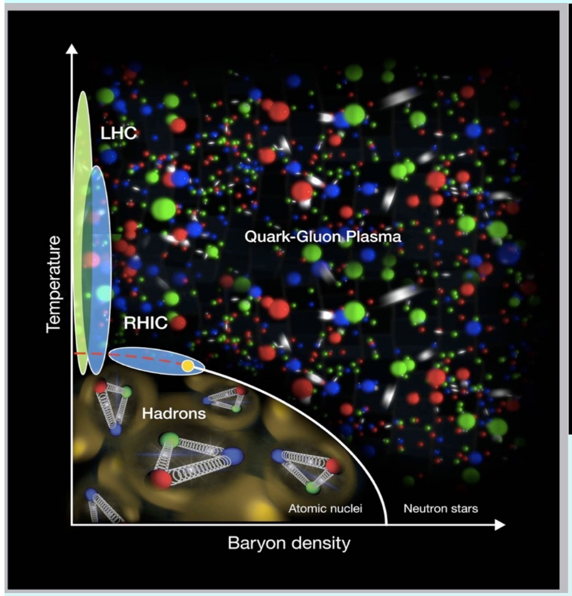
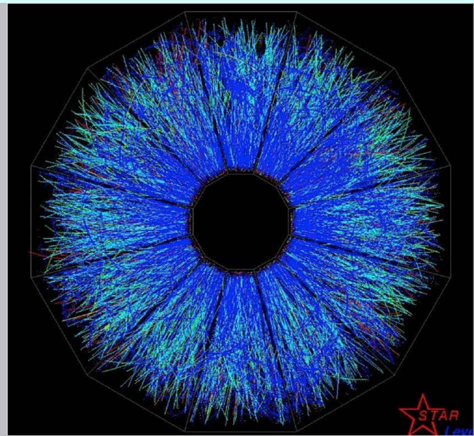
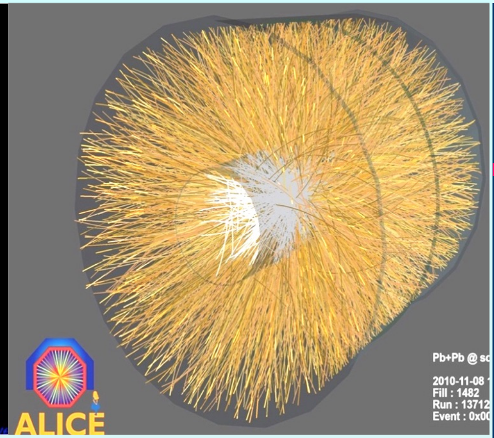
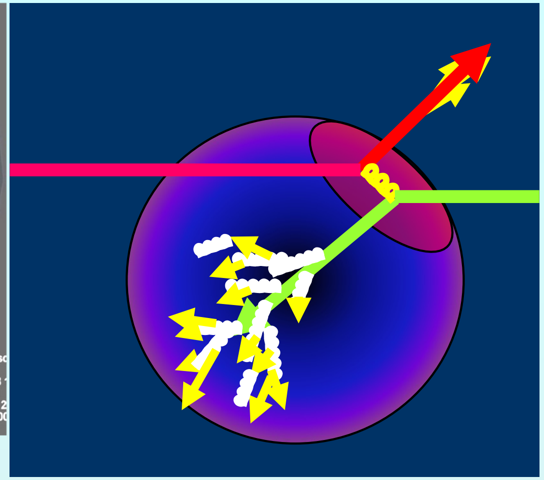
A Plasma of Quarks and Gluons









ISCO 2023 at OIST

Barbara Jacak

UC Berkeley & LBNL

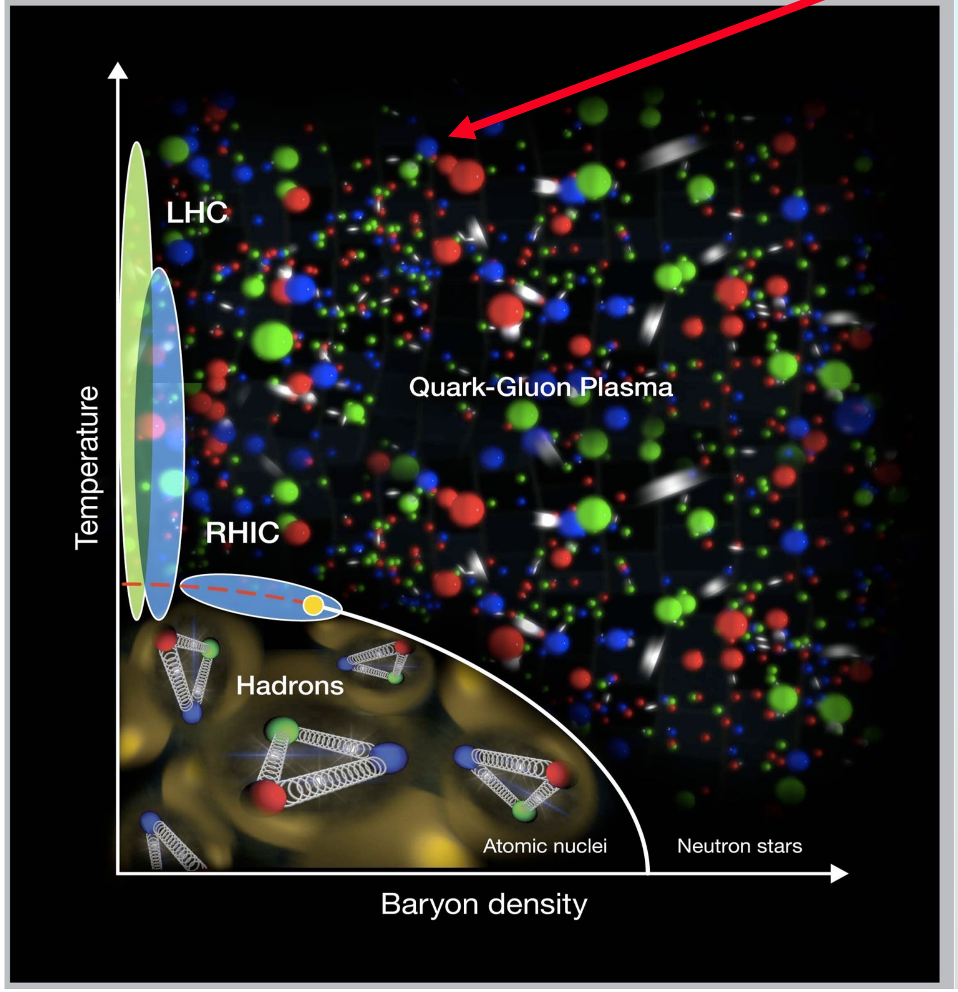
March 3, 2023

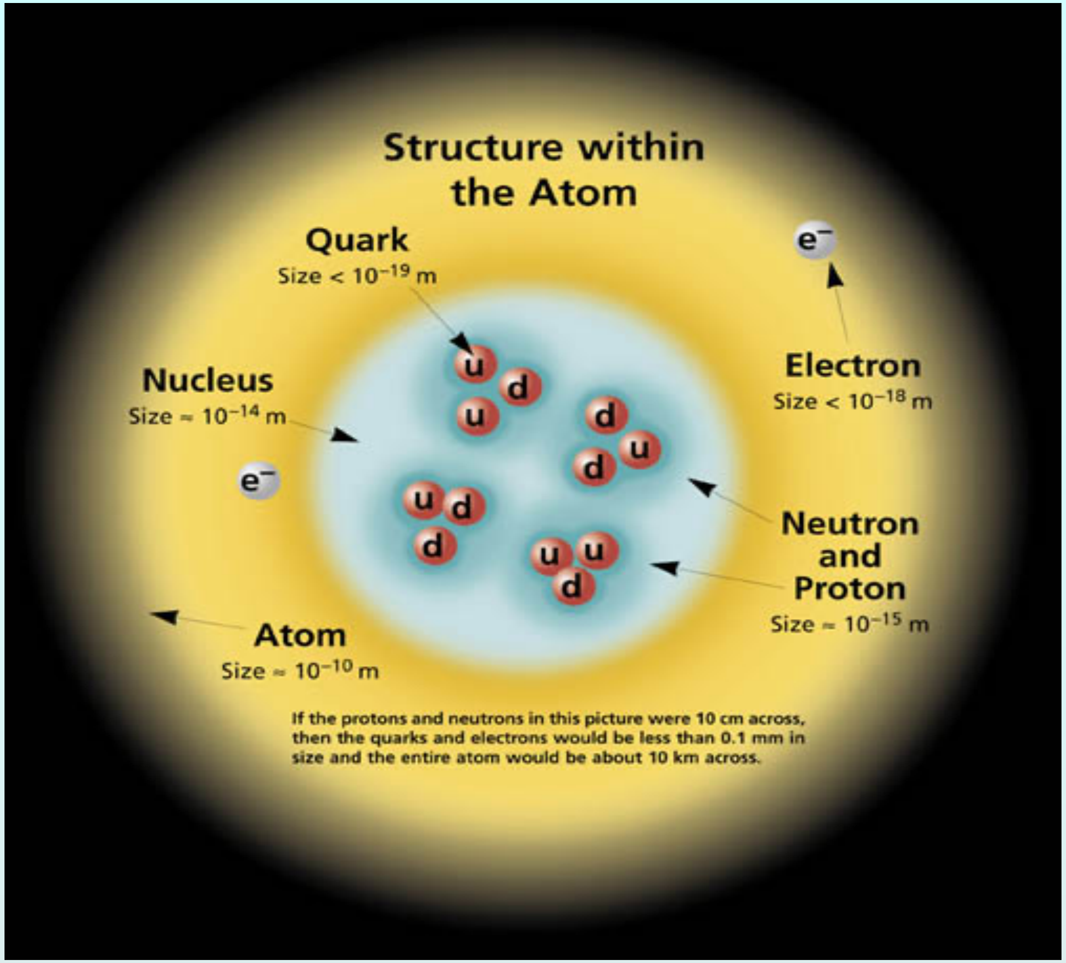
Quarks and gluons?

quarks bind together by exchanging gluons

Heat nuclei to T > 10^{12} K

(> trillion degrees!)



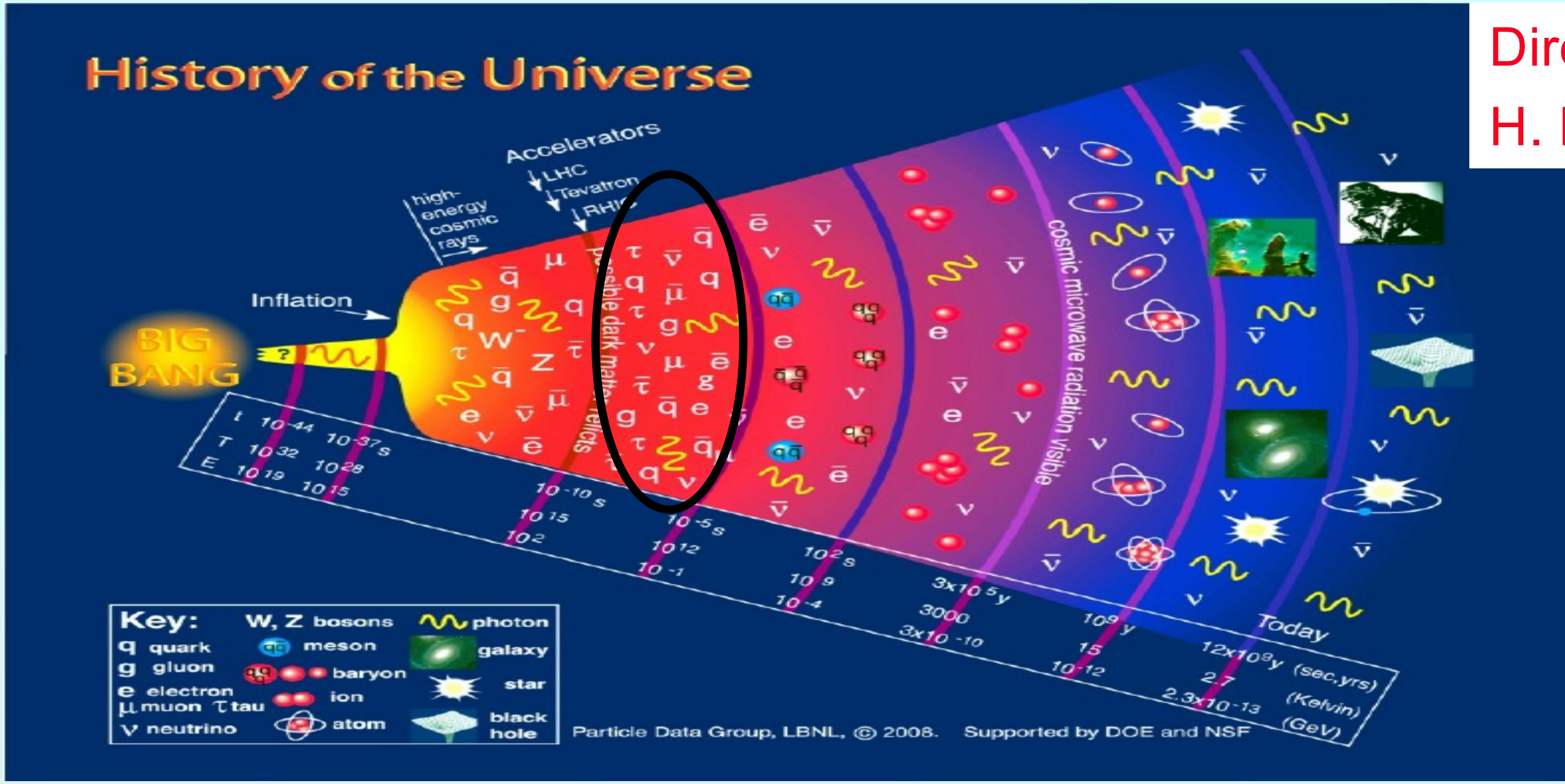


Liberate the quarks

What is this stuff?

How does it work?????

Quark gluon plasma in early universe



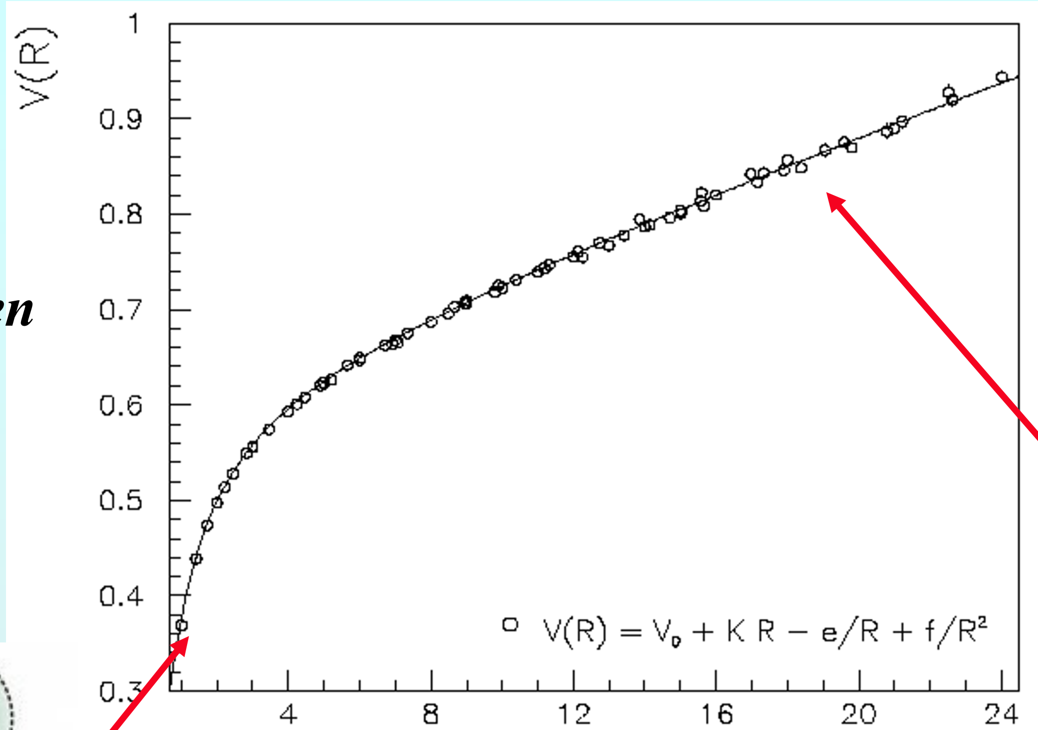
Director:
H. Murayama

QGP likely also in core of massive neutron stars G.Baym

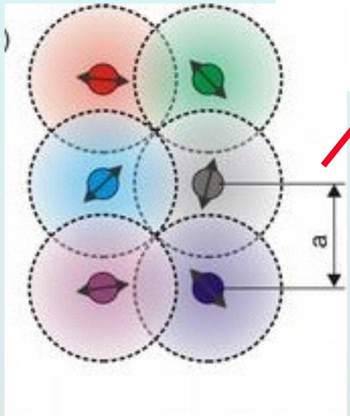
- **Electromagnetic interactions: photons are exchanged electrically uncharged**
- **Interaction between quarks = strong interaction**
  Force is carried by exchanged particles: gluons
  Both quarks and gluons have a "color charge"

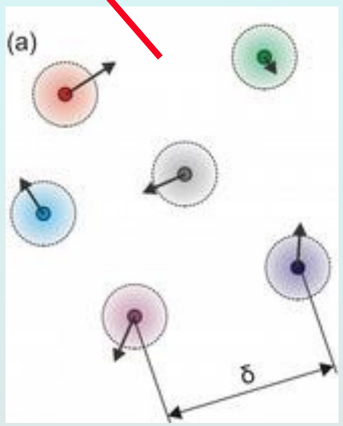
The force between quarks is funny

Potential or force between two quarks



Distance between two quarks





At small distances, very little force. Quarks are essentially free of each other.

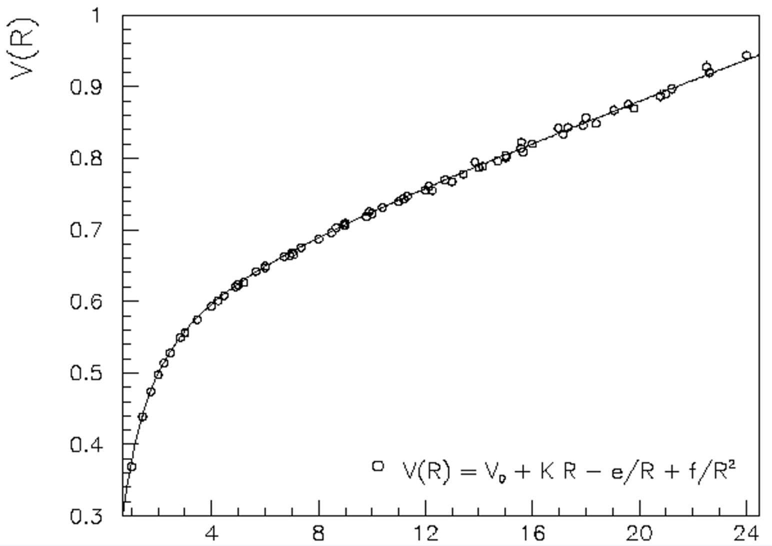
At large distances the force gets stronger, confines quarks inside the particles we observe

The theory of quarks & gluons: Quantum Chromodynamics (QCD)

Calculating is a challenge

enchange 1, 2 … many gluons

Use a lattice of quarks & gluons



T. Hatsuda

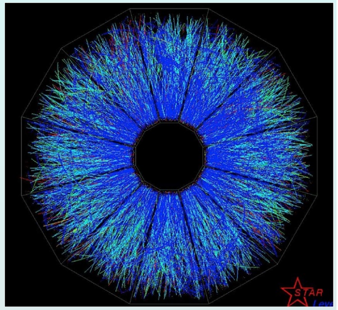
At high temperature:

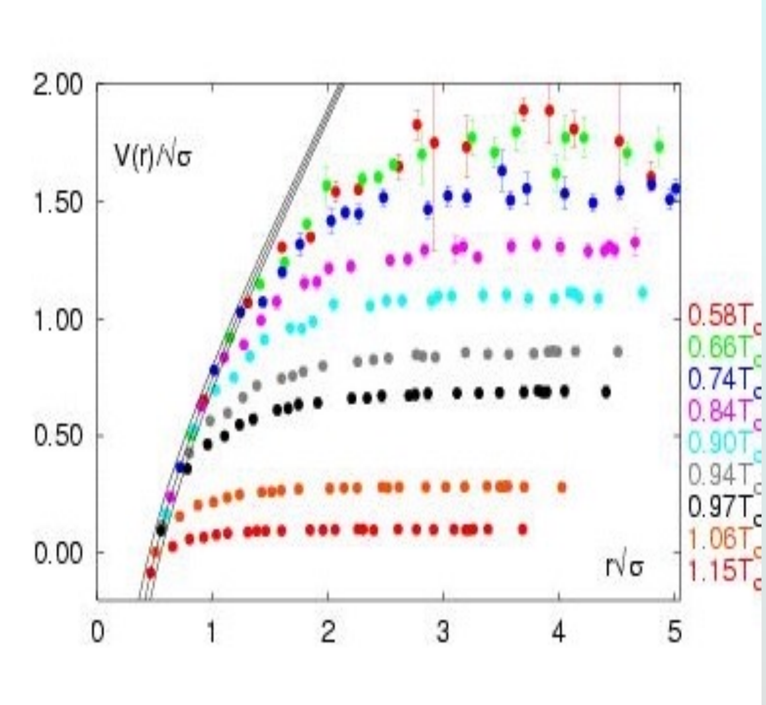
Many new particles produced

E=mc²

The force is screened

so it gets weaker





Need T > 150 MeV

(> 10^{12} degrees)

To enter plasma phase

The heaters

Large Hadron Collider

CERN in Geneva

Pb+Pb @ 2.76 TeV/A

Relativistic Heavy Ion Collider

Brookhaven in New York

Au+Au @ 200 MeV/A

Collide heavy nuclei for max temperature & volume

p+p and p+A for comparison

In the LHC tunnel

energy stored in each of the colliding beams equivalent to an ICE at 150 km/h (350 MJ)

but only the smalles part of this energy is released in the collisions
(one part in 10^{11} each time the bunches are crosssing)

energy stored in the magnets: 10 GJ

great care must be taken!

How much energy in one collision?

at the LHC

energy released in a single collision is macroscopic:

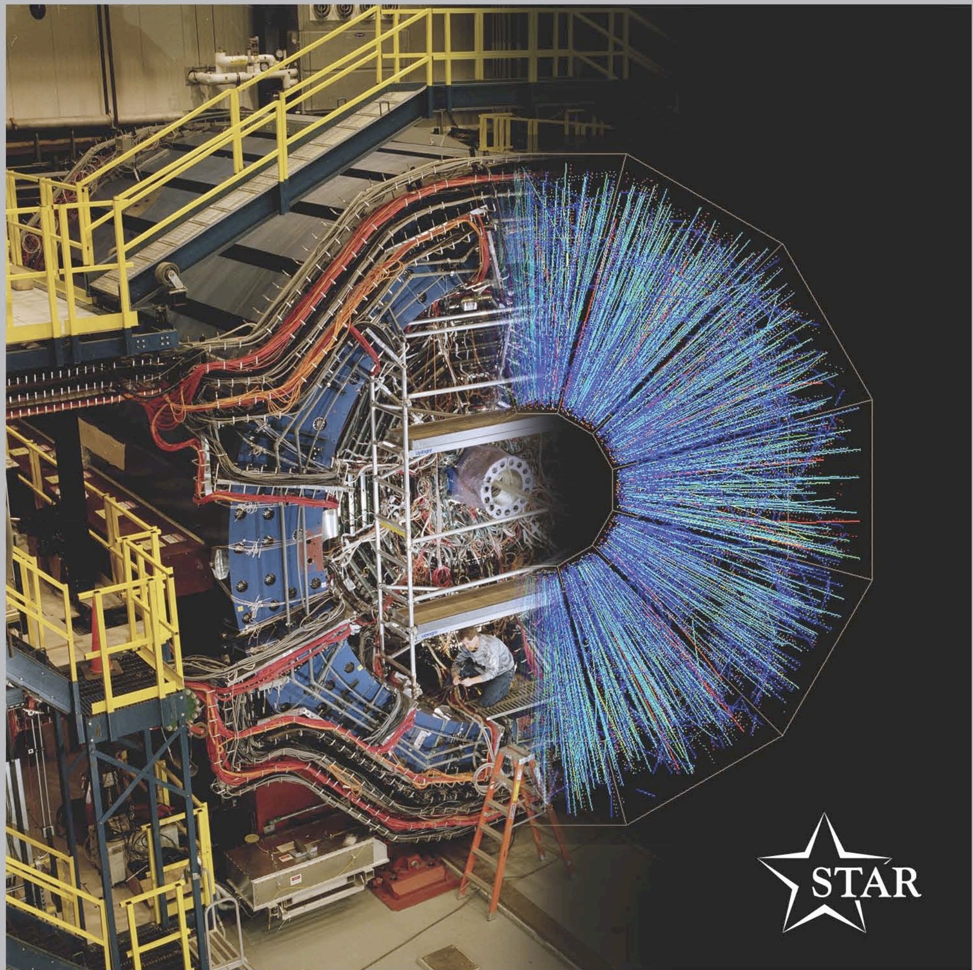
collision of 2 lead nuclei 208 x 2.7 + 208 x 2.7 TeV = 1123 TeV
= 0.18 mJ

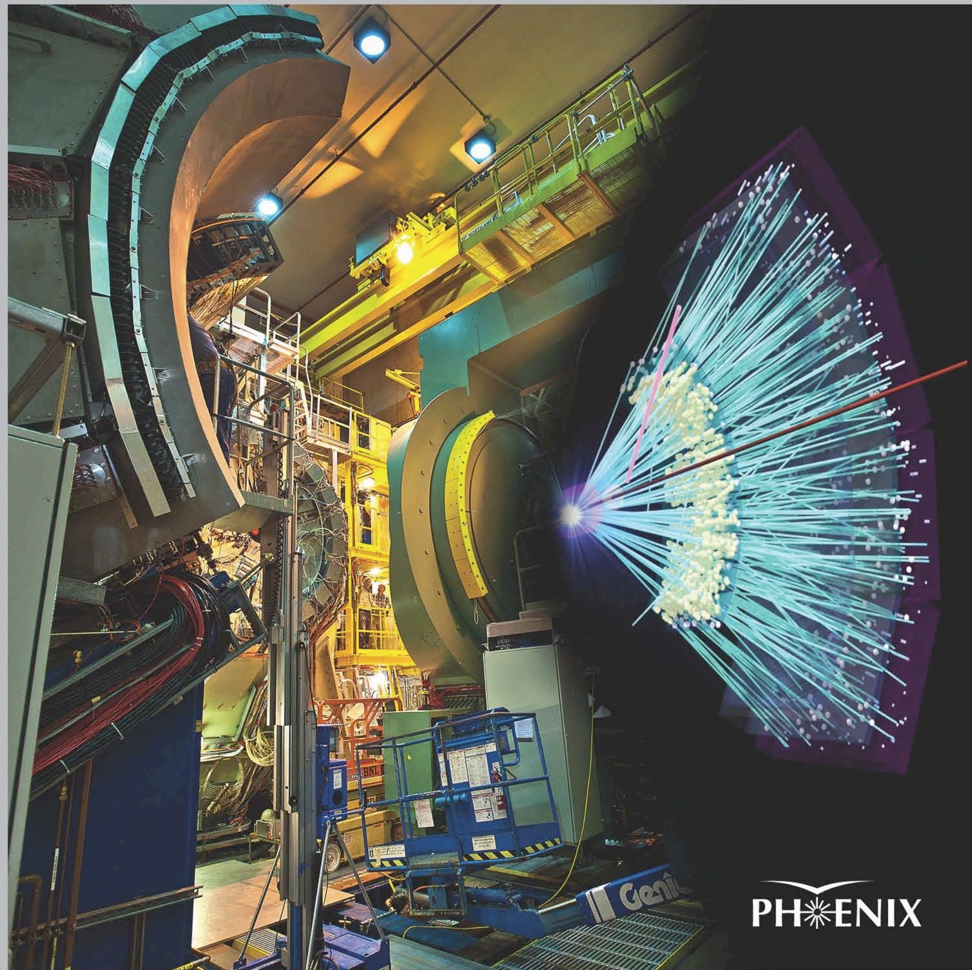
5800 time the mass of the 2 nuclei!

one could hear the collisions! 

