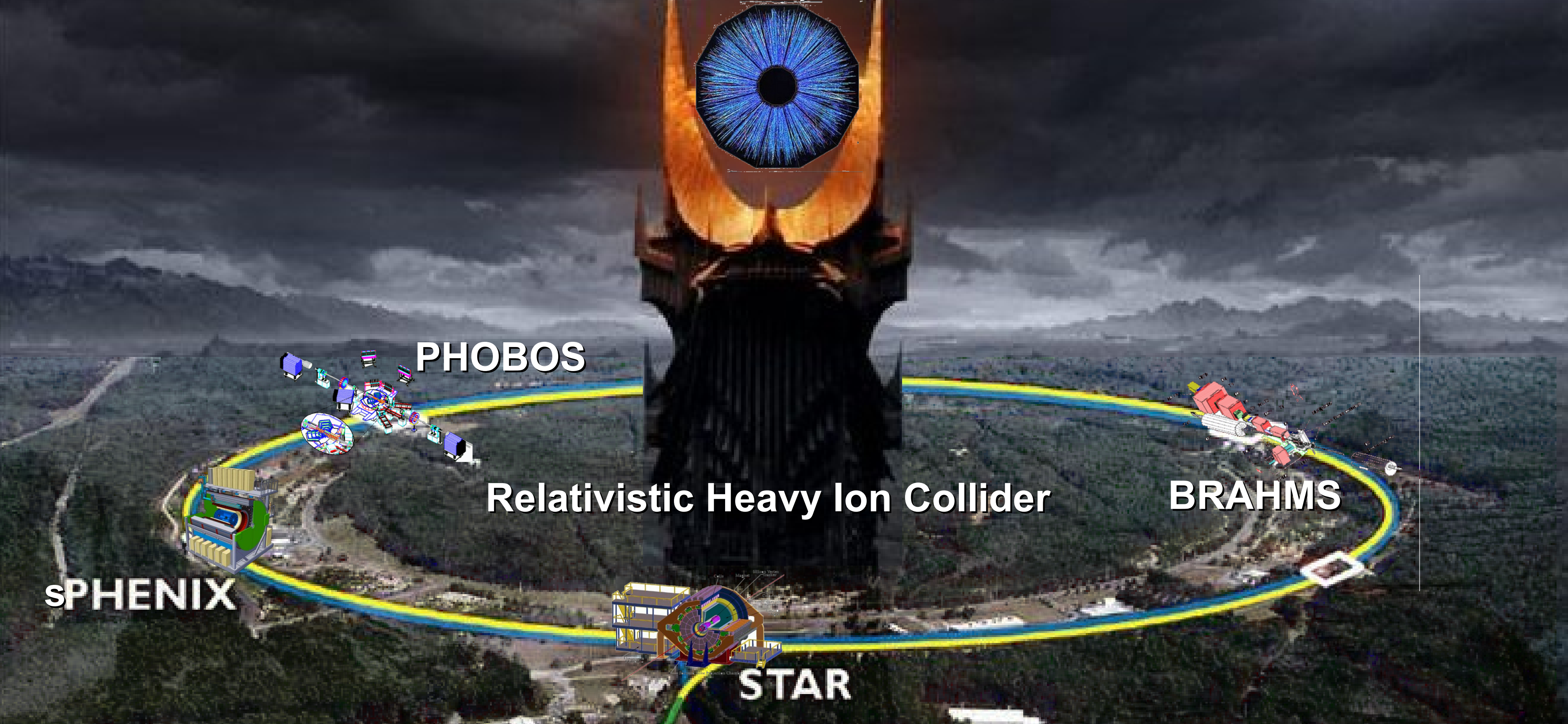
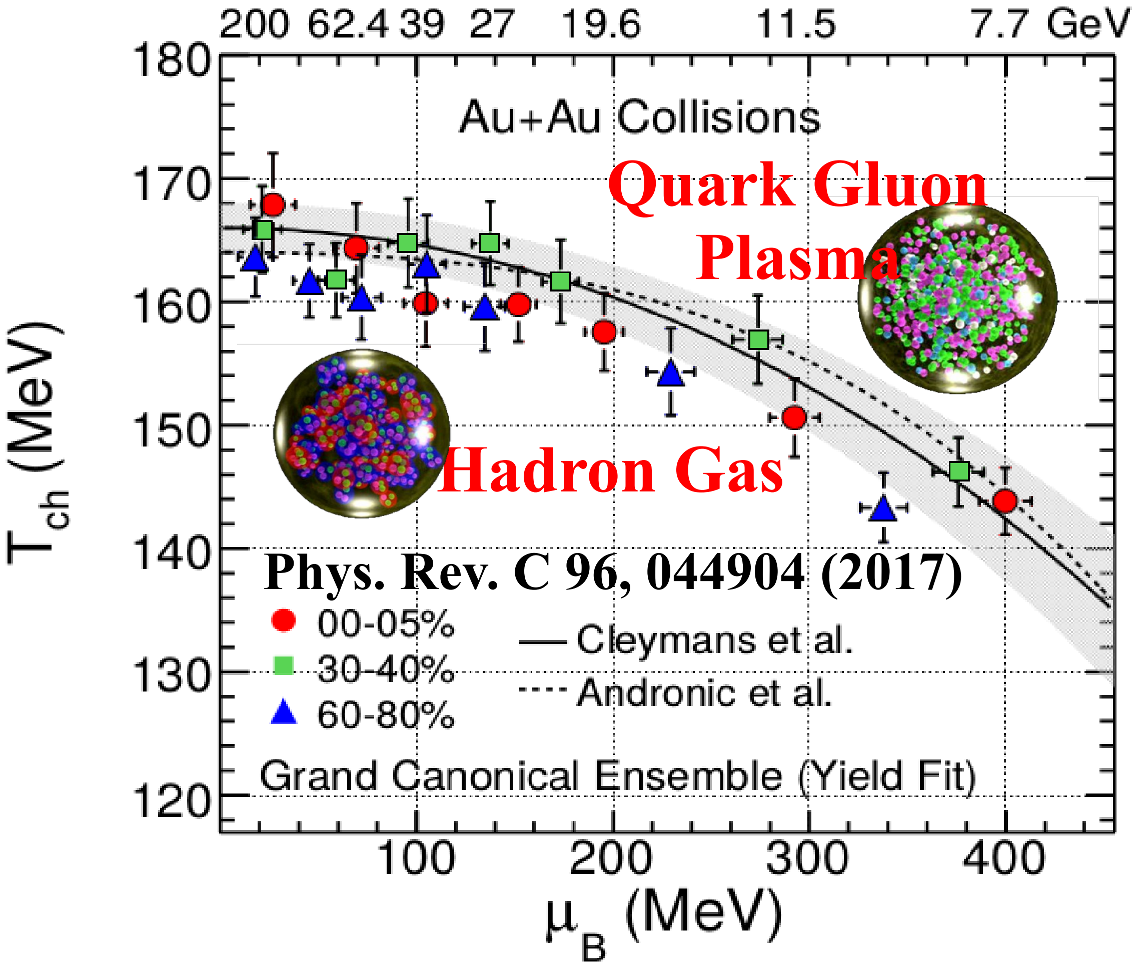
Quantifying properties of liquid nuclei

Or how I built my undergraduate army

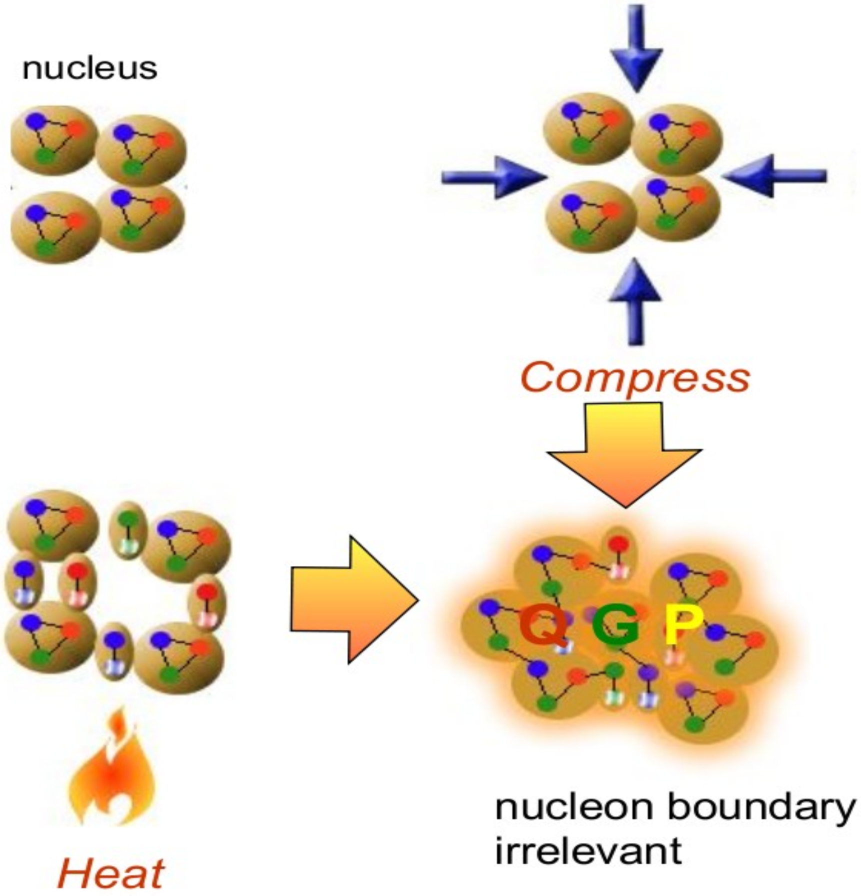
Christine Nattrass, University of Tennessee, Knoxville



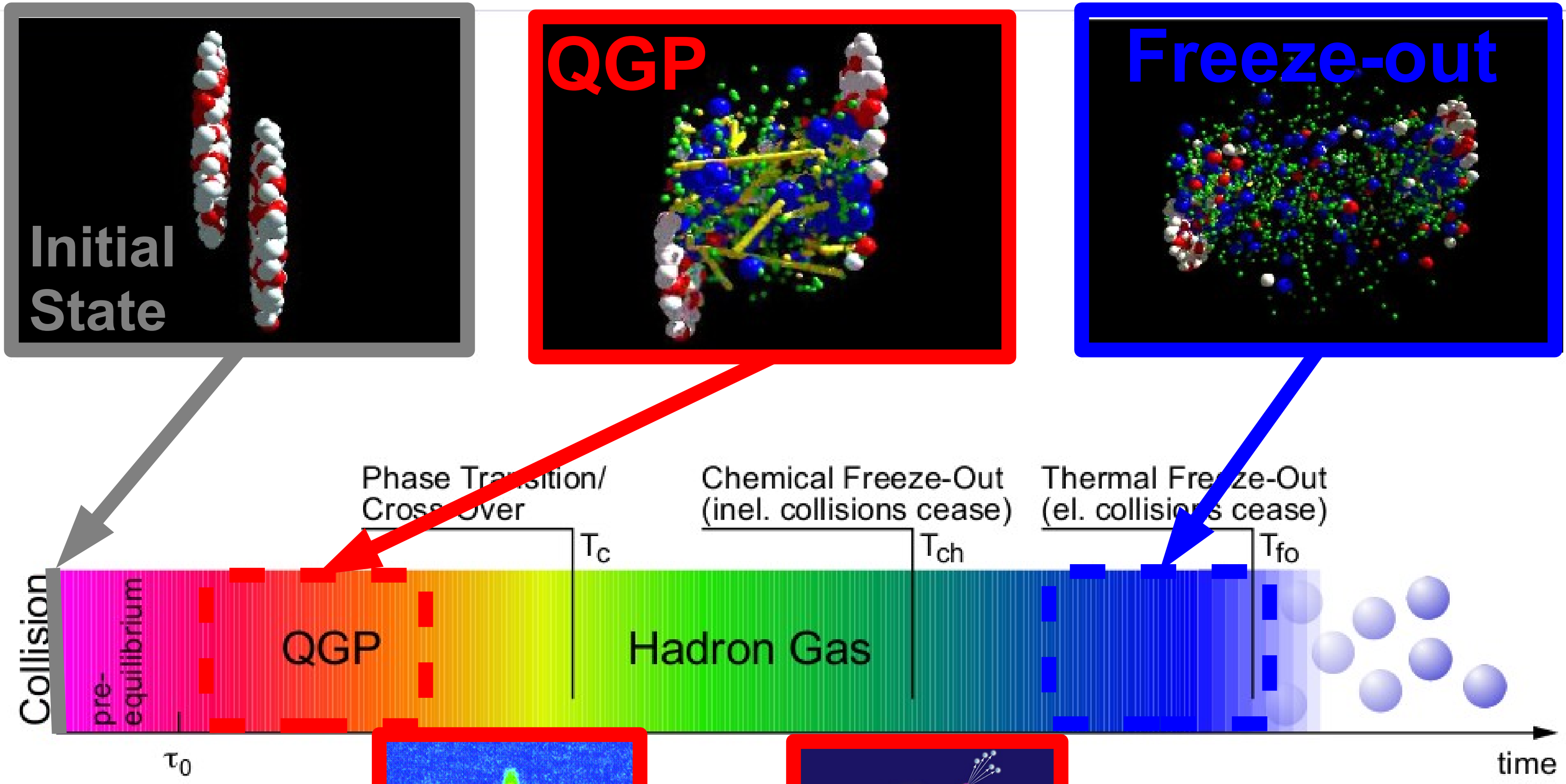
QCD Phase Diagram



How to make a Quark Gluon Plasma

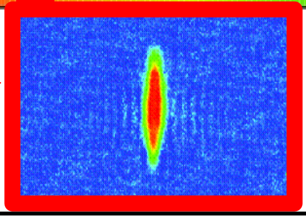


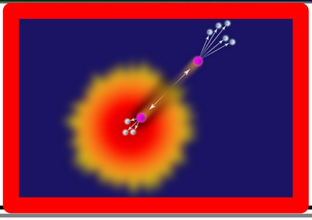
The phase transition in the laboratory



Hydrodynamical flow

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

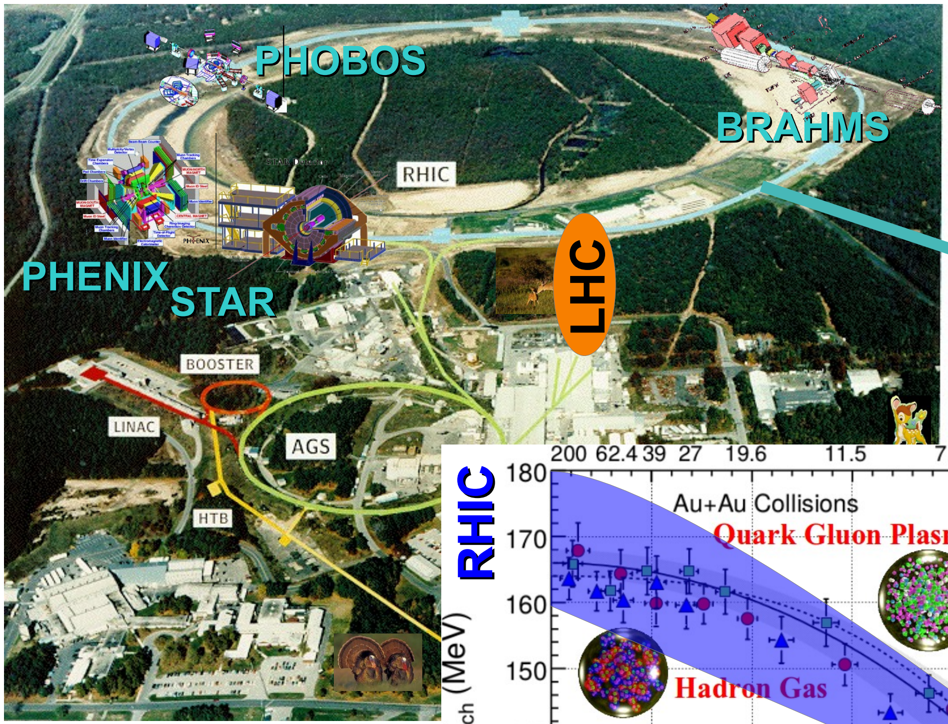


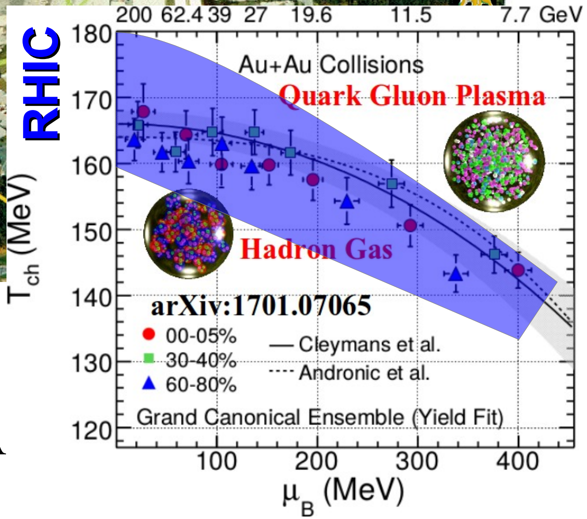


Jet quenching

https://physics.aps.org/articles/v7/97

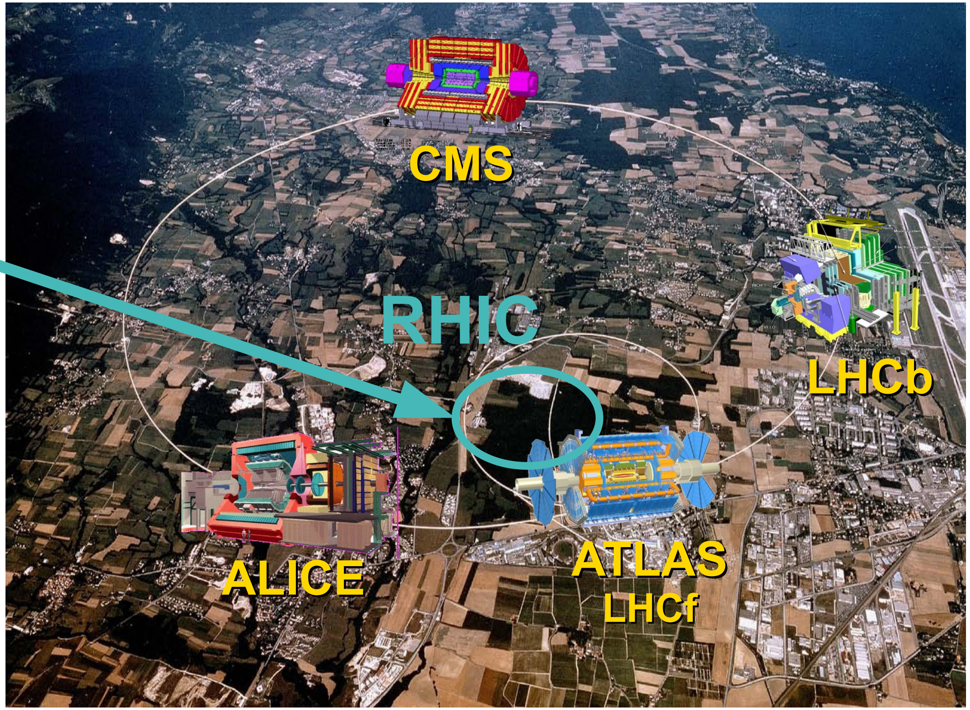
Relativistic Heavy Ion Collider





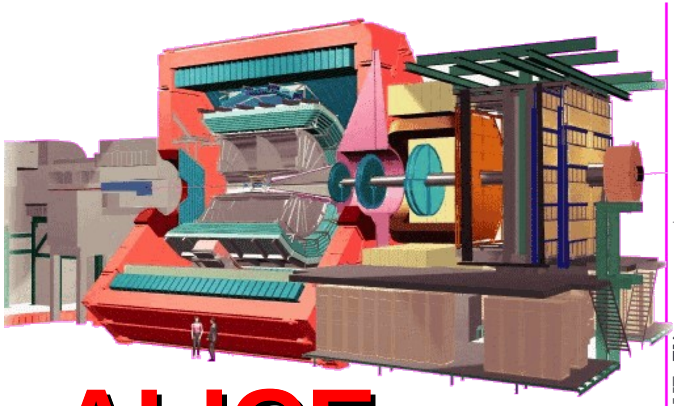
Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, A
$\sqrt{s_{NN}}$ = 9 - 200 GeV

