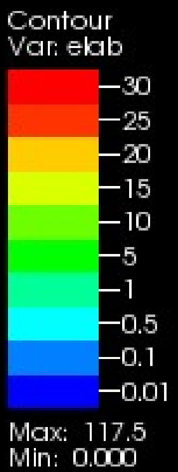
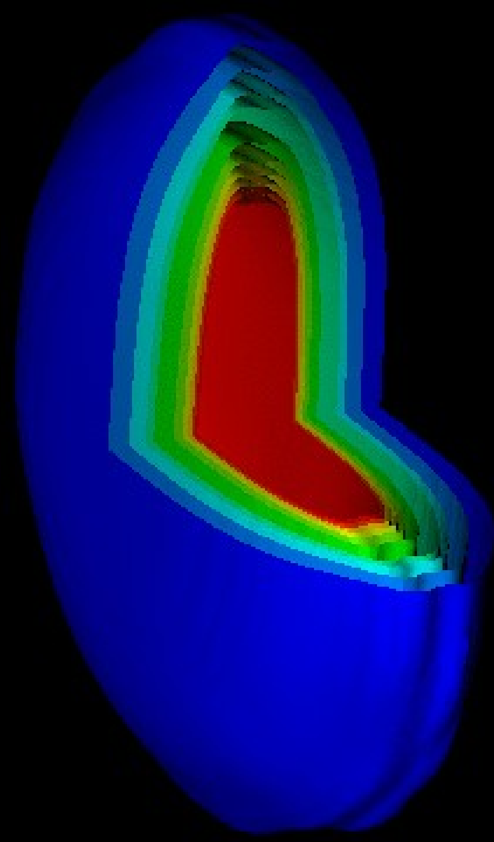
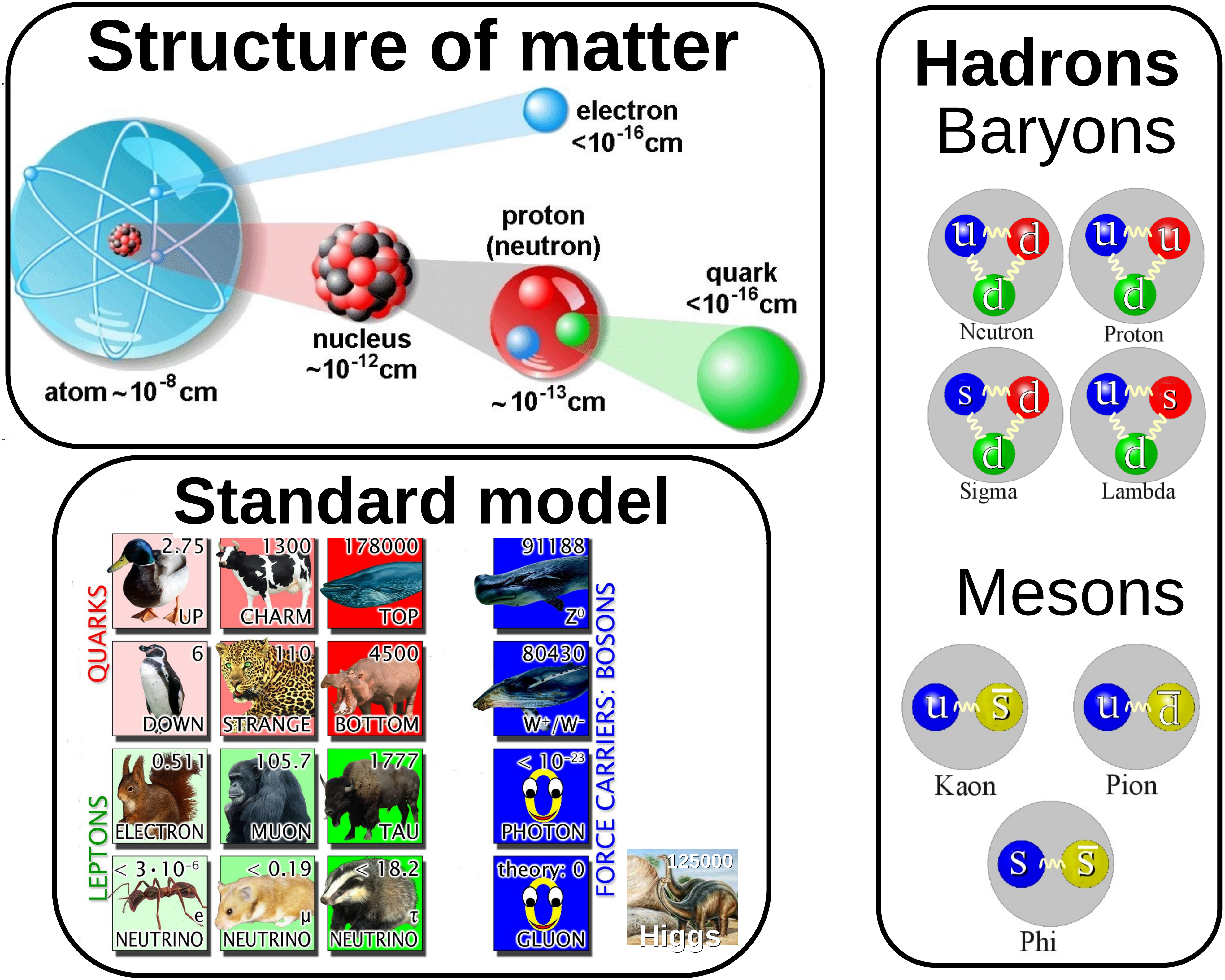
Melting Nuclei





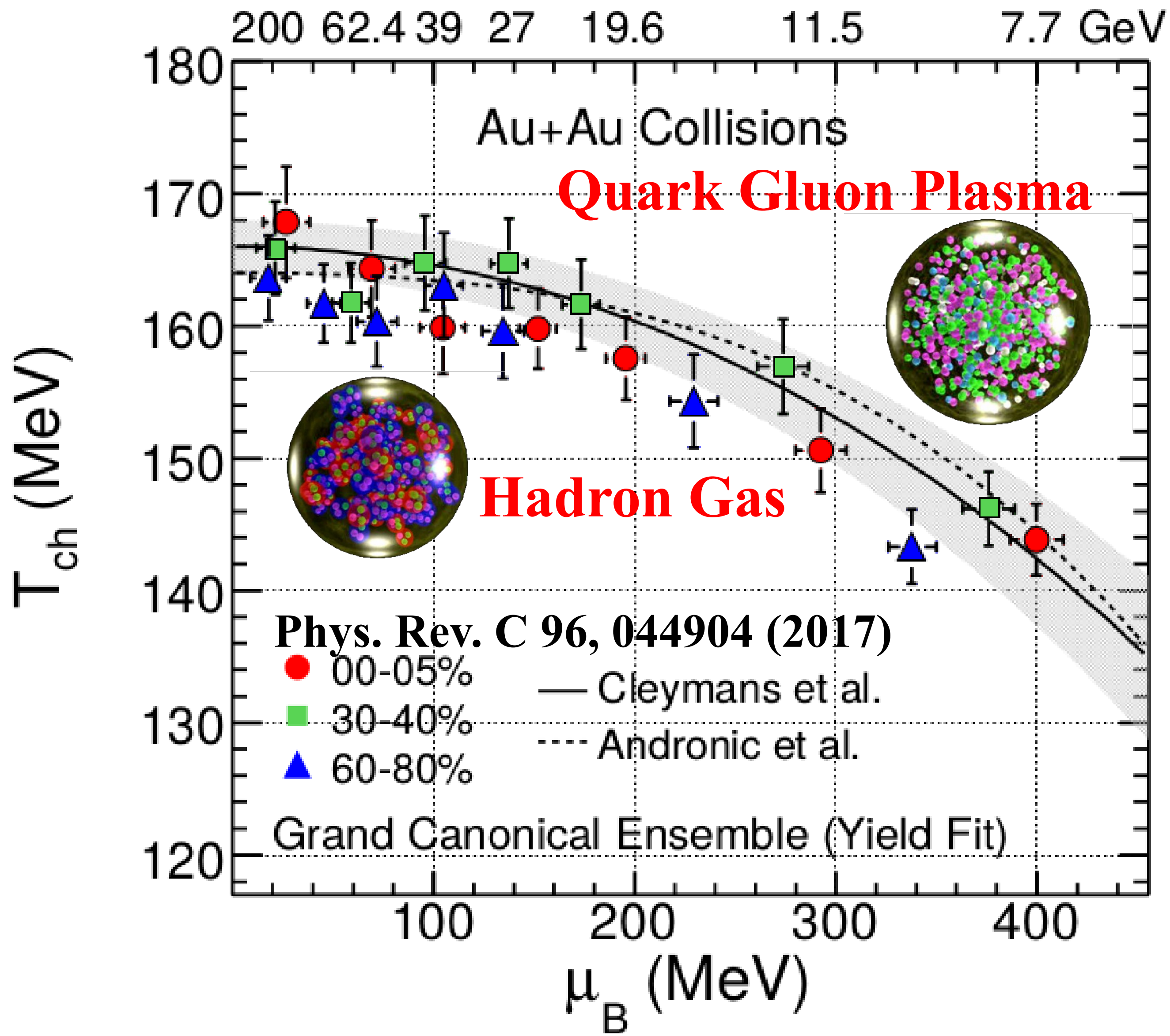
Christine Nattrass
University of Tennessee at Knoxville

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

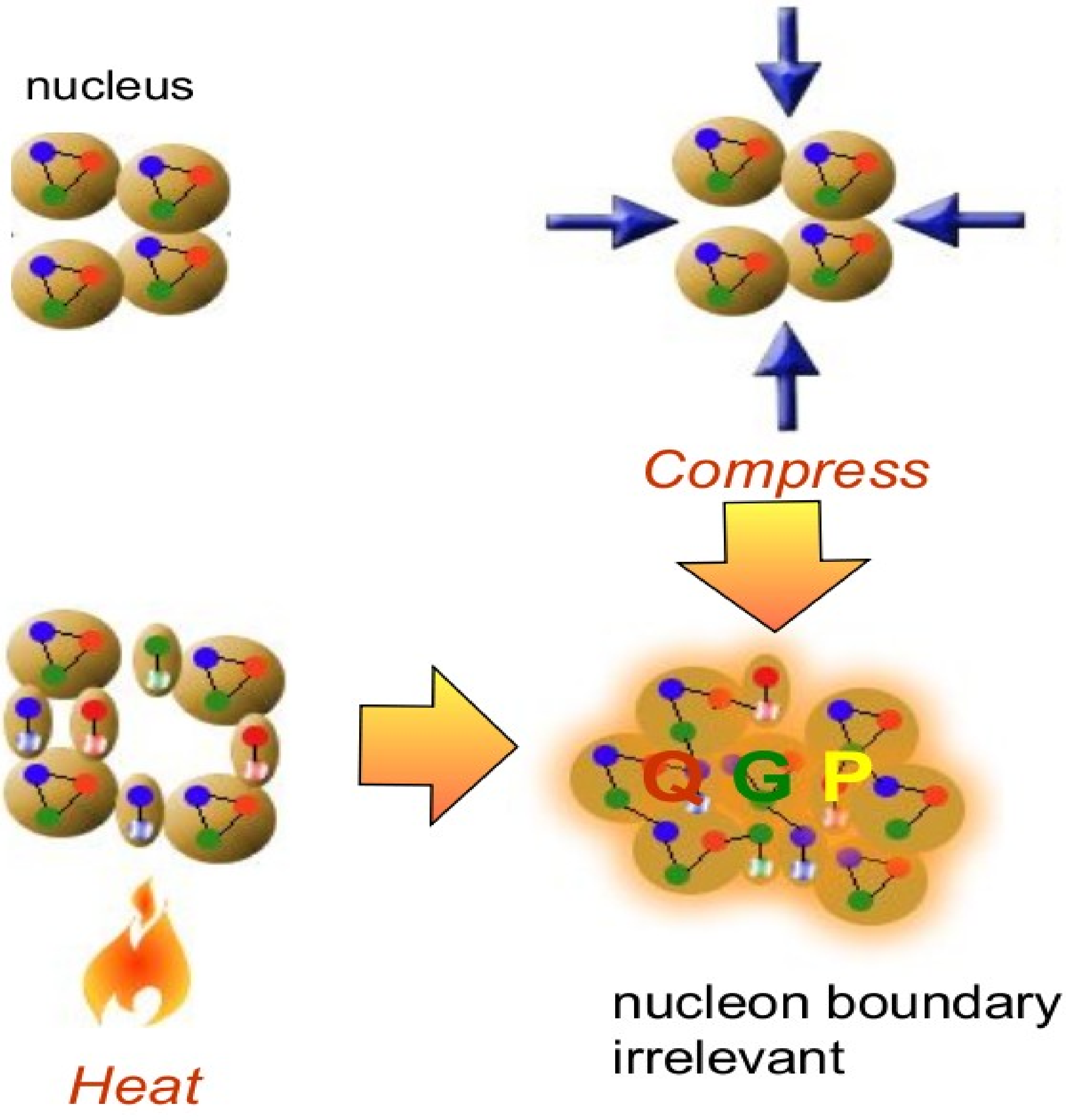


Structure of matter
electron
<10^-16 cm
proton
(neutron)
quark
<10^-16 cm
nucleus
~10^-12 cm
atom ~ 10^-8 cm
~ 10^-13 cm
Standard model
QUARKS
2.75
UP
1300
CHARM
178000
TOP
6
DOWN
110
STRANGE
4500
BOTTOM
LEPTONS
0.511
ELECTRON
105.7
MUON
1777
TAU
< 3·10^-6
e
NEUTRINO
< 0.19
μ
NEUTRINO
< 18.2
τ
NEUTRINO
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

QCD Phase Diagram

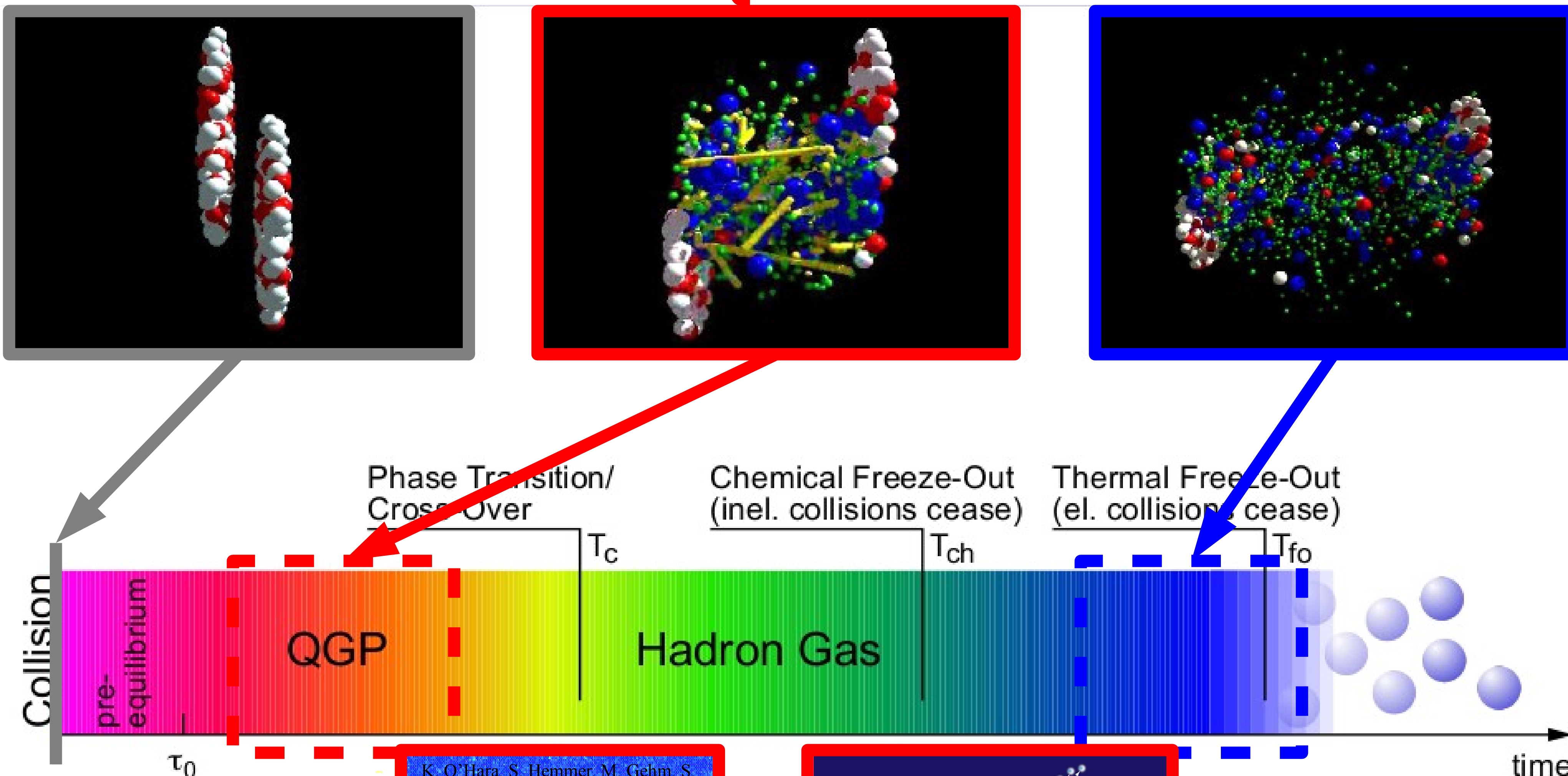


How to make a Quark Gluon Plasma

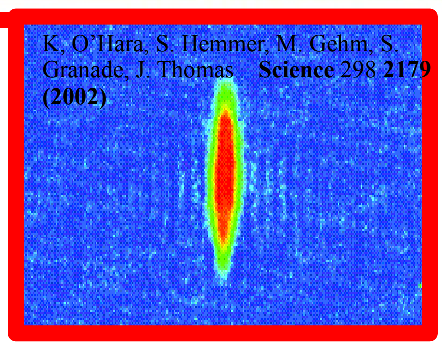


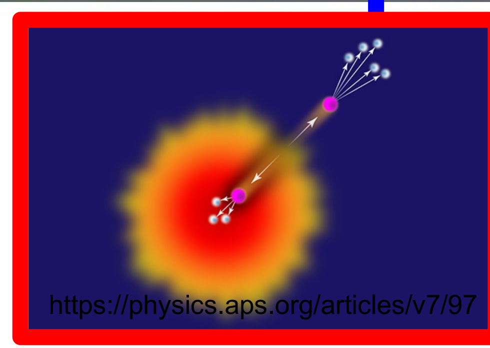
The phase transition in the laboratory

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



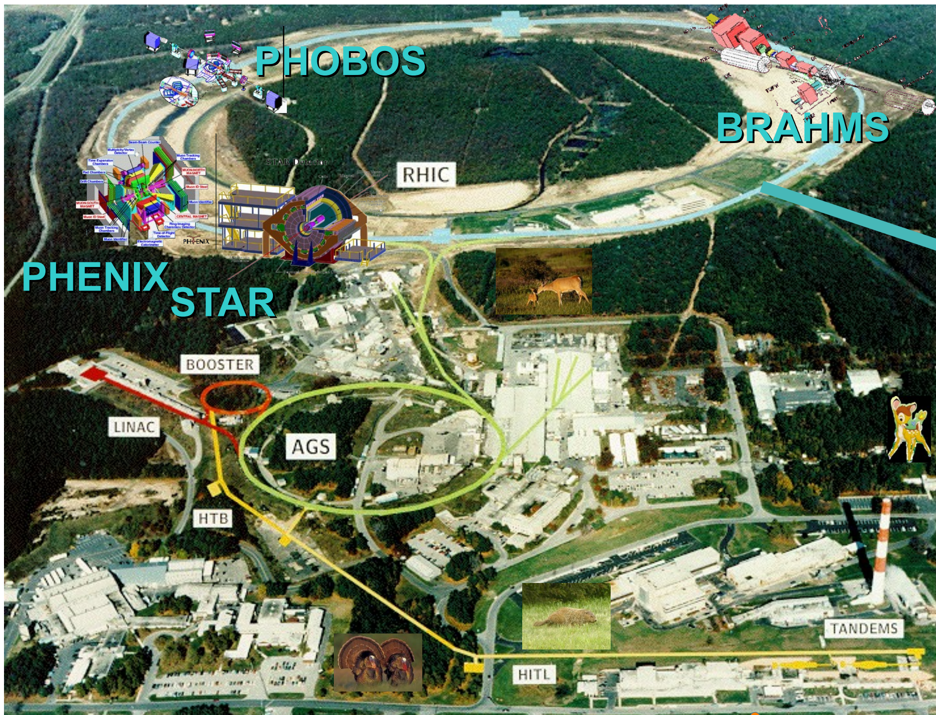
Hydrodynamical flow





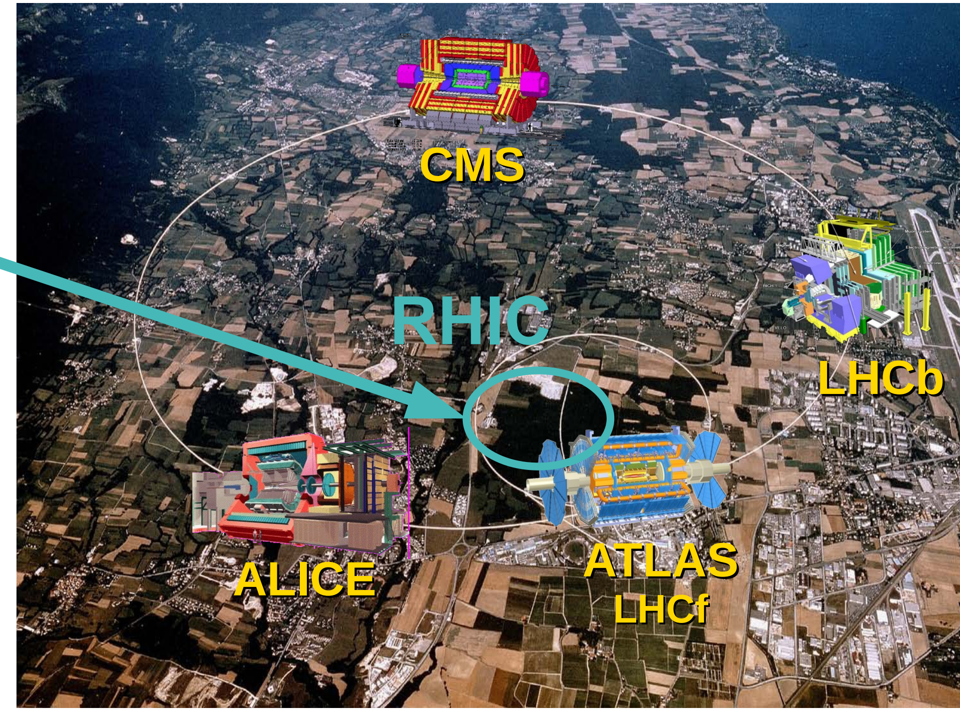
Jet quenching

Relativistic Heavy Ion Collider

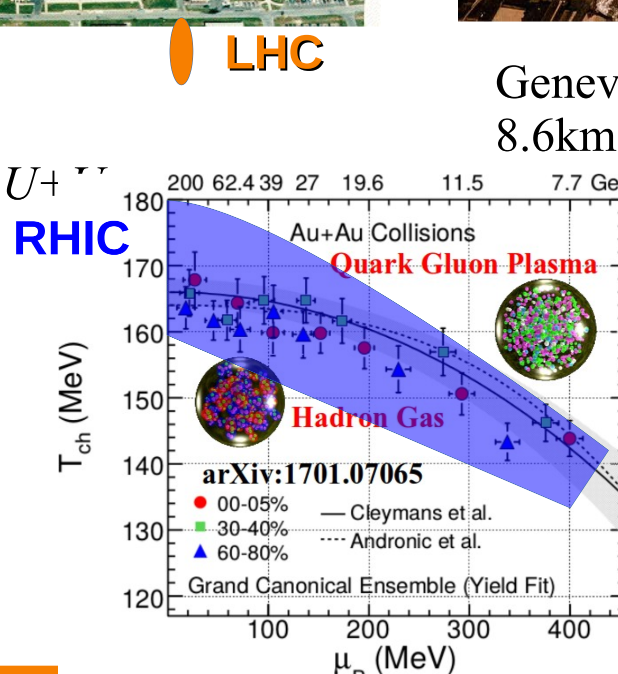


Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

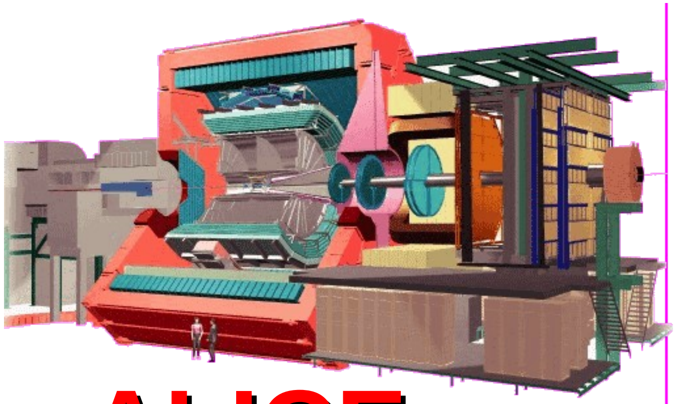
Large Hadron Collider



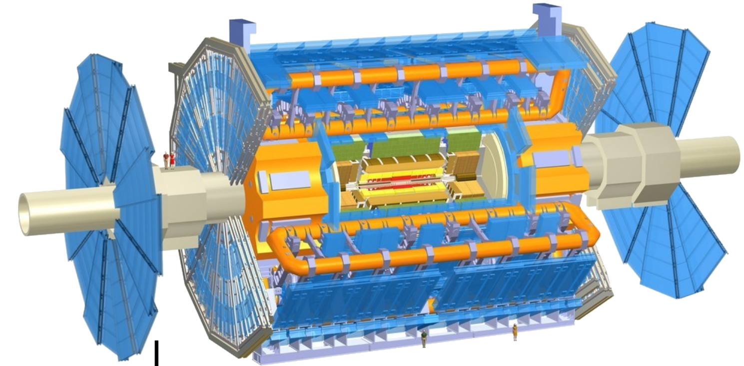
Geneva, Switzerland
8.6km diameter
+*Pb*, Pb+Pb
2.76 GeV, *5.5 TeV*



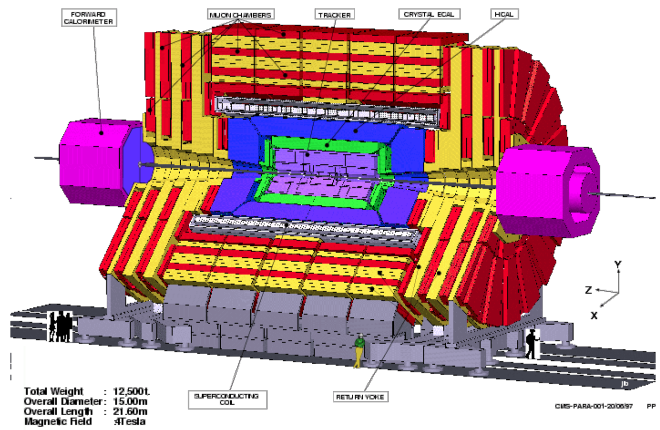
Particle Detectors



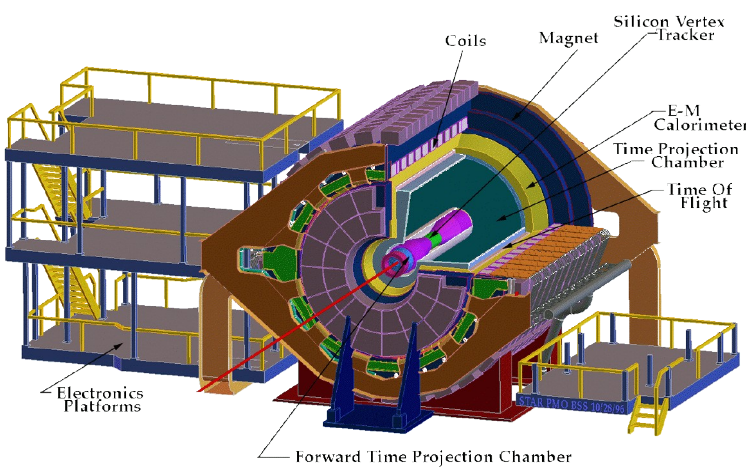
ALICE



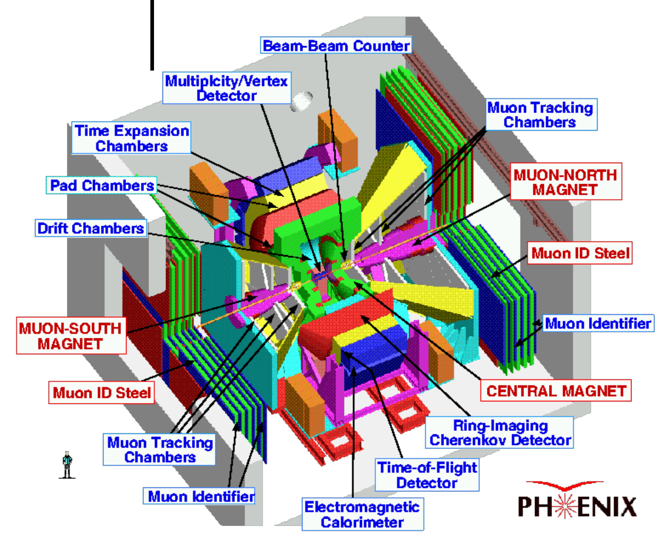
ATLAS



CMS

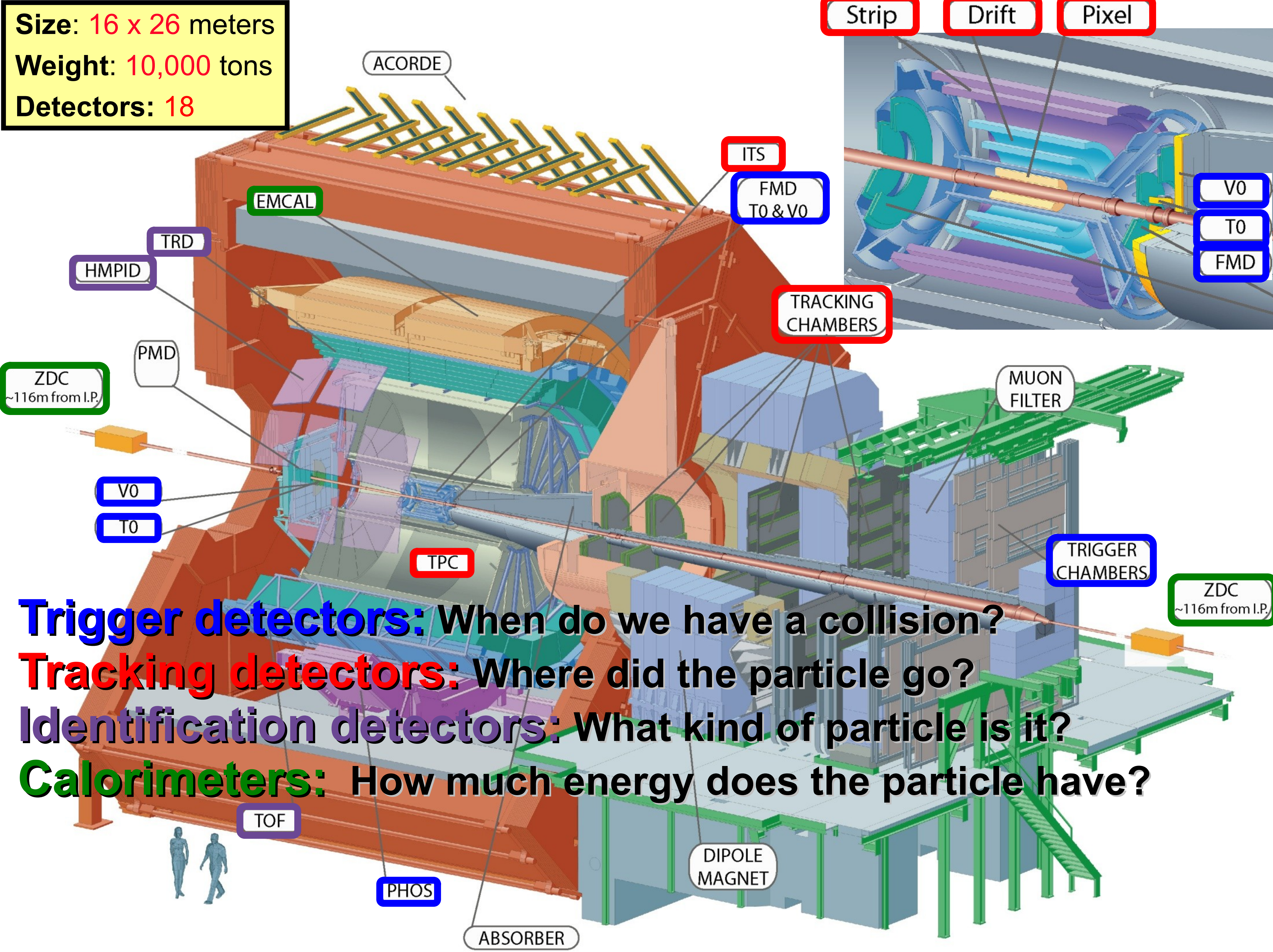


STAR



PHENIX

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



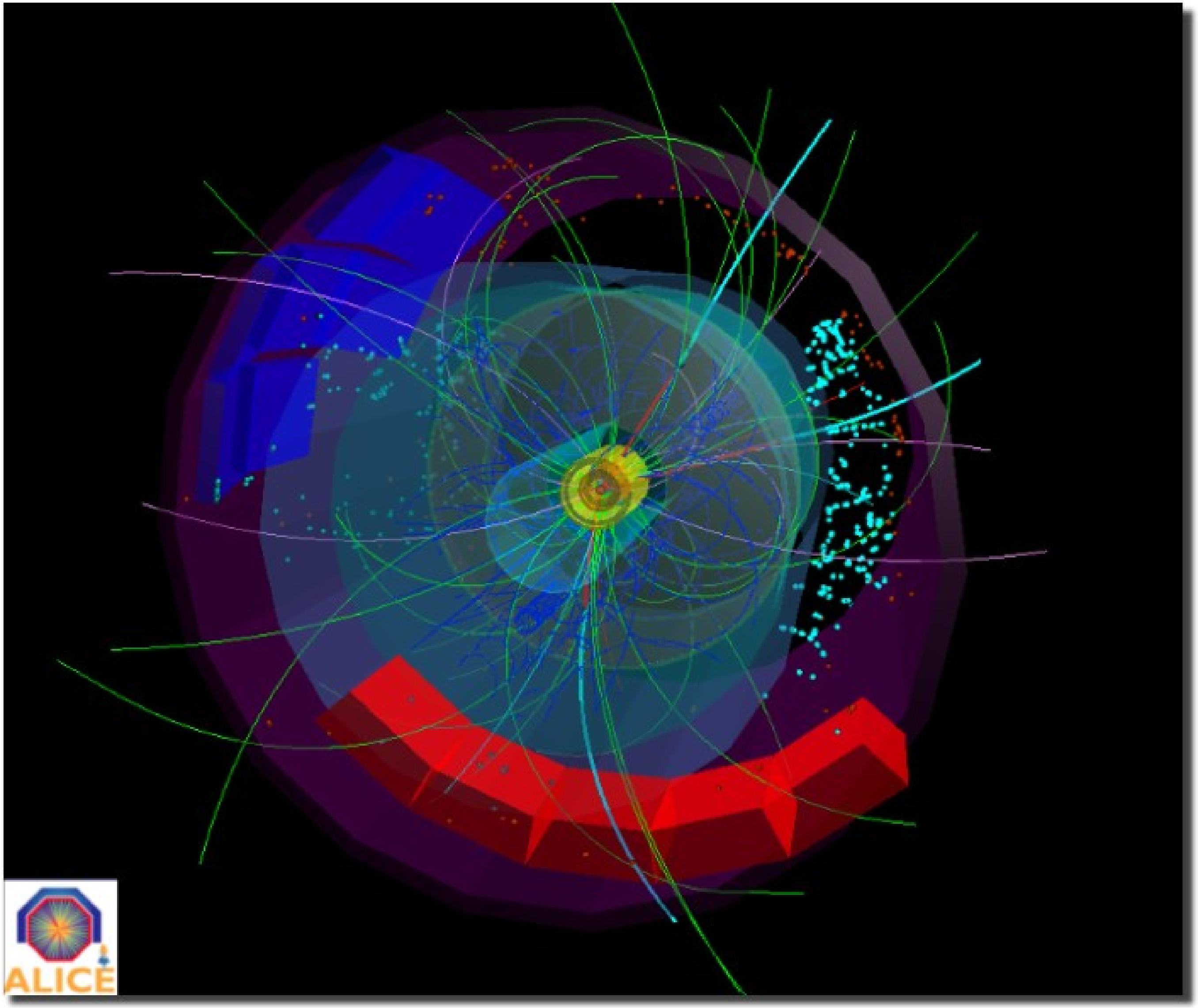
Trigger detectors: When do we have a collision?

