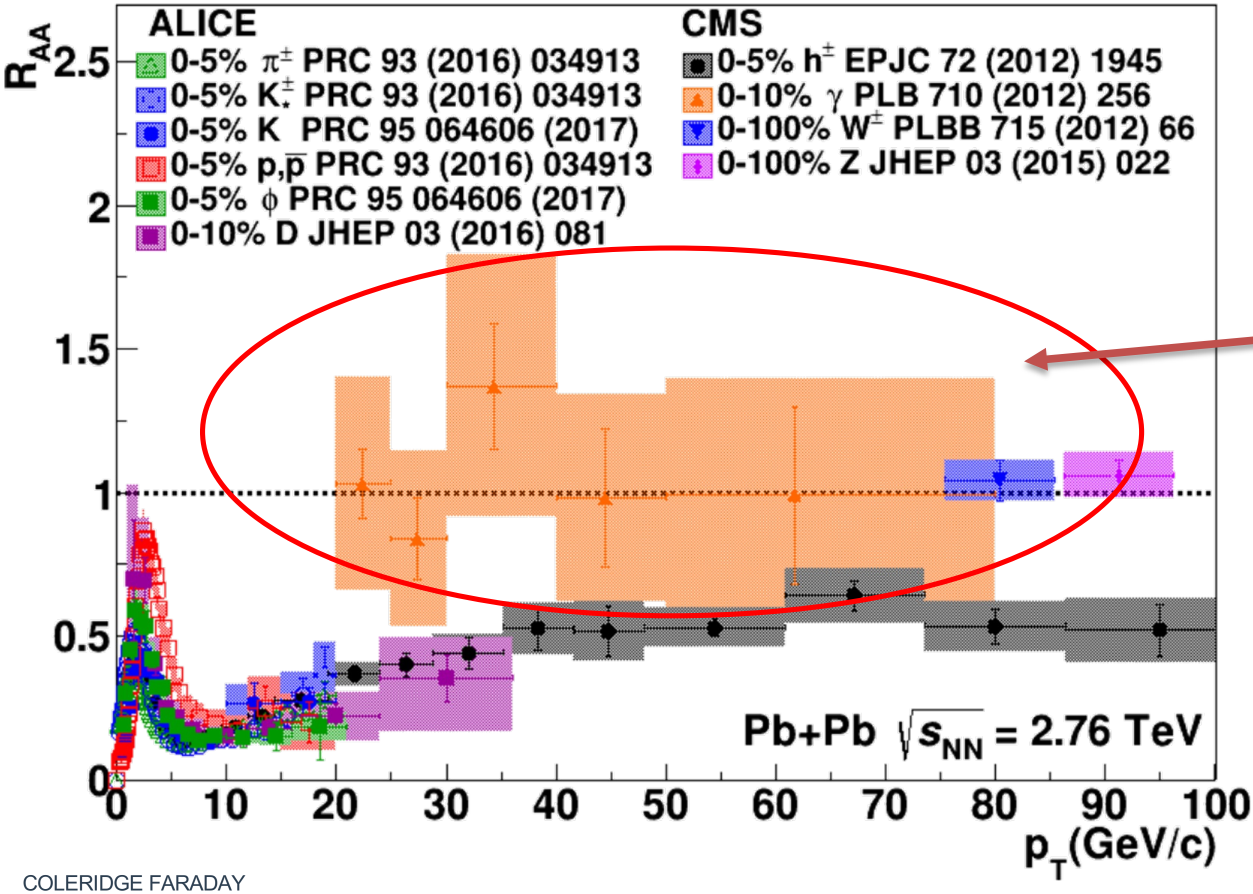
Experimental confirmation



- $R_{AA} \ll 1$ indicates energy loss

S. Cao and X.-N. Wang, Rept. Prog. Phys. 84, 024301 (2021), arXiv:2002.04028 [hep-ph].

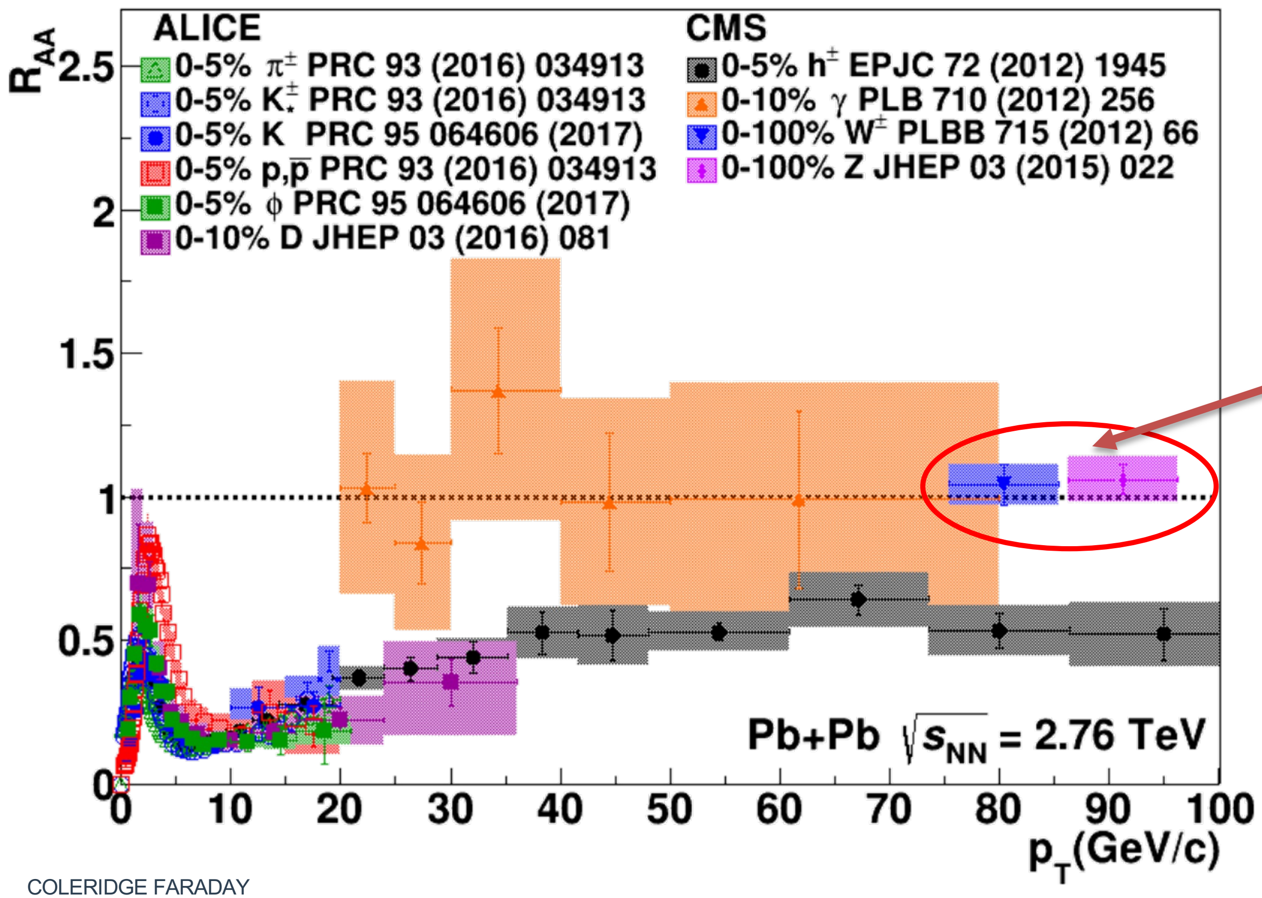
