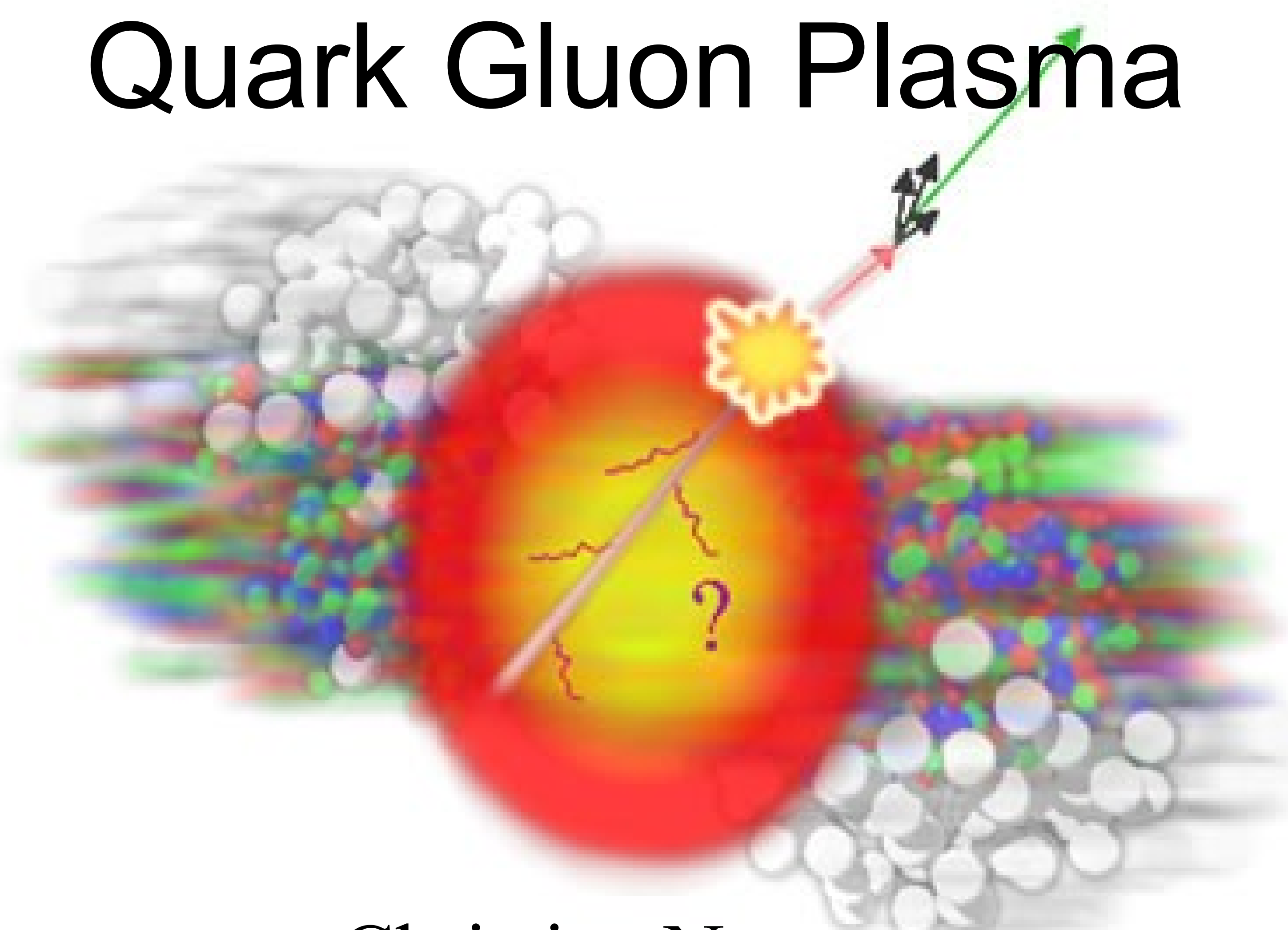
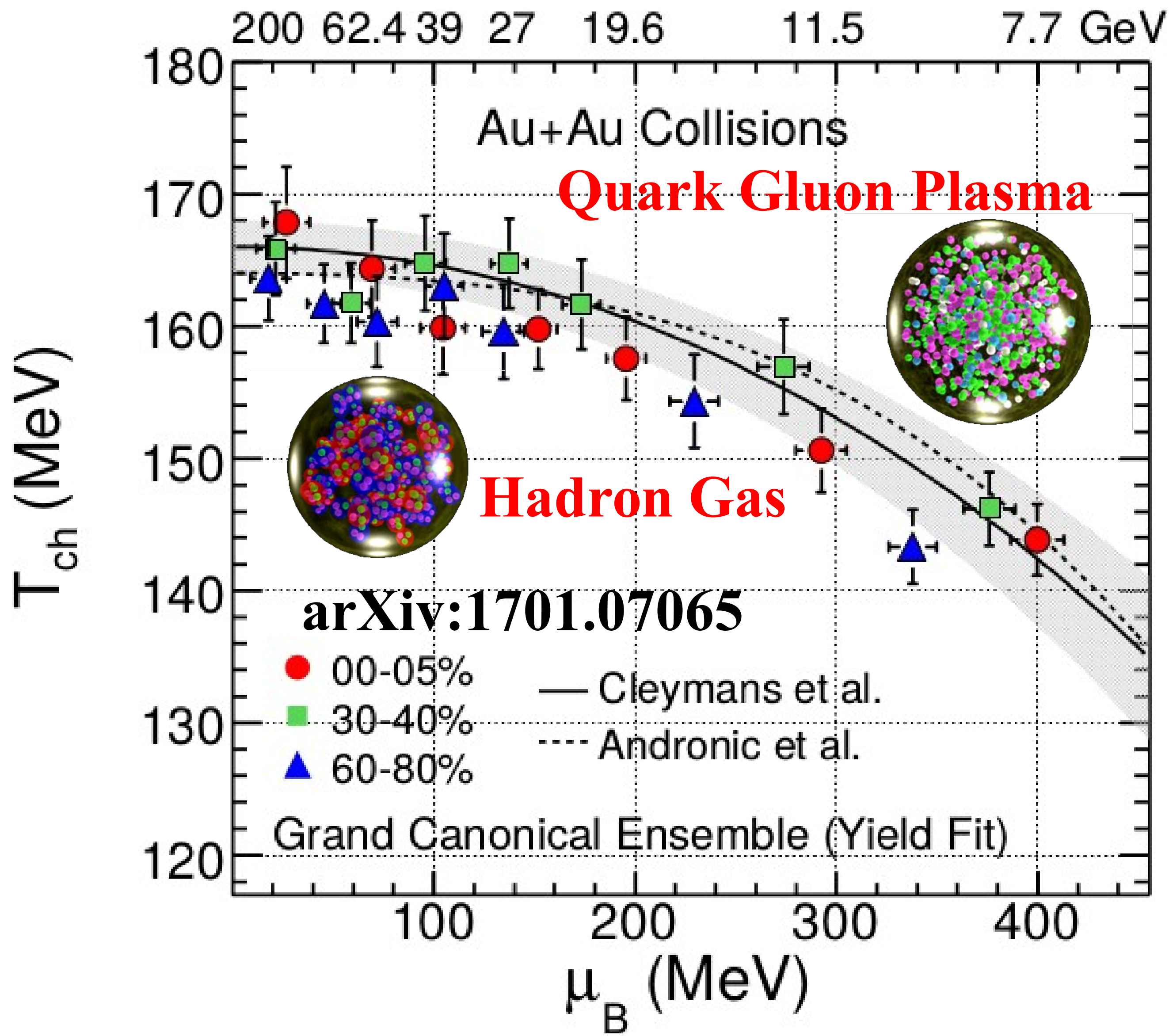
The little bang: understanding the Quark Gluon Plasma