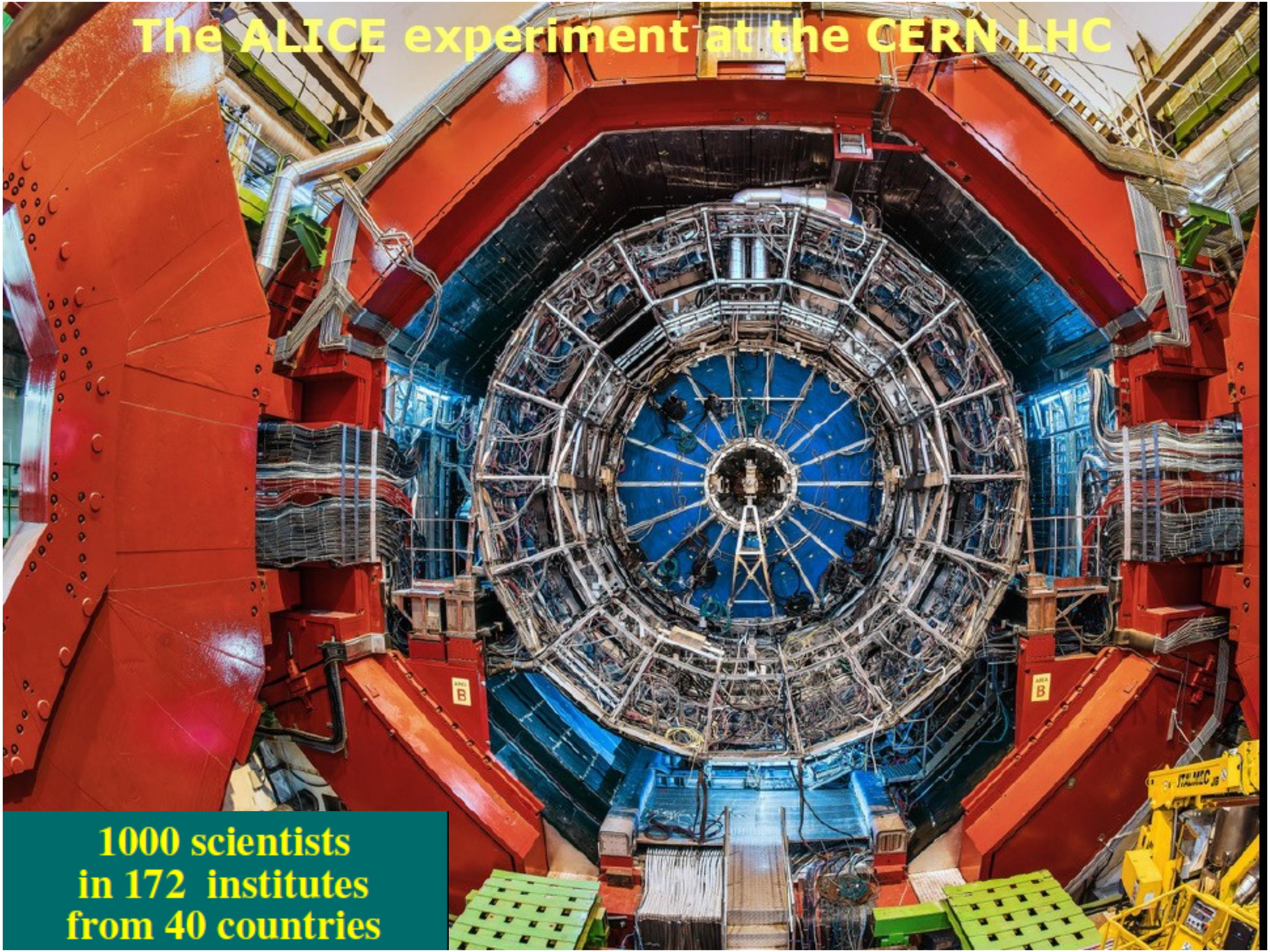
if they didn't happen in vacuum ...

Experiments at RHIC





The ALICE experiment at the CERN LHC

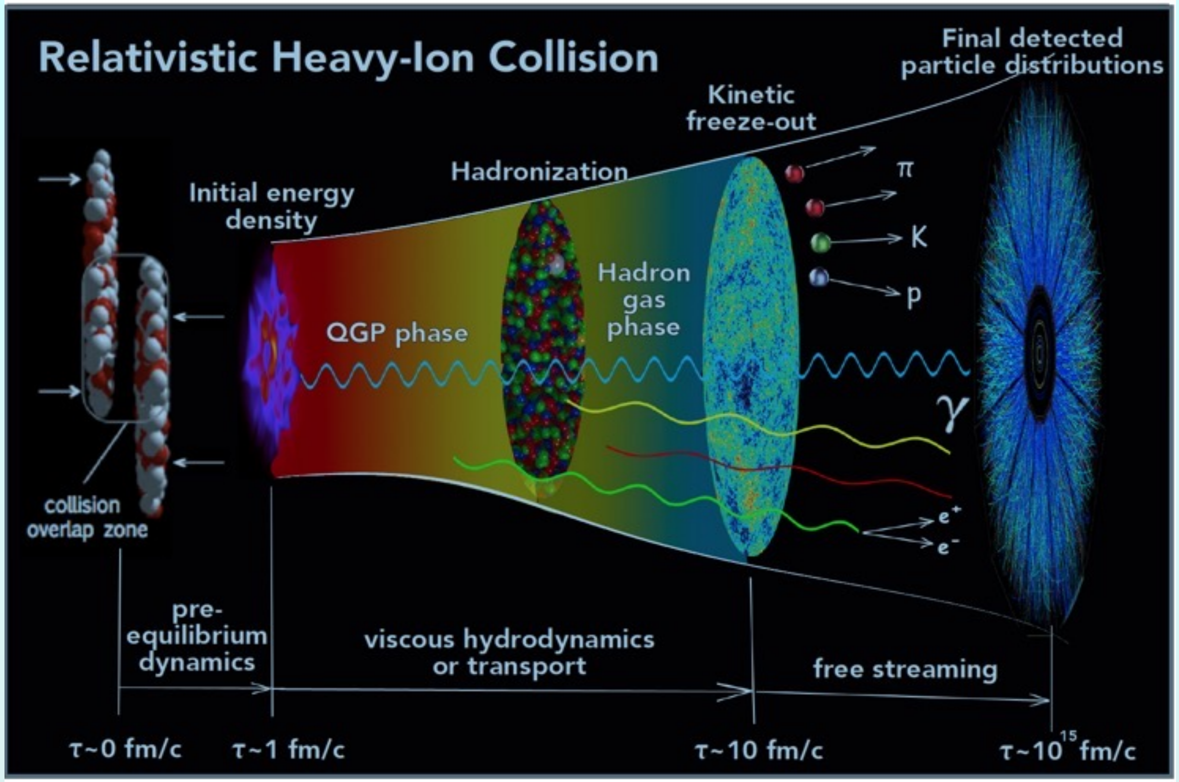


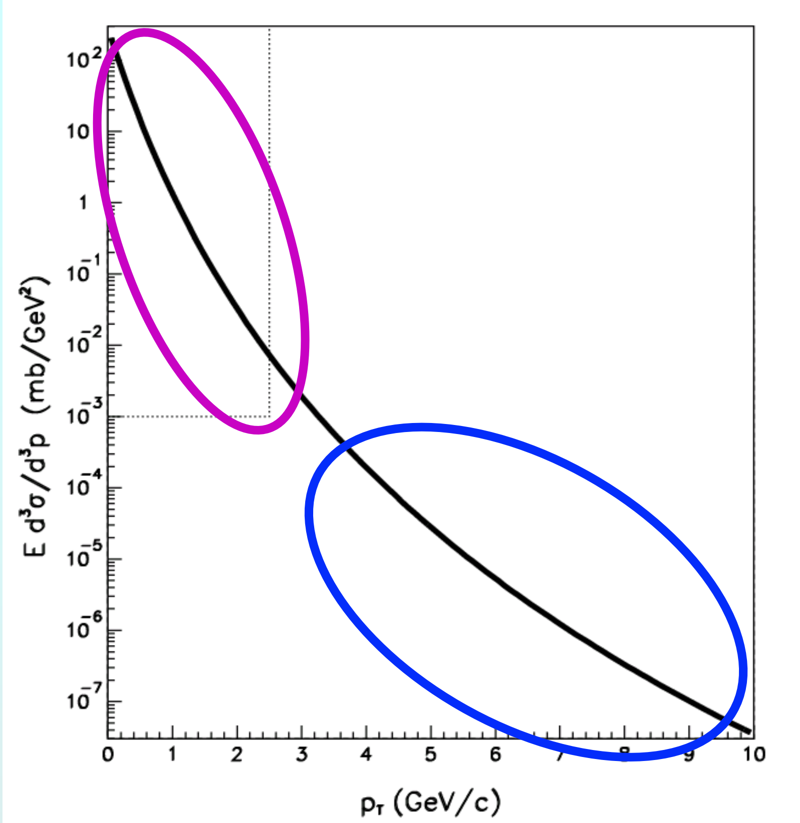
**1000 scientists
in 172 institutes
from 40 countries**

Inside the Time Projection Chamber

Nuclear collision timeline

plasma lives ~3x10^{-23} seconds, ~10^{-12} cm across



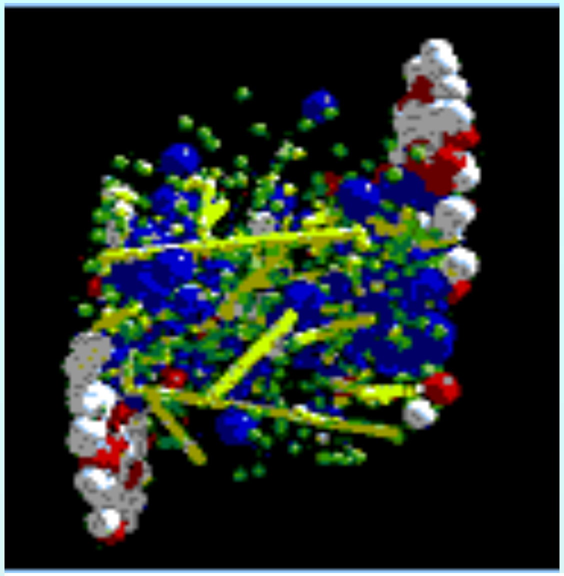


Study with particles coming out

- radiated from bulk medium: "internal" plasma probes
- large E_{tot} (high p or M) set scale other than T(plasma)
  autogenerated "external" probe
  Can calculate w/perturbative QCD
  control probe: photons - EM, not strong interaction

Is the collision hot enough?

Hottest Science Experiment on the Planet*

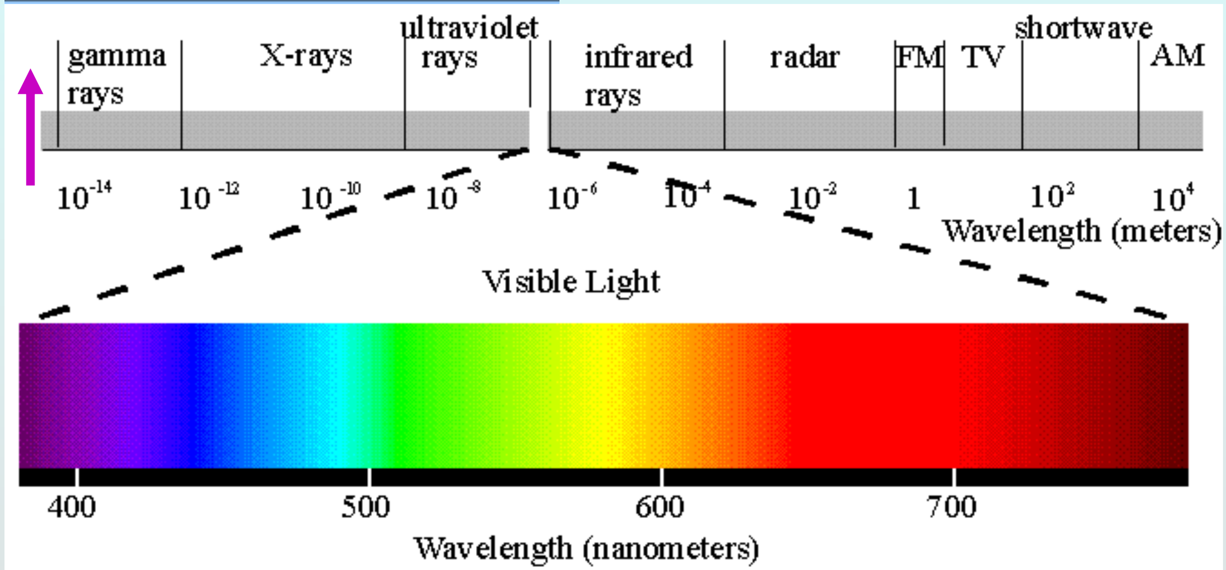


plasma lives for 3×10^{-23} s

droplet is 10^{-12} cm across

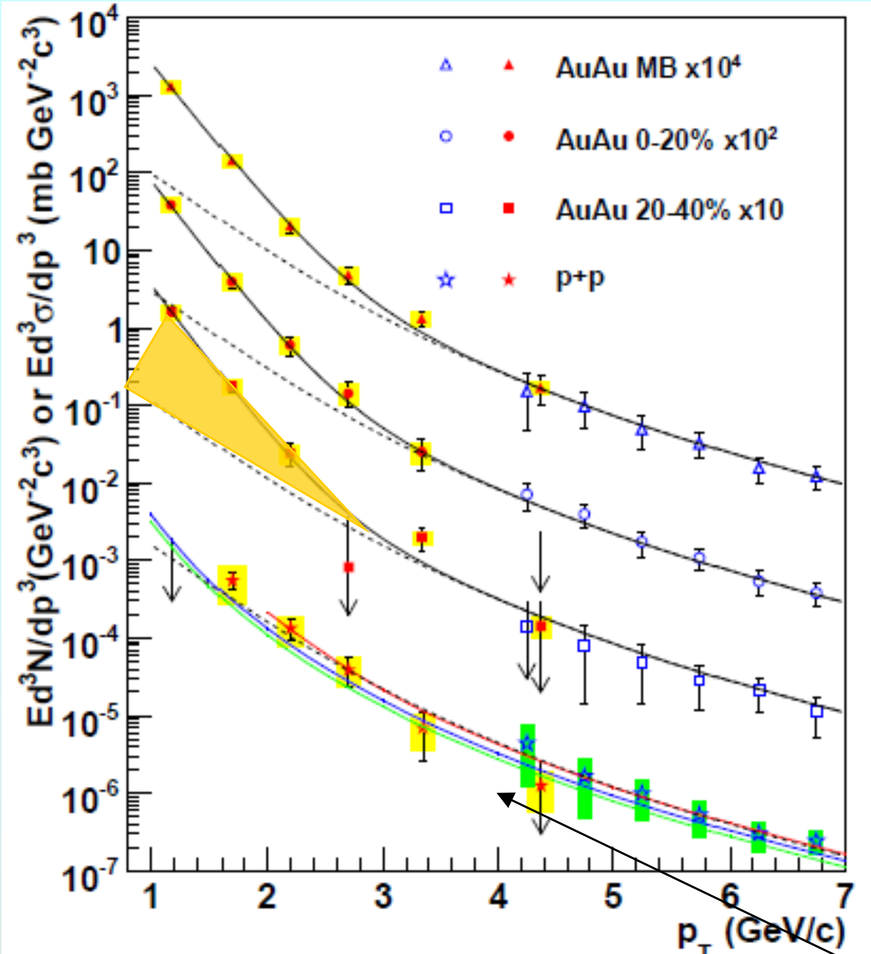
can't use a thermometer!

So we look at radiation

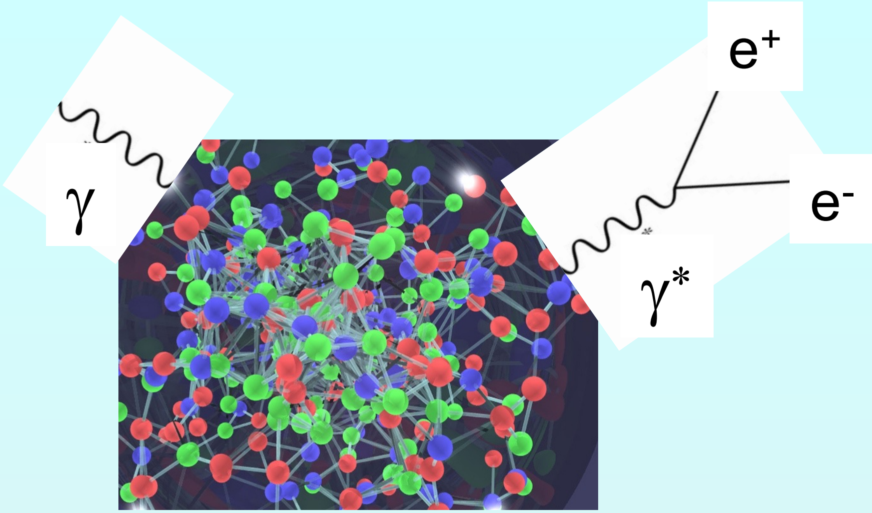


* According to Discover Magazine (2010)

Thermal radiation



PRL 104, 132301 (2010)



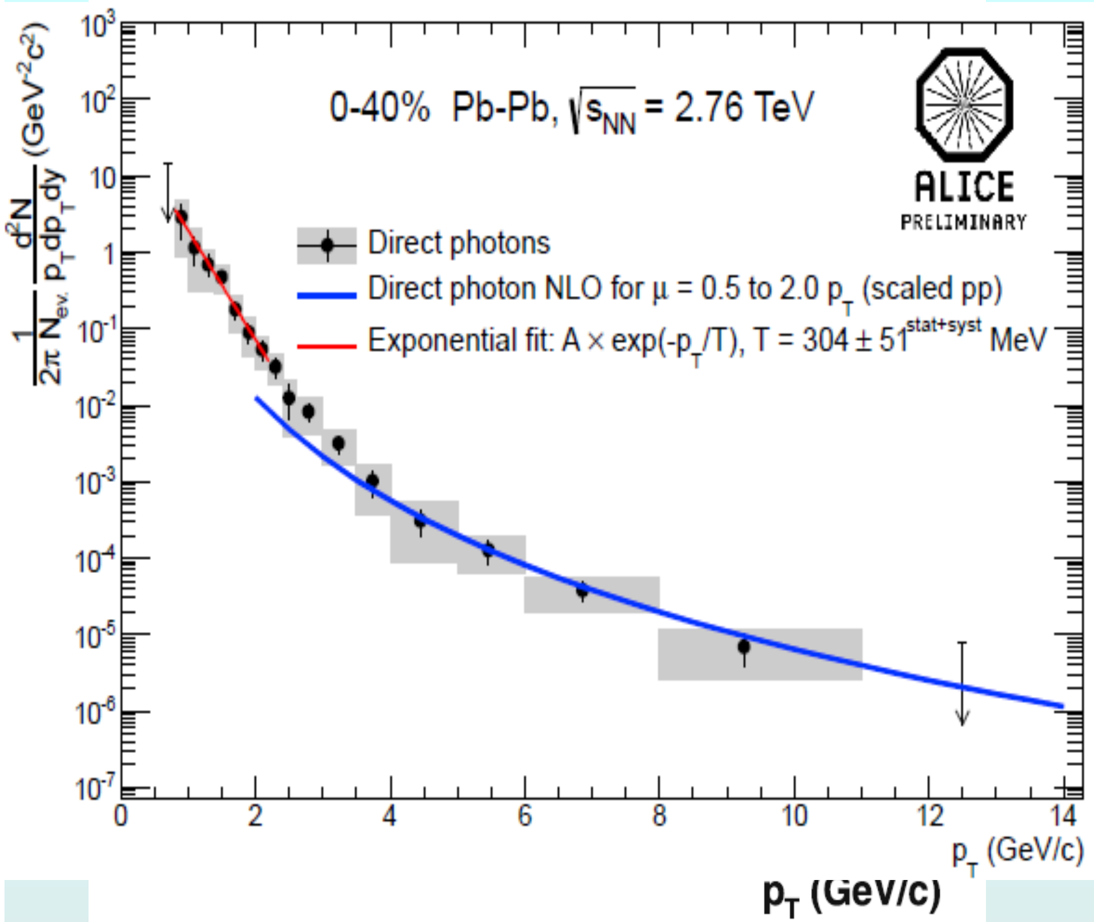
Low mass, high p_T e^+e^- → nearly real photons

Large enhancement above p+p in the thermal region

pQCD γ spectrum (Compton scattering @ NLO) agrees with p+p data

A. Monnai

direct photons: $T_{init} > T_c$!



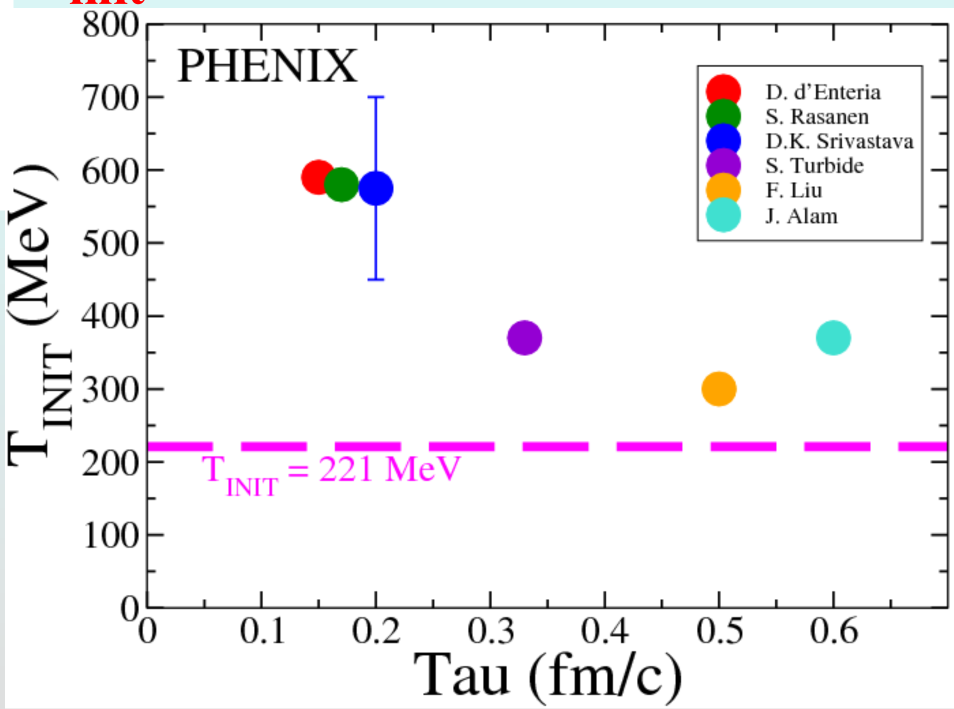
- **Exponential fit in p_T:**

T_{avg} = 221 ±23 ±18 MeV

But, a hot system expands!

