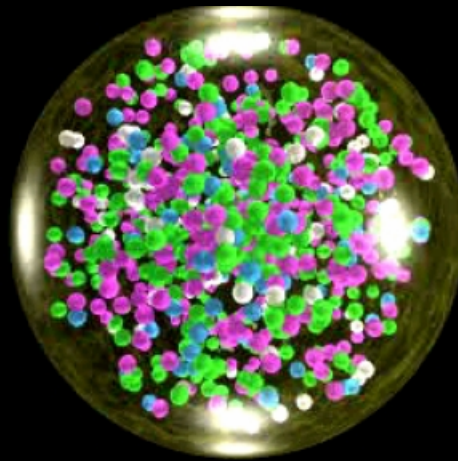
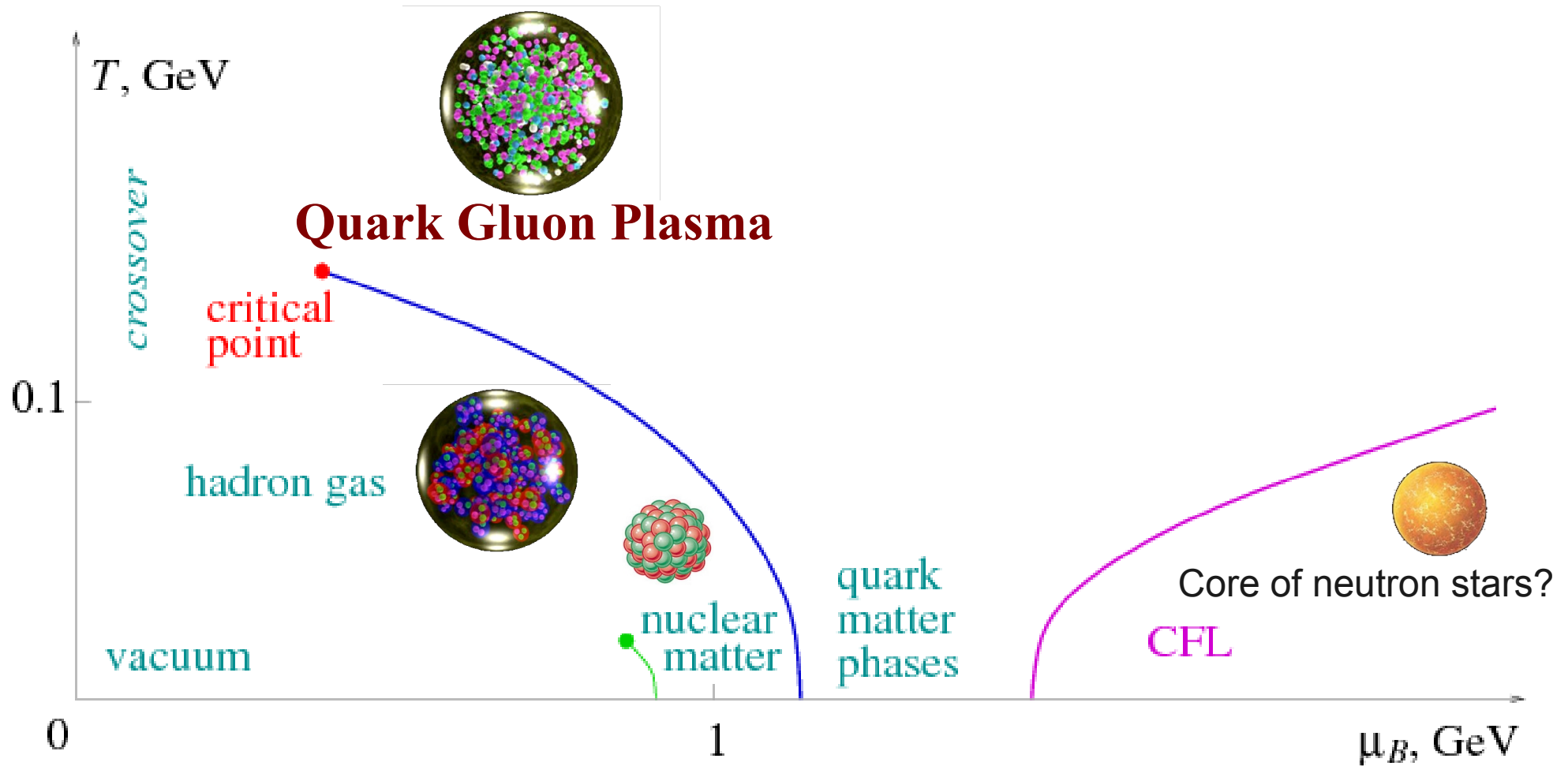


*The little bang: understanding  
the quark gluon plasma*



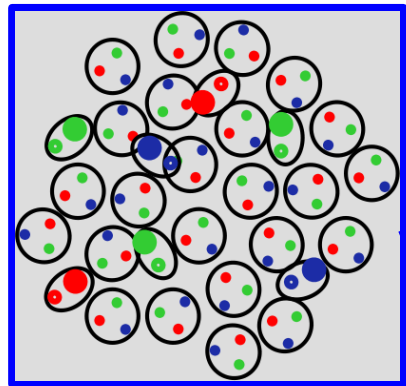
*Christine Nattrass  
University of Tennessee at Knoxville*

# Phase diagram of nuclear matter

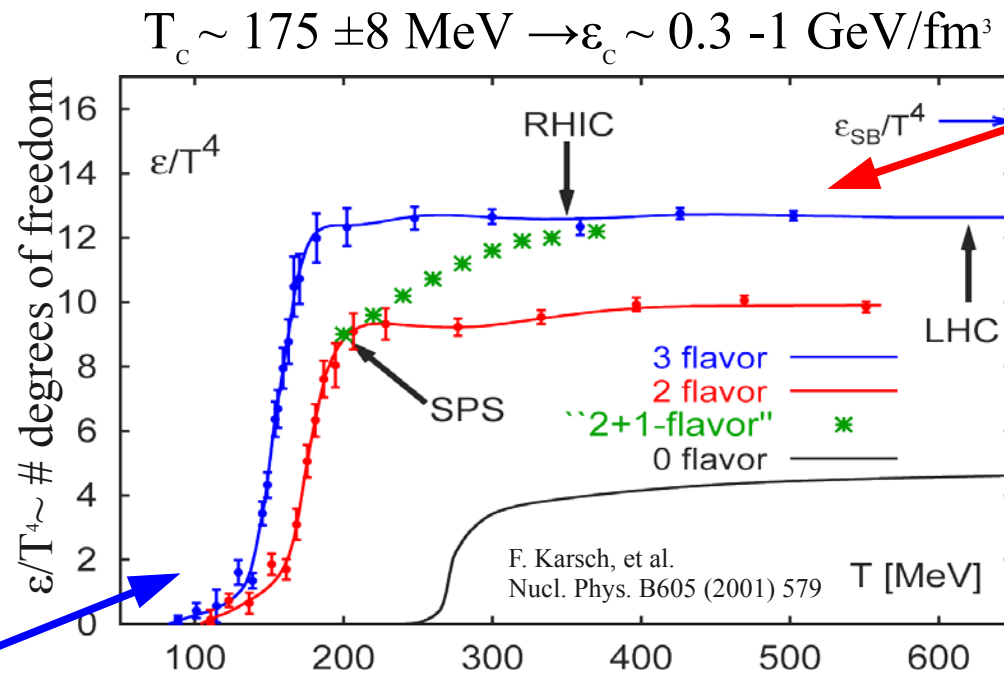


**Quark Gluon Plasma** – a *liquid* of quarks and gluons created at temperatures above  $\sim 170$  MeV ( $2 \cdot 10^{12}$  K) – over a million times hotter than the core of the sun

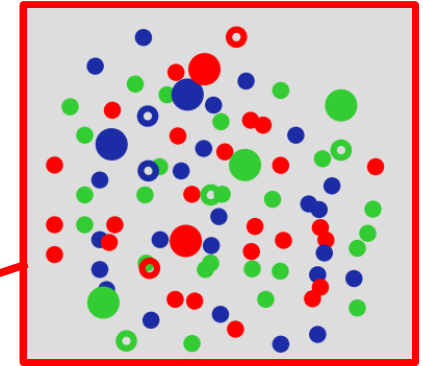
# Exploring QCD at high temperatures



Confined - fewer degrees of freedom

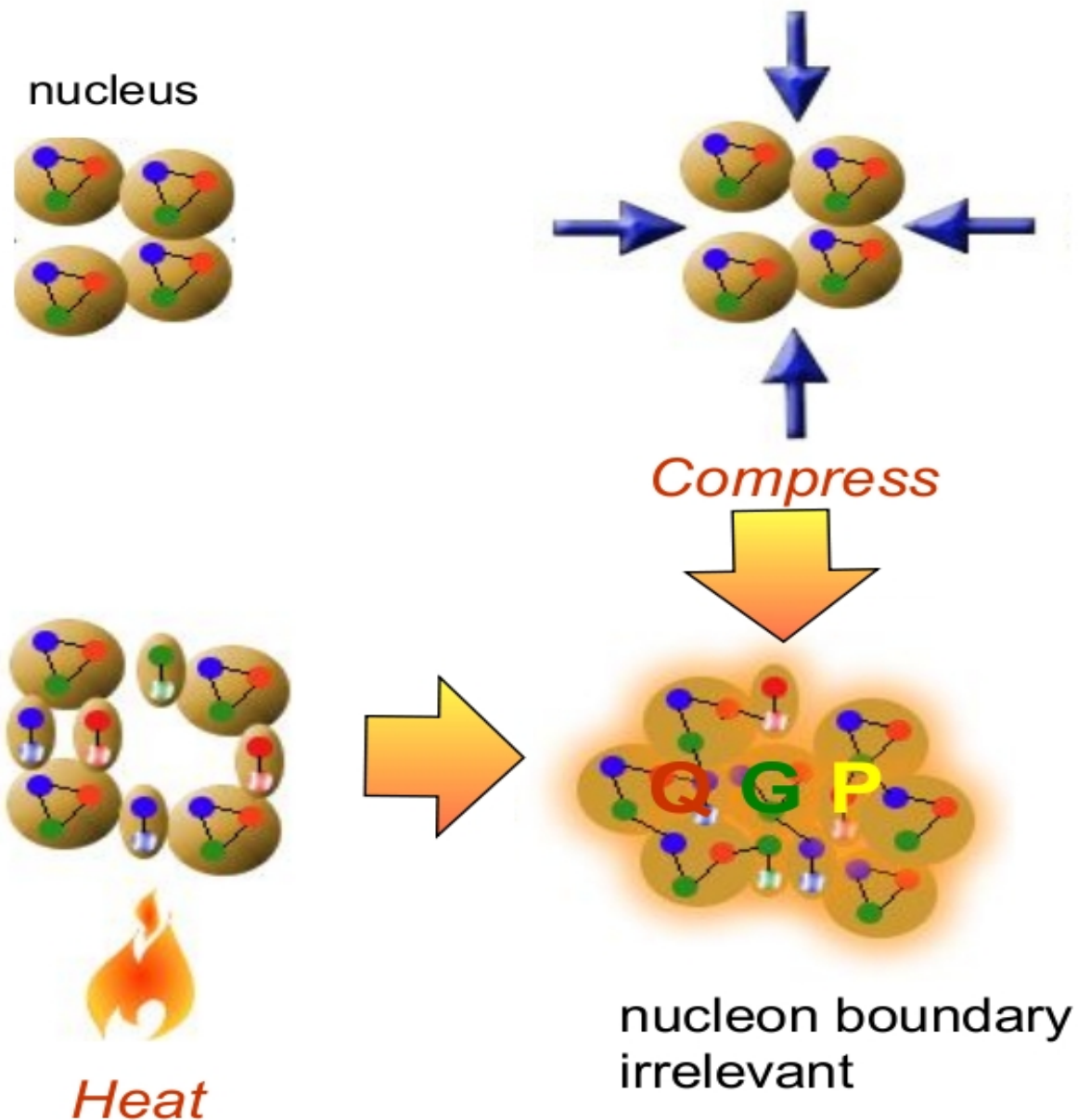


Quark-gluon plasma

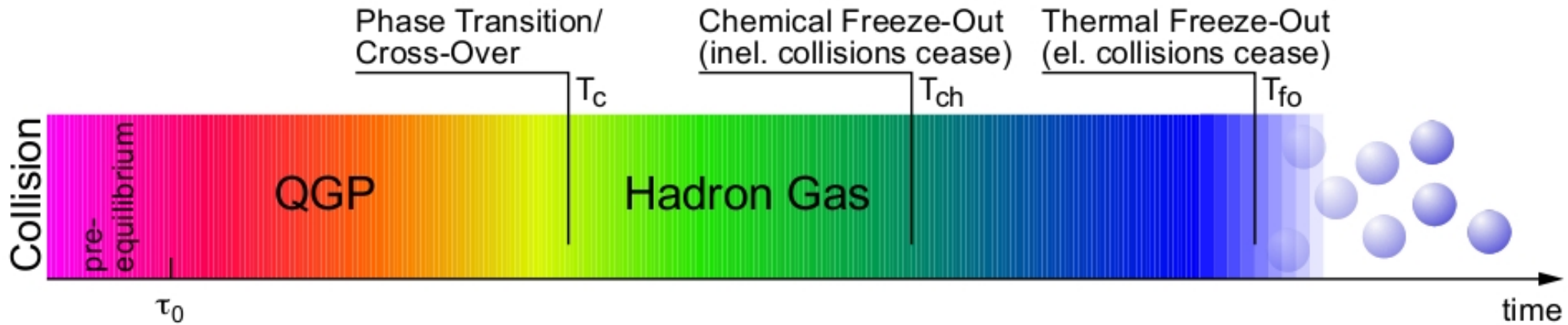
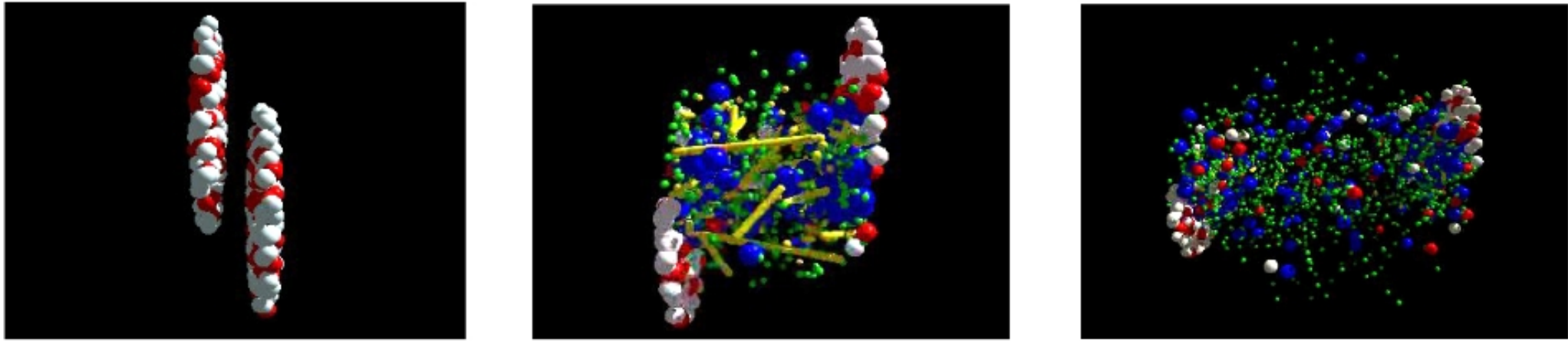


