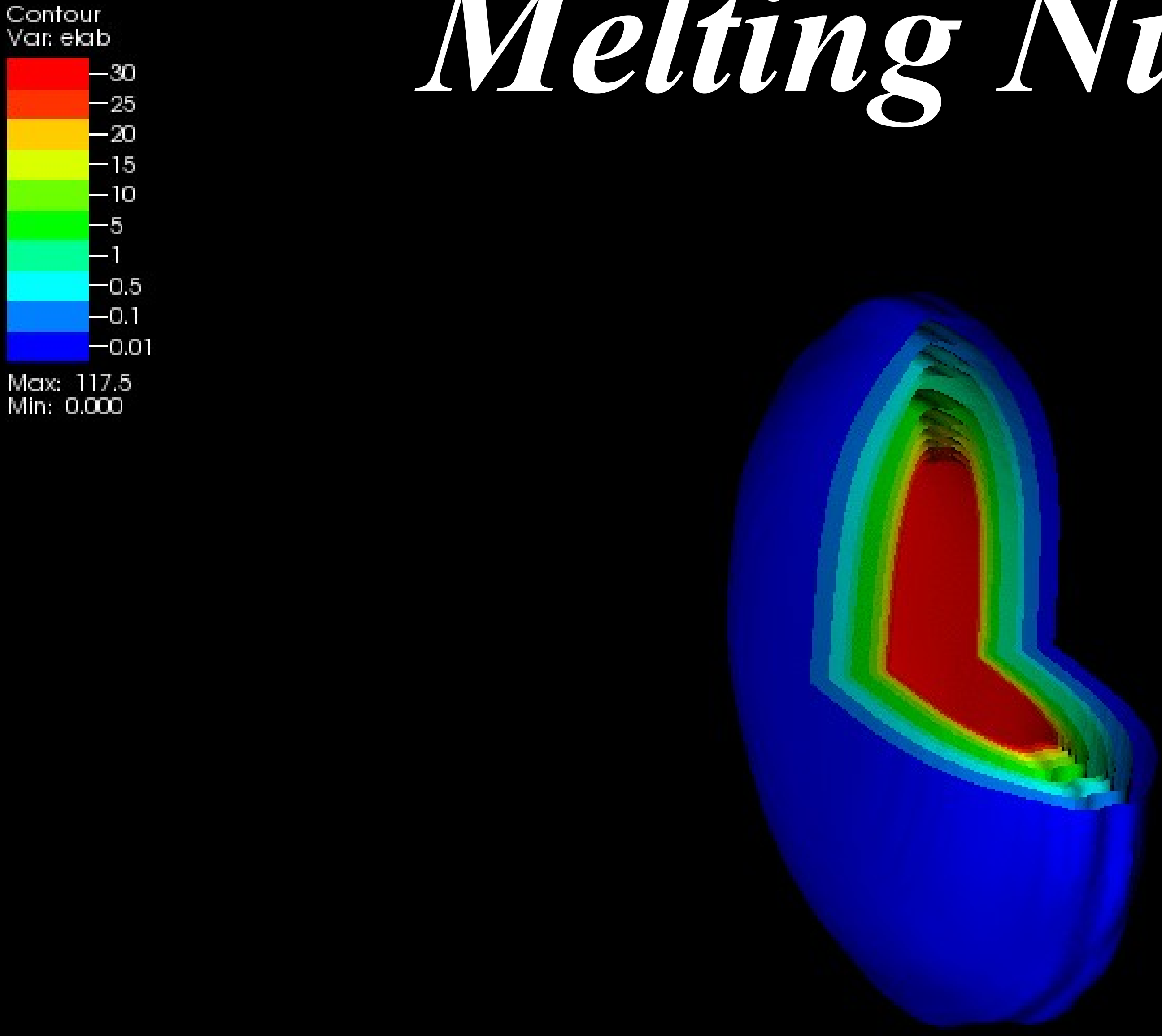
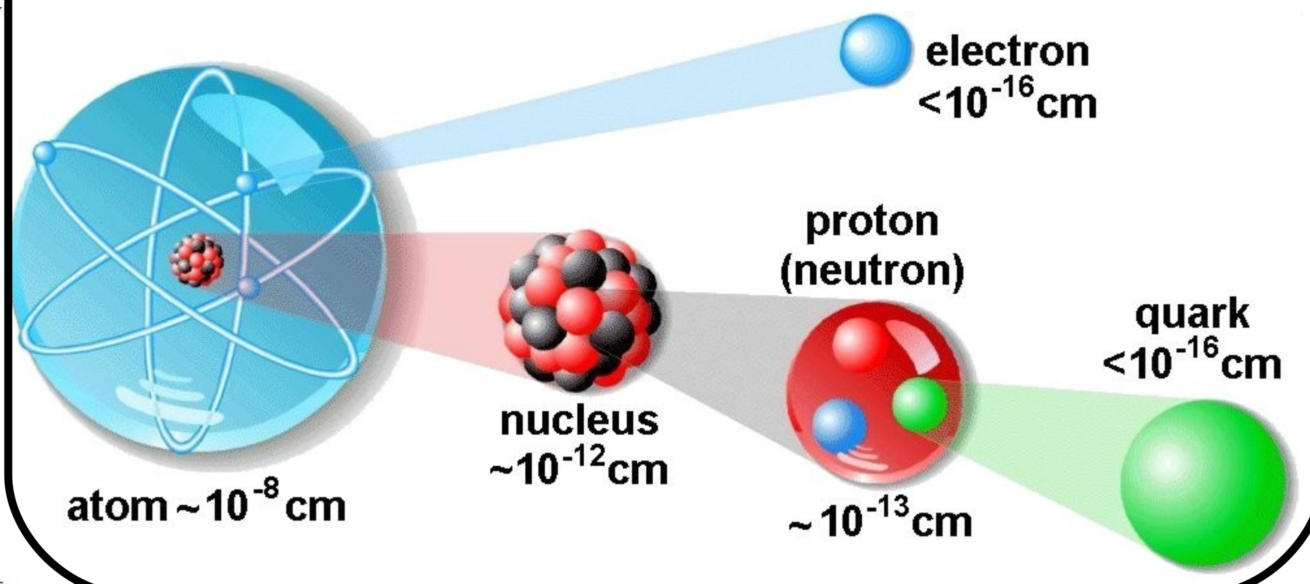
Melting Nuclei



Christine Nattrass
University of Tennessee at Knoxville

Calculations done on the Titan supercomputer by the CJet collaboration https://sites.google.com/site/cjetsite/

