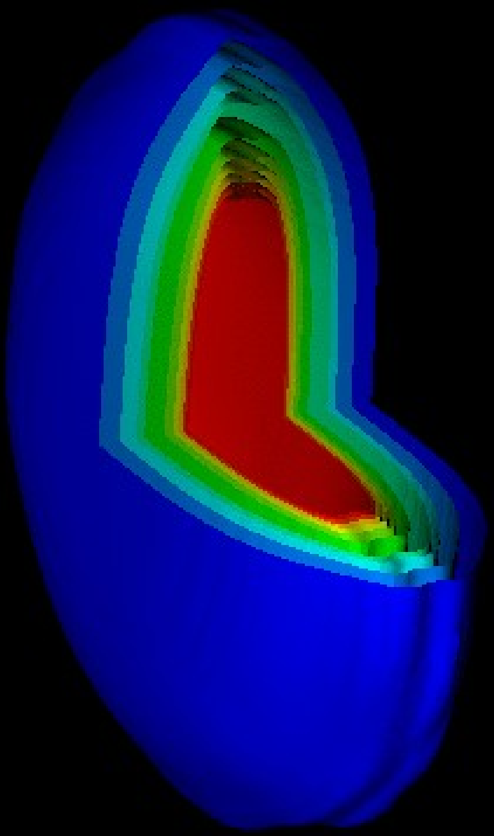
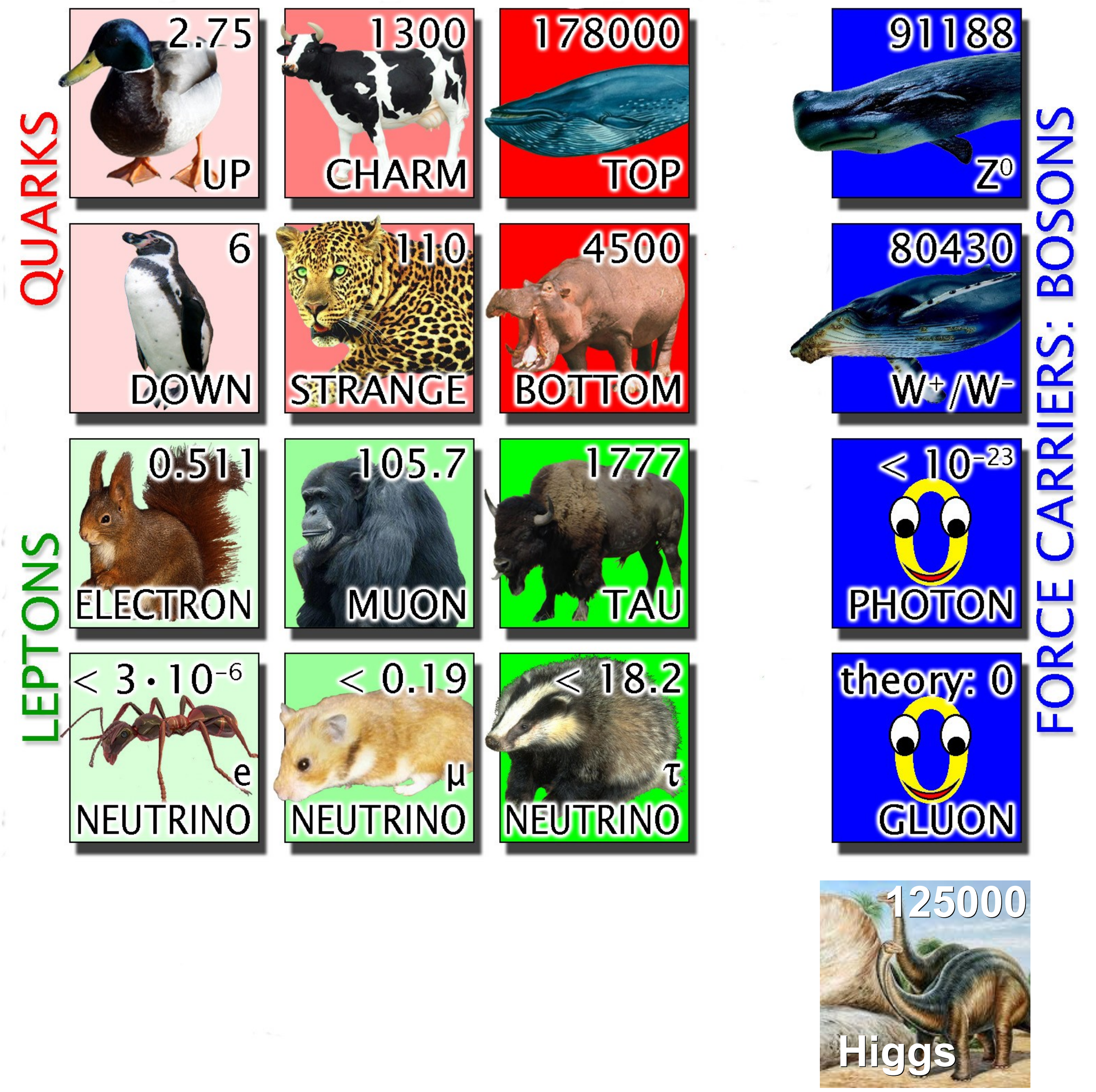
The little bang: understanding the Quark Gluon Plasma



Christine Nattrass
University of Tennessee at Knoxville

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

The Standard Model



Weak force

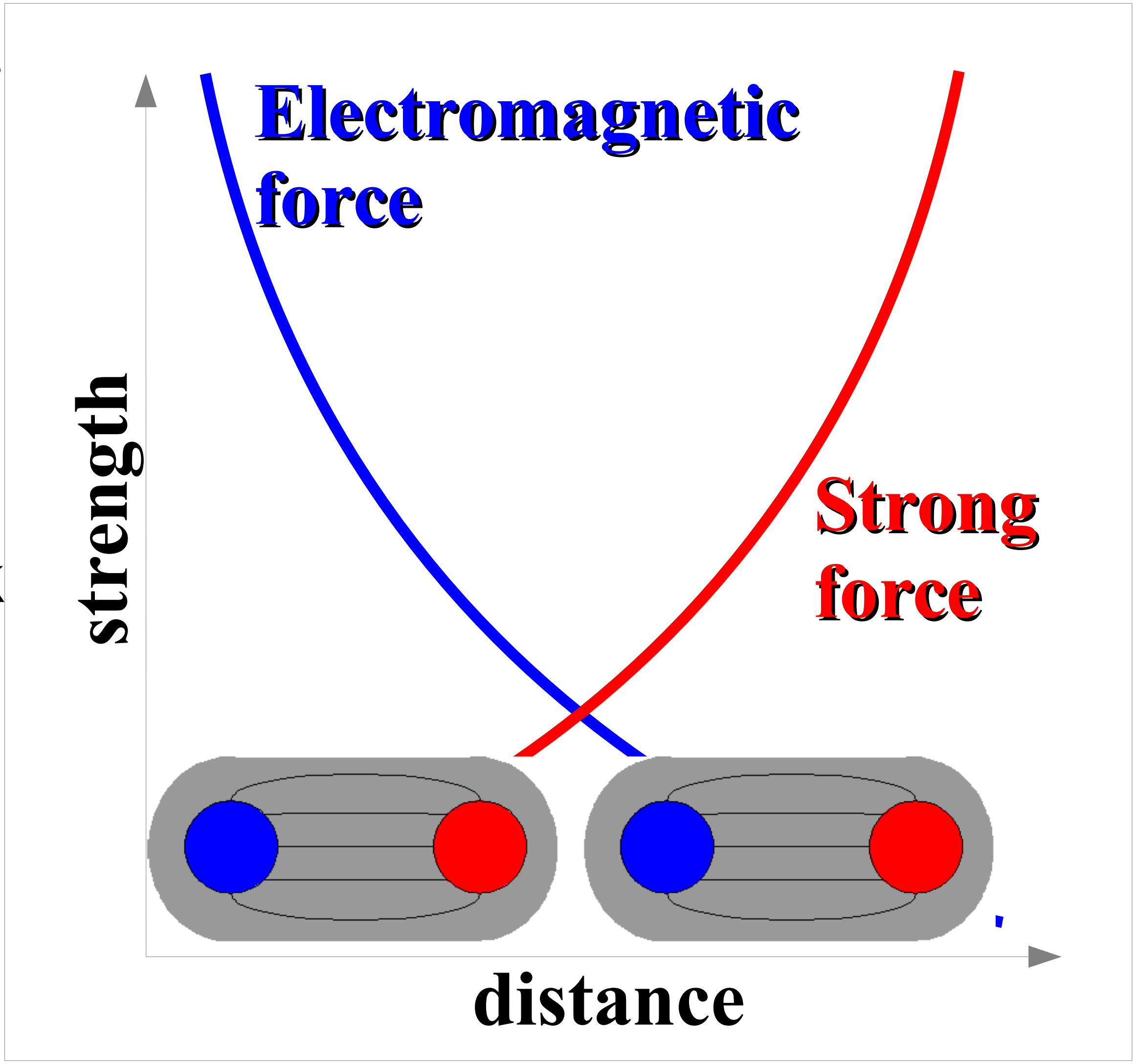
Electromagnetic force

Strong force

http://e4.physik.uni-dortmund.de/bin/view/ATLAS/SmBilder?PhotoarchivePlugin_page=1&PhotoarchivePlugin_view=detailed

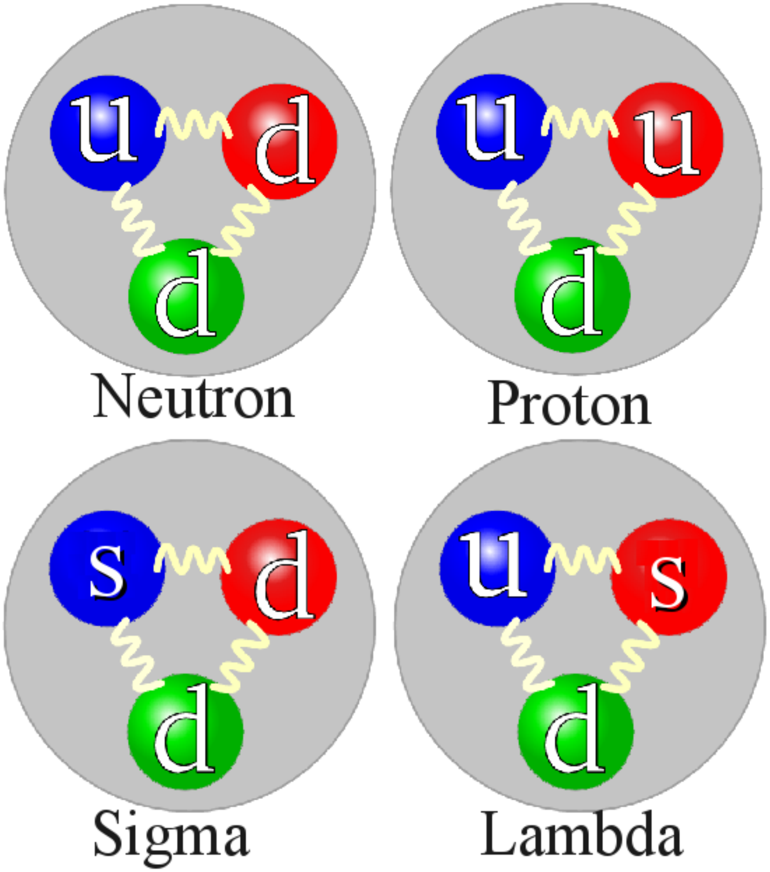
What keeps the nucleus together?

- Electric force: gets weaker as two objects get pulled apart
- Strong force: gets *stronger* as two objects get pulled apart – like a rubber band
- As we pull apart the quark and antiquark in a meson, at some point it takes less energy to make a quark-antiquark pair than to pull them further apart
- No free quarks - **confinement**



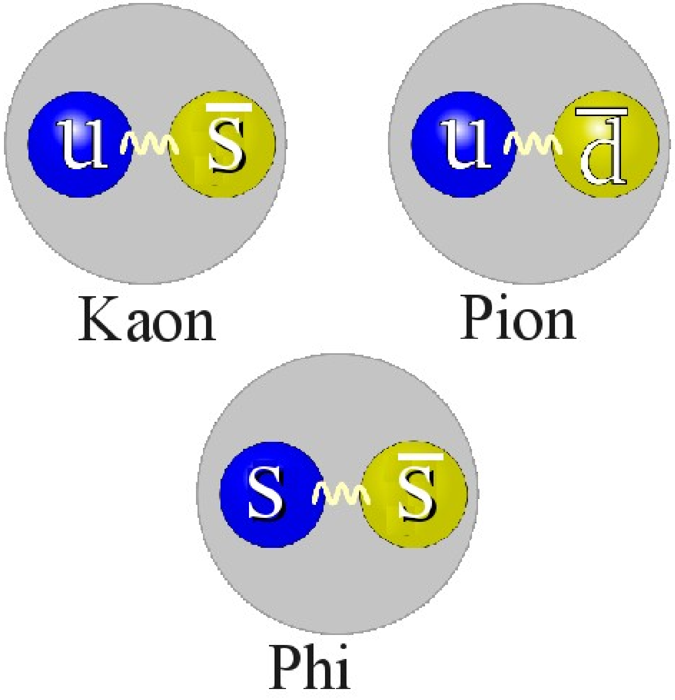
Hadrons

Baryons



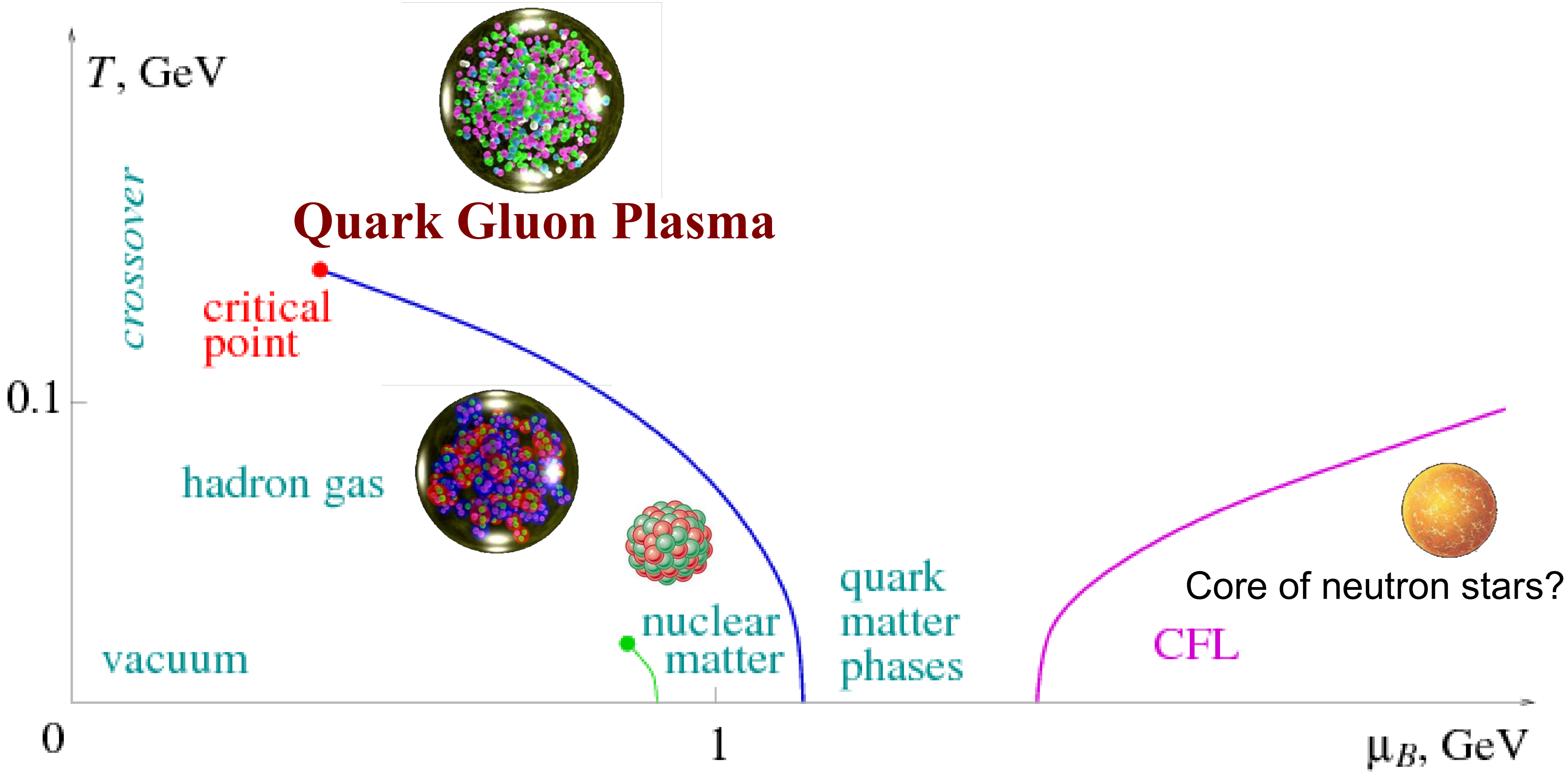
- 3 quarks/antiquarks
- Color charge: red-green-blue

Mesons



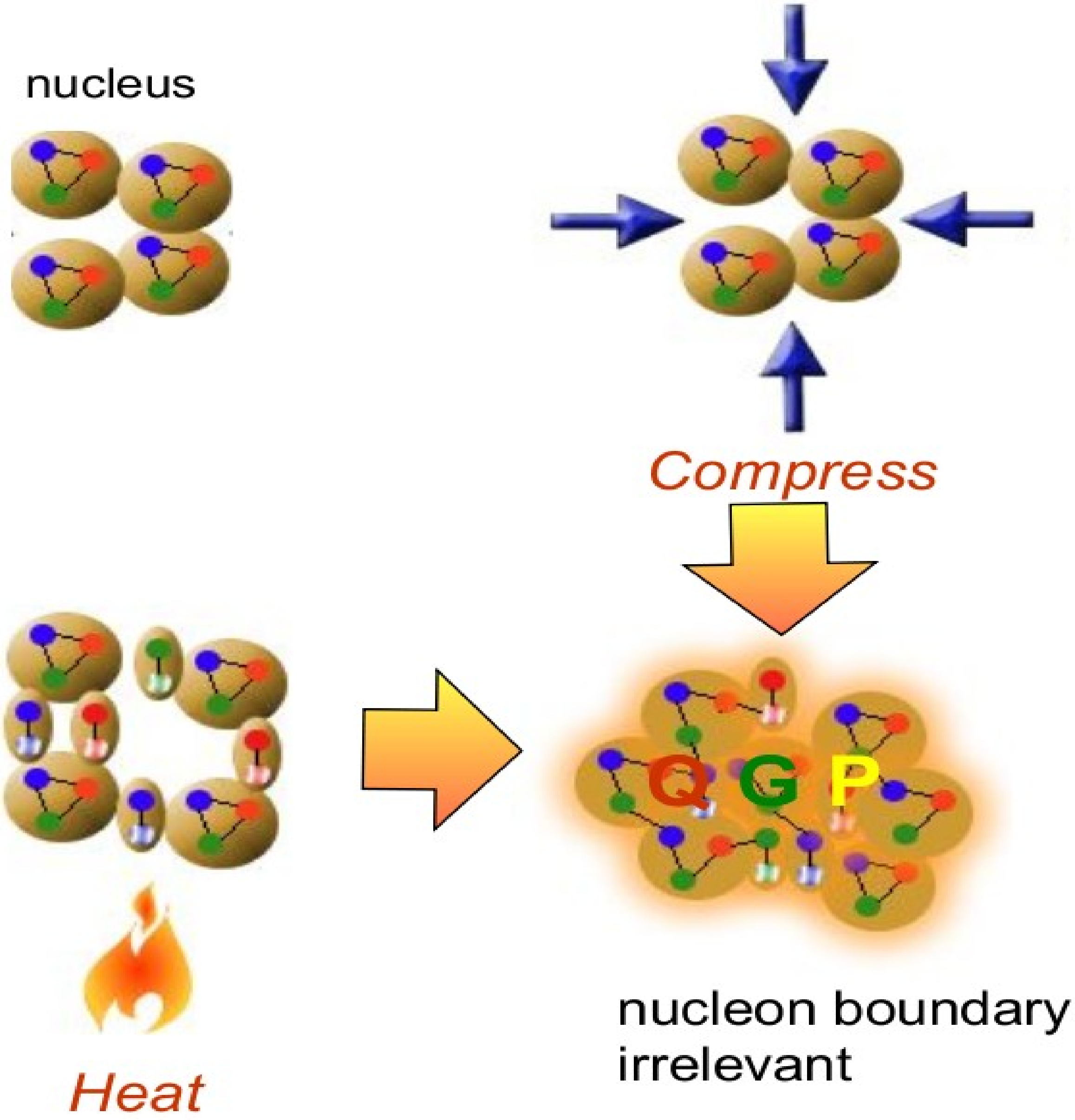
- Quark-antiquark
- Color charge: blue - anti-blue