How do we *know* this is energy loss?



No suppression of photons which do not interact with the QGP

S. Cao and X.-N. Wang, Rept. Prog. Phys. 84, 024301 (2021), arXiv:2002.04028 [hep-ph].

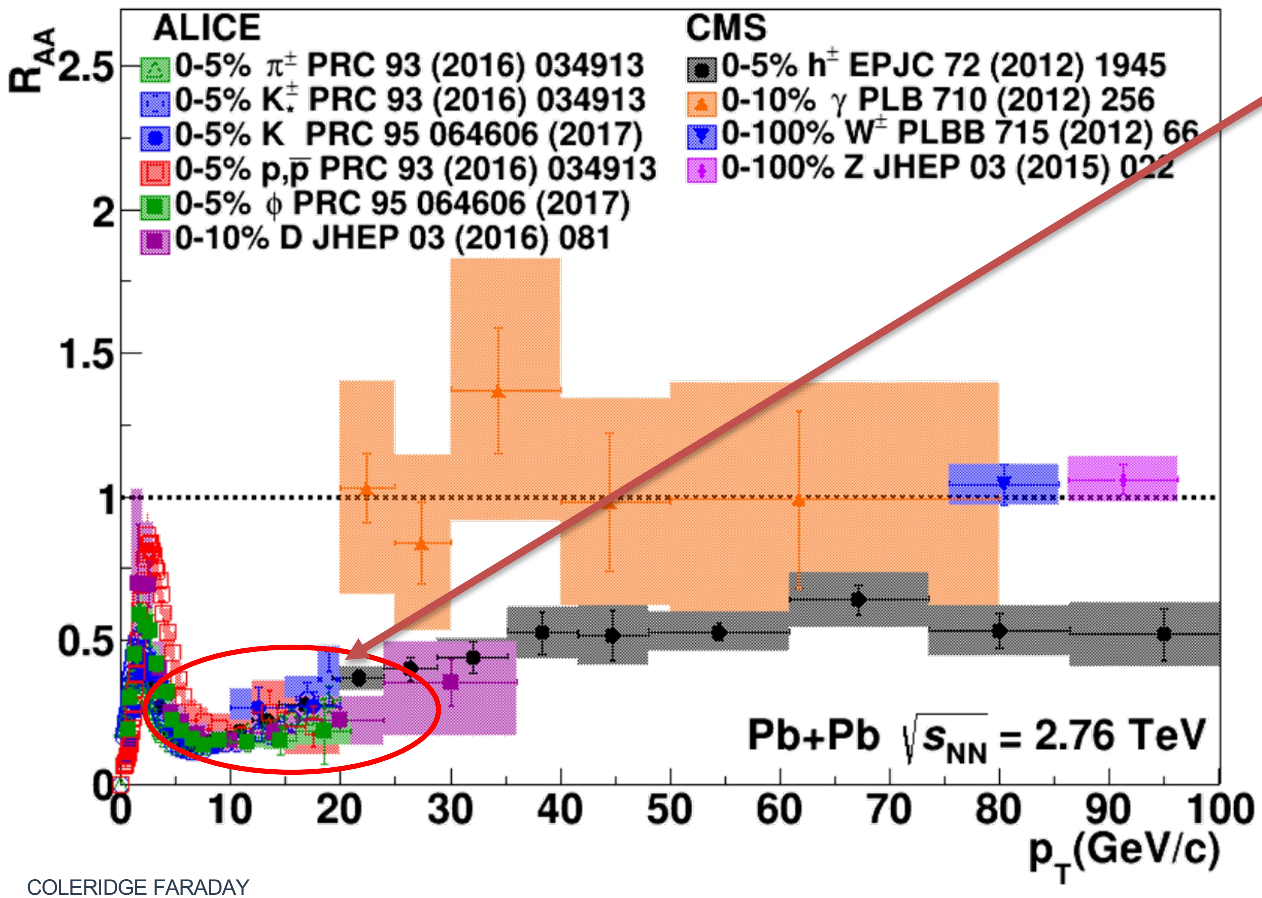
How do we *know* this is energy loss?



