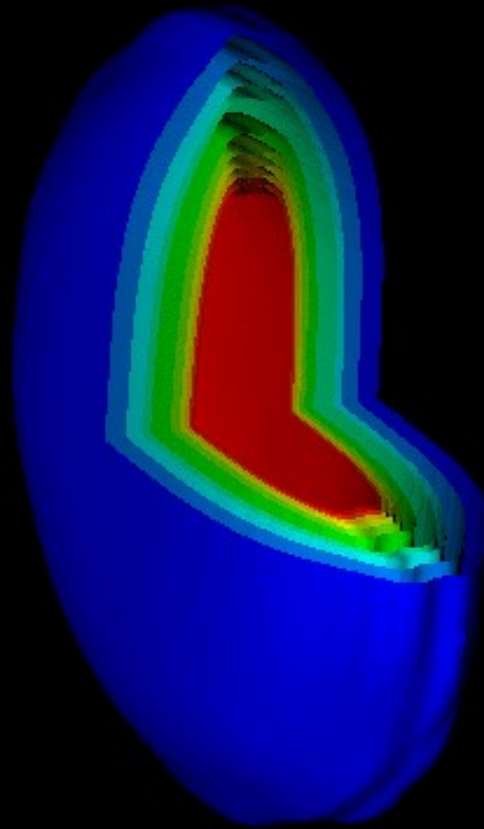
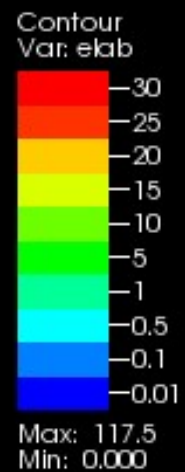
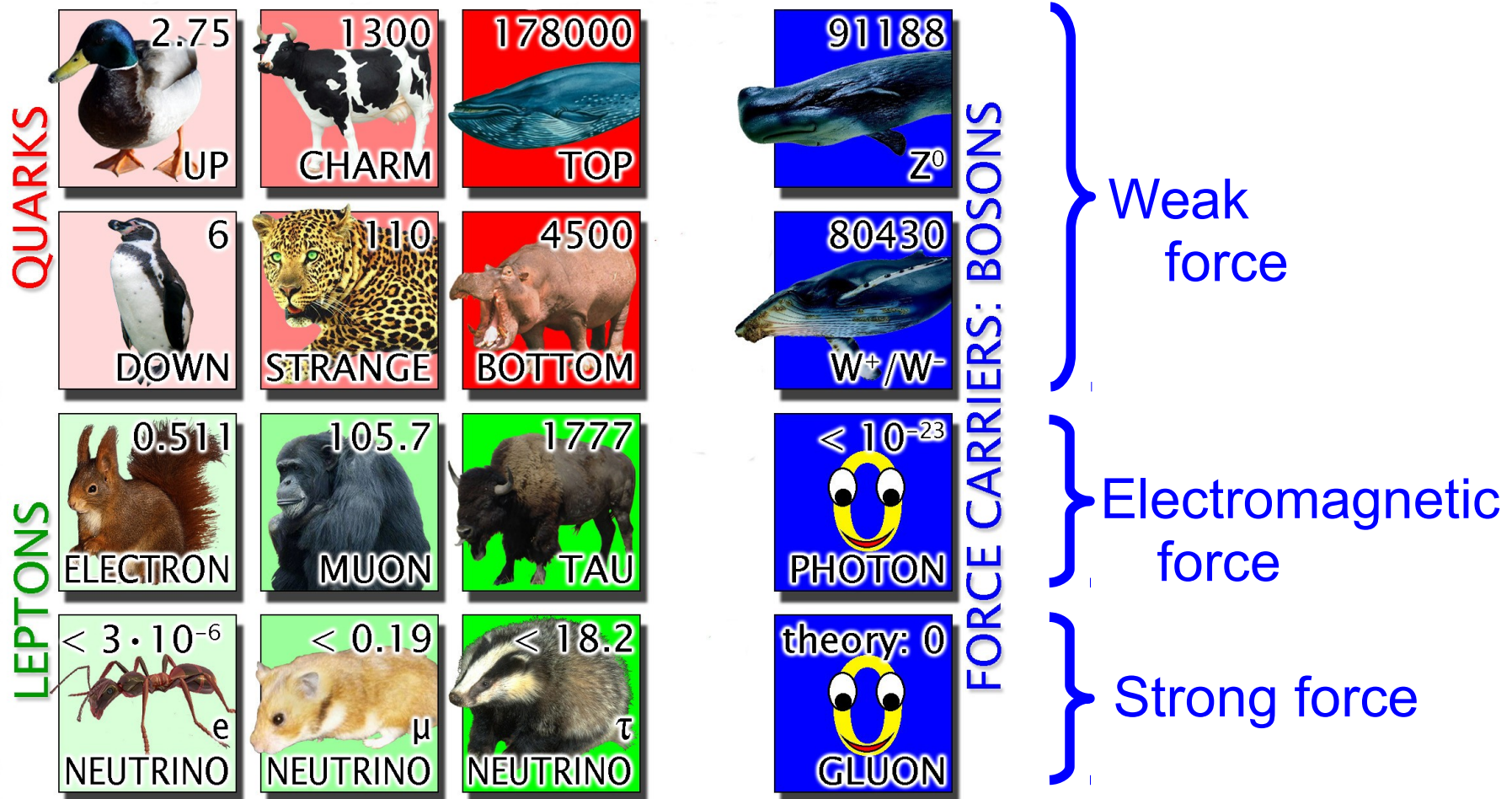


# *Probing the quark gluon plasma*



*Christine Nattrass*  
*University of Tennessee at Knoxville*

# The Standard Model

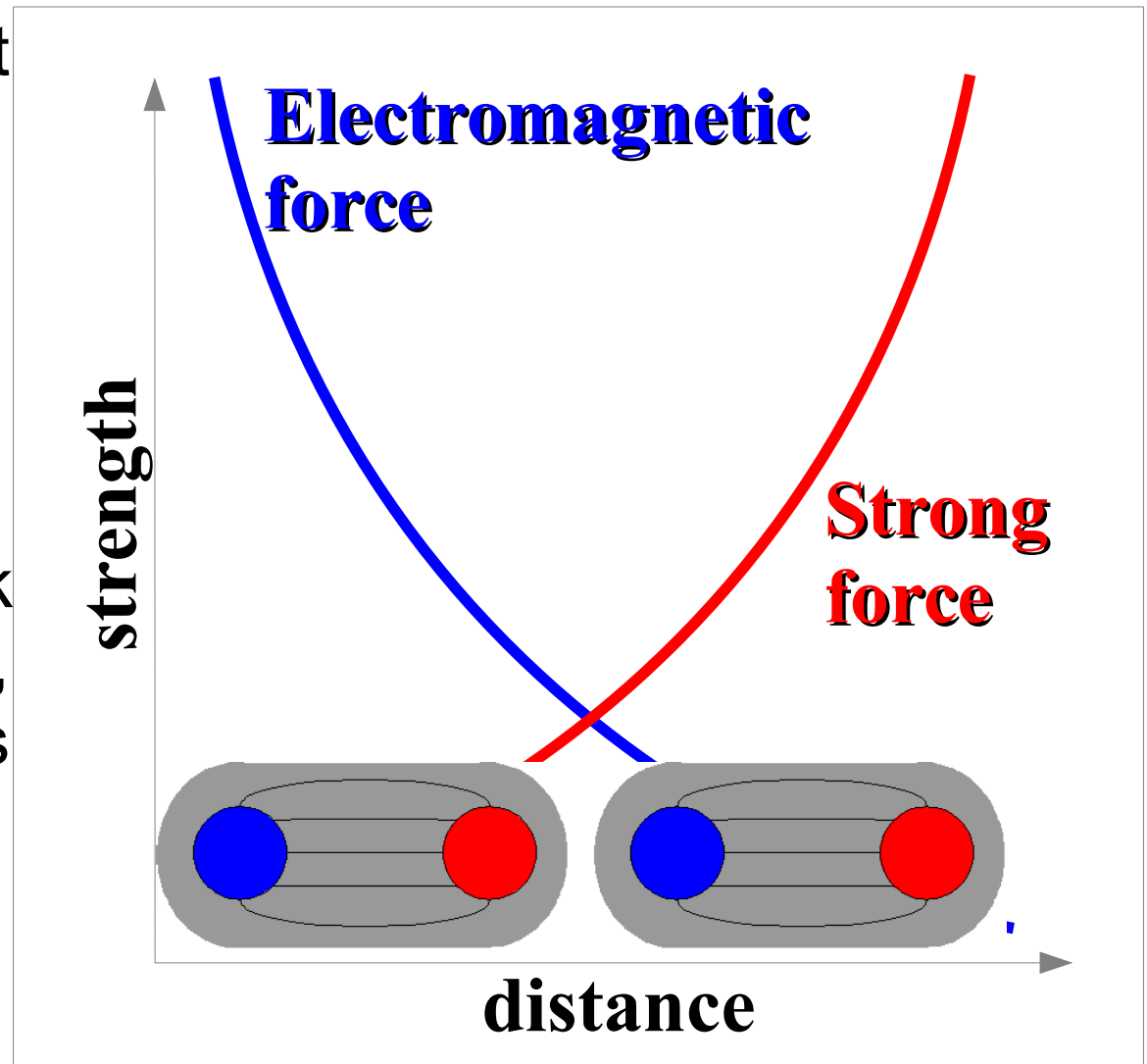


## The Standard Model fundamental particle zoo

[http://e4.physik.uni-dortmund.de/bin/view/ATLAS/SmBilder?PhotoarchivePlugin\\_page=1&PhotoarchivePlugin\\_view=detailed](http://e4.physik.uni-dortmund.de/bin/view/ATLAS/SmBilder?PhotoarchivePlugin_page=1&PhotoarchivePlugin_view=detailed)

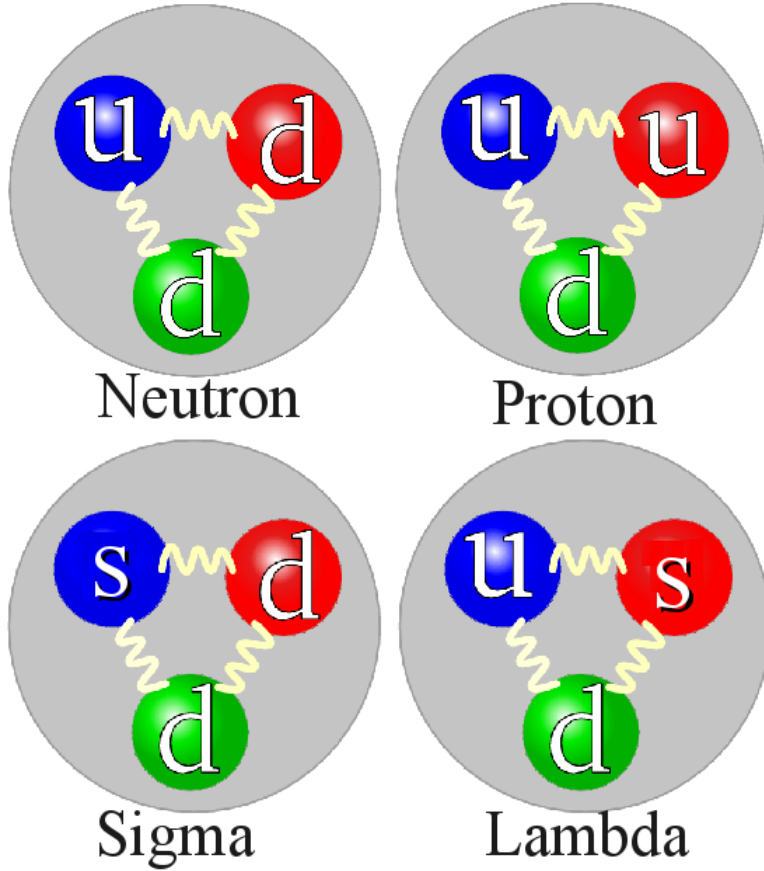
# What keeps the nucleus together?

- 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**

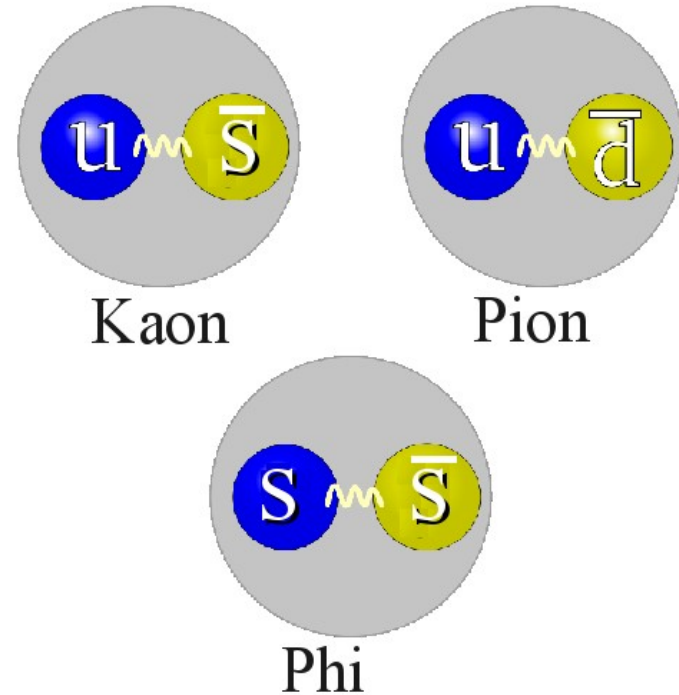


# Hadrons

## Baryons



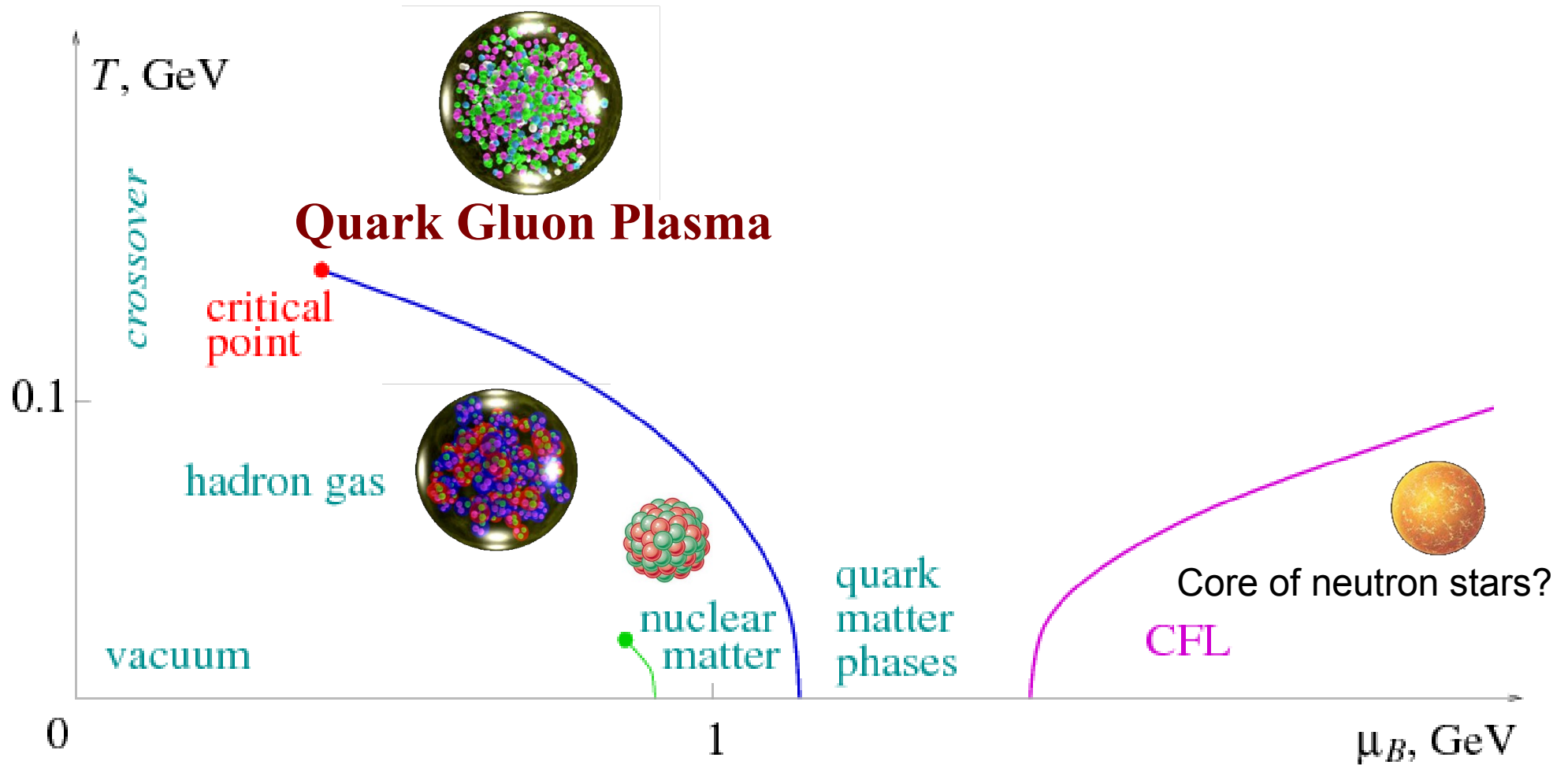
## Mesons



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

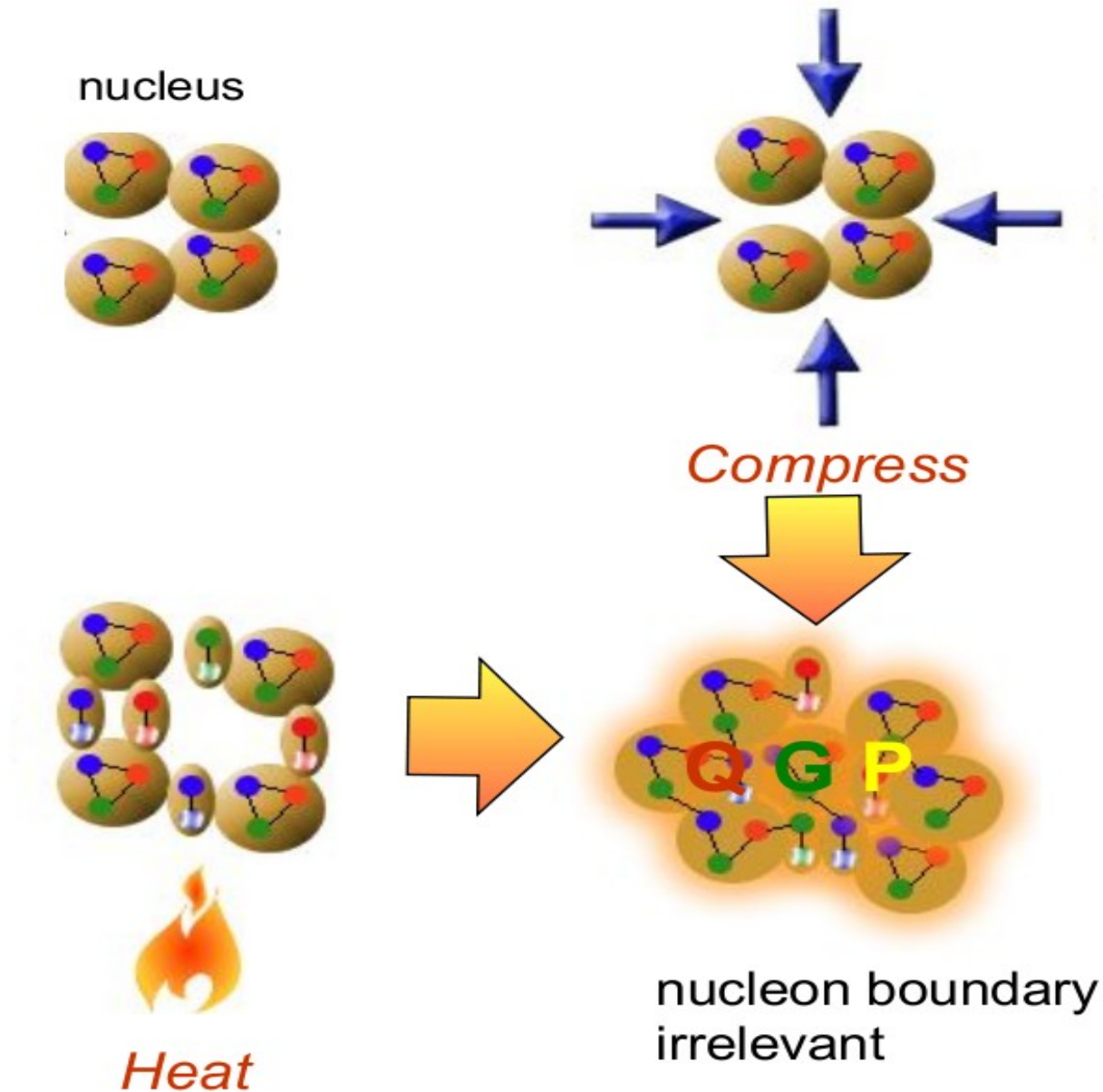
- Quark-antiquark
- Color charge: blue - anti-blue