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

How to make a Quark Gluon Plasma



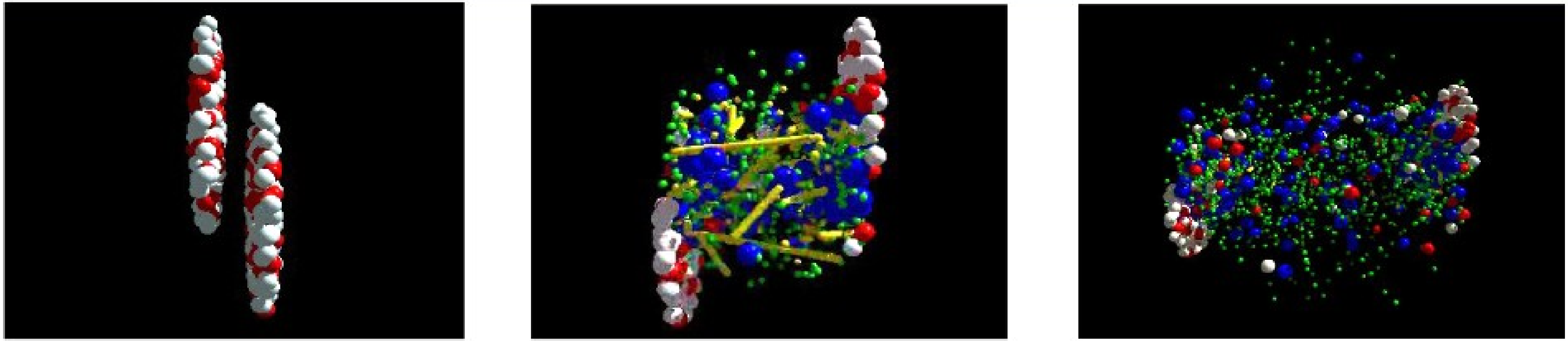
nucleus

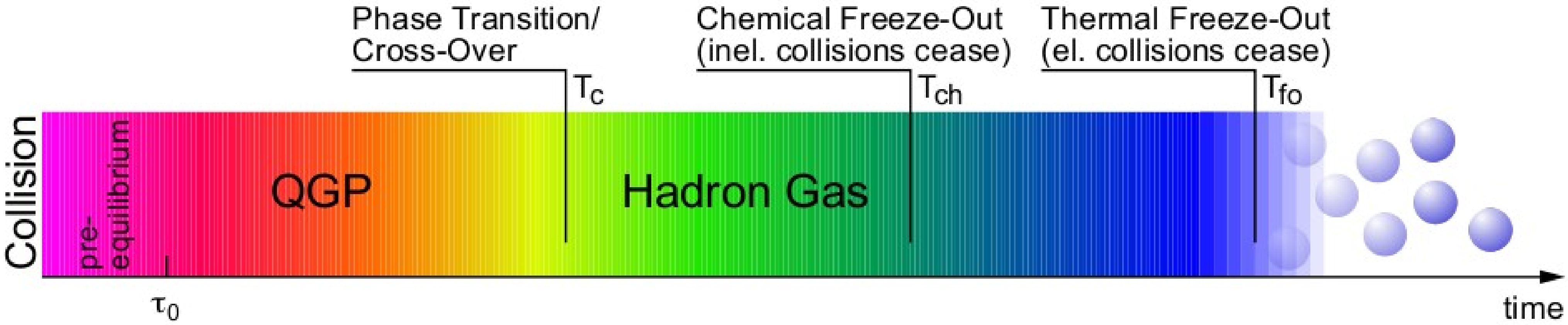
Compress

Heat

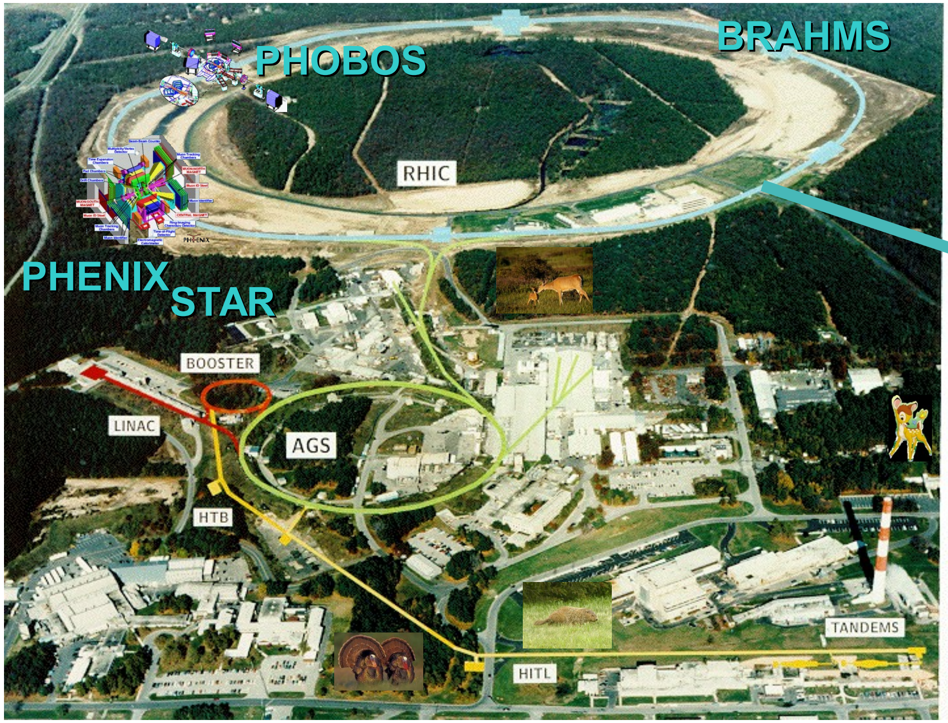
nucleon boundary
irrelevant

The phase transition in the laboratory



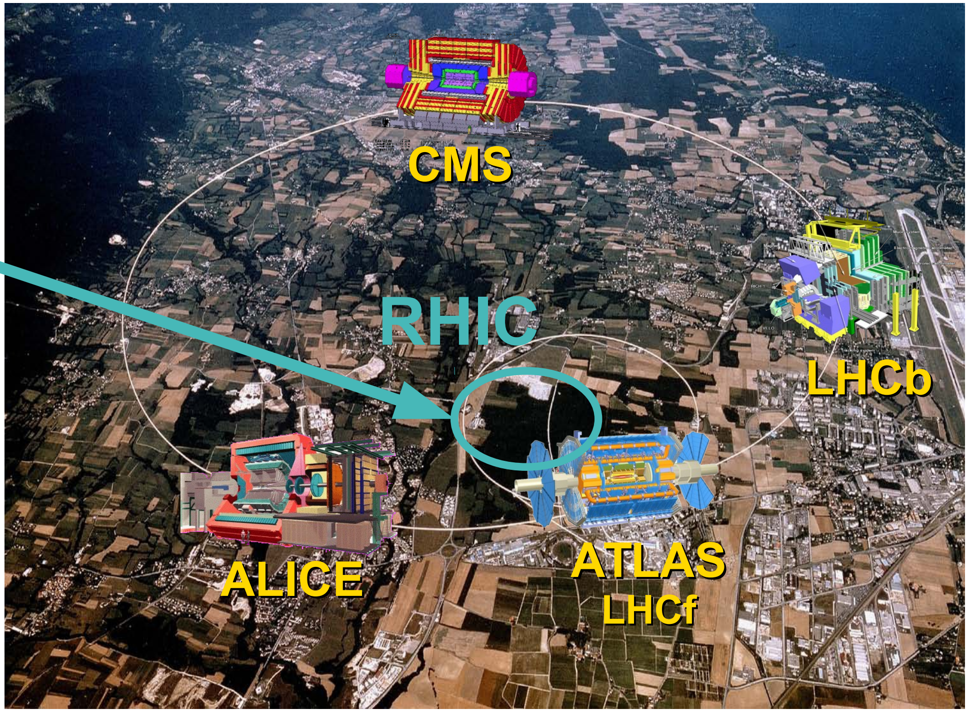


Relativistic Heavy Ion Collider

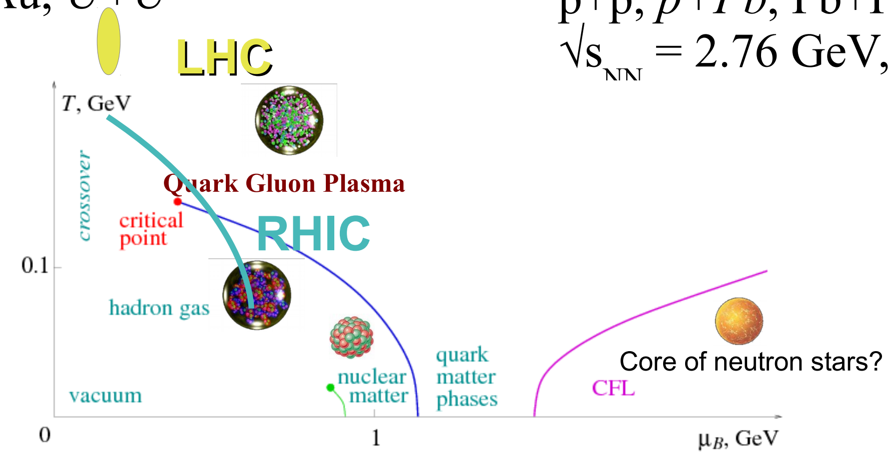


Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+U*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

Large Hadron Collider



Geneva, Switzerland
8.6km diameter
p+p, *p+Pb*, Pb+Pb
$\sqrt{s_{NN}}$ = 2.76 GeV, *5.5 TeV*



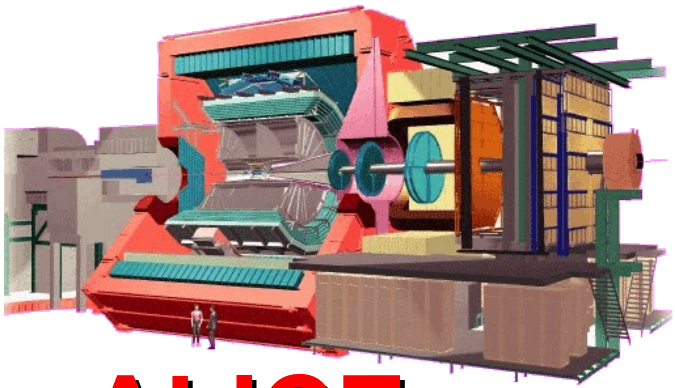
Comparison of colliders

	RHIC	**LHC**	
$\sqrt{s_{NN}}$ (GeV)	9-200	2760, 5500	*center of mass energy*
$dN_{ch}/d\eta$	~1200	~1600	*number of particles*
T/T_c	1.9	3.0-4.2	*temperature*
ε (GeV/fm^3)	5	12, 16	*energy density*
τ_{QGP} (fm/c)	2-4	>10	*lifetime of QGP*

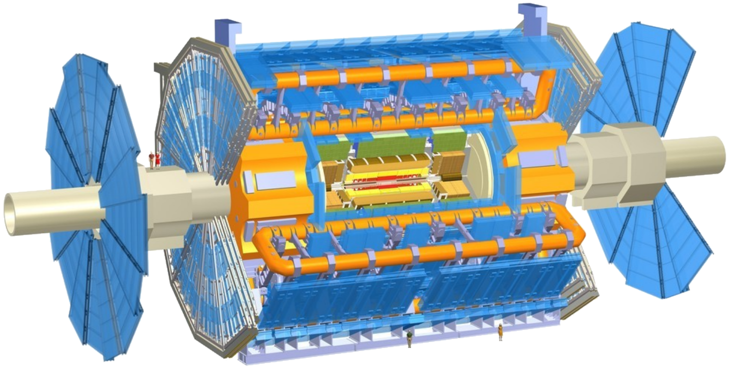
<u>RHIC and LHC:</u>

Cover 2 –3 decades of energy ($\sqrt{s_{NN}}$= 9 GeV –5 TeV)

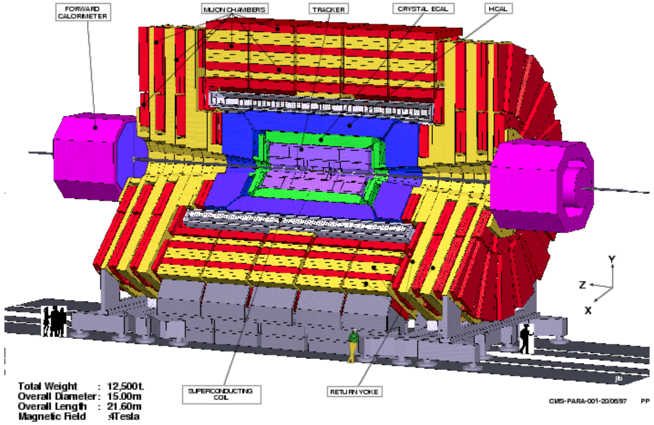
To discover the properties of hot nuclear matter at T ~ 150 –600 MeV



ALICE

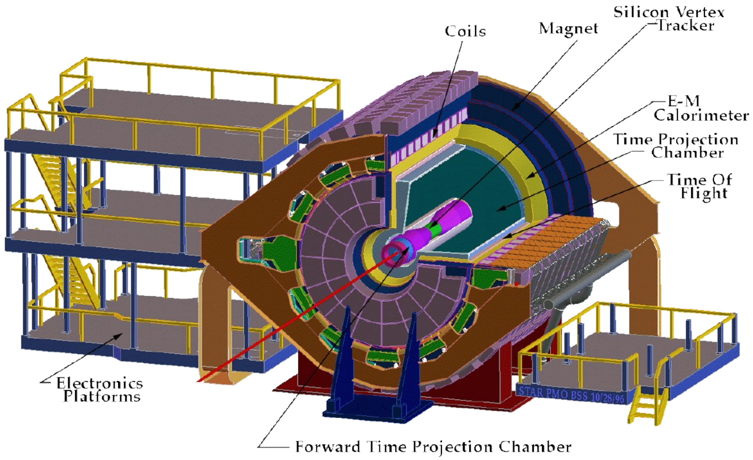


ATLAS

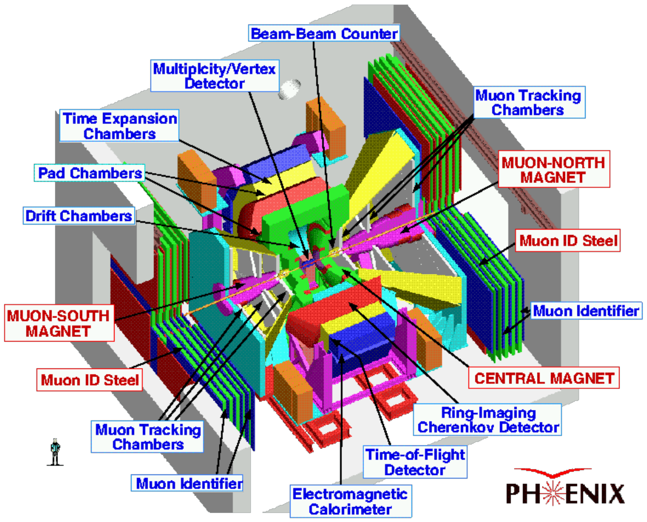


Total Weight : 12,500t.
Overall Diameter: 15.00m
Overall Length : 21.60m
Magnetic Field :4Tesla

CMS



STAR

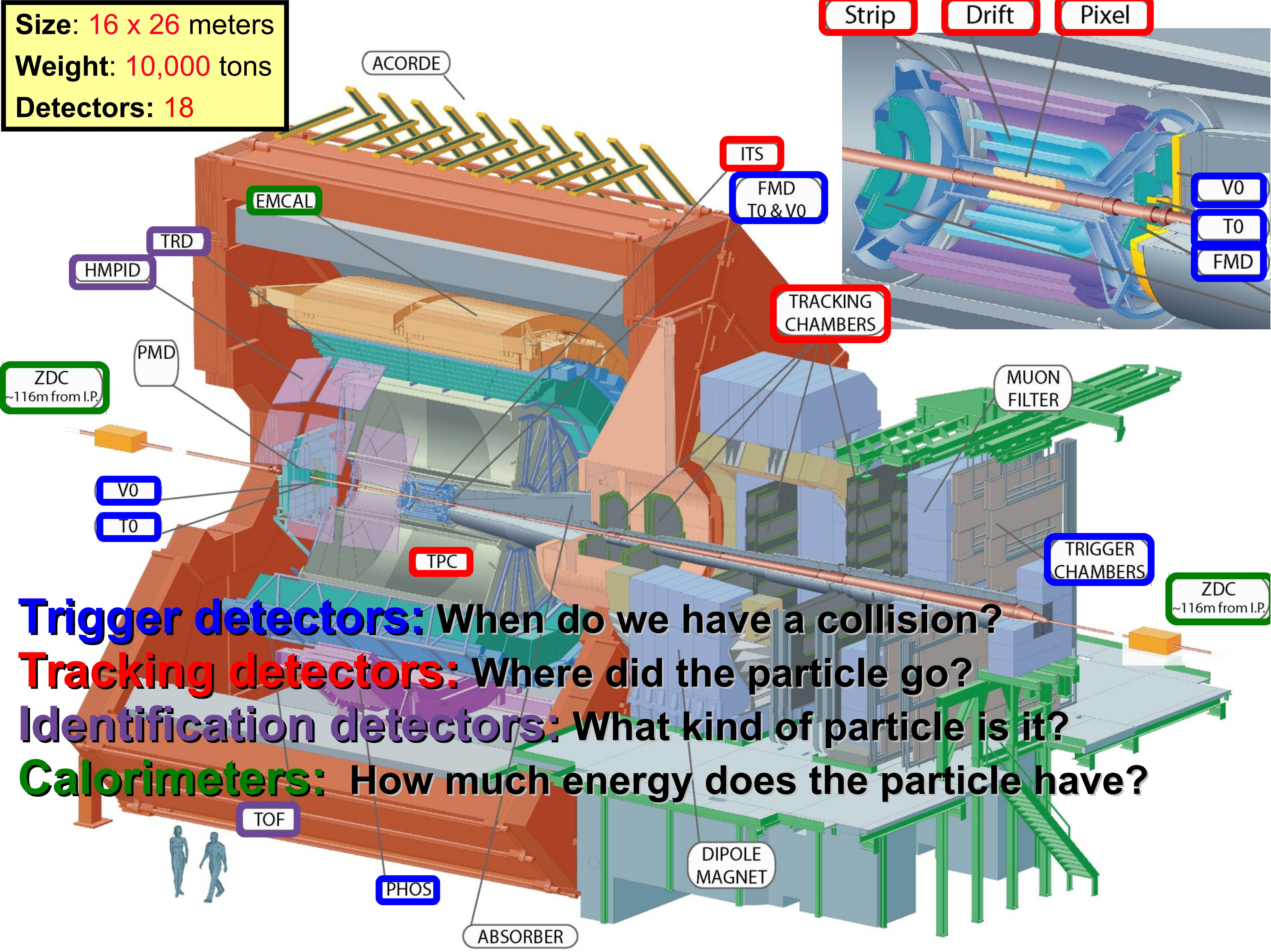


PHENIX

Interesting observables

- Different hadronization mechanisms
  → Identify particle types
- Collective motion of particles
  → Low momentum acceptance
- Even common processes are not well understood
  → Do not need 4π acceptance or high rates

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



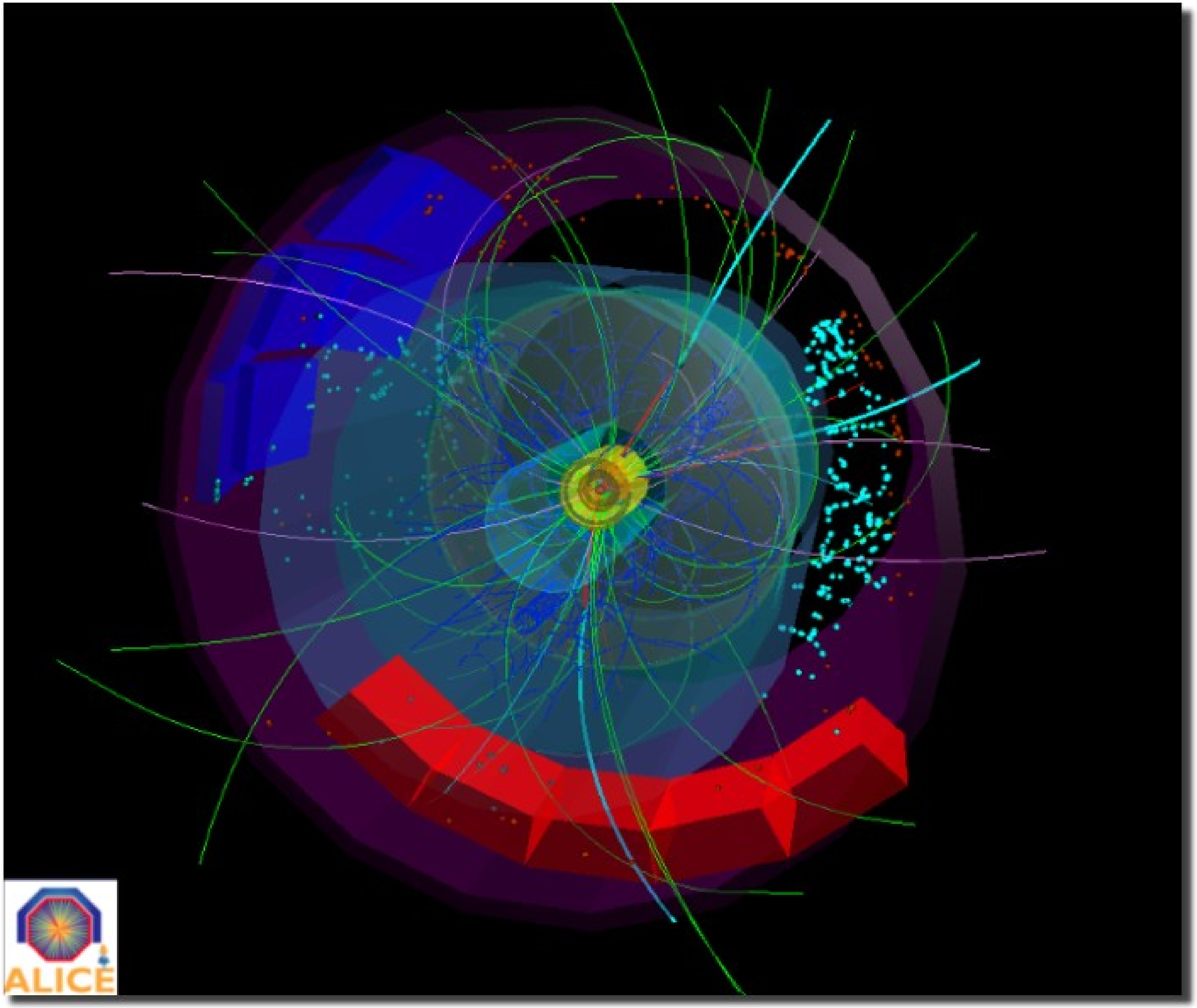
Trigger detectors: When do we have a collision?