Tracking detectors: Where did the particle go?

Identification detectors: What kind of particle is it?

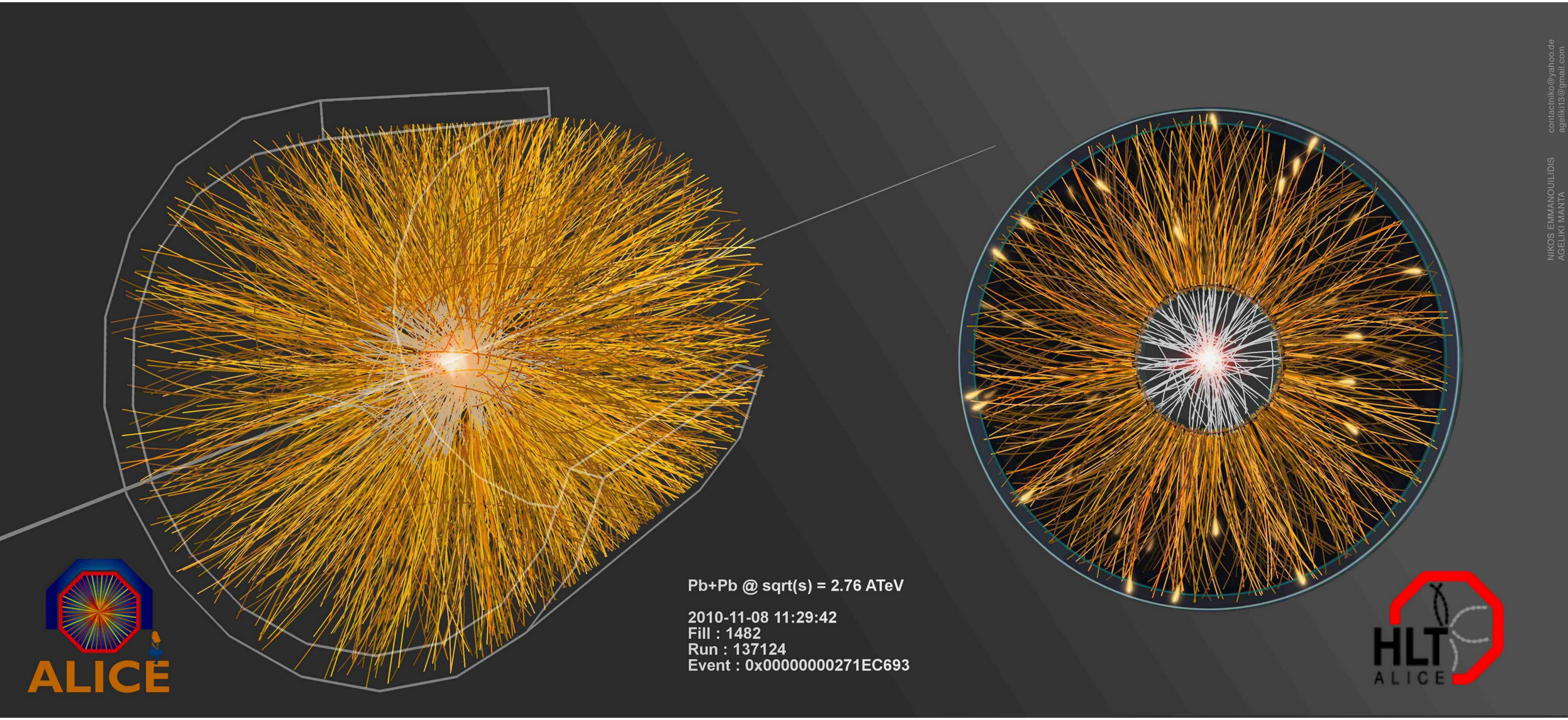
Calorimeters: How much energy does the particle have?

p+p collisions



3D image of each collision

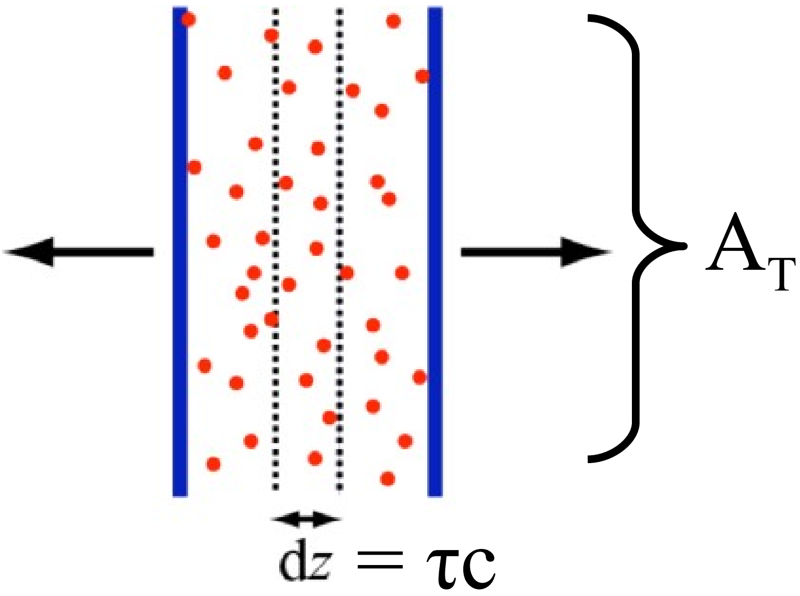
Pb+Pb collisions



Forming the QGP

How can we estimate the energy density?

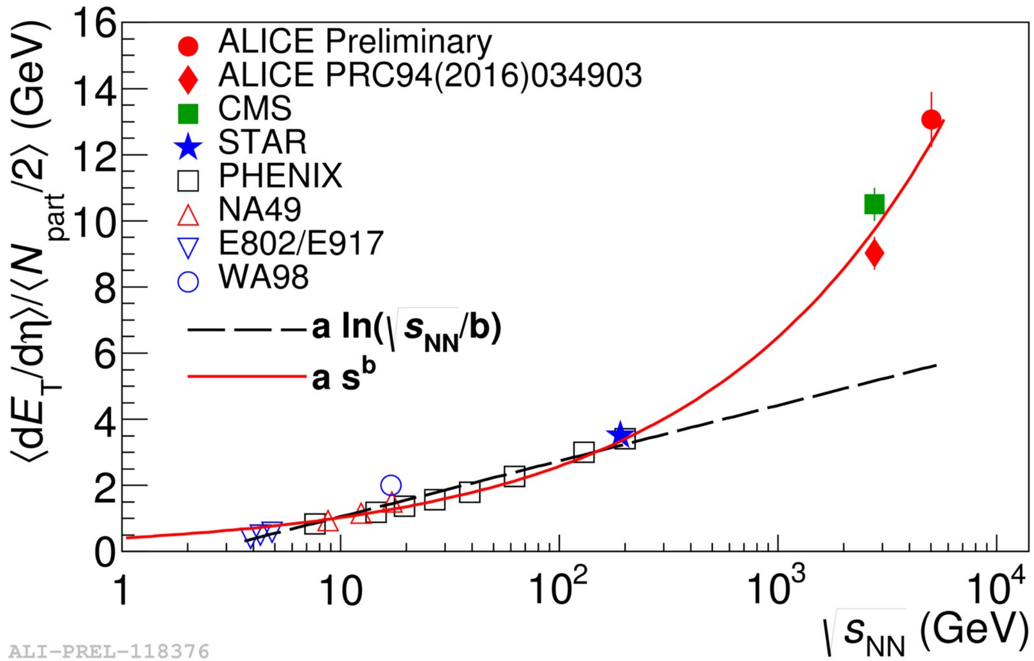
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



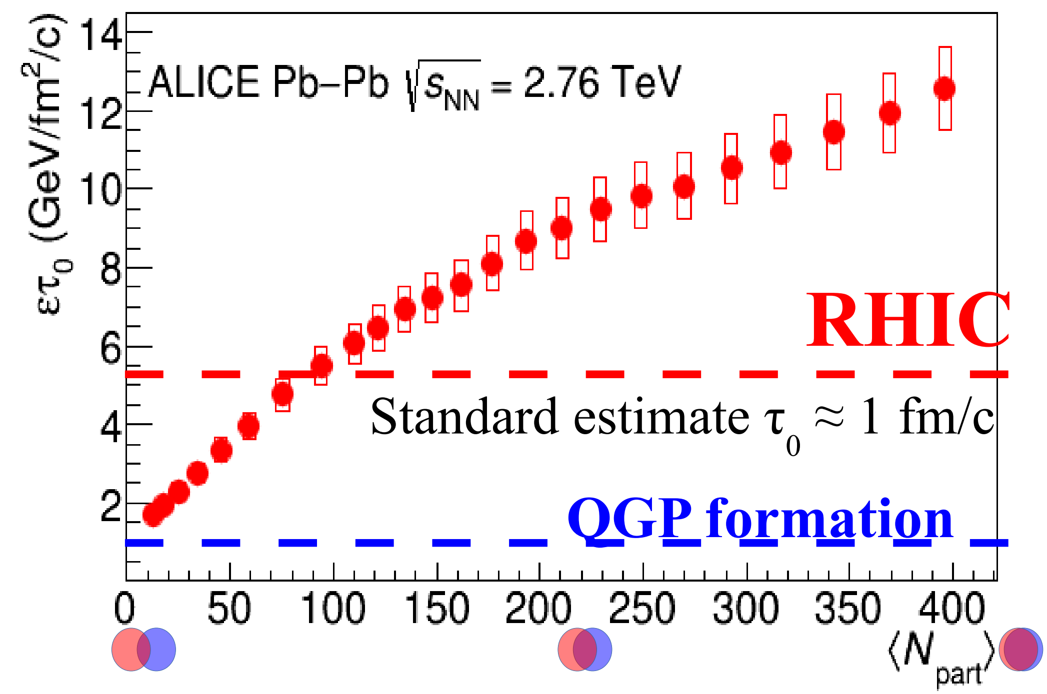
$$\epsilon = \frac{1}{V}\frac{dE_T}{dy} = \frac{J}{A_T \tau c}\frac{dE_T}{d\eta}$$

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

Energy dependence from dE_T/dy



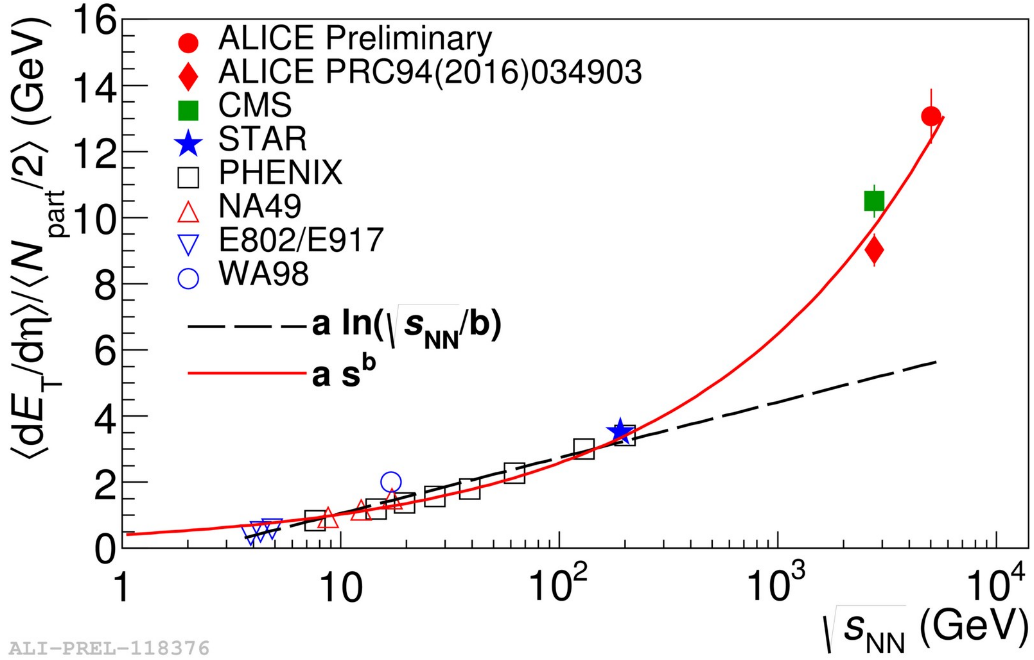
Collision energy

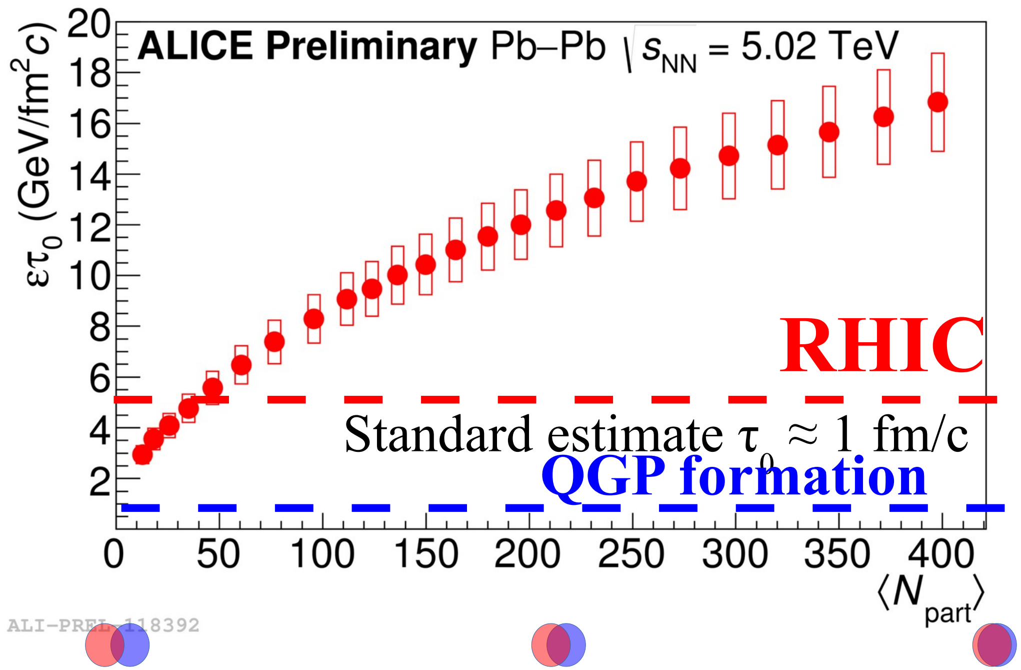


$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

➔ Higher than extrapolations of RHIC data

Energy dependence from dE_T/dy





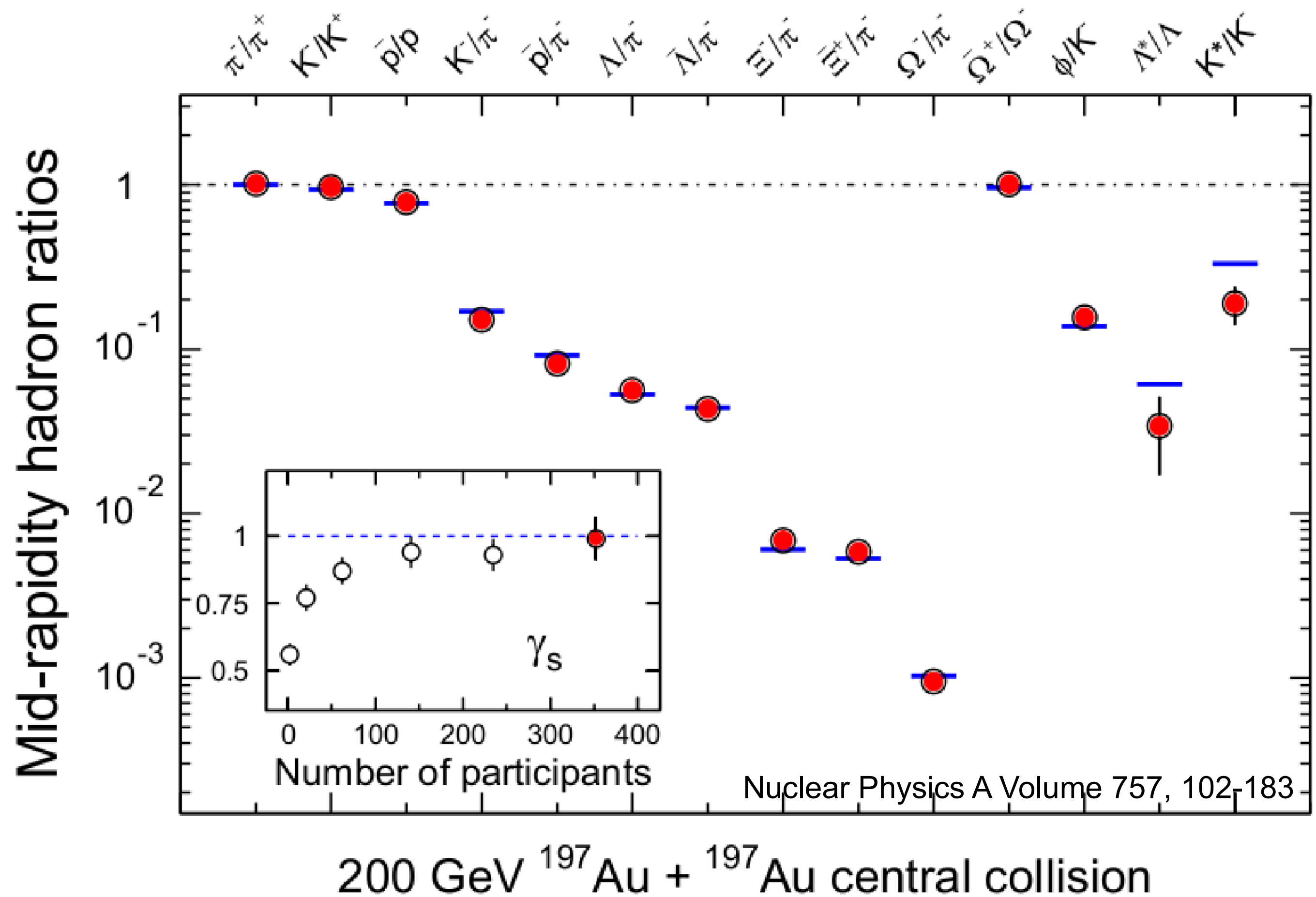
$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

➔ Higher than extrapolations of RHIC data

QGP Chemistry

Chemistry - equilibrium

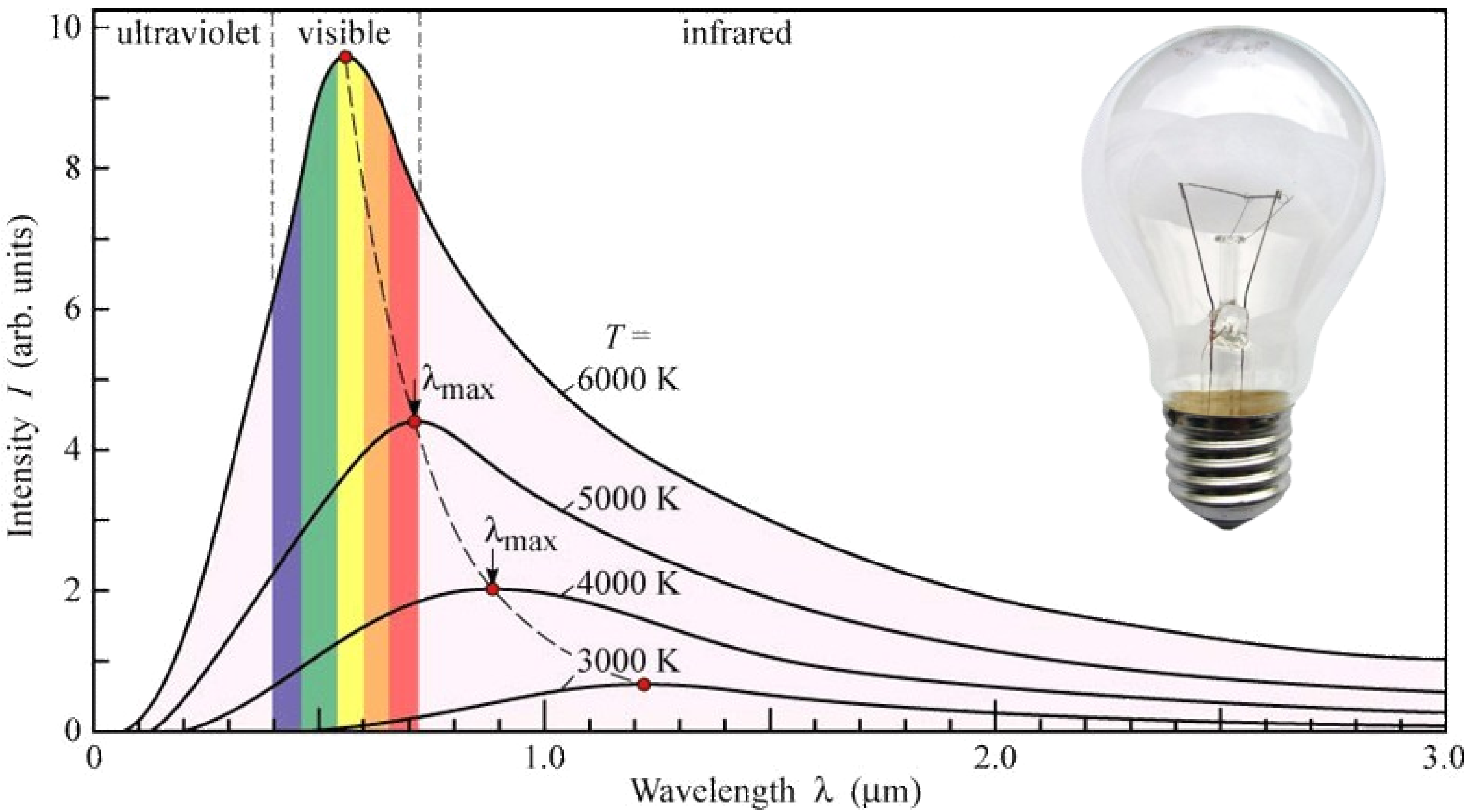
T~170 MeV



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

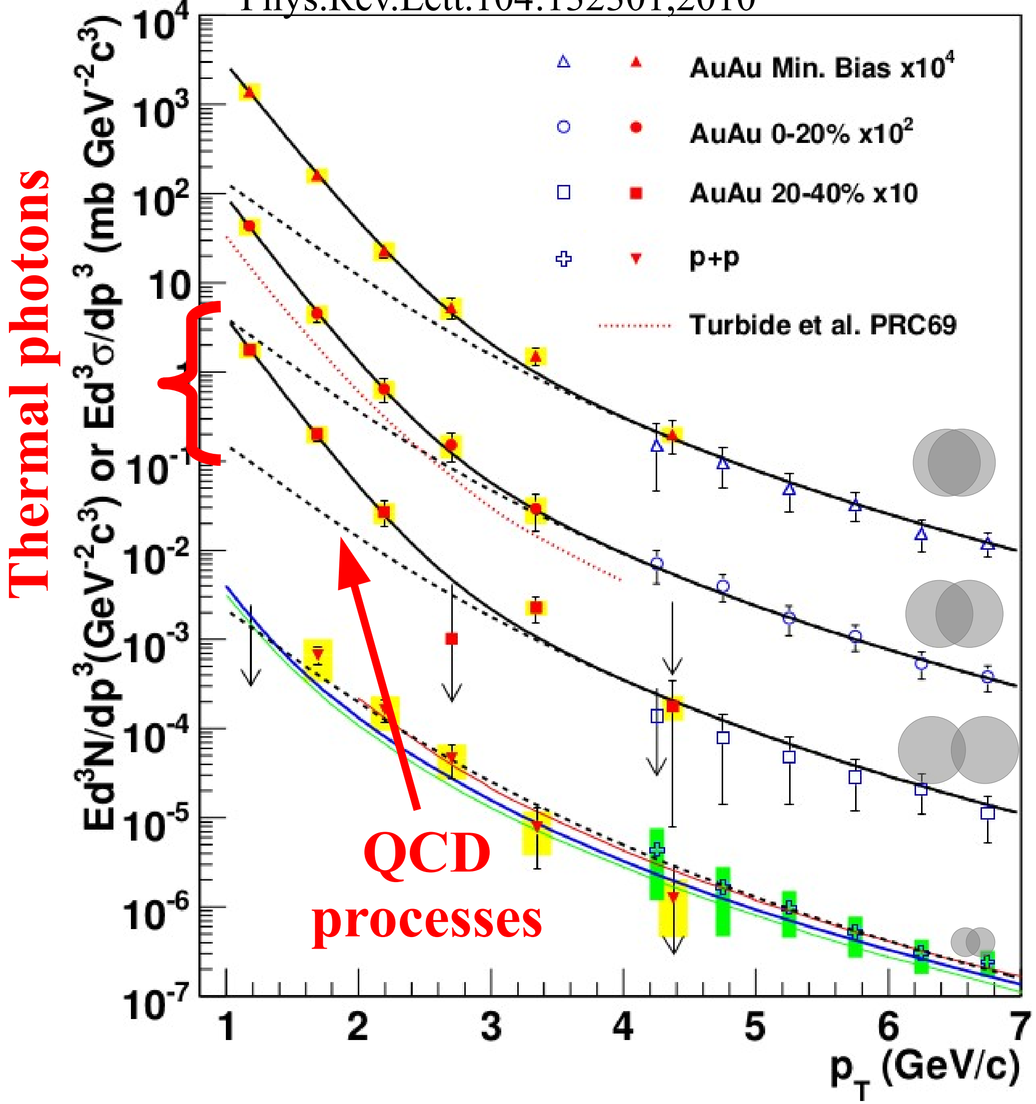
QGP Thermometers

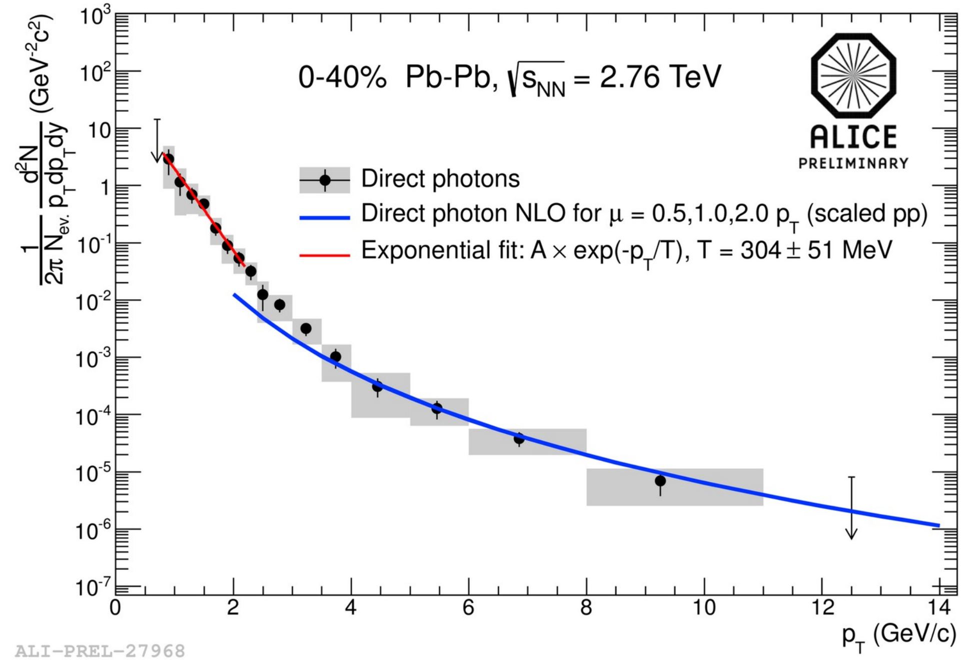
Measuring temperature



Thermal photons

Phys.Rev.Lett.104:132301,2010



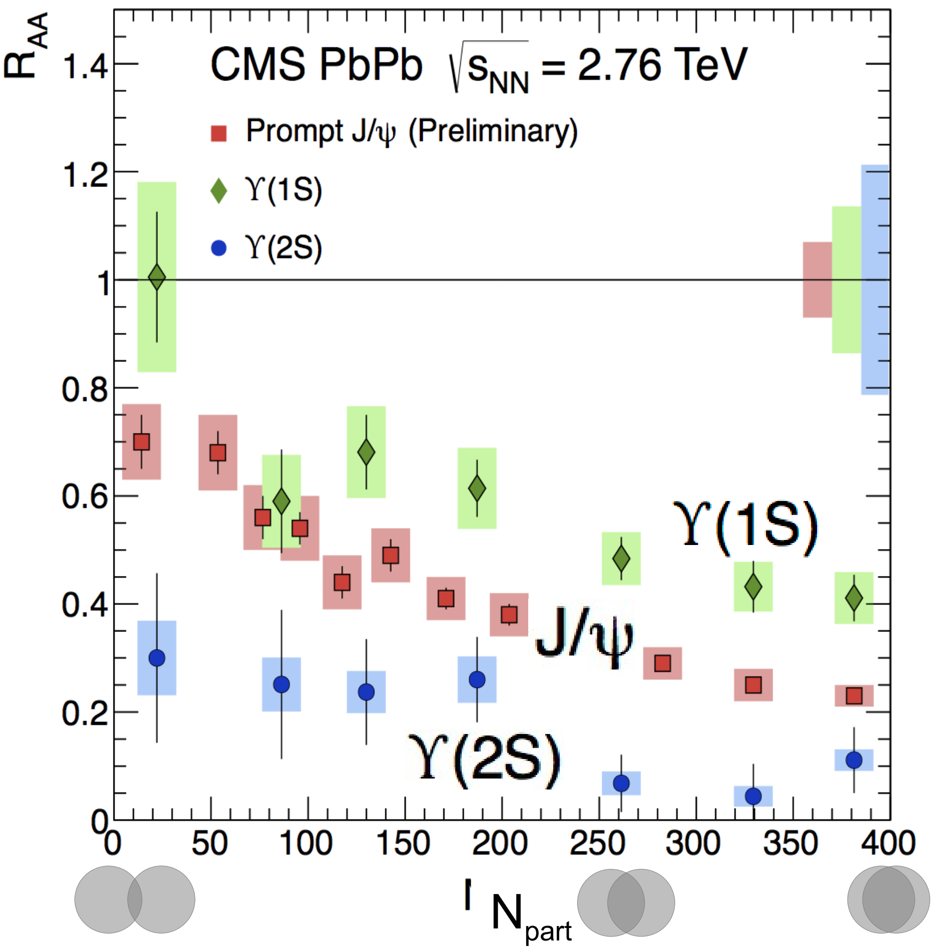


ALICE collaboration:
Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
Inverse slope: T = 304 +/-51

