

Title: Quark Gluon Plasma at RHIC (and in QCD and String Theory)

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Abstract:



# Quark-Gluon Plasma at RHIC (and in QCD and String Theory)

**W.A. Zajc**  
**PASCOS 2008**  
**Perimeter Institute**



# Science Questions



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**X Uninteresting question:**





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- ❑ What happens when I crash two gold nuclei together?**



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**☞ What fundamental *thermal* properties of our gauge theories of nature can be investigated experimentally?**



# The Thermal Universe

- $10 \text{ GeV} / \text{fm}^3$   
 $\sim 10^{16} \text{ gm} / \text{cm}^3$
- $T \sim 170 \text{ MeV}$   
 $\sim 2 \times 10^{12} \text{ K}$



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- Conditions that prevailed  
 $\sim 10 \mu\text{s}$   
 after the Big Bang







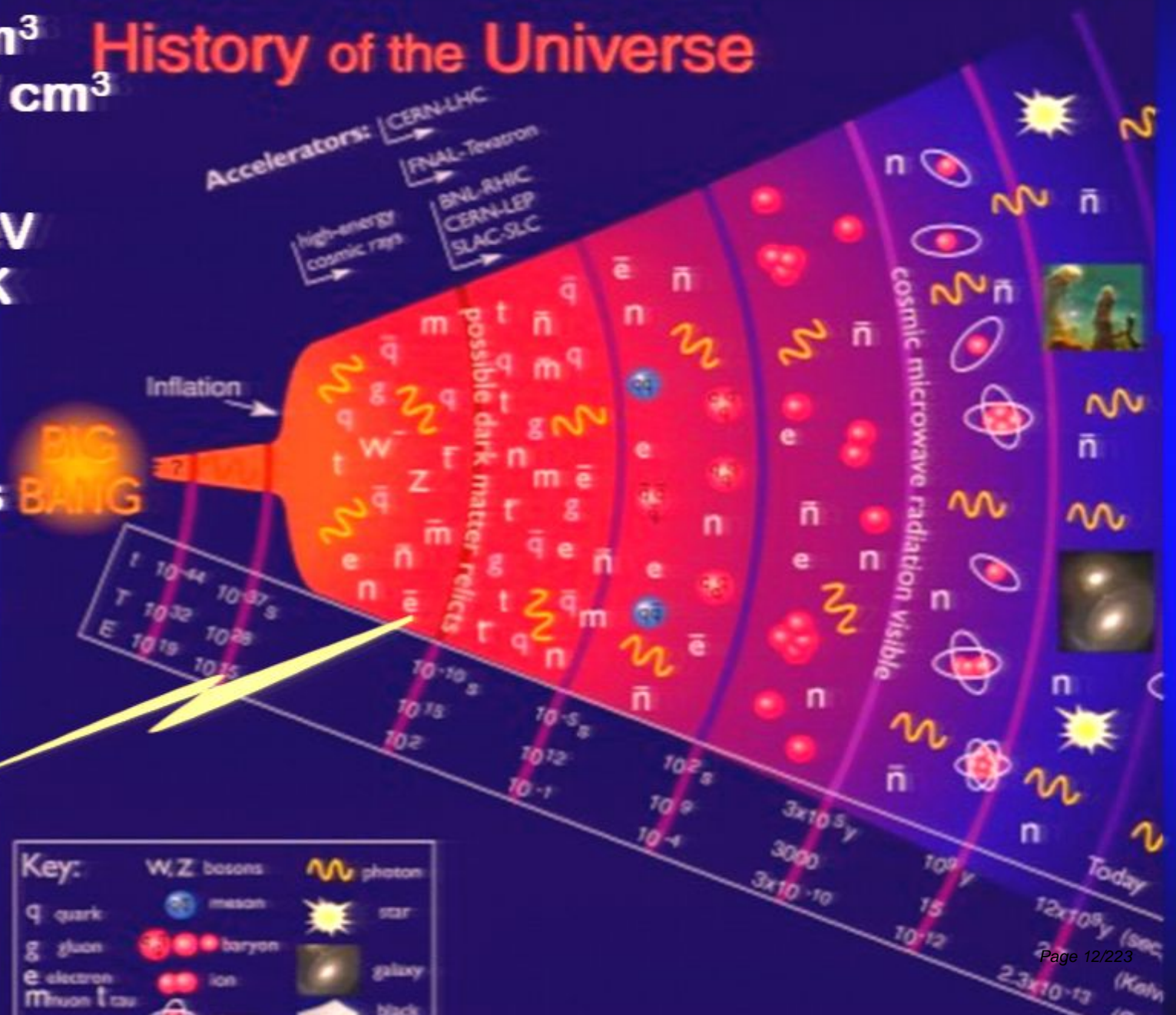
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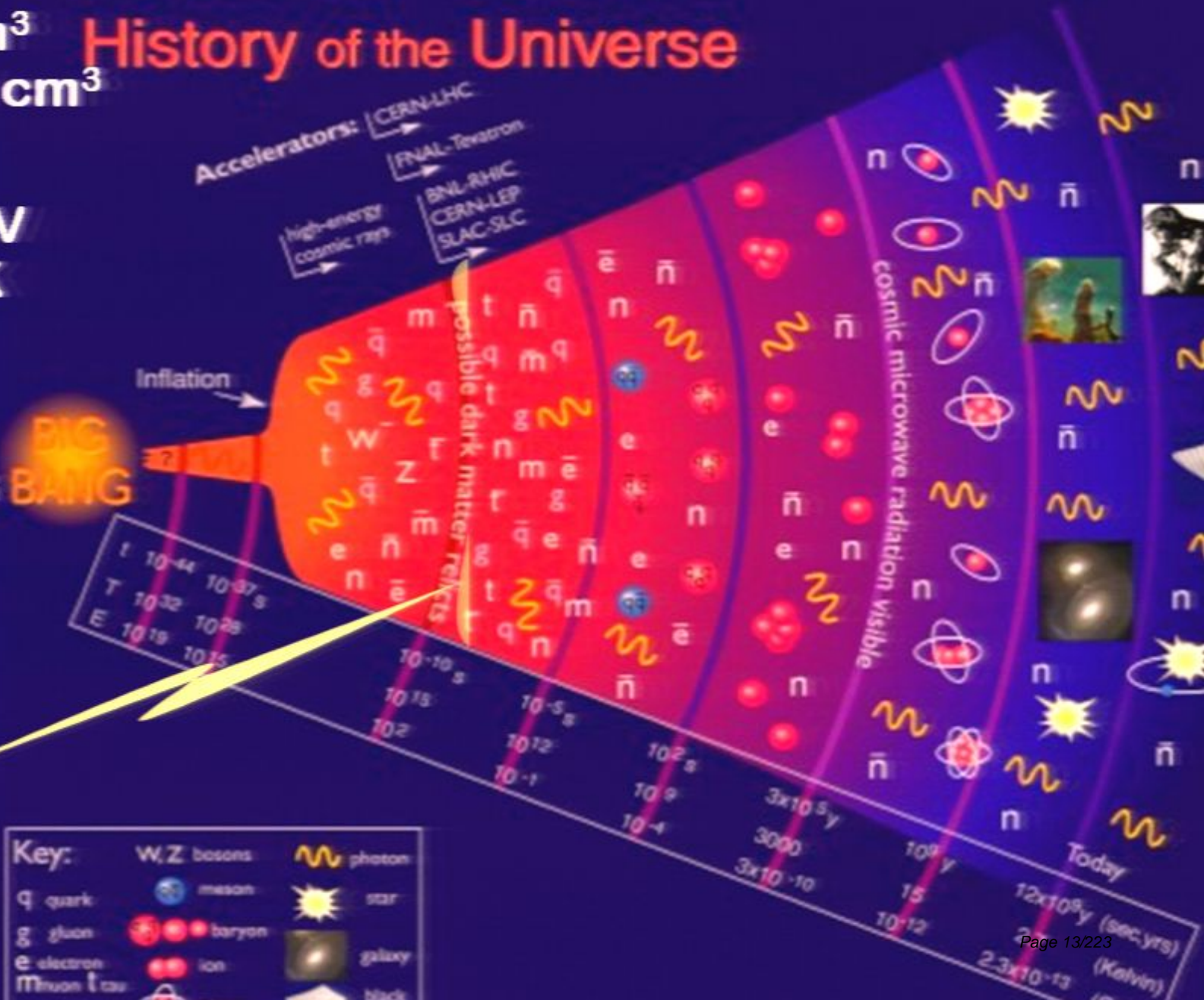
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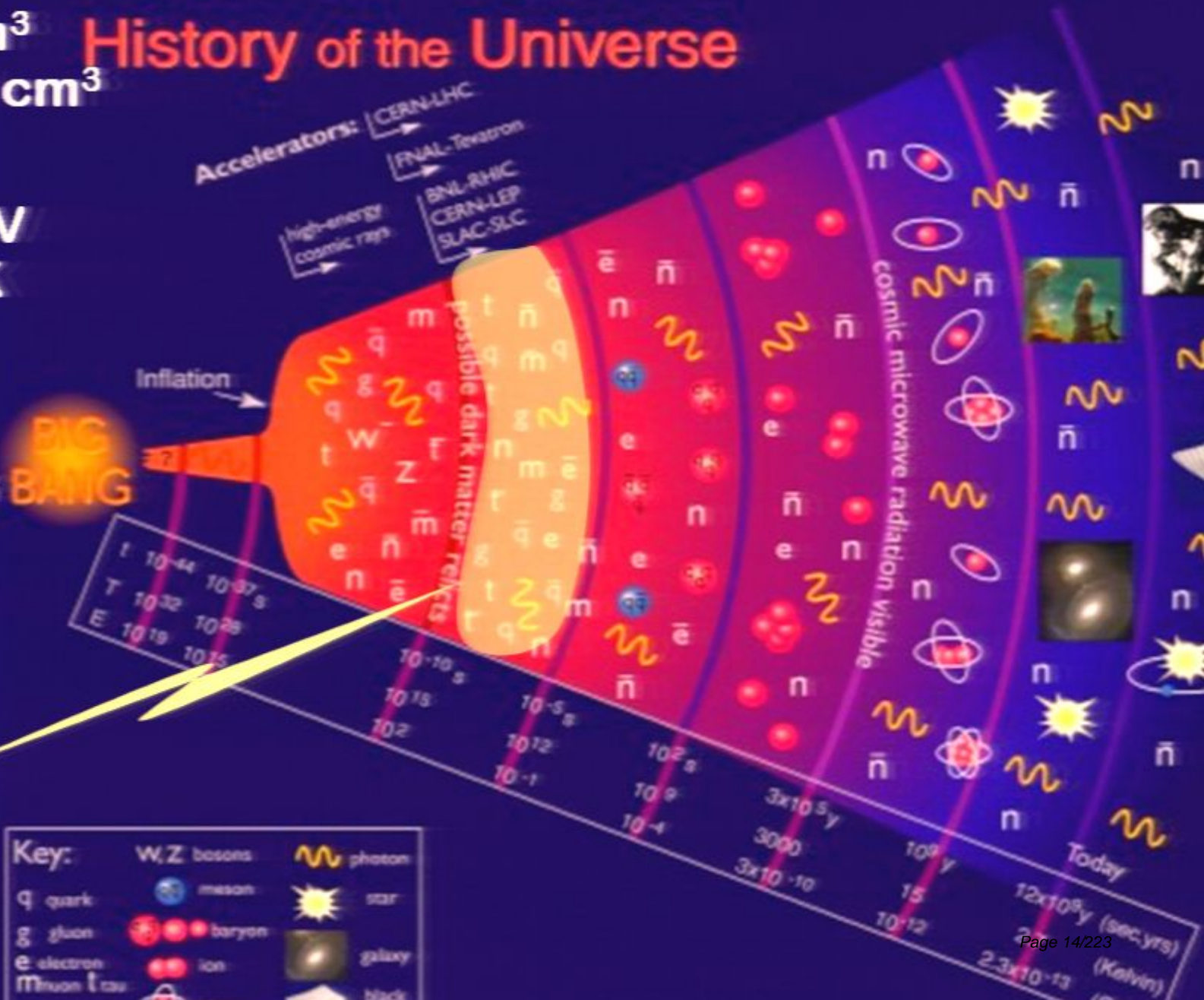
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## History of the Universe





**Nuclear Science** is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, charges, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as *Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly cooled? What is the origin of the nuclei found on Earth?*

[illegible]

*Nonlinear matter can exist in several phases. When collisions occur inside individual galaxies, and galaxies may respond from the outside fluid. At sufficiently high temperatures or densities, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow-background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.*

Subtle nuances form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the structure of nuclear conditions. In its present form, this chart contains about 2700 different nuclides. Nuclear Decay predicts that there are at least 4000 more to be discovered with  $Z \leq 112$ .

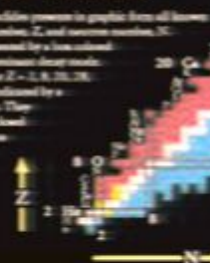


The diagram illustrates four types of radioactive decay, showing the 'before' and 'after' states of a nucleus:

- Alpha Decay:** A nucleus (e.g.,  $^{238}\text{U}$ ) decays into a daughter nucleus (e.g.,  $^{234}\text{Th}$ ) by emitting an alpha particle ( $^4\text{He}$ ).
- Beta Minus Decay:** A nucleus (e.g.,  $^{14}\text{C}$ ) decays into a daughter nucleus (e.g.,  $^{14}\text{N}$ ) by emitting an electron ( $e^-$ ).
- Beta Plus Decay:** A nucleus (e.g.,  $^{11}\text{C}$ ) decays into a daughter nucleus (e.g.,  $^{11}\text{B}$ ) by emitting a positron ( $e^+$ ).
- Gamma Decay:** An excited nucleus (e.g.,  $^{60}\text{Co}^*$ ) transitions to a lower energy state (e.g.,  $^{60}\text{Co}$ ) by emitting a gamma ray ( $\gamma$ ).

**Relativistic heavy ion collisions** are a means by which different particles in *alpha* decay, the nucleus releases a *2He* nucleus or *alpha* particle. In *alpha* decay, the nucleus of different elements or different and combinations for a proton and neutron in a nucleus and emits a neutron. A proton in the same for the stability of the nucleus. Furthermore, the emission of *alpha* particles, both *alpha* and beta decay change the original nucleus into a nucleus of a different element. In *alpha* decay, the nucleus must be ionized during by emitting a *helium-4* nucleus. The decay has been widely the physical properties of the atom.

The Chain of the Nightline presents in graphic form all known nuclei with atomic number,  $Z$ , and mass number,  $N$ . Each nucleus is represented by a black colored dot according to its predominant decay mode. Magic numbers (2 or  $Z = 2, 8, 20, 28, 50, 82$  and 126) are indicated by a rectangle on the chain. They correspond to major shell levels and show regions of greater nuclear binding energy.



**Colour Key**

- Stable
- Spontaneous fission
- Alpha particle emission
- Beta minus emission
- Beta plus emission or electron capture

A diagram of a nucleus, which is a cluster of neutrons and protons. The neutrons are represented by blue spheres, and the protons by red spheres. The entire cluster is surrounded by a yellow, cloud-like region representing the strong field. Labels with arrows point to various components: 'neutron' points to a blue sphere, 'proton' points to a red sphere, 'strong field' points to the yellow cloud, 'quark' points to a small red dot inside a proton, and 'electromagnetic field' points to the space around the nucleus. Scale indicators are present:  $10^{-15}\text{m}$  for the neutron and  $10^{-16}\text{m}$  for the quark.

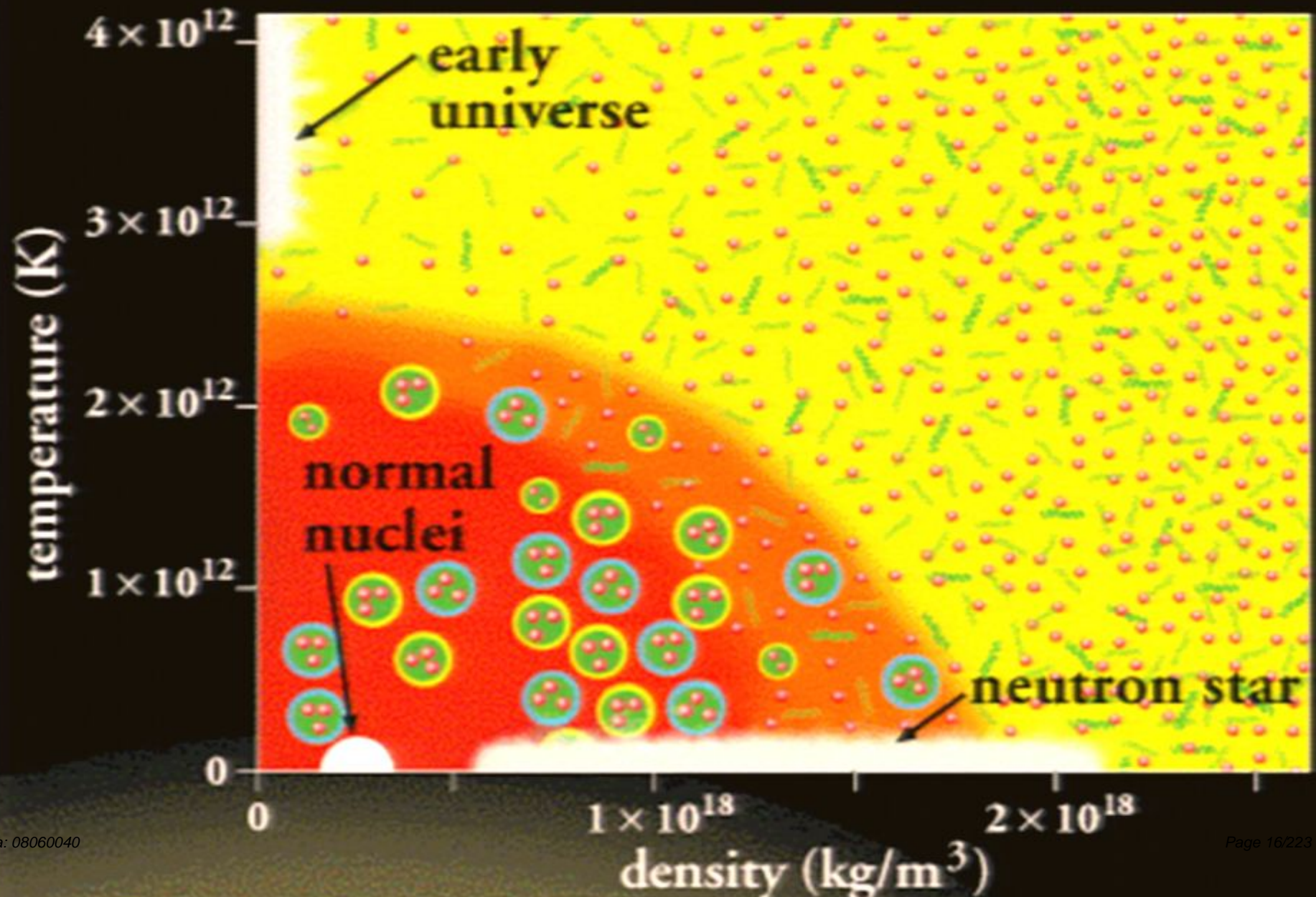
*In an atom, electrons move around the nucleus in discrete orbits up to  $n = 7$ . If the number of electrons in the discrete orbit is less than or equal to 2, the orbit would have a shell name.*

*In the early stages of cellular evolution, of our own and other ones, beings are, like to firm bodies, swimming easily in the form of photons (light) and consciousness. During the later stages of cellular evolution, more massive nuclei up to real beyond particles are synthesized by fusion. The increasing the number of neurons that come from the State, scientists recently have demonstrated that consciousness now have a more greater than ever.*





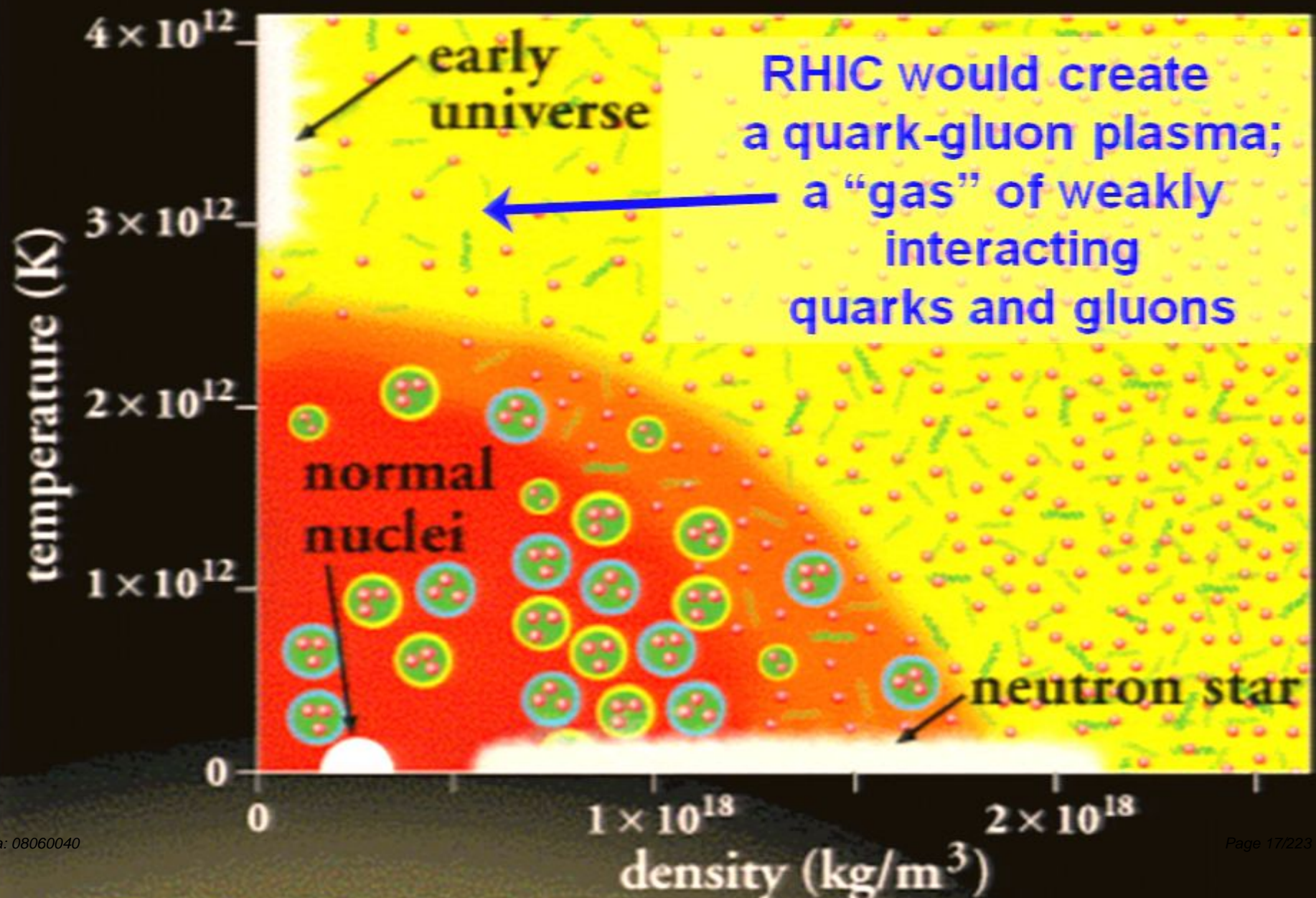
# Expectations circa 2000







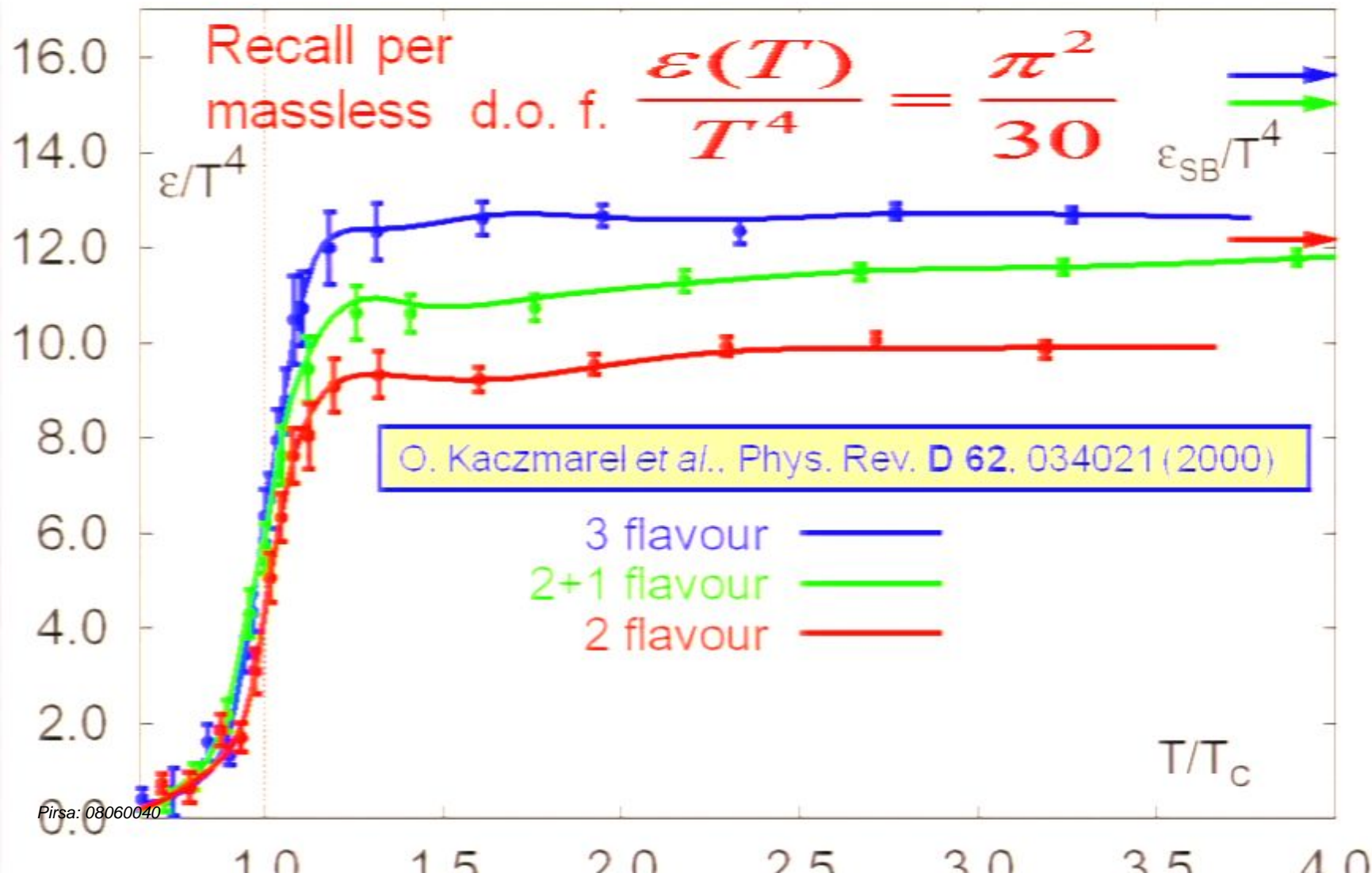
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- Lattice within ~80% of “ideal gas” Stefan-Boltzmann limit  
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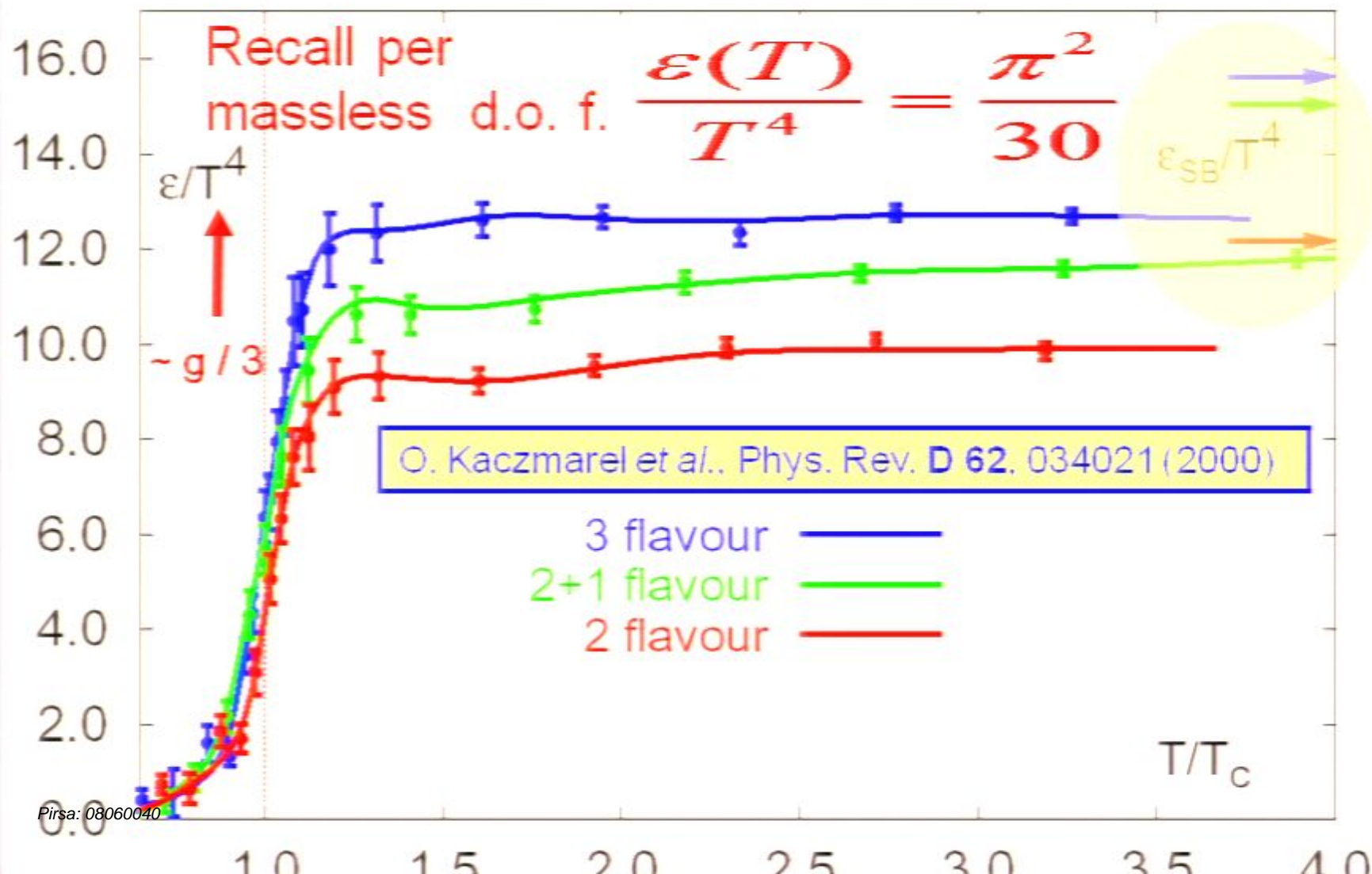






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- **Large  $\sqrt{s}$**   $\Rightarrow$

- ◆ Access to reliable pQCD probes
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    - ◆ To provide definitive experimental evidence for/against Quark Gluon Plasma (QGP)

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    - ◆ Potential for upgrades in response to discoveries





# RHIC and Its Experiments







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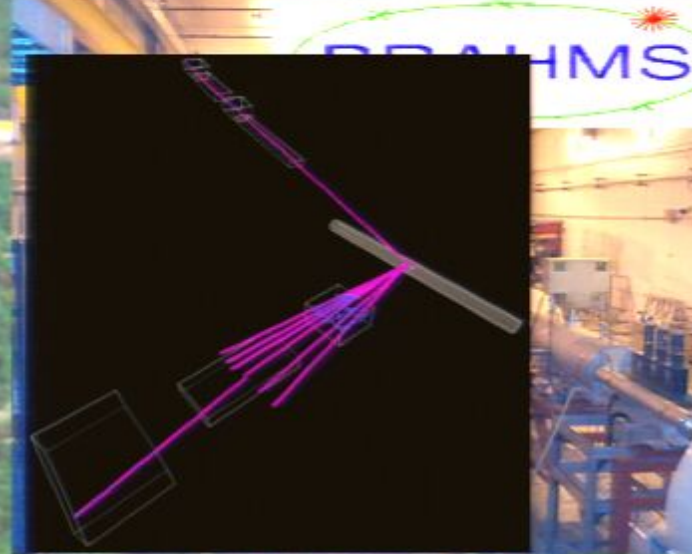
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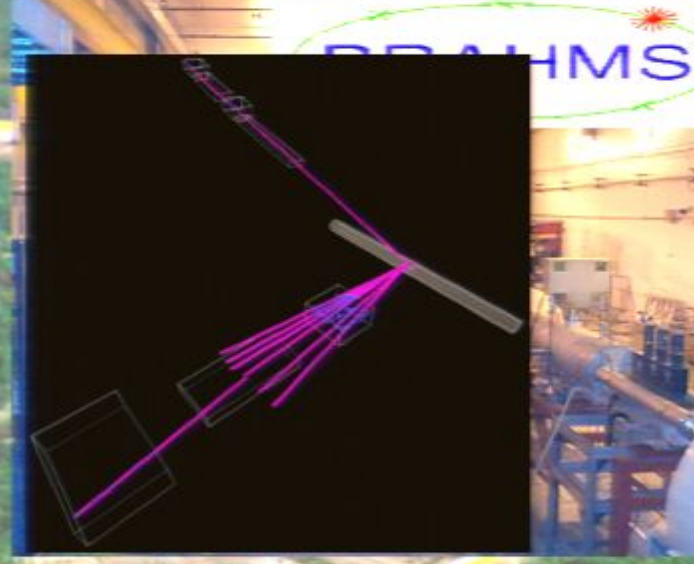
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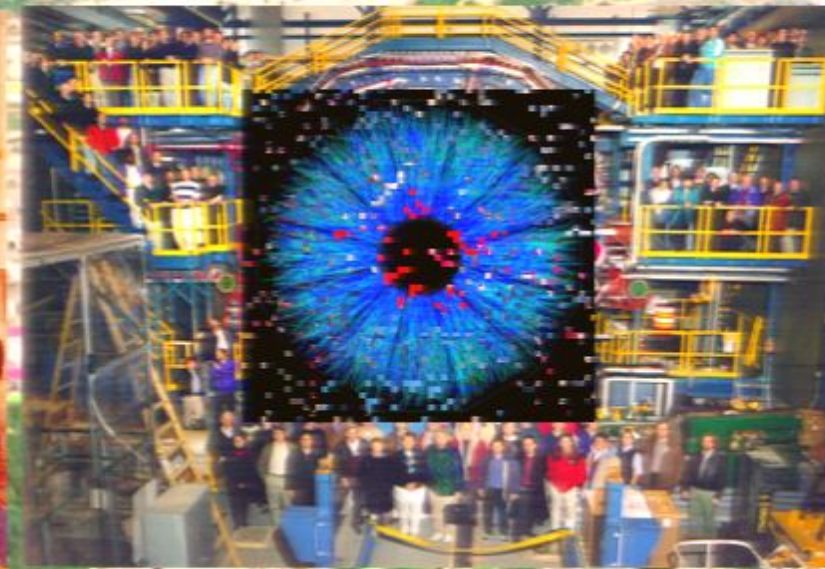
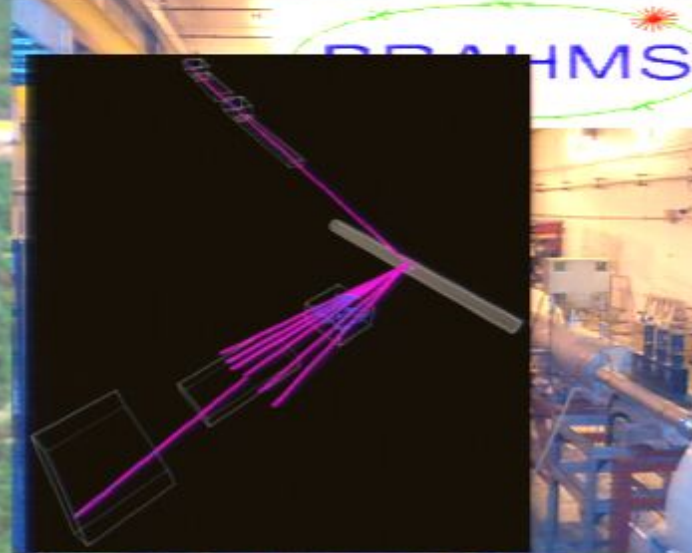
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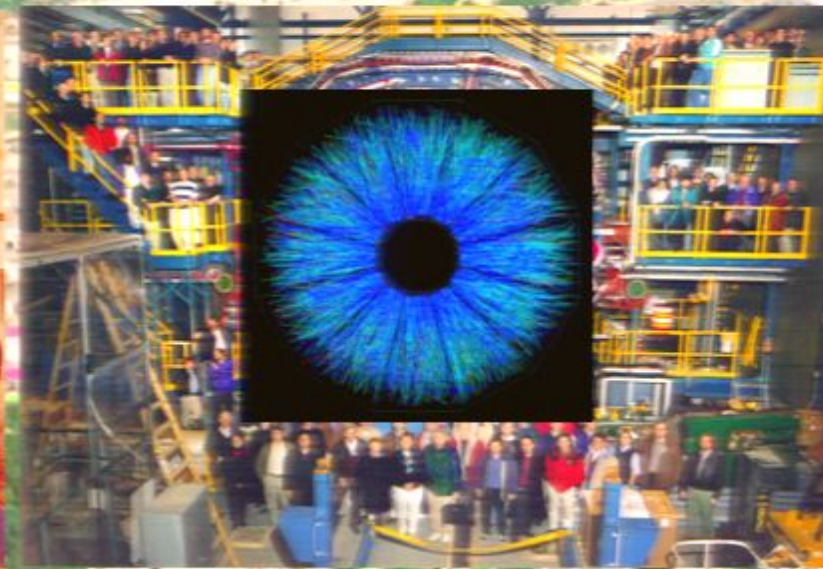
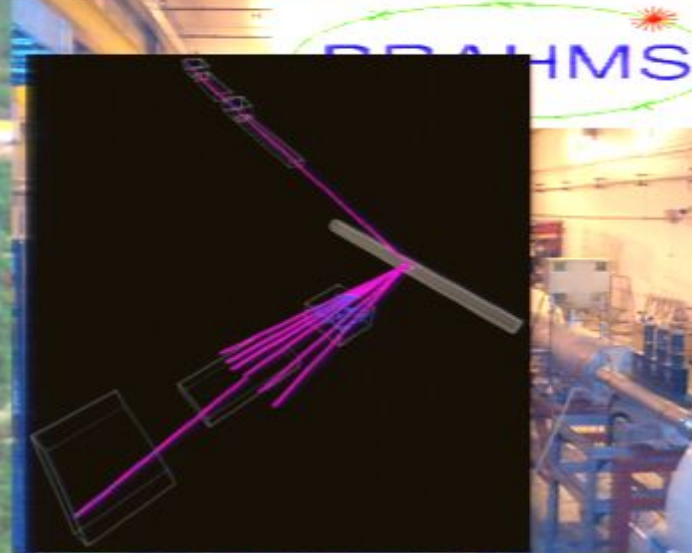
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# Since Then...