Large Hadron Collider

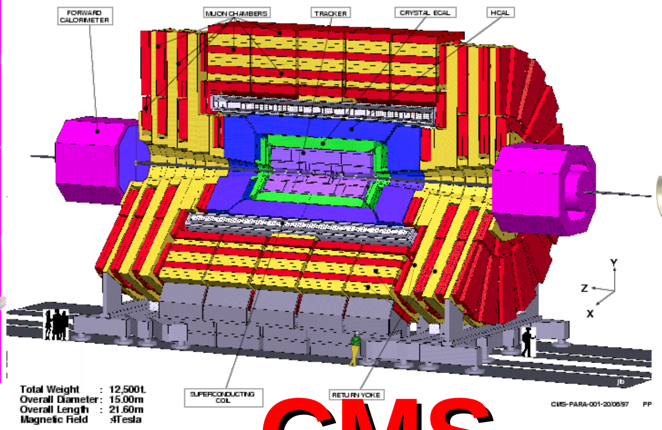


Geneva, Switzerland
8.6km diameter
p+p, *p+Pb*, Pb+Pb
$\sqrt{s_{NN}}$ = 2.76 GeV, *5.5 TeV*

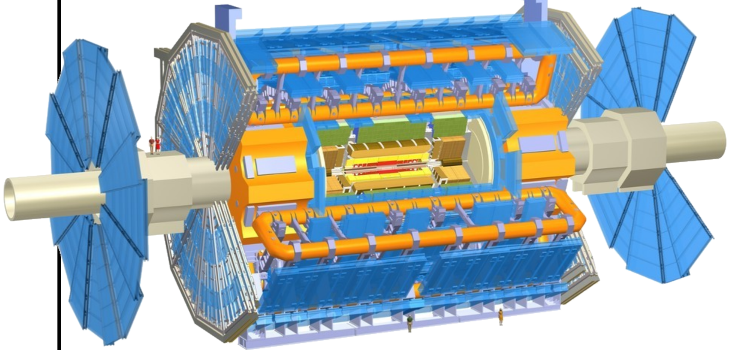
Particle Detectors



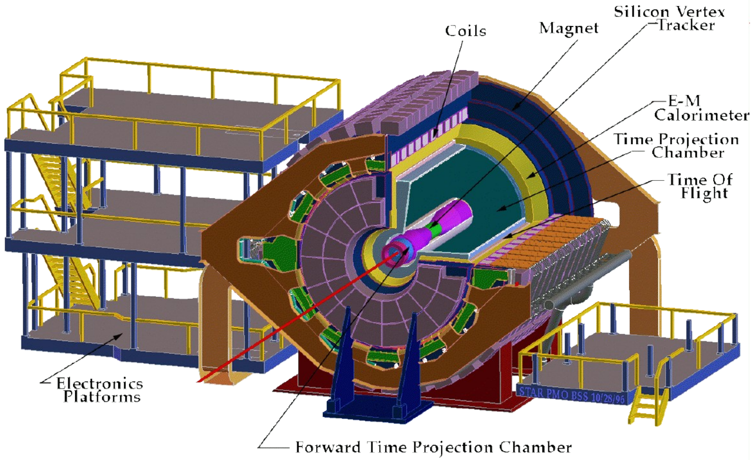
ALICE



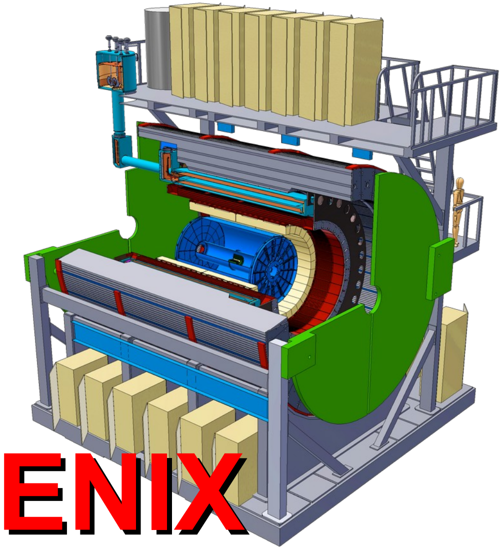
CMS



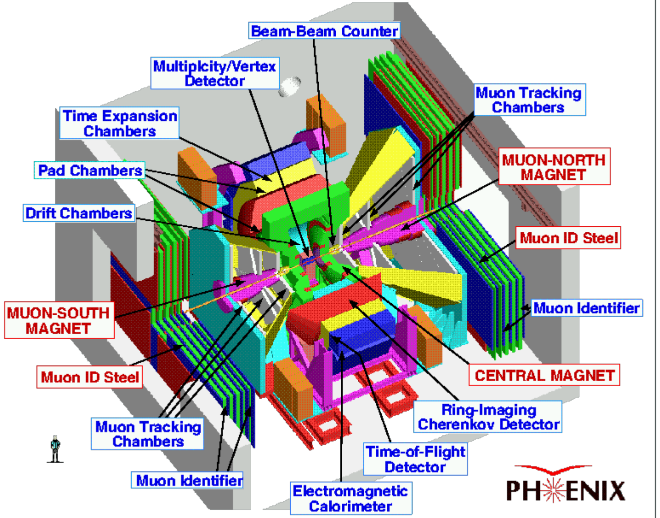
ATLAS



STAR

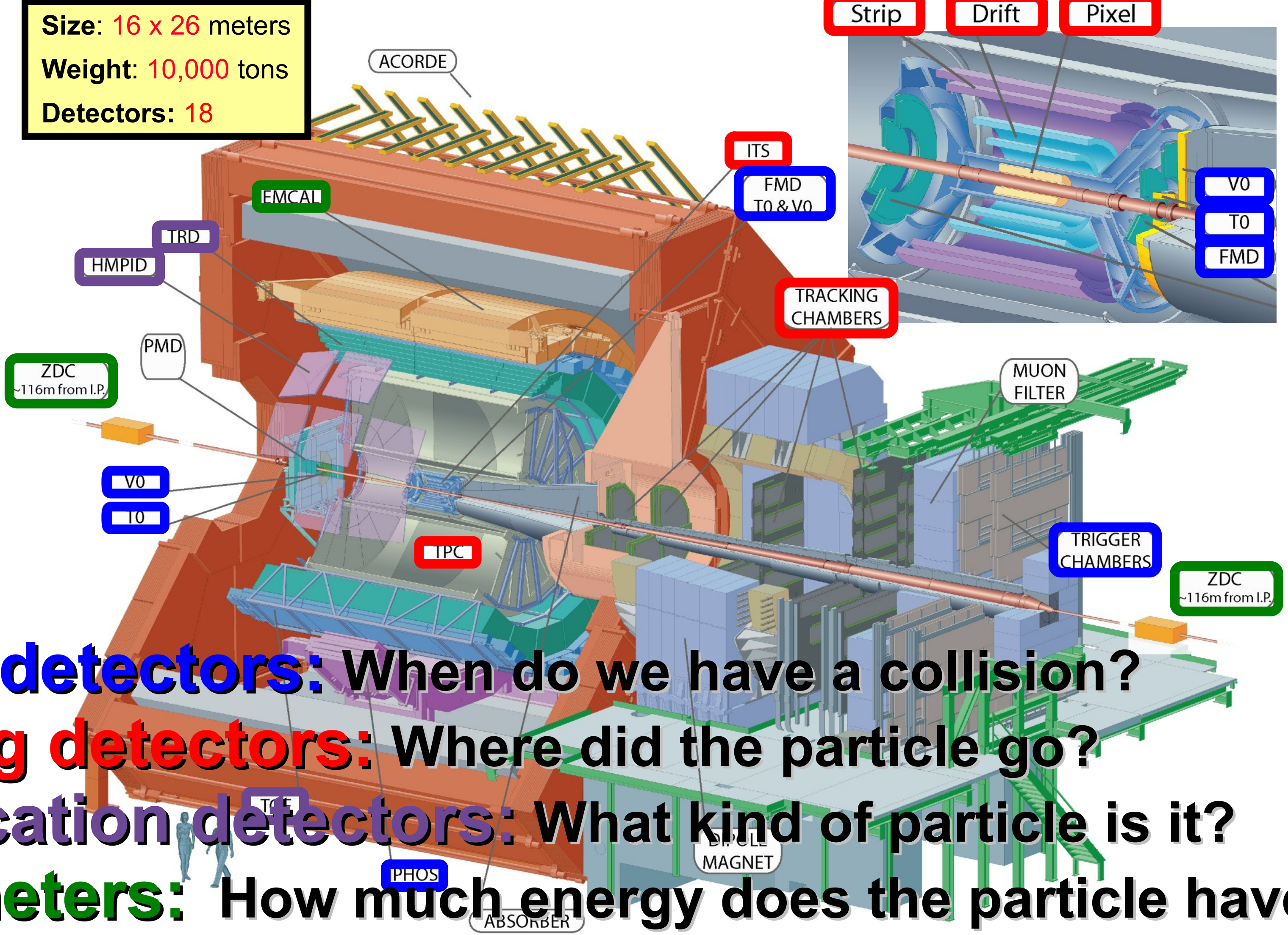


sPHENIX



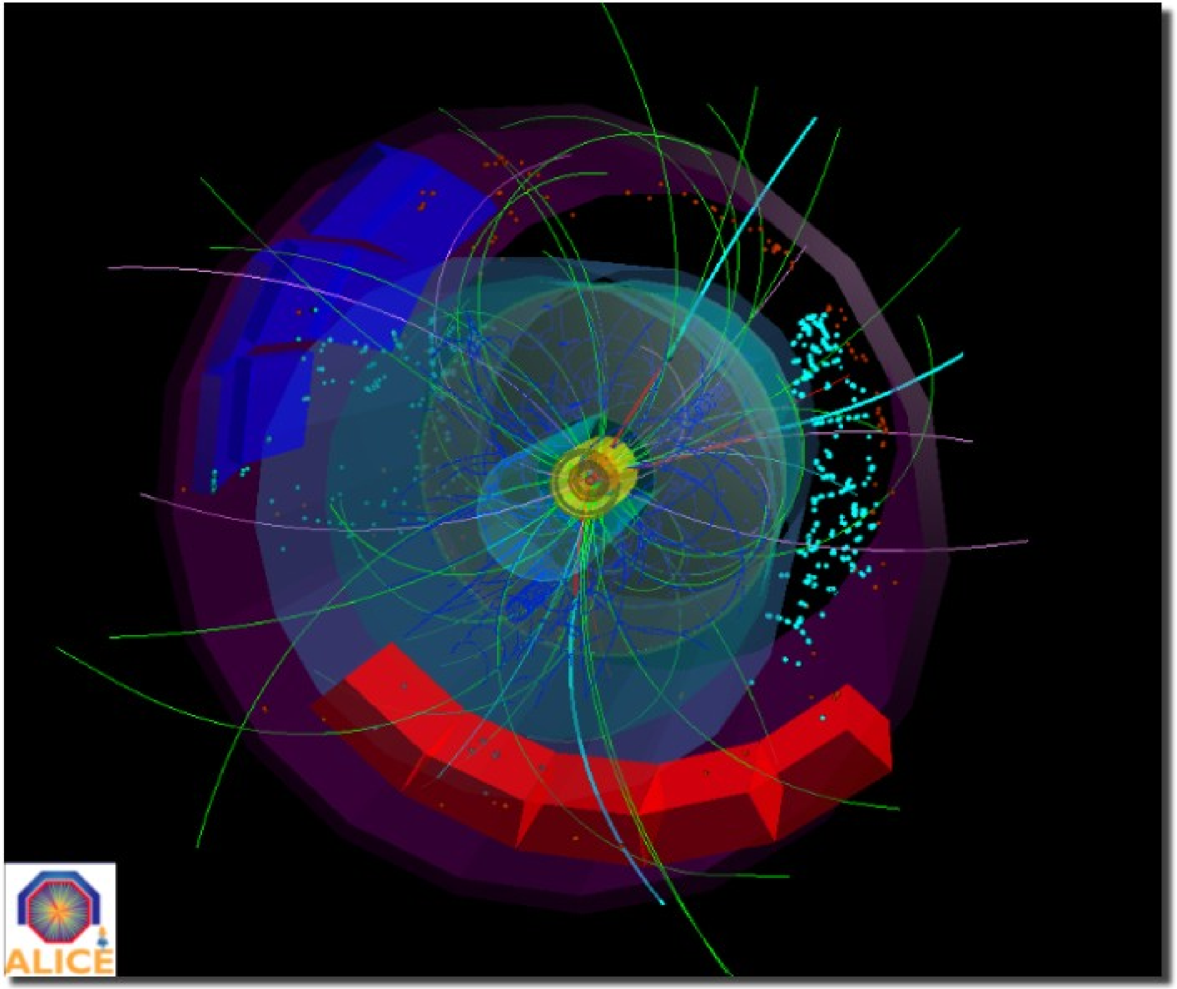
PHENIX

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

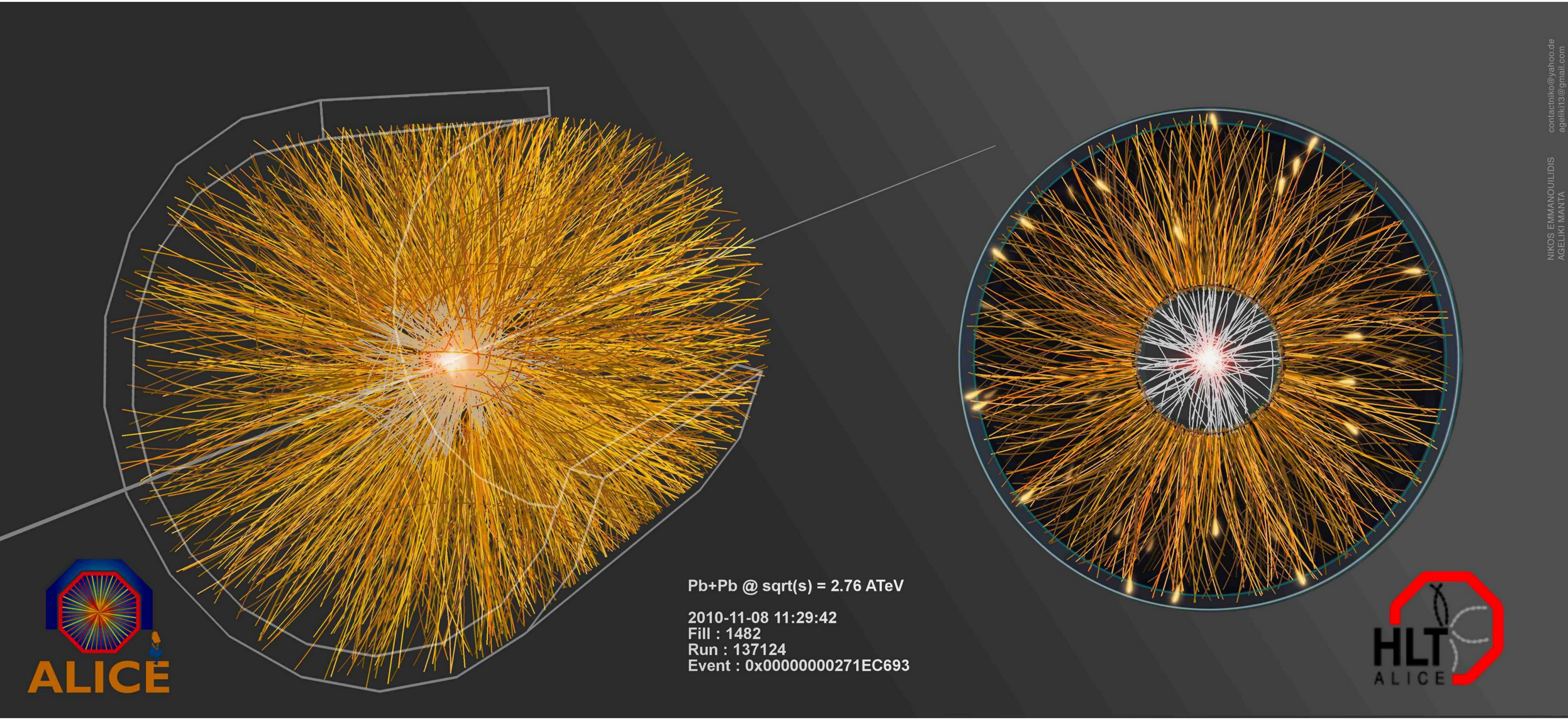


Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?

p+p collisions



Pb+Pb collisions



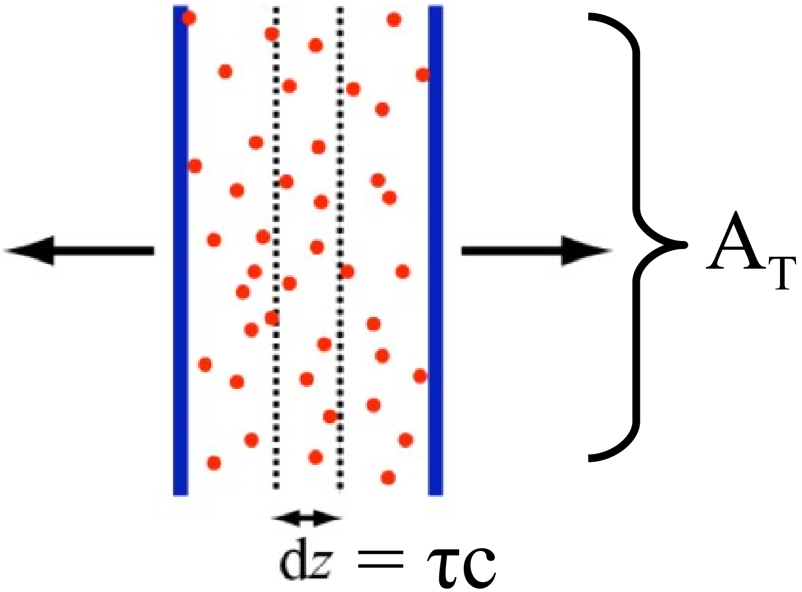
Forming the QGP

How can we estimate the energy density?