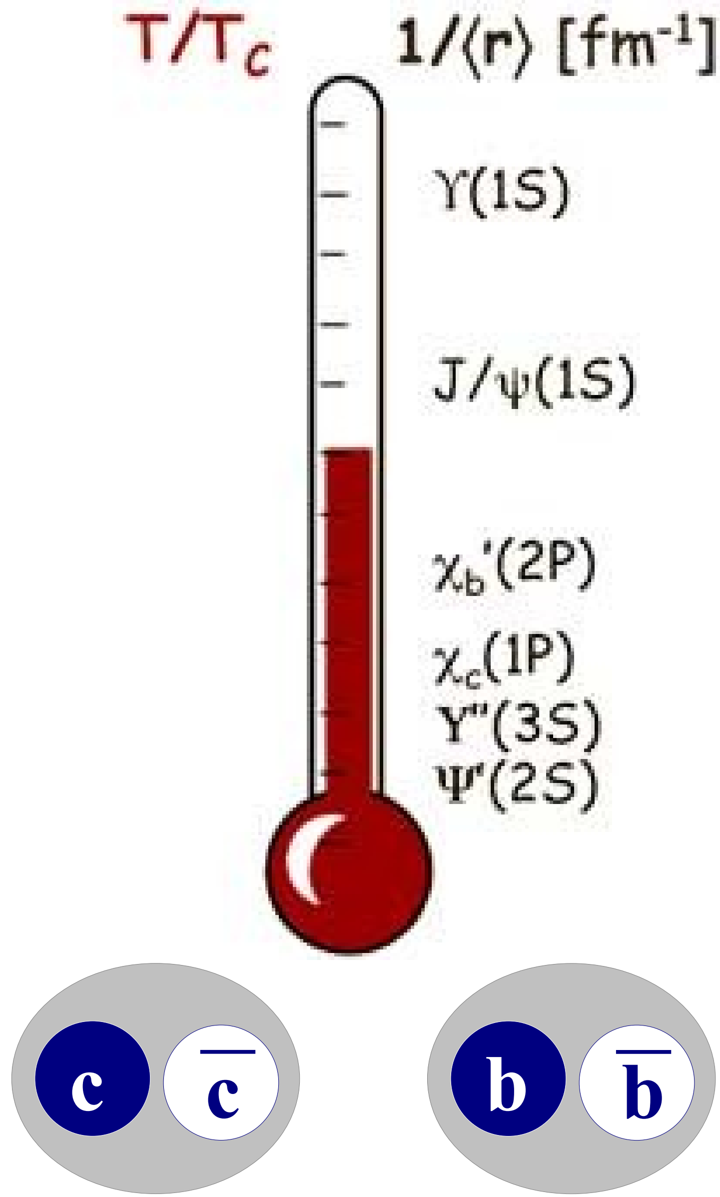
PHENIX collaboration: Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
Inverse slope: T = 221 +/- 19 (stat) +/- 19 (syst) MeV

Building a quarkonium-thermometer

CMS-PAS HIN-11-011

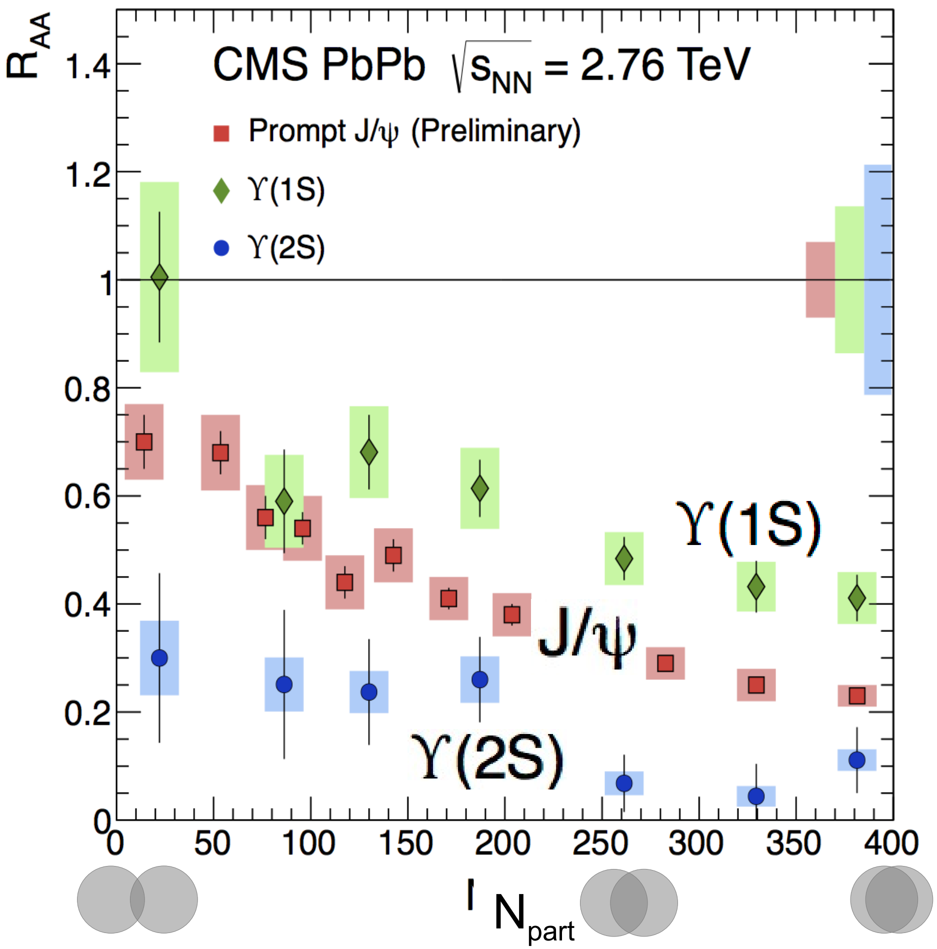


Clear hierarchy in R_{AA} of different quarkonium states

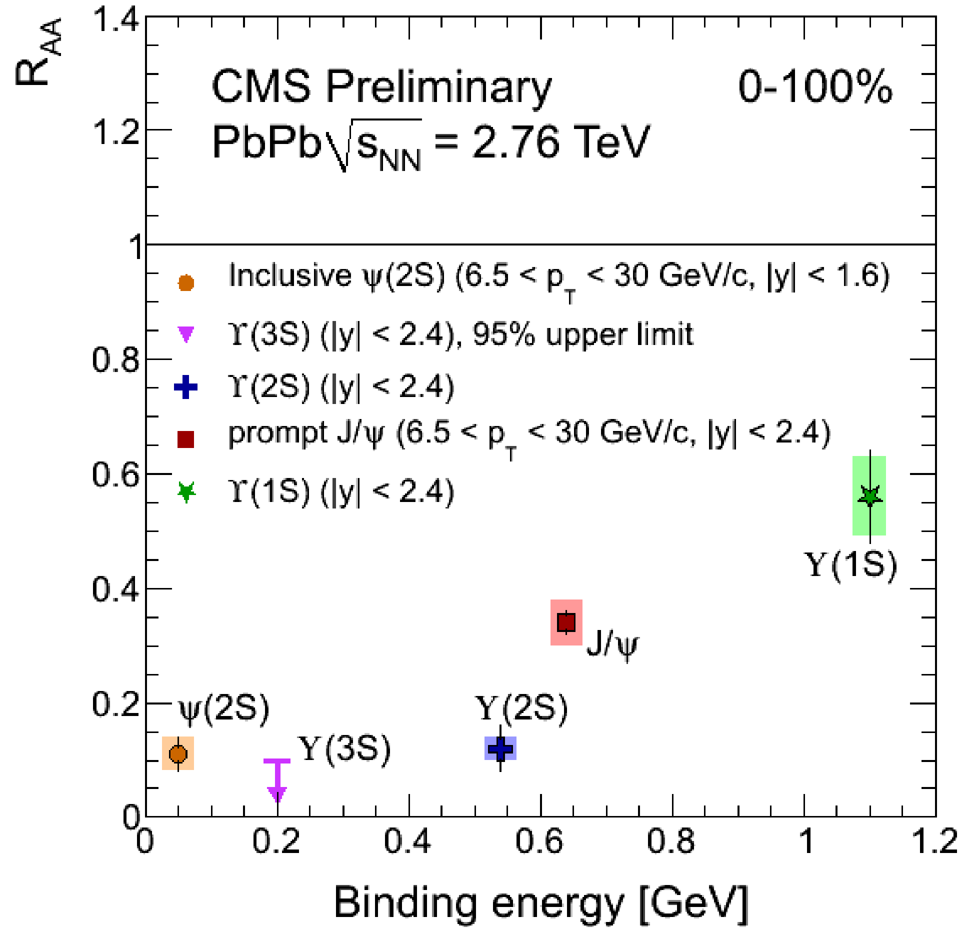


Building a quarkonium-thermometer

CMS-PAS HIN-11-011



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



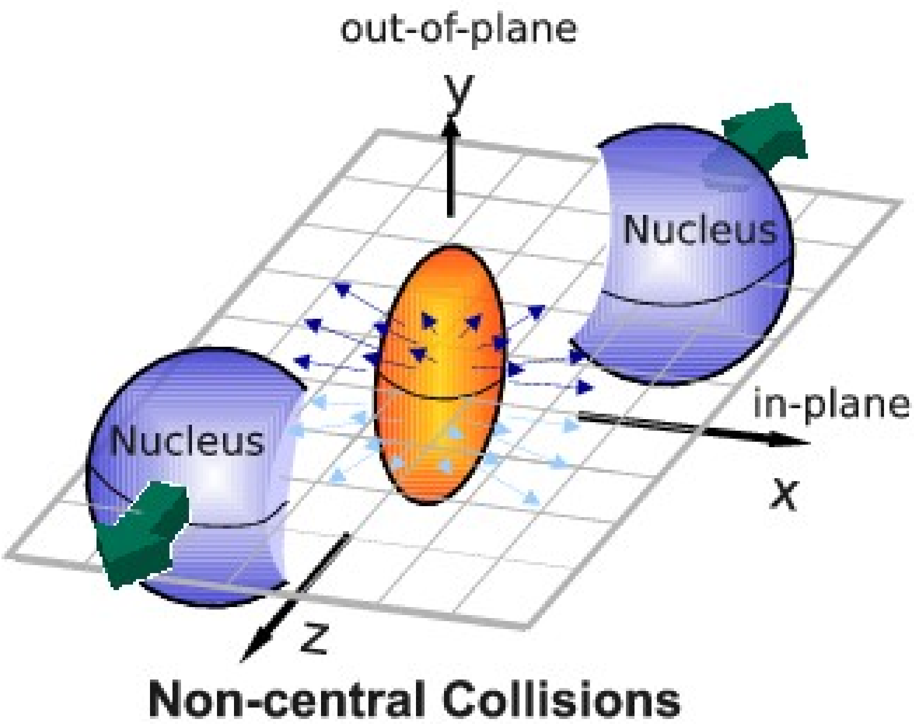
Clear hierarchy in R_{AA} of different quarkonium states

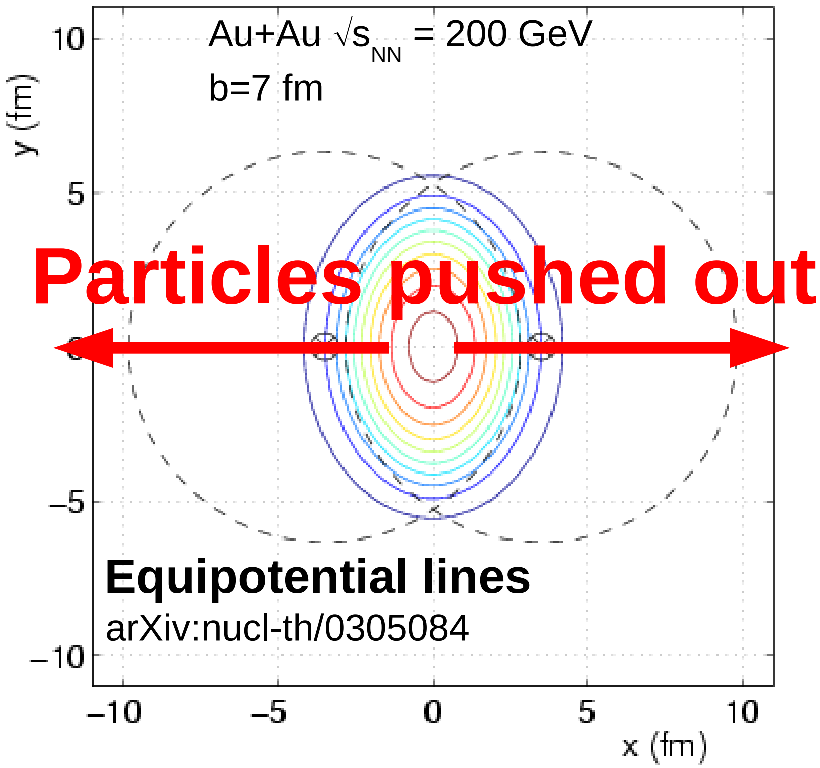
Expected in terms of binding energy

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

QGP Fluid Dynamics

If we have a fluid...



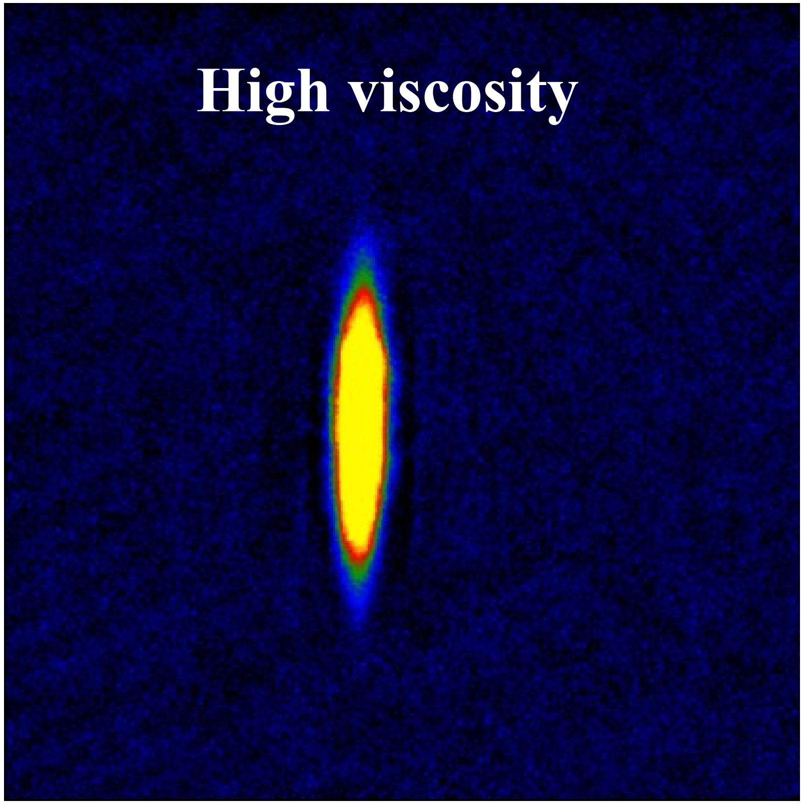


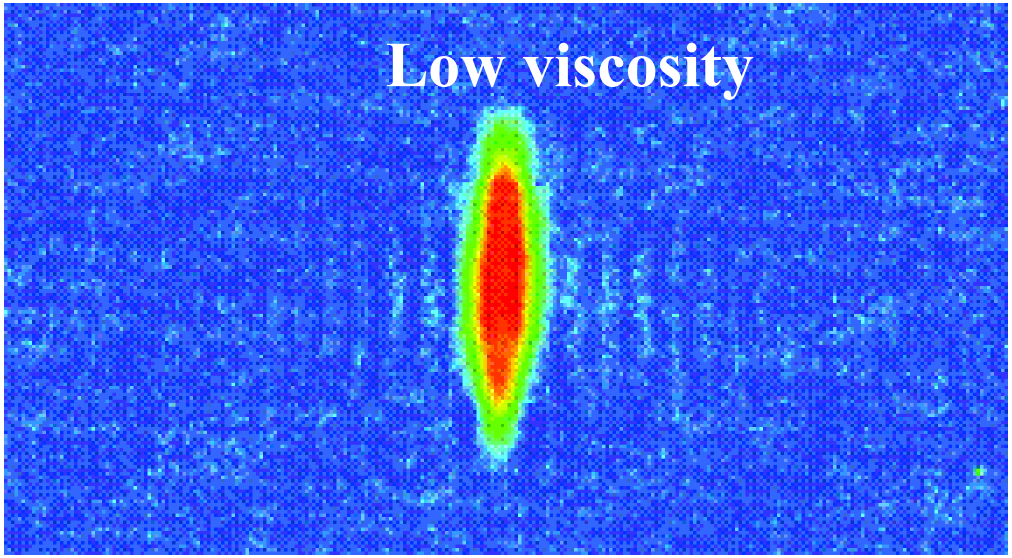
- Initial overlap asymmetric → pressure gradients
- Momentum anisotropy → Fourier decomposition:

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

What does this mean?

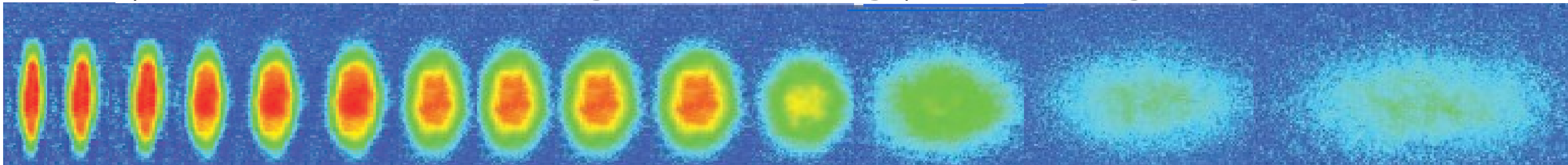
- Same phenomena observed in gases of strongly interacting atoms
  - K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**





What does it mean?

Same phenomena observed in gases of strongly interacting atoms



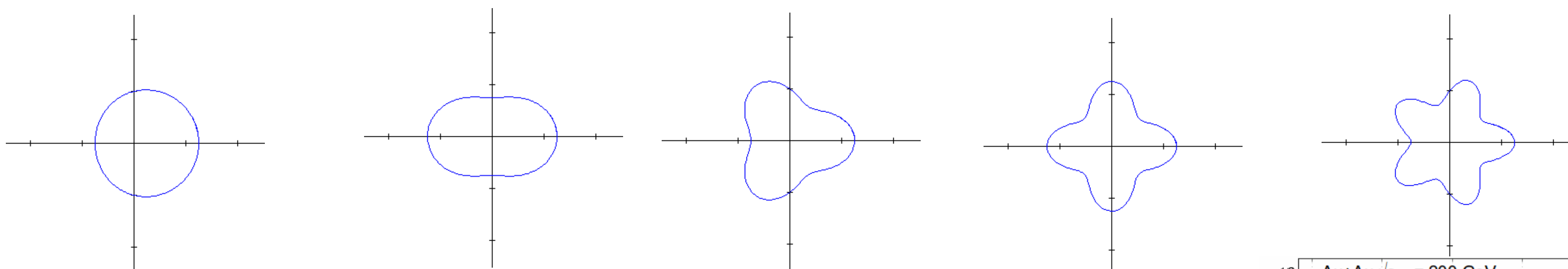
K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**

Time →

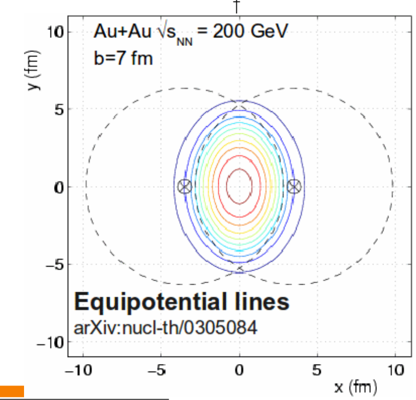
Initial state anisotropies converted to final state anisotropies

Fourier decomposition:

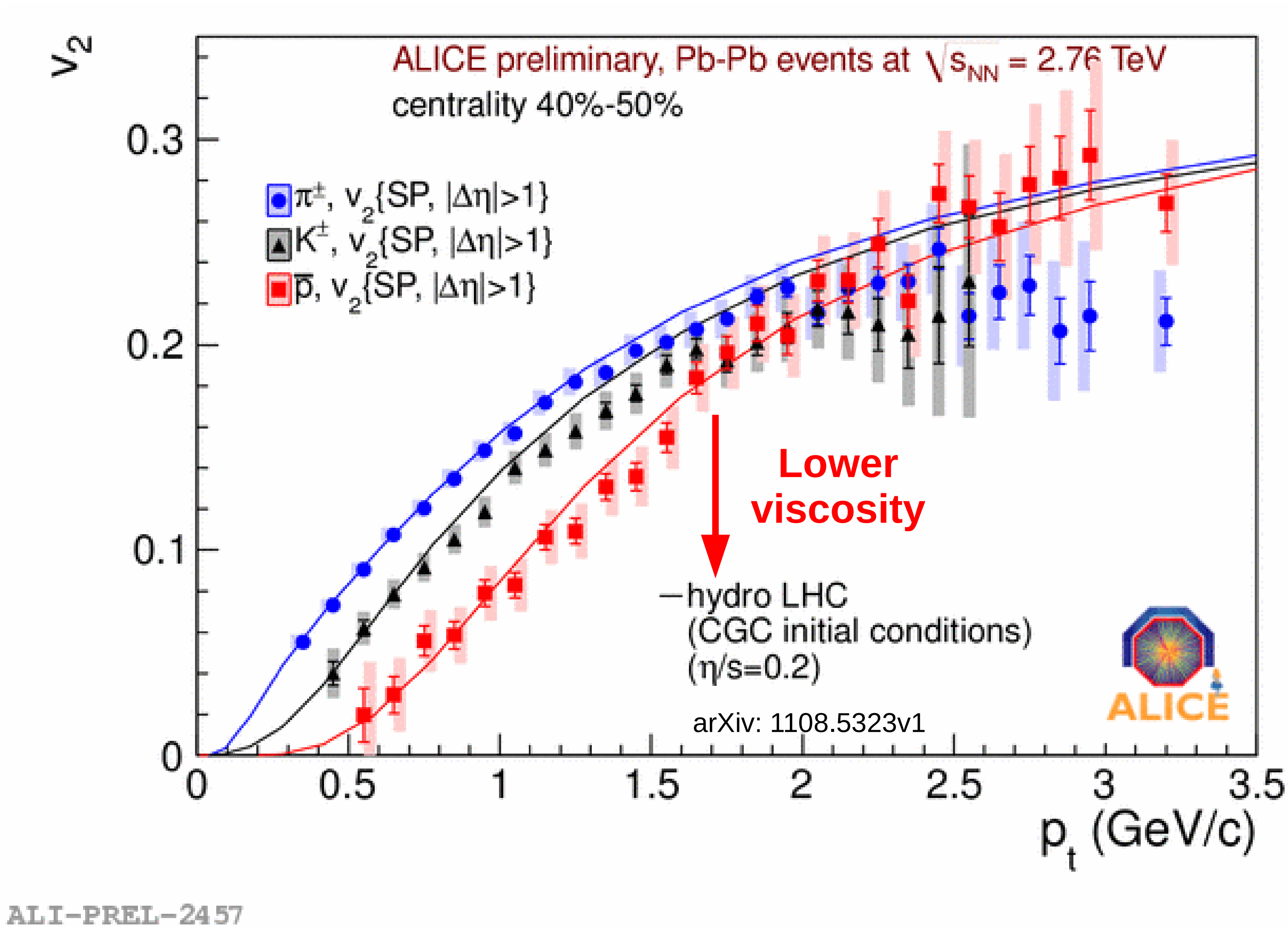
$$\frac{d^2N}{dp_T\,d\phi} \approx 1 + 2v_1\cos(d\phi) + 2v_2\cos(2d\phi) + 2v_3\cos(3d\phi) + 2v_4\cos(4d\phi) + 2v_5\cos(5d\phi) + \ldots$$



Offset measured



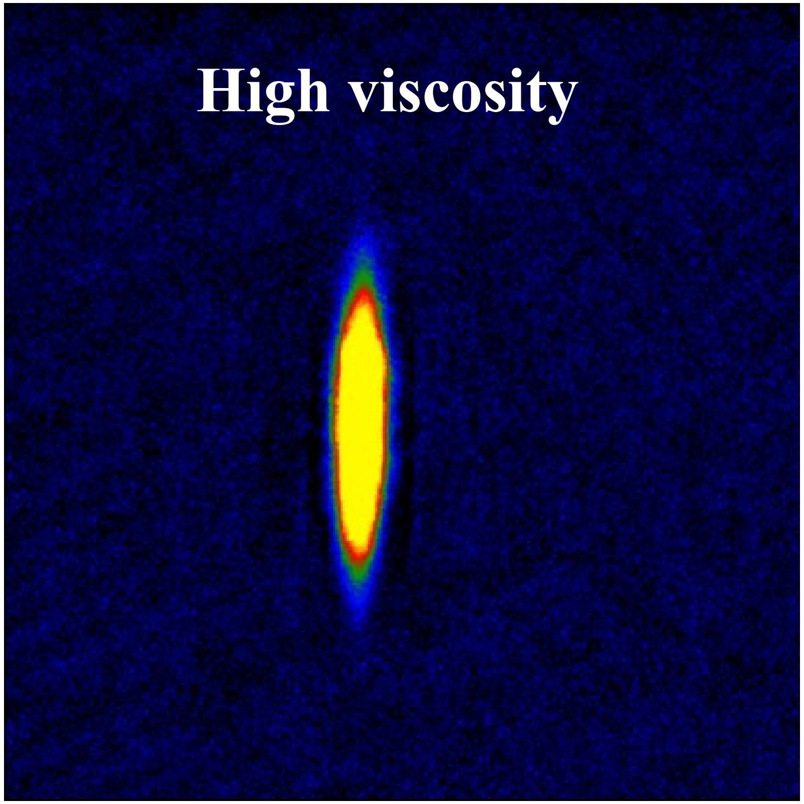
Does this describe the data?

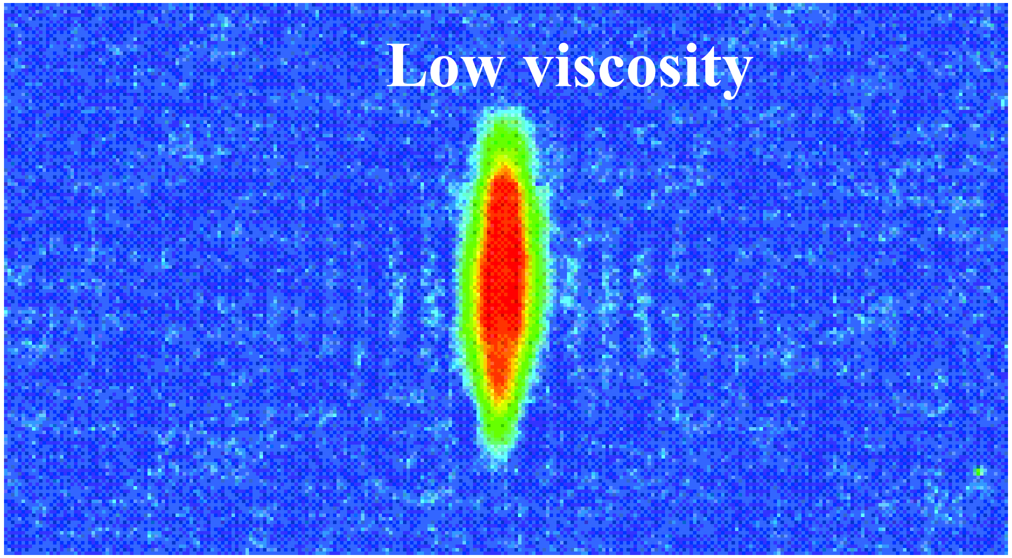


Yes!

What does this mean?

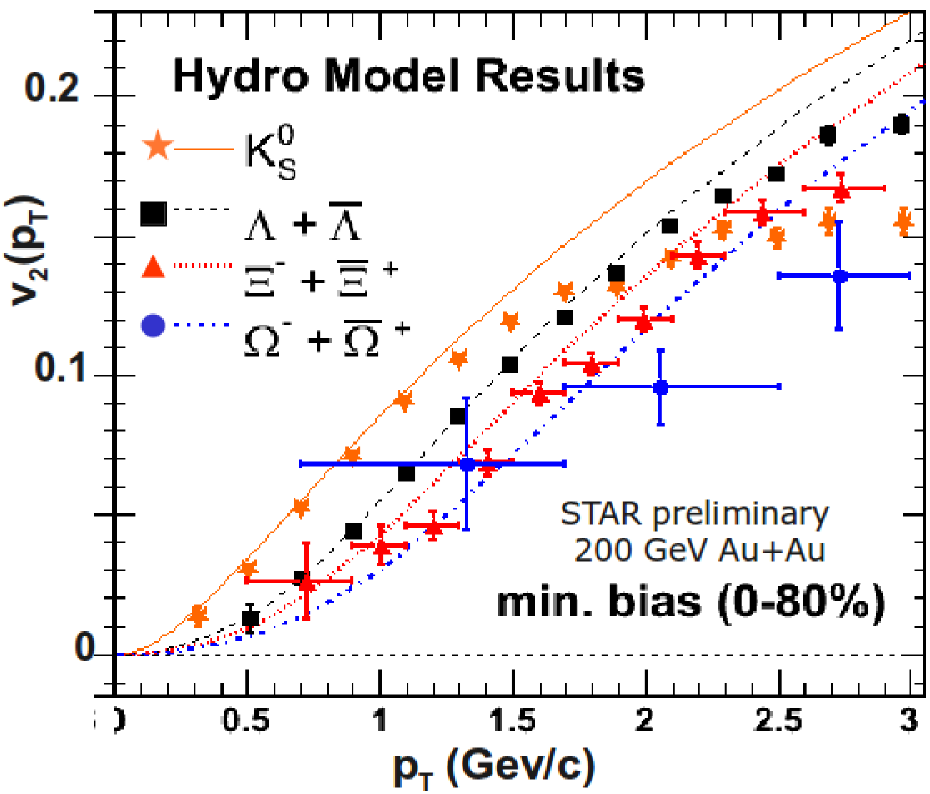
- Same phenomena observed in gases of strongly interacting atoms
  - K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**

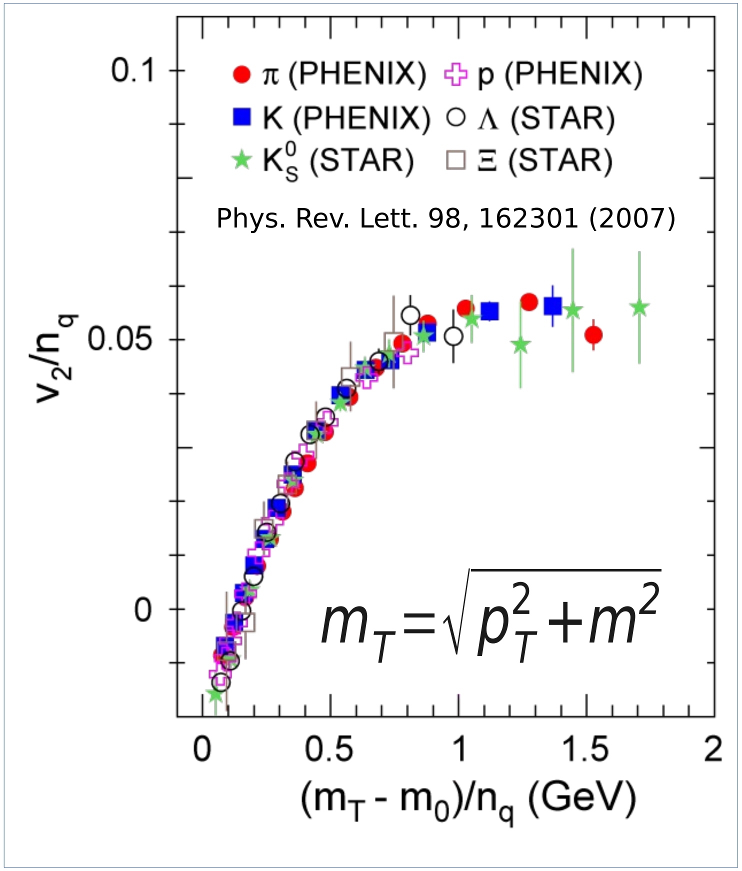




The Quark Gluon Plasma has a very low viscosity

More data





Mass ordering:
$v_2(K) > v_2(\Lambda) > v_2(\Xi)$

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

We have a liquid of quarks and gluons!