- **Use hydrodynamics models to reproduce data**

$T_{init} \geq$ 300 MeV

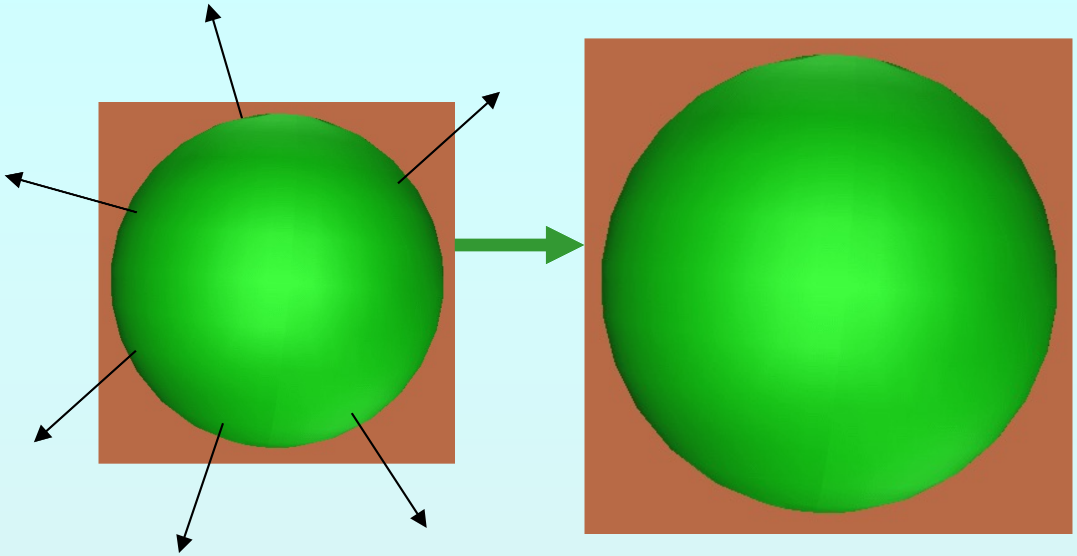


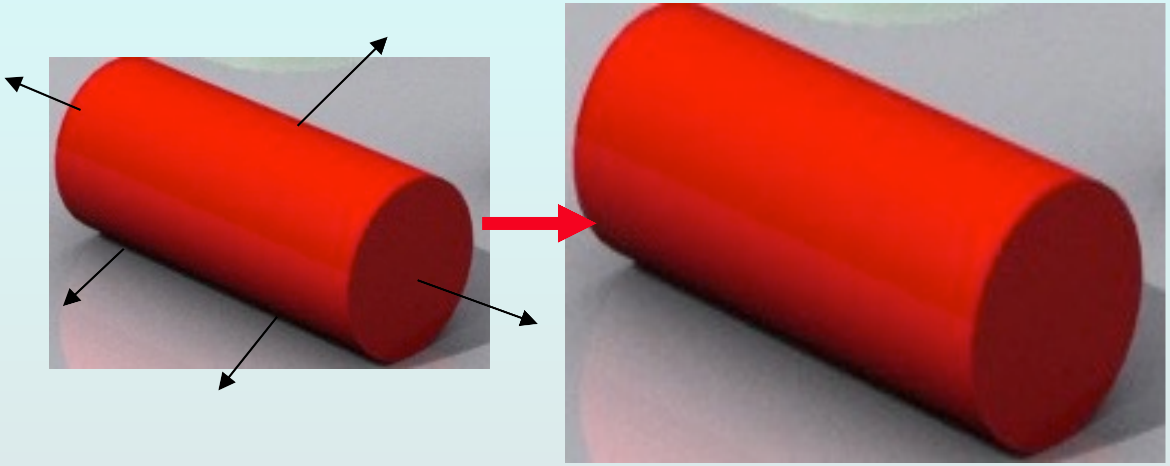
NB: T_c ~ 150 MeV

@ LHC T_{avg} = 304±51 MeV

T ~ 30% higher than at RHIC

Collective flow: a common velocity boost

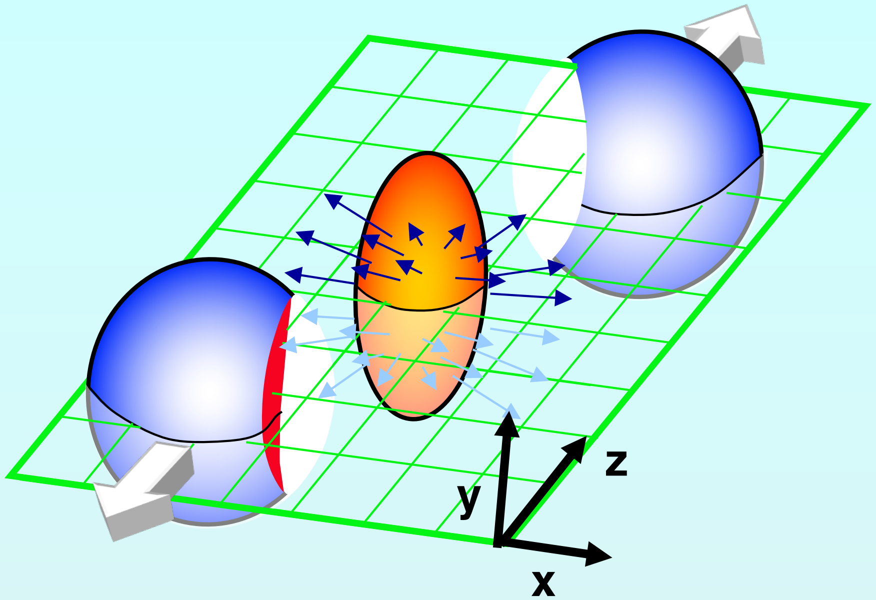


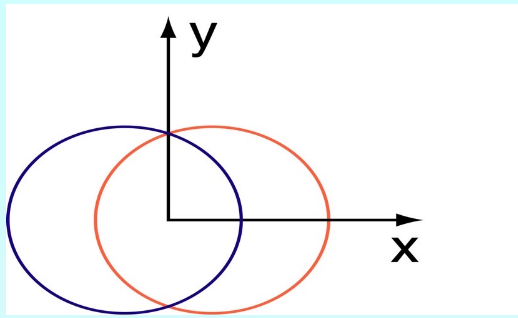


Model expansion of the system with fluid dynamics

A. Monnai

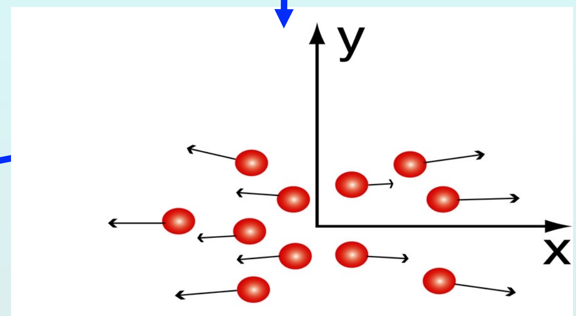
Watch QGP blow up → collective flow (v_2)

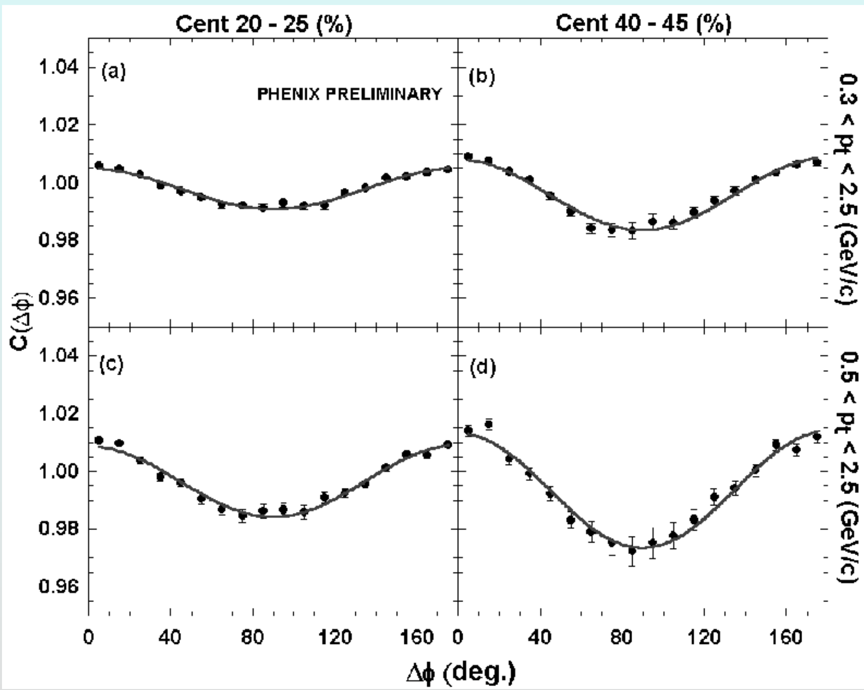




Almond shape overlap region in coordinate space

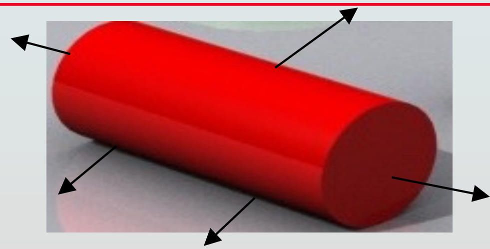
momentum space



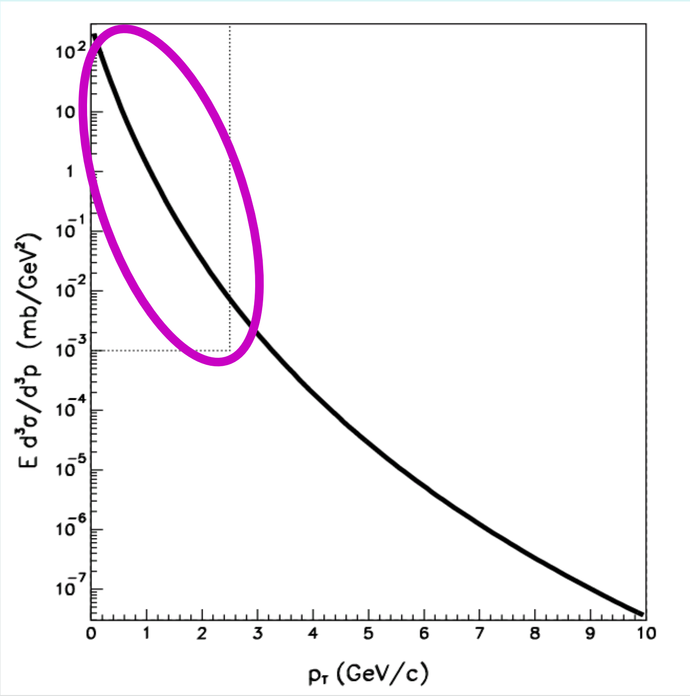


$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

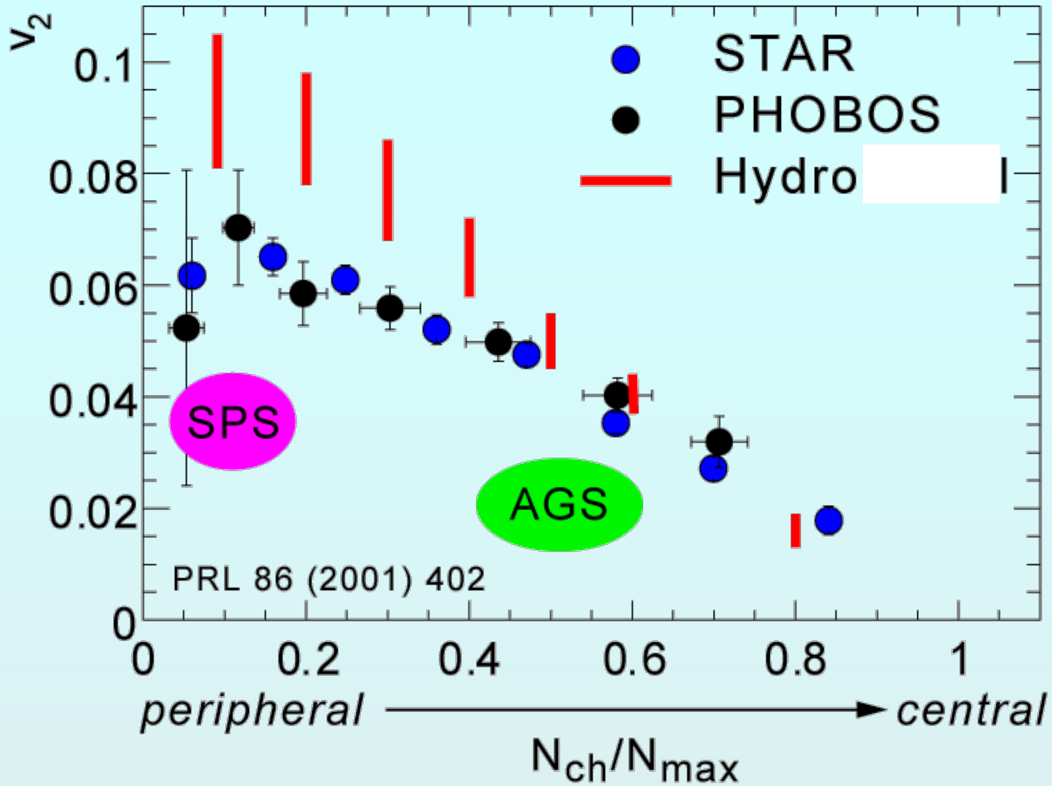
"elliptic flow"



Plasma properties



Compare v_2 to hydrodynamics



"perfect liquid"

Reproduce the data when:

system has deconfined quarks and gluons

viscosity is approximately zero (freely flowing liquid)

Discovery: Hot QCD matter is *strongly coupled*

- viscosity is near limit predicted for equilibrium systems from the uncertainty principle (& string theorists!)

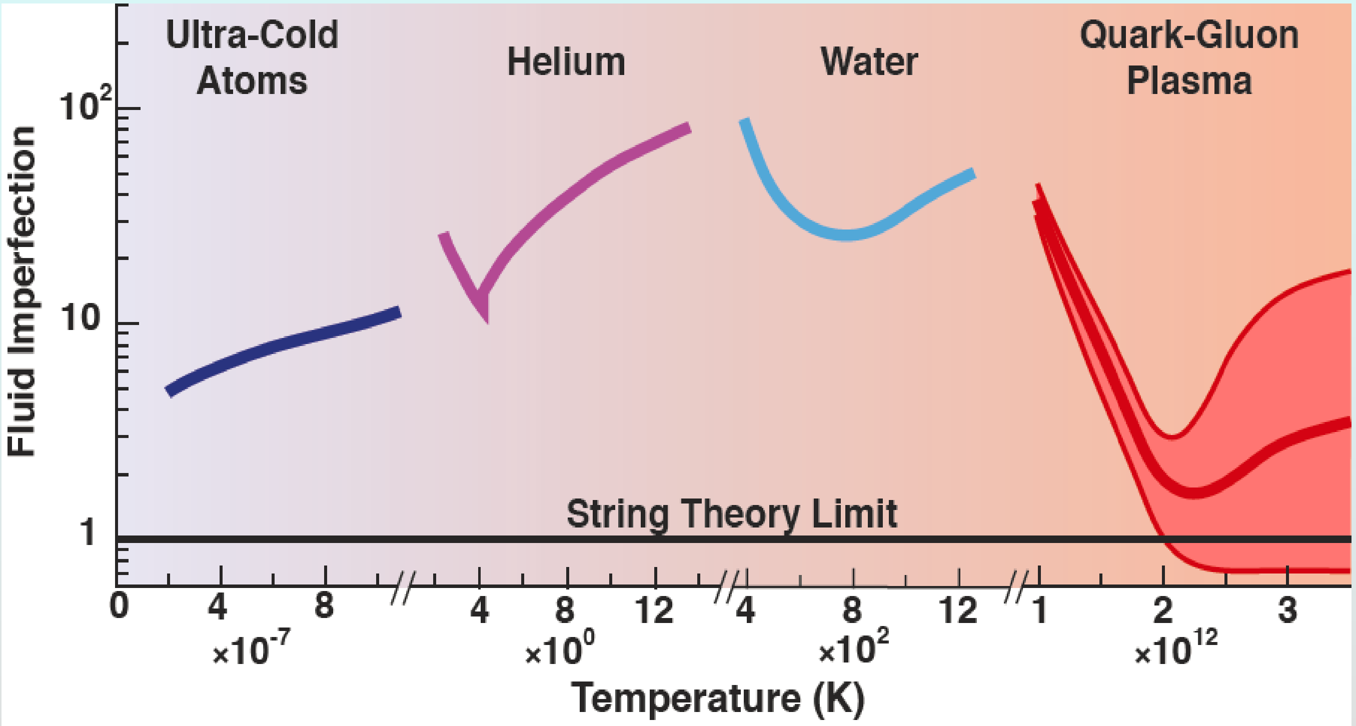
$$\eta/s \geq \hbar/4\pi$$

Use duality of quantum field theory to black holes

- Low viscosity = low resistance to transverse waves

-> many interactions, large cross section

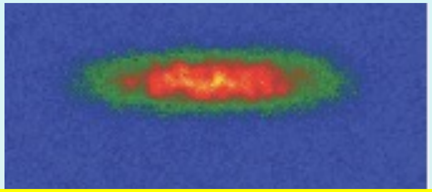
η/s *2π

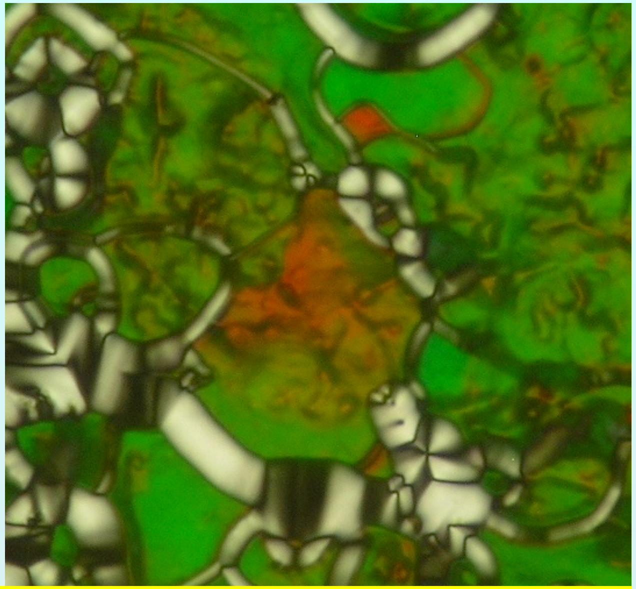


Many types of strongly coupled matter

Quark gluon plasma is like other systems with strong coupling - all flow and exhibit phase transitions

Cold atoms: coldest & hottest matter on earth are alike!





Dusty plasmas &

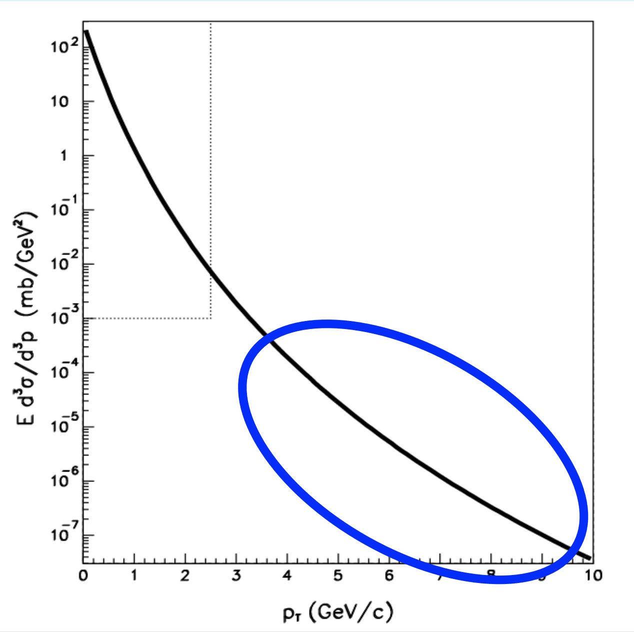
In all these cases have a competition:

Attractive forces ⇔ repulsive force or kinetic energy

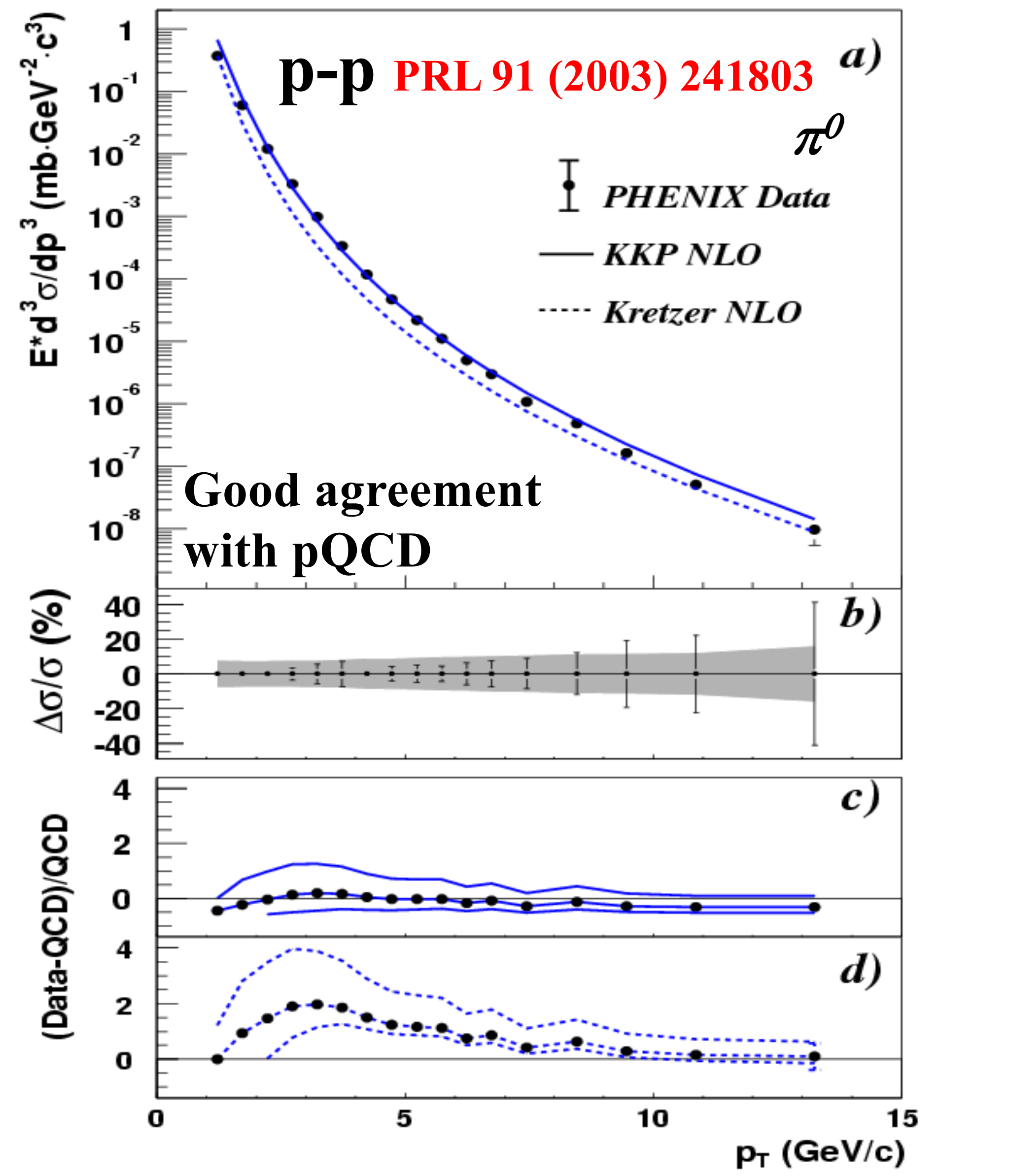
High T_c superconductors: magnetic vs. potential energy

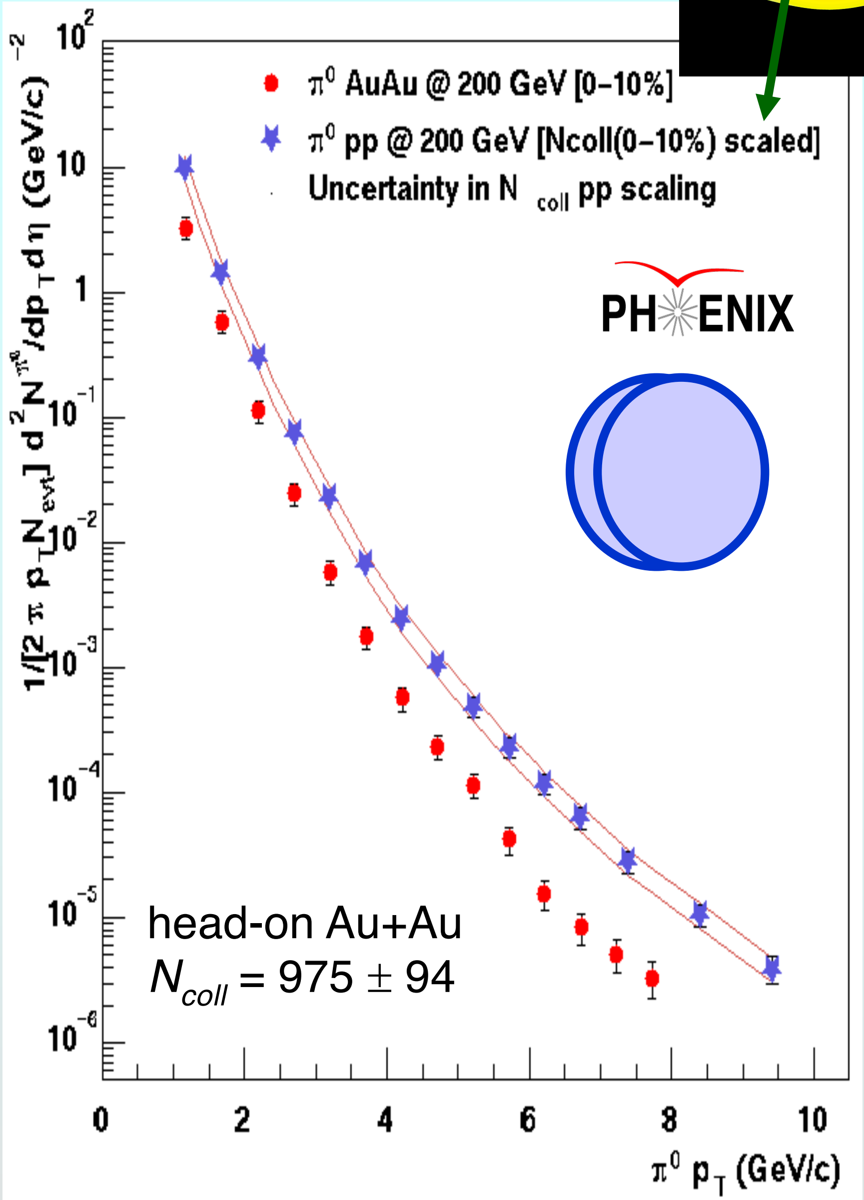
Result: many-body interactions, not pairwise!

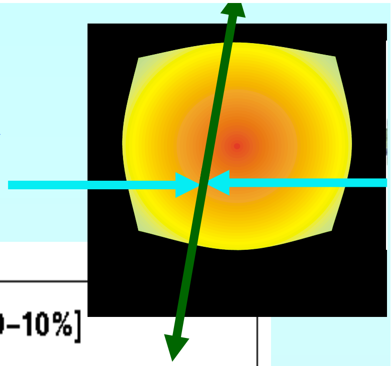
How does the plasma transport energy?