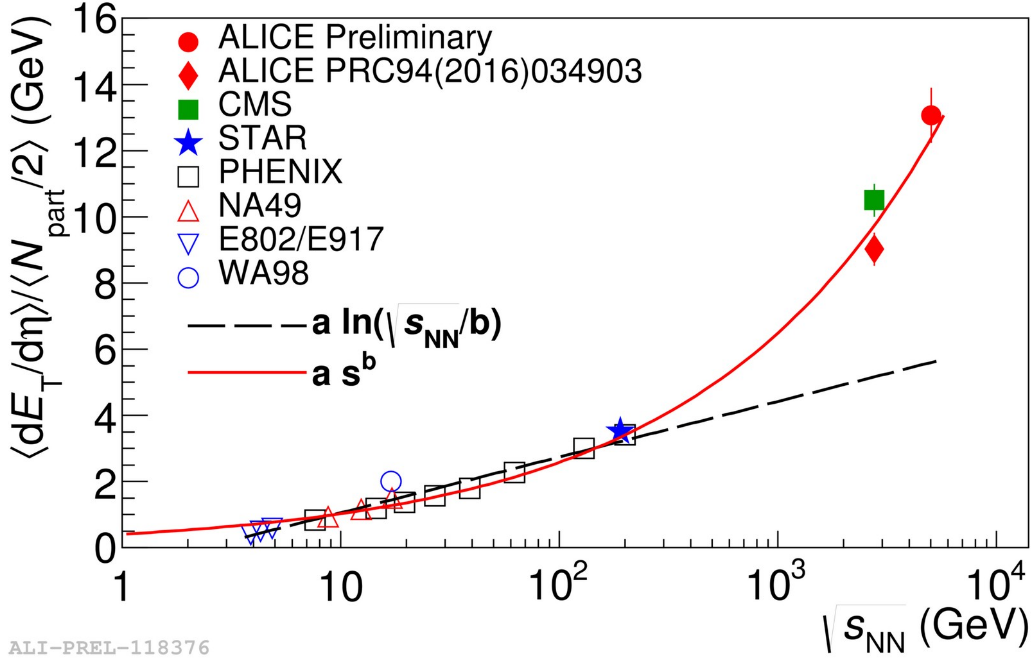
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε

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

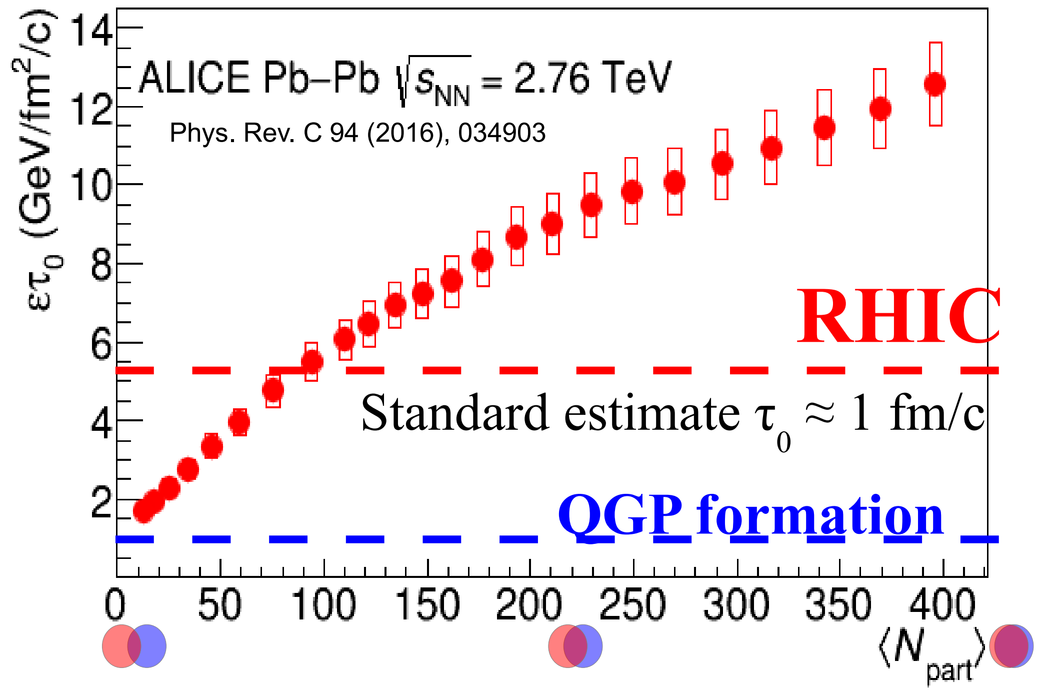
- QGP formation for $\varepsilon > 0.5$ GeV/fm^3



Energy dependence from dE_T/dy



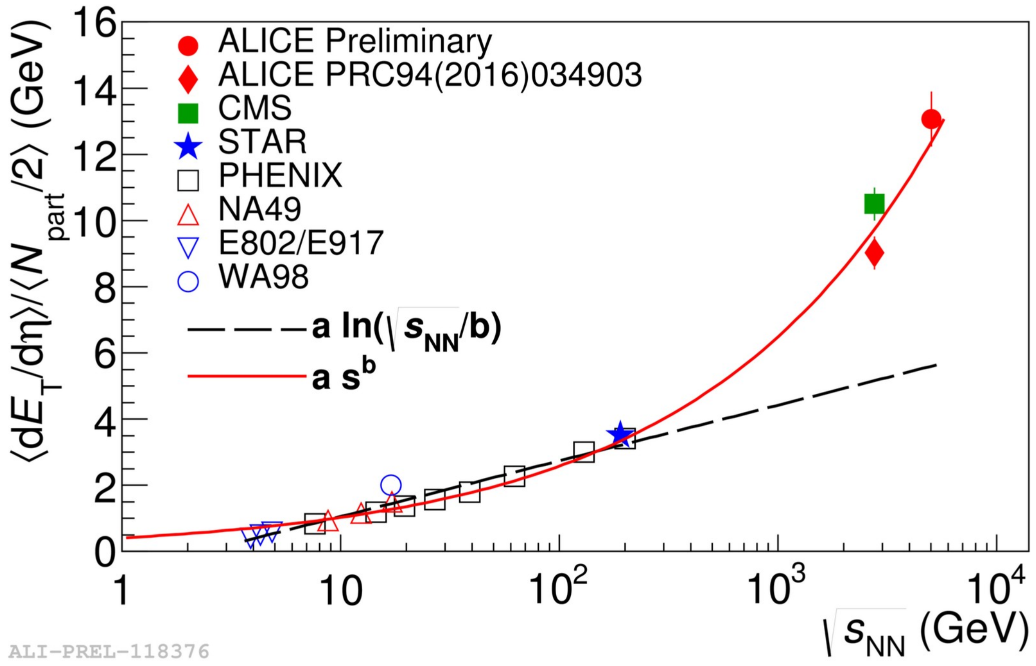
Collision energy

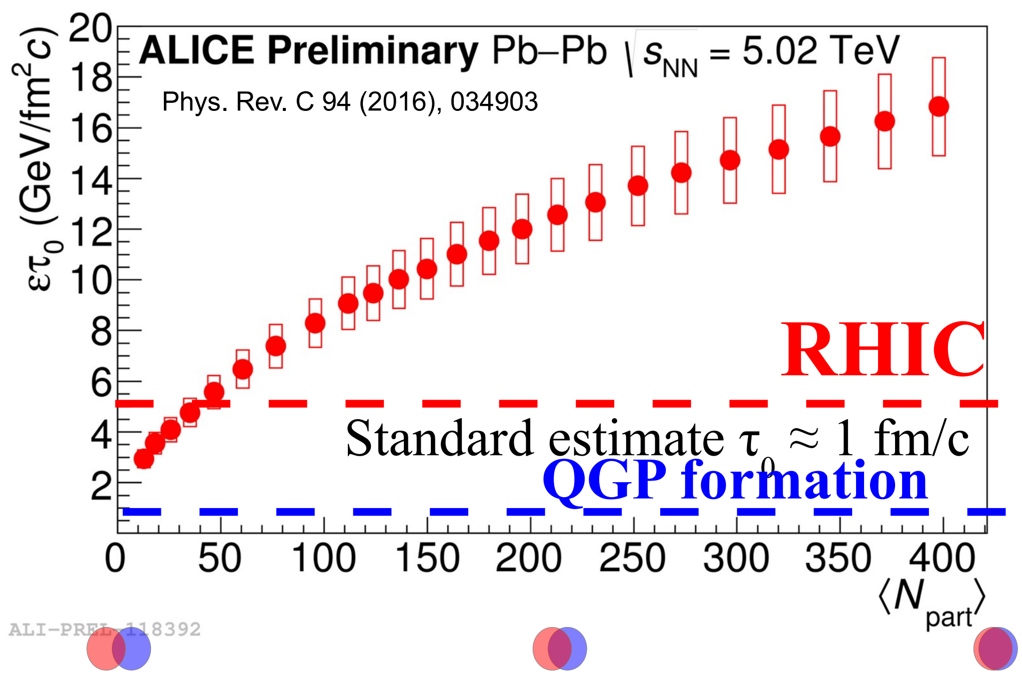


$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

➔ Higher than extrapolations of RHIC data

Energy dependence from dE_T/dy





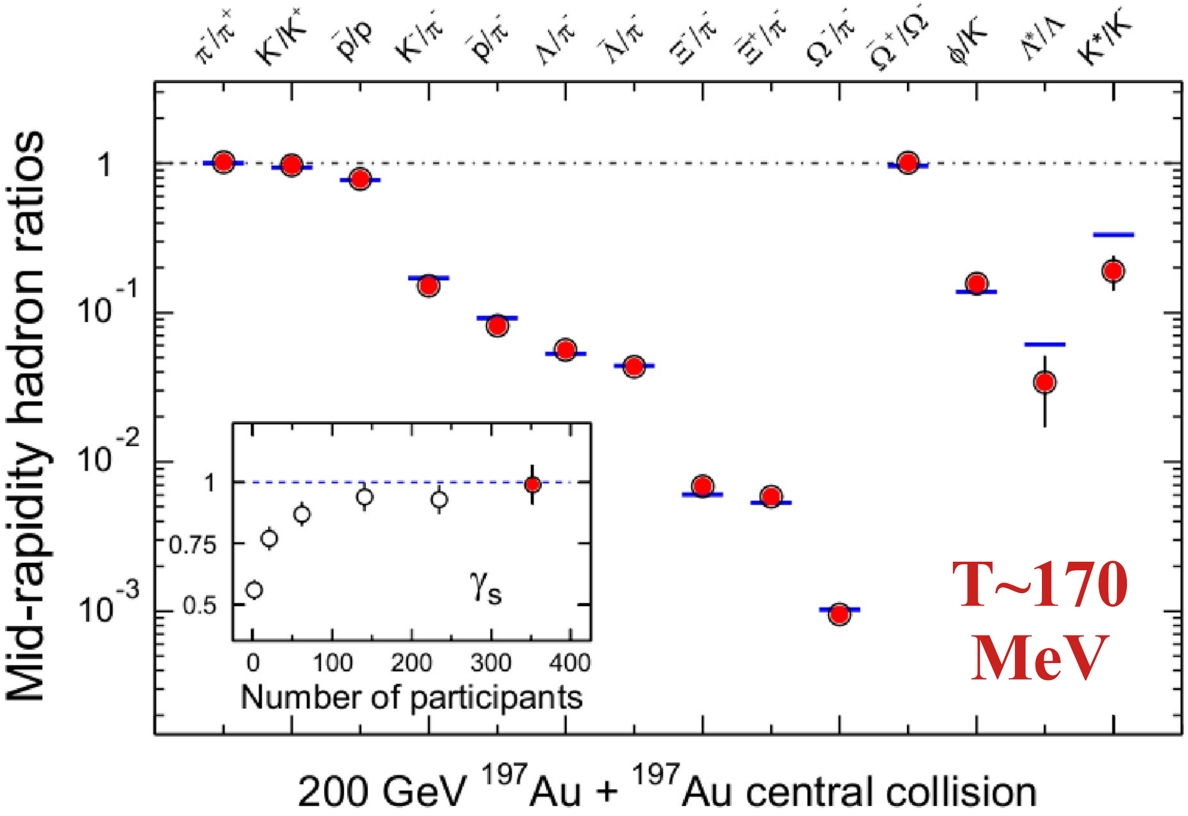
Collision energy

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

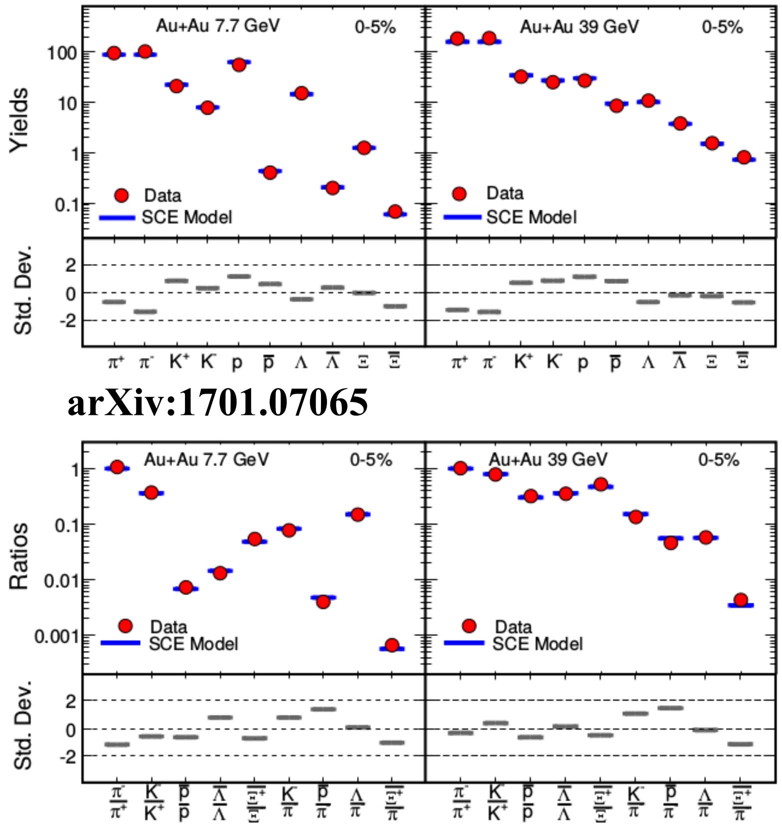
➔ Higher than extrapolations of RHIC data