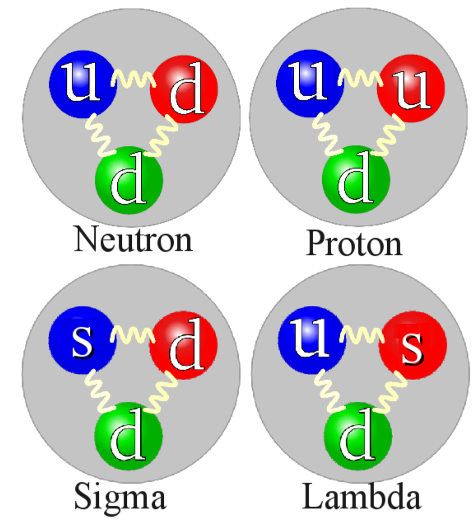
Structure of matter



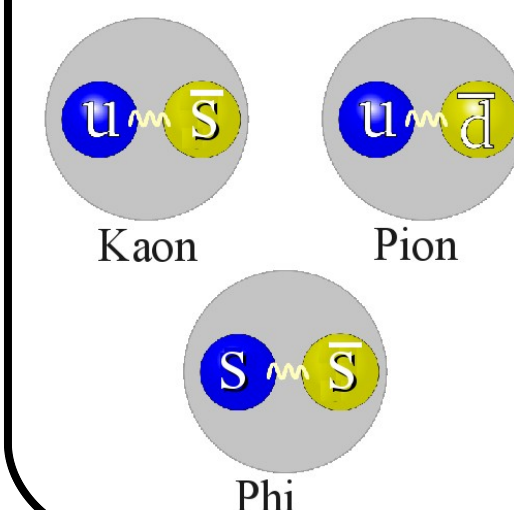
Standard model

Hadrons

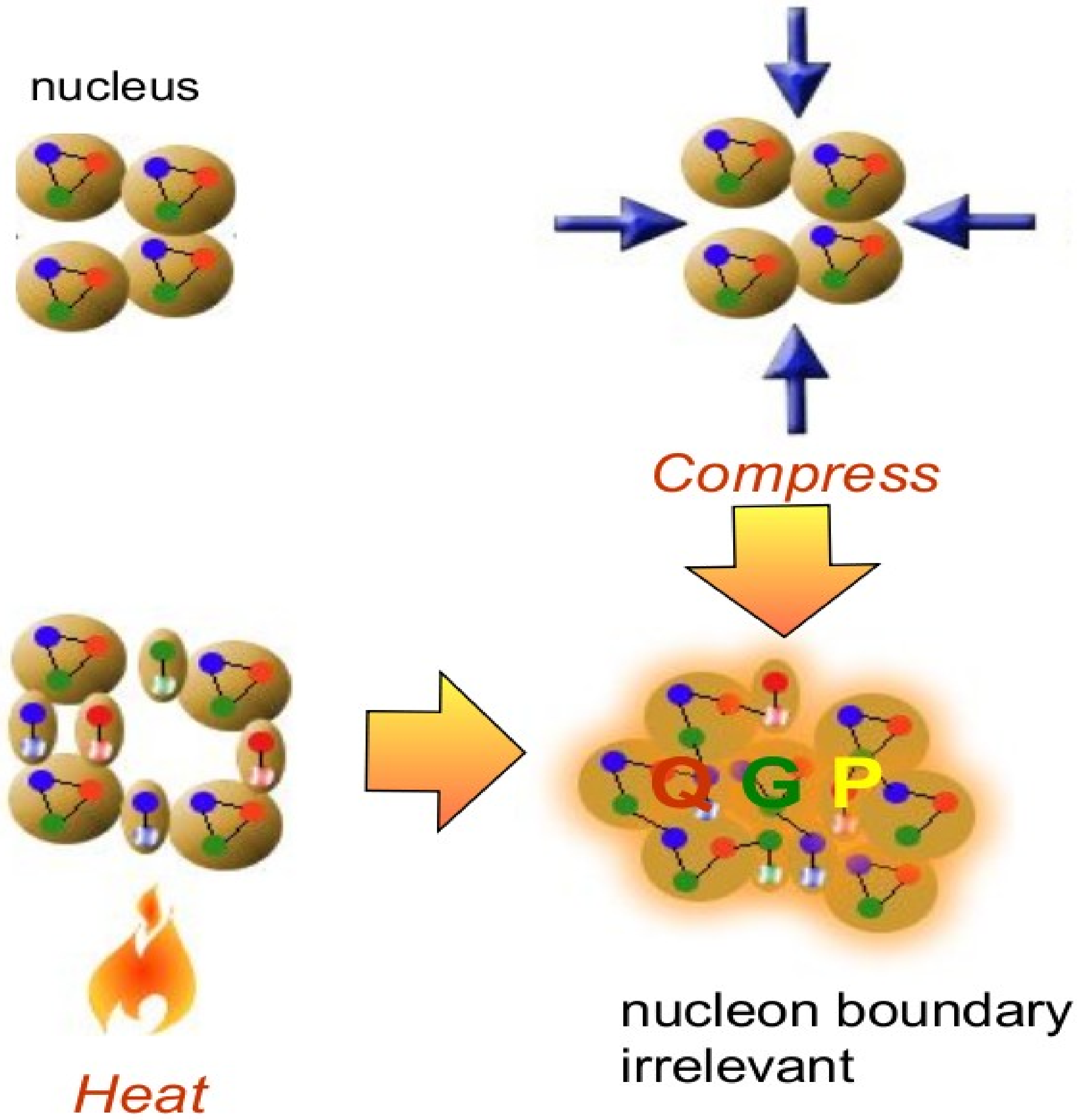
Baryons



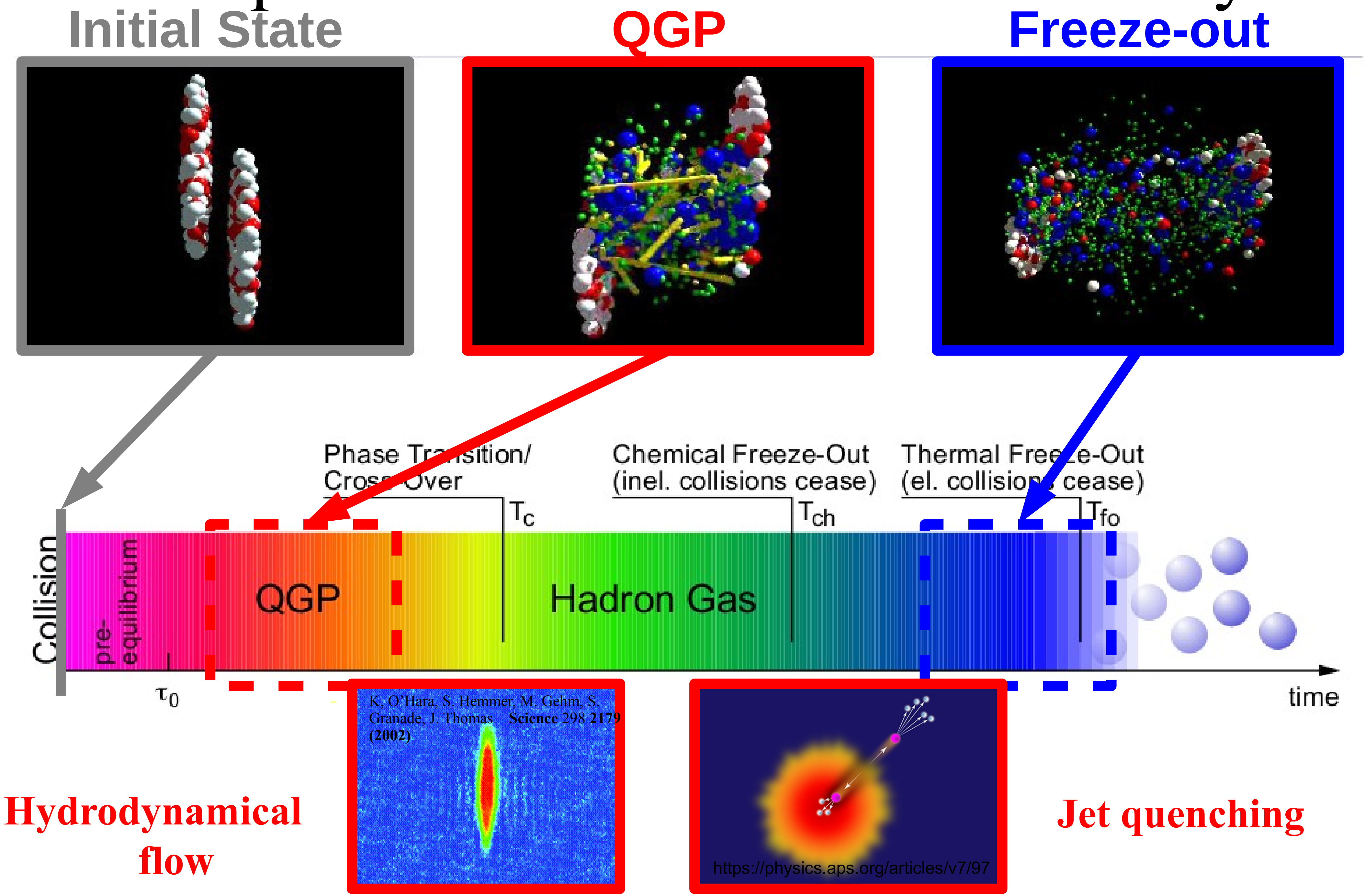
Mesons



How to make a Quark Gluon Plasma



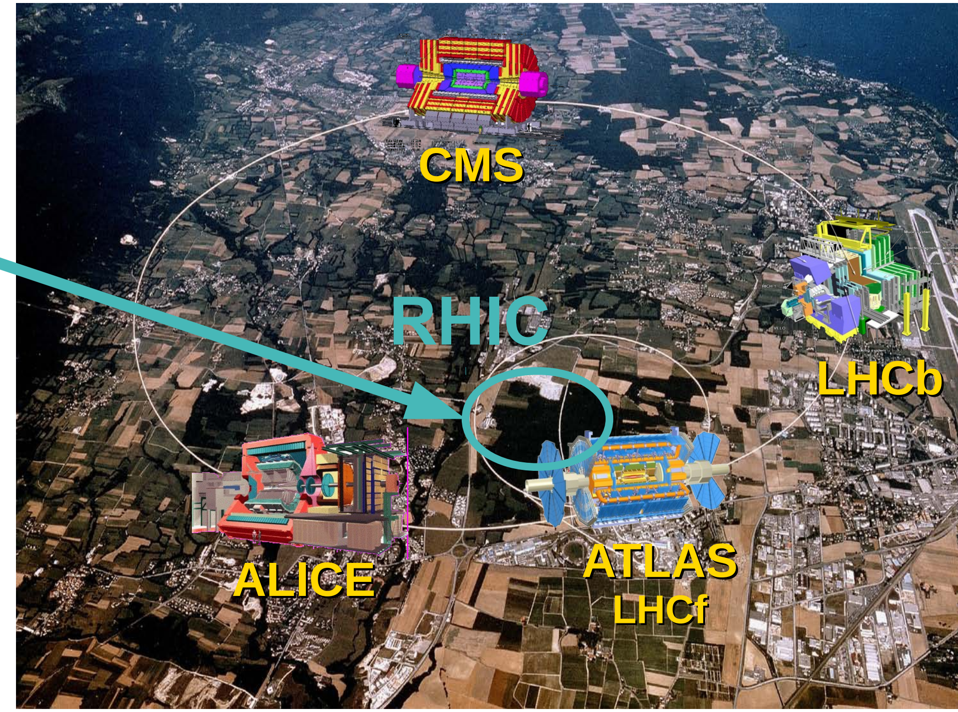
The phase transition in the laboratory



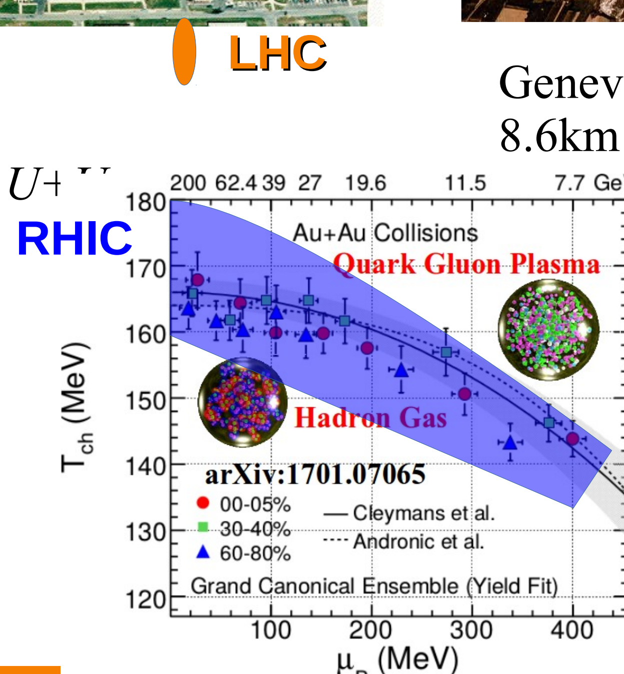
Relativistic Heavy Ion Collider

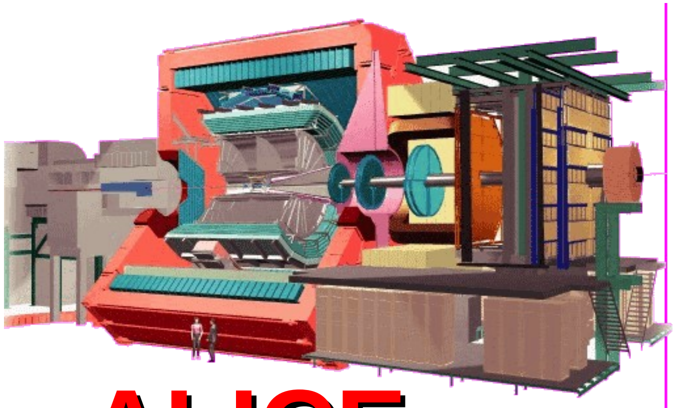
Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