No suppression of W's and Z's which do not interact with the QGP

S. Cao and X.-N. Wang, Rept. Prog. Phys. 84, 024301 (2021), arXiv:2002.04028 [hep-ph].

How do we *know* this is energy loss?



Equal suppression of π, K, and ϕ mesons

- u, d, s are expected to have similar energy loss
- $\pi = u\,\bar{u}, \quad K = u\,\bar{s},$
  $$\phi = s\,\bar{s}$$
- Mass of ϕ is 7 times that of π, so if hadrons lost energy would expect significantly different energy loss

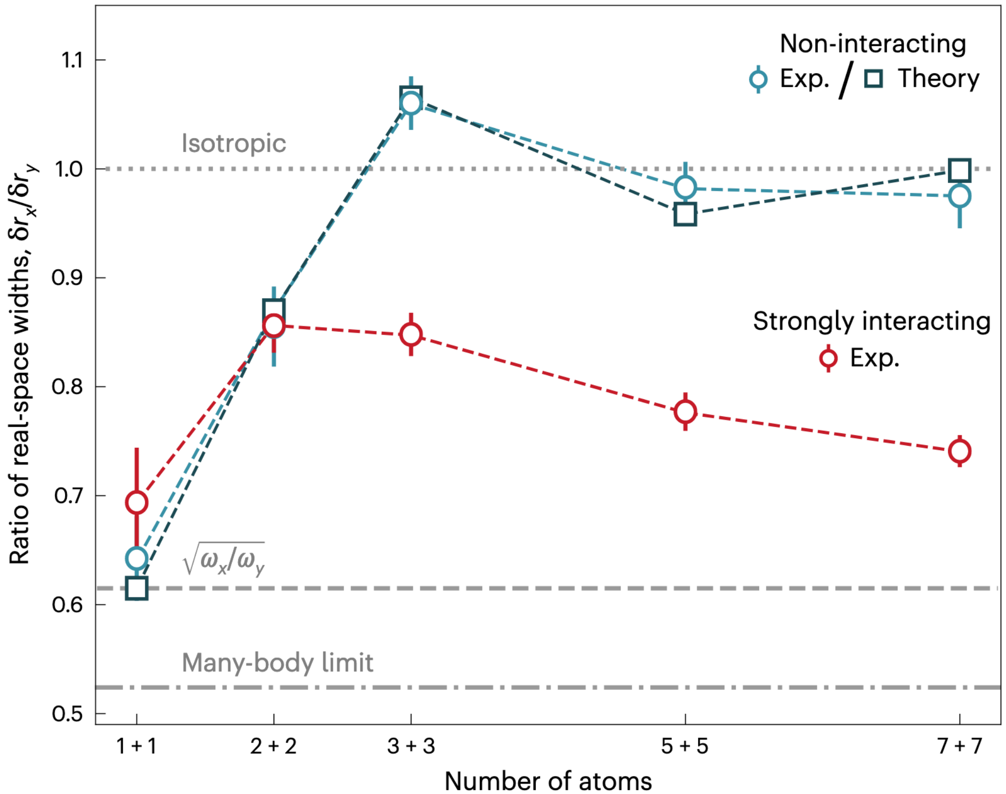
=> Partons lose energy!