- Accelerator complex
- Experiments:
- Science
- Future





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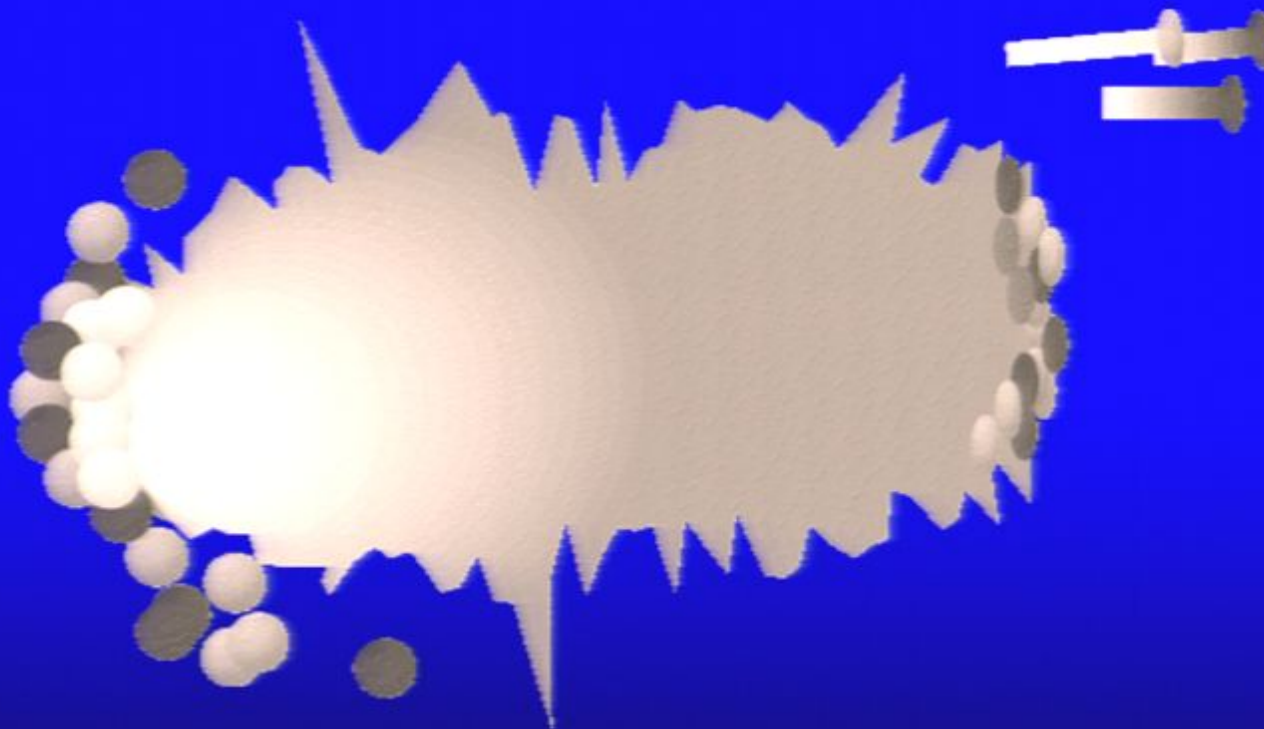
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  - **Demonstrated ability to upgrade**
  - **Key science questions identified**
  - **Accelerator and experimental upgrade program underway to perform that science**



# Approach

Will present *sample* of results from various points of the collision process:

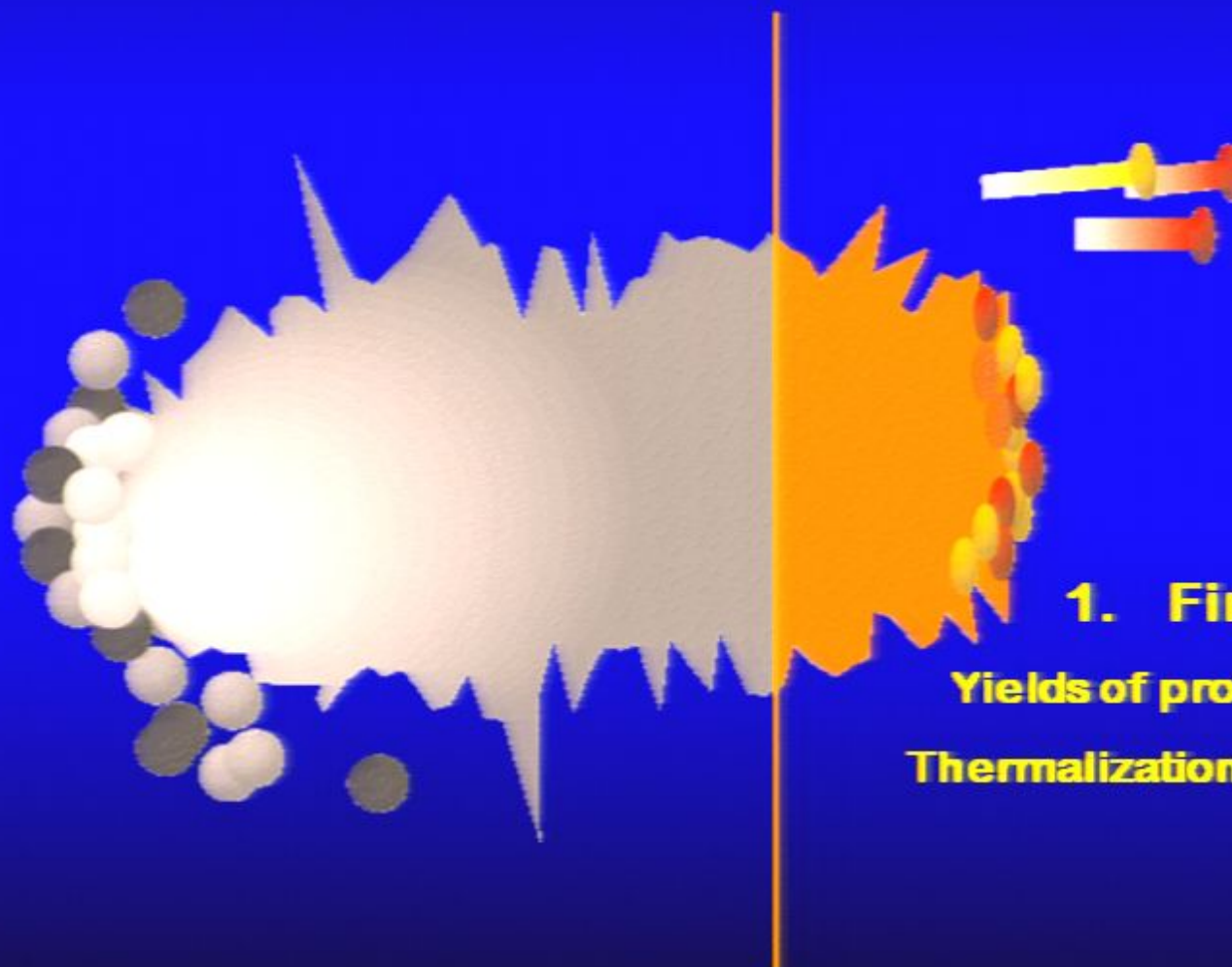






# Approach

Will present *sample* of results from various points of the collision process:



## 1. Final State

Yields of produced particles

Thermalization, Hadrochemistry

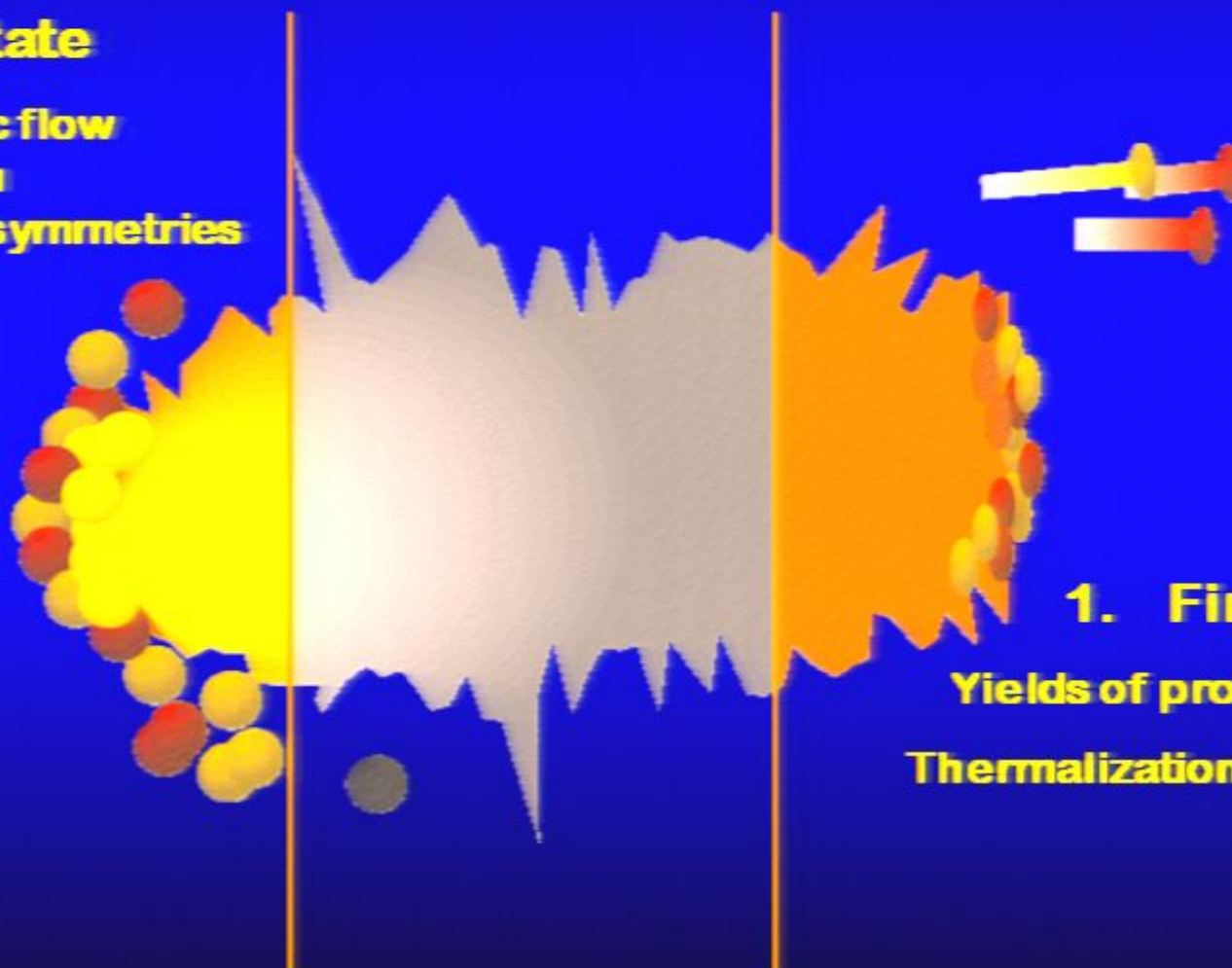


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Will present *sample* of results from various points of the collision process:

## 2. Initial State

Hydrodynamic flow  
from  
initial spatial asymmetries



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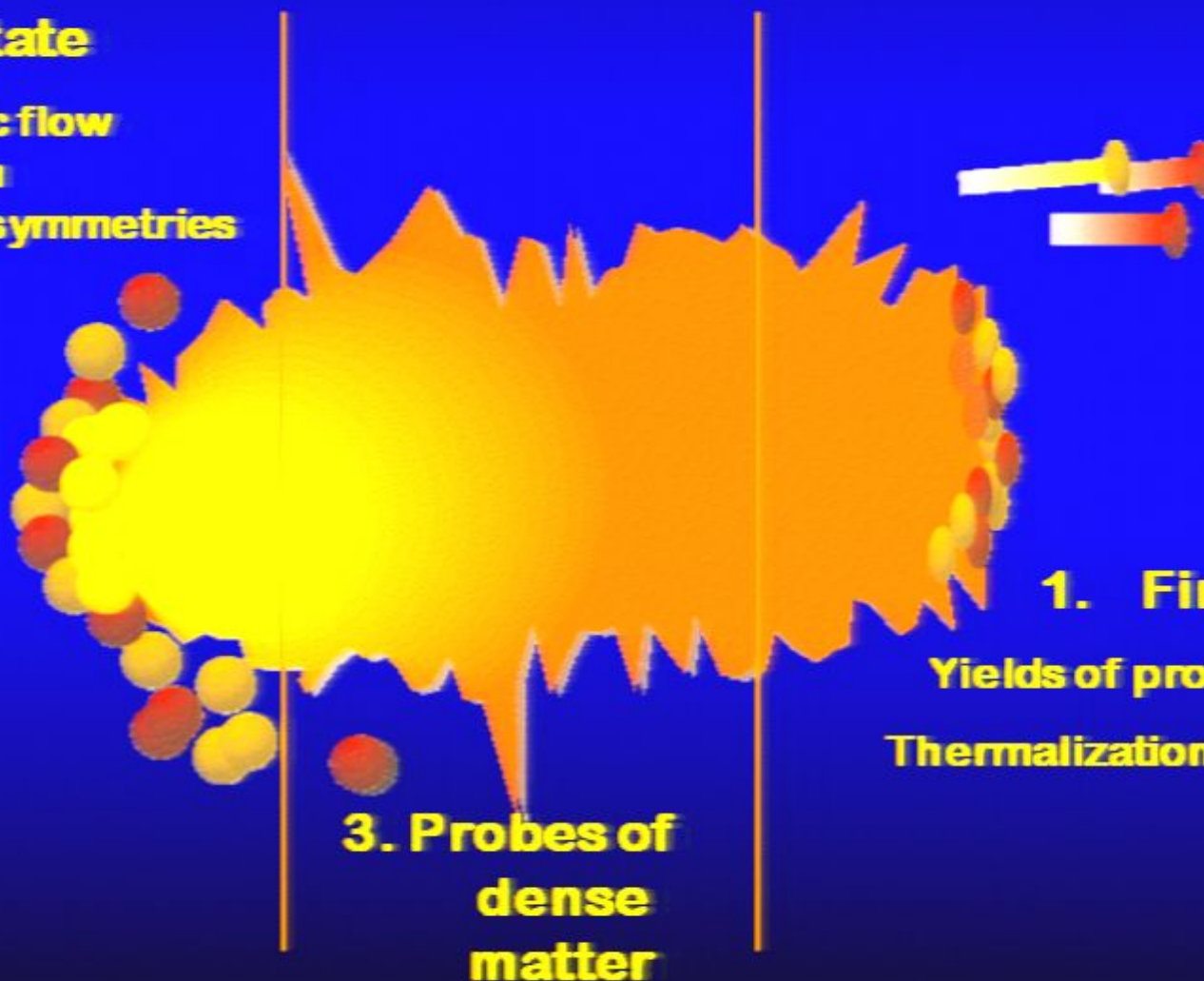


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Thermalization, Hadrochemist

## 3. Probes of dense matter



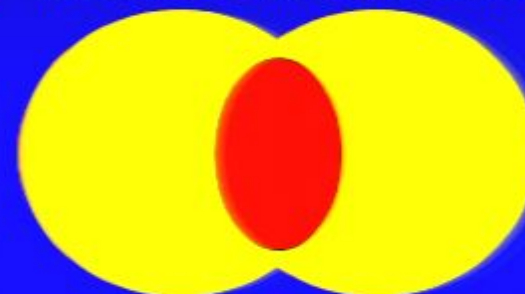
# Assertion

- In these complicated events, we have (*a posteriori*) control over the event geometry:

- Degree of overlap- e.g. [0-10%] “most central” events

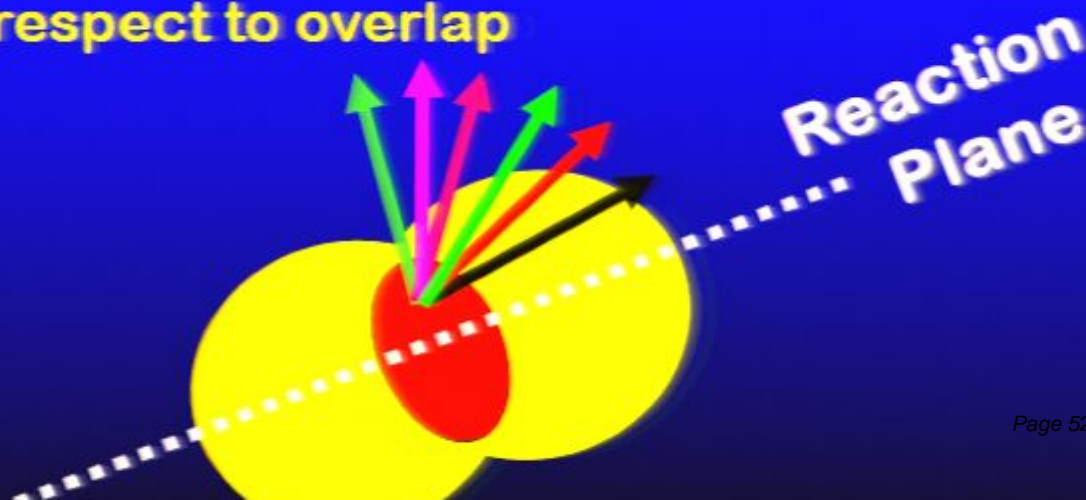


“Central”



“Peripheral”

- Orientation with respect to overlap

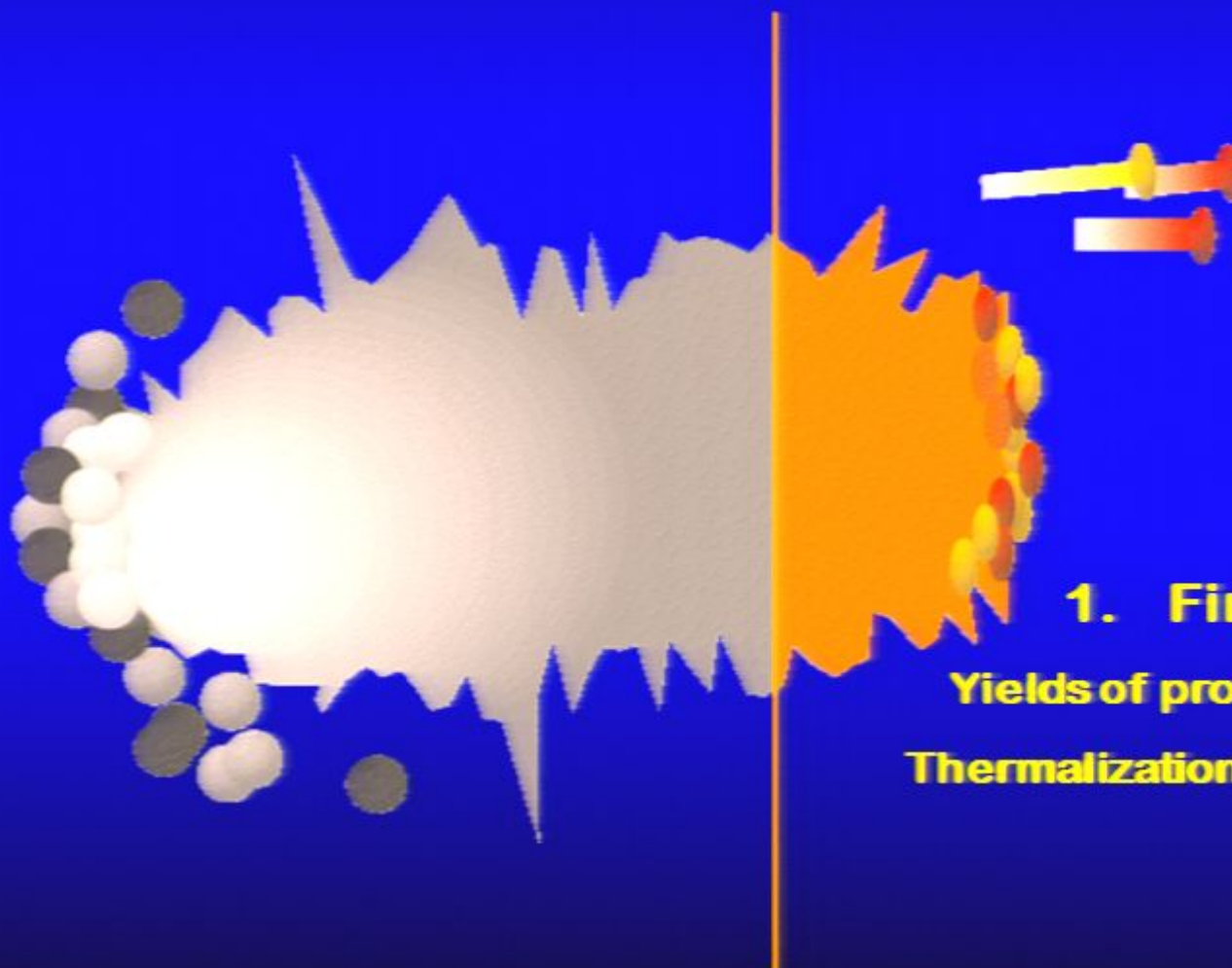






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Does the huge abundance of final state particles reflect a *thermal* distribution?:



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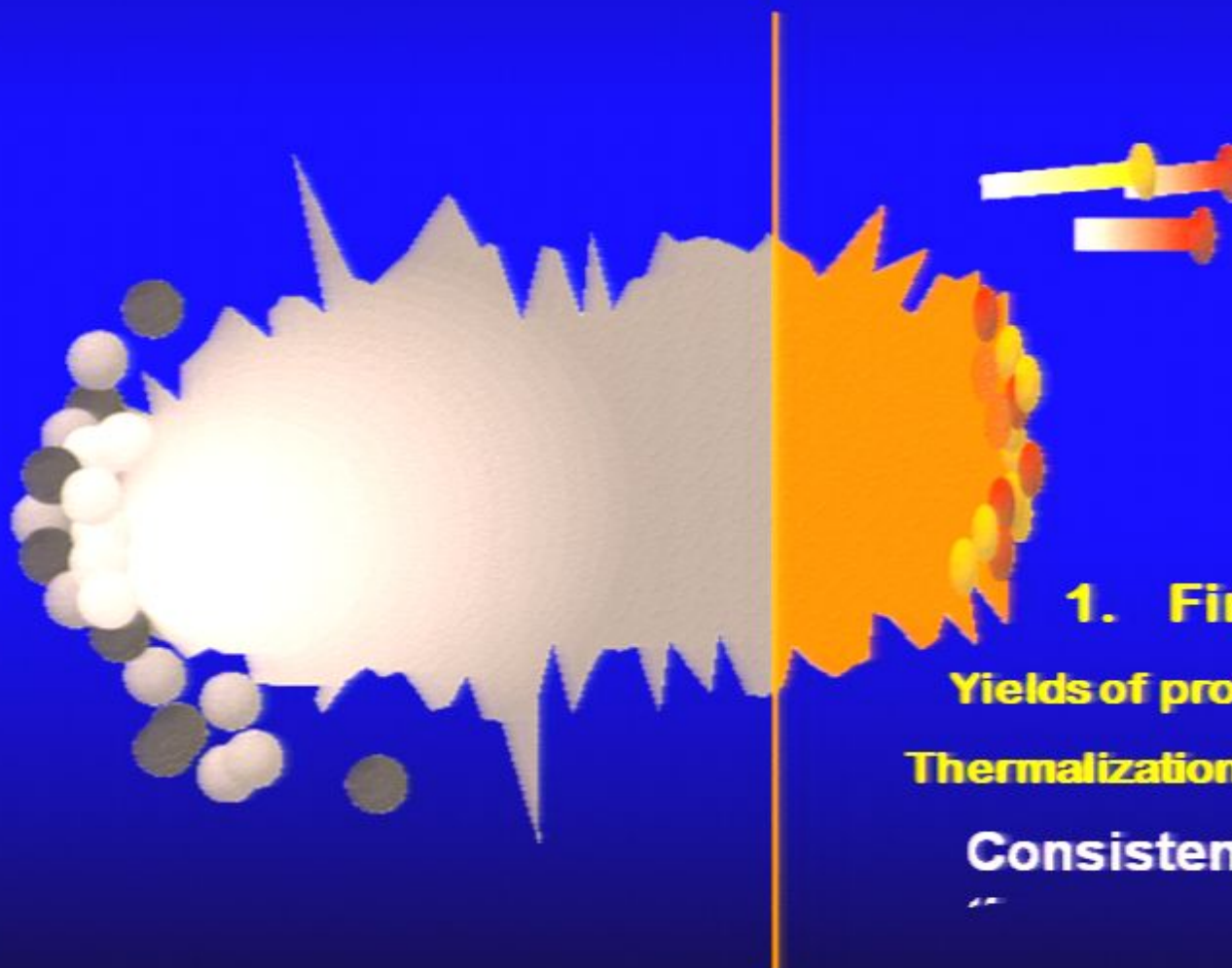
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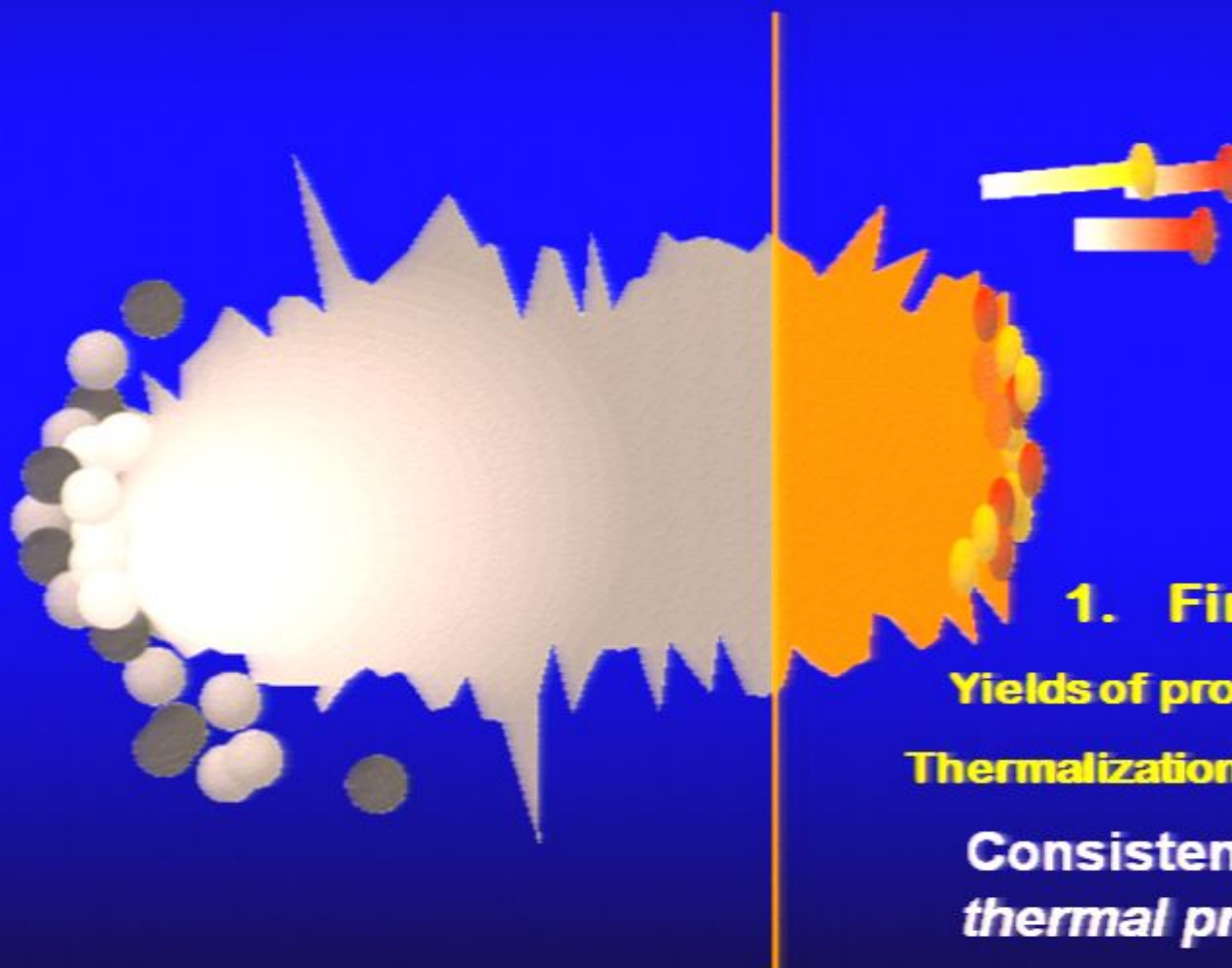
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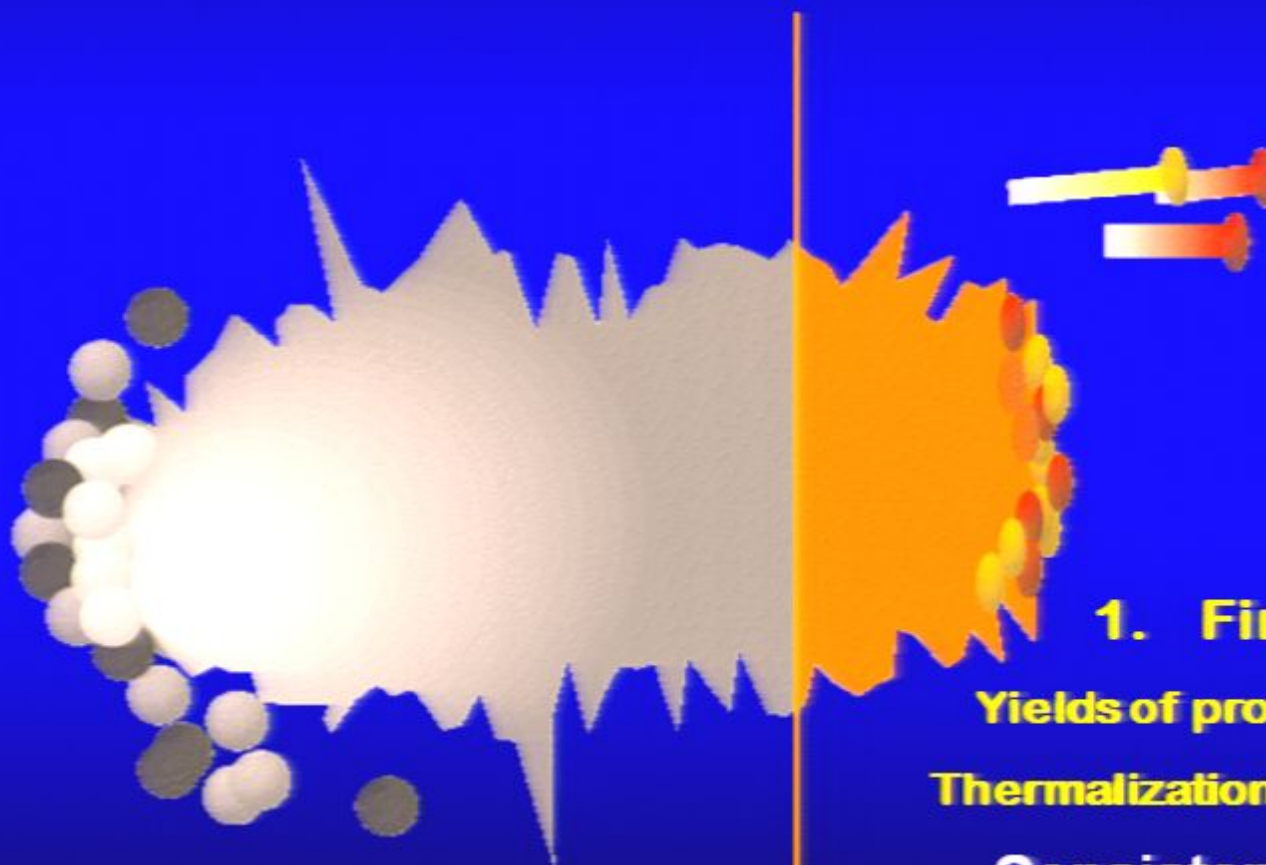
Thermalization, Hadrochemistry

Consistent with  
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Consistent with  
*thermal production*





# RHIC's Two Major Discoveries



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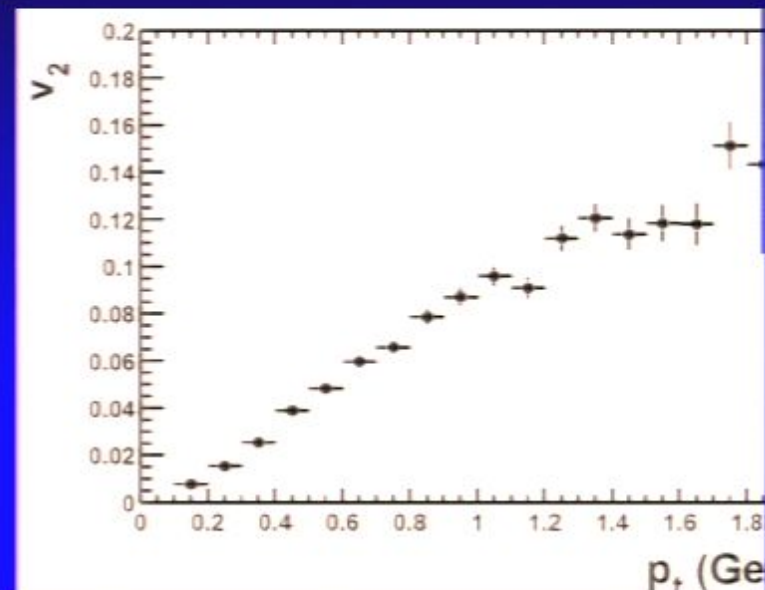
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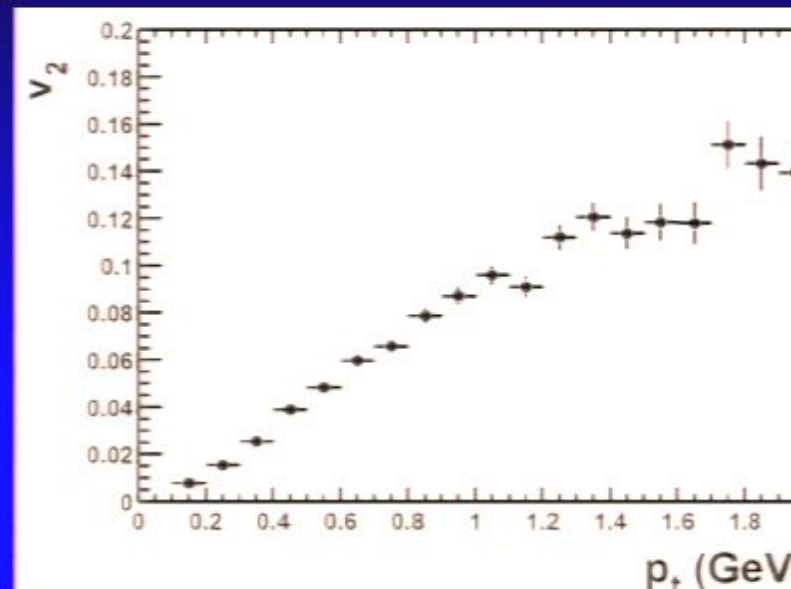
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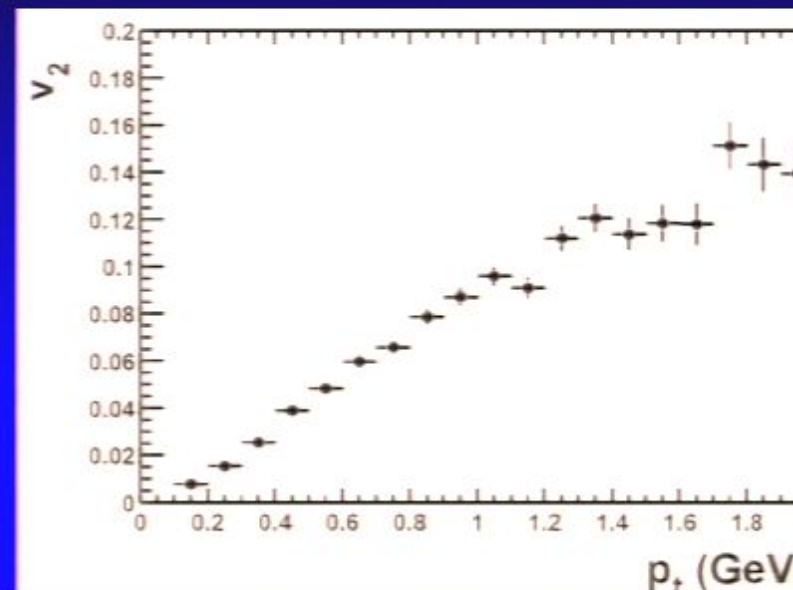