Large Hadron Collider

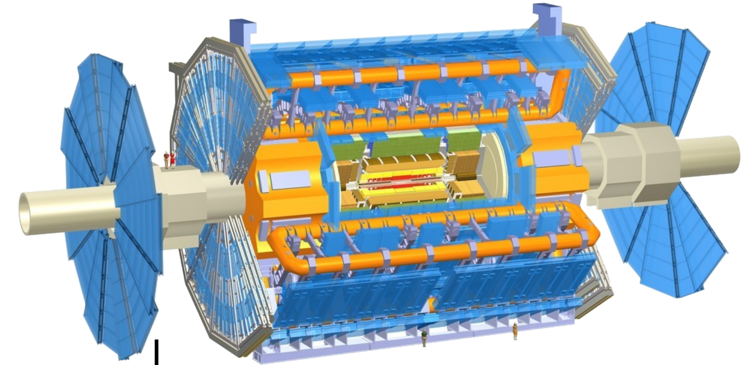


Geneva, Switzerland
8.6km diameter
+*Pb*, Pb+Pb
2.76 GeV, *5.5 TeV*

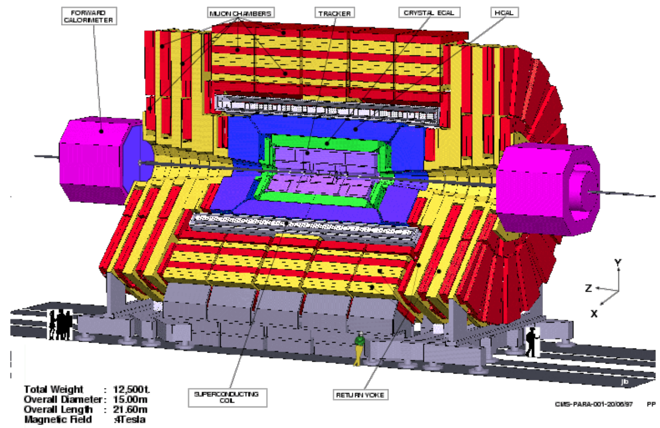




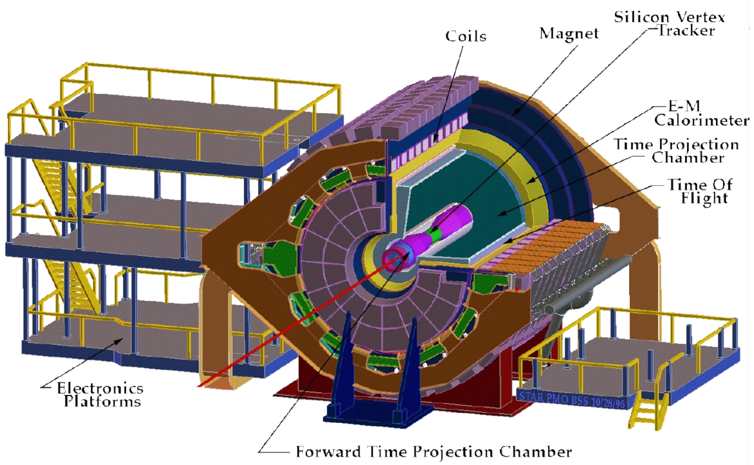
ALICE



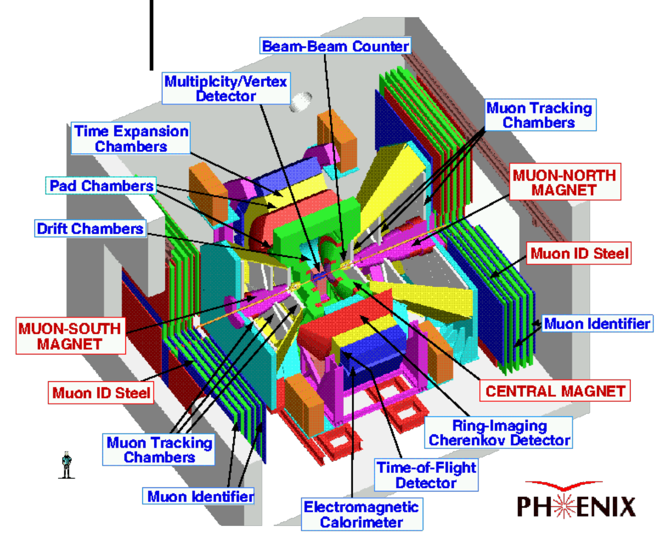
ATLAS



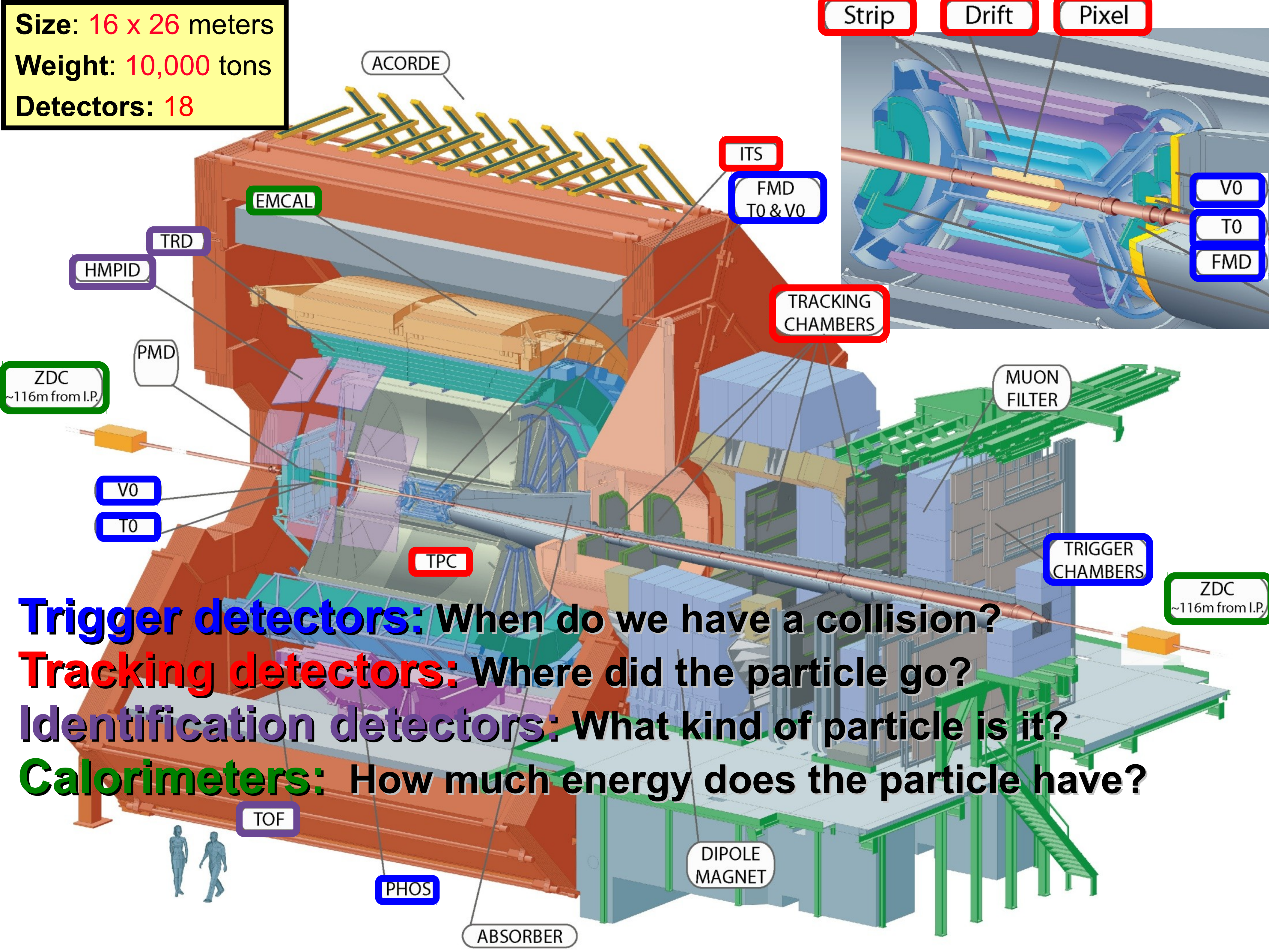
CMS



STAR

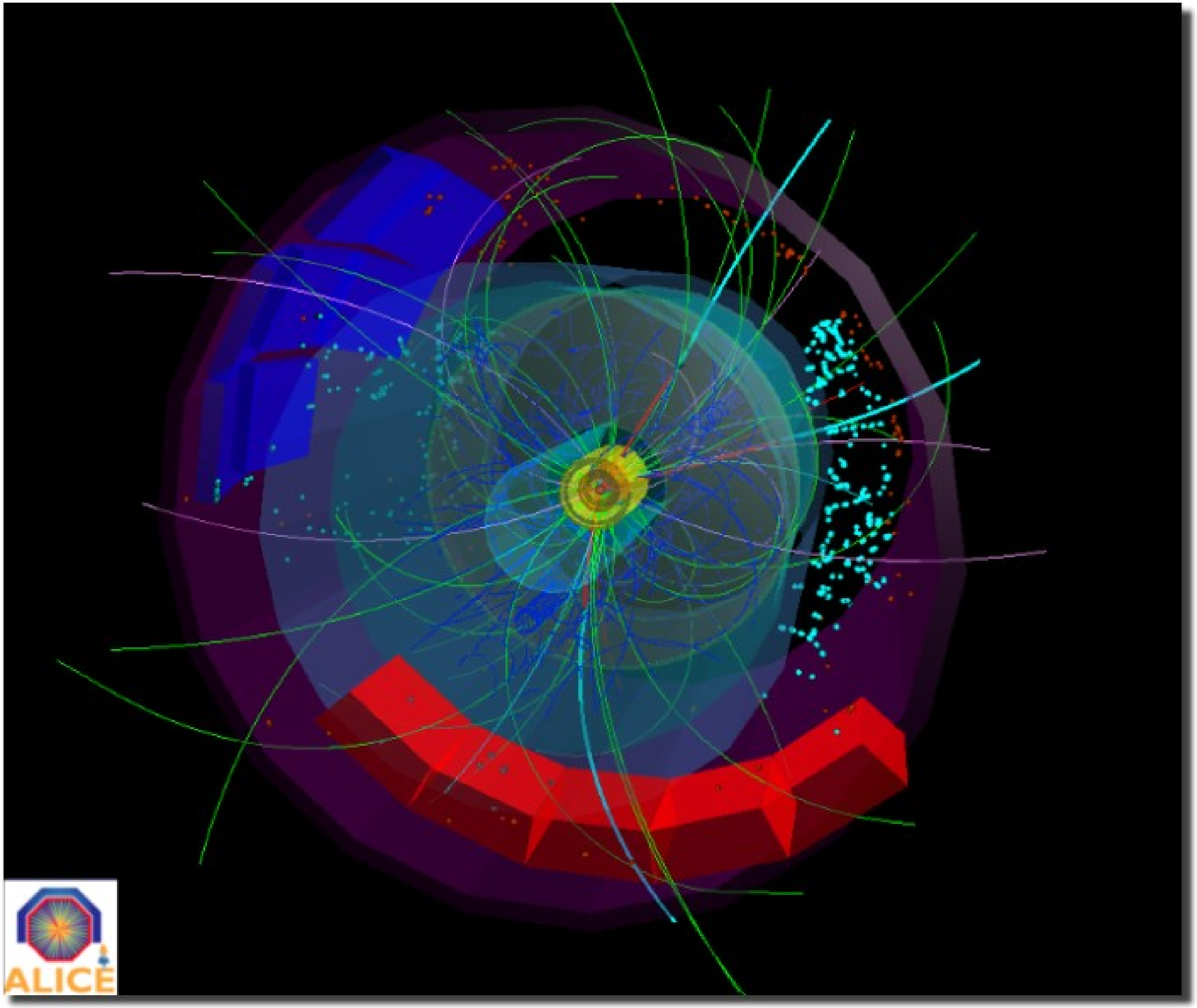


PHENIX



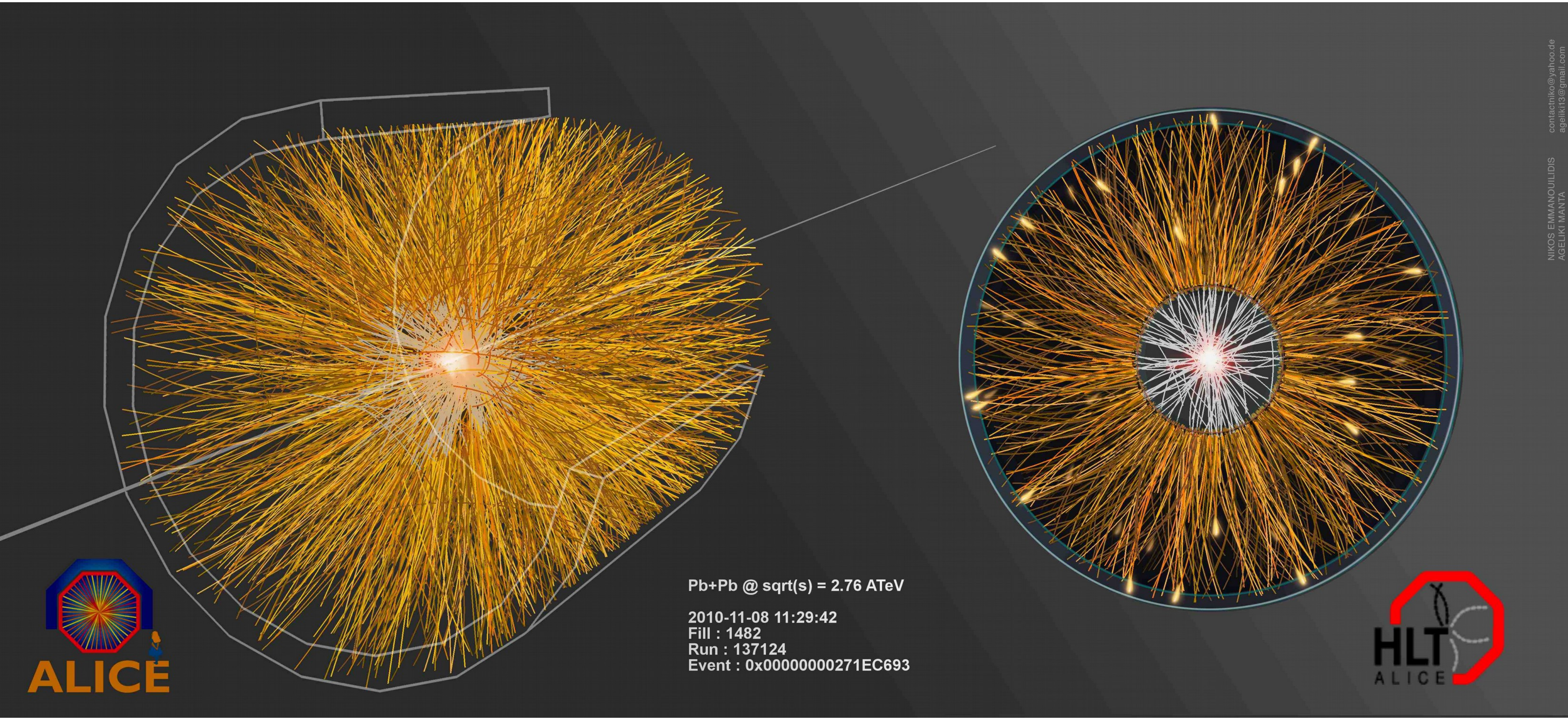
Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18
ACORDE
Strip
Drift
Pixel
ITS
FMD
T0 & V0
V0
T0
FMD
EMCAL
TRD
HMPID
TRACKING
CHAMBERS
PMD
ZDC
~116m from I.P.
MUON
FILTER
V0
T0
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?
TOF
DIPOLE
MAGNET
PHOS
ABSORBER

p+p collisions



3D image of each collision

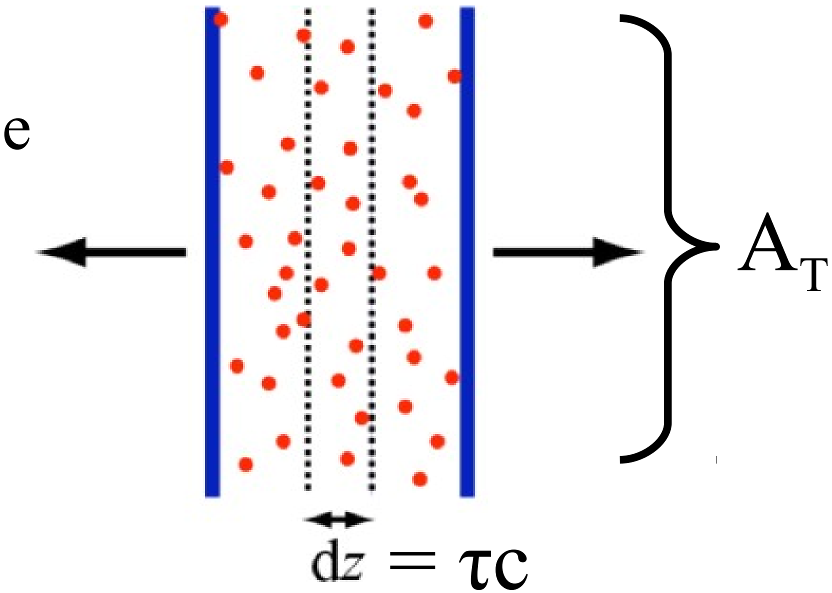
Pb+Pb collisions



QGP Energy Density

How can we estimate the energy density?

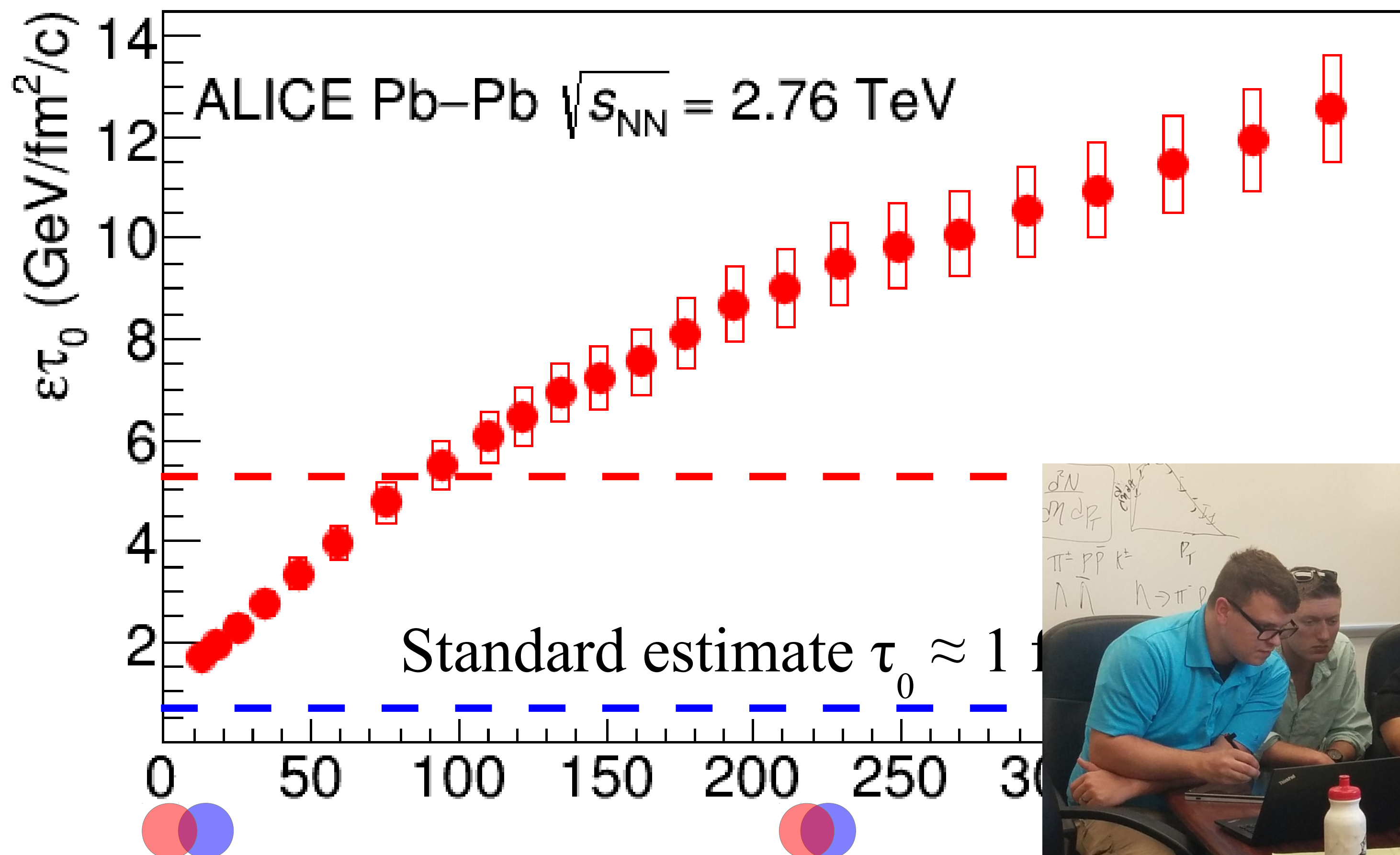
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



$$\epsilon = \frac{1}{V}\frac{dE_T}{dy} = \frac{J}{A_T \tau c}\frac{dE_T}{d\eta}$$

- QGP formation for $\varepsilon > 0.5$ GeV/fm^3

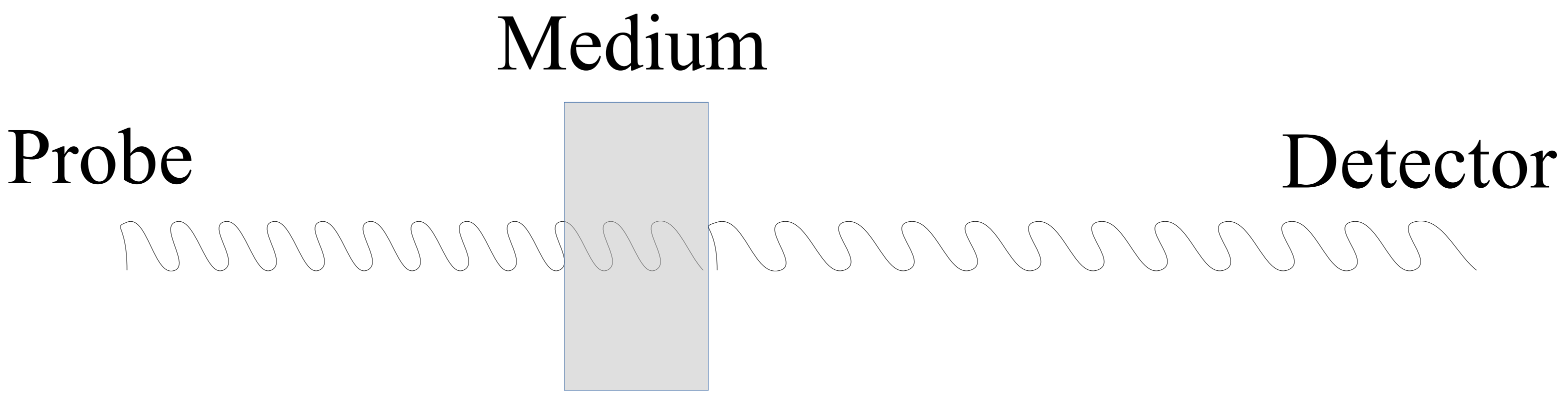
Energy density



$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

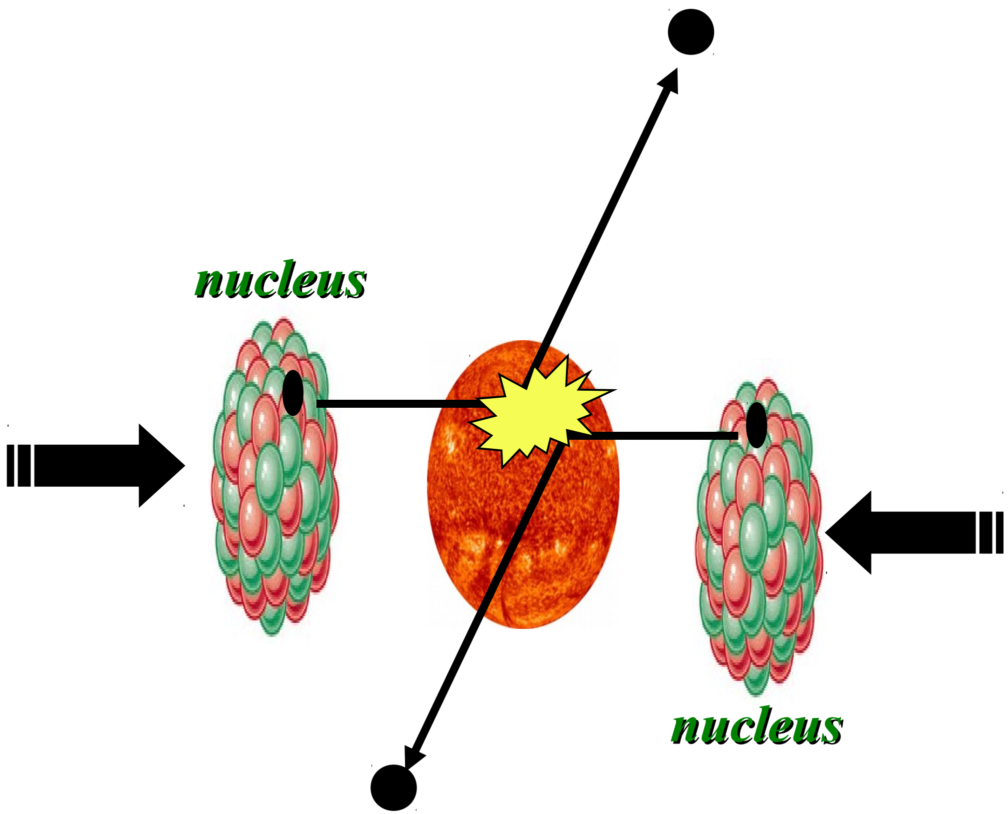
QGP Spectroscopy

Probing the Quark Gluon Plasma



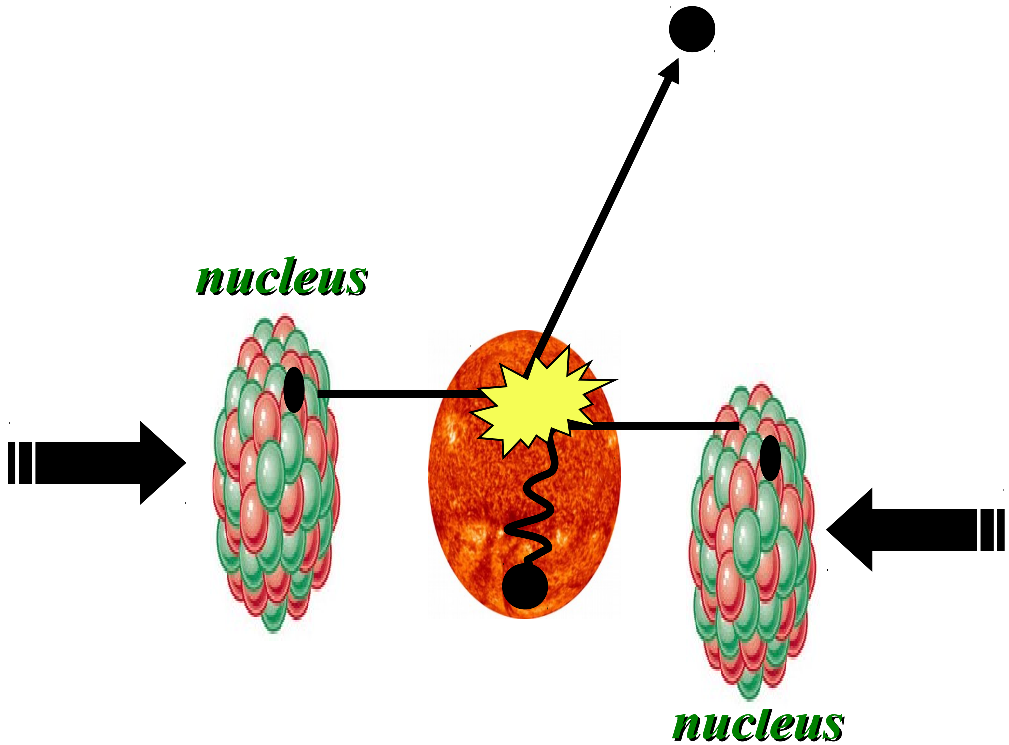
Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