S. Cao and X.-N. Wang, Rept. Prog. Phys. 84, 024301 (2021), arXiv:2002.04028 [hep-ph].


Small
Systems

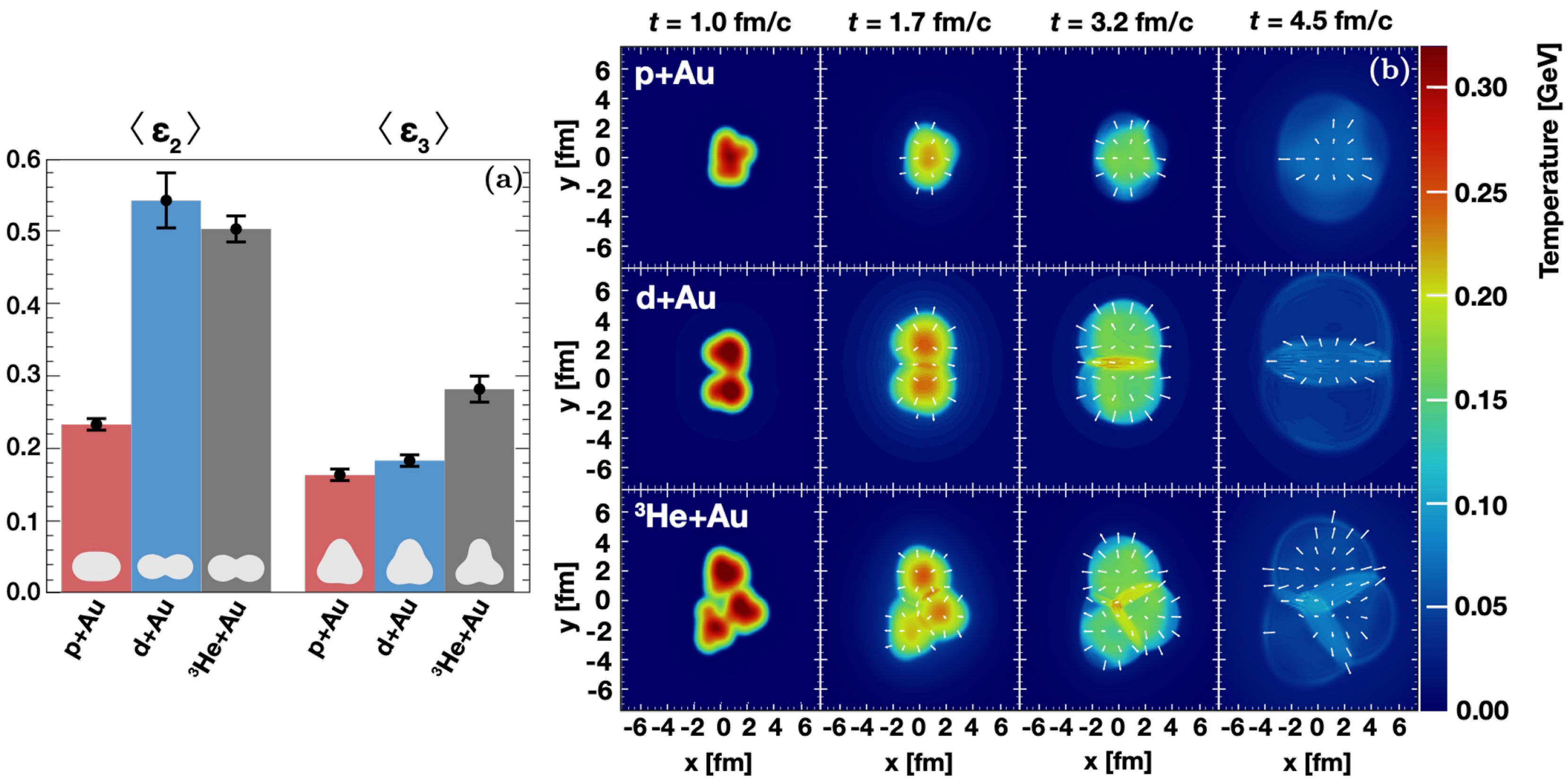
When does collective behaviour turn on?

- **How many particles do you need before they behave collectively?**
- **From statistical mechanics, you might say ~ 1 mole ~ 10^{23}**
- **Cold atom experiments indicate that the answer is 6!**



S. Brandstetter, P. Lunt, C. Heintze, G. Giacalone, L. H. Heyen, M. Gałka, K. Subramanian, M. Holten, P. M. Preiss, S. Floerchinger, and S. Jochim, Nat. Phys. **21**, 1 (2025).

QGP in p / d / He3 + A collisions?