Tracking detectors: Where did the particle go?

Identification detectors: What kind of particle is it?

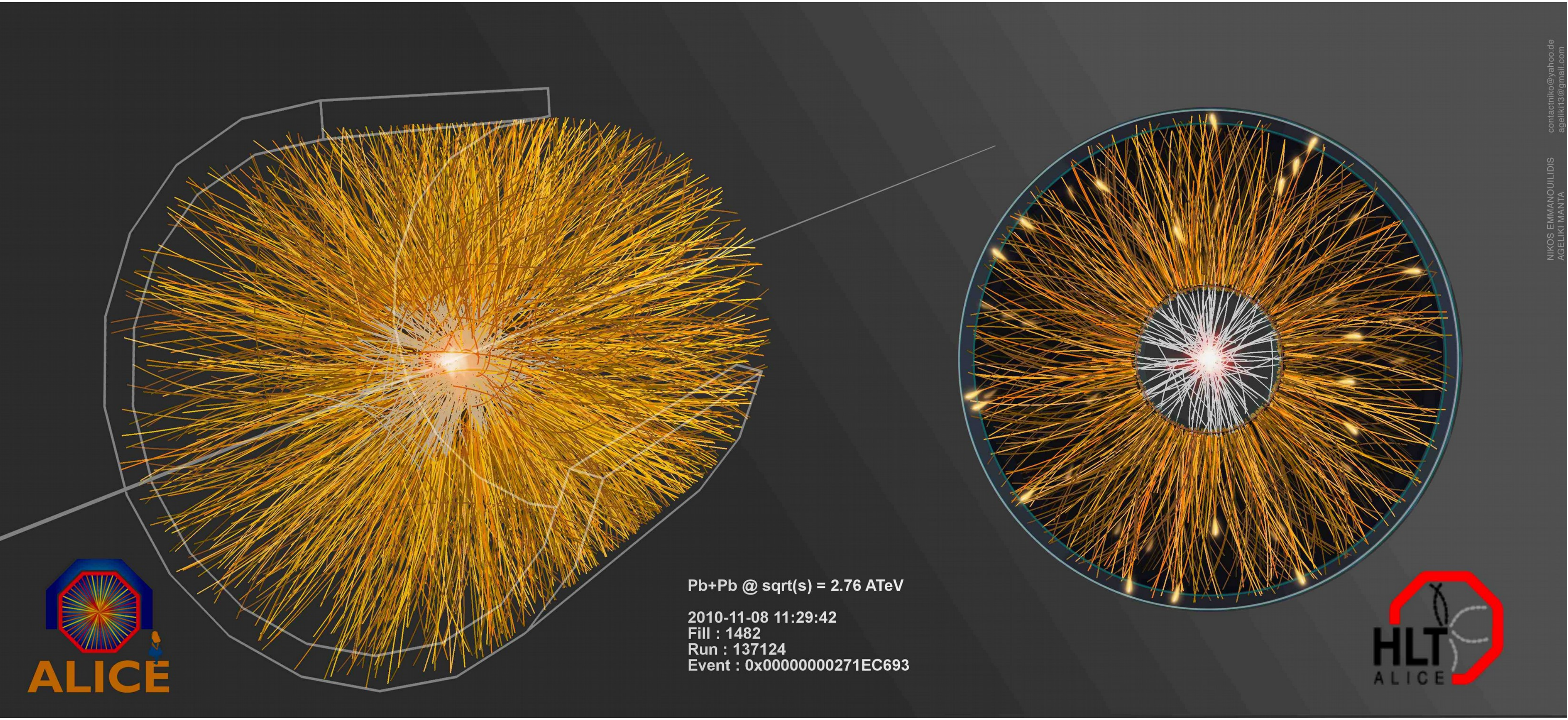
Calorimeters: How much energy does the particle have?

p+p collisions



3D image of each collision

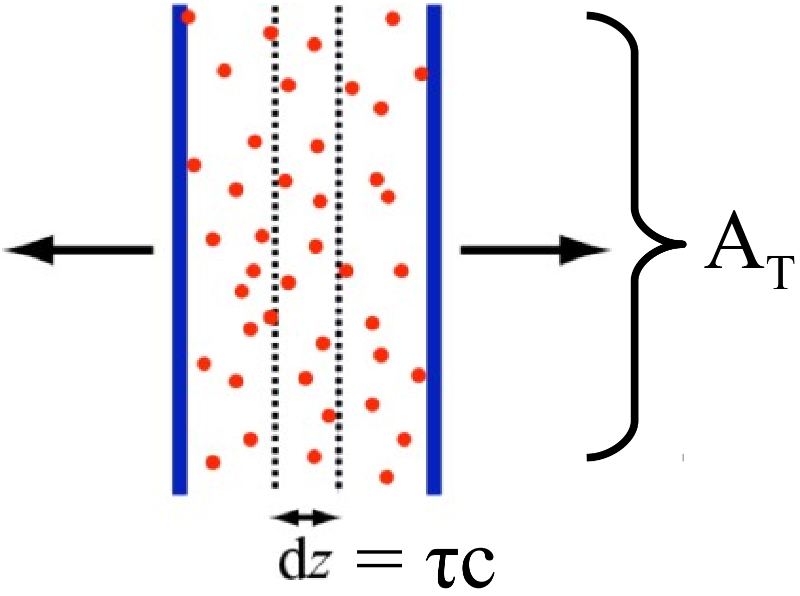
Pb+Pb collisions



QGP Energy Density

How can we estimate the energy density?

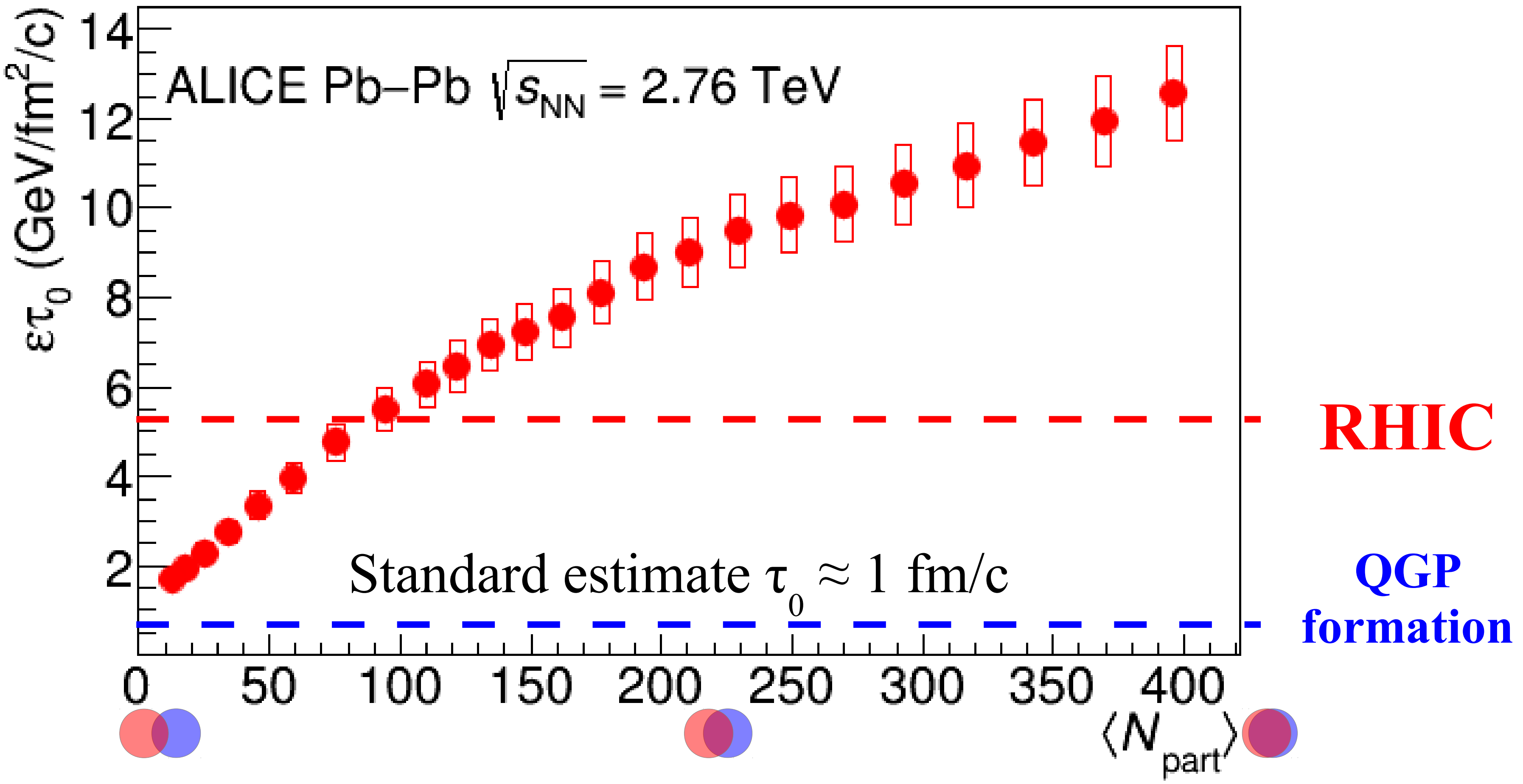
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



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

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

Energy density

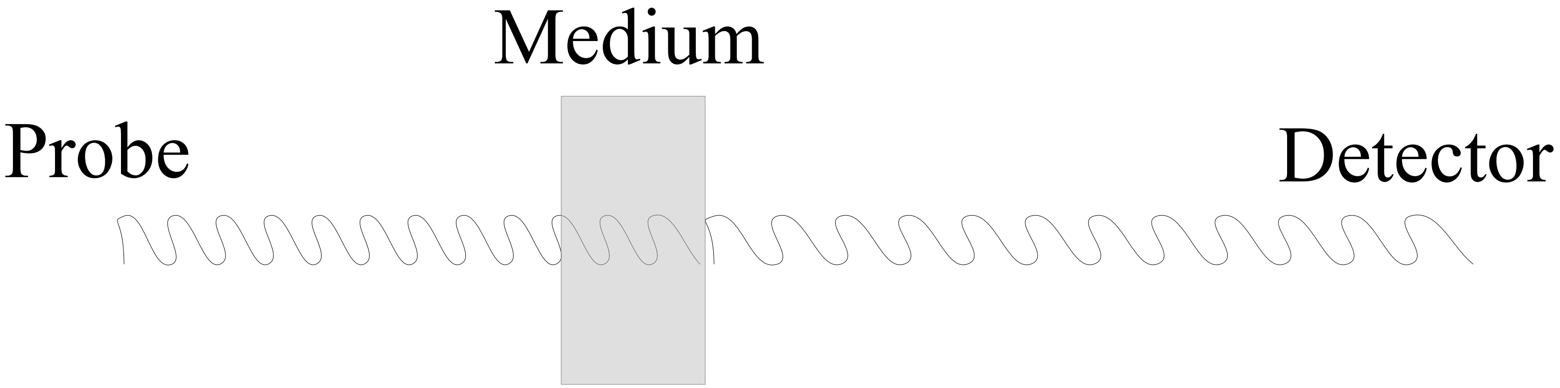


Standard estimate $\tau_0 \approx 1$ fm/c

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

QGP Spectroscopy

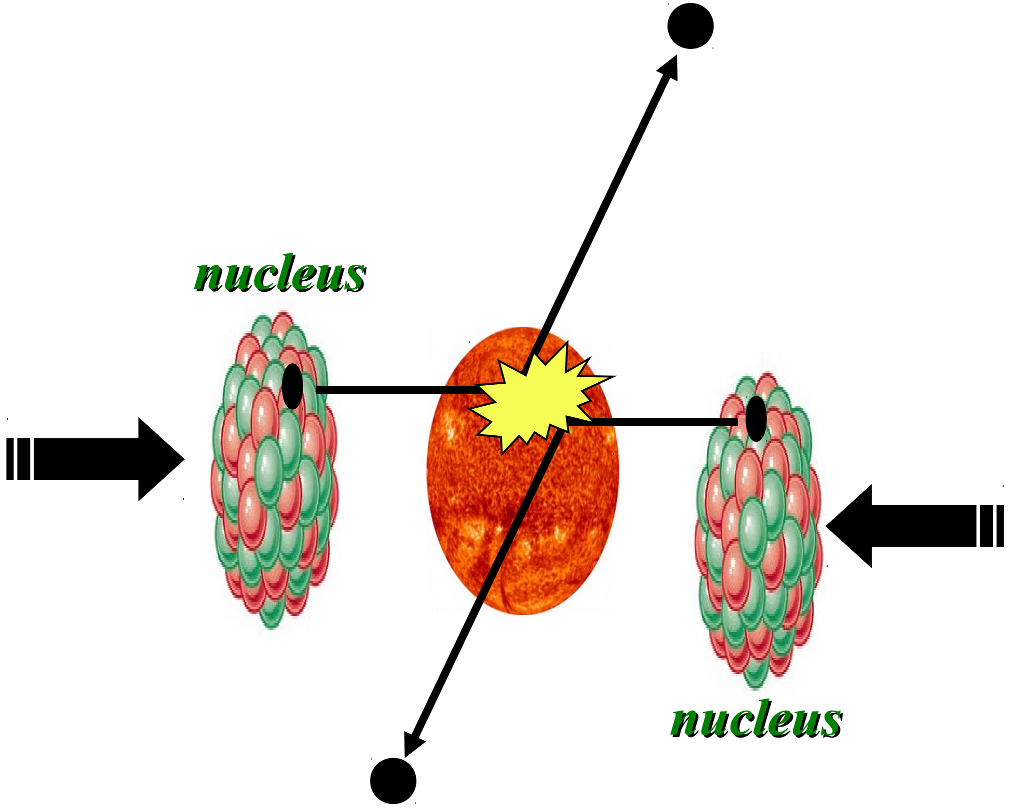
Probing the Quark Gluon Plasma



Want a probe which traveled through the collision

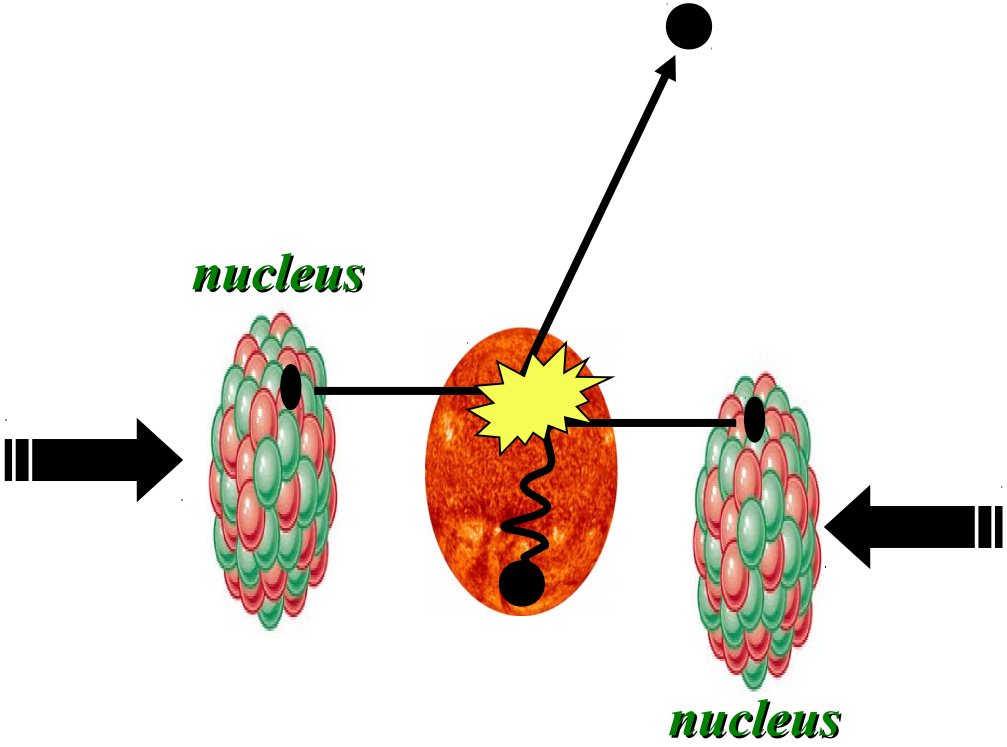
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



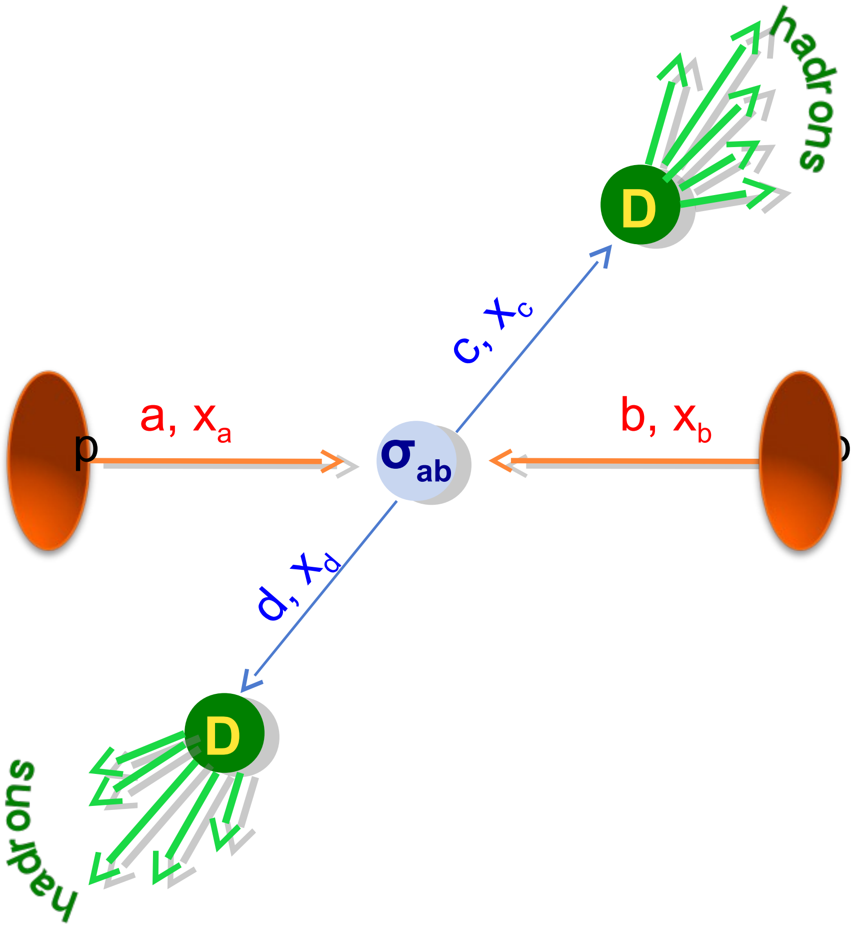
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