What do we learn about the QGP?

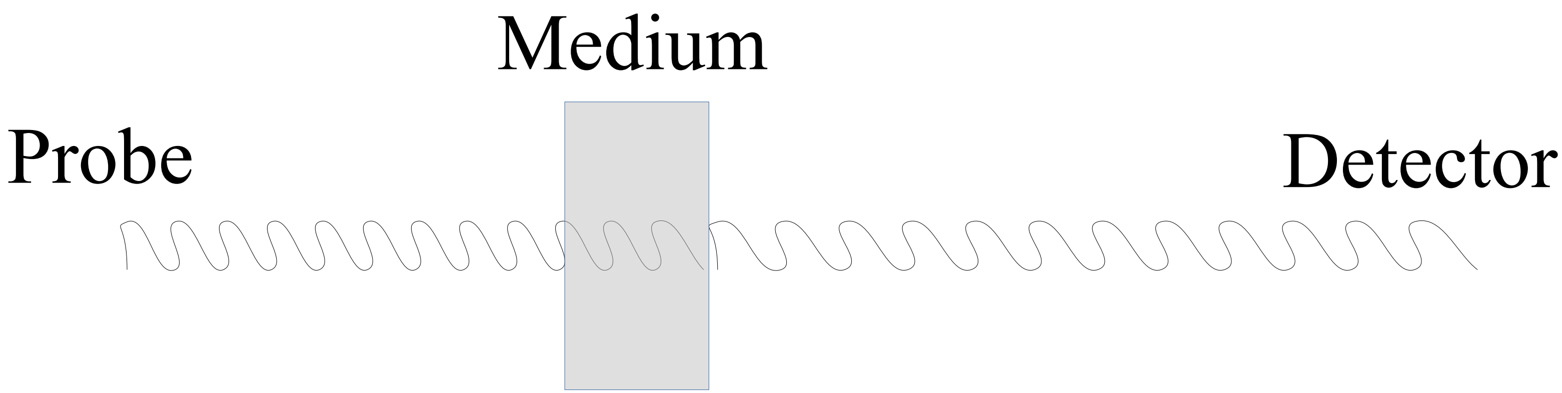
- Hydrodynamics works →
  - (local) thermalization
  - image of the initial state
- Really low viscosity
  - Near AdS/CFT bound
  - $\eta/S \sim 1/4\pi$

The QGP is the perfect liquid!

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

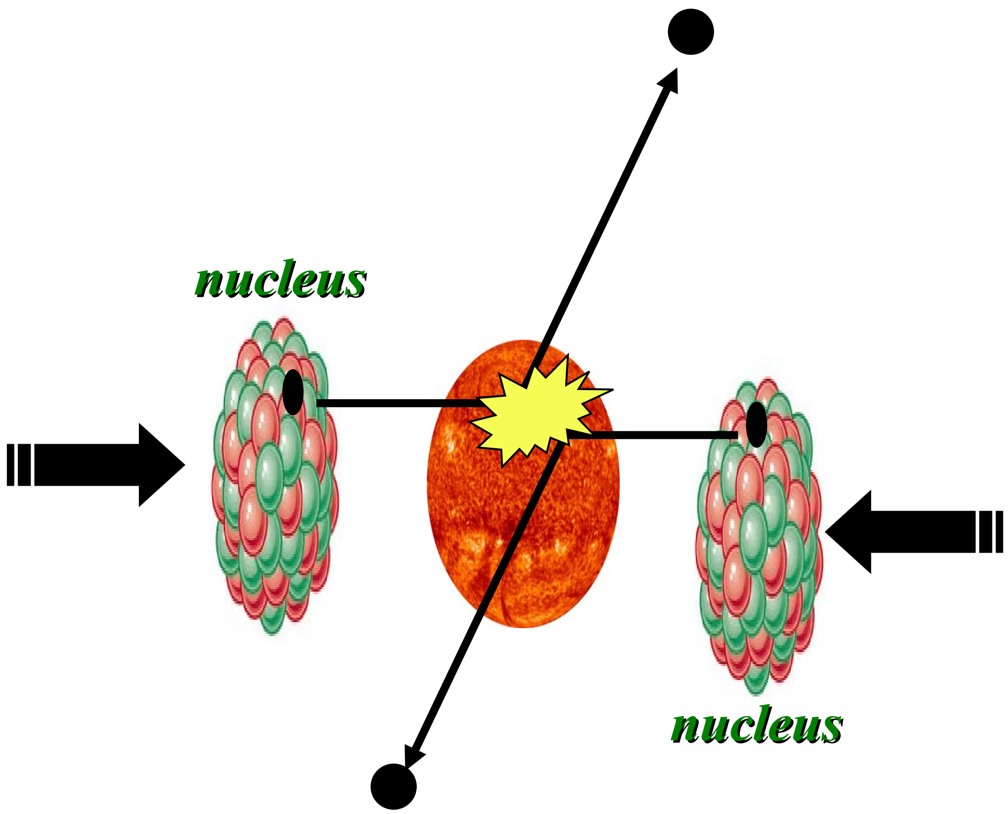
QGP Spectroscopy: Jets Part 1

Probing the Quark Gluon Plasma



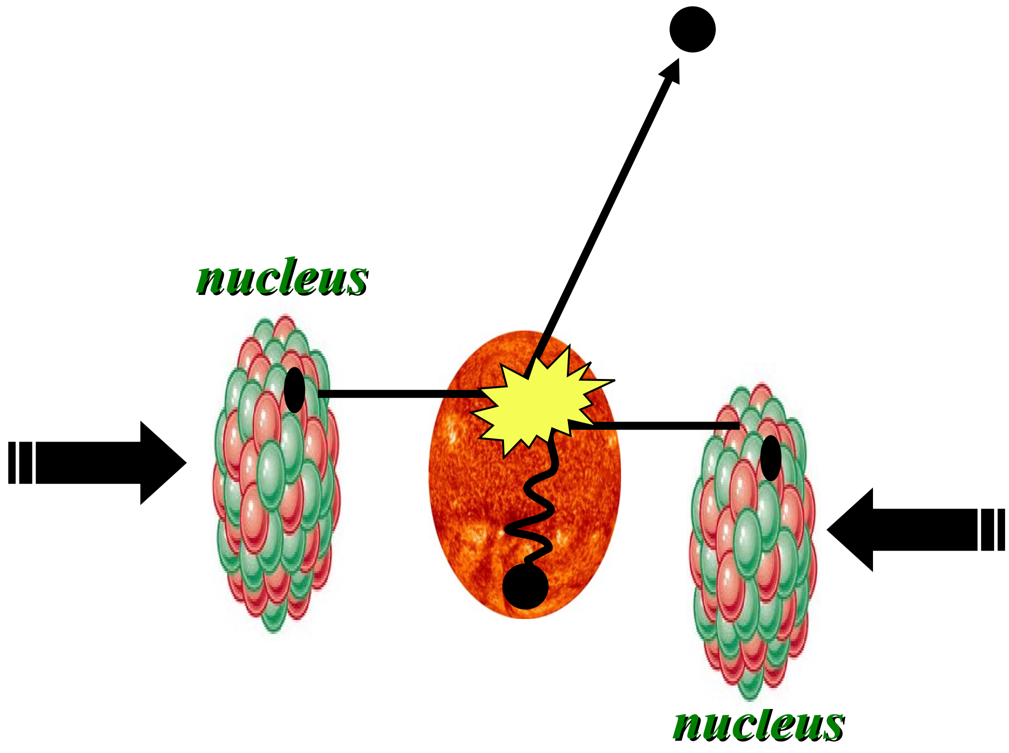
Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



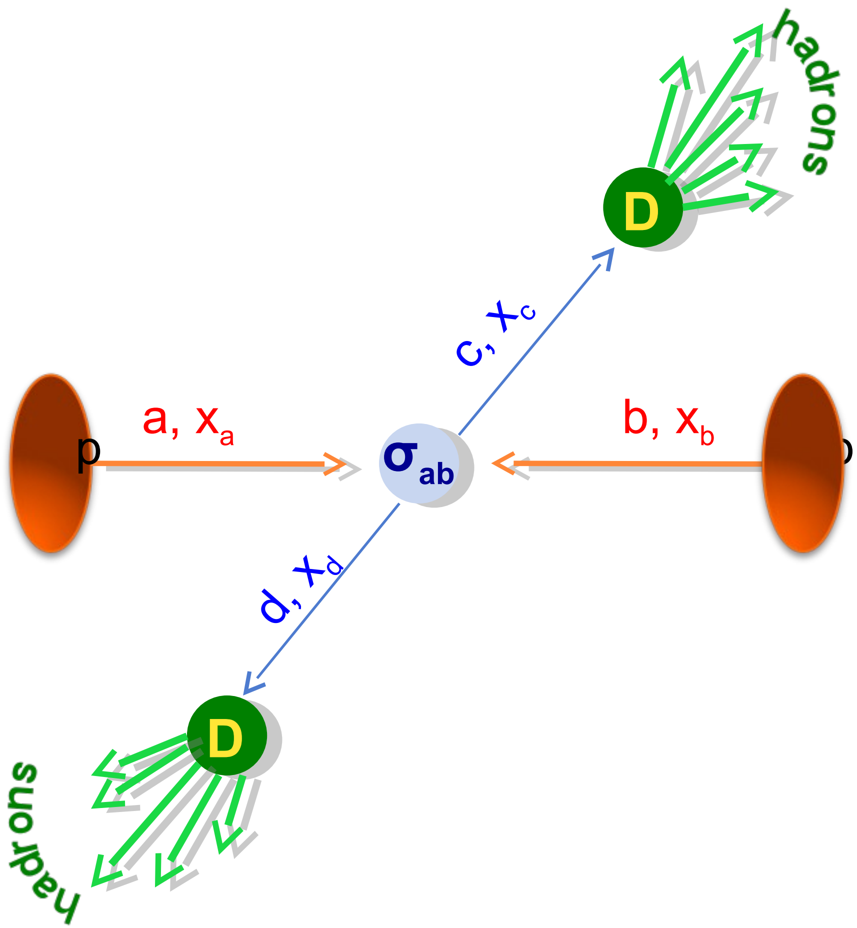
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

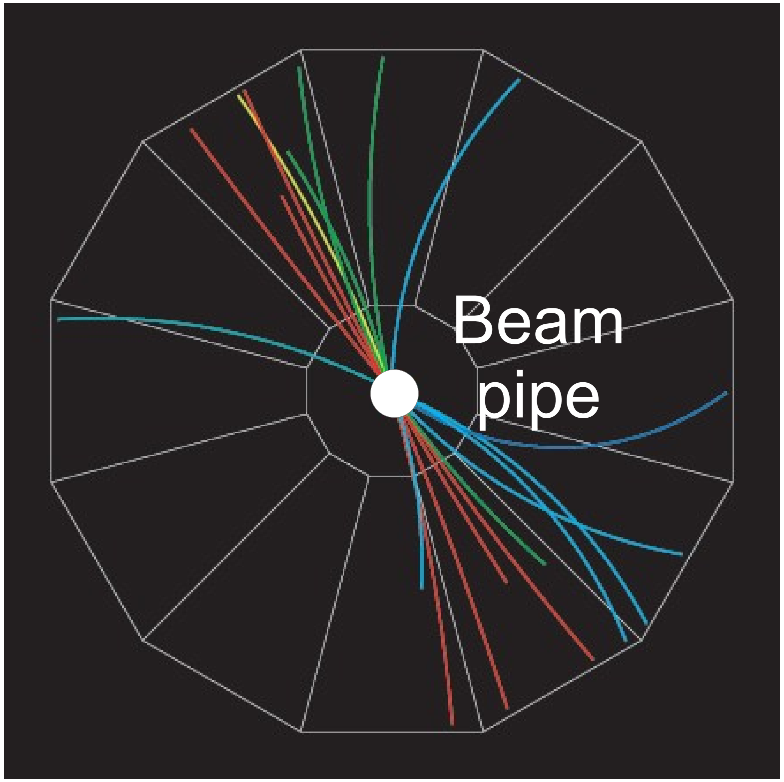


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets

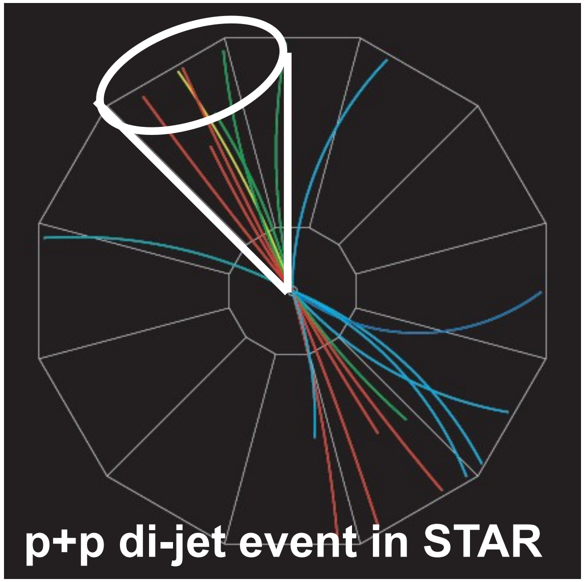


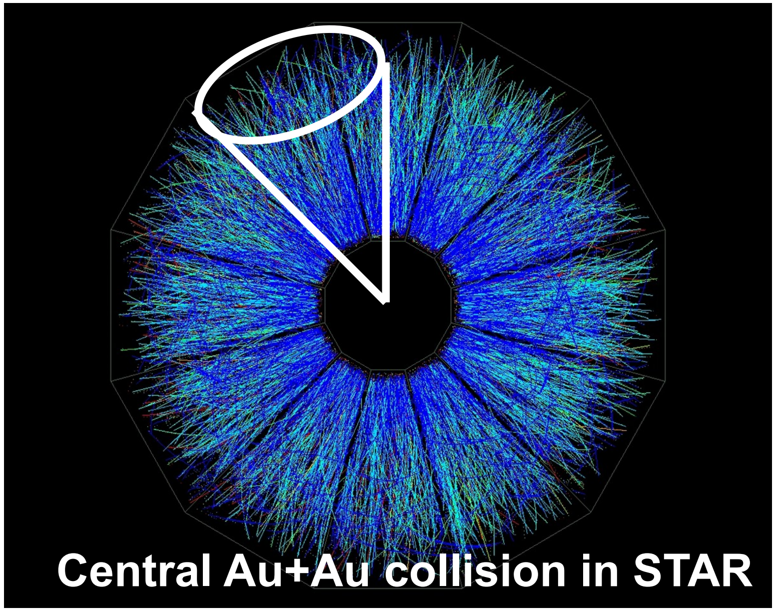
p+p → dijet



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

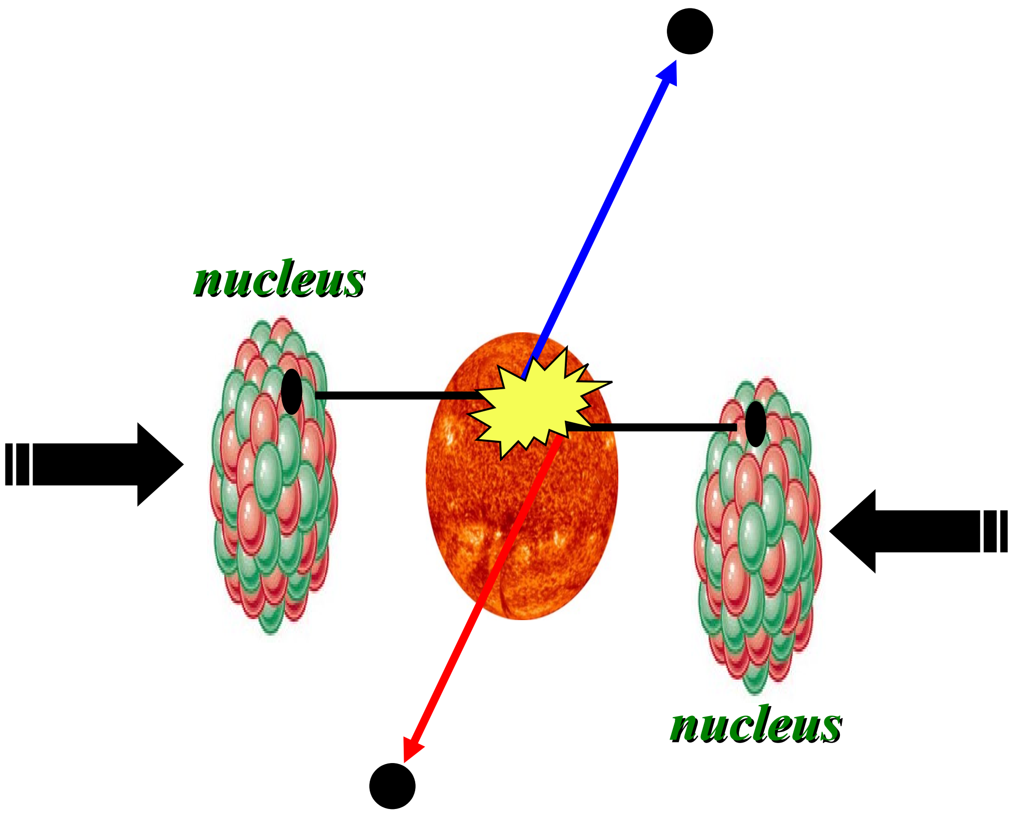
Jet reconstruction



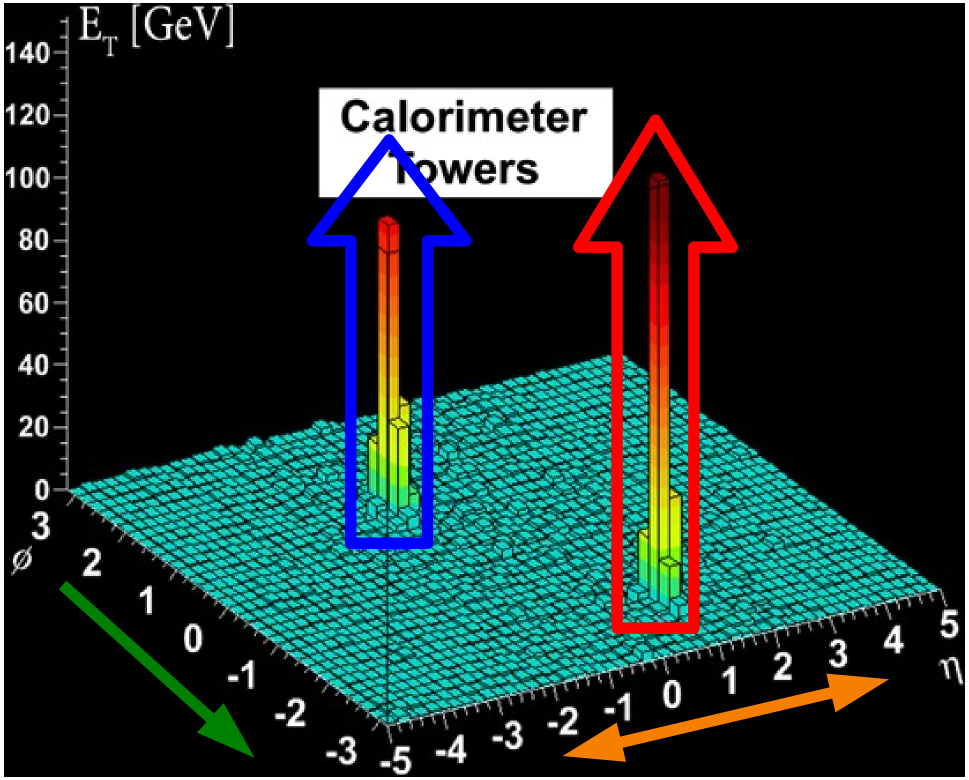


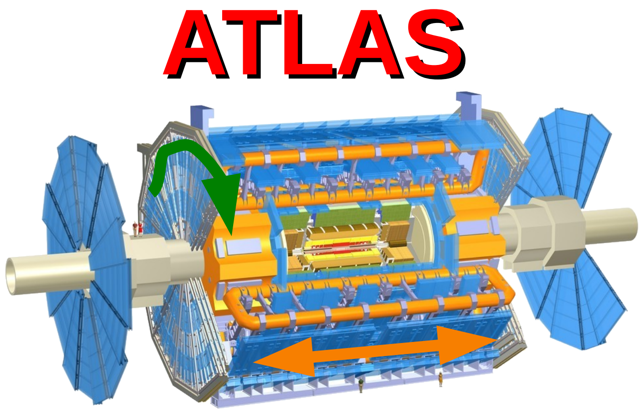
- Identify all of the particles in the jet → parton energy, momentum
- Difficult in heavy ion collisions – but possible!

Jets

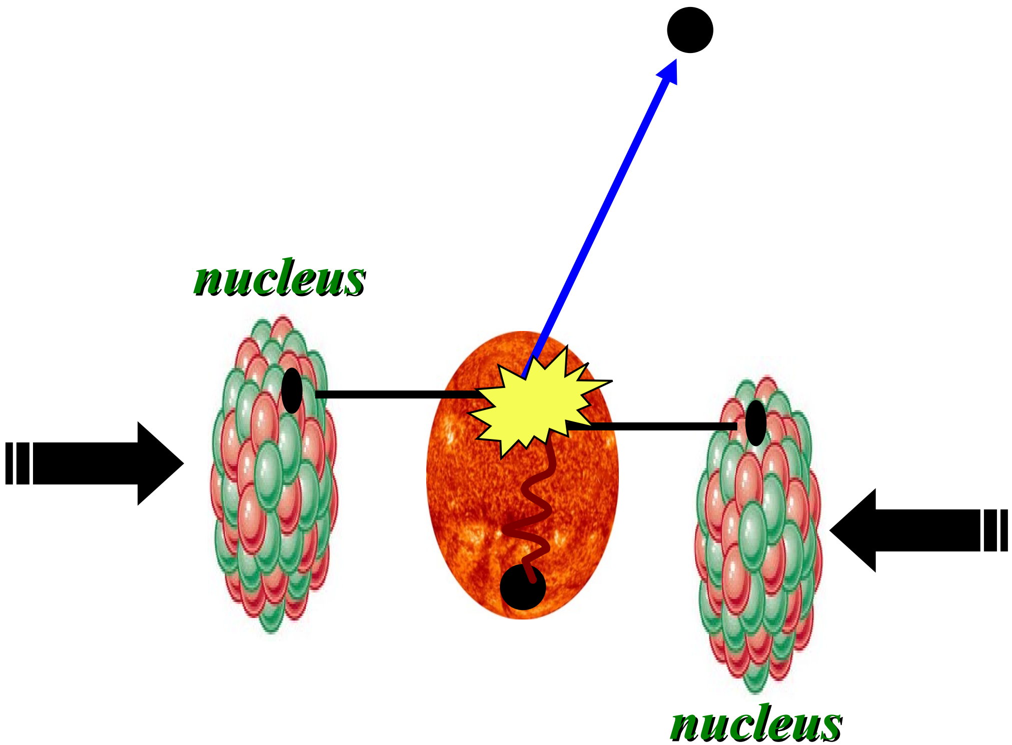


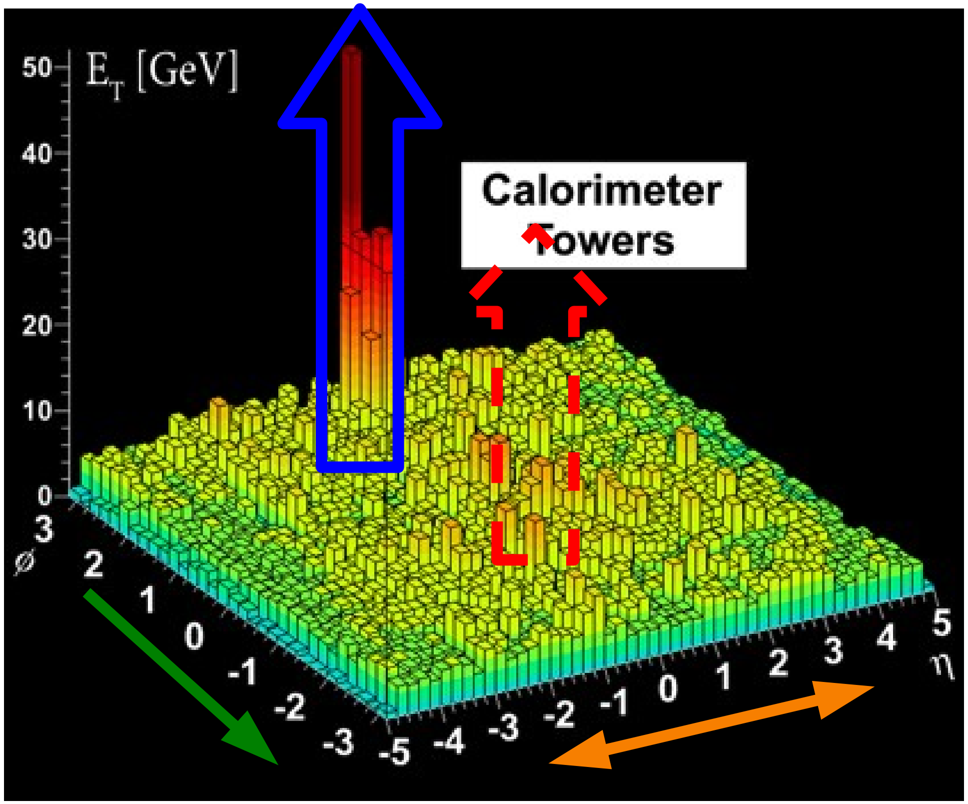
Phys.Rev.Lett. 105 (2010) 252303

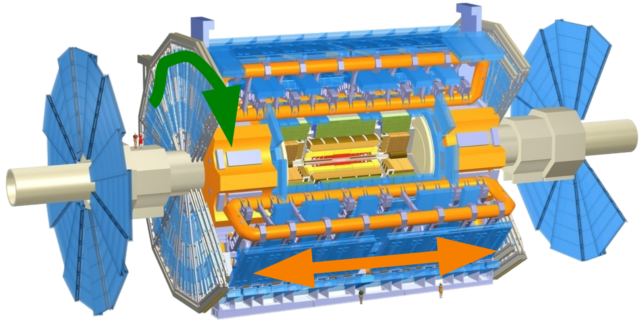




Quenched jets





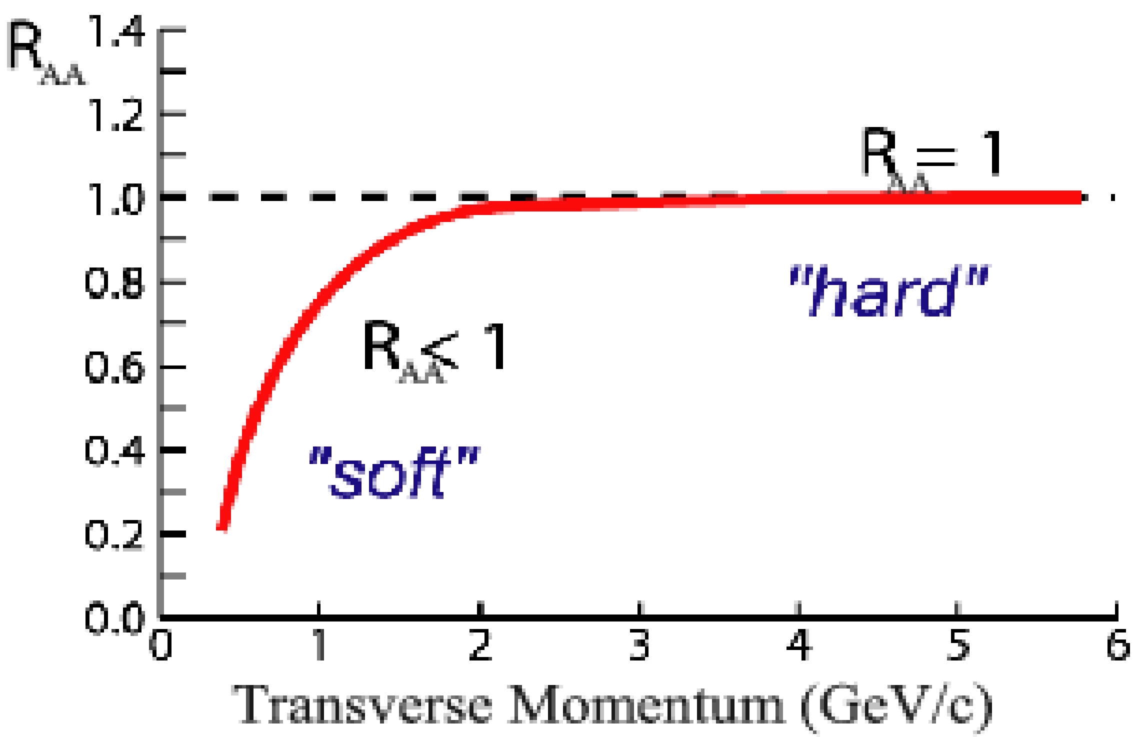


- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
- Phys. Rev. Lett. 105, 252303 (2010)

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

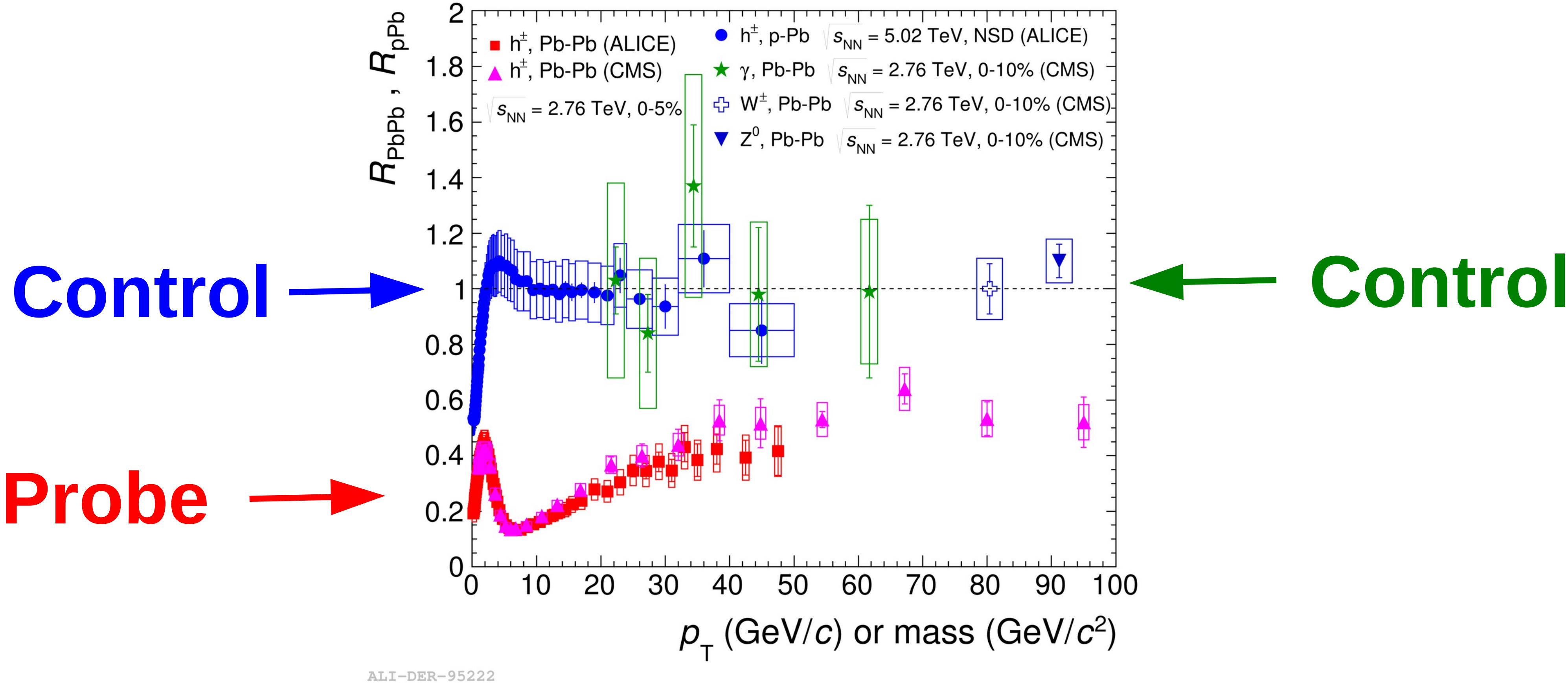
$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$