QGP Chemistry

Chemistry - equilibrium



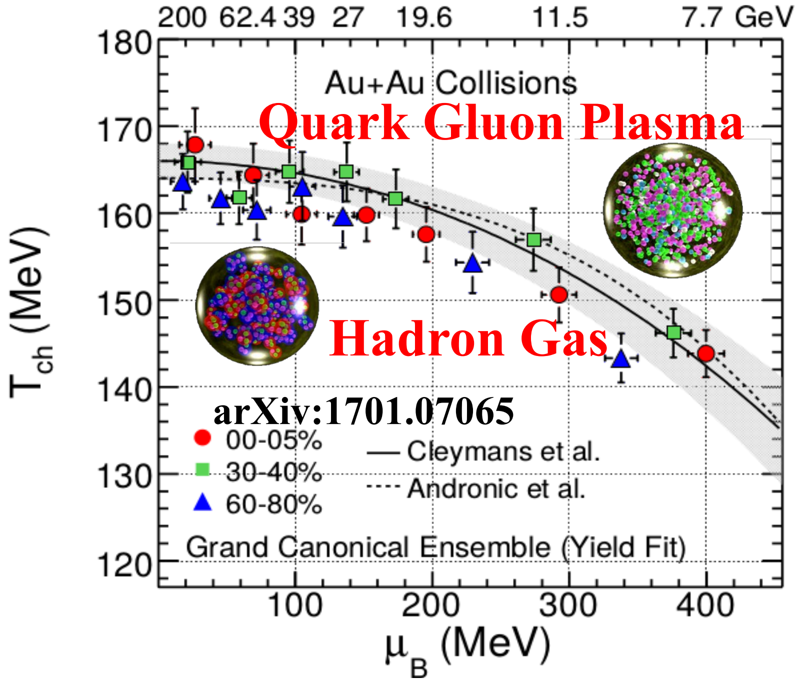
T~170 MeV

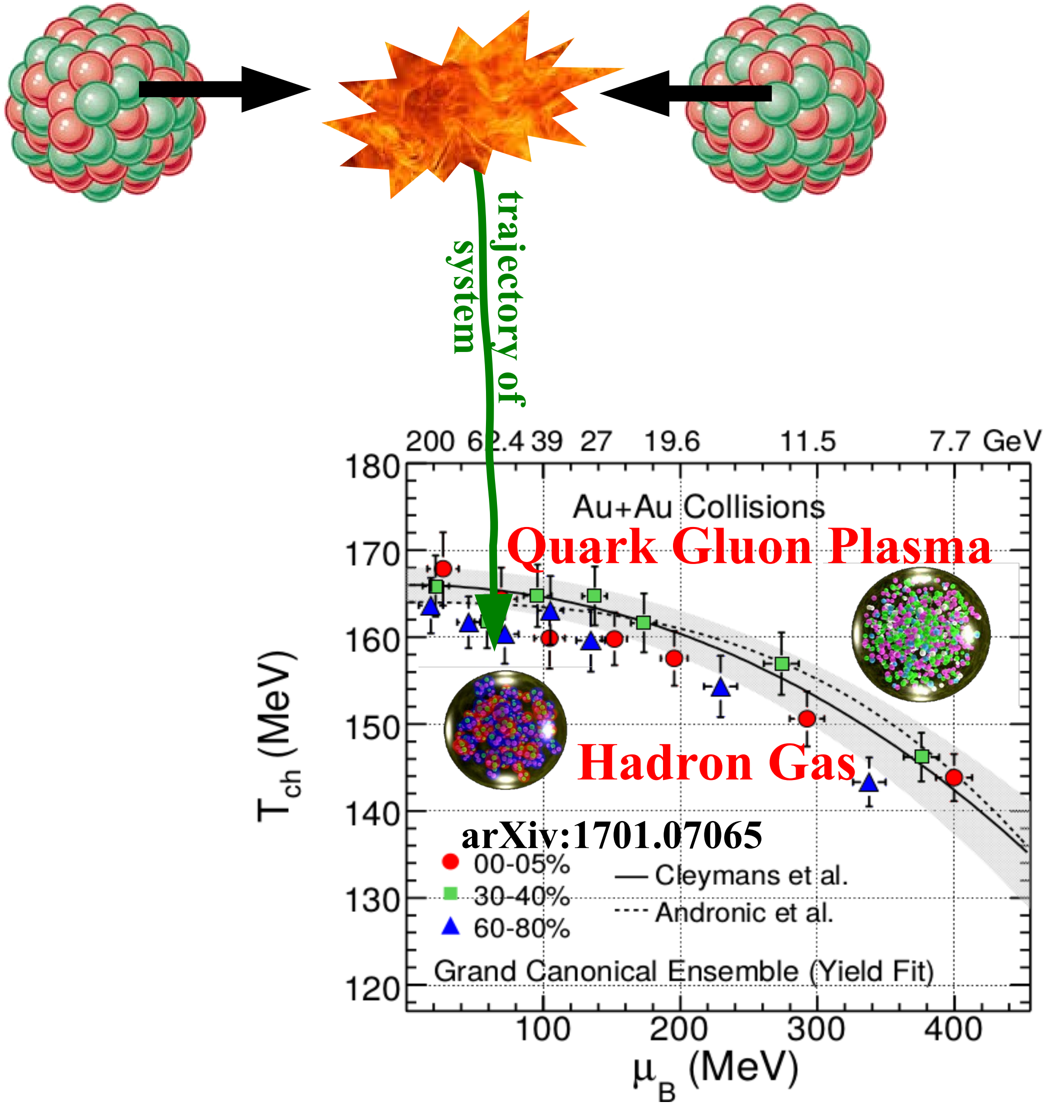


arXiv:1701.07065

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

Nuclear Physics A Volume 757, 102-183

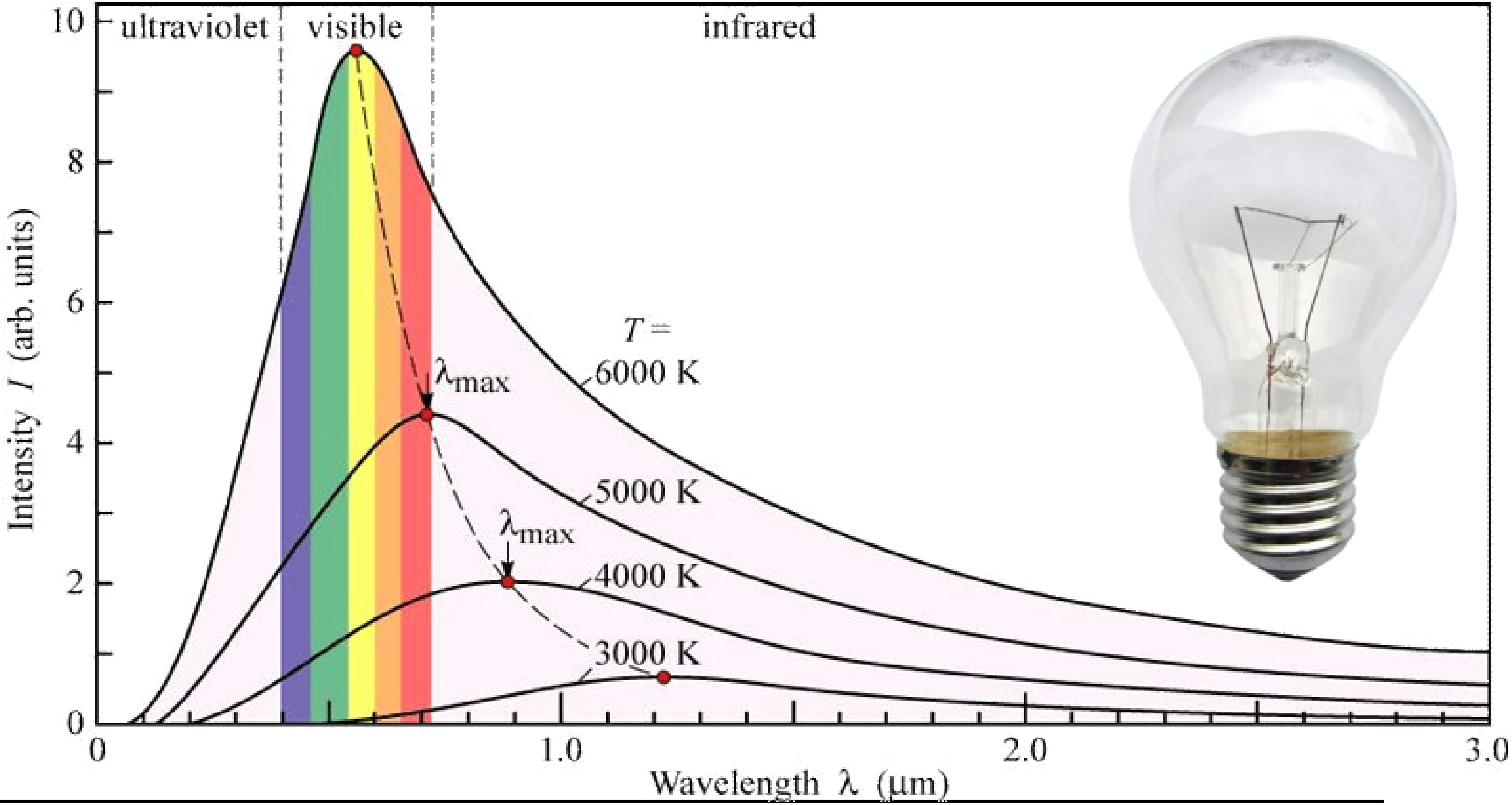

200 62.4 39 27 19.6 11.5 7.7 GeV
Au+Au Collisions
Quark Gluon Plasma
Hadron Gas
arXiv:1701.07065
00-05%
30-40%
60-80%
Cleymans et al.
Andronic et al.
Grand Canonical Ensemble (Yield Fit)
T_ch (MeV)
μ_B (MeV)
180
170
160
150
140
130
120
100
200
300
400



trajectory of
system
200 62.4 39 27 19.6 11.5 7.7 GeV
Au+Au Collisions
Quark Gluon Plasma
Hadron Gas
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)

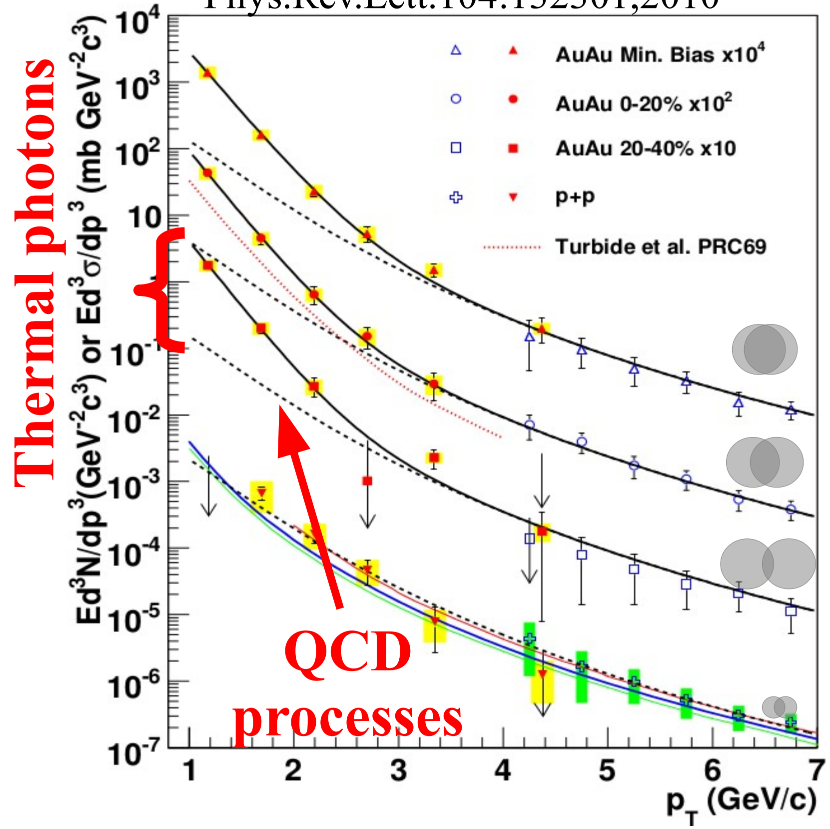
QGP Thermometers

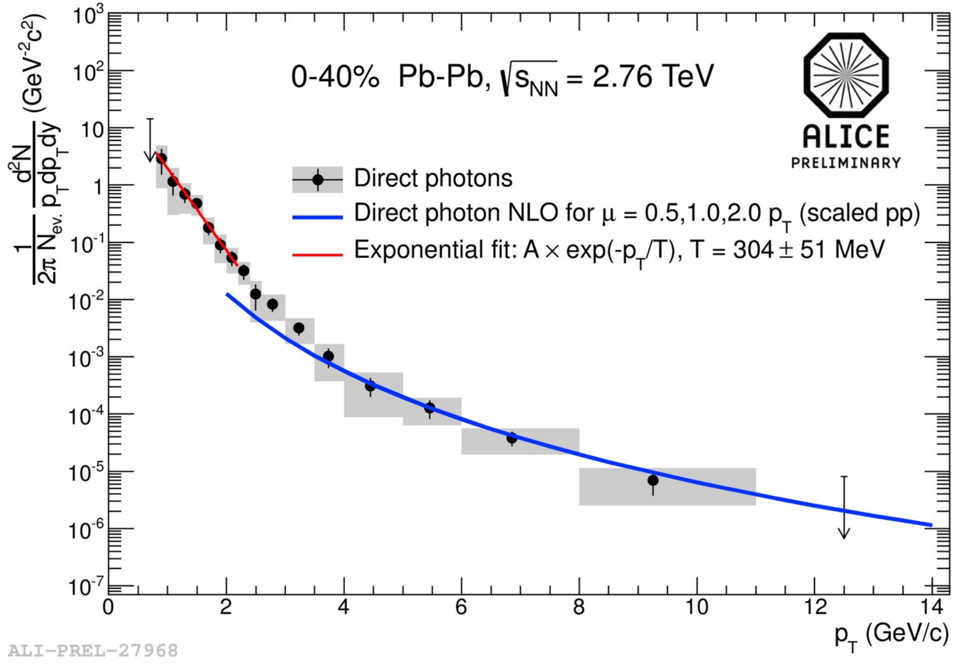
Measuring temperature



Thermal photons

Phys.Rev.Lett.104:132301,2010





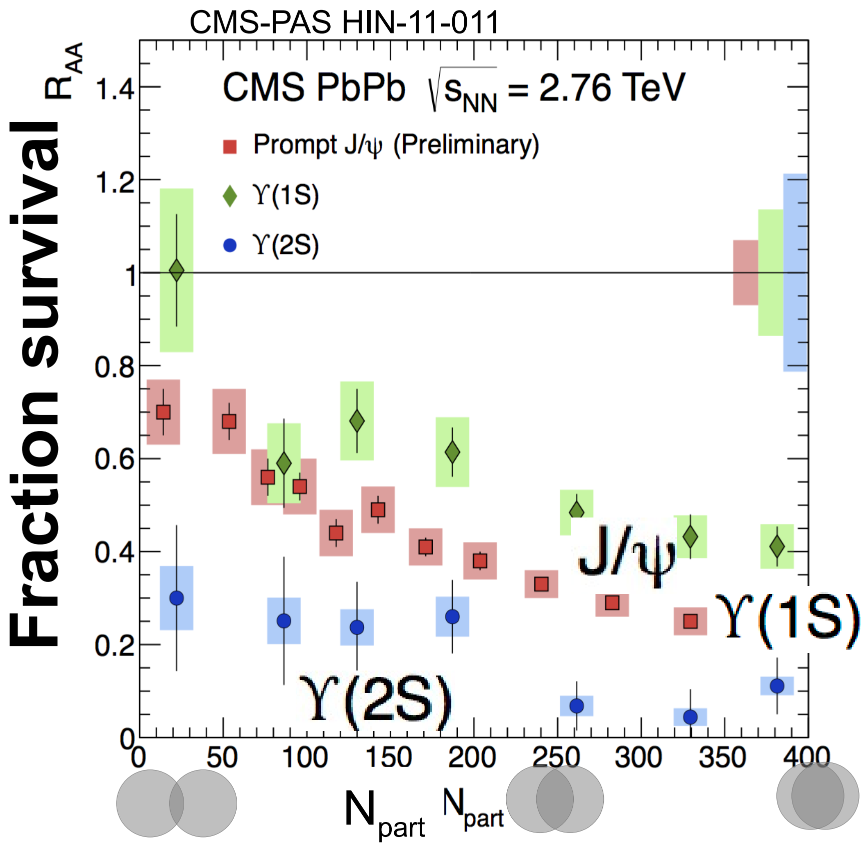
ALICE collaboration: Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