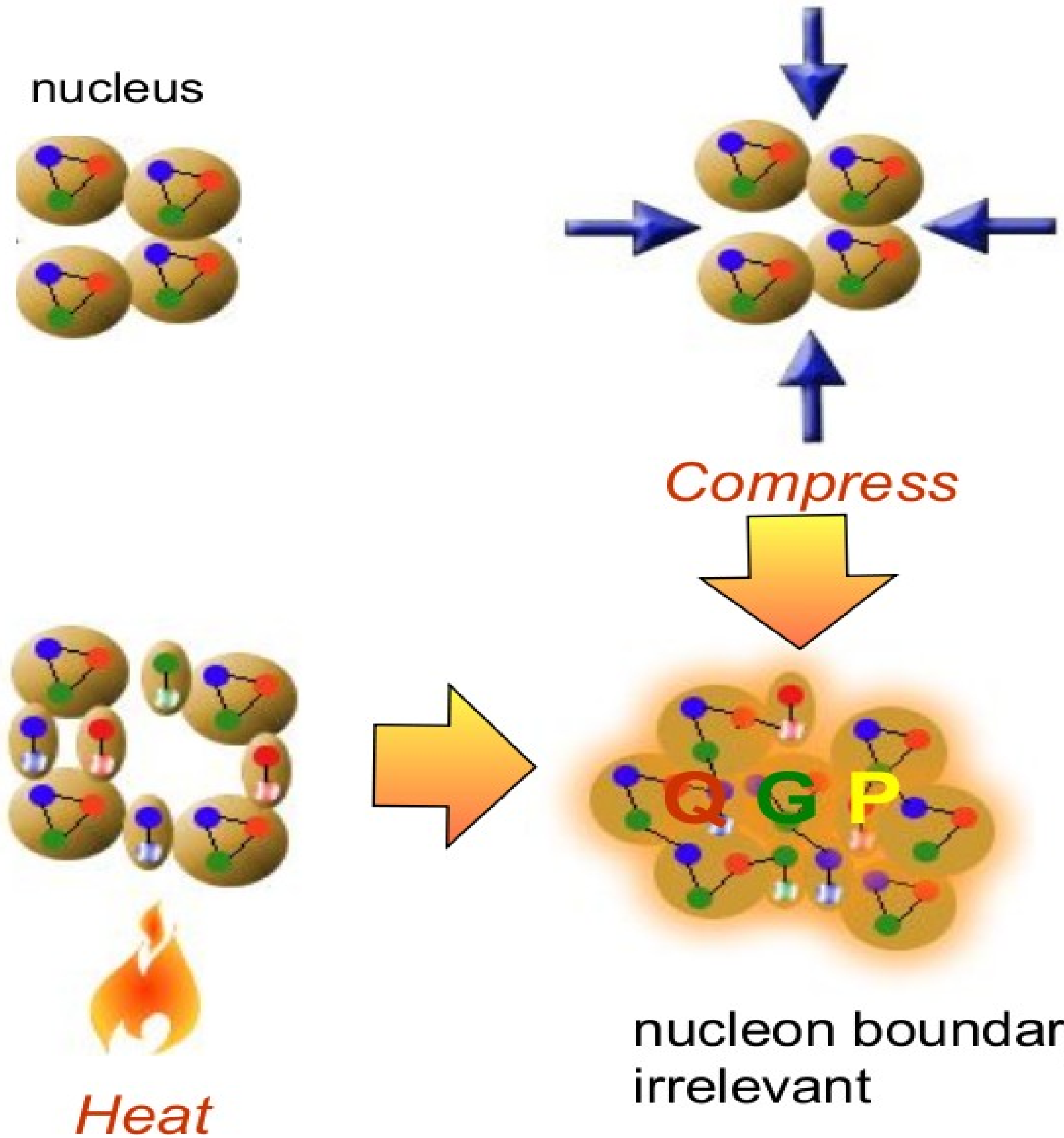


Christine Nattrass
University of Tennessee, Knoxville

QCD Phase Diagram

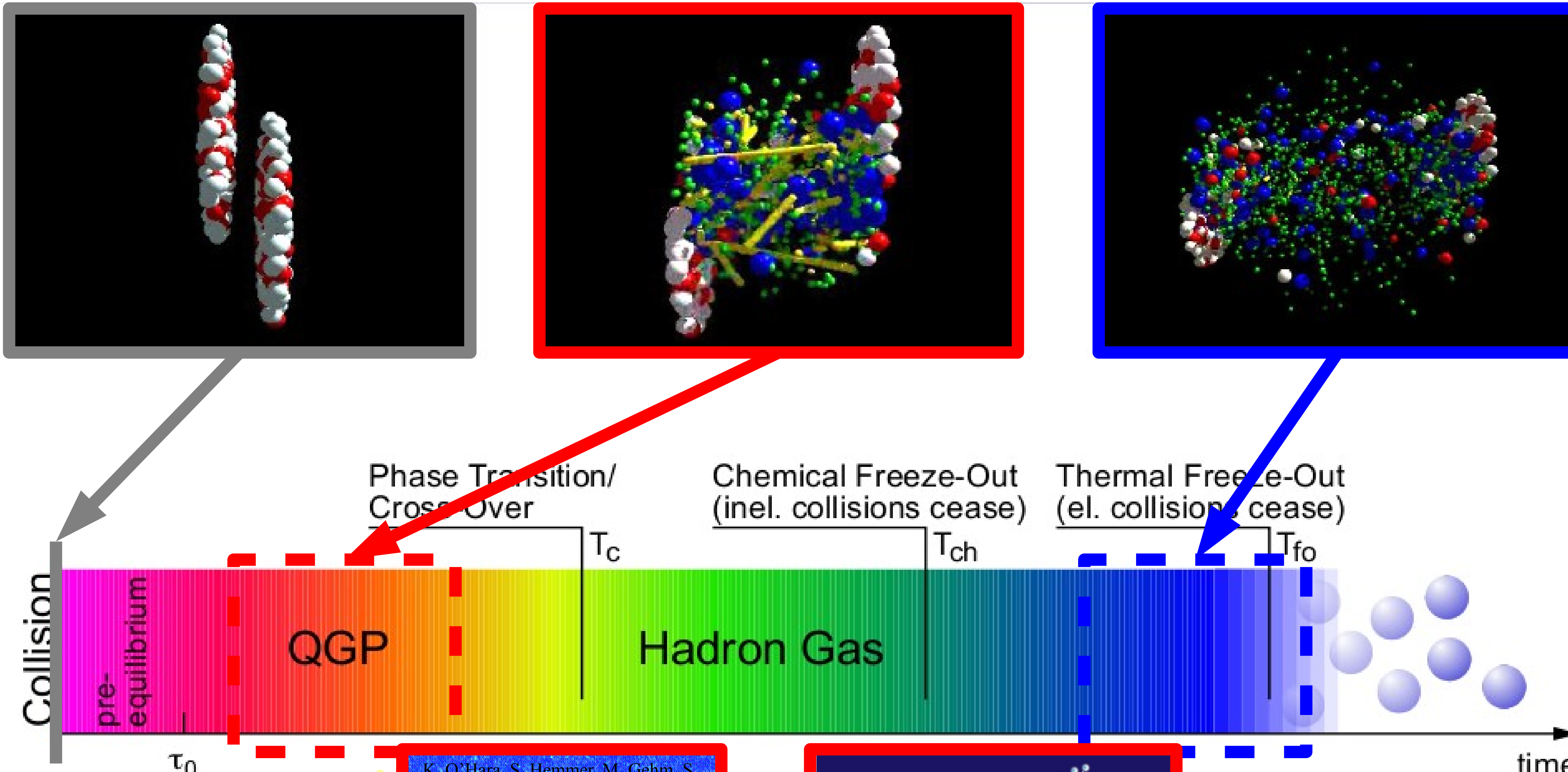


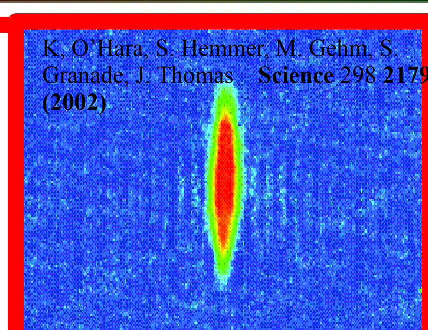
How to make a Quark Gluon Plasma

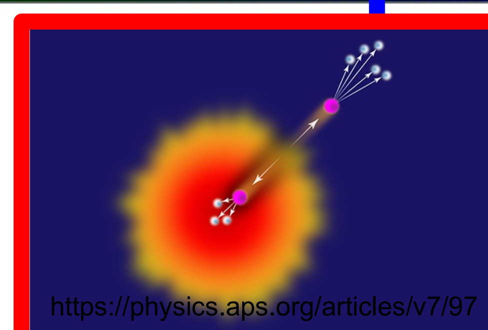


The phase transition in the laboratory

Initial State **QGP** **Freeze-out**





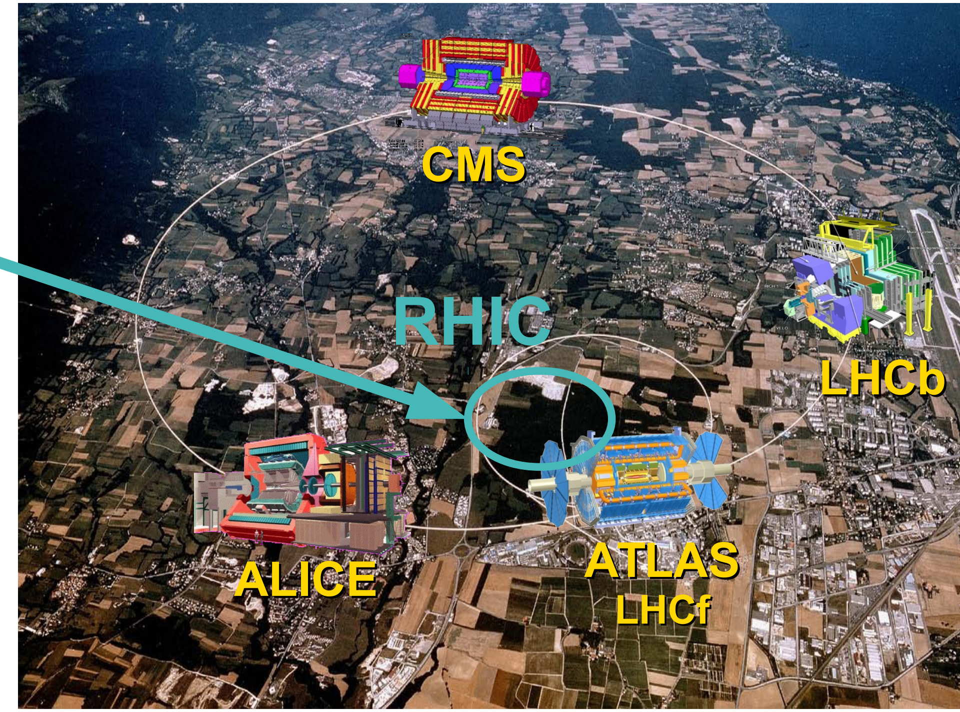


Hydrodynamical flow

Jet quenching

Relativistic Heavy Ion Collider

Large Hadron Collider

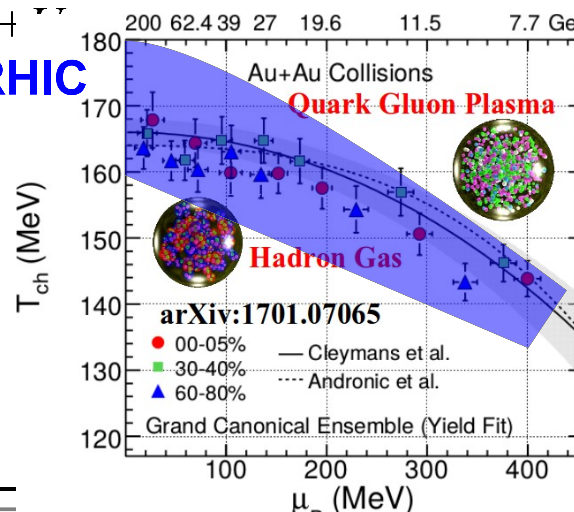


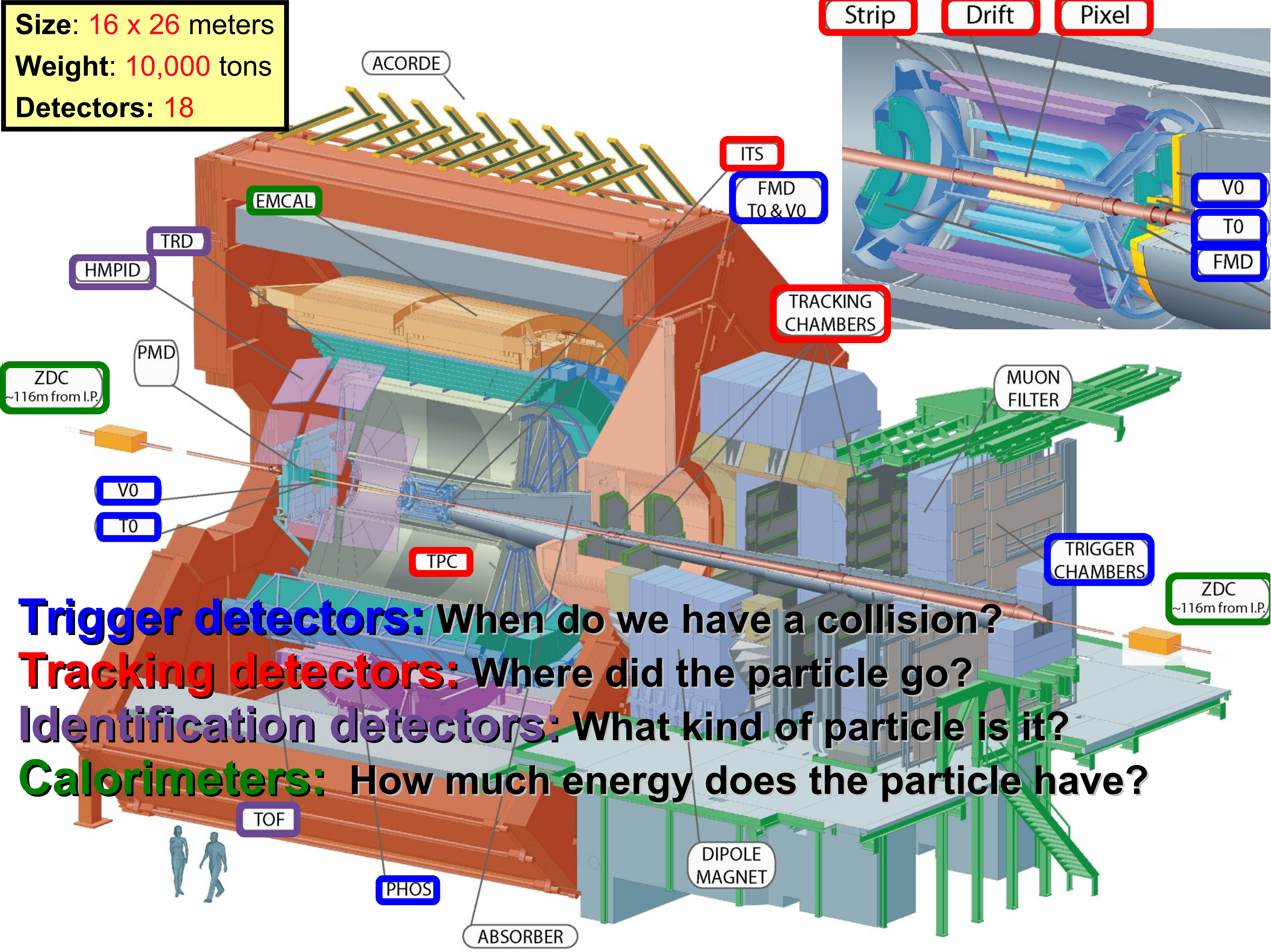
Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

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

LHC

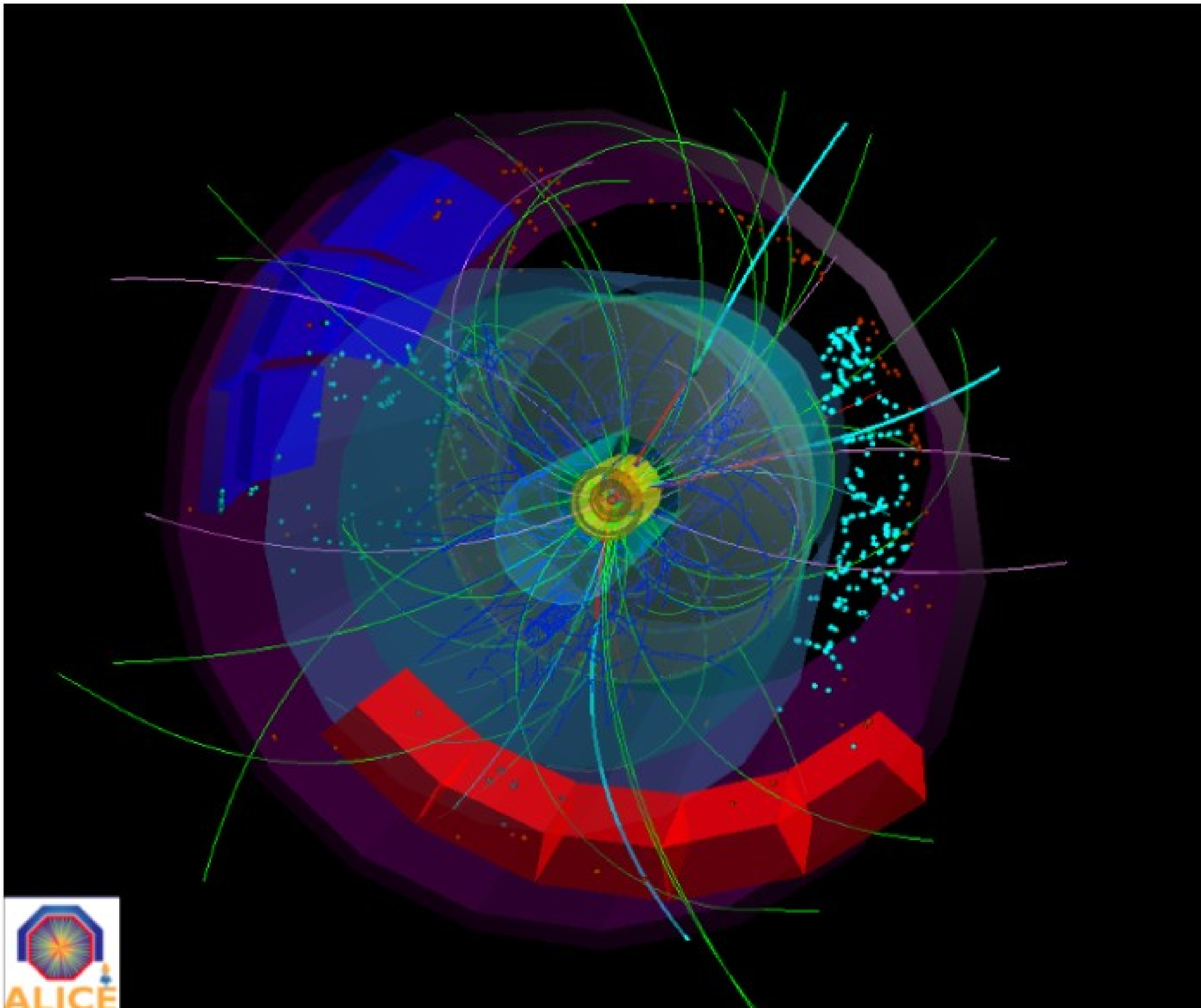
RHIC





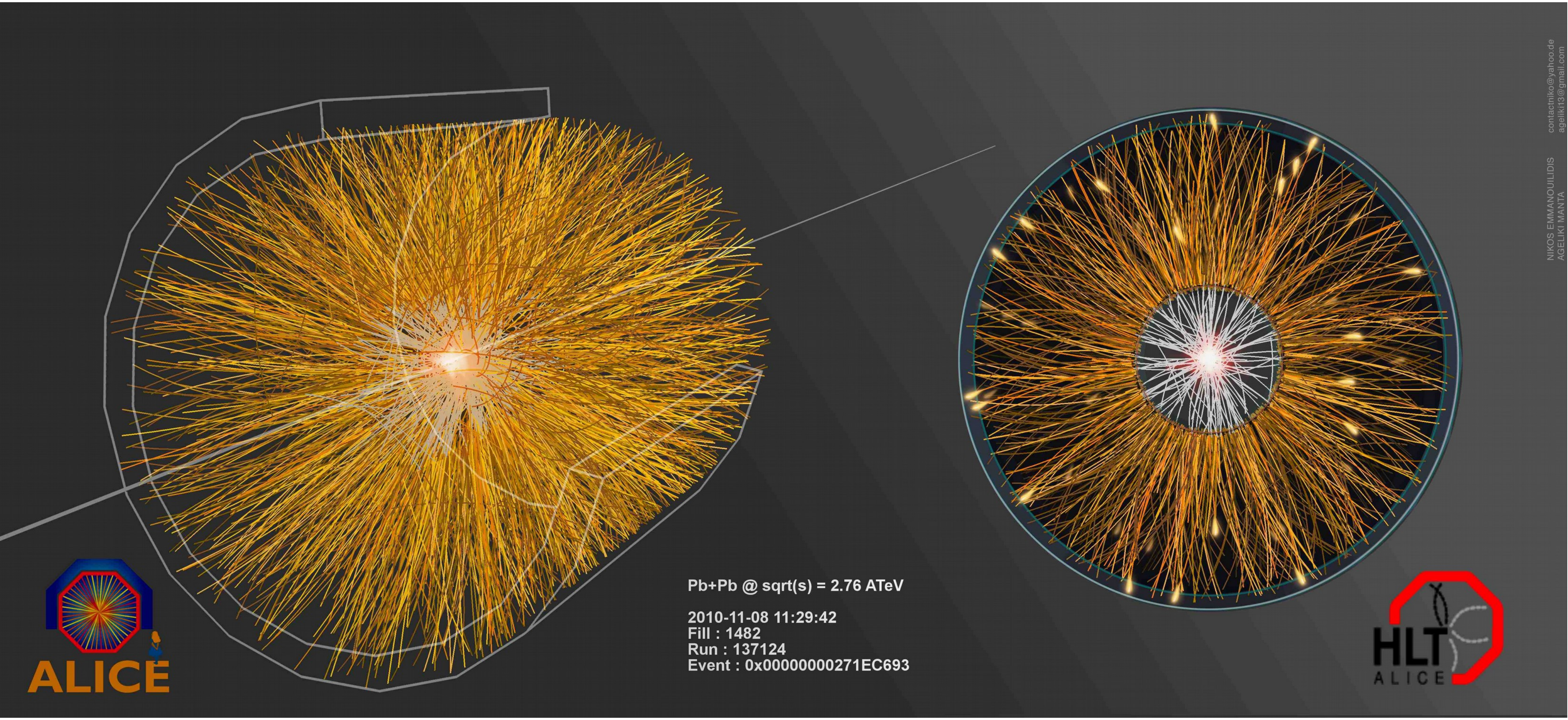
Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18
ACORDE
Strip
Drift
Pixel
ITS
FMD
T0 & V0
EMCAL
TRD
HMPID
V0
T0
FMD
TRACKING
CHAMBERS
PMD
ZDC
~116m from I.P.
MUON
FILTER
V0
T0
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
Trigger detectors: When do we have a collision?
Tracking detectors: Where did 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