# Phase diagram of nuclear matter

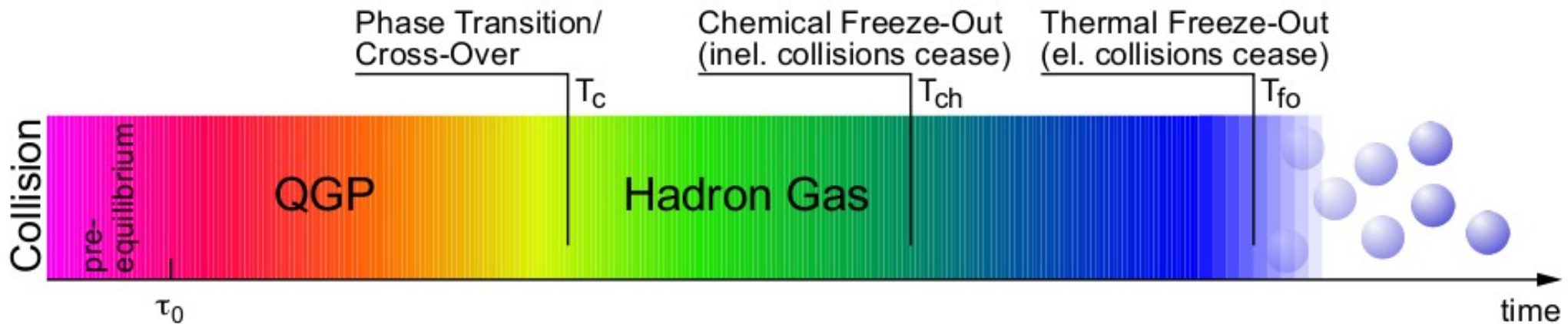
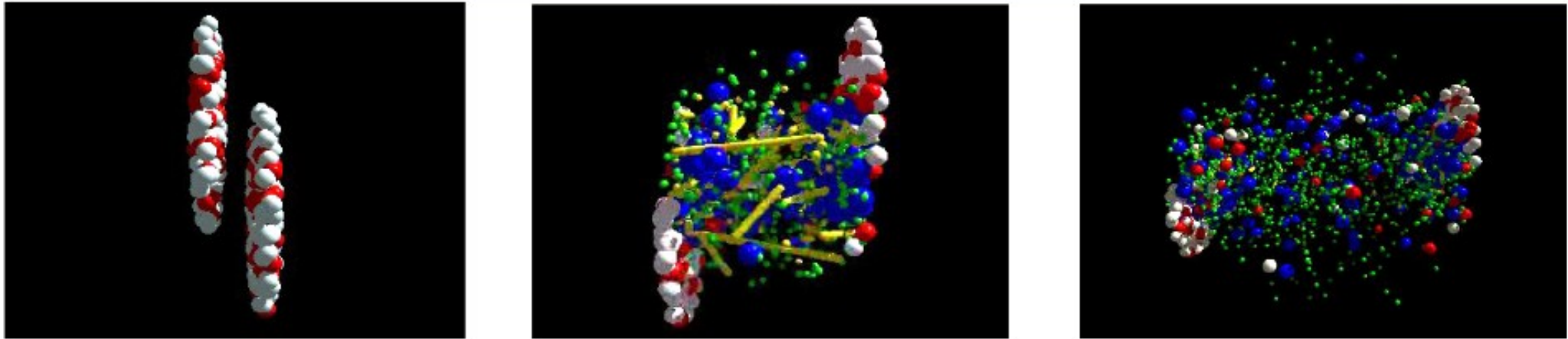


**Quark Gluon Plasma** – a *liquid* of quarks and gluons created at temperatures above  $\sim 170$  MeV ( $2 \cdot 10^{12}$  K) – over a million times hotter than the core of the sun

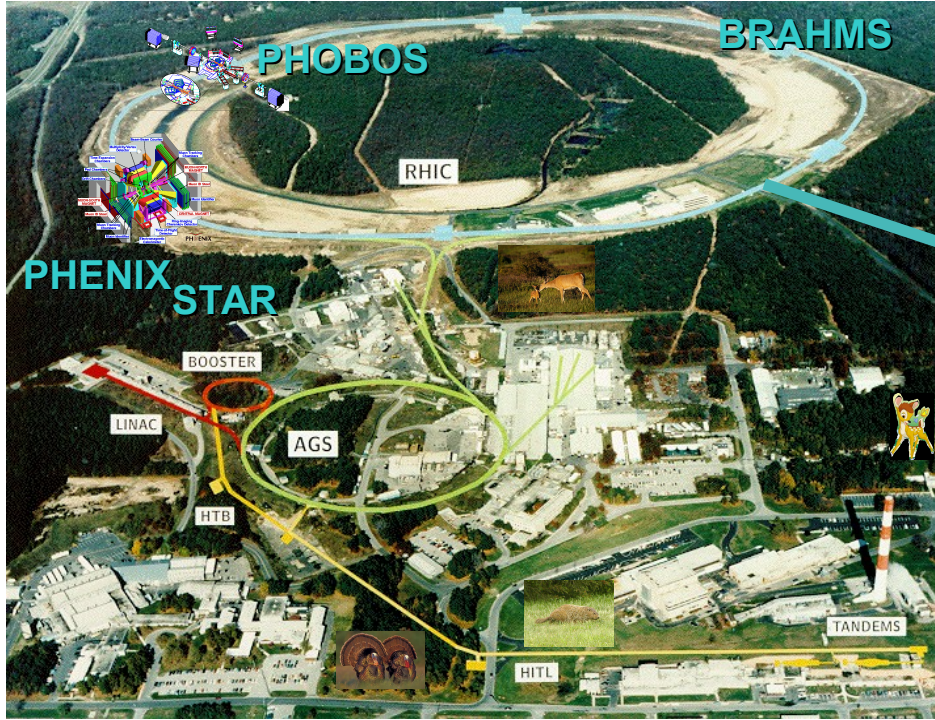
# How to make a Quark Gluon Plasma



# The phase transition in the laboratory

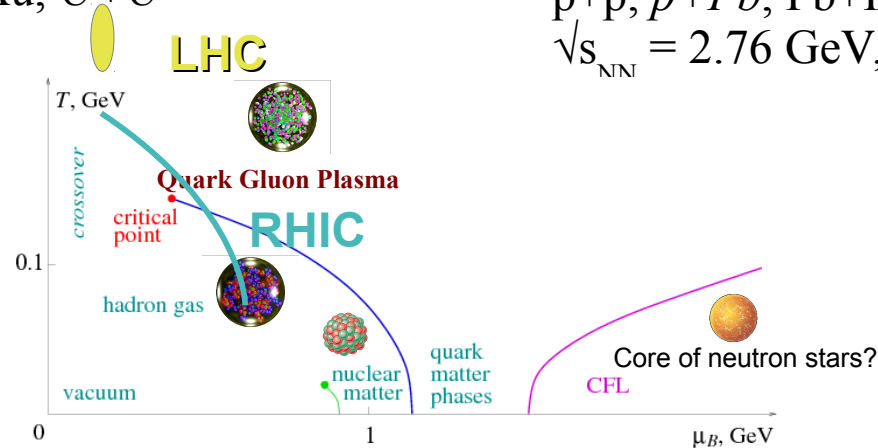


# Relativistic Heavy Ion Collider

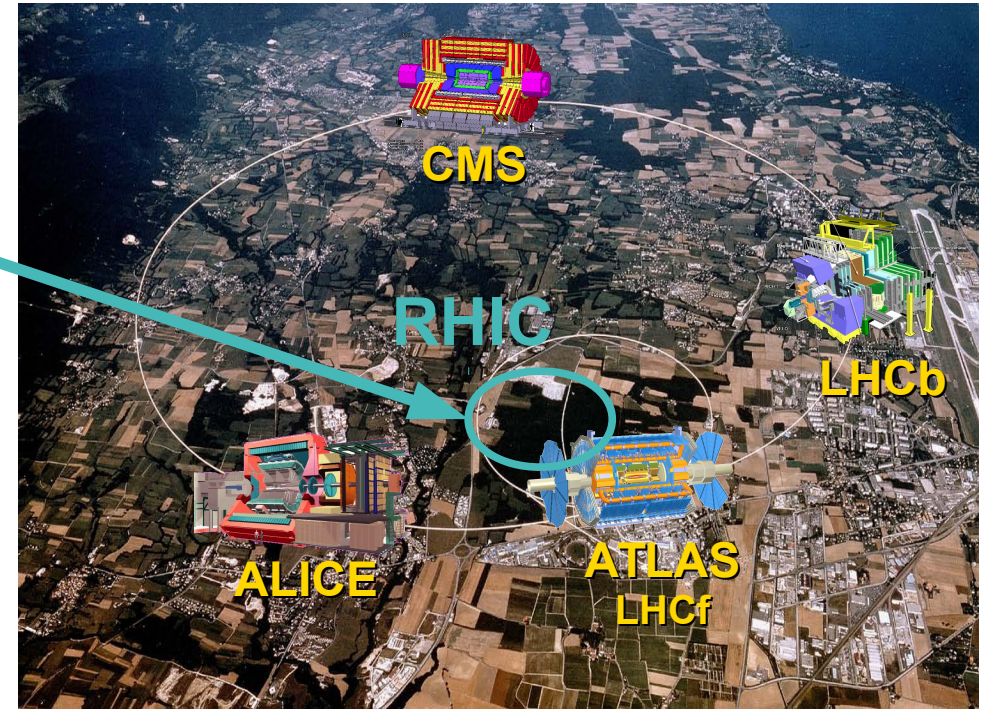


Upton, NY  
1.2km diameter

$p+p, d+Au, Cu+Cu, Au+Au, U+U$   
 $\sqrt{s}_{NN} = 9 - 200 \text{ GeV}$



# Large Hadron Collider



Geneva, Switzerland  
8.6km diameter

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

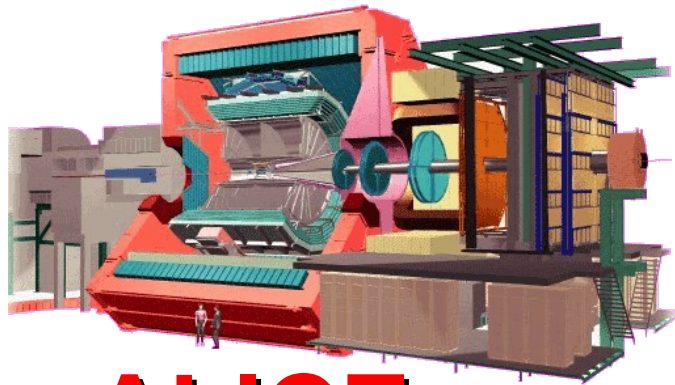
# Comparison of colliders

	<b>RHIC</b>	<b>LHC</b>	
$\sqrt{s_{NN}}$ (GeV)	9-200	2760, 5500	<i>center of mass energy</i>
$dN_{ch}/d\eta$	$\sim 1200$	$\sim 1600$	<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>
$\tau_{QGP}$ (fm/c)	2-4	$>10$	<i>lifetime of QGP</i>

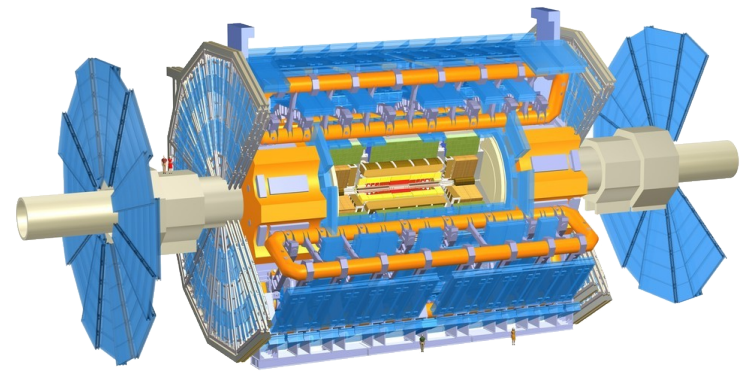
## RHIC and LHC:

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

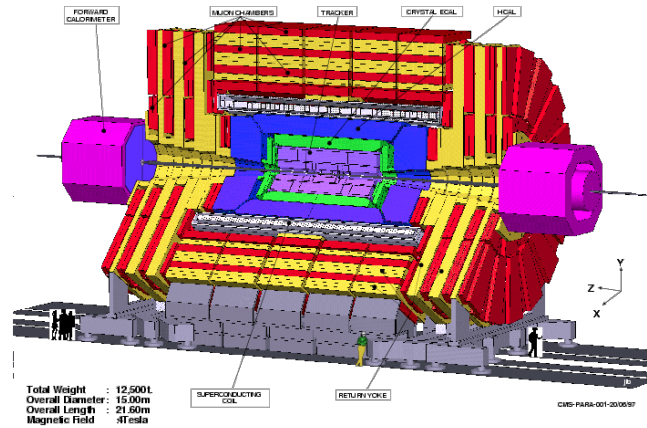
To discover the properties of hot nuclear matter at  $T \sim 150 - 600 \text{ MeV}$



