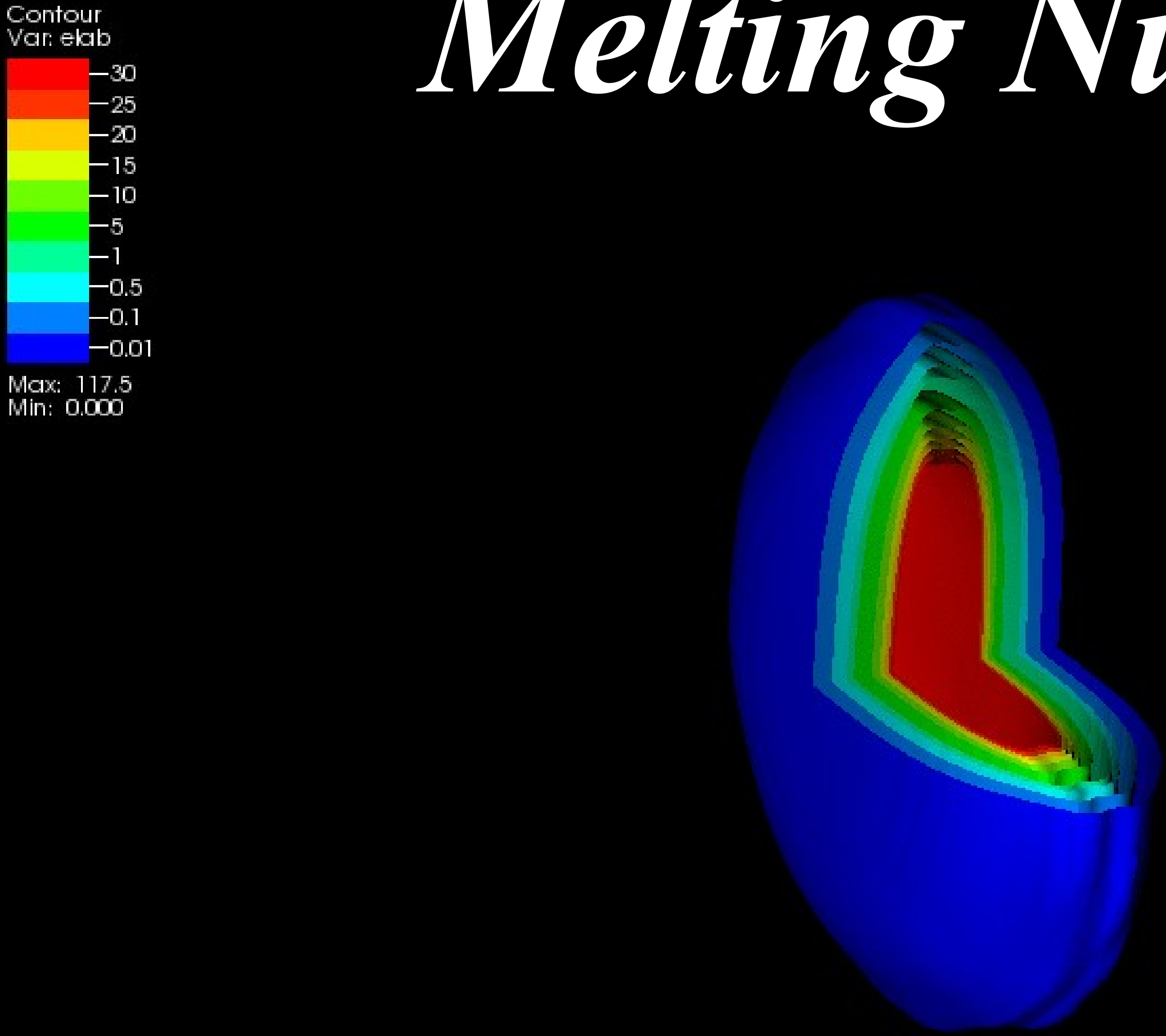
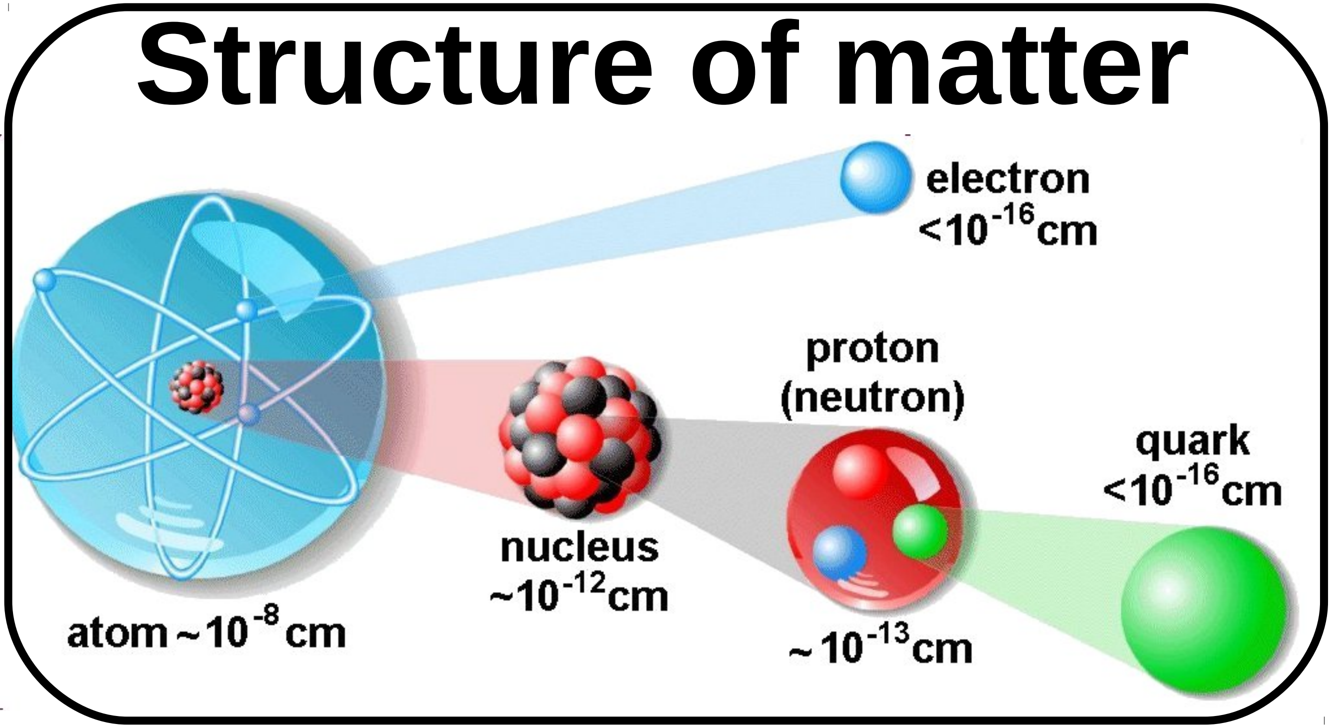
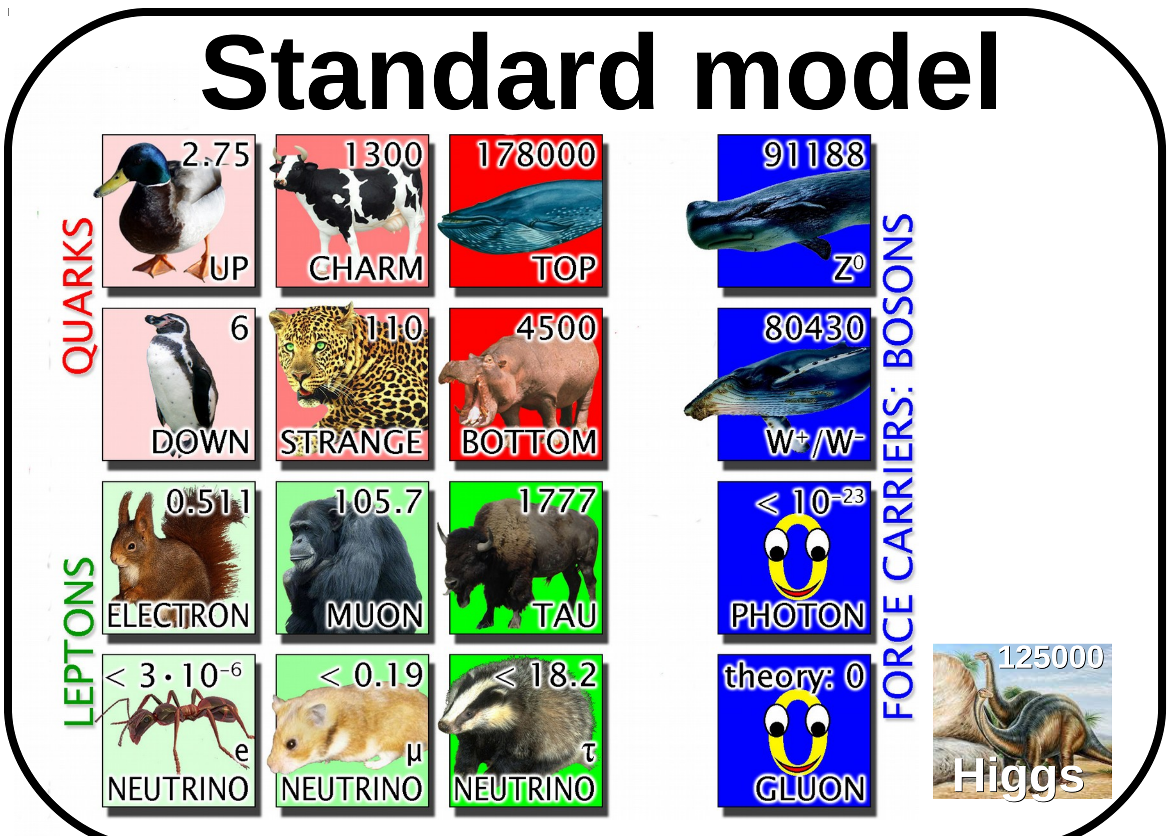
Melting Nuclei

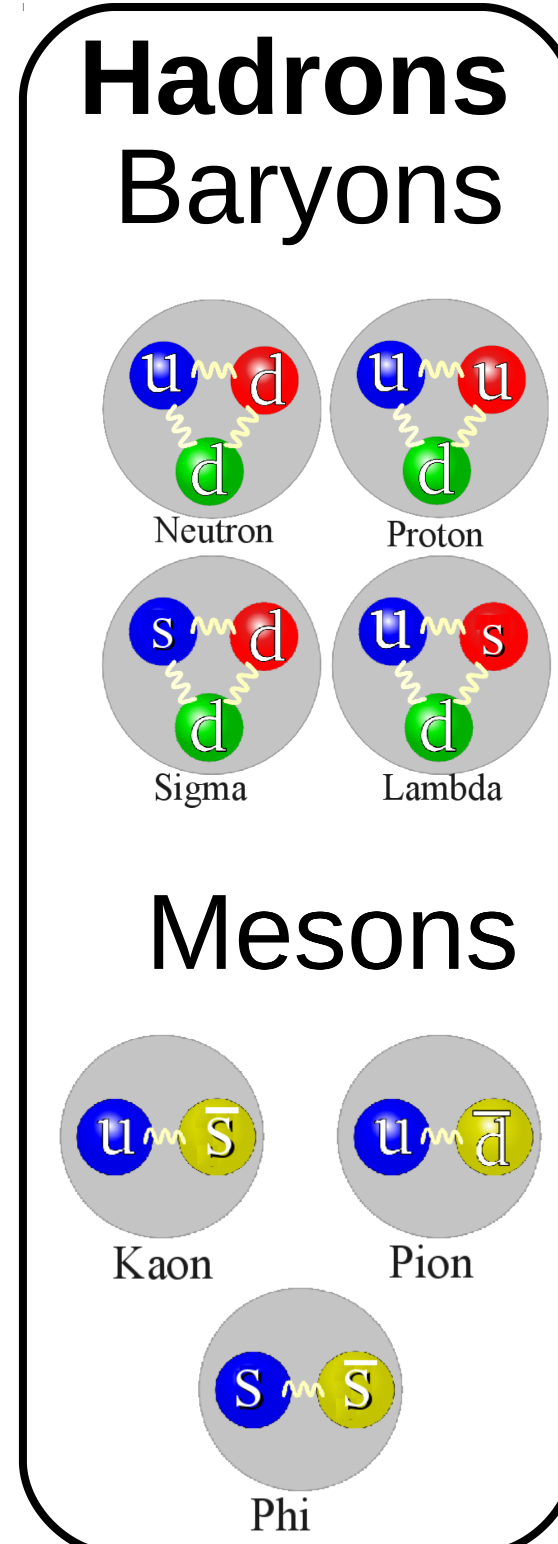


Christine Nattrass
University of Tennessee at Knoxville

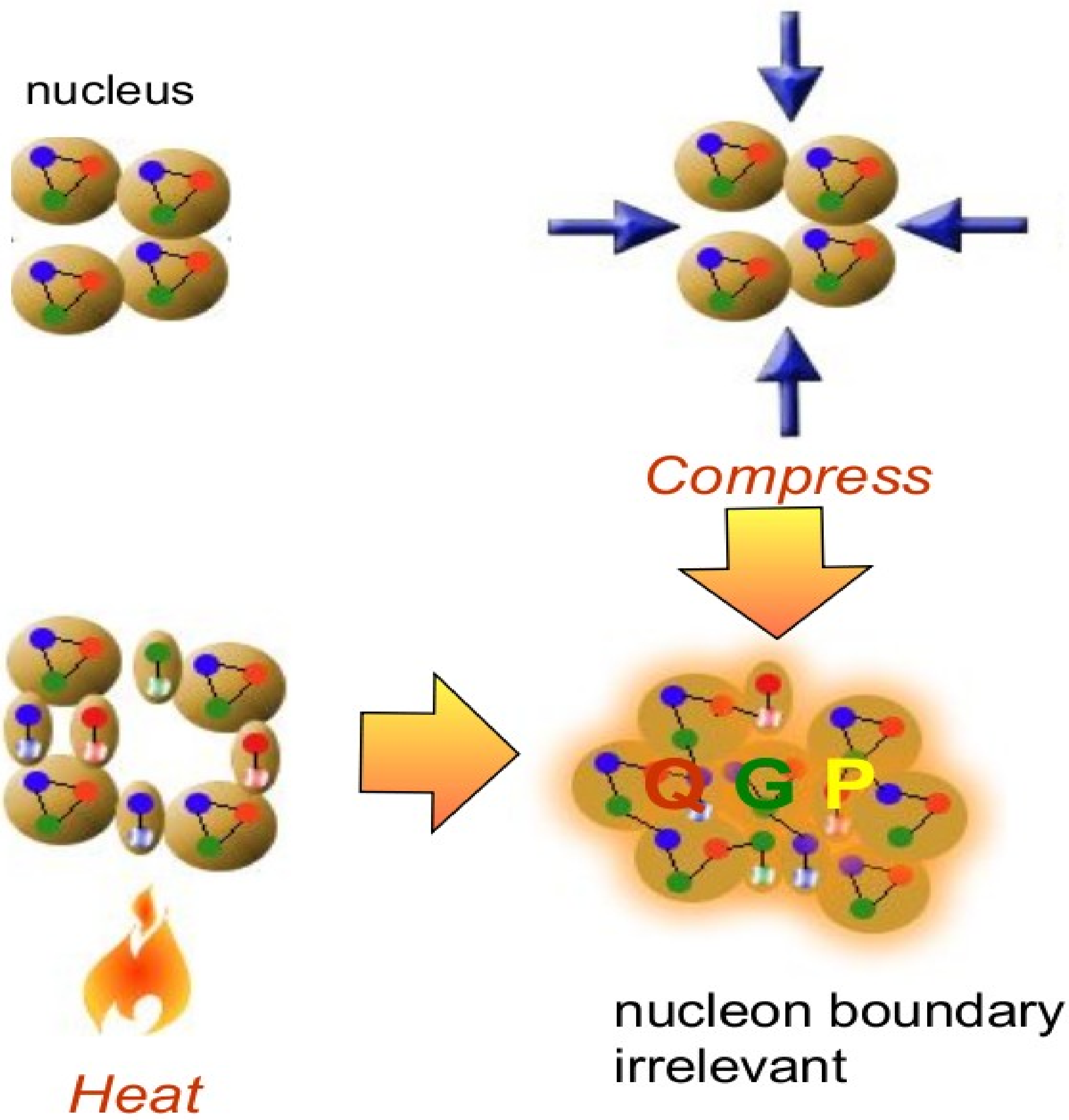
Calculations done on the Titan supercomputer by the CJet collaboration https://sites.google.com/site/cjetsite/


Structure of matter
electron
<10^-16 cm
proton
(neutron)
quark
<10^-16 cm
nucleus
~10^-12 cm
atom ~10^-8 cm
~10^-13 cm