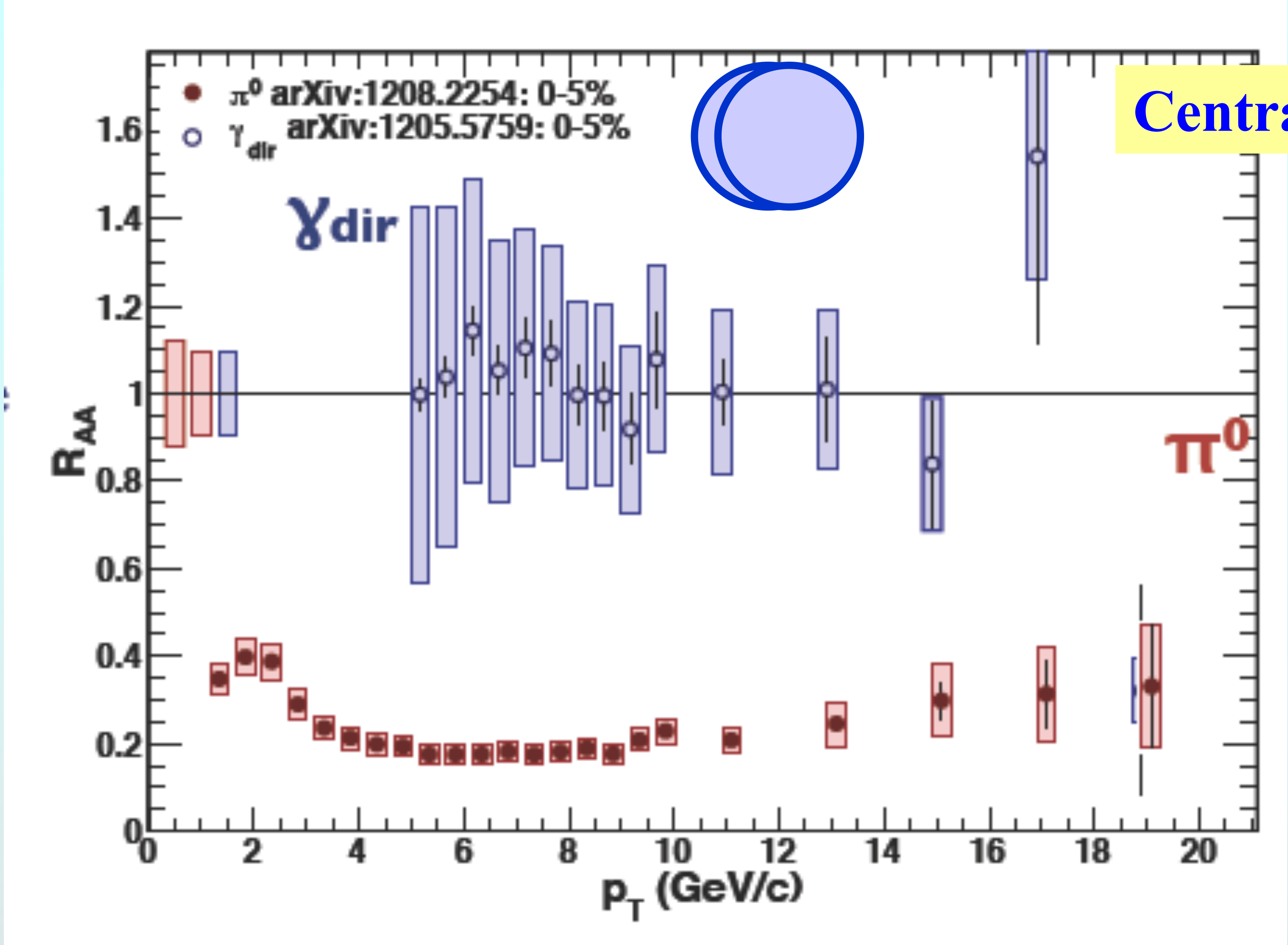
Opacity via "external probe" of plasma







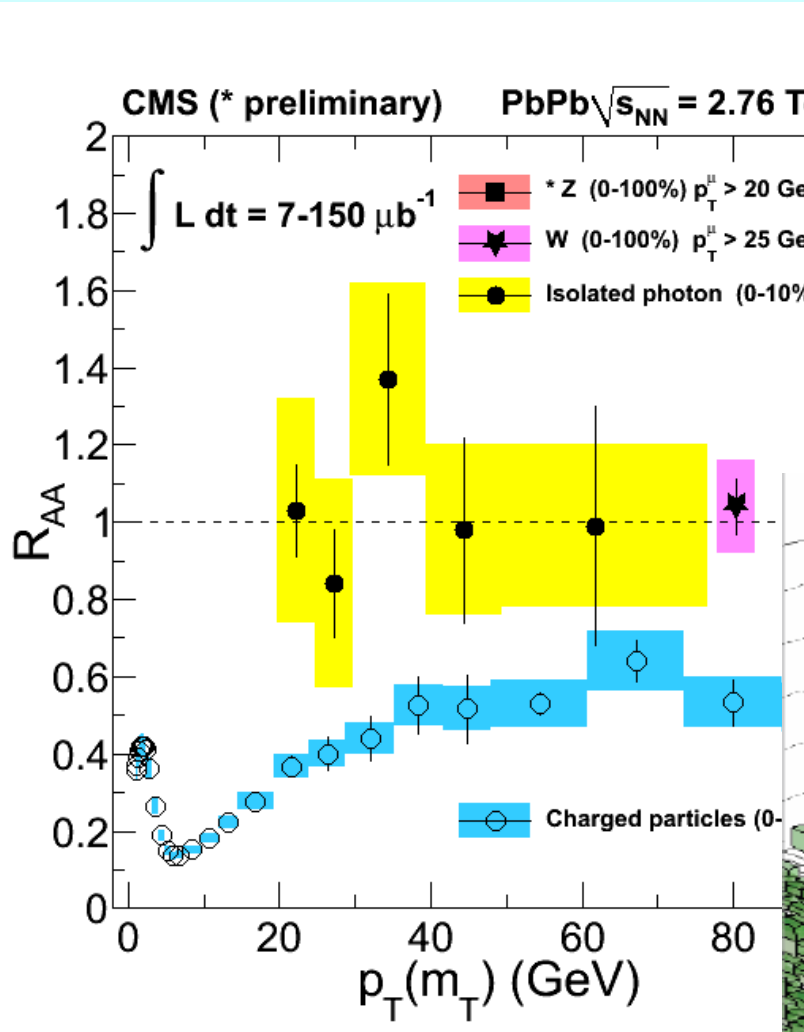
colored objects lose energy, photons don't

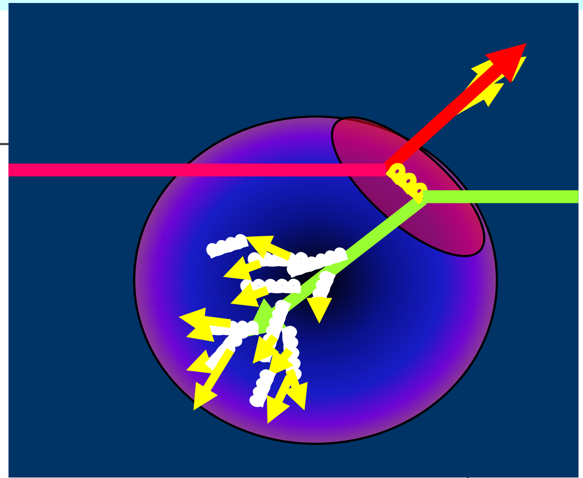


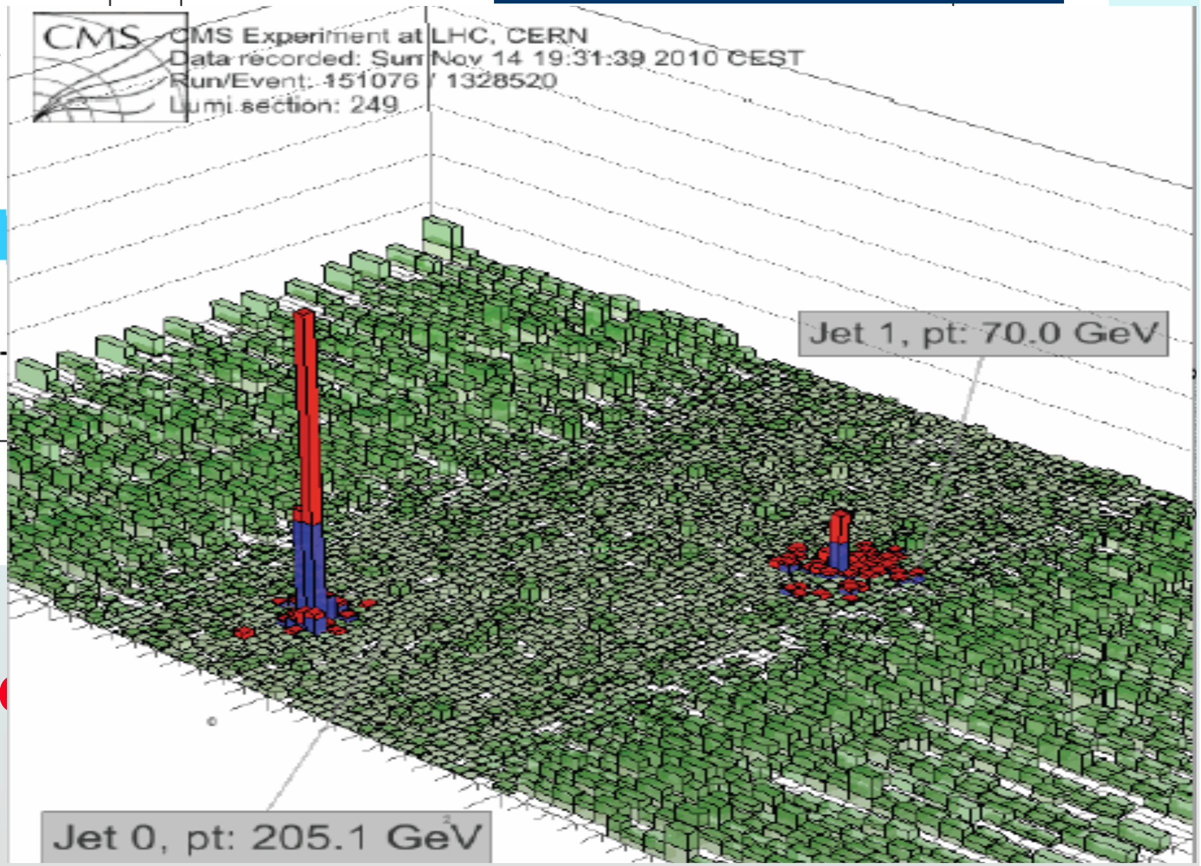
Central Au + Au

$$R_{AA}(p_T) = \frac{d^2N^{AA} / dp_T d\eta}{T_{AA} d^2\sigma^{NN} / dp_T d\eta}$$

Energy loss even by very energetic q & g







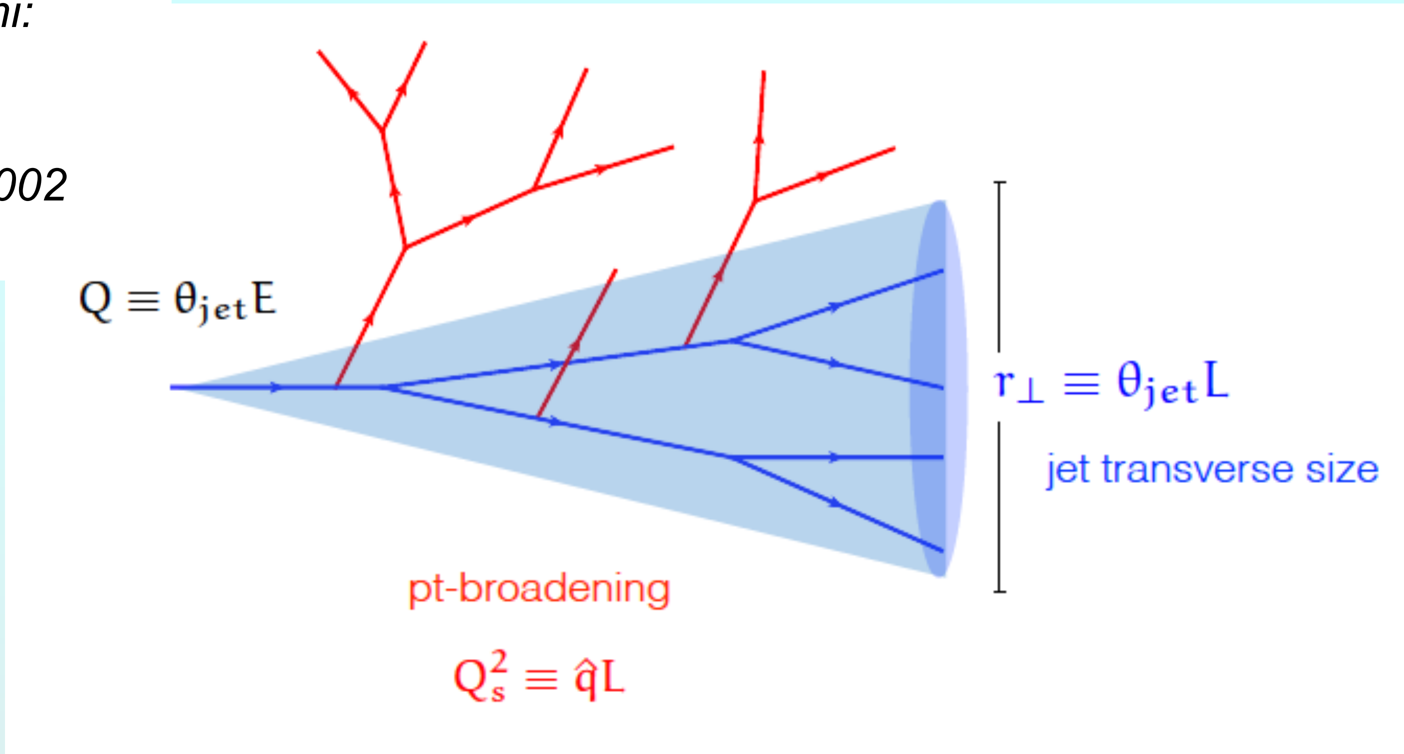
- LHC experiments r

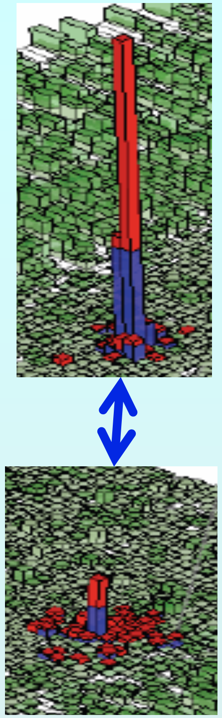
Interactions inside the plasma

Jet formation not instantaneous

Y. Mehtar-Tani: 1602.01047

Blaizot, et al, PRL114, 222002 (2015)





High energy q, g "hadronize" outside the plasma

collide in the plasma & radiate extra gluons

produce secondary particles at larger angle

Lower energy jets hadronize inside the plasma

Splittings are calculable by QCD

How much energy is lost?

- Quantify using a parameter called q-hat

  $\hat{q} = \sqrt{\mu^2/\lambda}$ λ=mean free path; μ=typical p_T transfer per scatter

  $\sim k_T^2/l$

- We find:

  $\hat{q}$ = 1.9 +/- 0.7 GeV^2/fm @ T=470 MeV *PRC90, 014909 (2014)*

  1.2 +/-0.3 GeV^2/fm @ T=370 MeV

  0.38 GeV^2/fm @ 150 MeV (not plasma) *arXiv:1910.07027*

- In cold nuclear matter

  $\hat{q}$ ~ 0.02 GeV^2/fm *arXiv:1907.11808*

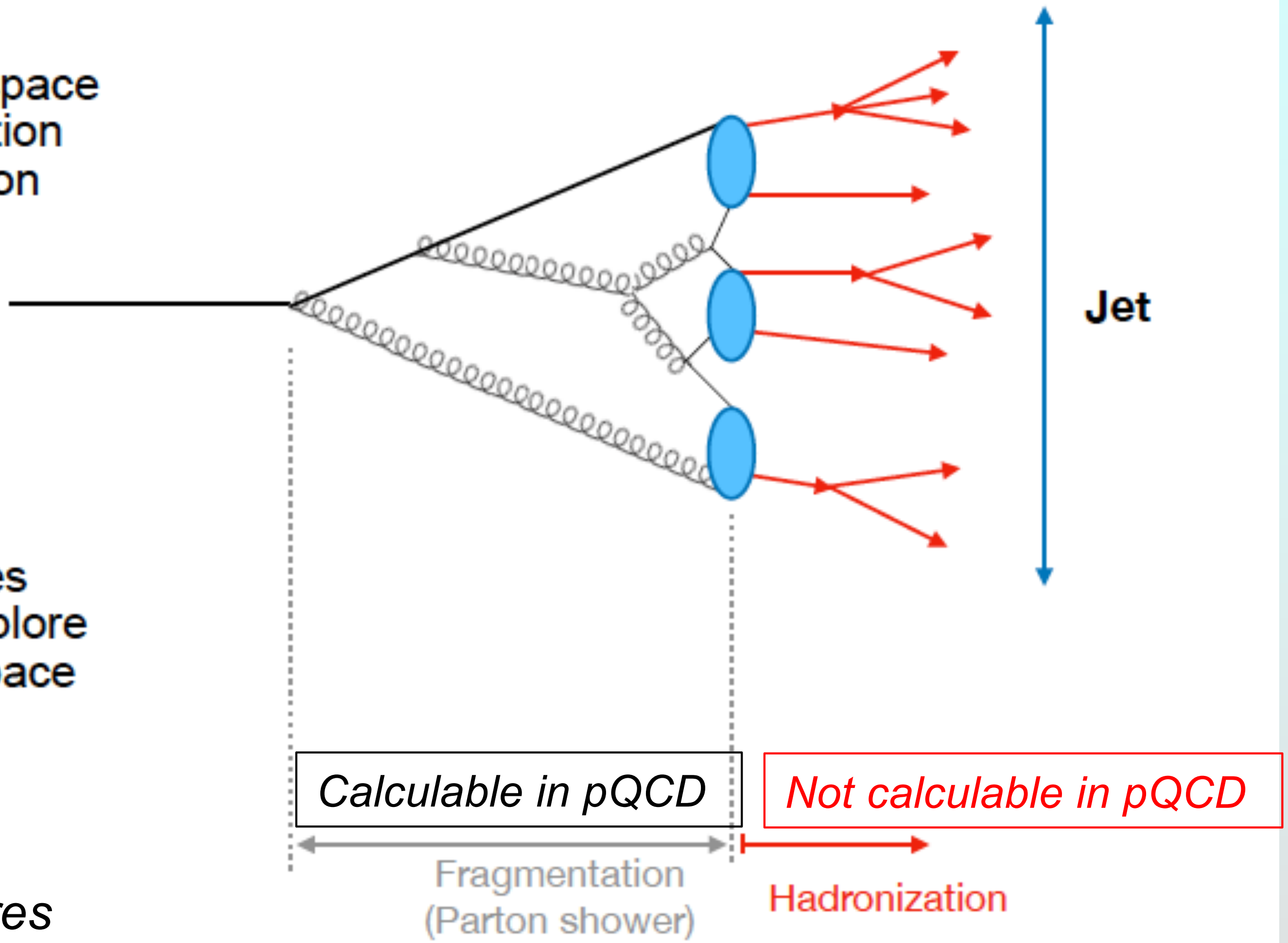
100 x more energy loss in hot plasma!

Shower evolution (how jets form)

Significant scale difference between parton from hard-scattering and hadrons measured in detector

Large phase space for jet formation and evolution

Suite of observables needed to explore this phase space



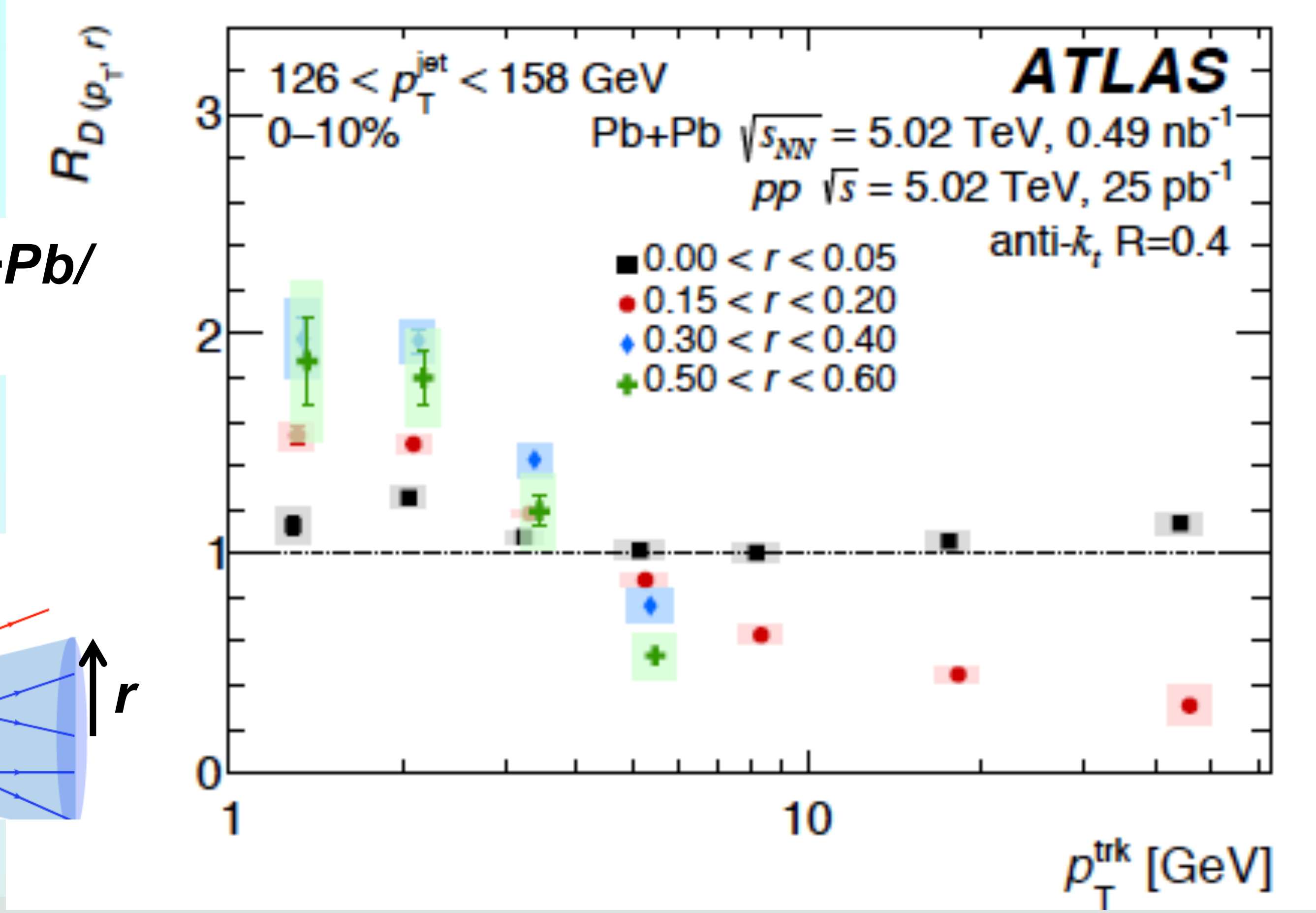
Rey Cruz Torres

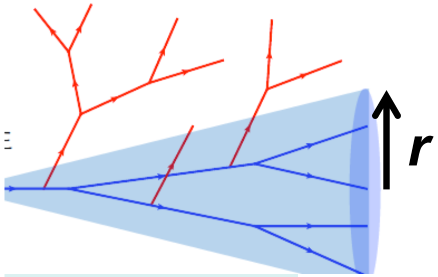
How energy is lost: look inside jets

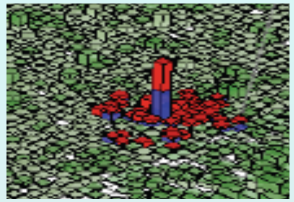
arXiv: 1908.05264

See also: CMS arXiv: 1803.00042

Pb+Pb/ p+p



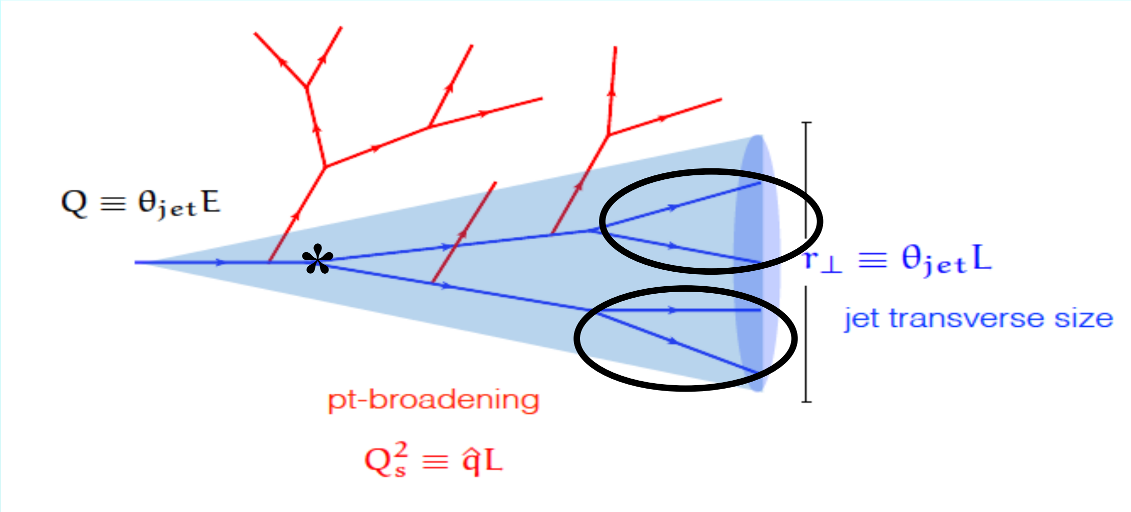




- **Excess soft particles at large jet radius**
- **Fewer particles at higher p_T**
- **Energy loss!**

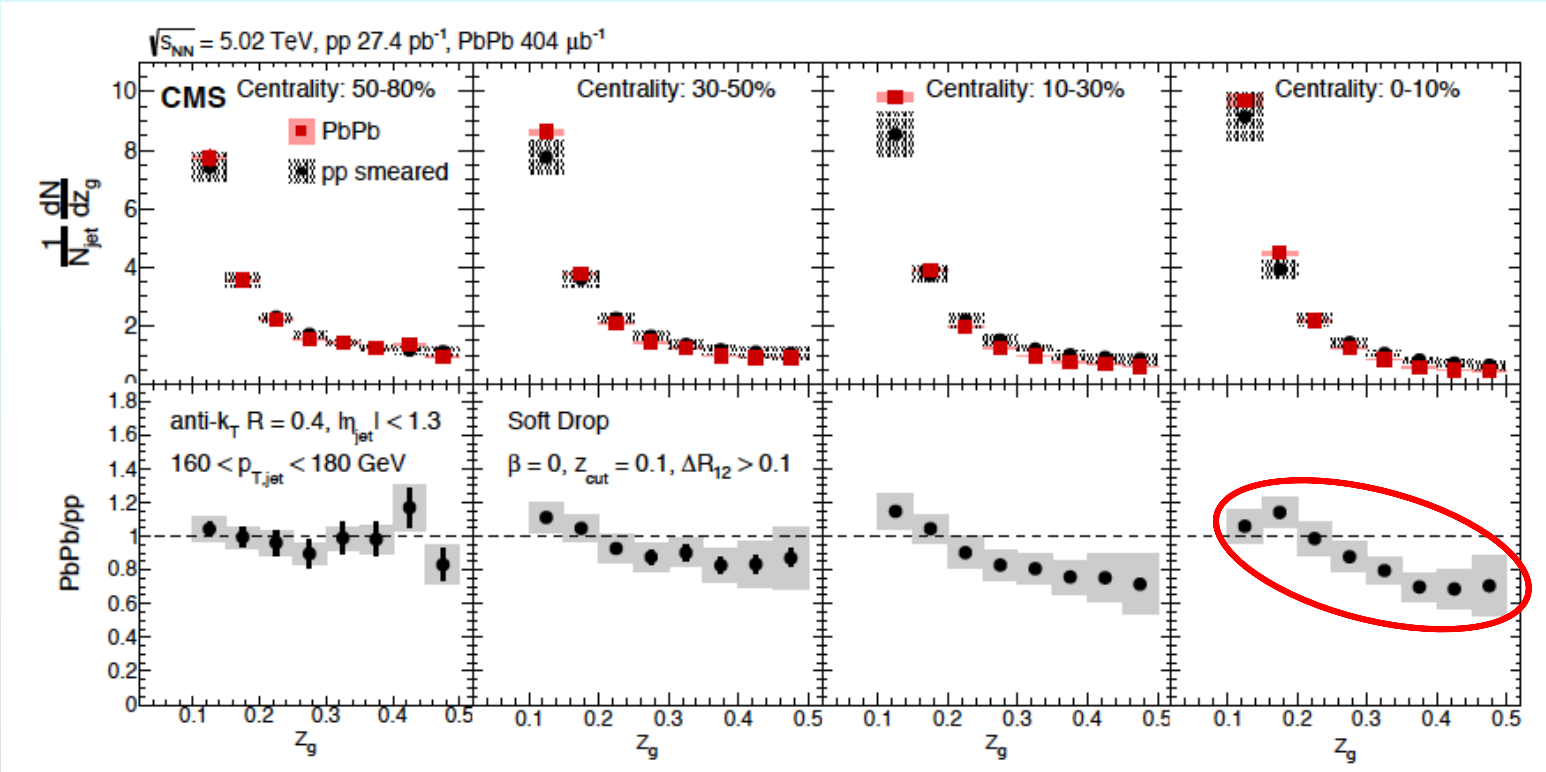
quantify: compare theory to the differential data

Structure within a jet



Does the plasma change the first gluon splitting?