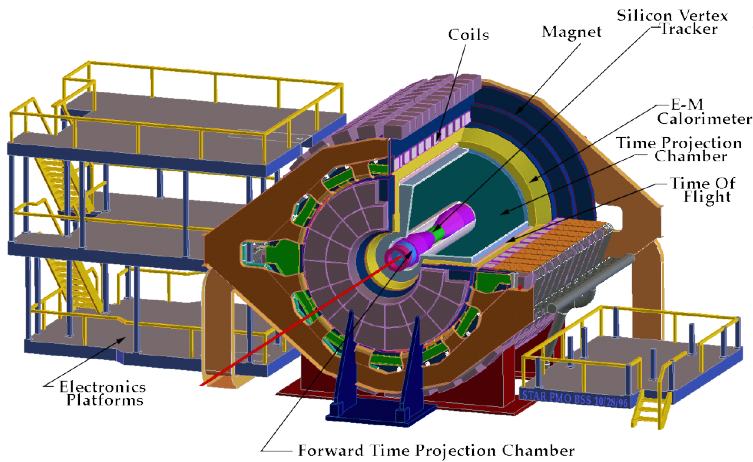
**ALICE**



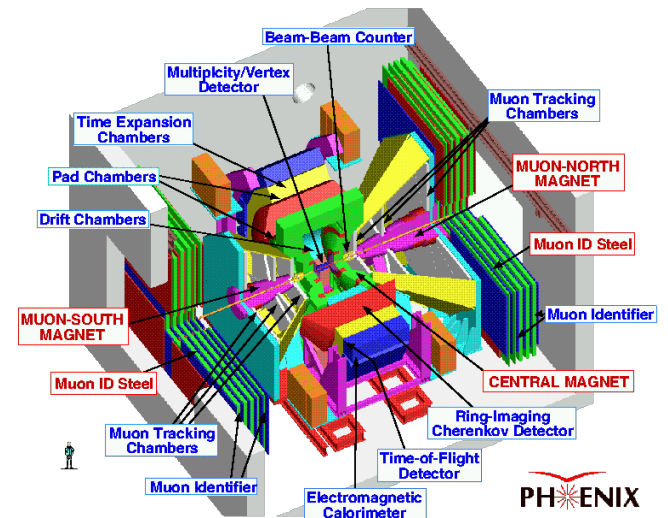
**ATLAS**



**CMS**



**STAR**

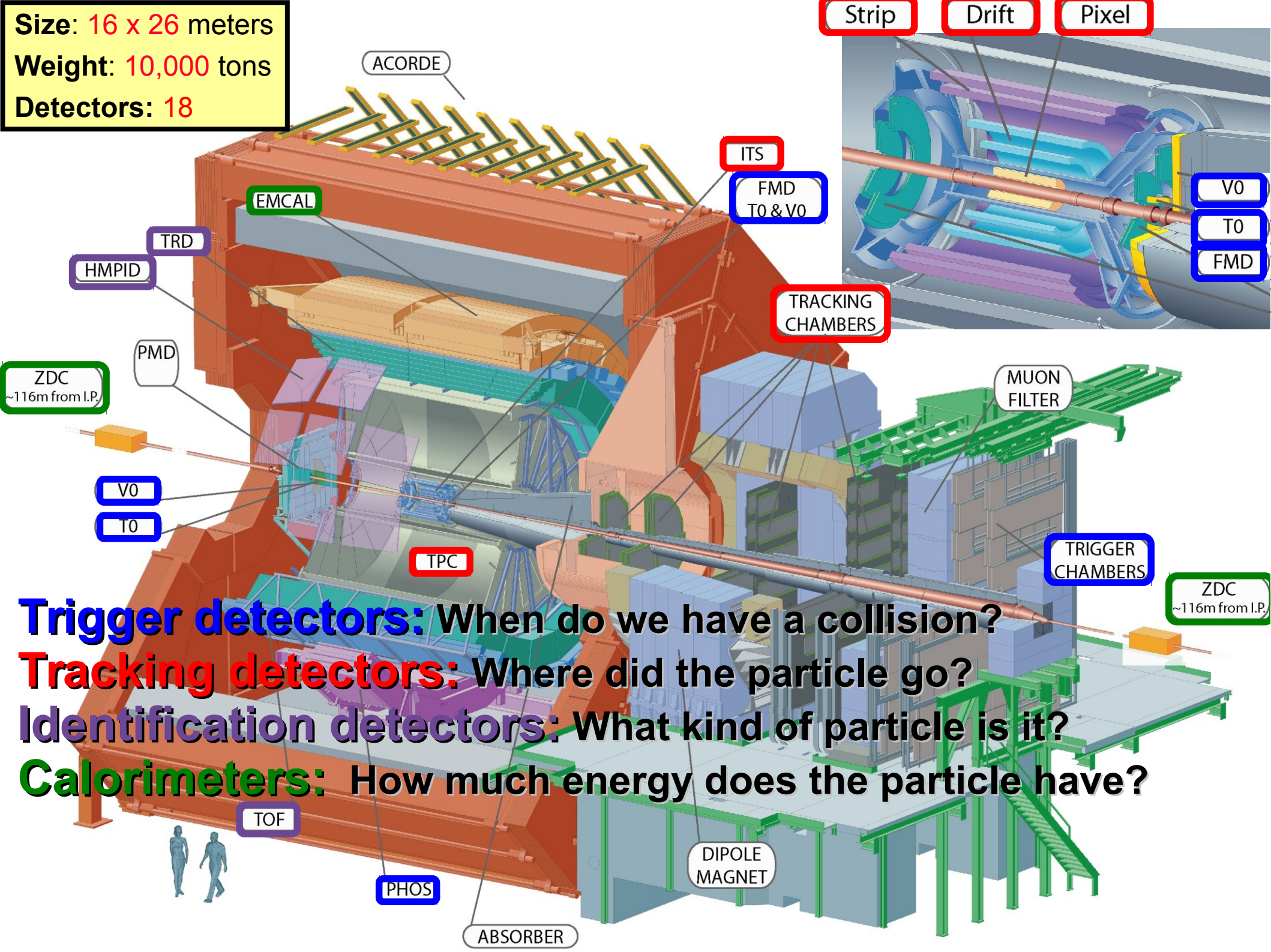


**PHENIX**

# Interesting observables

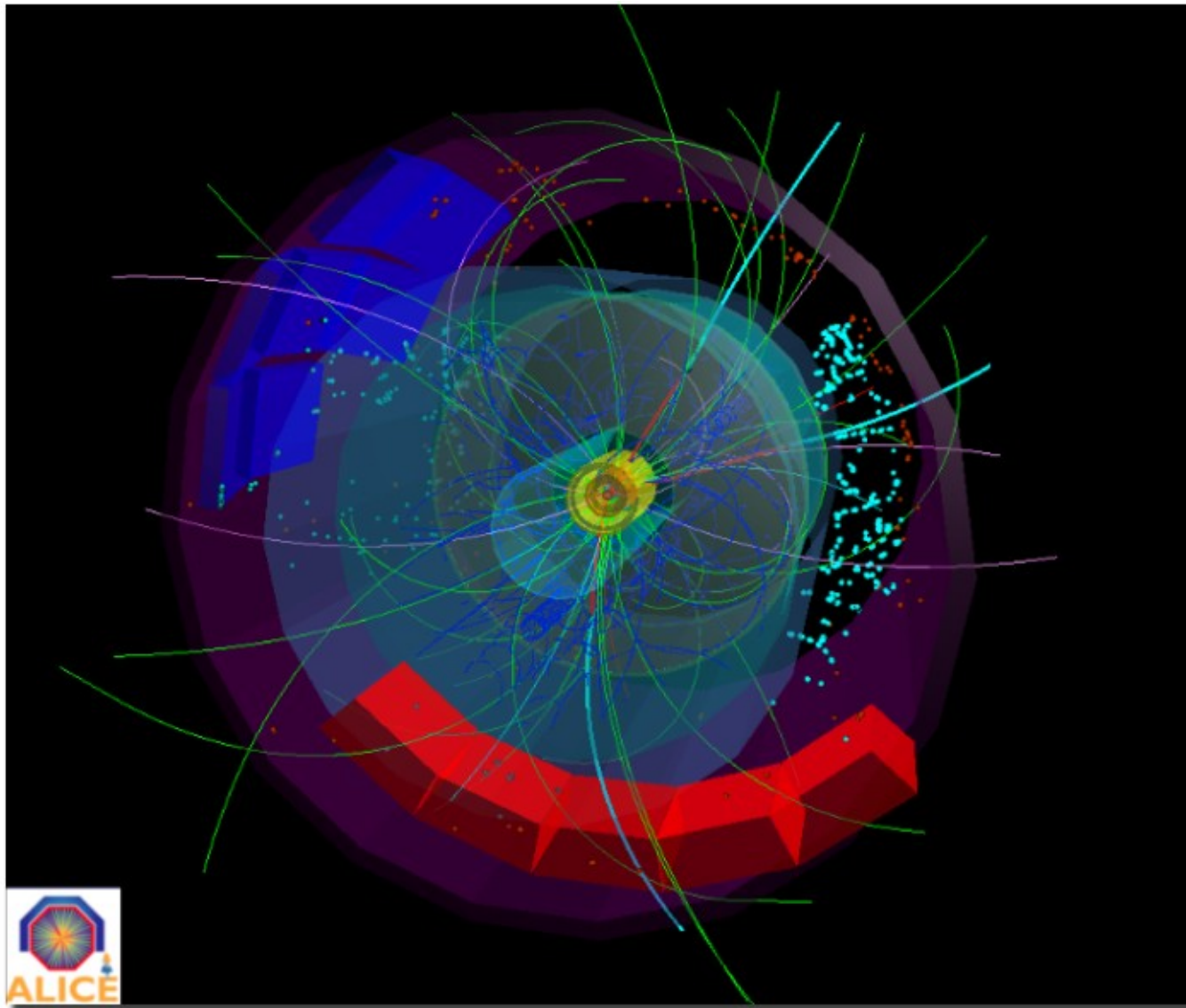
- Different hadronization mechanisms
  - Identify particle types
- Collective motion of particles
  - Low momentum acceptance
- Even common processes are not well understood
  - Do not need  $4\pi$  acceptance or high rates

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



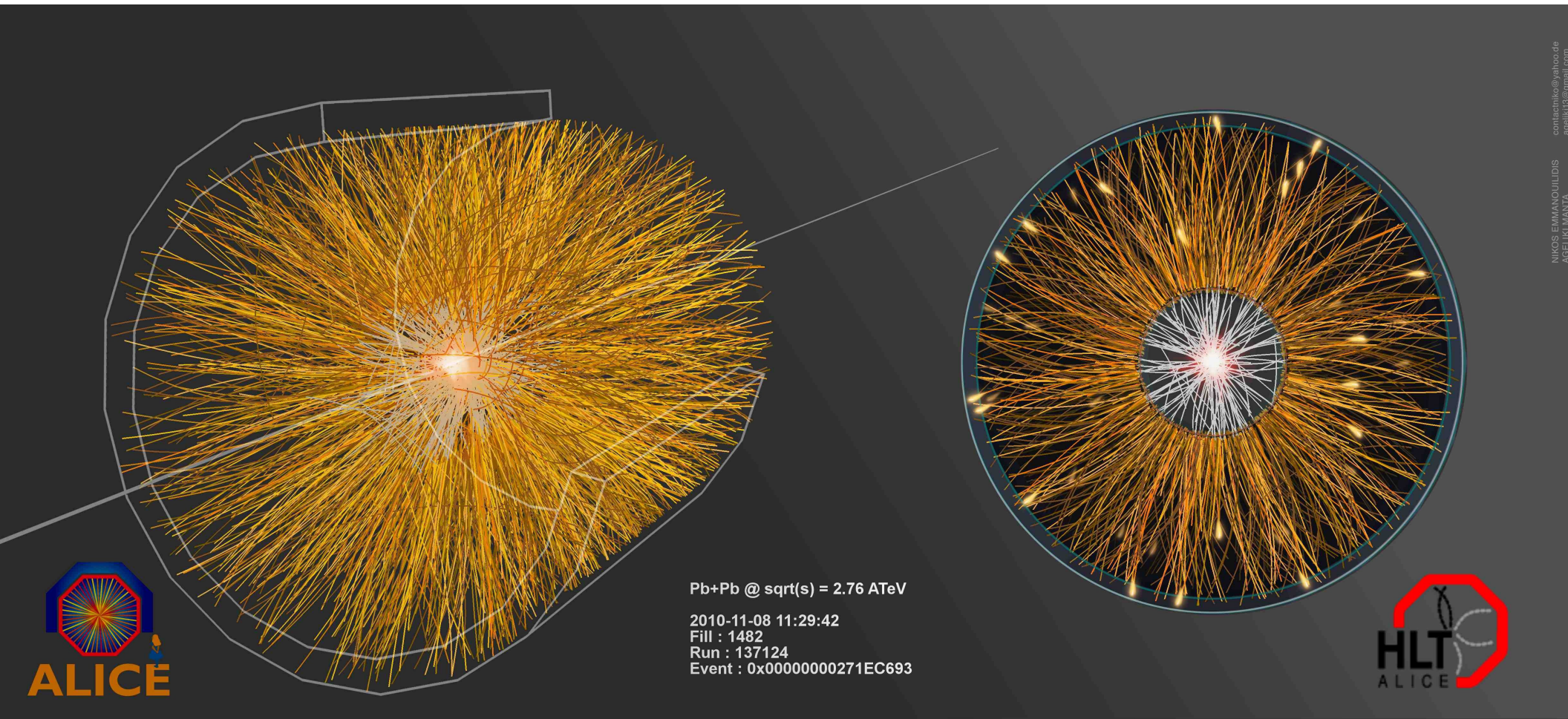
**Trigger detectors:** When do we have a collision?  
**Tracking detectors:** Where did the particle go?  
**Identification detectors:** What kind of particle is it?  
**Calorimeters:** How much energy does the particle have?

# p+p collisions

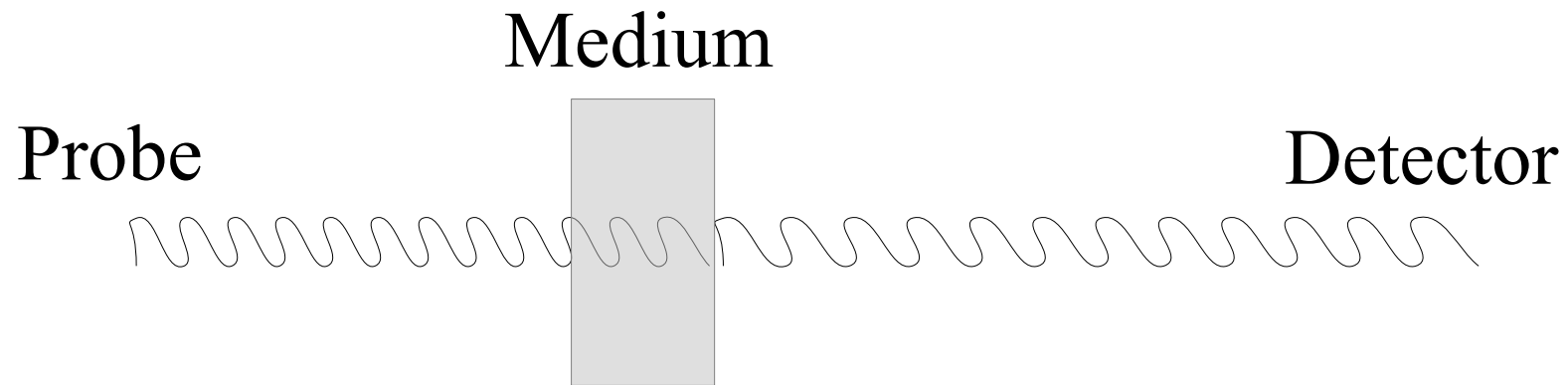


**3D image of each collision**

# Pb+Pb collisions

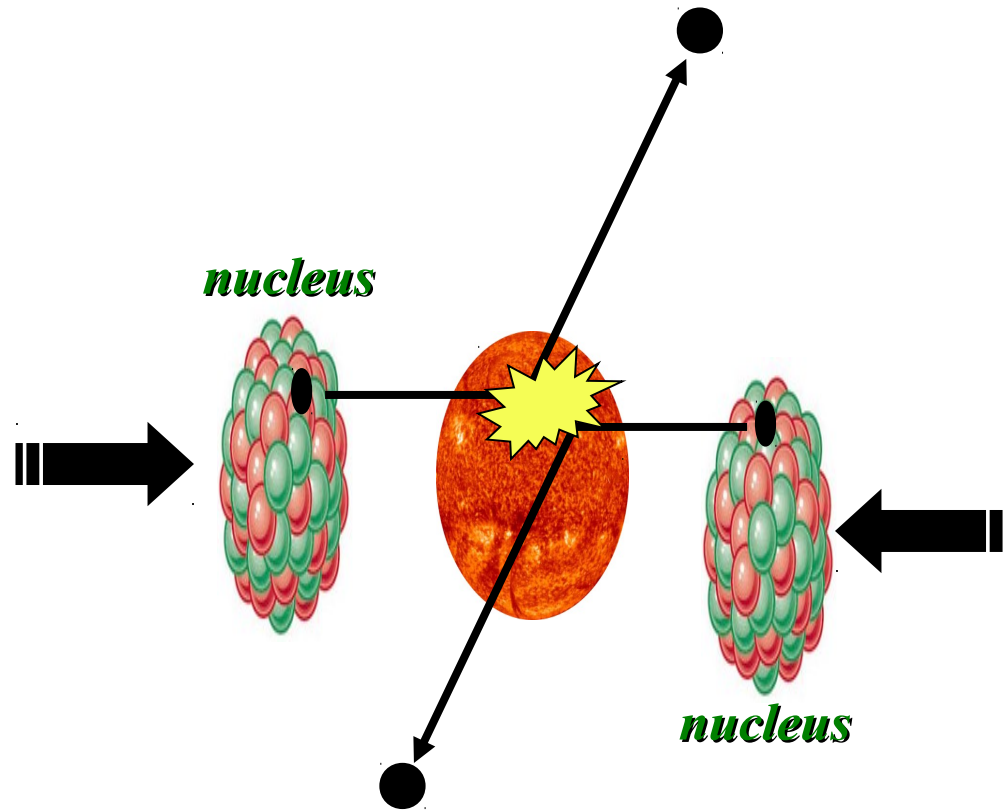


# Probing the Quark Gluon Plasma



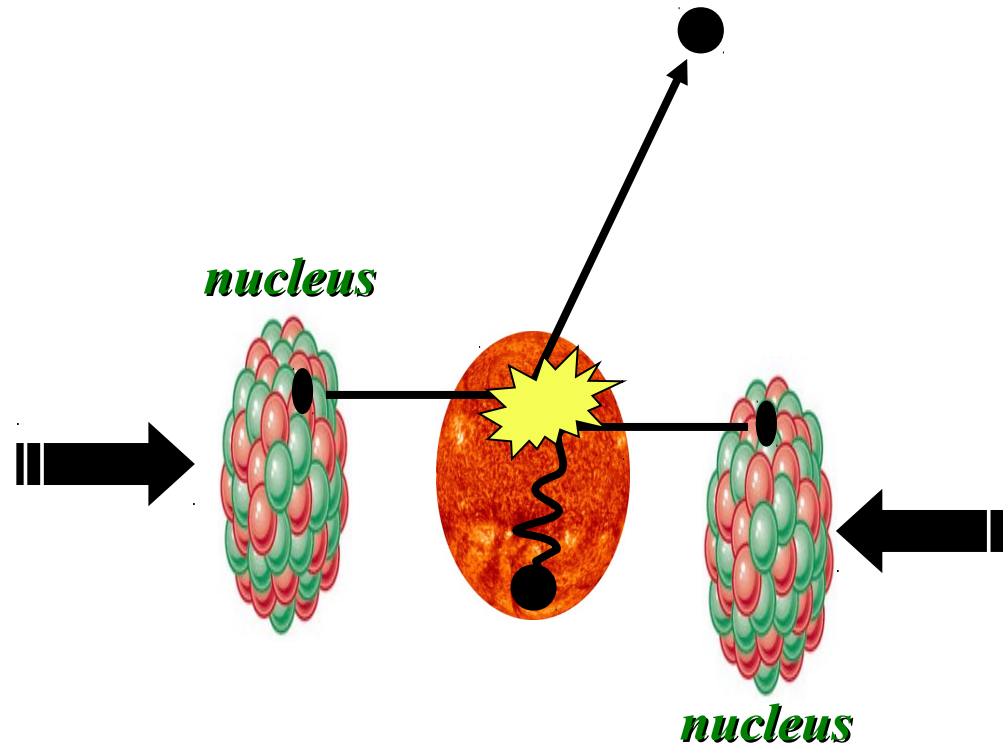
Want a probe which traveled through the collision  
QGP is very short-lived ( $\sim 1-10$  fm/c)  $\rightarrow$   
cannot use an external probe

# Probes of the Quark Gluon Plasma



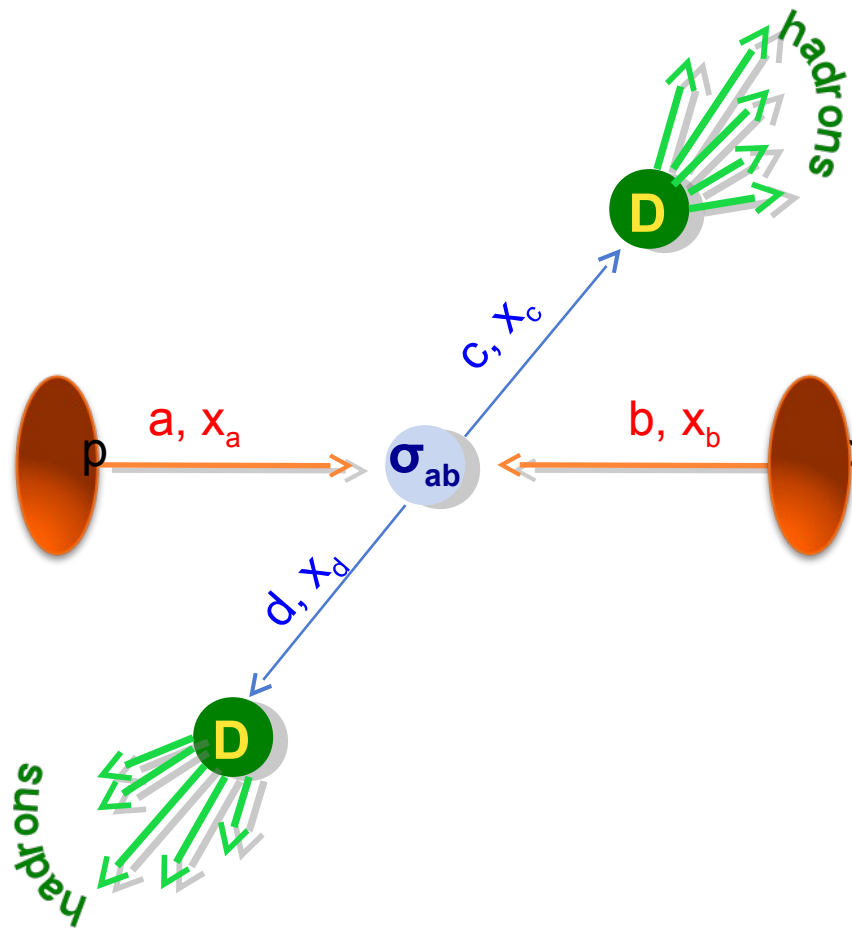
Want a probe which traveled through the medium  
QGP is short lived  $\rightarrow$  need a probe created in the collision

# Probes of the Quark Gluon Plasma

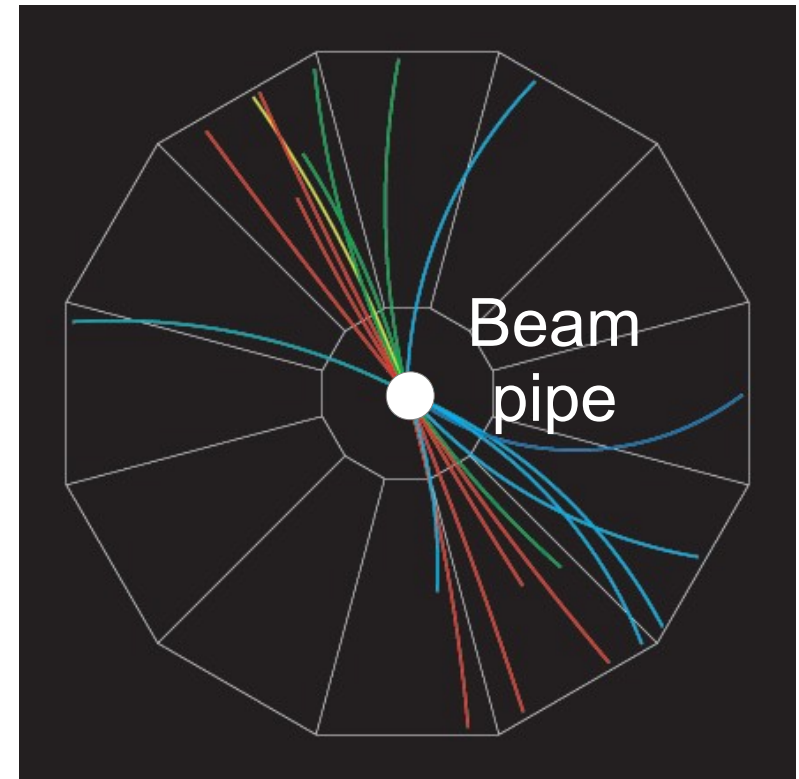


Want a probe which traveled through the medium  
QGP is short lived  $\rightarrow$  need a probe created in the collision  
We expect the medium to be dense  $\rightarrow$  absorb/modify probe

# Jets

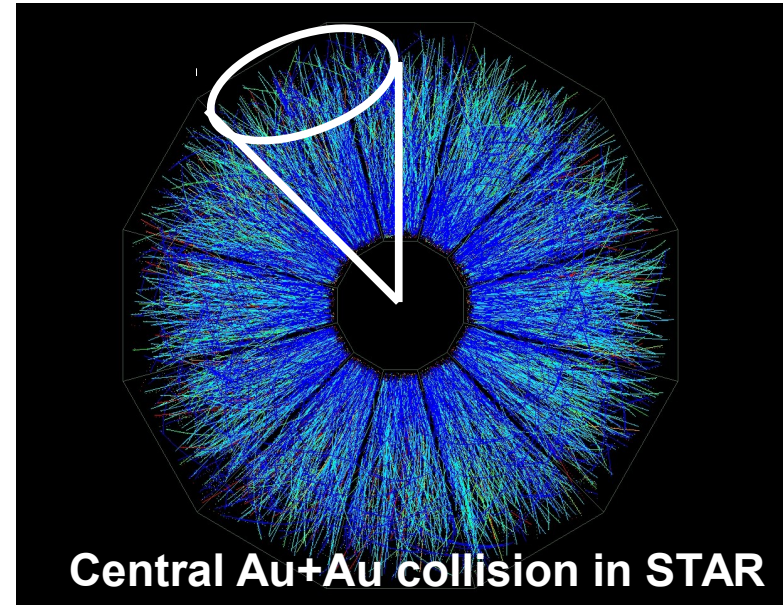
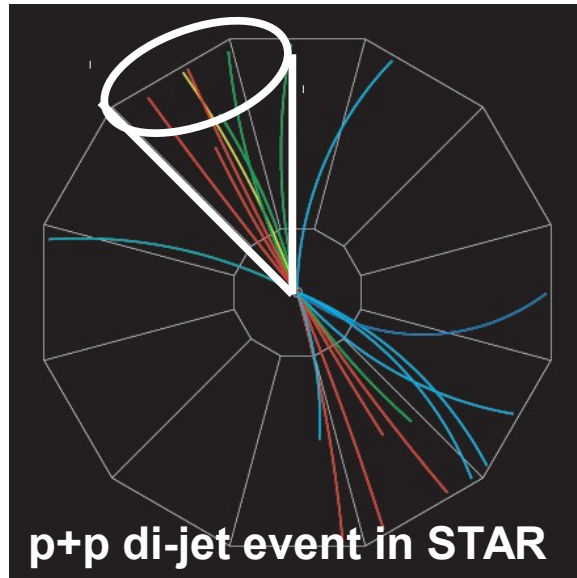