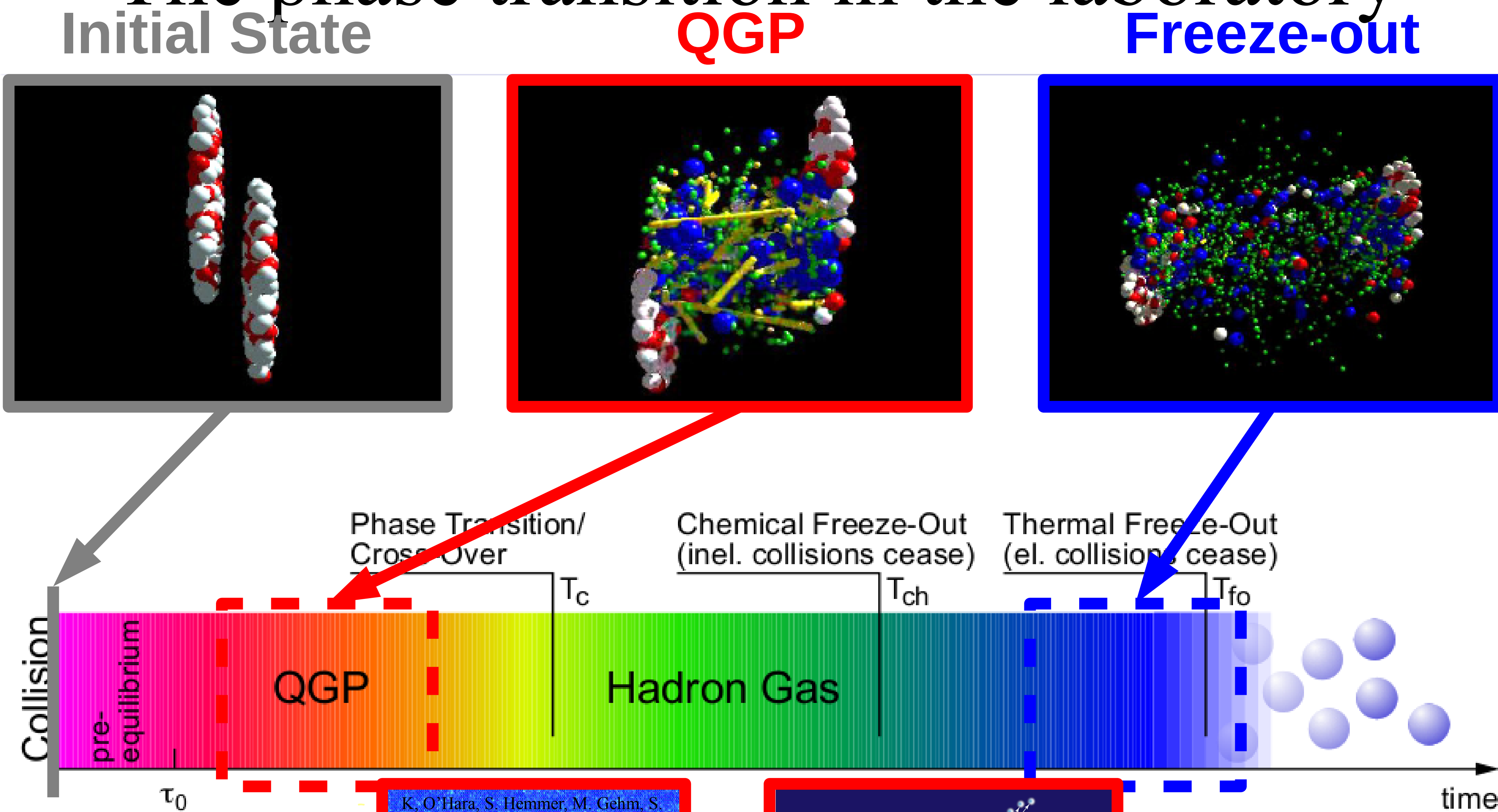

Standard model
QUARKS
2.75
UP
1300
CHARM
178000
TOP
6
DOWN
110
STRANGE
4500
BOTTOM
LEPTONS
0.511
ELECTRON
105.7
MUON
1777
TAU
< 3·10^-6
e
NEUTRINO
< 0.19
μ
NEUTRINO
< 18.2
τ
NEUTRINO
FORCE CARRIERS: BOSONS
91188
Z0
80430
W+/W-
< 10^-23
PHOTON
theory: 0
GLUON
125000
Higgs


Hadrons
Baryons
u d d
Neutron
u u d
Proton
s d d
Sigma
u s d
Lambda
Mesons
u s̄
Kaon
u d̄
Pion
s s̄
Phi

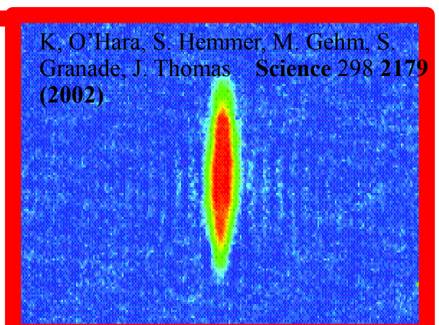
How to make a Quark Gluon Plasma

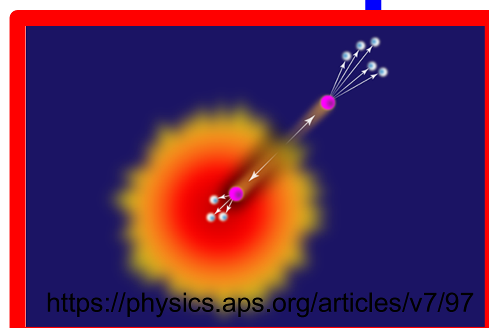


The phase transition in the laboratory



Hydrodynamical flow

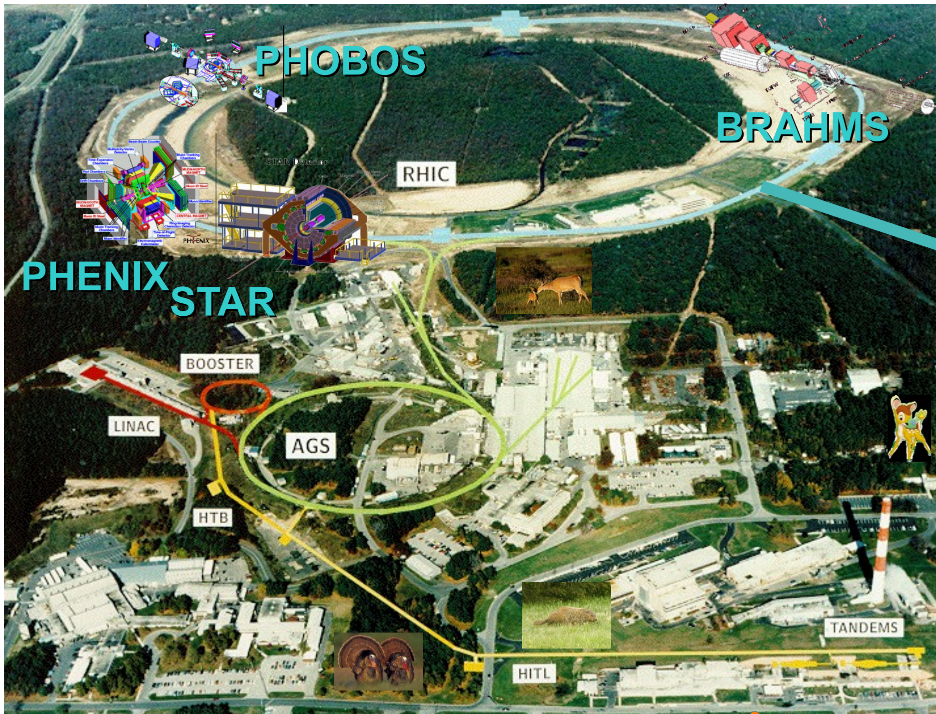


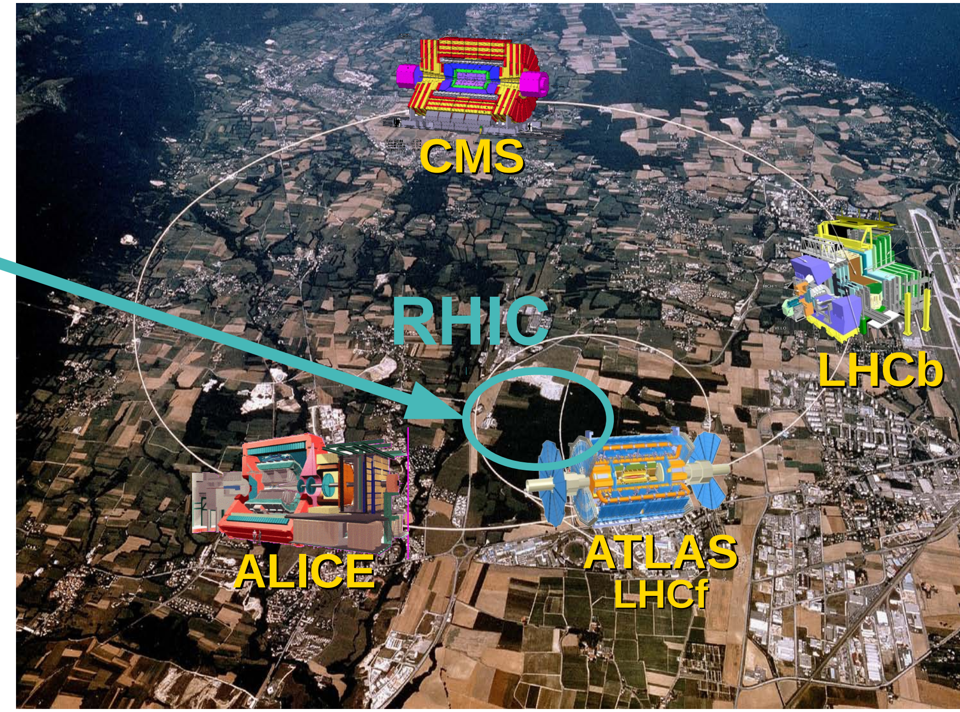


Jet quenching

Relativistic Heavy Ion Collider

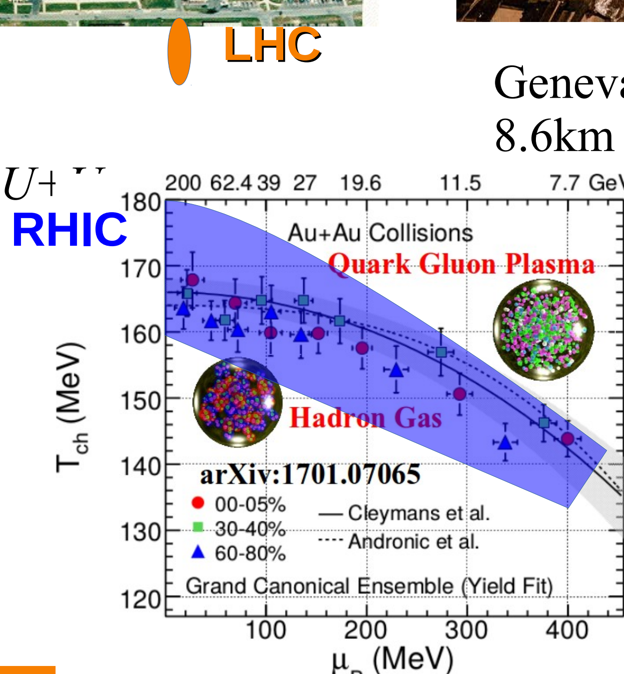
Large Hadron Collider



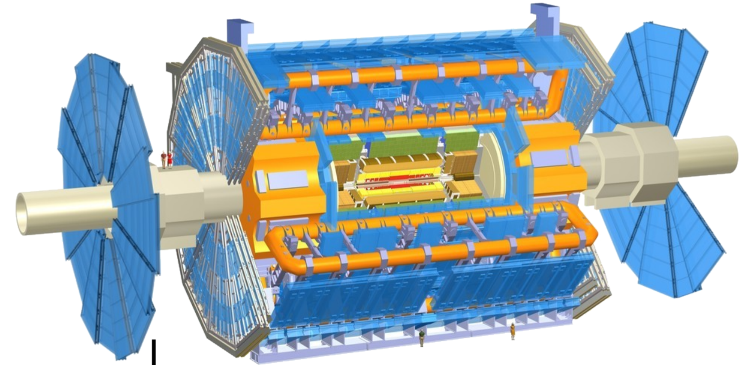


Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

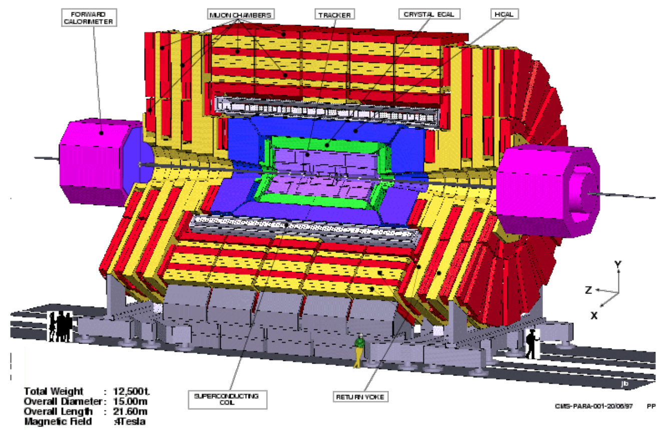
Geneva, Switzerland
8.6km diameter
+Pb, Pb+Pb
2.76 GeV, *5.5 TeV*