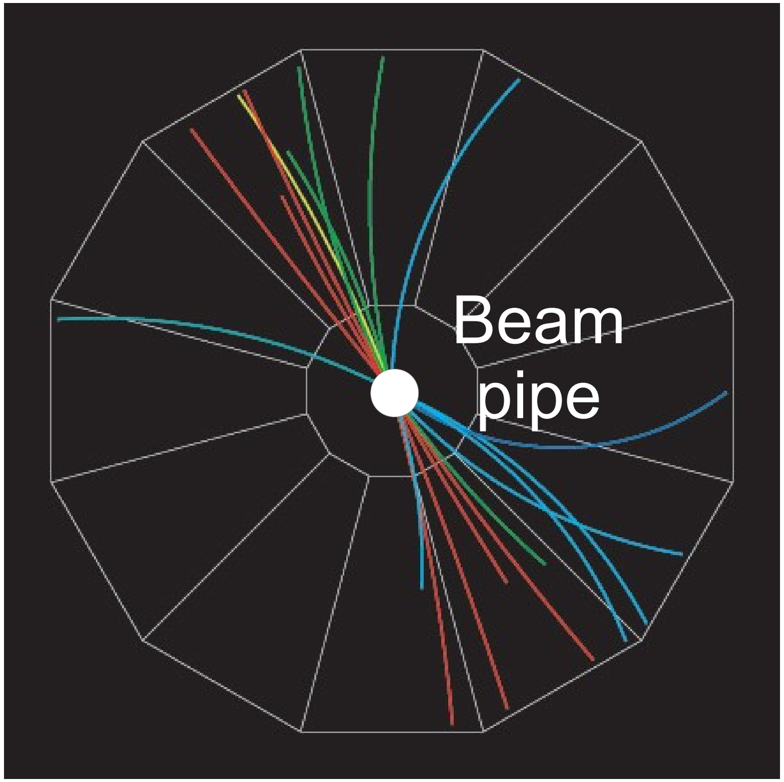


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets

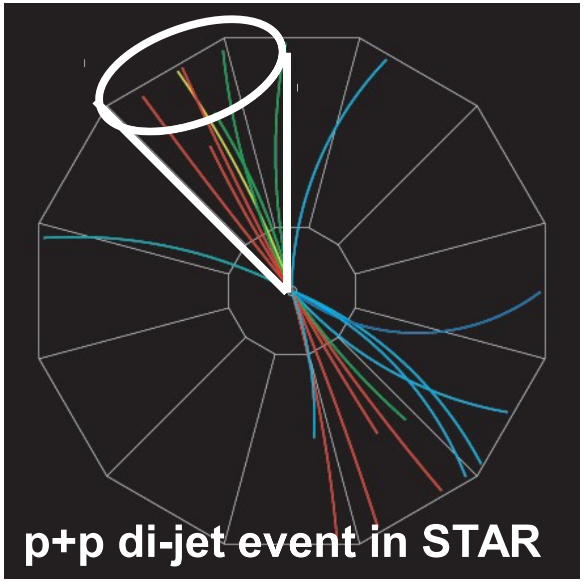


p+p → dijet

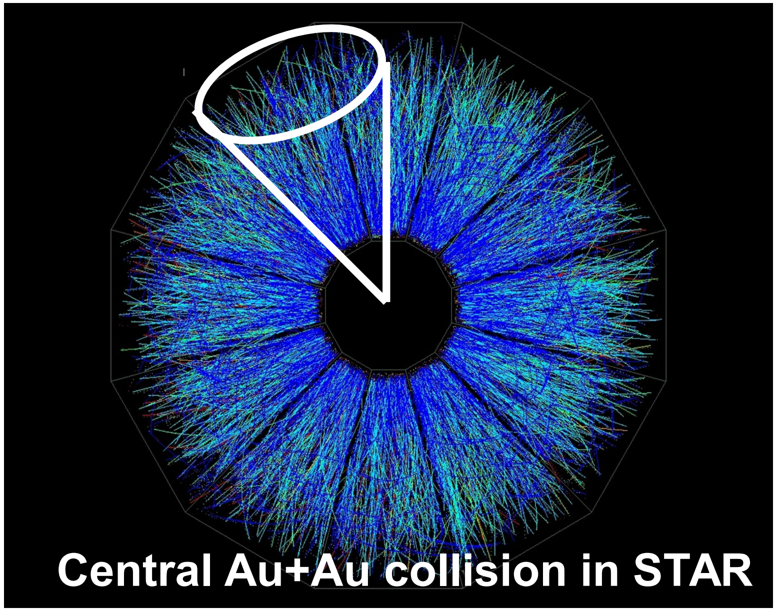


Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

Jet reconstruction



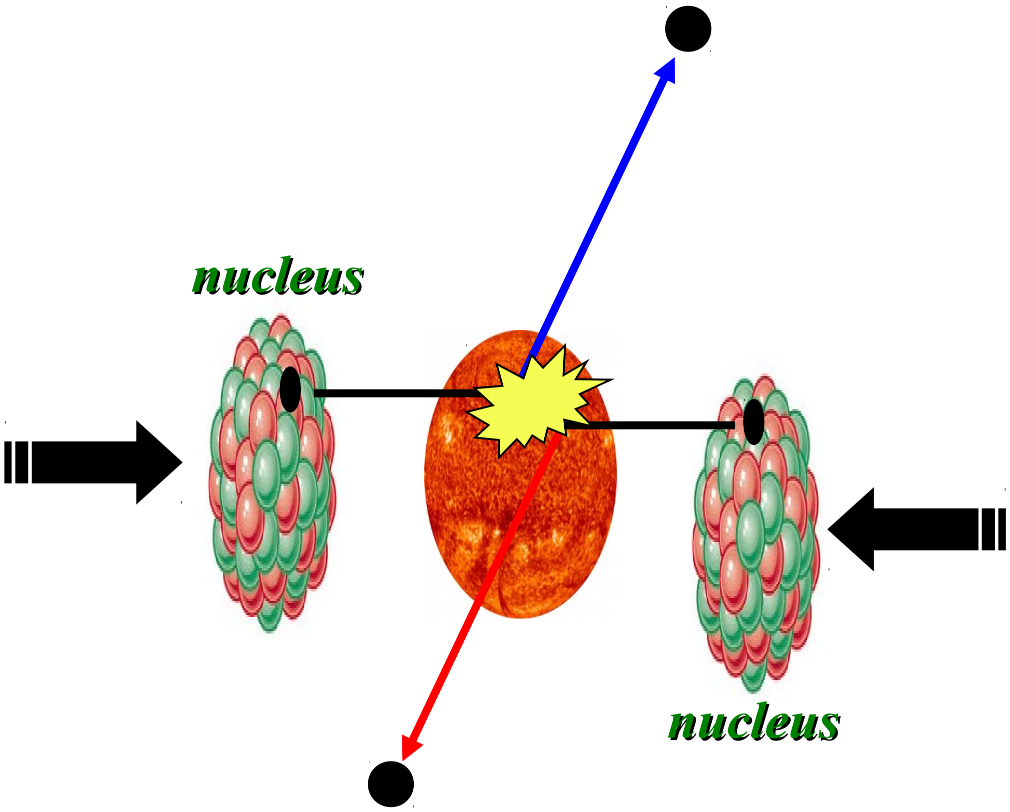
p+p di-jet event in STAR



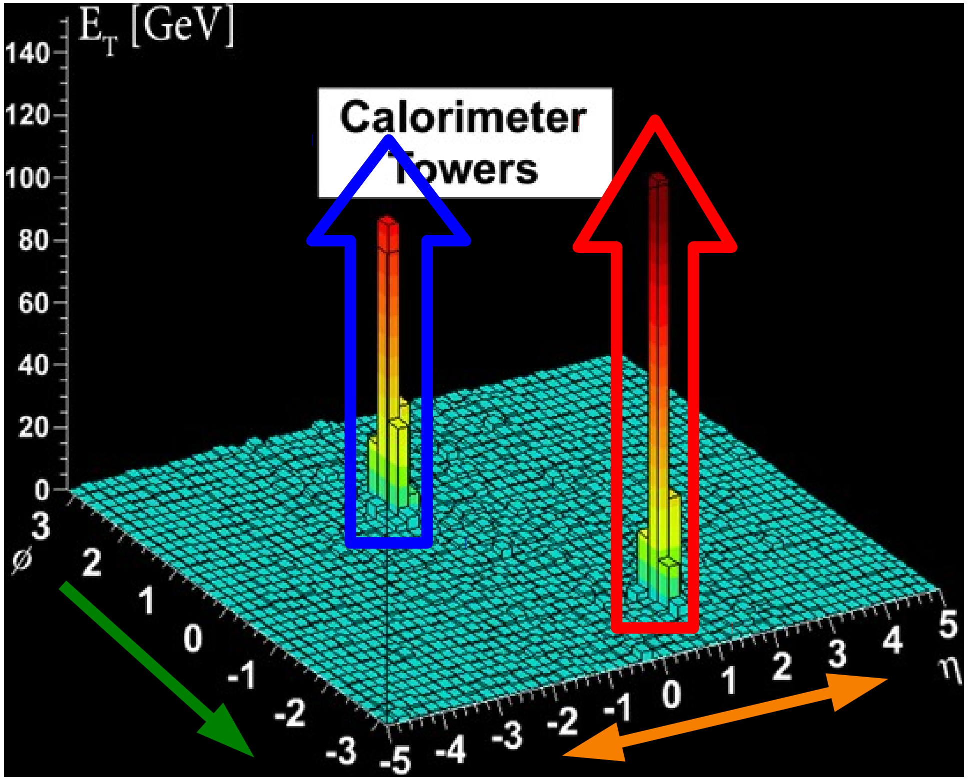
Central Au+Au collision in STAR

- Identify all of the particles in the jet → parton energy, momentum
- Difficult in heavy ion collisions – but possible!

Jets



Phys.Rev.Lett. 105 (2010) 252303



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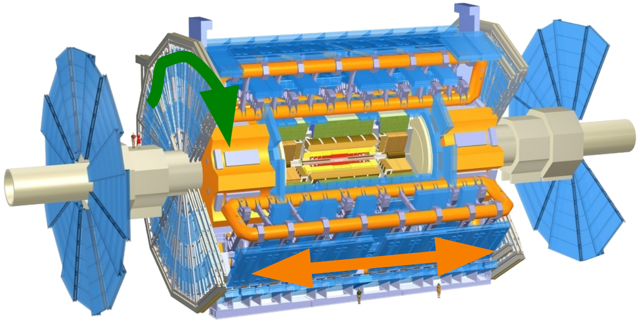
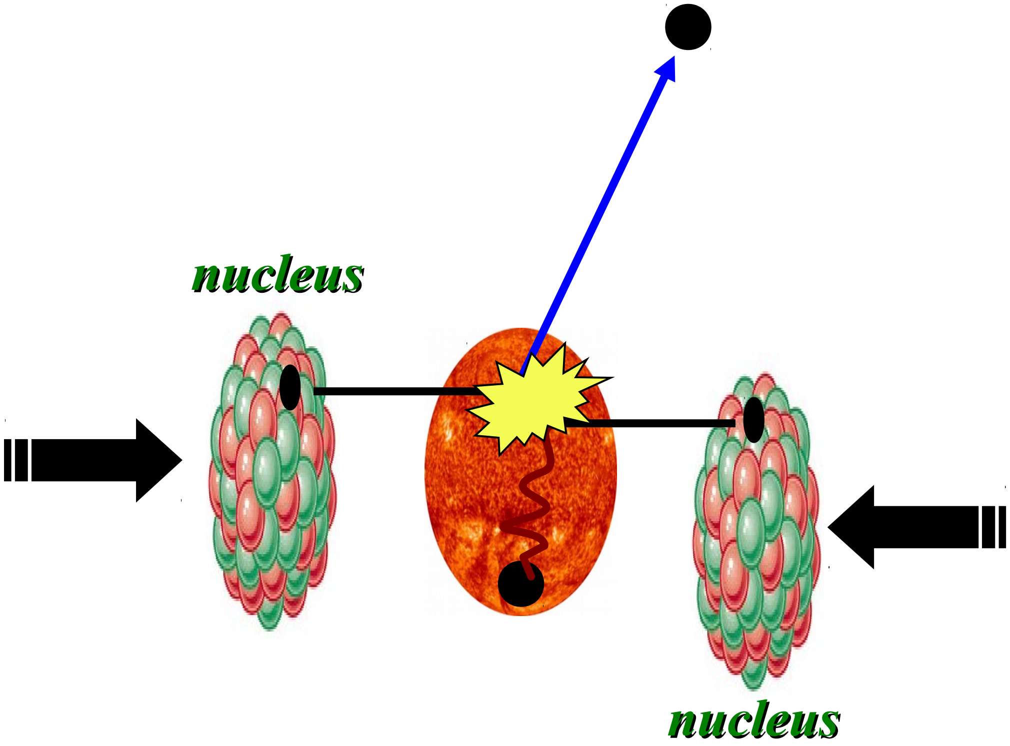
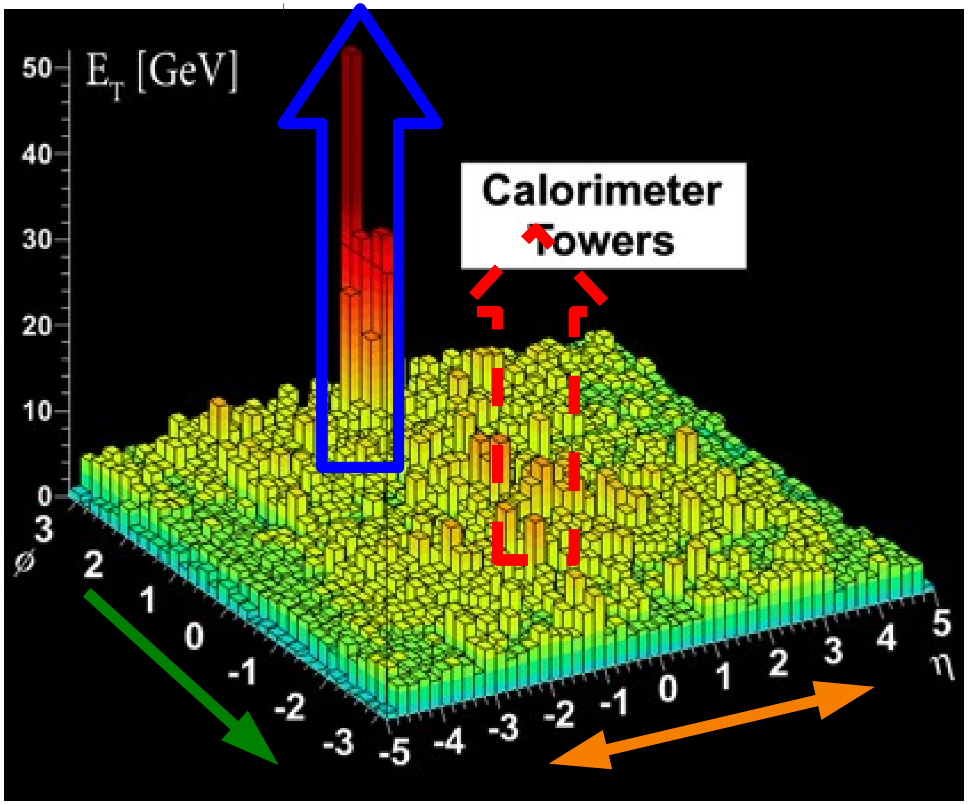


Quenched jets





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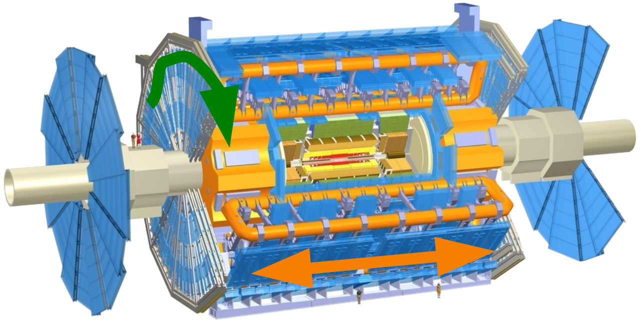
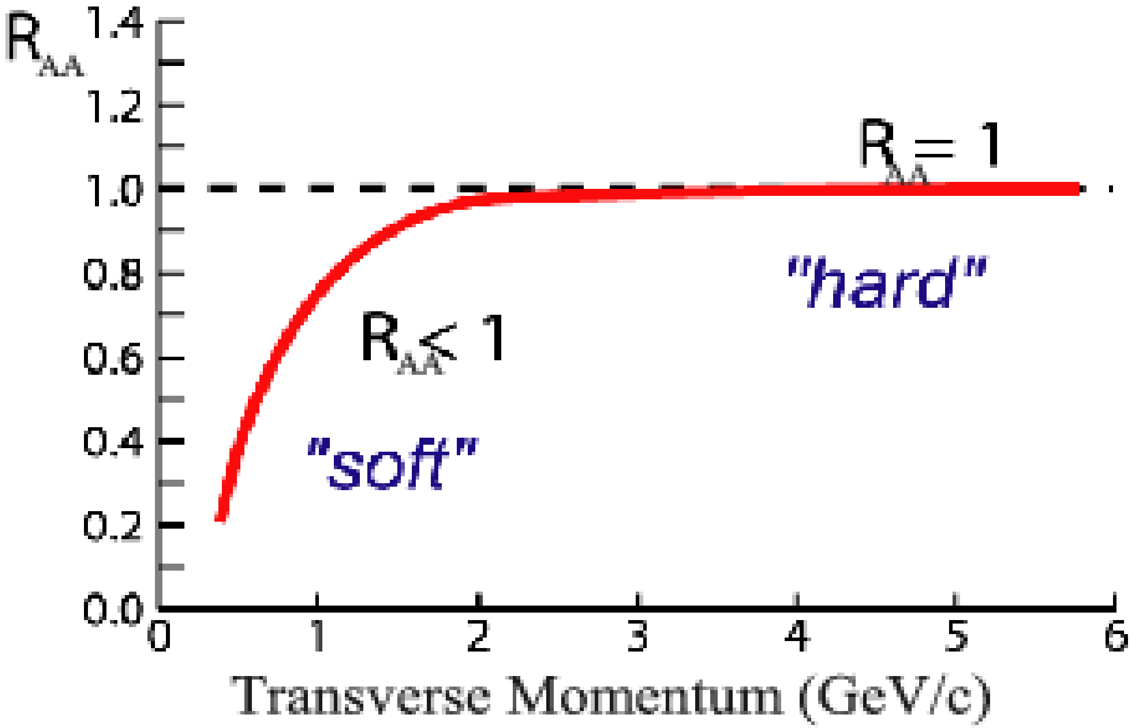


- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
- Phys. Rev. Lett. 105, 252303 (2010)