$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$



Yes!

Now: study other jet structure variables

So, what do we now know?

- **Quark gluon plasma flows with almost no friction**

  strong coupling & efficient momentum transport
  many-body interactions dominate the properties

- **qhat = 1.2 - 2 GeV^2/fm in QGP: 100x larger than in nuclei**

  QGP induces gluon radiation and collisions
  QGP is opaque to quarks and gluons

- **Cascade of gluon splittings is well modeled by QCD, until they reach low energy (& many body interactions matter)**

  Modified by QGP - make softer & more particles
  Narrowed jet core-> gluons lose more energy than quarks

- ***What about cold, very dense QCD matter???***

Inside nucleons and nuclei

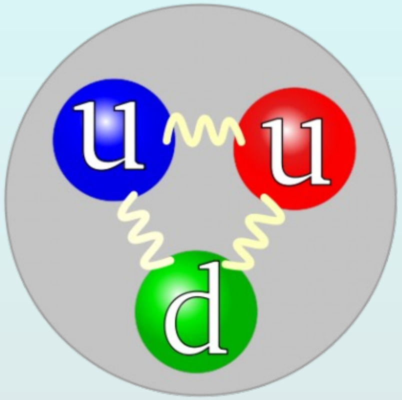
- **Discovery at RHIC:**

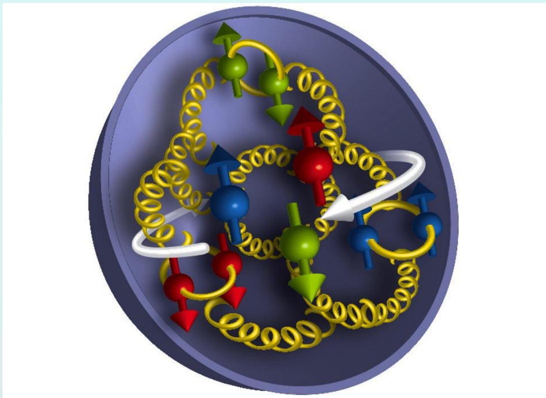
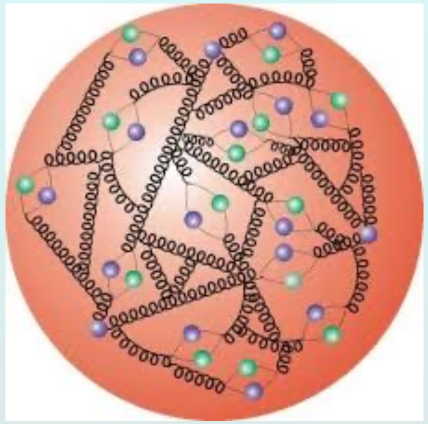
  Spin of the nucleon is spread out among the quarks and gluons!

  quarks & gluons in polarized proton also polarized

- **Implications:**

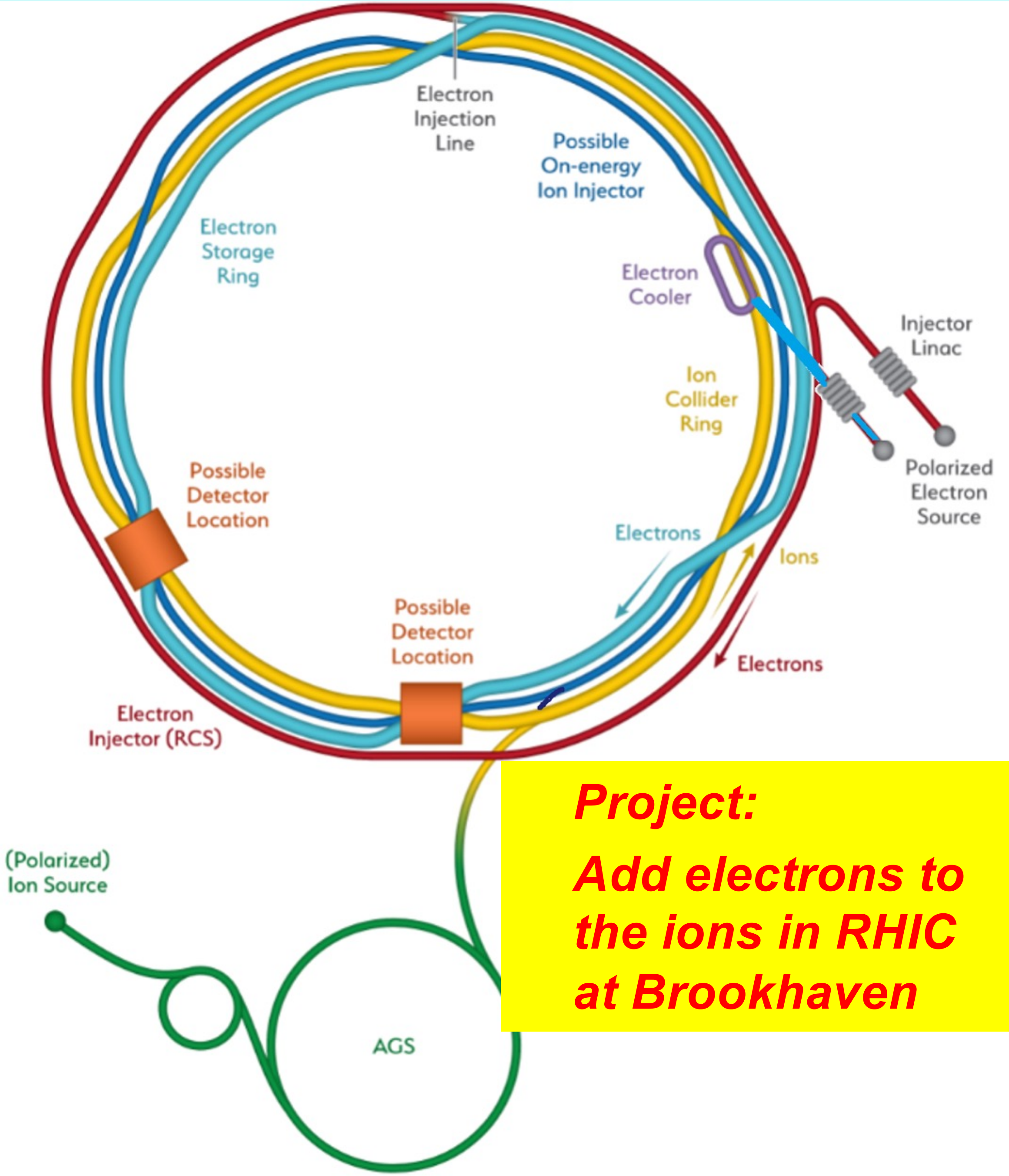
  Cold nuclear matter also strongly interacting when density of partons is large



- **Initial state of colliding Pb nuclei already has many-body interactions**

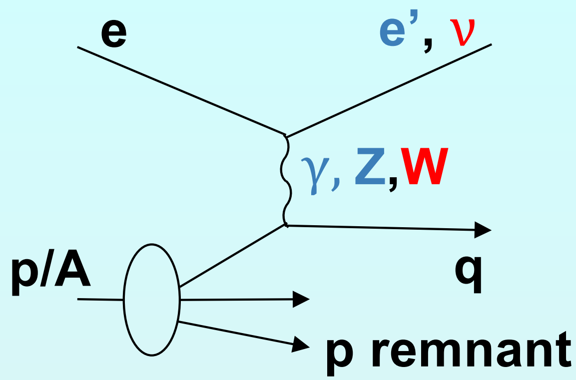
Study at future electron-ion collider



Project:

Add electrons to the ions in RHIC at Brookhaven

Scatter electrons from nuclei!



- √s = 30 to 140 GeV

Hadron Storage Ring
Electron Storage Ring
Electron Injector Synchrotron
Possible on-energy Hadron injector ring
Hadron injector complex

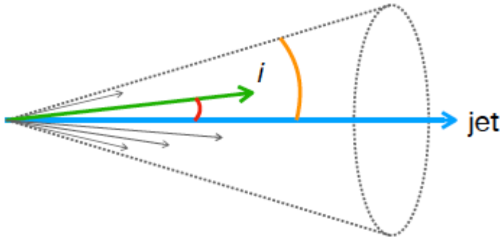
- **Backup**

Other interesting substructure variables

arXiv:2107.11303

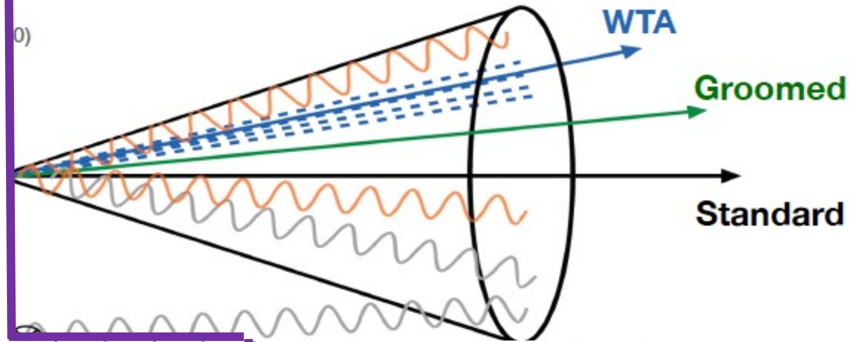
Includes both transverse-momentum and angular components with relative weights given by continuous parameter α

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}}\right)\left(\frac{\Delta R_{\text{jet},i}}{R}\right)^\alpha$$



$\alpha > 0 \rightarrow$ IRC-safe observable

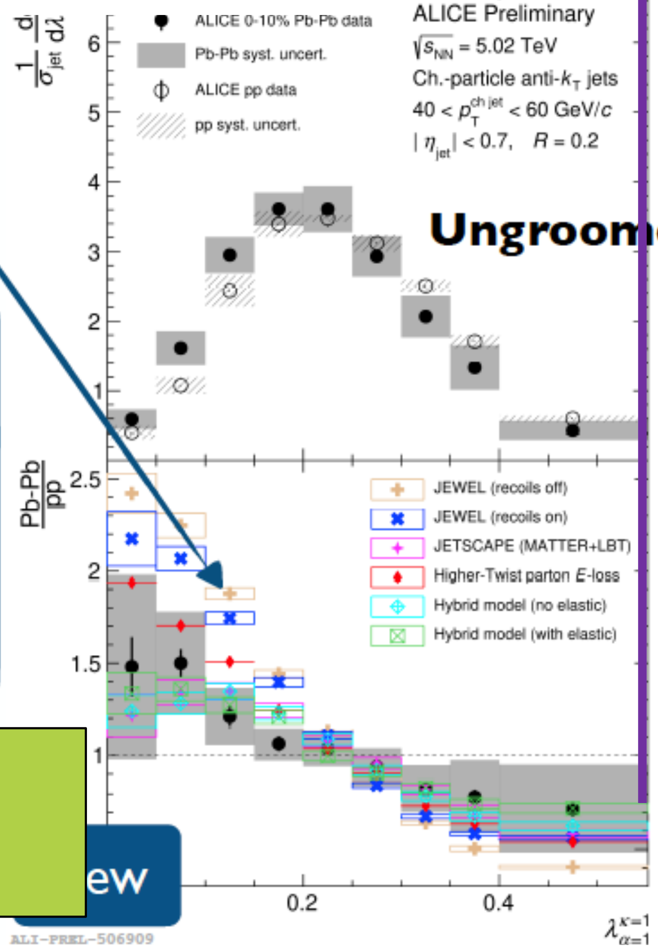
Jet axis difference

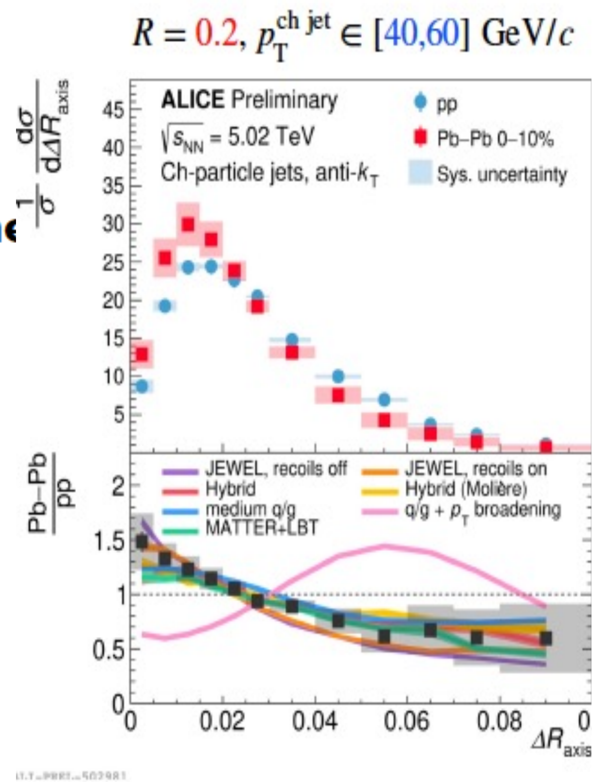


angularity

Models generally describe trends in data well, although some deviations

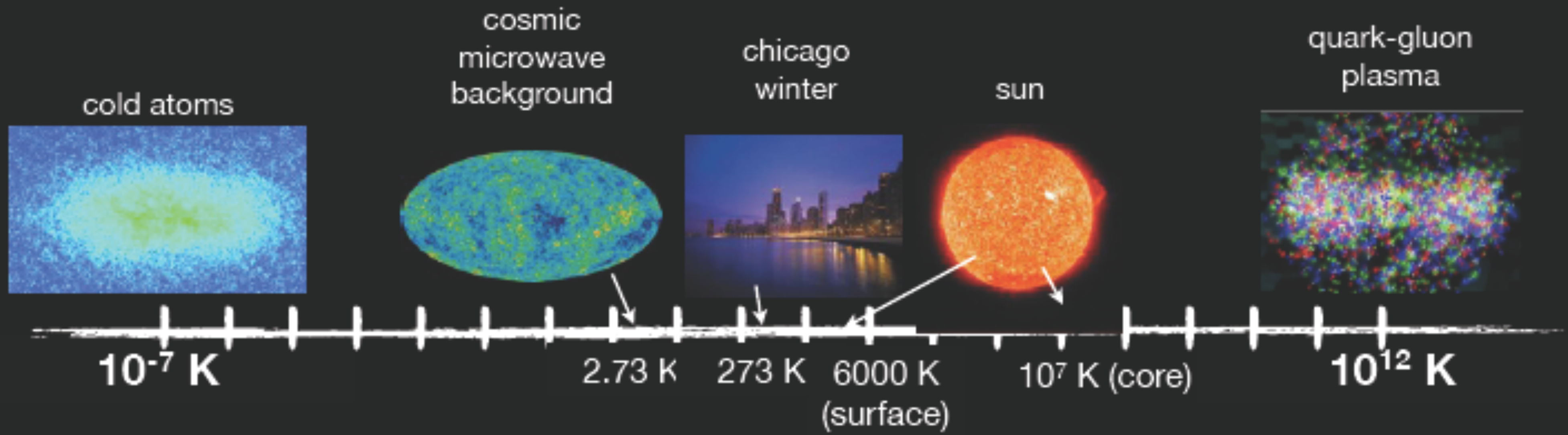
- JEWEL
  Zapp, EPJ C 74 2 (2014)
- JETSCAPE
  arXiv 2204.01163
- Higher Twist
  Chen, Zhang et al., CPC 45 (2021) 2, 024102
- Hybrid Model
  See Zach Hulcher, Tues 18:30





Jet core narrows (q vs. g?)
Theory agrees

273 K = 0°C



two nearly perfect liquids, completely different scales

difference in temperature : 10 billion billion (10^{19})

difference in volume : 1 million billion (10^{15})

difference in density : 10 million billion billion (10^{25})

perfect liquid is independent of <u>scale</u>

Thank you to my group!

Quantum ChromoDynamics (QCD)

- Field theory of strong interaction
  Chromo: color charge of quarks and gluons
  q: 3 colors, g: c & anti-c (8 types)
- Works well: key for Standard Model

- Quantum Electrodynamics (QED)
  for electromagnetic interactions
  exchanged particles are photons electrically uncharged

- Can see the photons (fortunately!)
  But particles with color are unstable
  Cannot “see” a single quark or gluon
  -> measure color neutral, composite: hadrons

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

Open questions

- **How can the QGP be hydrodynamic so quickly?**
  Lots of theoretical work ongoing - How to verify?
- **Are there (composite) quasiparticles in QGP?**
  Evidence that partons bounce off them??
- **What size QGP droplet can affect jets?**
  Systematically measure small systems
- **Quantify temperature dependence of QGP opacity**
  Jet substructure at multiple energies
- **Is there a coherence length in QGP, below which splittings are not resolved?**
  Scale dependence of jet substructure in data and theory

Quantum Chromodynamics

Theory of quarks, gluons, and their interactions

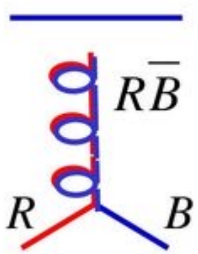
QCD Lagrangian

$$\boxed{\begin{aligned} L = &\bar{q}\left(i\gamma^{\mu}\partial_{\mu} - m\right)q \\ &- g_s\left(\bar{q}\gamma^{\mu}T_a q\right)G^a_{\mu} \\ &- \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a \end{aligned}}$$

q kinetic energy and mass

qg interaction, coupling g_s

g kinetic energy and self interactions



q propagator

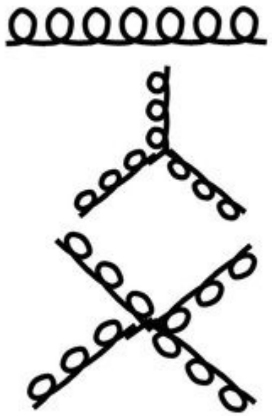
qg vertex

$$G^a_{\mu\nu} = \partial_{\mu}G^a_{\nu} - \partial_{\nu}G^a_{\mu} - g_s f_{abc}G^b_{\mu}G^c_{\nu}$$ $\rightarrow$ last term symbolically in gluon fields G^a_{μ} :

$$G^a_{\mu\nu}G^{\mu\nu}_a \propto \quad G^2 \quad + g_s\, G^3 \quad + g_s^2\, G^4$$

g kinetic energy

g self-interactions given by non-abelian SU(3) gauge group, only one coupling g_s



g propagator

3-gluon vertex

4-gluon vertex

Small viscosity/entropy

Viscosity: *inability* to transport momentum & sustain a wave

internal friction damps waves

low η → large σ, transports momentum across fluid

normal QCD: σ not so large

large σ in QGP→ strongly coupled!

large σ → many-body interactions when the density is high

$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f$$

$$\bar{p} \sim T$$

Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

So dense QCD matter should also strongly affect quarks & gluons transiting it

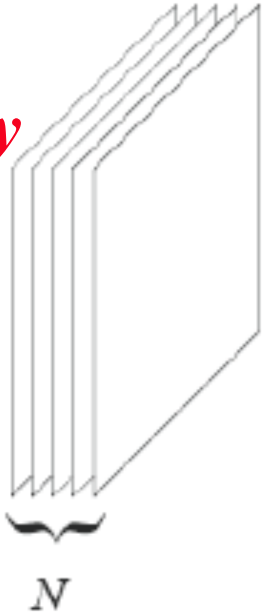
"Gauge gravity duality"

Stack of N D3-branes in type IIB string theory: described in two different pictures:

As a quantum field theory of degrees of freedom on the branes: $\mathcal{N} = 4$ supersymmetric Yang-Mills theory

As string theory on a the curved spacetime (induced by the matter density on the branes)

Field theory of quarks and gluons



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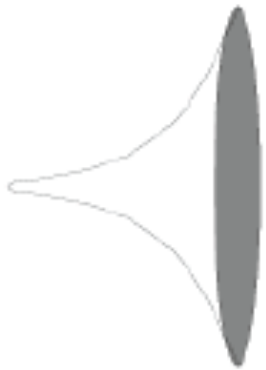
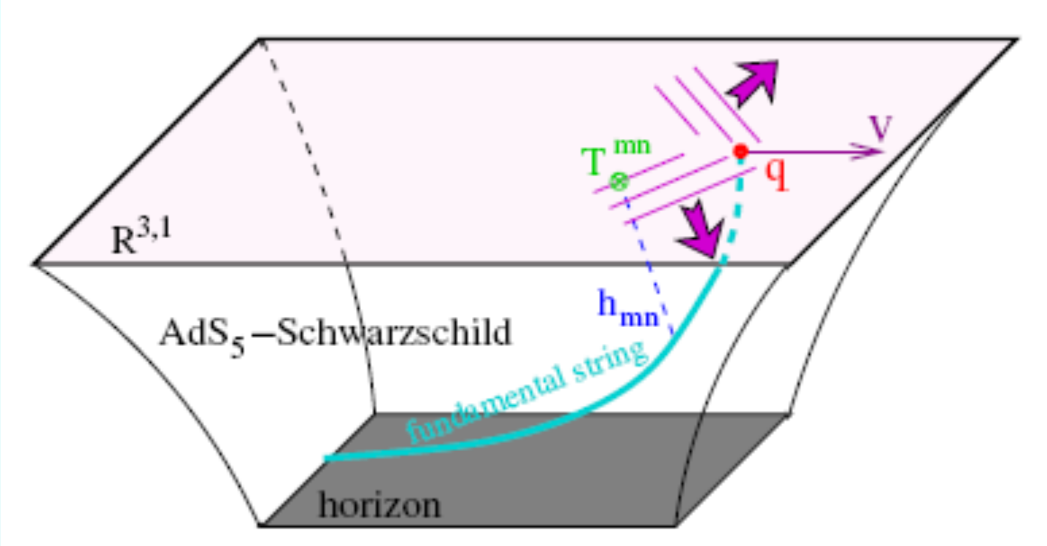


situation near a black hole (but with an extra dimension)

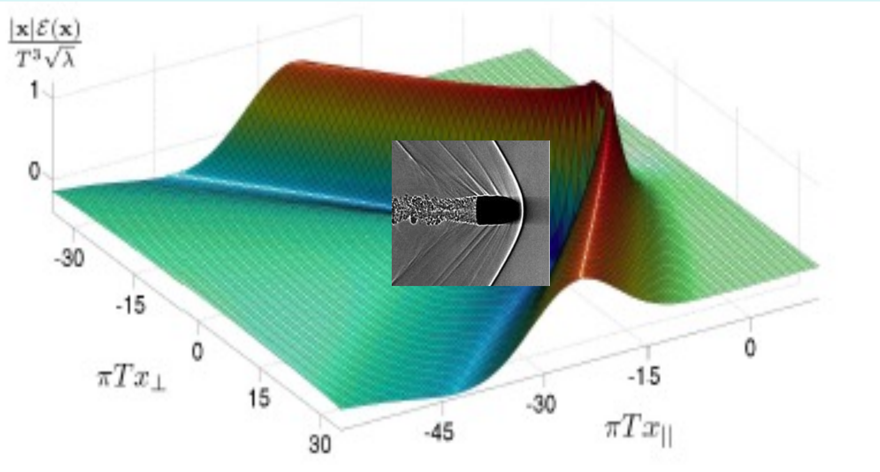
The limit of infinitely strong coupling in gauge theory is the limit when string theory becomes Einstein's general relativity

AdS/CFT correspondence and the Quark-Gluon Plasma – p.5/

Also explain heavy quark energy loss



Chesler & Yaffe, 0706.0368(hep-th)



String theory: yes

Theory:

.Quark gluon plasma stops heavy charm quarks

.Even the heavier b quarks!!