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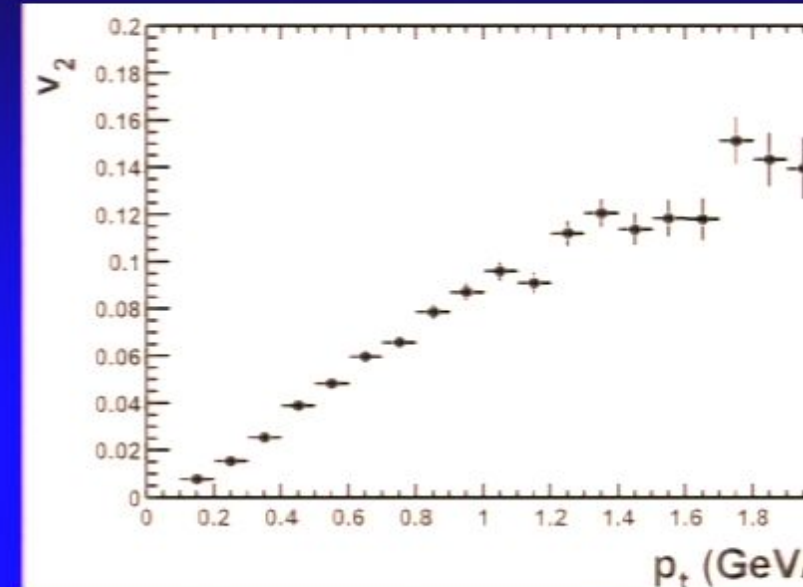


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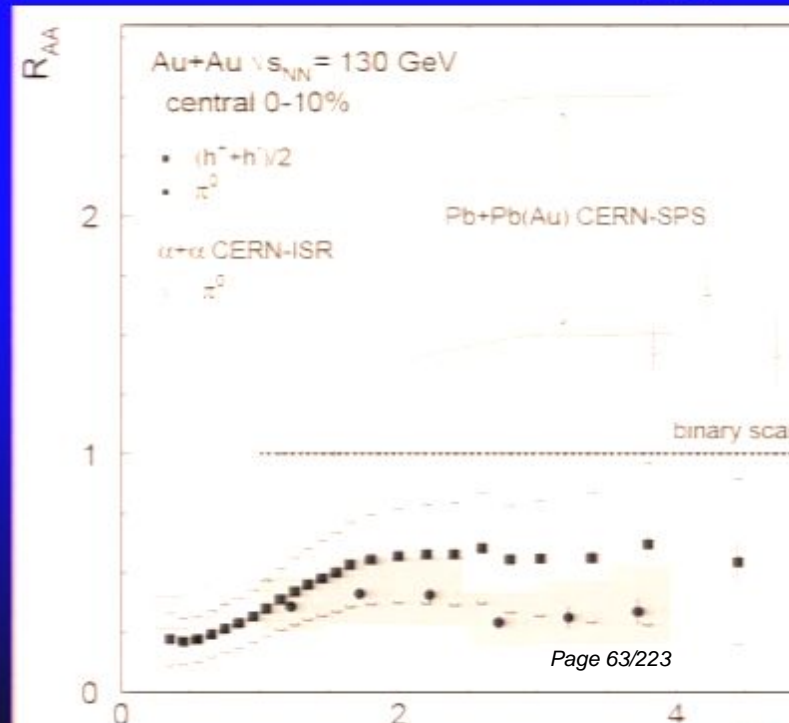
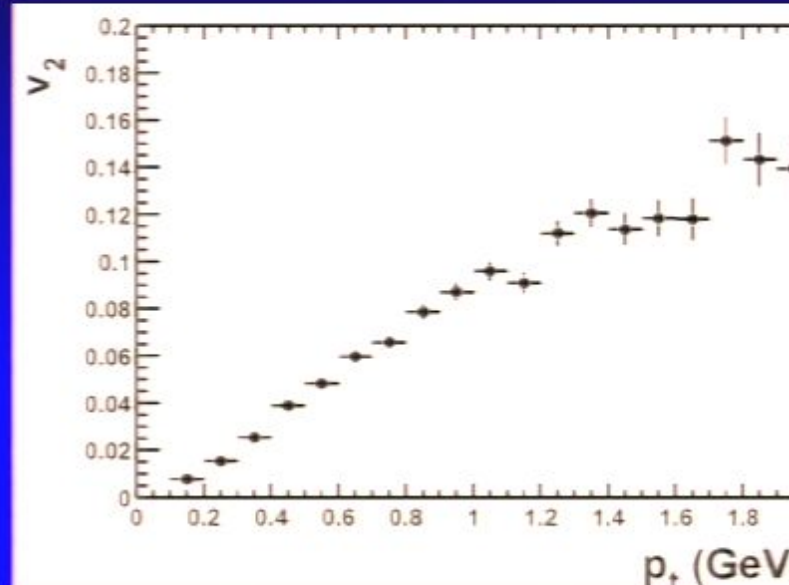
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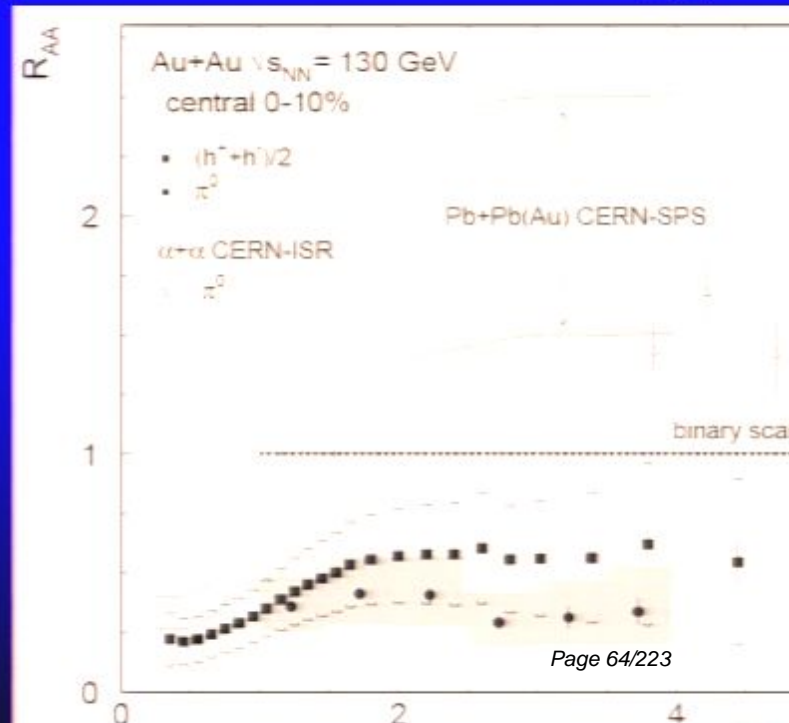
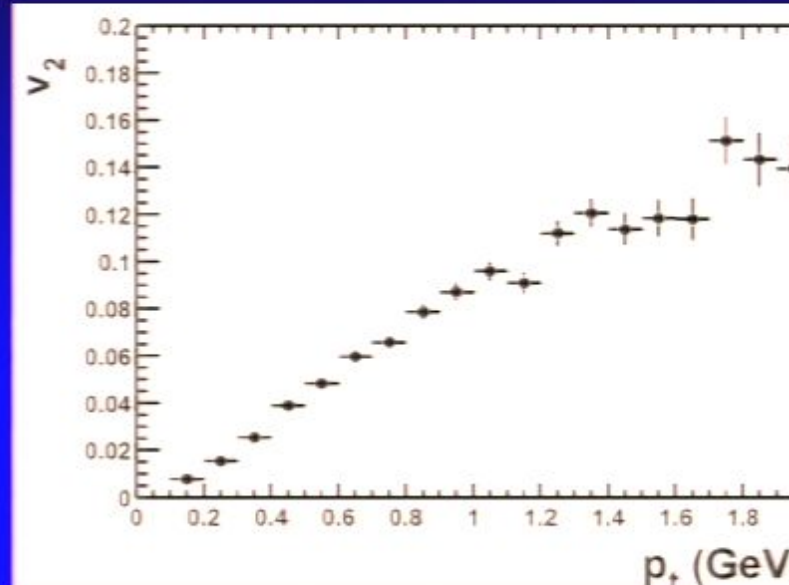
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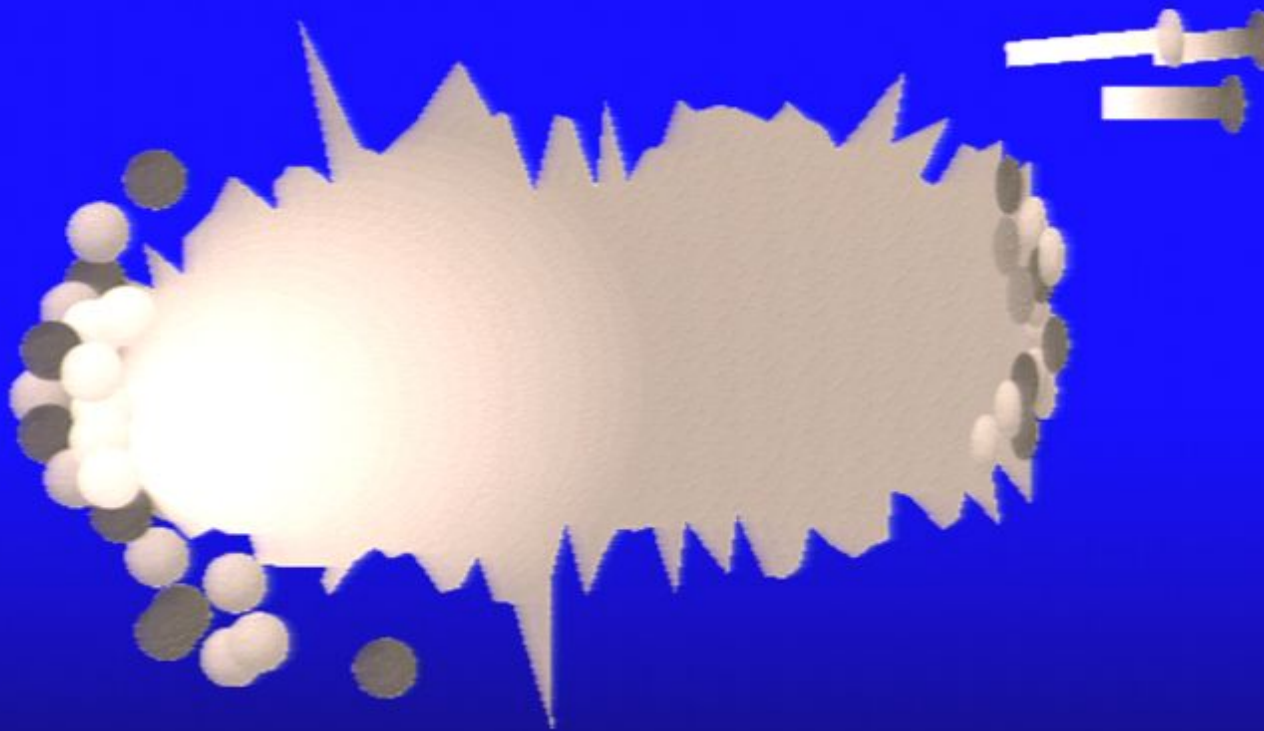






# Initial State

**How are the initial state densities and asymmetries imprinted on the detected distributions?**



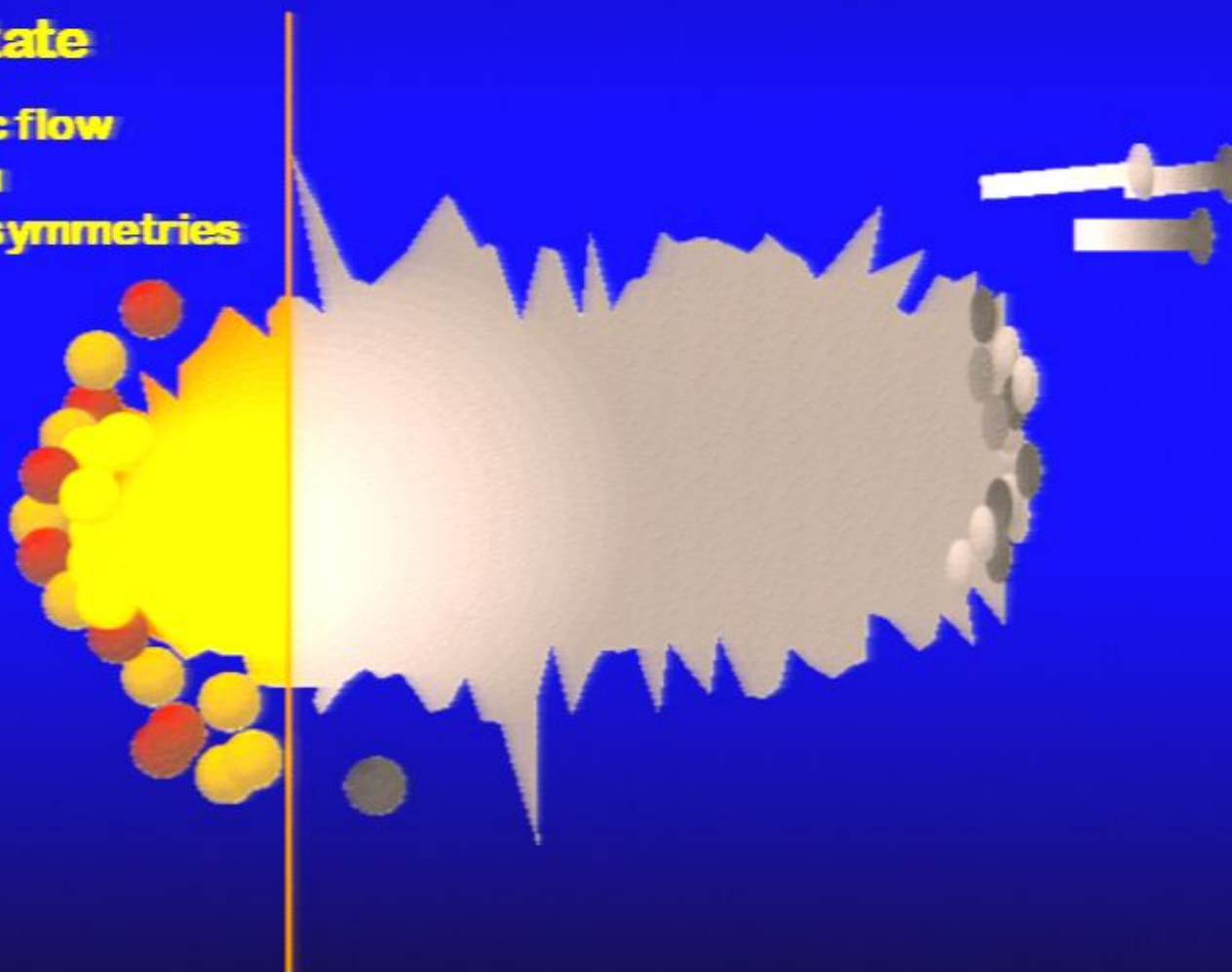


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## 3. Initial State

Hydrodynamic flow  
from  
initial spatial asymmetries

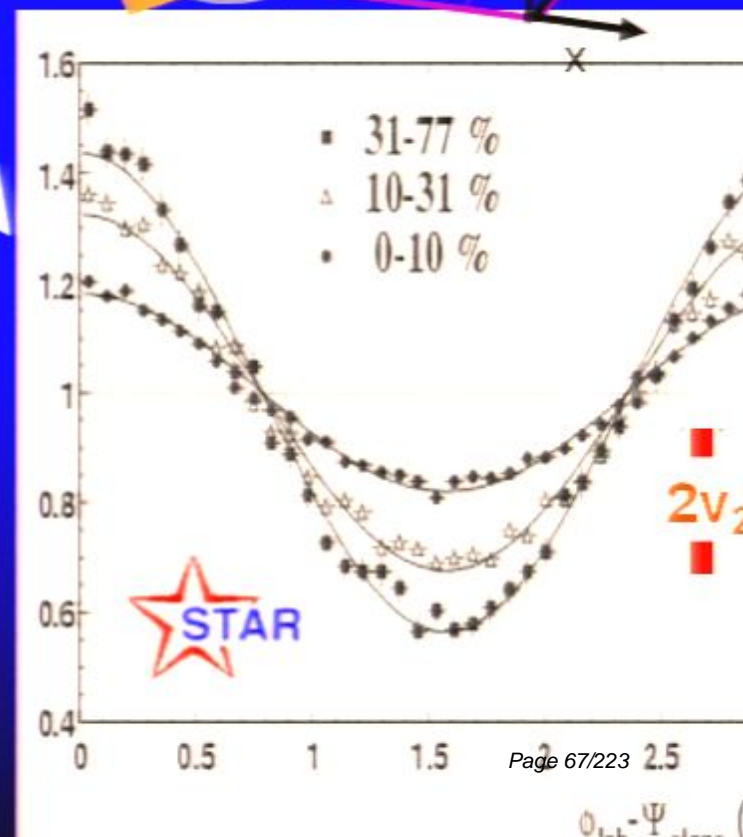
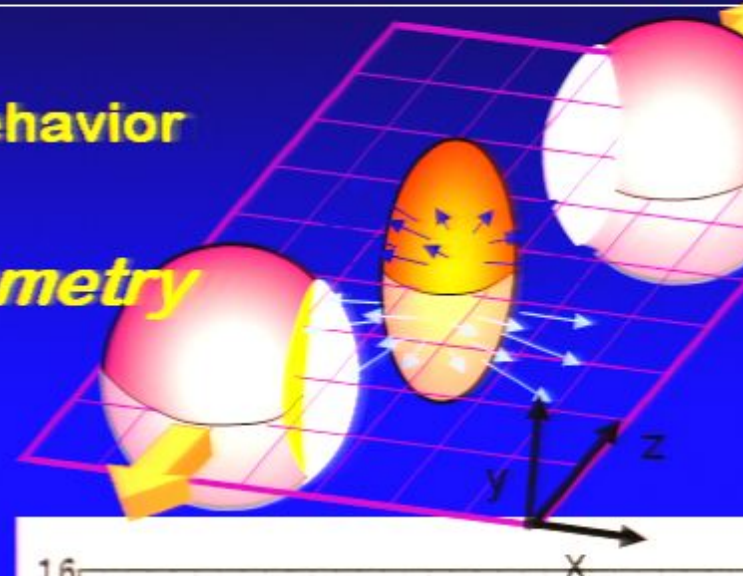






# Motion Is Hydrodynamic

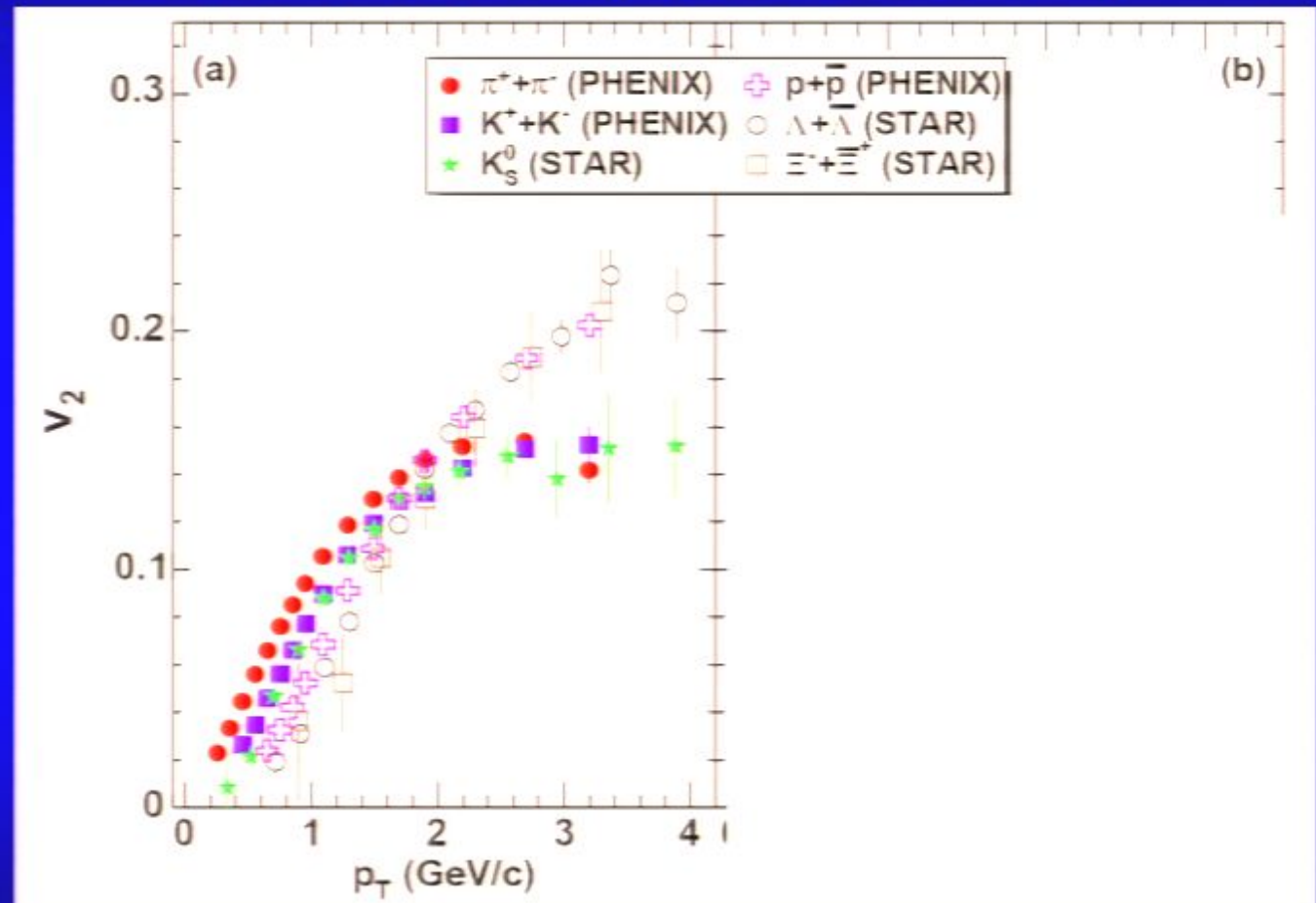
- When does thermalization occur?
  - Strong evidence that final state bulk behavior reflects the initial state geometry
- Because the initial *azimuthal asymmetry* persists in the final state
 
$$dn/d\phi \sim 1 + 2 v_2(p_T) \cos(2\phi) + \dots$$





# The “Flow” Is *Perfect*

- The “fine structure”  $v_2(p_T)$  for different mass particles shows good agreement with ideal (“perfect fluid”) hydrodynamics

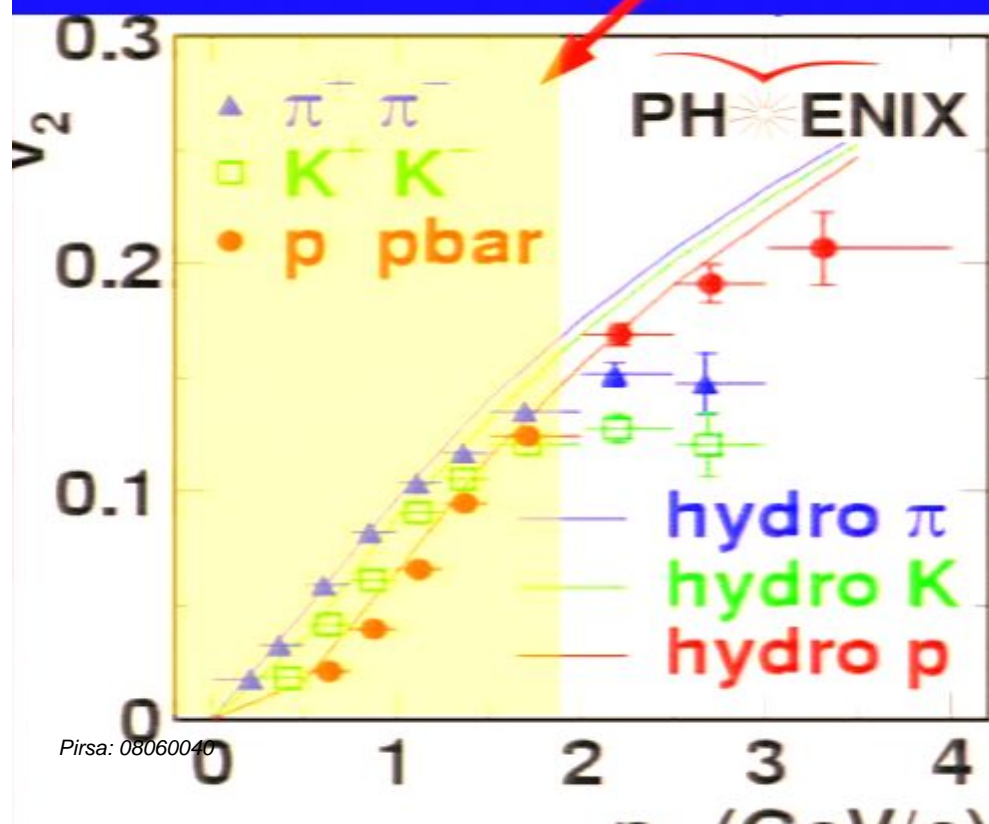
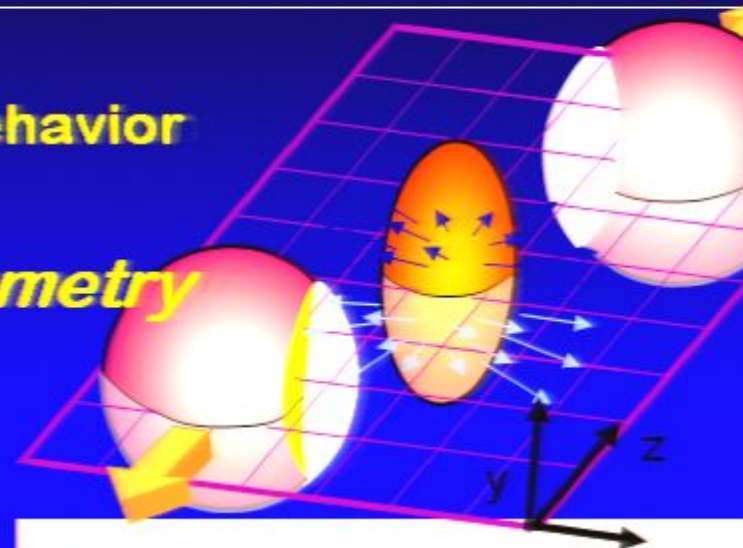




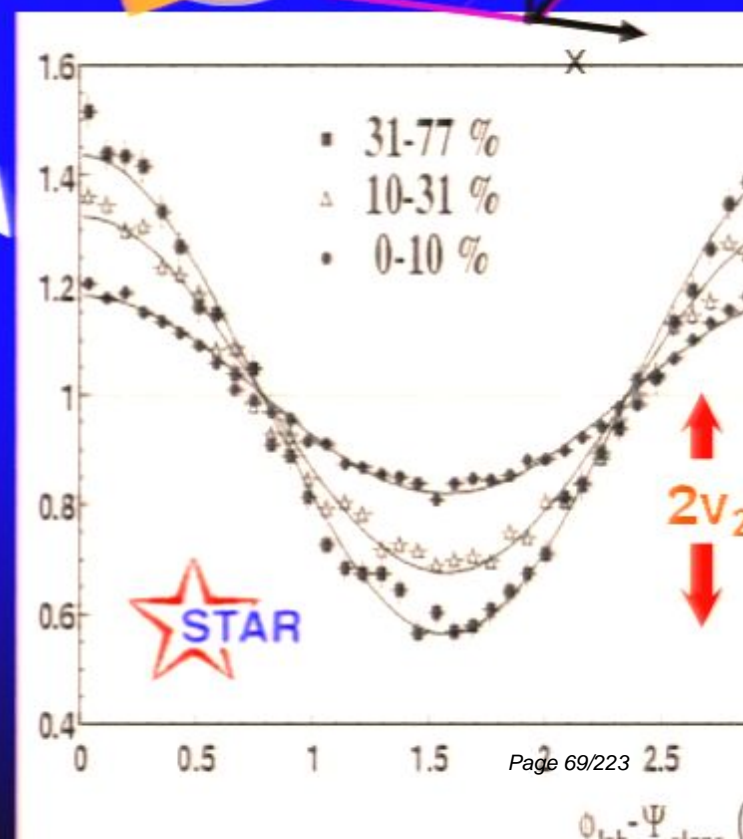


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Pirsa: 08060040



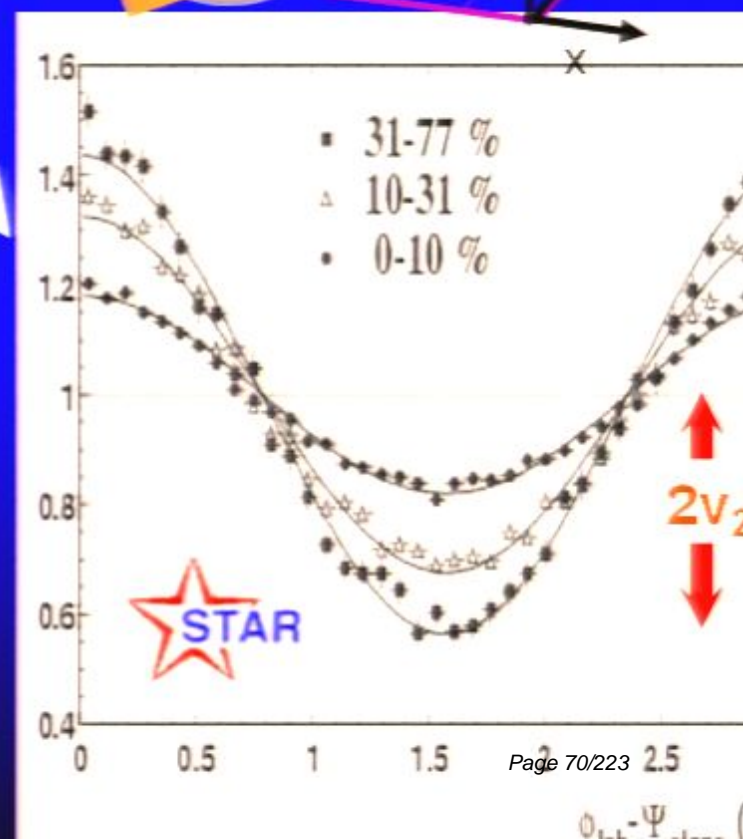
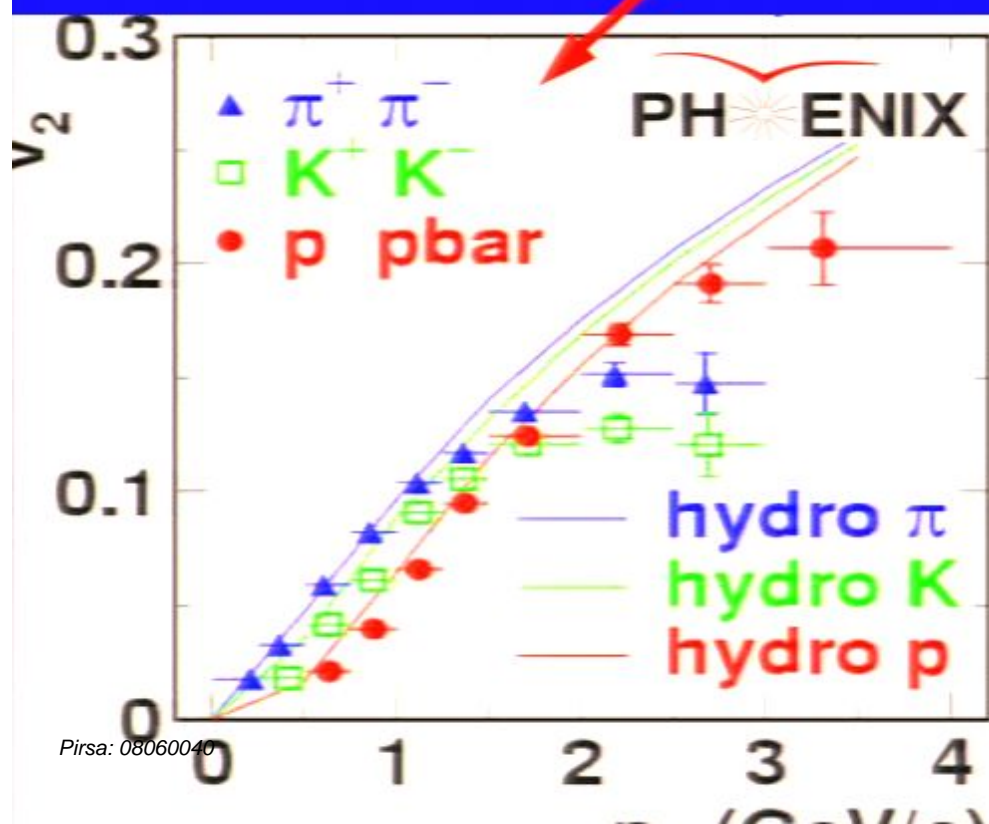
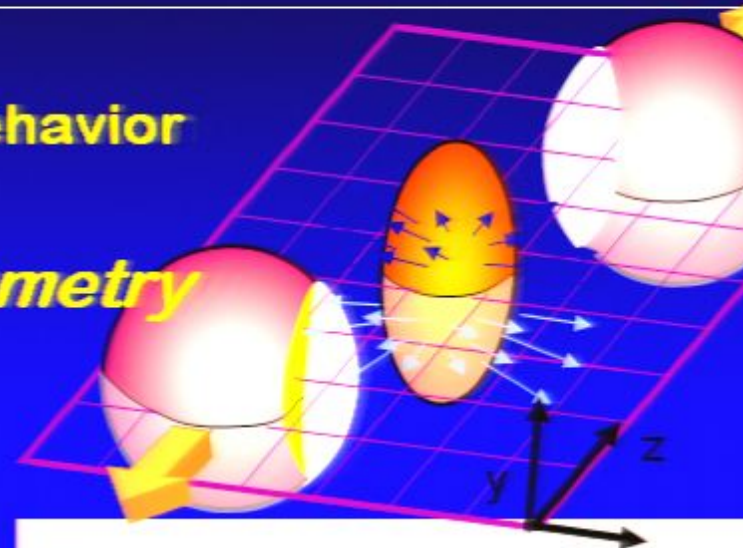
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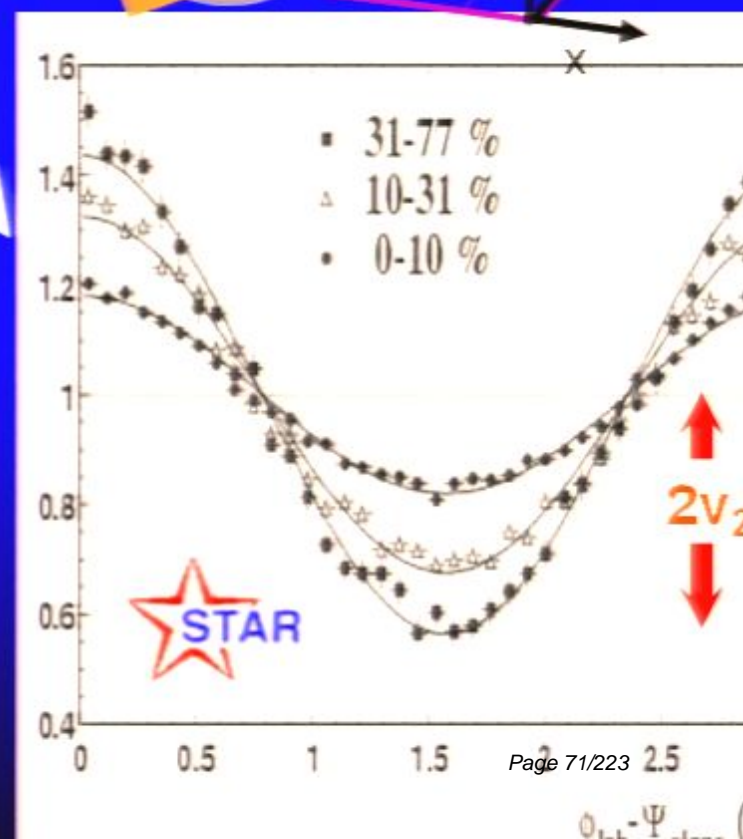
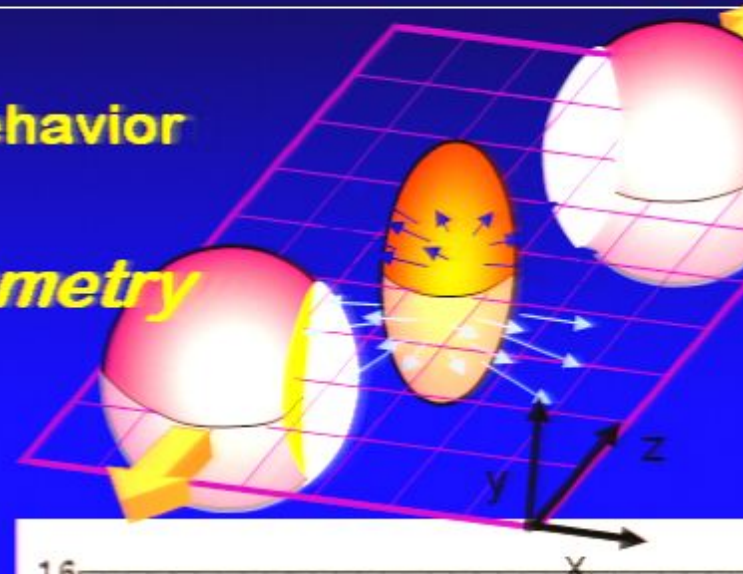