Deconfined - more degrees of freedom

# How to make a Quark Gluon Plasma



# The phase transition in the laboratory



# Relativistic Heavy Ion Collider

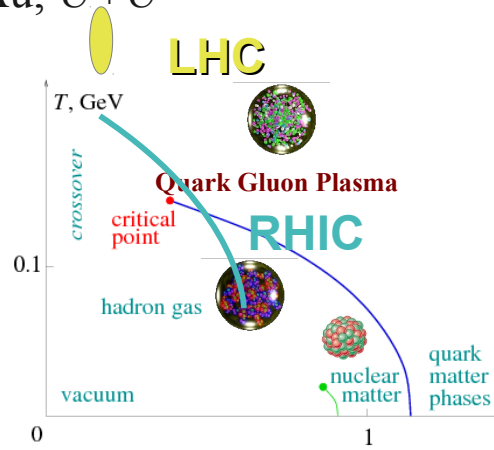


Upton, NY

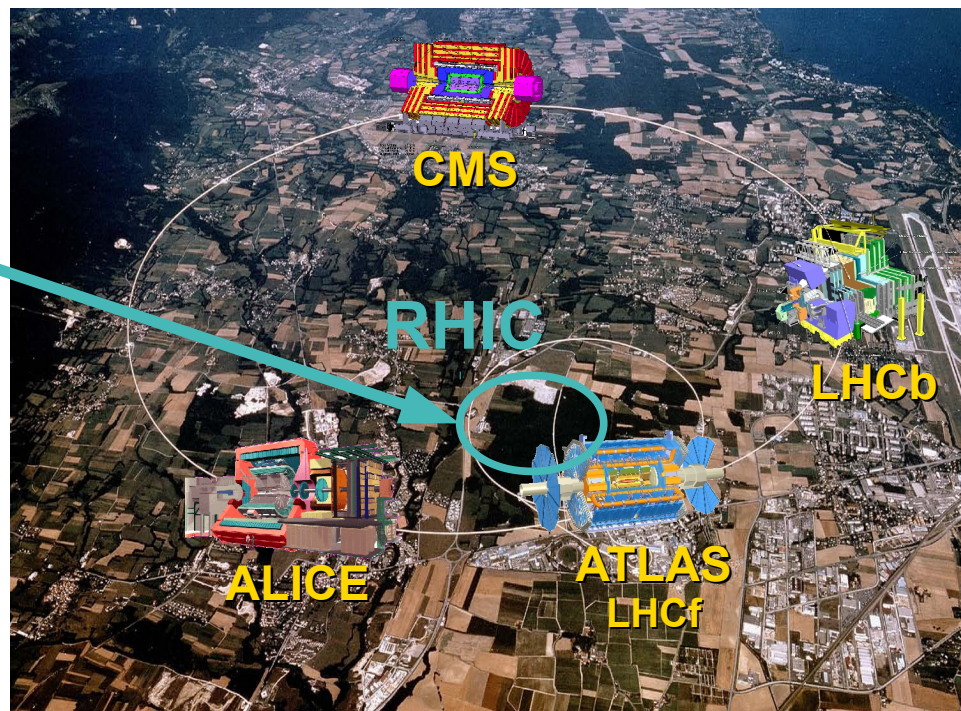
1.2km diameter

p+p, d+Au, Cu+Cu, Au+Au, U+U

$\sqrt{s}_{NN} = 9 - 200 \text{ GeV}$



# Large Hadron Collider



Geneva, Switzerland

8.6km diameter

p+p, p+Pb, Pb+Pb

$\sqrt{s}_{NN} = 2.76 \text{ GeV}, 5.5 \text{ TeV}$

# Comparison of colliders

	<b>RHIC</b>	<b>LHC</b>	
$\sqrt{s}_{\text{NN}}$ (GeV)	9-200	2760, 5500	<i>center of mass energy</i>
$dN_{\text{ch}}/d\eta$	$\sim 1200$	$\sim 1600, ??$	<i>number of particles</i>
$T/T_c$	1.9	3.0-4.2	<i>temperature</i>
$\varepsilon$ (GeV/fm <sup>3</sup> )	5	$\sim 15$	<i>energy density</i>
$\tau_{\text{QGP}}$ (fm/c)	2-4	$>10$	<i>lifetime of QGP</i>

## RHIC and LHC:

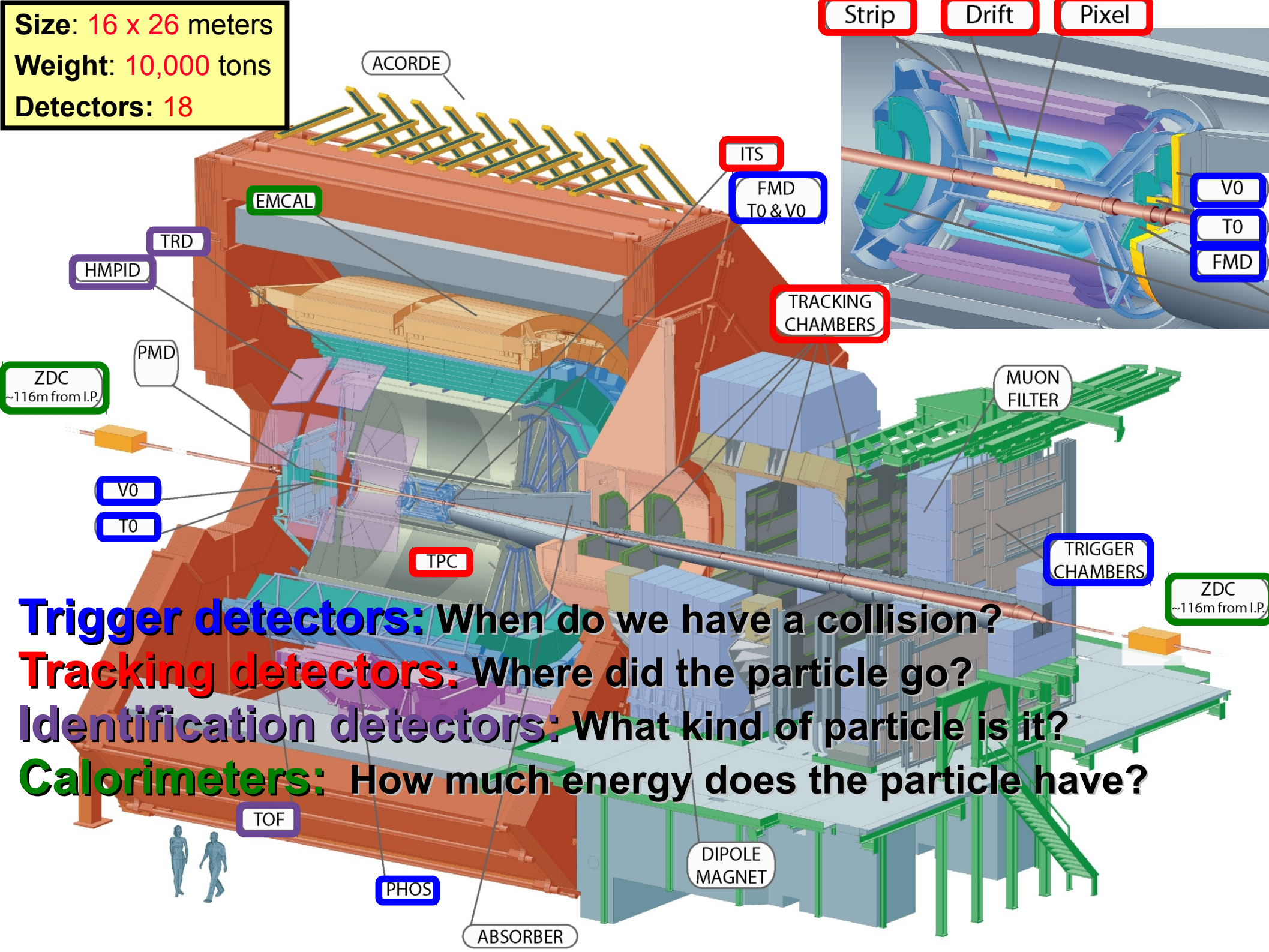
Cover 2 –3 decades of energy ( $\sqrt{s}_{\text{NN}} = 9 \text{ GeV} - 5.5 \text{ TeV}$ )

To discover the properties of hot nuclear matter at  $T \sim 150 - 600 \text{ MeV}$

# Interesting observables

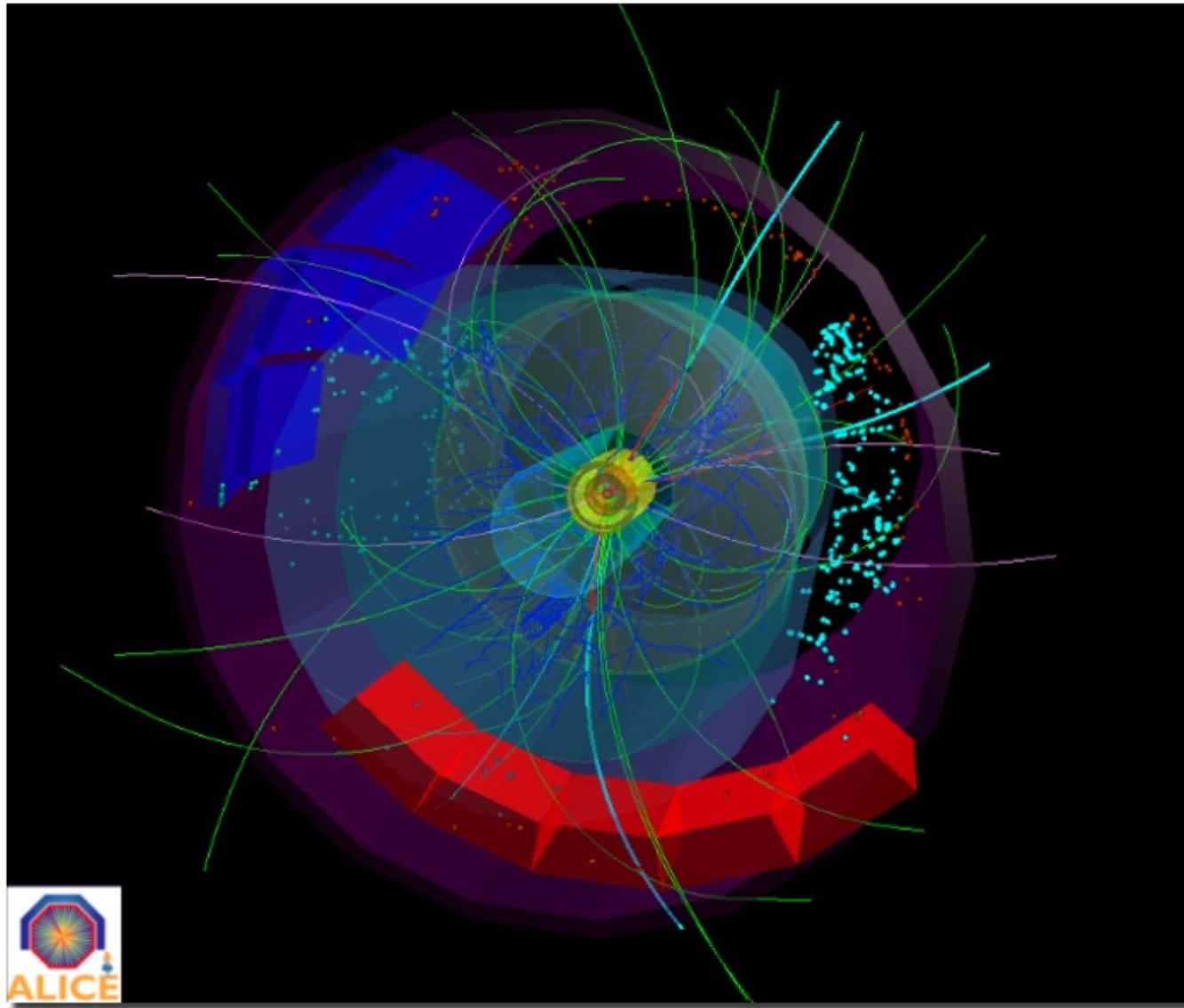
- Different hadronization mechanisms
  - Identify particle types
- Collective motion of particles
  - Low momentum acceptance
- Even common processes are not well understood
  - Do not need  $4\pi$  acceptance or high rates

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



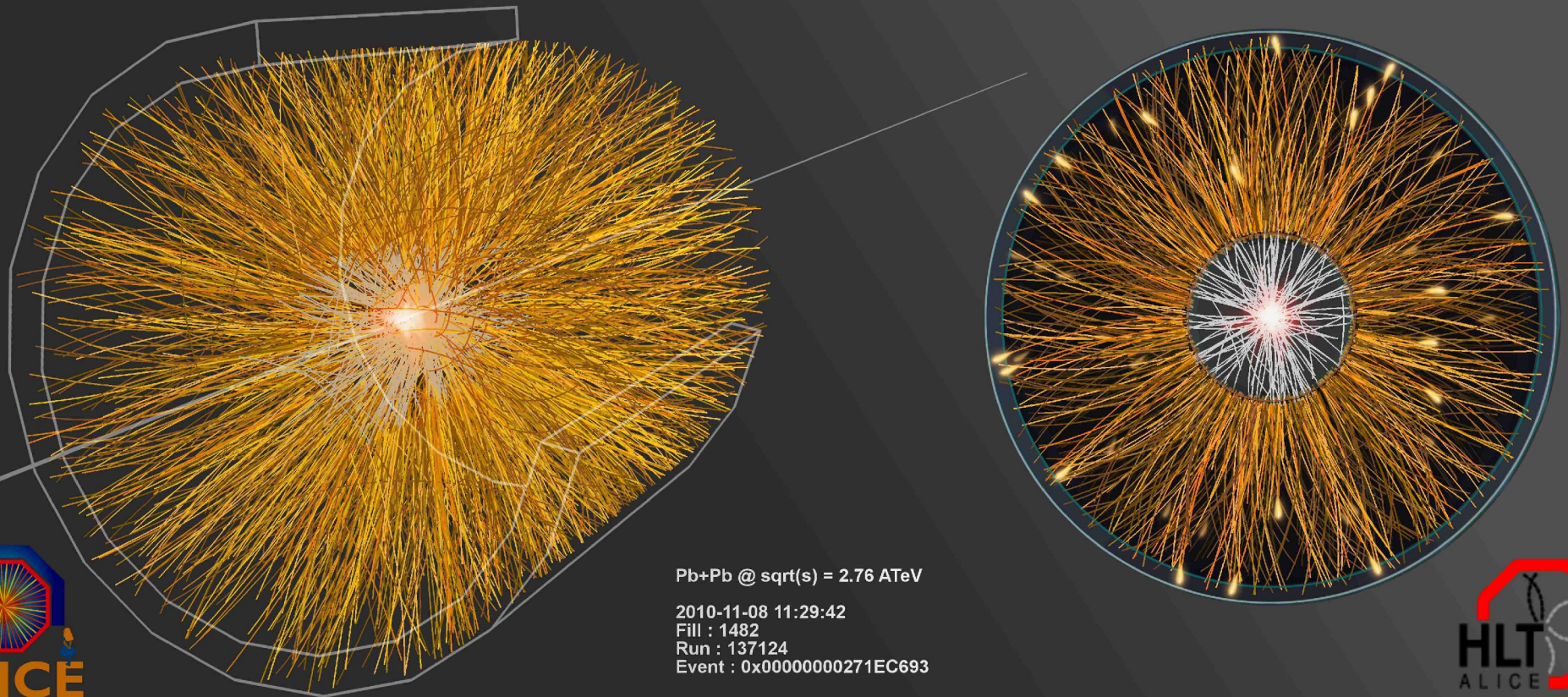
**Trigger detectors:** When do we have a collision?  
**Tracking detectors:** Where did the particle go?  
**Identification detectors:** What kind of particle is it?  
**Calorimeters:** How much energy does the particle have?