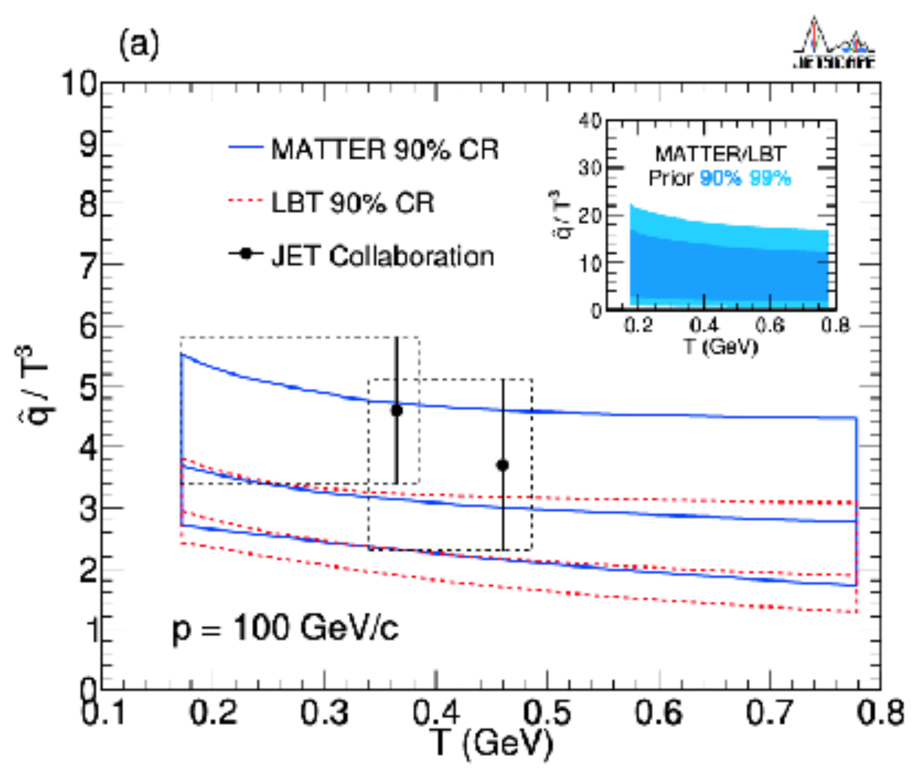
Experiment:

.Charm stopped

.Beauty less so

Data + theory = transport

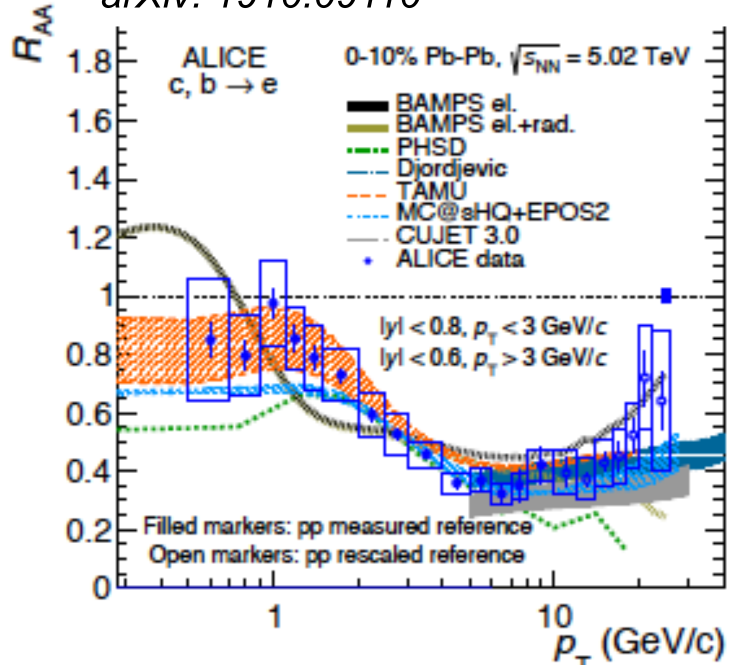
Heavy quark energy loss dominated by collisions at low p_T, radiation at high p_T. Light + heavy: precision

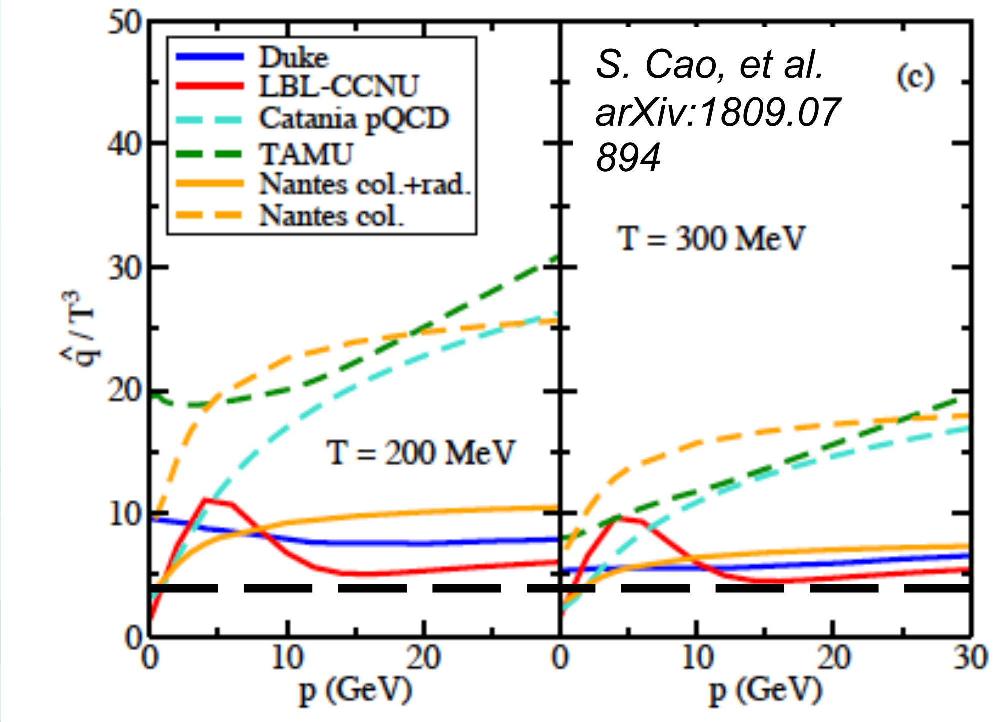


RHIC and LHC data analyzed by JETSCAPE collaboration:

S. Cao et al., arXiv: 2102.11337

arXiv: 1910.09110





Heavy quark R_{AA} fits

Is there a mass effect on g radiation?

- **Soft gluon radiation spectrum**

$$dP = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{k_\perp^2\, dk_\perp^2}{(k_\perp^2+\omega^2\theta_0^2)^2}, \quad \theta_0 \equiv \frac{M}{E},$$

Dokshitzer, et al. J.Phys.G17,1602 (1991)
Dokshitzer & Kharzeev, PL B519, 199 (2001)

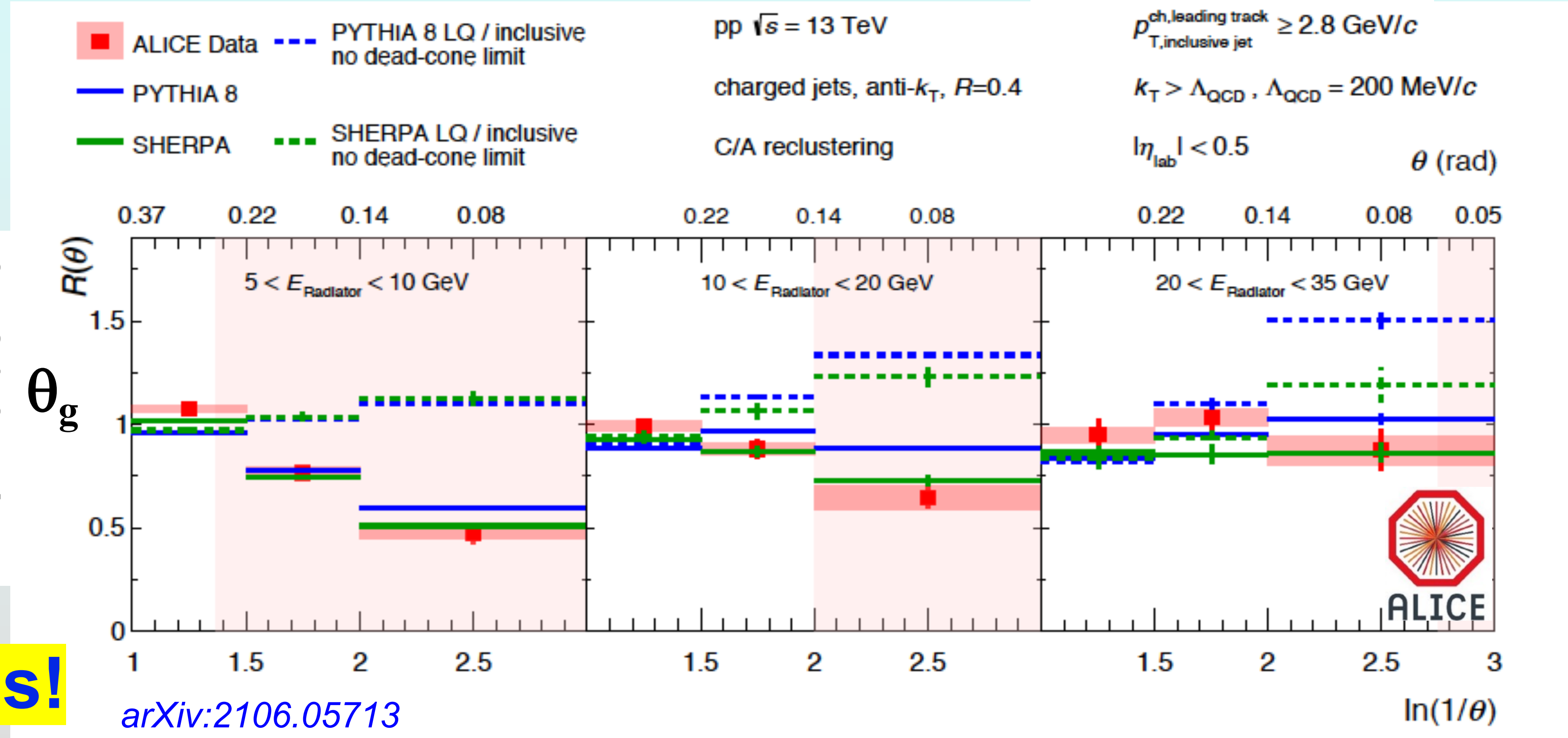
Large M suppresses small angle radiation (phase space effect)

Known as "dead cone effect"

ALICE D-tagged vs. inclusive jets in p+p

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

HF/ inclusive θ_g



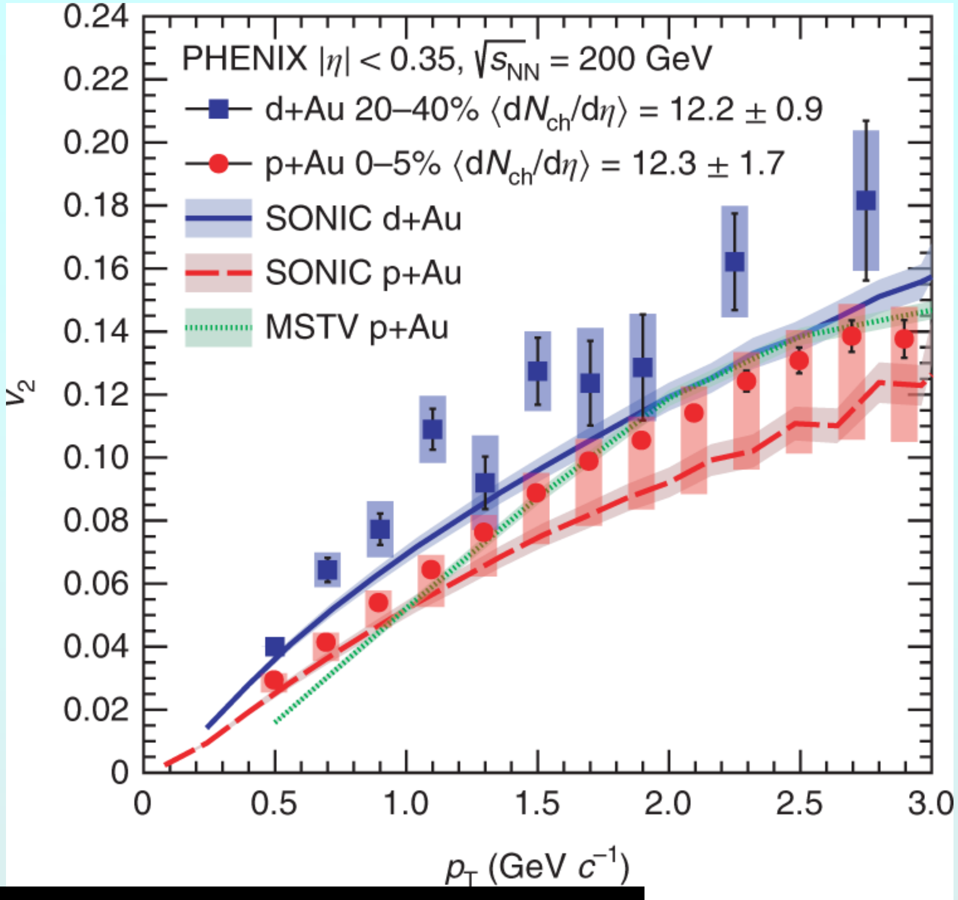
Yes!

arXiv:2106.05713

Eeek! Hydrodynamics in small systems!

PHENIX Collaboration

Nature Physics (2018)

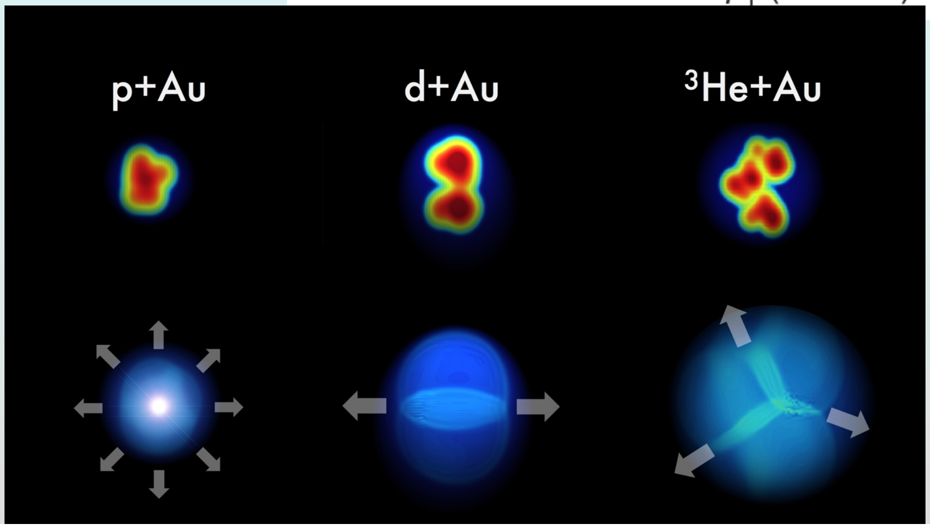


Not big & dense

See collective flow!

Seeded by initial geometry

Droplet of QGP?



How can pressure build up before this tiny system evaporates??

Parton energy loss

- **Quantify by q-hat**

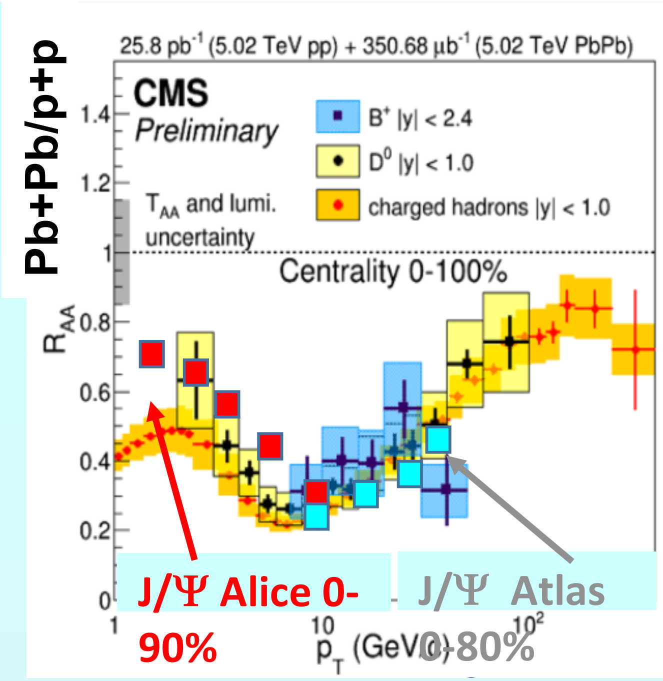
  $\hat{q} = \sqrt{\mu^2/\lambda}$ λ=mean free path;

  μ=typical p_T transfer per scatter

  $\sim k_T^2/l$

- **Constrain theory by measured R_{AA}**

  Parton interactions in expanding QGP



Many body q & g interactions!

- **For a 10 GeV parton**

  $\hat{q}$ = 1.9 +/- 0.7 GeV²/fm @ T=470 MeV

  1.2 +/-0.3 GeV²/fm @ T=370 MeV

  JET Collaboration PRC90, 014909 (2014)

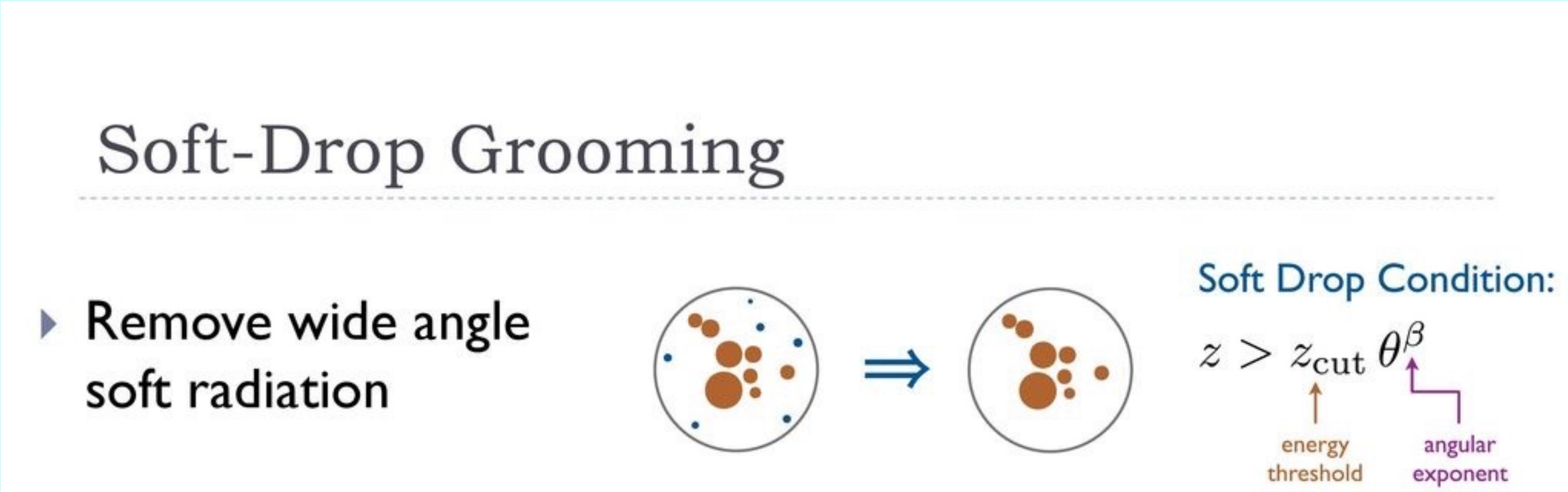
  0.38 GeV²/fm @ 150 MeV(hot hadron gas)

  arXiv:1910.07027: Dorau, Rose, Pablos & Elfner

  0.02 GeV²/fm in cold nuclear matter

  arXiv:1907.11808: Ru, Kang, Wang, Xing & Zhang

For early splitting: "groom" the jets

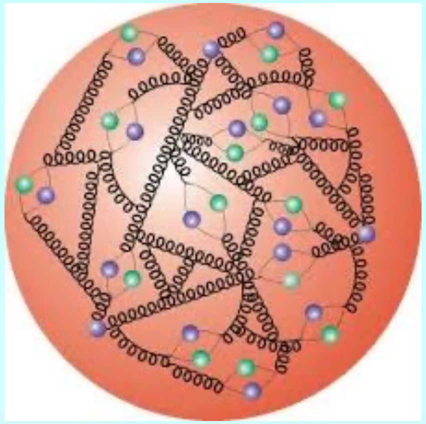


- **Grooming works on *hadrons* or *partons***
- **Calculate hard parton splittings with perturbative QCD**
- **Important to benchmark the jets in p+p collisions if we want to look for modification by the plasma!**

HOW ABOUT COLD, DENSE QCD MATTER?

Is it strongly coupled too?

Look deep inside nuclei



- **3 valence quarks + gluons + sea quarks**

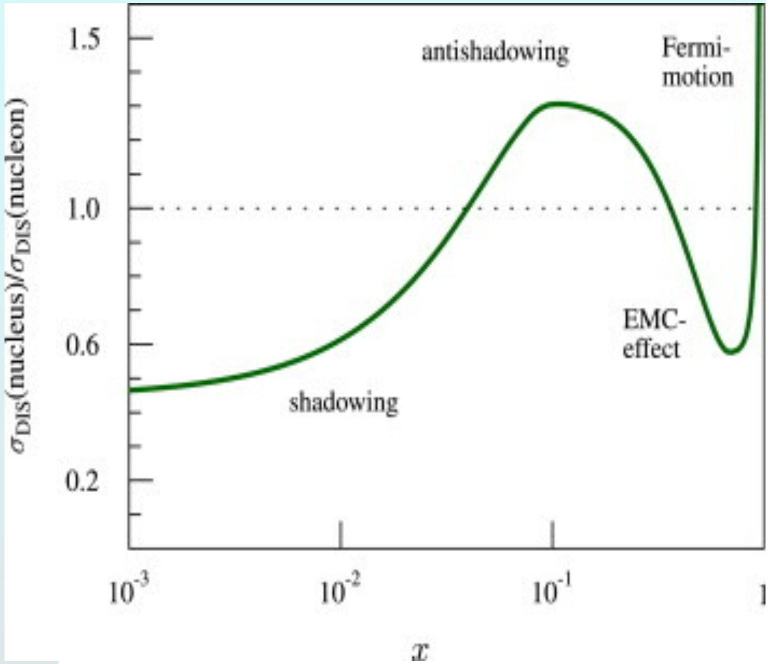
  Gluons split into quarks + antiquarks

  Measured by scattering electrons (γ transfer)

- **Count quark and gluon densities vs. momentum fraction they carry**

  x is momentum fraction in ∞ momentum frame (i.e. in proton beam frame)

  Q^2 is photon virtuality (effective mass)



- **For p, n inside nucleus:**

  densities are different!

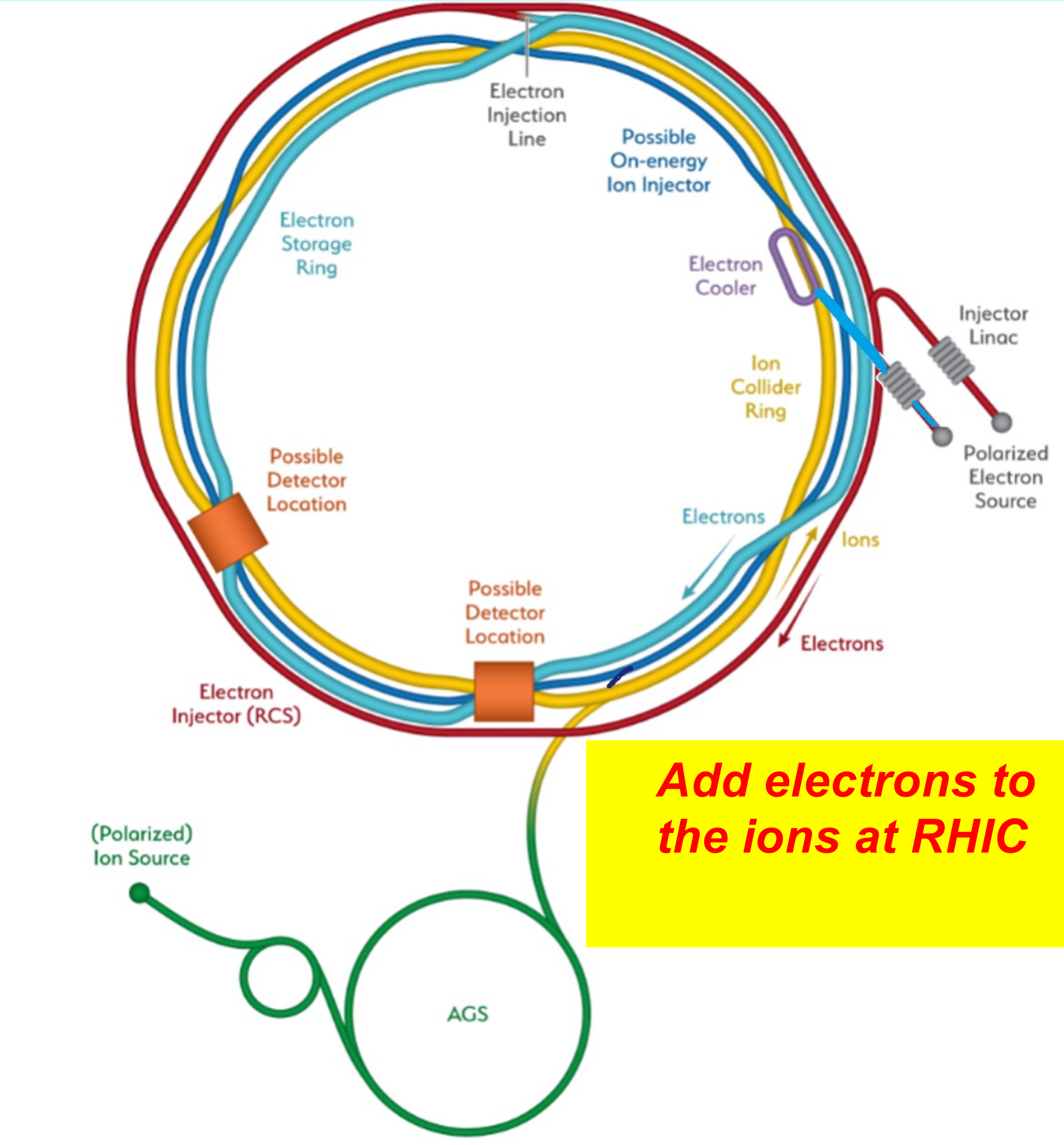
  q, g from different nucleons interact

  Higher density –> gluons can fuse

  @ higher x values than in isolated protons

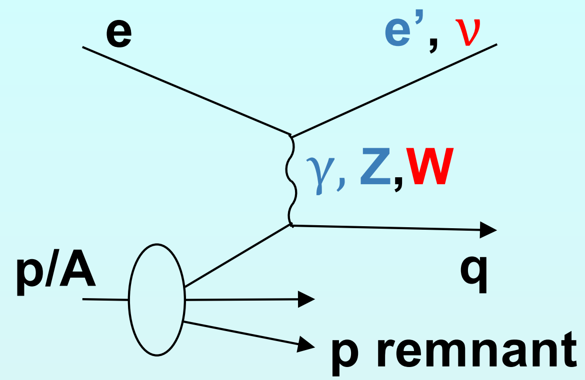
  – **Scale goes as $x_s \sim A^{1/3}$**

Electron-ion collider at Brookhaven



Add electrons to the ions at RHIC

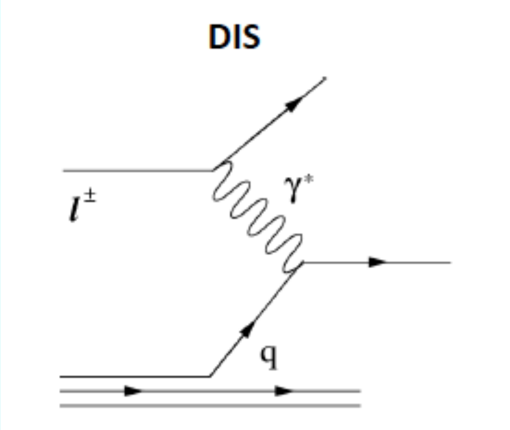
Scatter electrons from nuclei!