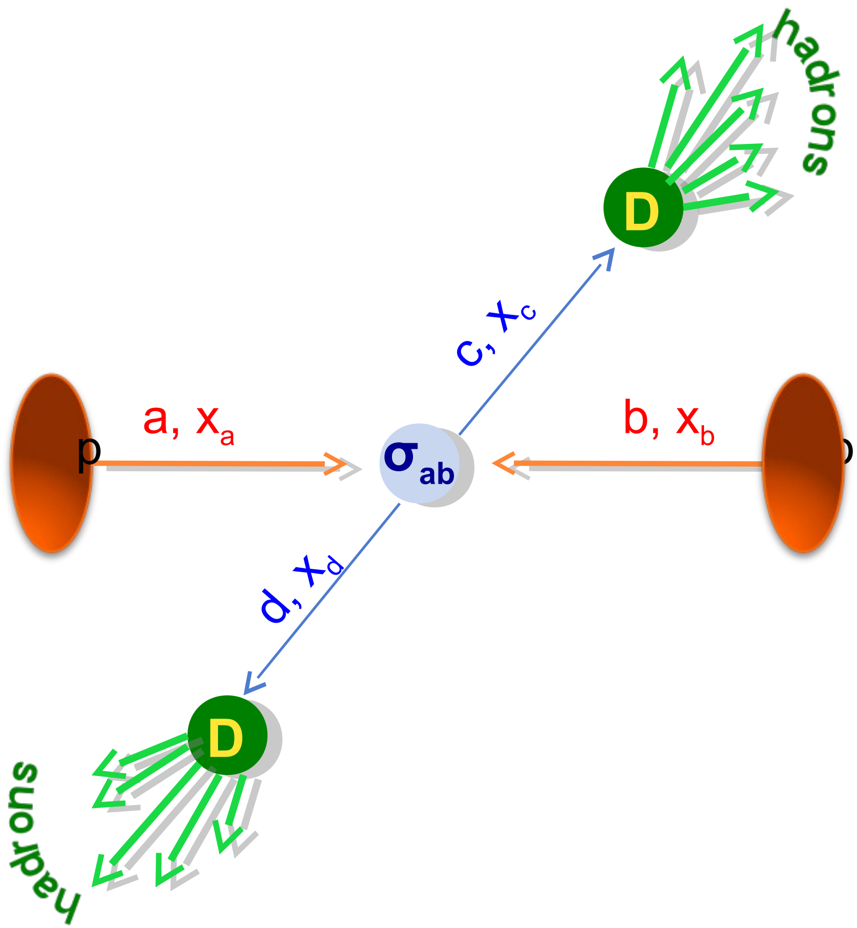
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

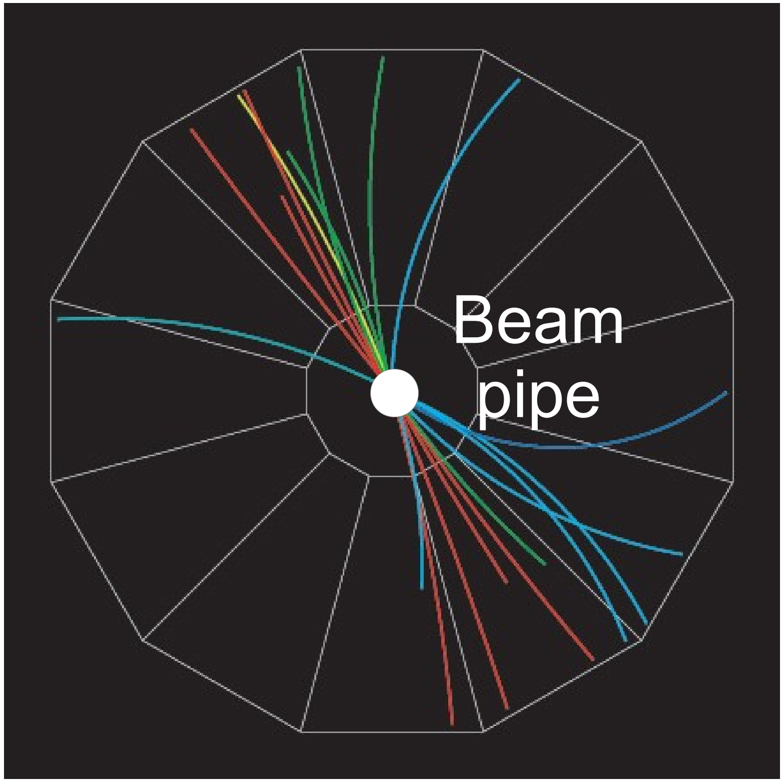


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets



p+p → dijet

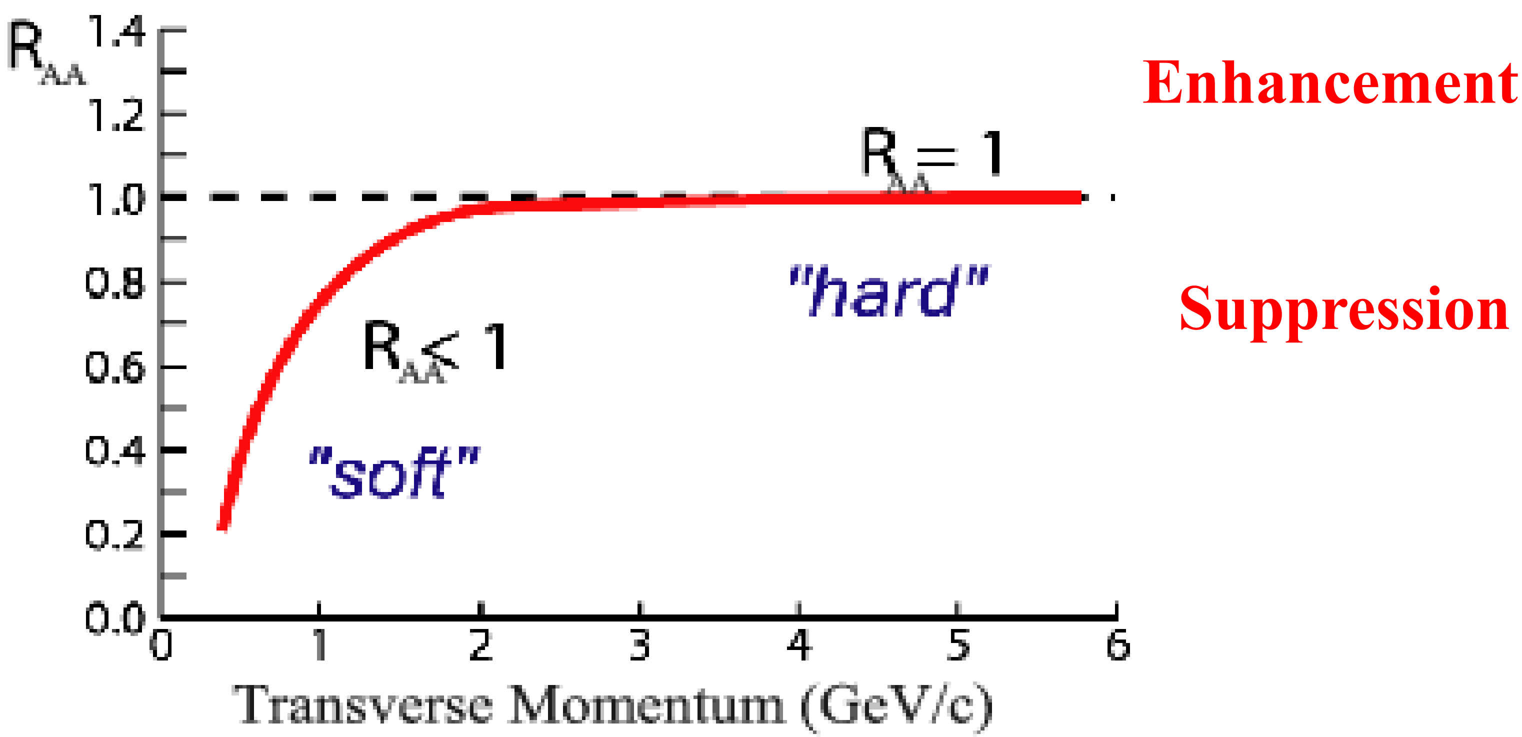


Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

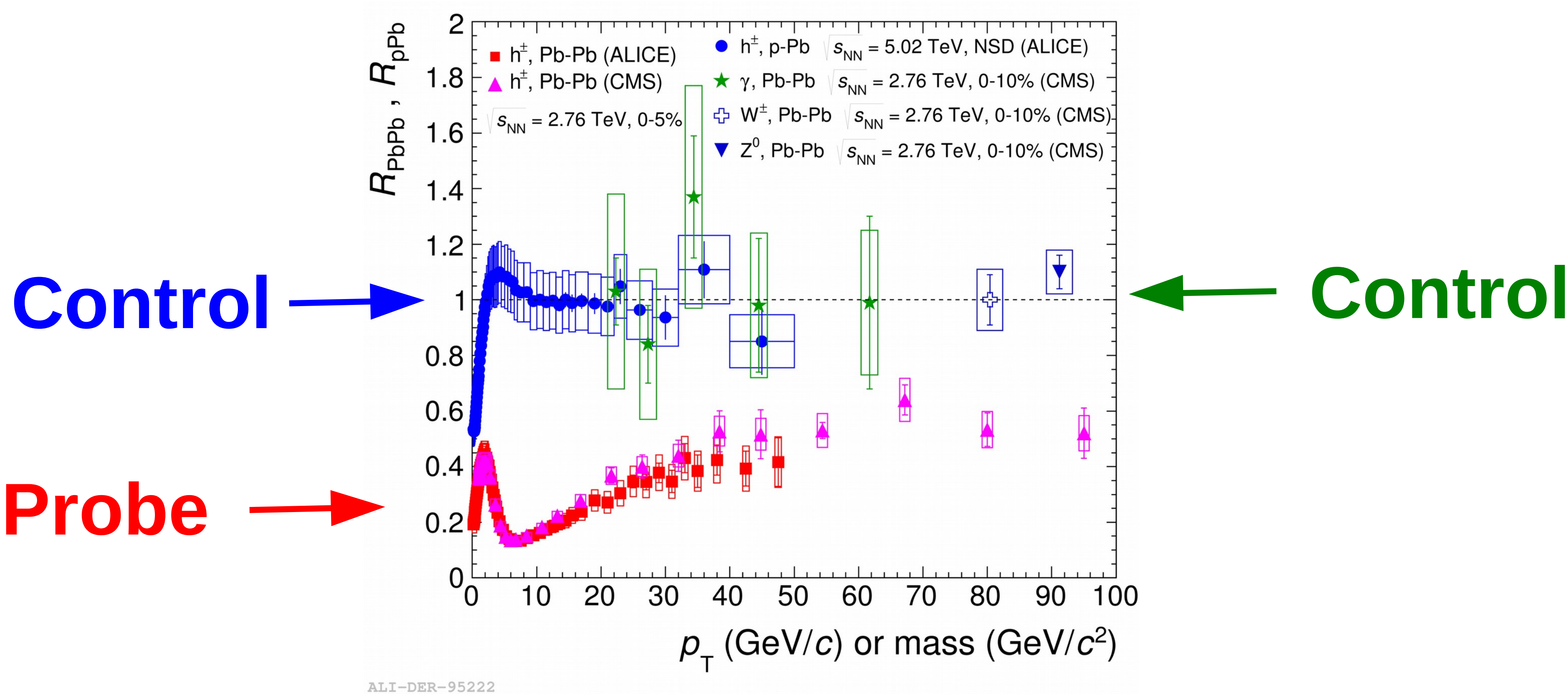
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-p_T probes (jets) are suppressed, this is evidence of jet quenching

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$

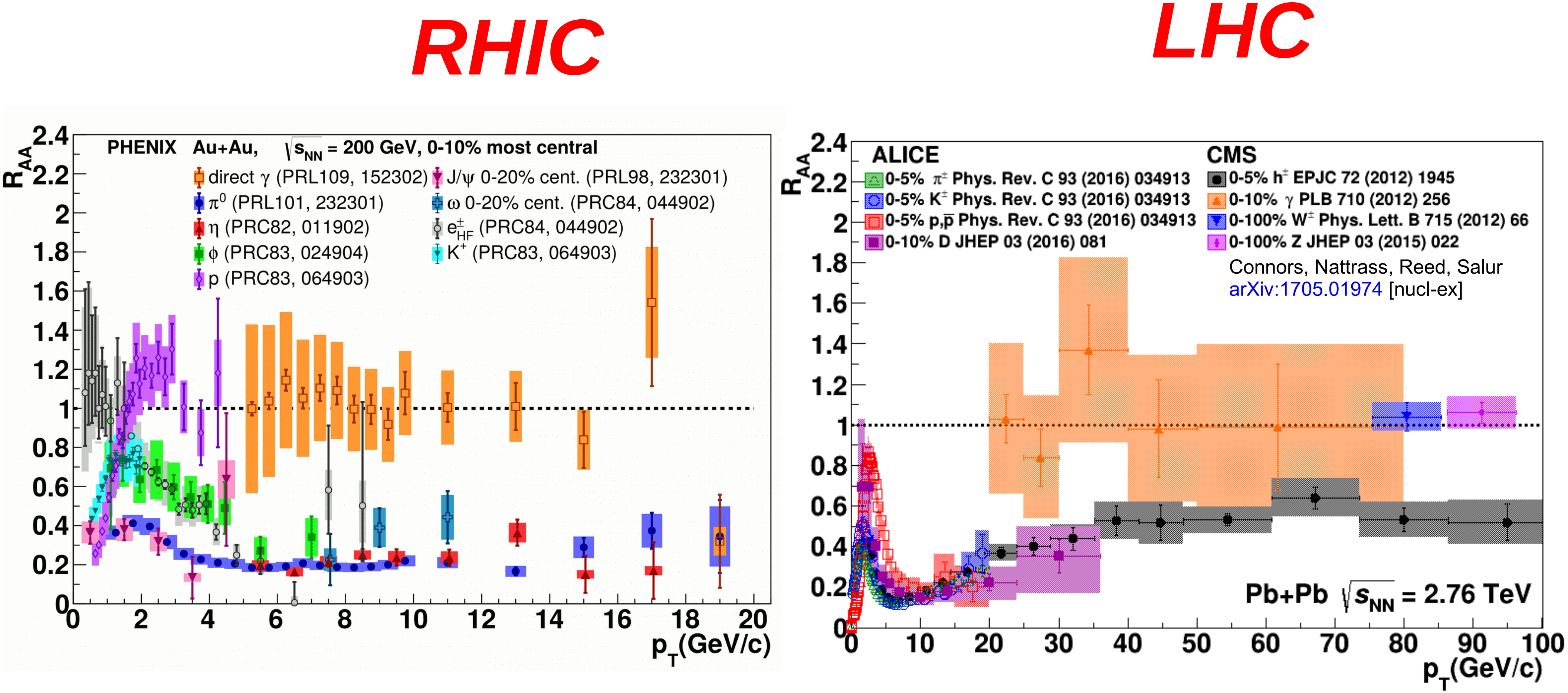


Nuclear modification factor

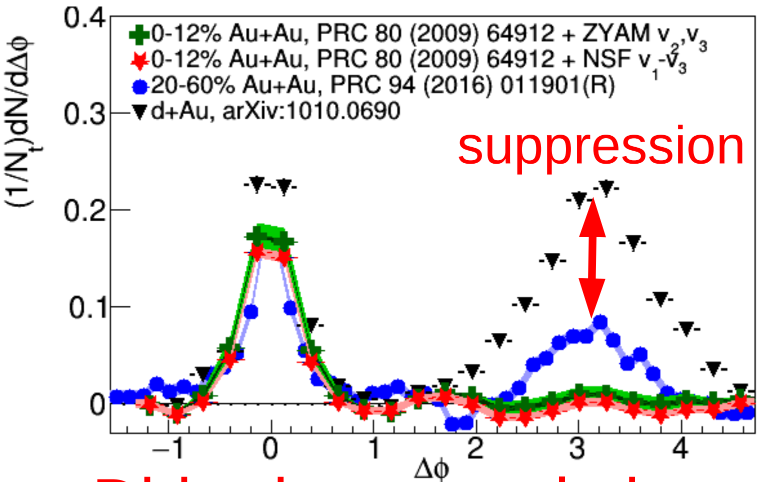


- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb

Nuclear modification factor R_{AA}



- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them - even heavy quarks!