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

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

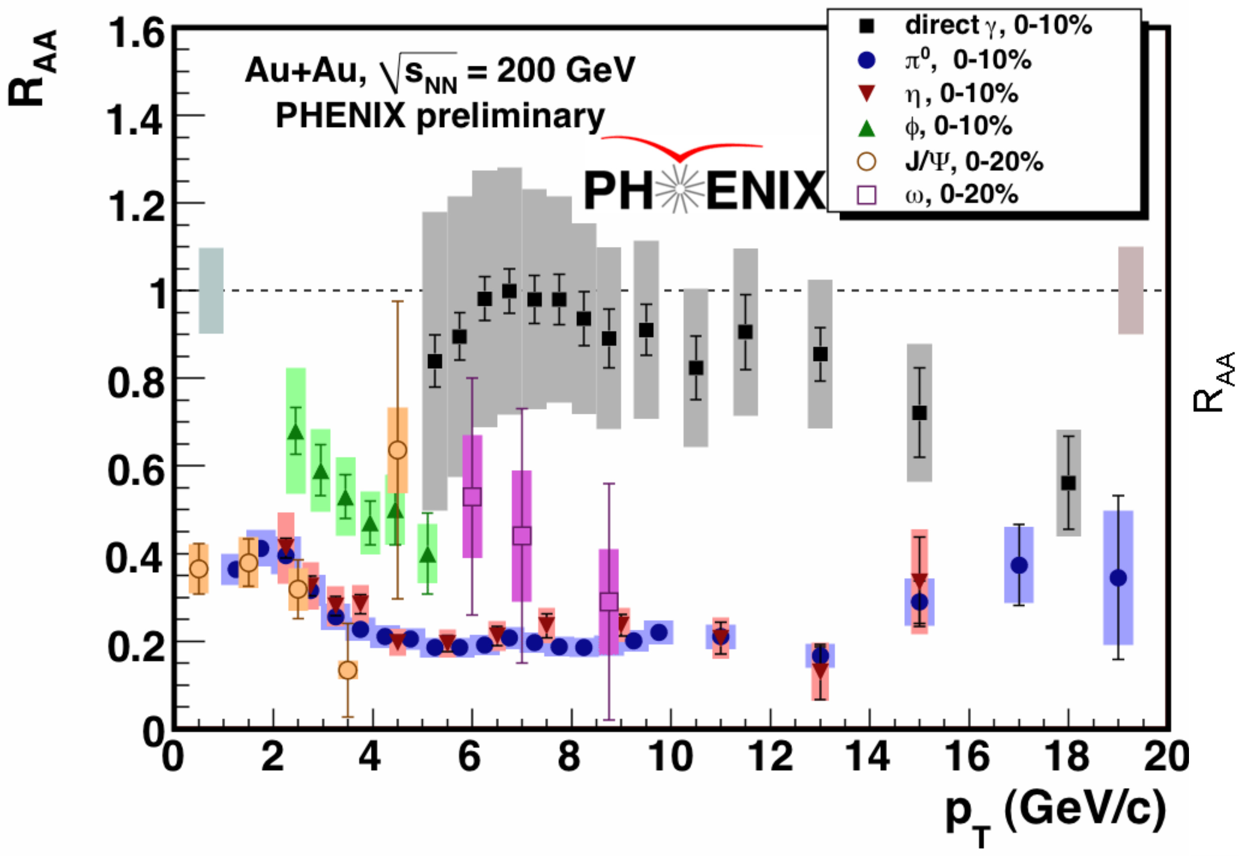


Enhancement

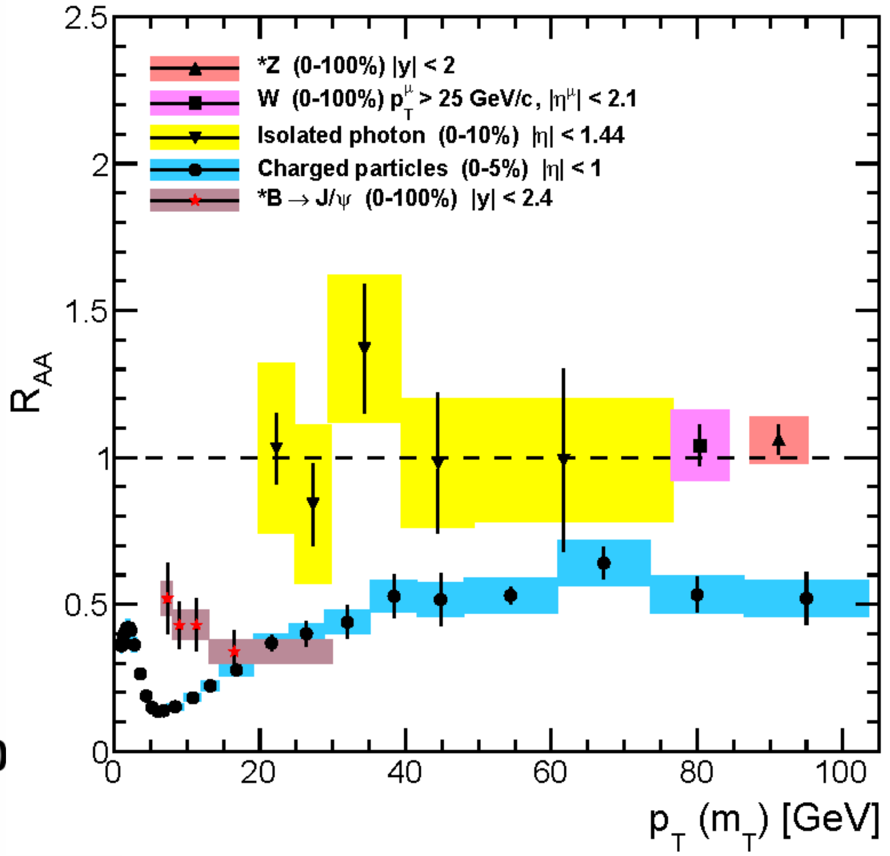
Suppression

Nuclear modification factor R_{AA}

RHIC



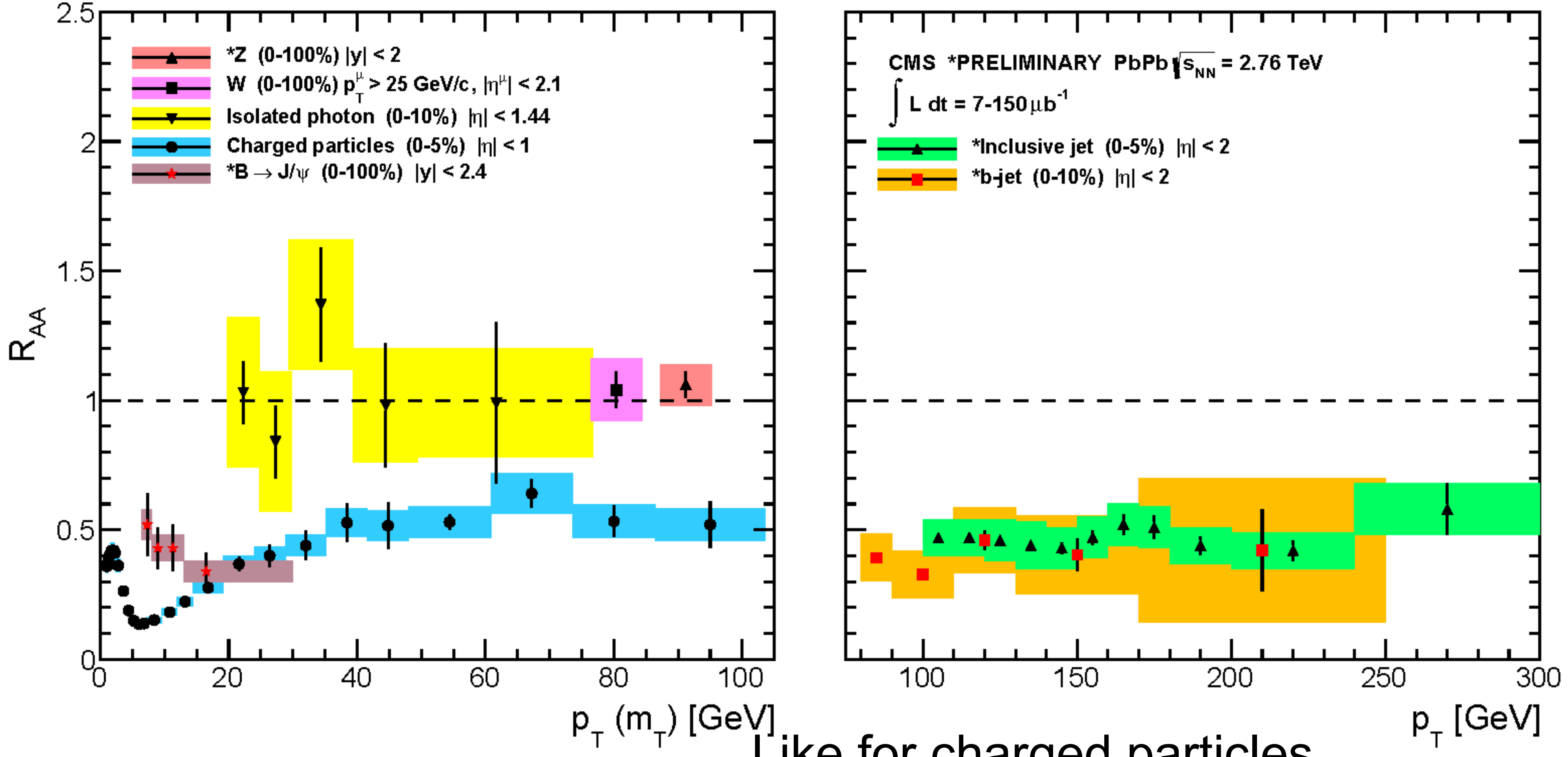
LHC



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

Nuclear modification factor R_{AA} at LHC

Fully unfolded inclusive jet R_{AA}
pp 2.76 TeV reference



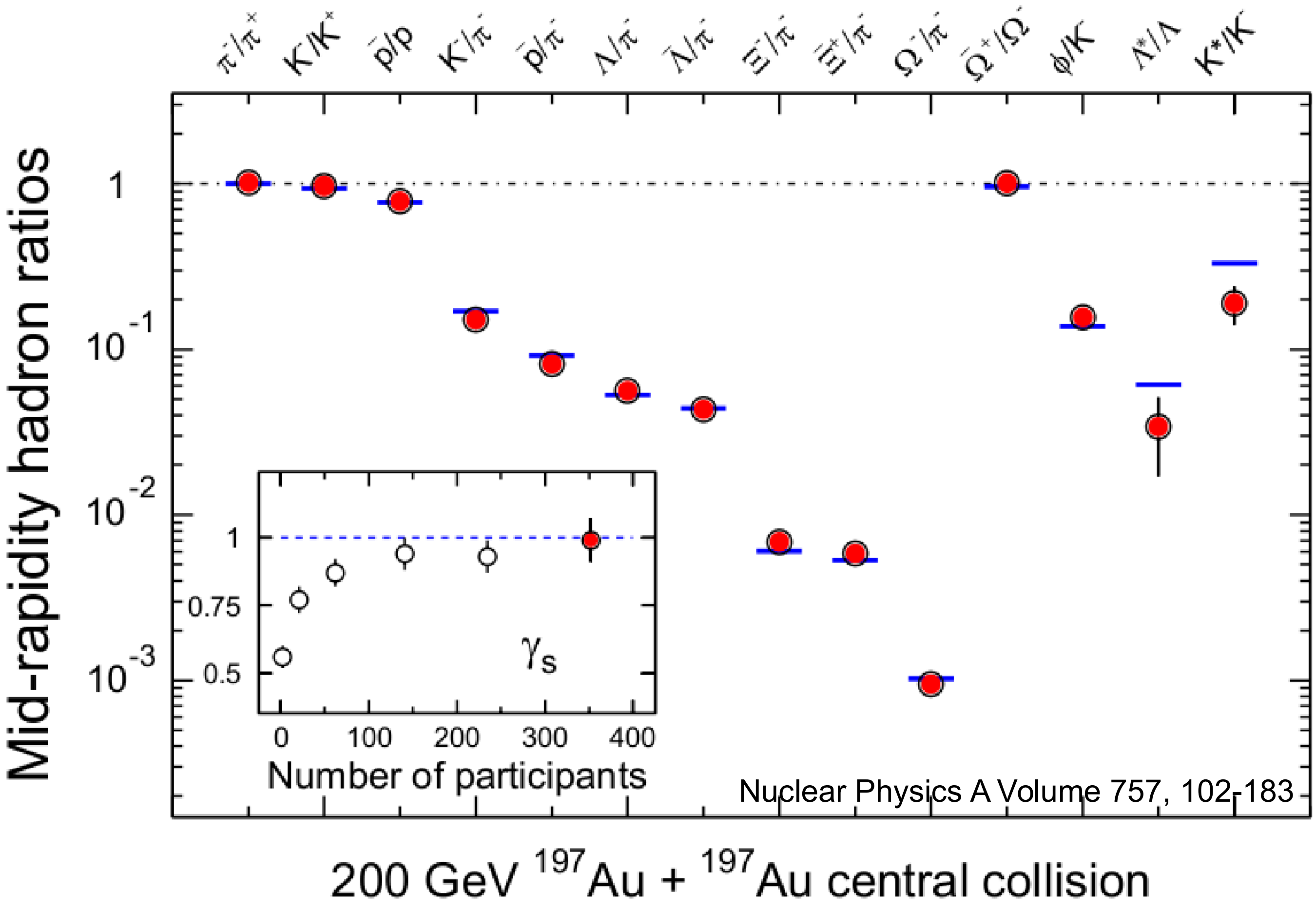
CMS-PAS HIN-12-001

Like for charged particles, high-p_T jet R_{AA} flat at ≈ 0.5

QGP Chemistry

Chemistry - equilibrium

T~170 MeV

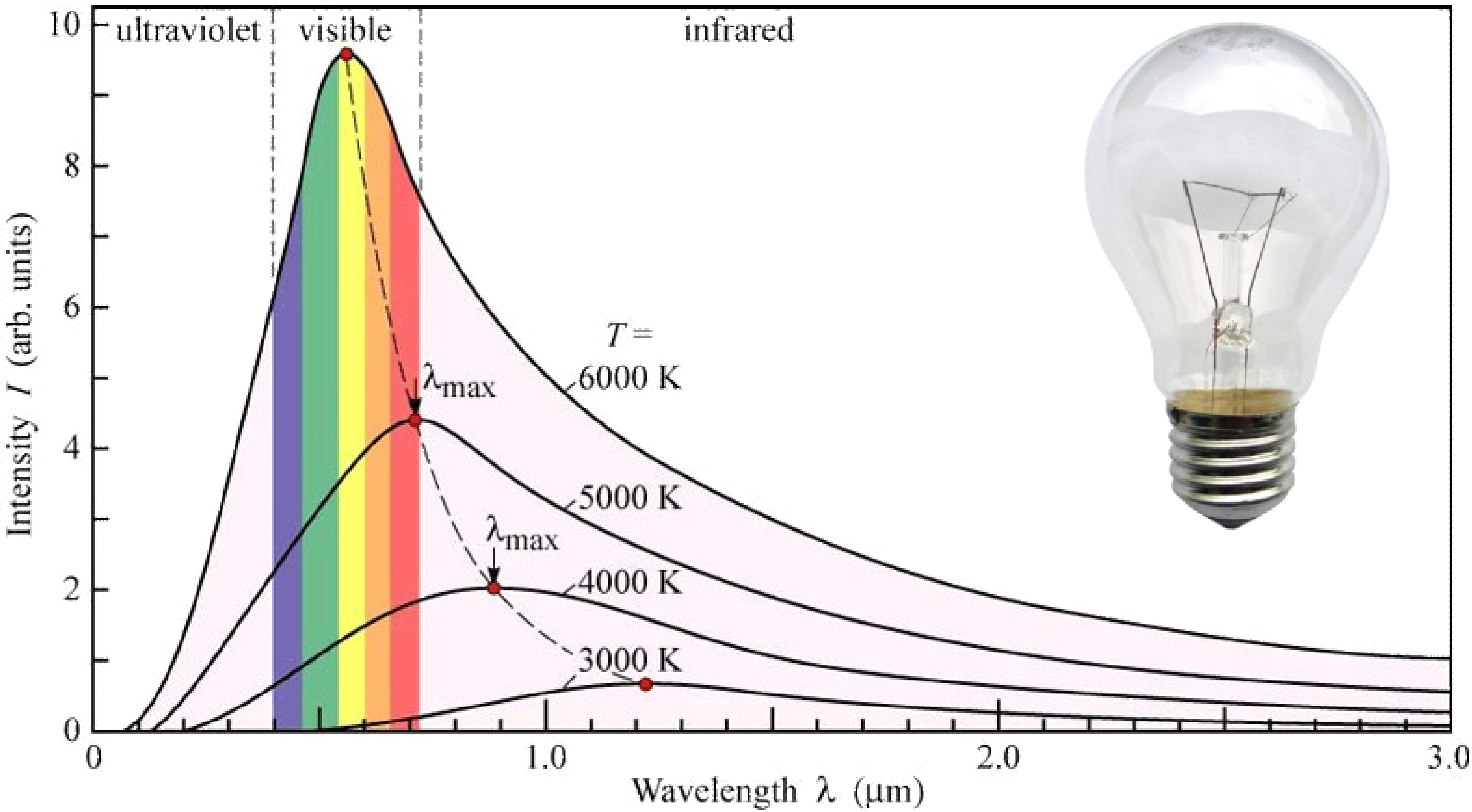


Nuclear Physics A Volume 757, 102-183

- Ratios of particles expected from a model
- Even strange quarks are at equilibrium!

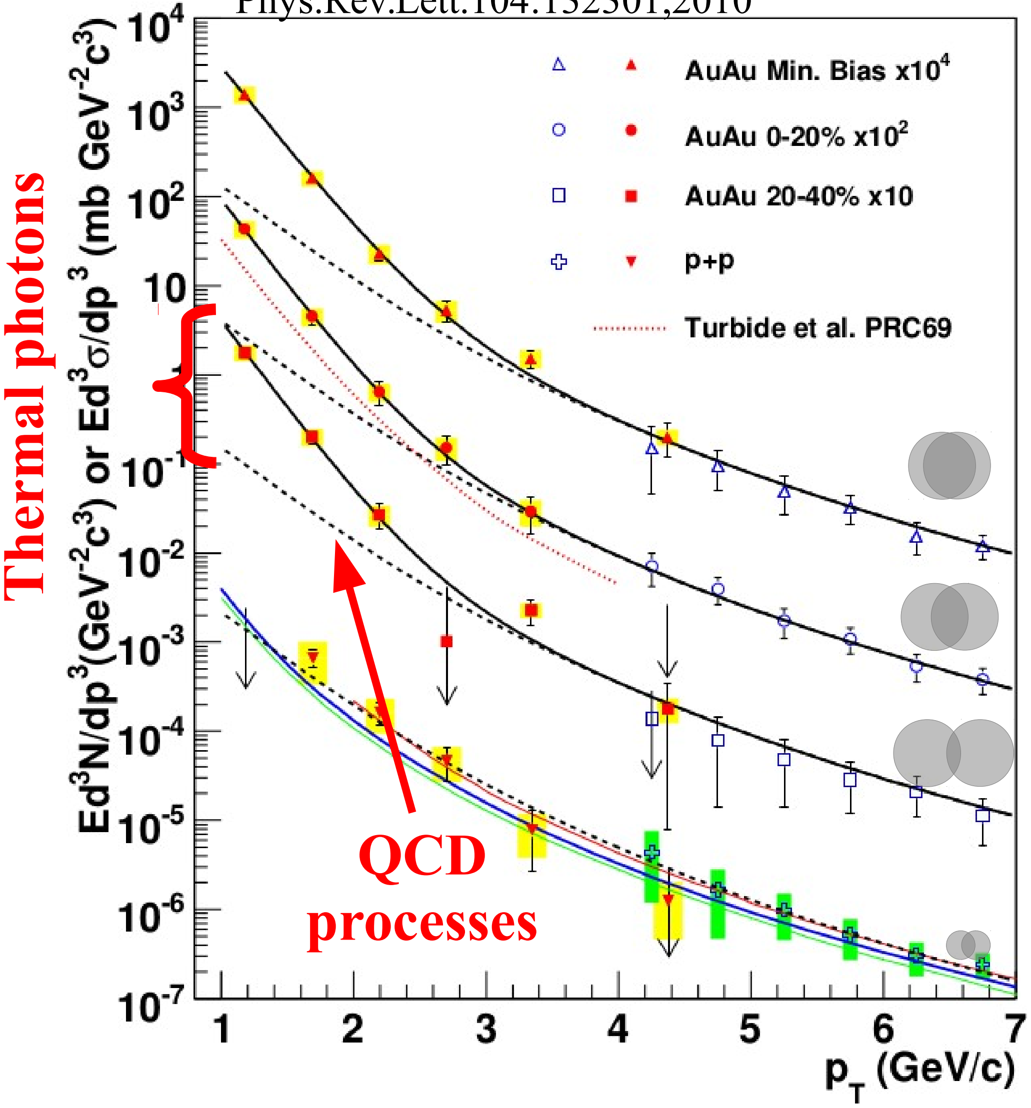
QGP Thermometers

Measuring temperature



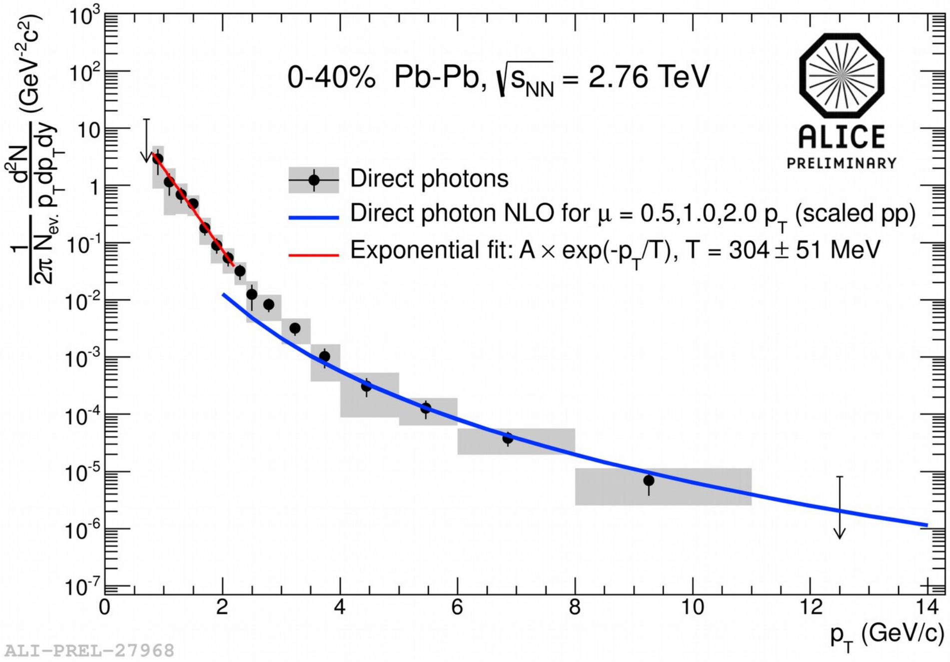
Thermal photons

Phys.Rev.Lett.104:132301,2010



Thermal photons

QCD processes

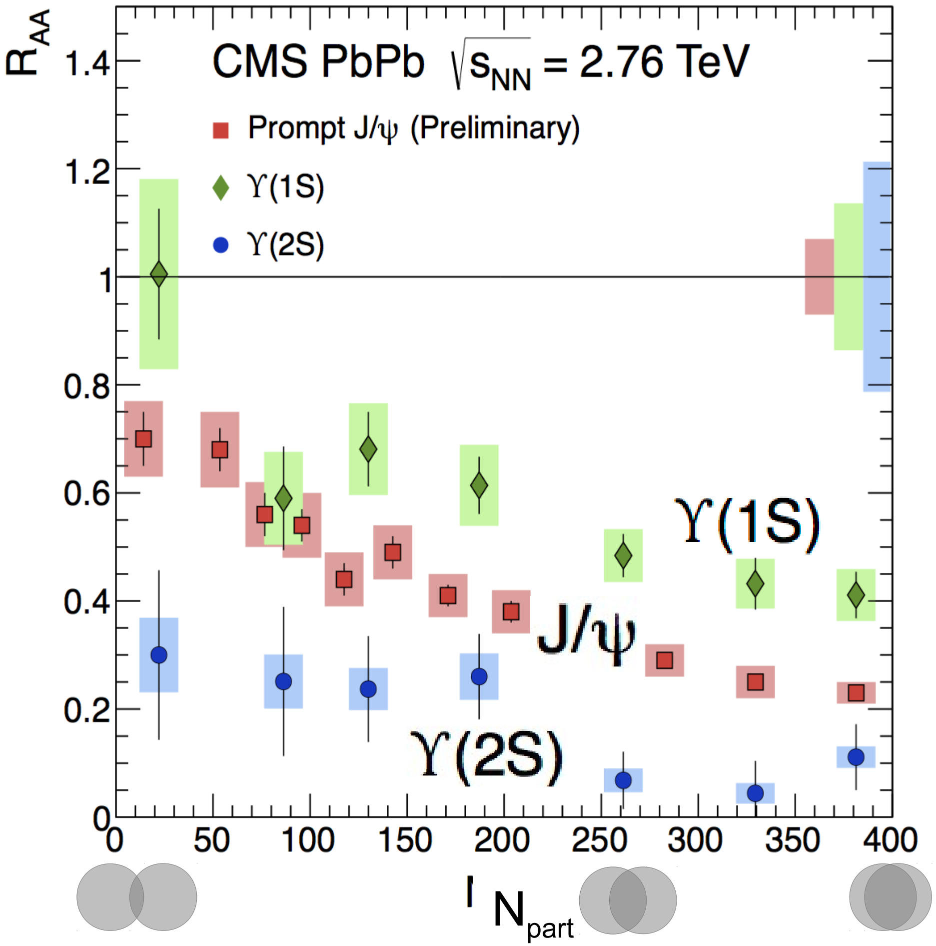


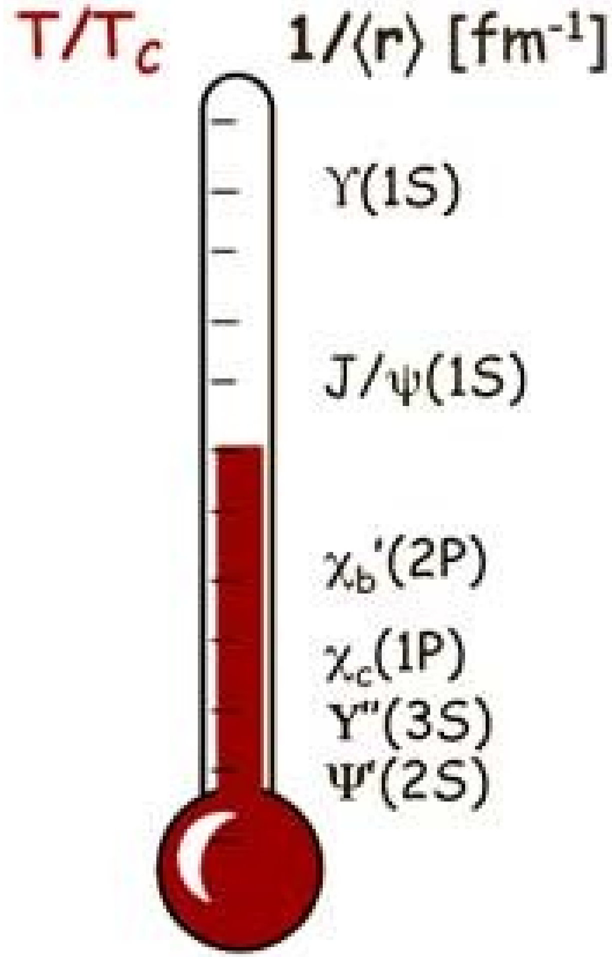
ALICE collaboration:
Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
Inverse slope: T = 304 +/-51