- $\sqrt{s}$ = 30 to 140 GeV

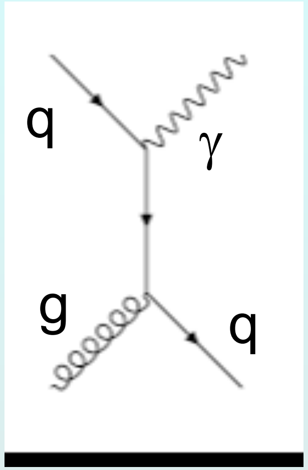
Hadron Storage Ring
Electron Storage Ring
Electron Injector Synchrotron
Possible on-energy Hadron injector ring
Hadron injector complex

See quarks & gluons with electron beam?



- **Deep inelastic scattering**

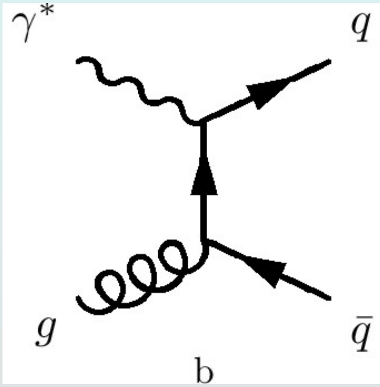
  scatter virtual γ off the q charge
- **"See" gluons when quark distributions don't scale with energy transfer from the electron**



- **Seeing gluons more directly:**

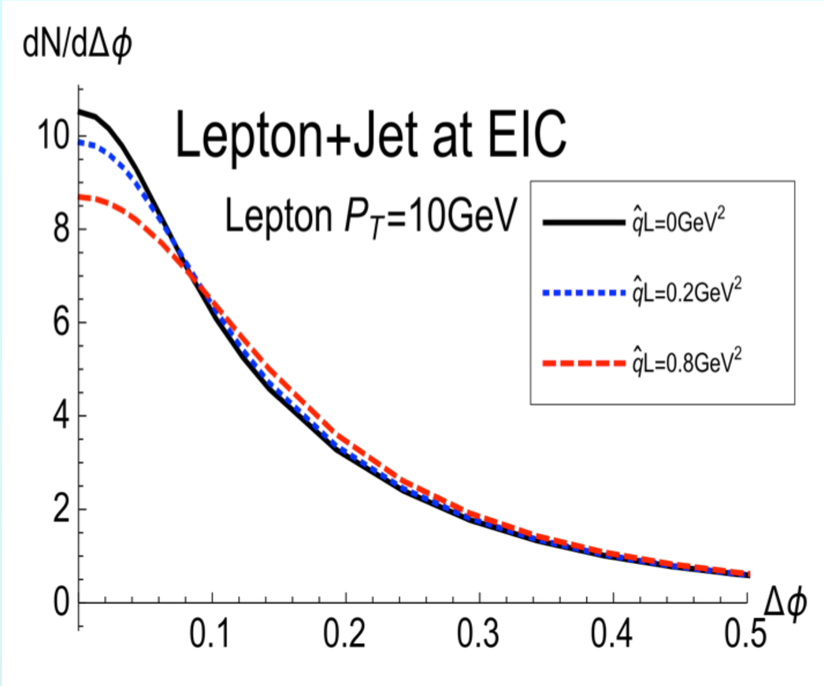
  in p+p: QCD Compton scattering

  in e+p: γ + g -> c$\bar{c}$
  photon-gluon fusion



Jet's fate in cold, dense QCD matter

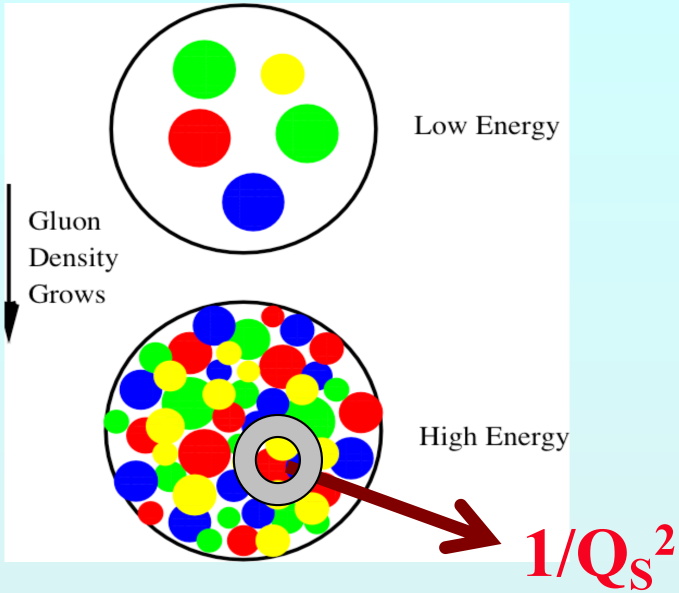
- Energy & angle balance
  via lepton-jet correlations
  compare energy loss to
  hot, denser QCD matter



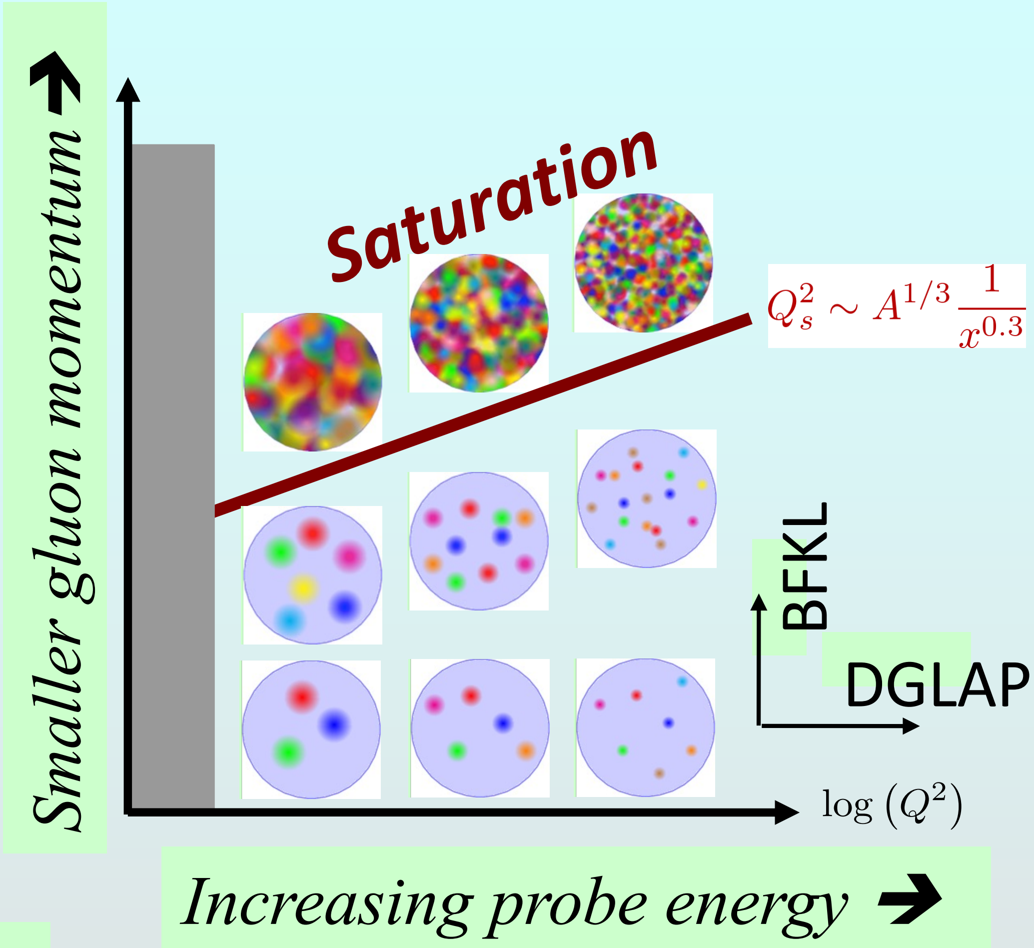
- Jet broadening?

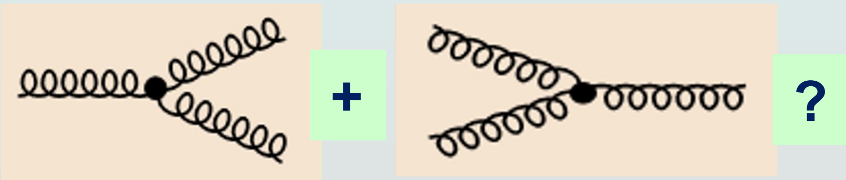
- Jet substructure
  Energy flow/shower development
  Quantum # correlation in jets
  Hadron formation in jets
  Jet angularities

Deep in a nucleus: gluons are numerous



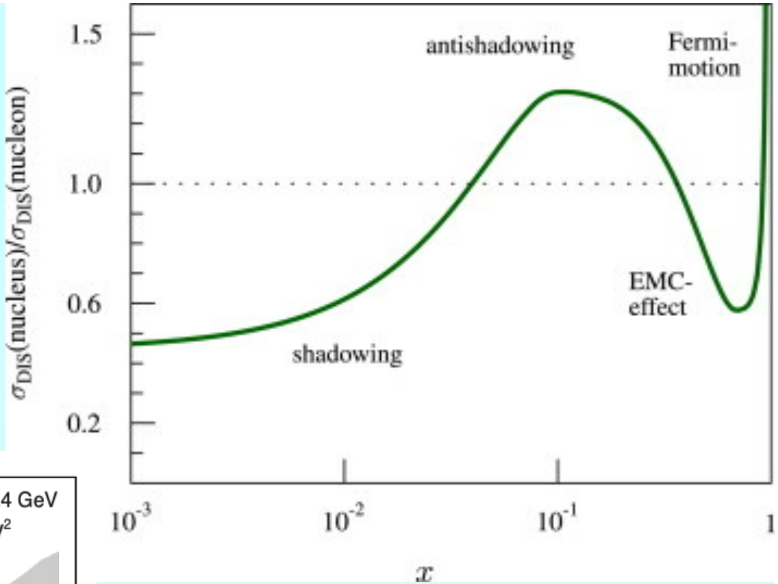
- ***At high density, what? gluon # saturates?***



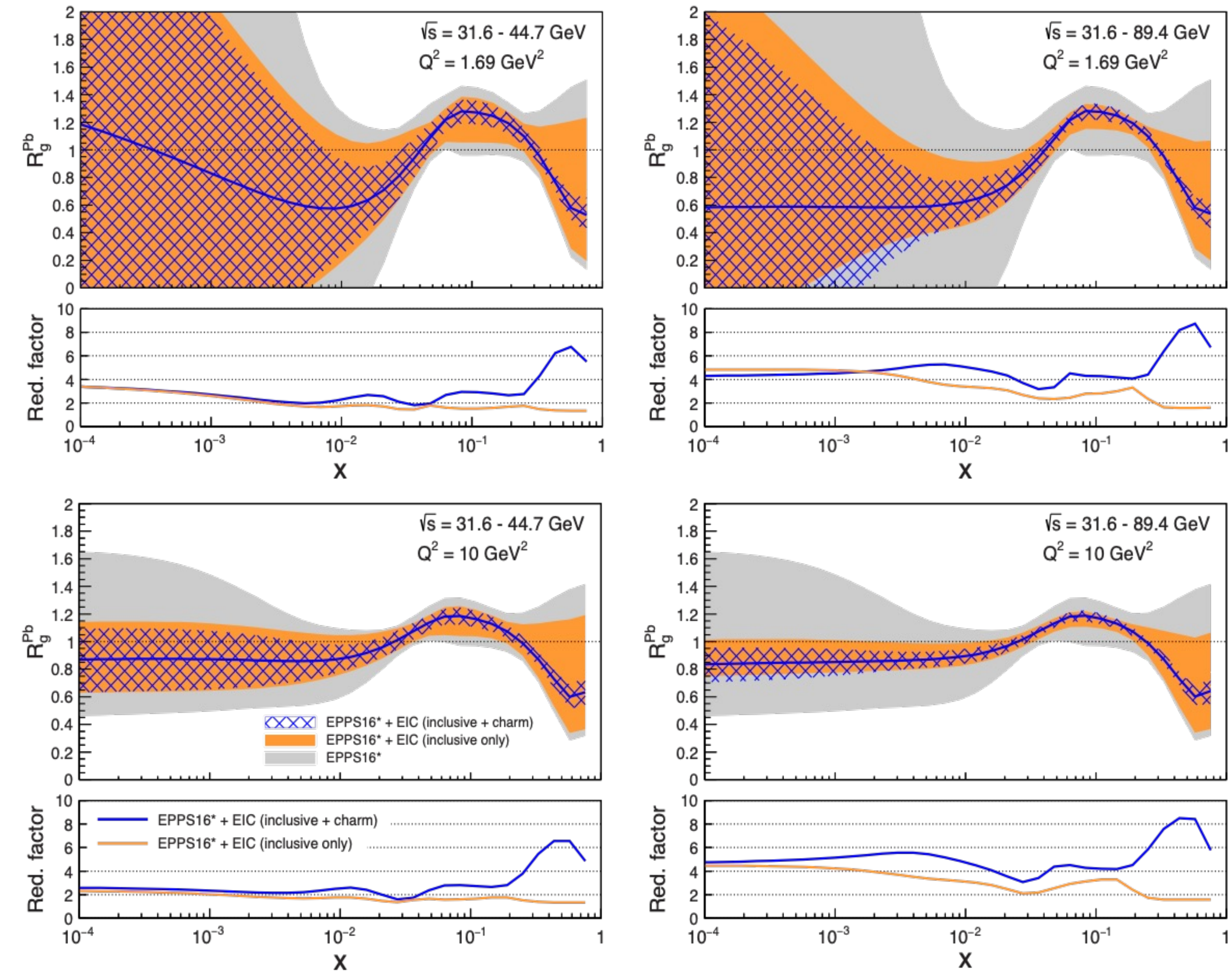


Nuclear PDF's

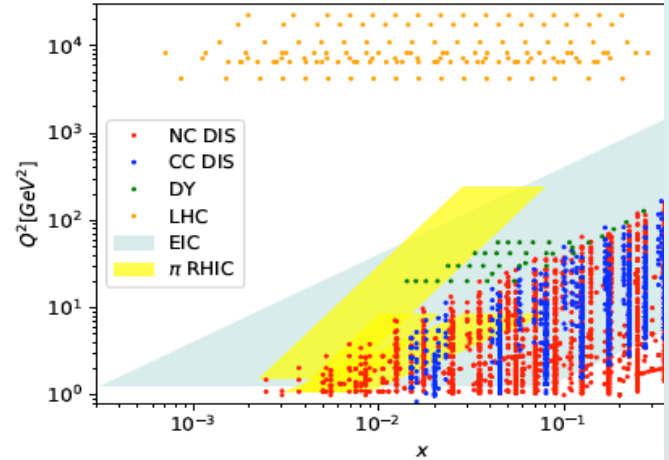
- **Inside nucleus: densities modified**
  q, g from different nucleons interact



arXiv:1708.01527

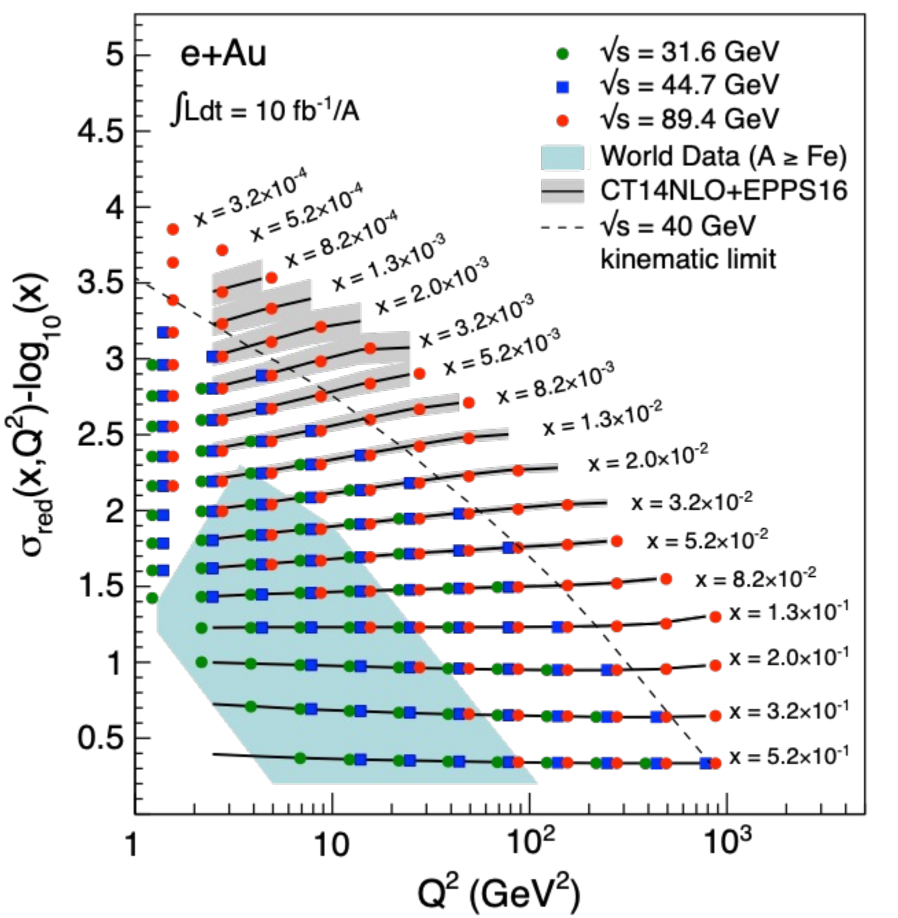


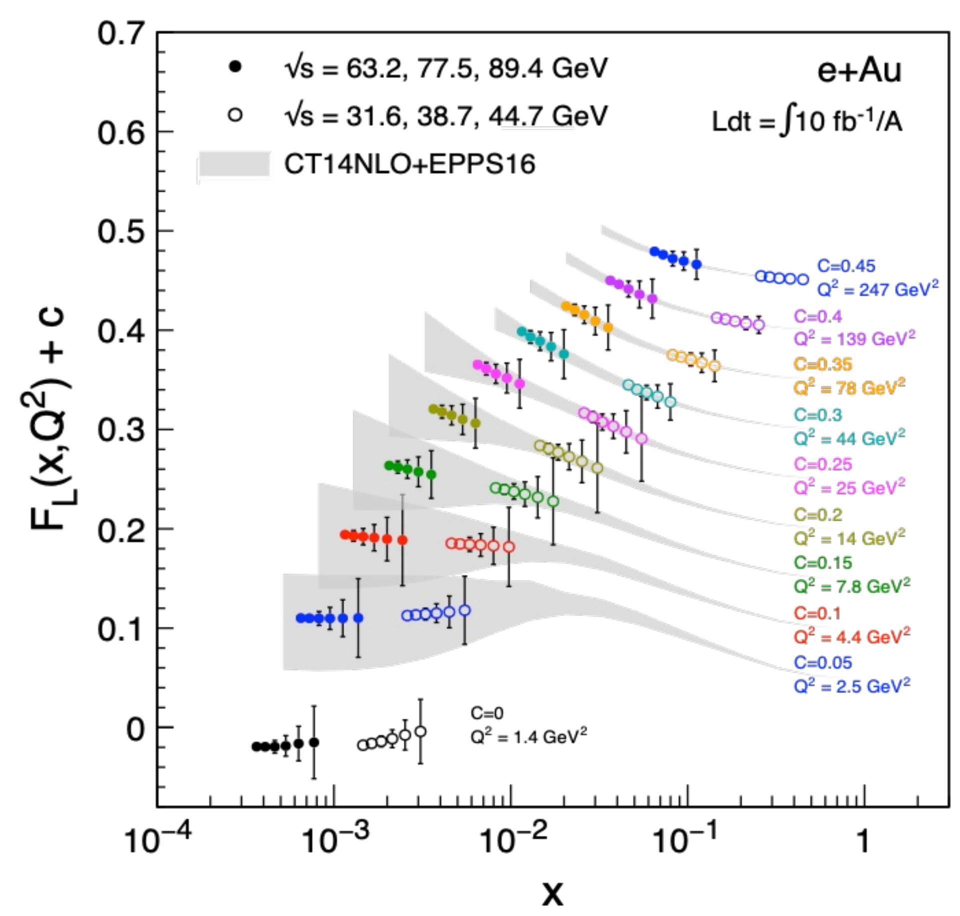
Inclusive DIS off nuclear beams



The measurements

arXiv:1708.01527

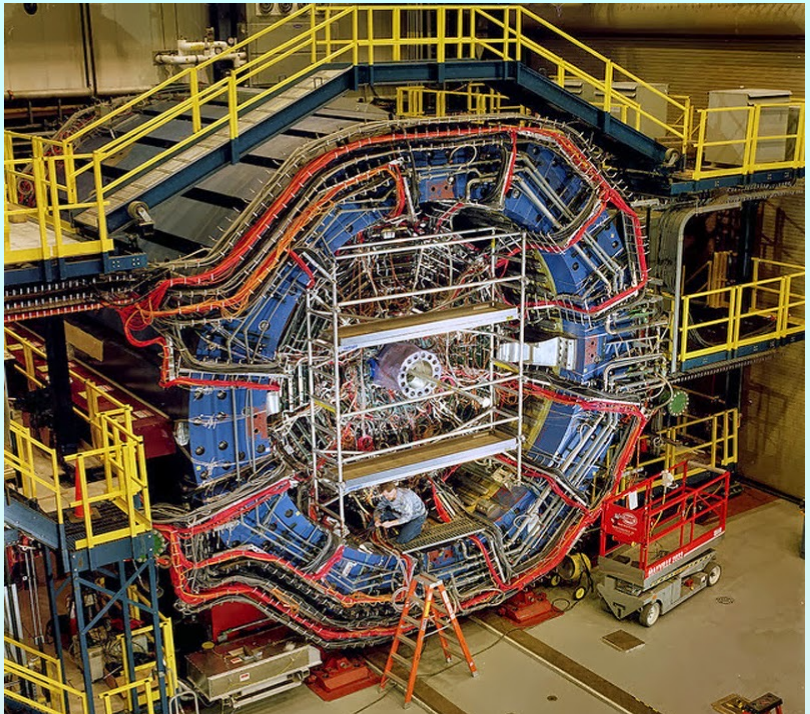


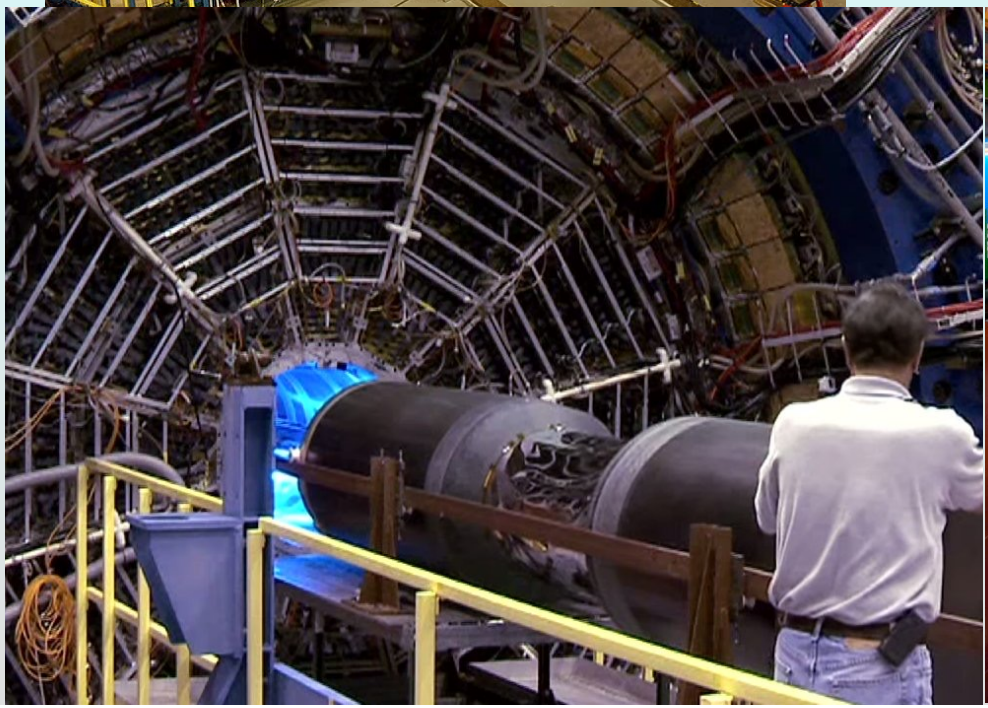


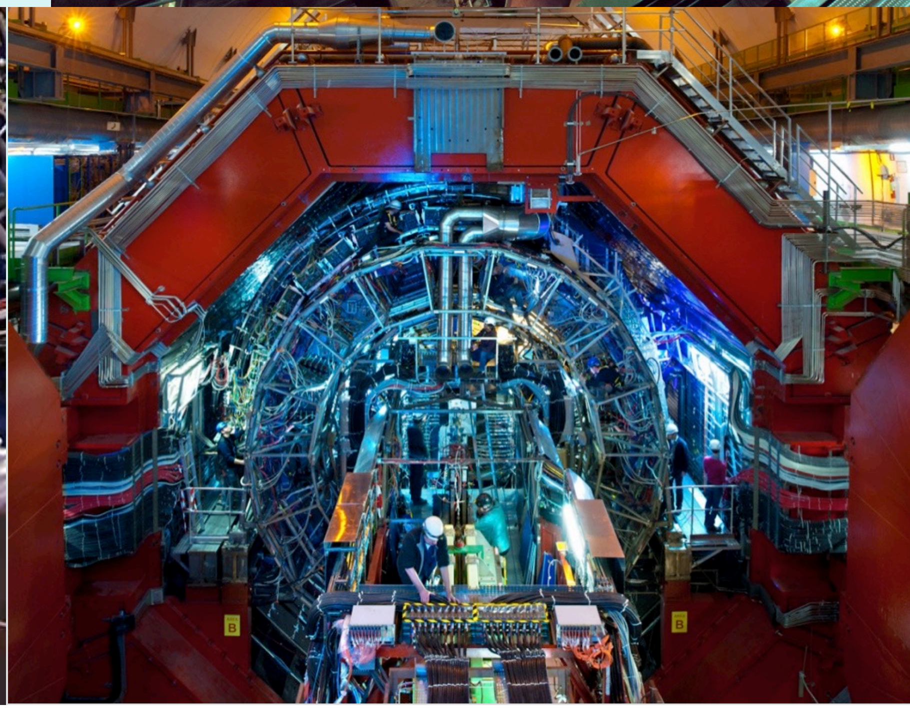
$$\sigma_{red} = F_2 - y^2/Y_+ F_L \quad Y_+ = 1 + (1 - y)^2 \quad F_2 = \Sigma e_q^2(xq^2 + \overline{x}q^2)$$

DIS with associated charm for F_2^{charm} and F_L^{charm} to extract gluon distributions

Big detectors measure emitted particles







Mystery of rapid hydrodynamics*

- One of the key questions for hot QCD
  But it's very hard to measure directly!
- Coherent scattering?
  - Parton interactions in hot, dense QCD and cold, dense QCD should be similar
- Rapid expansion driven loss of initial state memory (hydrodynamic attractor) causing out-of-equilibrium hydrodynamic behavior?
- Pre-existing many-body interactions?