# p+p collisions



**3D image of each collision**

# Pb+Pb collisions



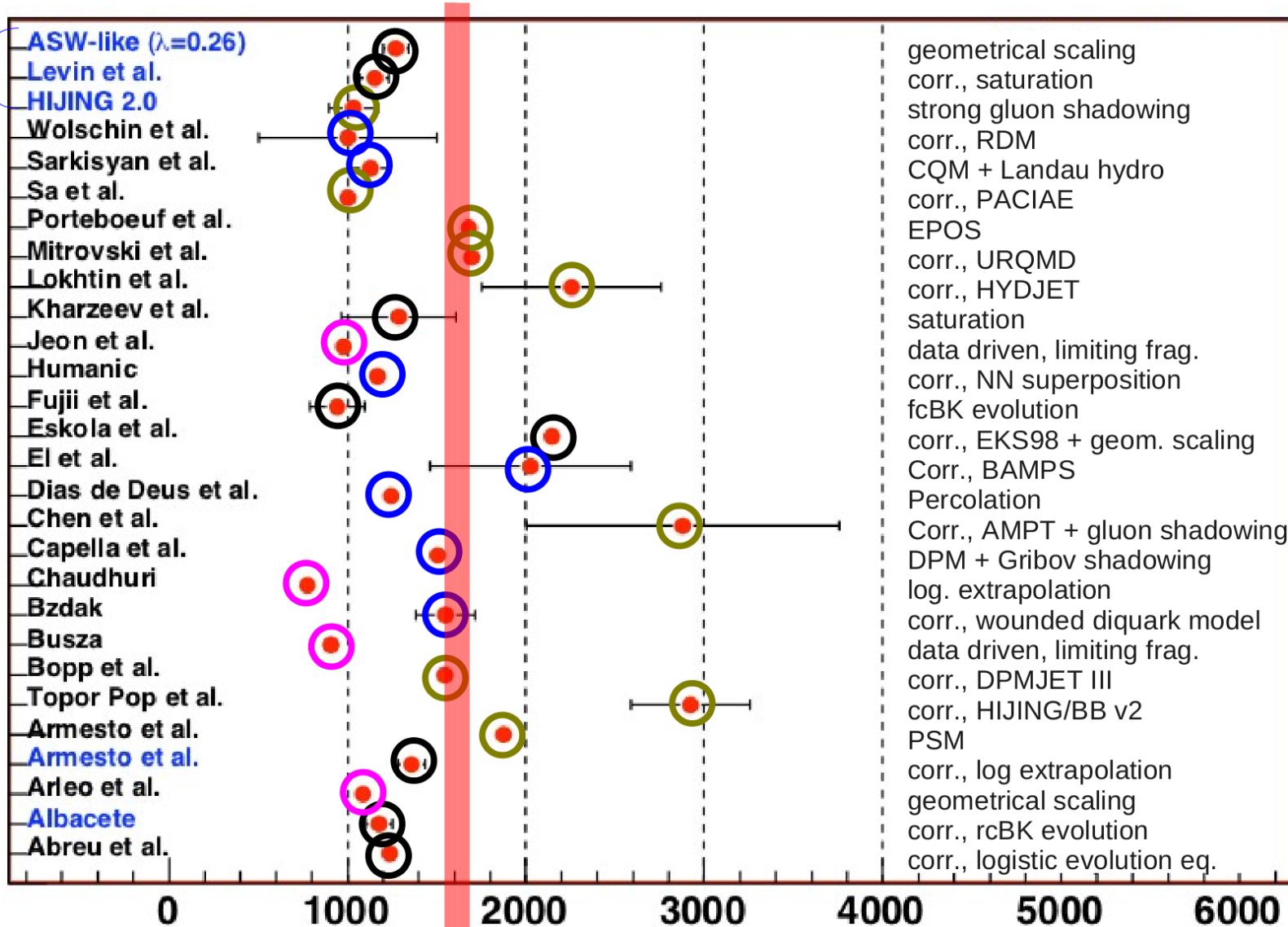
contactniko@yahoo.de  
agelek13@gmail.com  
NIKOS EMMANOULIDIS  
AGELEKI MANTA

# Multiplicity in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV

Measured  $dN_{ch}/d\eta = 1584 \pm 76$  (sys.)

PRL, 105, 252301 (2010)

Post-pp



Monte Carlo, coherence via collectivity, strong gluon saturation

Saturation ideas

Data driven, limiting frag.

Miscellaneous: superposition, WNM, diffusion eqs., DPM + shadowing/percolation

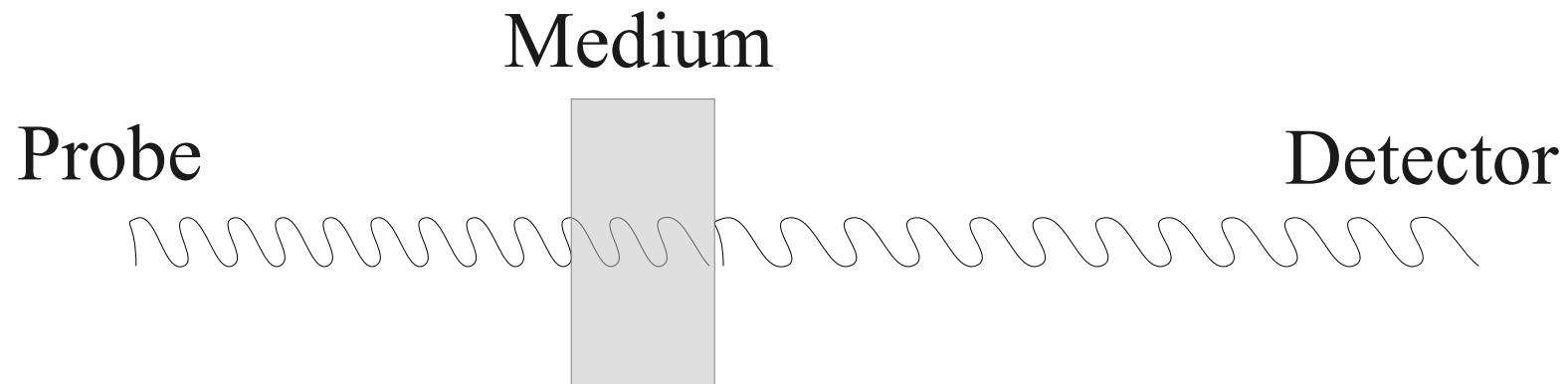
Compilation from N. Armesto

# How do we study a QGP?

<b>Tool</b>	<b>Analogous to:</b>
Thermal photons, charmonium	Thermometer
Hard probes – jets, heavy flavor (charm & beauty), direct photons	Spectroscopy – probe travels through the medium, changes indicate interaction with the medium
Hydrodynamical flow	Measurements of viscosity
Particle ratios	Measuring chemical composition in a solution

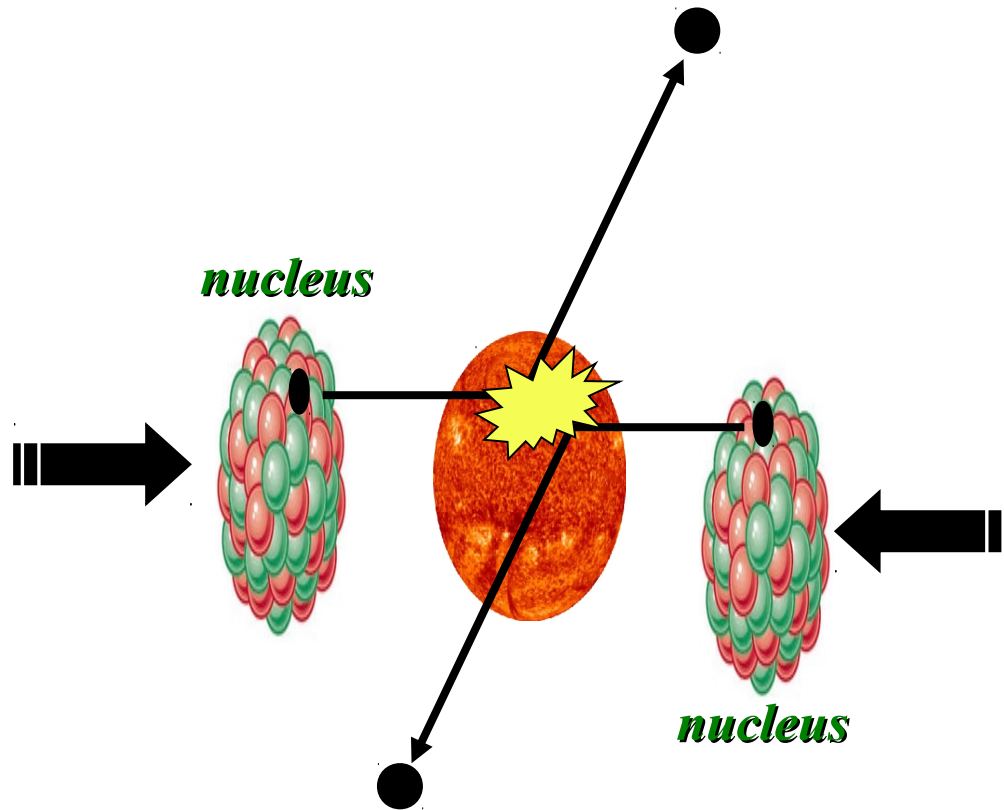
# Hard probes

# Probing the Quark Gluon Plasma



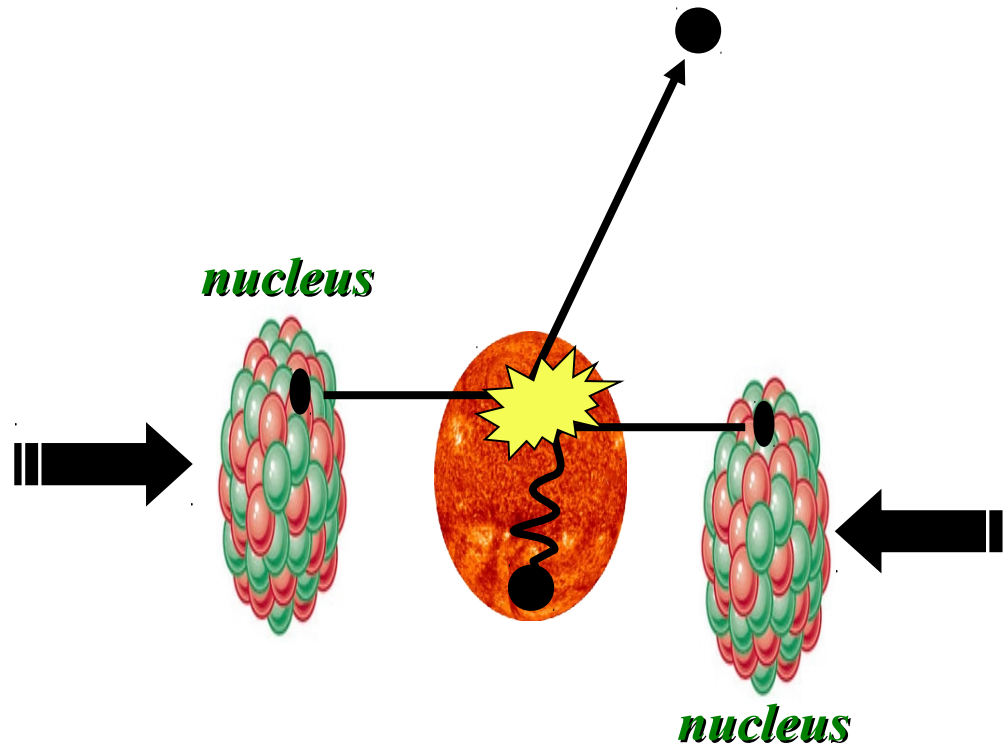
Want a probe which traveled through the collision  
QGP is very short-lived ( $\sim 1-10$  fm/c)  $\rightarrow$   
cannot use an external probe

# Probes of the Quark Gluon Plasma



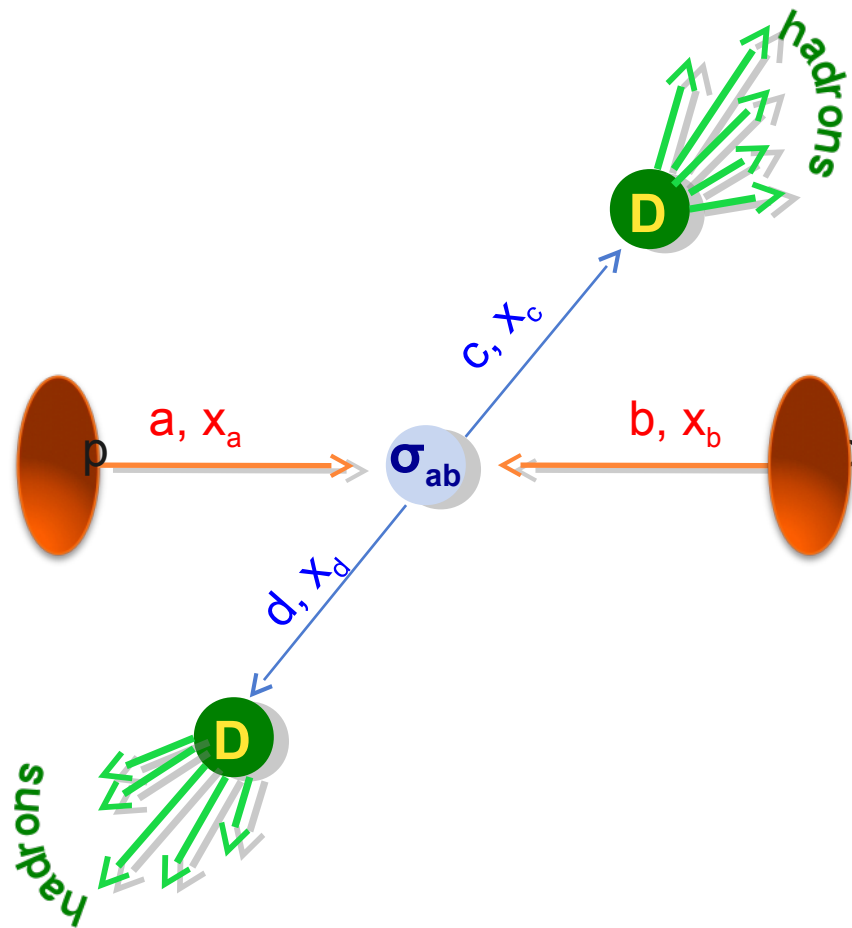
Want a probe which traveled through the medium  
QGP is short lived  $\rightarrow$  need a probe created in the collision