**p+p → dijet**



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

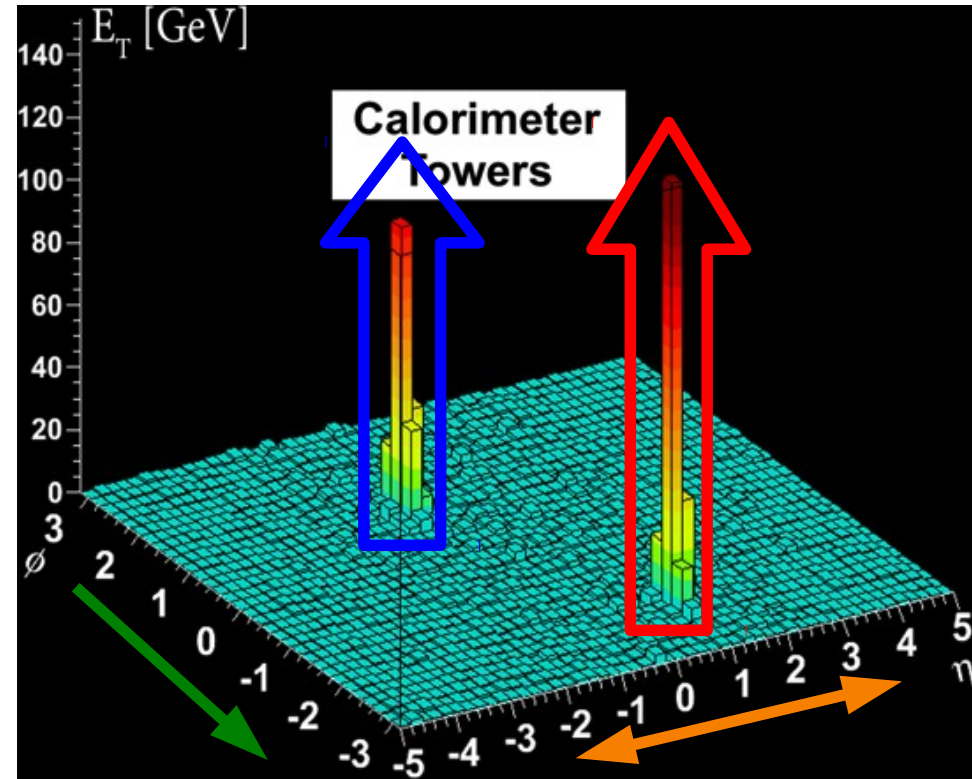
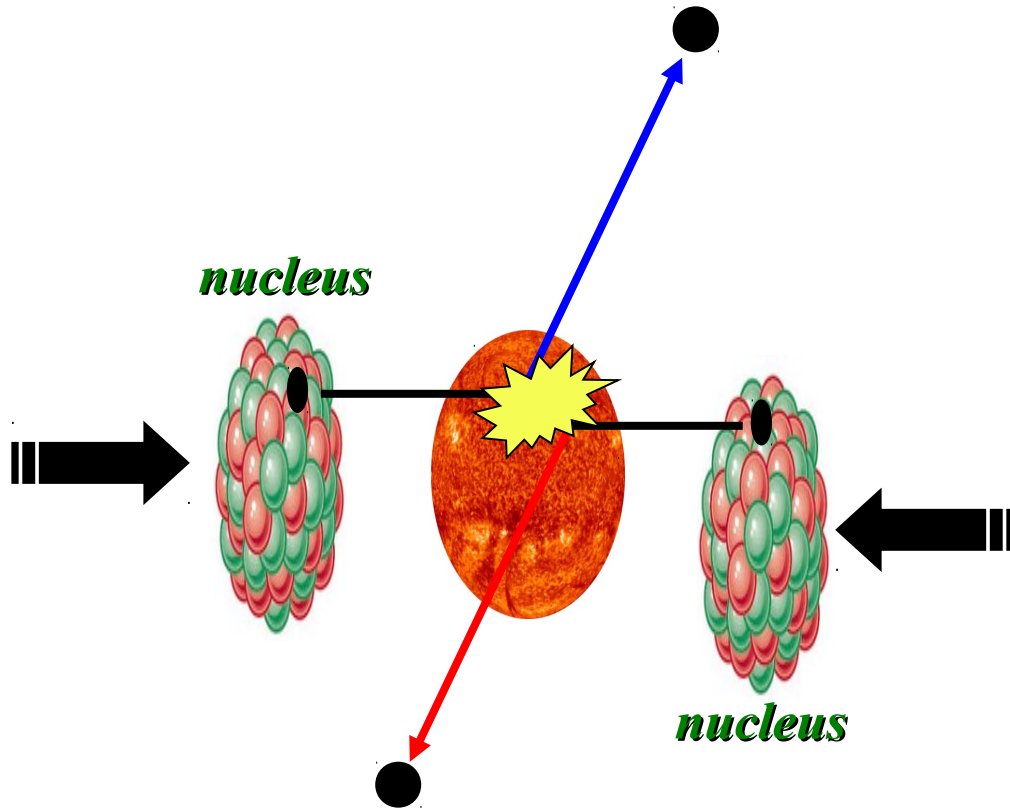
# Jet reconstruction



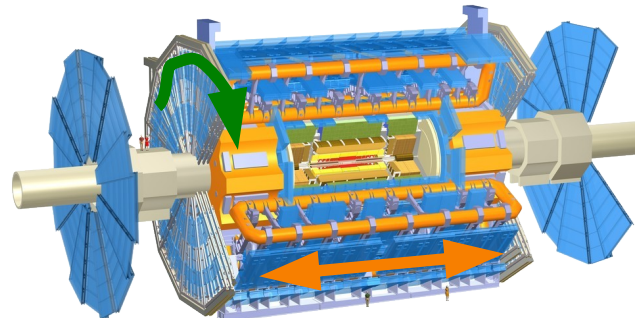
- Identify all of the particles in the jet  $\rightarrow$  parton energy, momentum
- Difficult in heavy ion collisions – but possible!

# Jets

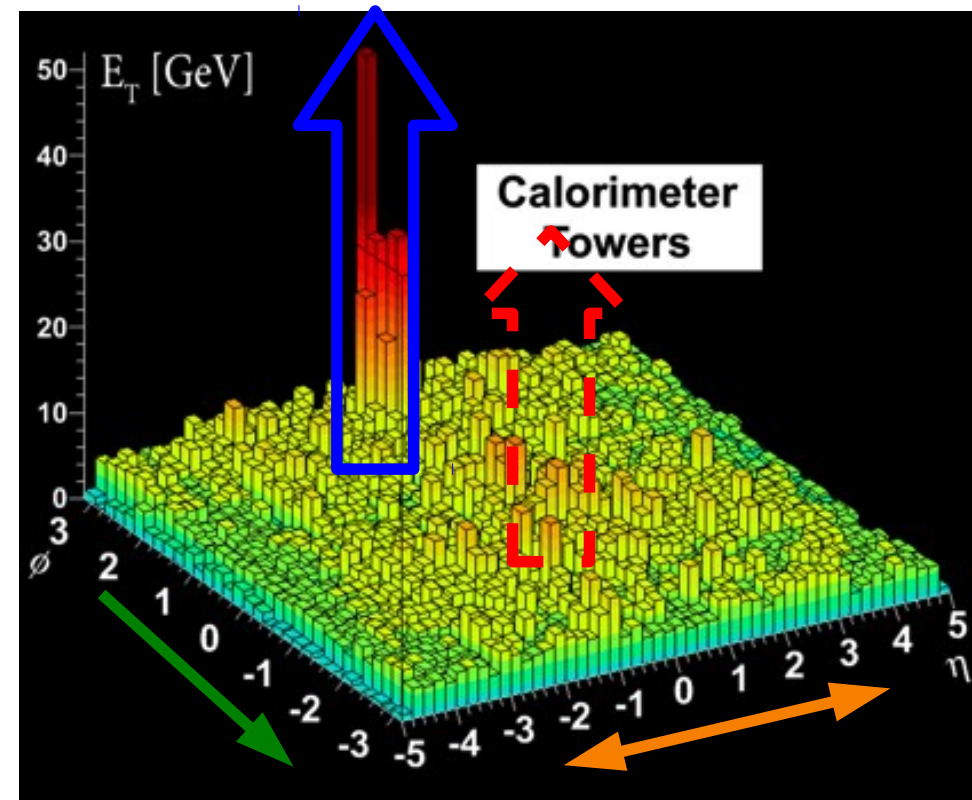
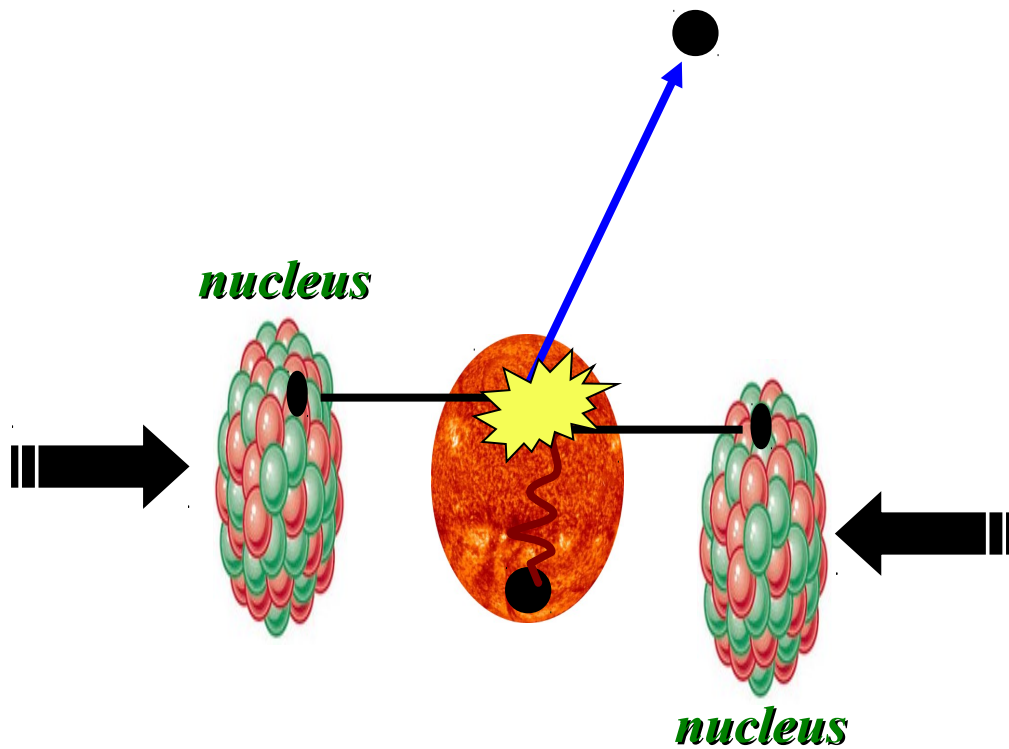
Phys.Rev.Lett. 105 (2010) 252303



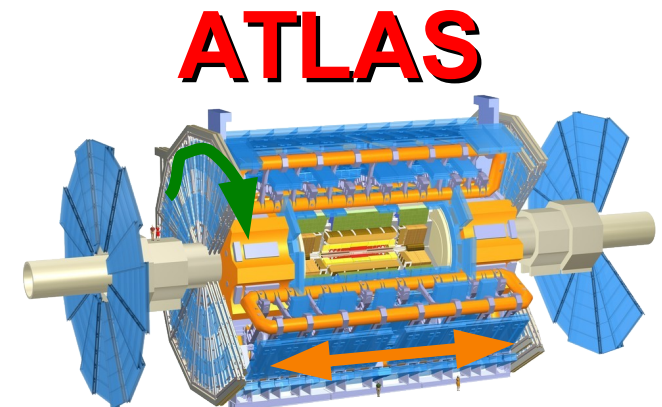
## ATLAS



# Quenched jets

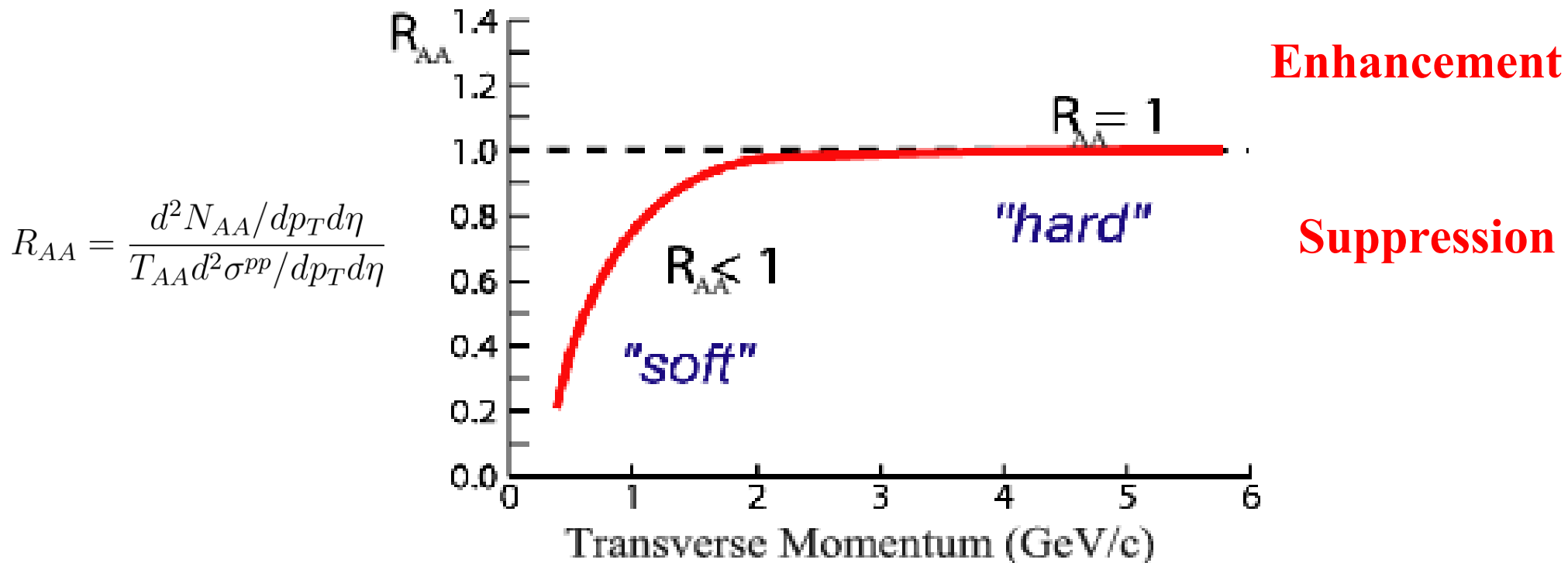


- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
- Phys. Rev. Lett. 105, 252303 (2010)



# Nuclear modification factor

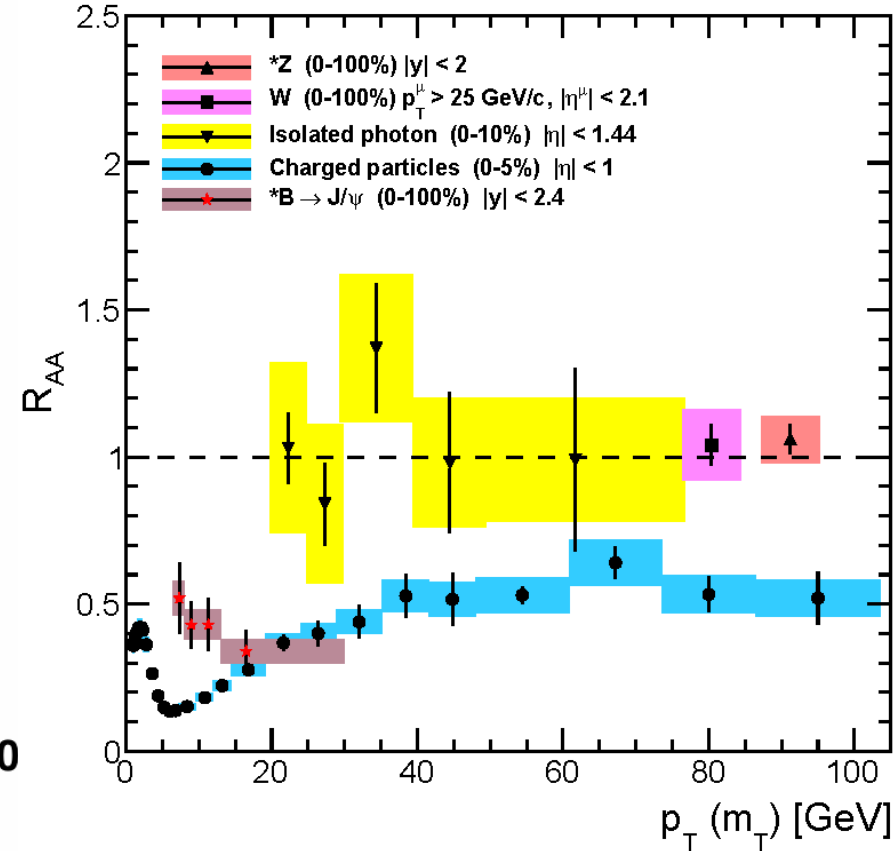
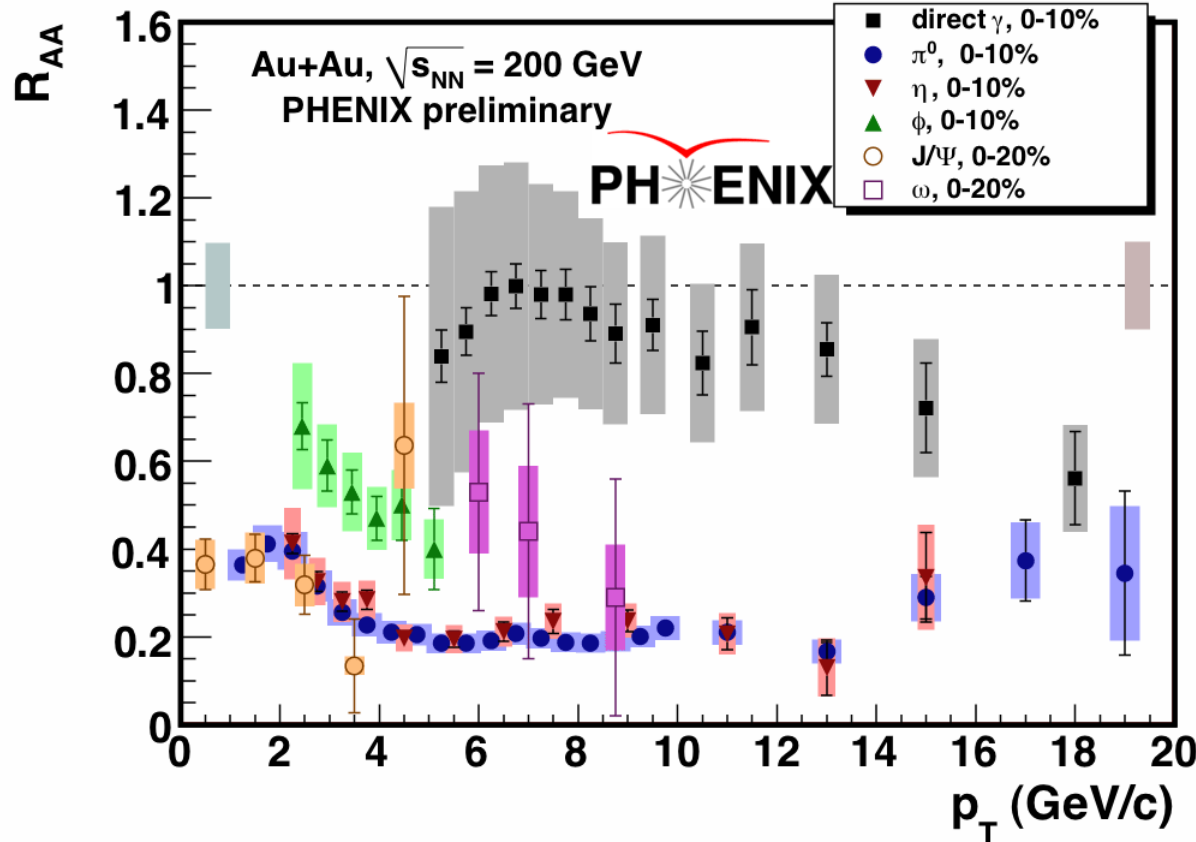
- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high- $p_T$  probes (jets) are suppressed, this is evidence of jet quenching