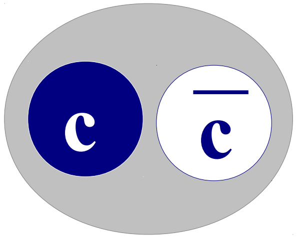
PHENIX collaboration: Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
Inverse slope: T = 221 +/- 19 (stat) +/- 19 (syst) MeV

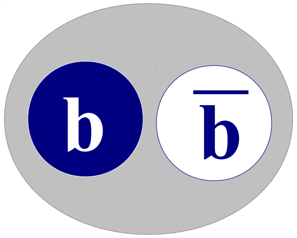
Building a quarkonium-thermometer

CMS-PAS HIN-11-011







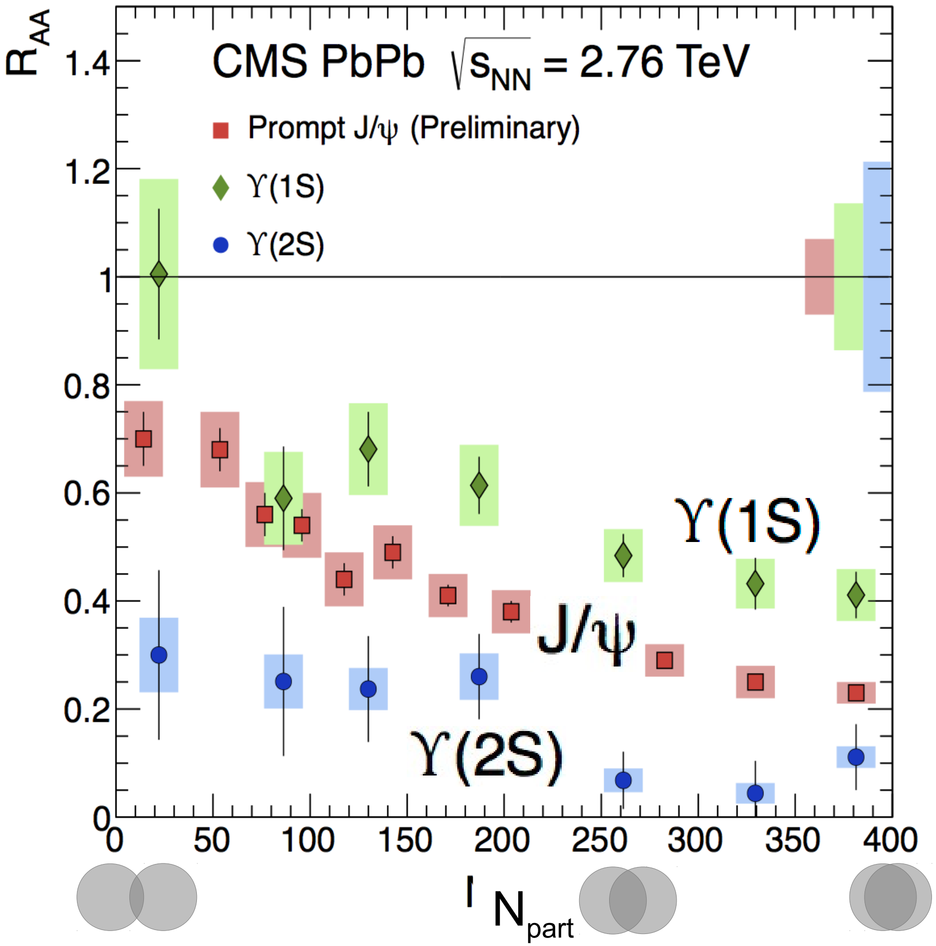


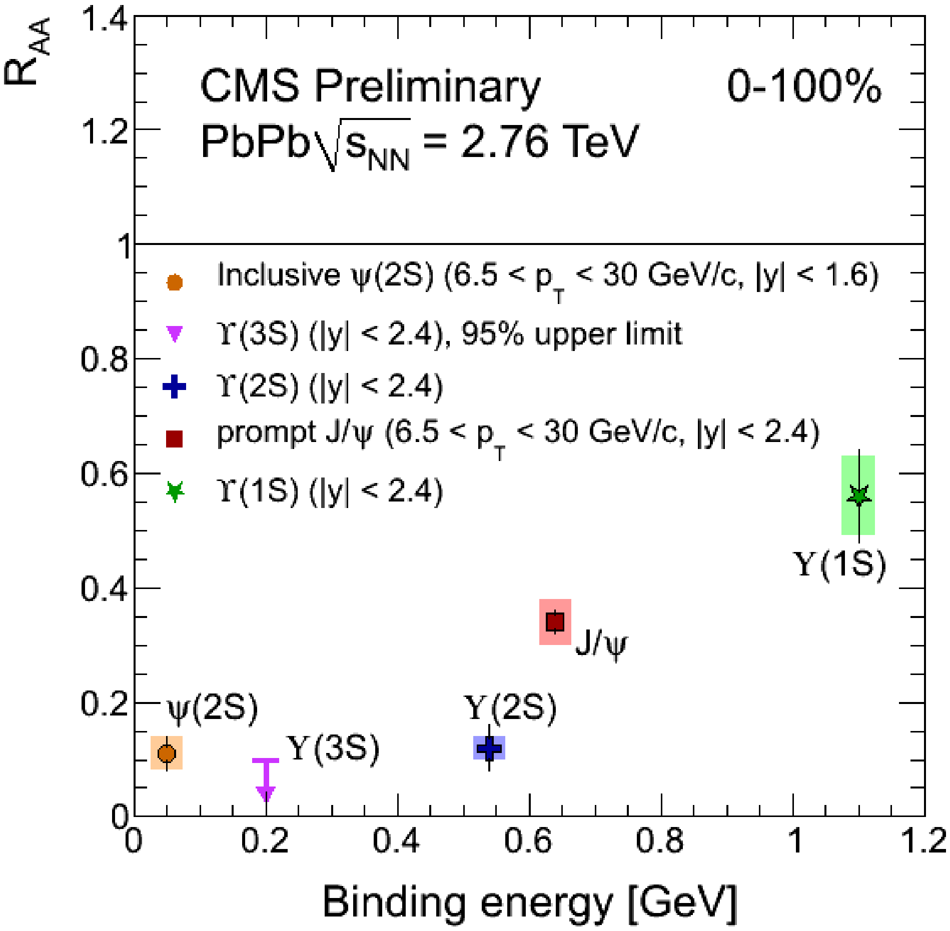
Clear hierarchy in R_{AA} of different quarkonium states

Building a quarkonium-thermometer

CMS-PAS HIN-11-011

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





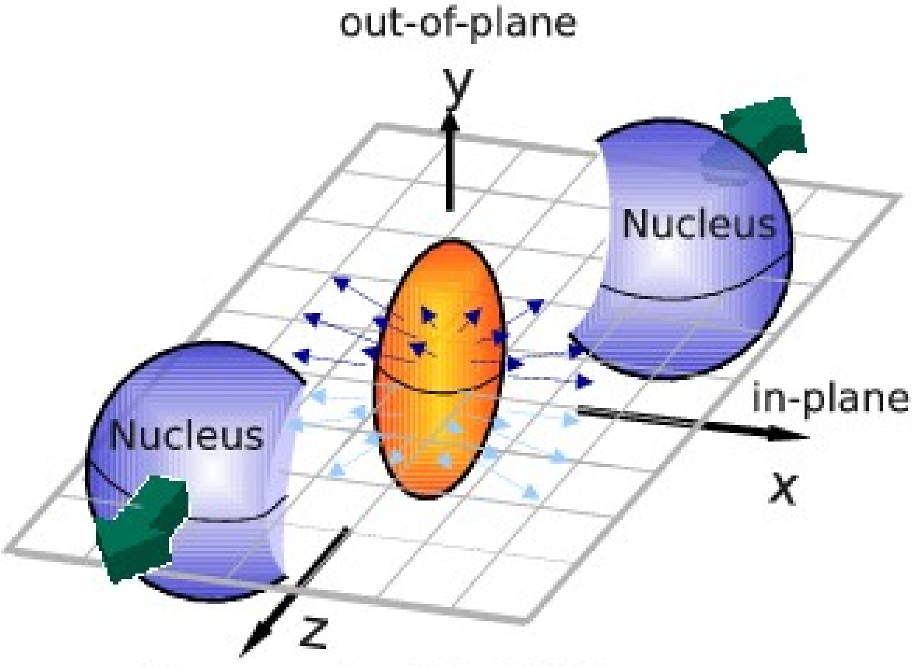
Clear hierarchy in R_{AA} of different quarkonium states

Expected in terms of binding energy

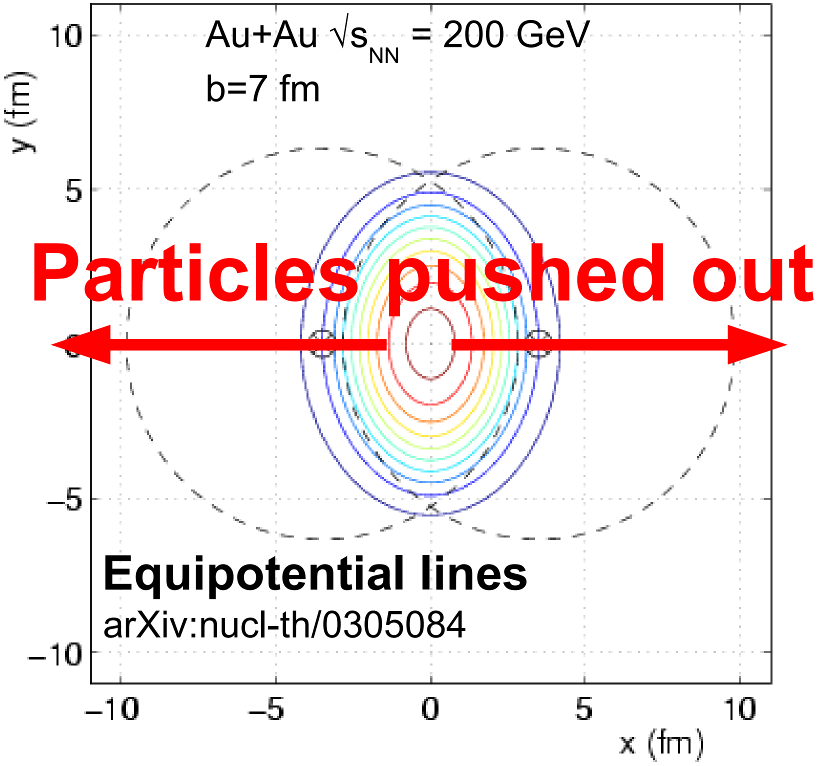
CMS-PAS HIN-12-014, HIN-12-007

QGP Fluid Dynamics

If we have a fluid...



Non-central Collisions



Particles pushed out

Equipotential lines

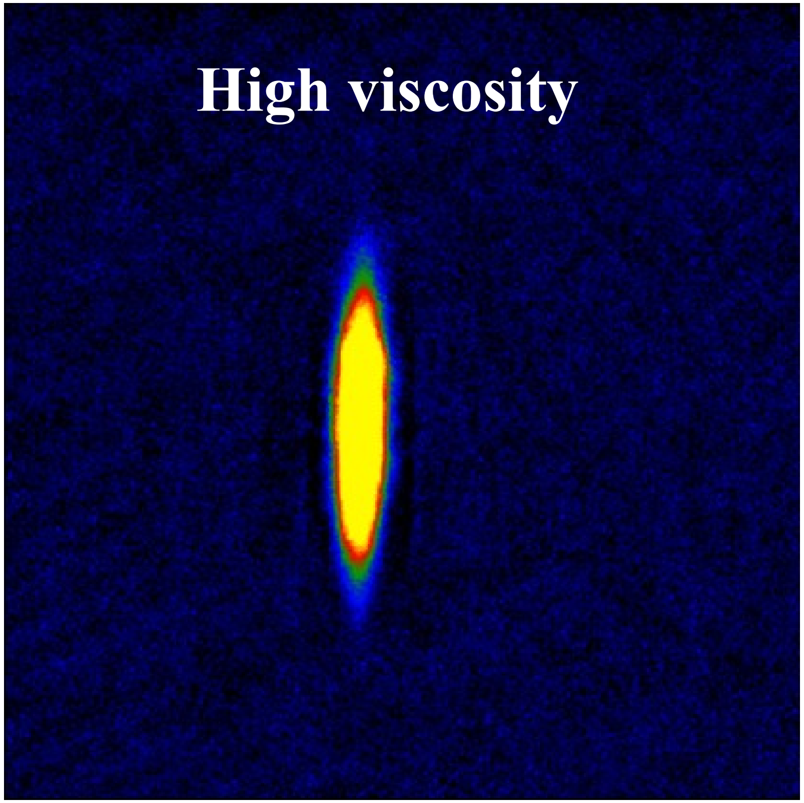
arXiv:nucl-th/0305084

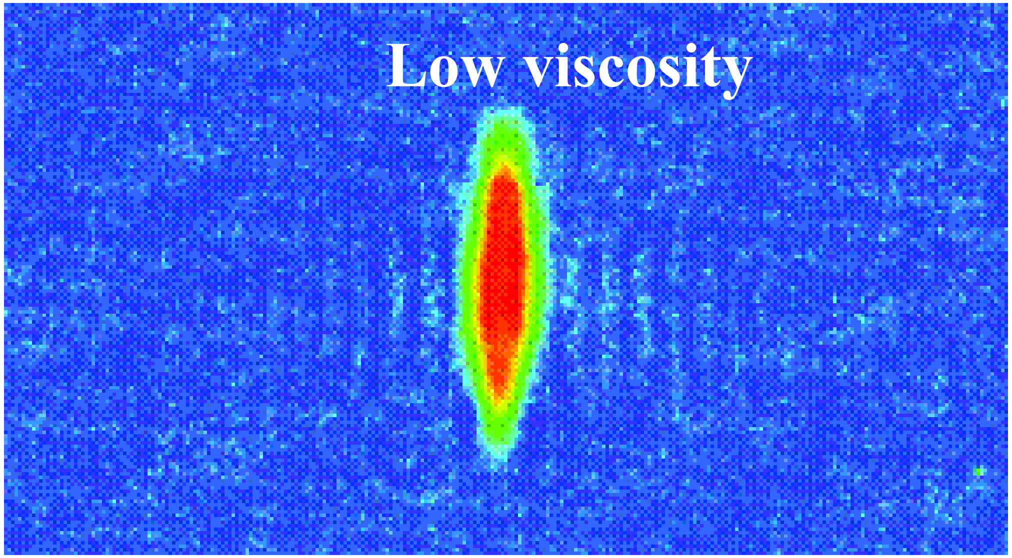
- Initial overlap asymmetric → pressure gradients
- Momentum anisotropy → Fourier decomposition:

$$\frac{d^2N}{dp_T\, d\varphi} \approx 1 + 2v_1\cos(d\varphi) + 2v_2\cos(2d\varphi) + 2v_3\cos(3d\varphi) + 2v_4\cos(4d\varphi) + 2v_5\cos(5d\varphi) + \ldots$$

What does this mean?

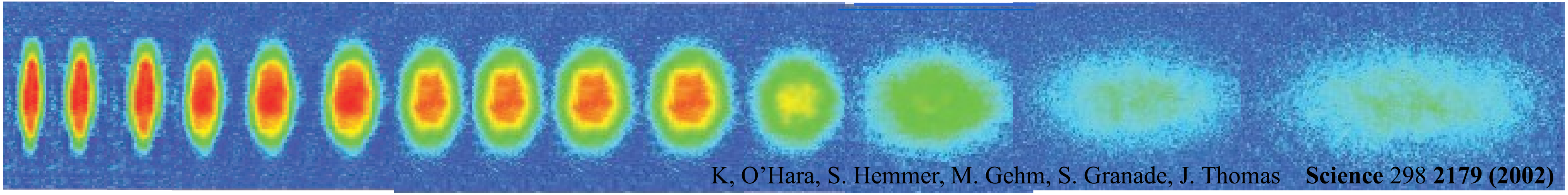
- Same phenomena observed in gases of strongly interacting atoms
  - K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**





What does it mean?