Enhancement

Suppression

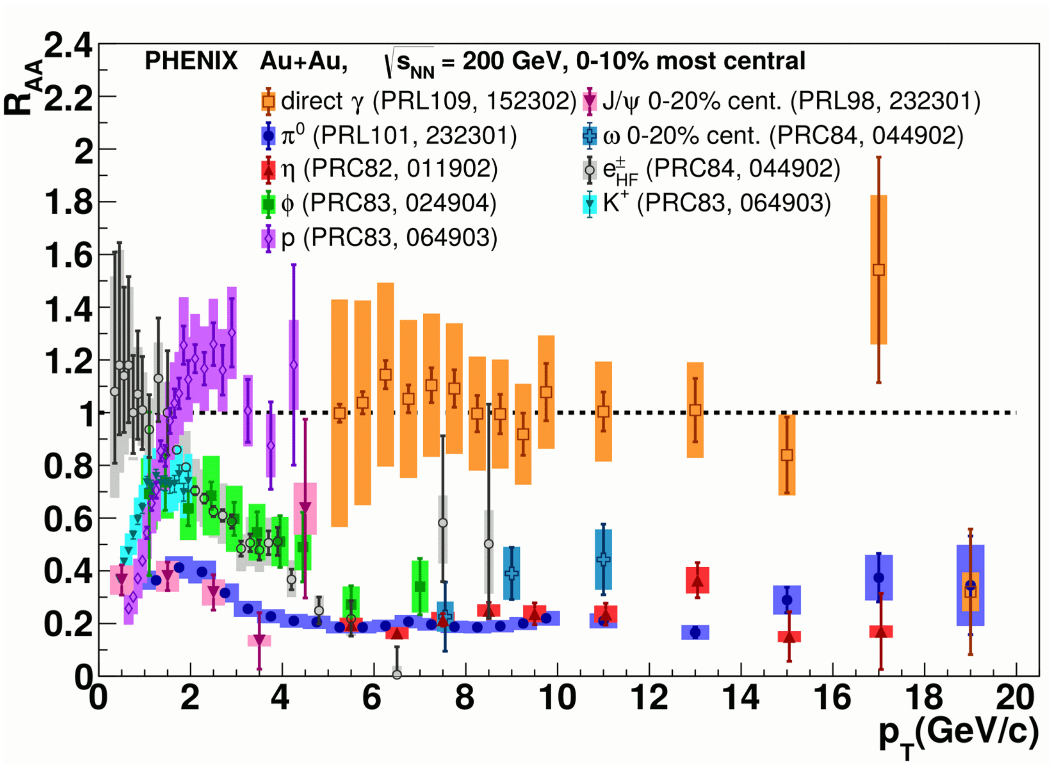
Nuclear modification factor



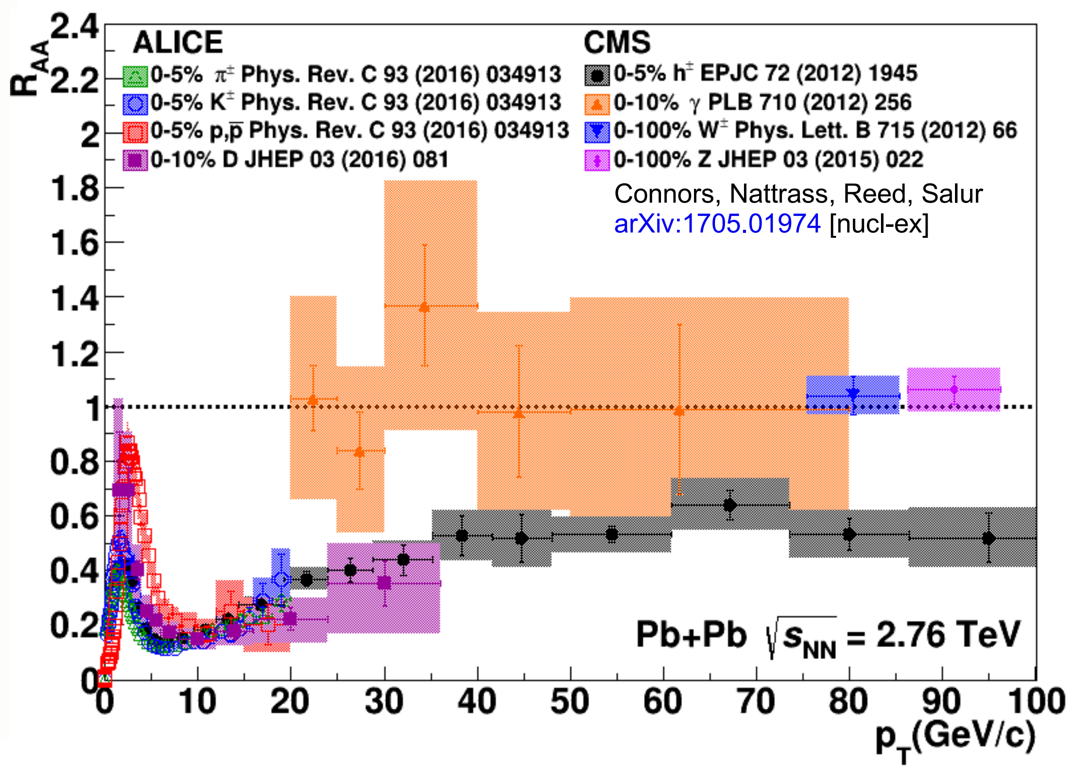
- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb

Nuclear modification factor R_{AA}

RHIC



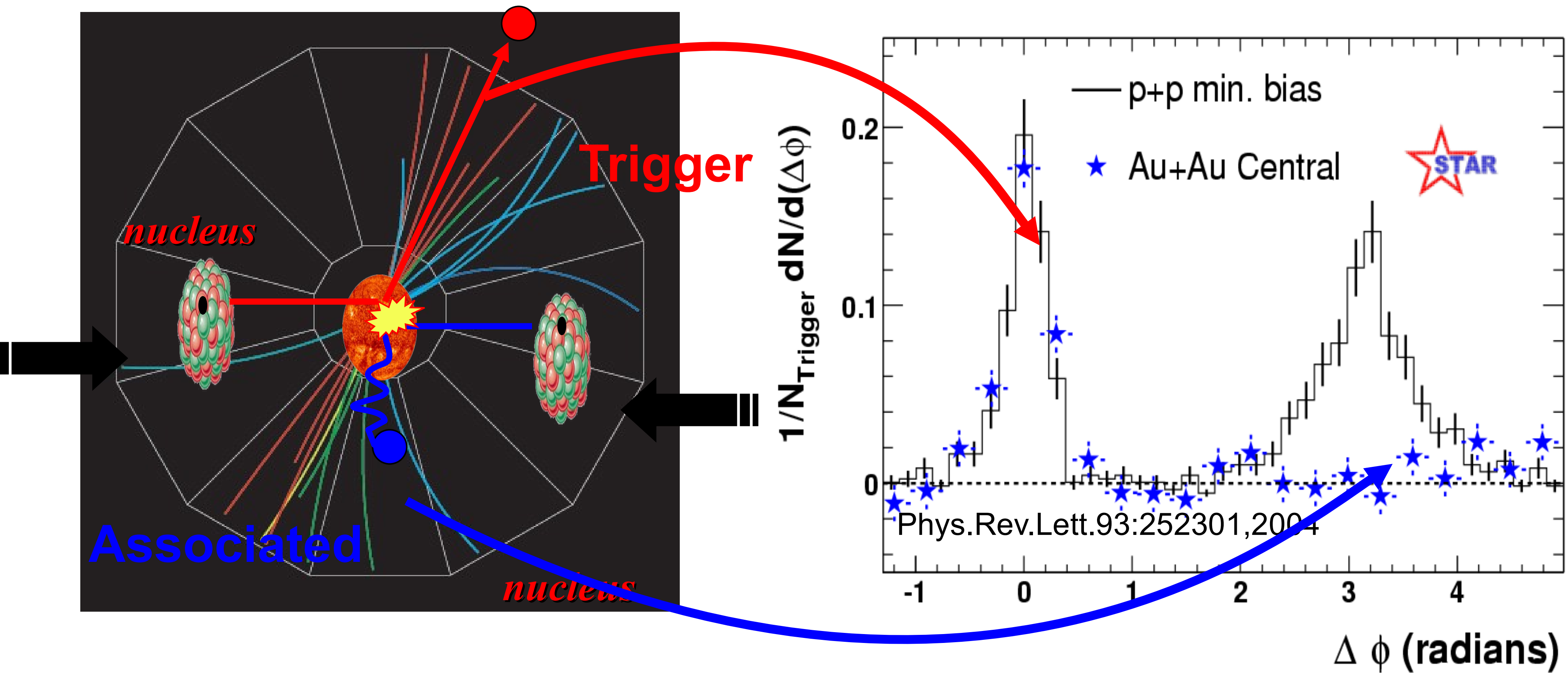
LHC



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

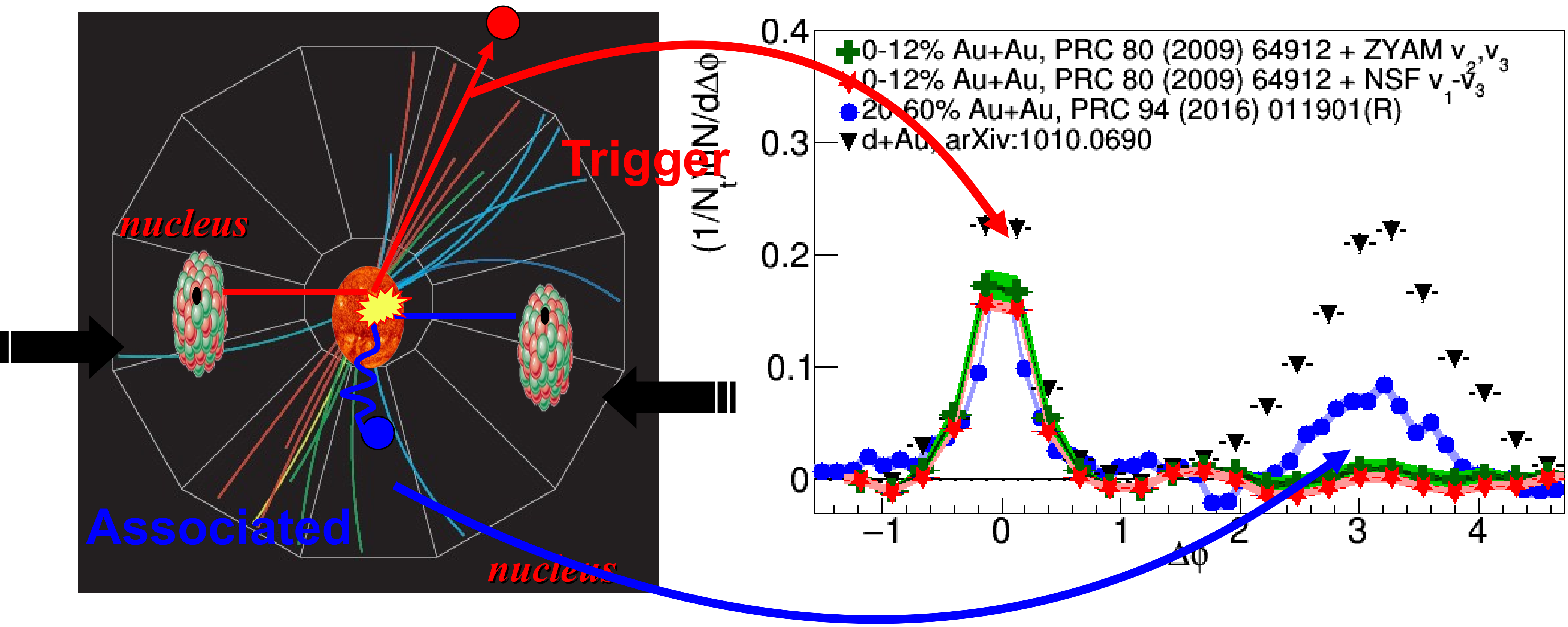
Di-hadron correlations

p+p → dijet



Di-hadron correlations

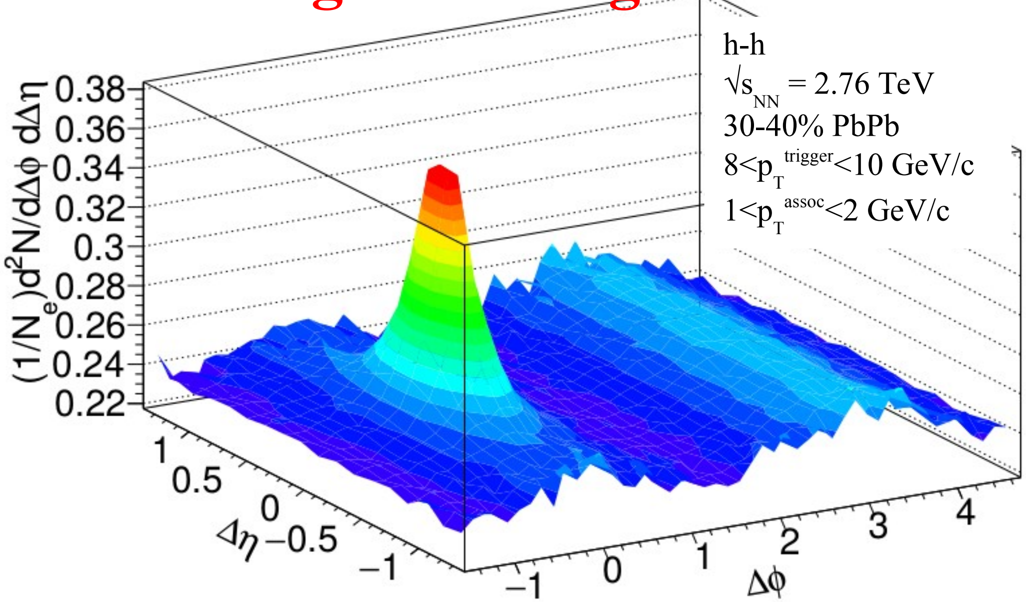
p+p → dijet



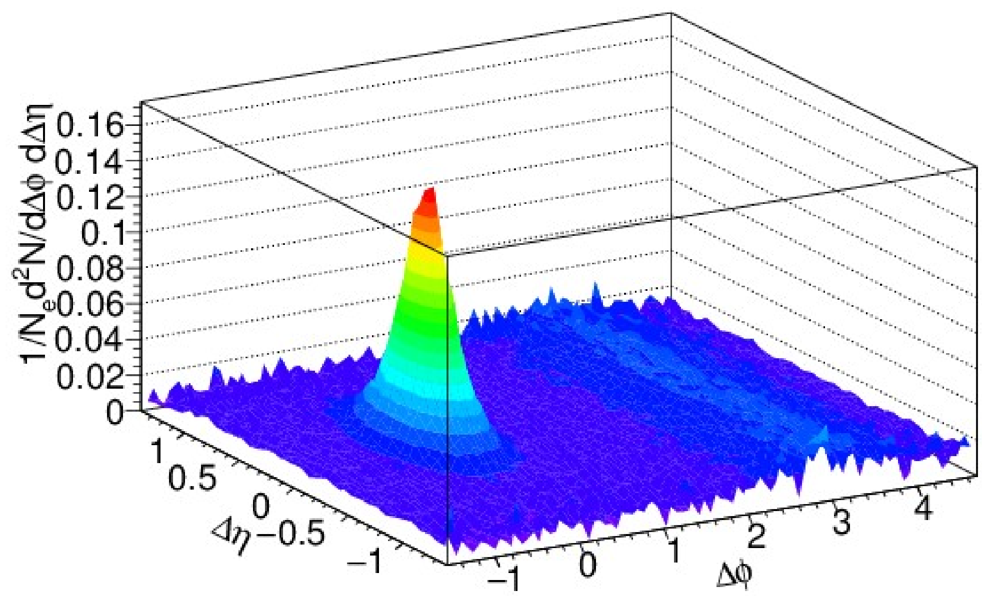
Updated to include latest information about background

Signal+background

Signal+background



Signal only



QGP Spectroscopy: Jets Part 2

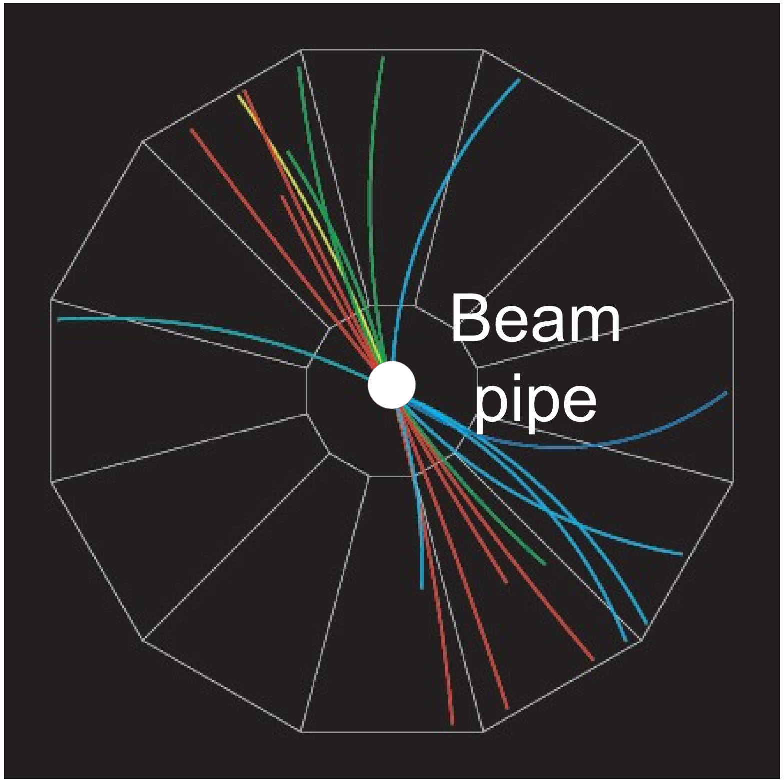
What is a jet?

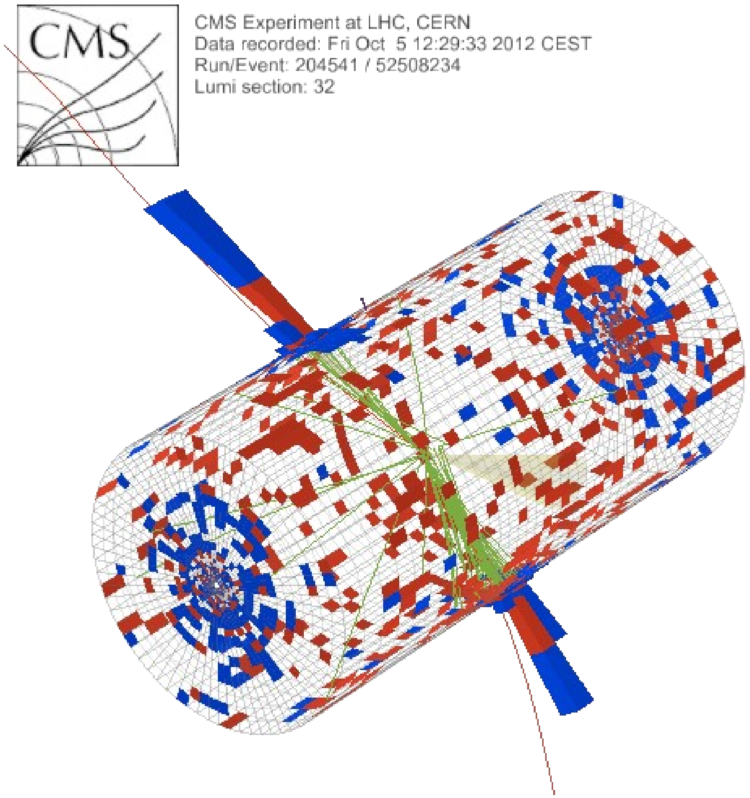
What is a jet?

A measurement of a jet is a measurement of a parton.

What is a jet?

p+p dijet





Jets in principle

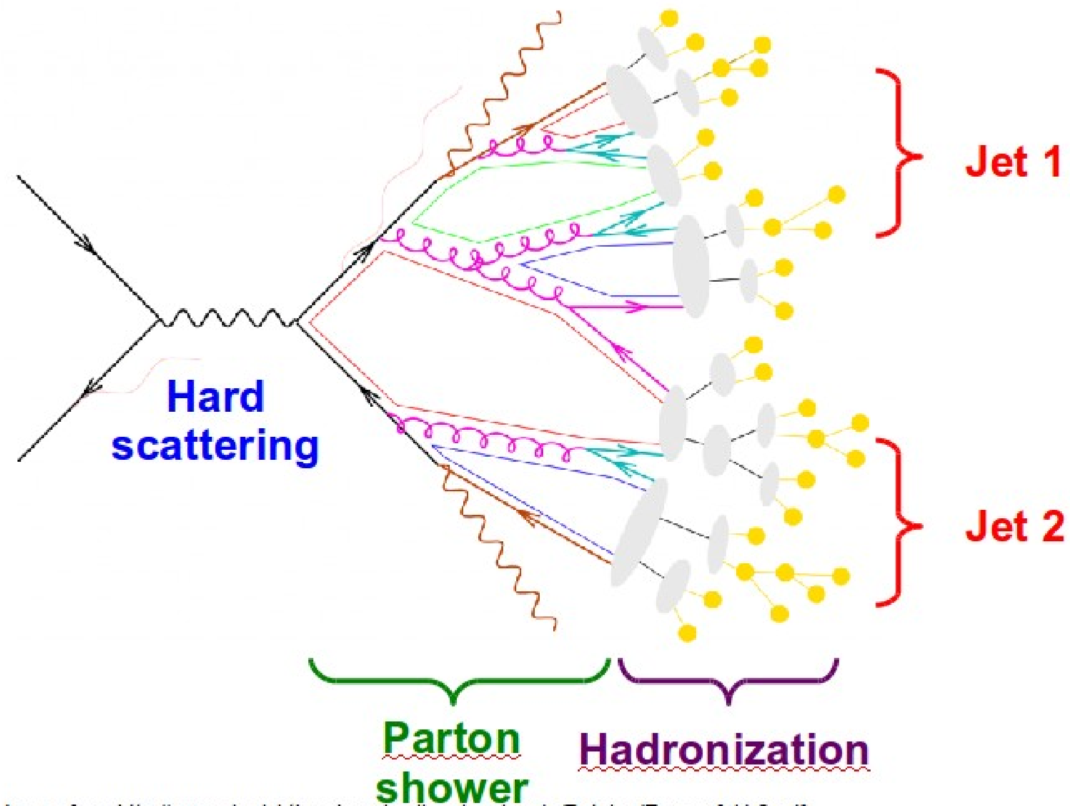
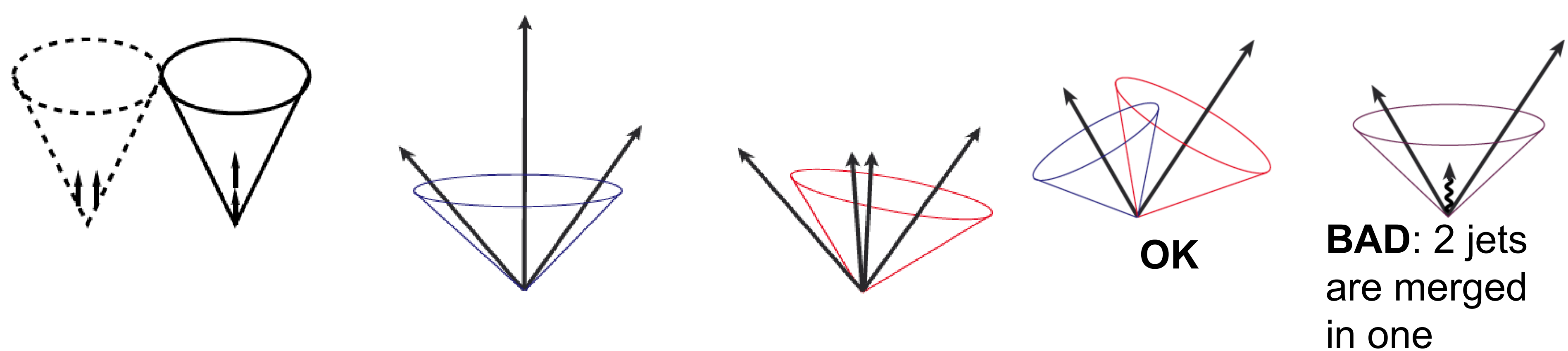
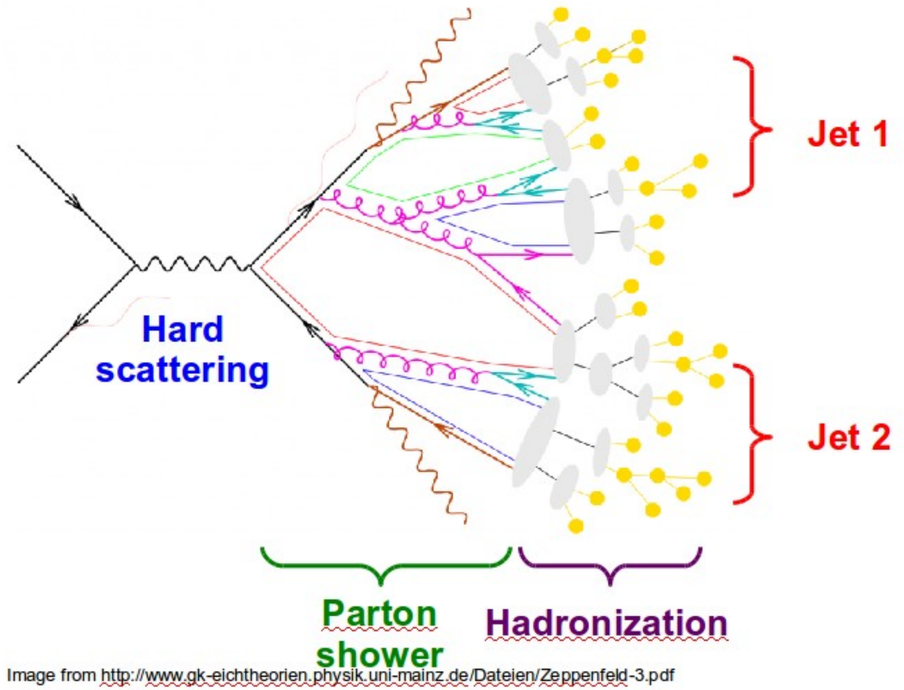


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet measures **partons**
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and colinear safe



Jet finding in pp collisions

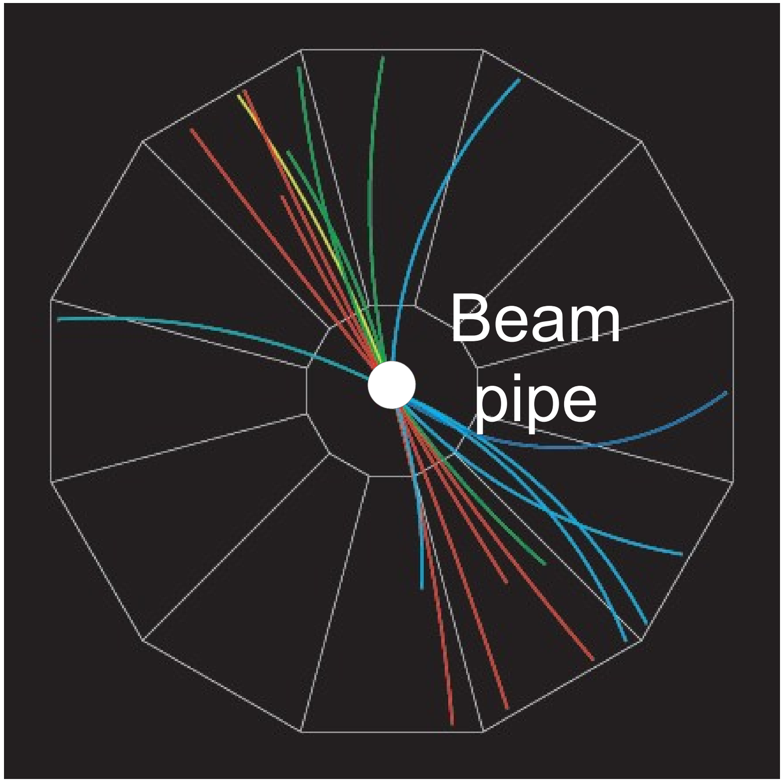


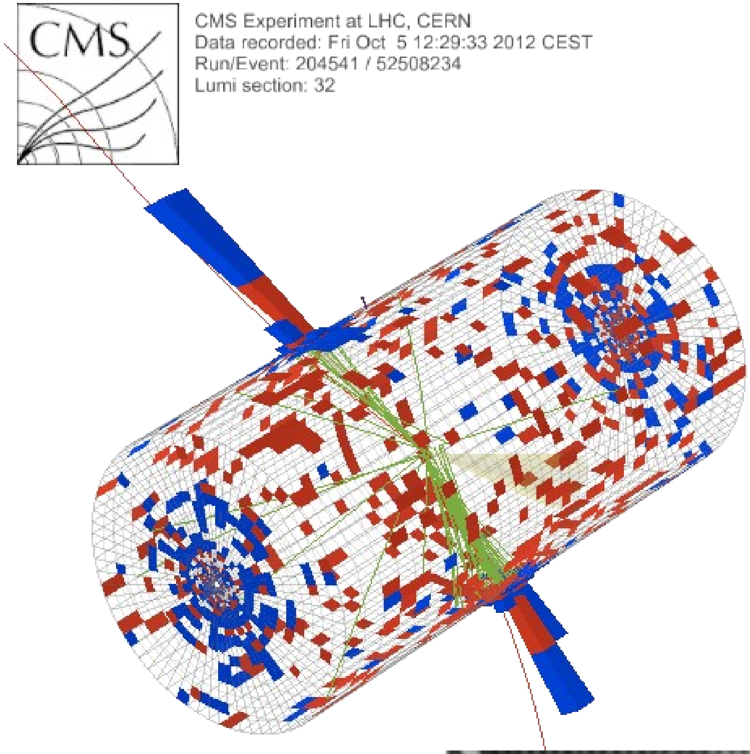
- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm
    JHEP 0804 (2008) 063 [arXiv:0802.1189]
- Depends on hadronization
- Ideally
  - Infrared safe
  - Colinear safe

Snowmass Accord: Theoretical calculations and experimental measurements should use the same jet finding algorithm. Otherwise they will not be comparable.

What is a jet?

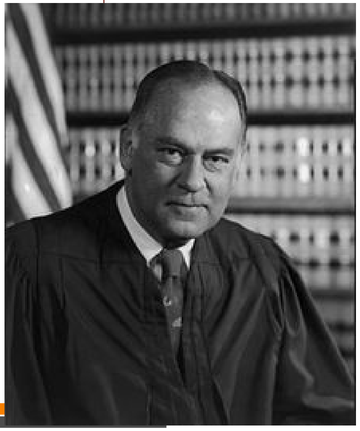
p+p dijet





"I know it when I see it"

US Supreme Court Justice Potter Stewart,
Jacobellis v. Ohio



A jet is what a jet finder finds.