# Nuclear modification factor $R_{AA}$

**RHIC**

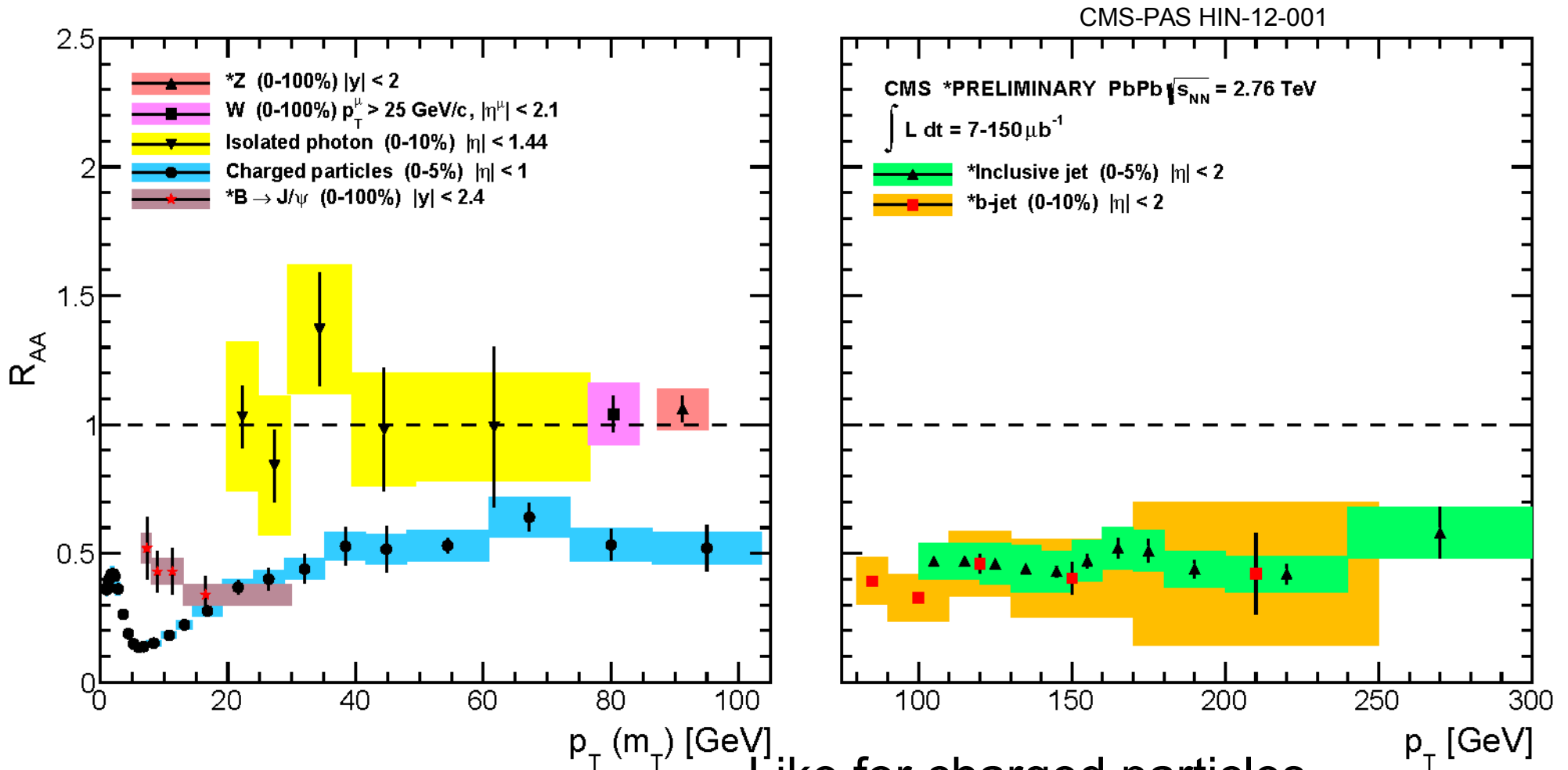
**LHC**



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

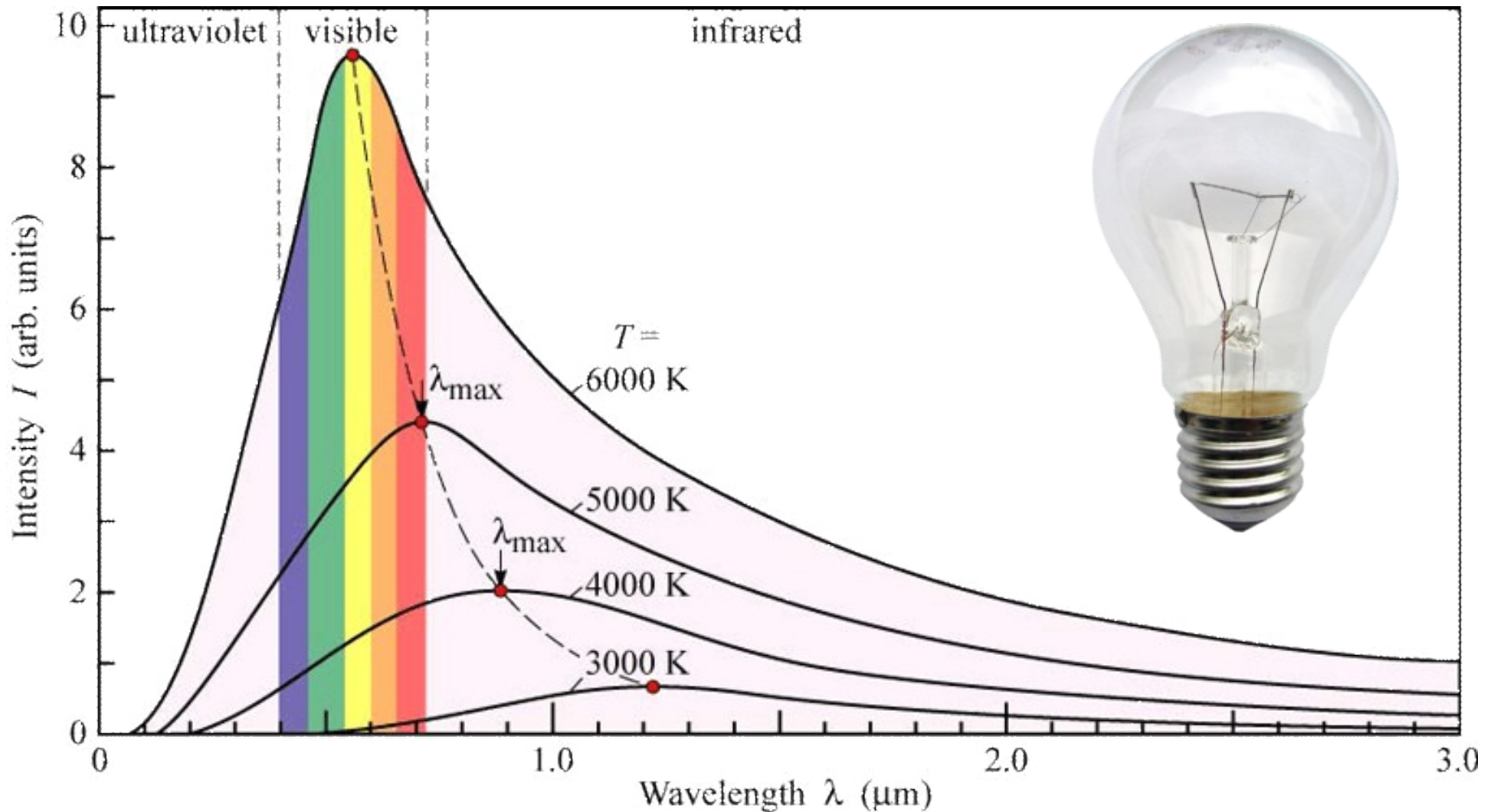
# Nuclear modification factor $R_{AA}$ at LHC

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



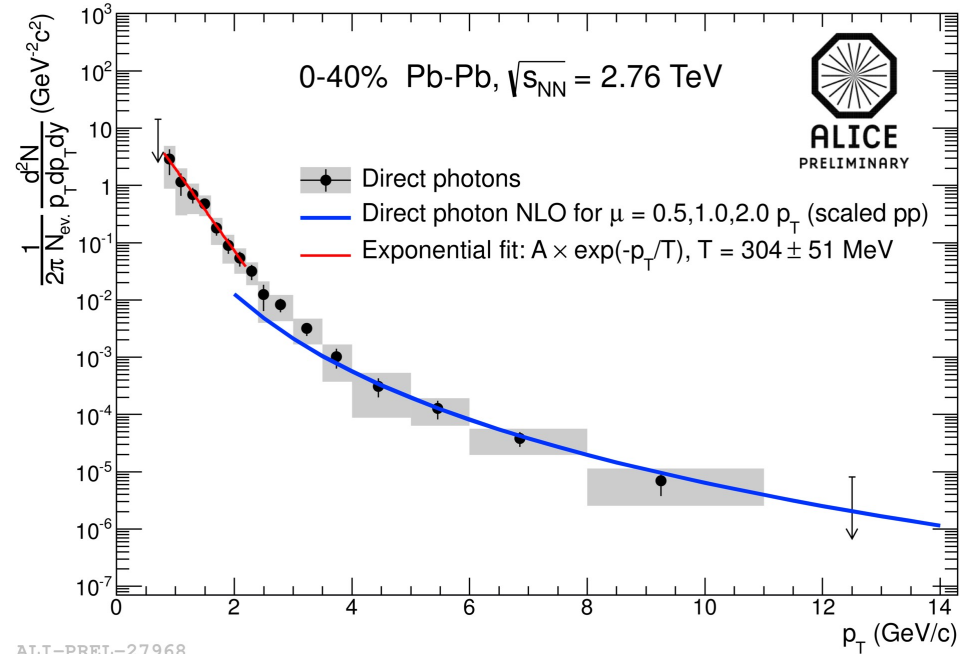
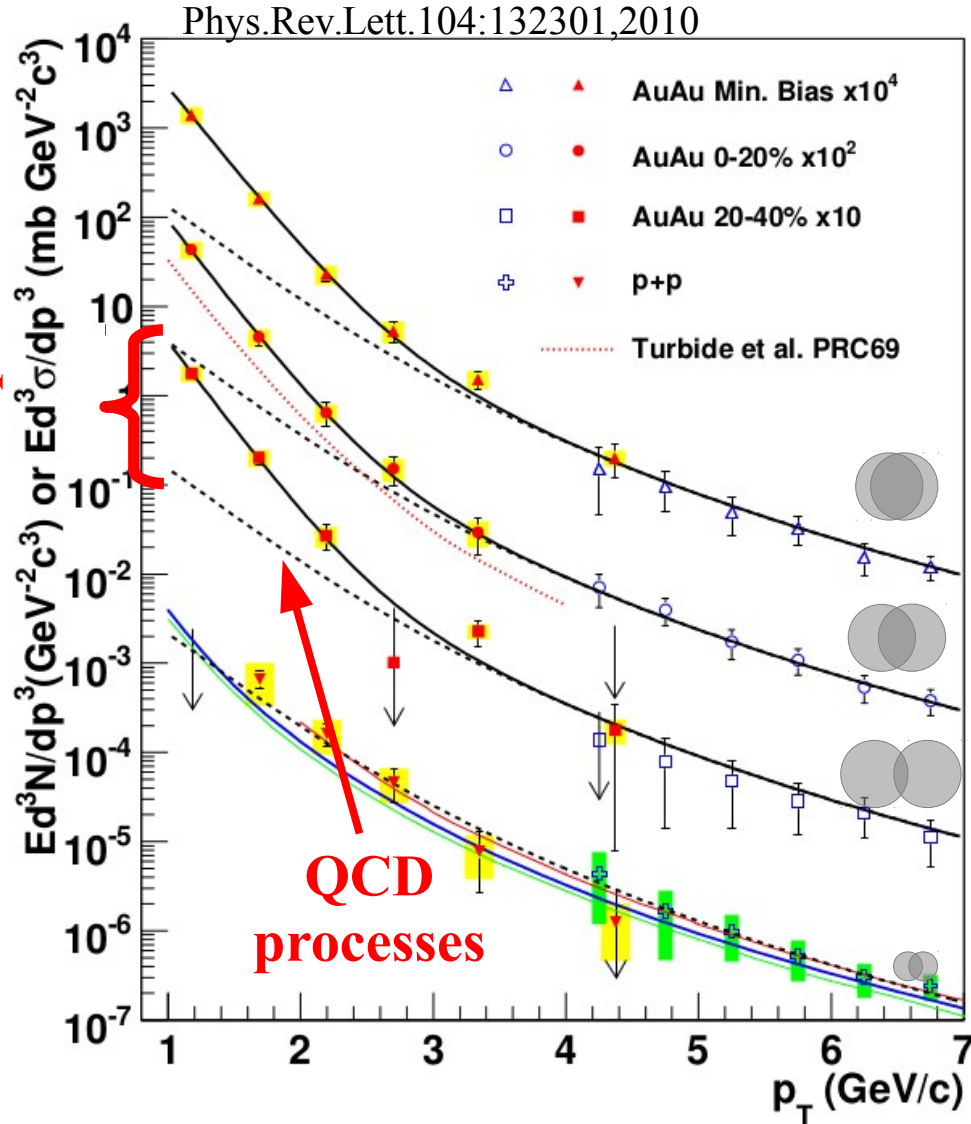
Like for charged particles,  
high- $p_T$  jet  $R_{AA}$  flat at  $\approx 0.5$

# Measuring temperature



# Thermal photons

Thermal photons



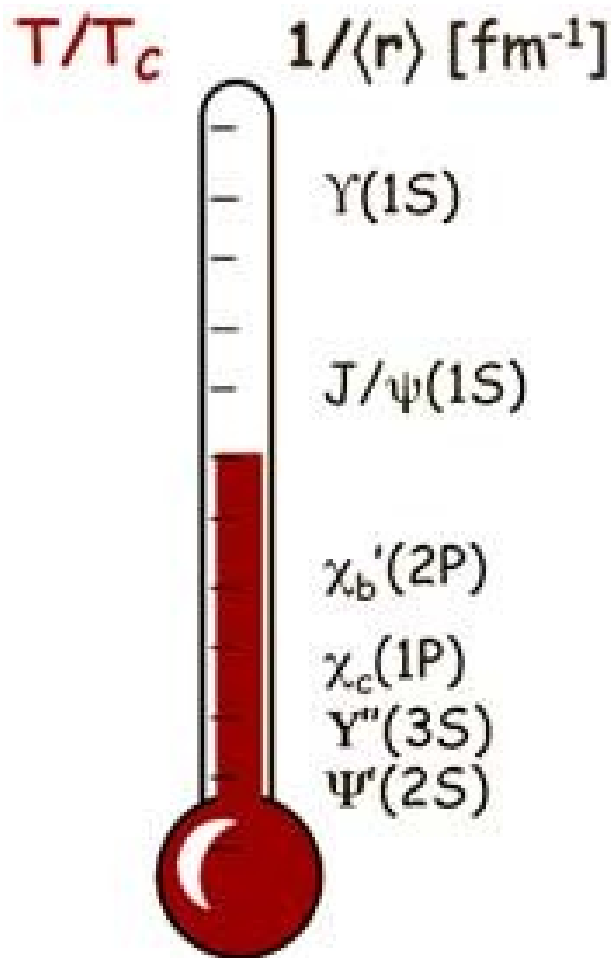
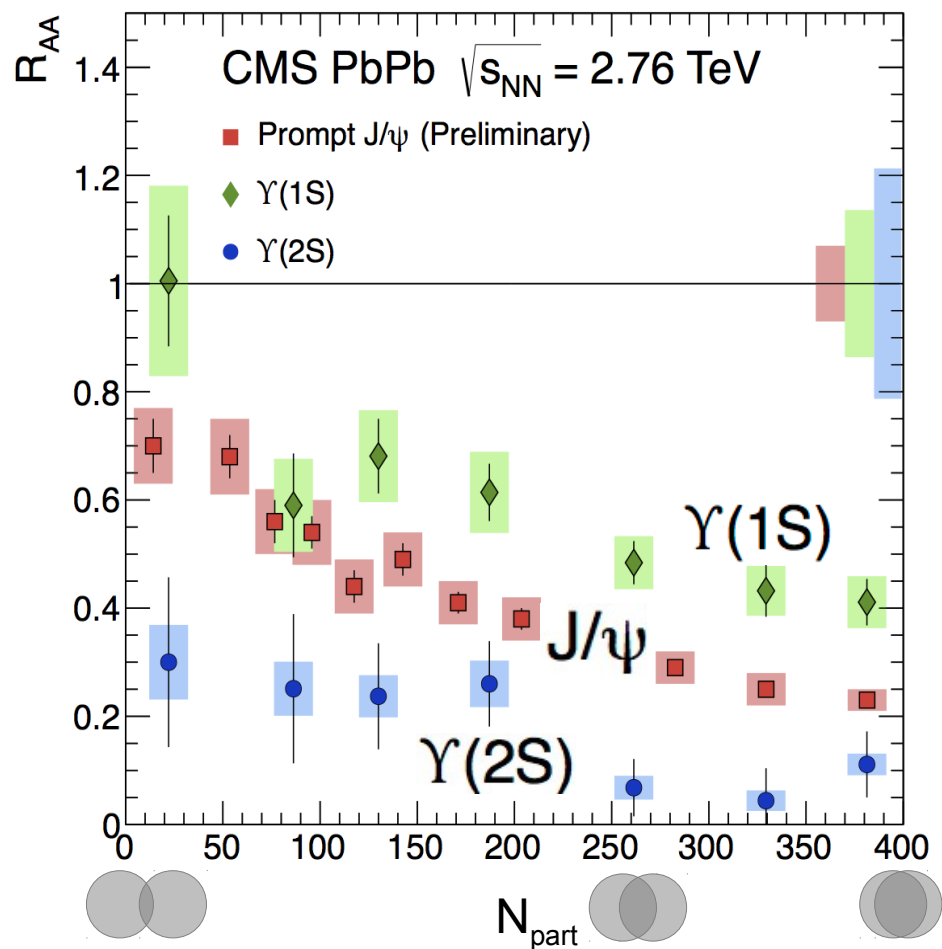
**ALICE collaboration:**  
Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV  
**Inverse slope:  $T = 304 \pm 51$**

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

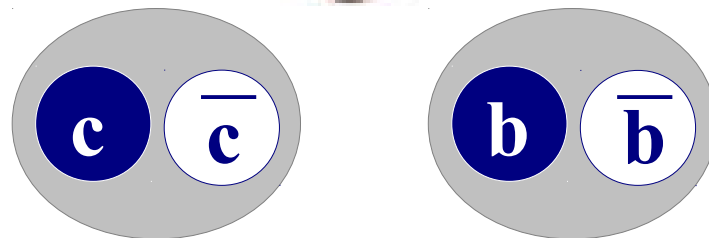
**Inverse slope:  $T = 221 \pm 19$  (stat)  $\pm 19$  (syst) MeV**