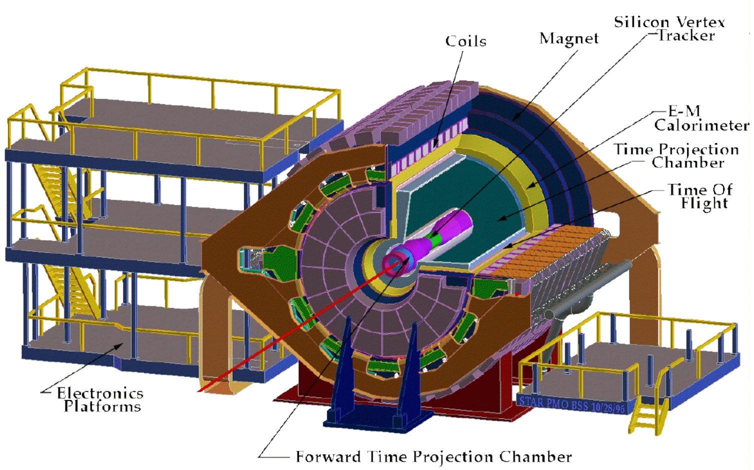
ALICE



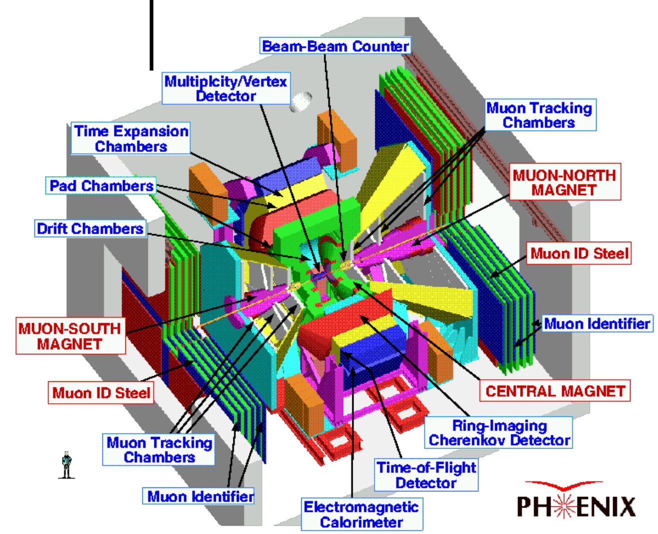
ATLAS



CMS

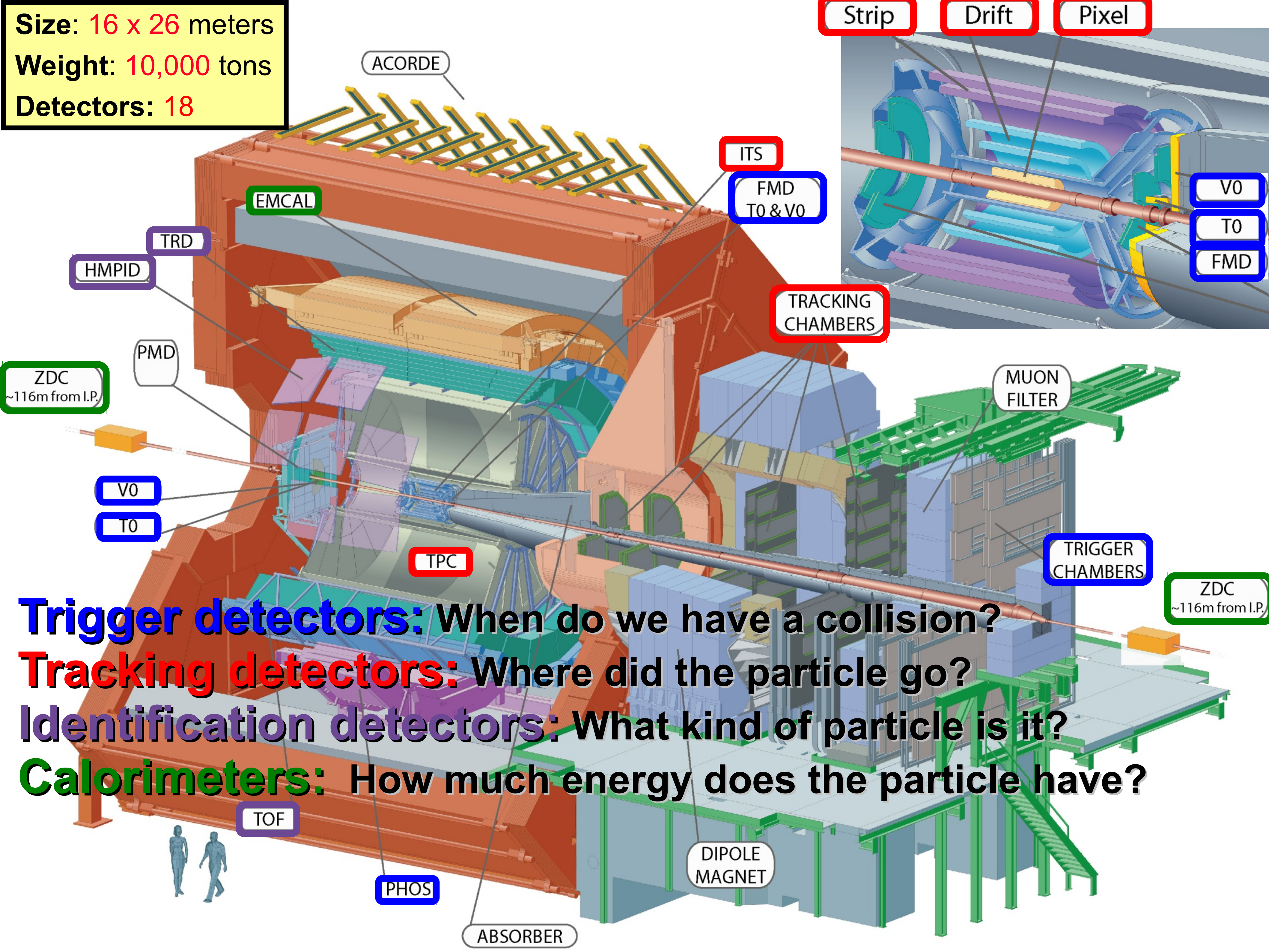


STAR



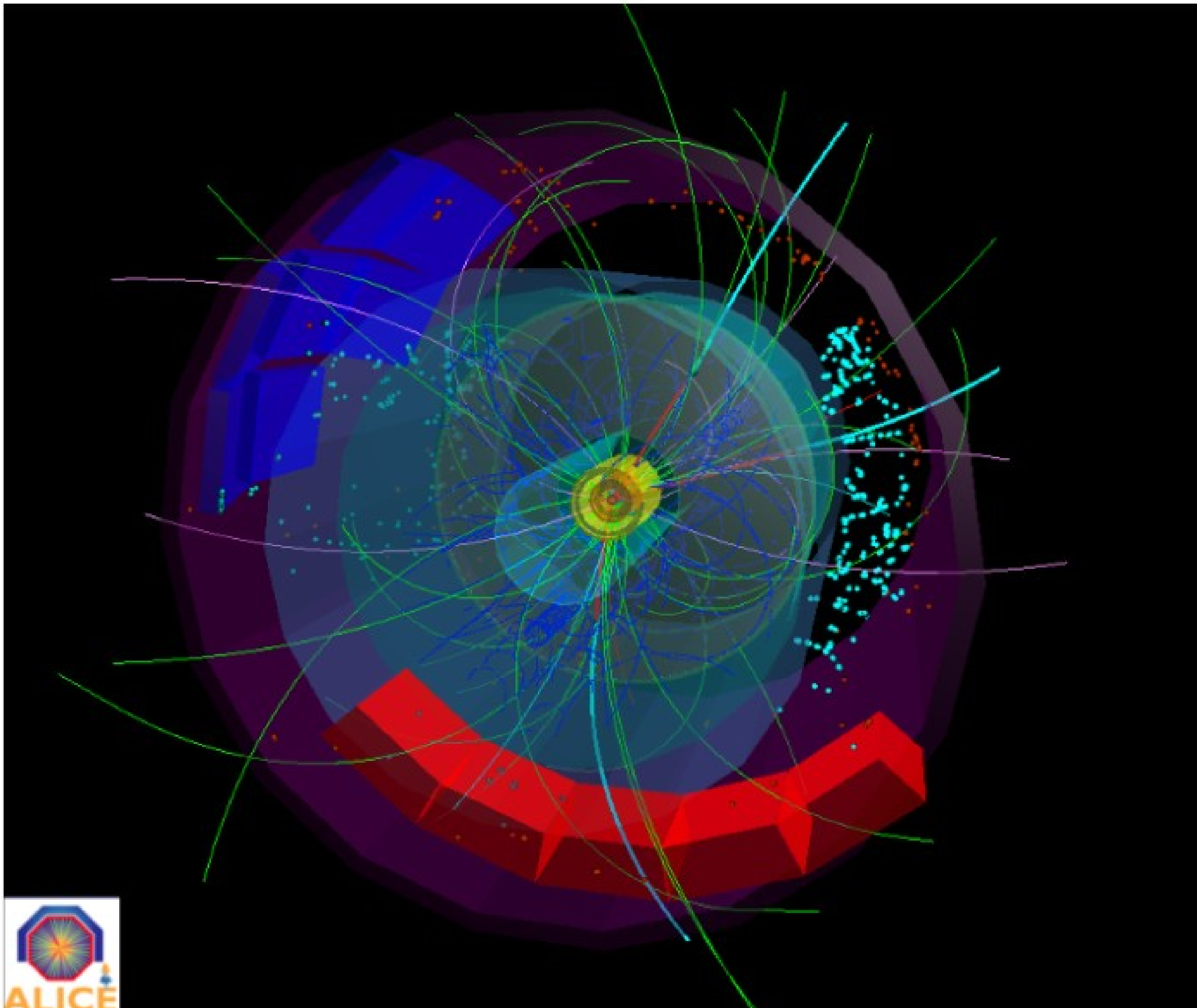
PHENIX

Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18



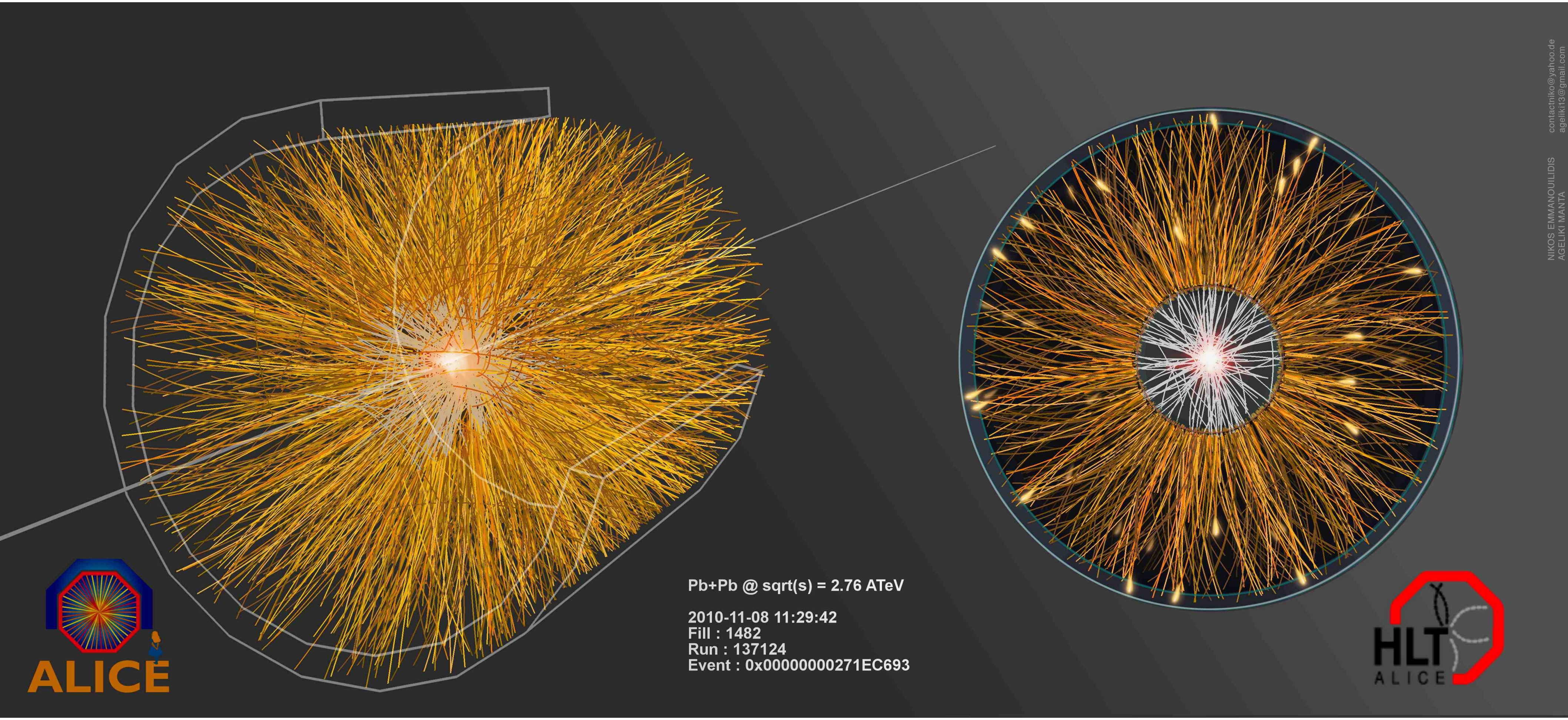
Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?

p+p collisions



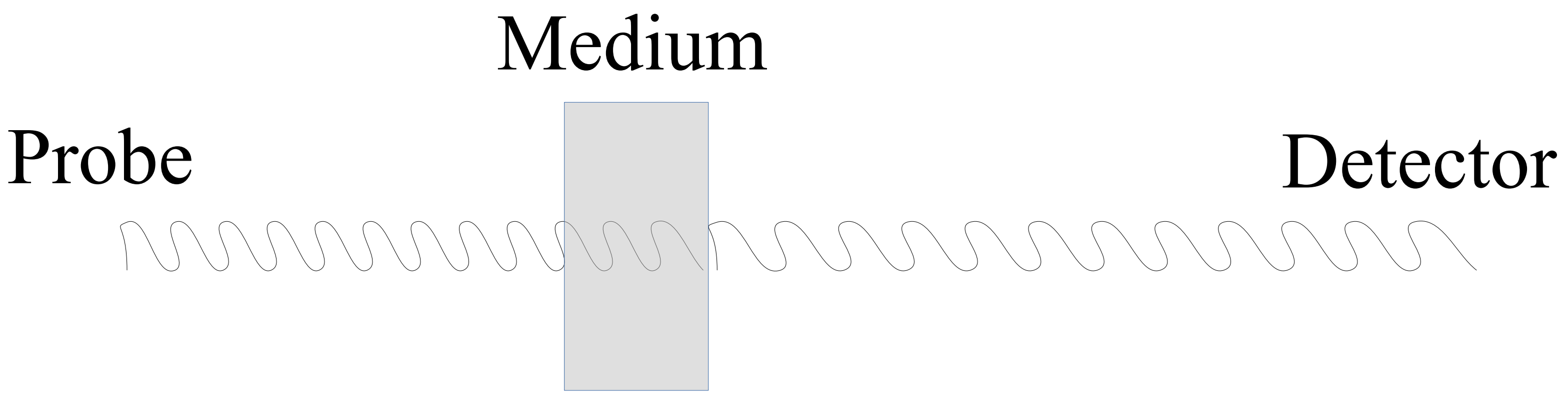
3D image of each collision

Pb+Pb collisions



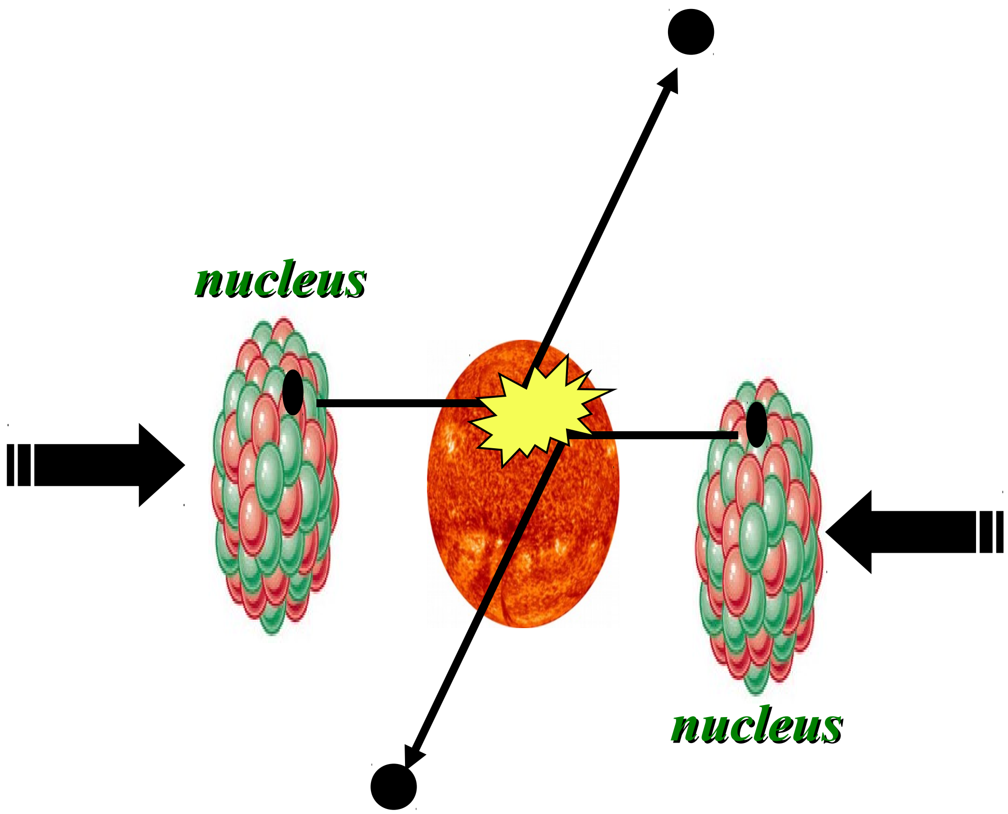
QGP Spectroscopy

Probing the Quark Gluon Plasma



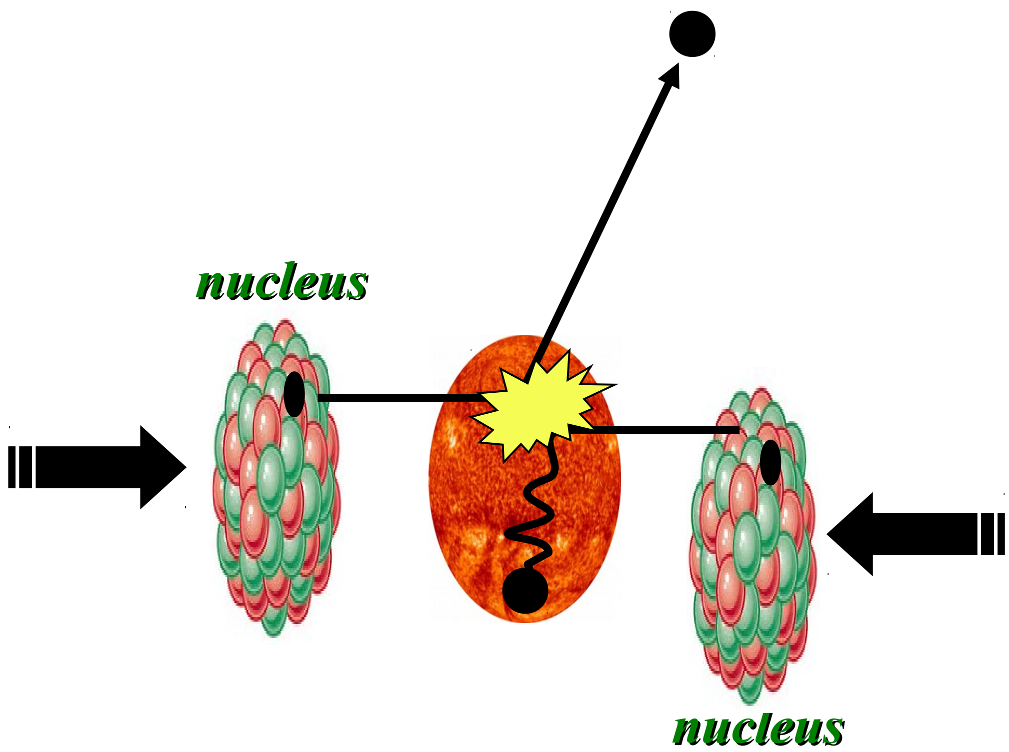
Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



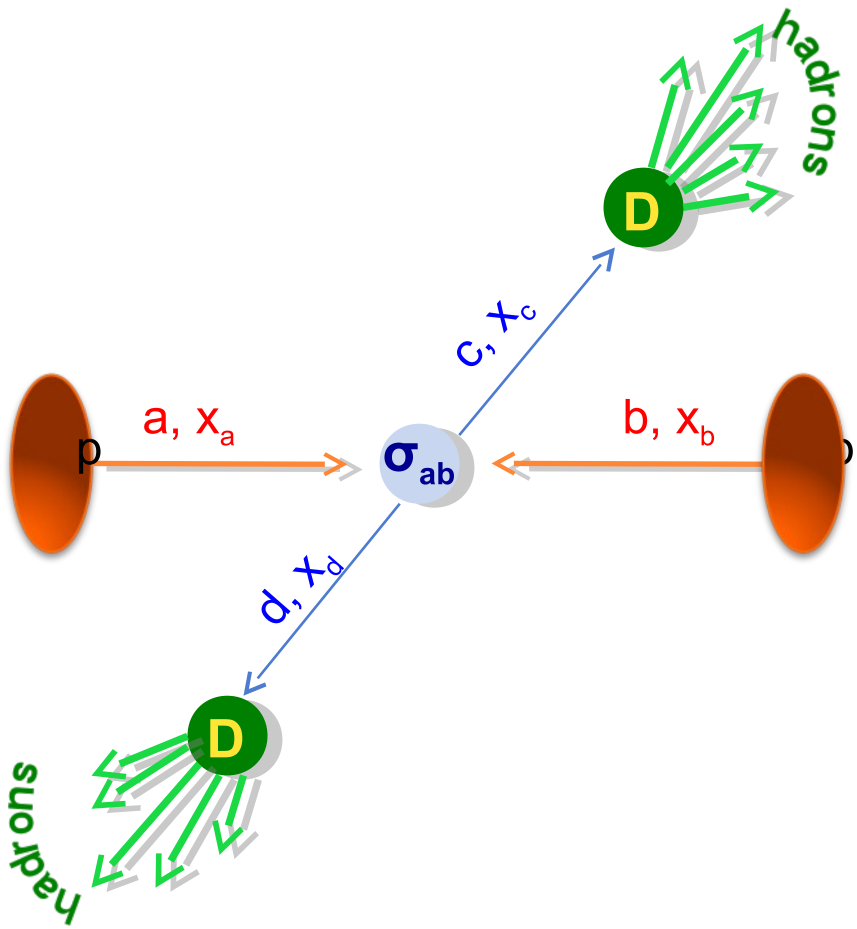
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