# Probes of the Quark Gluon Plasma

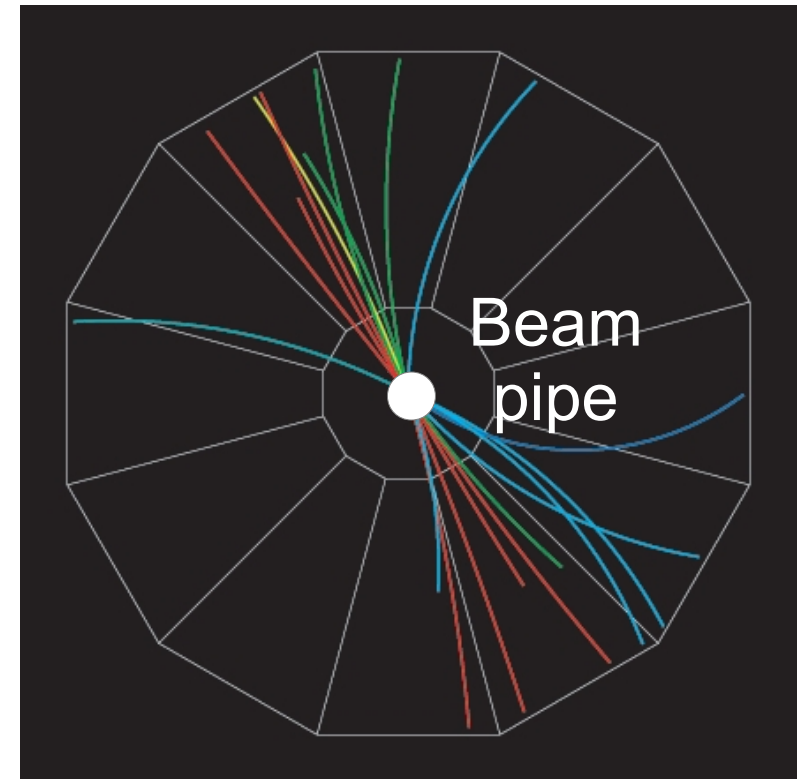


Want a probe which traveled through the medium  
QGP is short lived  $\rightarrow$  need a probe created in the collision  
We expect the medium to be dense  $\rightarrow$  absorb/modify probe

# Jets

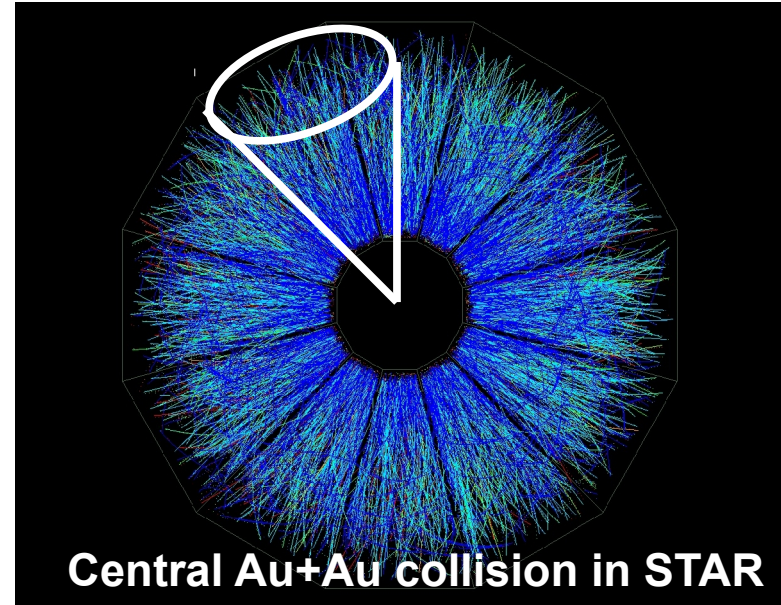
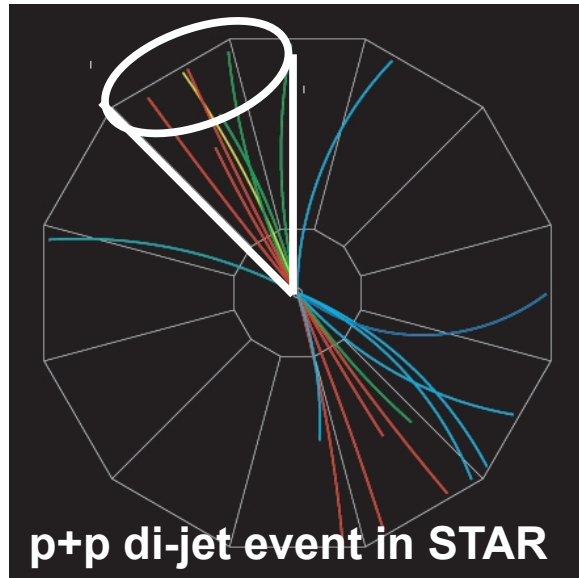


$p+p \rightarrow$  dijet



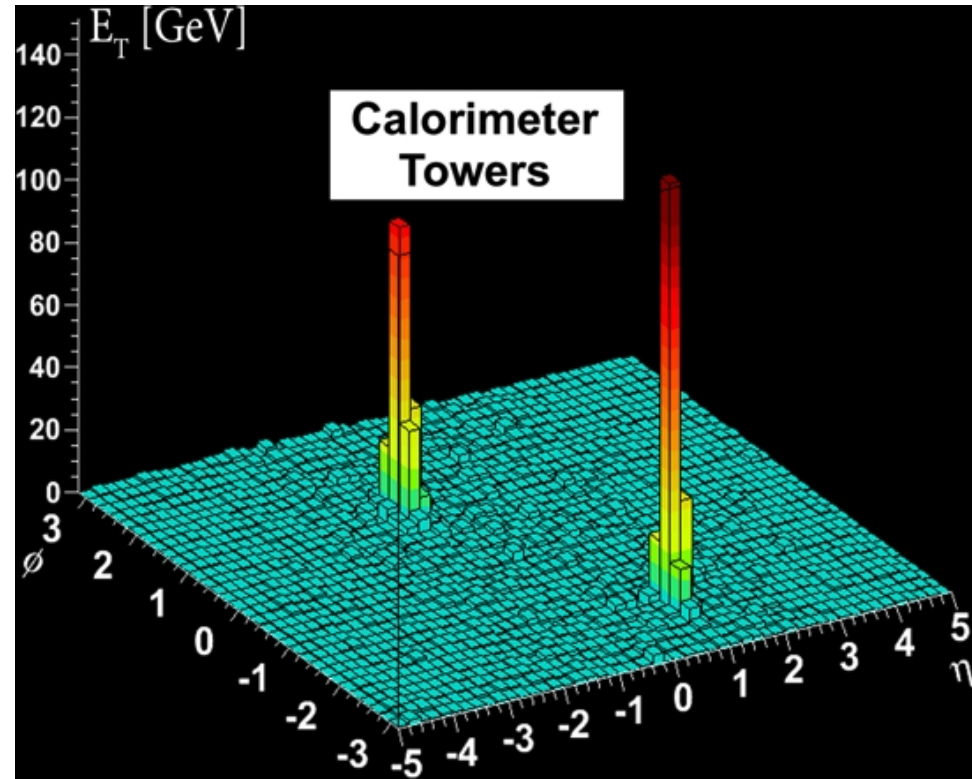
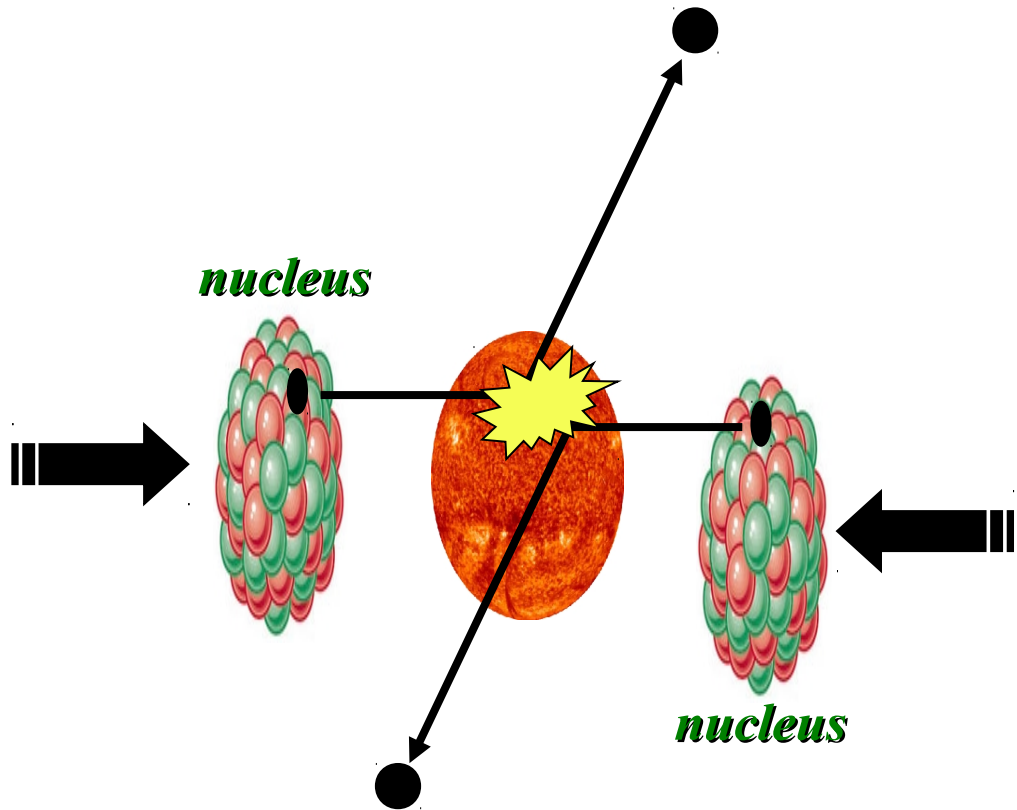
**Jets** – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

# Jet reconstruction



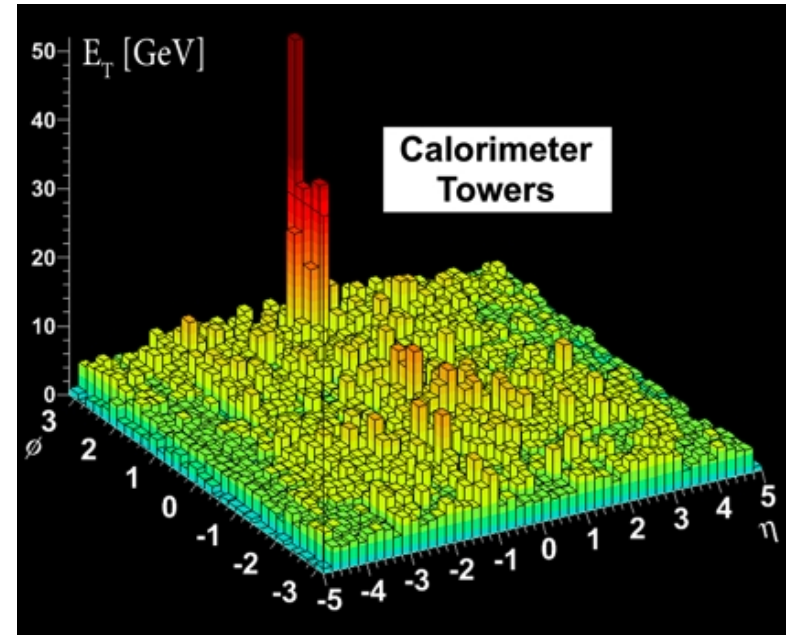
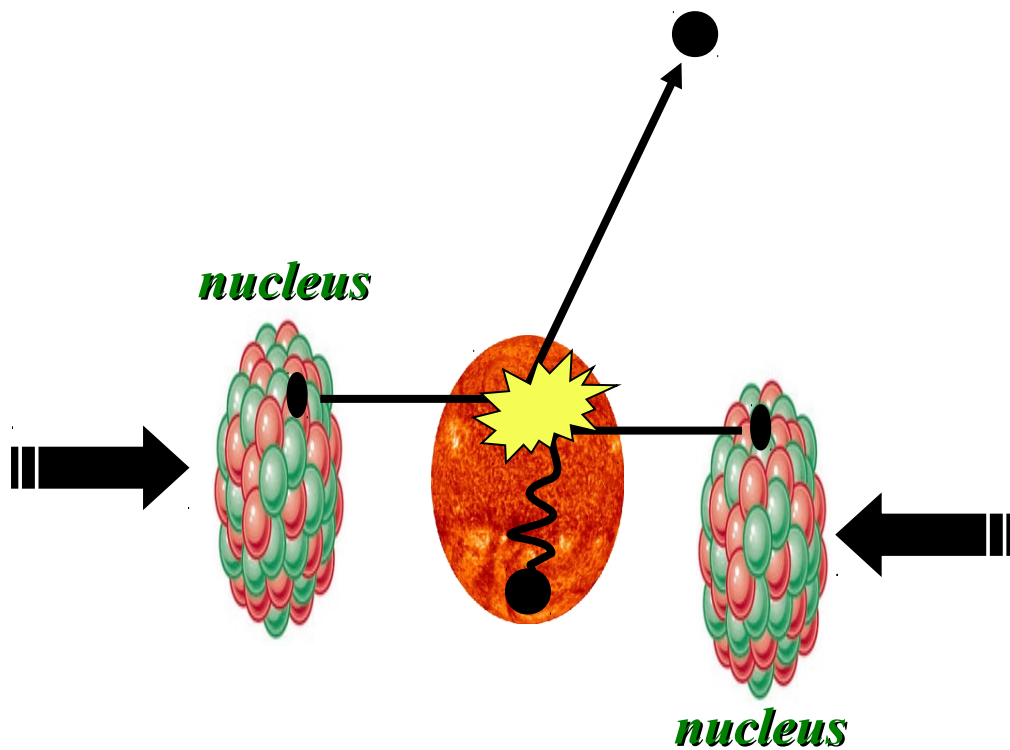
- Identify all of the particles in the jet  $\rightarrow$  parton energy, momentum
- Difficult in heavy ion collisions – but possible!