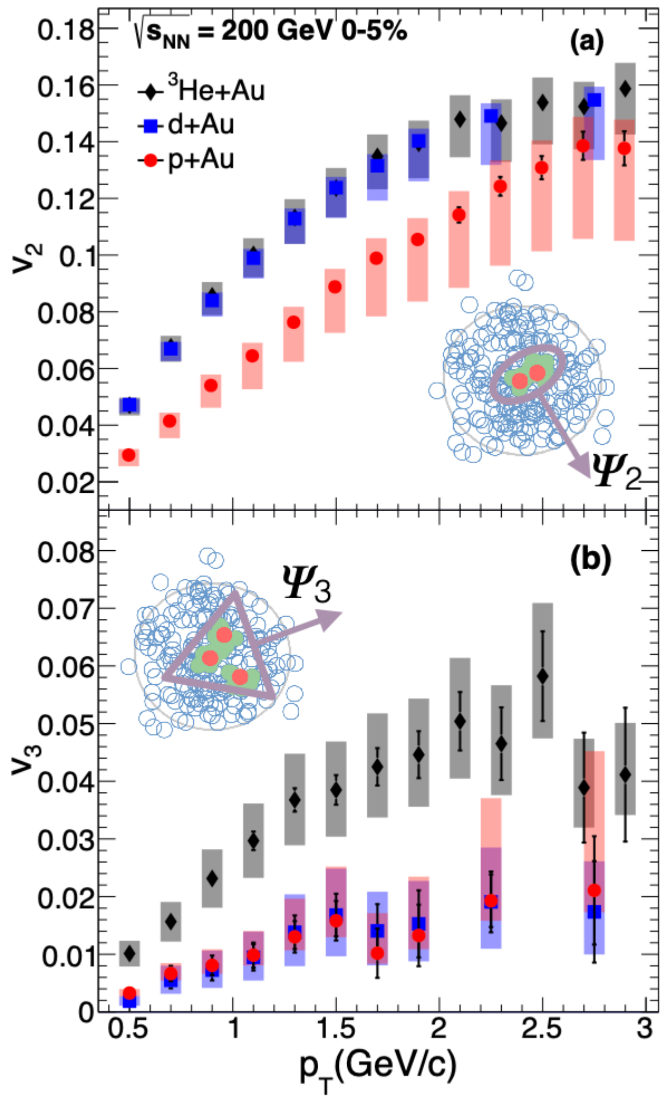


PHENIX, Nat. Phys. **15**, 214 (2019).

QGP in p / d / He3 + A?

Larger v_2 in dA and larger v_3 in He3A
$\Rightarrow$ v_n are created by medium response to the geometry!

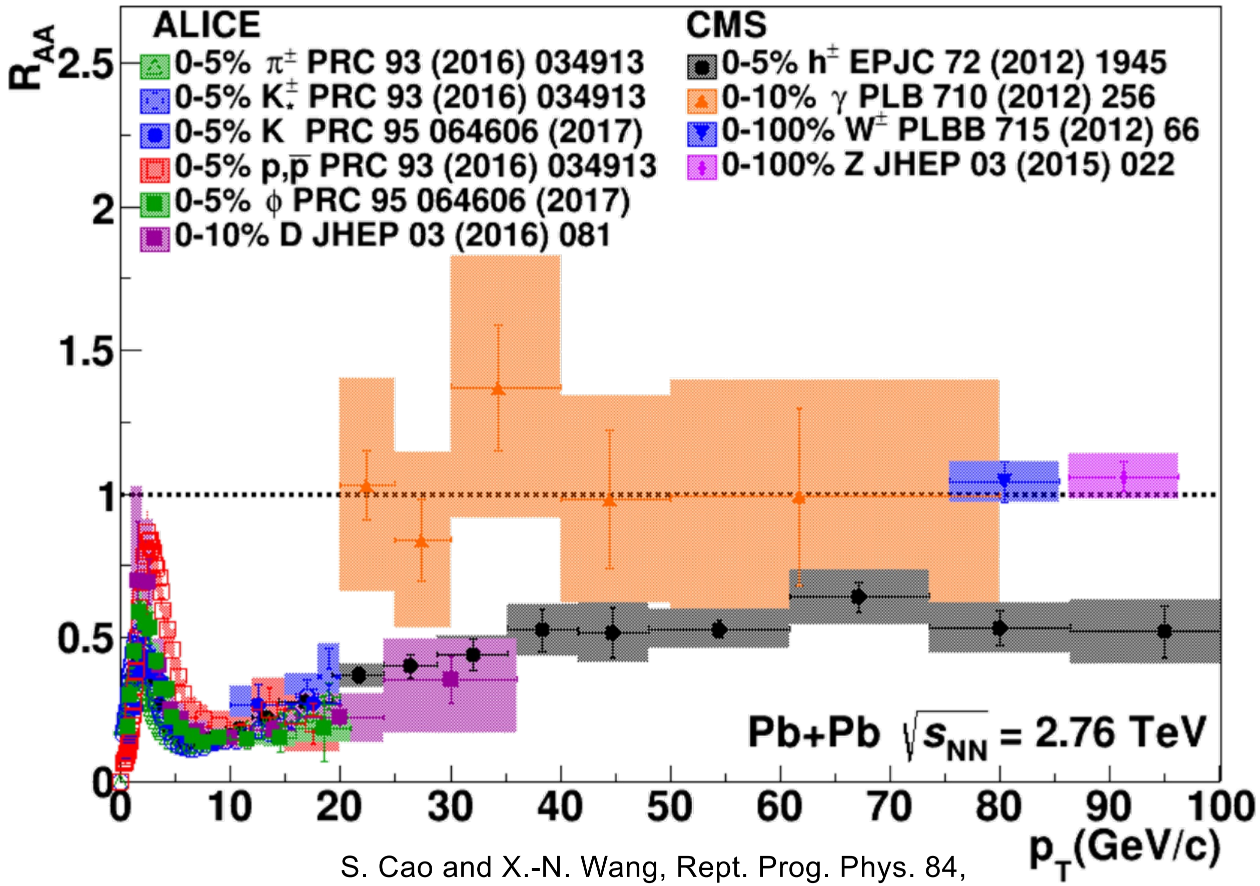
Indicates QGP formation in small systems?