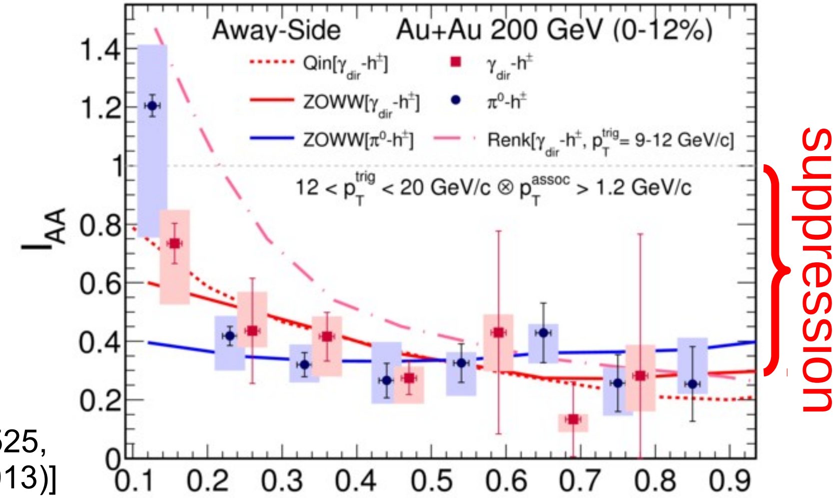


Di-hadron correlations

[Too many to list]

Jet v_2

[Phys.Lett. B 753 (2016) 511-525, Phys. Rev. Lett.111 152301 (2013)]

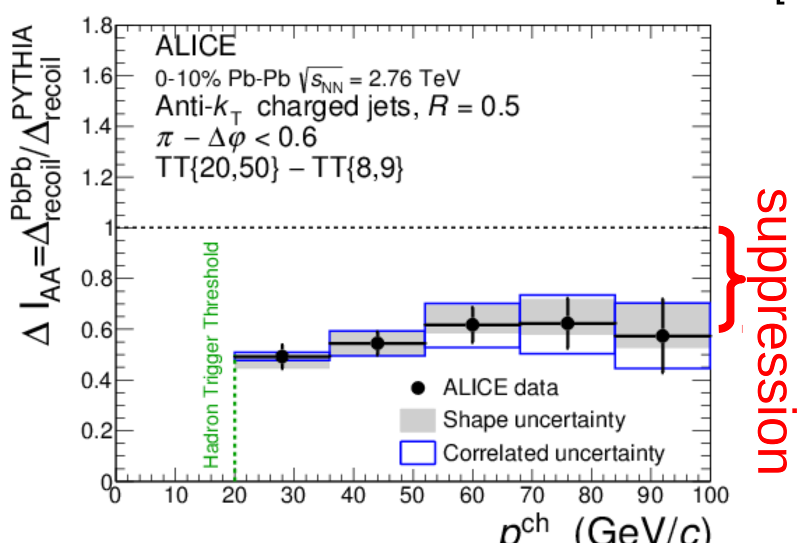


γ-hadron correlations

[Phys.Rev.C80:024908,2009, Phys.Rev.D82:072001,2010, Phys.Rev.C82:034909,2010 Physics Letters B 760 (2016)]

γ-jet correlations

[Phys. Lett. B 718 (2013) 773]

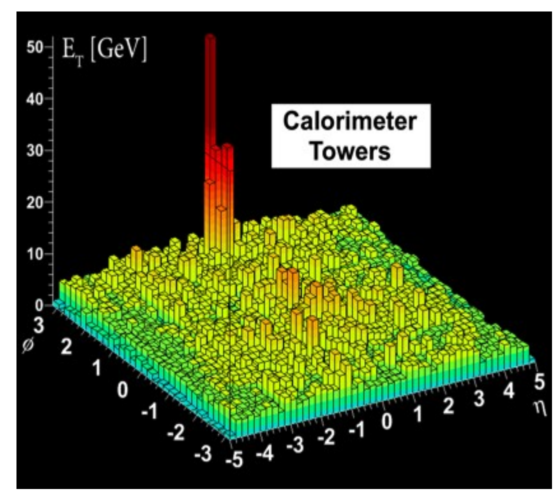


Hadron-jet correlations

[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]

High-p_T hadron v_2

[too many to list]



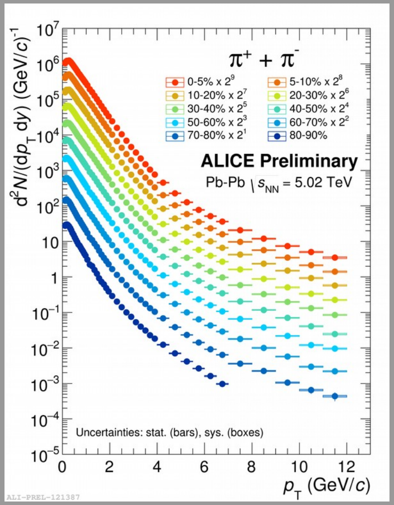
Dijet asymmetry

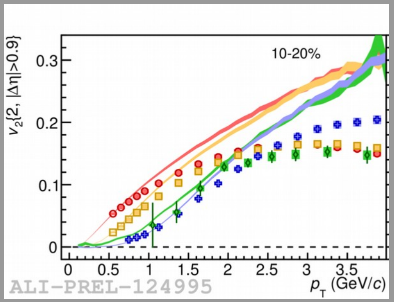
[Phys.Rev.C84:024906,2011, Phys. Lett. B 712 (2012) 176, Phys.Rev.Lett.105:252303,2010, Phys. Rev. Lett. 119, 062301 (2017)]

Bayesian Statistical Analysis

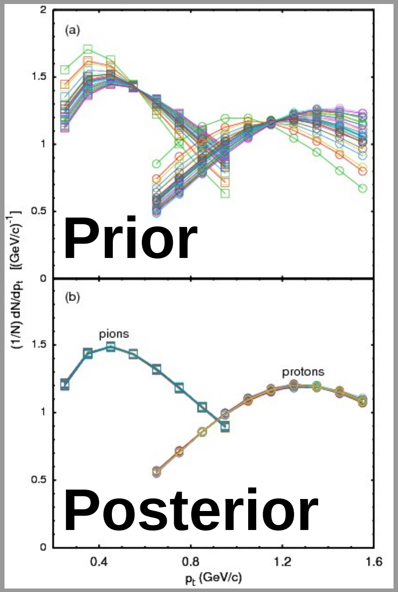
Models and Data Analysis Initiative

http://madai.us

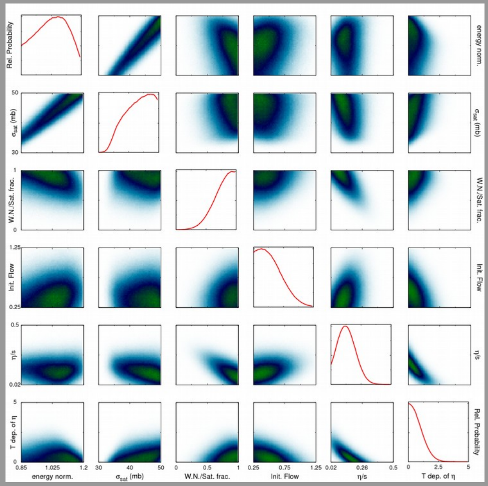




Data



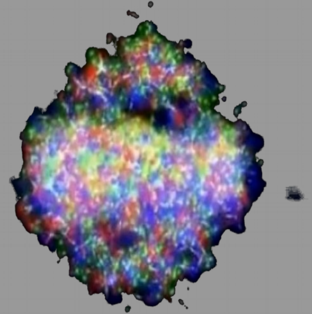
Optimization



Constraint of QGP properties

Novak et al, Phys.Rev. C89 (2014) no.3, 034917

Monte Carlo models



Model emulation

1) Run full model ~1000 times
2) MCMC parameter search uses emulator (interpolator) in lieu of full model

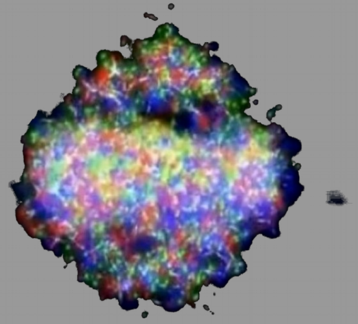
JETSCAPE

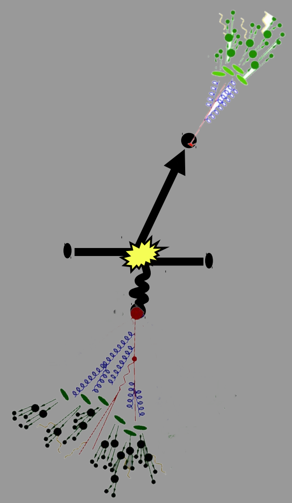
Event generator

Jet **E**nergy-loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelope

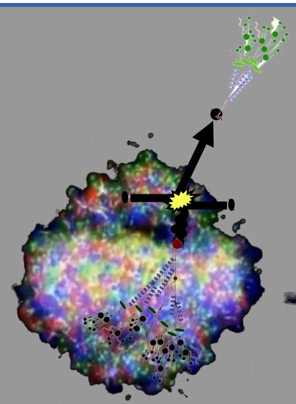
http://jetscape.wayne.edu/

Realistic medium





Realistic jets



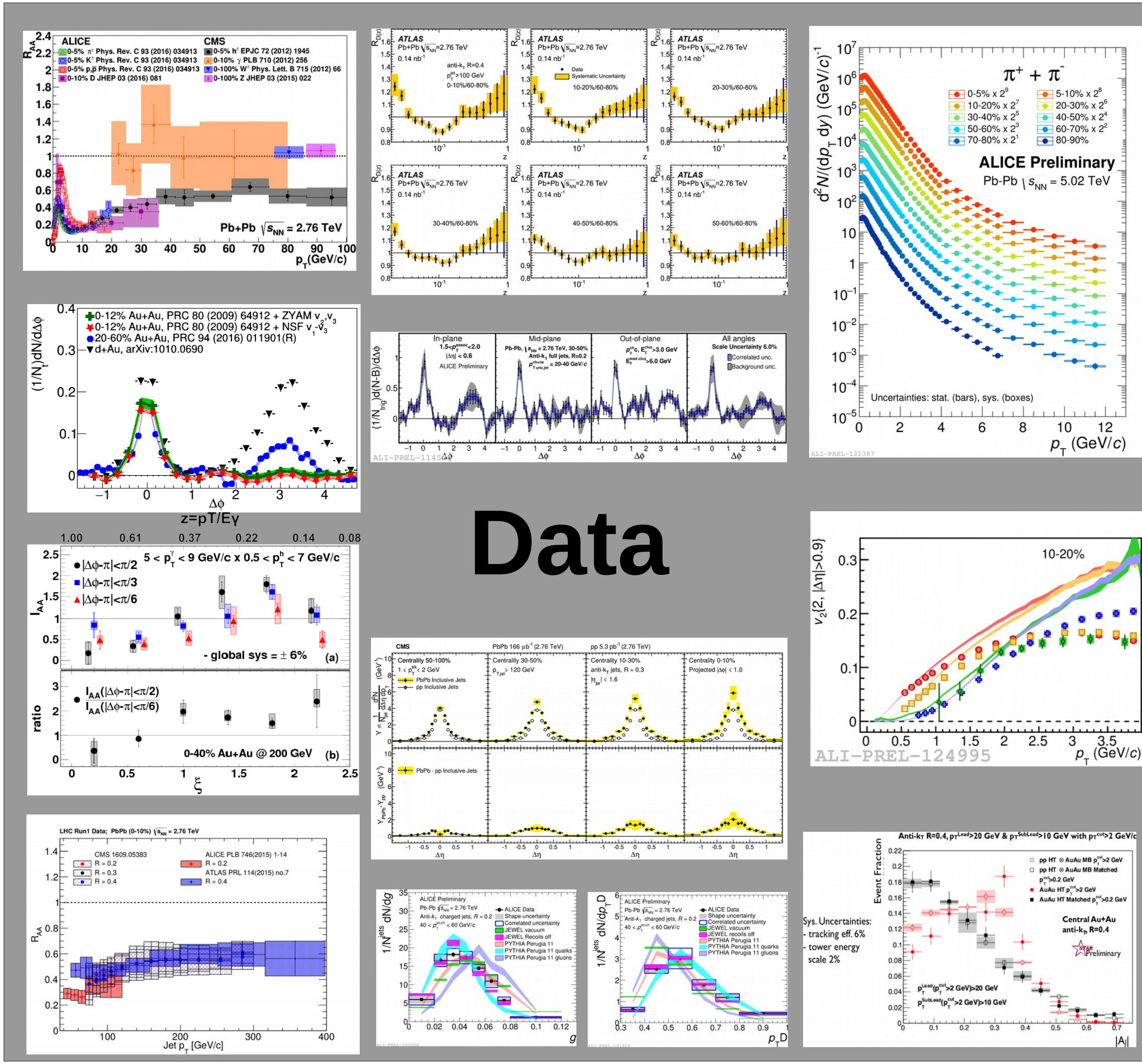
Realistic Monte Carlo Model

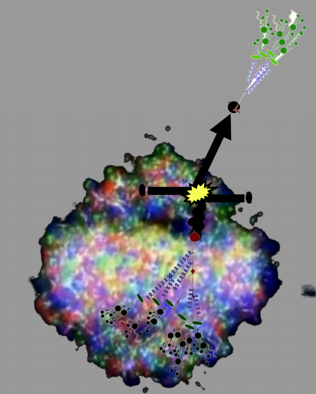
Experimental techniques

Realistic theoretical calculations

JETSCAPE

Event Generator + Bayesian Statistical analysis





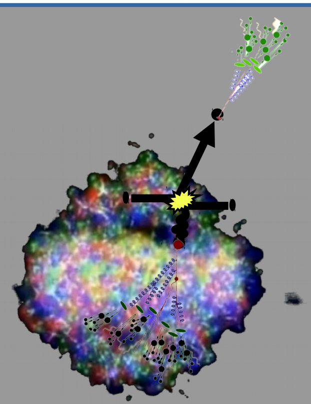
Realistic theoretical calculations

Bayesian Statistical Analysis

Constraint of QGP properties

RIVET

Robust **I**ndependent **V**alidation of **E**xperiment and **T**heory

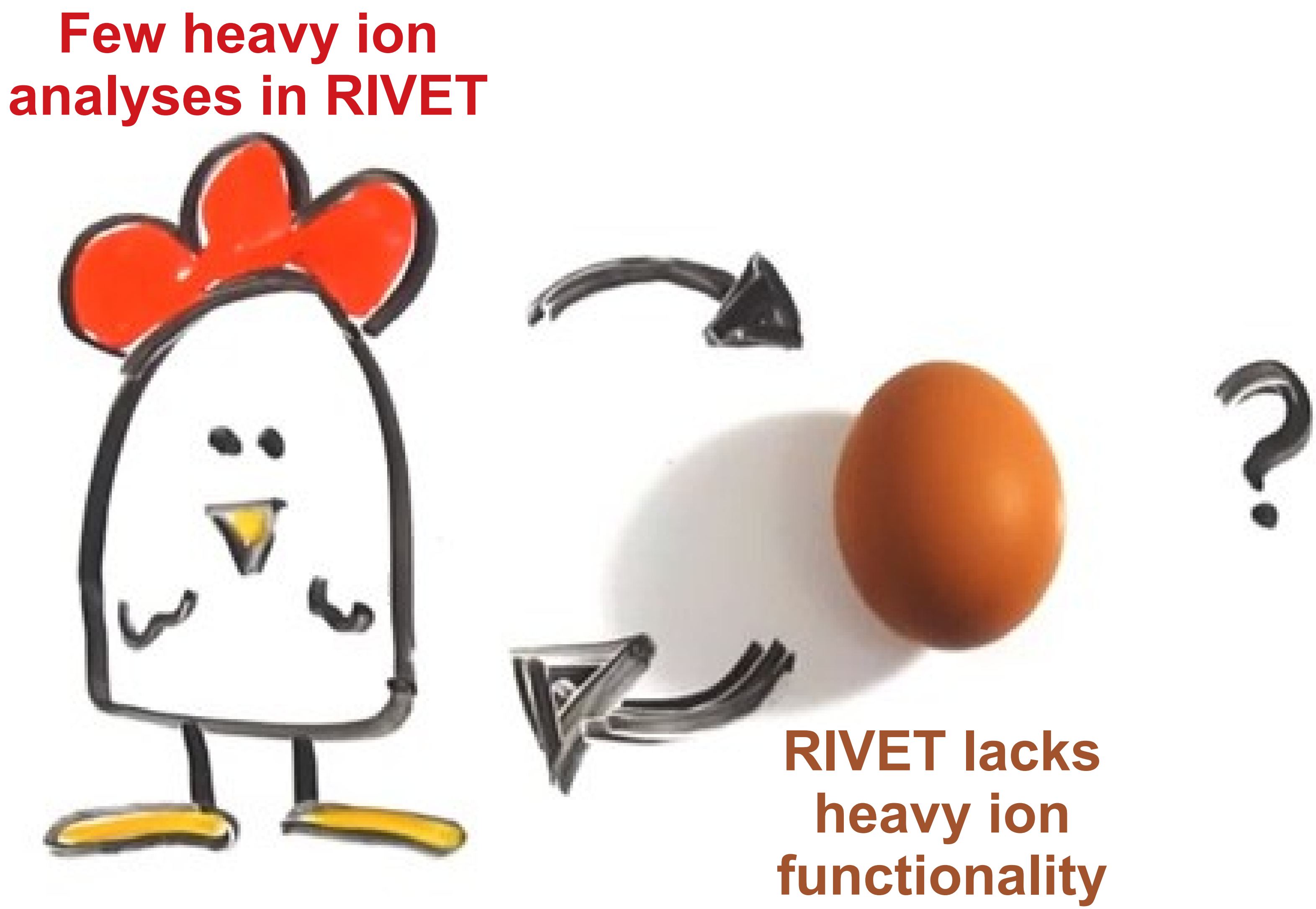


Realistic Monte Carlo Model

Experimental techniques

Realistic theoretical calculations

Works here



http://iterated-reality.com/en/2015/03/17/the-chicken-or-the-egg-causality-dilemma-solved-by-unity-consciousness/

https://i.ytimg.com/vi/mZnv6LXD9qs/maxresdefault.jpg

UTK RIVET Group Summer 2018

James Neuhaus
Jerrica Wilson
Mariah McCreary
Ricardo Santos (Berea)
Austin Schmier
4 undergrads + 1 beginning grad student
Redmer Bertens (post doc)

Before: 3 heavy ion analyses implemented
After: 9 heavy ion analyses, 2 more in progress

Course-based undergraduate research experience

CBE—Life Sciences Education, Vol. 15, No. 2 | Articles

Free Access

Early Engagement in Course-Based Research Increases Graduation Rates and Completion of Science, Engineering, and Mathematics Degrees

Stacia E. Rodenbusch, Paul R. Hernandez, Sarah L. Simmons, and Erin L. Dolan

Jennifer Knight, Monitoring Editor:

Published Online: 13 Oct 2017 | https://doi.org/10.1187/cbe.16-03-0117

Sections View Article Tools Share

Abstract

National efforts to transform undergraduate biology education call for research experiences to be an integral component of learning for all students. Course-based undergraduate research experiences, or CUREs, have been championed for engaging students in research at a scale that is not possible through apprenticeships in faculty research laboratories. Yet there are few if any studies that examine the long-term effects of participating in CUREs on desired student outcomes, such as graduating from college and completing a science, technology, engineering, and mathematics (STEM) major. One CURE program, the Freshman Research Initiative (FRI), has engaged thousands of first-year undergraduates over the past decade. Using propensity score–matching to control for student-level differences, we tested the effect of participating in FRI on students' probability of graduating with a STEM degree, probability of graduating within 6 yr, and grade point average (GPA) at graduation. Students who completed all three semesters of FRI were significantly more likely than their non-FRI peers to earn a STEM degree and graduate within 6 yr. FRI had no significant effect on students' GPAs at graduation. The effects were similar for diverse students. These results provide the most robust and best-controlled evidence to date to support calls for early involvement of undergraduates in research.