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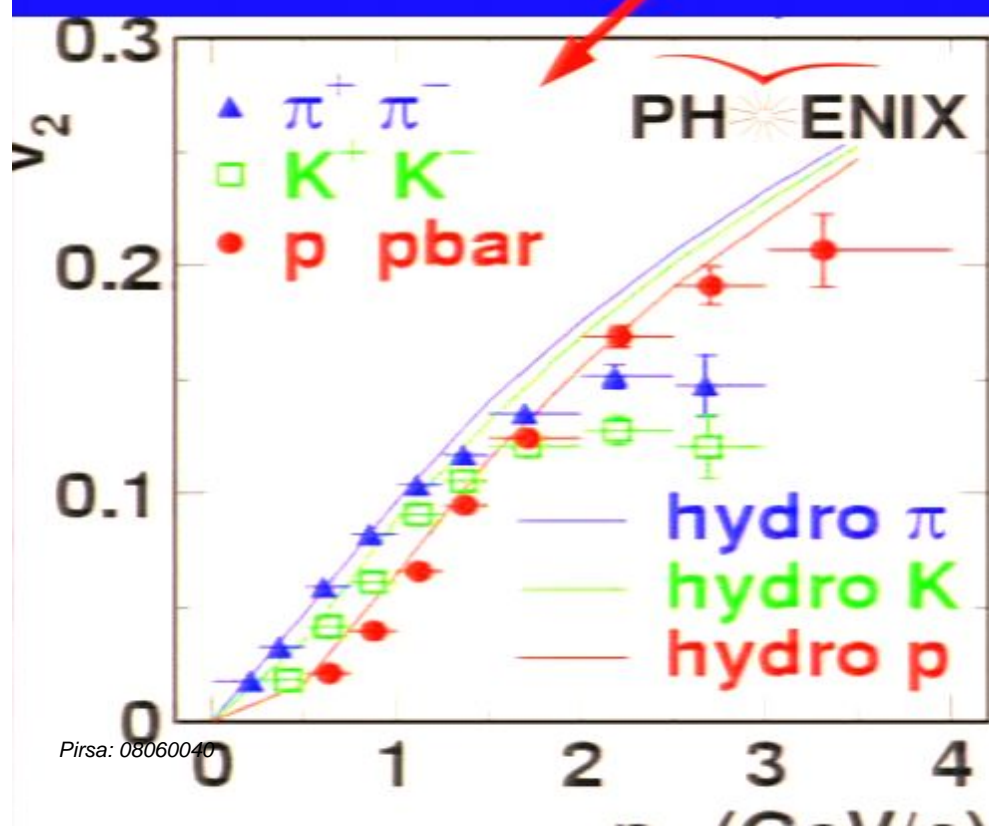
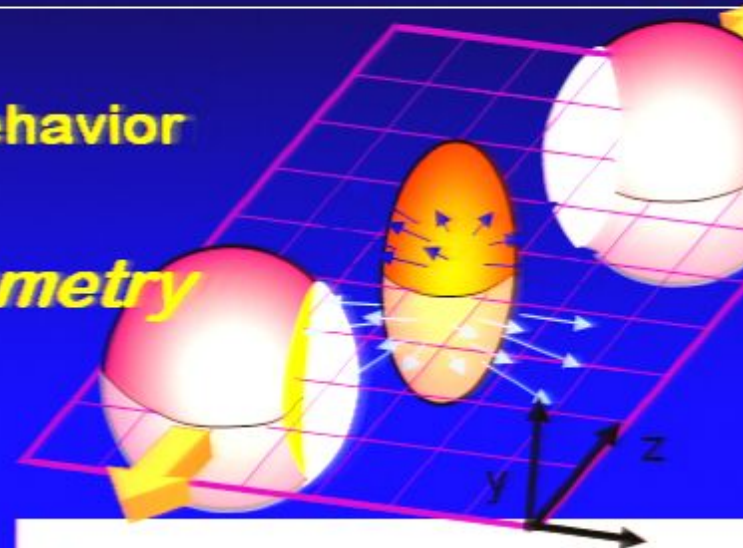
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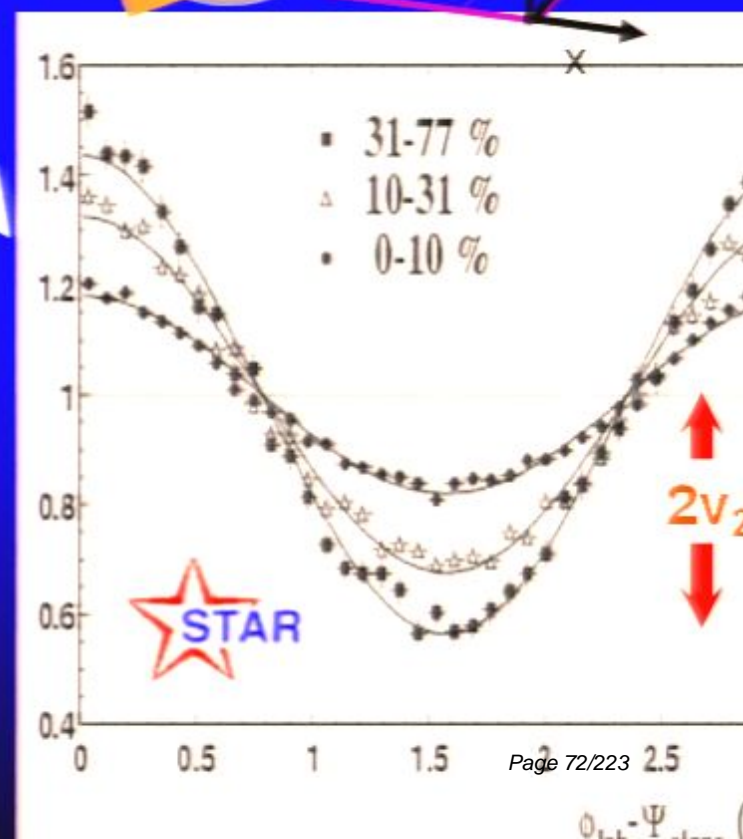


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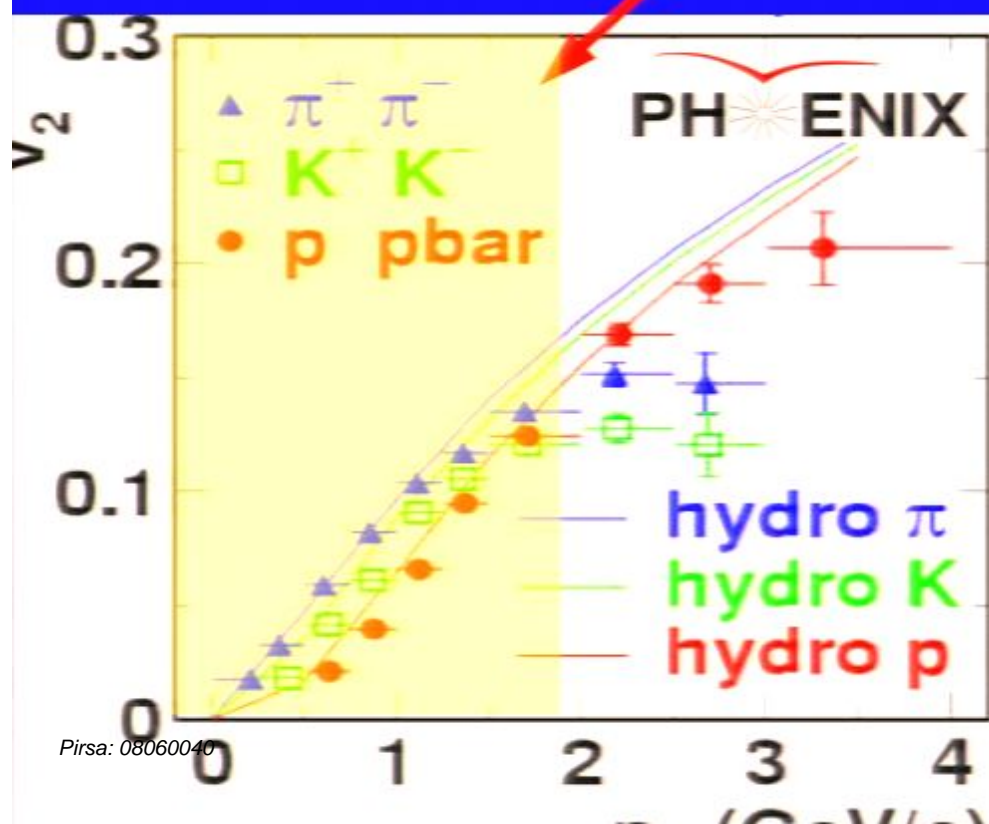
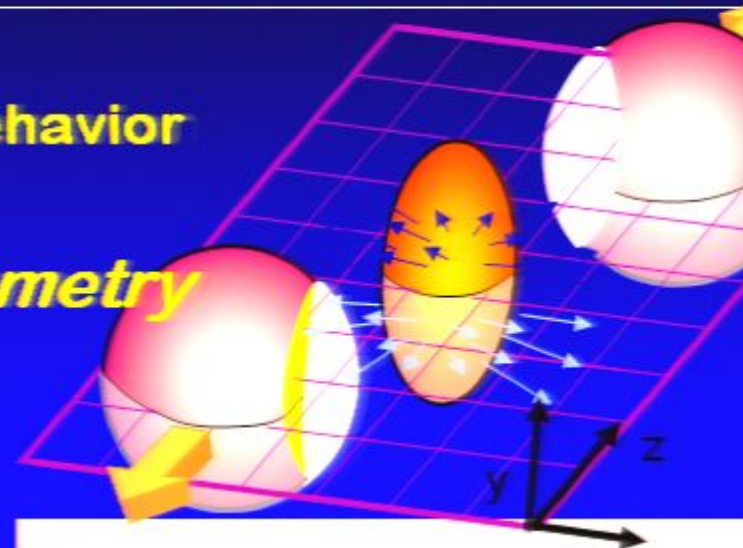
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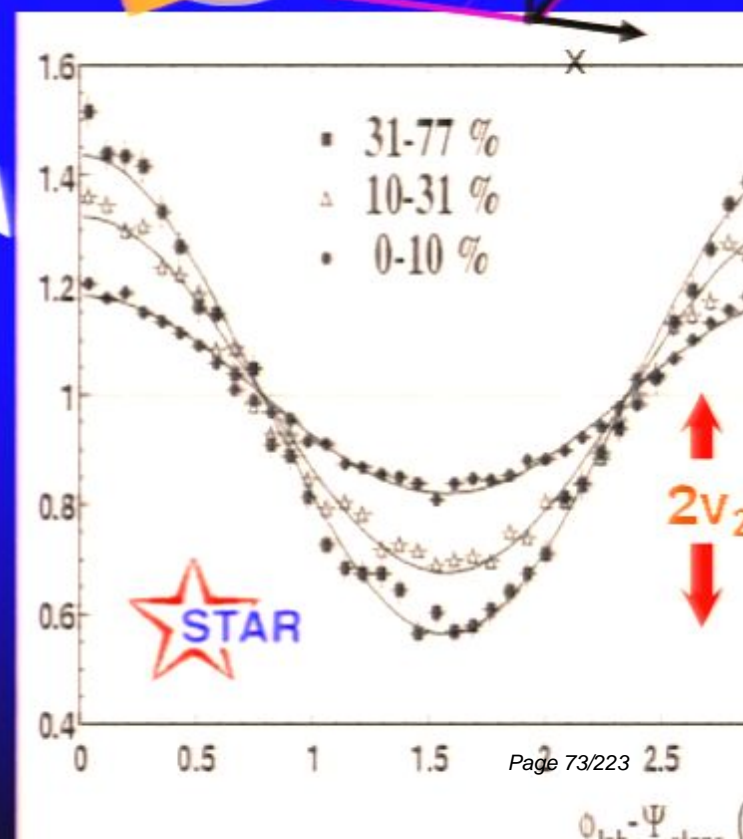


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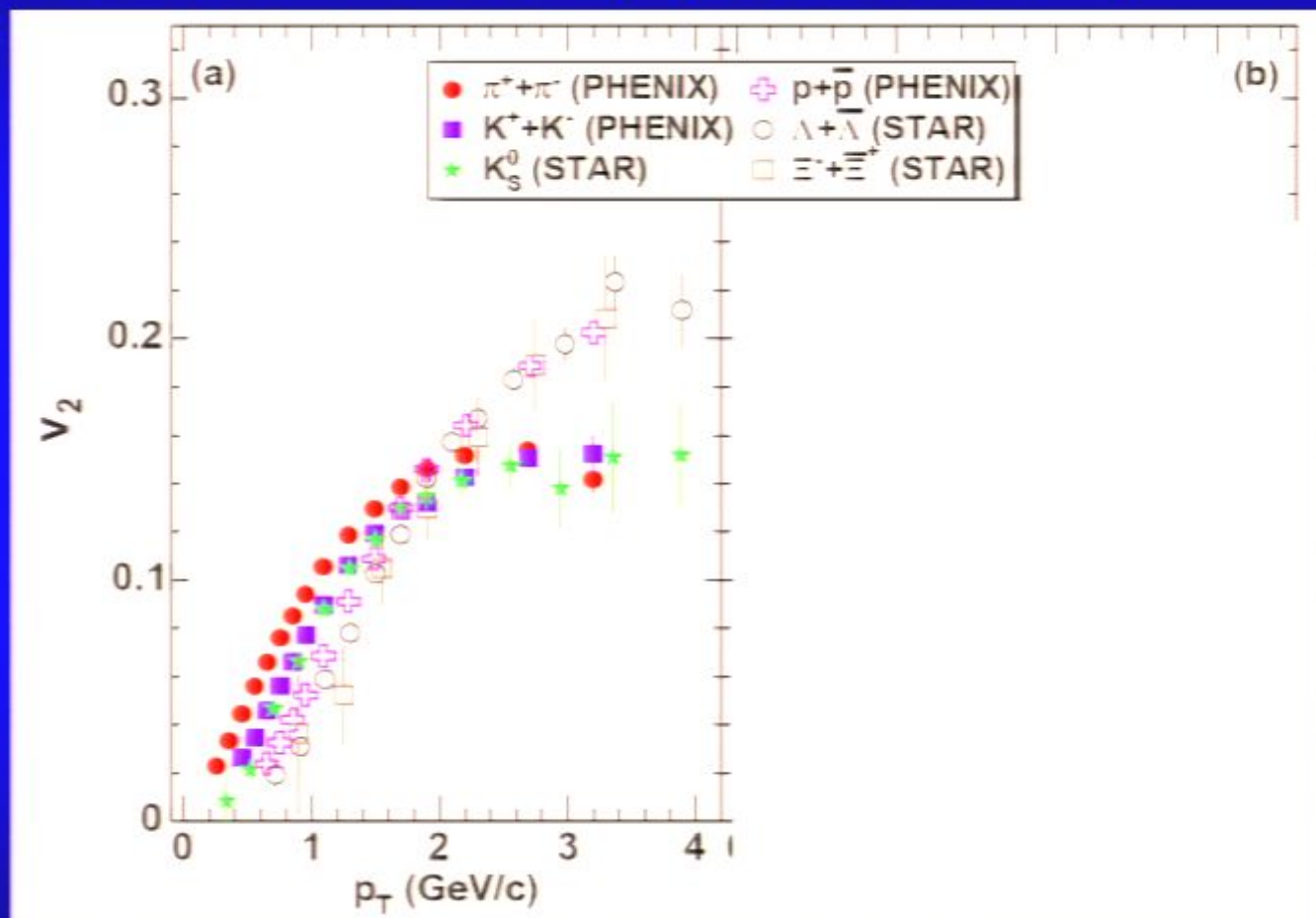


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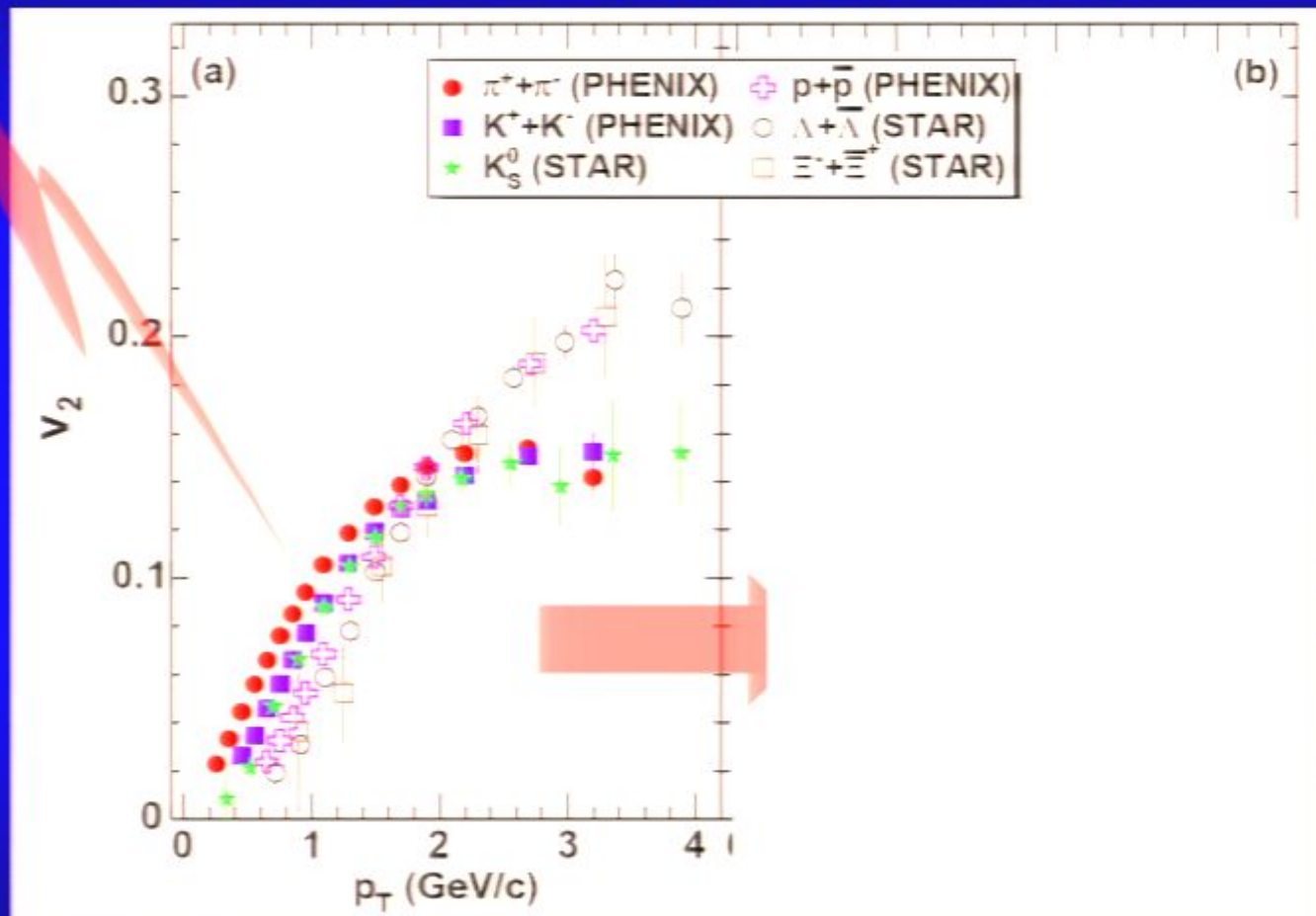






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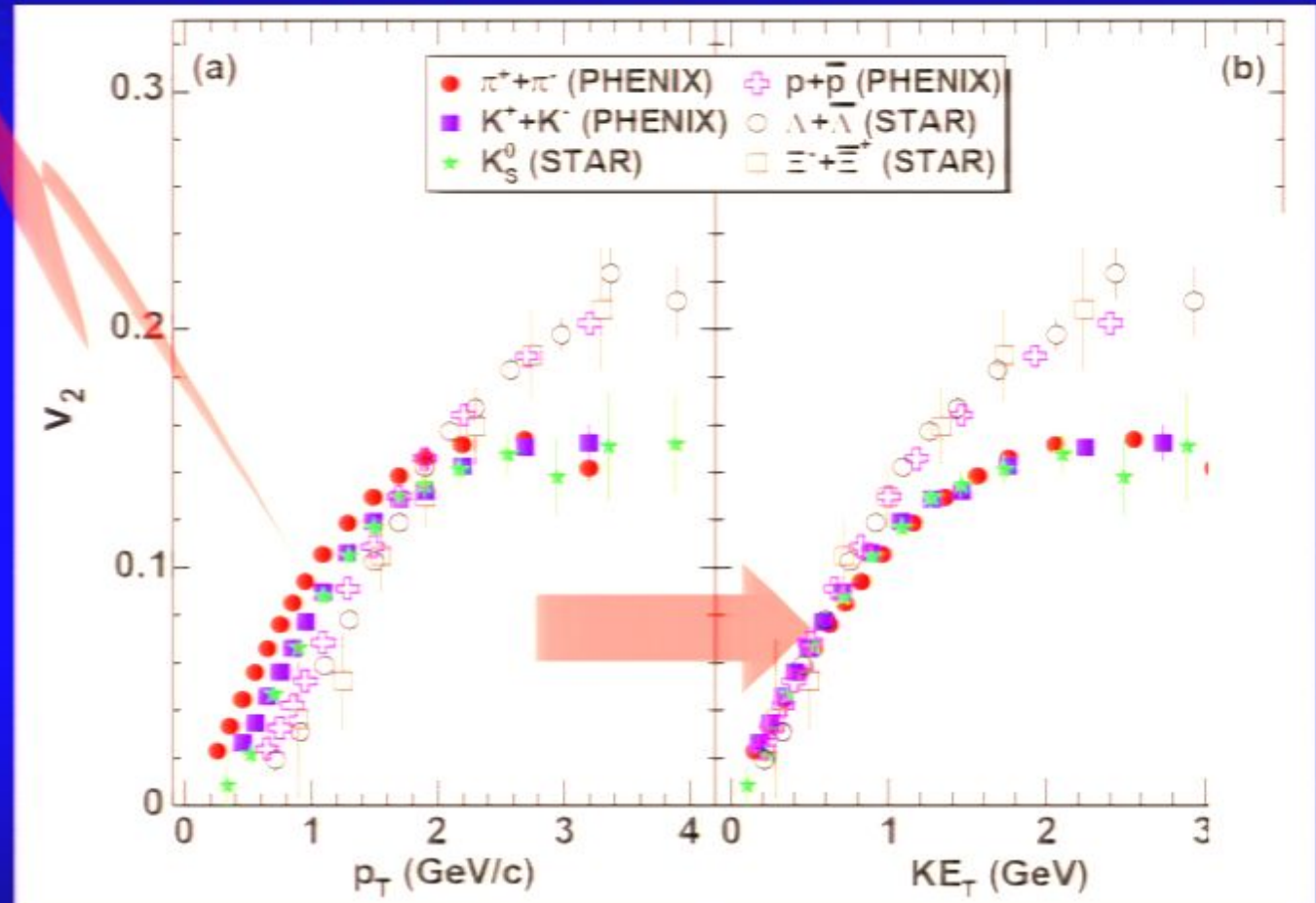




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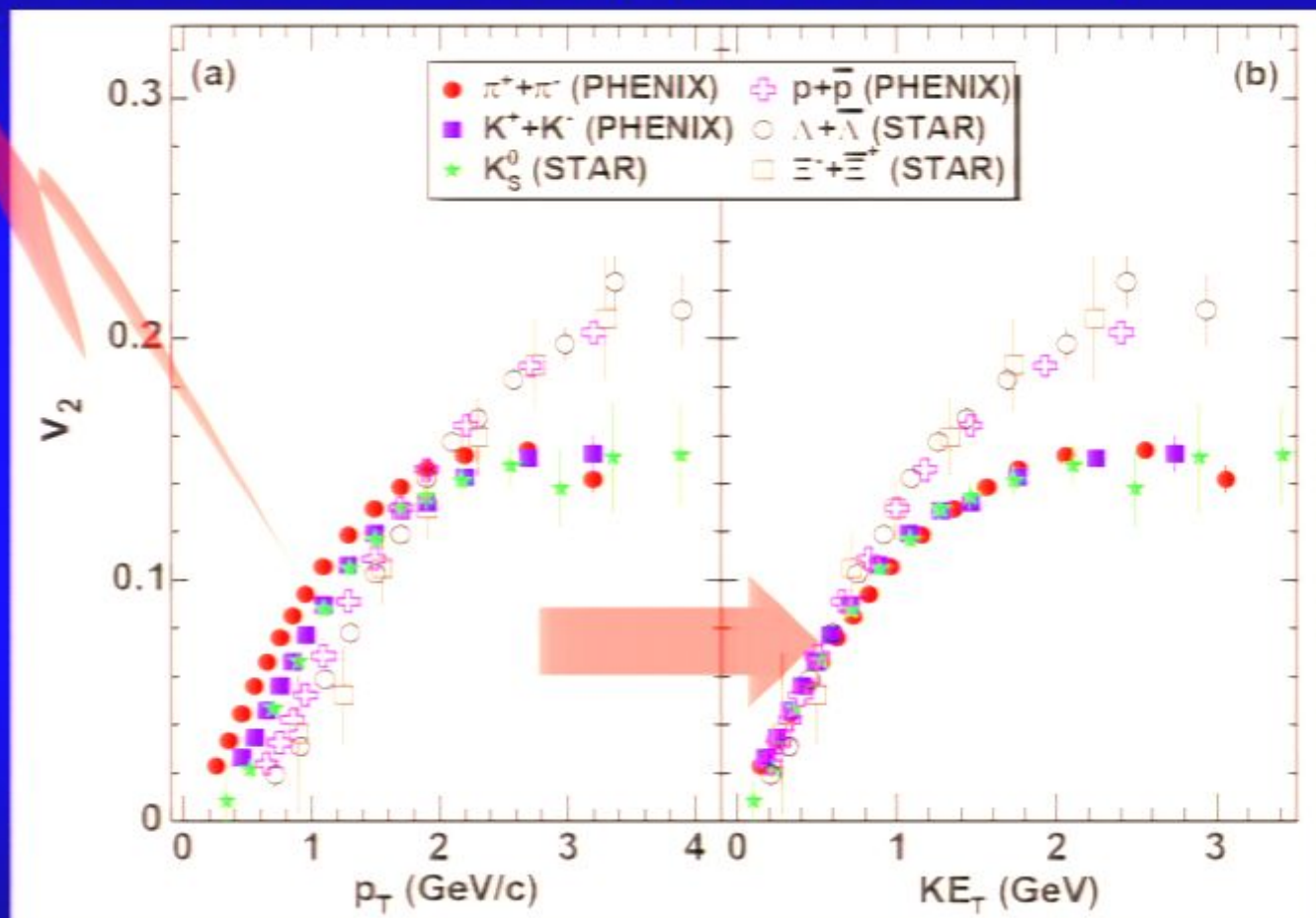




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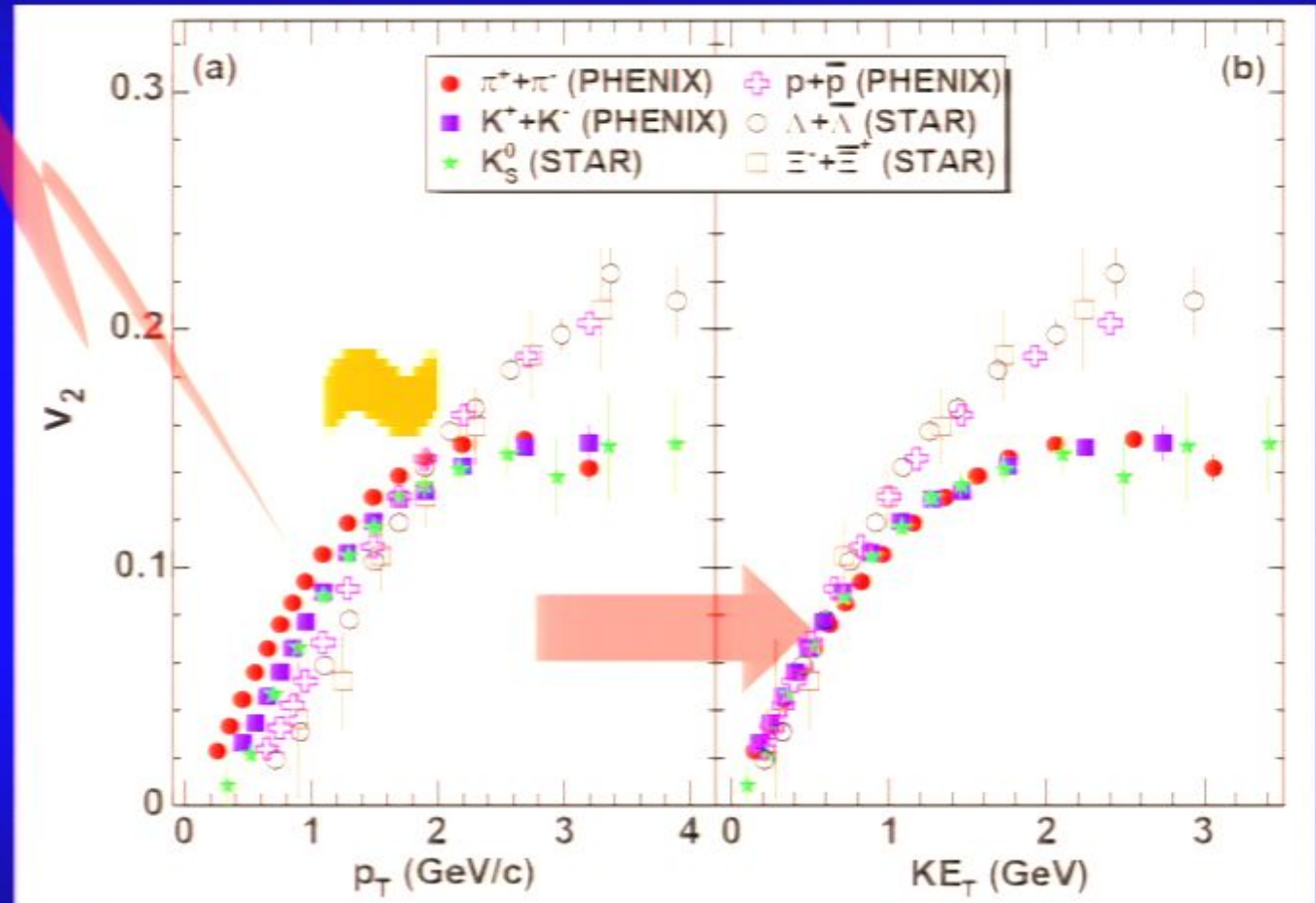




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- Roughly:  $\partial_\nu T^{\mu\nu} = 0 \rightarrow$  Work-energy theorem

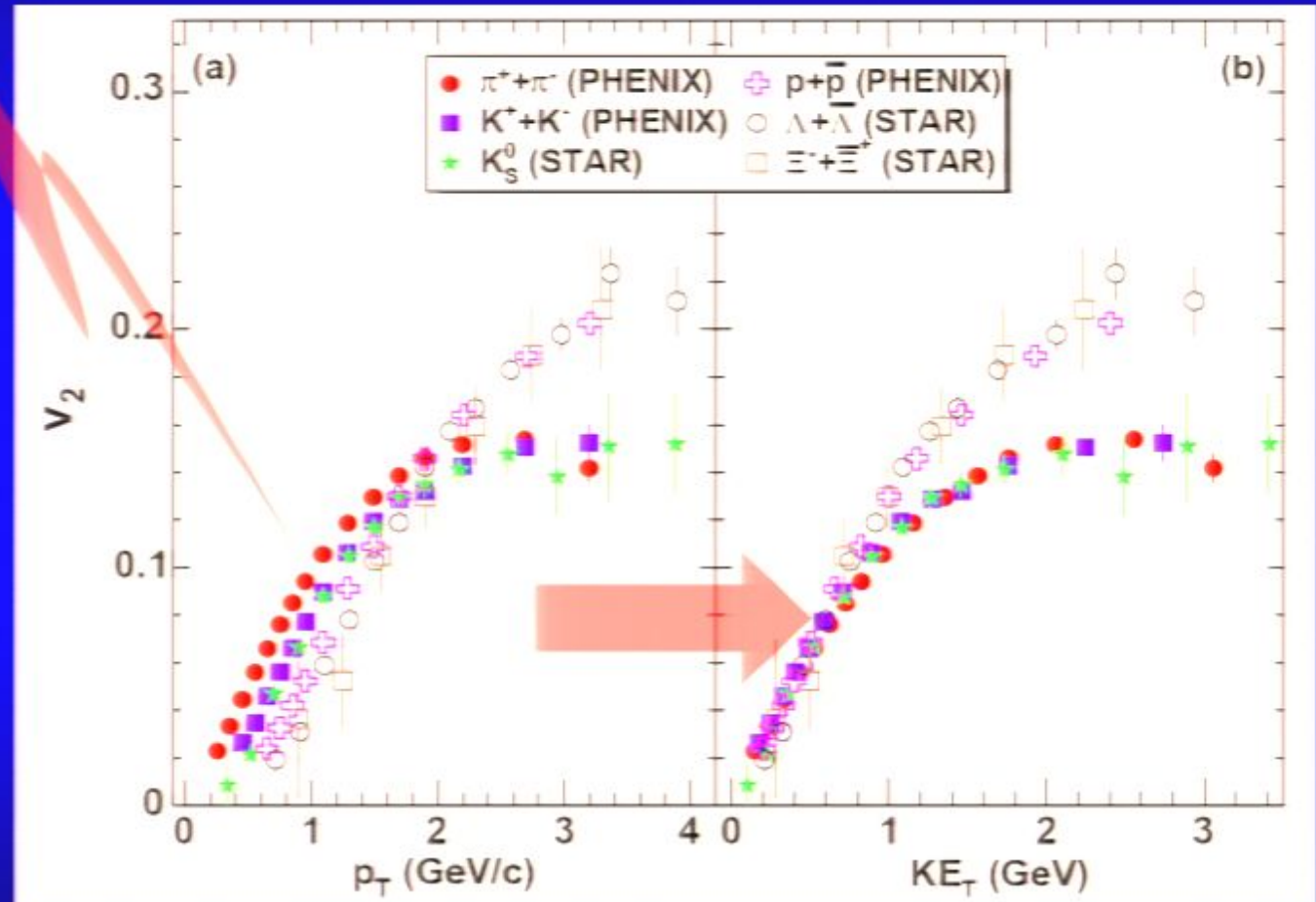
$$\rightarrow \int \nabla P d(\text{vol}) = \Delta E_K \cong m_T - m_0 \equiv \Delta KE_T$$





# The “Flow” Knows Quarks

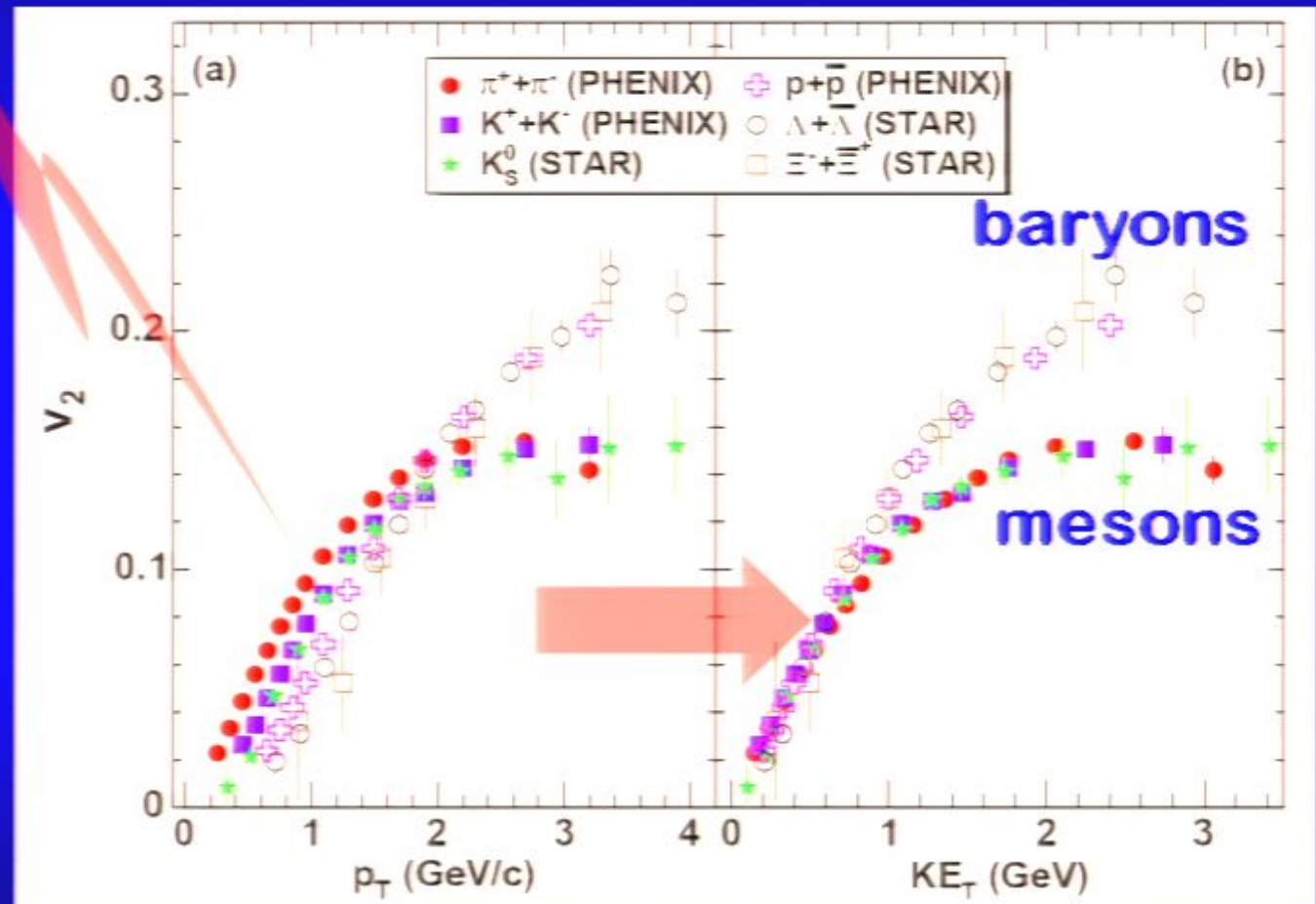
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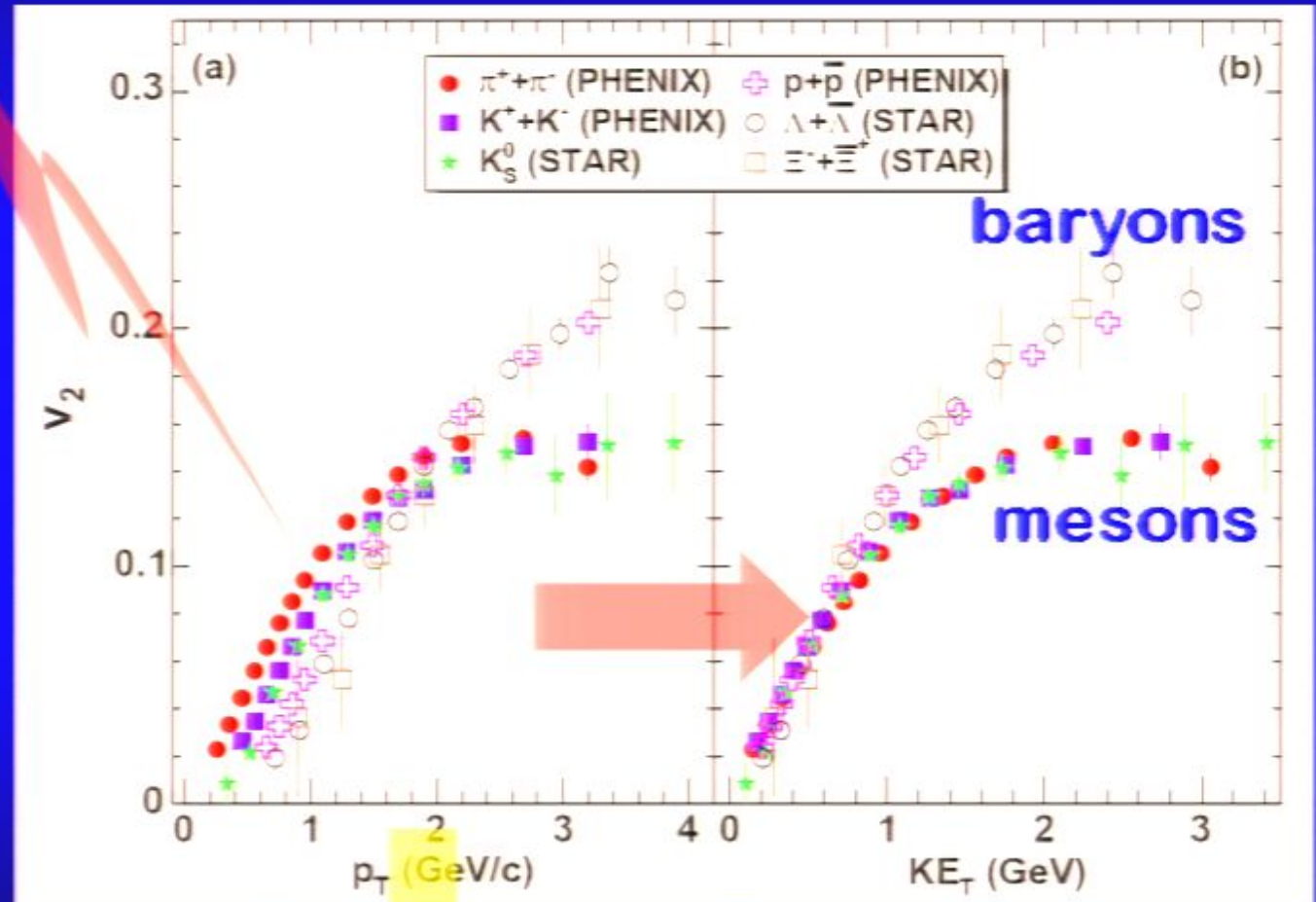