Same phenomena observed in gases of strongly interacting atoms



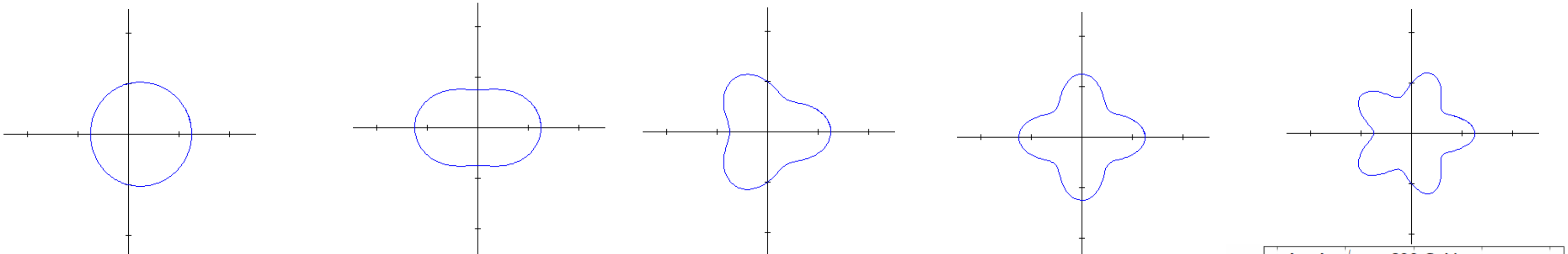
K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**

Time →

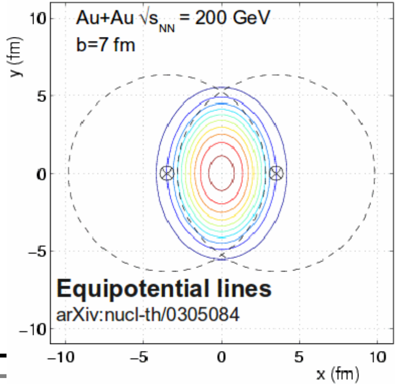
Initial state anisotropies converted to final state anisotropies

Fourier decomposition:

$$\frac{d^2N}{dp_T\,d\varphi} \approx 1 + 2v_1\cos(d\varphi) + 2v_2\cos(2d\varphi) + 2v_3\cos(3d\varphi) + 2v_4\cos(4d\varphi) + 2v_5\cos(5d\varphi) + \ldots$$

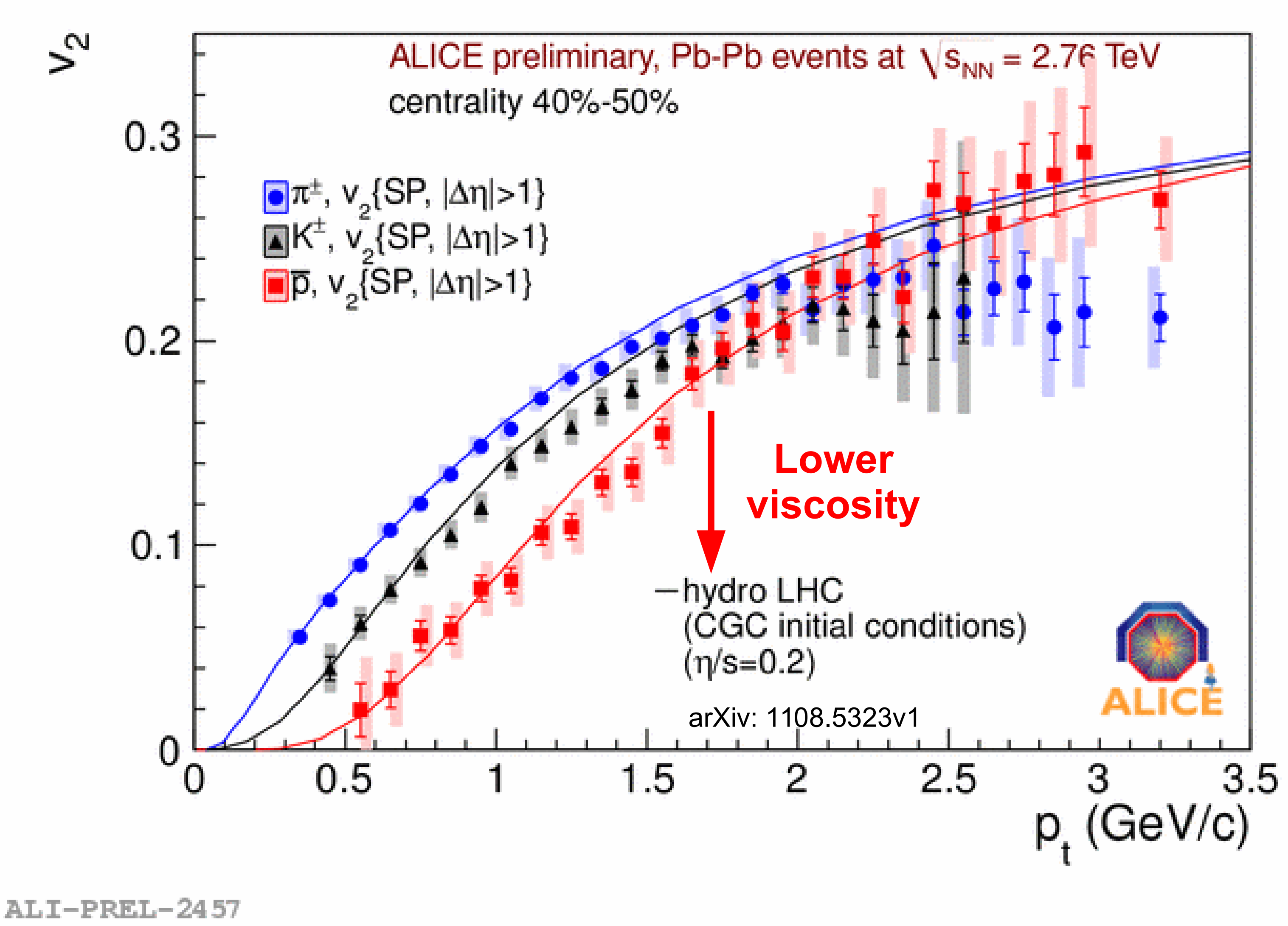


Offset measured



Equipotential lines
arXiv:nucl-th/0305084

Does this describe the data?

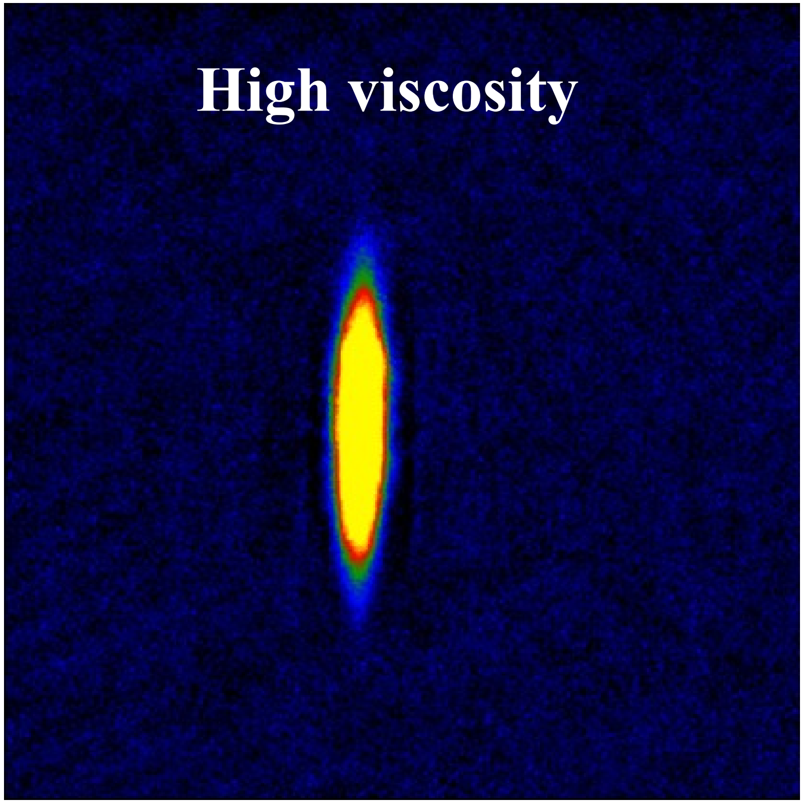


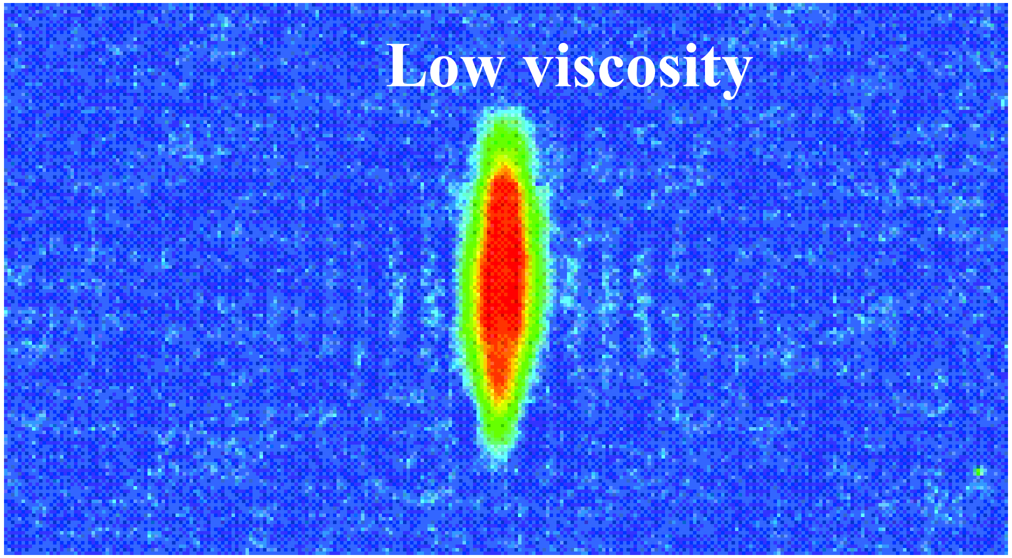
Lower viscosity

Yes!

What does this mean?

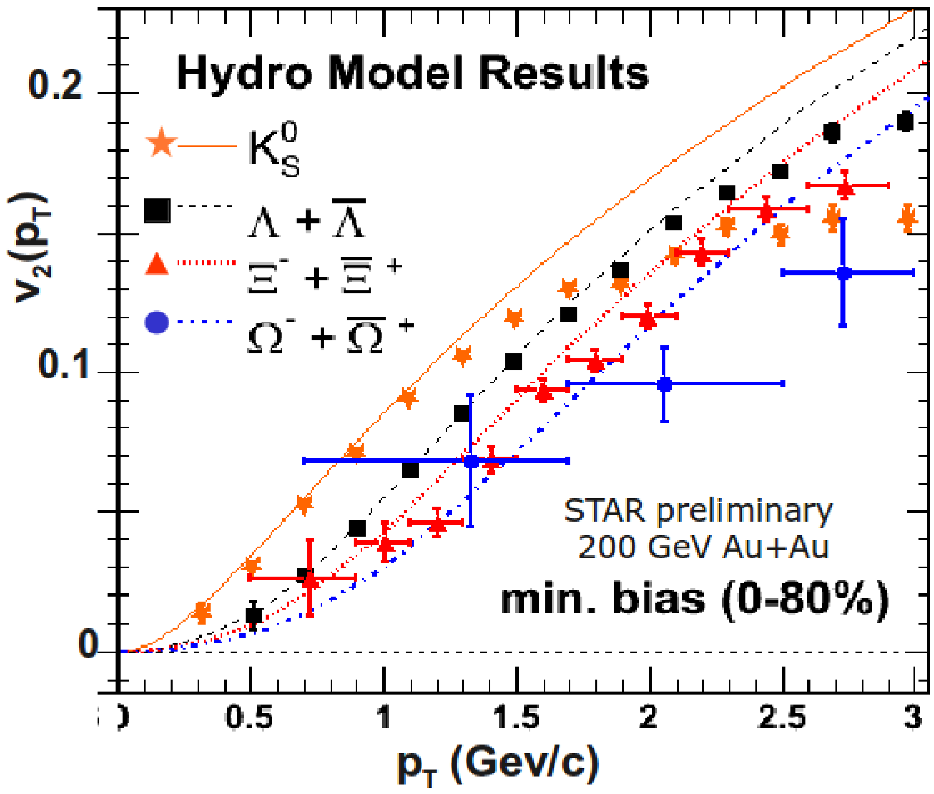
- Same phenomena observed in gases of strongly interacting atoms
  - K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**

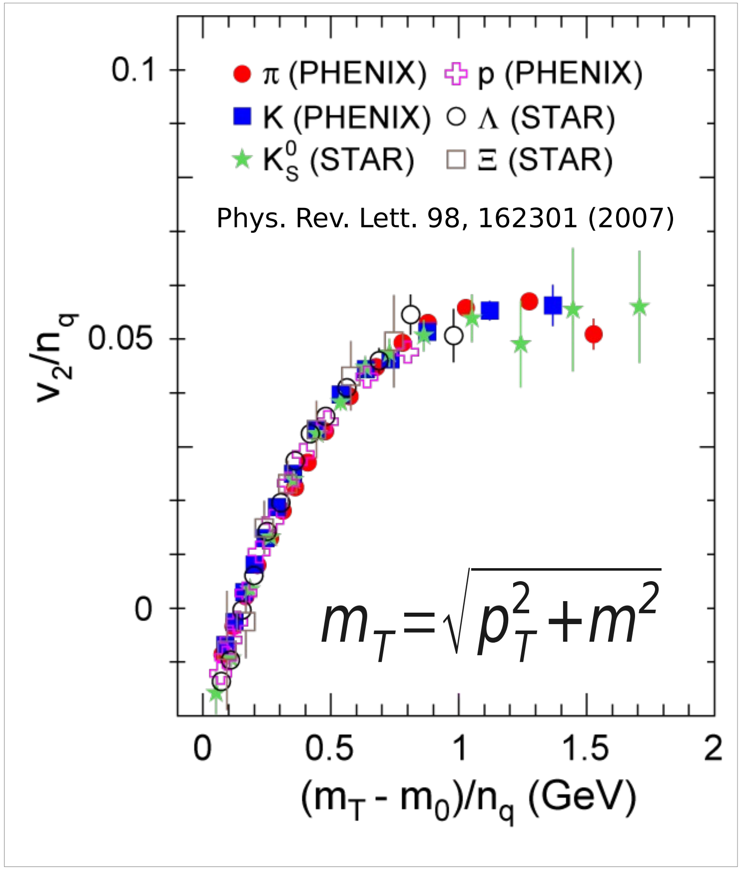




The Quark Gluon Plasma has a very low viscosity

More data





Mass ordering:

$v_2(K) > v_2(\Lambda) > v_2(\Xi)$

$v_2(p_T^{hadron}) \mu\ n_{quark} v_2(p_T^{quark})$

We have a liquid of quarks and gluons!

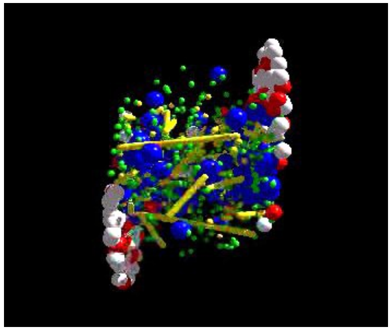
What do we learn about the QGP?

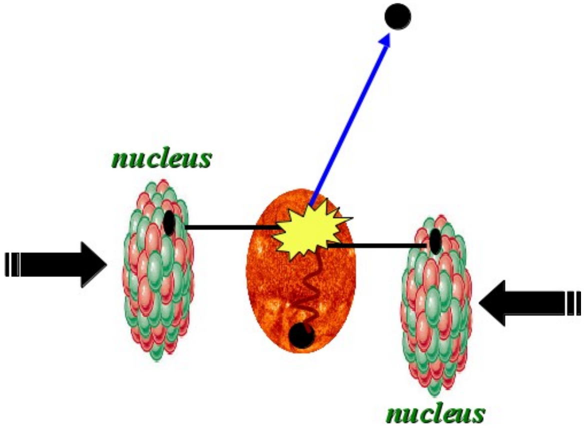
- Hydrodynamics works →
  - (local) thermalization
  - image of the initial state
- Really low viscosity
  - Near AdS/CFT bound
  - $\eta/S \sim 1/4\pi$

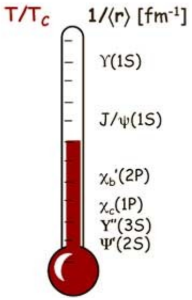
The QGP is the perfect liquid!

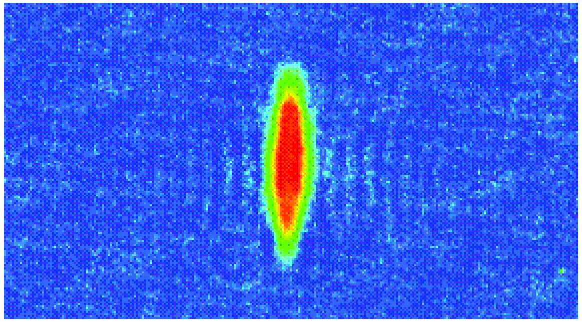
(not the gas of “free” quarks and gluons we expected)

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 transparent to colored probes and translucent to electromagnetic probes...
- ...and an extremely hot and dense...
- ...perfect liquid.

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

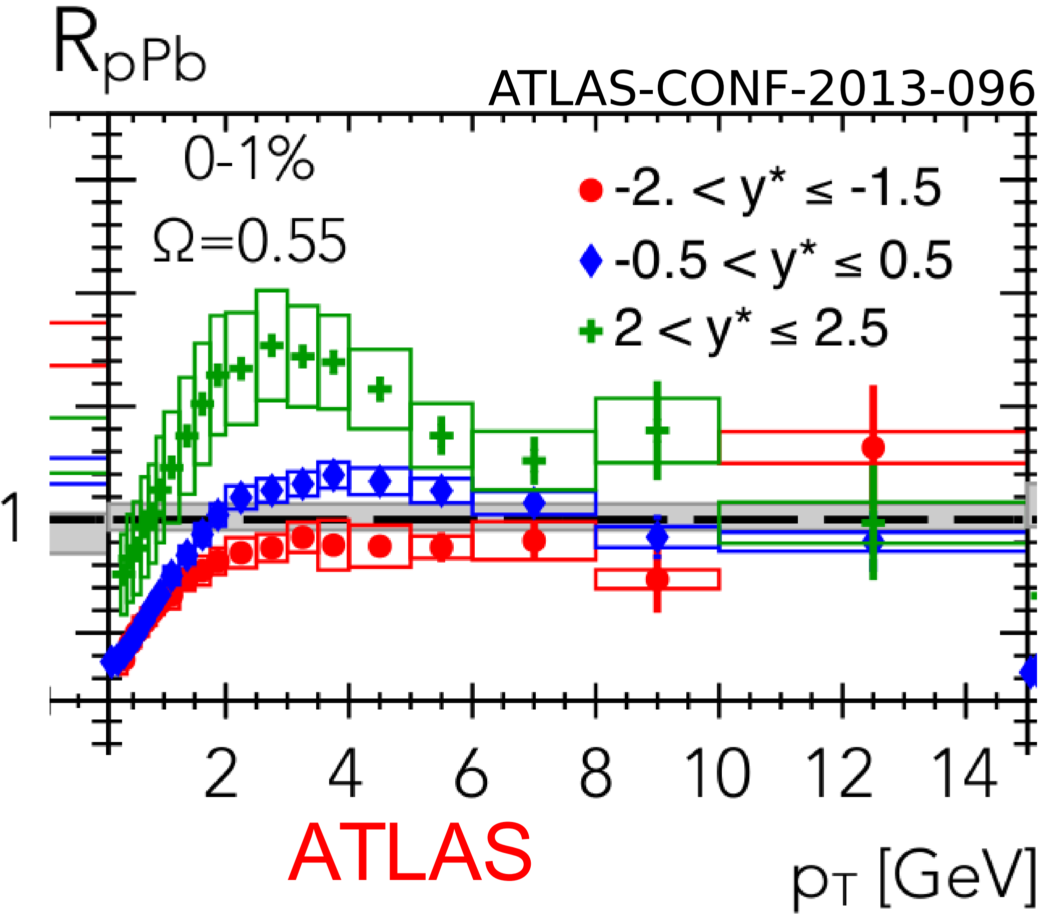
- STAR
  - University of California at Davis
  - University of California Los Angelos
  - University of Houston
  - University of Illinois at Chicago
  - Creighton University (masters only)
  - Kent State University
  - Michigan State University
  - Ohio State University
  - Purdue University
  - Texas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

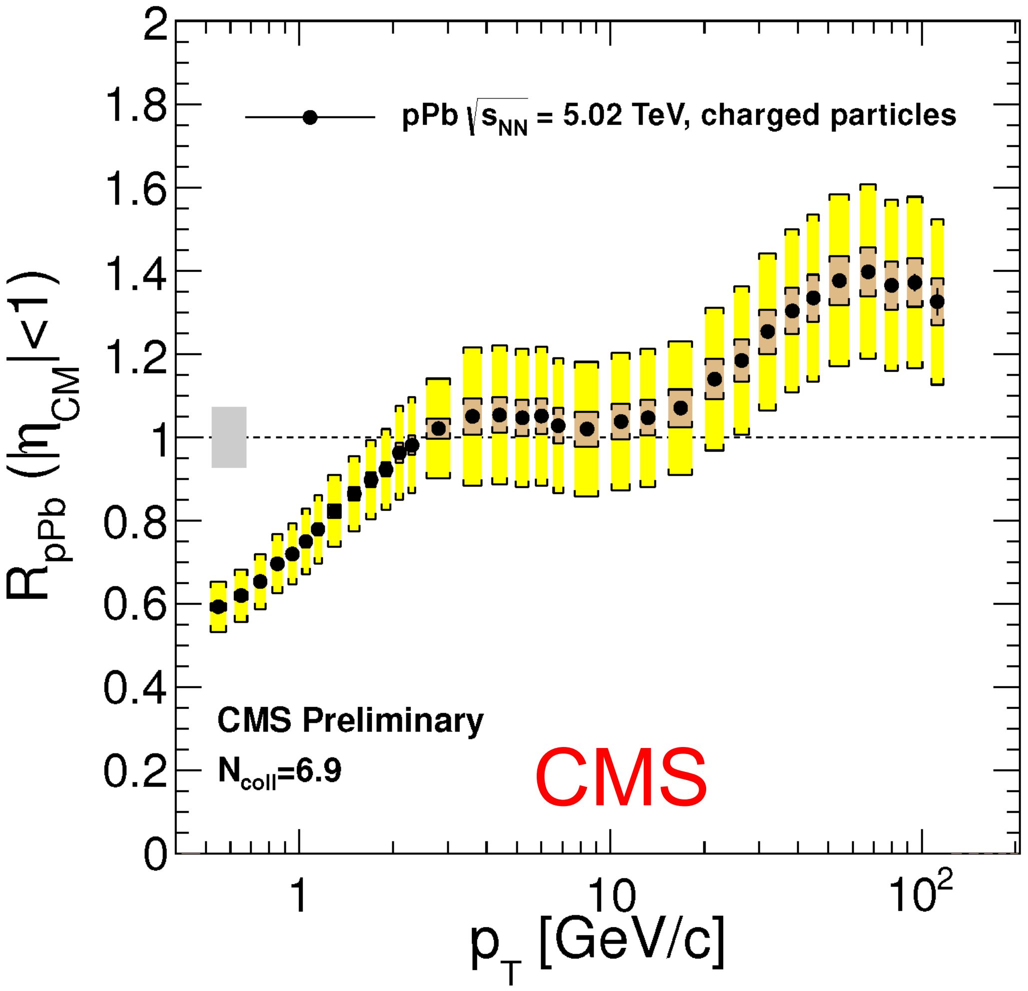
US Universities with graduate programs in experimental heavy ion physics