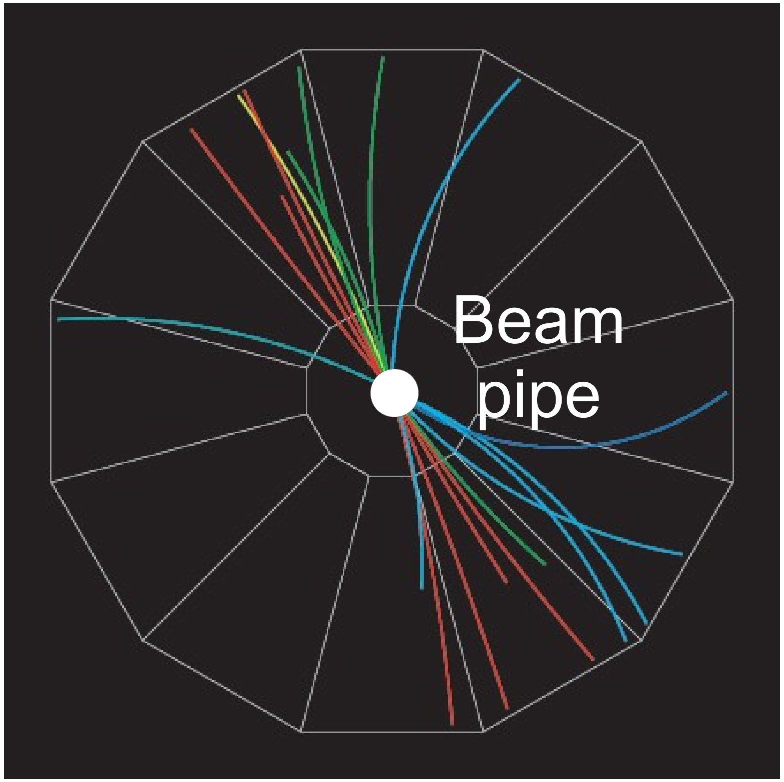


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets



p+p → dijet

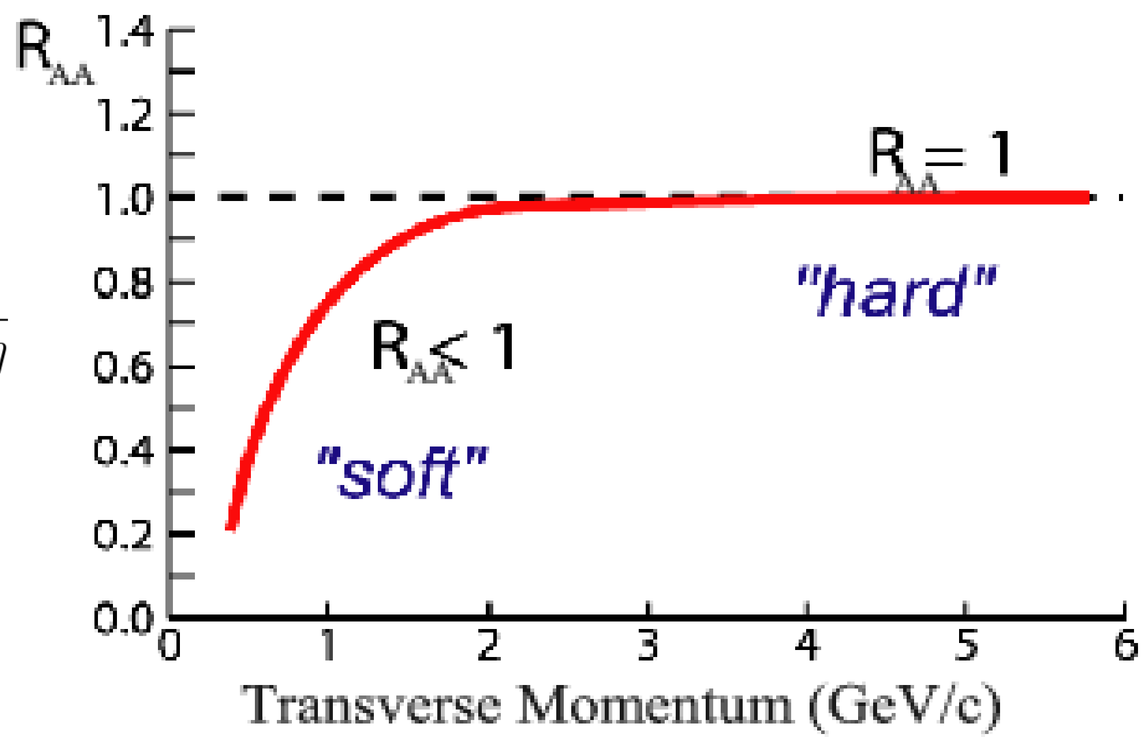


Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

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

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



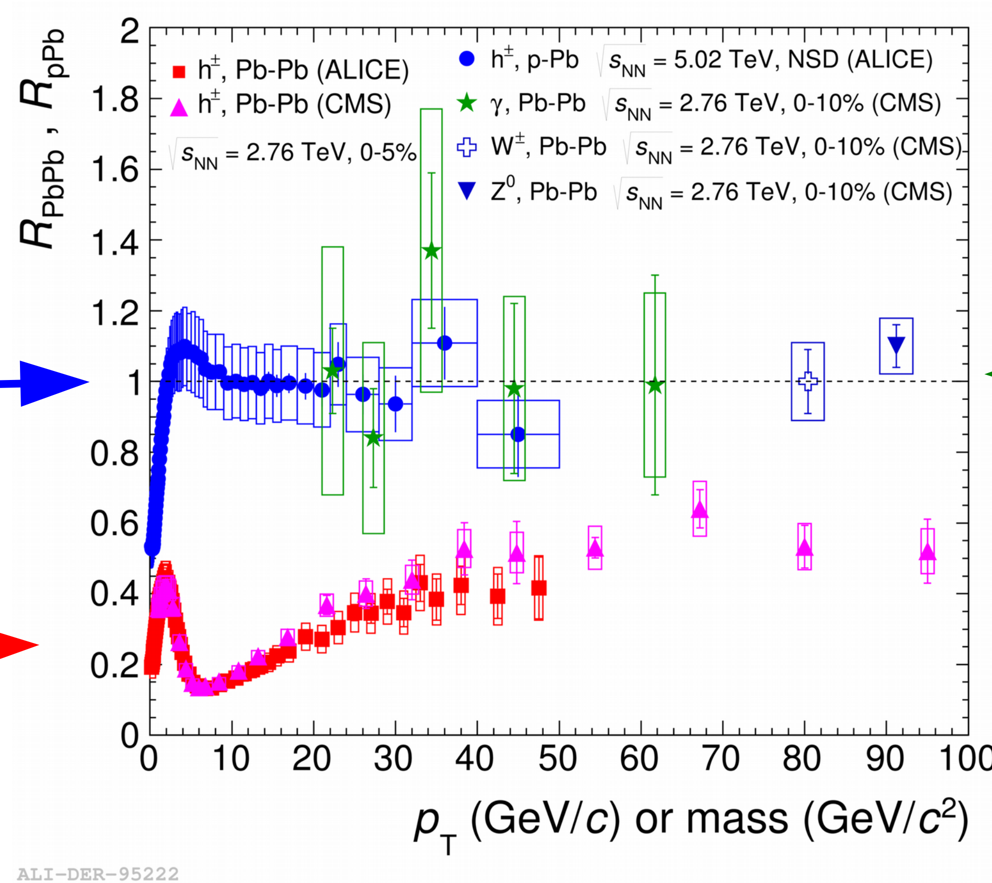
Enhancement

Suppression

Nuclear modification factor

Control

Probe

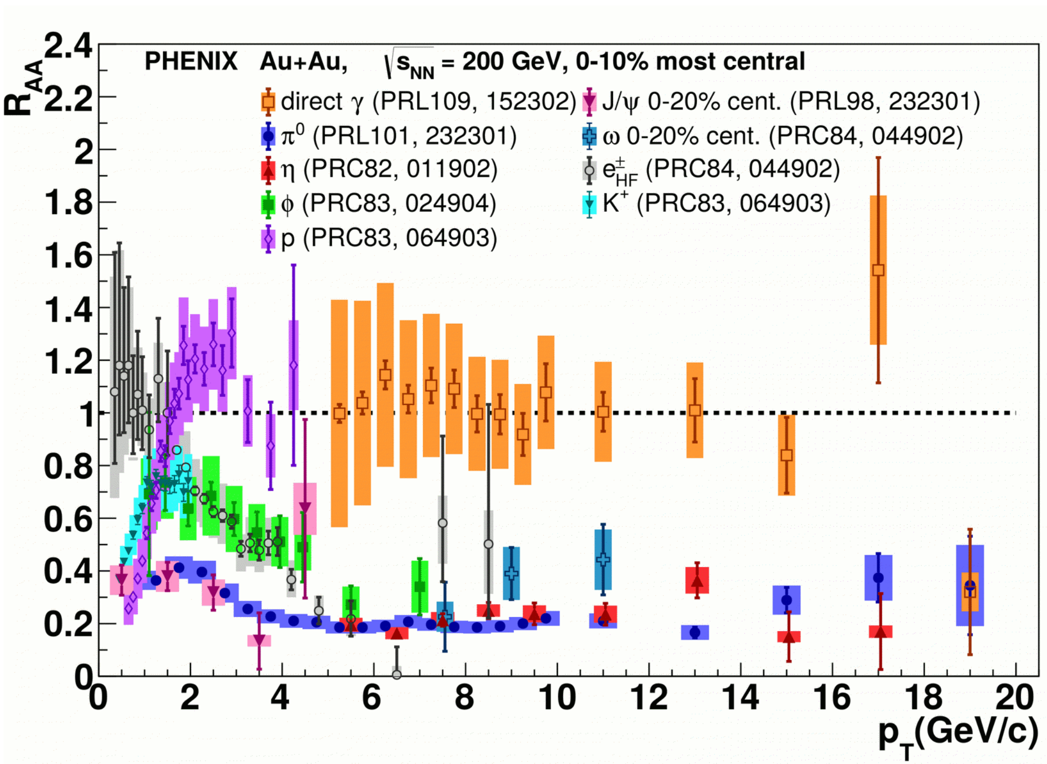


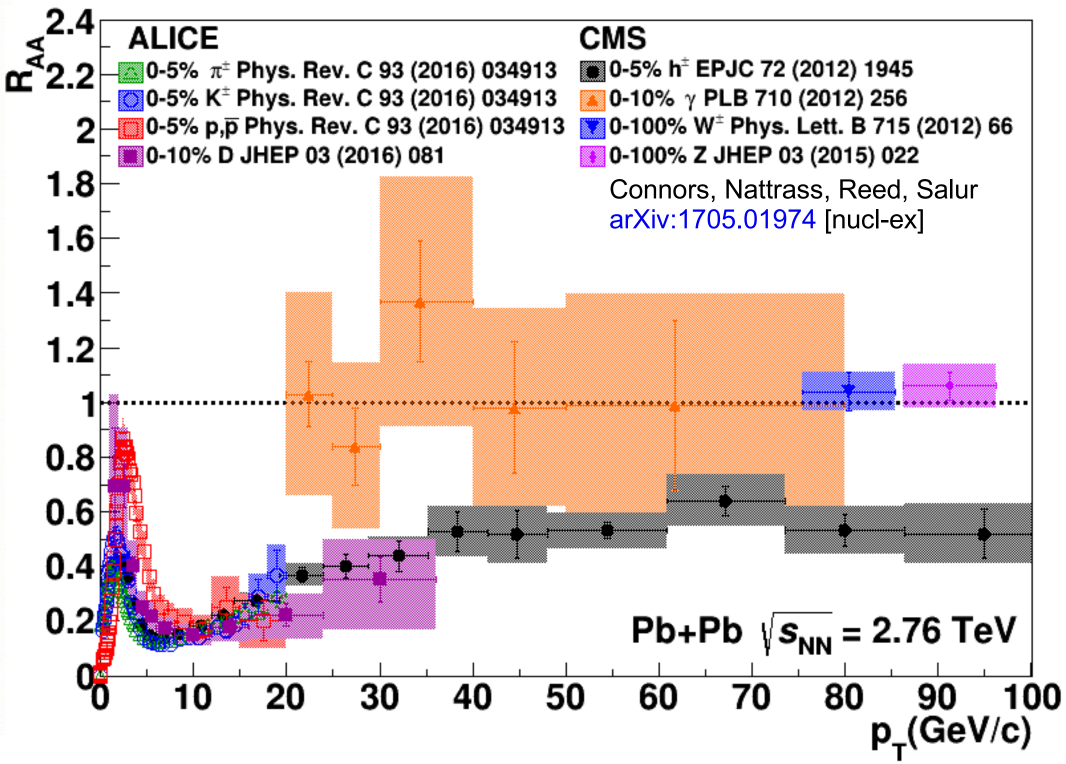
Control

- 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}

RHIC **LHC**

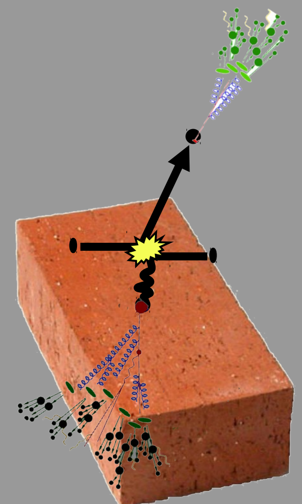




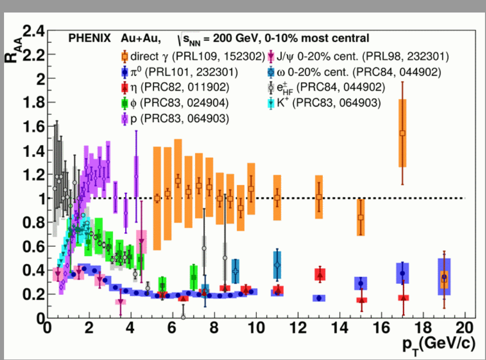
- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them - even heavy quarks!

JET collaboration

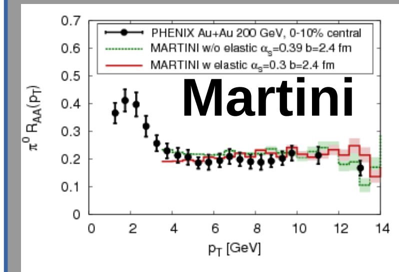
Phys. Rev. C 90, 014909 (2014)