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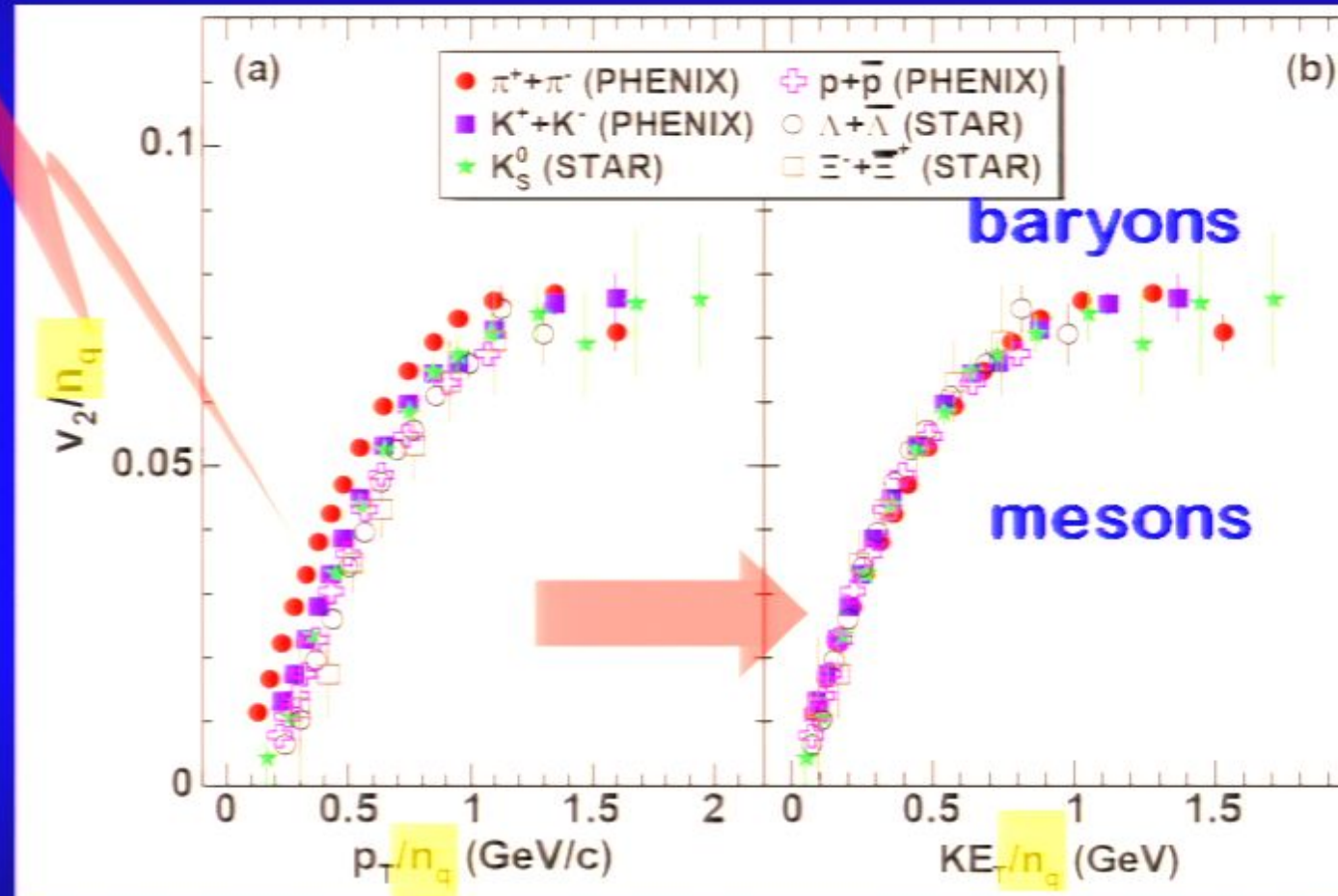


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$$\eta_{H_2O} \sim 1 \times$$



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$\eta$





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$$\eta_{Pitch} \sim 2.3$$



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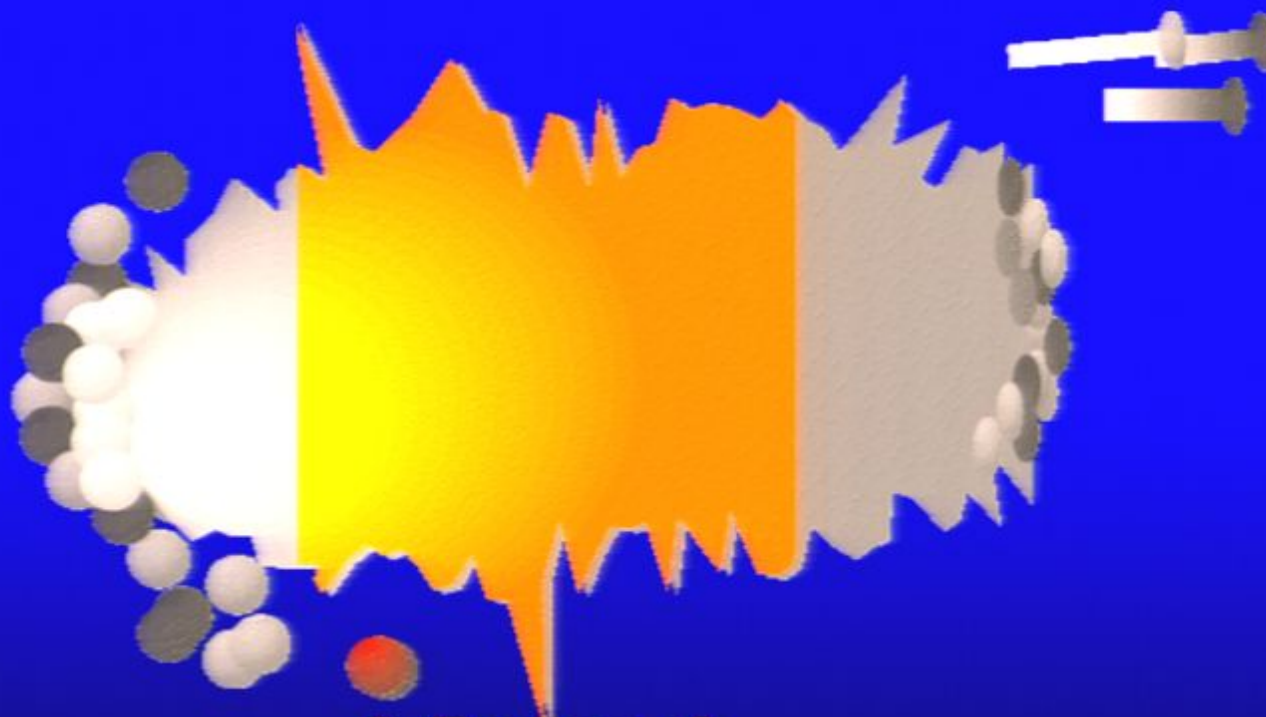
?



# Probes of Dense Matter

**Q. How dense is the matter?**

**A. Do pQCD Rutherford scattering on deep interior using “auto-generated” probes:**



**2. Probes of  
dense  
matter**





# Baseline p+p Measurements with pQCD

- Consider measurement of  $\pi^0$ 's in p+p collisions at RHIC.
- Compare to pQCD calculation

$$d\sigma = f_{a/A}(x_a, \mu^2) \otimes f_{b/B}(x_b, \mu^2)$$

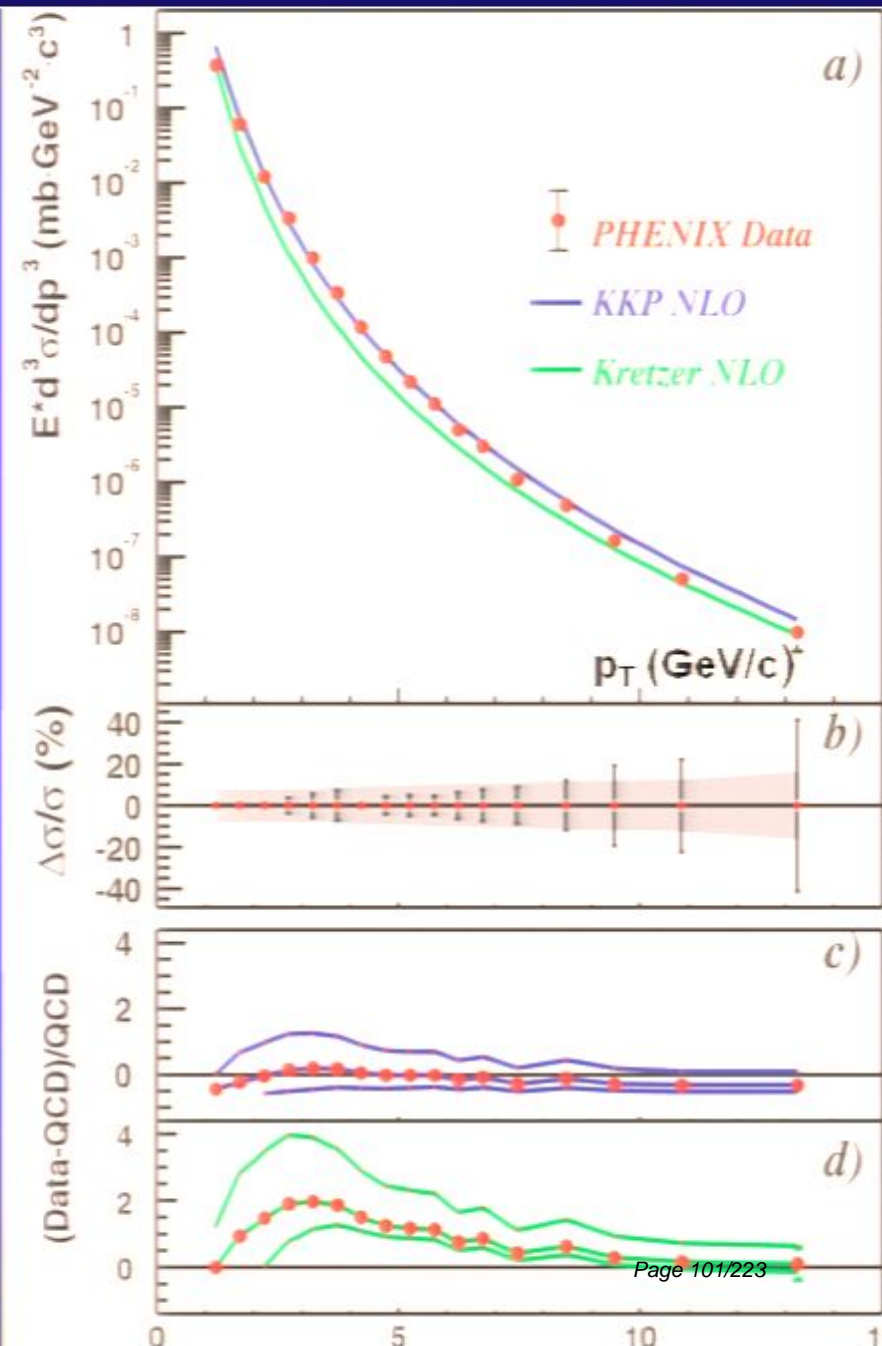
- parton distribution functions, for partons a and b
- measured in DIS, universality

$$\hat{\otimes} d\sigma(a+b \rightarrow c+d)$$

- perturbative cross-section (NLO)
- requires hard scale
- factorization between pdf and cross section

$$\otimes D_{h/c}(z_h, \mu^2)$$

- fragmentation function
- measured in e+e-





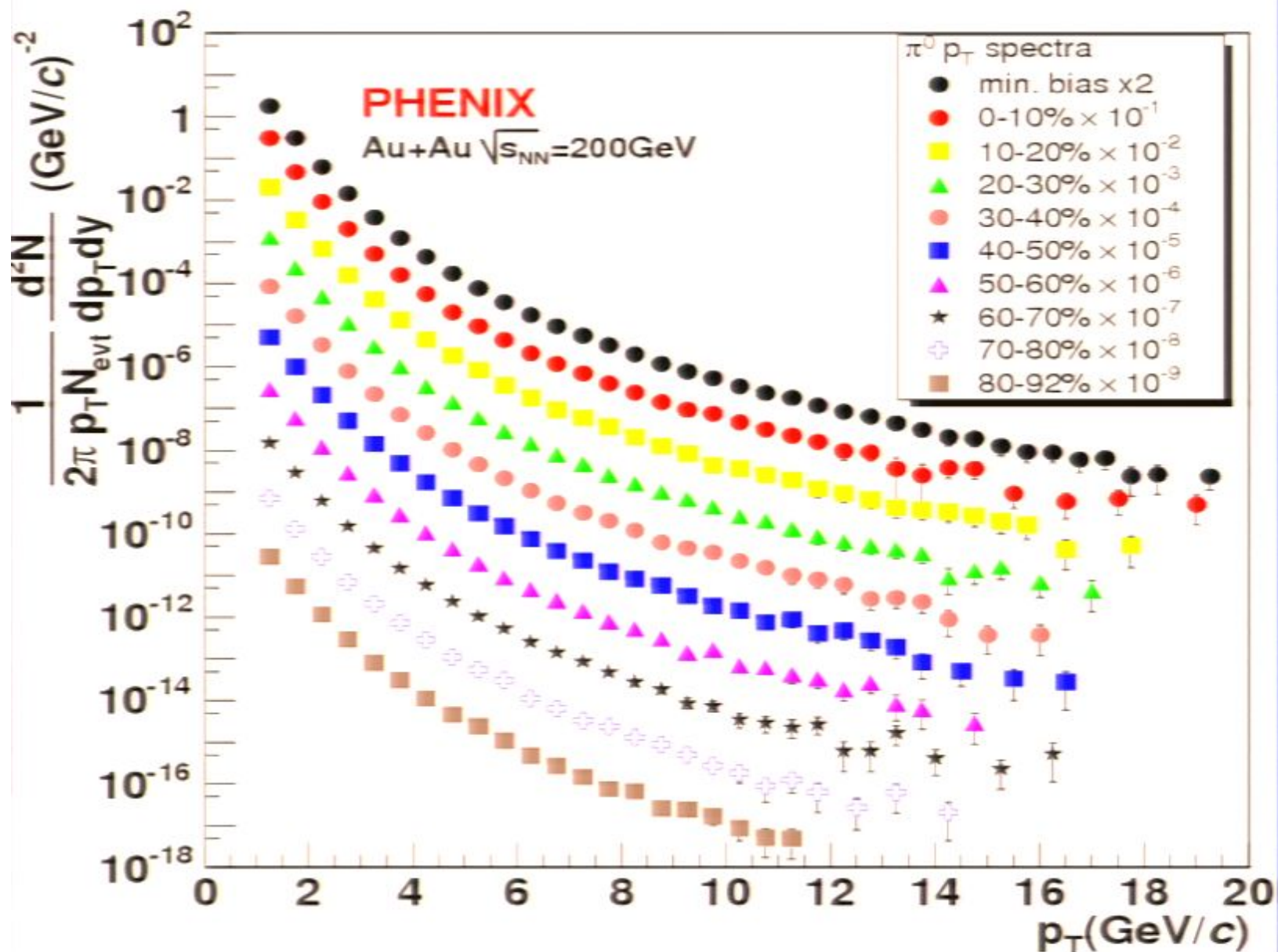
# Au+Au: Systematic Suppression Pattern





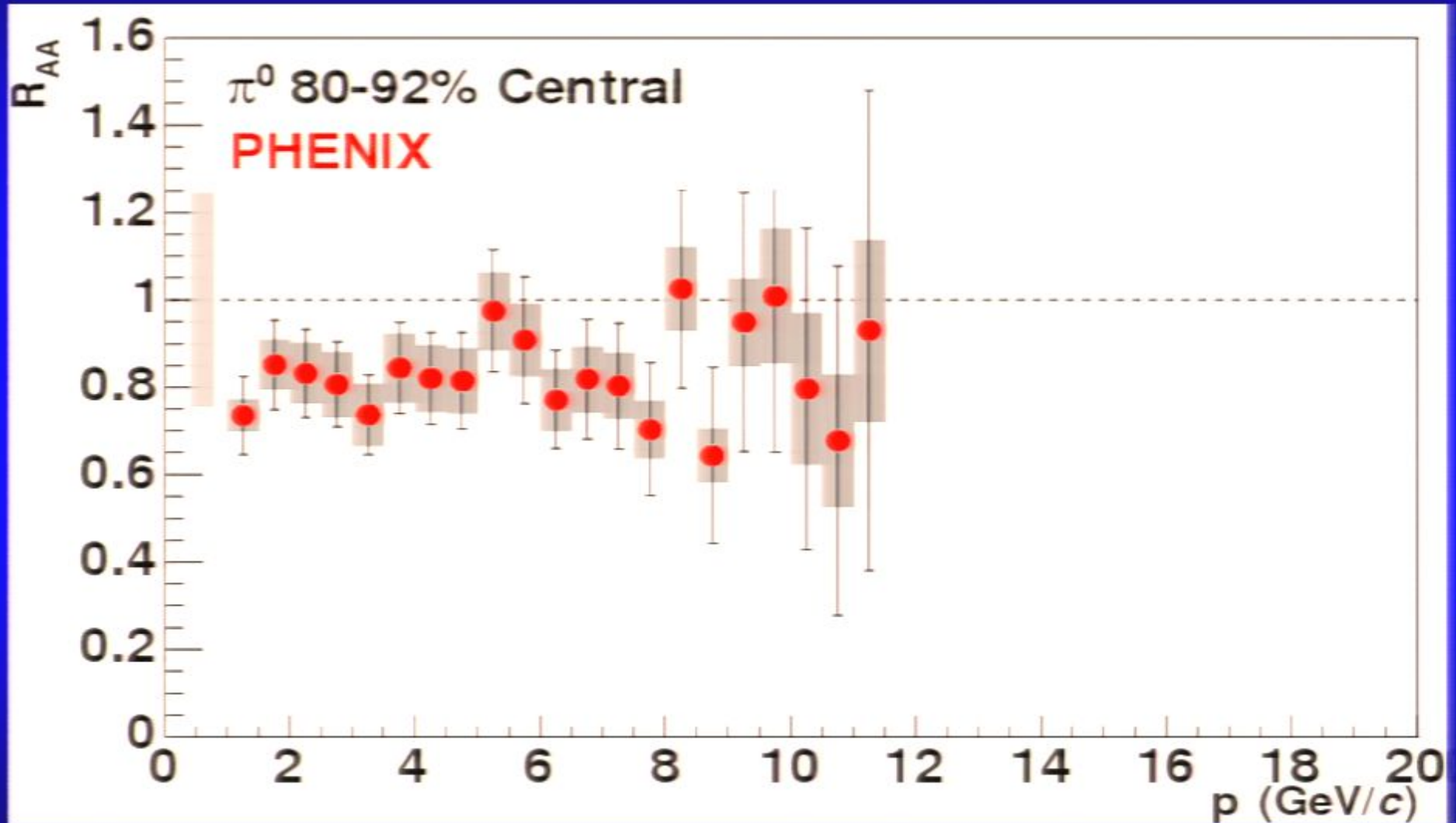


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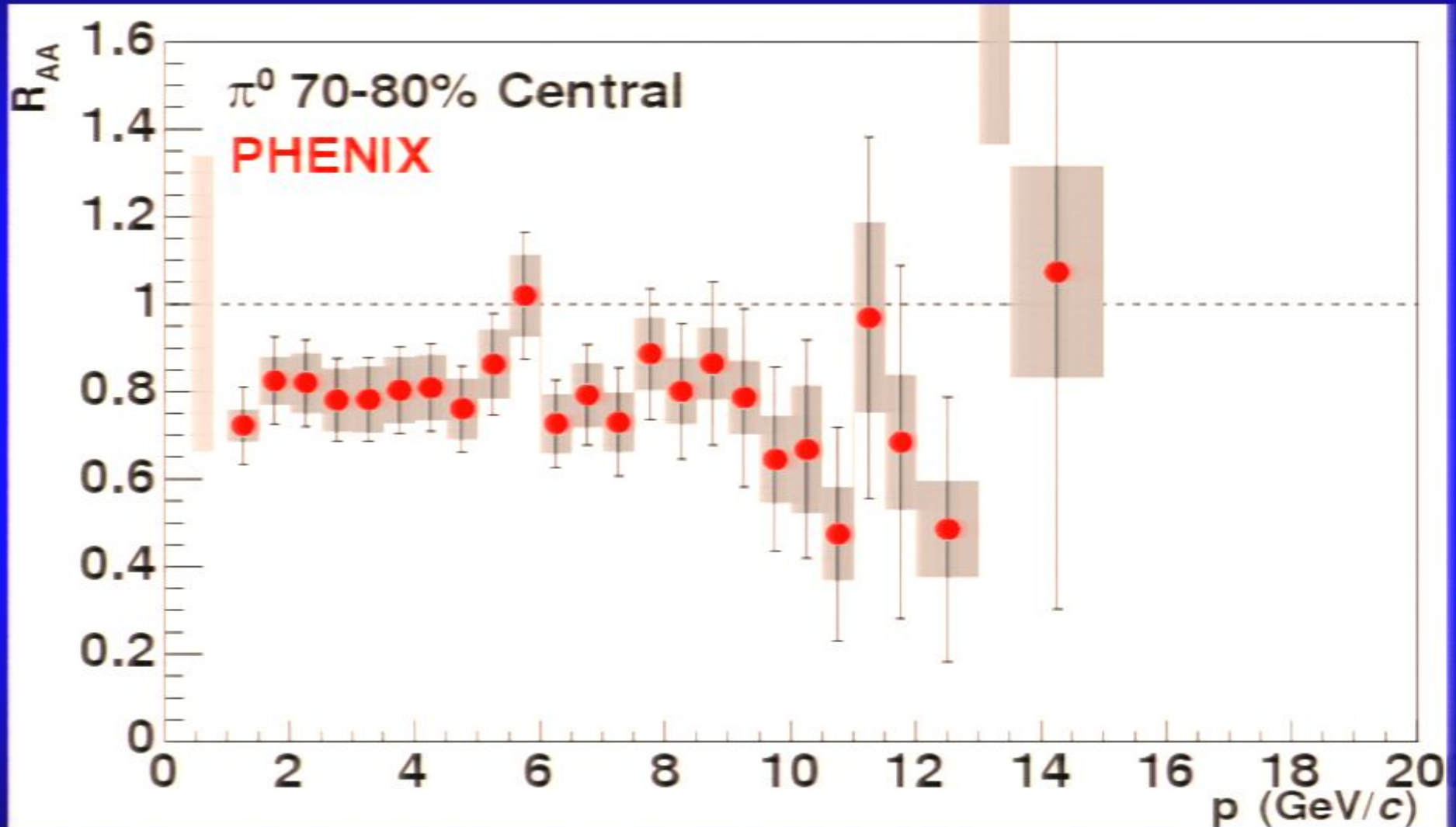
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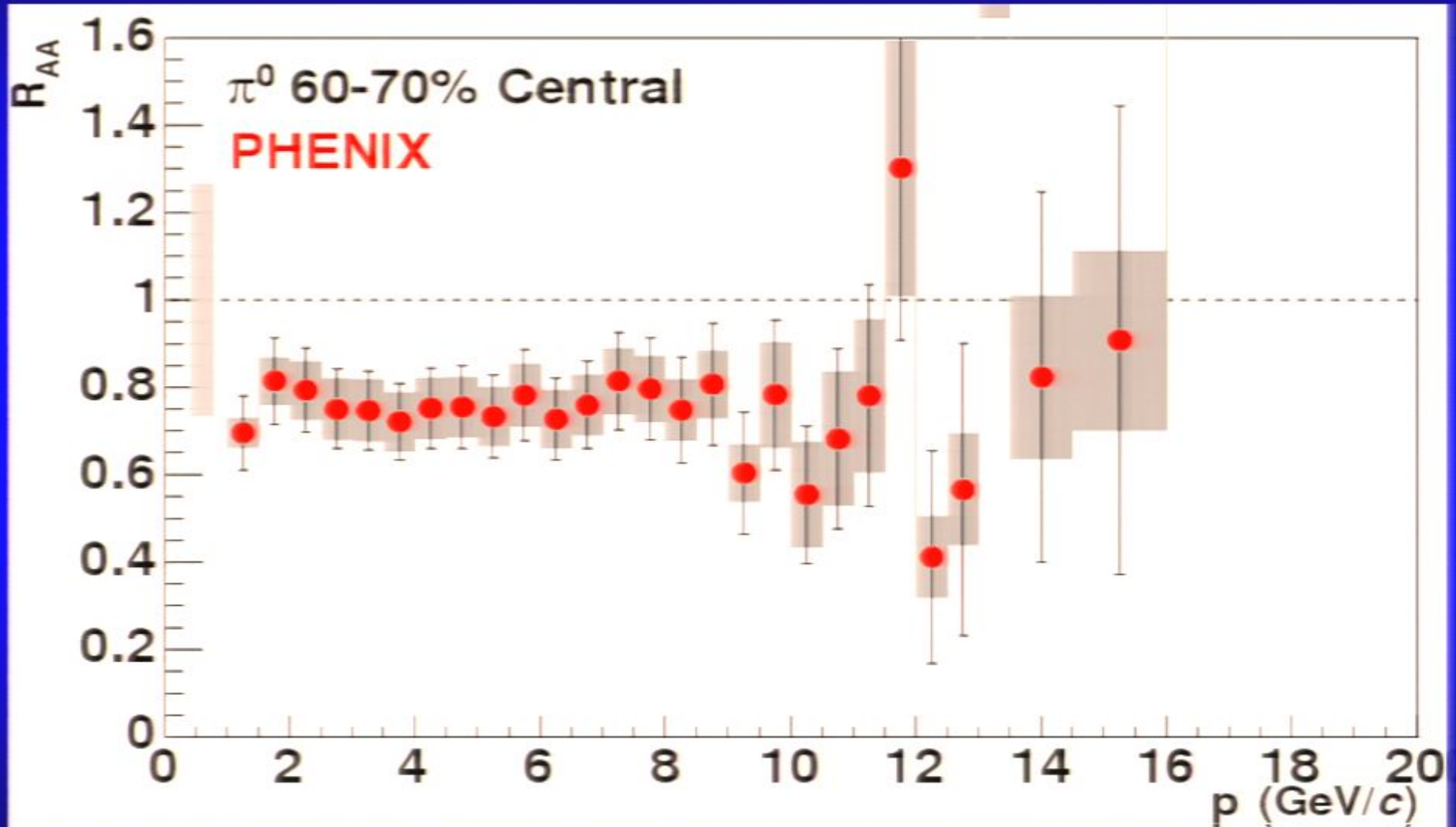


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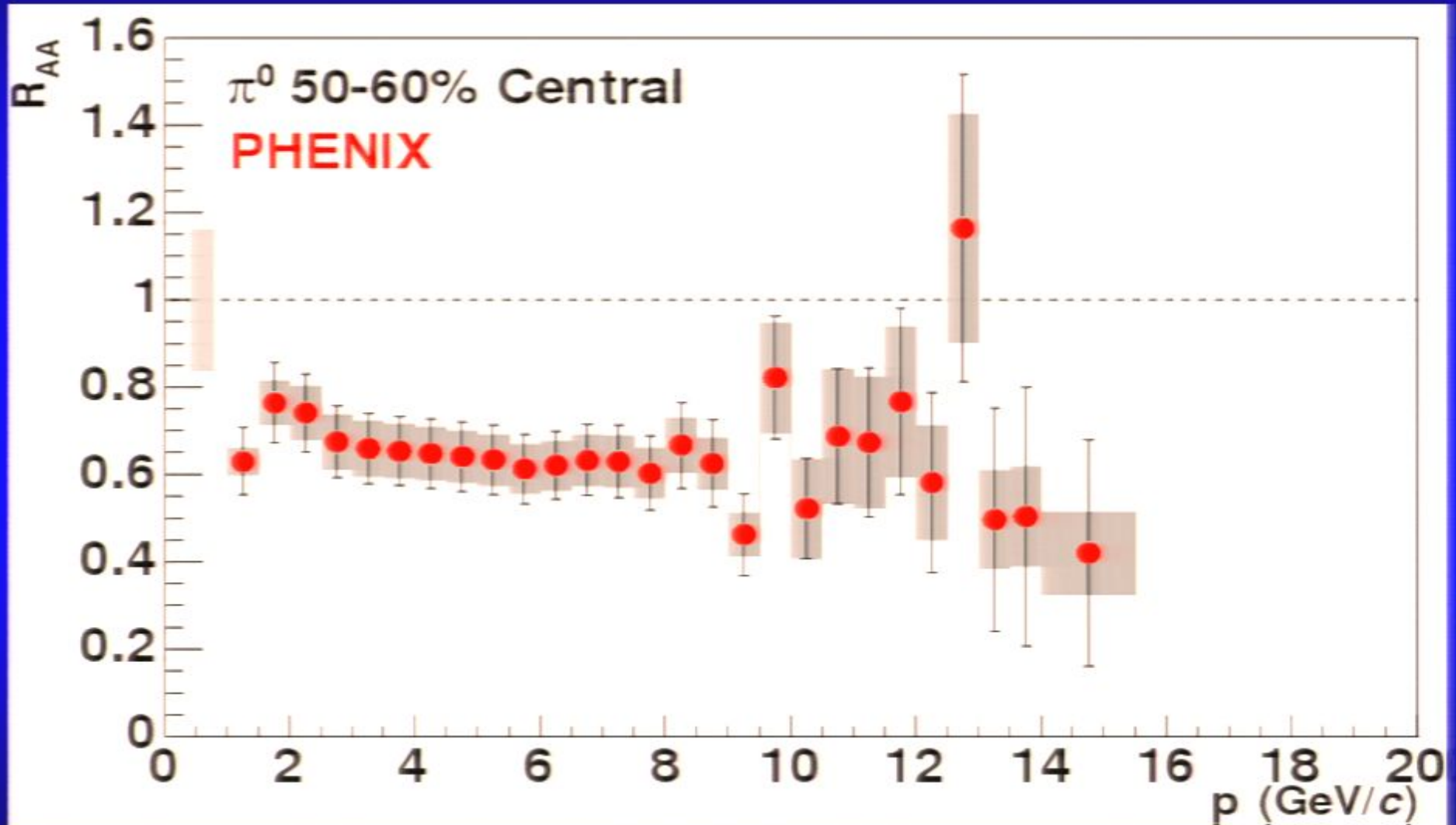
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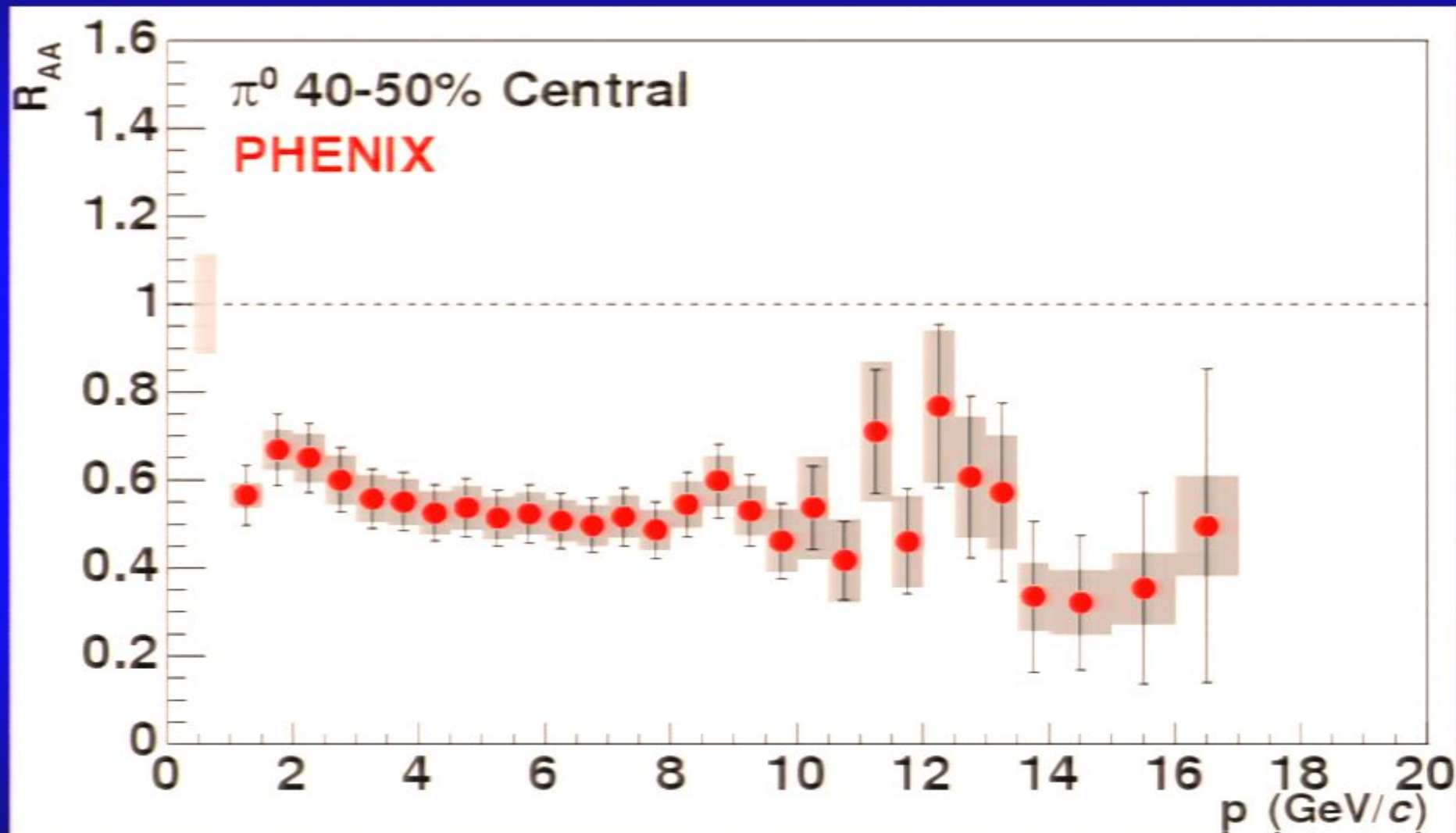