The missing puzzle piece

Recall:

- Energy loss is an important observable for establishing that a QGP is formed
- If a QGP is formed, then high energy particles should interact with it and lose energy



S. Cao and X.-N. Wang, Rept. Prog. Phys. 84, 024301 (2021), arXiv:2002.04028 [hep-ph].

No energy loss in small systems?

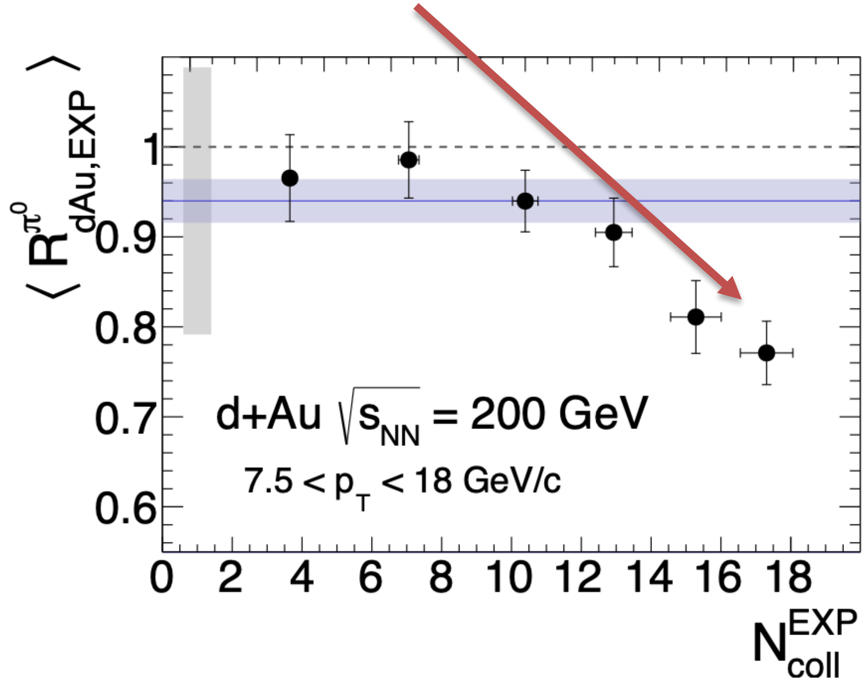
Energy loss measurements in small systems have been inconclusive due to

- Difficulties on the theory side
  - Does hydrodynamics work in small systems?
  - How must energy loss models be adapted to small systems?
- Difficulties on the experimental side:
  - Applicability of Glauber model?
  - Factorization of the high momentum and low momentum parts of a collision?

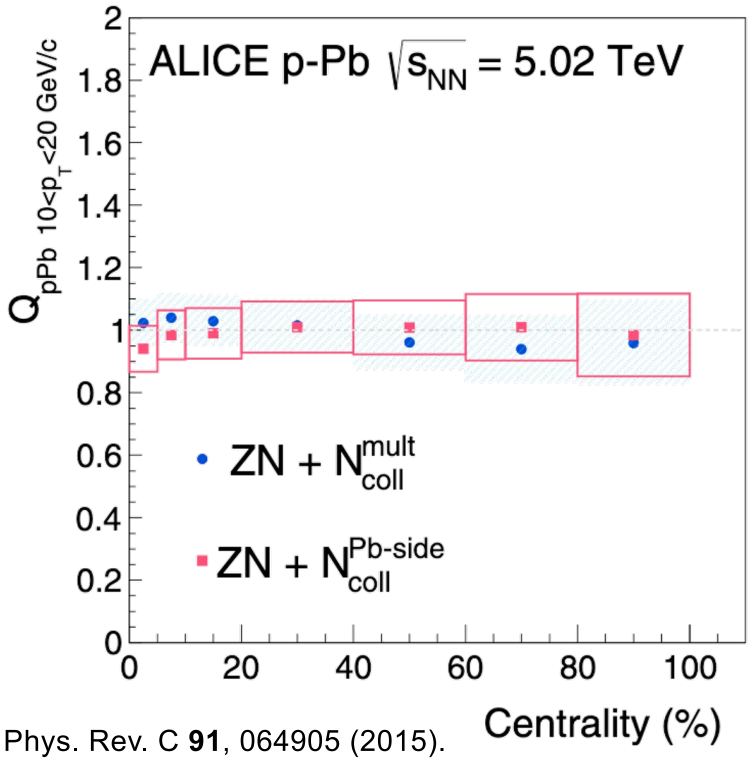
S. Cao and X.-N. Wang, Rept. Prog. Phys. 84, 024301 (2021), arXiv:2002.04028 [hep-ph].

Tension in experiment?