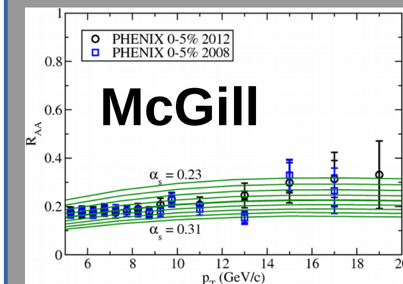


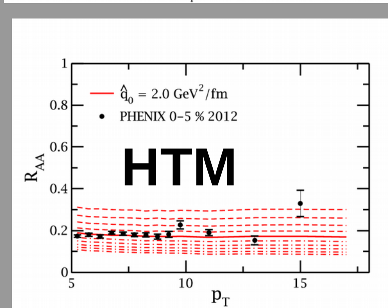
QGP brick + jet

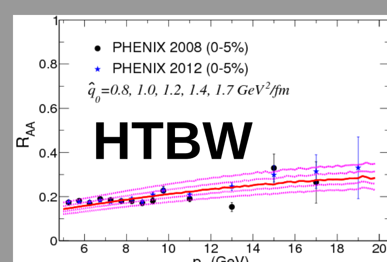


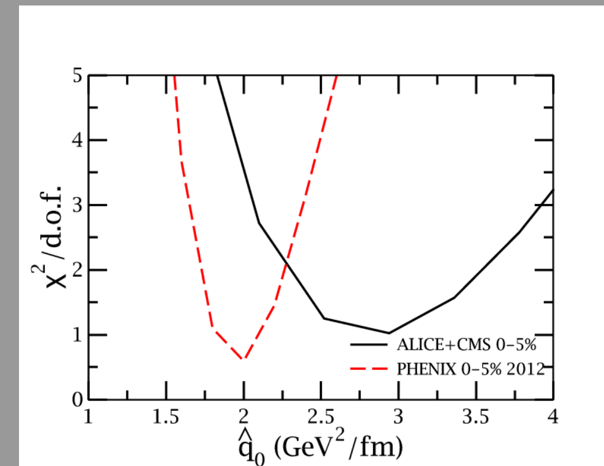
Data



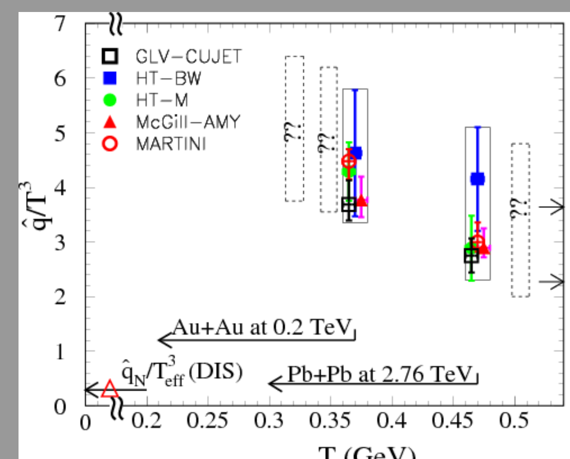








χ^2 *minimization*

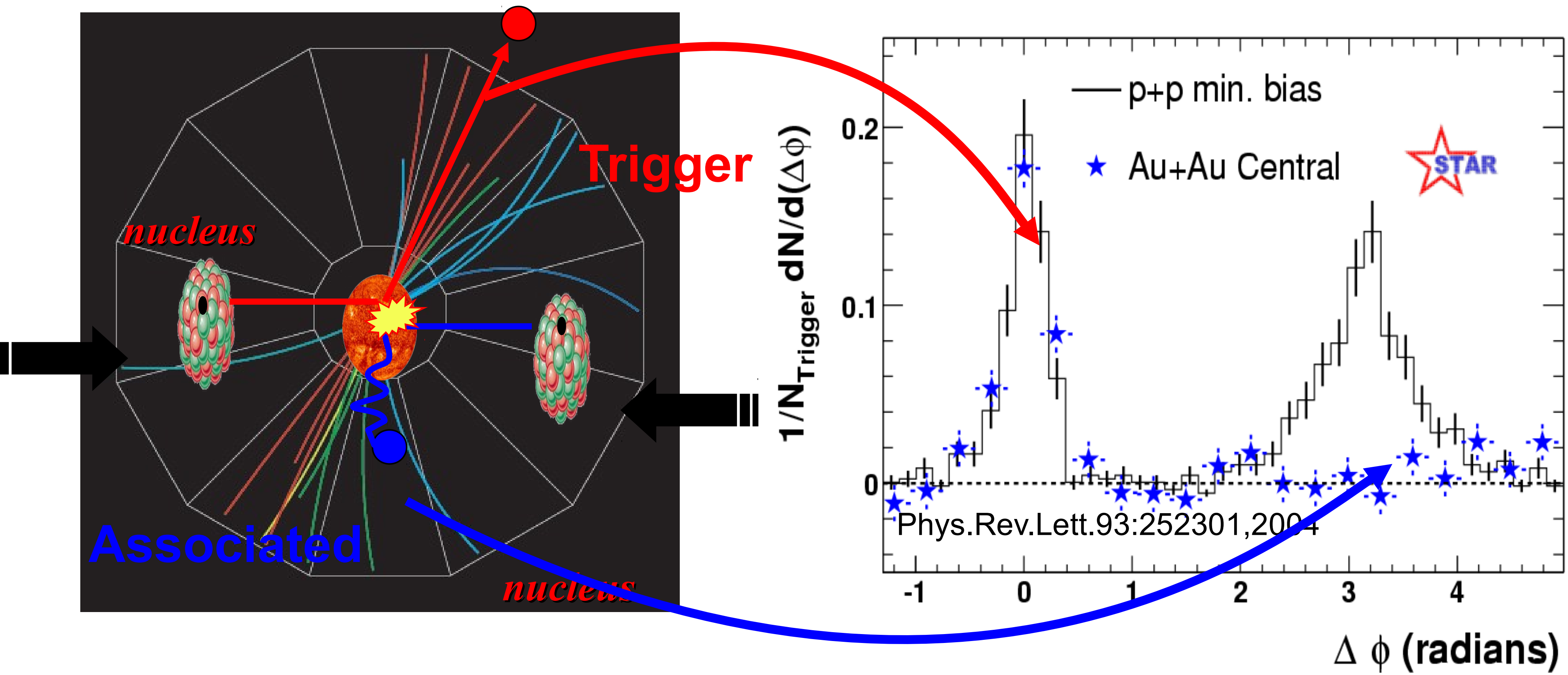


$\hat{q}=1.2\pm0.3\ \ GeV^2$ 200 GeV Au+Au

$\hat{q}=1.9\pm0.7\ \ GeV^2$ 2.76 TeV Pb+Pb

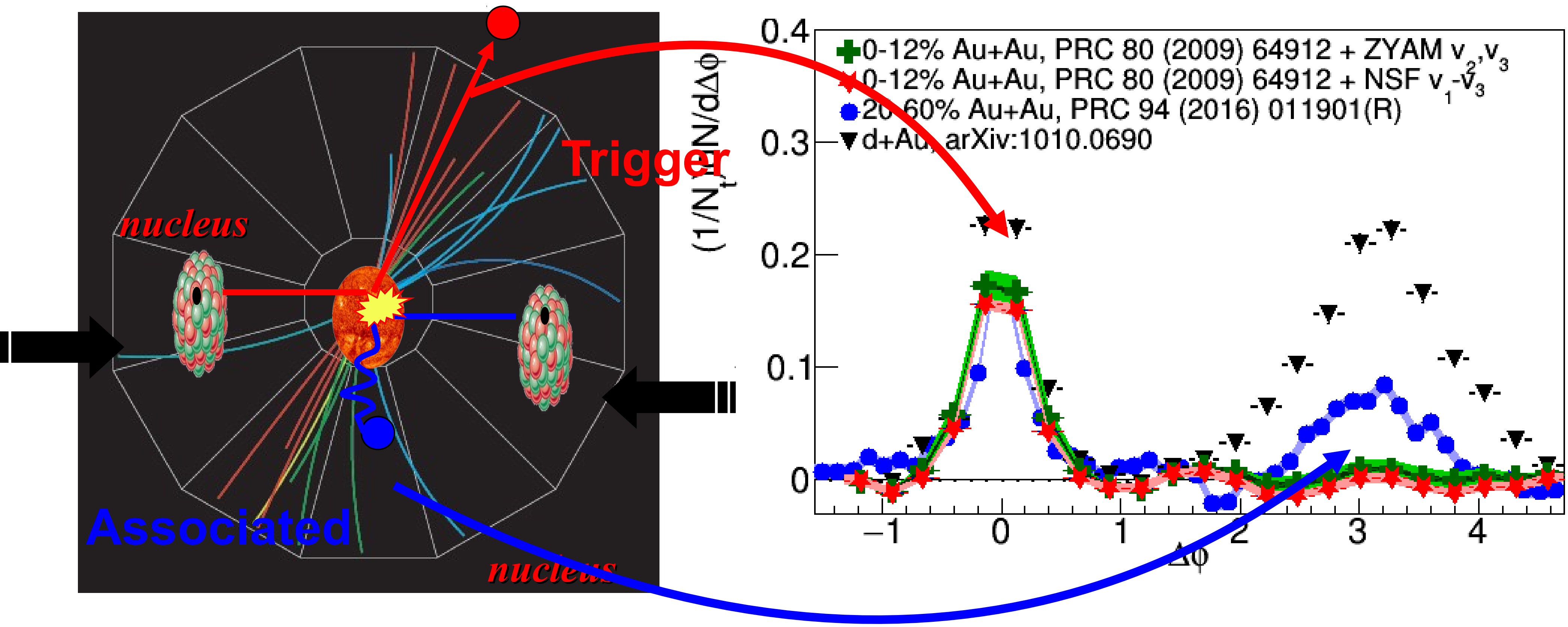
Di-hadron correlations

p+p → dijet

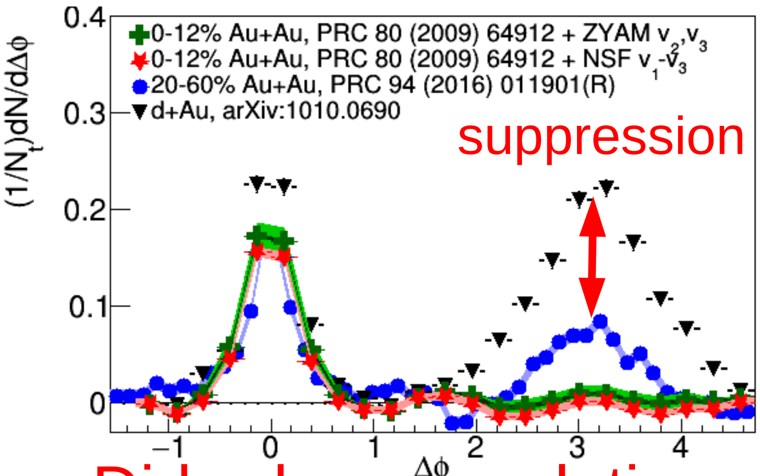


Di-hadron correlations

p+p → dijet



Updated to include latest information about background

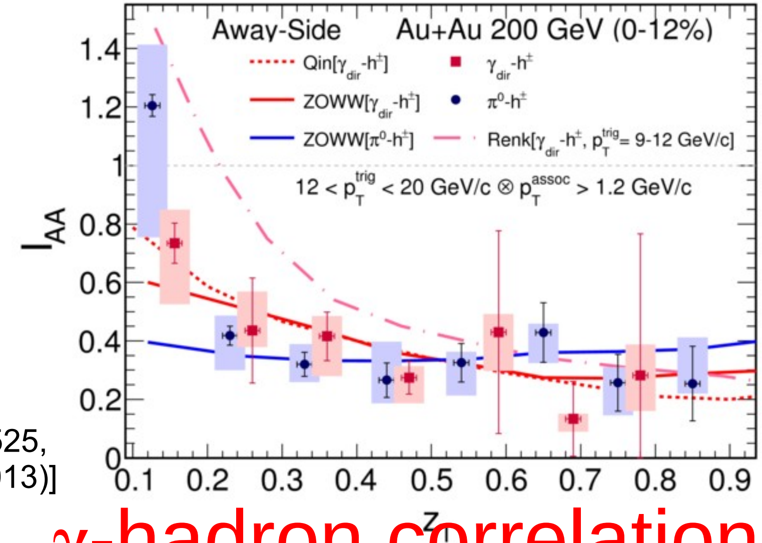


Di-hadron correlations

[Too many to list]

Jet v_2

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



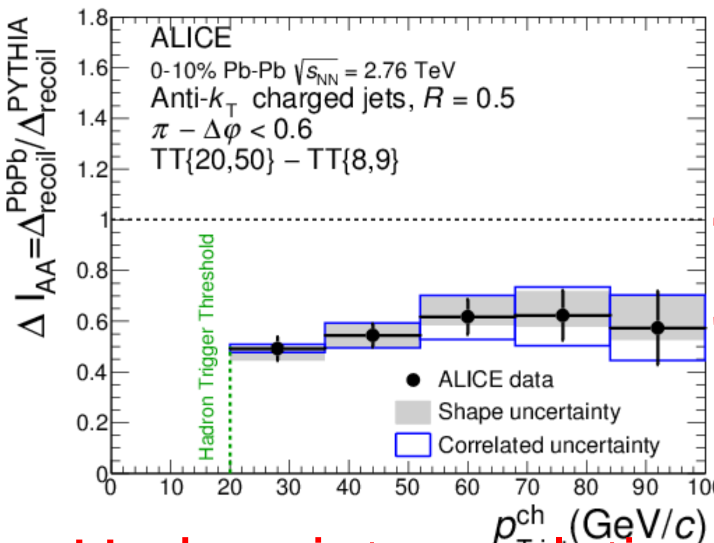
suppression

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

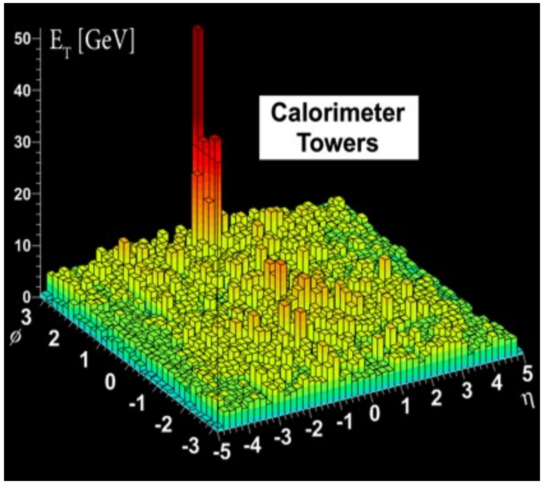
[Phys. Lett. B 718 (2013) 773]



suppression

High-p_T hadron v_2

[too many to list]



Hadron-jet correlations

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

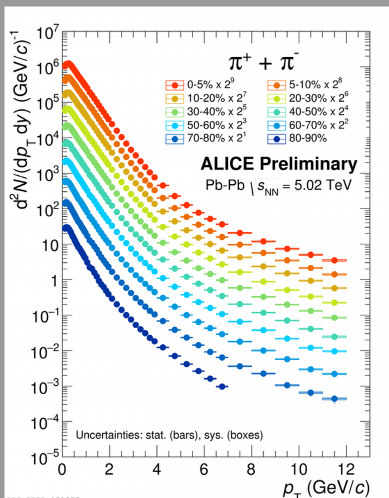
Dijet asymmetry

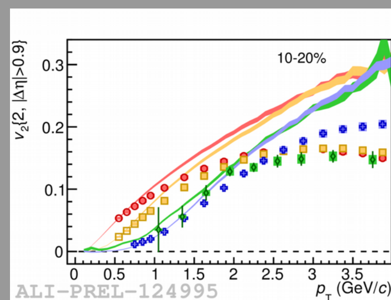
[Phys.Rev.C84:024906,2011, Phys. Lett. B 712 (2012) 176, Phys.Rev.Lett.105:252303,2010, Phys. Rev. Lett. 119, 062301 (2017)]

Bayesian Statistical Analysis

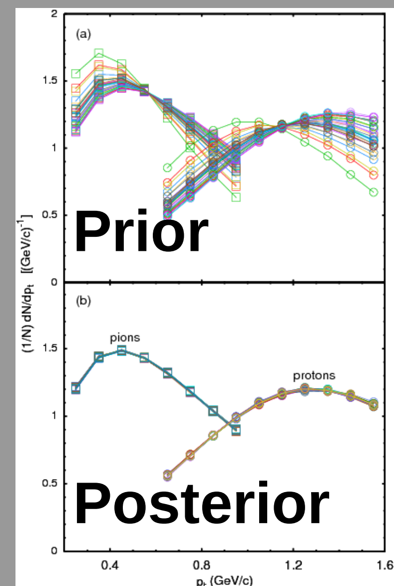
Models and Data Analysis Initiative

http://madai.us

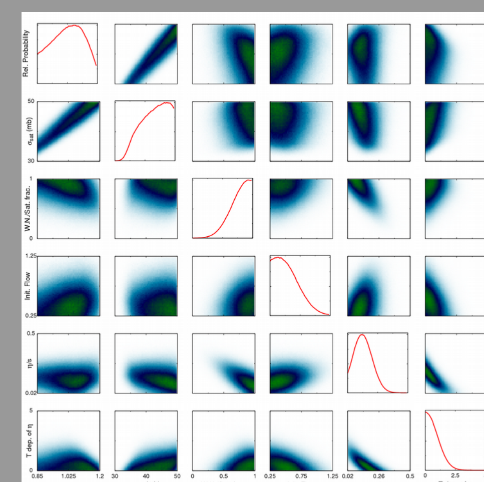




Data



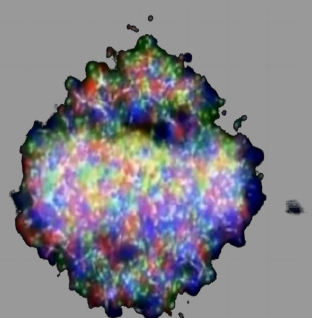
Optimization



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

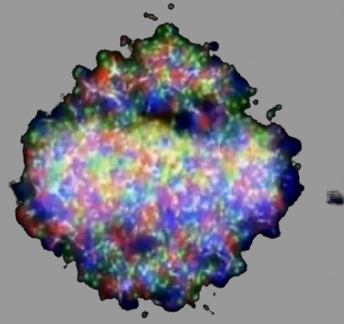
JETSCAPE

Event generator

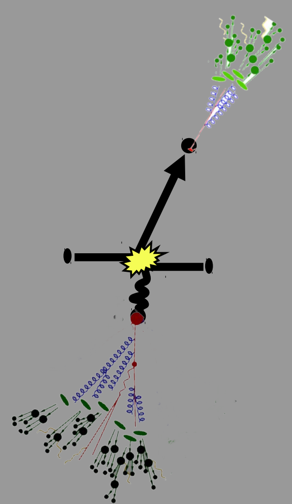
Jet **E**nergy-loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelope

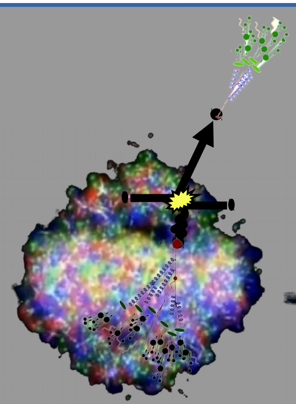
http://jetscape.wayne.edu/

Realistic medium



Realistic jets





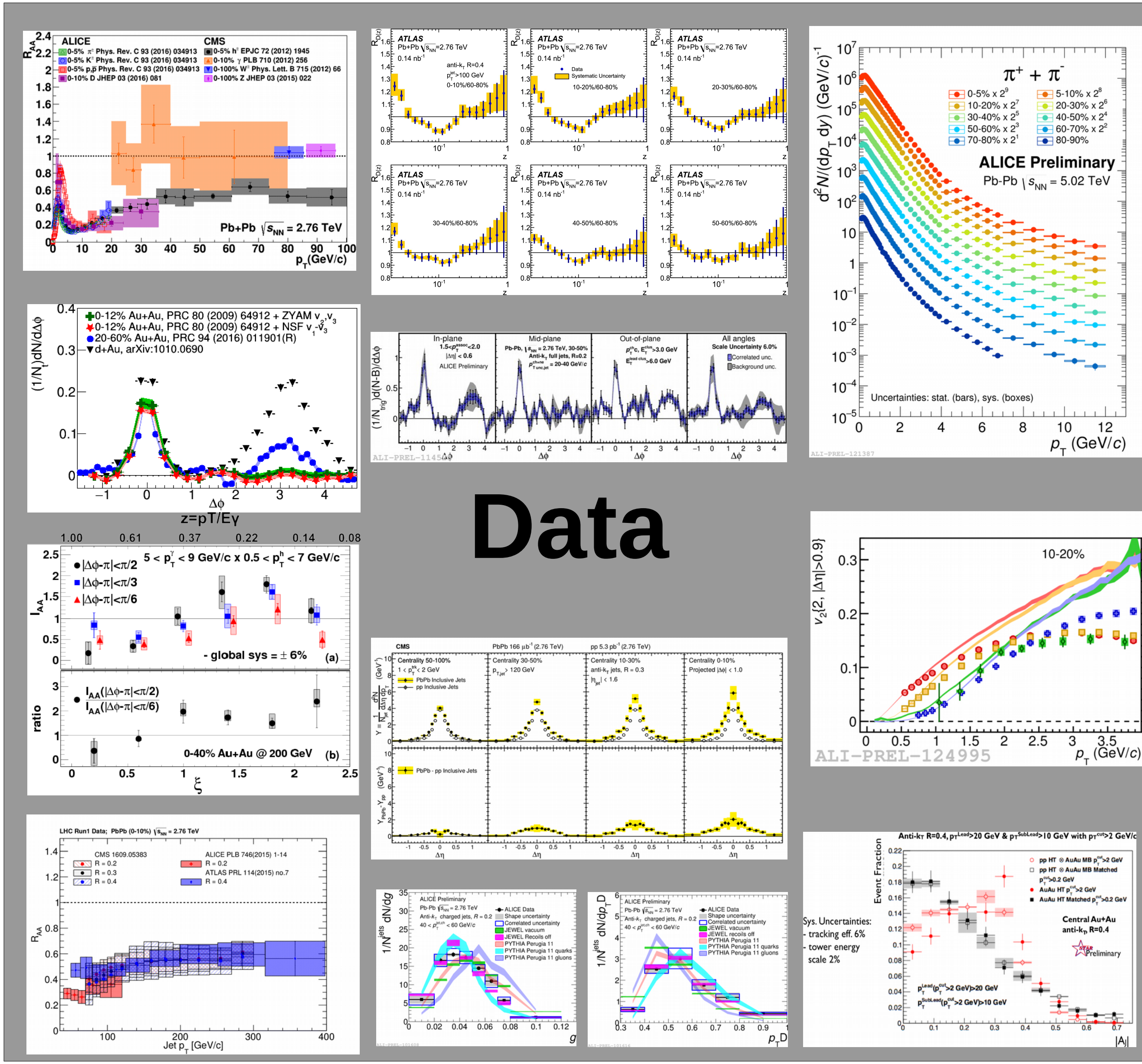
Realistic Monte Carlo Model

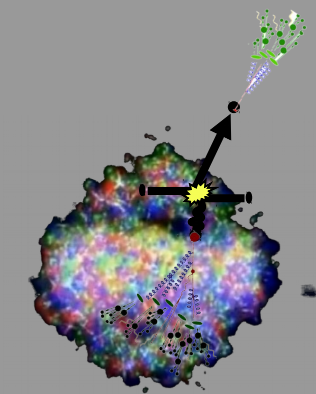
Experimental techniques

Realistic theoretical calculations

JETSCAPE

Event Generator + Bayesian Statistical analysis





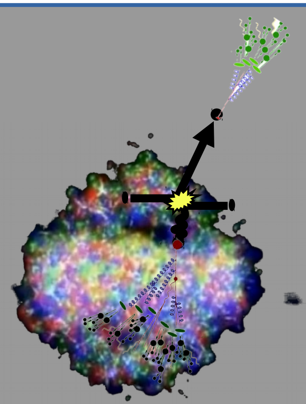
Realistic theoretical calculations

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

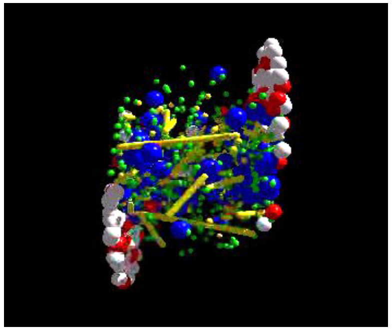
UTK JETSCAPE Group

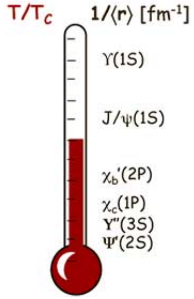
James Neuhaus
Jerrica Wilson
Mariah McCreary
Ricardo Santos (Berea)
Austin Schmier
4 undergrads + 1 beginning grad student
Redmer Bertens (post doc)

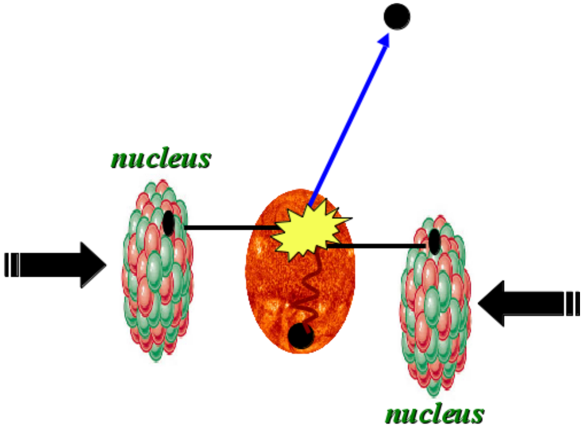
Before: 3 heavy ion analyses implemented
After: 9 heavy ion analyses, 2 more in progress

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

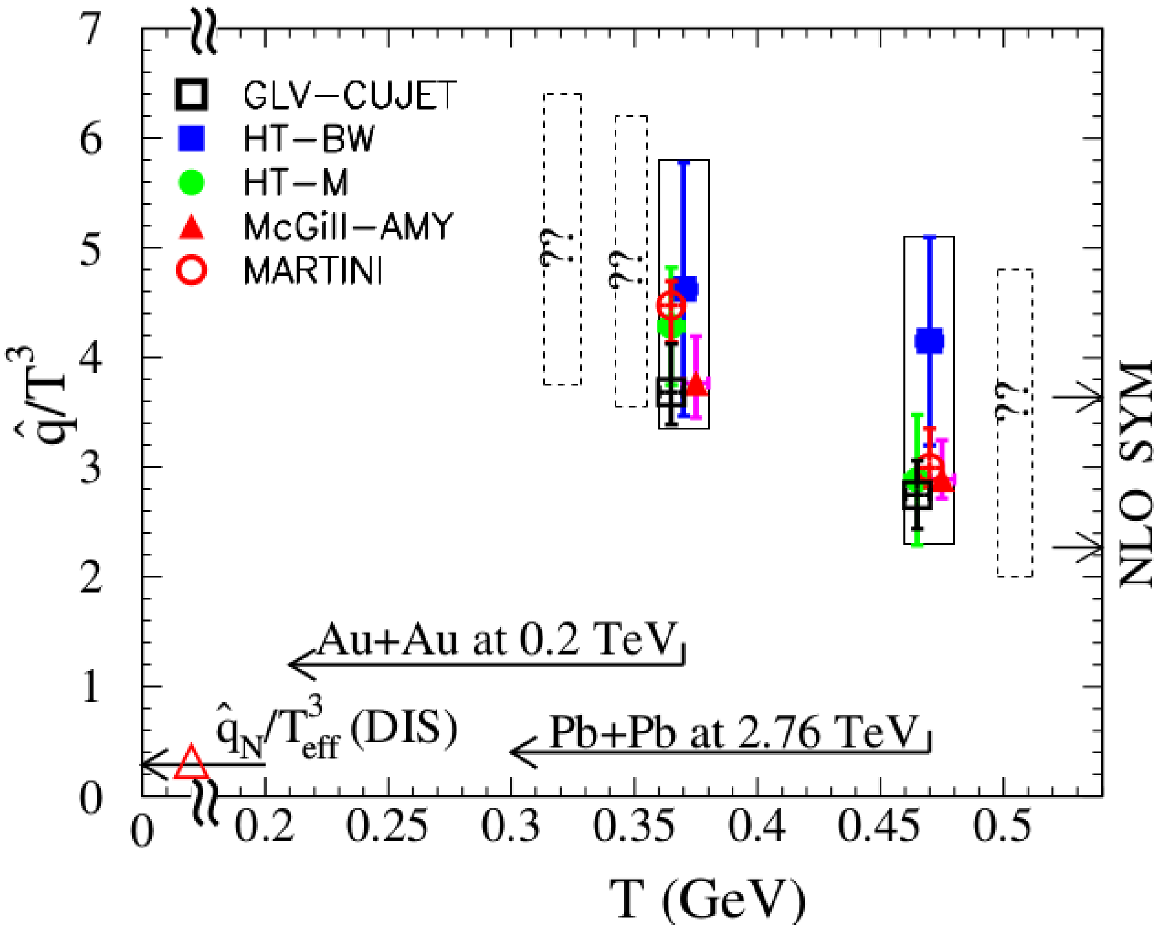
US Universities with graduate programs in experimental heavy ion physics