Phys 494 – Course-based Undergraduate Research Experience in Relativistic Heavy Ion Physics

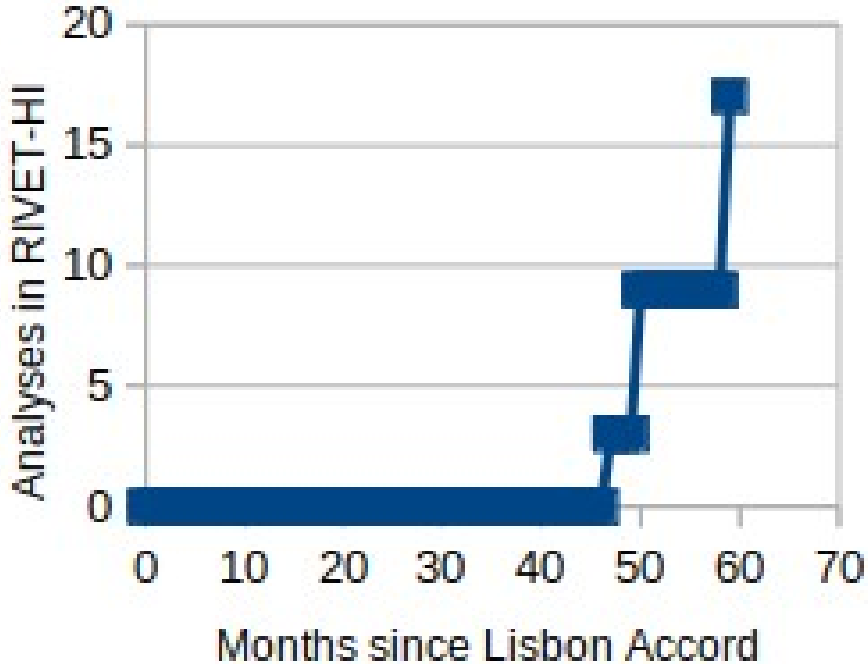
Instructor:
Dr. Christine Nattrass
Office: SERF 609
Phone: 974-6211
Email: christine.nattrass@utk.edu
Office hours: TBA

Teaching assistant: N/A

Class time & Location: TR 12:40-1:55 SERF 210

Course Description:
This course will incorporate undergraduates into a research project in high energy nuclear physics in a course setting. Each student will be responsible for implementing a heavy ion analysis in the program RIVET so that it can be used by the JETSCAPE collaboration to make comparisons between Monte Carlo models and data. Each student's project will be incorporated into a public software repository so that it is available to the field and, if possible, it will be validated by the relevant experiment and incorporated into the official RIVET software.

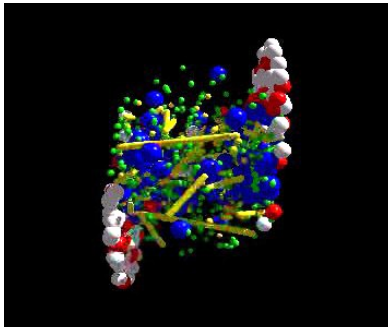
Projected analyses implemented in RIVET-HI*

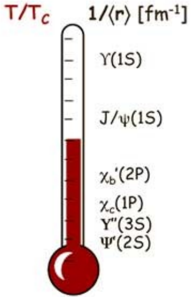


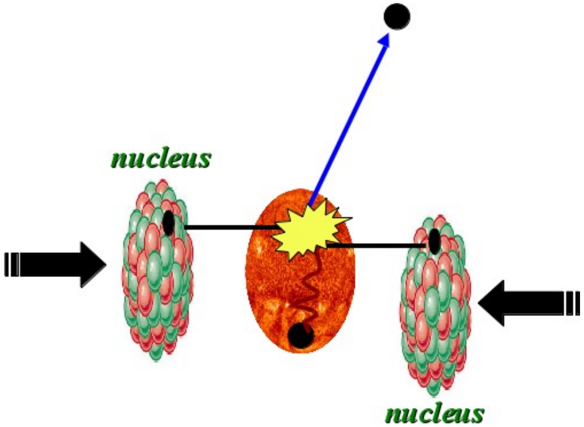
*Not yet checked in to RIVET-HI but in a UTK mirror

Take home messages

- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is extremely hot and dense...
- ...and opaque to colored probes and translucent to electromagnetic probes.







About me

- BS, Colorado State University, 2003
- PhD, Yale University, 2009
- Postdoc, University of Tennessee, Knoxville, 2009-2012
- Assistant prof, University of Tennessee, Knoxville 2012 –
- Active on issues related to women in physics and working on being a more effective ally for people of color
- Parent
- Brew beer & wine, keep bees, avid cook, cyclist

Careers in high energy physics

- You should consider high energy physics if...
  - You like programming and working with computers
  - You're a people person – and don't mind working with 1000 people
  - You like to travel around the world – and work
  - You enjoy giving talks
- Common career options for people with a Ph.D. in high energy physics
  - Academia – research and teaching universities
  - Research at a National Laboratory
  - National security
  - Finance
  - Computer programming

What I spend my time doing

- Programming (c++) - analyzing data
- Writing and giving talks – 3 research talks, 1 seminar, 2 posters, 1 software tutorial, and lots of talks (>30) at internal meetings in 2010
- Hardware work: assembling & testing the detector
- Outreach: blogging for ALICE, giving tours of PHENIX to the public...
- Writing papers and conference proceedings
- Reviewing the work of my collaborators
- Reading papers
- Taking shifts – including being on call 24/7
- Teaching, advising students (undergrad & grad)
- Committee work

Resources

- US LHC blog and Facebook page
- Experiments
  - Relativistic Heavy Ion Collider: STAR PHENIX
  - Large Hadron Collider: ALICE ATLAS CMS LHCb TOTEM
- Event displays and pretty pictures from ALICE
- Really cool ATLAS event animation
- Links to articles in the press on PHENIX
- Scientific American article

US Universities with graduate programs in experimental heavy ion physics

Relativistic Heavy Ion Collider

- STAR
  - University of California at Davis
  - University of California Los Angelos
  - University of Houston
  - University of Illinois at Chicago
  - Creighton University (masters only)
  - Kent State University
  - Michigan State University
  - Ohio State University
  - Purdue University
  - Texas A&M University
  - University of Texas Austin
  - University of Washington
  - Wayne State University
  - Yale University
- PHENIX
  - University of California Riverside
  - University of Colorado Boulder
  - Columbia University
  - Florida State University
  - Georgia State University
  - Iowa State University
  - Ohio University
  - State University of New York (Chemistry & Physics departments)
  - **University of Tennessee at Knoxville**
  - Vanderbilt University

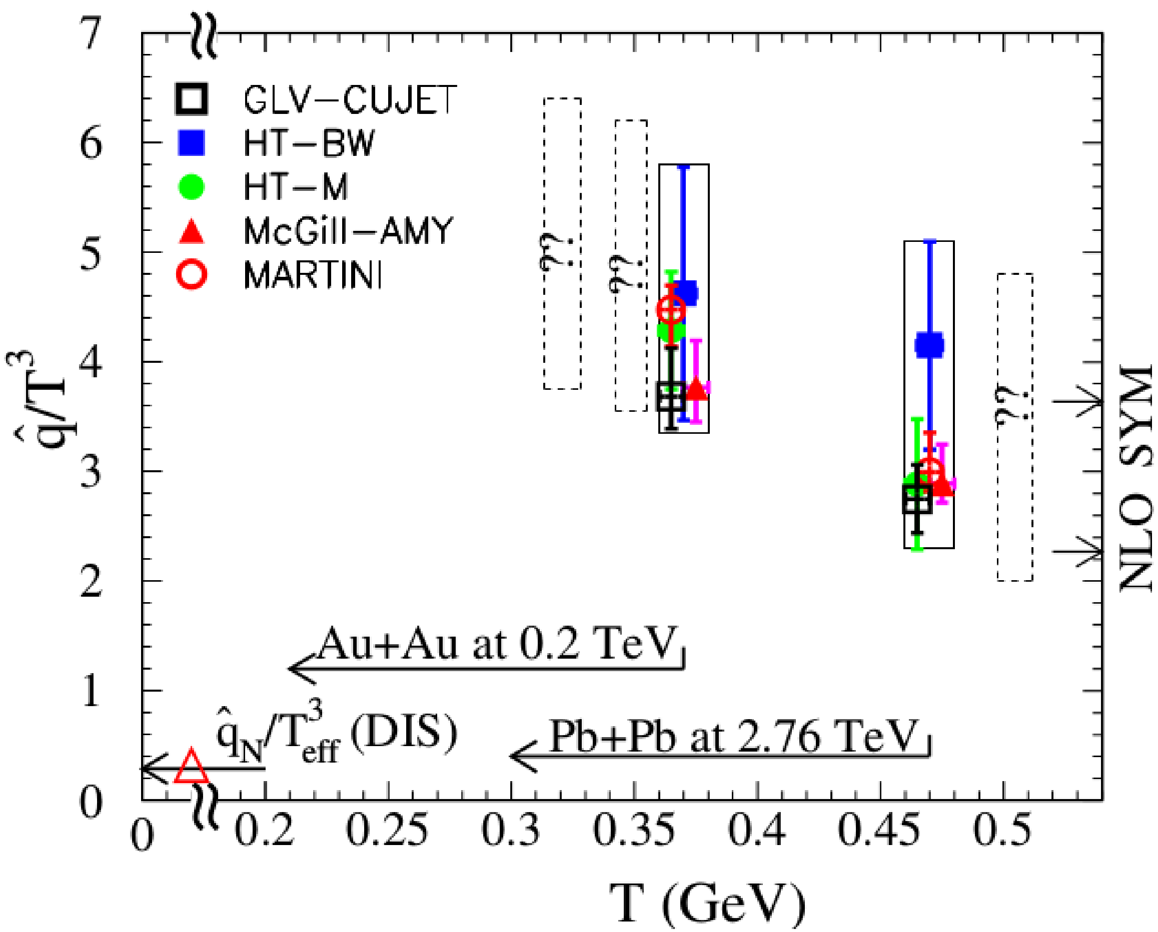
US Universities with graduate programs in experimental heavy ion physics

Large Hadron Collider

- ALICE
  - University of Texas Austin
  - Chicago State University
  - Ohio State University
  - Wayne State University
  - University of Texas Houston
  - **University of Tennessee Knoxville**
  - Yale University
  - Creighton University (masters only)
  - Purdue University
- CMS
  - University of California Davis
  - University of Illinois Chicago
  - University of Kansas
  - University of Maryland
  - University of Iowa
  - Rutgers University
  - Massachusetts Institute of Technology
  - Vanderbilt University
- ATLAS
  - Columbia University

Quantifying $\hat{q}$

Phys. Rev. C 90, 014909 (2014)



Jet Collaboration: For a 10 GeV quark traveling 4 fm

$\hat{q}$ ≈1.2±0.3 GeV^2/fm at τ_0=0.6 fm/c in Au+Au at $\sqrt{s_{NN}}$=200 GeV

→loses 2.2 Gev

$\hat{q}$≈1.9±0.7 GeV^2/fm in Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

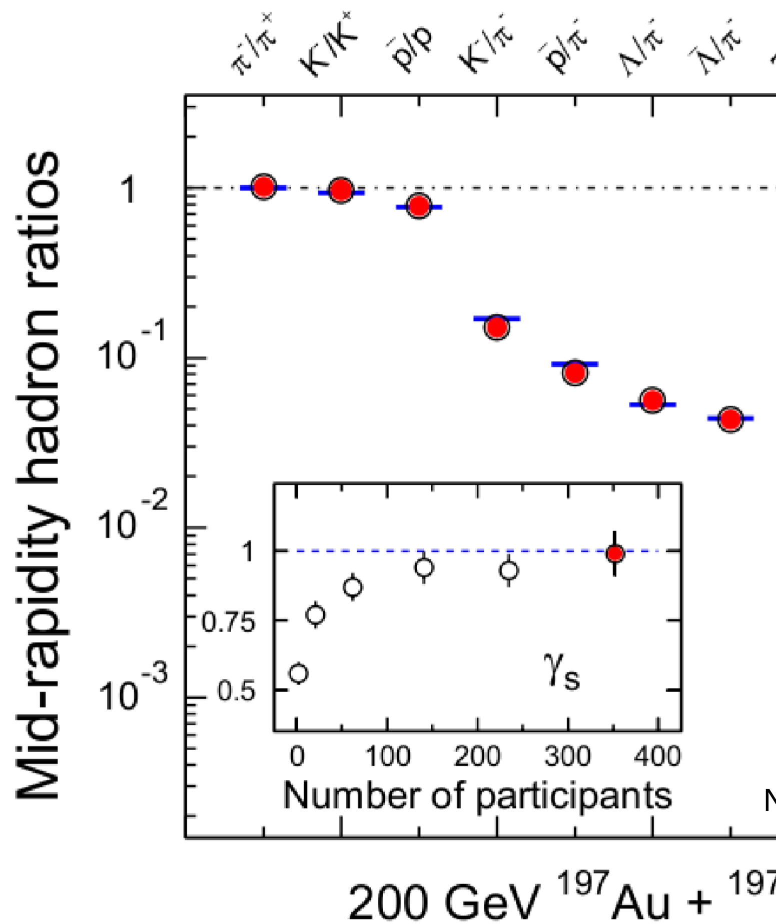
→loses 2.8 Gev

$$\hat{q}=Q^2/L$$

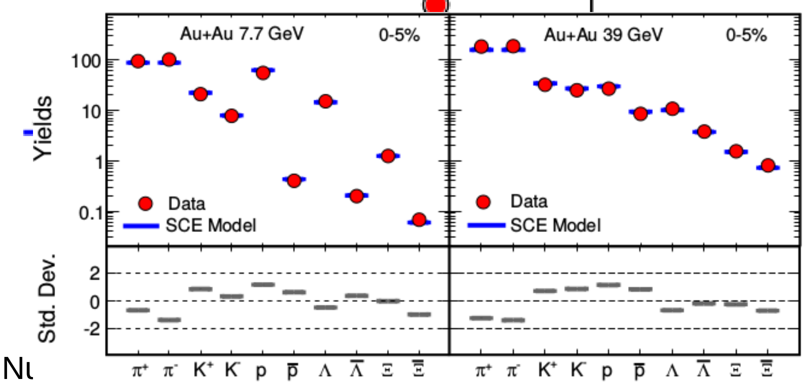
Q = Momentum transfer from parton to medium
L = path length