# Jets



- Quarks and gluons are confined – we don't see them outside of mesons and baryons
- Instead we see a cone of particles around the outgoing quark or gluon
- Looking at jets analogous to spectroscopy

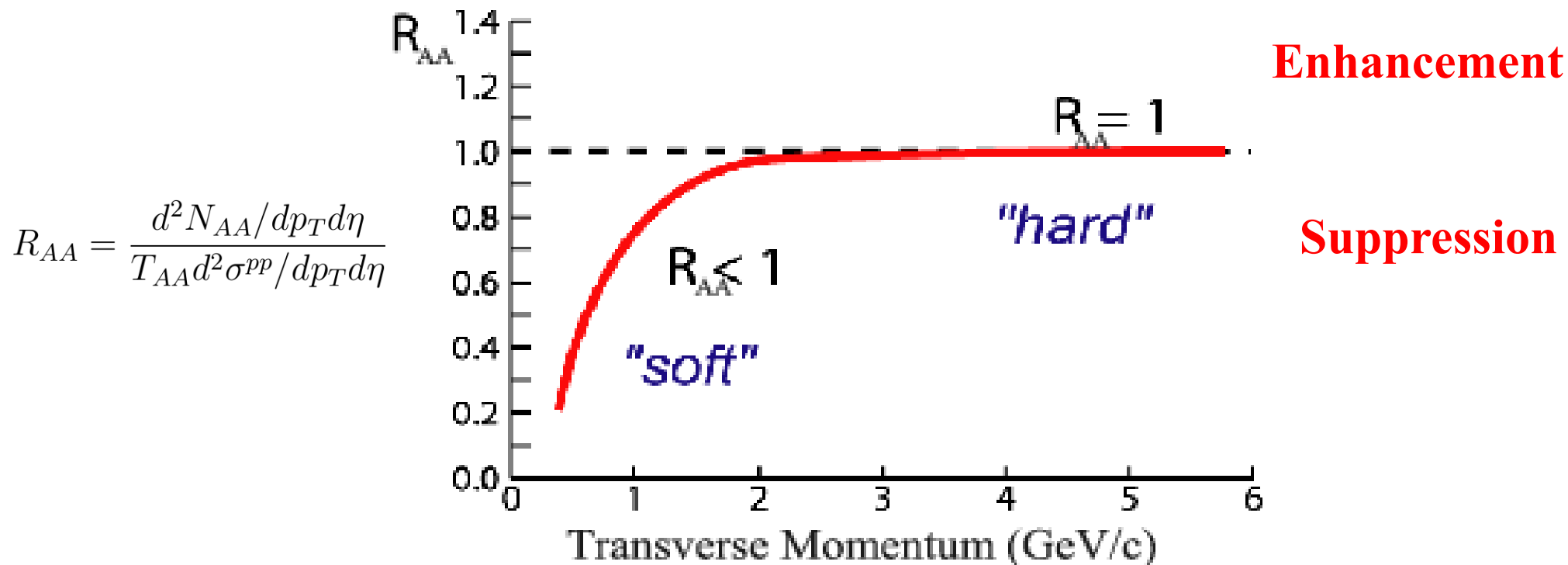
# Quenched jets



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

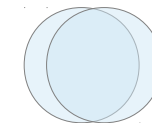
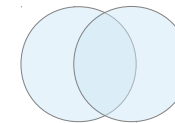
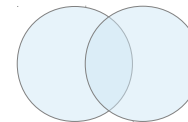
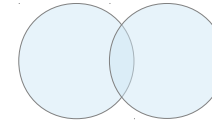
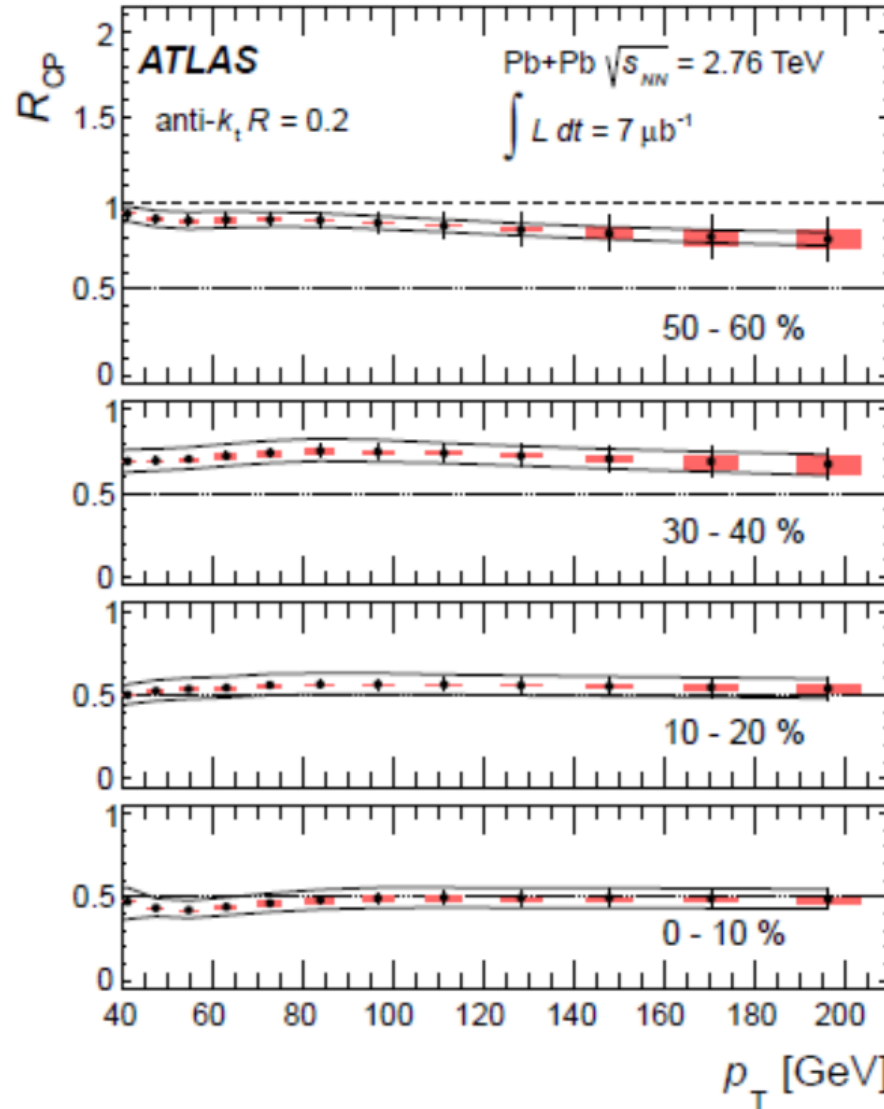
# Nuclear modification factor

- 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



# Jet nuclear modification factor\*

arXiv:1208.1967 [hep-ex] Submitted to Phys. Lett.B

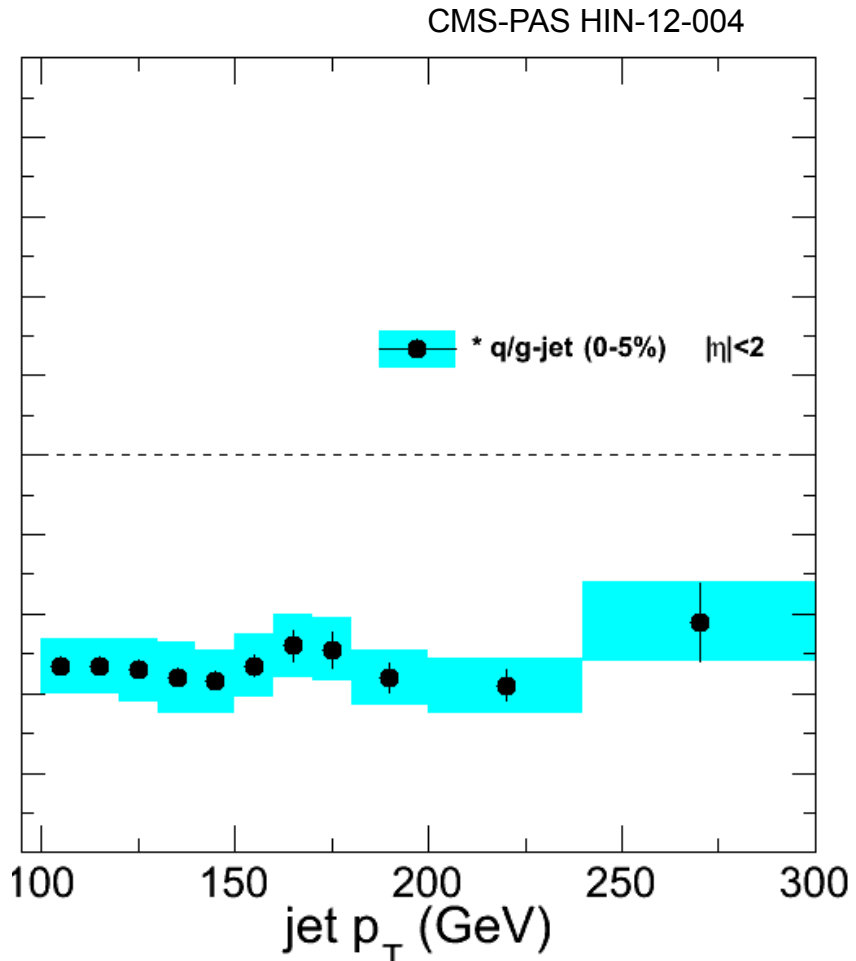
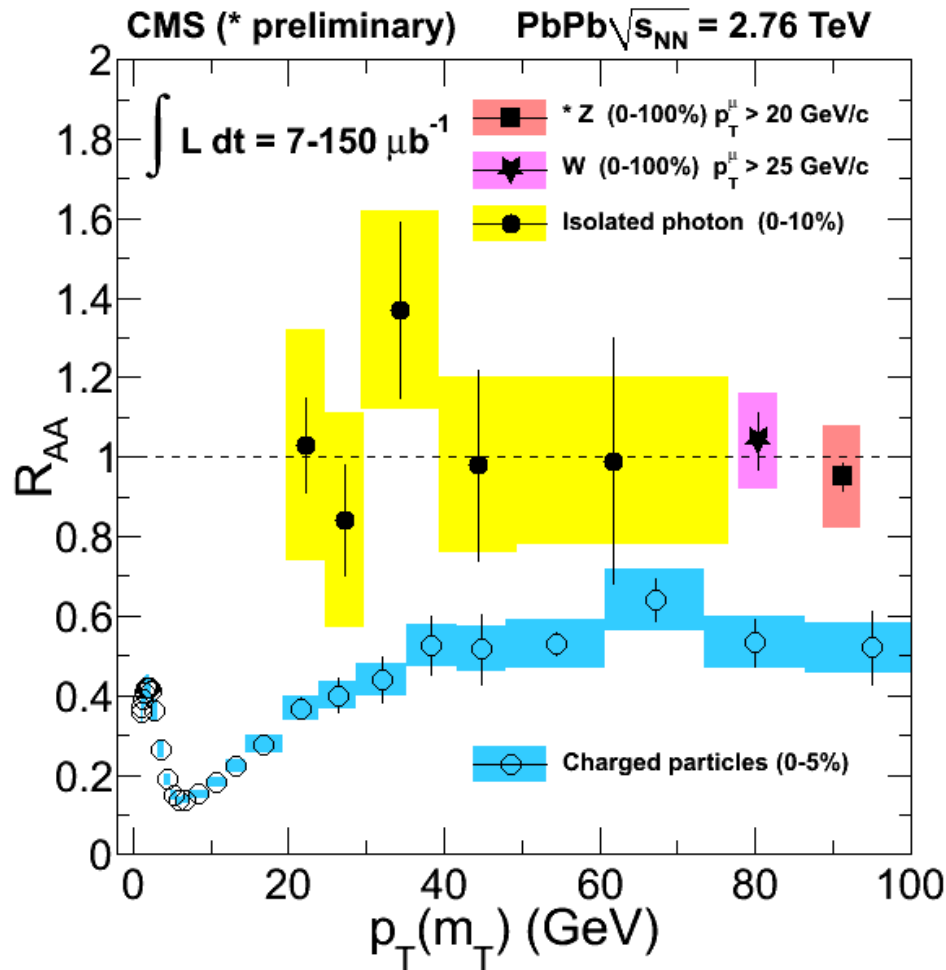


ATLAS  
collaboration  
Anti- $k_T$  algorithm  
 $R=0.2$

\* $R_{cp}$  is the ratio of central to peripheral A+A collisions instead of A+A collisions to p+p