Jet finding in AA collisions

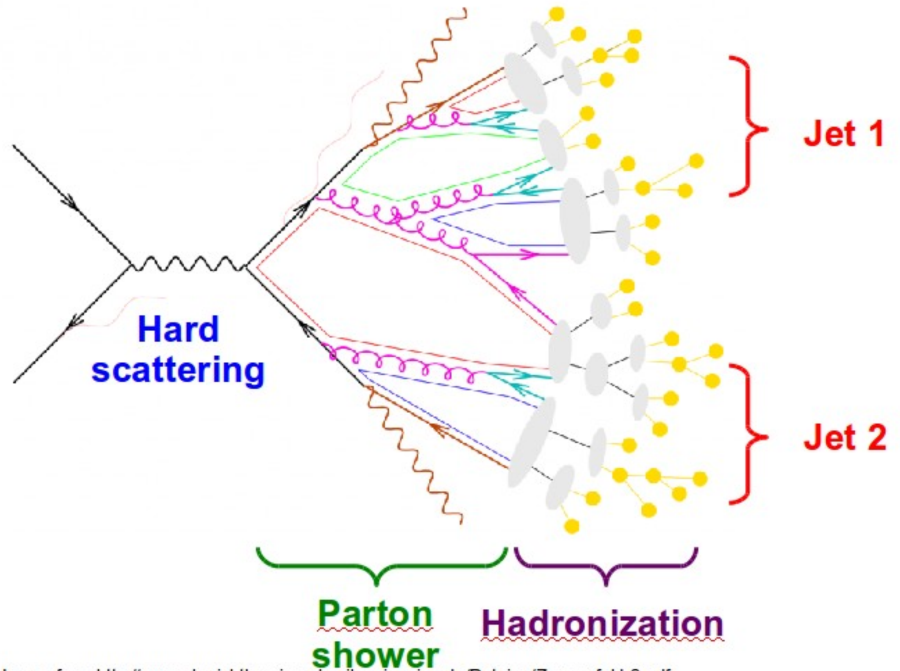
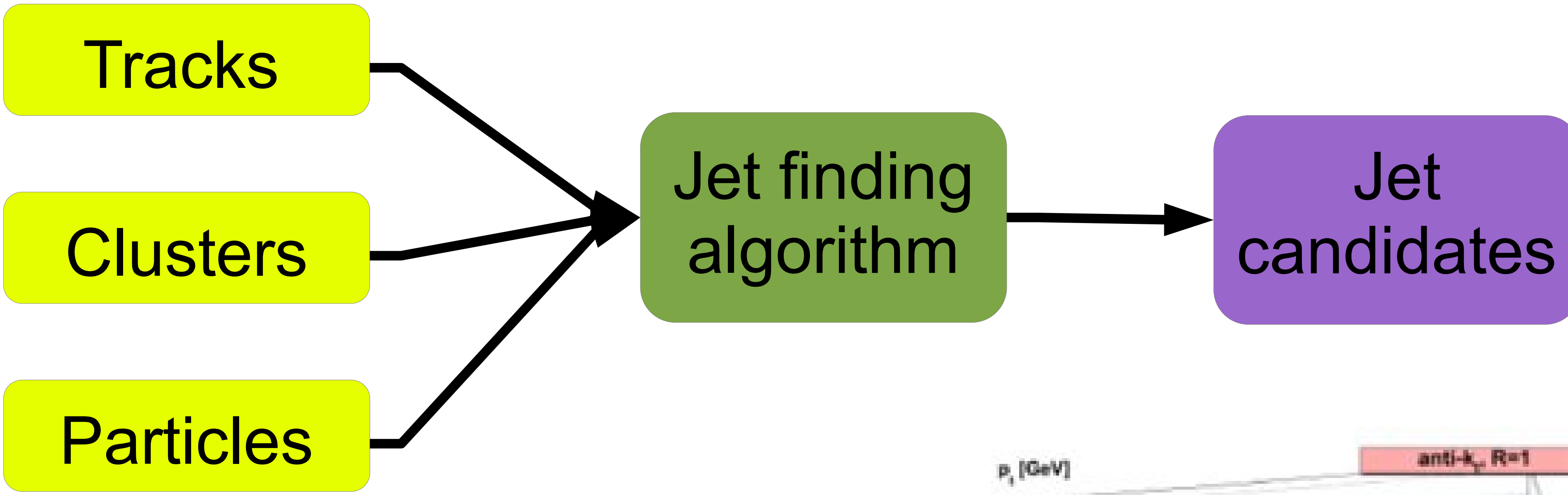


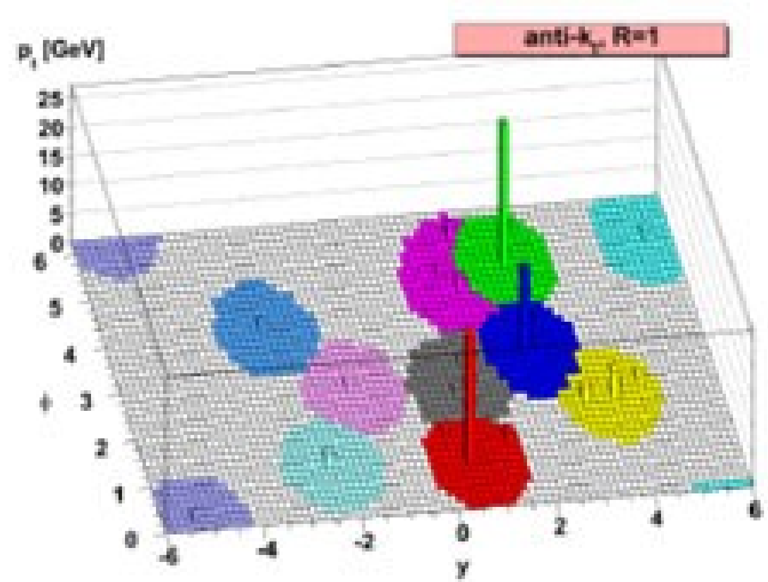
Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm
    JHEP 0804 (2008) 063 [arXiv:0802.1189]
- Combinatorial jet candidates
- Energy smearing from background
- Sensitive to methods to suppress combinatorial jets and correct energy
- Focus on narrow/high energy jets

Jet finding algorithms



- Any list of objects works as input
- Use the same algorithm on theory & experiment
- Output only as good as input



M. Cacciari, G. P. Salam, G.Soyez, JHEP 0804:063,2008

Area-based background subtraction

Cacciari & Salam, PLB659:119–126,2008

Particles, clusters

k_T algorithm

$$k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

- For all *i,j* calculate:

$$d_{ij} = min(p_{T,i}^2, p_{T,j}^2)\Delta R_{ij}^2$$

$$d_{iB} = p_{T,i}$$

- Combine smallest d_{ij}.

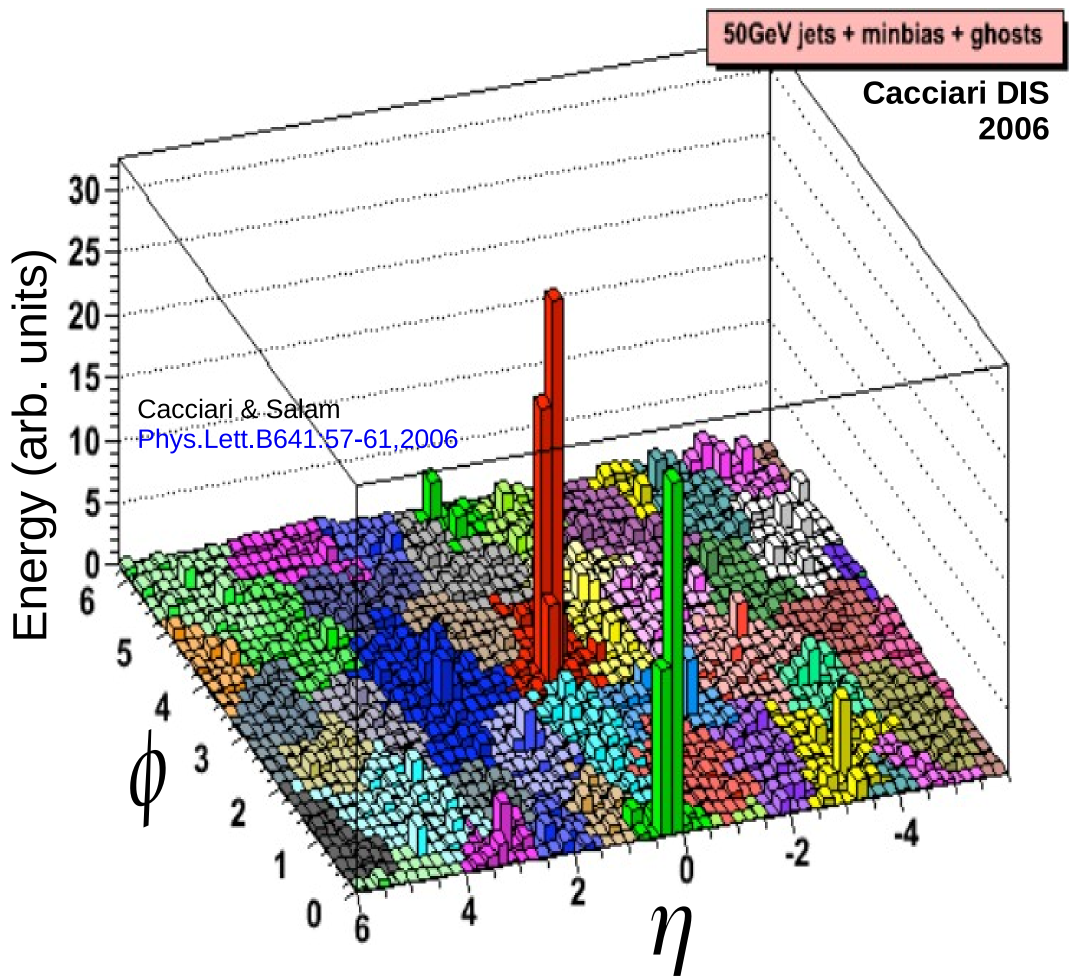
  If d_{iB} smallest, $d_{iB} \rightarrow$ jet

Repeat until no particles left

Jet candidates

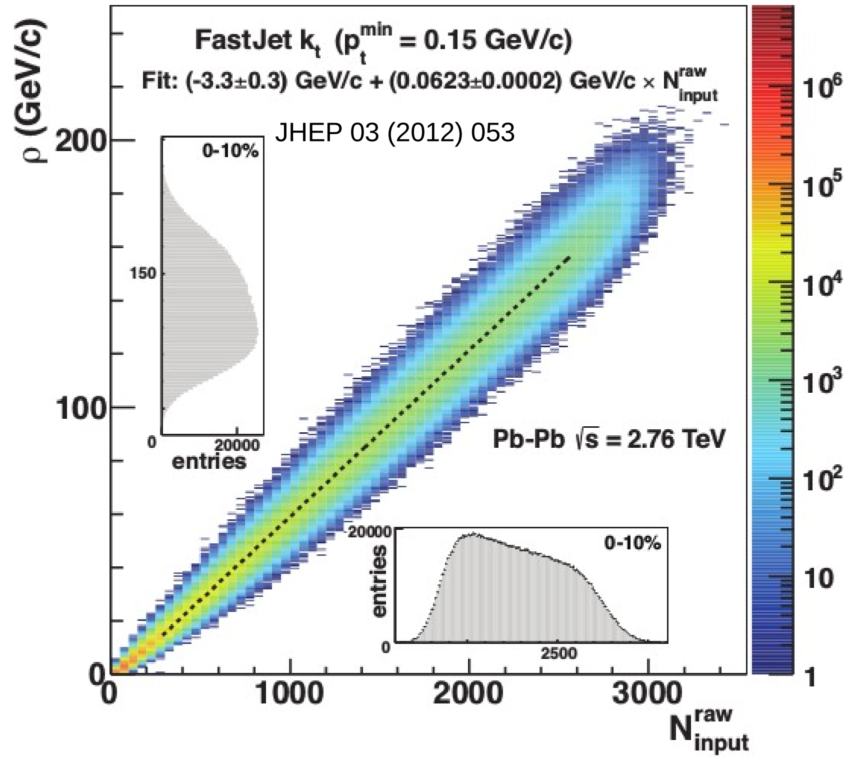
Median $\rho = p_T/A$

$$p_T^{jet} = p_T^{reco} - \rho_{median} A^{jet}$$



Focus on smaller angles

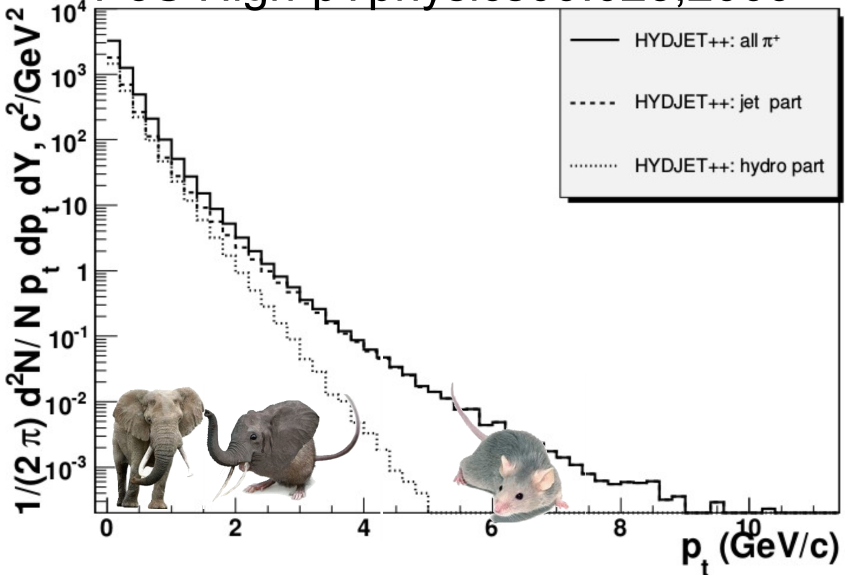
- Pros
  - Background is smaller
  - Background fluctuations smaller
- Cons:
  - Modifications expected at higher R
  - Biases sample towards quarks



Focus on high p_T

- Pros:
  - Reduces combinatorial background
- Cons:
  - Cuts signal where we expect modifications
  - Could bias towards partons which have not interacted
  - Biases sample towards quarks

PoS High-pTphysics09:023,2009



ALICE/STAR

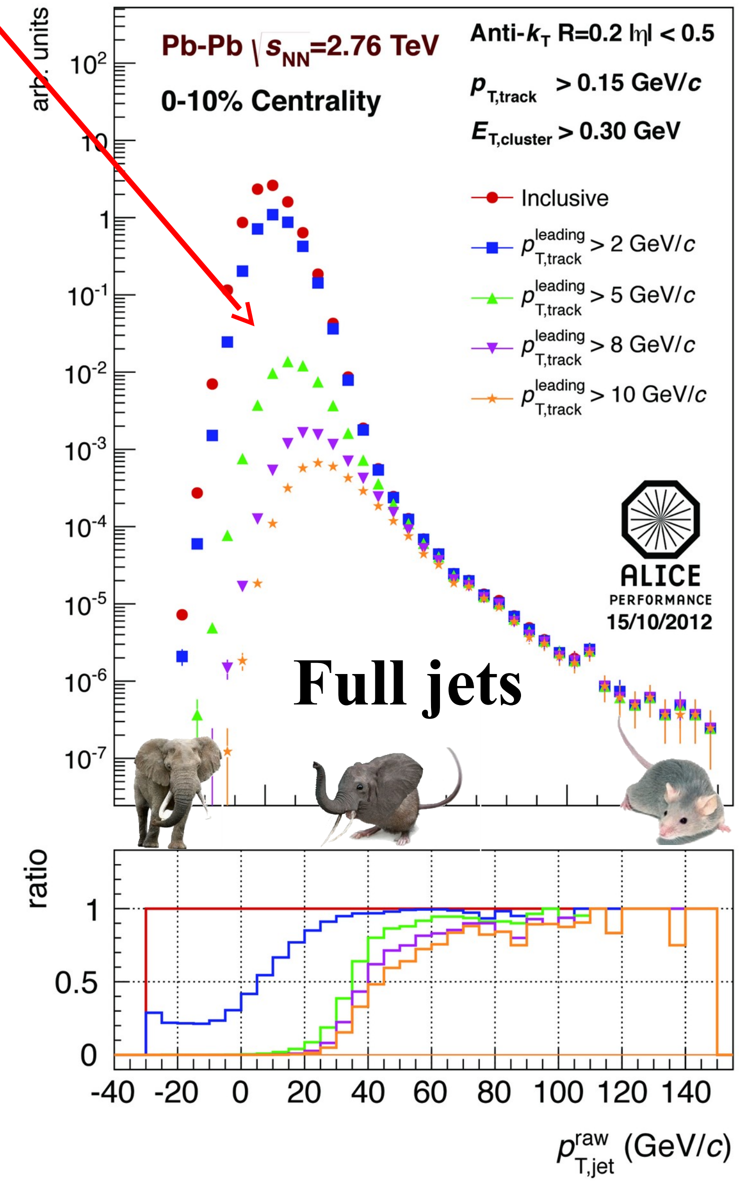
Combinatorial "jets"

- Estimate combinatorial jet contributions and its fluctuations from data
- Require leading track $p_T > 5$ GeV/c
  - Suppresses combinatorial "jets"
  - Biases fragmentation
- No threshold on constituents
- Limited to small R

Measured spectra:

$$p_{T,jet}^{unc} = p_{\mathrm{T,jet}}^{rec} - \rho A$$

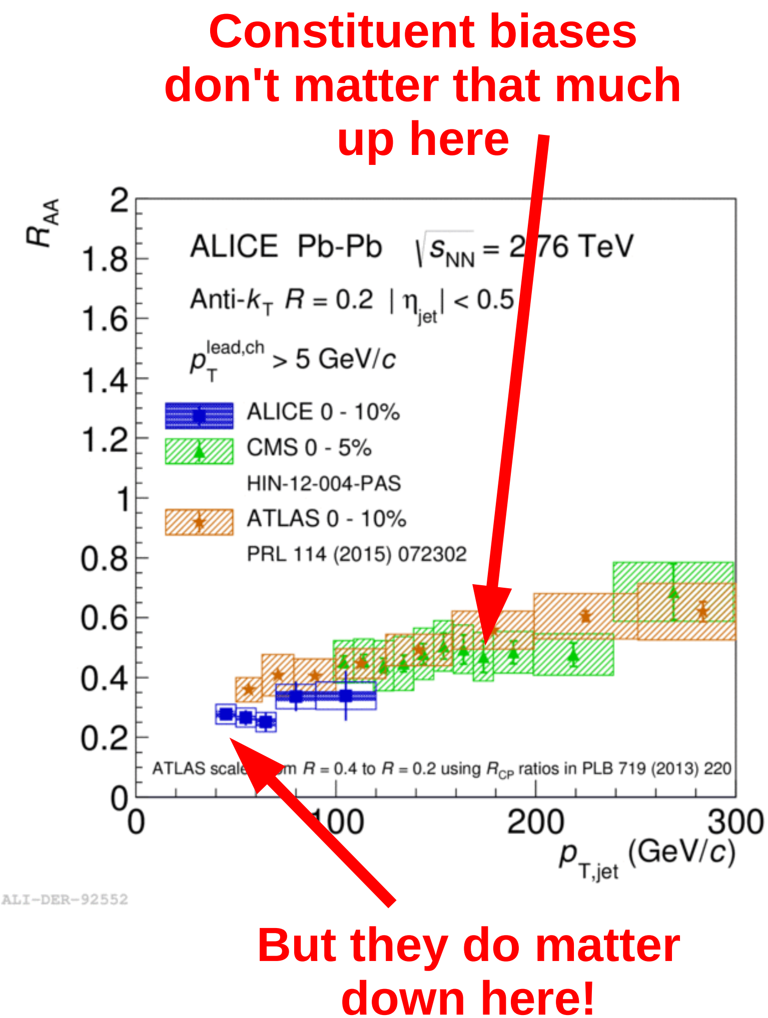
Where $p_{\mathrm{T,jet}}^{rec}, A$ comes from FastJet anti-k_T algorithm



ERF-44496

ATLAS

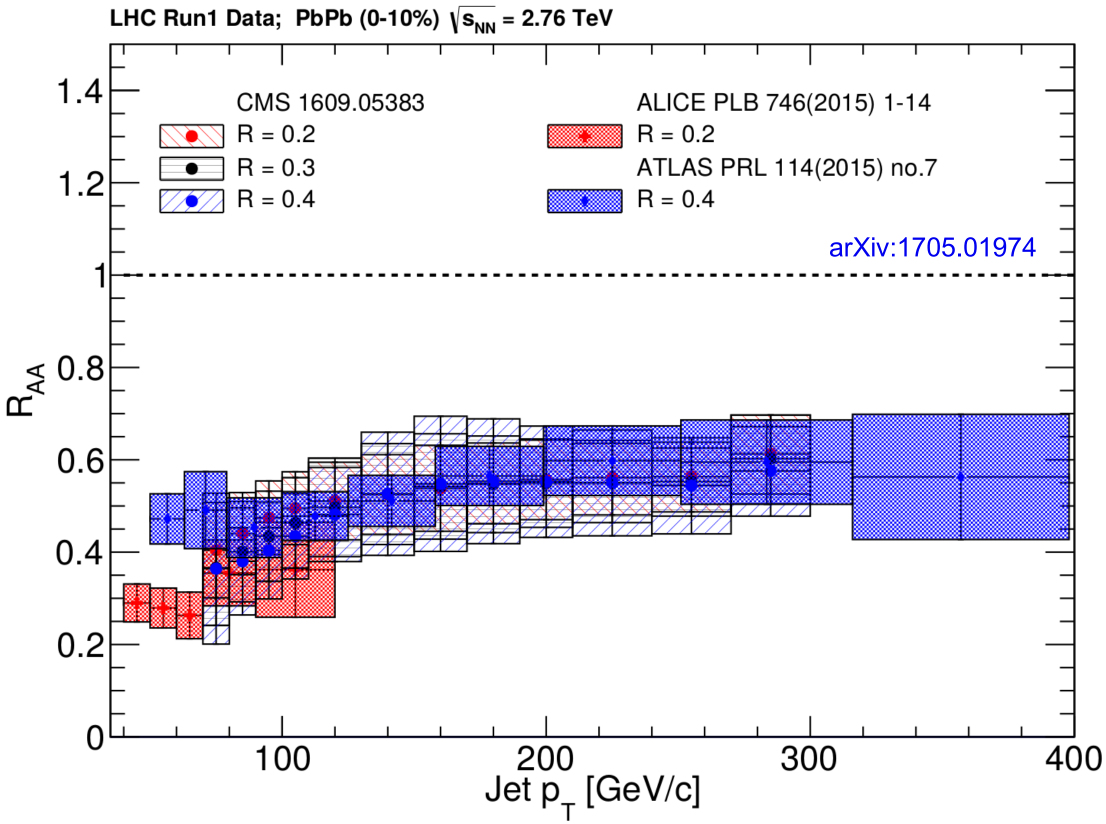
- Iterative procedure
  - **Calorimeter jets:** Reconstruct jets with R=0.2. v_2 modulated <Bkgd> estimated by energy in calorimeters excluding jets with at least one tower with $E_{tower} > \langle E_{tower} \rangle$
    Track jets: Use tracks with p_T>4 GeV/c
  - Calorimeter jets from above with E>25 GeV and track jets with p_T>10 GeV/c used to estimate background again.
- Calorimeter tracks matching one track with p_T>7 GeV/c or containing a high energy cluster E >7 GeV are used for analysis down to E_{jet} = 20 GeV

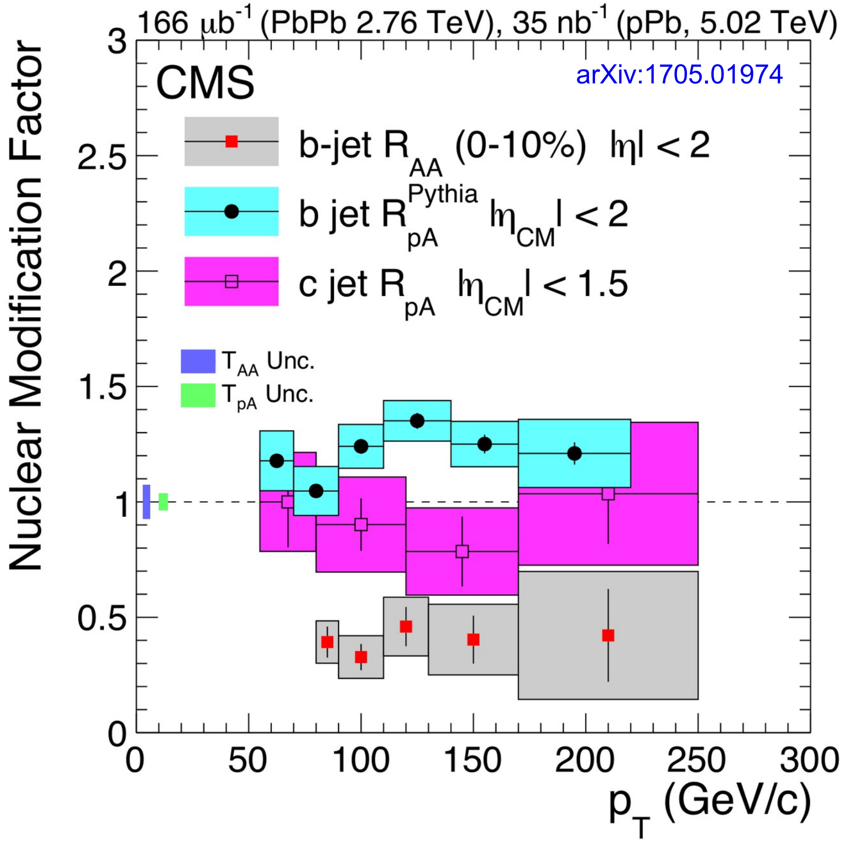


Definitely imposes a bias, especially at 20 GeV!
We should treat that bias as a tool, not a handicap

Phys. Lett. B 719 (2013) 220-241

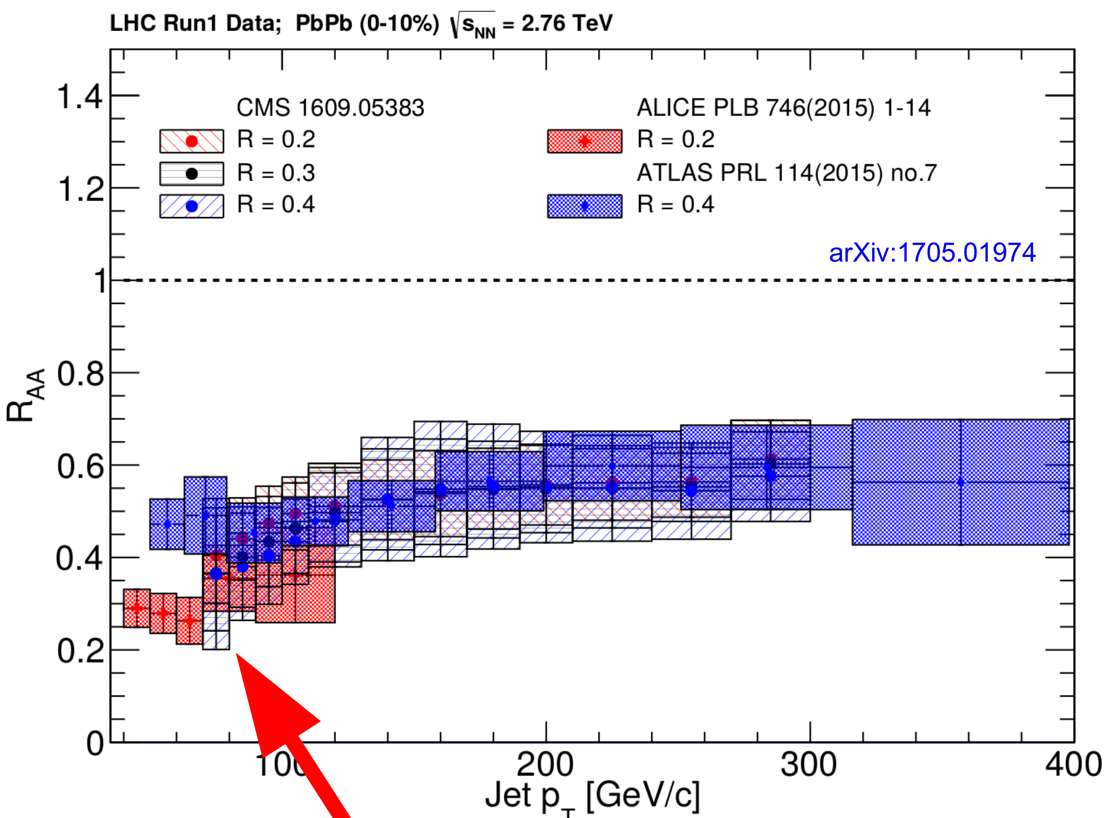
Jet R_{AA}

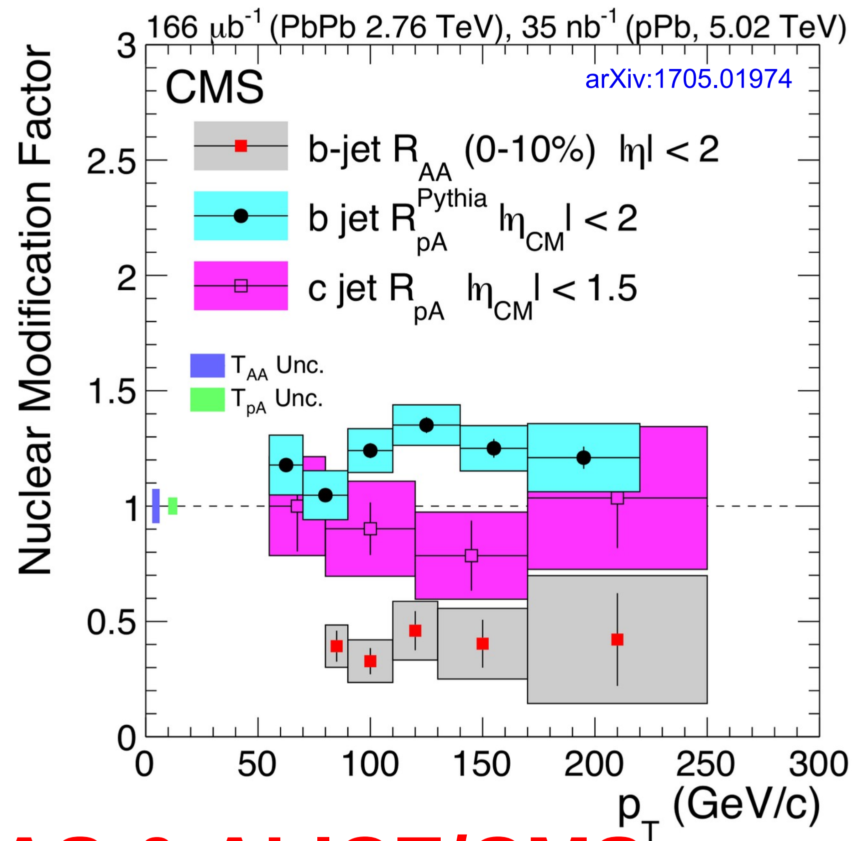




- Jet R_{AA} also demonstrates suppression
- Similar suppression of heavy quark jets?

Jet R_{AA}





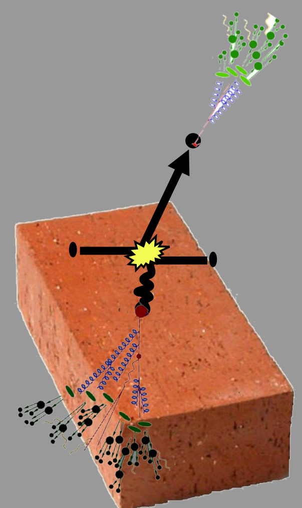
Tension between ATLAS & ALICE/CMS

- Jet R_{AA} also demonstrates suppression
- Similar suppression of heavy quark jets?