QGP Chemistry

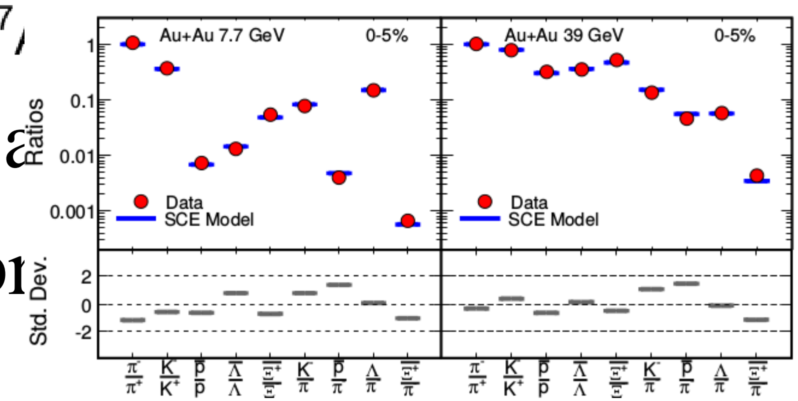
Chemistry - equilibrium



T~170 MeV

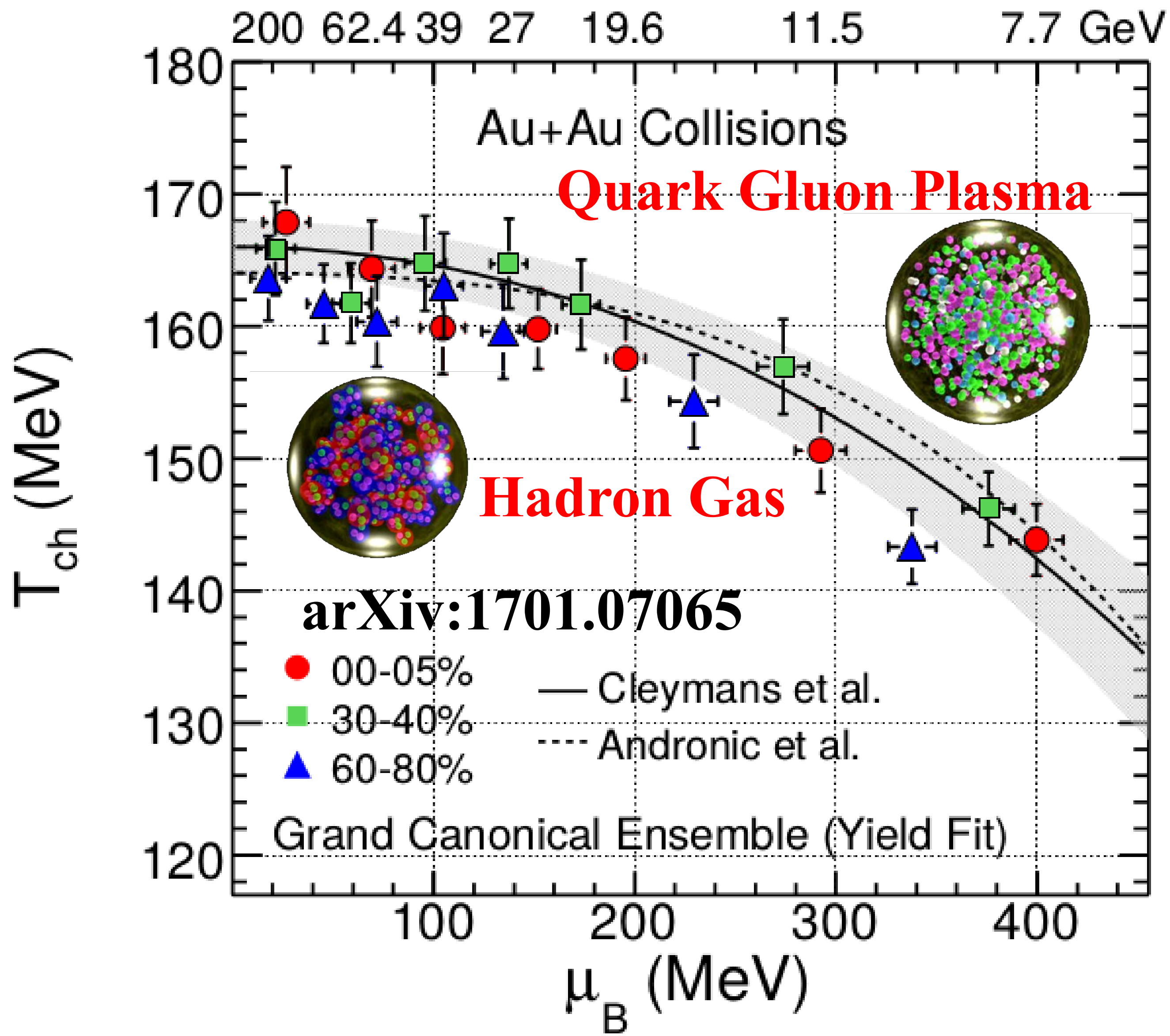


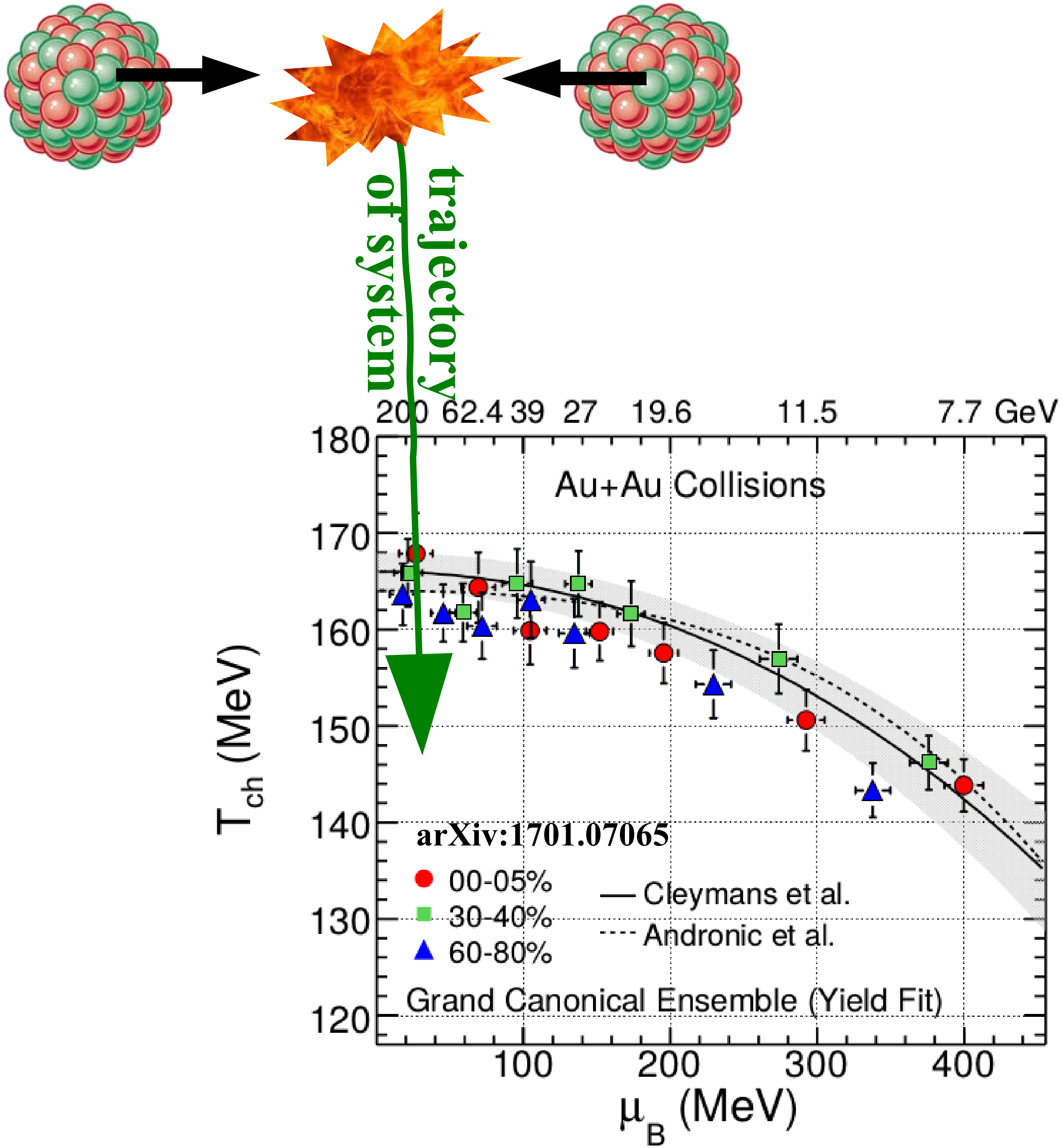
arXiv:1701.07065



- Ratios of particles expected from a
- Even strange quarks are at equilibr

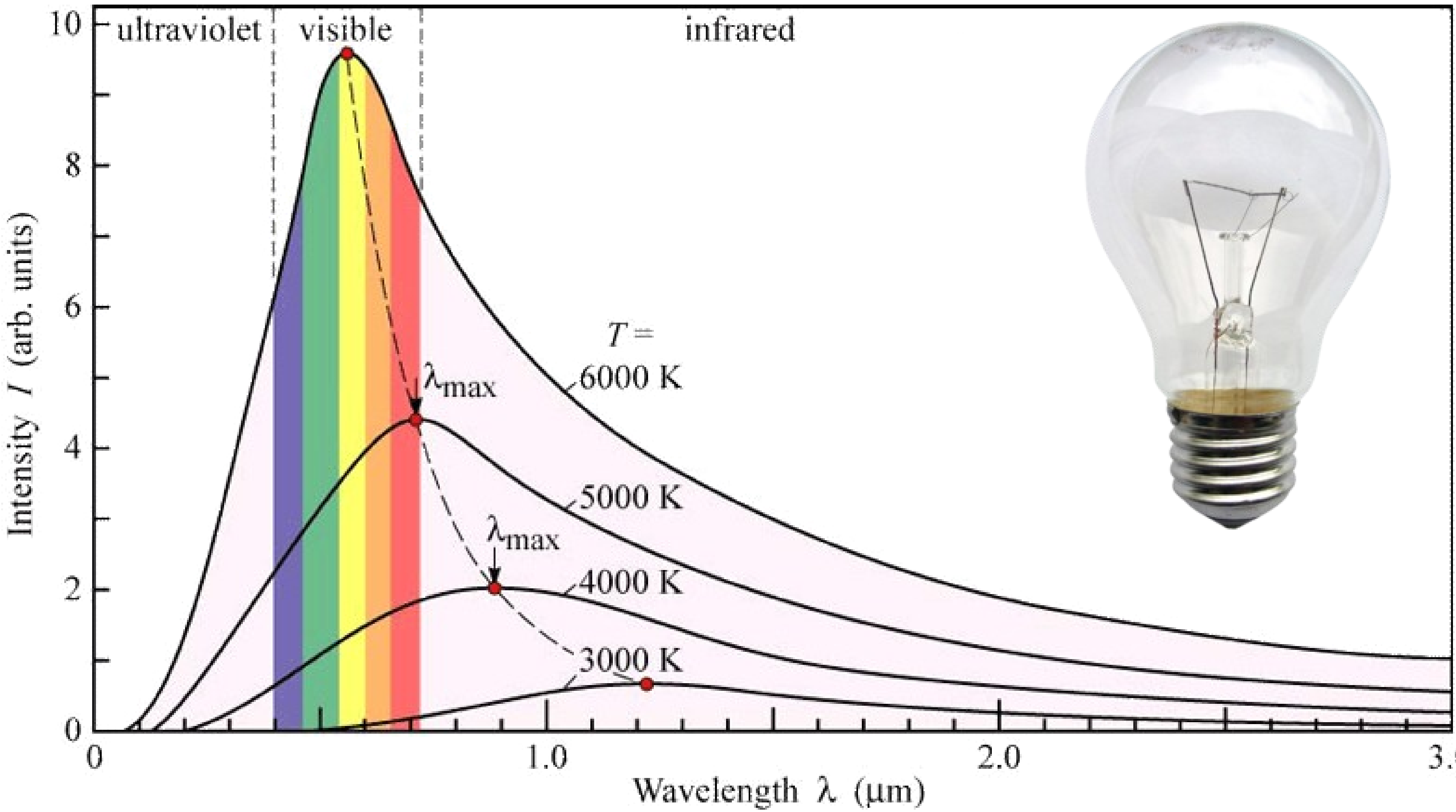
QCD Phase Diagram




trajectory
of system
200 62.4 39 27 19.6 11.5 7.7 GeV
Au+Au Collisions
arXiv:1701.07065
00-05%
30-40%
60-80%
Cleymans et al.
Andronic et al.
Grand Canonical Ensemble (Yield Fit)
T_ch (MeV)
μ_B (MeV)
180
170
160
150
140
130
120
100
200
300
400