Suppression at RHIC



No suppression at LHC

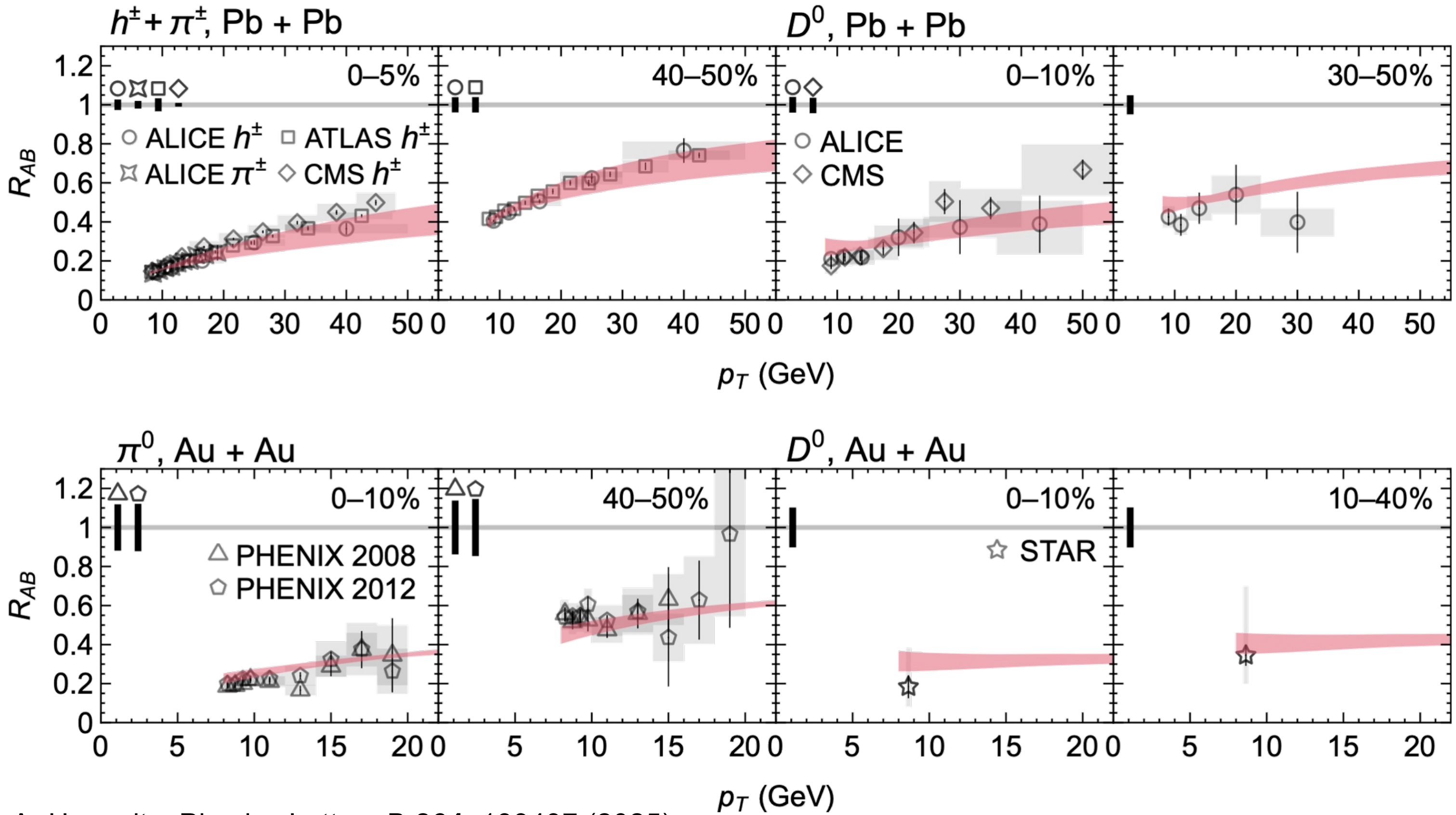


PHENIX, Phys. Rev. Lett. **134**, 022302 (2025). ALICE, Phys. Rev. C **91**, 064905 (2015).

What is the theoretical expectation?

What we did:

- Constrain our one-parameter, pQCD-based model with a statistical analysis of all heavy-ion data