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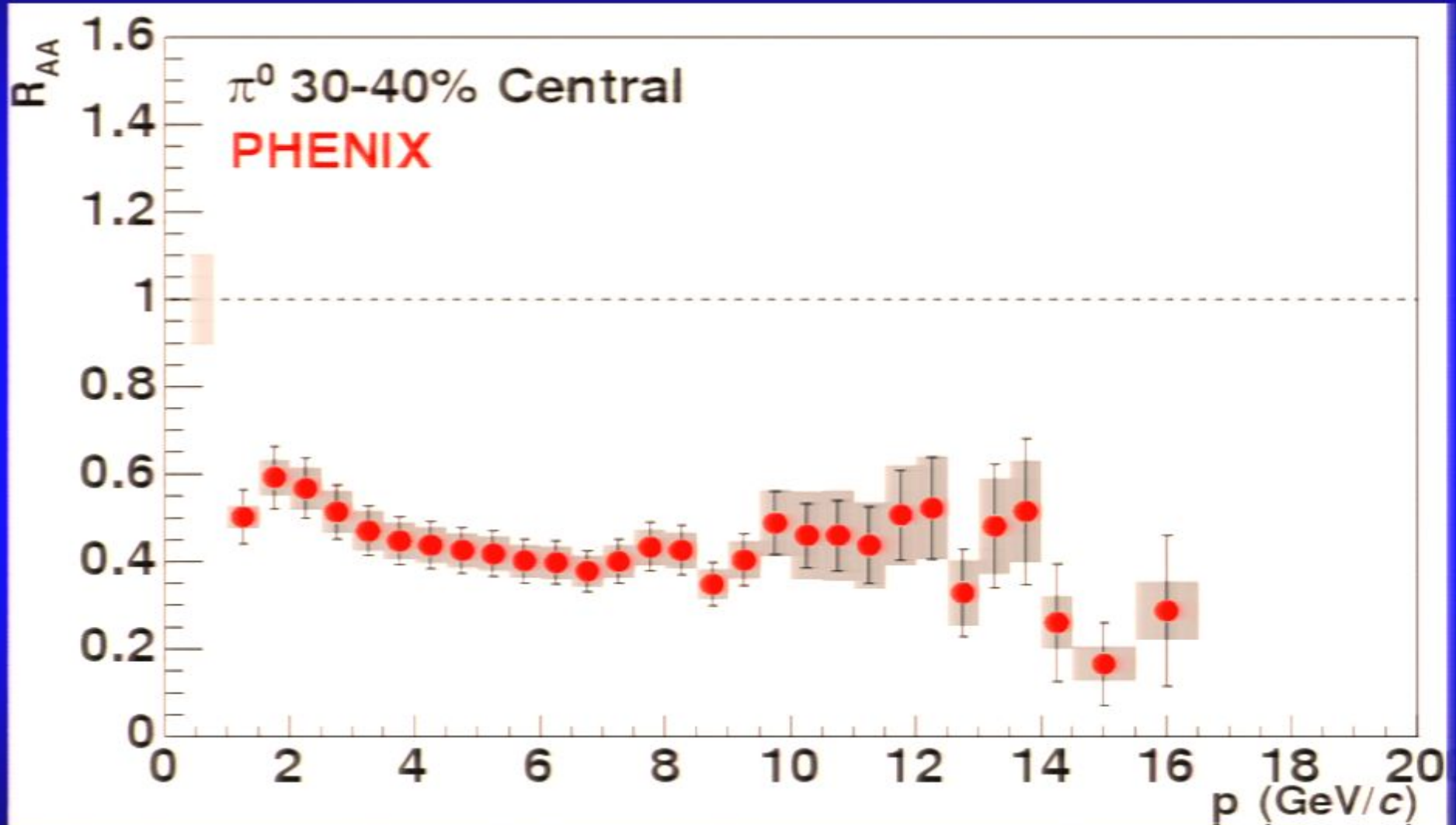
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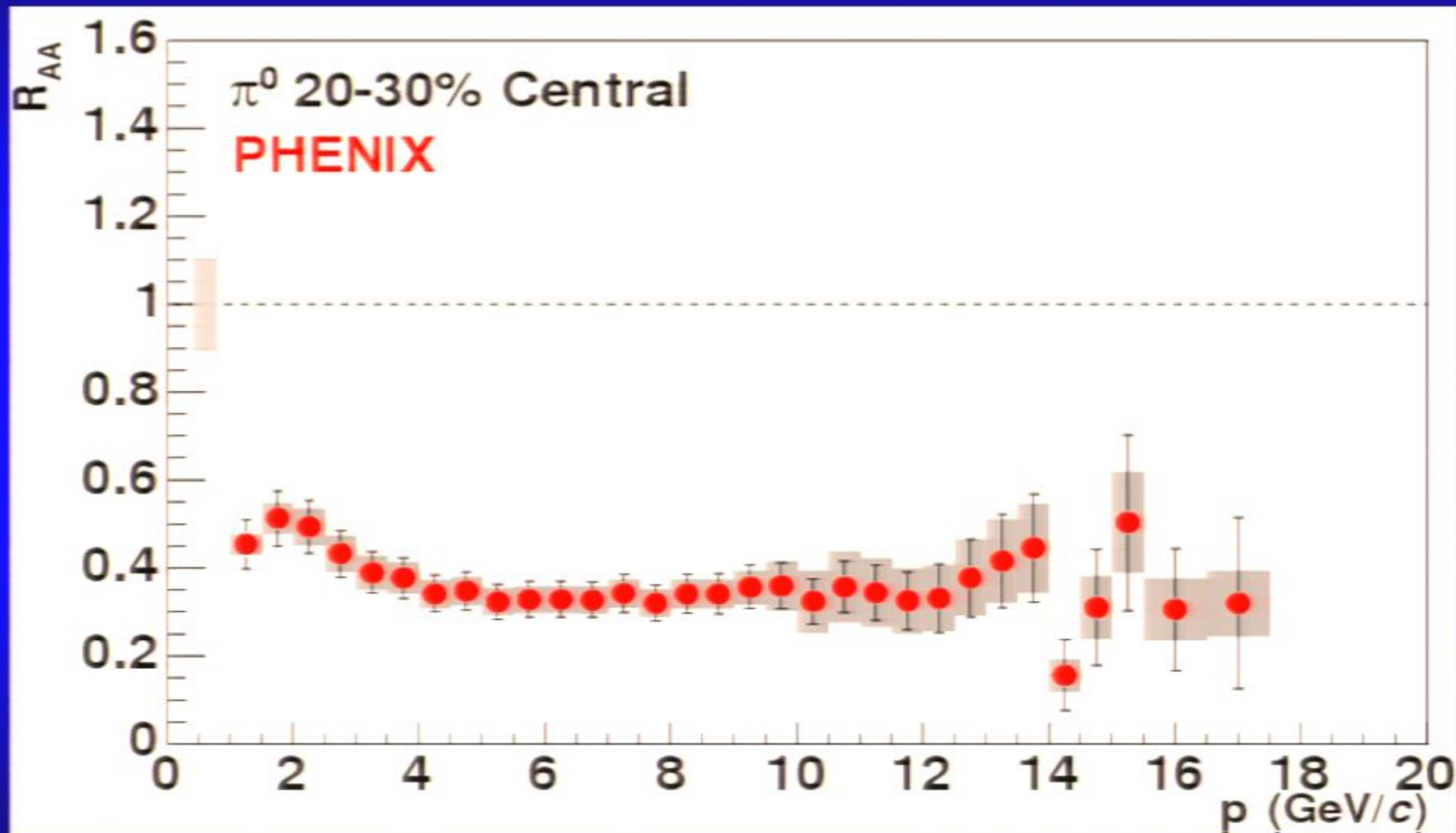


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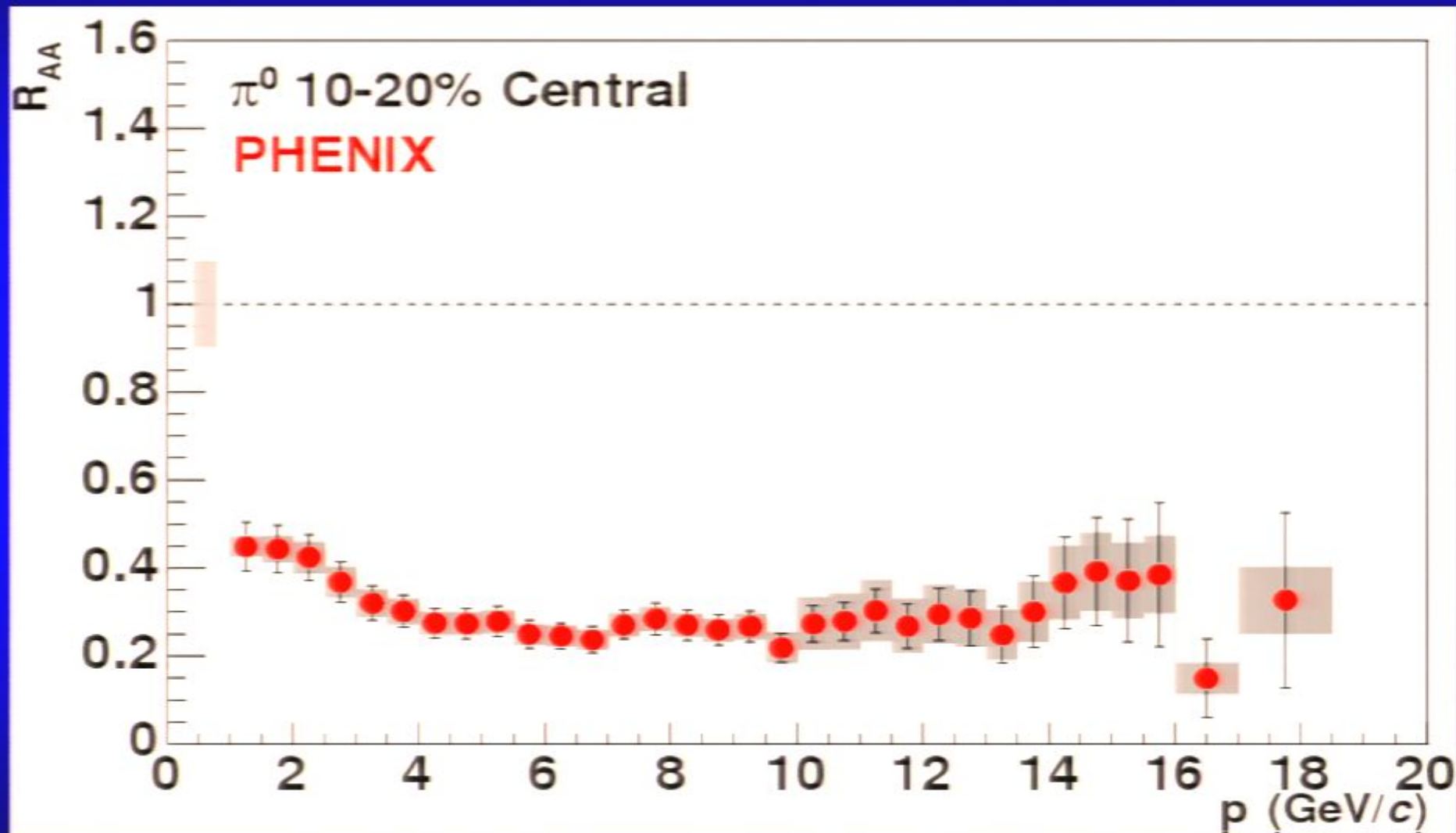
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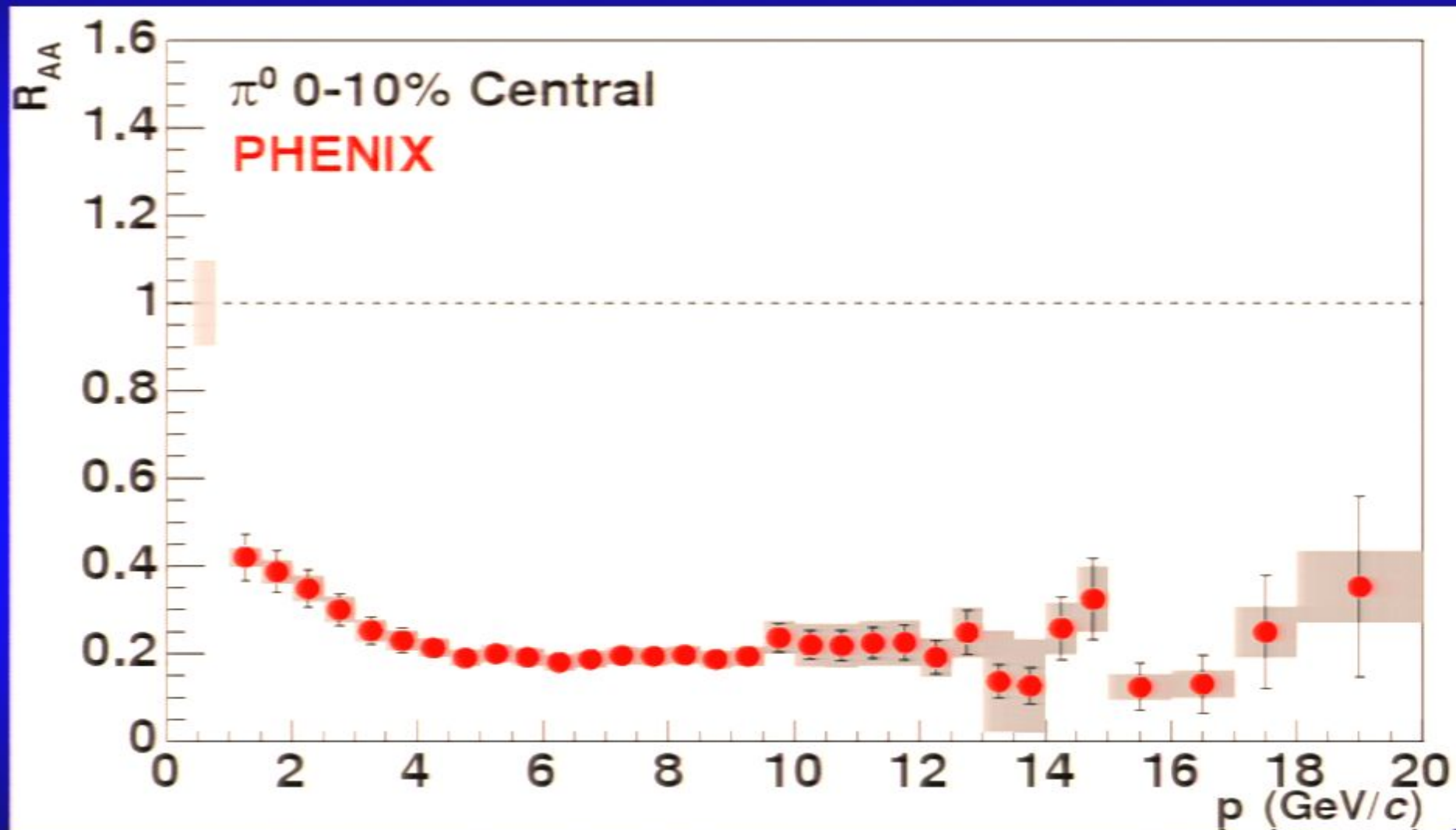


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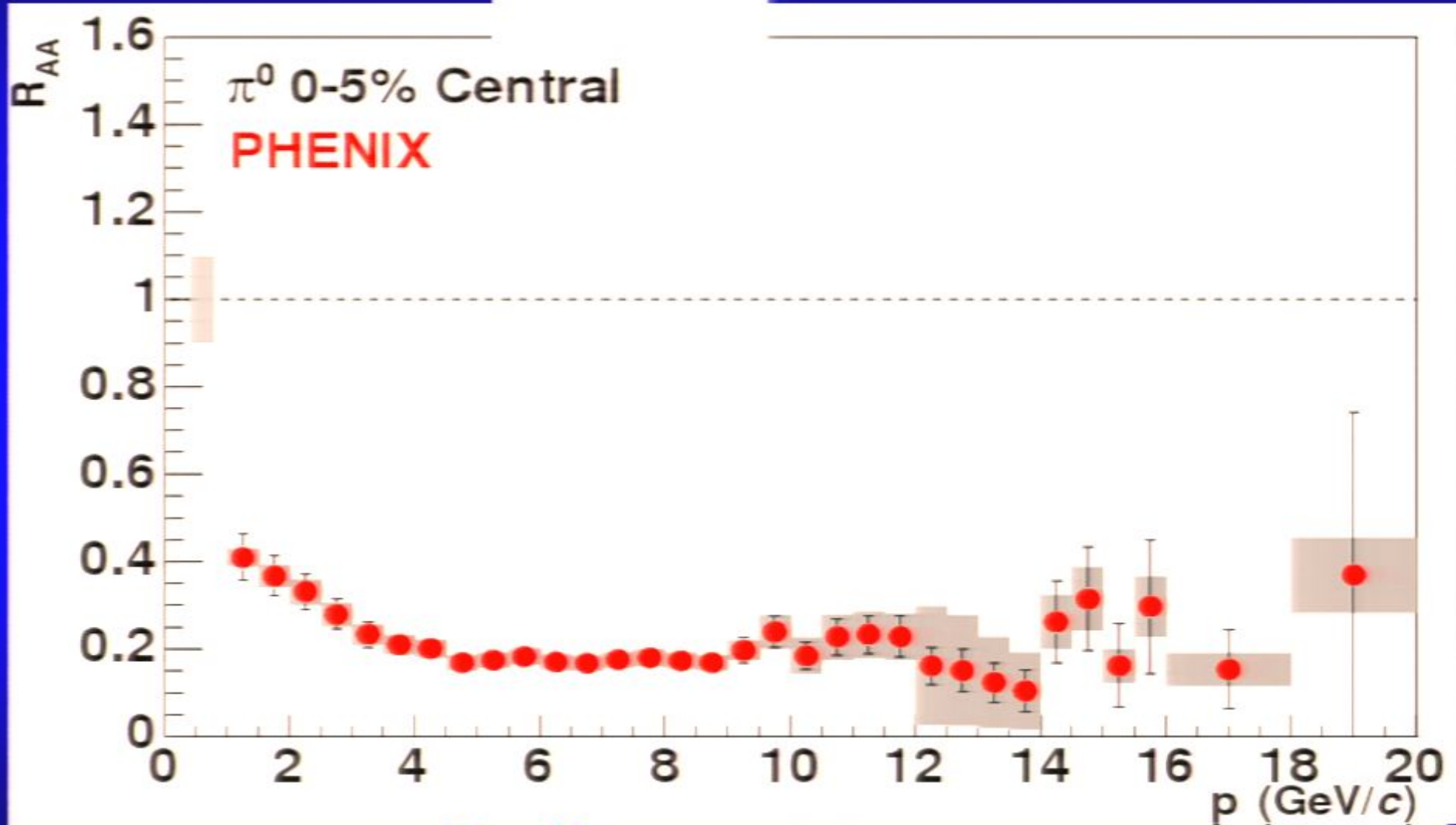
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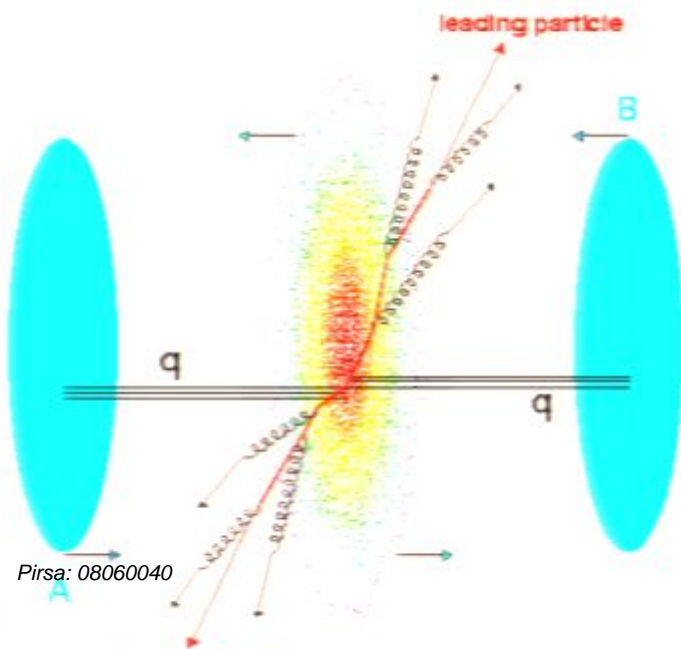
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# The Matter is Opaque

- STAR azimuthal correlation function shows ~ complete absence of “away-side” jet



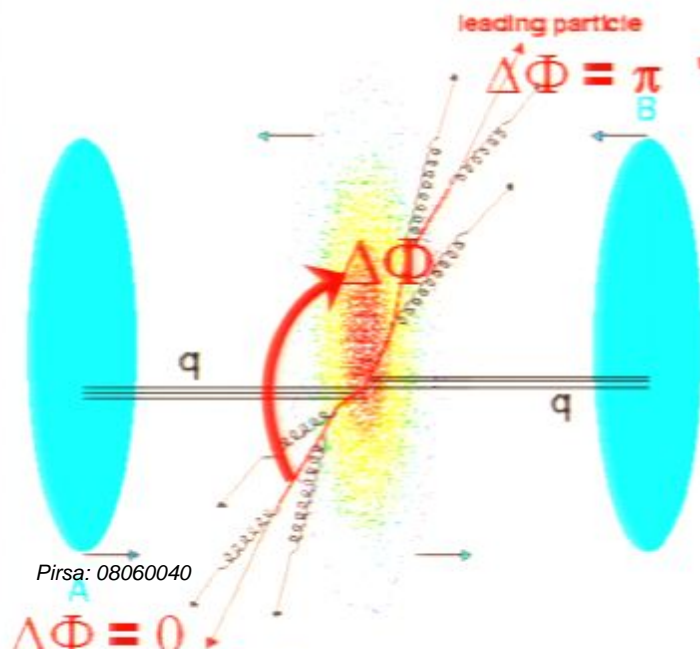
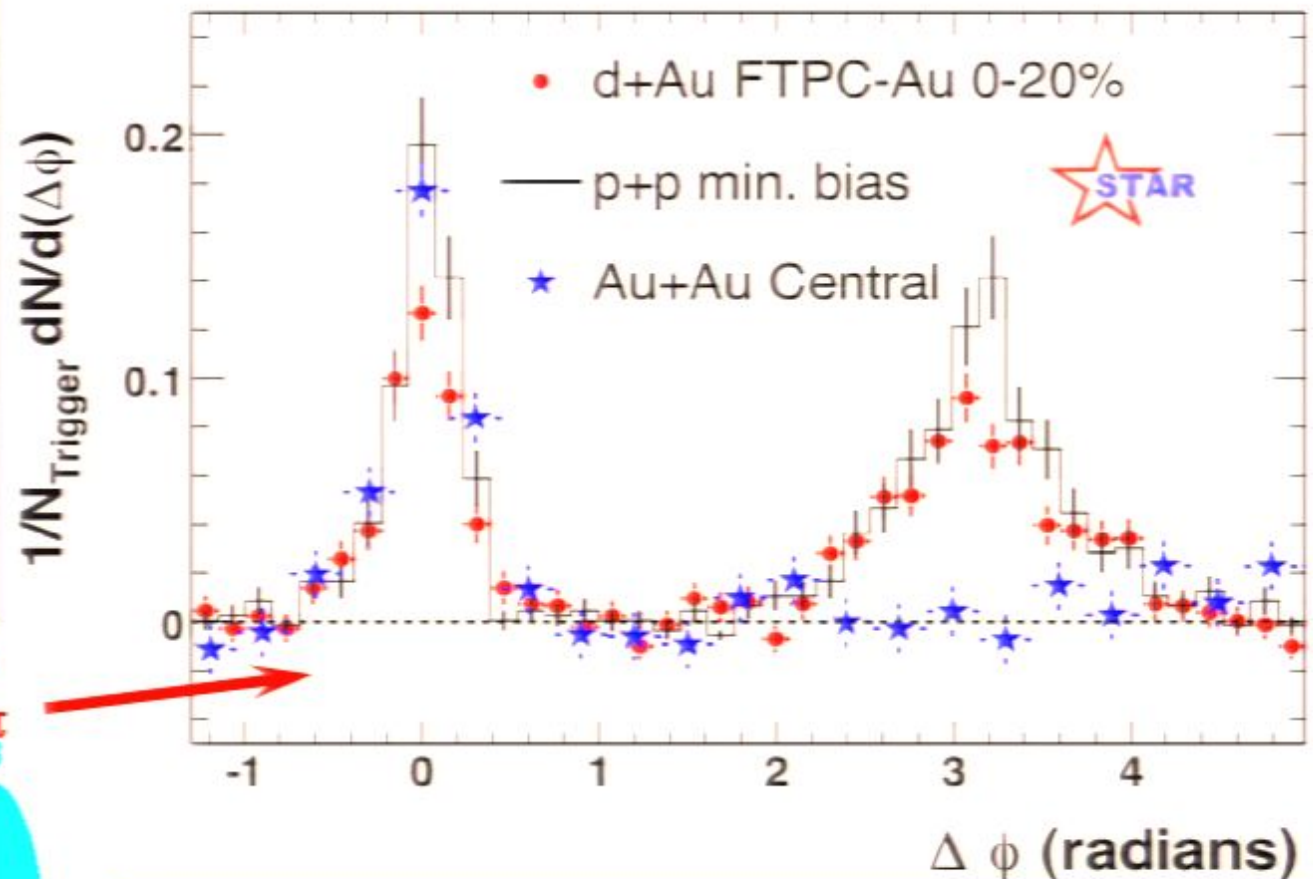






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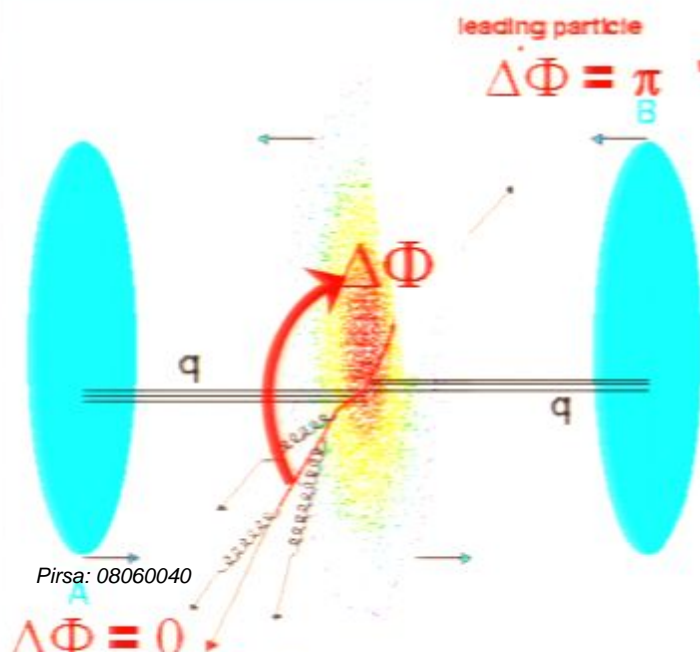
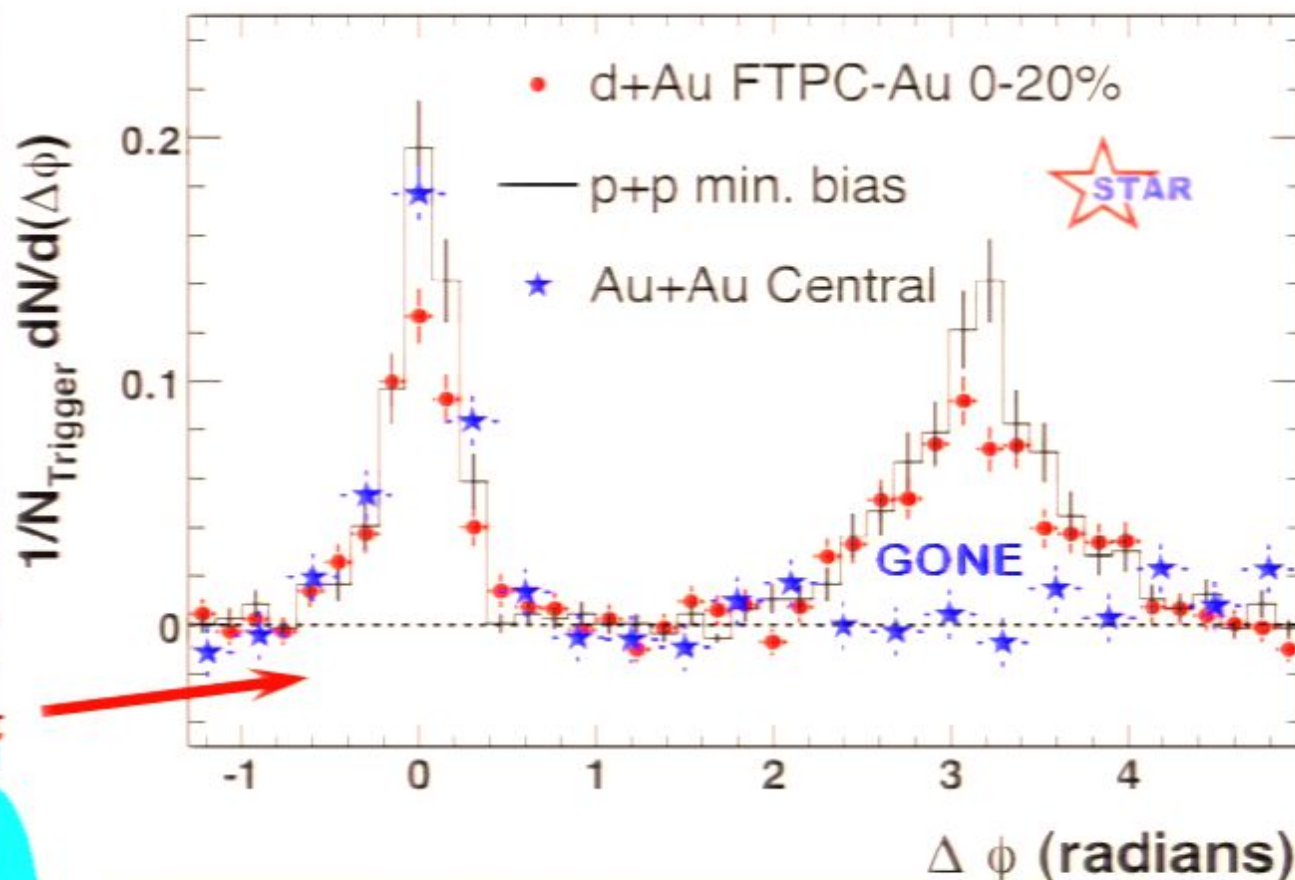






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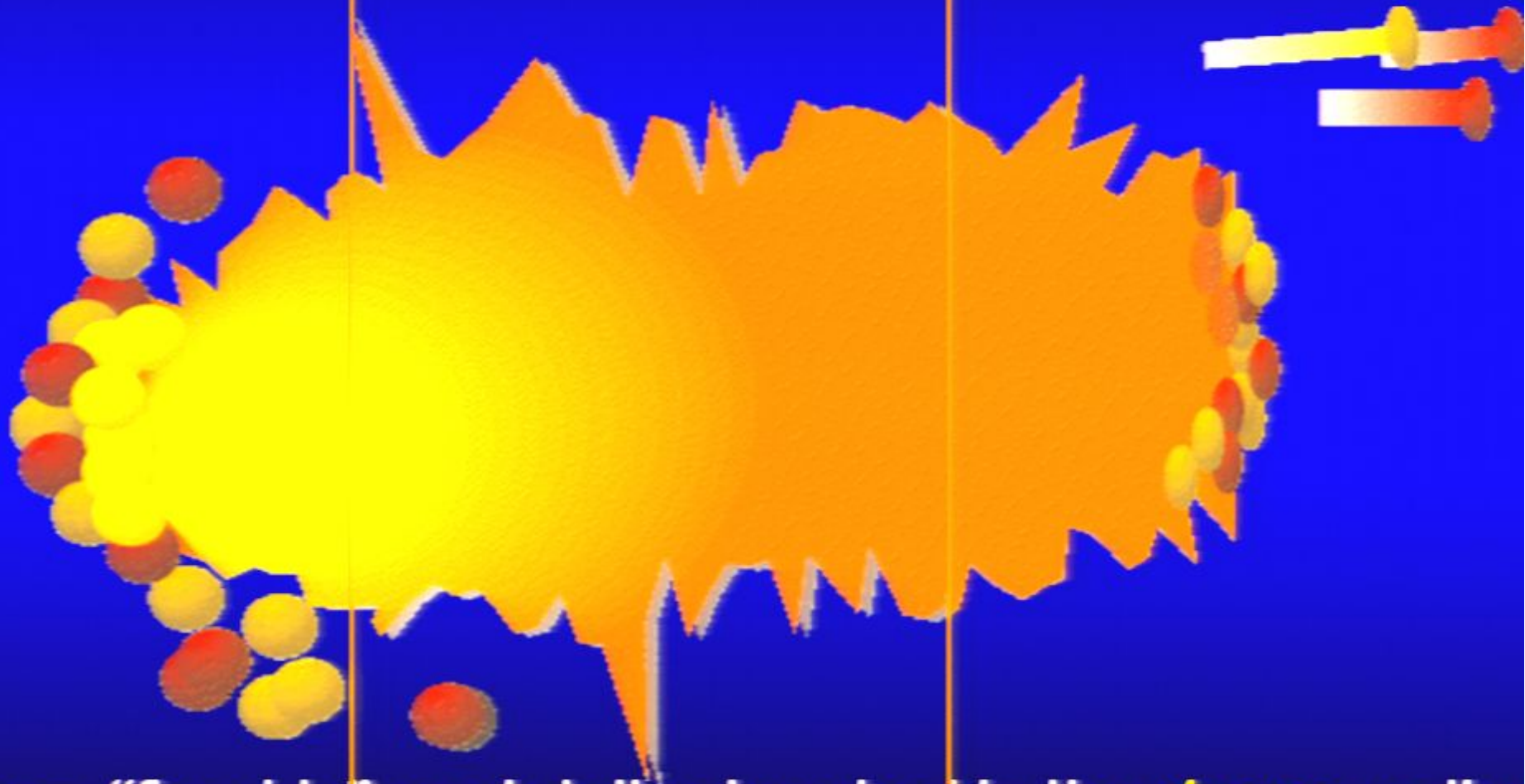


Partner in hard scatter is  
*completely absorbed*  
 in the dense medium



# Schematically (Partons)

Scattered partons on the “near side” *lose energy*, but emerge;



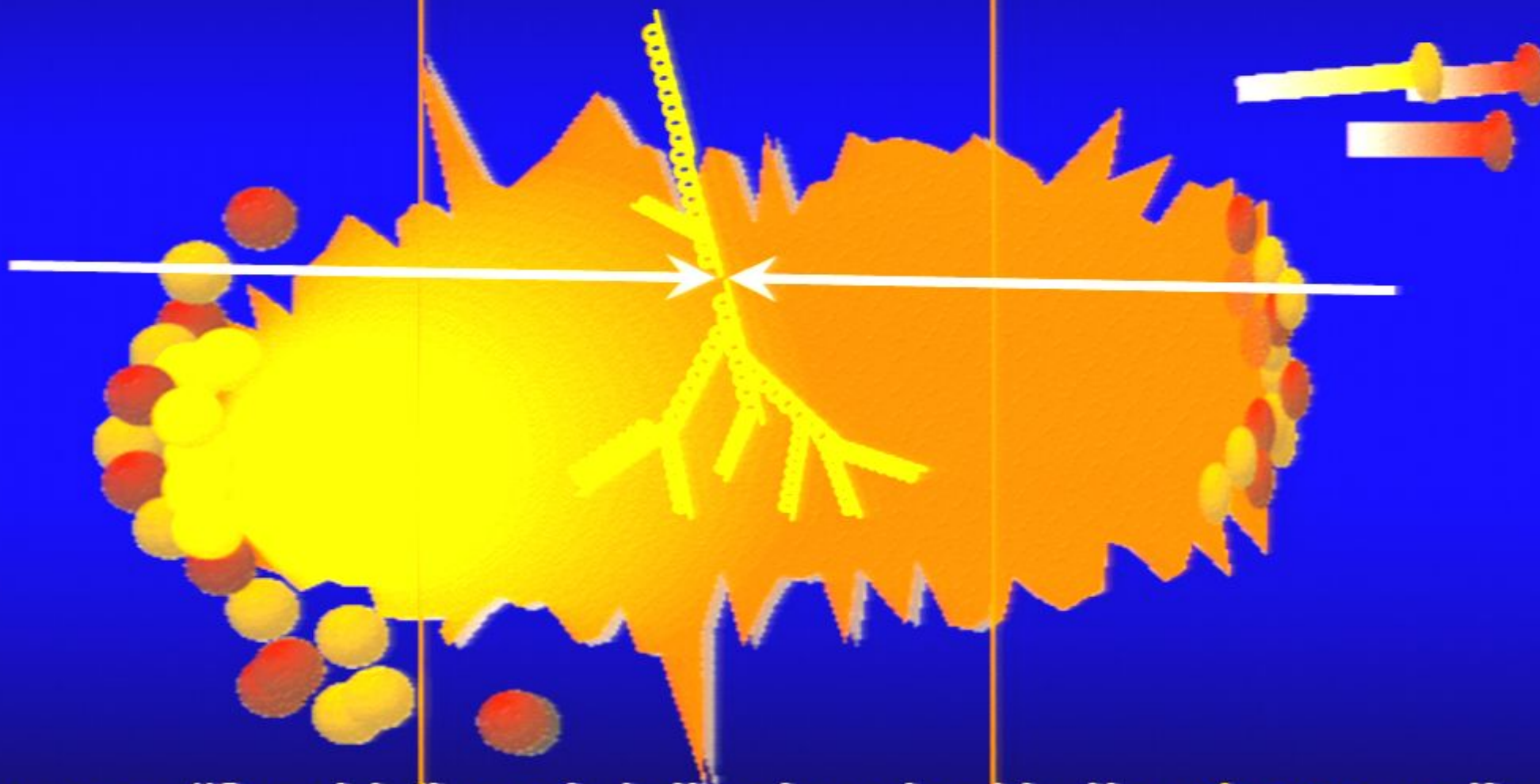
those on “far side” are totally absorbed in the *dense* medium





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- Any engineer will tell you
  - **Kinematic viscosity**  $\eta / \rho \sim [\text{Velocity}] \times [\text{Length}]$   
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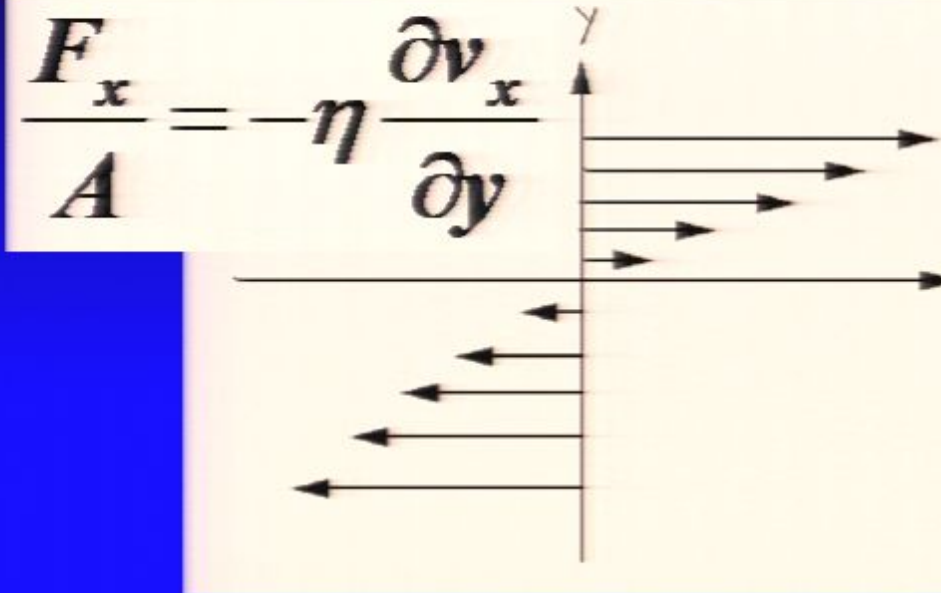
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- The initial discoveries at RHIC clearly demonstrated:
  - ☞ Essentially perfect fluid behavior of extraordinarily dense matter
  - ☞ Matter about as far away from “asymptotically free gas” as possible
- How to quantify these statements?