Large Hadron Collider

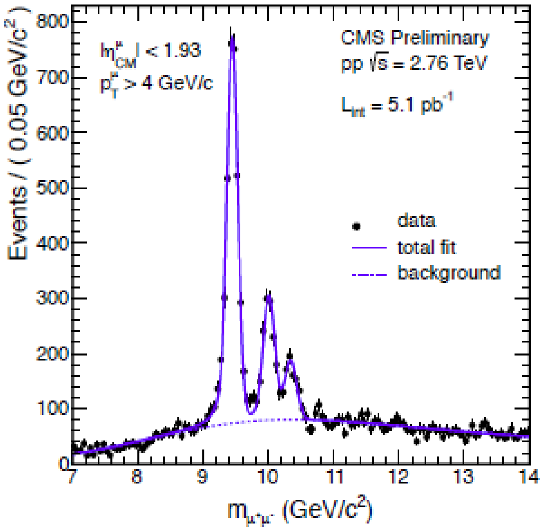
- ALICE
  - University of Texas Austin
  - Chicago State University
  - Ohio State University
  - Wayne State University
  - University of Texas Houston
  - **University of Tennessee Knoxville**
  - Yale University
  - Creighton University (masters only)
  - Purdue University
- CMS
  - University of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

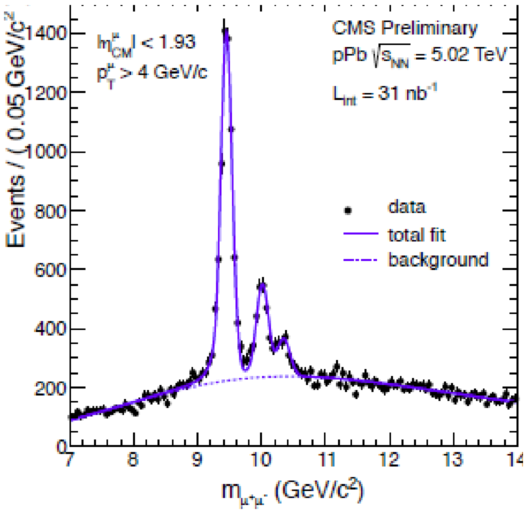
p+Pb as a control

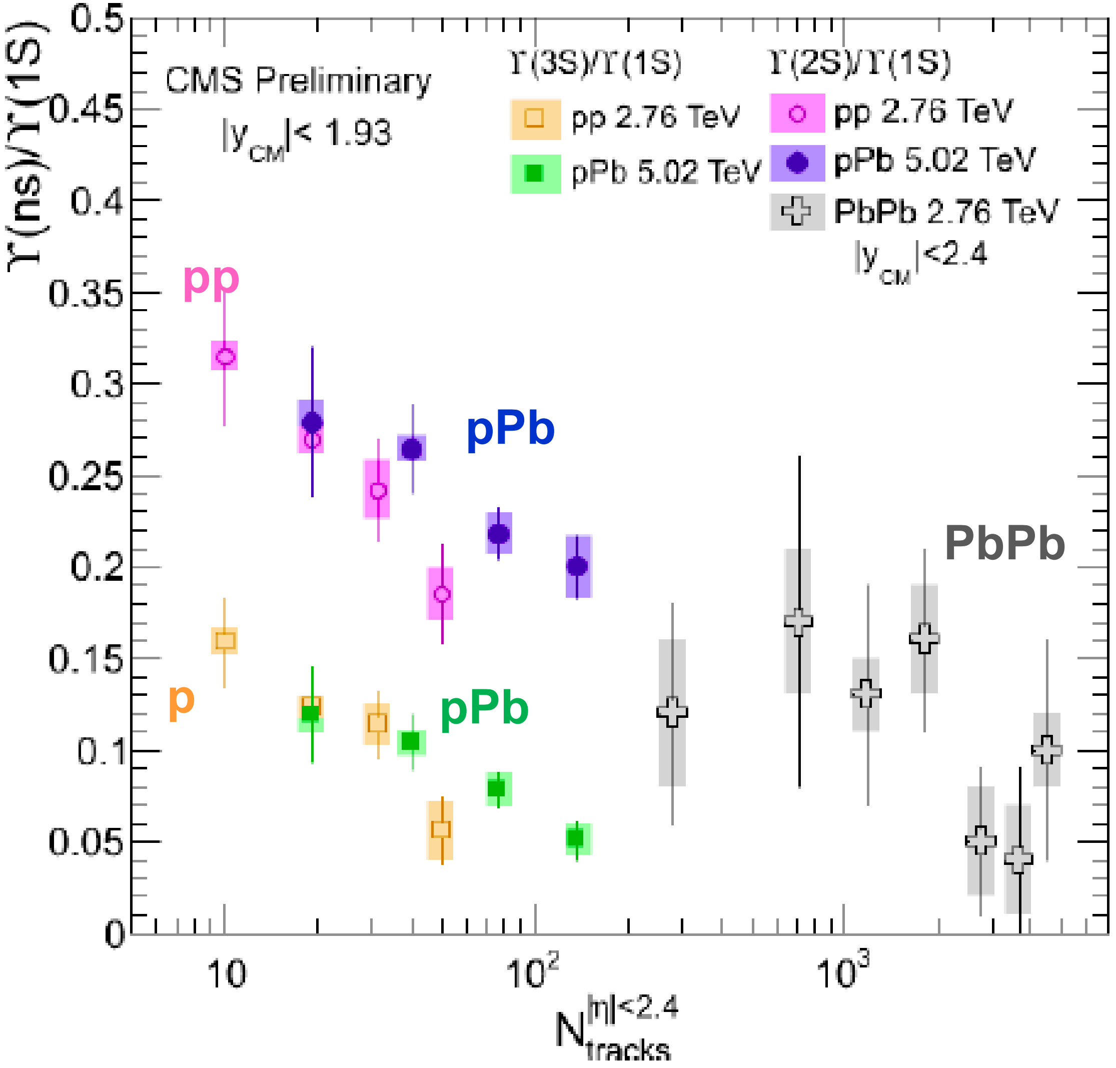




Suppression of quarkonia in p+Pb

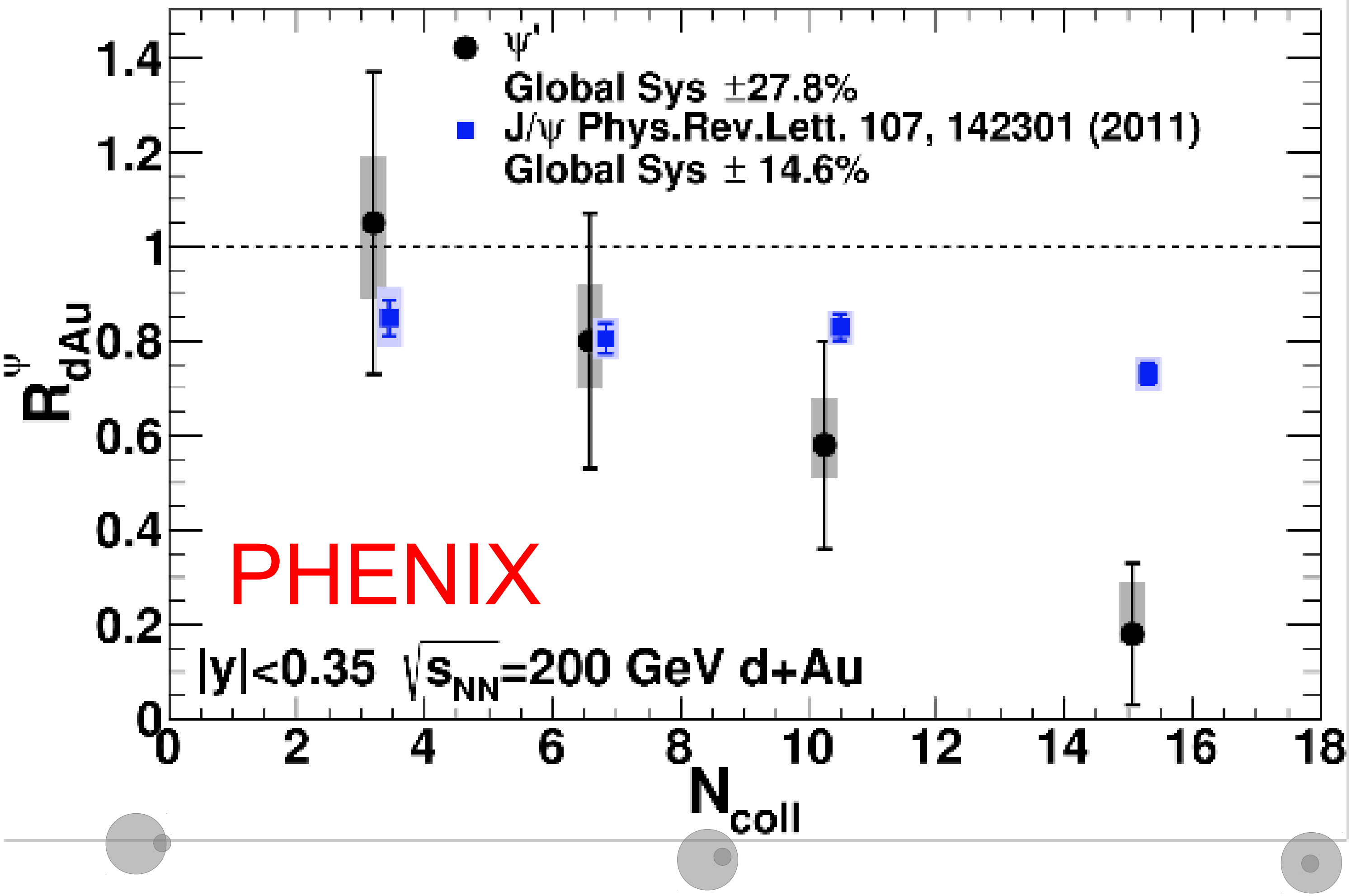




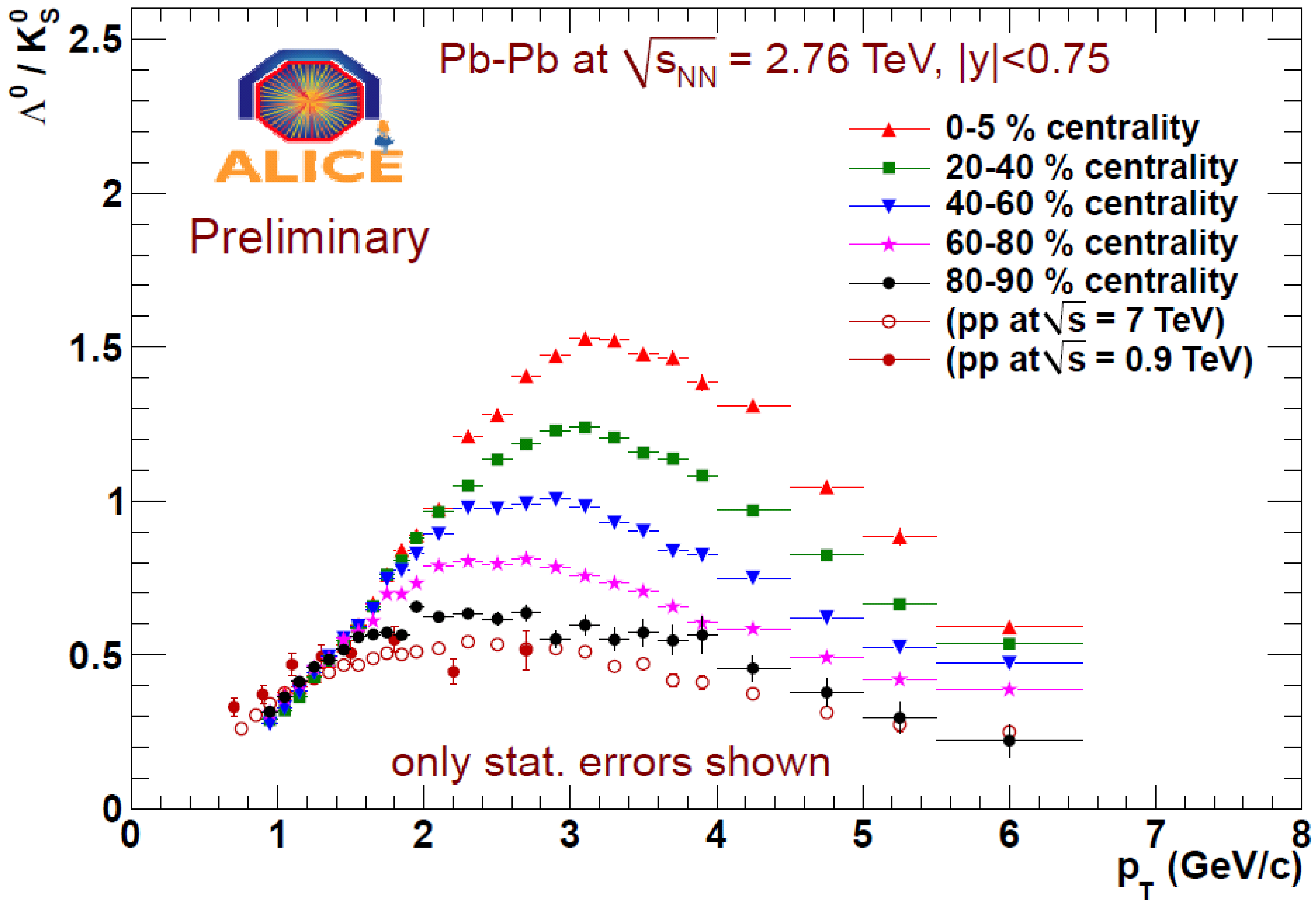


Suppression of quarkonia in d+Au

arXiv:1315.5516, to be publ PRL

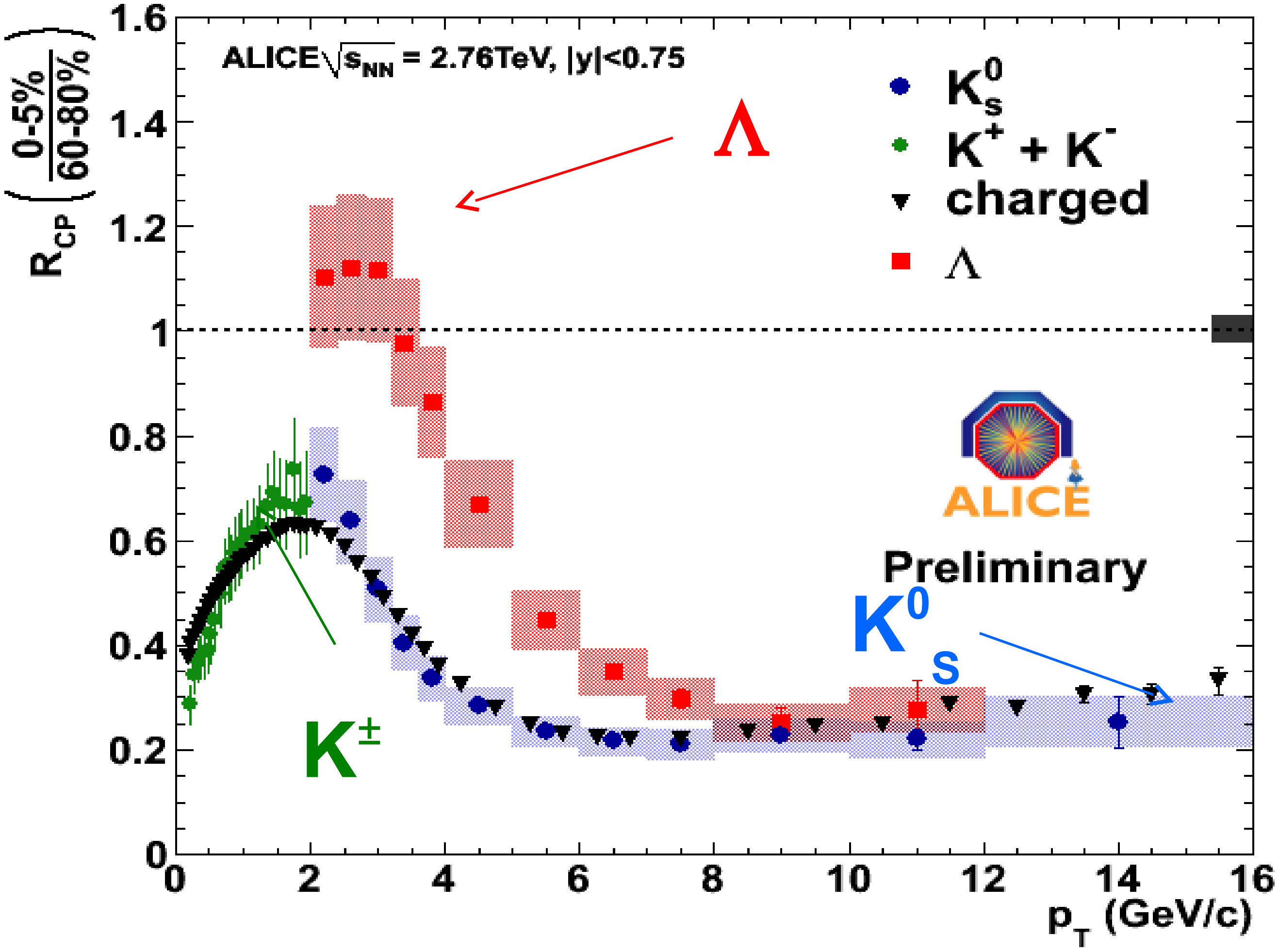


Baryon anomaly: Λ/K^0_S



Pb+Pb

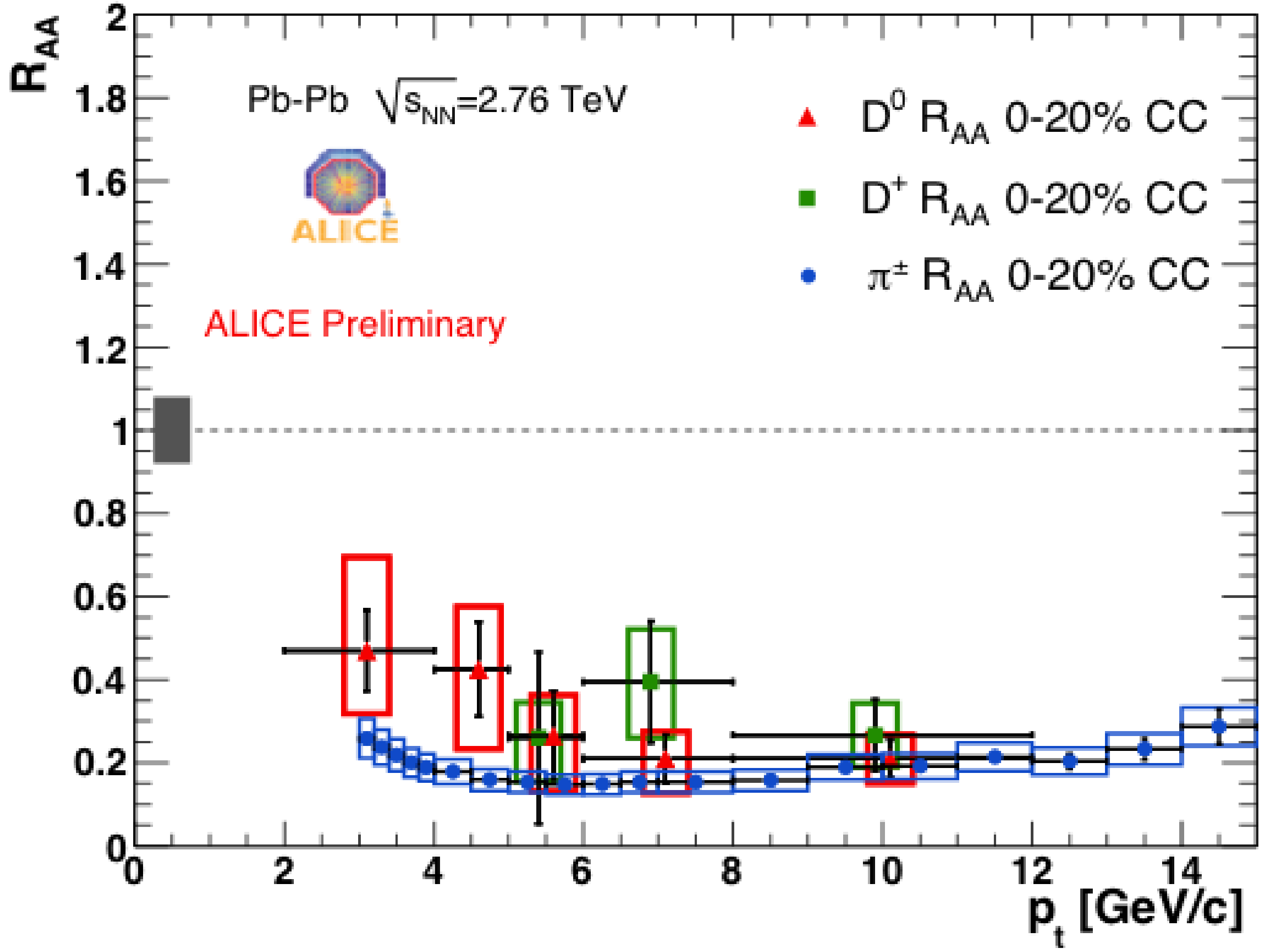
Nuclear modification factor (R_{AA})



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

Pb+Pb

Charm nuclear modification factor



Pb+Pb