# Nuclear modification factors

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

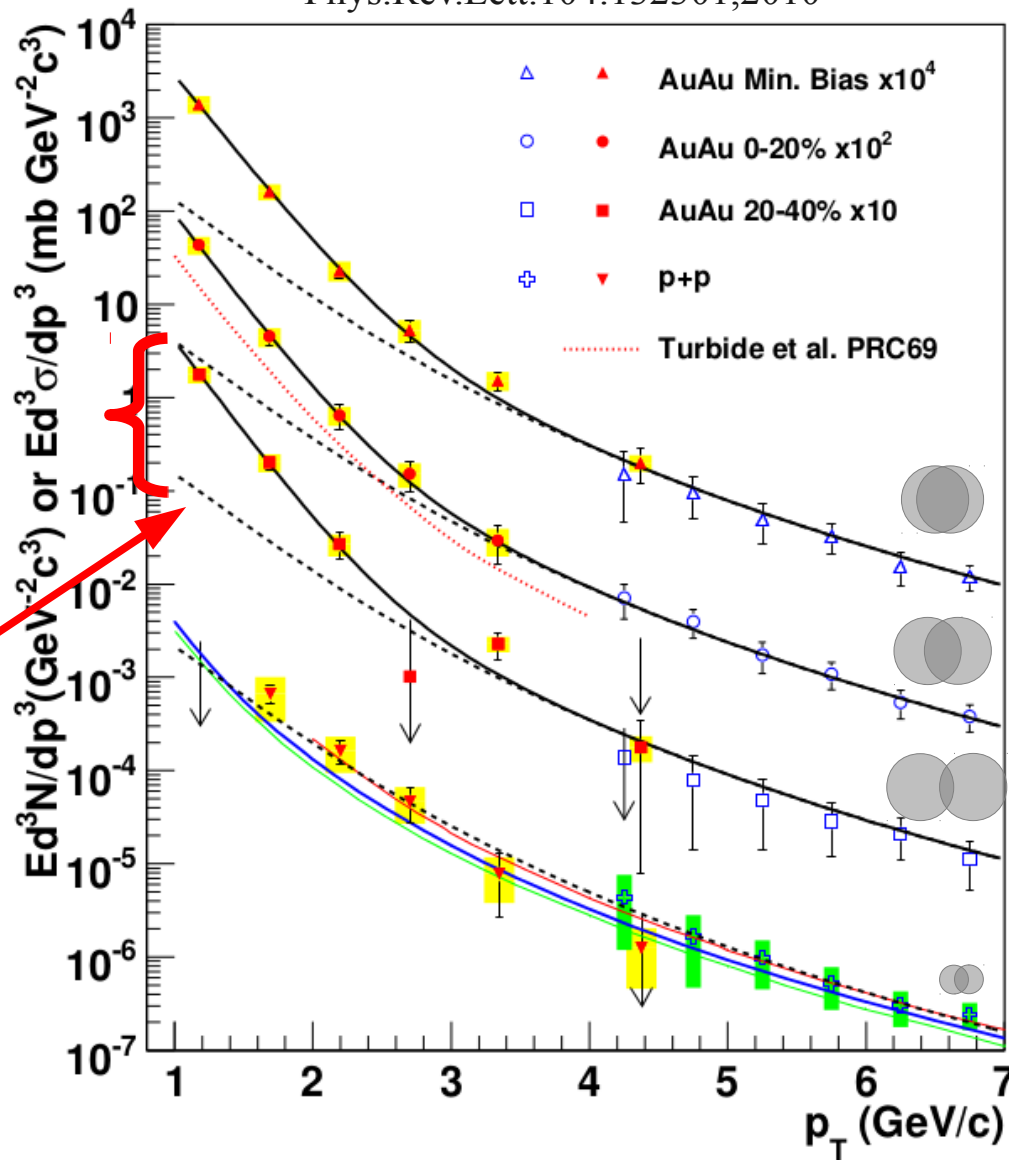


Like for charged particles,  
high- $p_T$  jet  $R_{AA}$  flat at  $\approx 0.5$

# Measuring temperature

# Thermal photons

Phys.Rev.Lett.104:132301,2010



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

**Inverse slope:**  
 $T = 221 \pm 19 \text{ (stat)} \pm 19 \text{ (syst) MeV}$

**Consistent with models with**  
 $T = 300\text{-}600 \text{ MeV}$

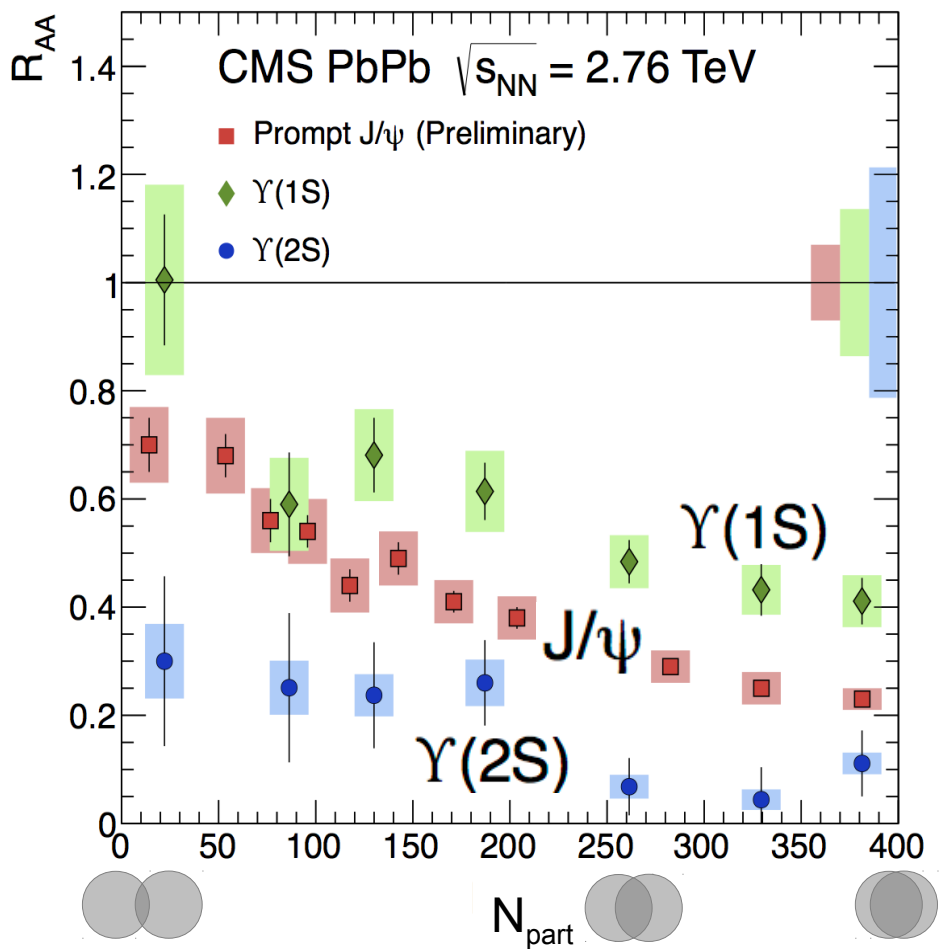
$T_c \sim 170 \text{ MeV}$

**Thermal photons**

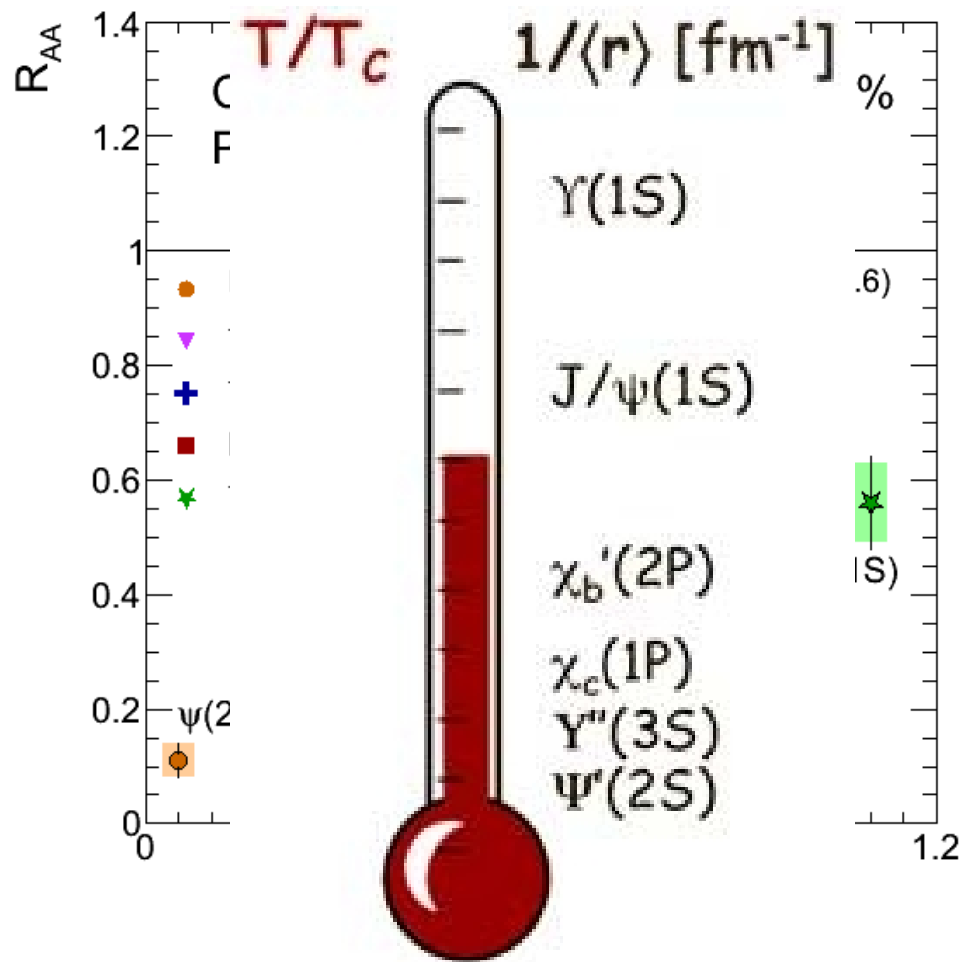
**QCD processes**

# Building a quarkonium-thermometer

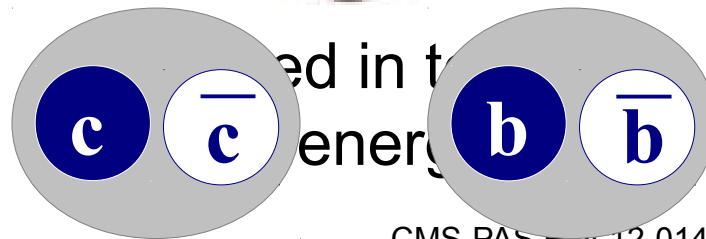
CMS-PAS HIN-11-011



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



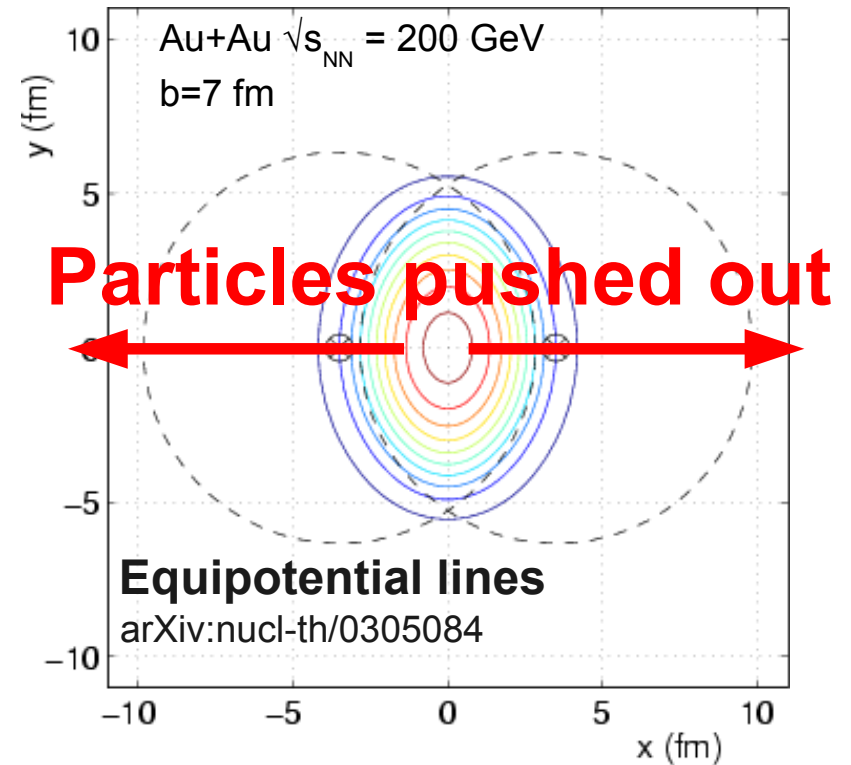
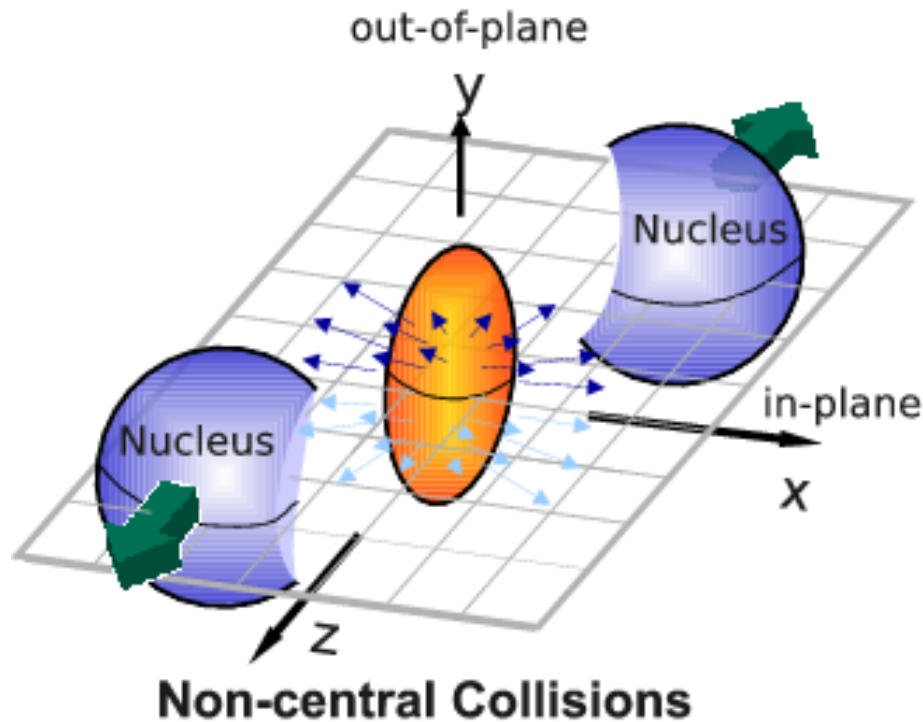
Clear hierarchy in  $R_{AA}$  of different quarkonium states



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

# Collective flow

# If we have a fluid...

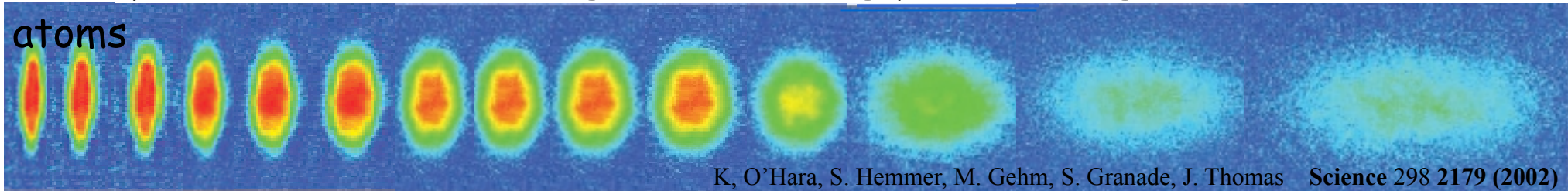


- Initial overlap asymmetric  $\rightarrow$  pressure gradients
- Momentum anisotropy  $\rightarrow$  Fourier decomposition:

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

# What does it mean?

Same phenomena observed in gases of strongly interacting



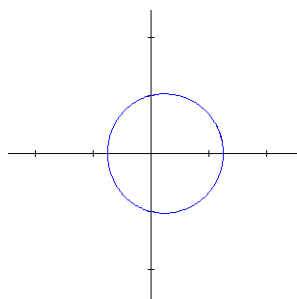
K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas *Science* 298 2179 (2002)

Time

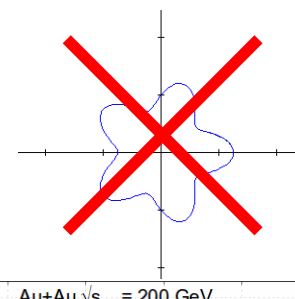
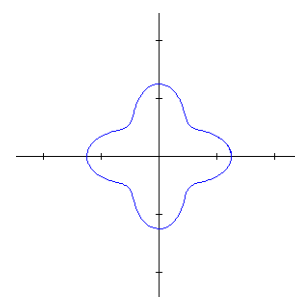
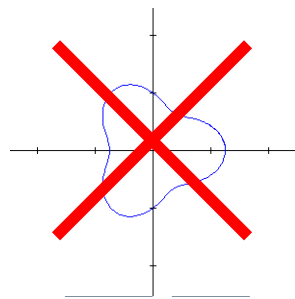
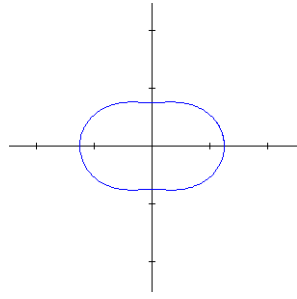
**Initial state anisotropies converted to final state anisotropies**

Fourier decomposition:

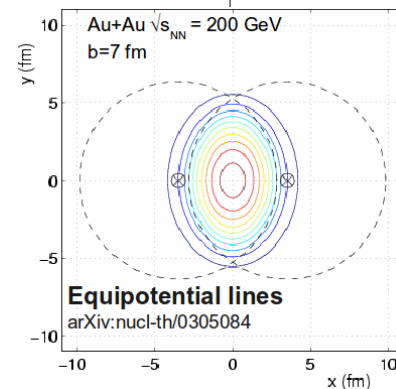
$$\frac{d^2 N}{dp_T d\varphi} \approx 1 + 2 v_1 \cos(d\varphi) + 2 v_2 \cos(2d\varphi) + 2 v_3 \cos(3d\varphi) + 2 v_4 \cos(4d\varphi) + 2 v_5 \cos(5d\varphi) + \dots$$