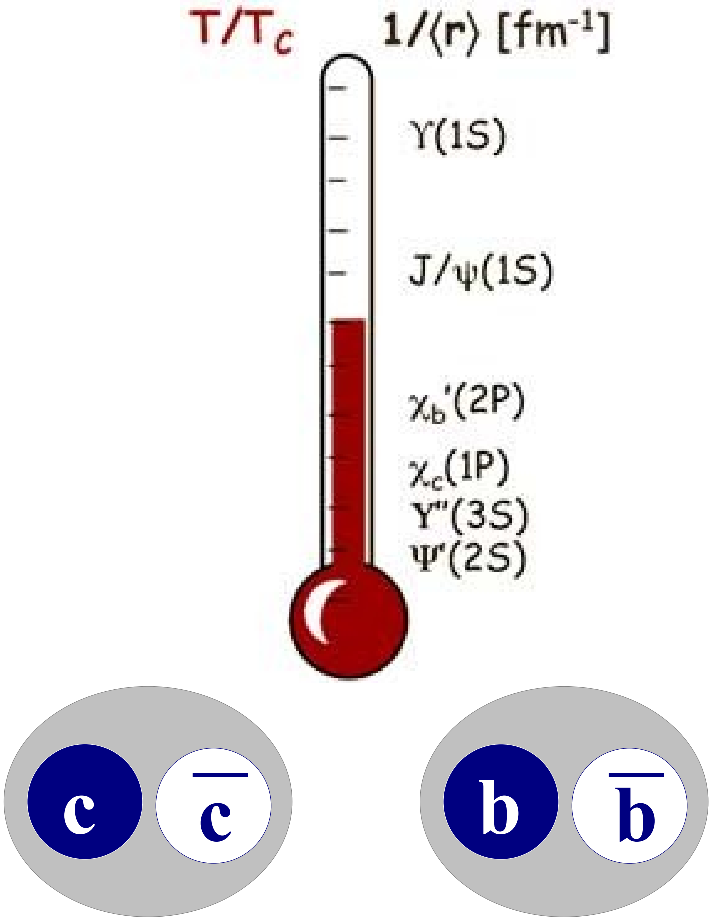
Inverse slope: T = 304 +/-51

PHENIX collaboration: Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV

Inverse slope: T = 221 +/- 19 (stat) +/- 19 (syst) MeV

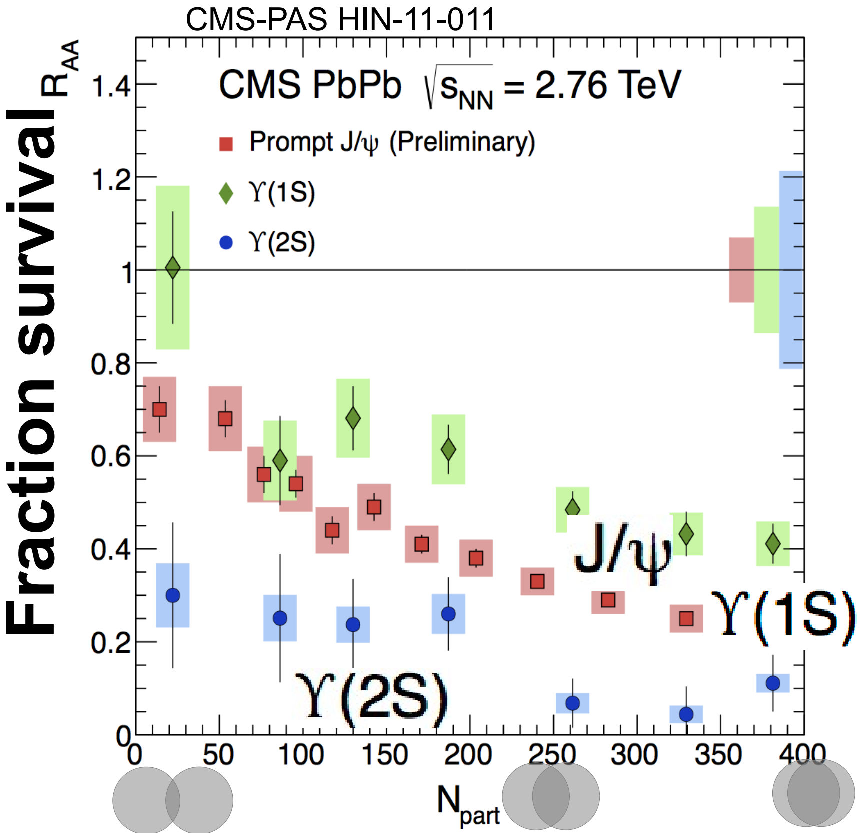
Building a quarkonium-thermometer



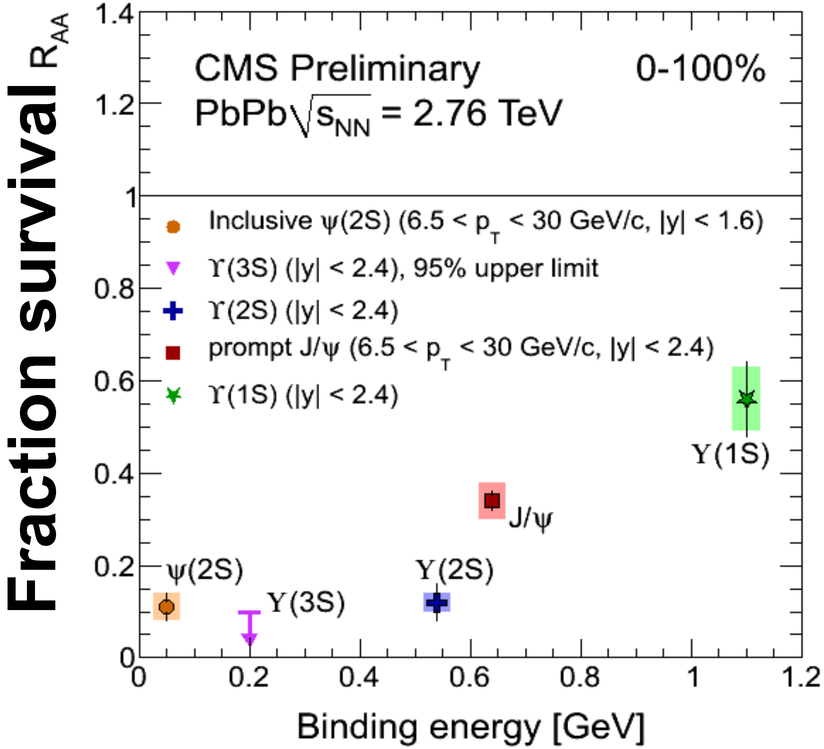


Clear hierarchy in R_{AA} of different quarkonium states

Building a quarkonium-thermometer



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

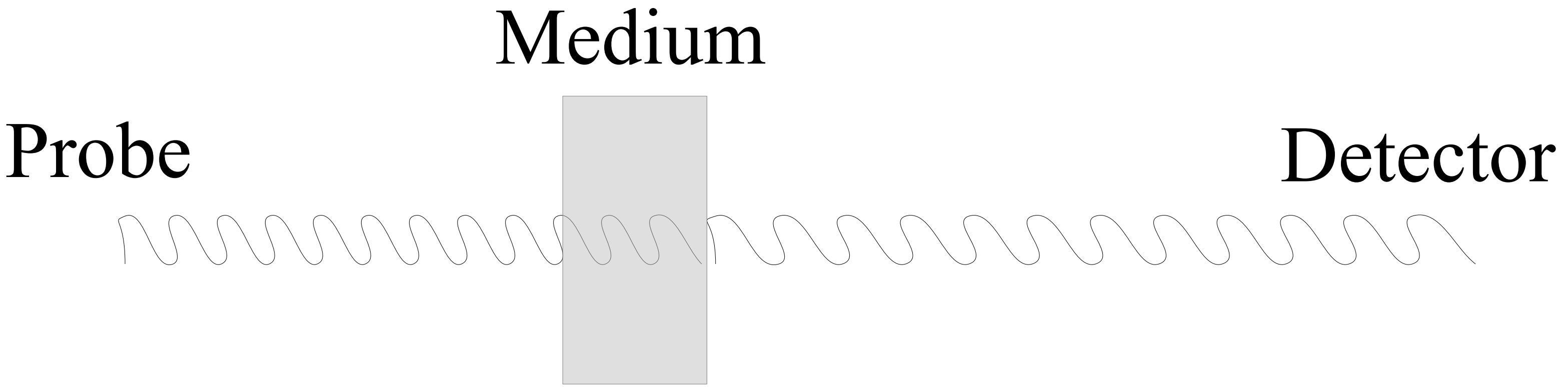


Clear hierarchy in R_{AA} of different quarkonium states

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

QGP Spectroscopy

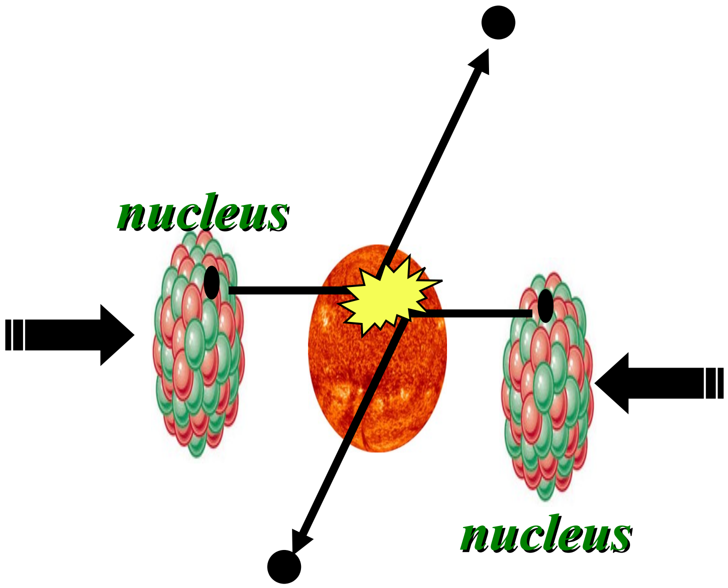
Probing the Quark Gluon Plasma



Want a probe which traveled through the collision

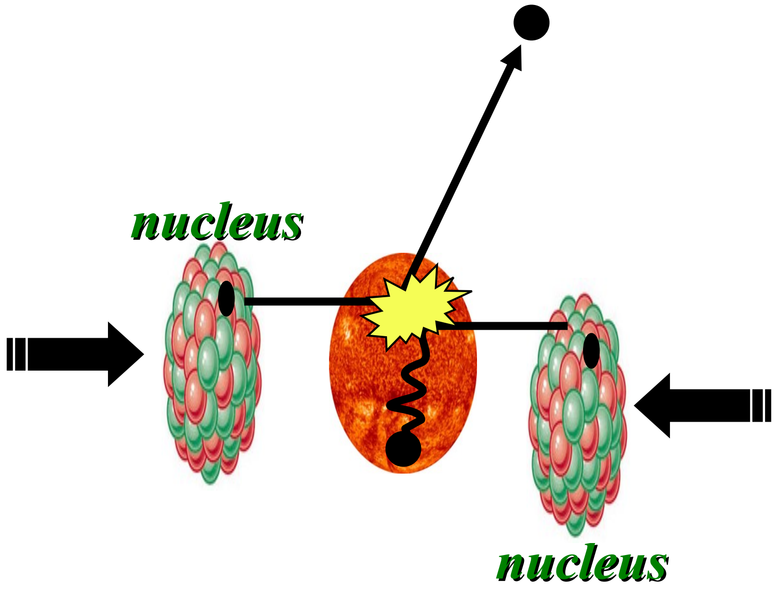
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



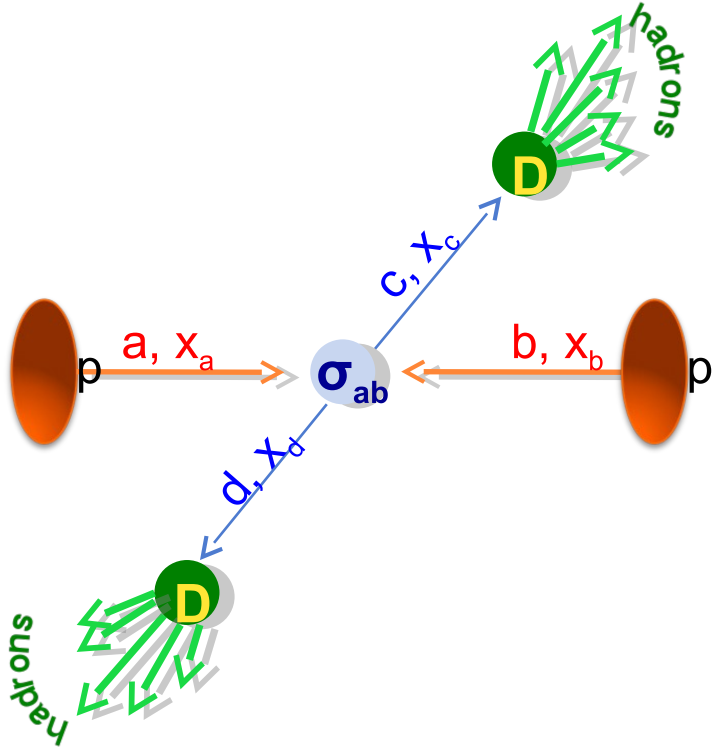
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

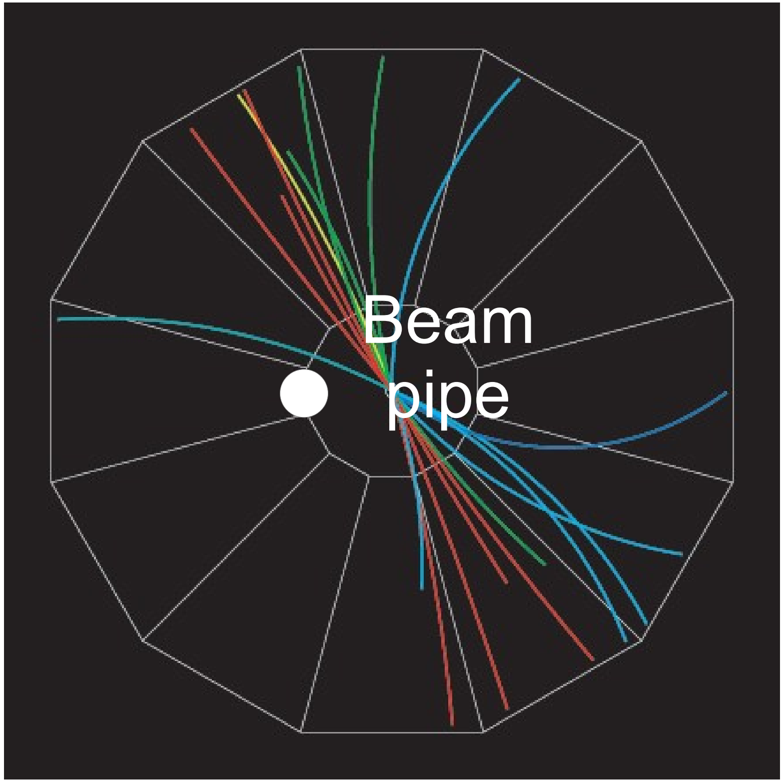


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets

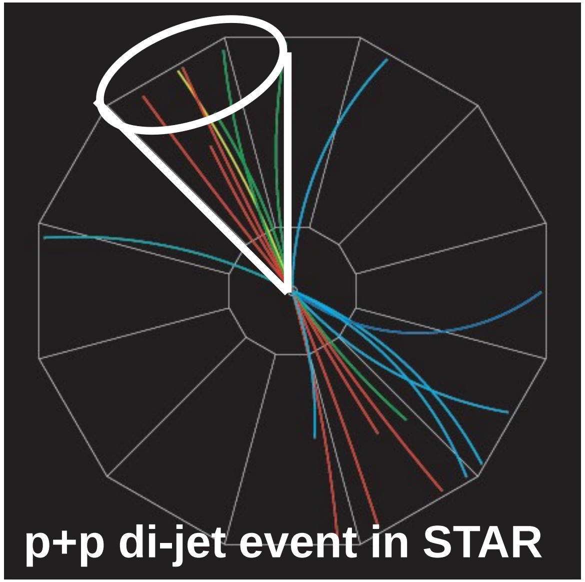


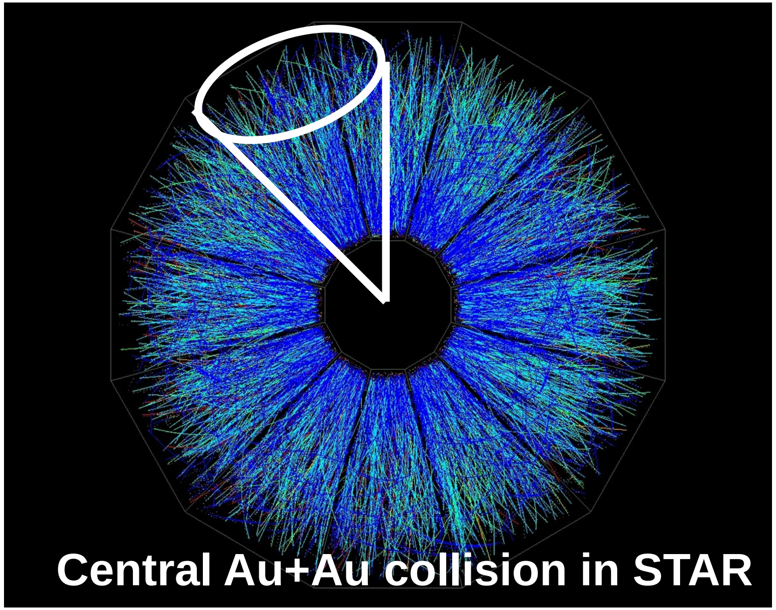
p+p → dijet



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

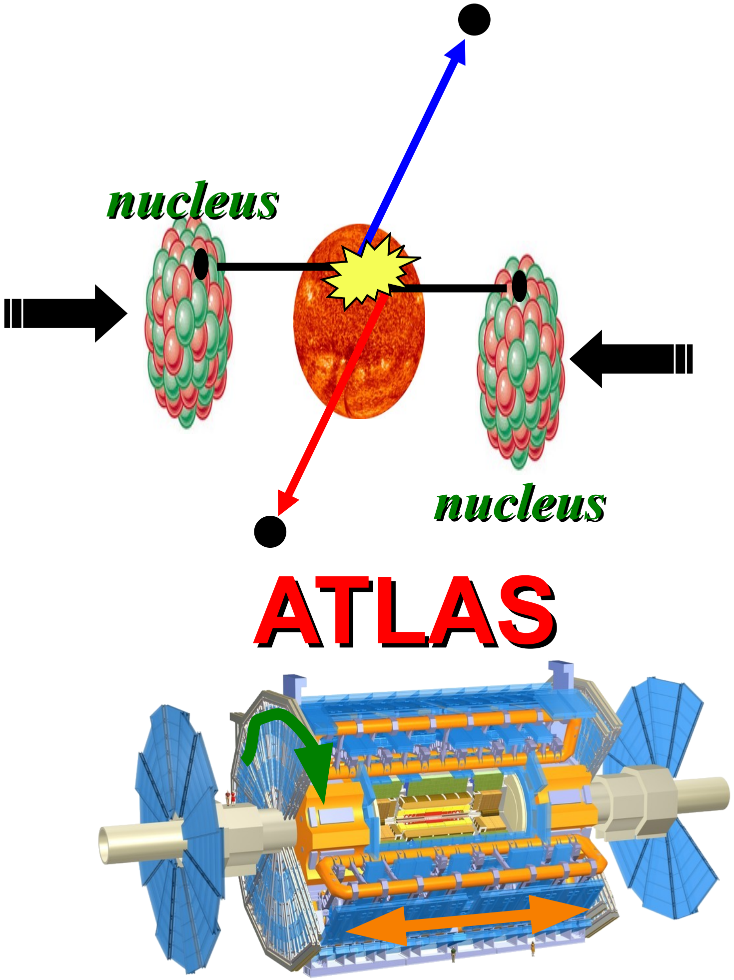
Jet reconstruction



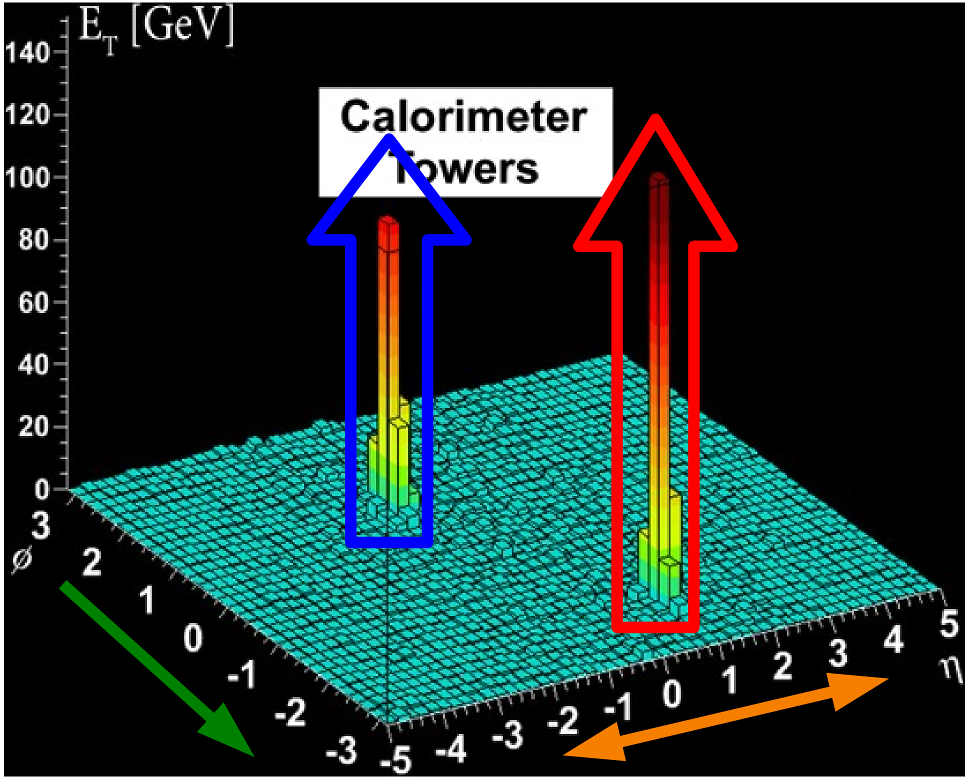


- Identify all of the particles in the jet → parton energy, momentum
- Difficult in heavy ion collisions – but possible!