# Viscosity 101

- Parameterizes momentum transport between “layers”



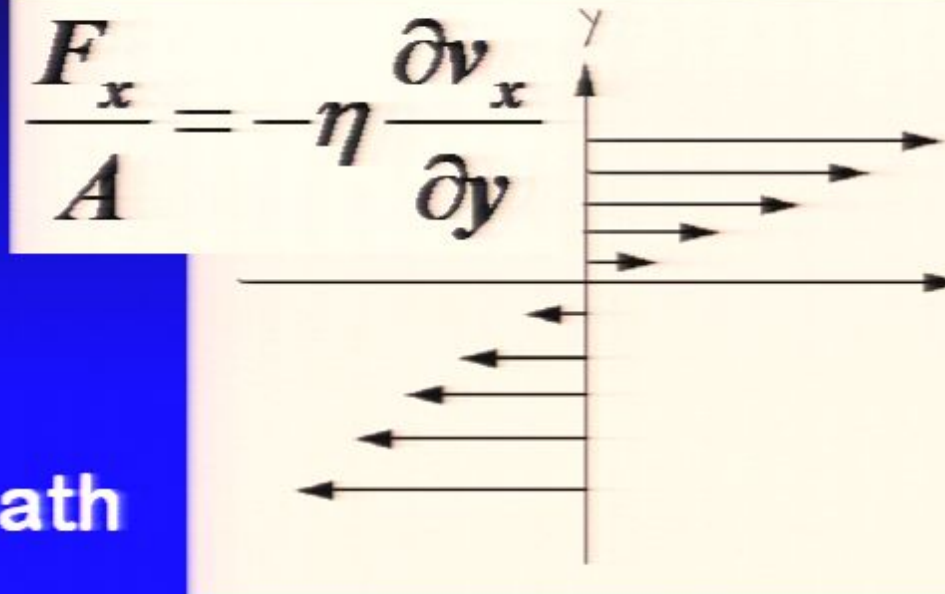


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⇒ Viscosity ~ mean free path

$$\eta \sim$$





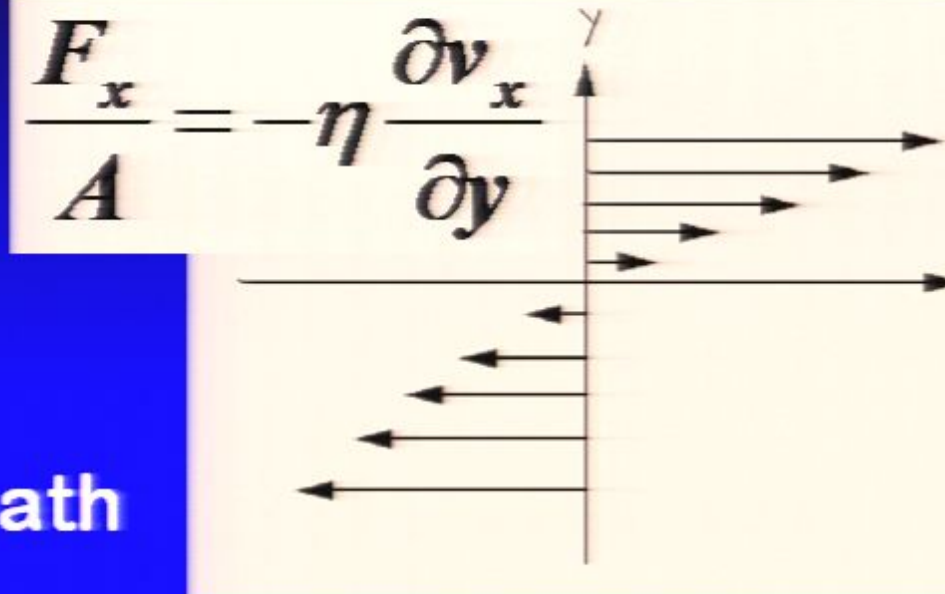


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$$\eta \sim n \bar{p} \lambda_{mfp}$$





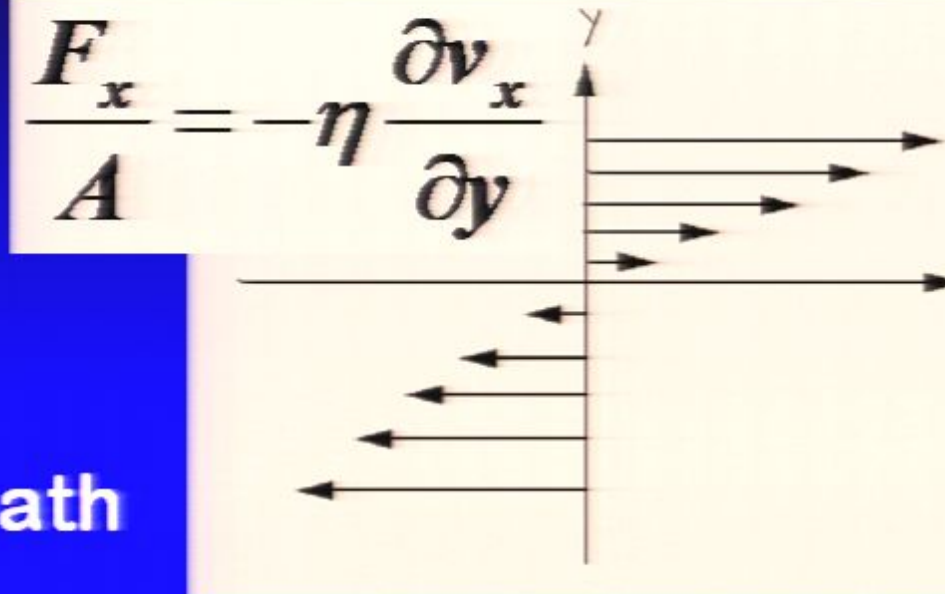
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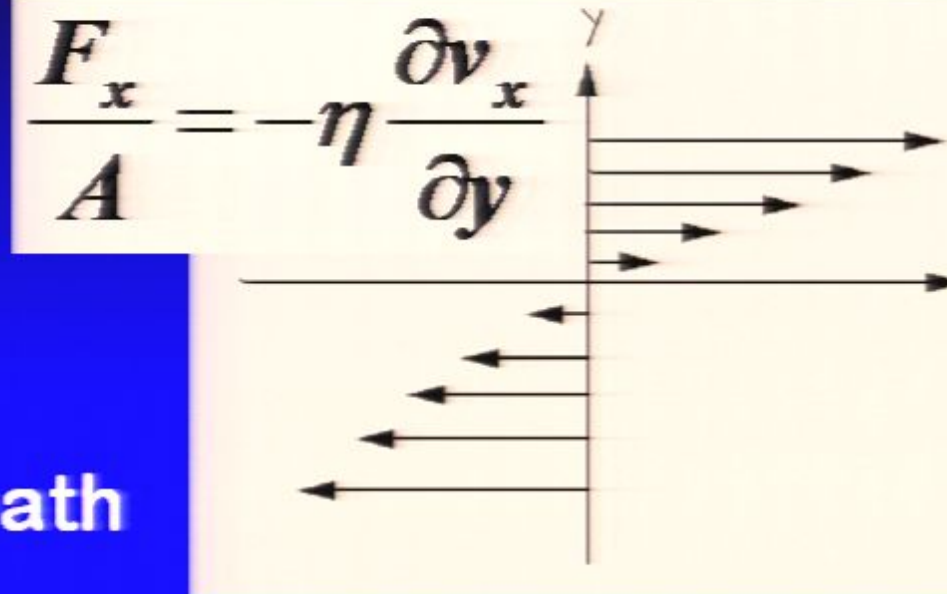
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□ “Ideal hydro” →  $\lambda_{mfp} \rightarrow 0 \rightarrow \eta \rightarrow 0$







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☞ “Strong coupling”  $\Rightarrow$  “small viscosity” - but:



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- “*A Viscosity Bound Conjecture*”,  
P. Kovtun, D.T. Son, A.O. Starinets, [hep-th/0405231](http://arxiv.org/abs/hep-th/0405231)

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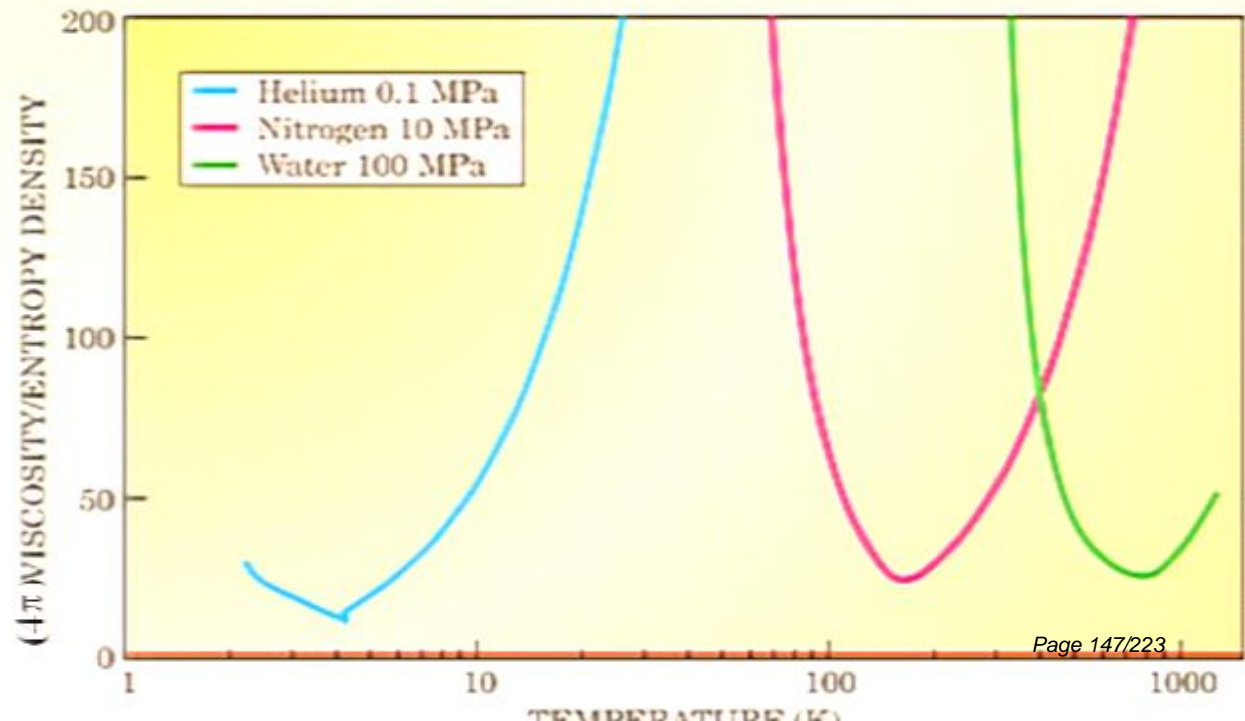
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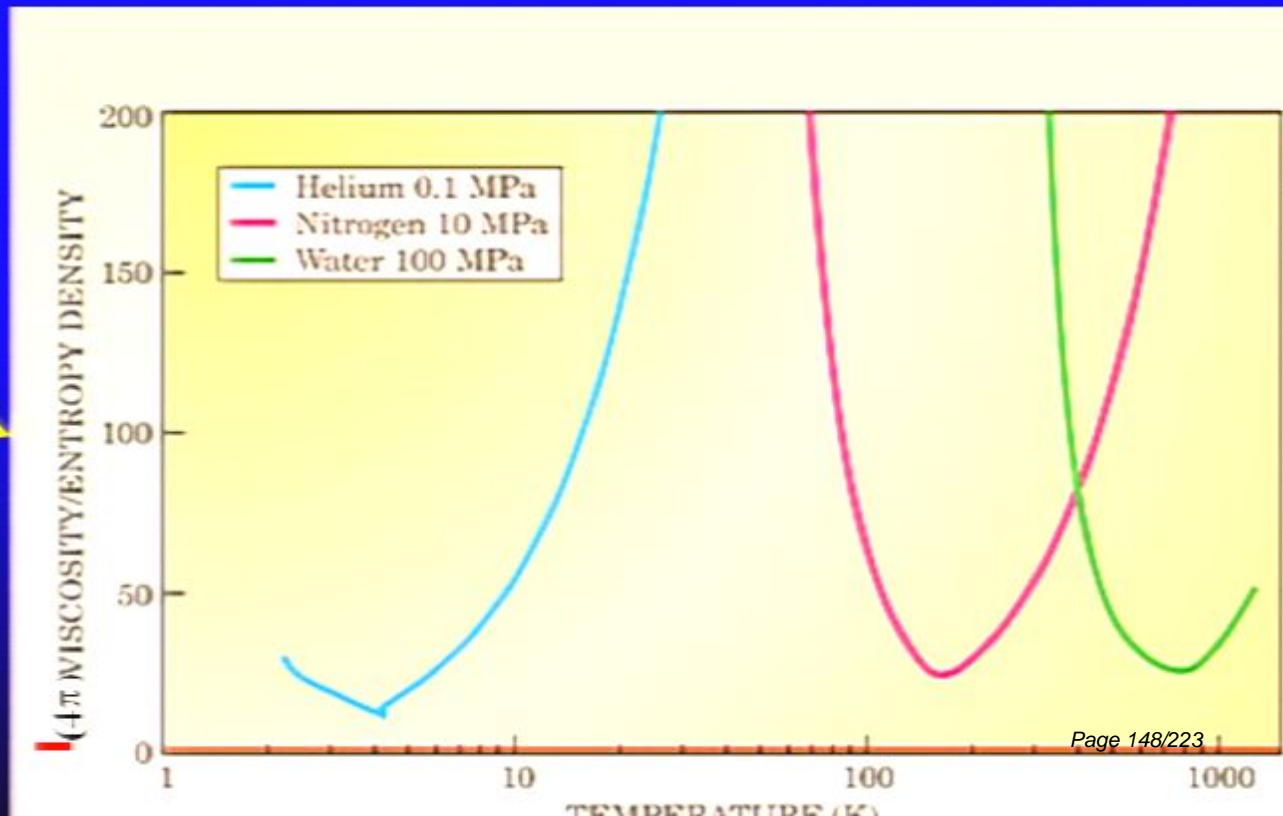
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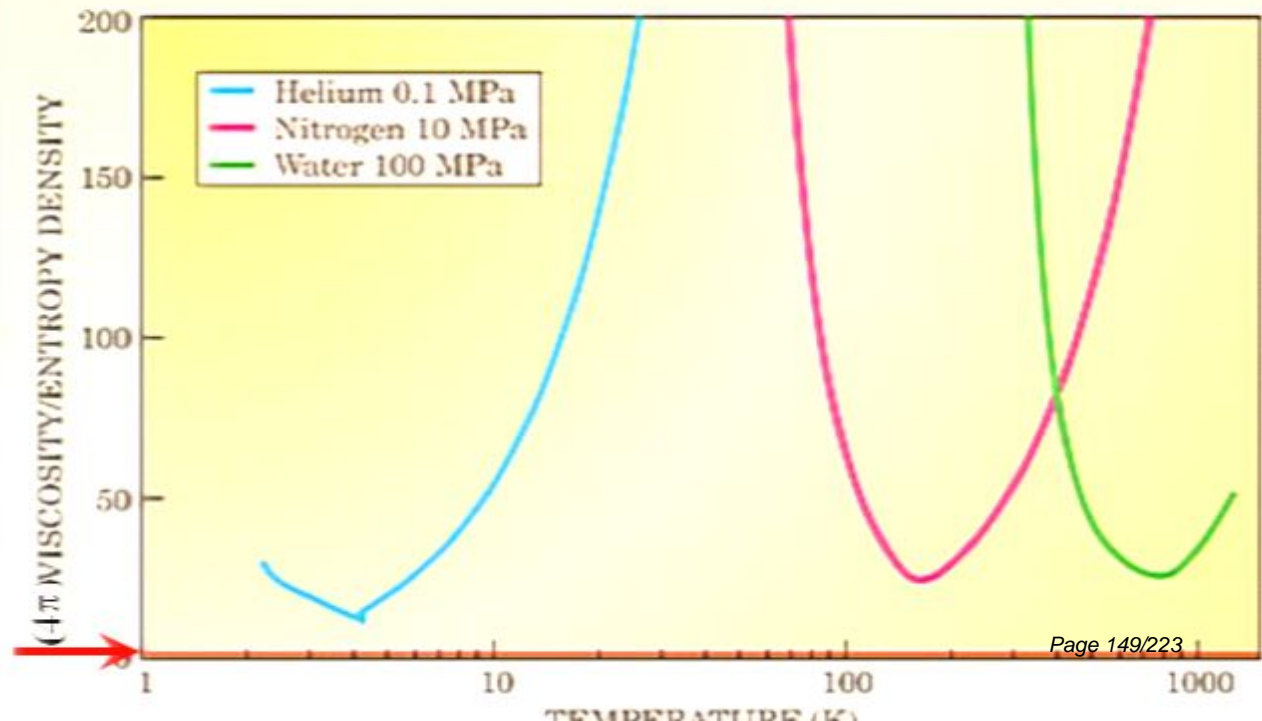
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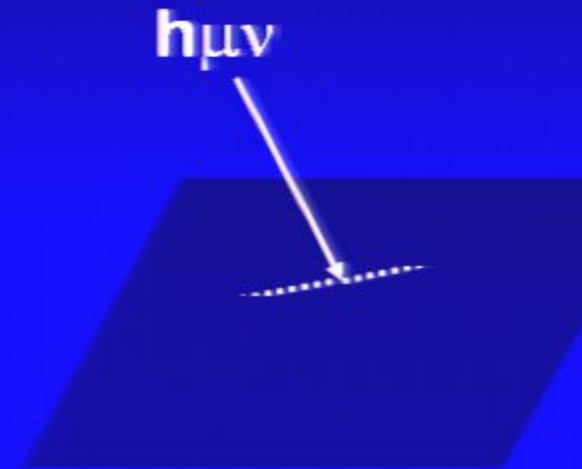
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- **Exploit** Maldacena's "D-dimensional strongly coupled gauge theory  $\Leftrightarrow$  (D+1)-dimensional stringy gravity"
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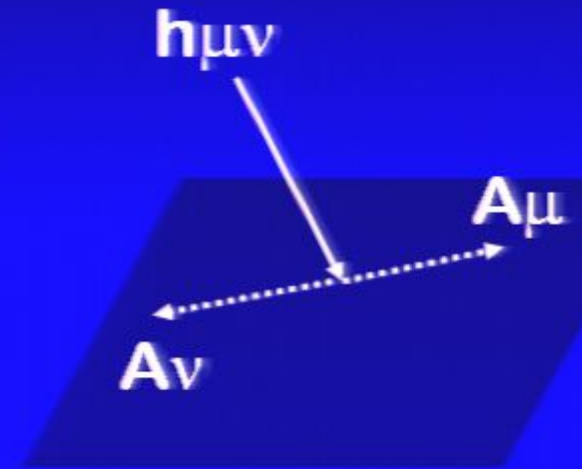






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See next talk: K. Rajagopal

- Conjectured** to be a lower bound "for all relativistic quantum field theories at finite temperature and zero chemical potential".

- See** "Viscosity in strongly interacting quantum field theories from black hole physics", P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett.94:111601, 2005, [hep-th/0405231](https://arxiv.org/abs/hep-th/0405231)





# Measuring (Estimating) $\eta/s$

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- **FLOW: *Has the QCD Critical Point Been Signaled by Observations at RHIC?***,  
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$$\frac{\eta}{s} =$$

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$$\frac{\eta}{s} = (1.1 \pm 0.2 \pm 1.2) - \frac{1}{4}$$

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$$\frac{\eta}{s} = \dots$$



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- **DRAG, FLOW: *Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at  $\sqrt{s_{NN}} = 200$  GeV*** (PHENIX Collaboration),  
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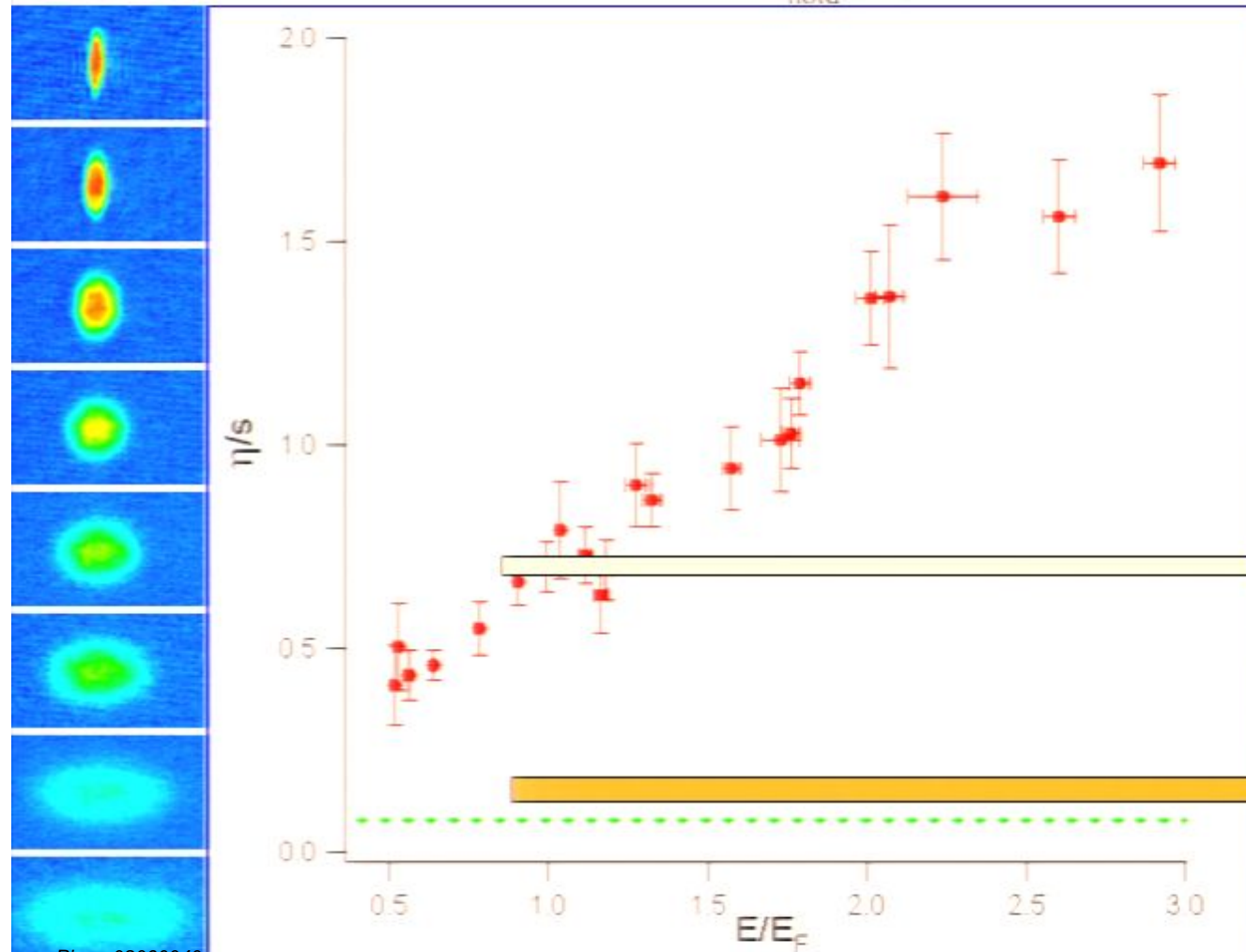
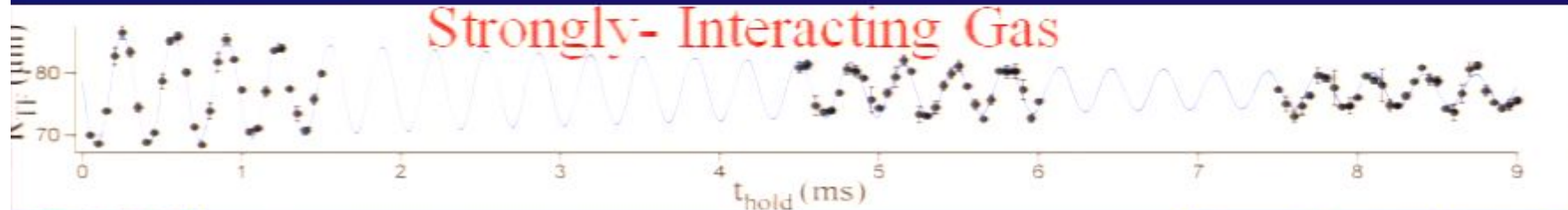
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$$\frac{\eta}{s} = (1.3 - 2. - \frac{4}{4})$$



# Compare to the Competition



- Damping of breathing mode in cold Fermi gas
- (All figures courtesy of John Thomas, Duke University)

$^3\text{He}, ^4\text{He}$   
near  $\lambda$ -point

RHIC data  
QGP simulations  
String-theory  $1/4\pi$





# Our Problem Is Much Harder

- **Non-relativistic: Damping given by**

$$\dot{E} = -\frac{1}{2} \int d^3x \eta(x) \left( \partial_i v_j + \partial_j v_i - \frac{2}{3} \delta_{ij} \partial_k v_k \right)^2$$





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Answer:



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Denoting the comoving derivative by a dot, i.e. using  $u^\mu \nabla_\mu \tau = \dot{\tau}$  etc. we see that the second law



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# Viscosity Information from Relativistic Nuclear Collisions: How Perfect is the Fluid Observed at RHIC?, P. Romatschke and U. Romatschke, Phys. Rev. Lett. 99:172301, 2007

- **Signature:**  
 $dN/dy, v_2, \langle p_T \rangle$
- **Calculation:**  
**2<sup>nd</sup> order causal viscous hydro:**

$$\begin{aligned}
 (\epsilon + p)Du^\mu &= -\nabla^\mu p - \Delta^\mu_\alpha d_\beta \Pi^{\alpha\beta}, \\
 D\epsilon &= -(\epsilon + p)\nabla_\mu u^\mu + \frac{1}{2}\Pi^{\mu\nu}\nabla_\mu u_\nu, \\
 \Delta^\mu_\alpha \Delta^\nu_\beta D\Pi^{\alpha\beta} &= -\frac{\Pi^{\mu\nu}}{\eta} + \frac{\eta}{\eta} \nabla^\mu u^\nu - 2\Pi^{\alpha\beta} \omega_{\alpha\beta}^\mu \\
 &\quad + \frac{1}{2}\Pi^{\mu\nu} [5D \ln T - \nabla_\alpha u^\alpha], \quad (2)
 \end{aligned}$$

(Glauber IC's)

- **Payoff Plots:**

$$\Rightarrow \frac{\eta}{s} = (0 - 2.0) \frac{1}{4\pi}$$

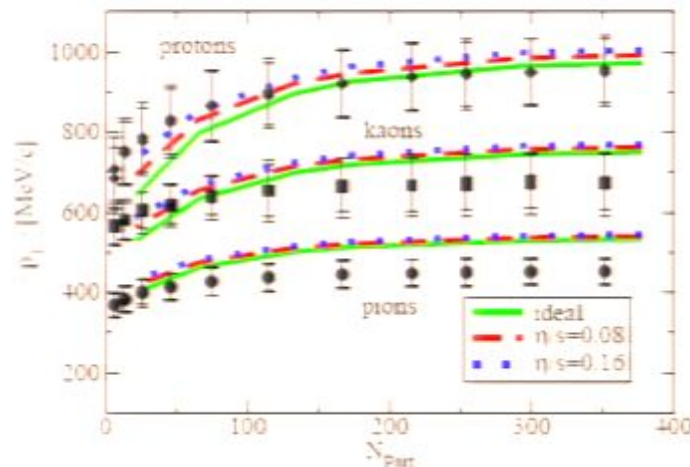
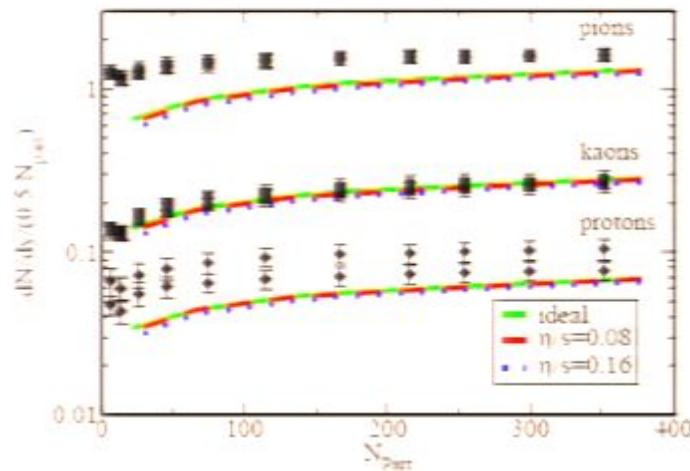


FIG. 2. Total multiplicity  $dN/dy$  and mean momentum for  $\pi^+, \pi^-, K^+, K^-, p$  and  $\bar{p}$  from PHENIX [23] for Au+Au collisions at  $\sqrt{s} = 200$  GeV, compared to our hydrodynamic model for various viscosity ratios  $\eta/s$ .

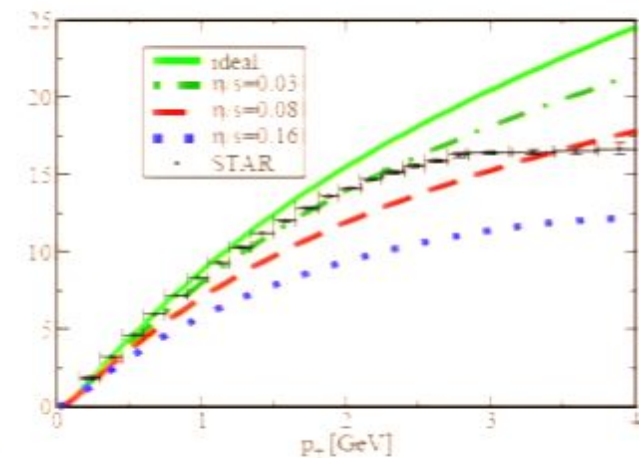
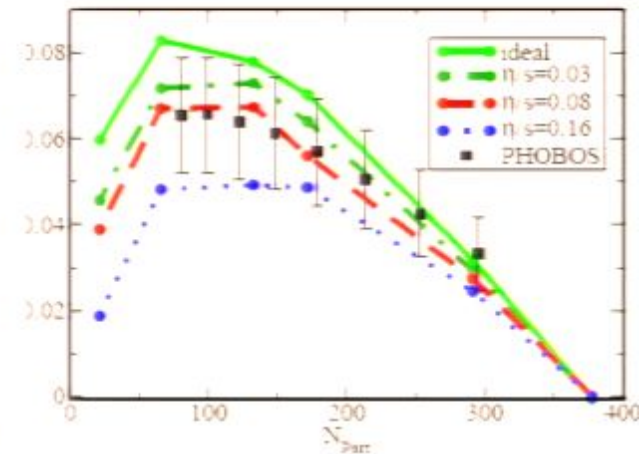


FIG. 3. PHOBOS [24] data on  $p_T$  integrated  $v_2$  and STAR [25] data on minimum bias  $v_2$ , for charged particles in Au+Au collisions at  $\sqrt{s} = 200$  GeV, compared to our hydrodynamic model for various viscosity ratios  $\eta/s$ . Error bars for PHOBOS data show 90% confidence level systematic errors while STAR only statistical errors are shown.



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- Can AdS/CFT also be applied to the strong energy loss in the fluid?





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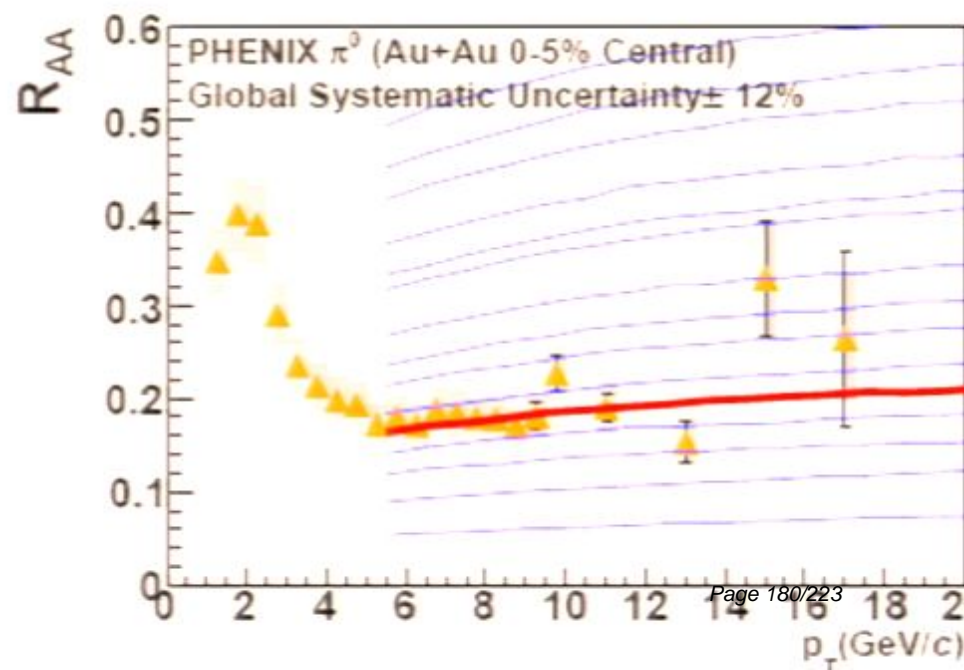
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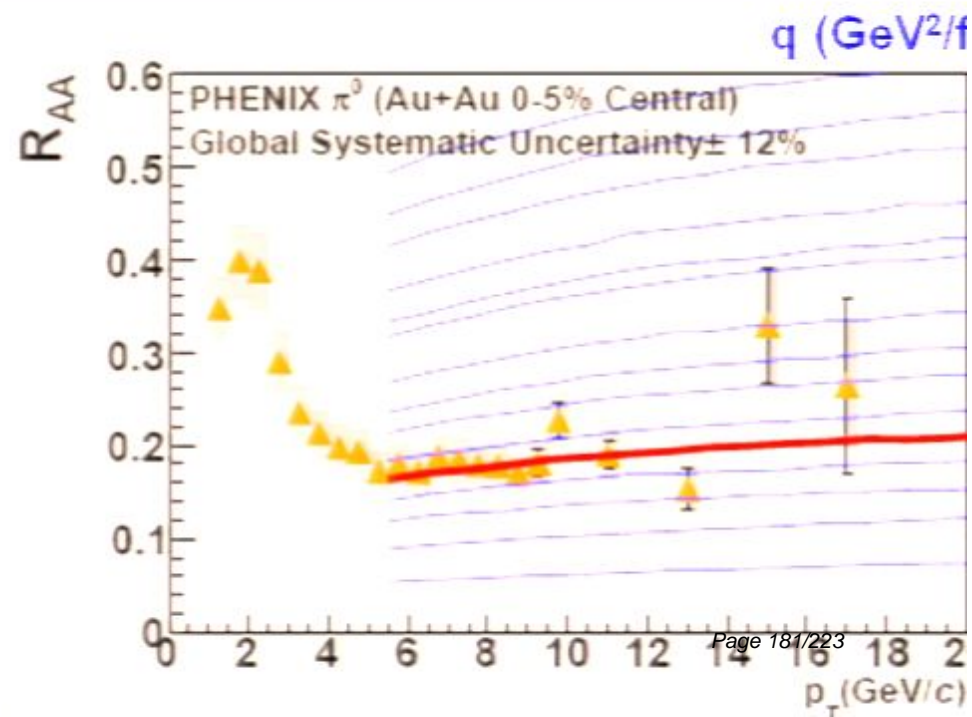




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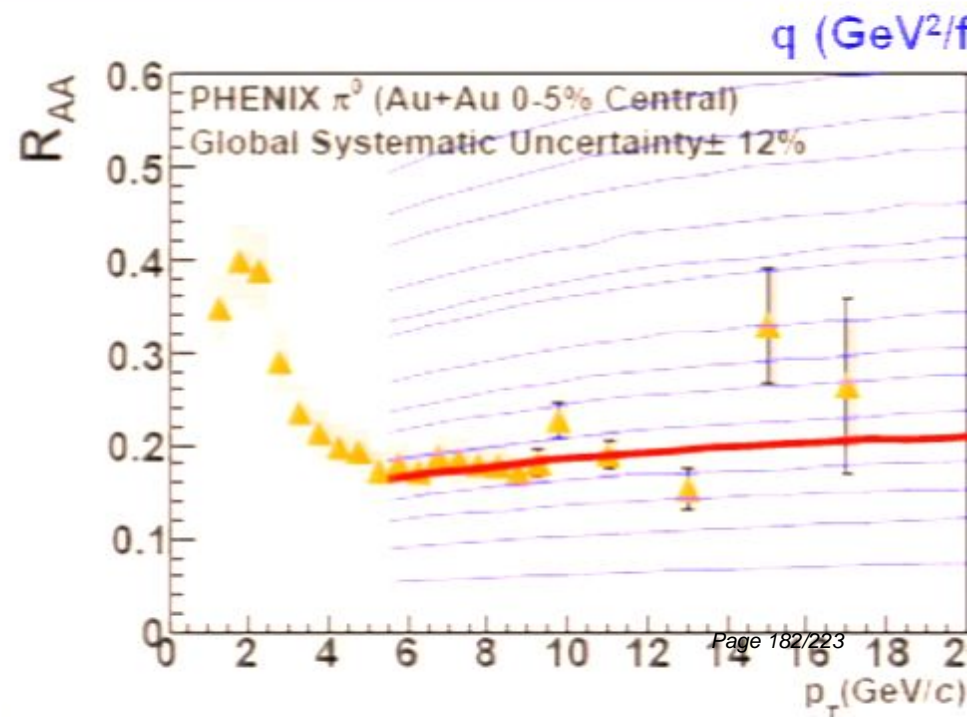