# Building a quarkonium-thermometer

CMS-PAS HIN-11-011

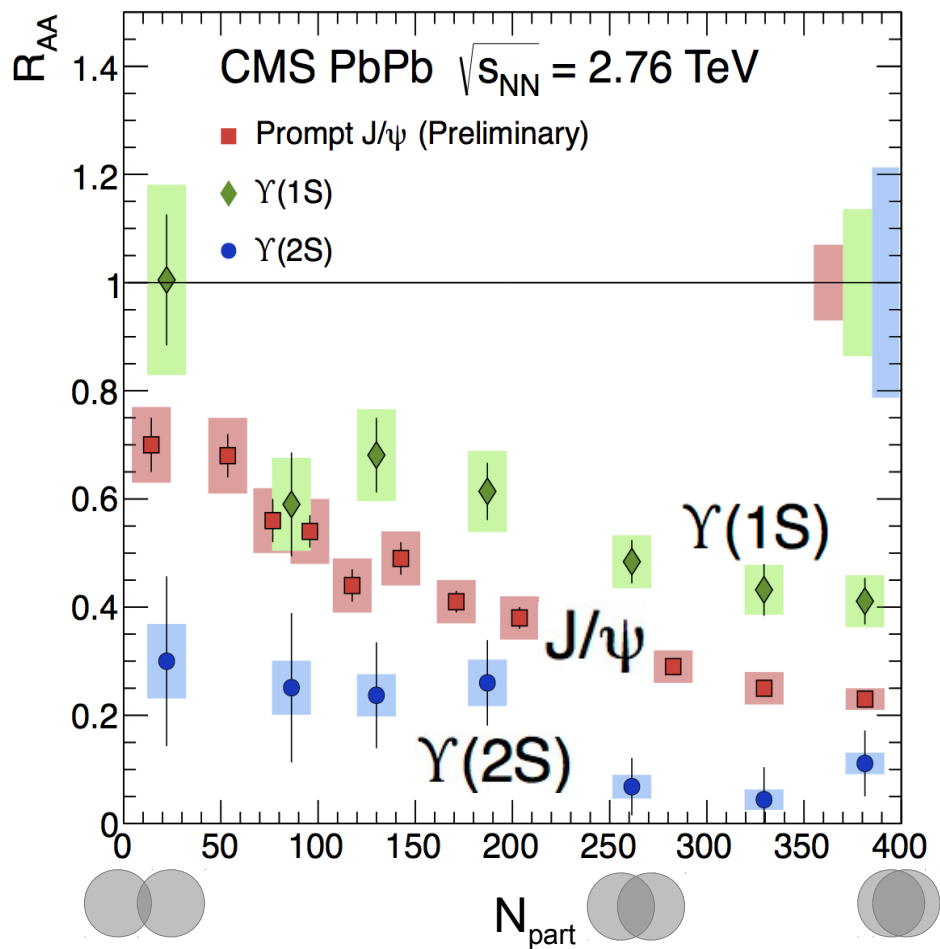


Clear hierarchy in  $R_{AA}$  of different quarkonium states



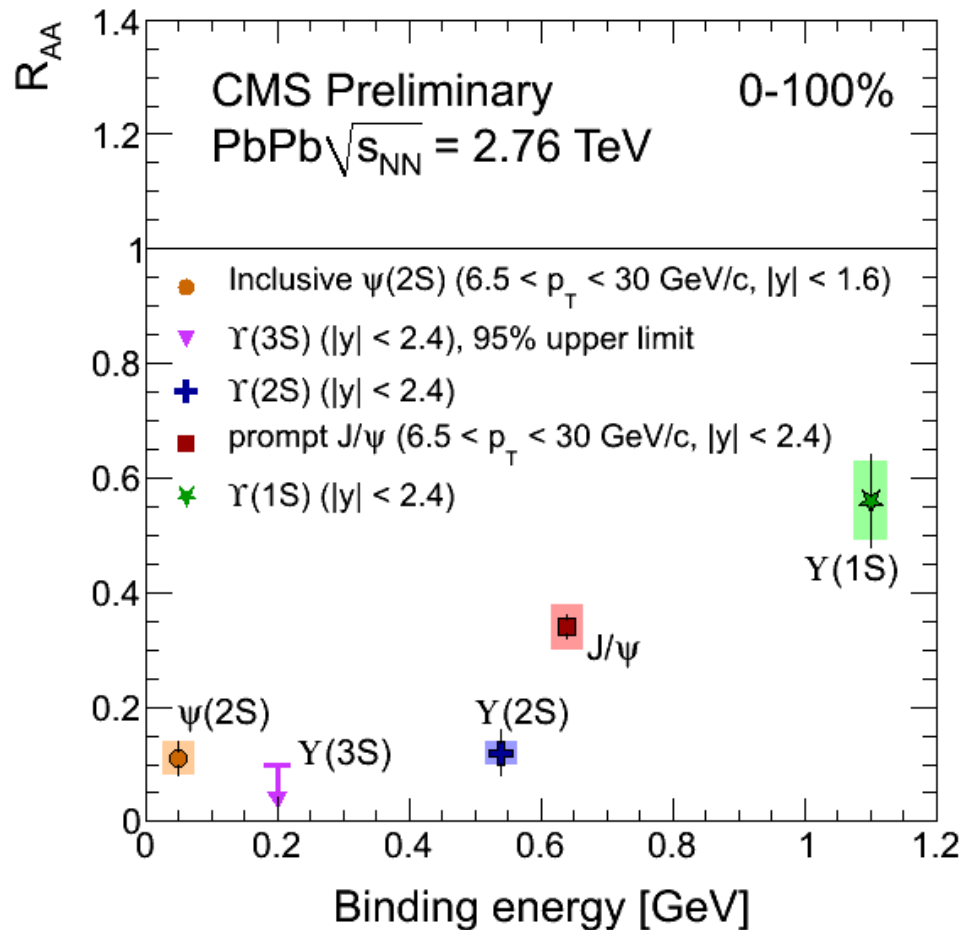
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CMS-PAS HIN-11-011



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

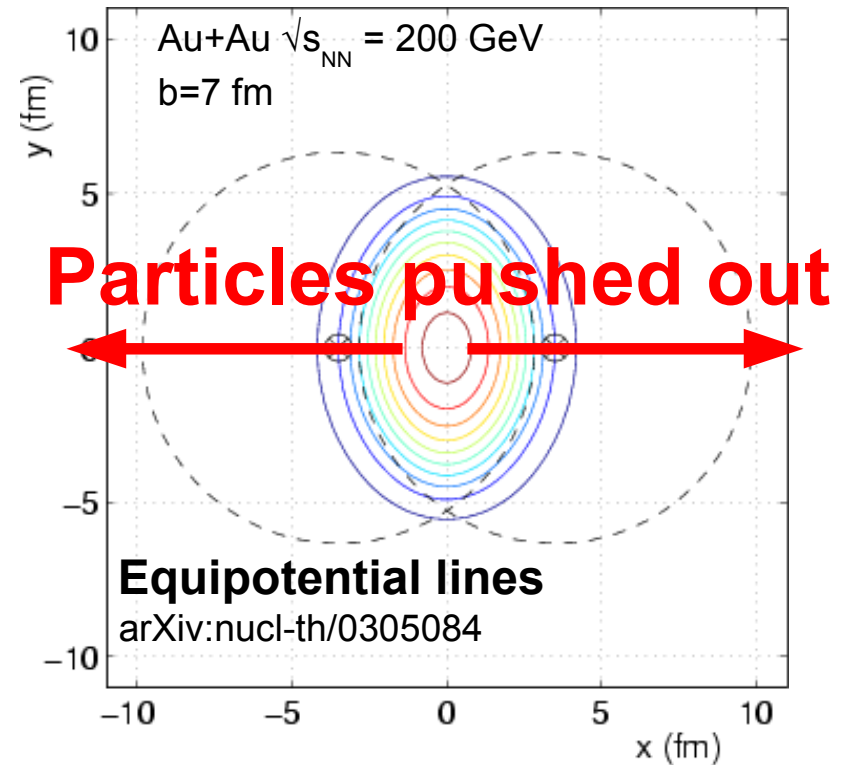
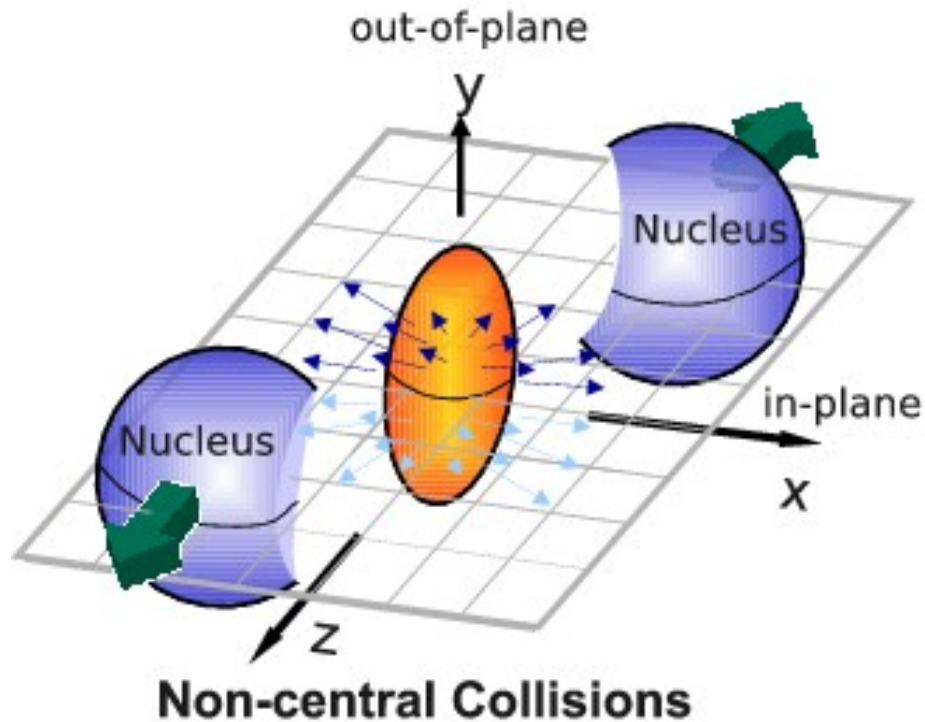
Note:  $6.5 < p_T < 30$  GeV for J/ψ and ψ(2s)



Expected in terms of binding energy

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

# If we have a fluid...



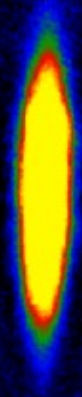
- Initial overlap asymmetric  $\rightarrow$  pressure gradients
- Momentum anisotropy  $\rightarrow$  Fourier decomposition:

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

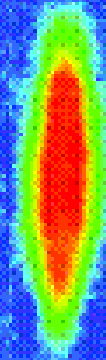
# What does this mean?

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

High viscosity

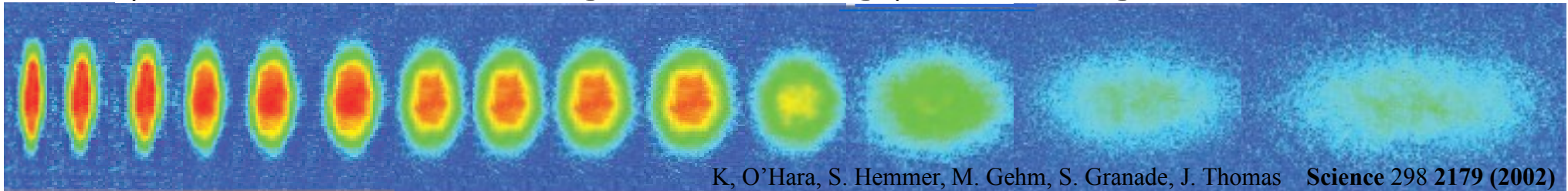


Low viscosity



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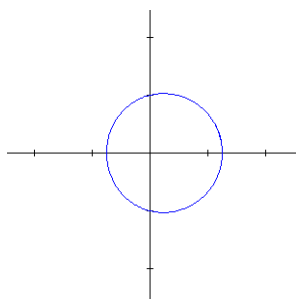


Time  $\longrightarrow$

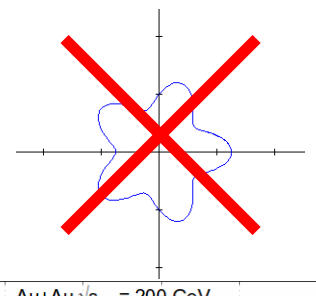
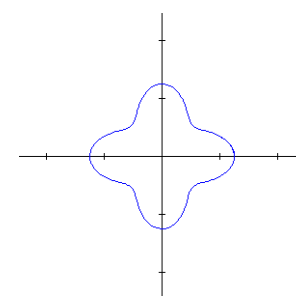
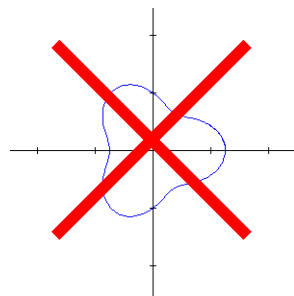
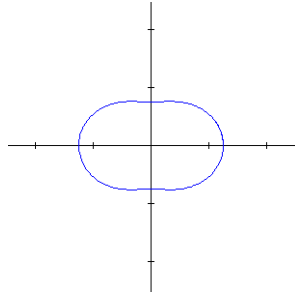
**Initial state anisotropies converted to final state anisotropies**

Fourier decomposition:

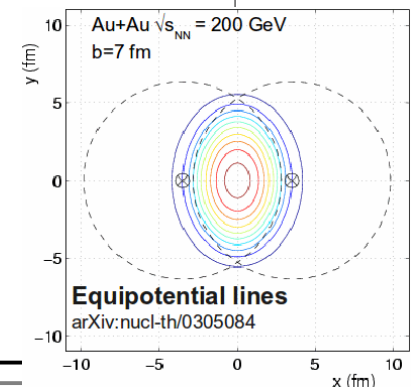
$$\frac{d^2 N}{dp_T d\varphi} \approx 1 + 2v_1 \cos(d\varphi) + 2v_2 \cos(2d\varphi) + 2v_3 \cos(3d\varphi) + 2v_4 \cos(4d\varphi) + 2v_5 \cos(5d\varphi) + \dots$$



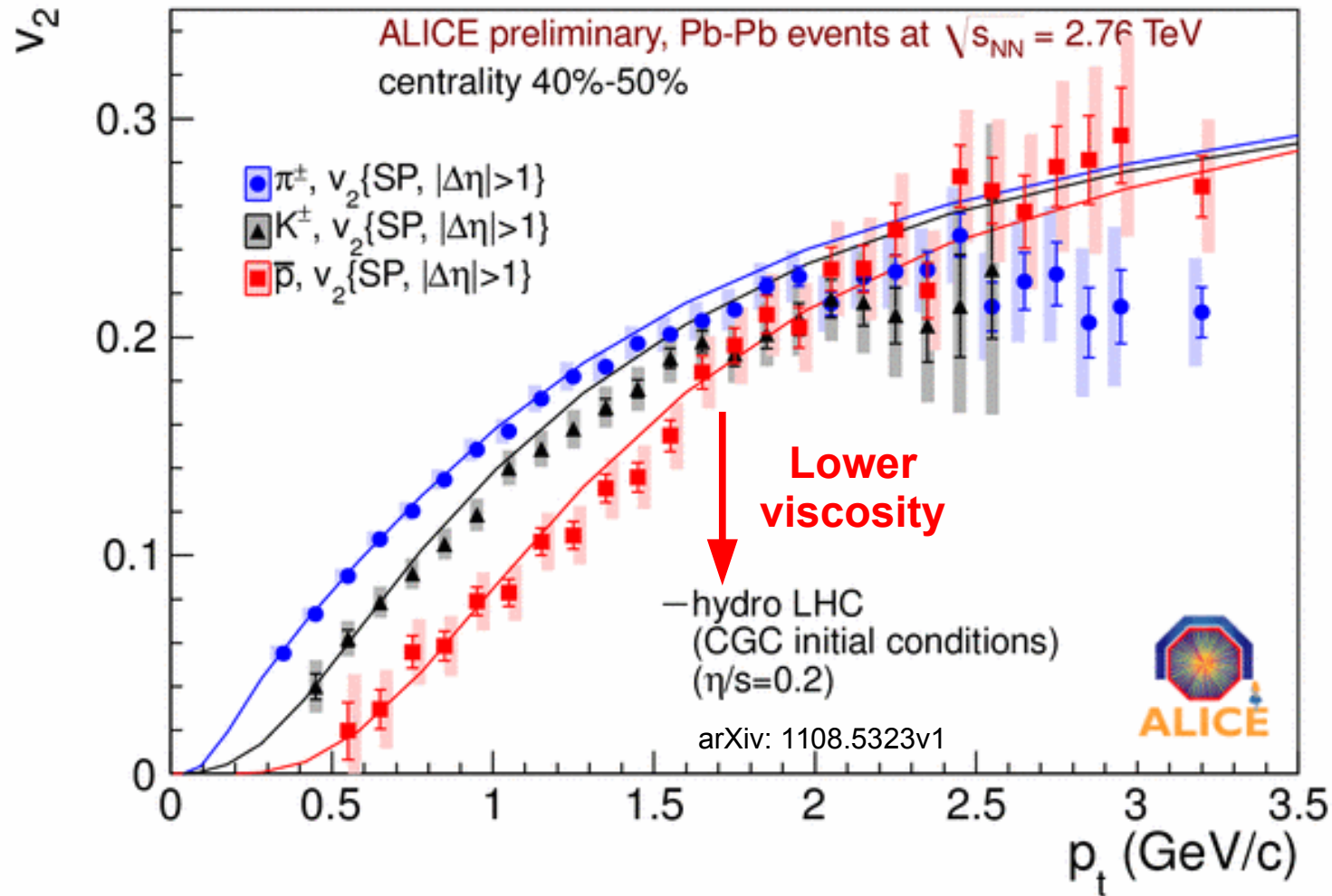
Offset  
measured



**Nuclei are symmetric  $\rightarrow$   
No odd coefficients**



# Does this describe the data?



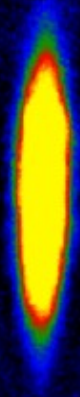
ALI-PREL-2457

**Yes!**

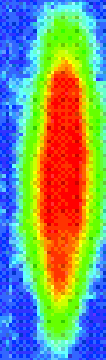
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High viscosity

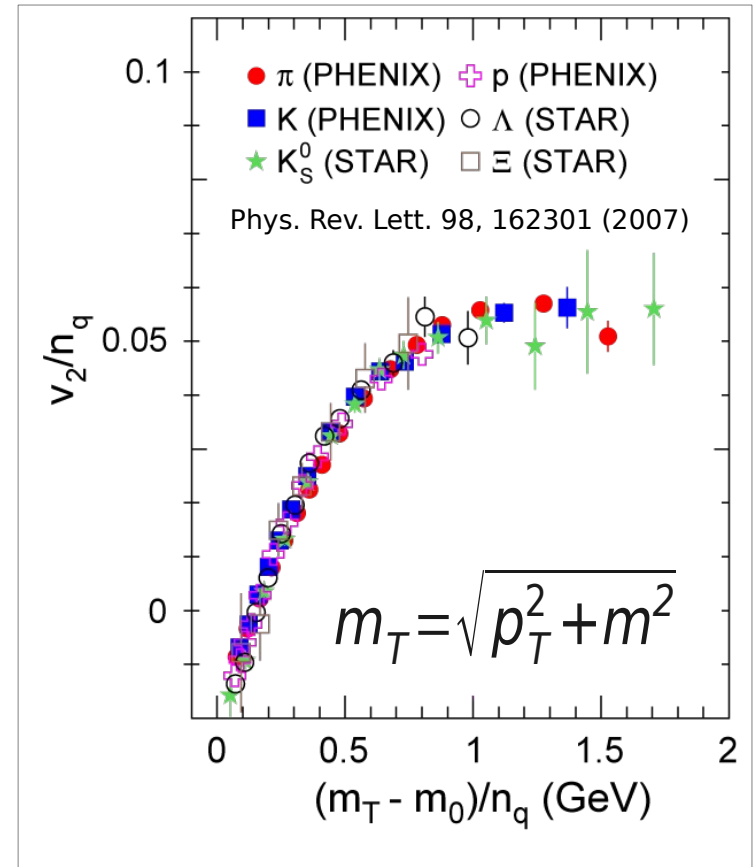
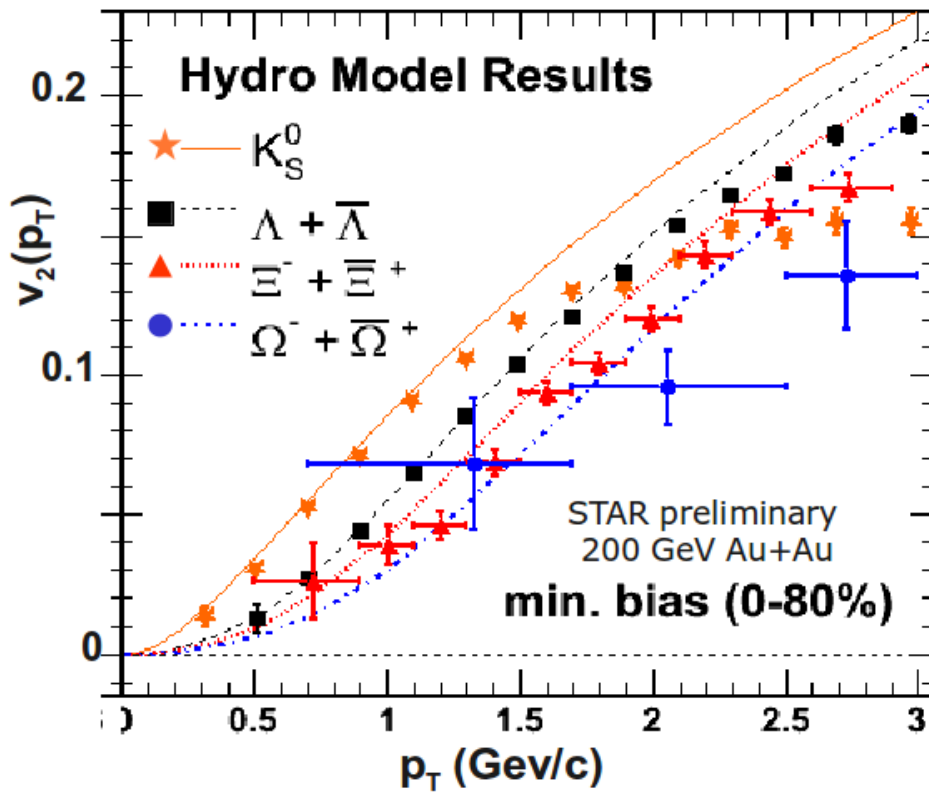


Low viscosity



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

# More data



Mass ordering:

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

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

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

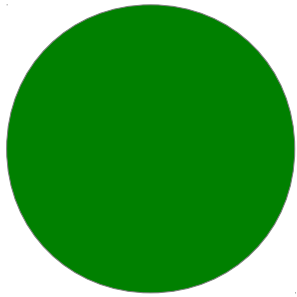
# What do we learn about the QGP?