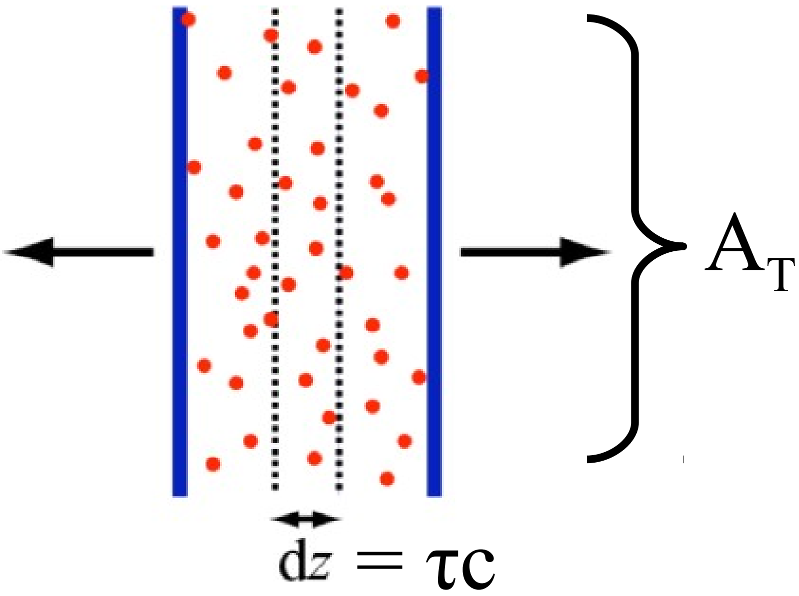
Pb+Pb collisions



QGP Energy Density

How can we estimate the energy density?

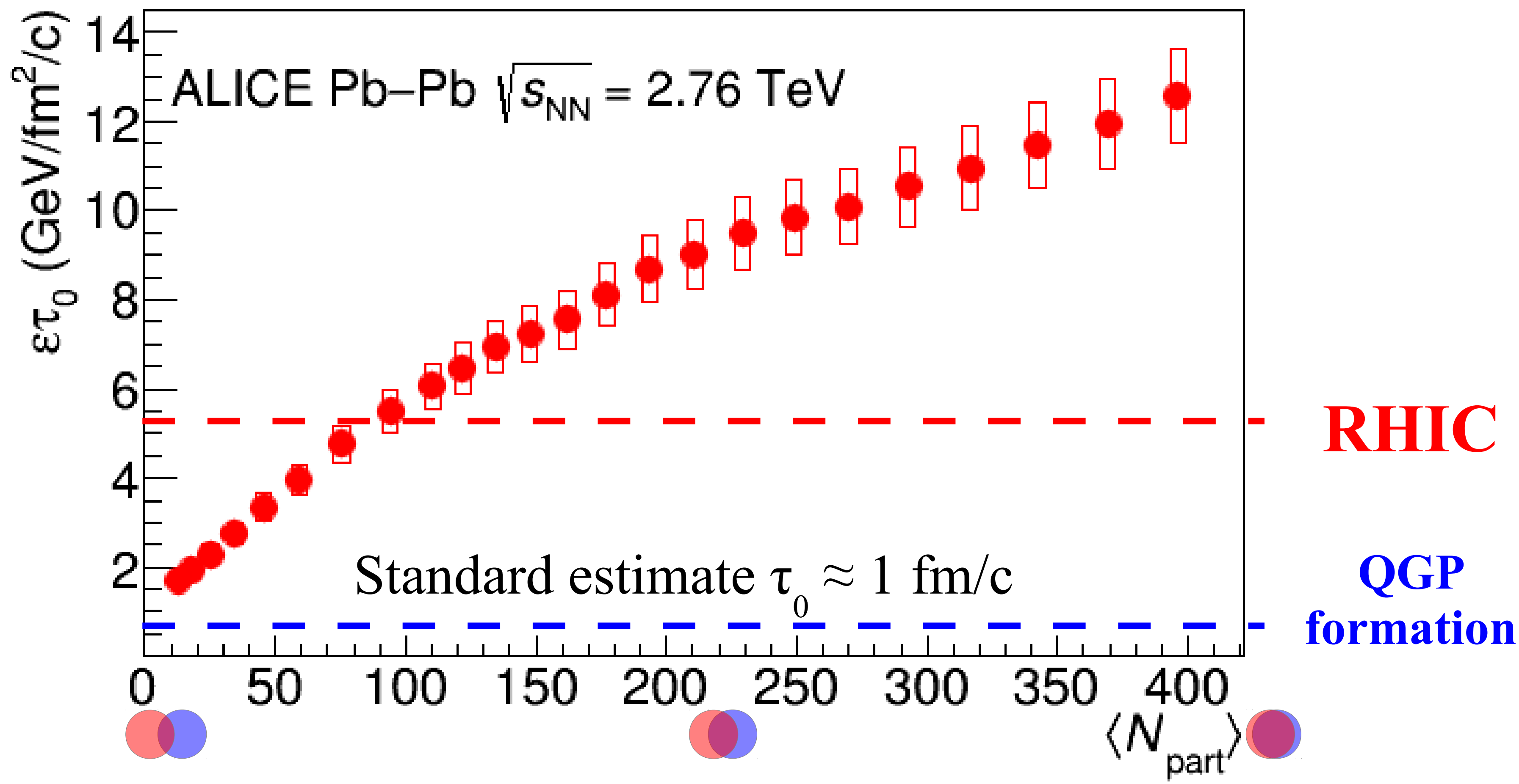
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



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

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

Energy density

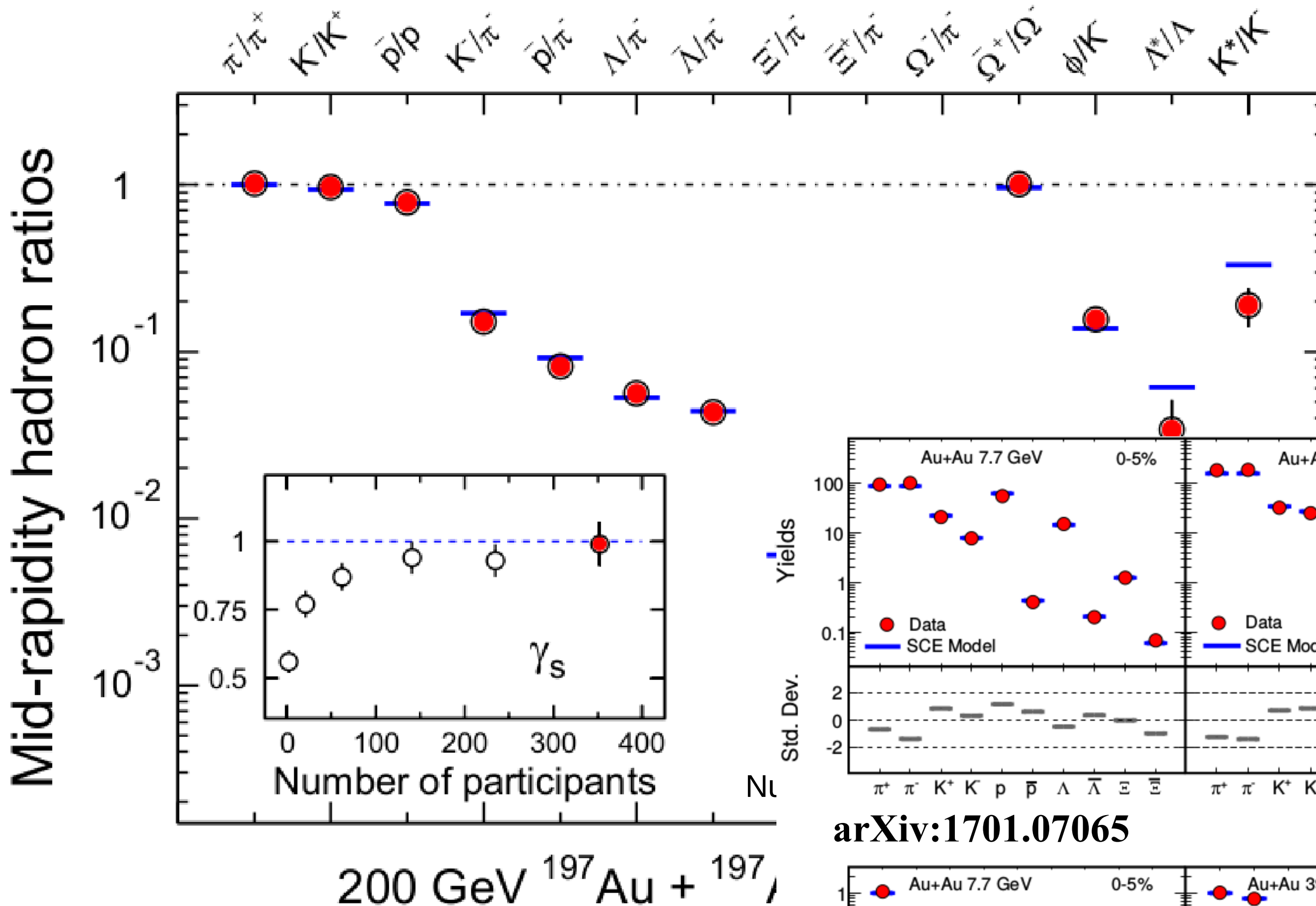


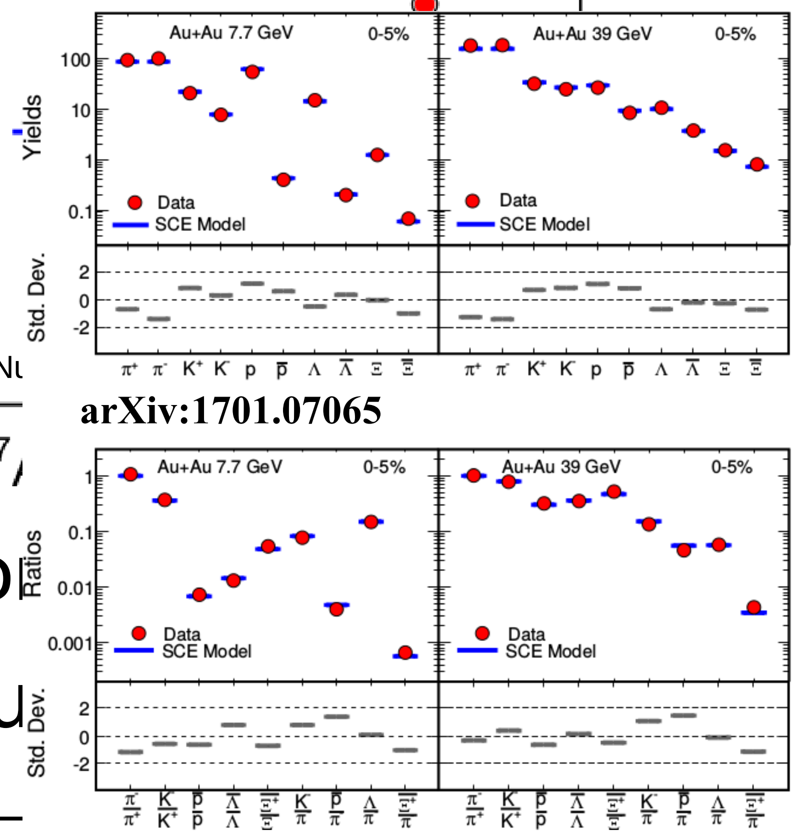
$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