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

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

→ loses 2.2 Gev

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

→ loses 2.8 Gev

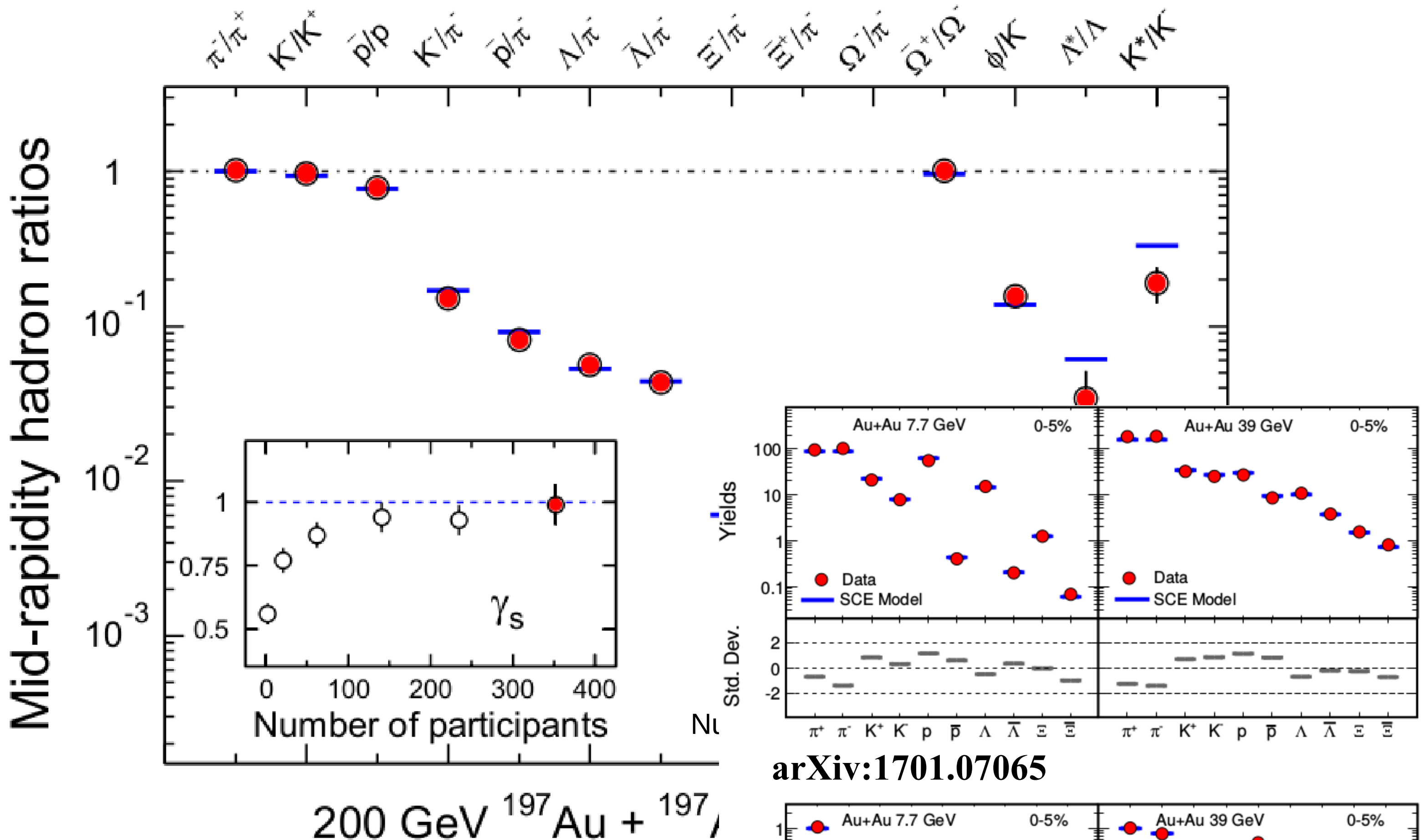
$$\hat{q} = Q^2 / L$$

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

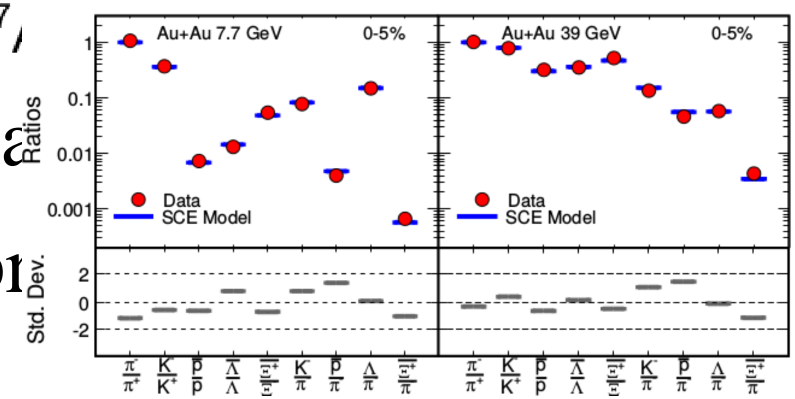
QGP Chemistry

Chemistry - equilibrium

T~170 MeV

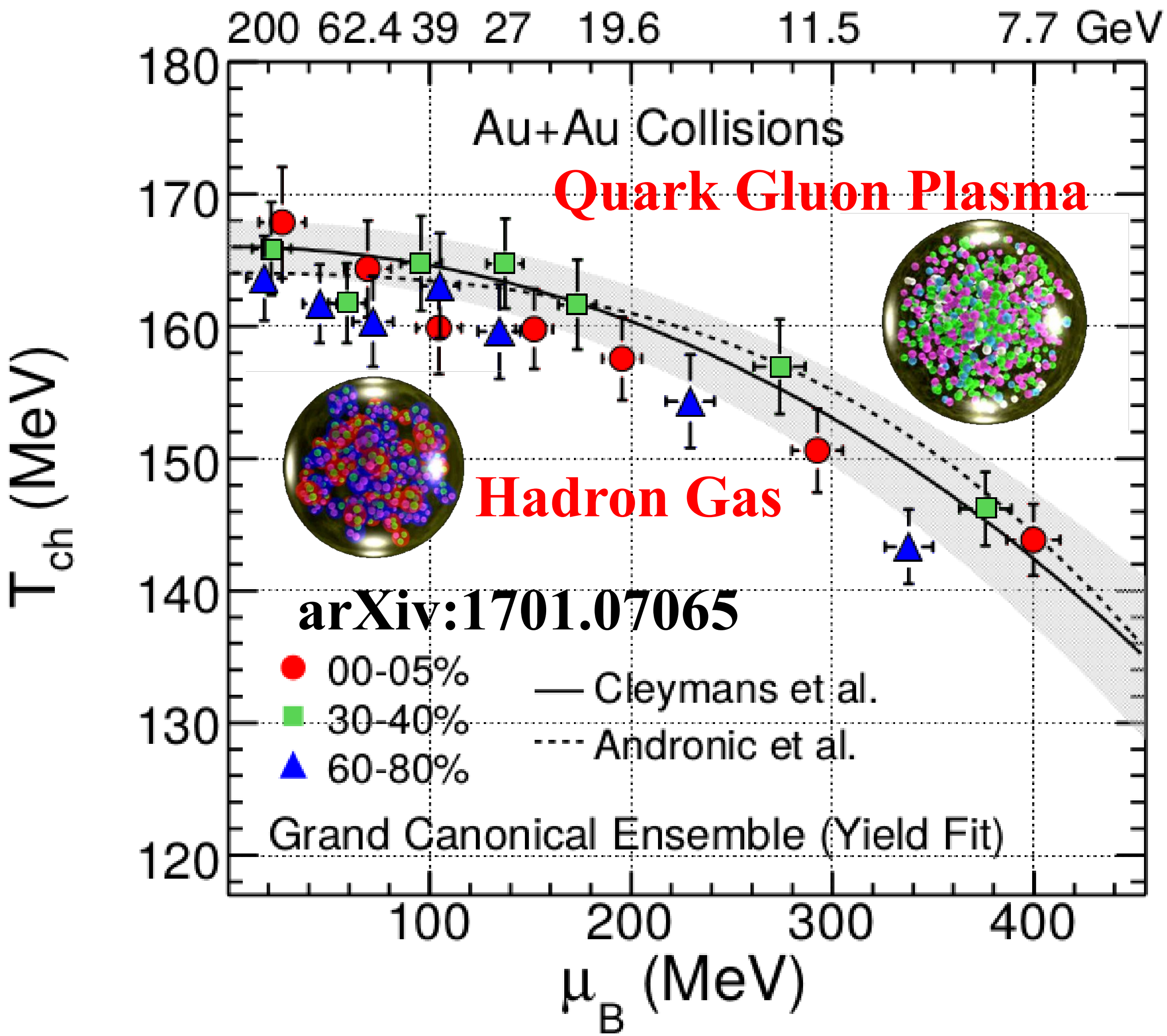


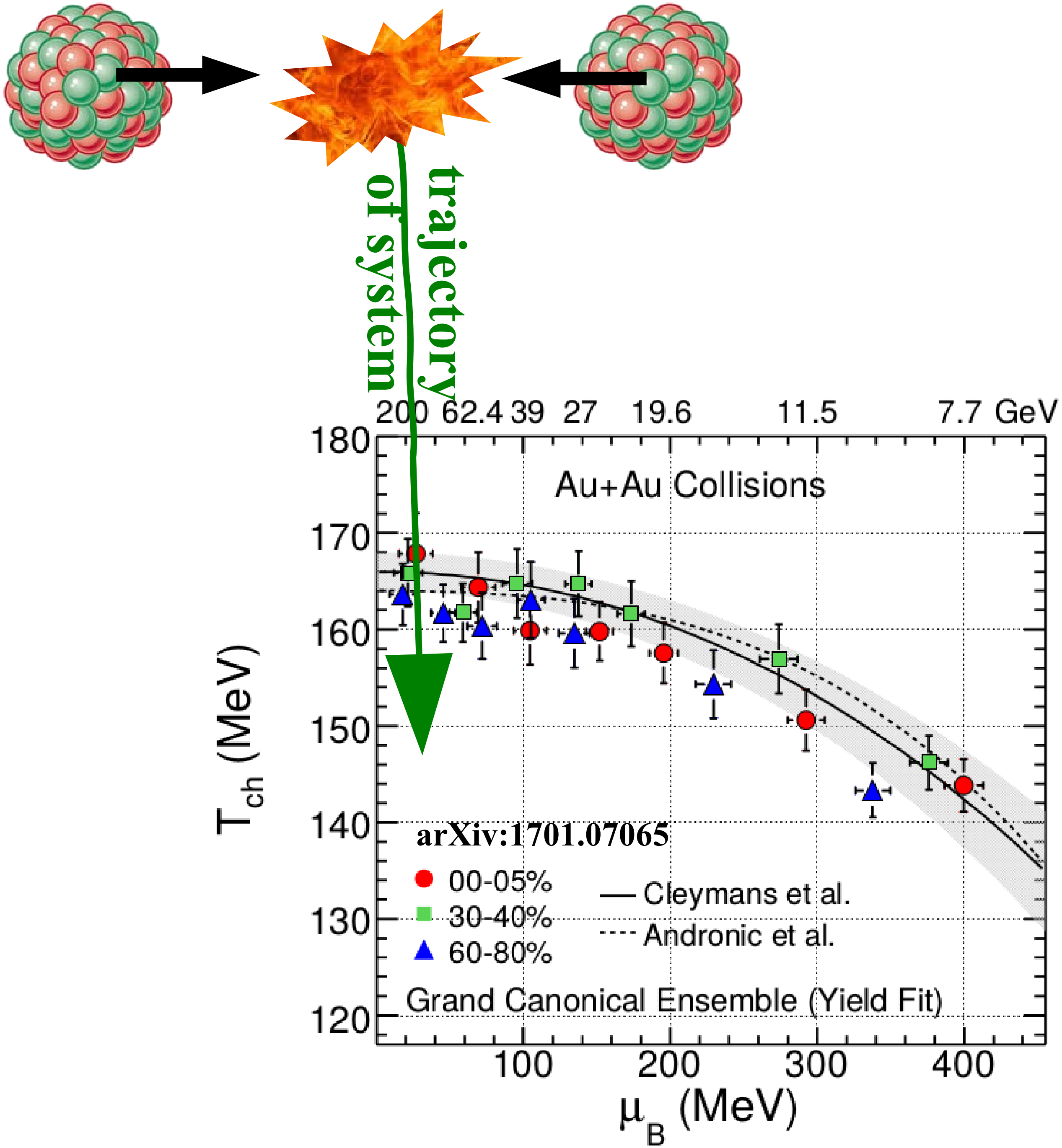
arXiv:1701.07065



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

QCD Phase Diagram

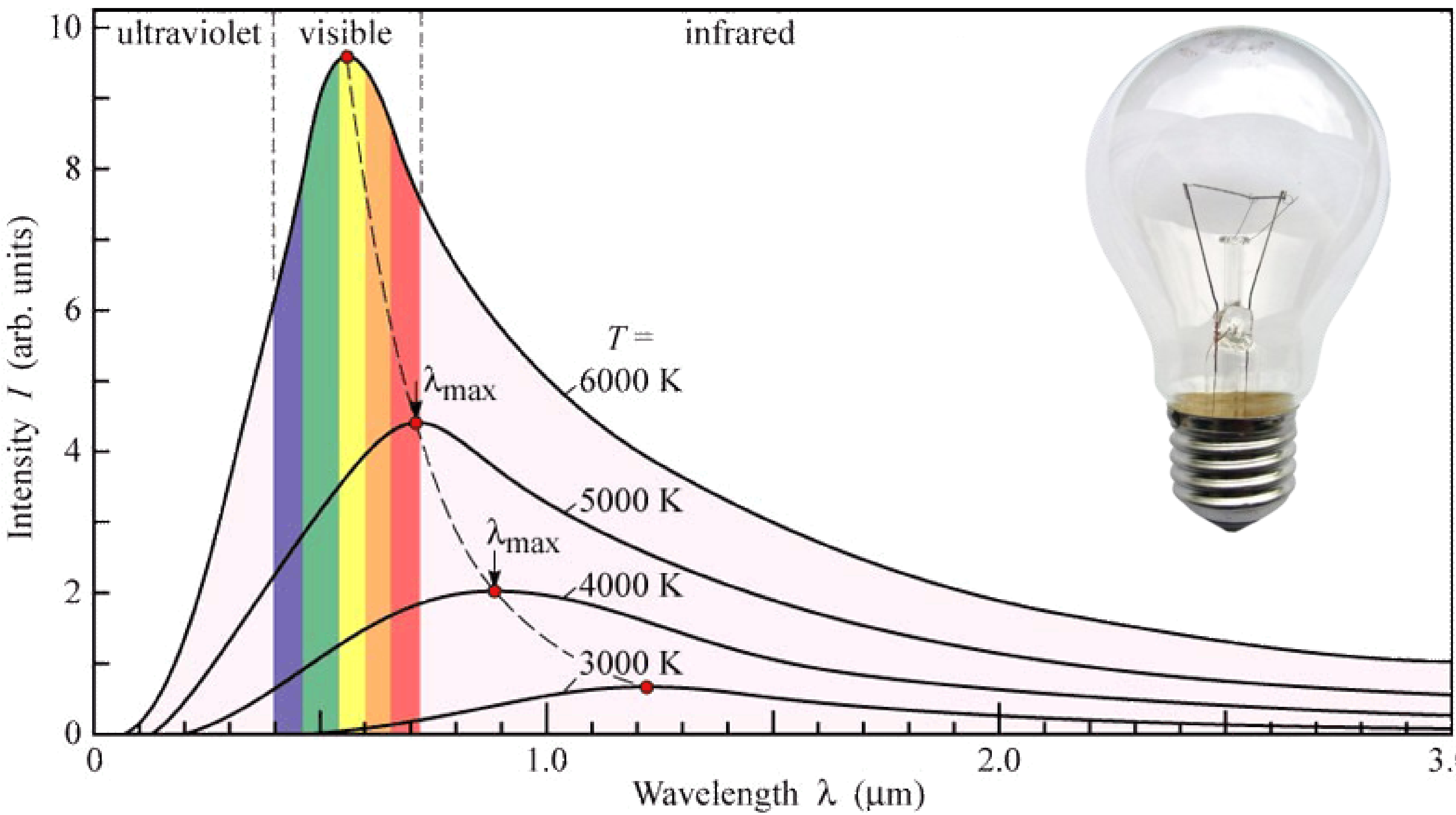




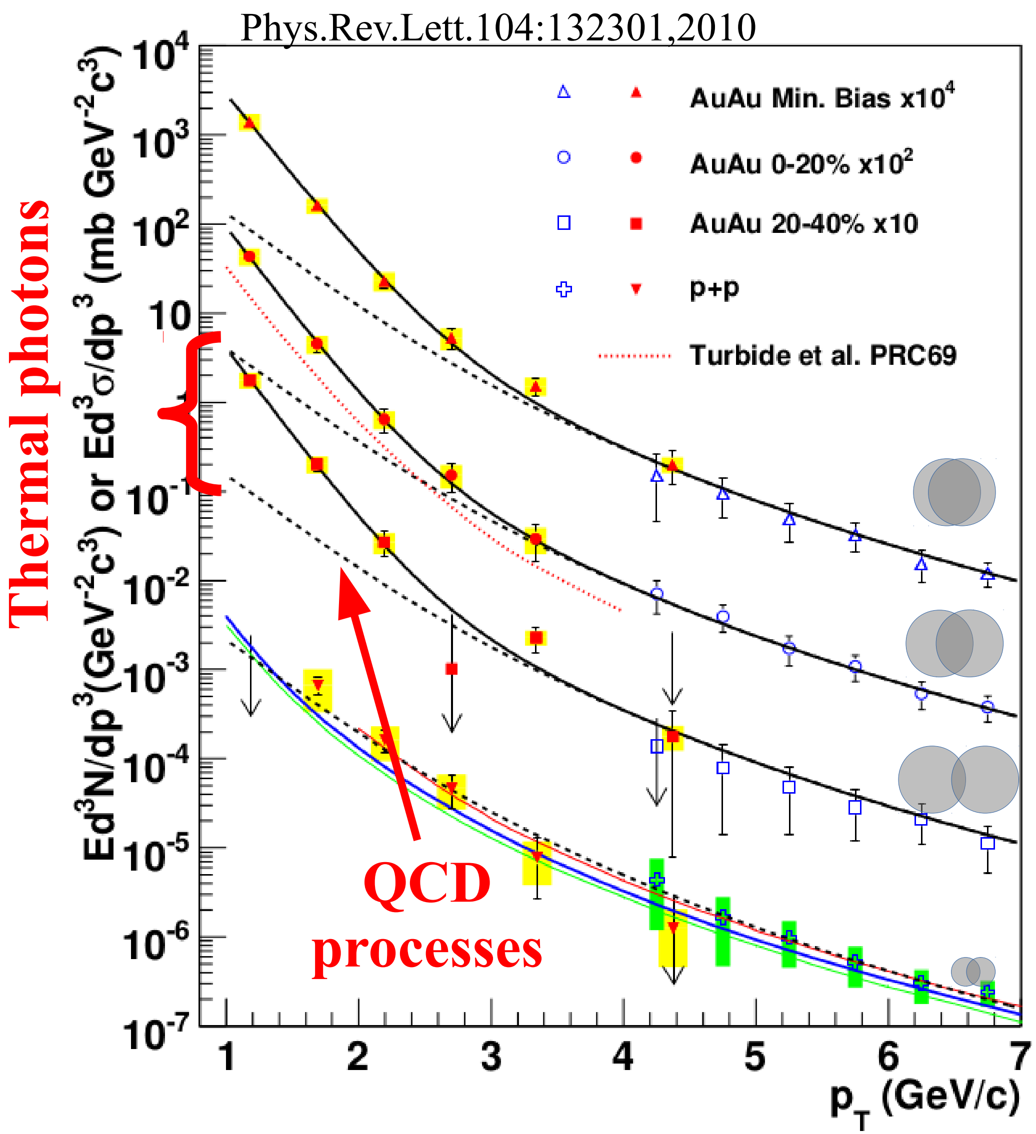
trajectory of system
200 62.4 39 27 19.6 11.5 7.7 GeV
Au+Au Collisions
arXiv:1701.07065
00-05%
30-40%
60-80%
Cleymans et al.
Andronic et al.
Grand Canonical Ensemble (Yield Fit)
T_{ch} (MeV)
μ_B (MeV)

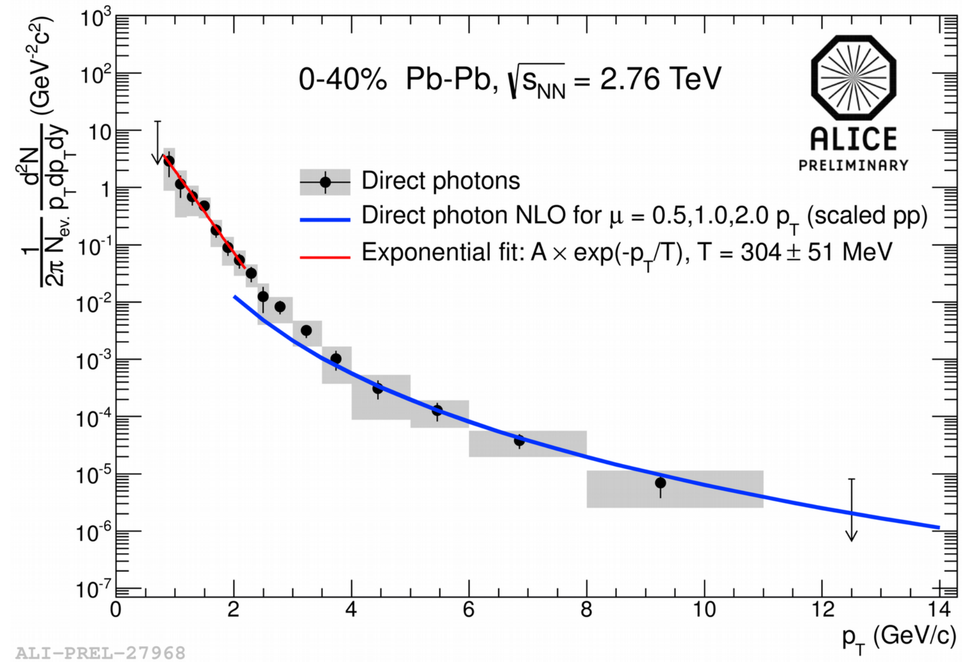
QGP Thermometers

Measuring temperature



Thermal photons



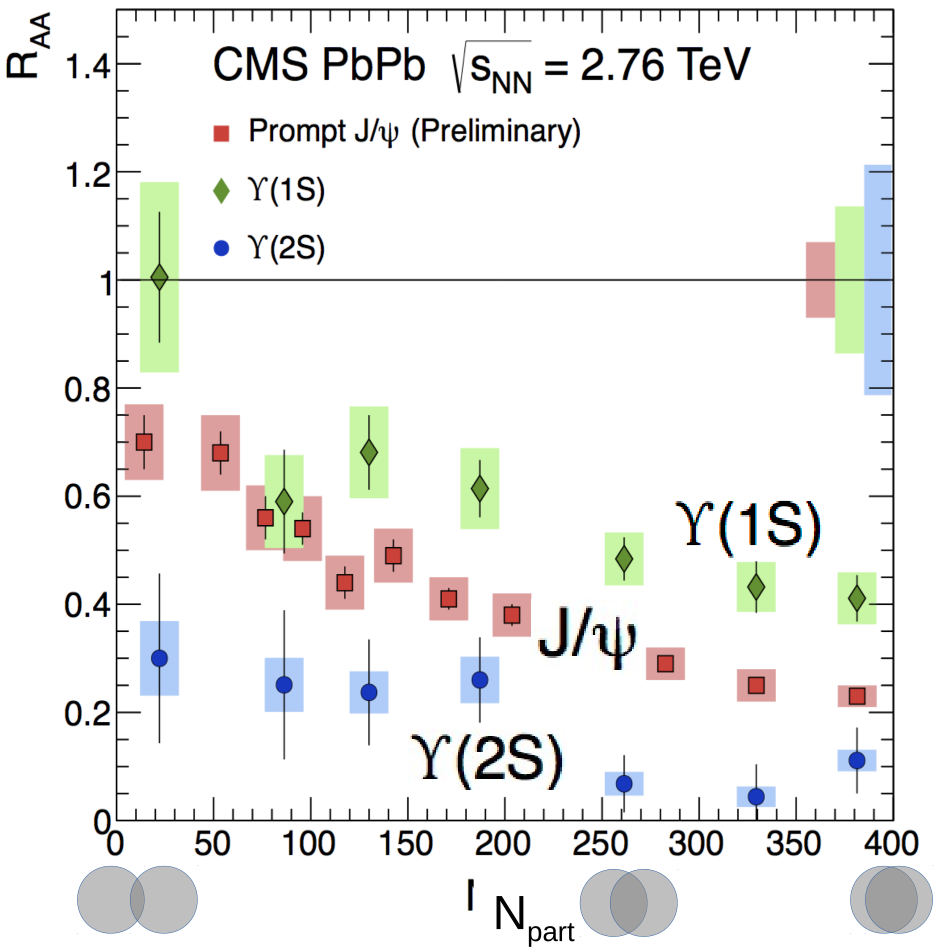


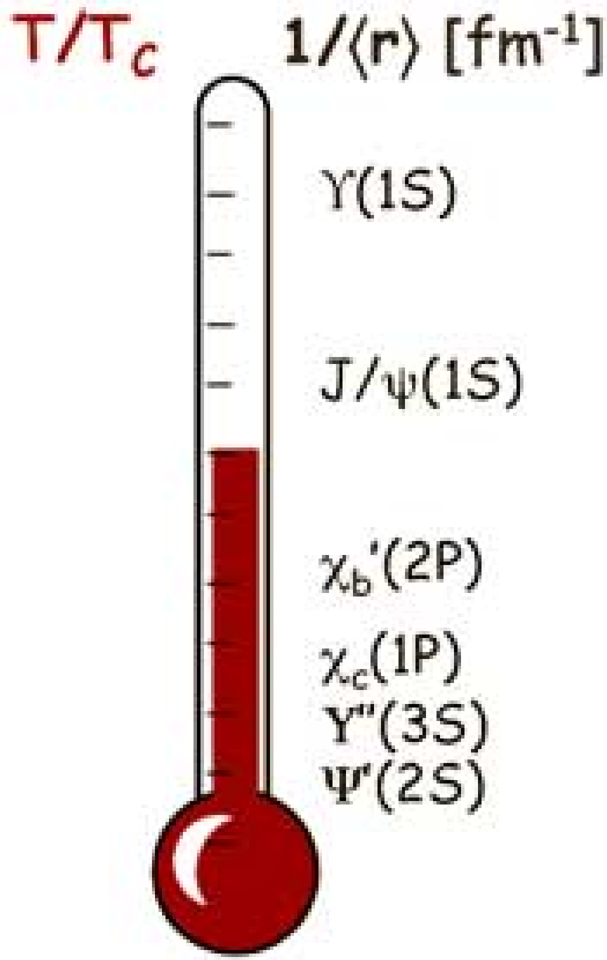
ALICE collaboration:
Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
Inverse slope: T = 304 +/-51