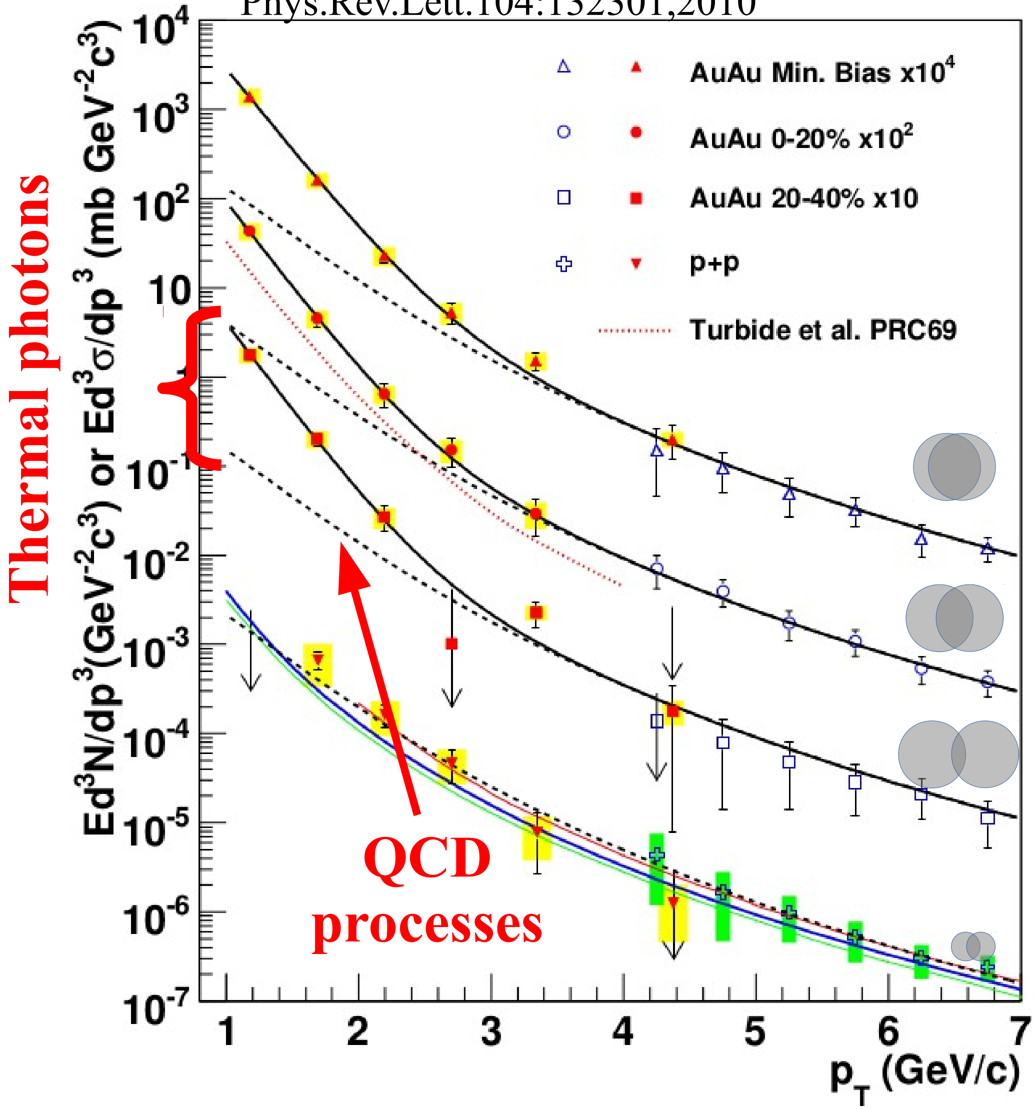
QGP Thermometers

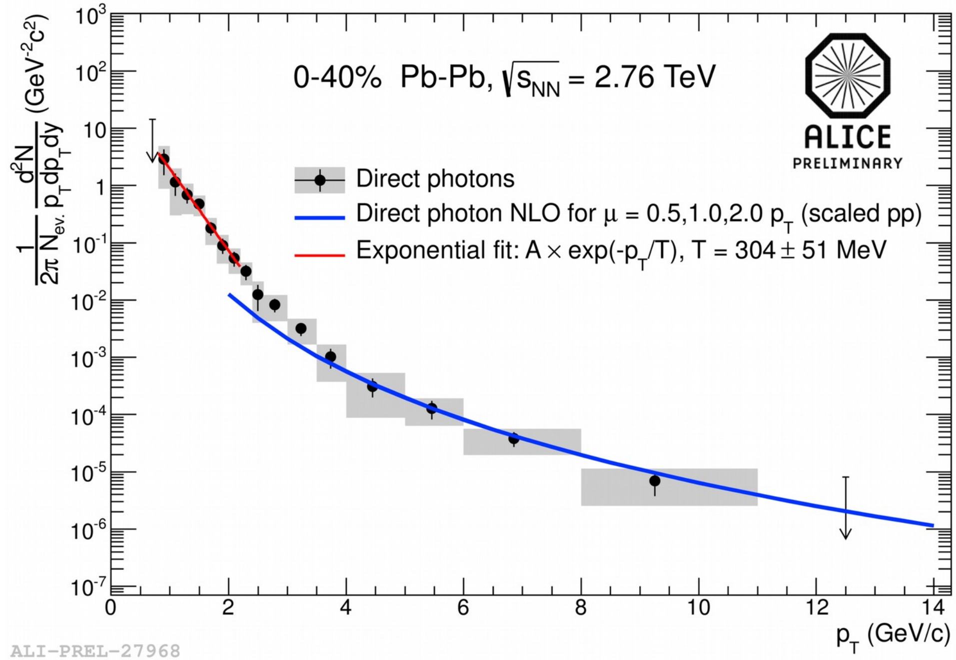
Measuring temperature



Thermal photons

Phys.Rev.Lett.104:132301,2010



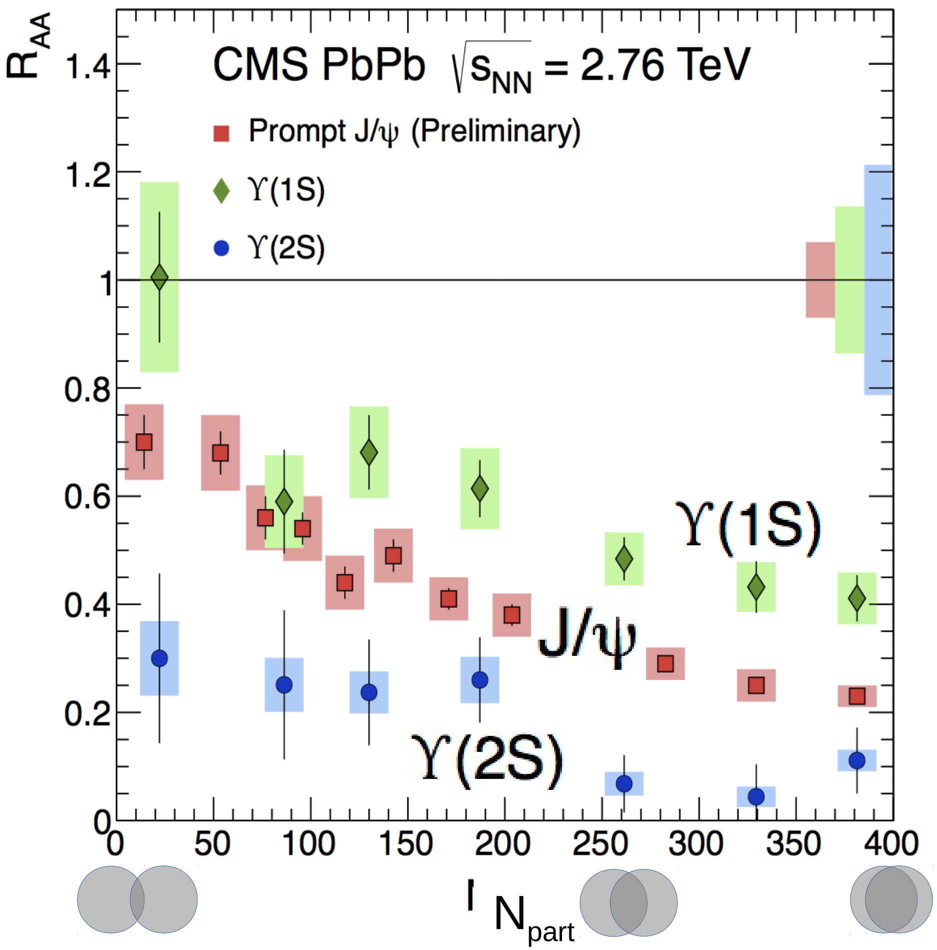


ALICE collaboration:
Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
Inverse slope: T = 304 +/-51

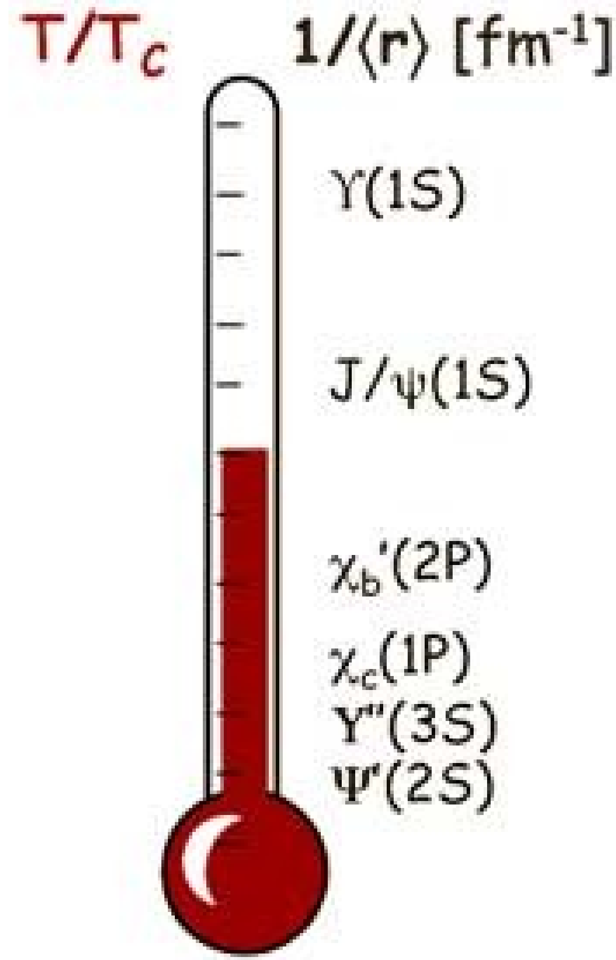
PHENIX collaboration: Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
Inverse slope: T = 221 +/- 19 (stat) +/- 19 (syst) MeV

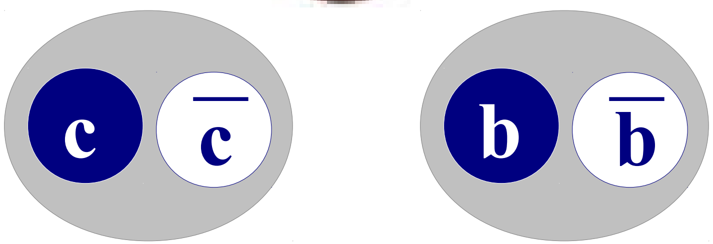
Building a quarkonium-thermometer

CMS-PAS HIN-11-011



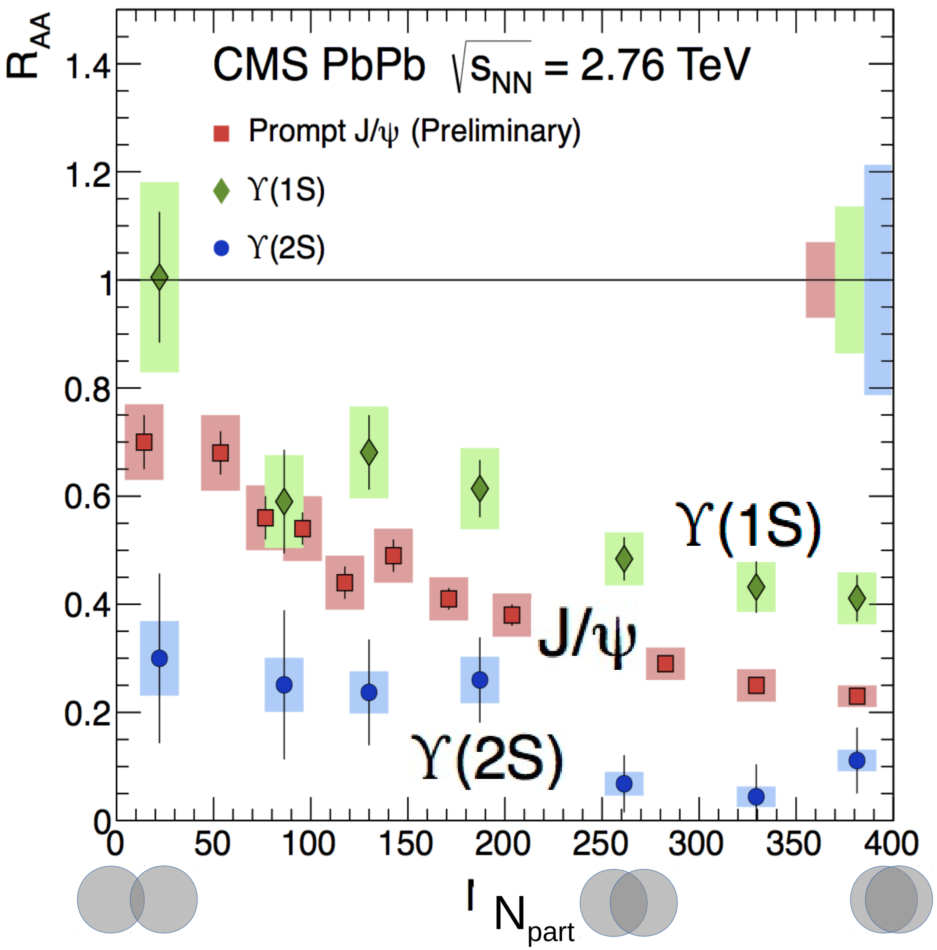
Clear hierarchy in R_{AA} of different quarkonium states



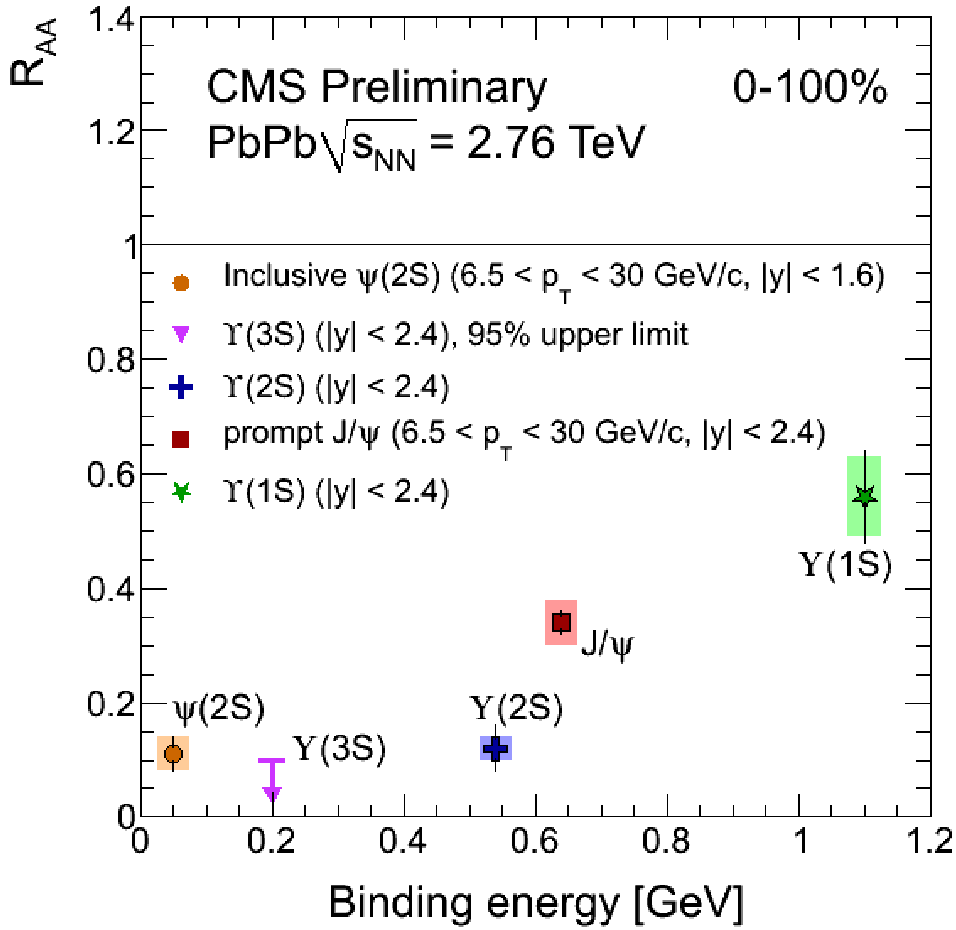


Building a quarkonium-thermometer

CMS-PAS HIN-11-011



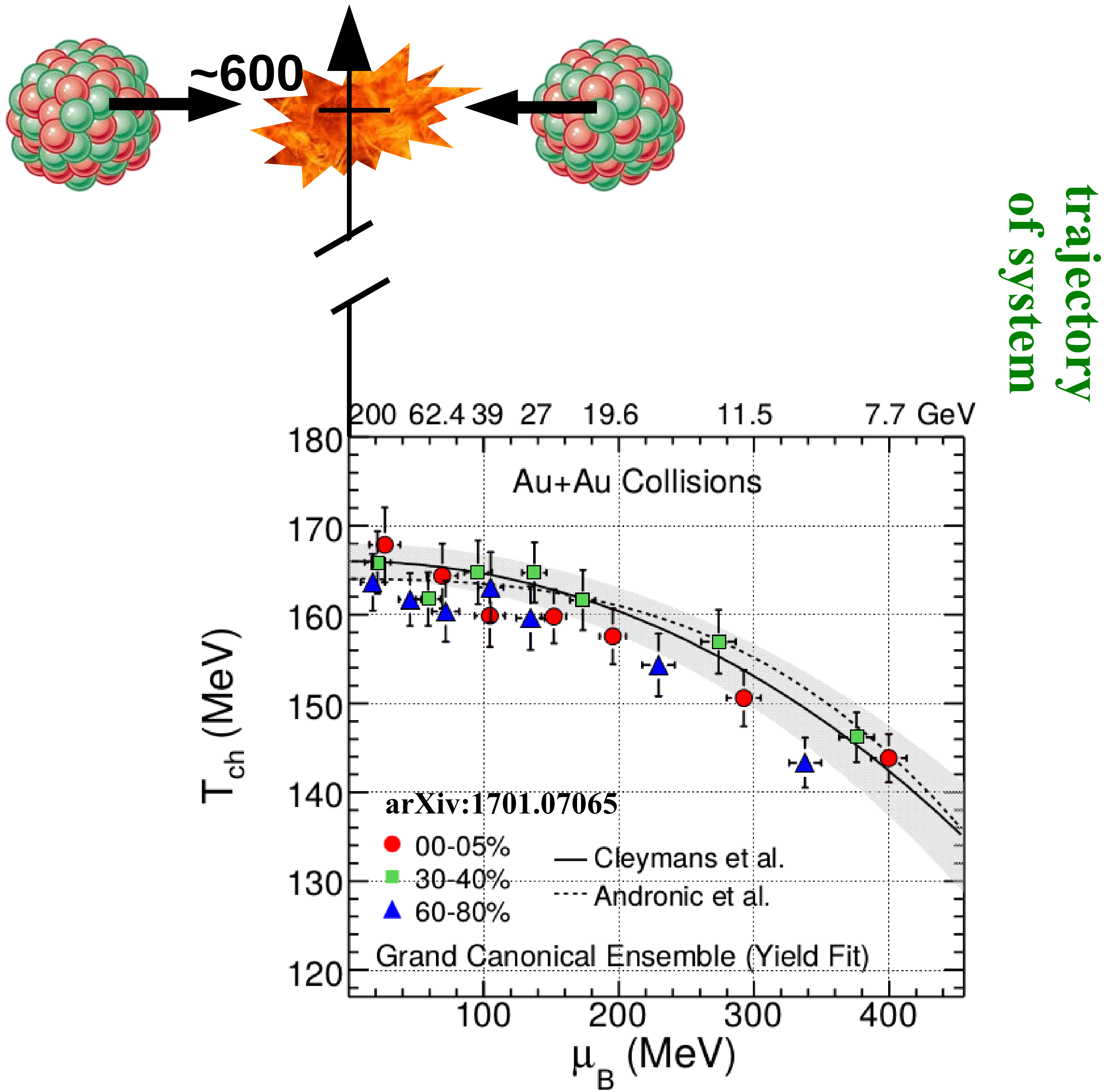
Note: 6.5<p_T<30 GeV for J/ψ and ψ(2s)



Clear hierarchy in R_{AA} of different quarkonium states

Expected in terms of binding energy

CMS-PAS HIN-12-014, HIN-12-007


~600
trajectory of system
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Au+Au Collisions
arXiv:1701.07065
00-05%
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60-80%
Cleymans et al.
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