QGP Chemistry

Chemistry - equilibrium

T~170 MeV

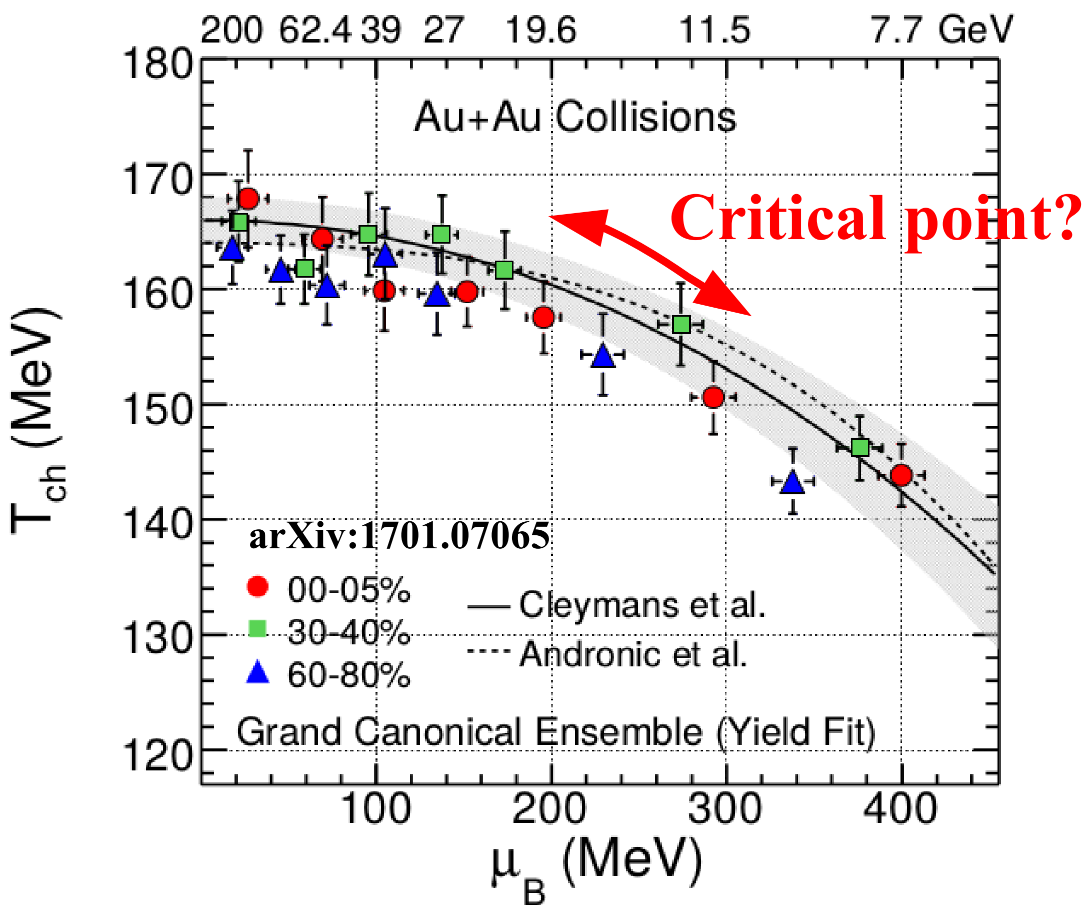




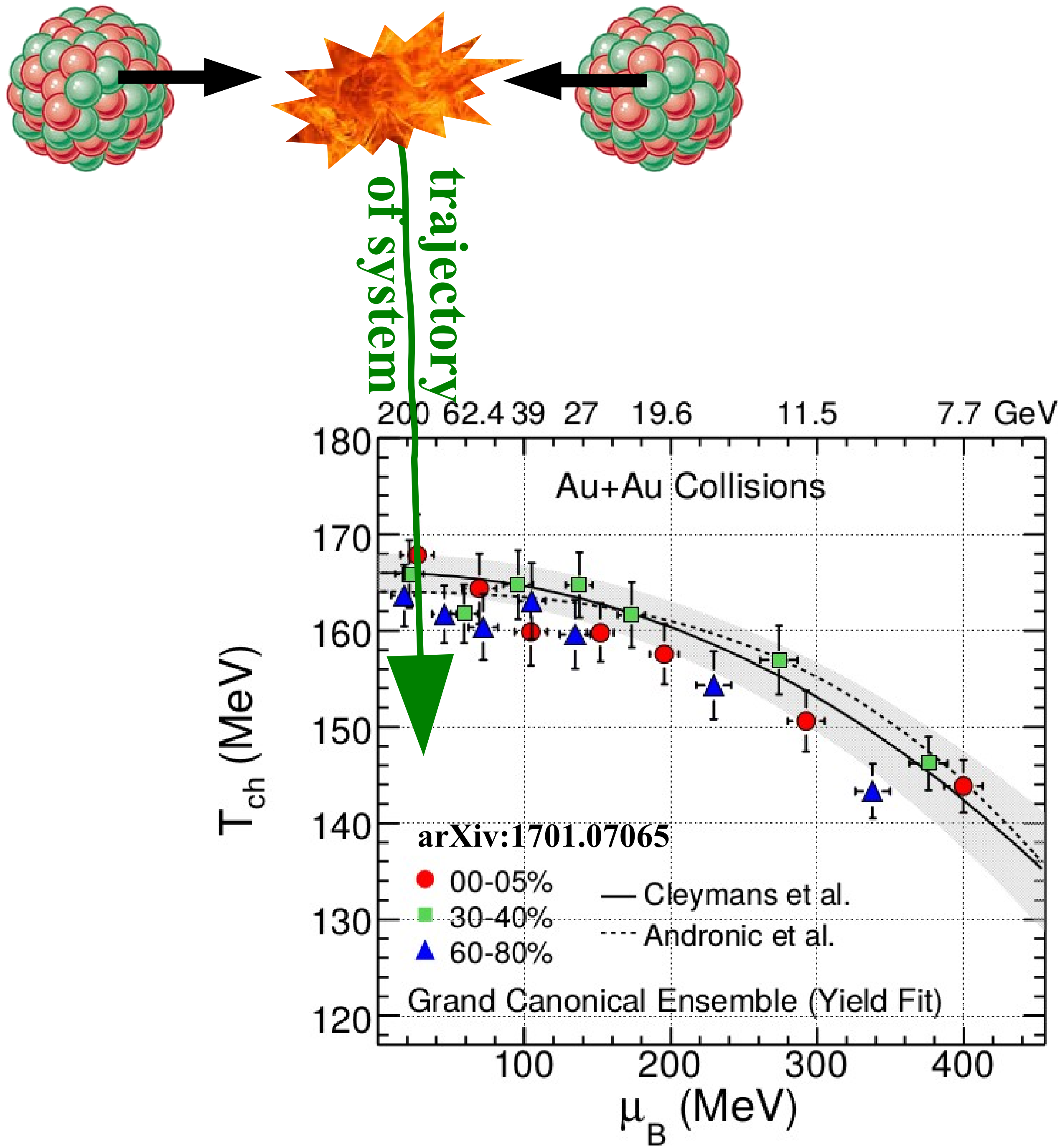
arXiv:1701.07065

- Ratios of particles expected fro
- Even strange quarks are at equ

Phase diagram of nuclear matter

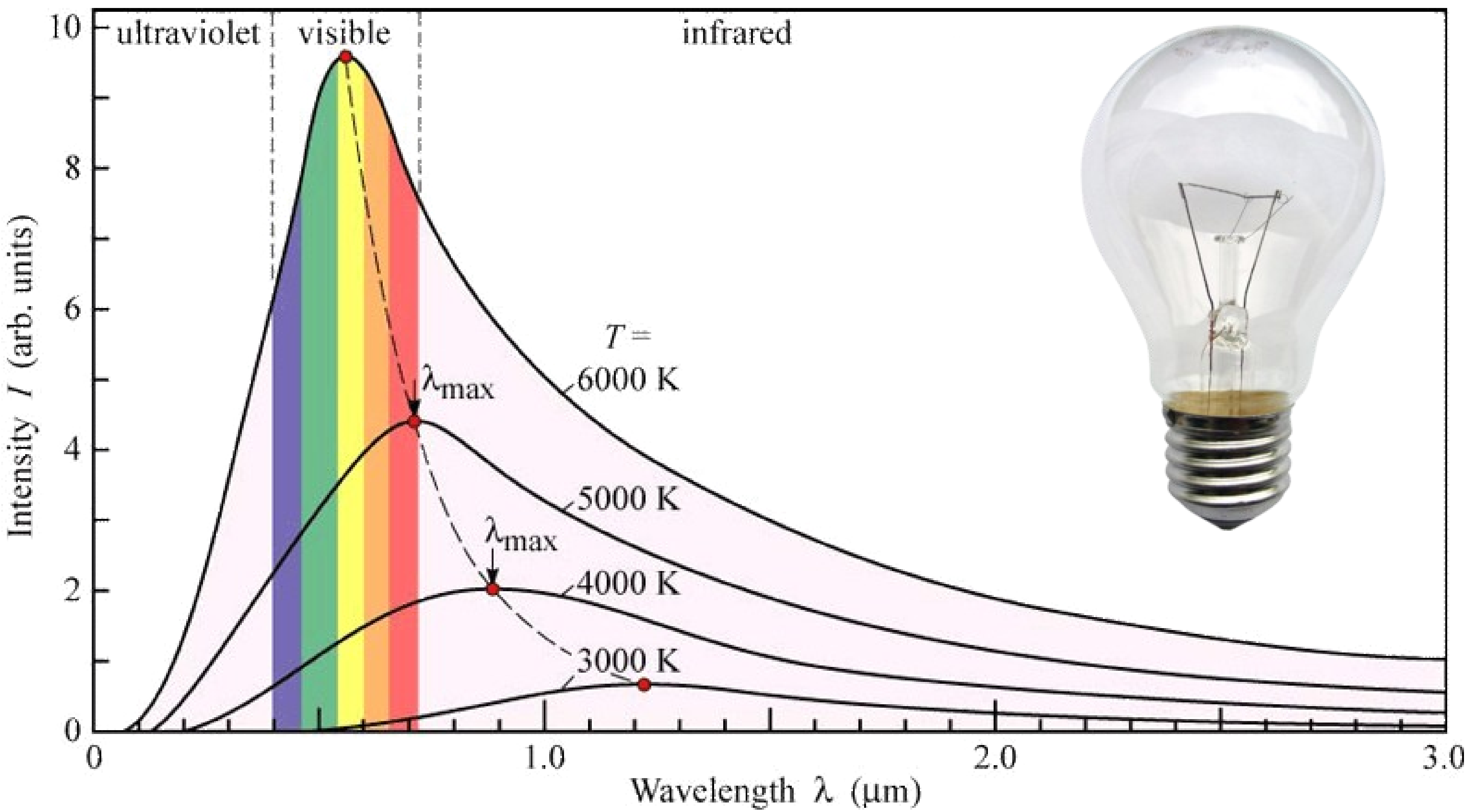


Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun


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)

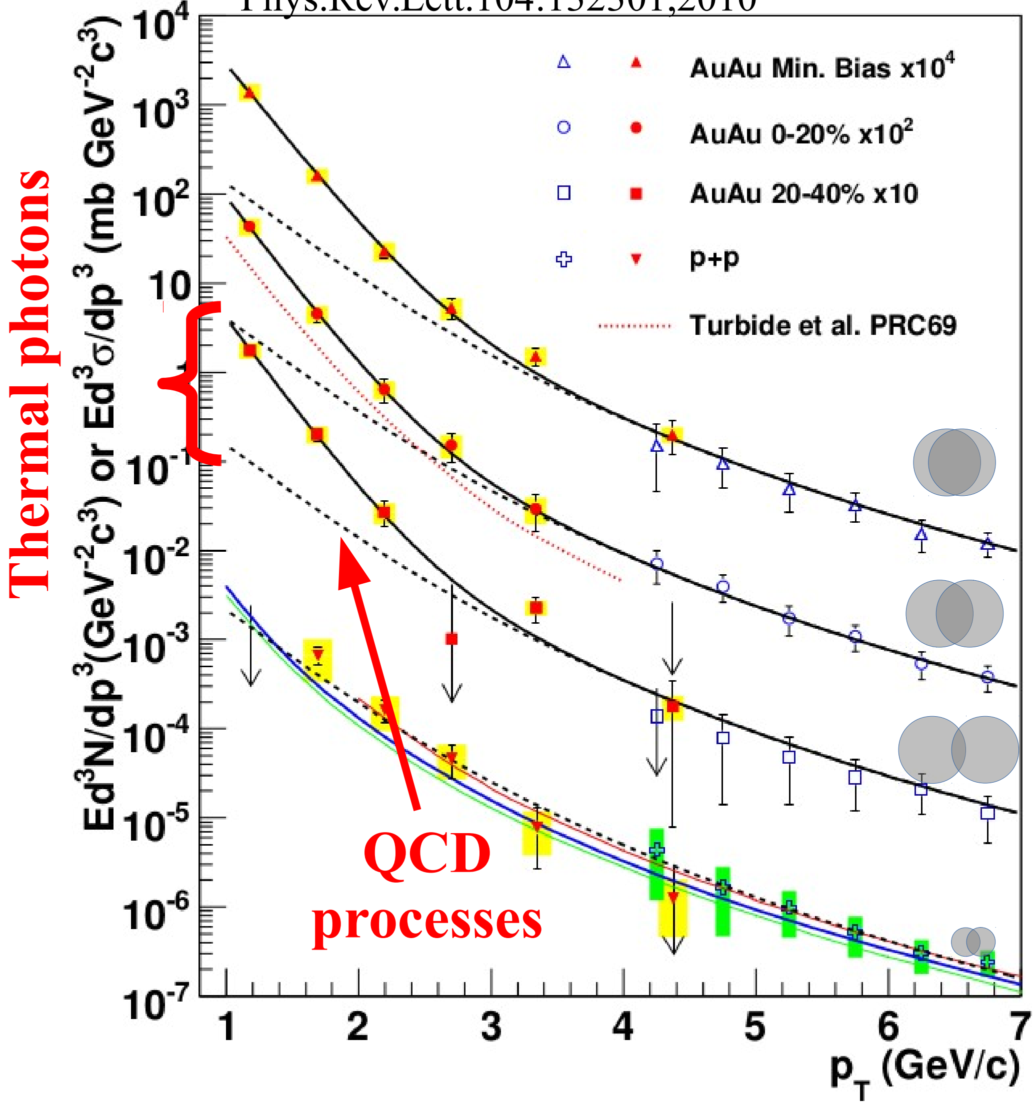
QGP Thermometers

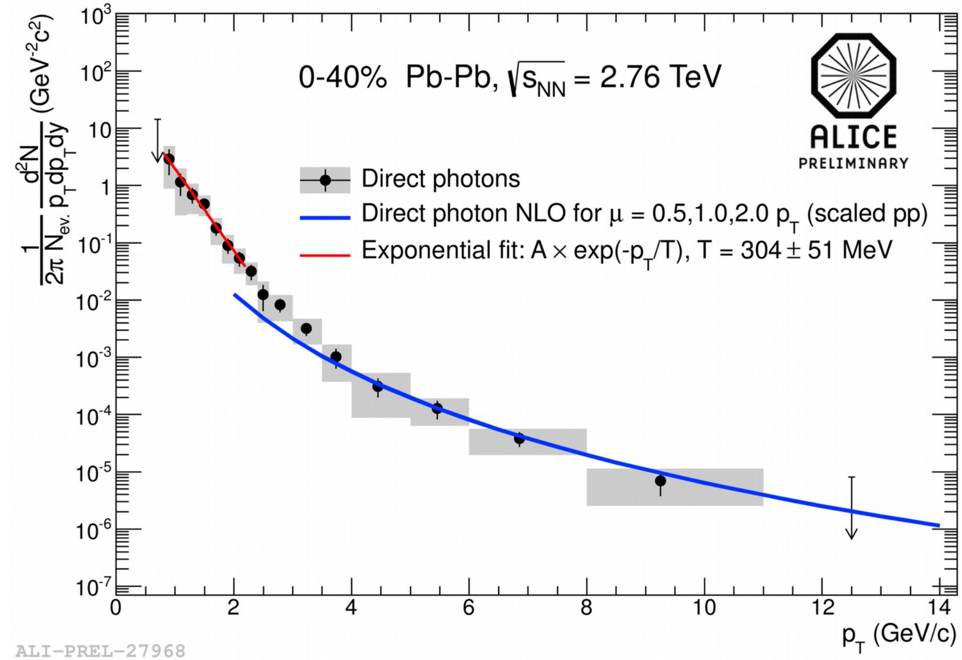
Measuring temperature



Thermal photons

Phys.Rev.Lett.104:132301,2010



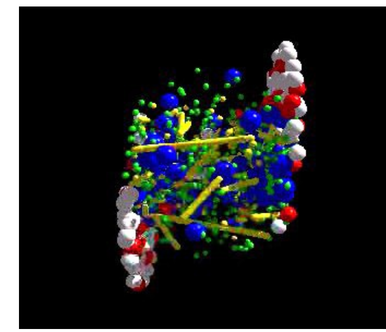


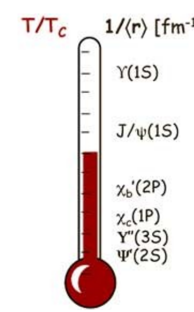
ALICE collaboration:
Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
Inverse slope: T = 304 +/-51

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

Take home messages

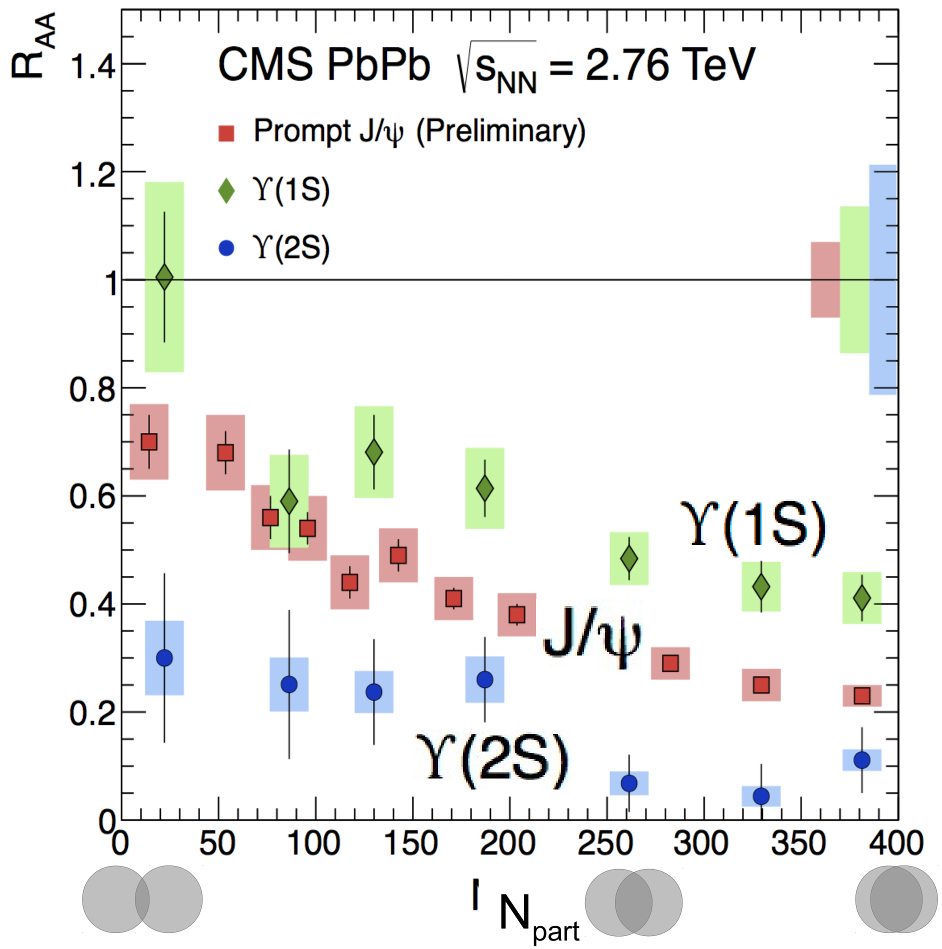
- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is extremely hot and dense.