** Full thermalization is not required for hydrodynamics*

Heavy quarks

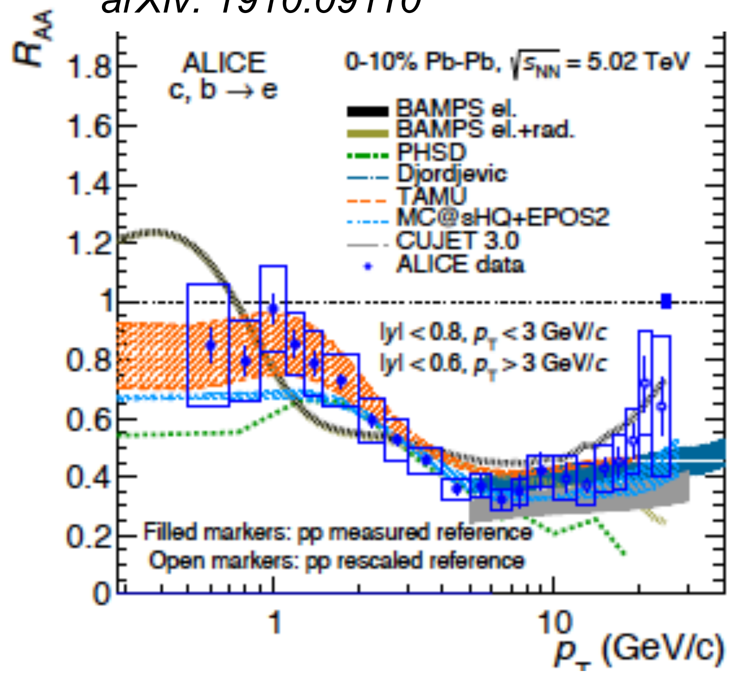
Lose energy too!

Dominated by collisions at low p_T

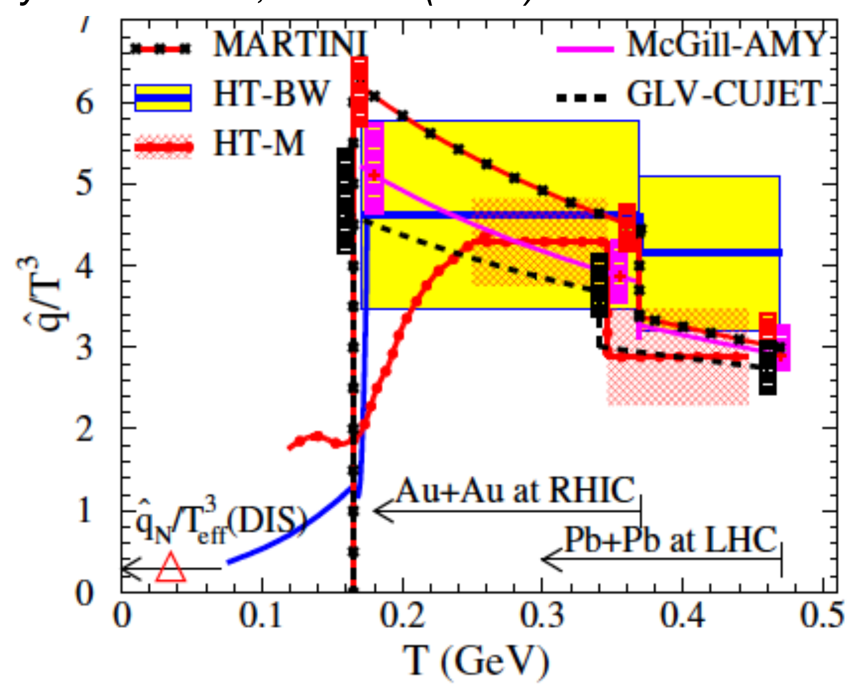
Radiation at high p_T

$$\hat{q} = \sqrt{\mu^2/\lambda}$$

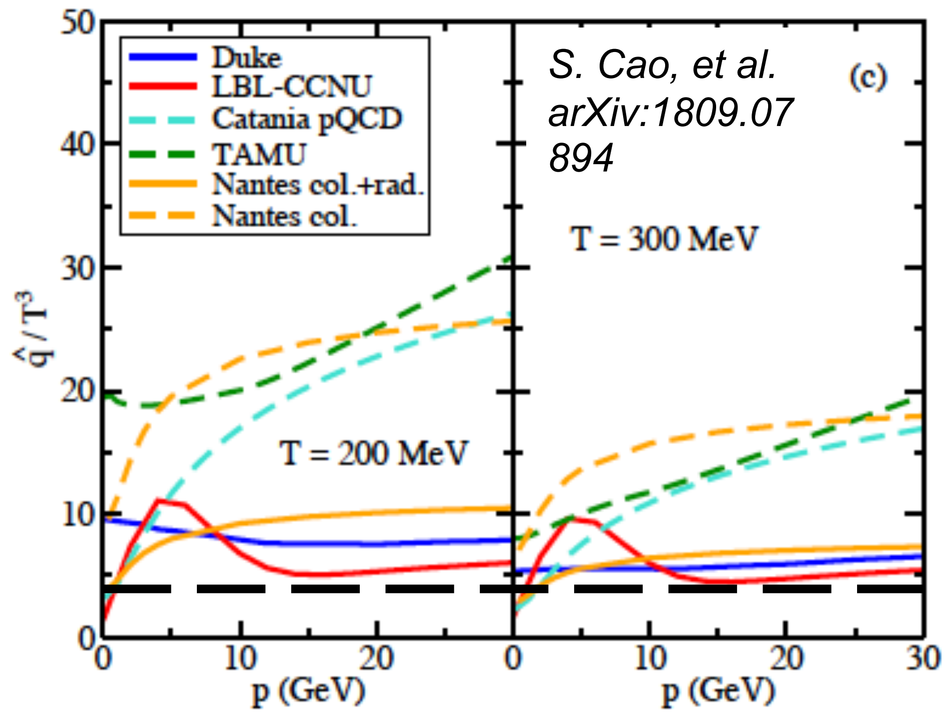
arXiv: 1910.09110



Phys. Rev. C 90, 014909 (2014)



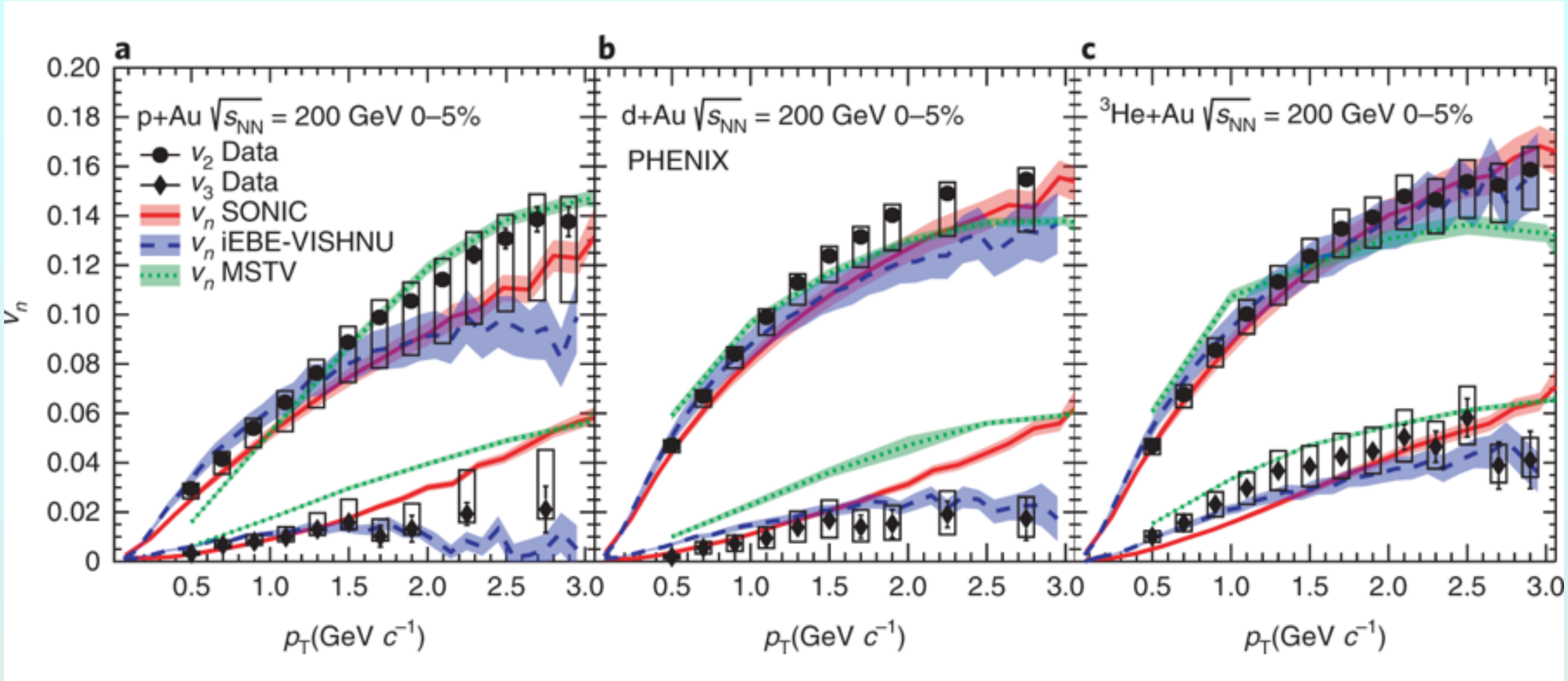
Light quark R_{AA} fits: JET collaboration



S. Cao, et al. arXiv:1809.07894

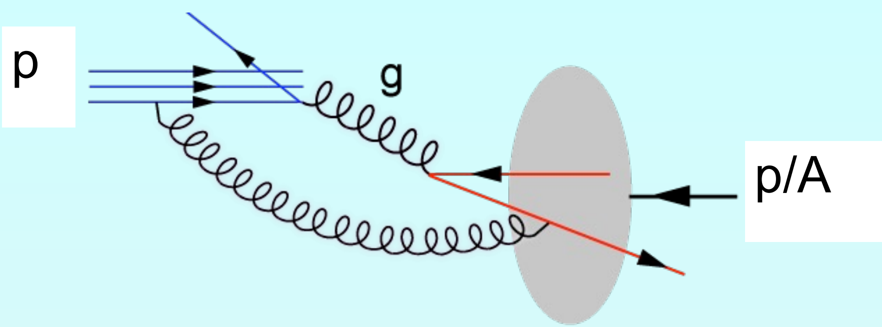
Heavy quark R_{AA} fits

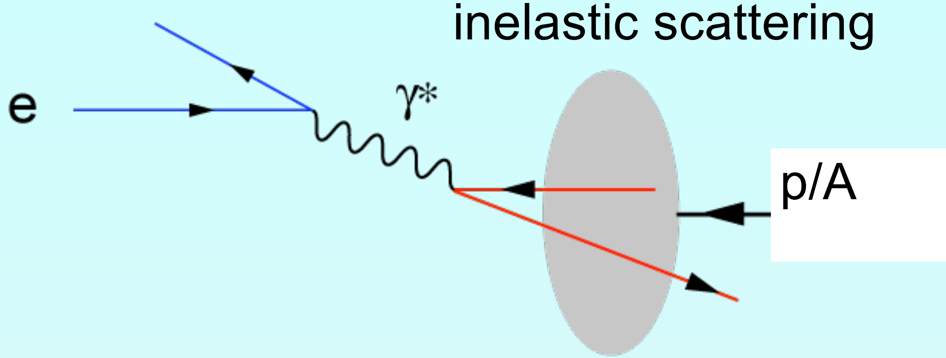
Hydro for p, d, ^{3}He + Au



PHENIX Collaboration
Nature Physics (2018)

Probe cold, dense matter: Collide e + A



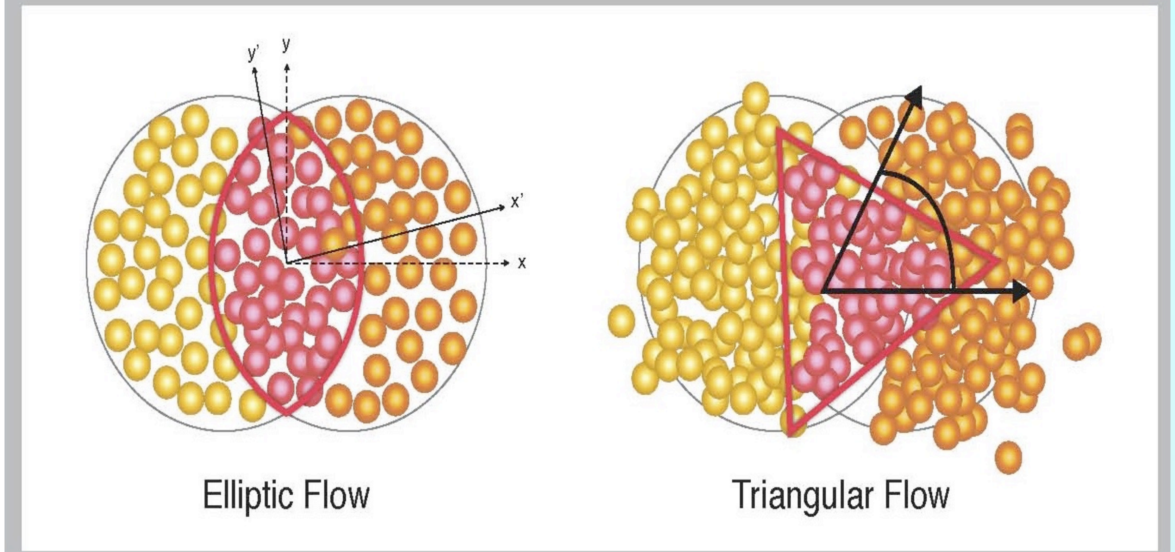


- Probe is a gluon
- Probe has structure!
- Dynamics of the probe mixed up with structure of the nucleus
- RHIC & LHC

- Point-like probe
- No strong interaction before high momentum transfer process
- Control probe kinematics by measuring scattered electron
- Needs Electron-Ion Collider

We'll also find out: will there be hydrodynamic flow if we excite a hot spot with a point particle??!

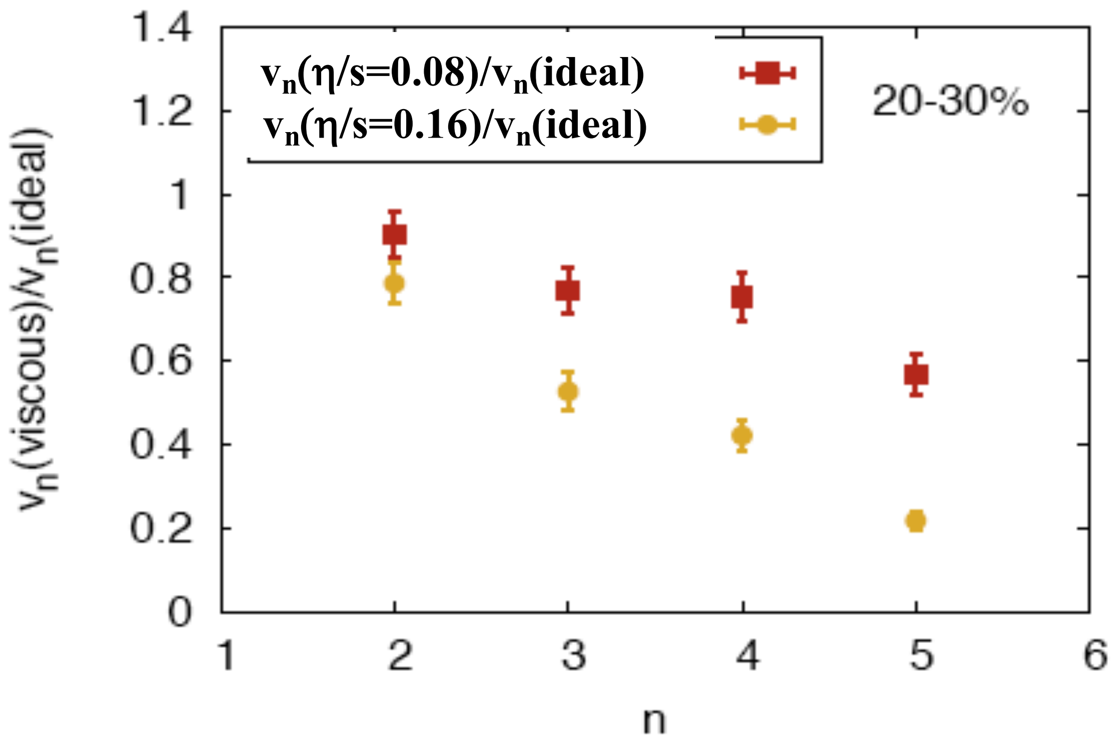
Quantify viscosity: Fourier coefficients



Nucleons move around inside the nucleus

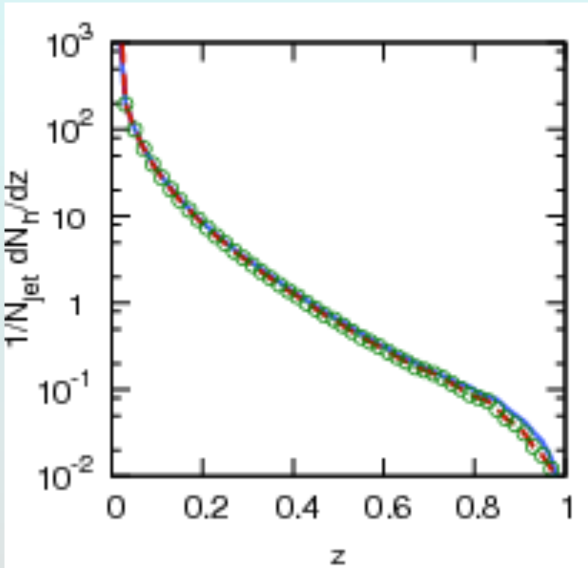
-> locations of NN scattering fluctuate

- Hydro gets it right if NN fluctuations included
- v_3, etc. more sensitive to the viscosity/entropy ratio (viscosity increases dissipation)
- η/s (QGP) = 0.085 – 0.11



Look at parton "fragmentation"

- Can't see a single quark or gluon in the detector
  They don't exist alone in nature for very long
- Colored objects radiate gluons (bremsstrahlung!)
  Angle ordered process in vacuum. In plasma - not.
- In final state these gluons become normal hadrons
  Measure a correlated bunch of hadrons – a "jet"
  Process of becoming a jet is called fragmentation



$z = p_{T\ hadron} / p_{T\ parton}$

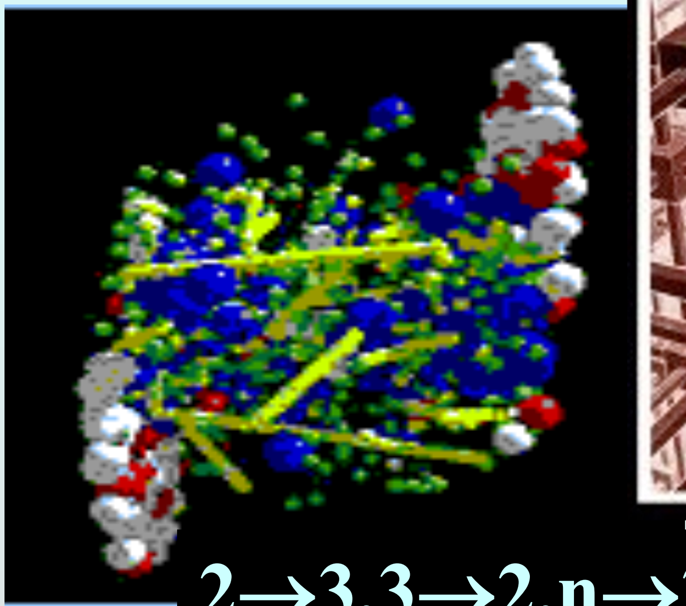
Transport properties of QGP

weak coupling limit

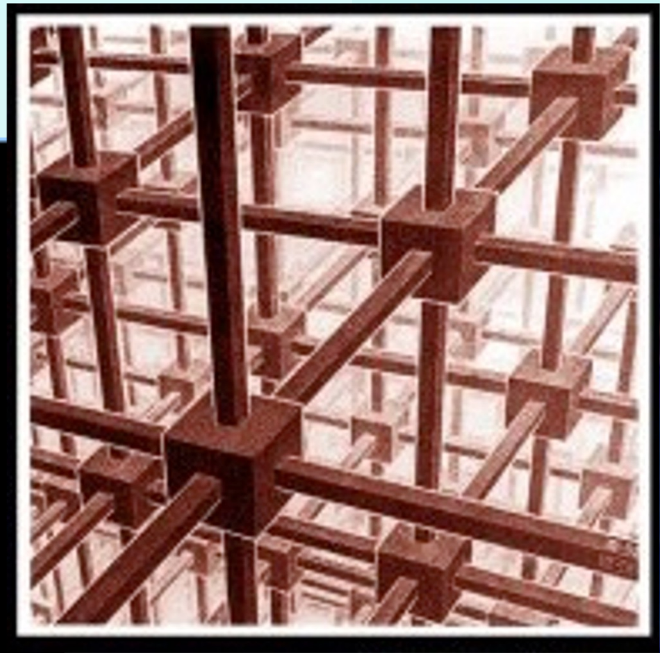
perturbative QCD

kinetic theory, cascades

interaction of particles



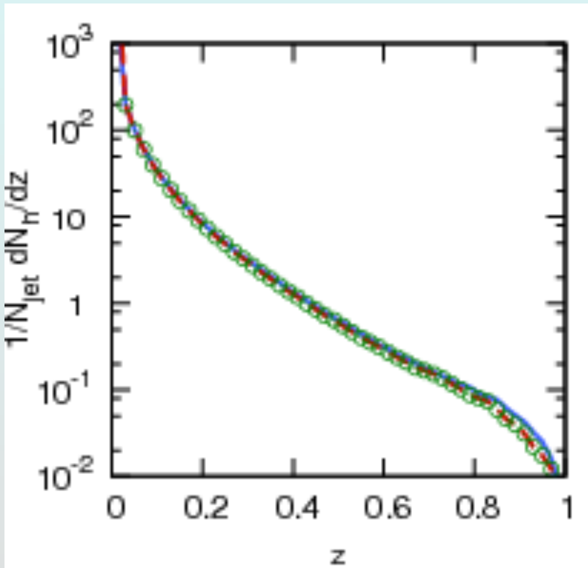
2→3,3→2,n→2…



Lattice QCD

Look at parton "fragmentation"

- **Can't see a single quark or gluon in the detector**
  They don't exist alone in nature for very long
- **Colored objects radiate gluons (bremsstrahlung!)**
  Angle ordered process in vacuum. In plasma???
- **In final state: the gluons become normal hadrons**
  - **Measure a correlated bunch of hadrons – a "jet"**
  - **Look at particle distribution inside**



$$z = p_{T\ hadron} / p_{T\ parton}$$

Process of becoming a jet is called fragmentation