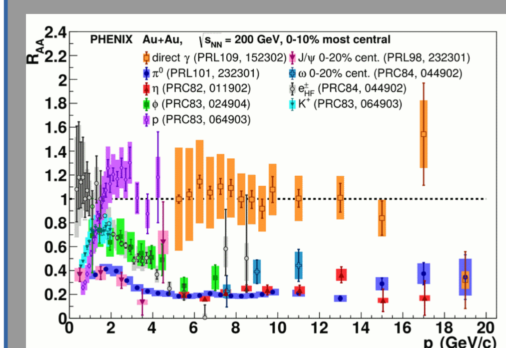
JETSCAPE

JET collaboration

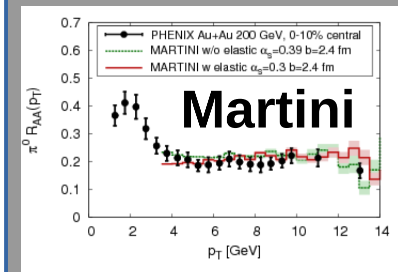
Phys. Rev. C 90, 014909 (2014)

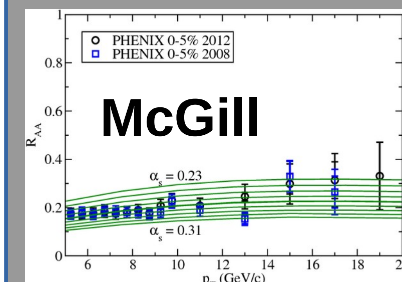


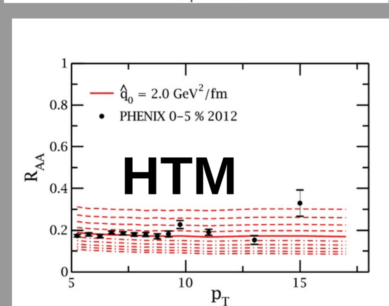
QGP brick + jet

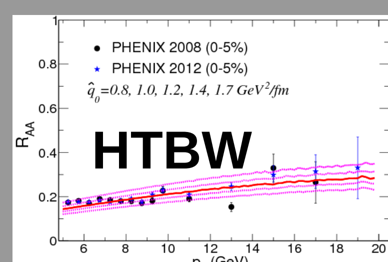


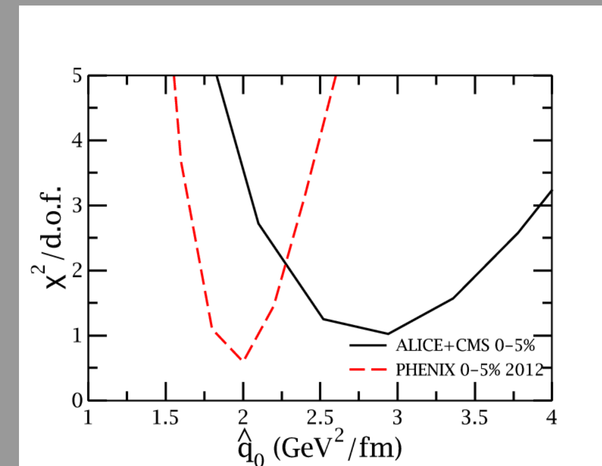
Data



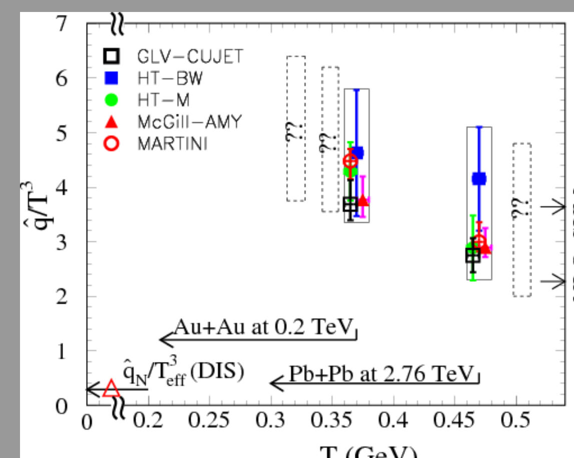








χ^2 minimization



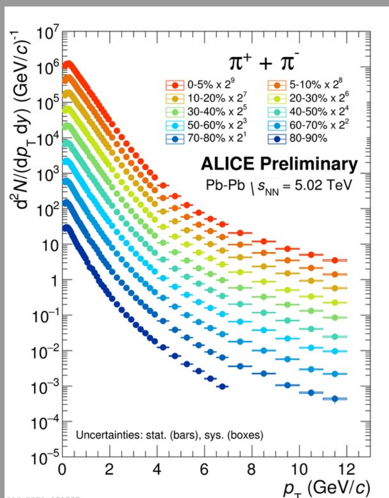
$\hat{q}=1.2\pm0.3\ \ GeV^2$ 200 GeV Au+Au

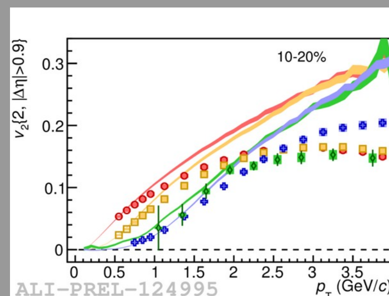
$\hat{q}=1.9\pm0.7\ \ GeV^2$ 2.76 TeV Pb+Pb

Bayesian Statistical Analysis

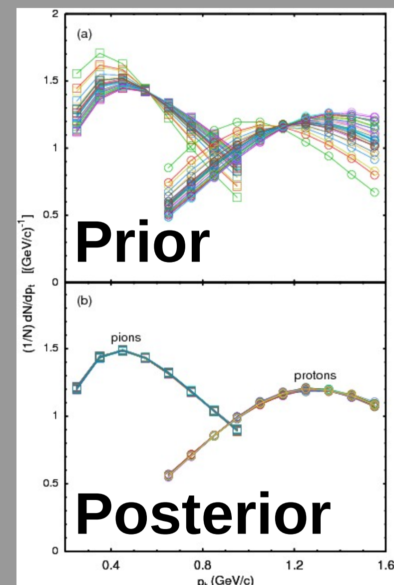
Models and Data Analysis Initiative

http://madai.us

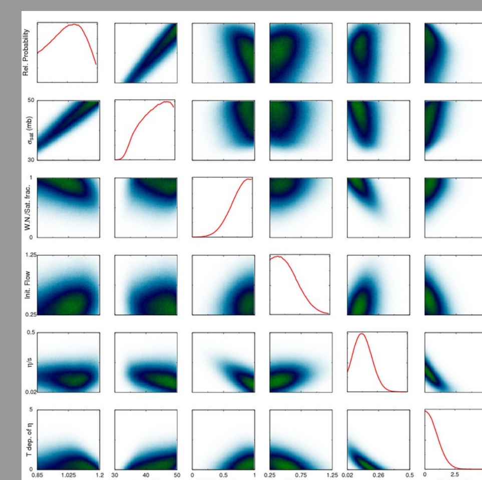




Data



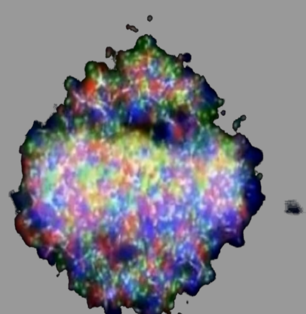
Optimization



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

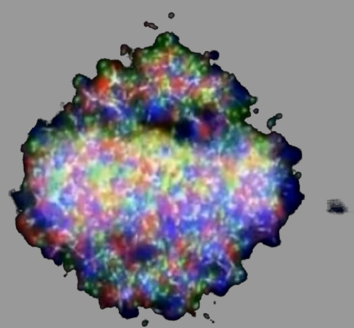
JETSCAPE

Event generator

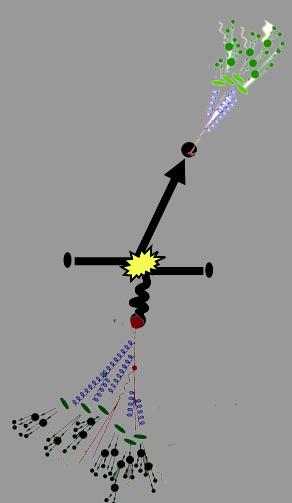
Jet **E**nergy-loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelope

http://jetscape.wayne.edu/

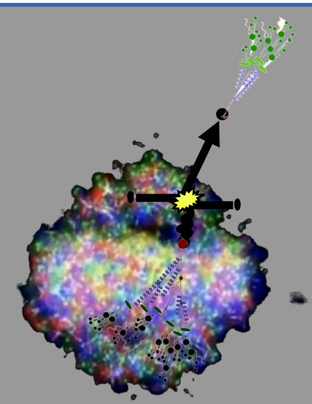
Realistic medium



Realistic jets



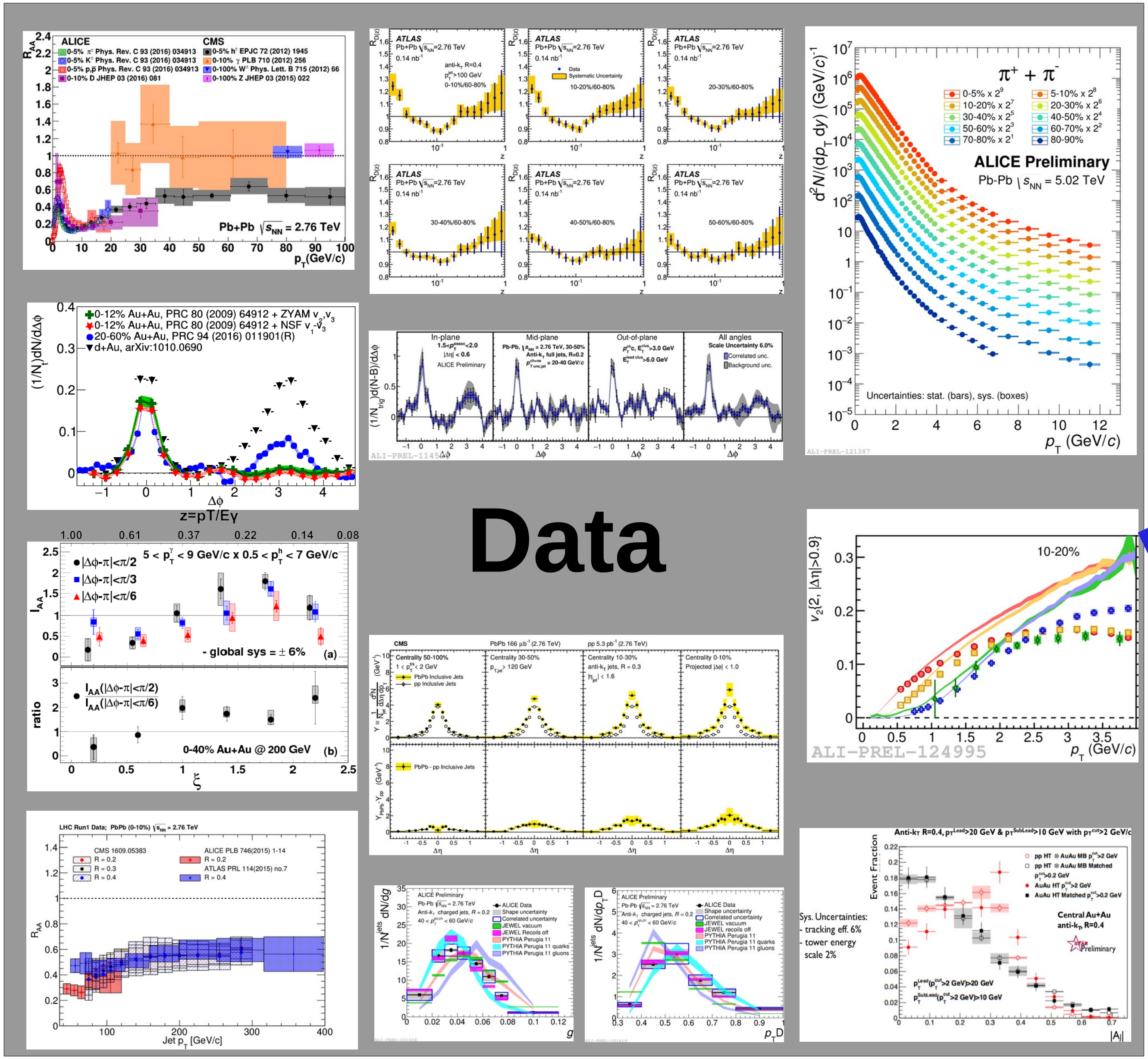
Realistic Monte Carlo Model

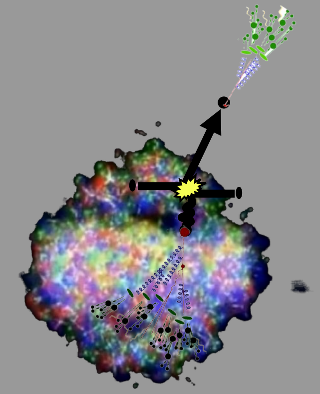


Experimental techniques

Realistic theoretical calculations

Event Generator + Bayesian Statistical analysis





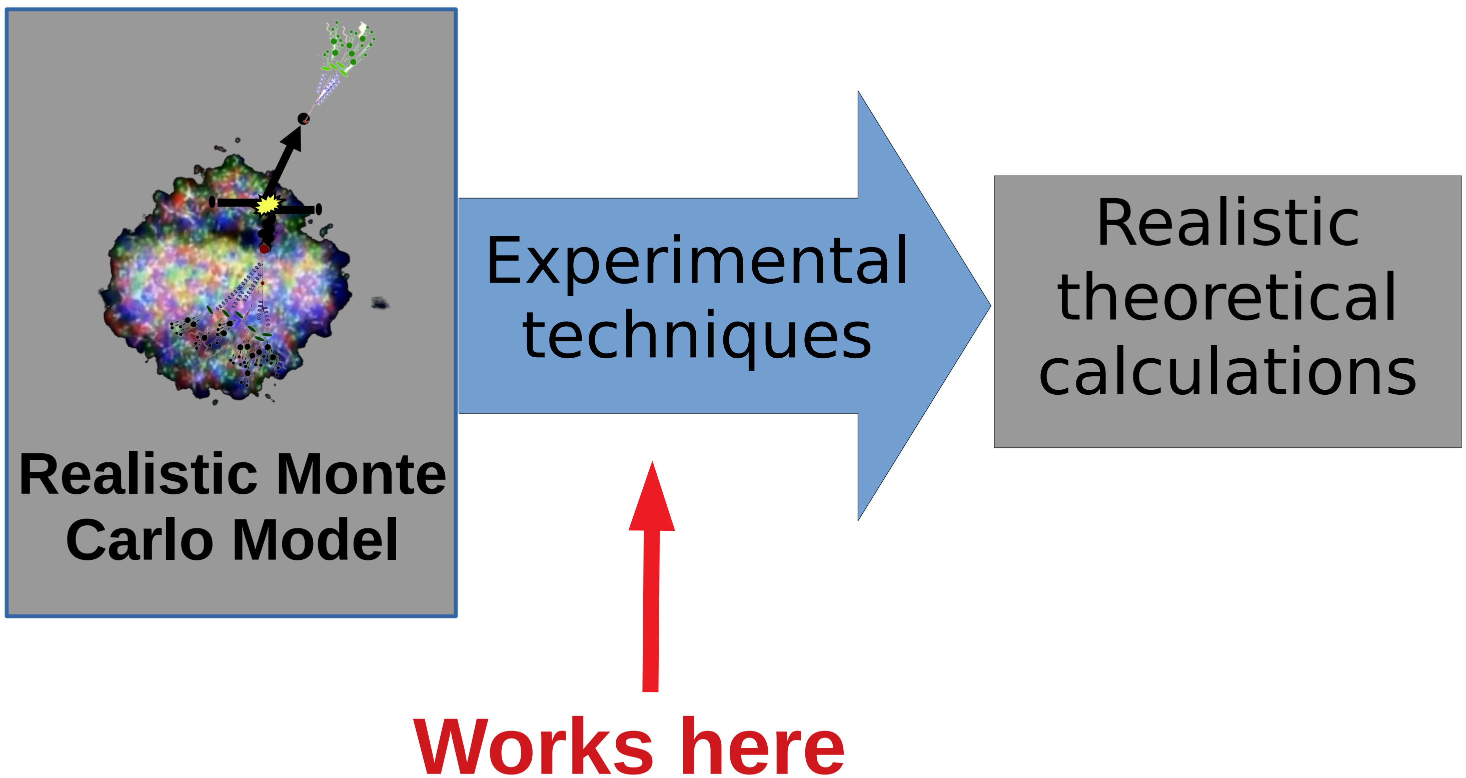
Realistic theoretical calculations

Bayesian Statistical Analysis

Constraint of QGP properties

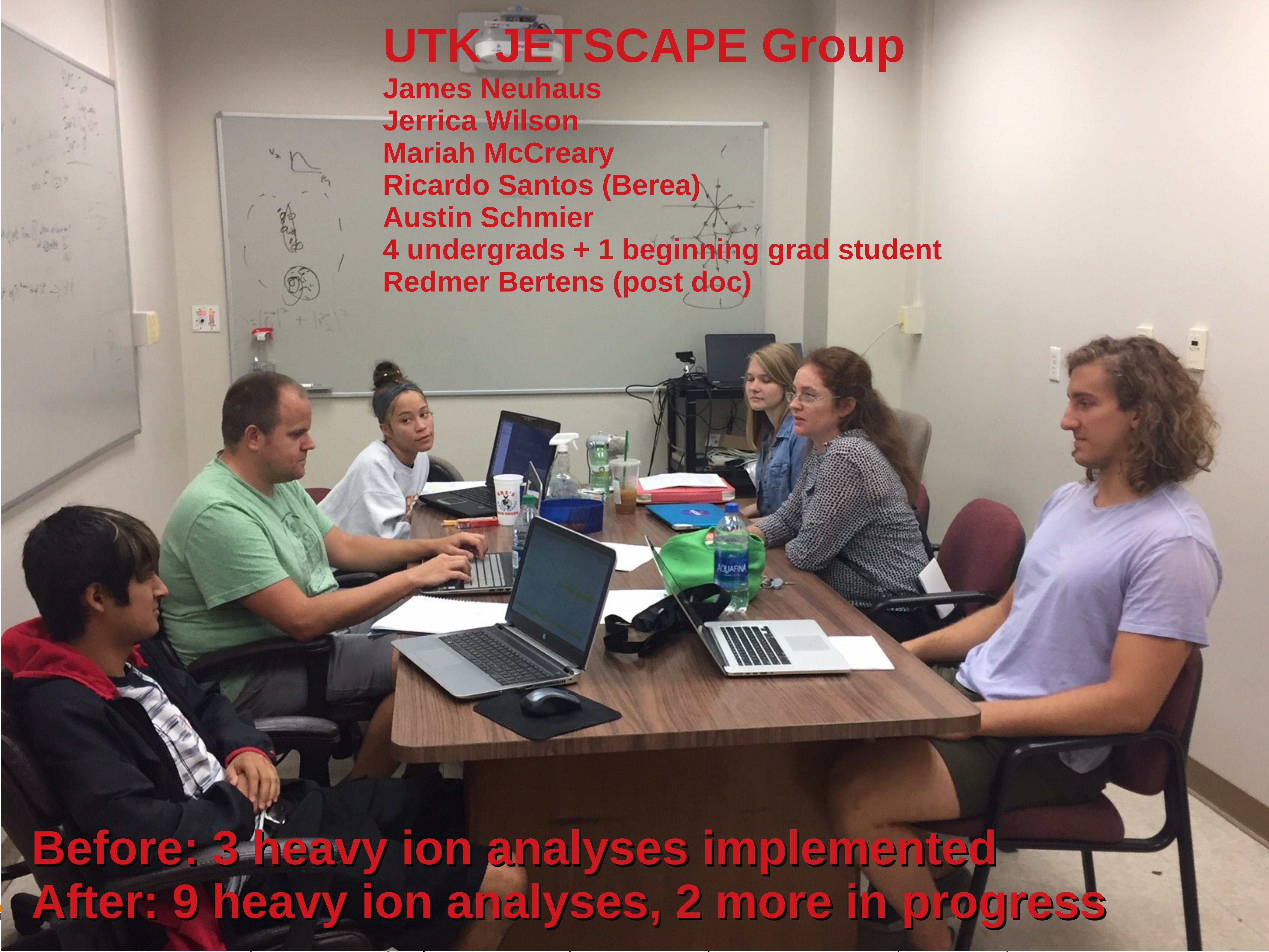
RIVET

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



UTK JETSCAPE Group

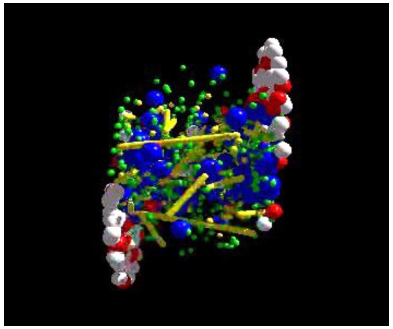
James Neuhaus
Jerrica Wilson
Mariah McCreary
Ricardo Santos (Berea)
Austin Schmier
4 undergrads + 1 beginning grad student
Redmer Bertens (post doc)

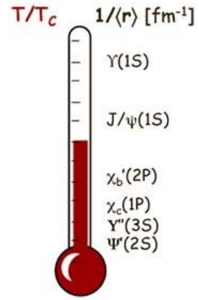


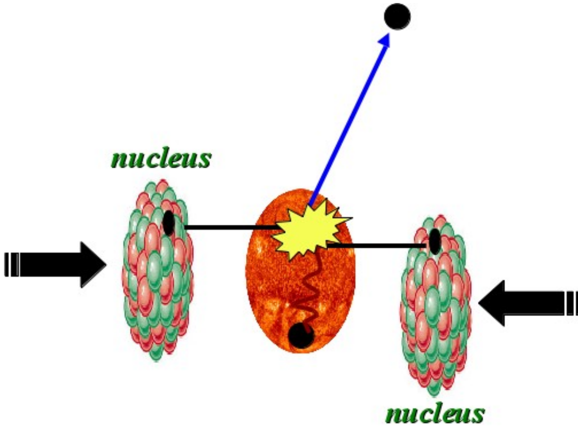
Before: 3 heavy ion analyses implemented
After: 9 heavy ion analyses, 2 more in progress

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

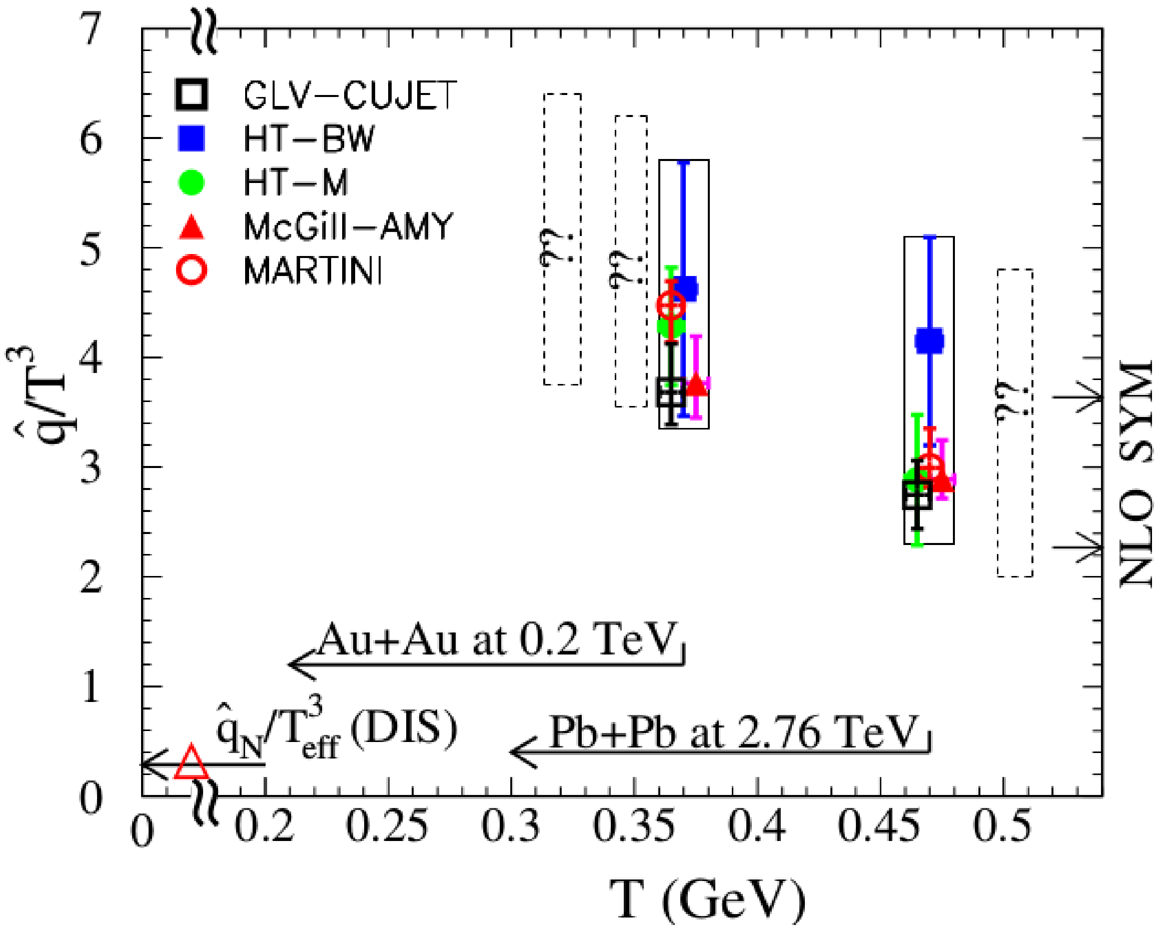
US Universities with graduate programs in experimental heavy ion physics

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

$\hat{q}$ ≈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

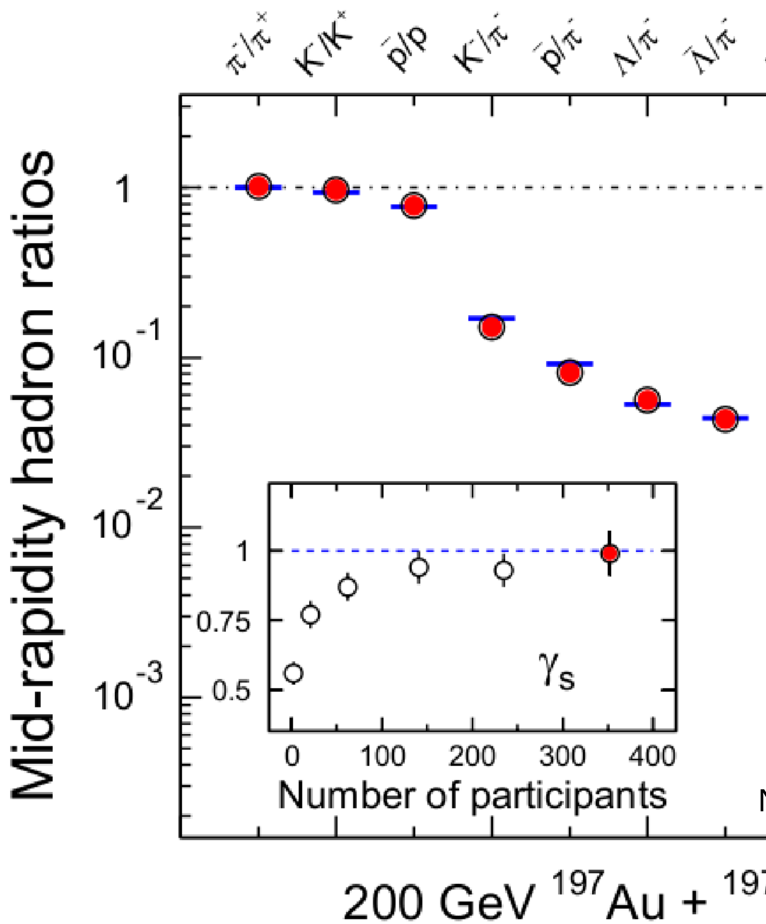
$$\hat{q} = Q^2 / L$$

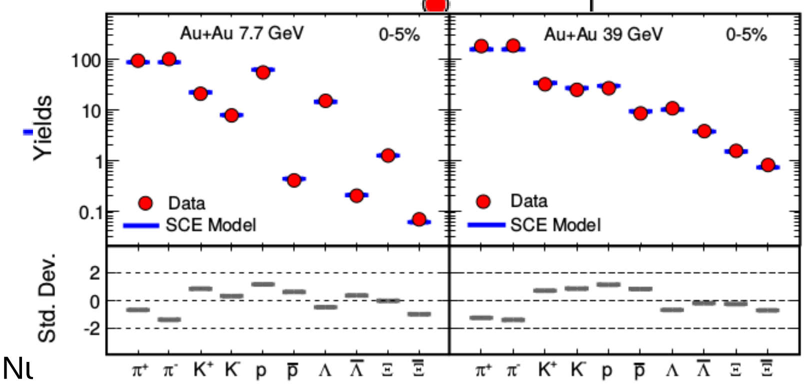
Q = Momentum transfer from parton to medium
L = path length