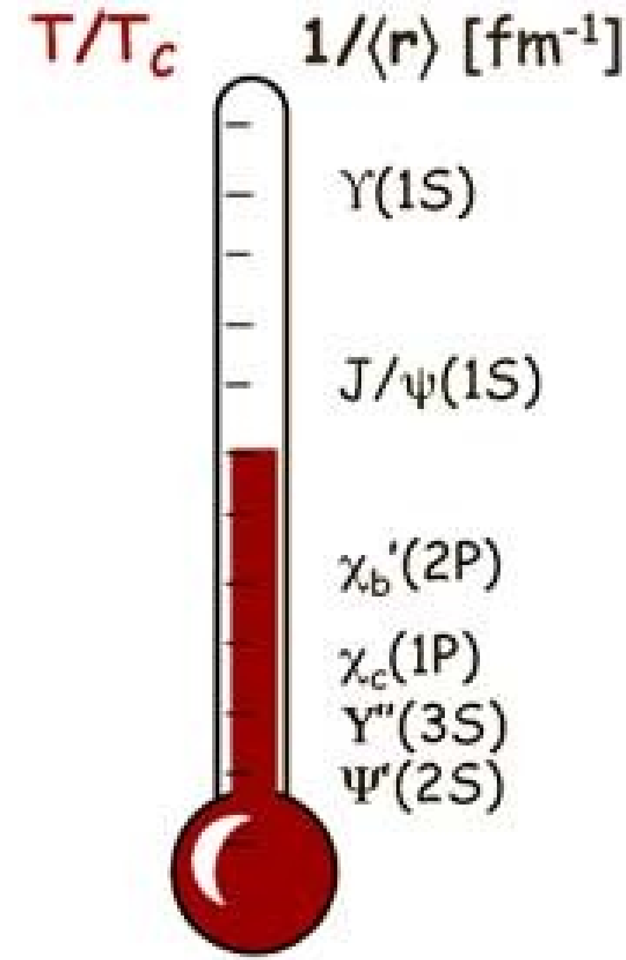


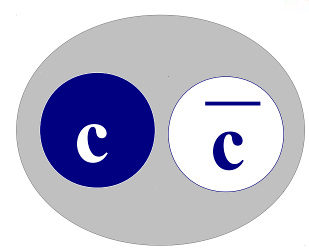
Building a quarkonium-thermometer

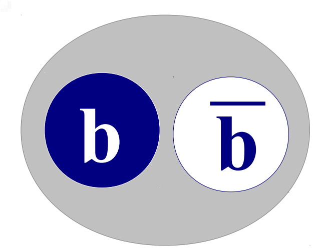
CMS-PAS HIN-11-011



Clear hierarchy in R_{AA} of different quarkonium states



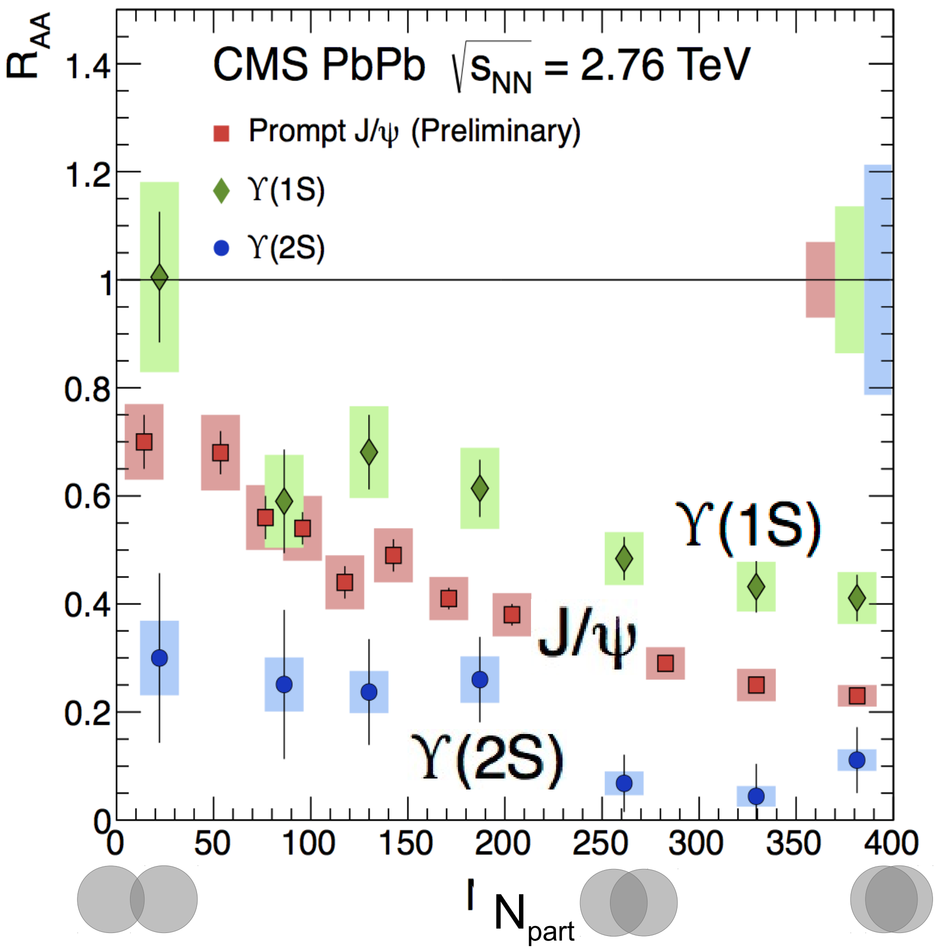


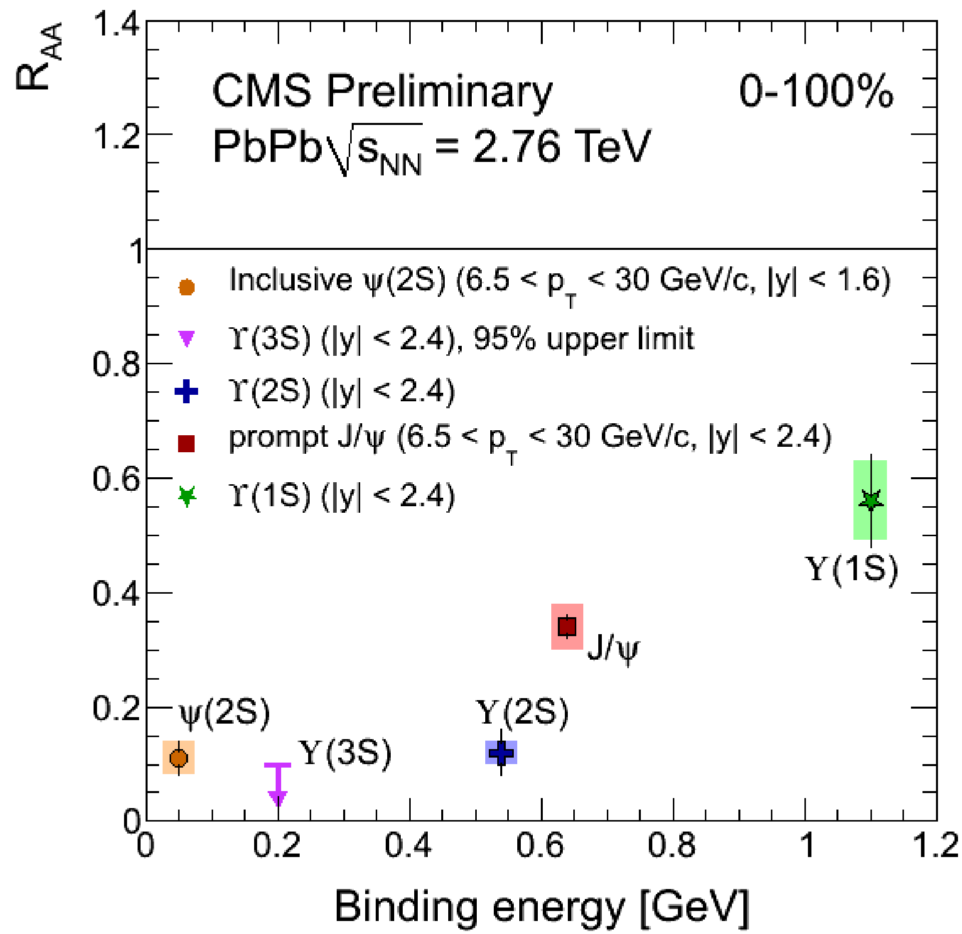


Building a quarkonium-thermometer

CMS-PAS HIN-11-011

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

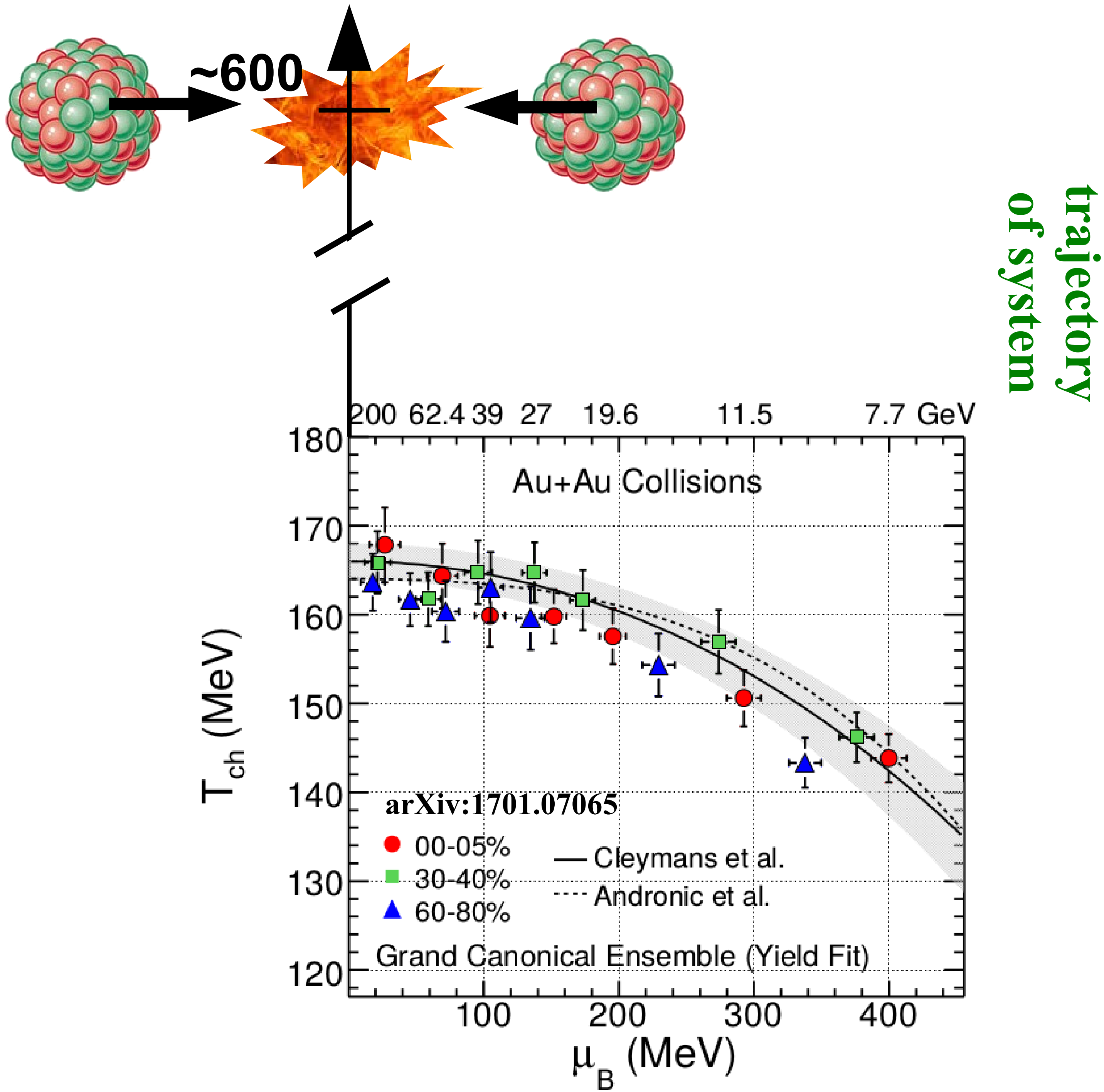




Clear hierarchy in R_{AA} of different quarkonium states

Expected in terms of binding energy

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


~600
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arXiv:1701.07065
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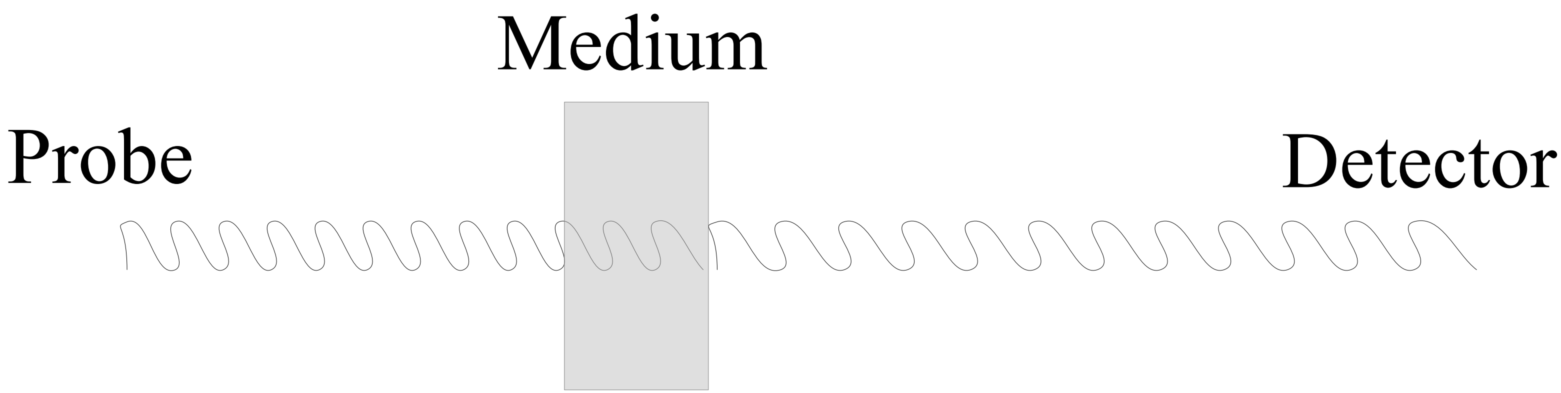
Cleymans et al.
Andronic et al.
Grand Canonical Ensemble (Yield Fit)
180
170
160
150
140
130
120
100
200
300
400
T_{ch} (MeV)
μ_B (MeV)
trajectory of system