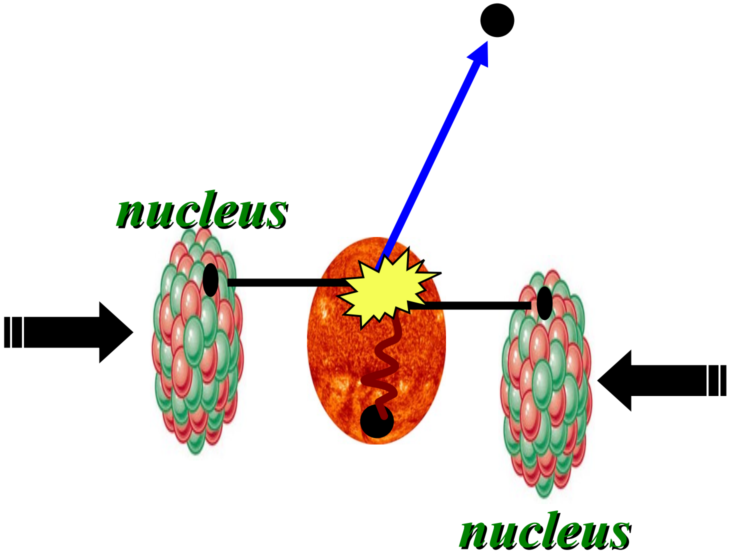
Jets

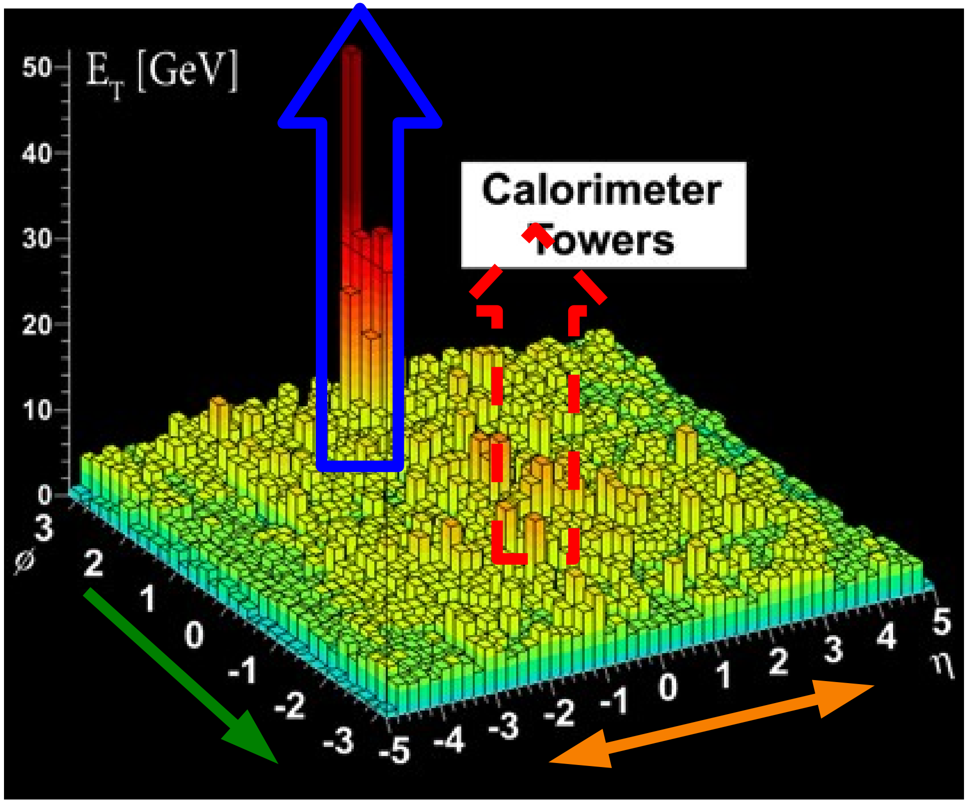


Phys.Rev.Lett. 105 (2010) 252303



Quenched jets

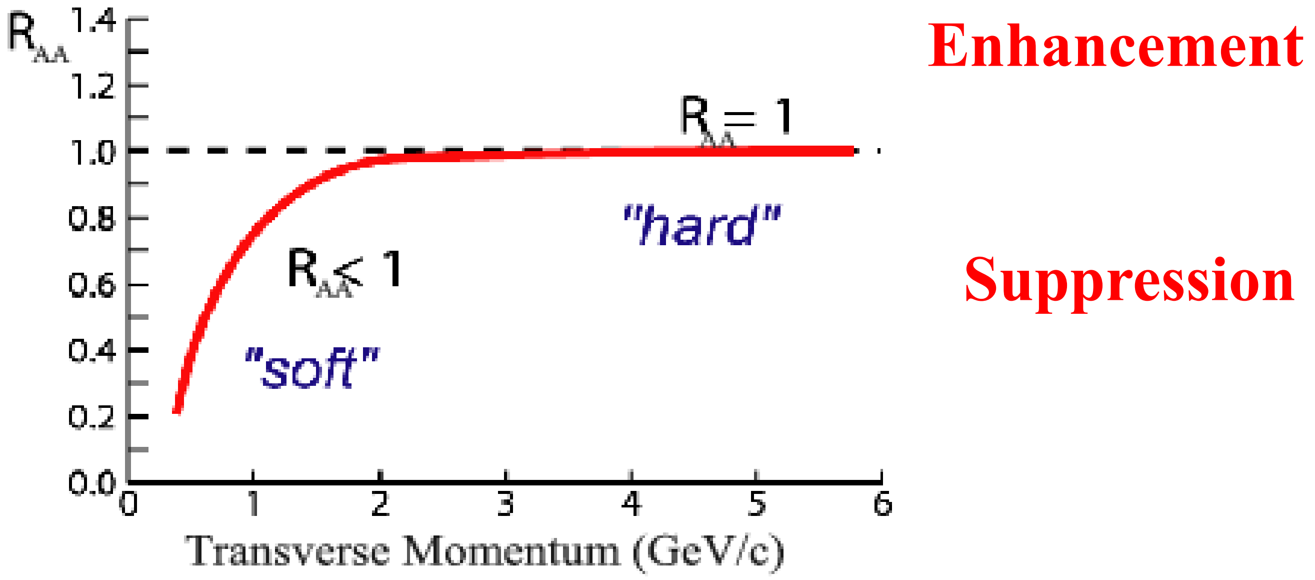




- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
- Phys. Rev. Lett. 105, 252303 (2010)

Nuclear modification factor

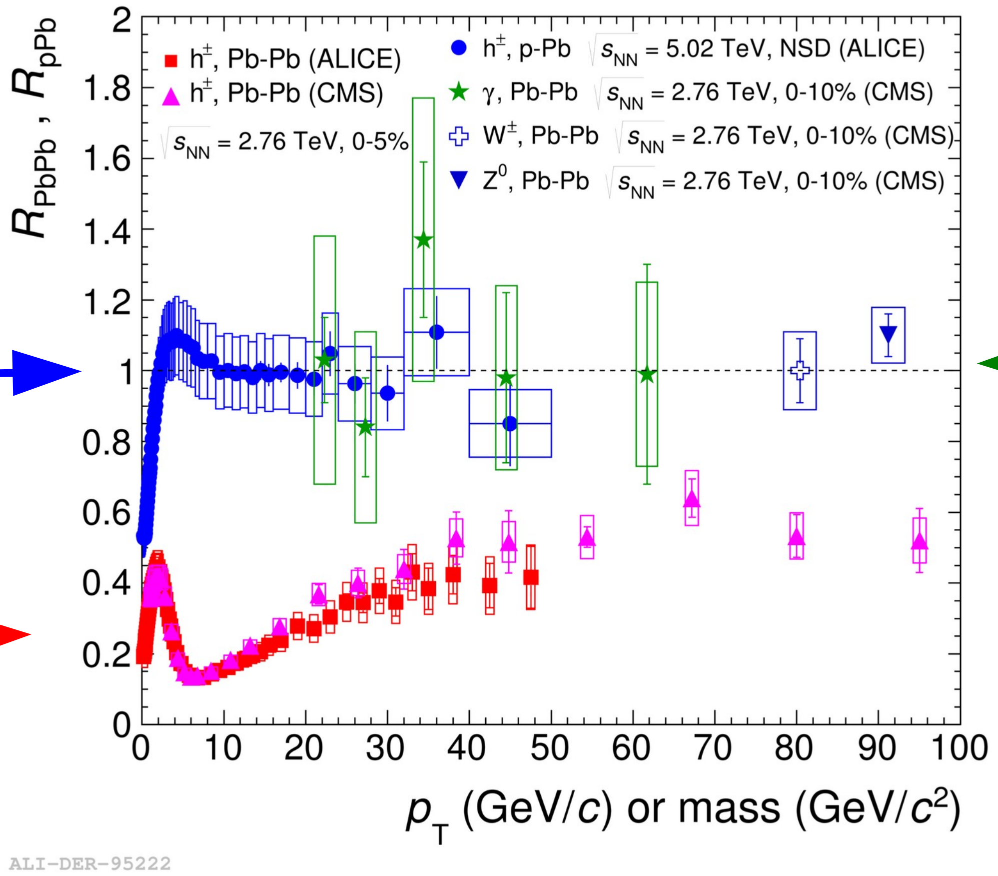
- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-p_T probes (jets) are suppressed, this is evidence of jet quenching



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

Nuclear modification factor

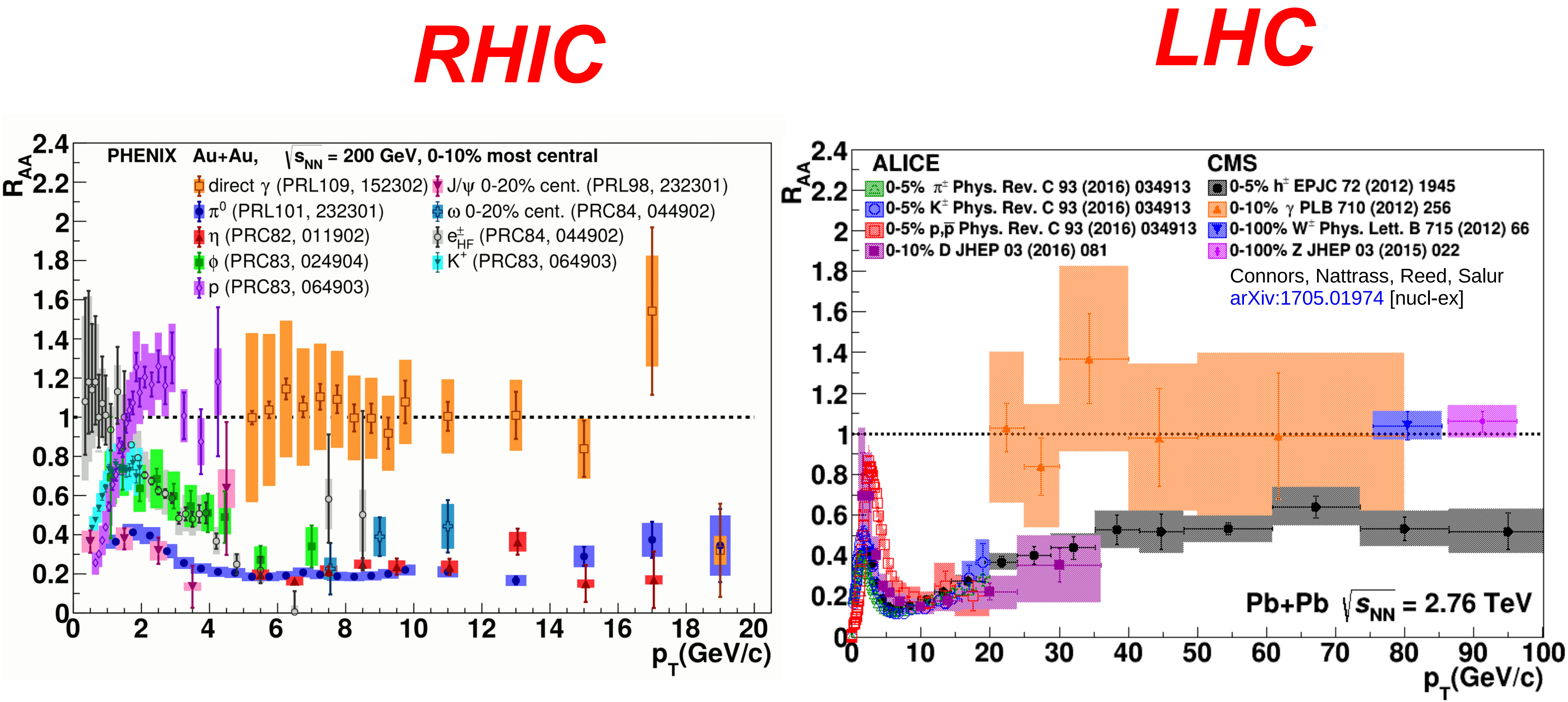
Control



Control

Probe

Nuclear modification factor R_{AA}

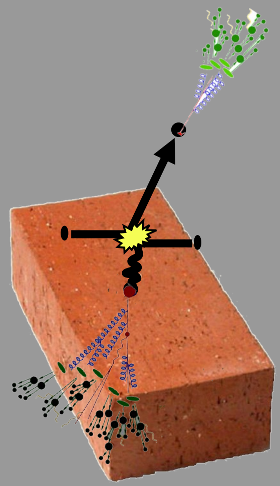


Electromagnetic probes – consistent with no modification – medium

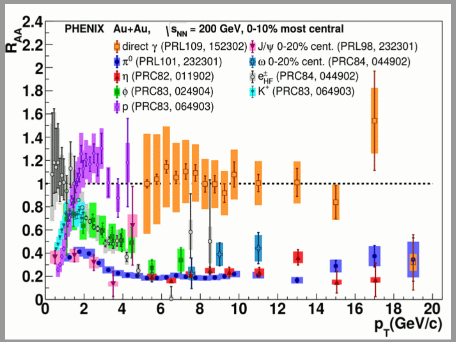
Towards quantitative understanding

JET collaboration

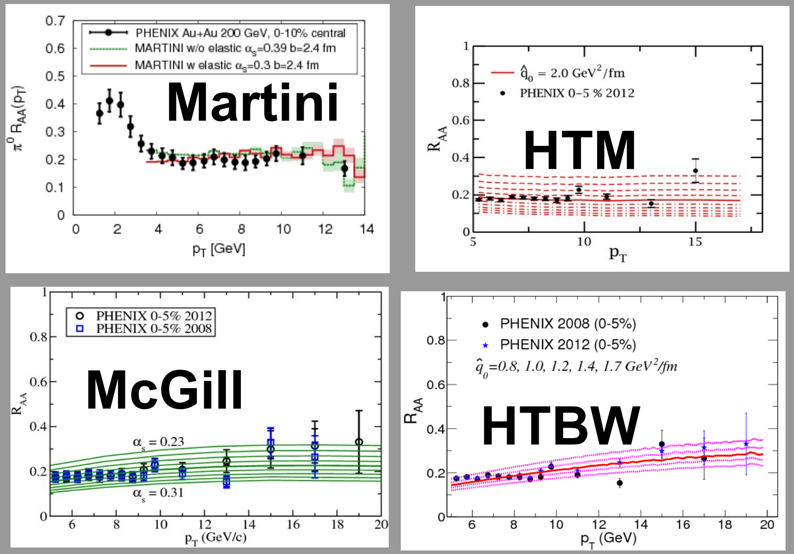
Phys. Rev. C 90, 014909 (2014)

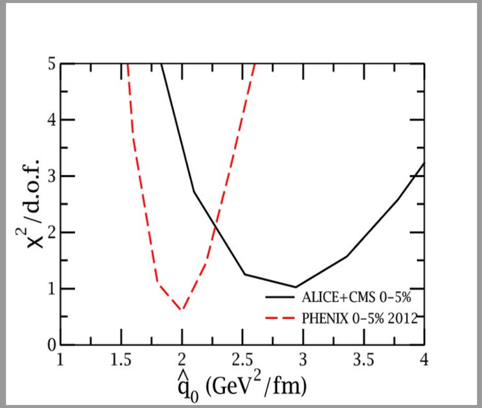


QGP brick + jet

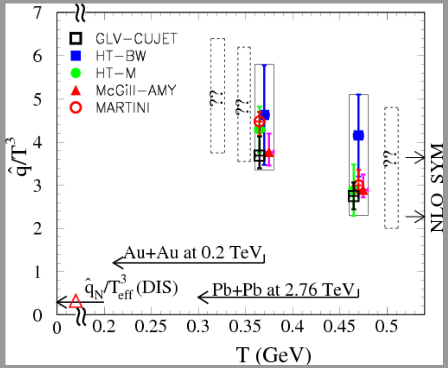


Data





χ^2 minimization



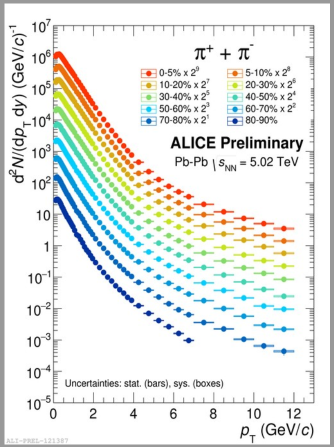
$\hat{q}=1.2\pm0.3\ \ GeV^2$ 200 GeV Au+Au

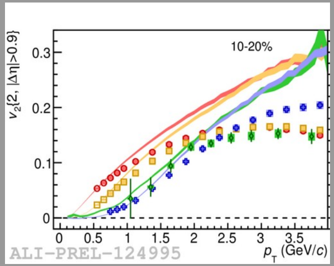
$\hat{q}=1.9\pm0.7\ \ GeV^2$ 2.76 TeV Pb+Pb