Offset  
measured



**Nuclei are symmetric →  
No odd coefficients**



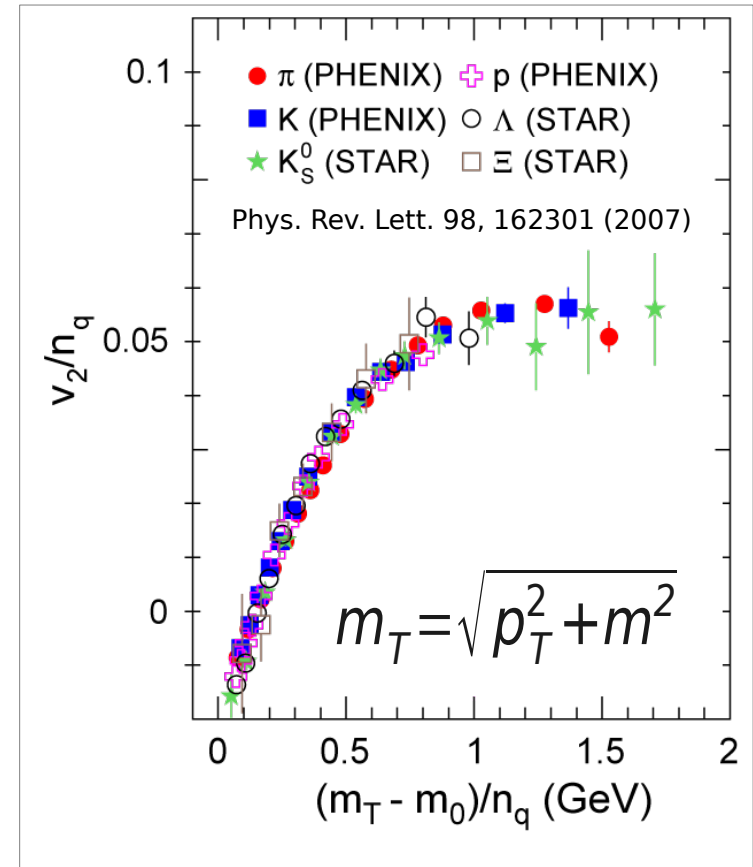
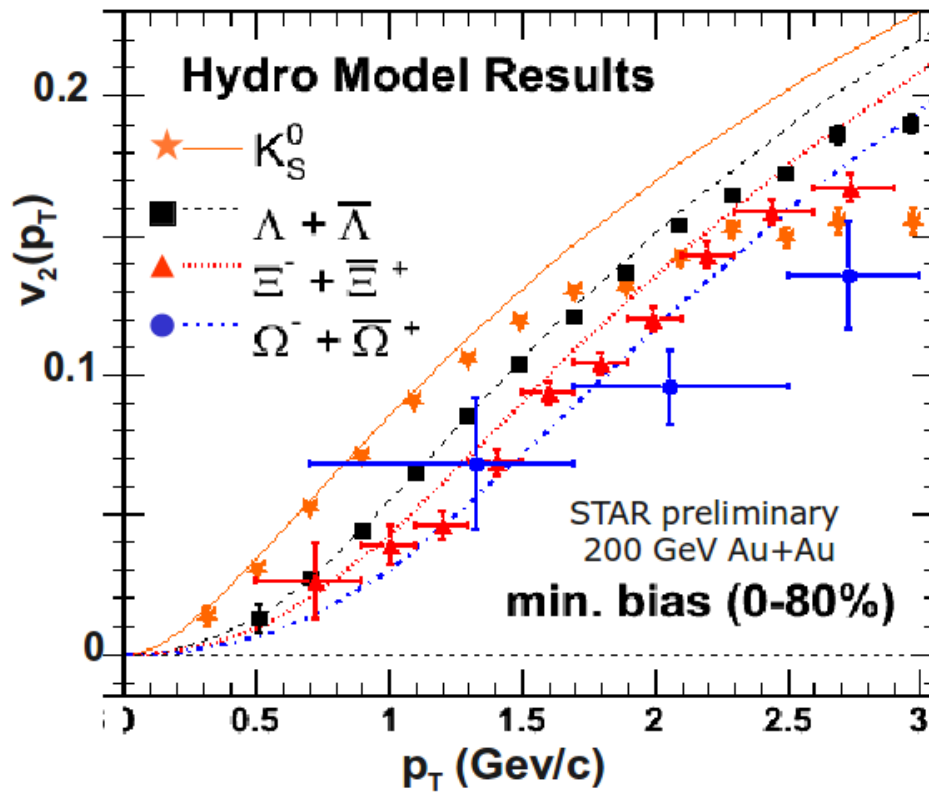
# Does this describe the data?



arXiv: 1108.5323v1

**Yes!**

# More data



Mass ordering:

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

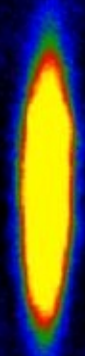
$$v_2(p_T^{\text{hadron}}) \mu n_{\text{quark}} v_2(p_T^{\text{quark}})$$

**We have a liquid of quarks and gluons!**

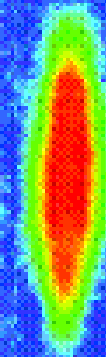
# What do we learn about the QGP?

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

**High viscosity**



**Low viscosity**



**The Quark Gluon Plasma has a very low viscosity**

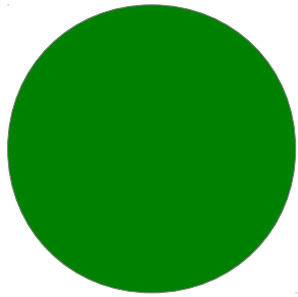
# What do we learn about the QGP?

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

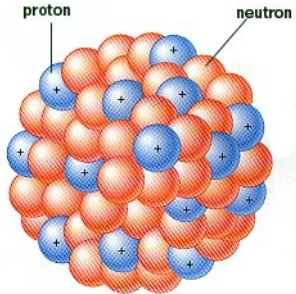


**The QGP is the perfect liquid!**

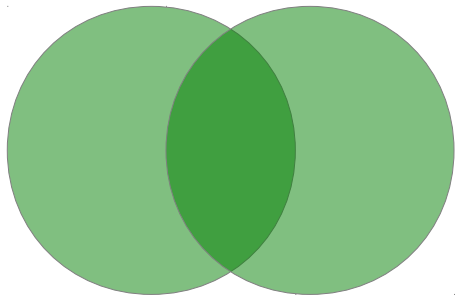
(not the gas of “free” quarks and gluons we expected)



This is not what a nucleus looks like

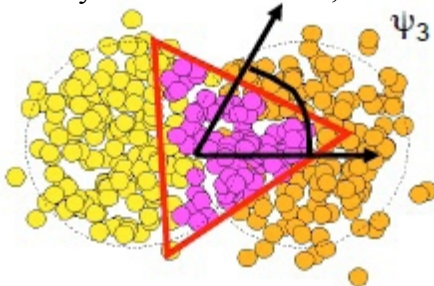


*This* is what a nucleus looks like



This is not what our collision looks like

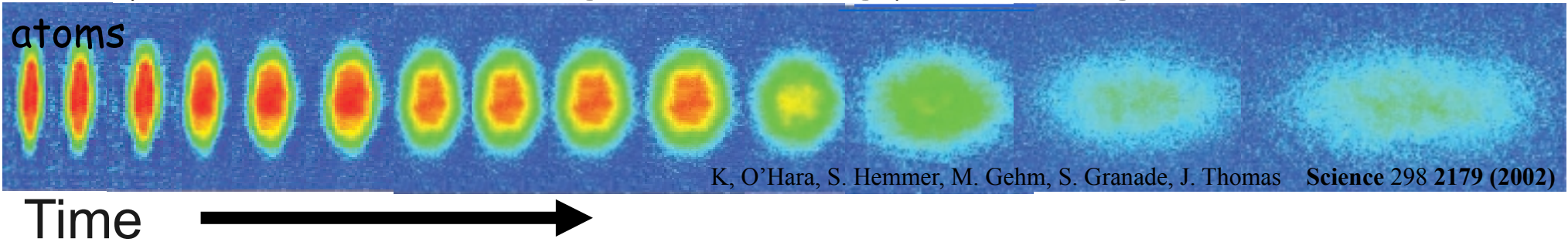
Phys.Rev.C81:054905,2010



This is what our collision looks like

# What does it mean?

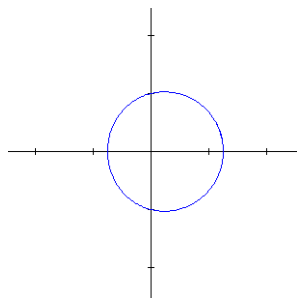
Same phenomena observed in gases of strongly interacting



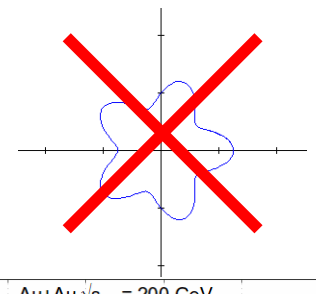
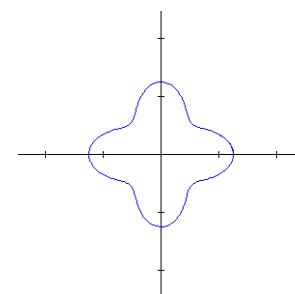
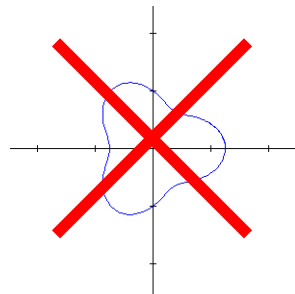
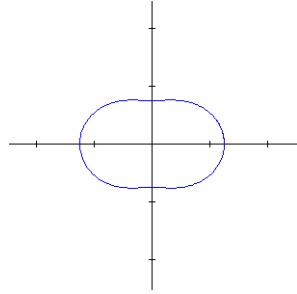
**Initial state anisotropies converted to final state anisotropies**

Fourier decomposition:

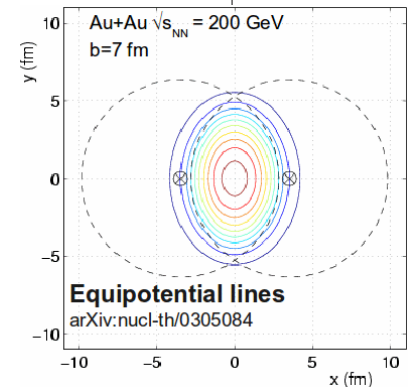
$$\frac{d^2 N}{dp_T d\varphi} \approx 1 + 2v_1 \cos(d\varphi) + 2v_2 \cos(2d\varphi) + 2v_3 \cos(3d\varphi) + 2v_4 \cos(4d\varphi) + 2v_5 \cos(5d\varphi) + \dots$$