QGP Spectroscopy

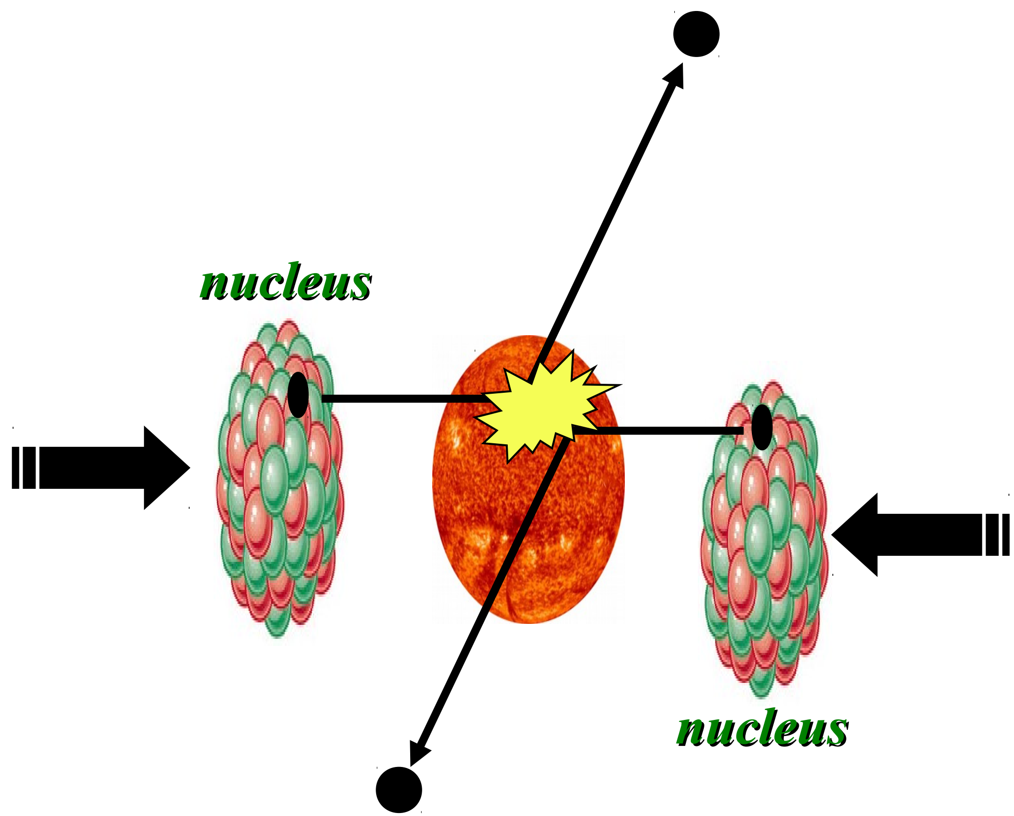
Probing the Quark Gluon Plasma



Want a probe which traveled through the collision

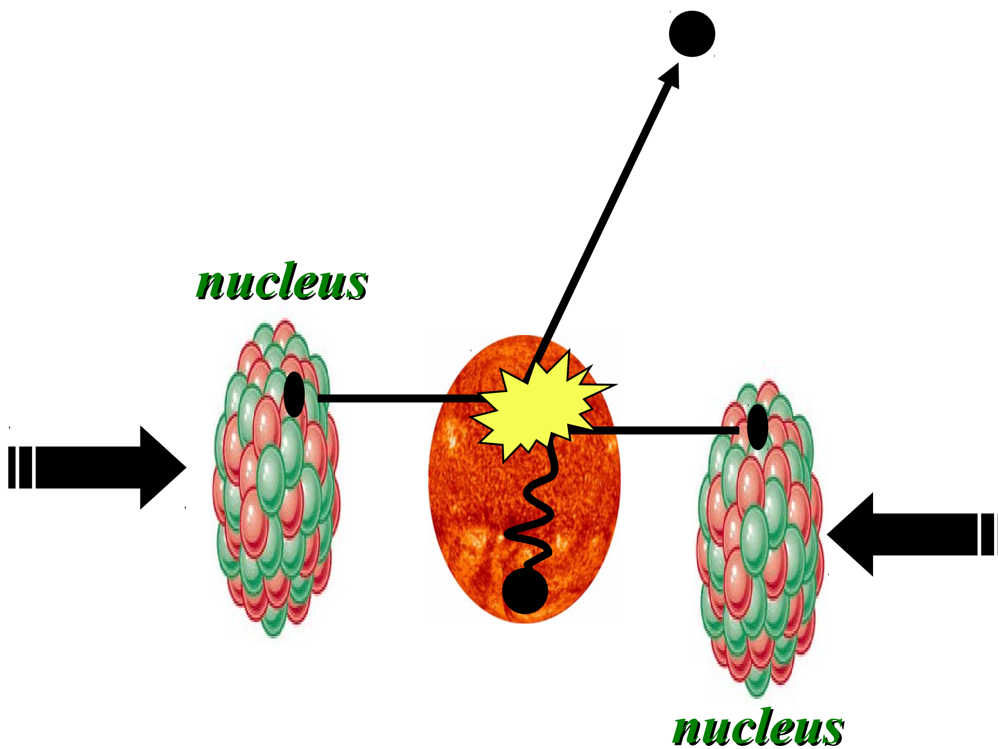
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