Bayesian Statistical Analysis

Models and Data Analysis Initiative

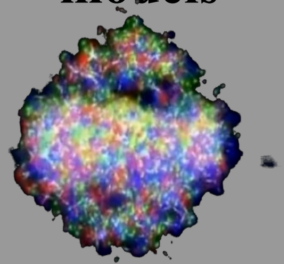
http://madai.us





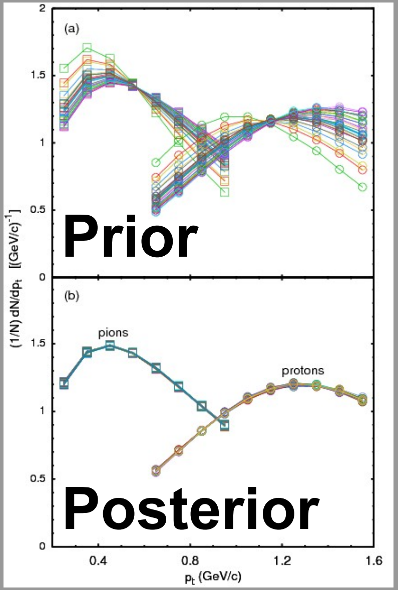
Data

Monte Carlo models

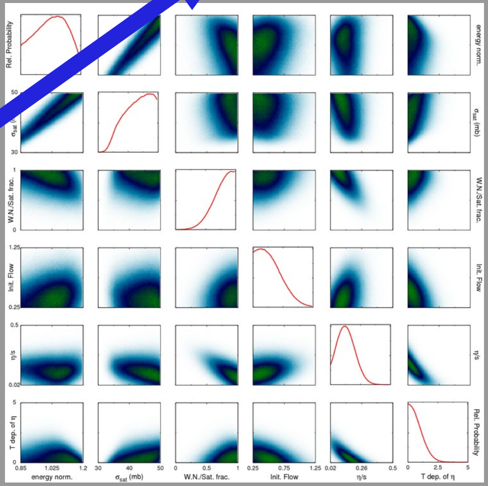


Model emulation

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



Optimization

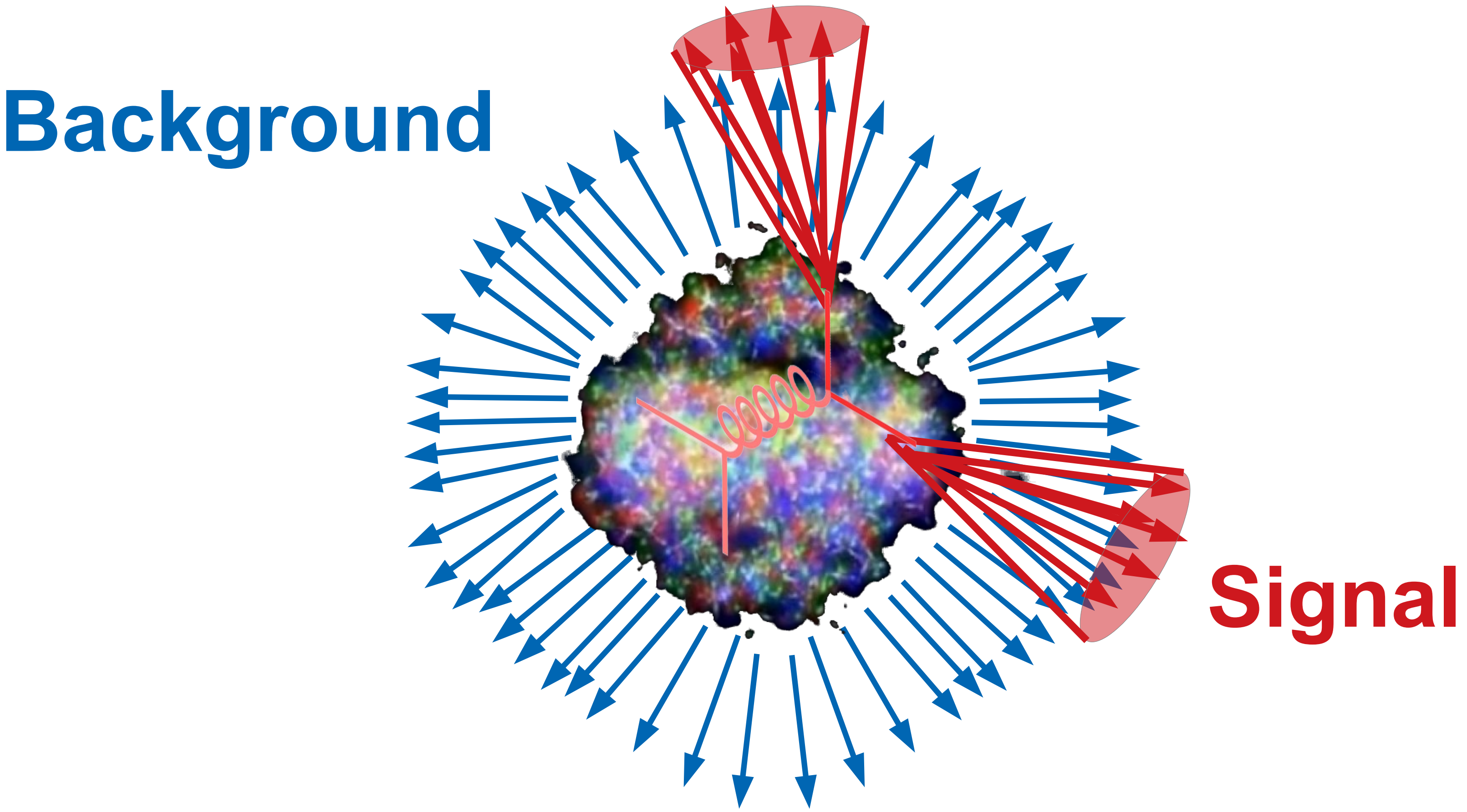


Constraint of QGP properties

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

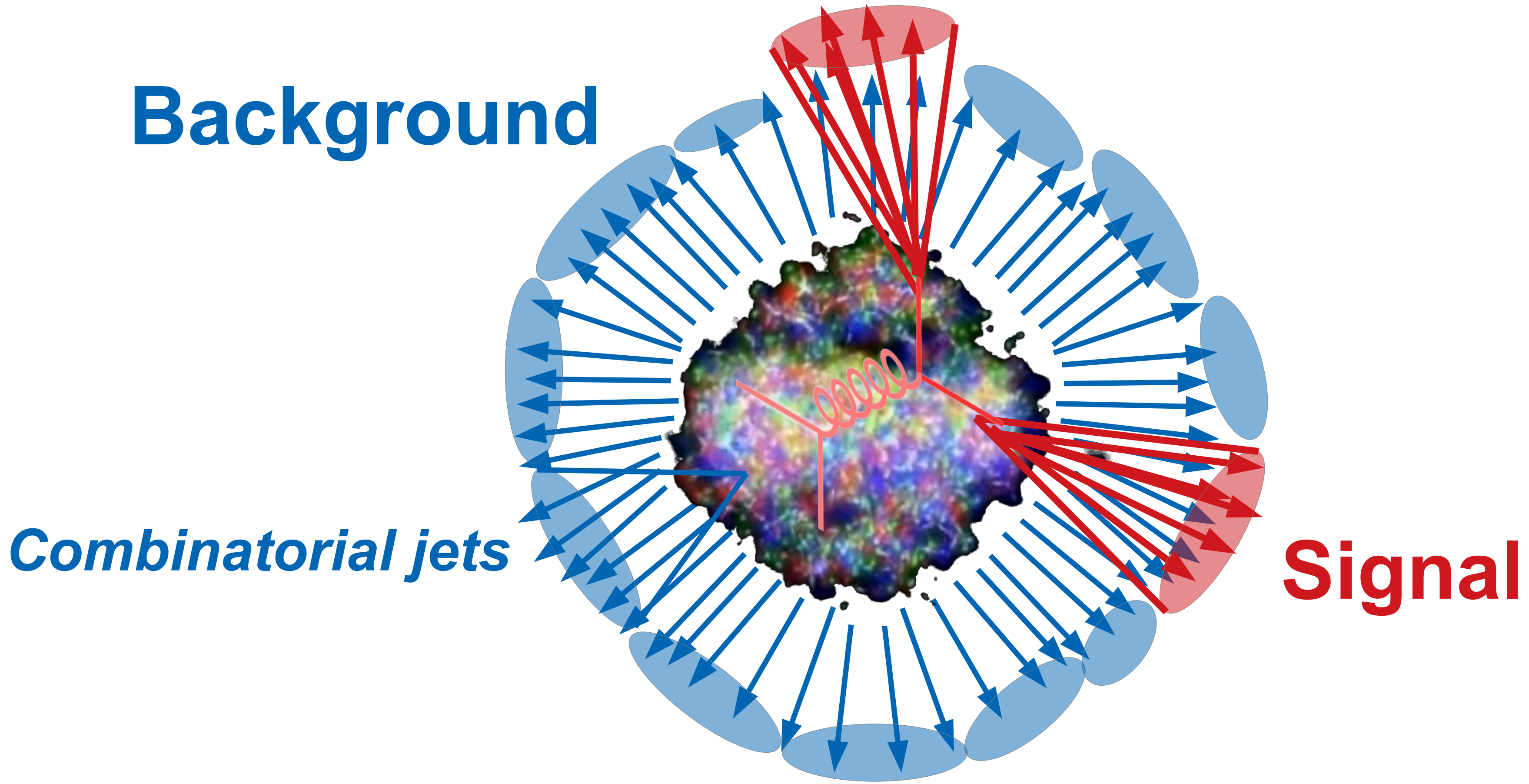
Signal vs Background:

The standard paradigm

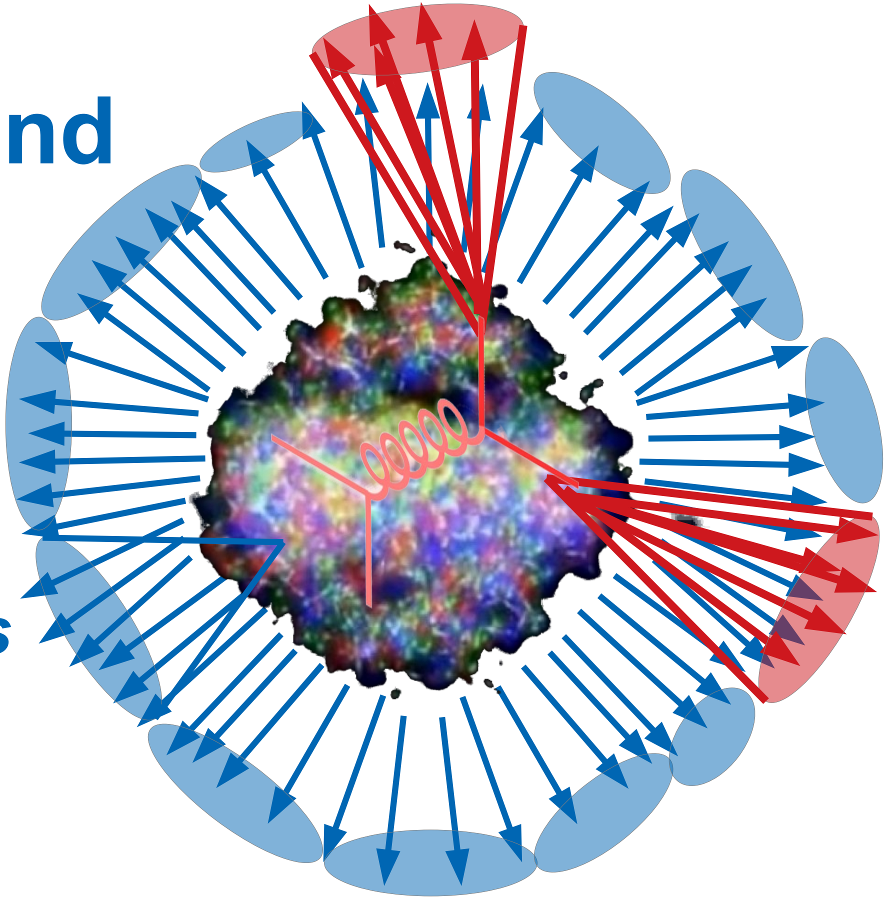


Signal vs Background:

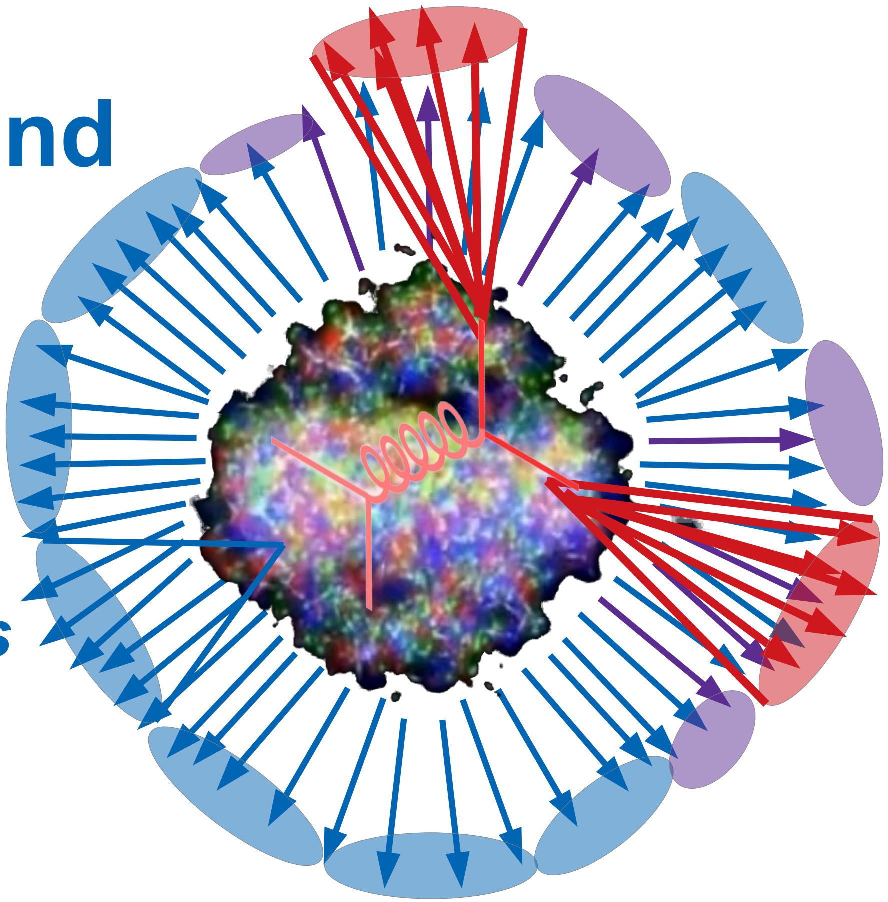
The standard paradigm



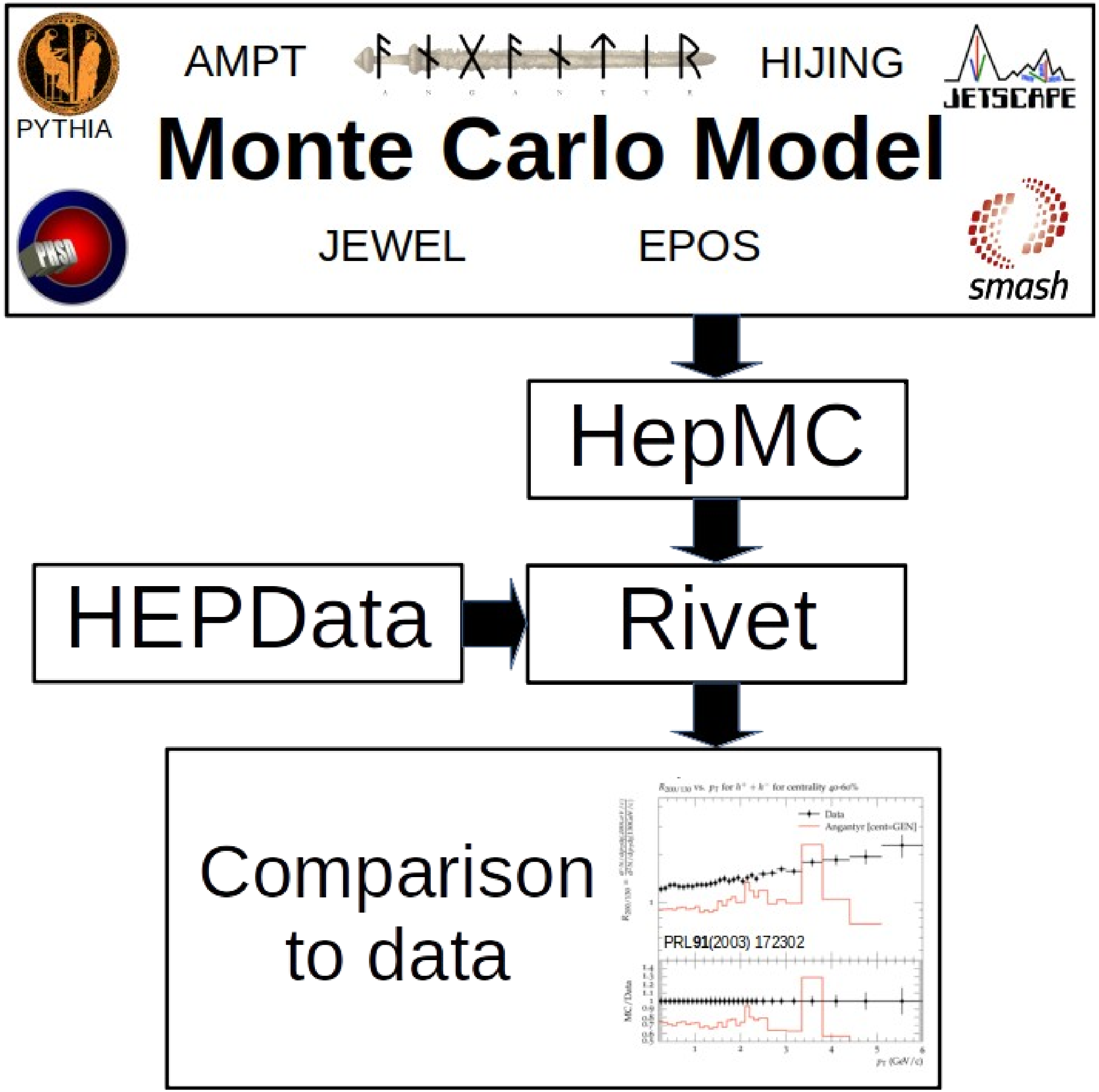
Signal vs Background:
The standard paradigm



Signal vs Background:
The standard paradigm



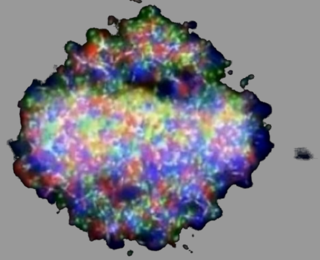
*Some gray areas


AMPT
HIJING
PYTHIA
JETSCAPE
Monte Carlo Model
JEWEL
EPOS
smash
HepMC
HEPData
Rivet
Comparison to data
Data
Angantyr [cent=GEN]
PRL91(2003) 172302

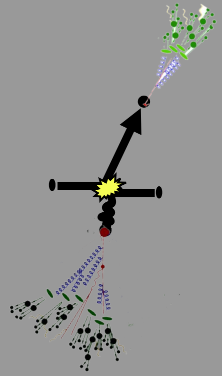
JETSCAPE Event generator

Jet **E**nergy-loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelope
http://jetscape.wayne.edu/