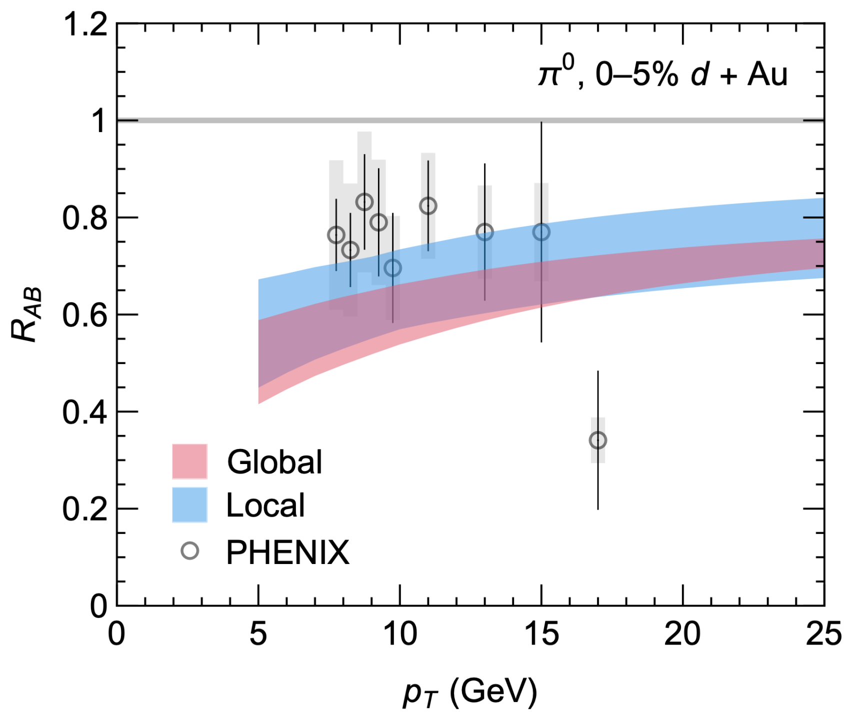


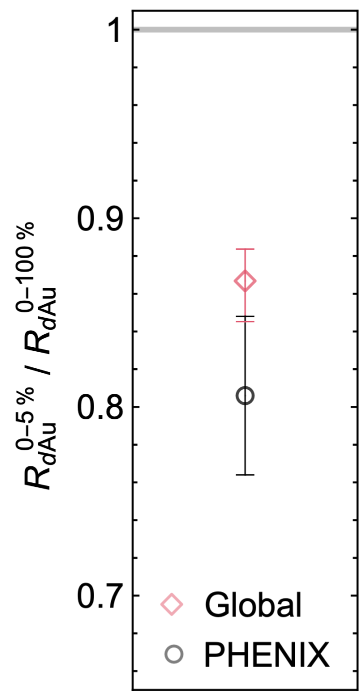
CF and W. A. Horowitz, Physics Letters B **864**, 139437 (2025).

CF and W. A. Horowitz, arXiv:2505.14568 [hep-ph] (2025).

What is the theoretical expectation?

- Used the constrained model to make predictions
- In qualitatively good agreement with PHENIX data

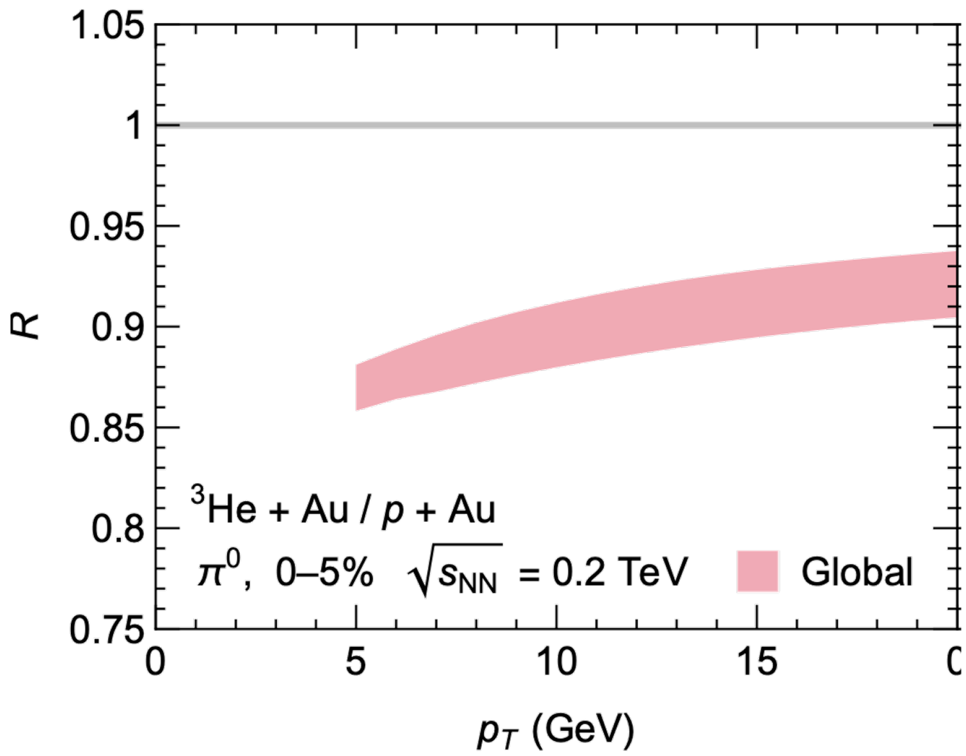




CF and W. A. Horowitz, Physics Letters B **864**, 139437 (2025).
CF and W. A. Horowitz, arXiv:2505.14568 [hep-ph] (2025).

Outlook

- Understanding energy loss in small systems is one of the last barriers to declaring QGP is formed in small systems
- Thermalization and collectivity in small systems helps us to understand fundamental statistical mechanics and potentially even the earliest microseconds of the universe
- Comparing the suppression in He3+Au and p+Au collision may help to disentangle energy loss from other effects



CF and W. A. Horowitz, arXiv:2505.14568 [hep-ph] (2025).

Thanks for your attention!

- If you want to learn more or are looking for a third year / honours project in our group (supervised by Assoc. Prof. Will Horowitz), send me an email: frdcol002@myuct.ac.za

- You can find my research papers at INSPIRE.