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

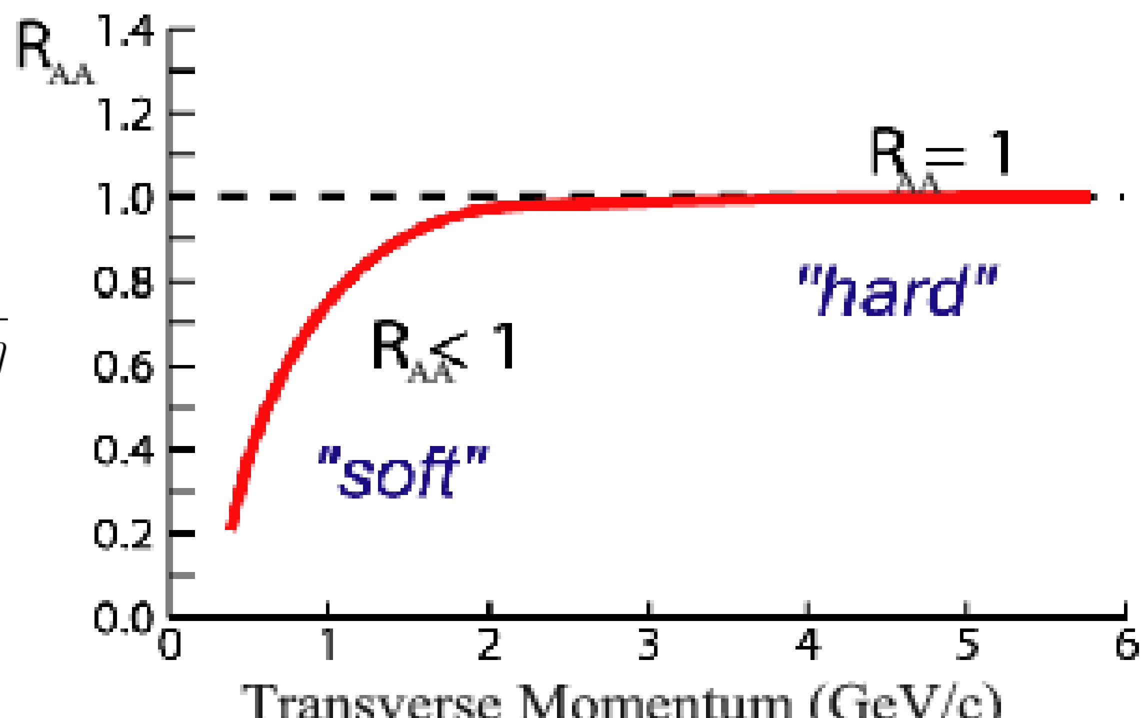


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

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

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



Enhancement

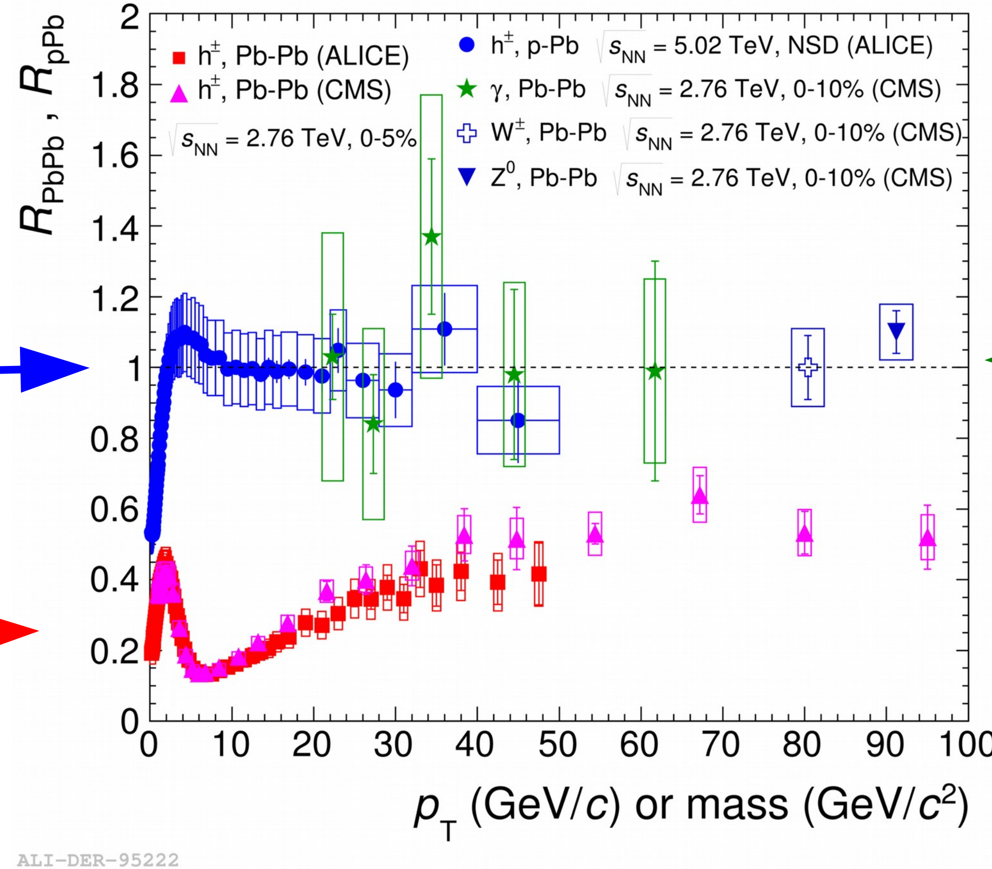
Suppression

Nuclear modification factor

Control

Control

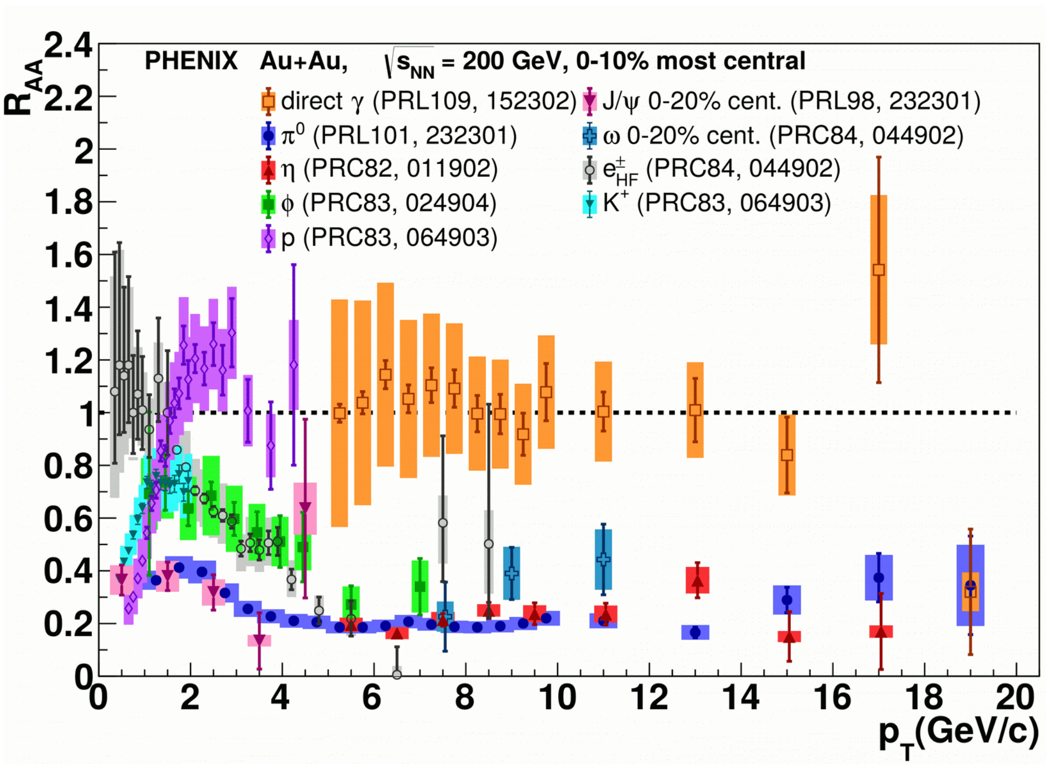
Probe

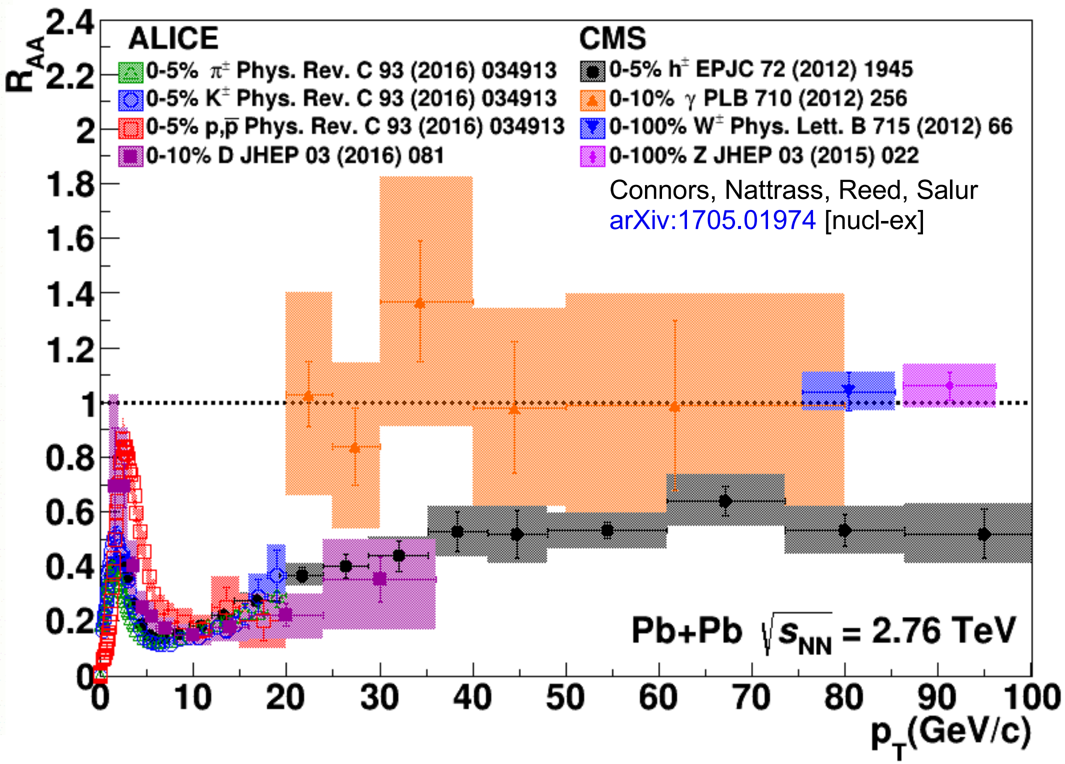


- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb

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!

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

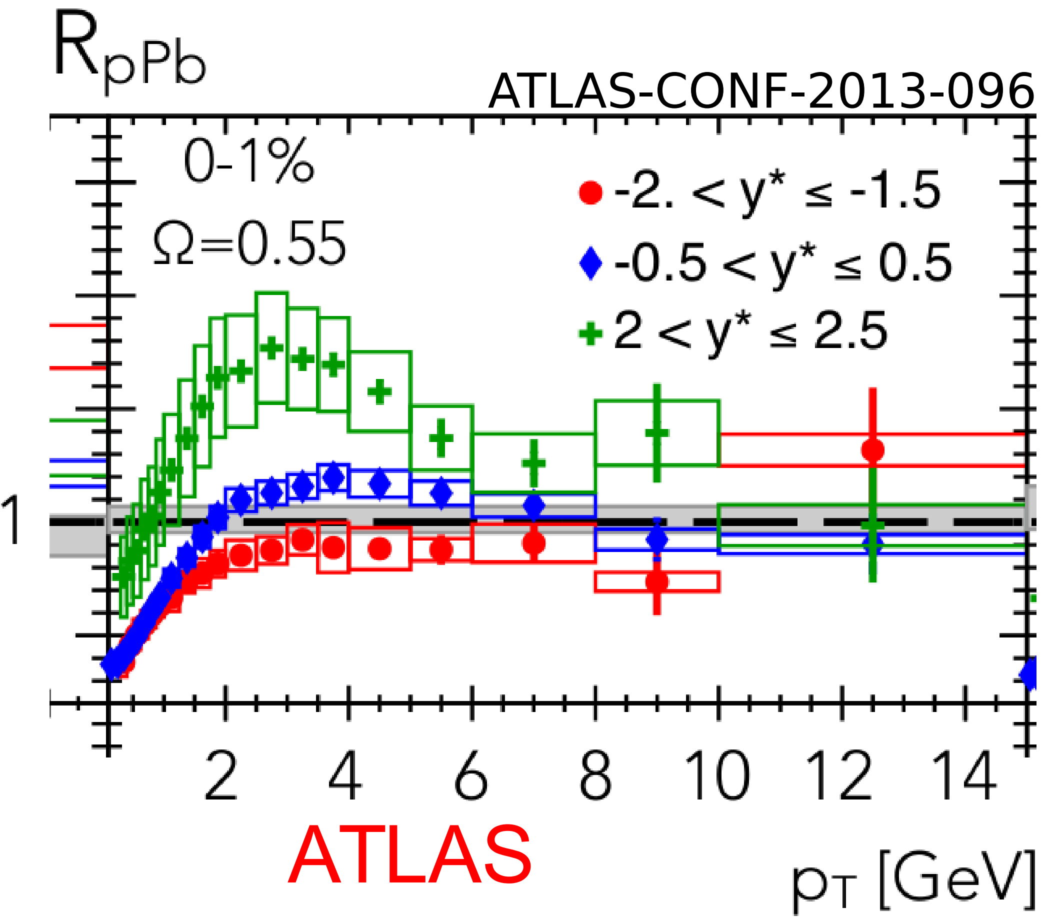
- STAR
  - University of California at Davis
  - University of California Los Angelos
  - University of Houston
  - University of Illinois at Chicago
  - Creighton University (masters only)
  - Kent State University
  - Michigan State University
  - Ohio State University
  - Purdue University
  - Texas 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

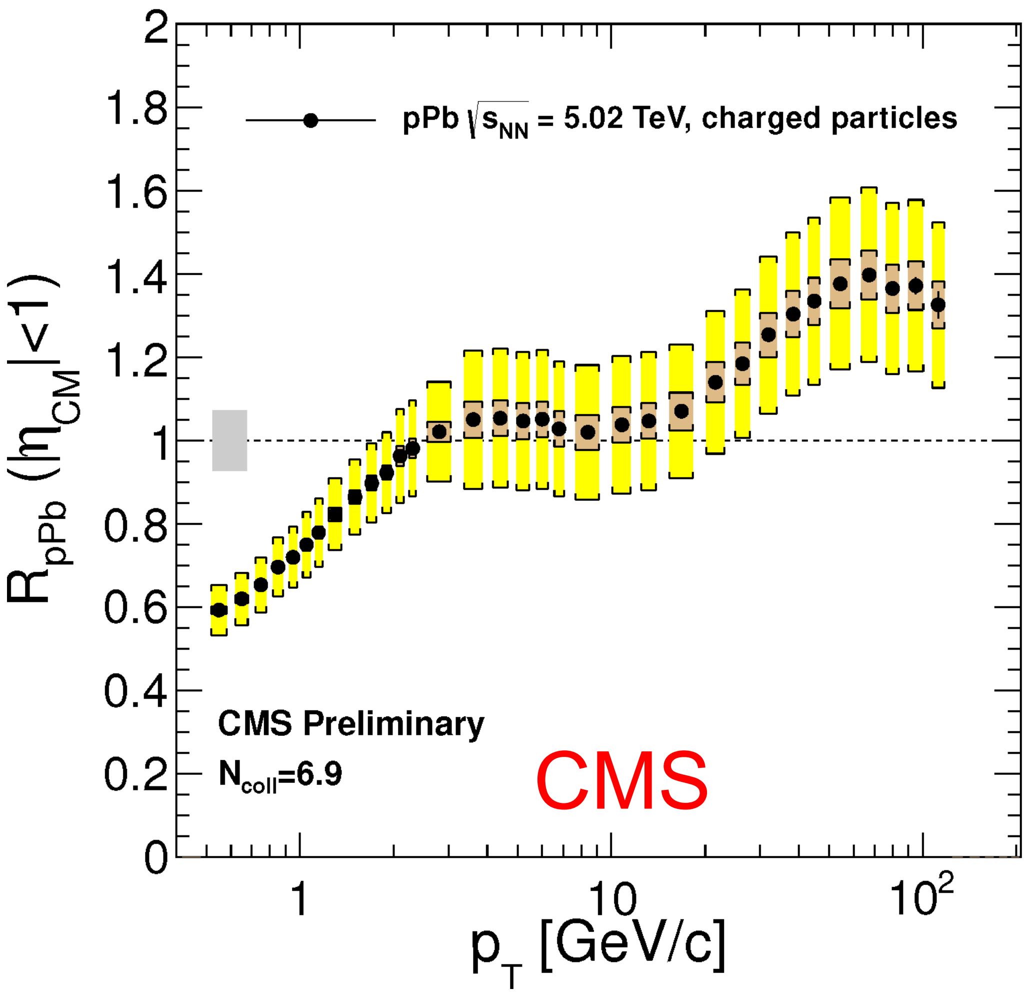
US Universities with graduate programs in experimental heavy ion physics

Large Hadron Collider

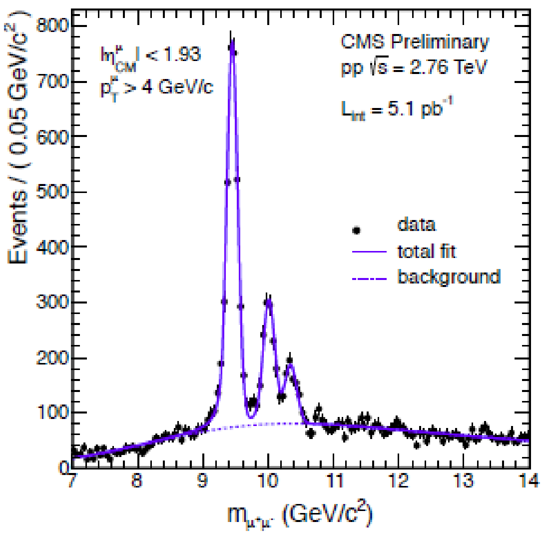
- ALICE
  - University of Texas Austin
  - Chicago State University
  - Ohio State University
  - Wayne State University
  - University of Texas Houston
  - **University of Tennessee Knoxville**
  - Yale University
  - Creighton University (masters only)
  - Purdue University
- CMS
  - University of 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