QGP Chemistry

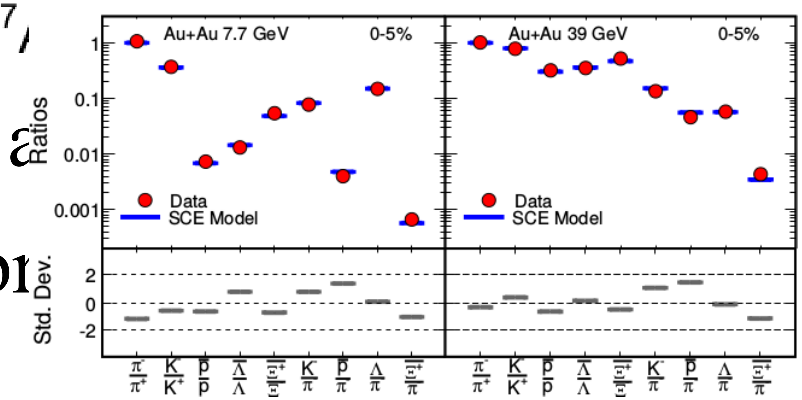
Chemistry - equilibrium

T~170 MeV



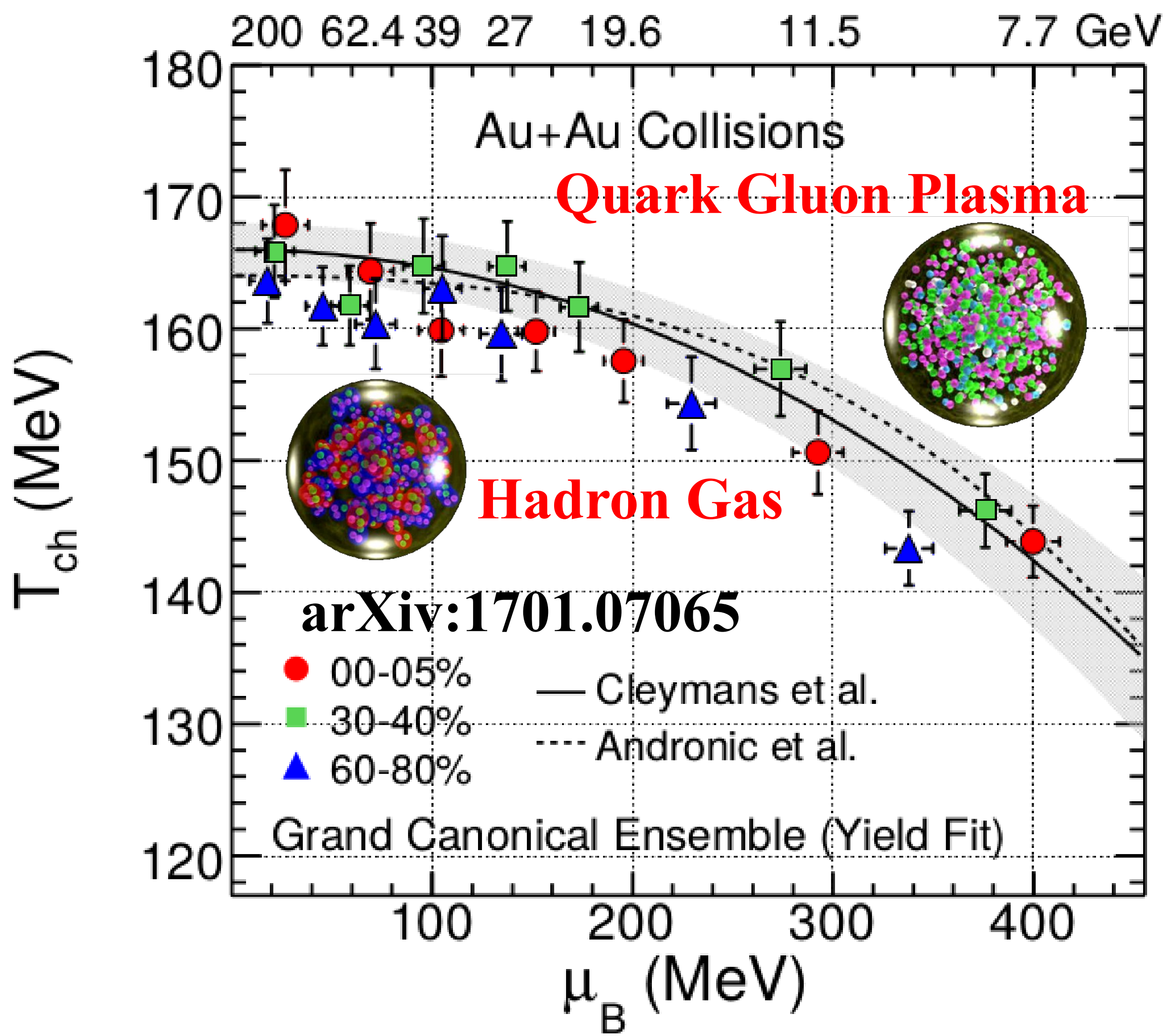


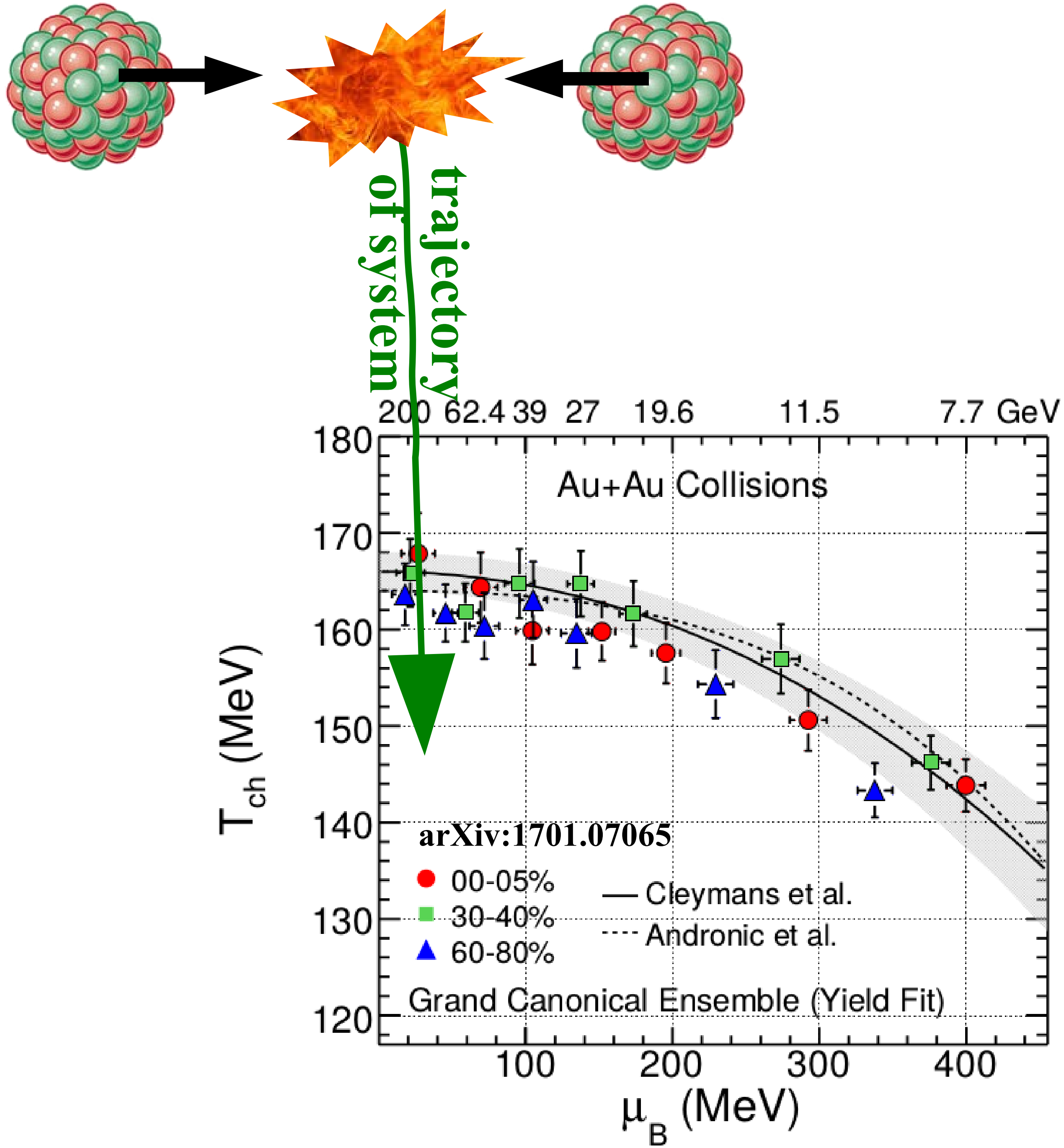
arXiv:1701.07065



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

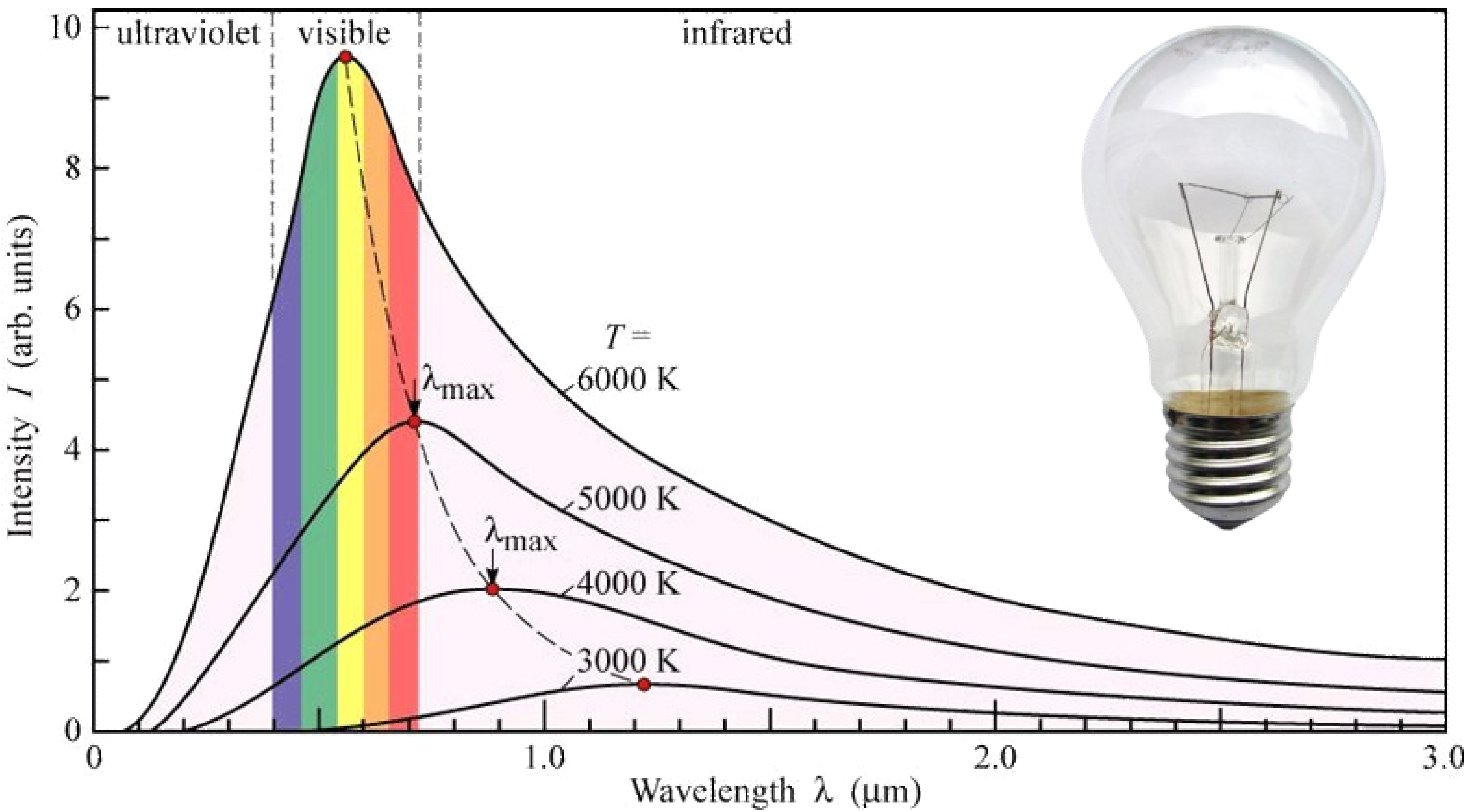
QCD Phase Diagram



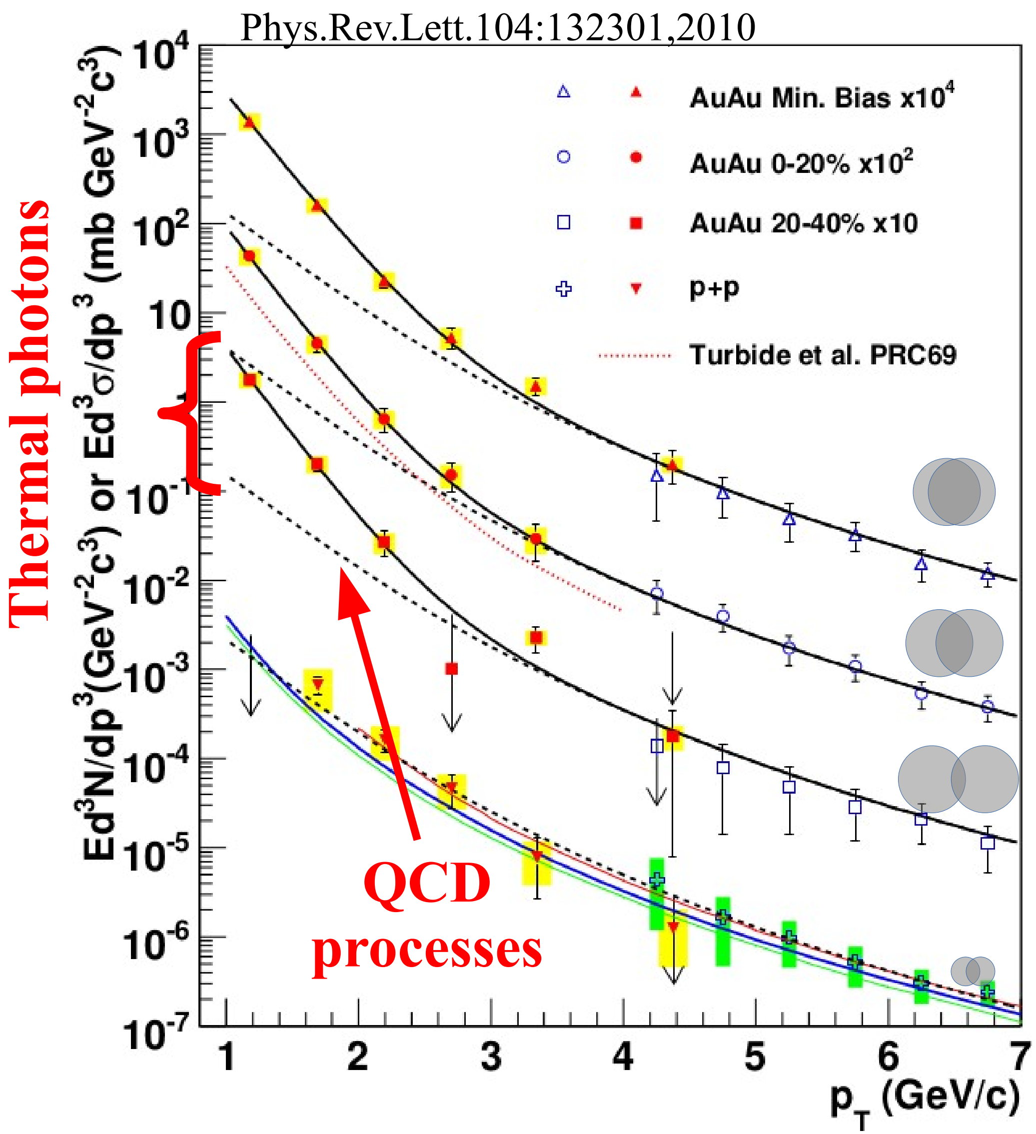

trajectory
of system
200 62.4 39 27 19.6 11.5 7.7 GeV
Au+Au Collisions
arXiv:1701.07065
00-05%
30-40%
60-80%
Cleymans et al.
Andronic et al.
Grand Canonical Ensemble (Yield Fit)
T_ch (MeV)
μ_B (MeV)

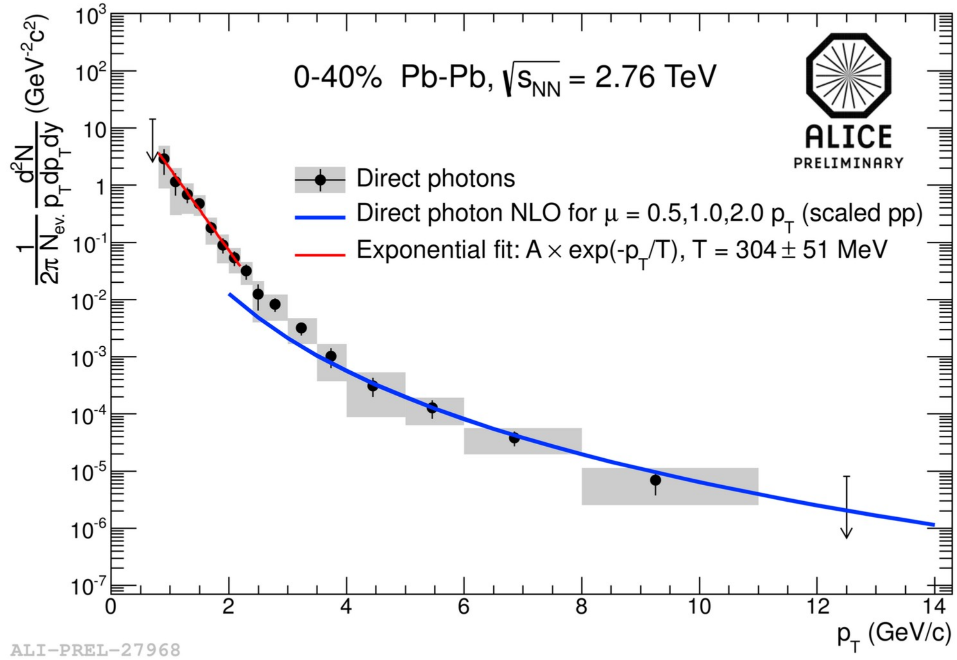
QGP Thermometers

Measuring temperature



Thermal photons

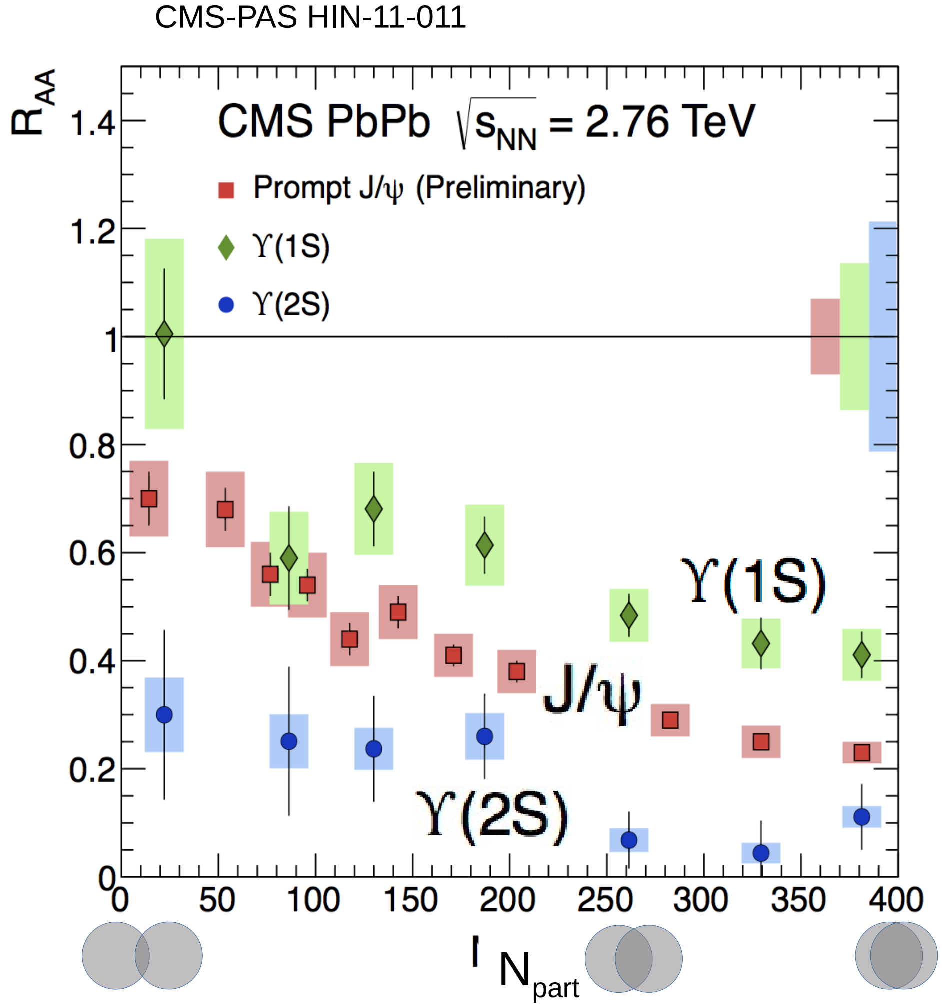




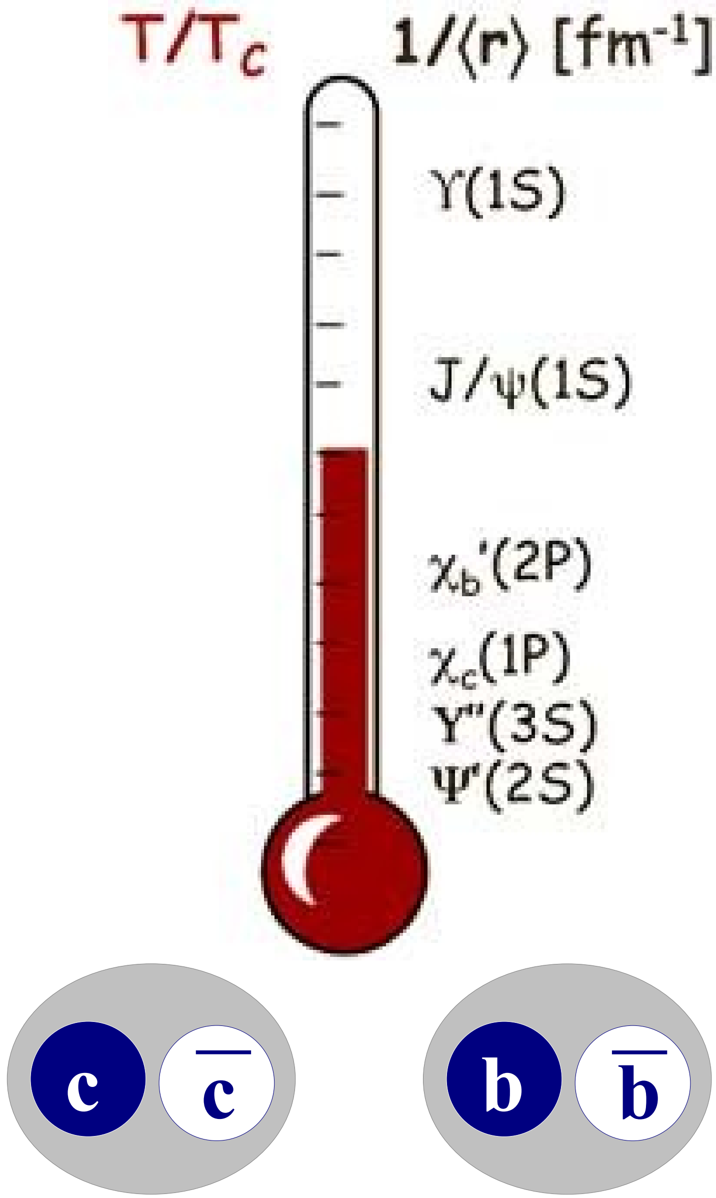
ALICE collaboration:
Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
Inverse slope: T = 304 +/-51

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

Building a quarkonium-thermometer

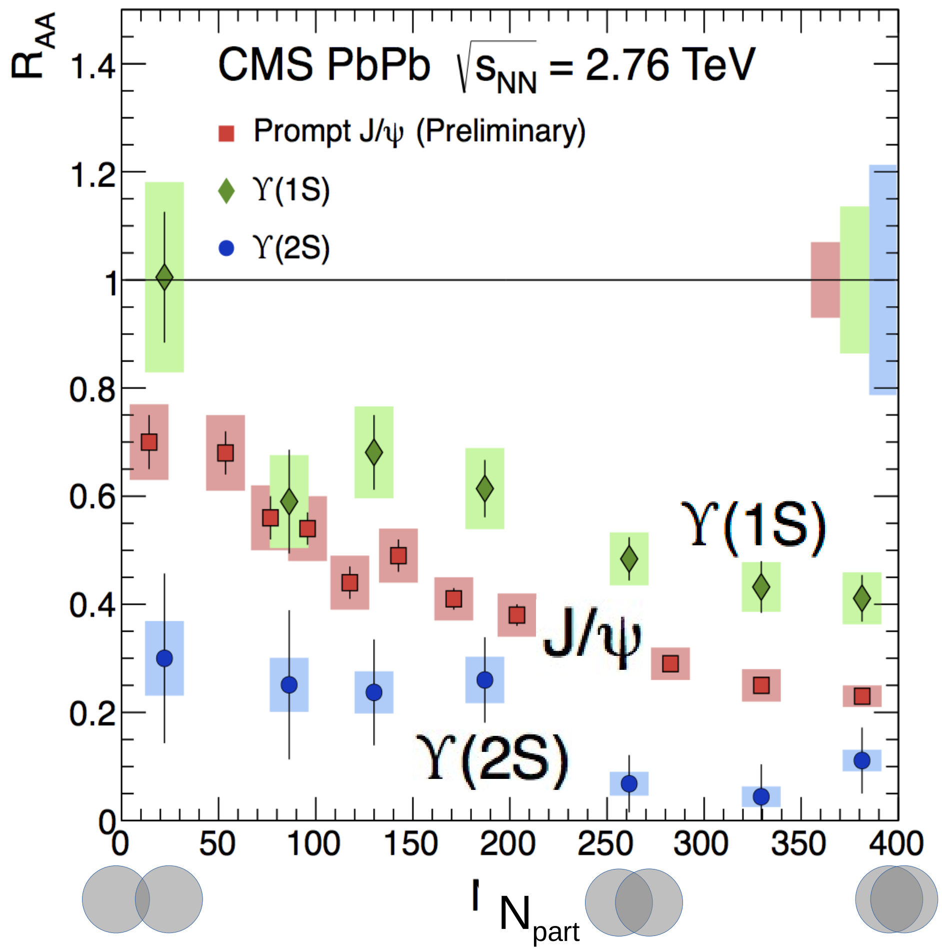


Clear hierarchy in R_{AA} of different quarkonium states

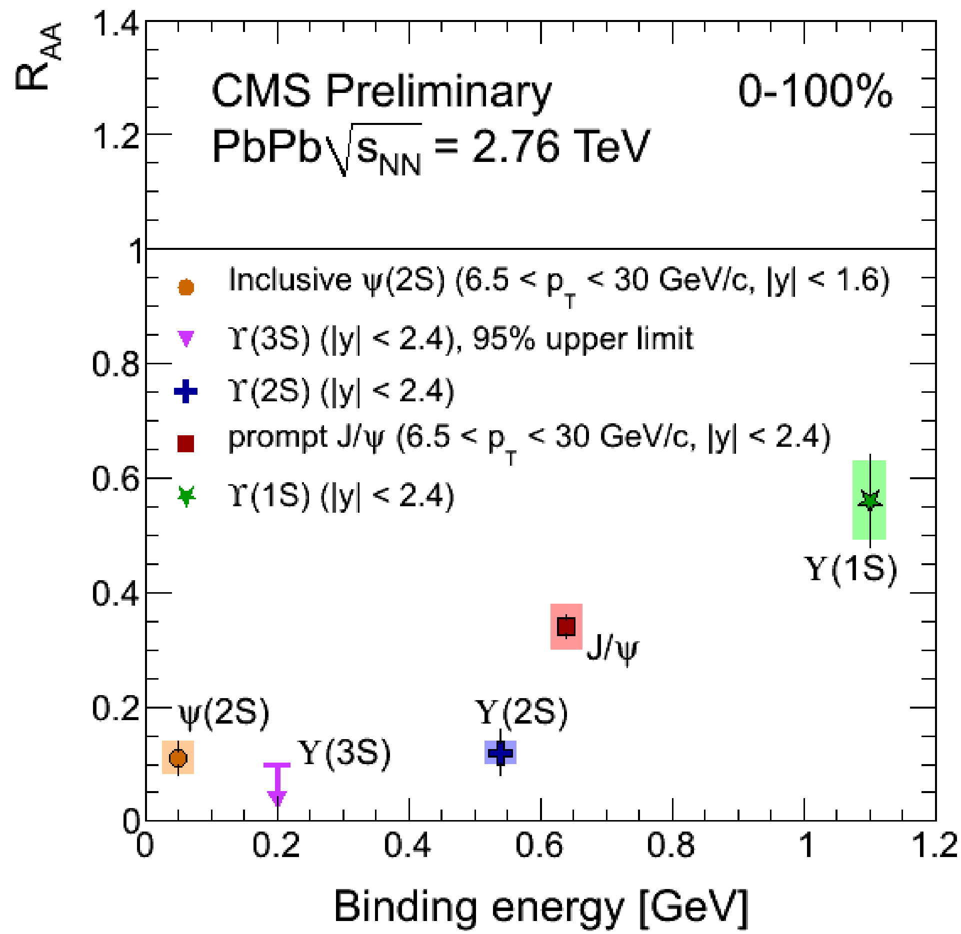


Building a quarkonium-thermometer

CMS-PAS HIN-11-011



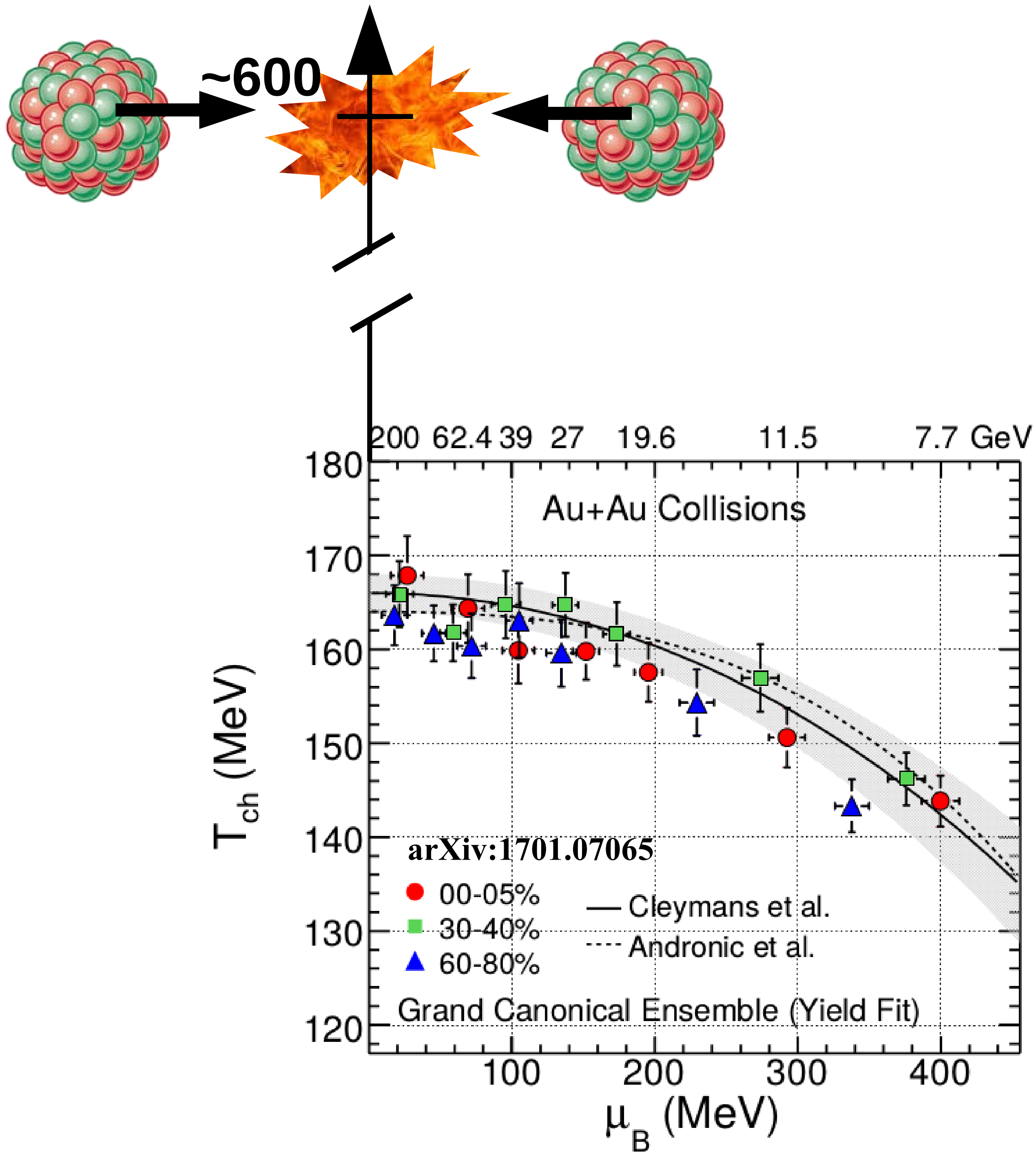
Note: 6.5<p_T<30 GeV for J/ψ and ψ(2s)



Clear hierarchy in R_{AA} of different quarkonium states

Expected in terms of binding energy

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

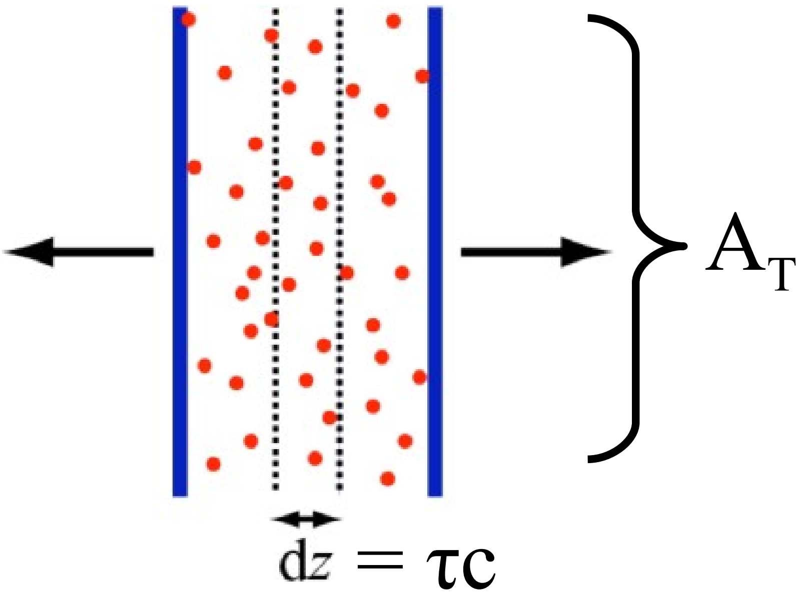


trajectory of system

QGP Energy Density

How can we estimate the energy density?

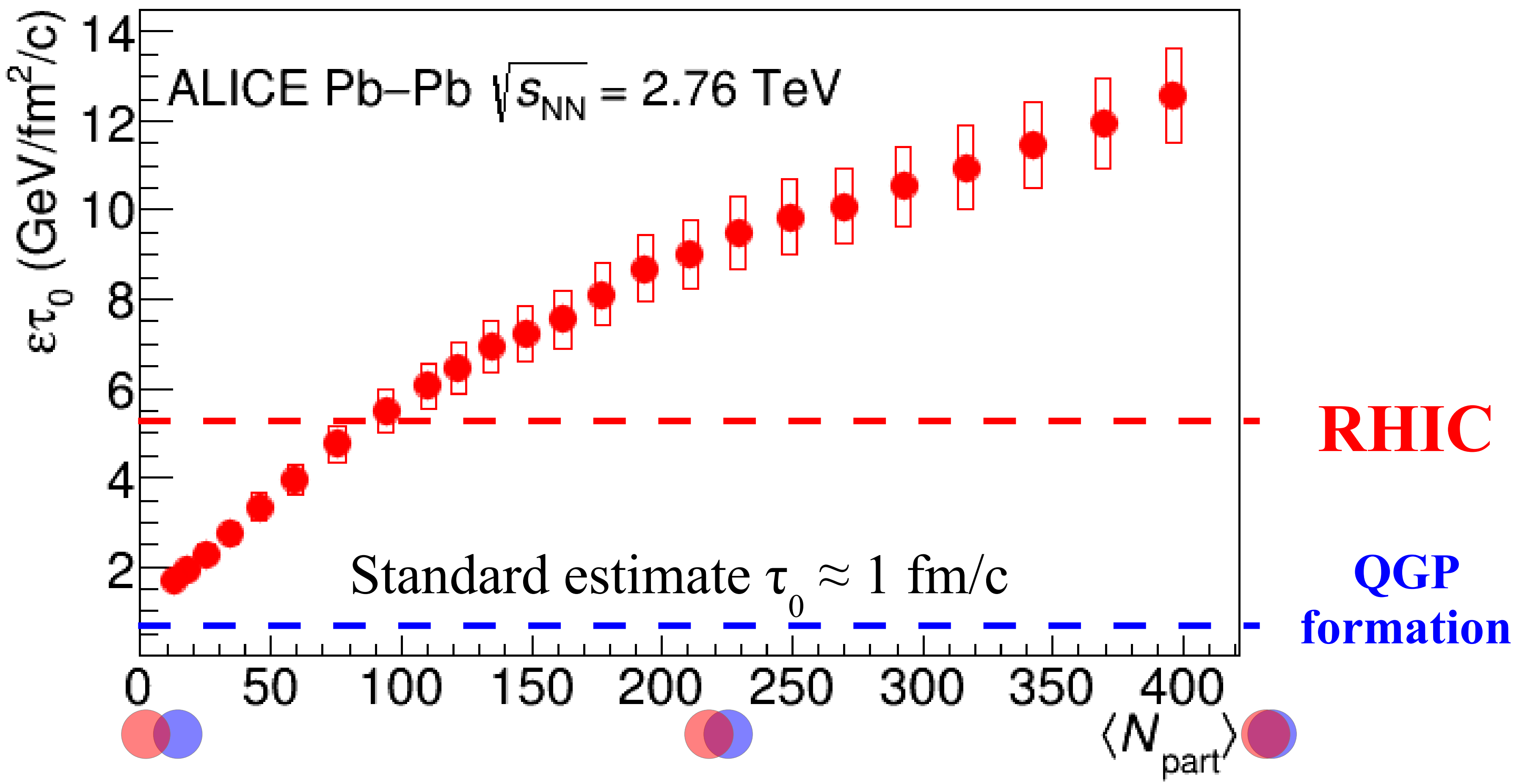
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



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

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

Energy density



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