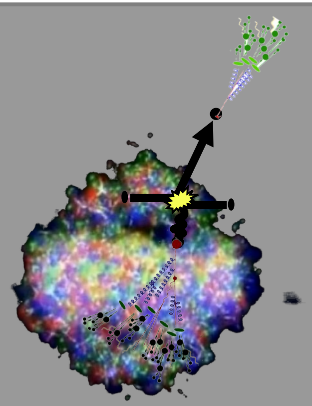
Realistic medium



Realistic jets



Realistic Monte Carlo Model

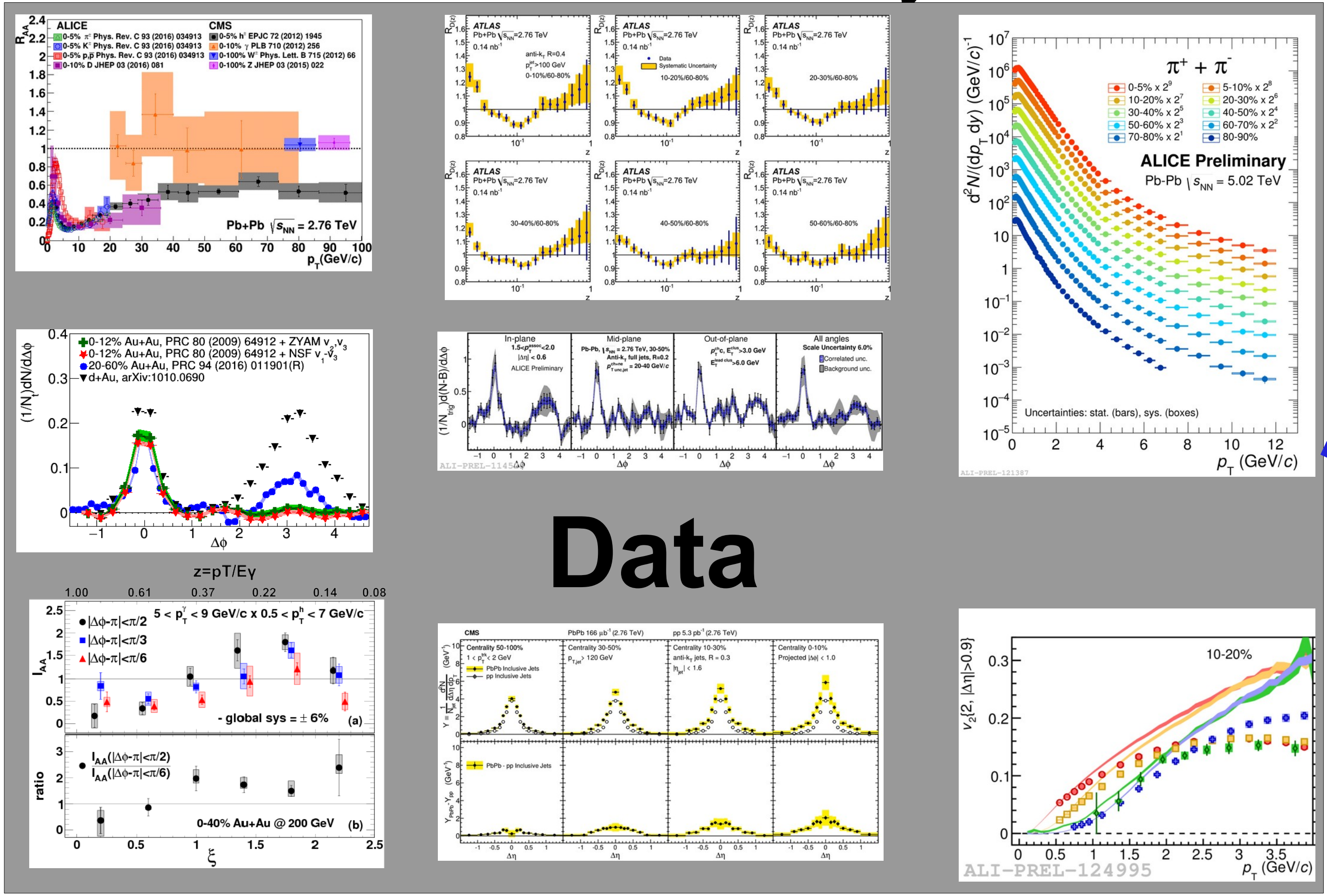


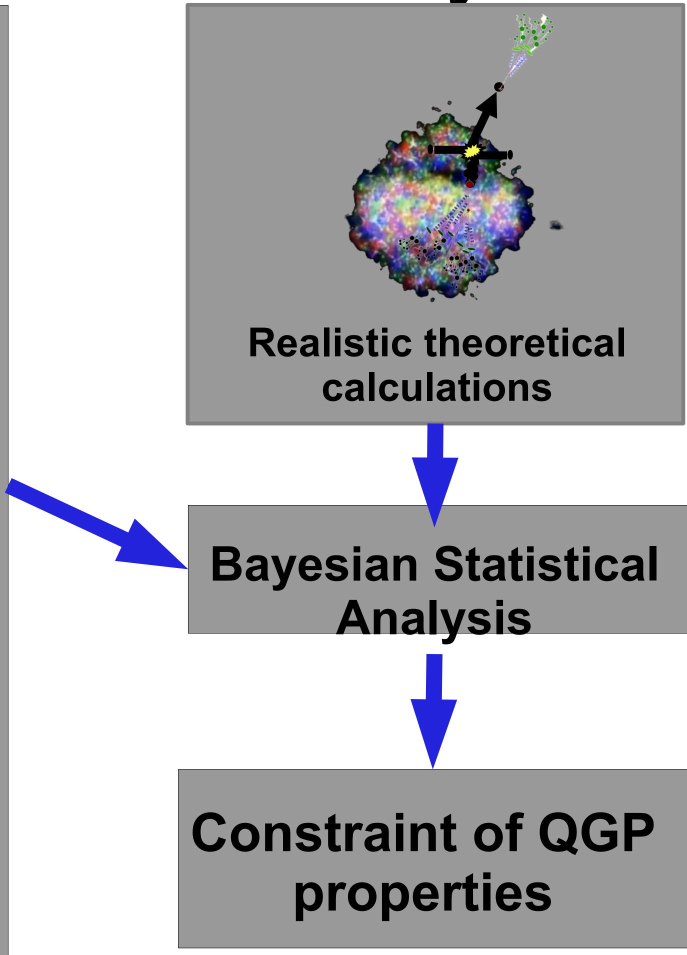
Experimental techniques

Realistic theoretical calculations

JETSCAPE

Event Generator + Bayesian Statistical analysis



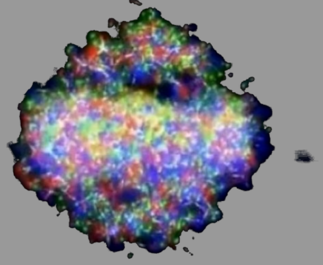


JETSCAPE Event generator

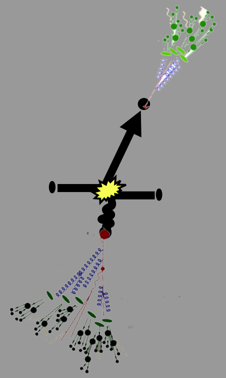
Jet **E**nergy-loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelope

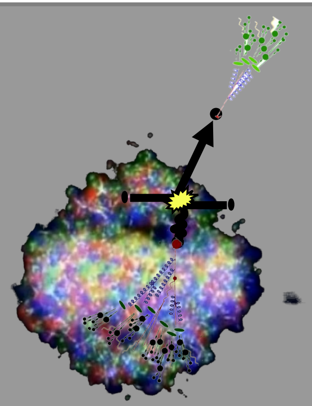
http://jetscape.wayne.edu/

Realistic medium



Realistic jets





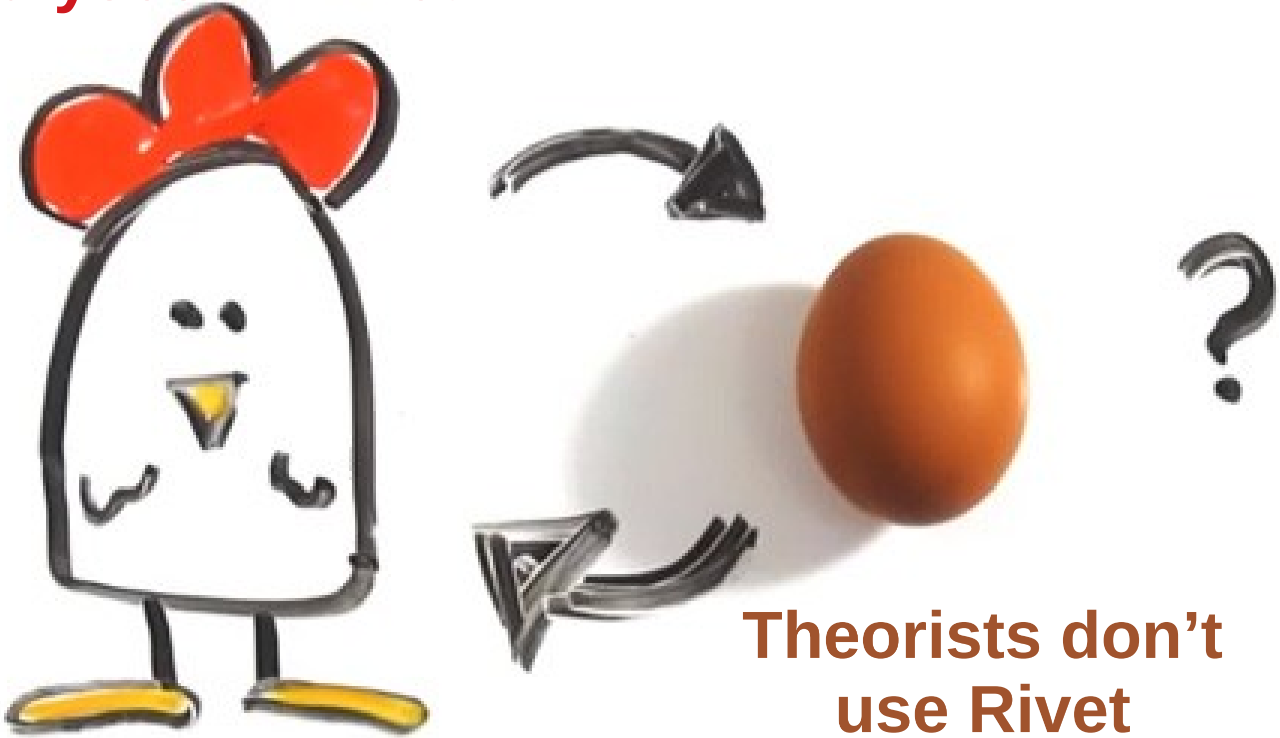
Realistic Monte Carlo Model

Experimental techniques

Realistic theoretical calculations

Works here

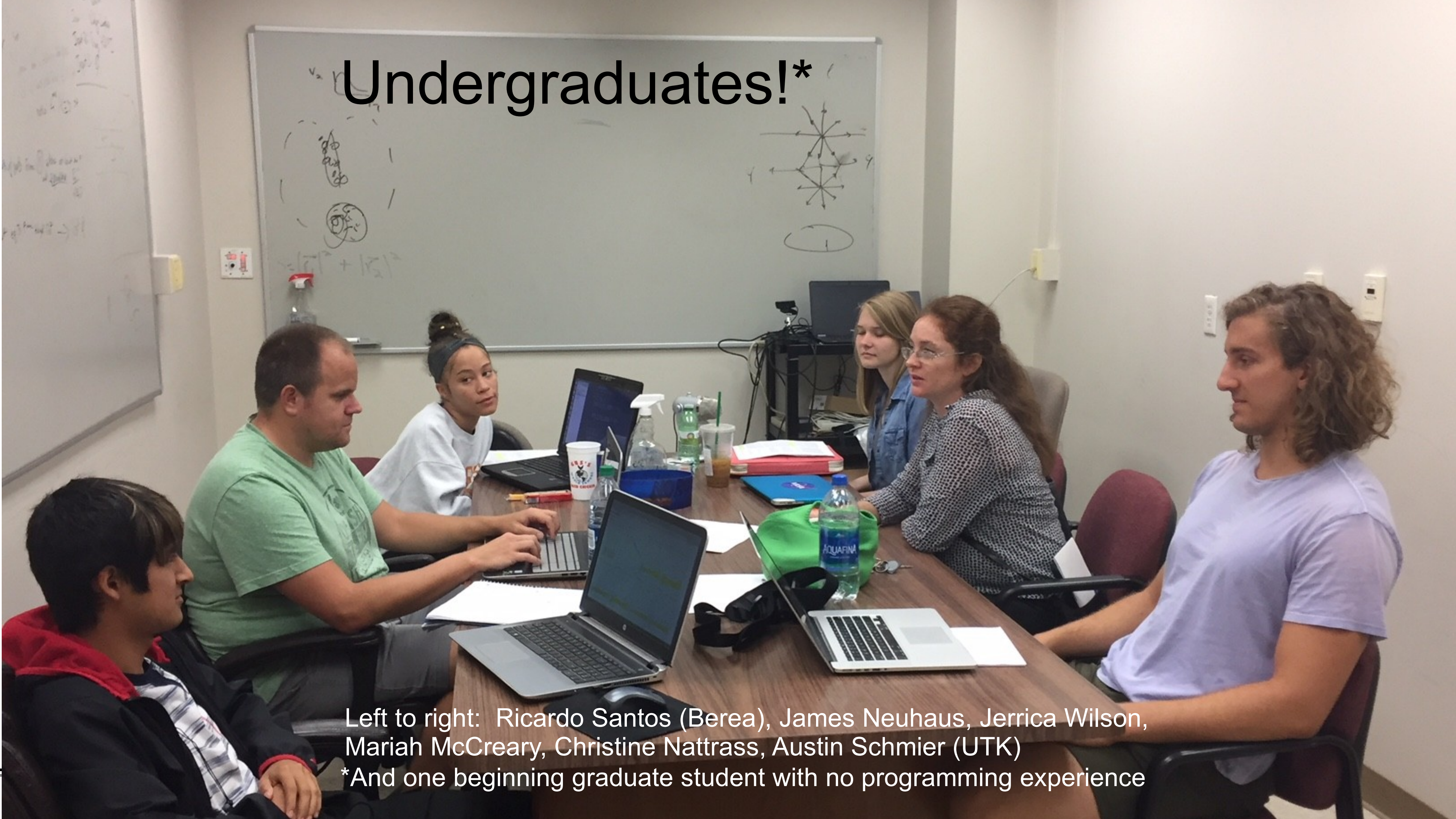
Few heavy ion analyses in Rivet



Theorists don't use Rivet

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

Undergraduates!*



Left to right: Ricardo Santos (Berea), James Neuhaus, Jerrica Wilson, Mariah McCreary, Christine Nattrass, Austin Schmier (UTK)

*And one beginning graduate student with no programming experience

Course-based undergraduate research experience

Ask me if you want more info!

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

Free Ac

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

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

Jennifer Knight, Monitoring Editor:

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

Sections View Article Tools Shai

Abstract

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

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

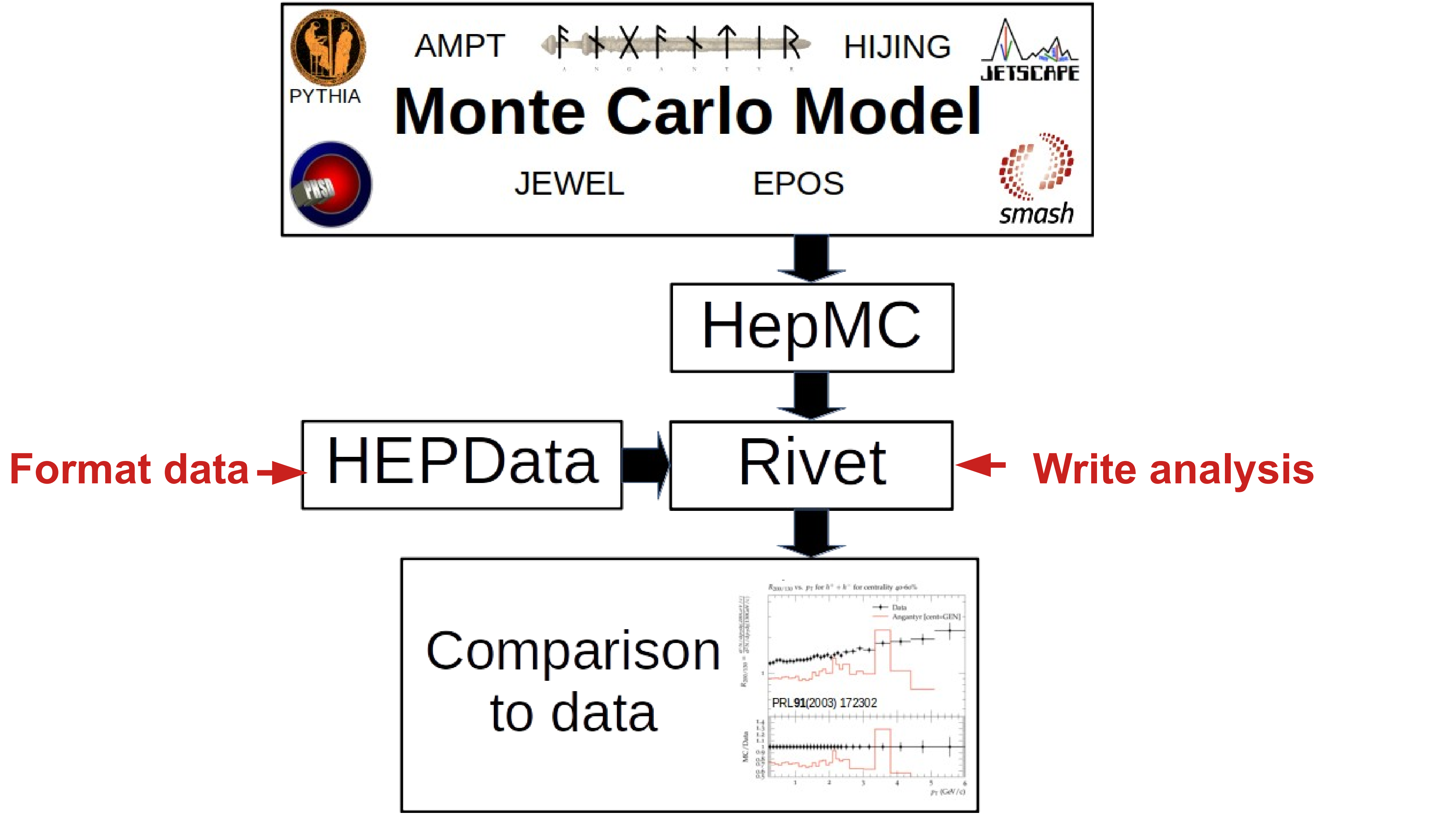
Instructor:
Dr. Christine Nattrass
Office: SERF 609
Phone: 974-6211
Email: christine.nattrass@utk.edu
Office hours: TBA

Teaching assistant: N/A

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

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

3 semesters	**All Rivet students**
15 students	22 students
8 women	11 women
3 minorities	7 minorities
3 non-traditional	4 non-traditional


PYTHIA
AMPT
HIJING
JETSCAPE
Monte Carlo Model
JEWEL
EPOS
smash
HepMC
Format data
HEPData
Rivet
Write analysis
Comparison to data
Data
Angantyr [cent=GEN]
PRL 91(2003) 172302

Skills

- Overview of high energy nuclear physics and how particle detectors work
- Read a technical paper and understand it well enough to implement an analysis
- Work well in a group where you are evaluated by the group's success
- Proficiency with the command line
- Write a piece of code in C++
- Code management with git
- Write a paper in latex
- Give a presentation

Keys to success

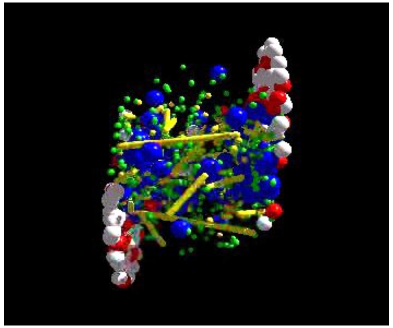
- The right project
  - High physics emphasis, few prerequisite skills
  - Useful output for the PI
  - Low cost for project failure
  - Not time-sensitive
  - Feasible in ~135 hours
- Diverse group of student skills, levels
- Previous PI experience supervising UG research
  - Especially on the topic of research

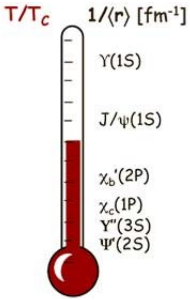
Diversity

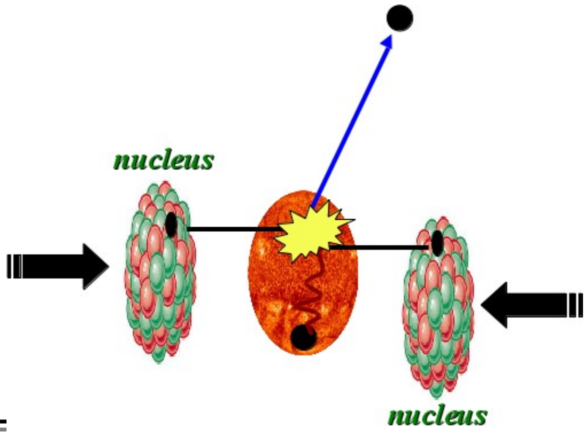
- Results definitely sensitive to the instructor
- Provides easy access to research
- Lowers effort/student to supervising undergraduates
  - Allows C students to demonstrate skills
  - Develops faculty connections to students

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.
- Build your own undergraduate army!







More information

- Introductory lectures on the QGP
- Overview of jets in heavy ion collisions
- My syllabus