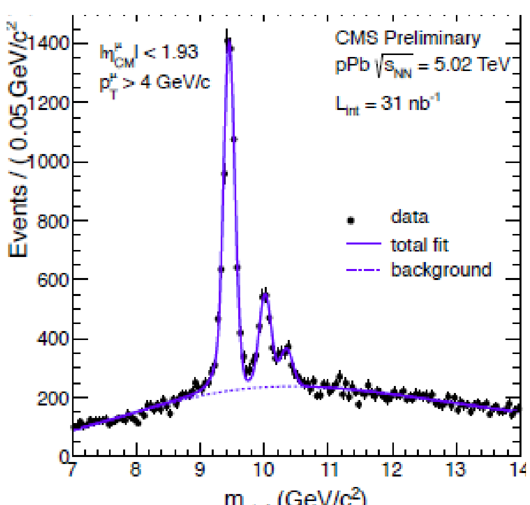
p+Pb as a control

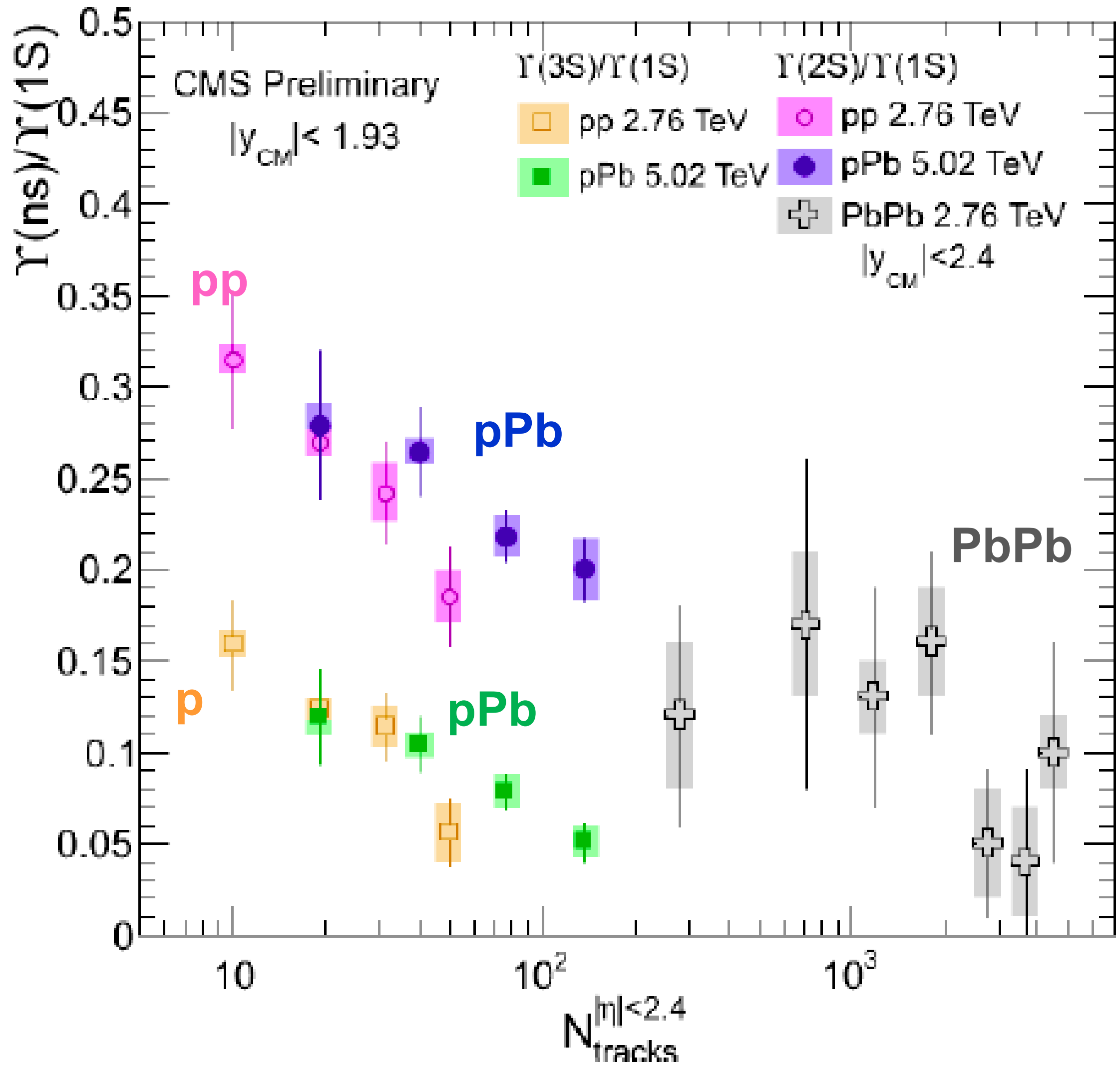




Suppression of quarkonia in p+Pb

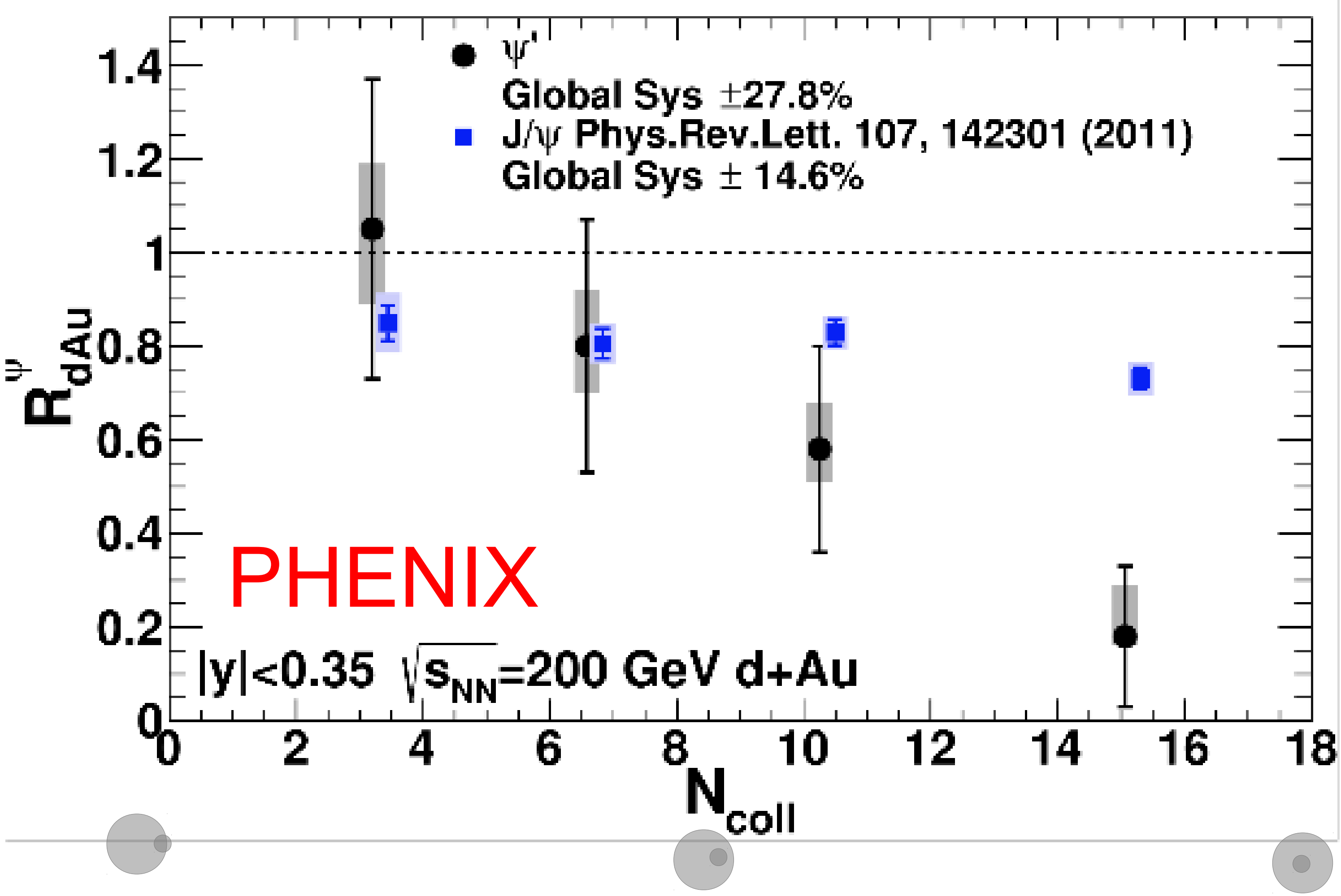




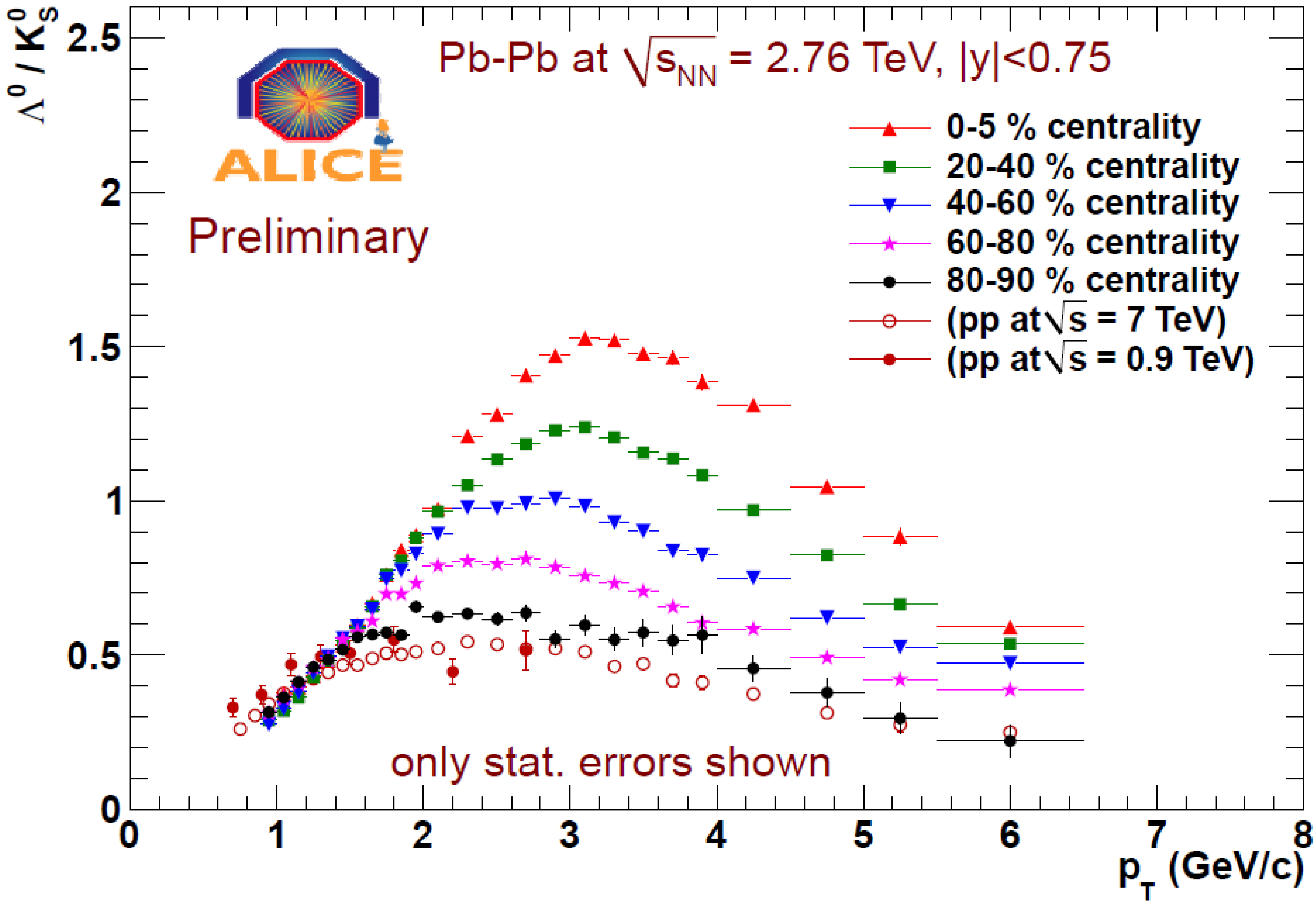


Suppression of quarkonia in d+Au

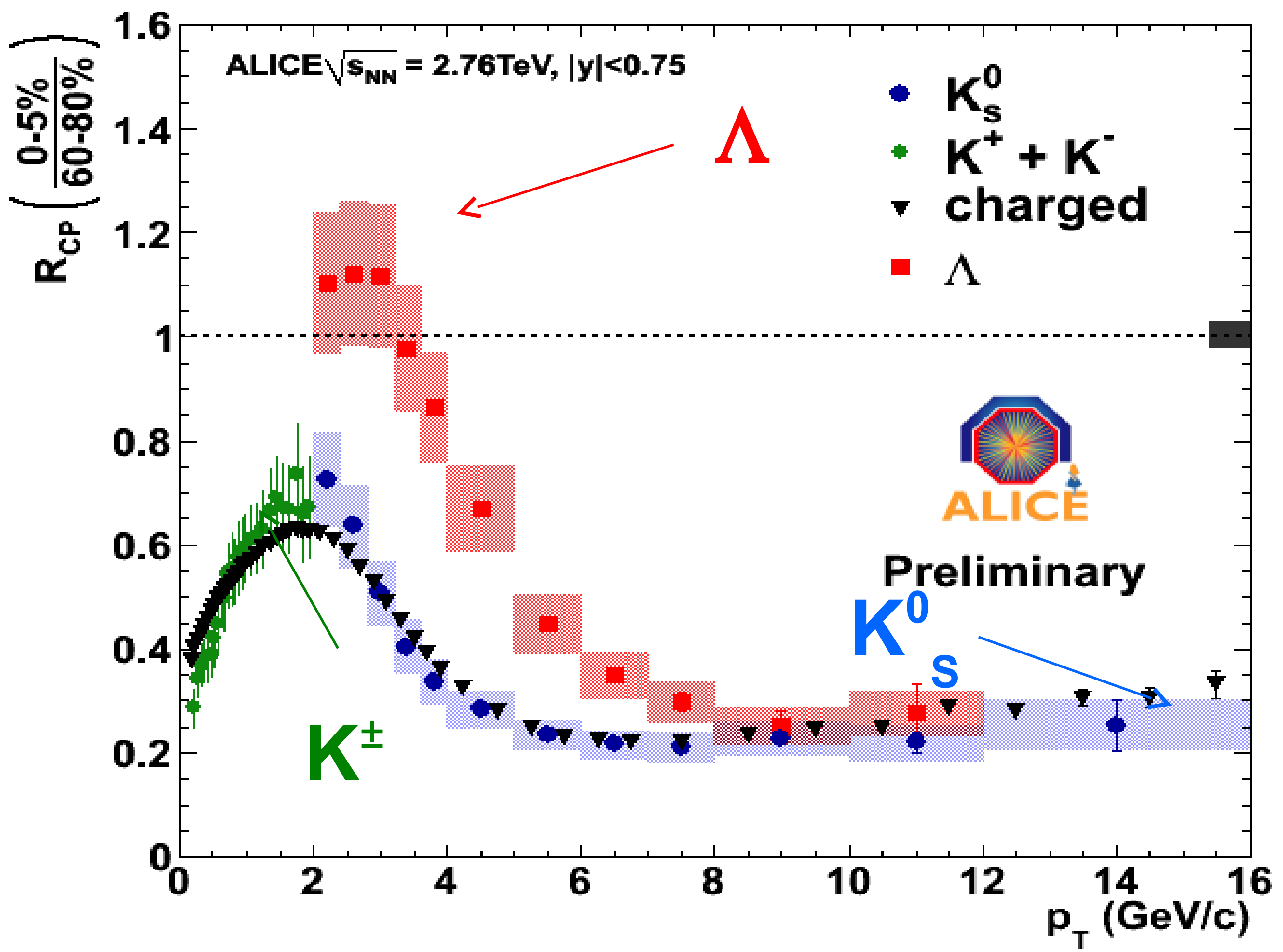
arXiv:1315.5516, to be publ PRL



Baryon anomaly: Λ/K^0_S



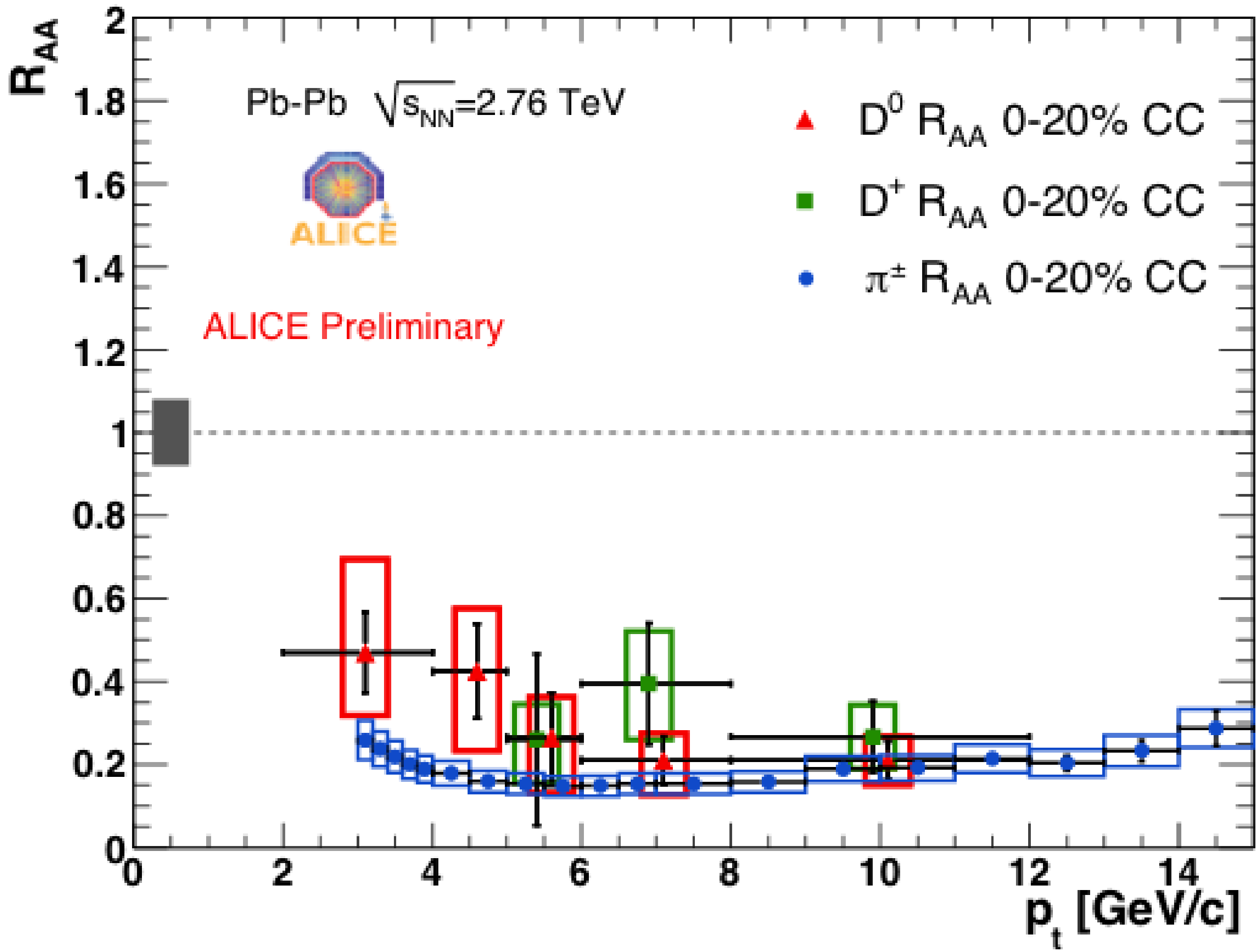
Nuclear modification factor (R_{AA})



$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

Pb+Pb

Charm nuclear modification factor



Pb+Pb