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

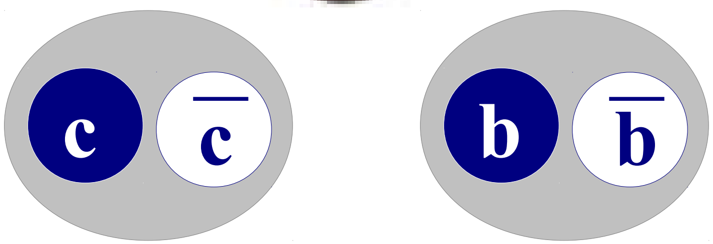
Building a quarkonium-thermometer

CMS-PAS HIN-11-011



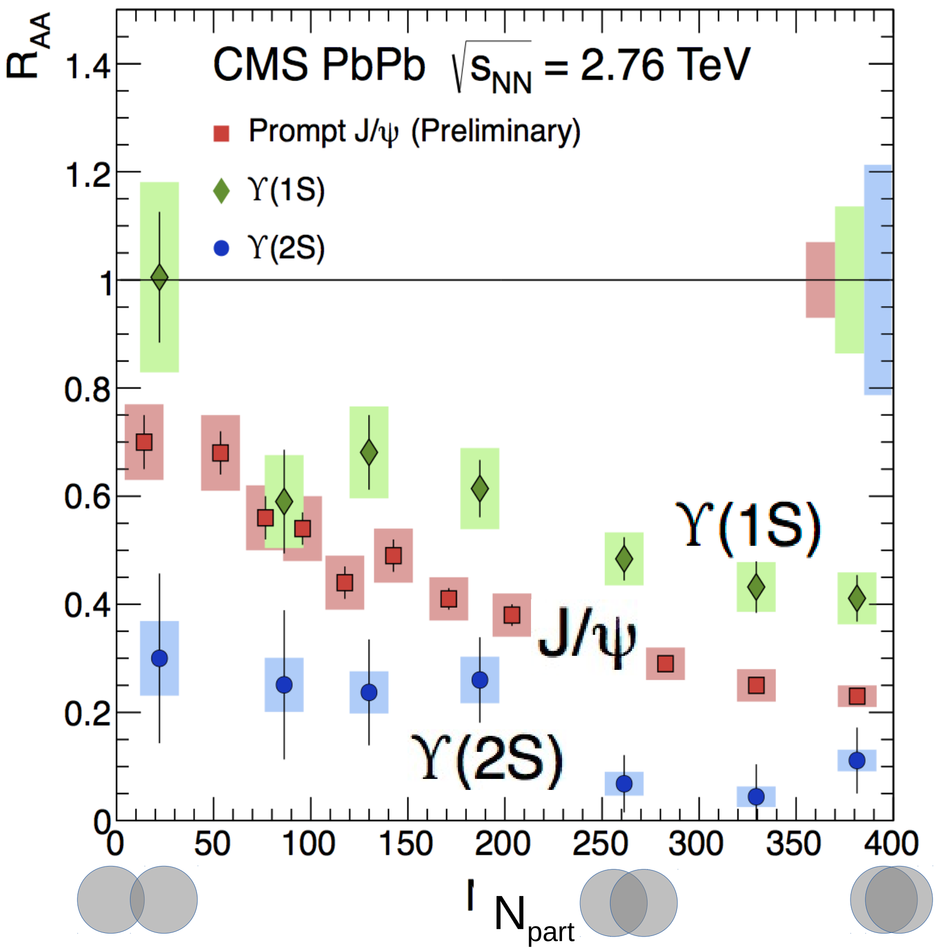


Clear hierarchy in R_{AA} of different quarkonium states

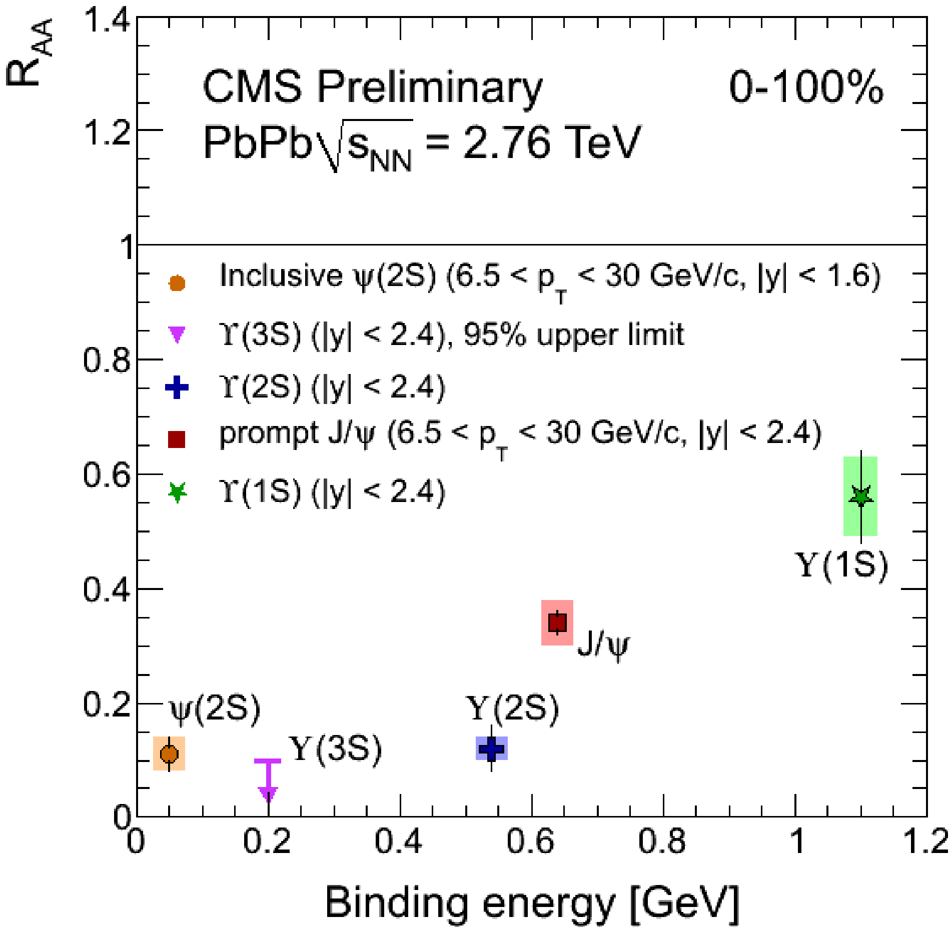


Building a quarkonium-thermometer

CMS-PAS HIN-11-011



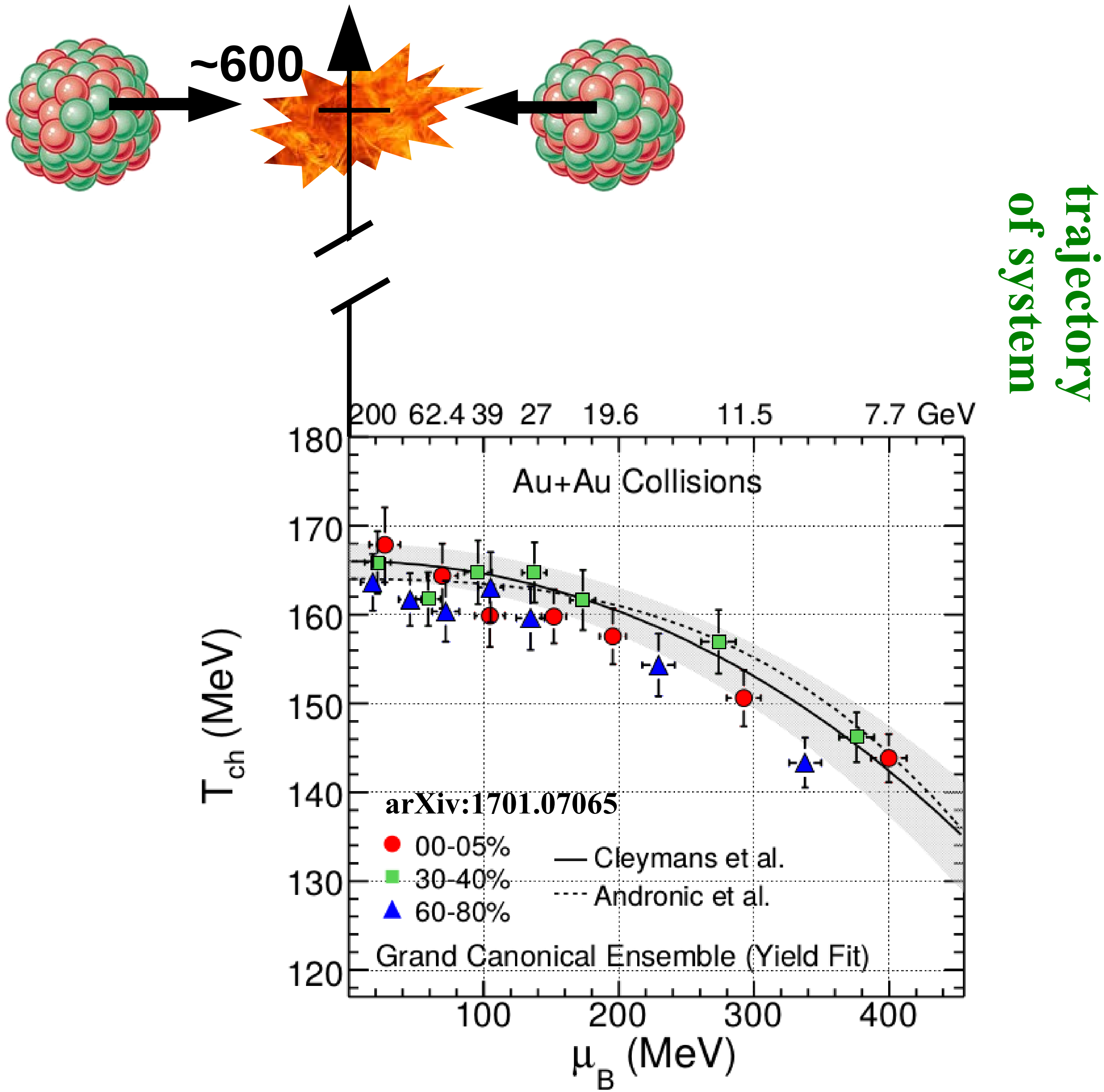
Note: 6.5<p_T<30 GeV for J/ψ and ψ(2s)



Clear hierarchy in R_{AA} of different quarkonium states

Expected in terms of binding energy

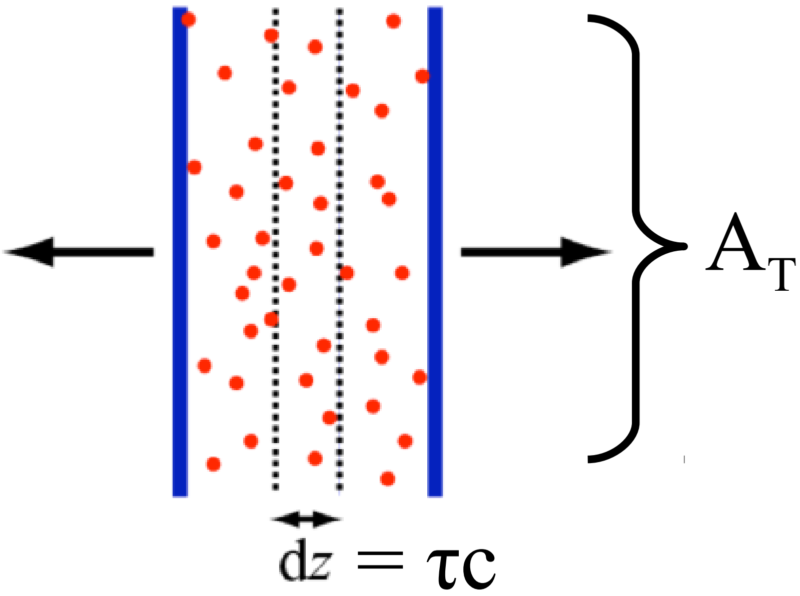
CMS-PAS HIN-12-014, HIN-12-007


~600
trajectory
of system
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)

QGP Energy Density

How can we estimate the energy density?

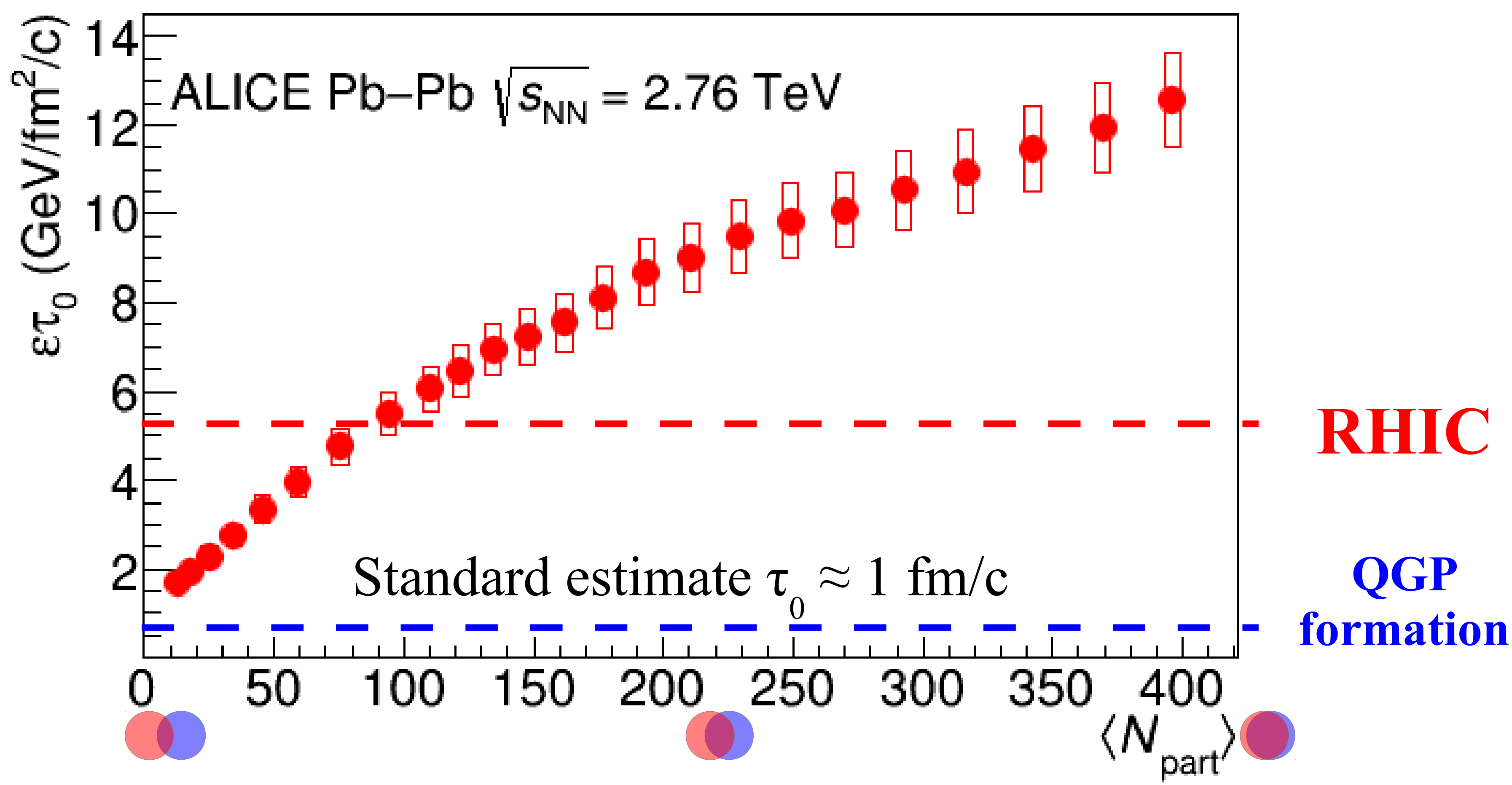
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



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

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

Energy density



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