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

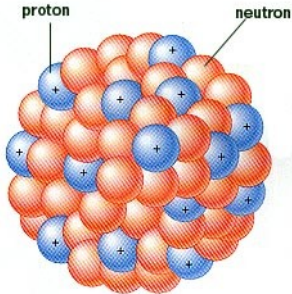


**The QGP is the perfect liquid!**

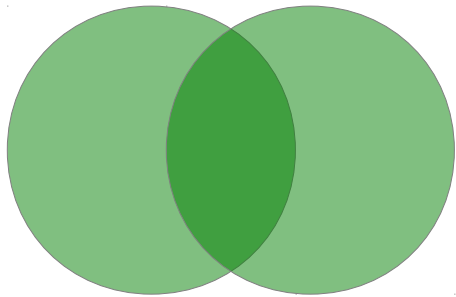
(not the gas of “free” quarks and gluons we expected)



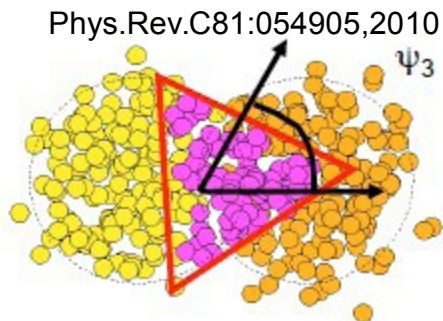
This is not what a nucleus looks like



*This* is what a nucleus looks like



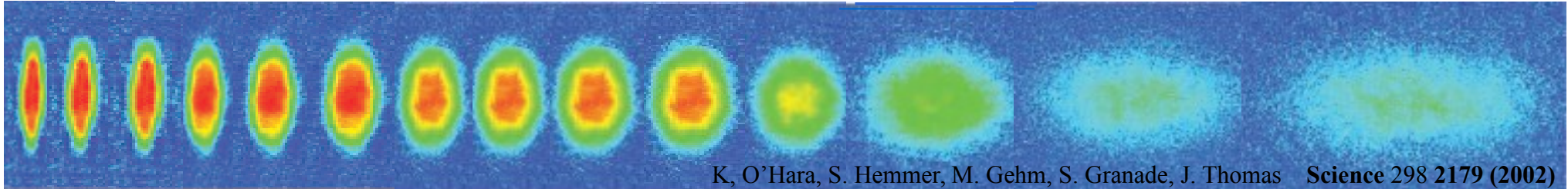
This is not what our collision looks like



This is what our collision looks like

# What does it mean?

Same phenomena observed in gases of strongly interacting atoms

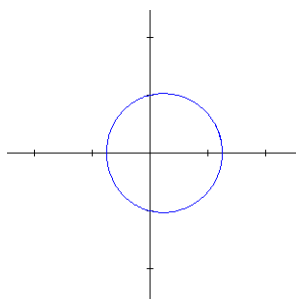


Time  $\longrightarrow$

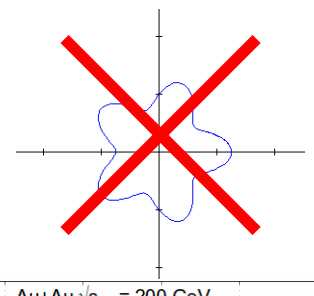
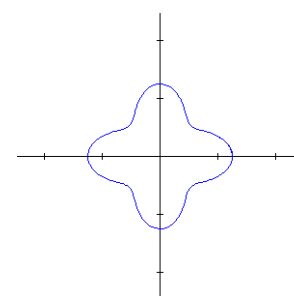
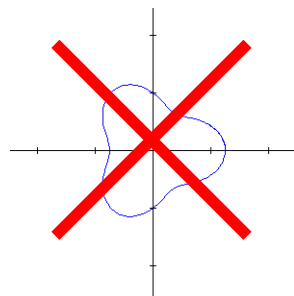
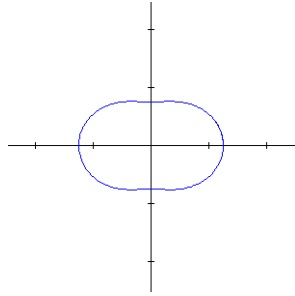
**Initial state anisotropies converted to final state anisotropies**

Fourier decomposition:

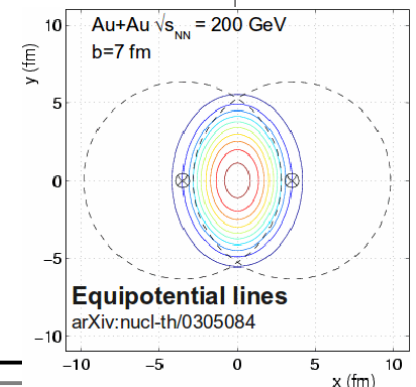
$$\frac{d^2 N}{dp_T d\varphi} \approx 1 + 2v_1 \cos(d\varphi) + 2v_2 \cos(2d\varphi) + 2v_3 \cos(3d\varphi) + 2v_4 \cos(4d\varphi) + 2v_5 \cos(5d\varphi) + \dots$$



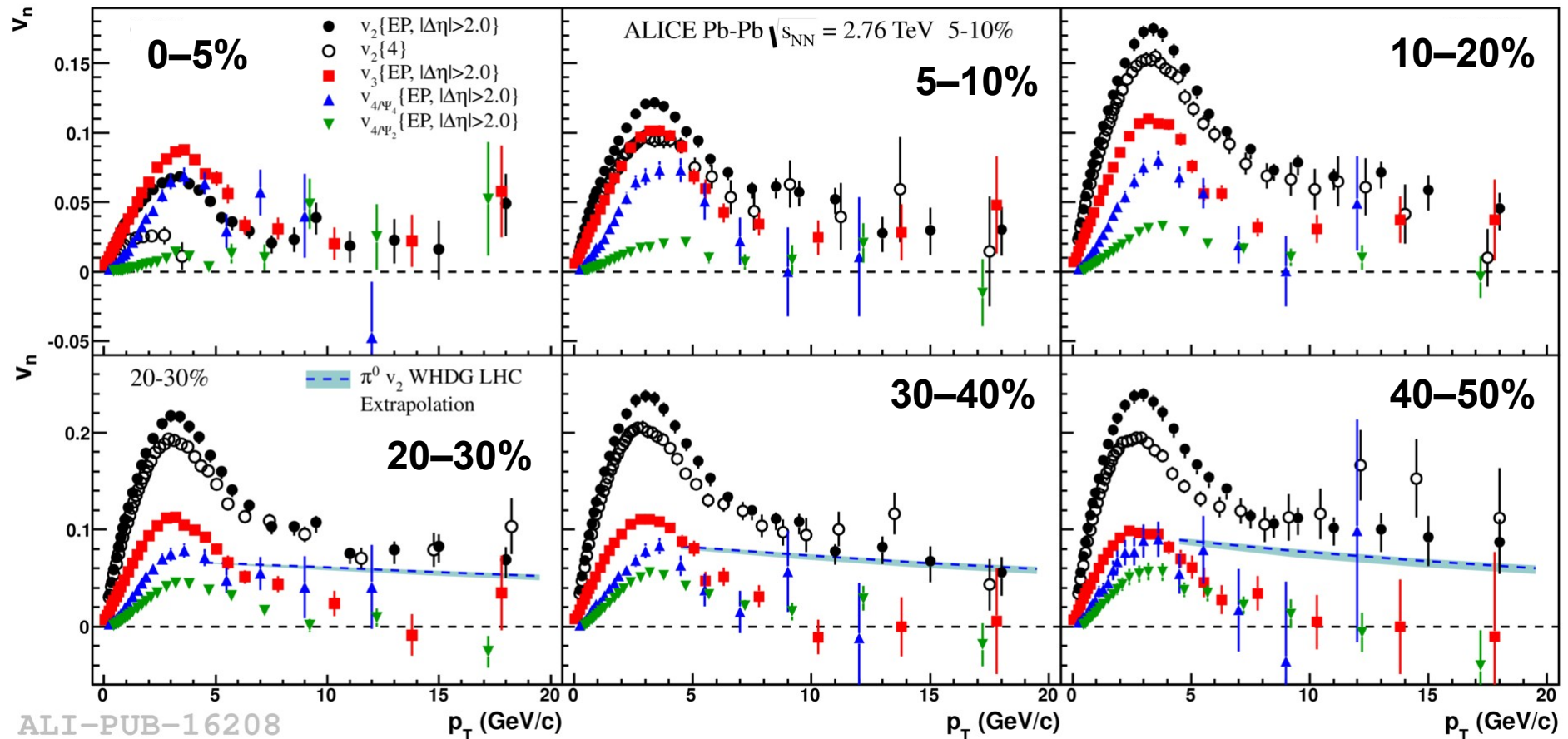
Offset  
measured



**Nuclei are symmetric  $\rightarrow$   
No odd coefficients**



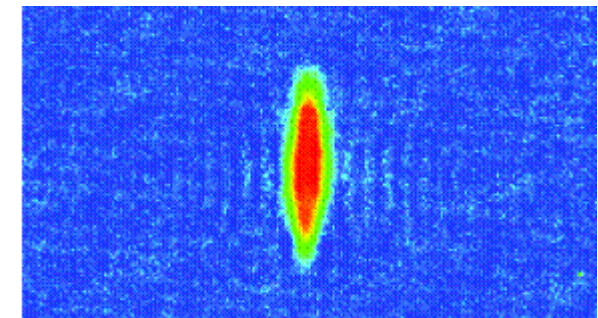
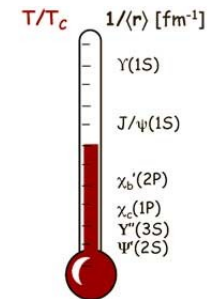
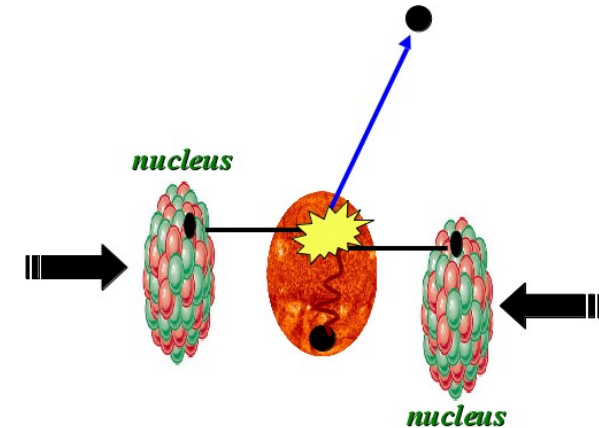
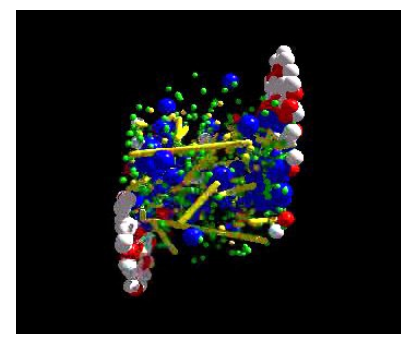
# Odd and even $v_n$



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

# 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.

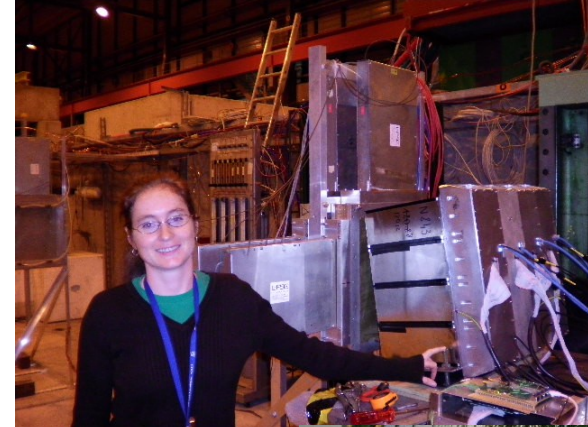


# Careers in high energy physics

- 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: [STARPHENIX](#)
  - 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 Angeles
- 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

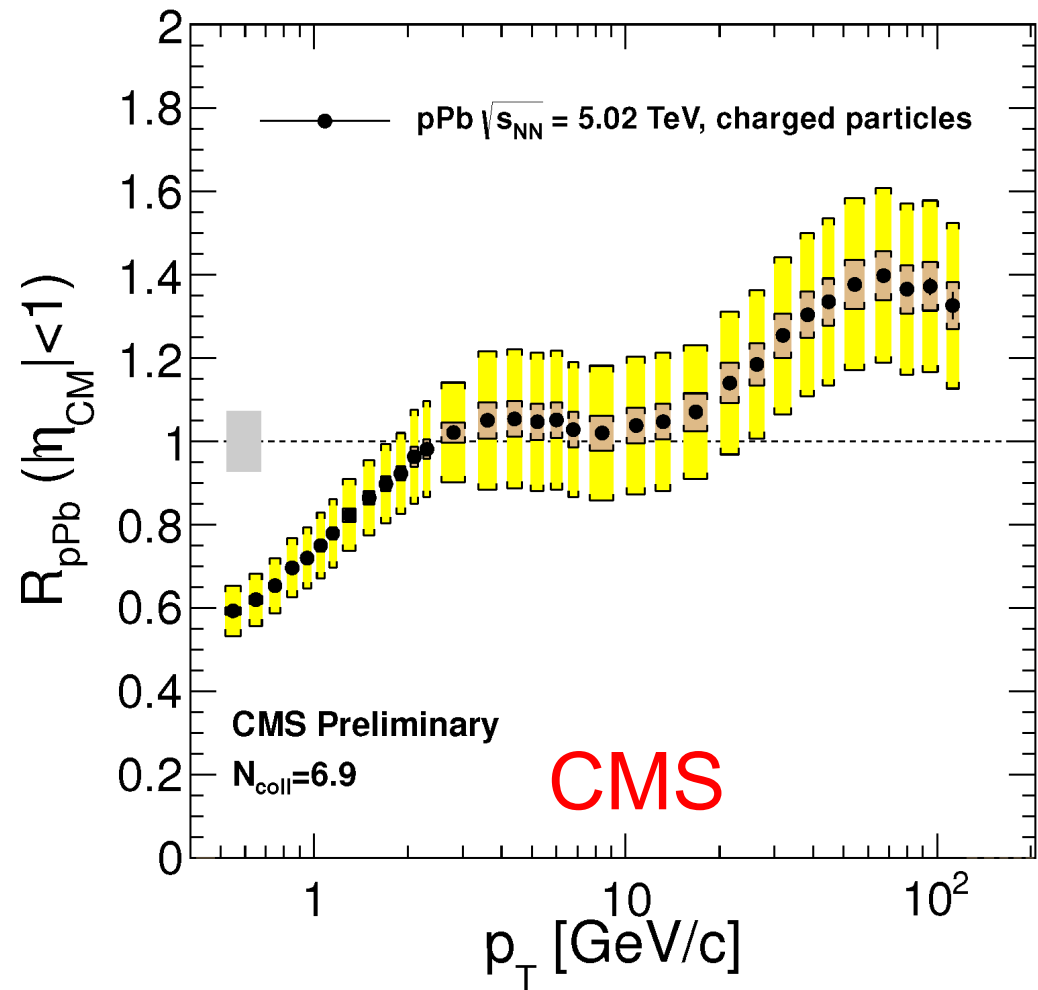
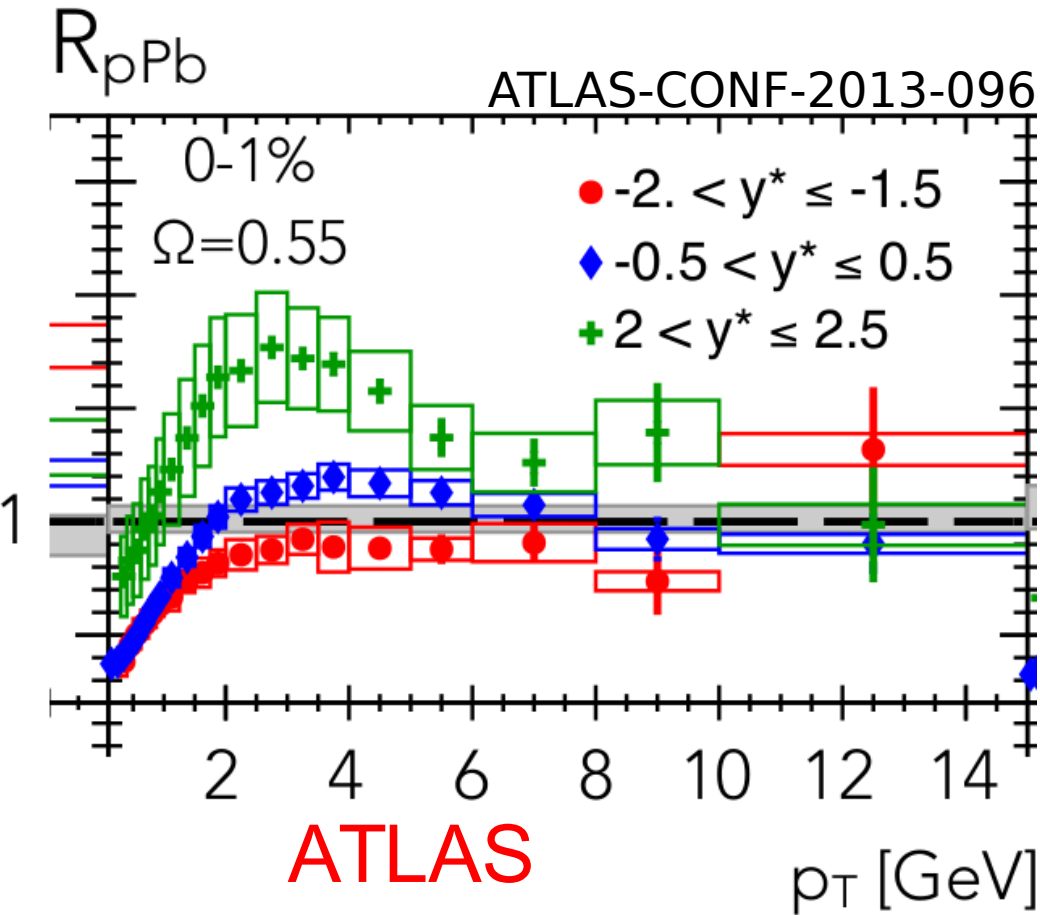
- CMS