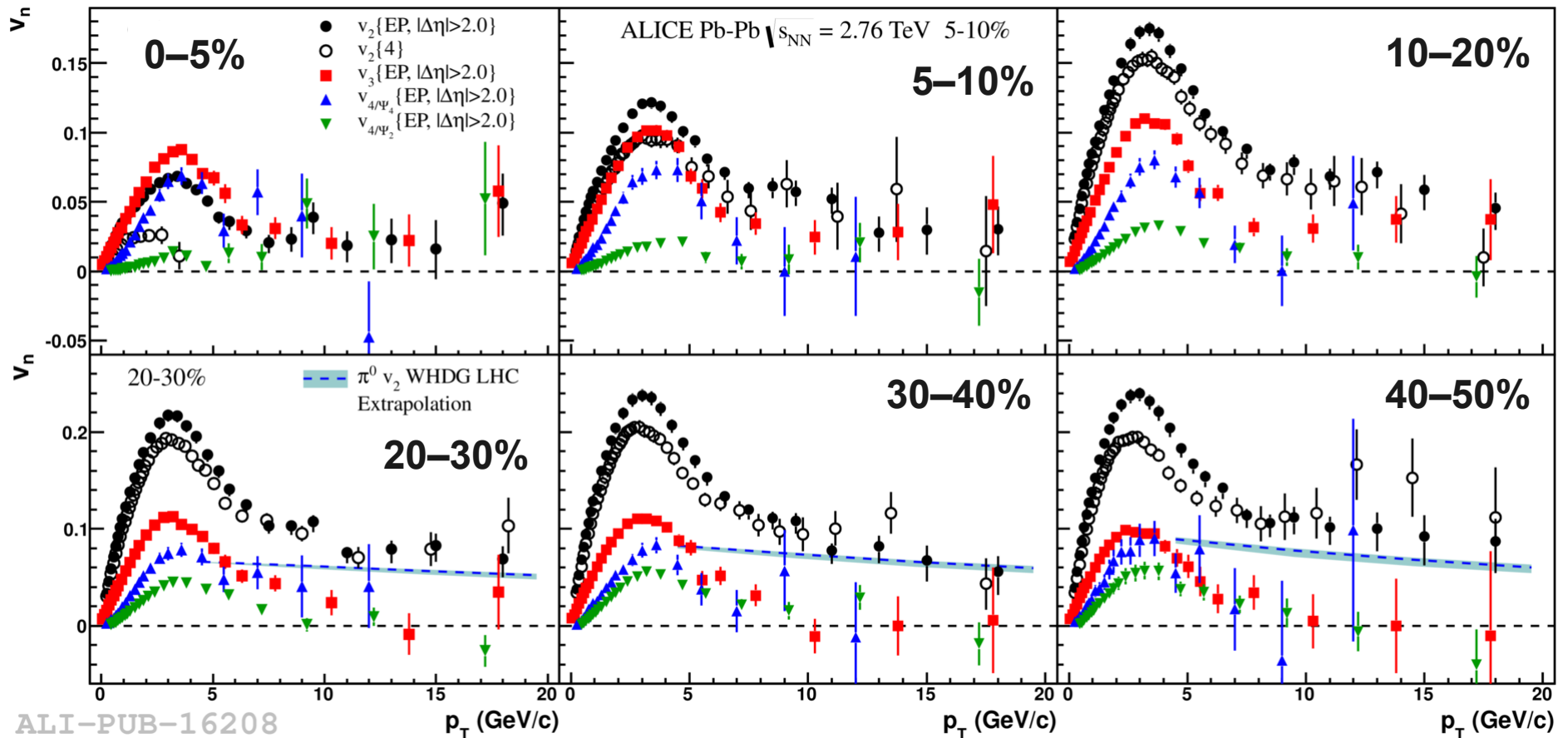
Offset  
measured



**Nuclei are symmetric →  
No odd coefficients**



# Odd and even $v_n$



Odd  $n$ : sensitive to fluctuations in the initial state

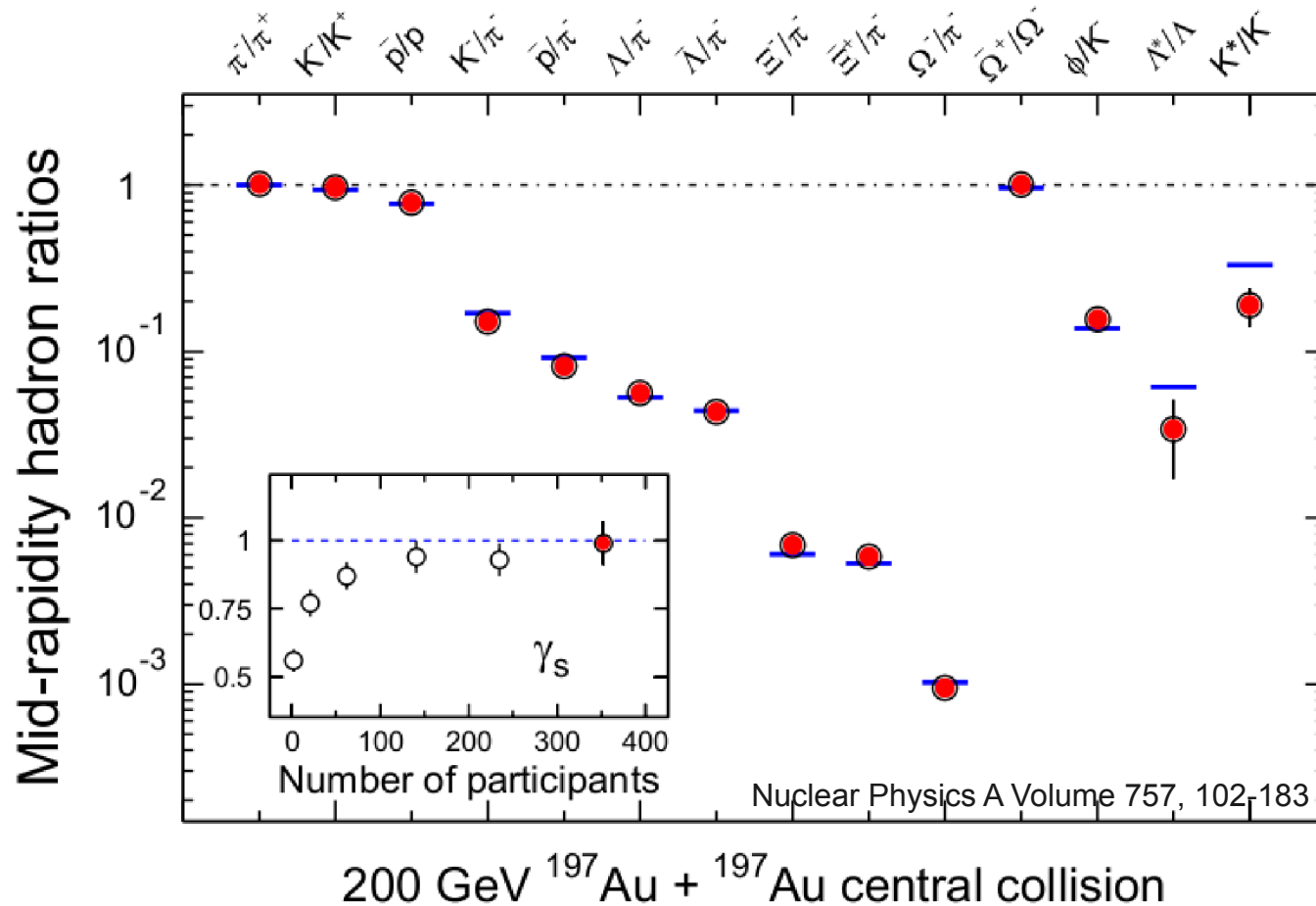
# Conclusions

- Form Quark Gluon Plasma in A+A collisions
- $T > T_c$
- Jet suppression  $\rightarrow$  strongly interacting medium
- Hydrodynamical flow  $\rightarrow$  low  $\eta/S$ , perfect liquid

# QGP Chemistry

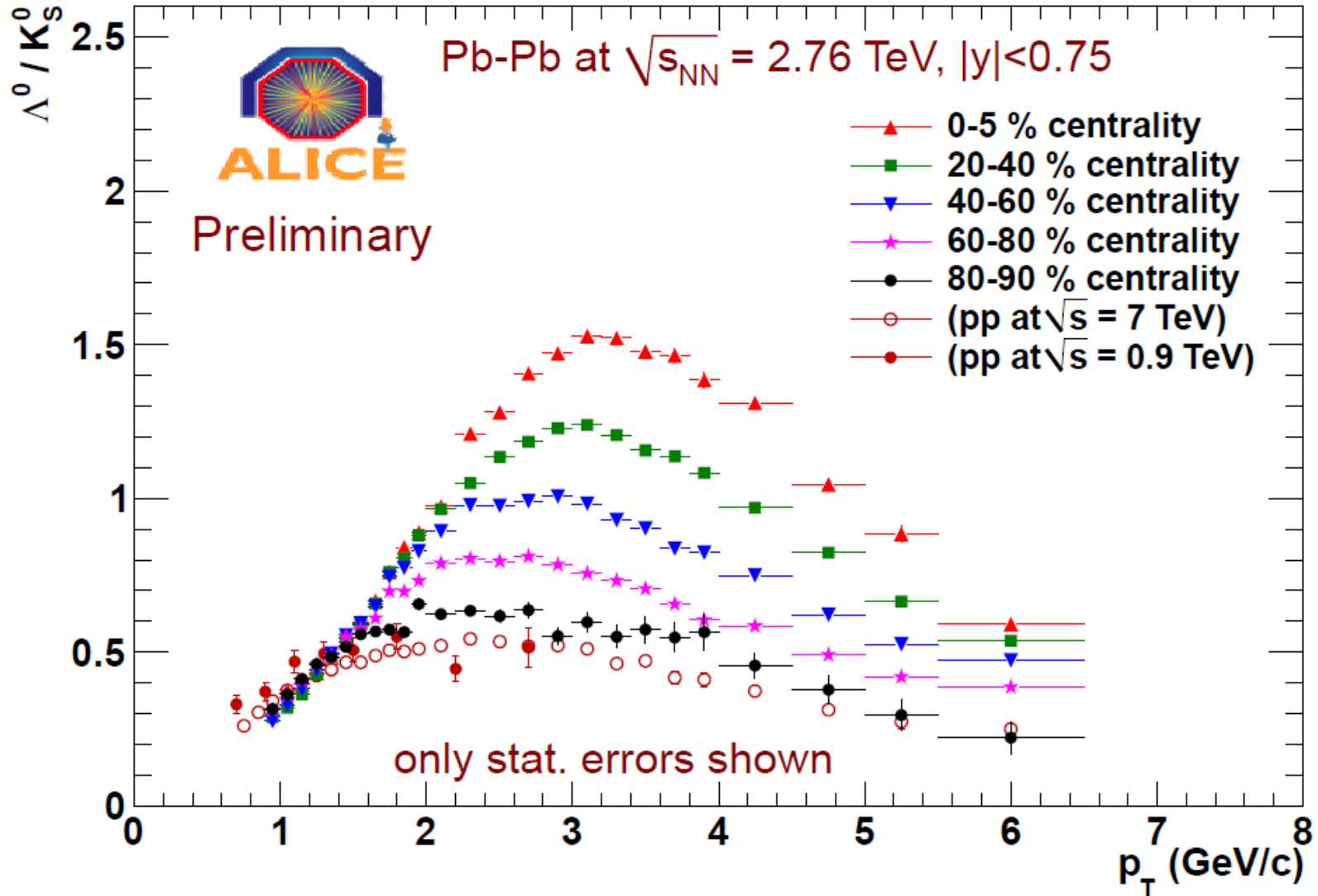
# Chemistry - equilibrium

$T \sim 170$   
MeV



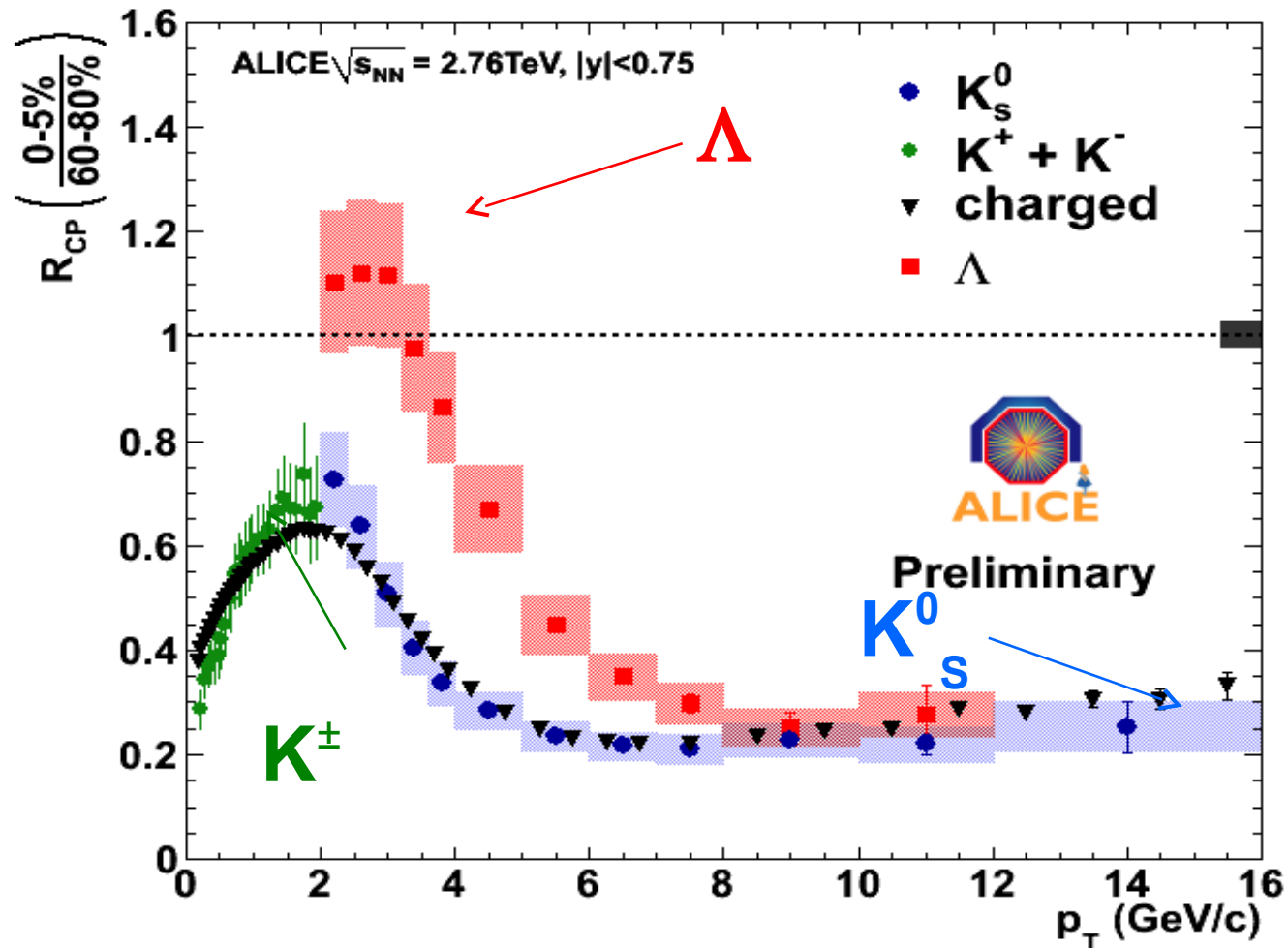
- Ratios of particles expected from a model
- Even strange quarks are at equilibrium!

# Baryon anomaly: $\Lambda/K_S^0$



Pb+Pb

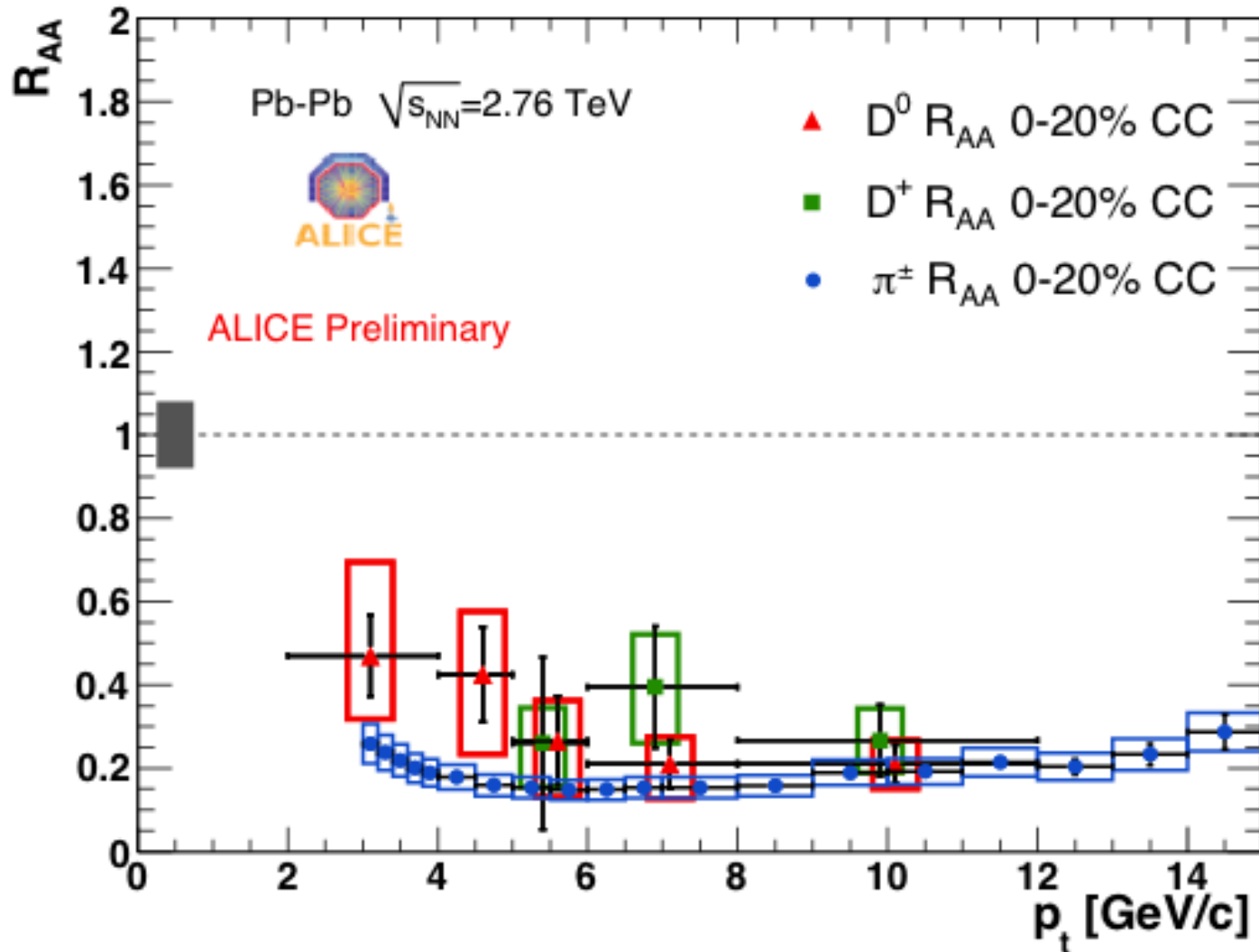
# Nuclear modification factor ( $R_{AA}$ )



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

**Pb+Pb**

# Charm nuclear modification factor



Pb+Pb

# Conclusions

- Form Quark Gluon Plasma in A+A collisions
- $T > T_c$
- Jet suppression  $\rightarrow$  strongly interacting medium
- Hydrodynamical flow  $\rightarrow$  low  $\eta/S$ , perfect liquid
- Quark chemistry modified in QGP