- 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

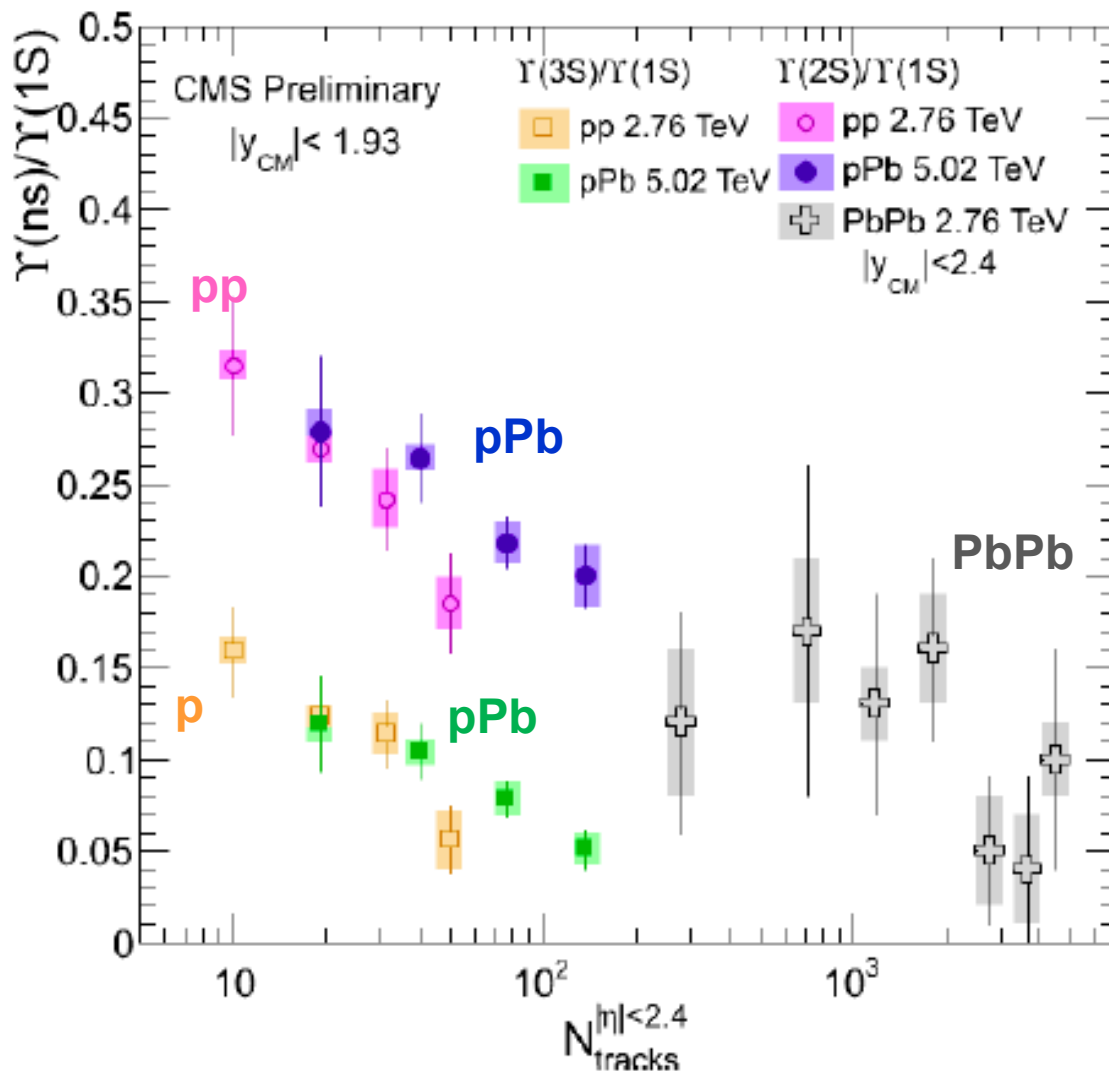
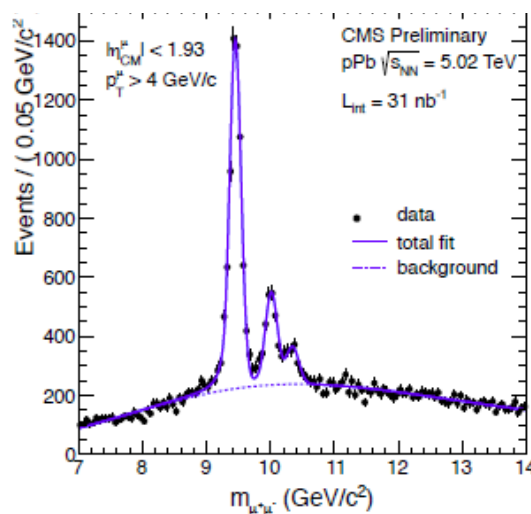
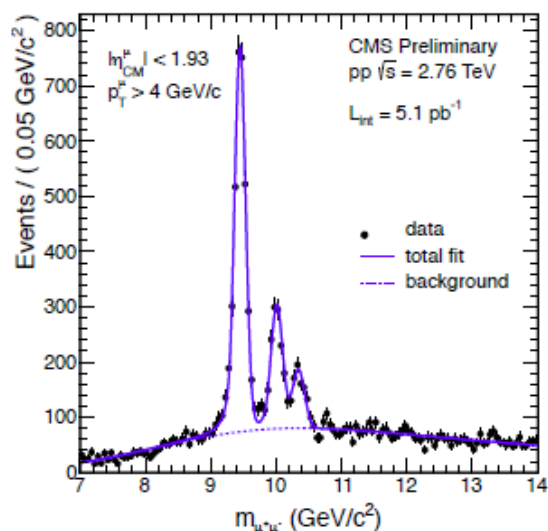
- ATLAS

- Columbia University

# p+Pb as a control

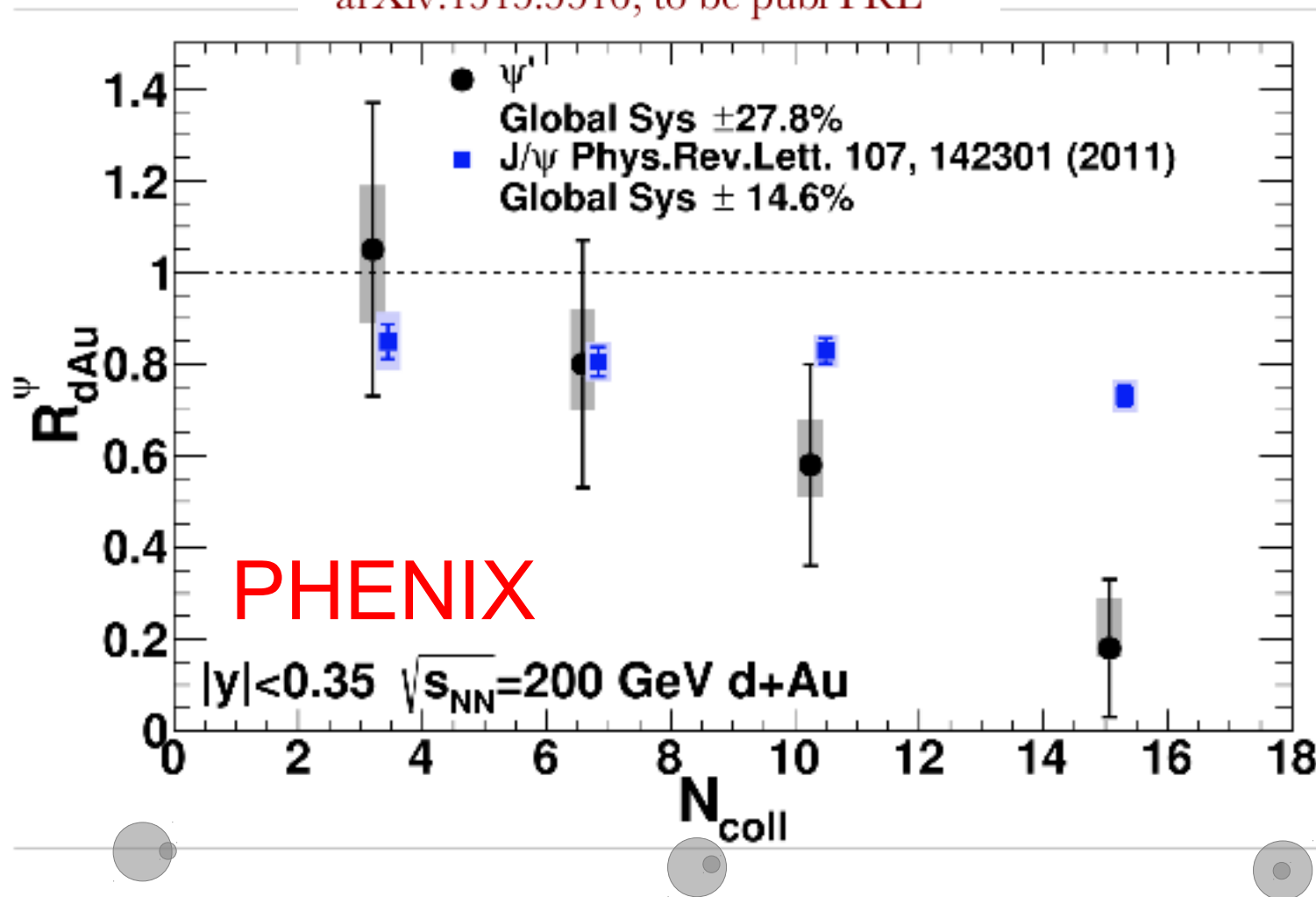


# Suppression of quarkonia in p+Pb



# Suppression of quarkonia in d+Au

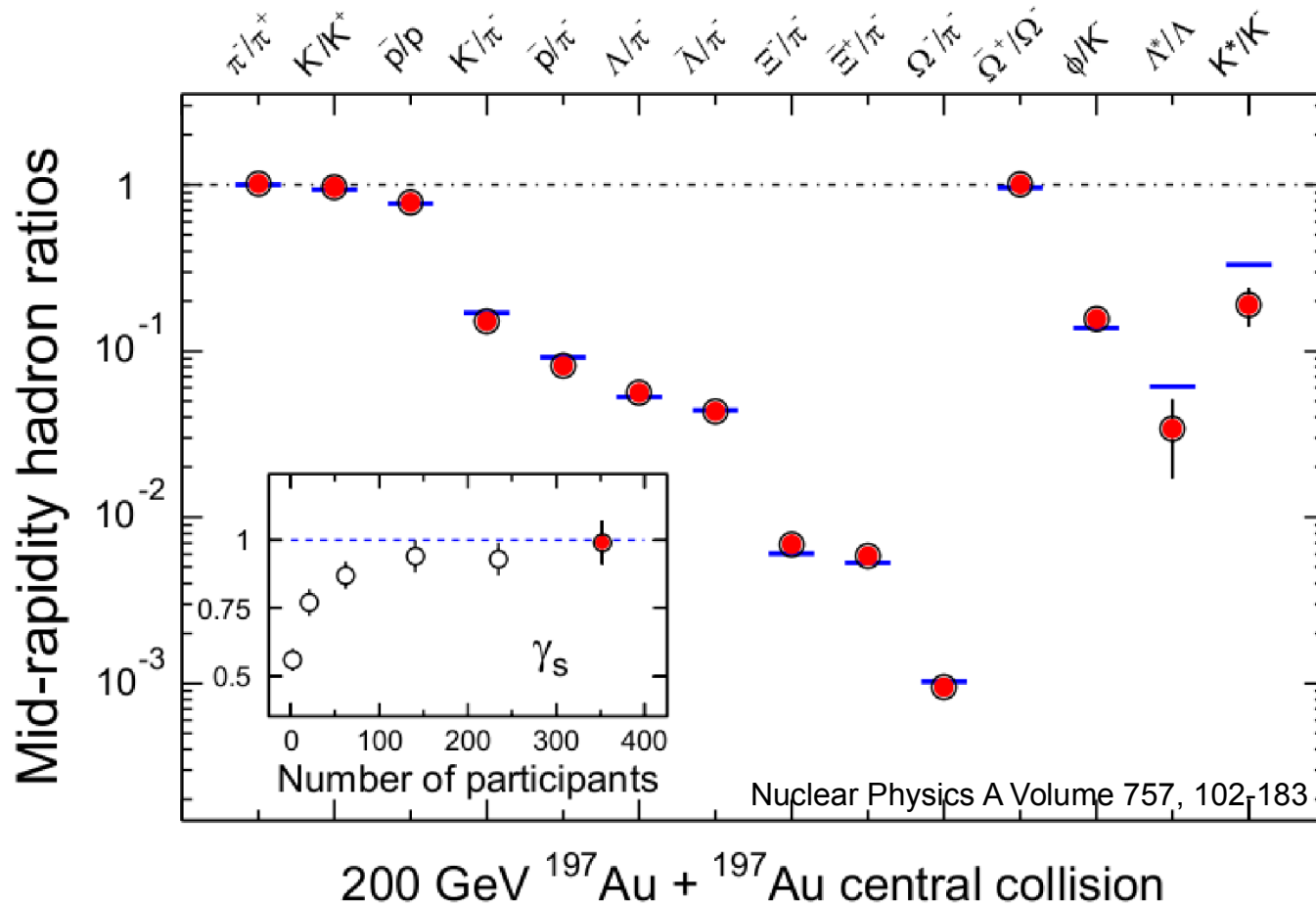
arXiv:1315.5516, to be publ PRL



# QGP Chemistry

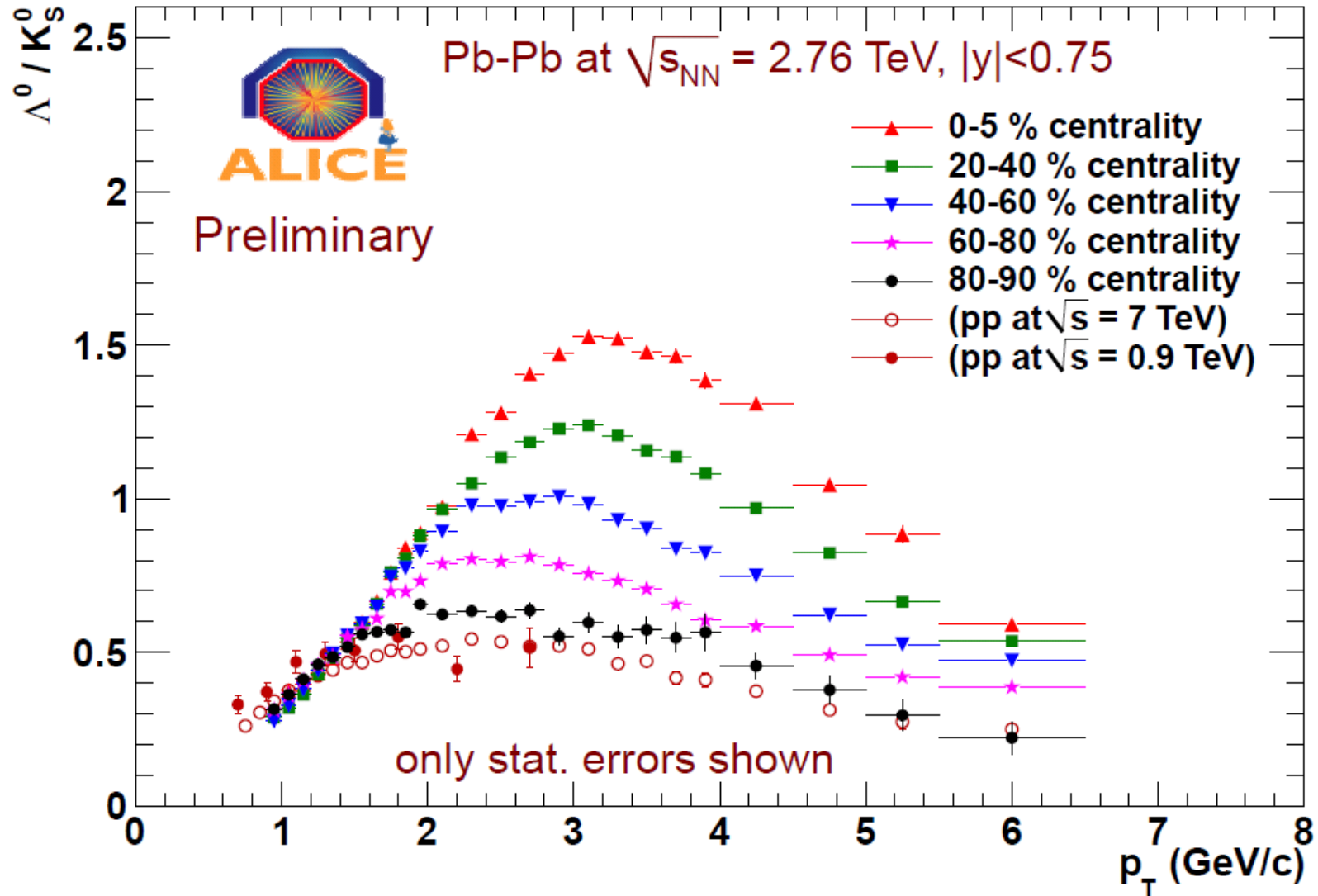
# Chemistry - equilibrium

**T~170  
MeV**

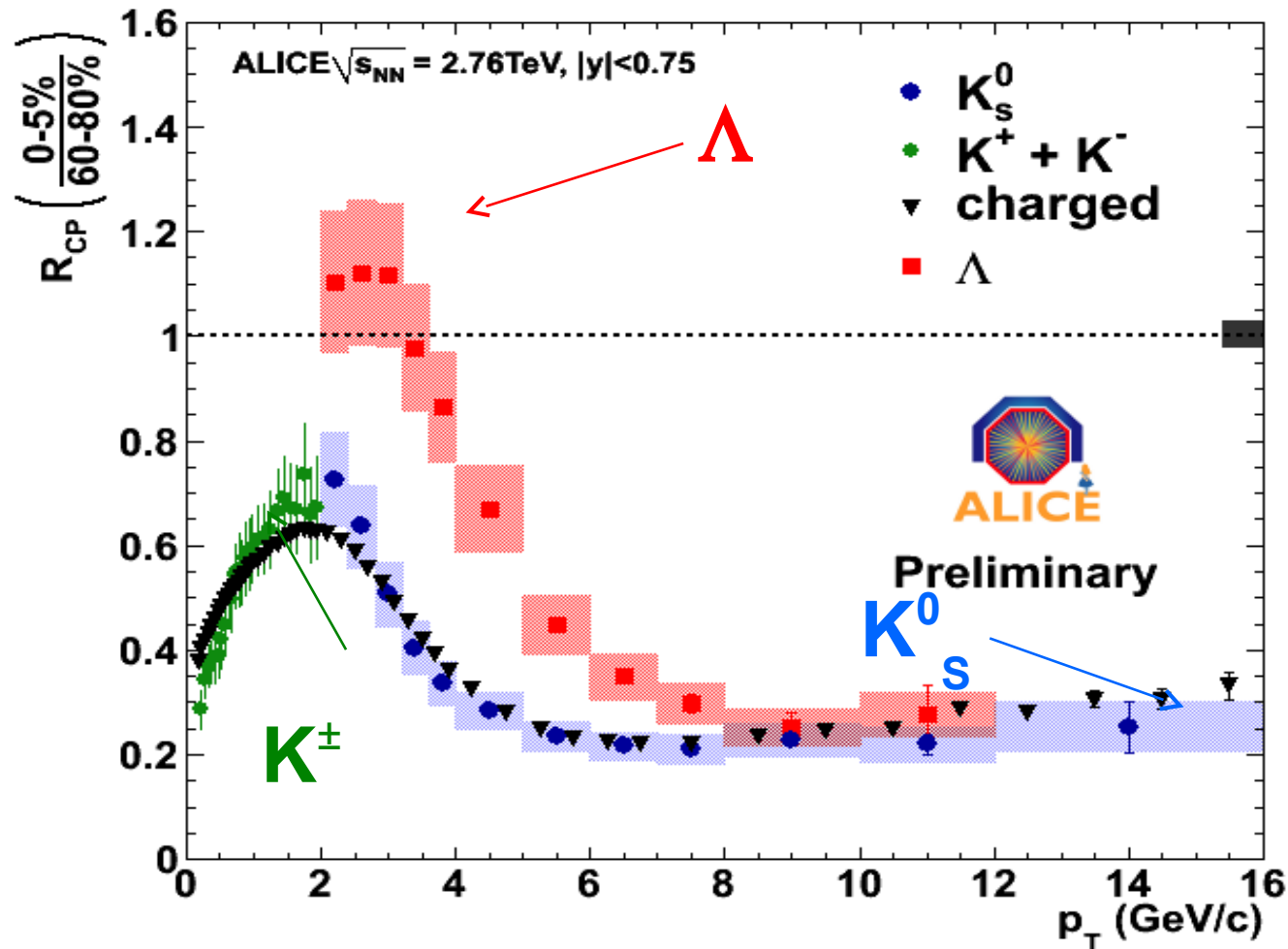


- Ratios of particles expected from a model
- Even strange quarks are at equilibrium!

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



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



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

# Charm nuclear modification factor