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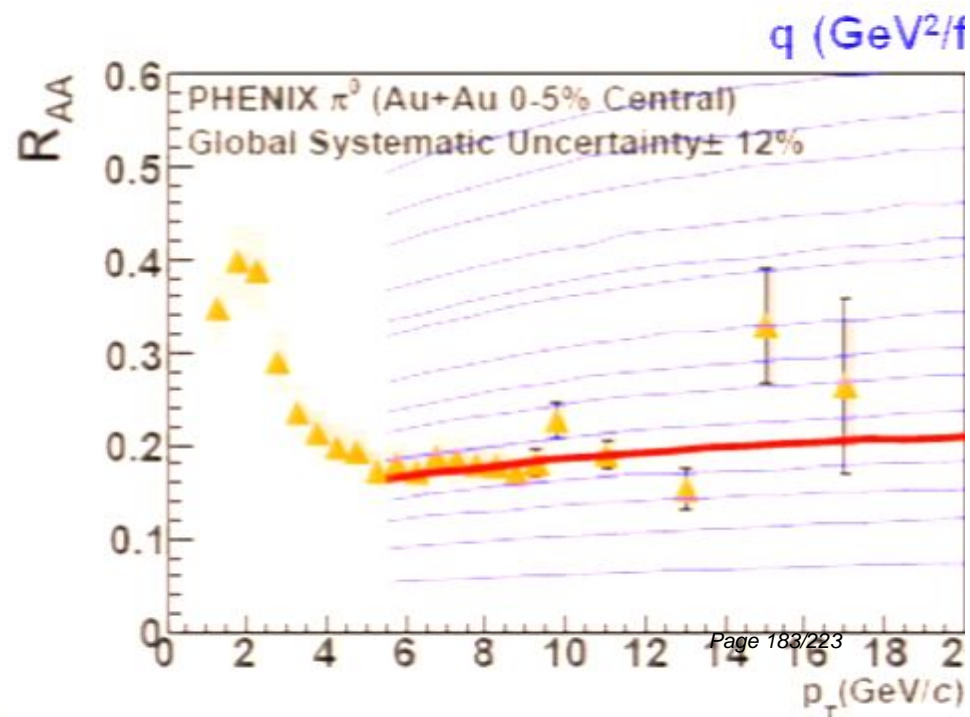




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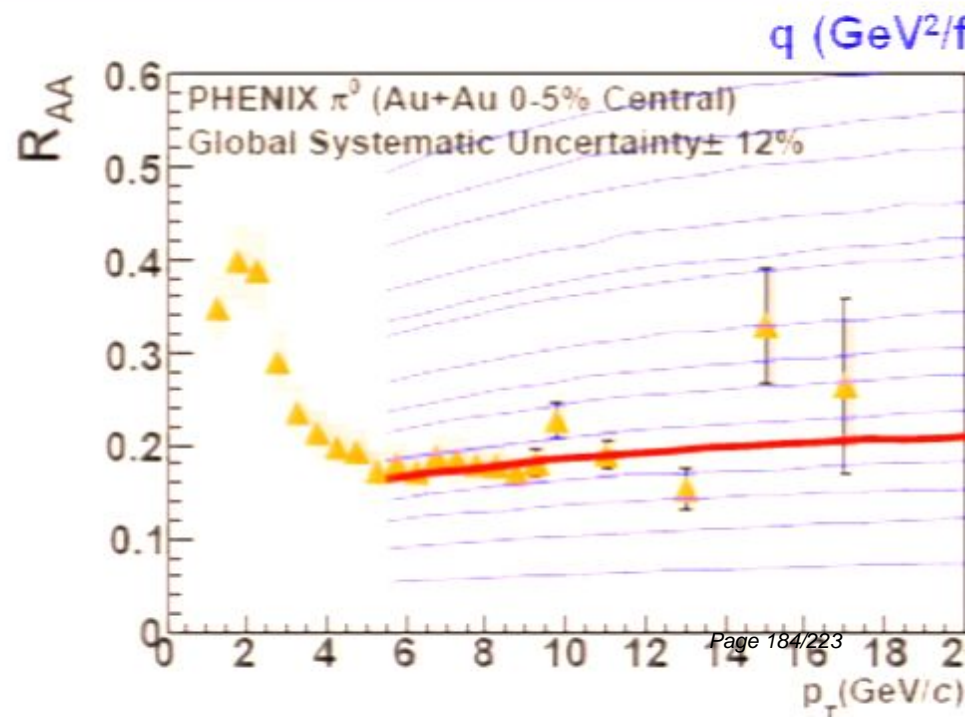




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## Wilson loop from AdS/CFT

Maldacena (1998); Rey and Yee (1998)

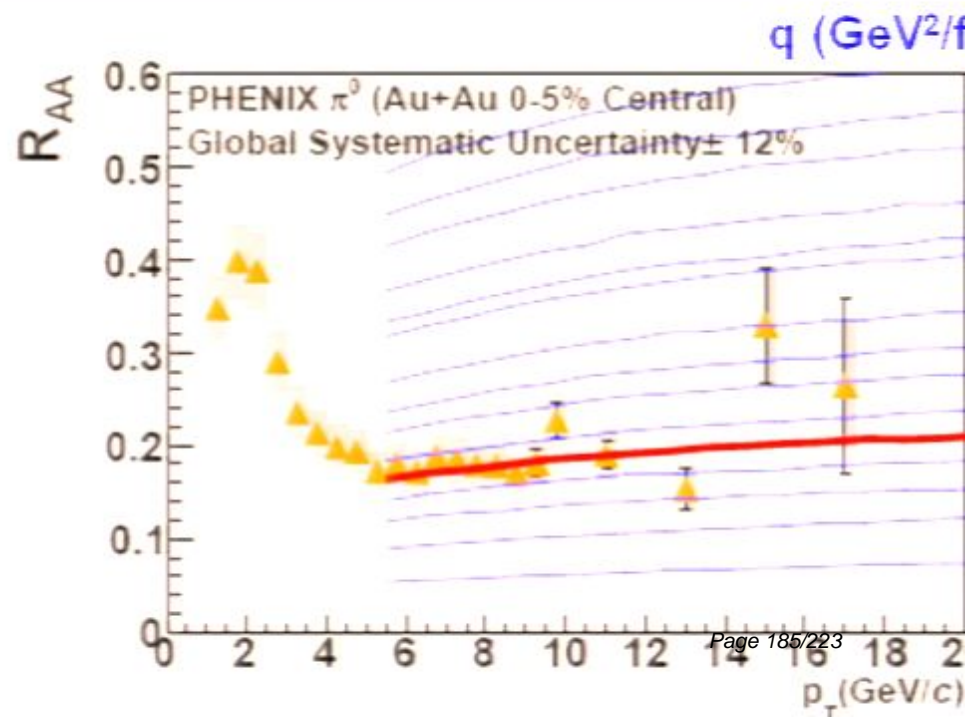
Recipe:  $\langle W(C) \rangle = \exp[iS(C)]$



Pirsa: 08060040

Black hole in AdS spacetime:

- radial coordinate  $r$ ,
- horizon:  $r=r_0$





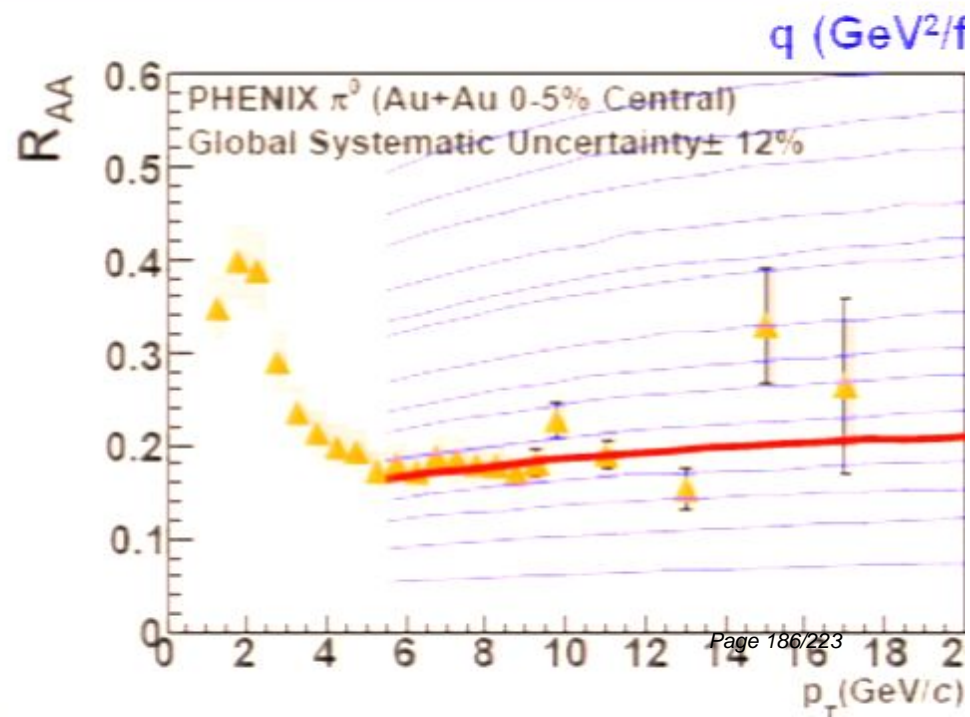
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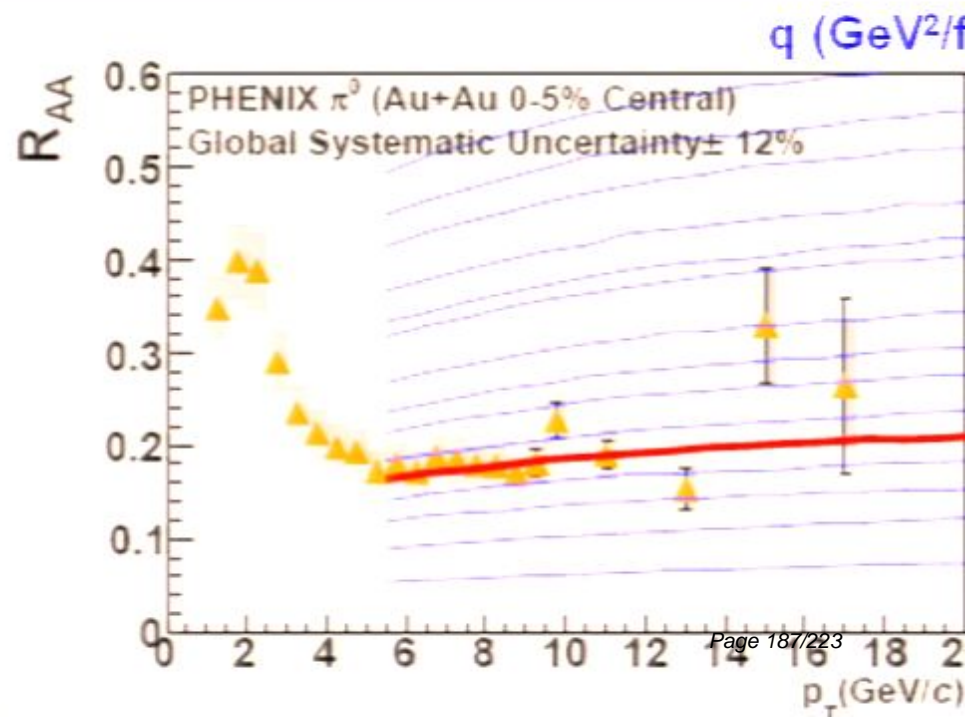
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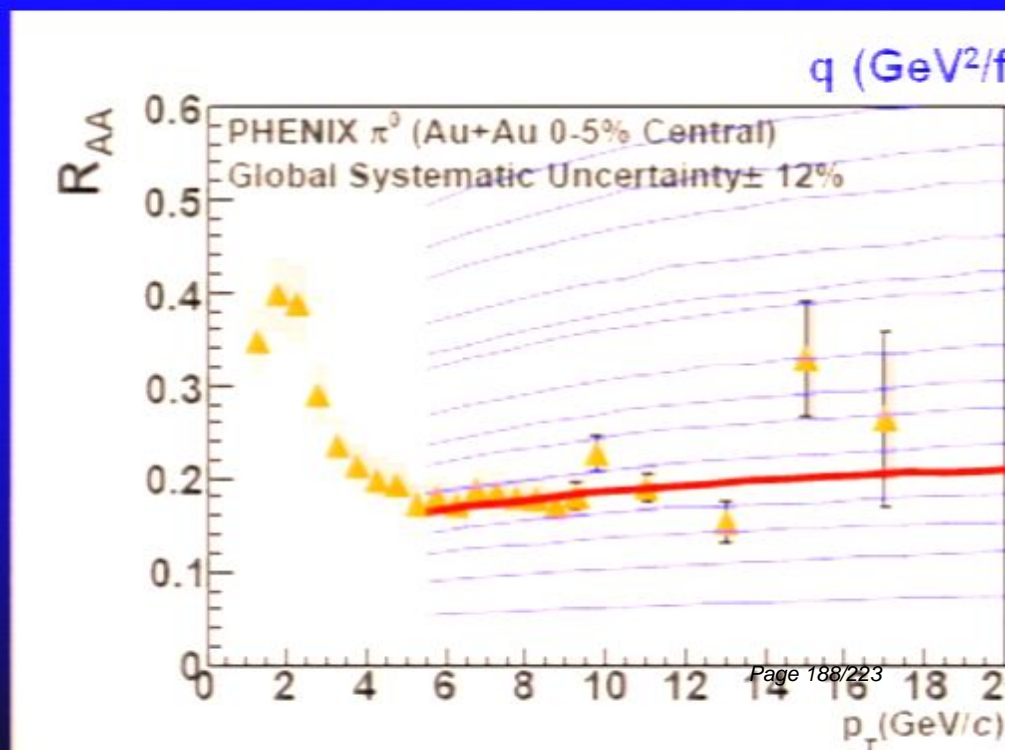
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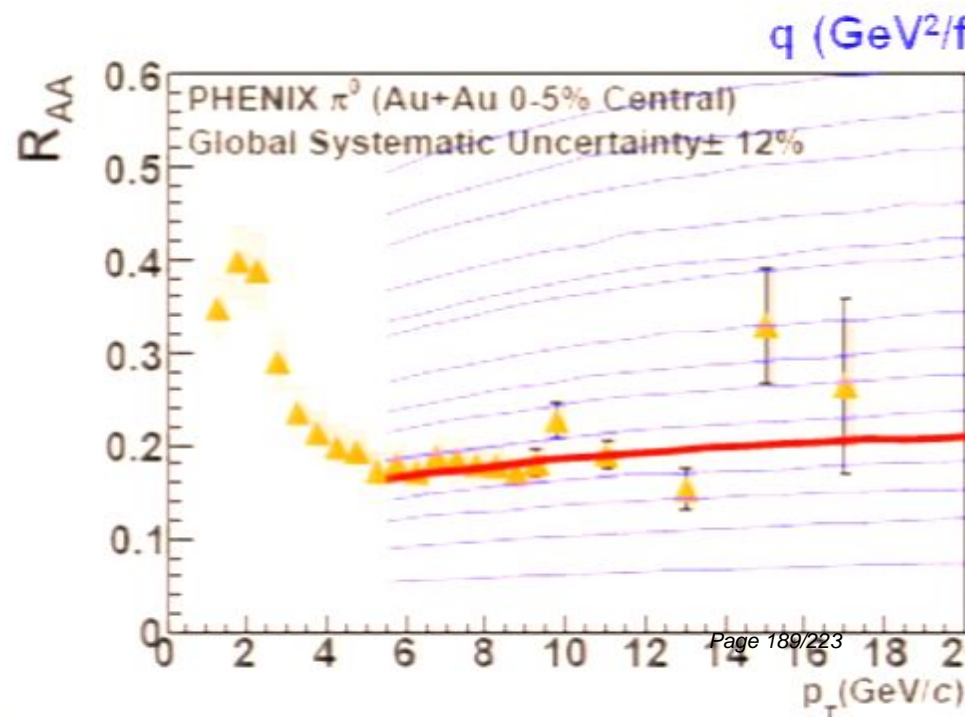
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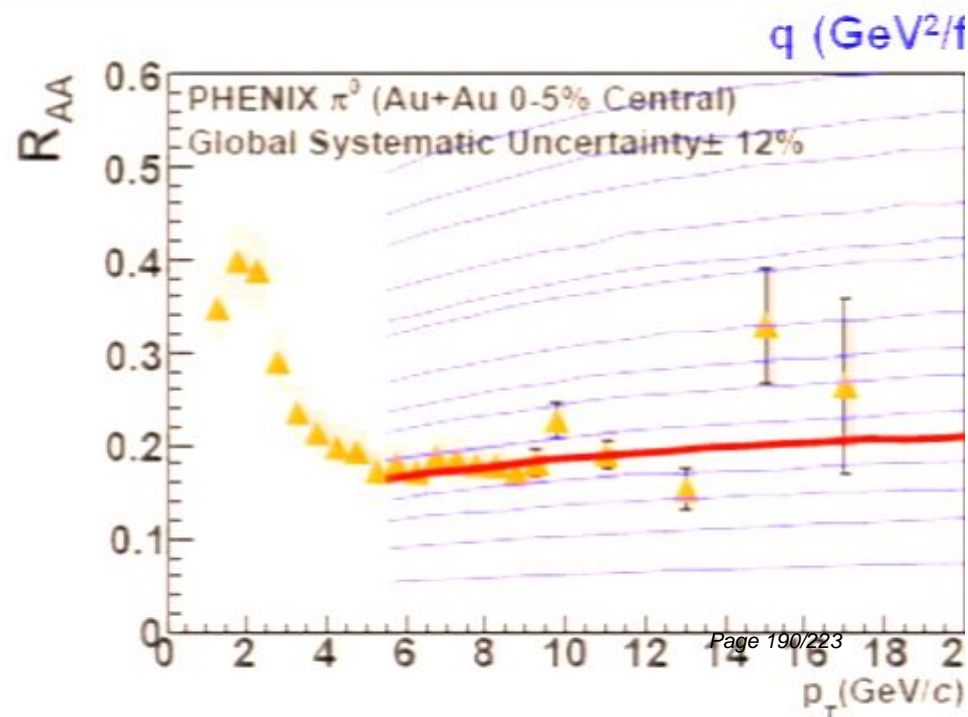
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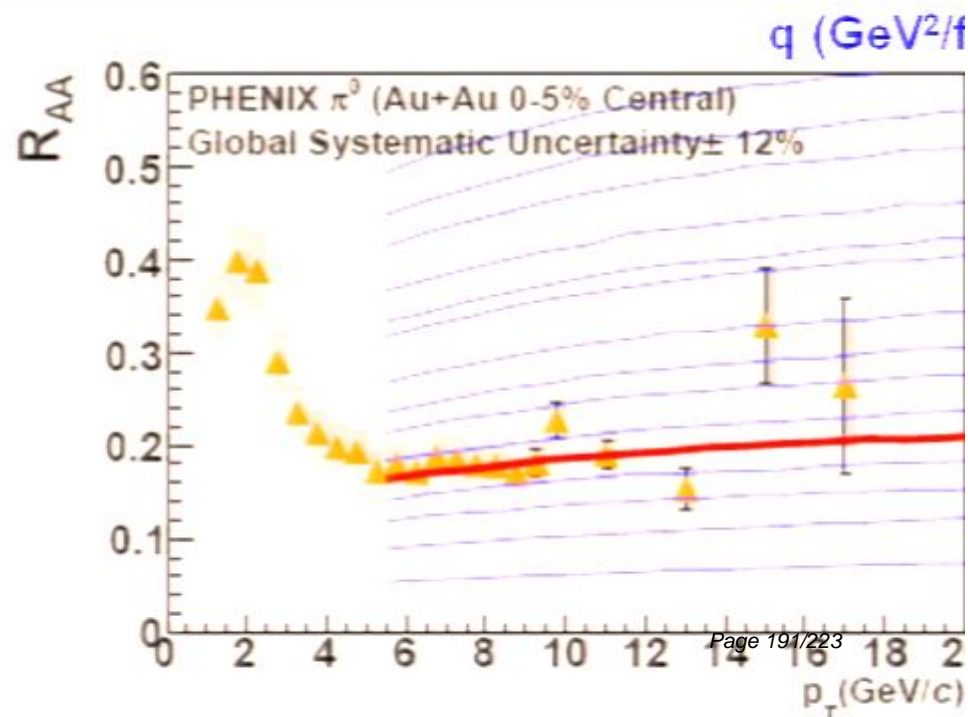
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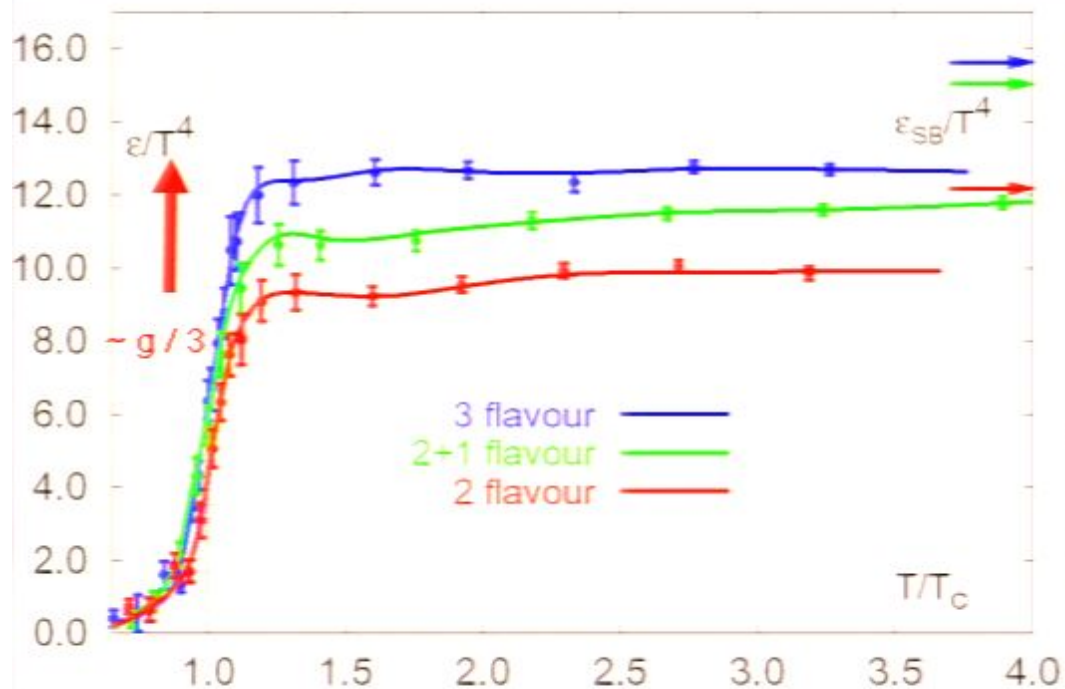
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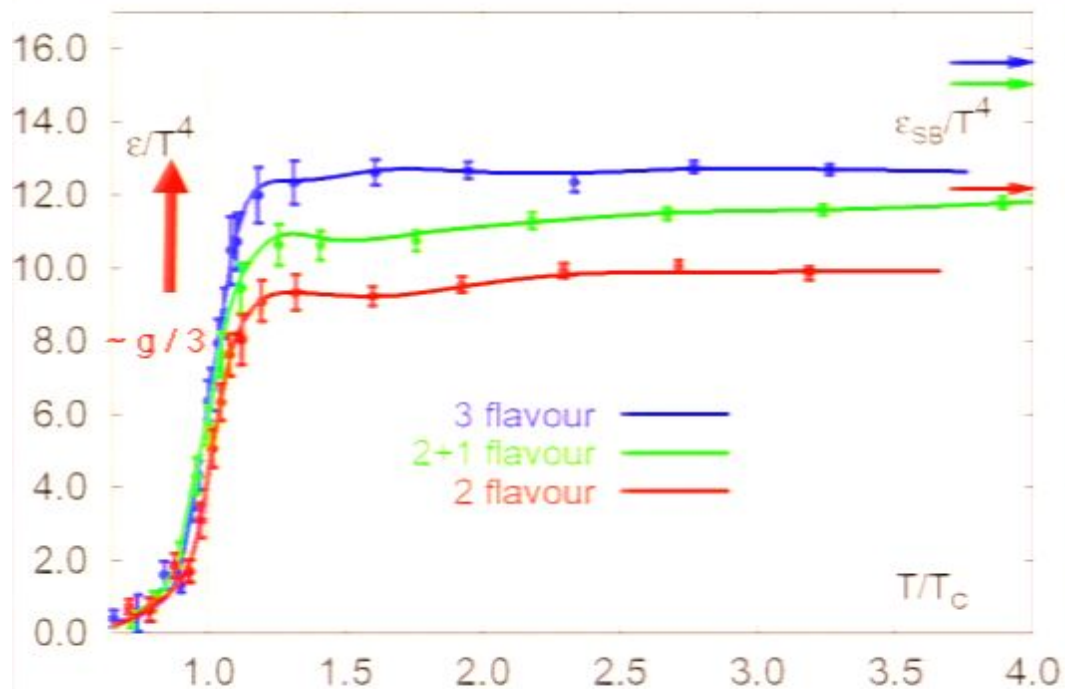
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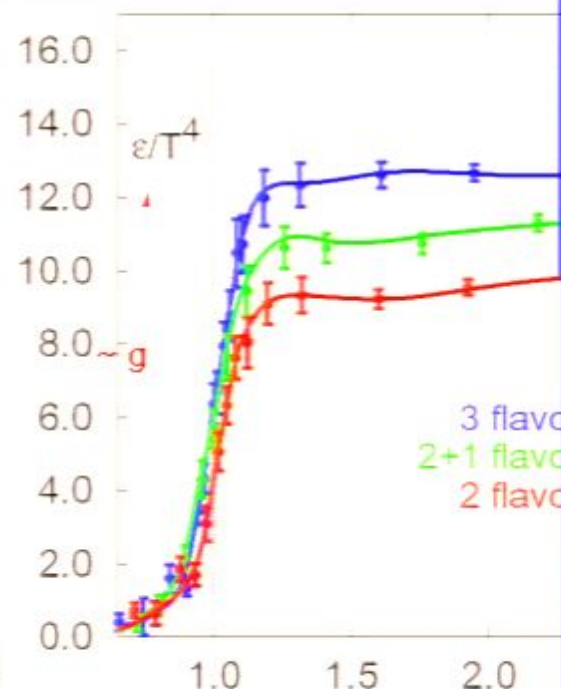
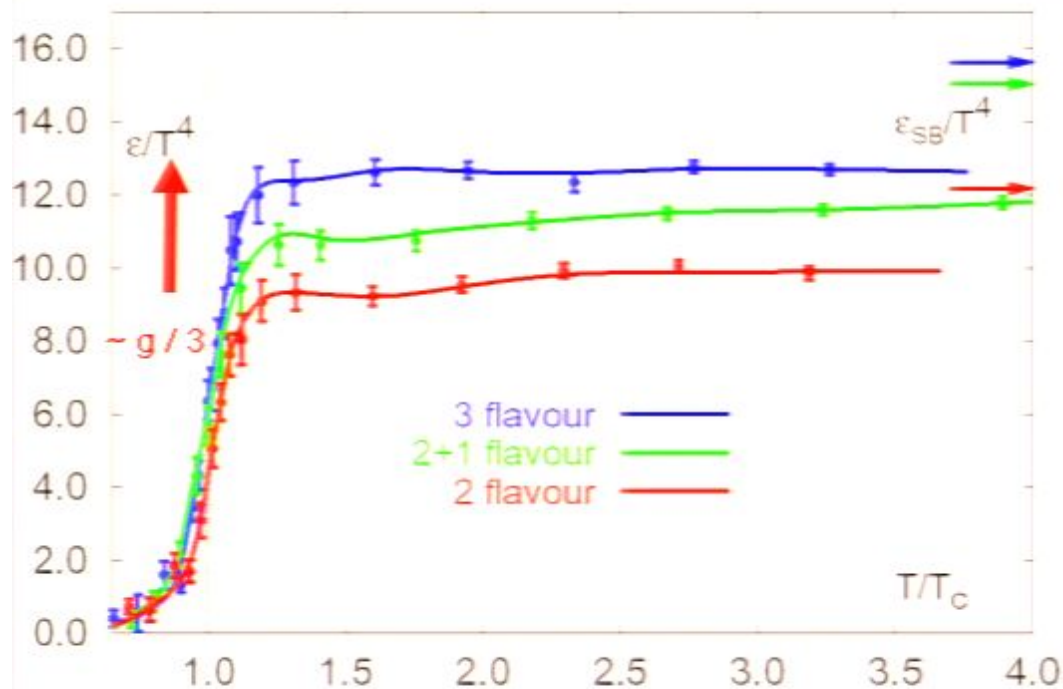


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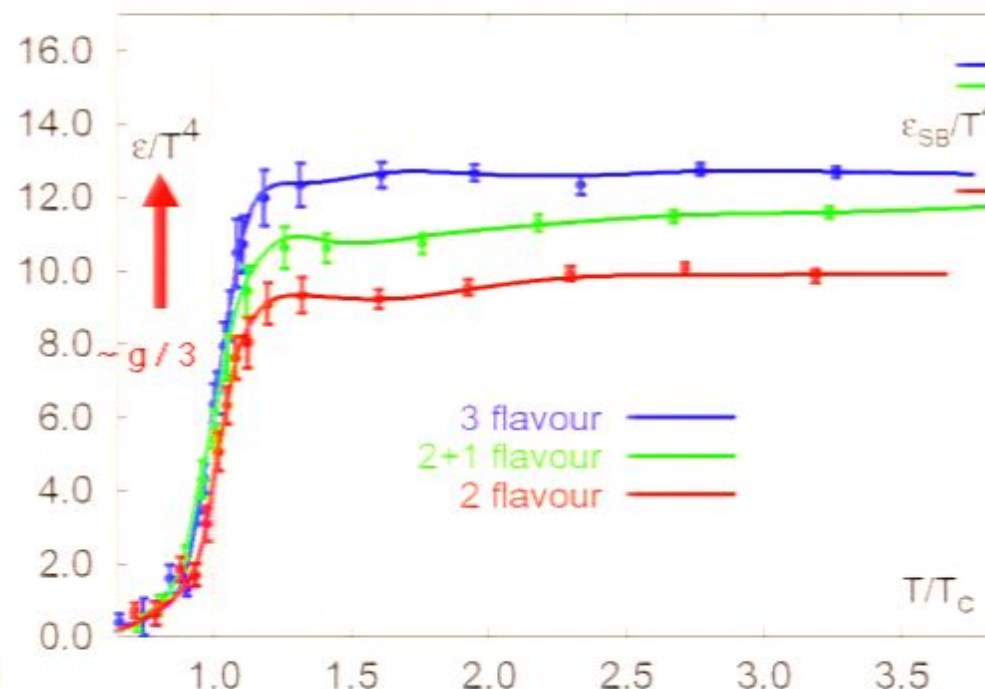
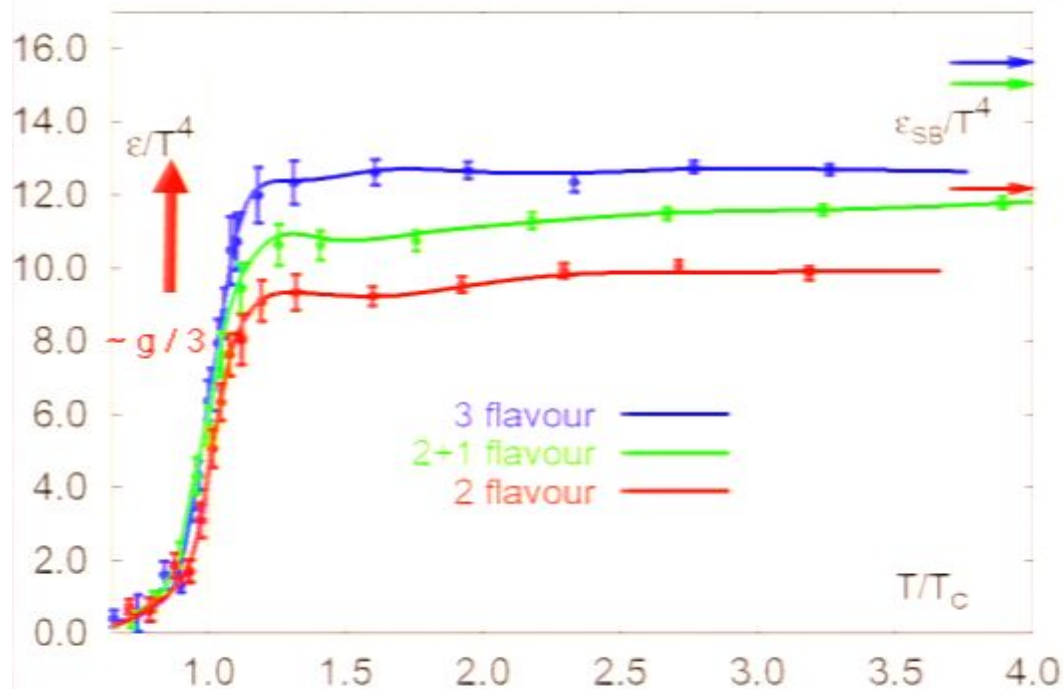


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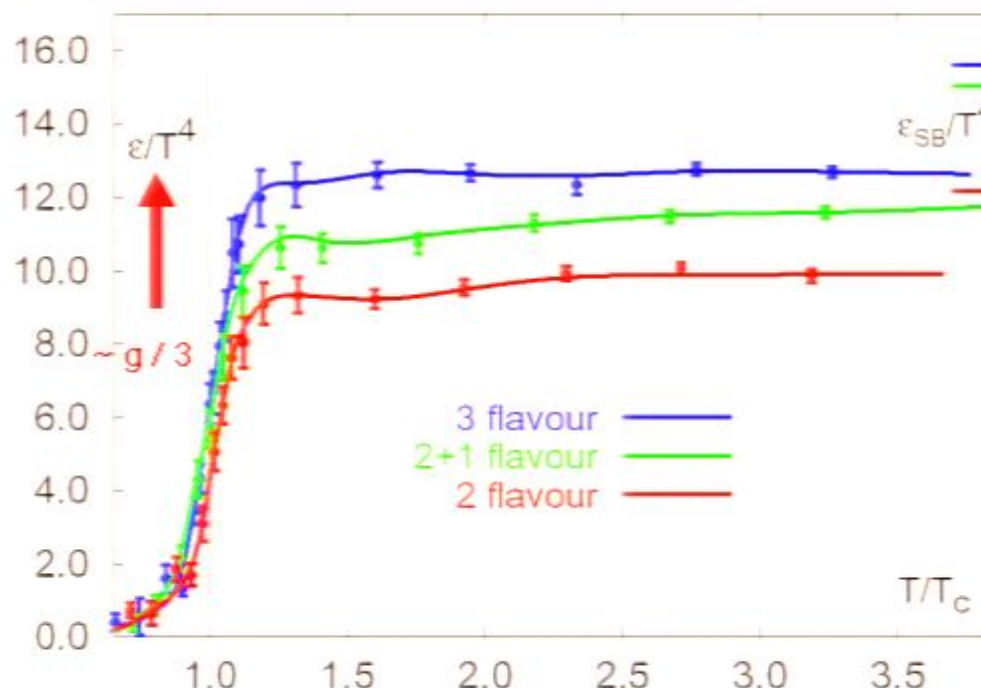
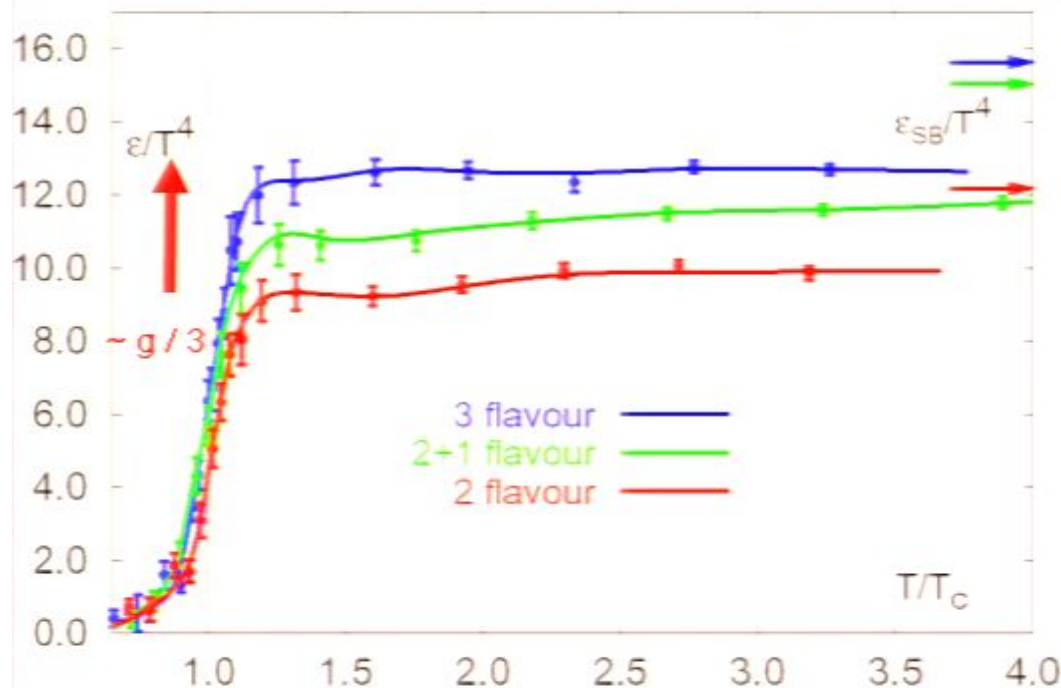


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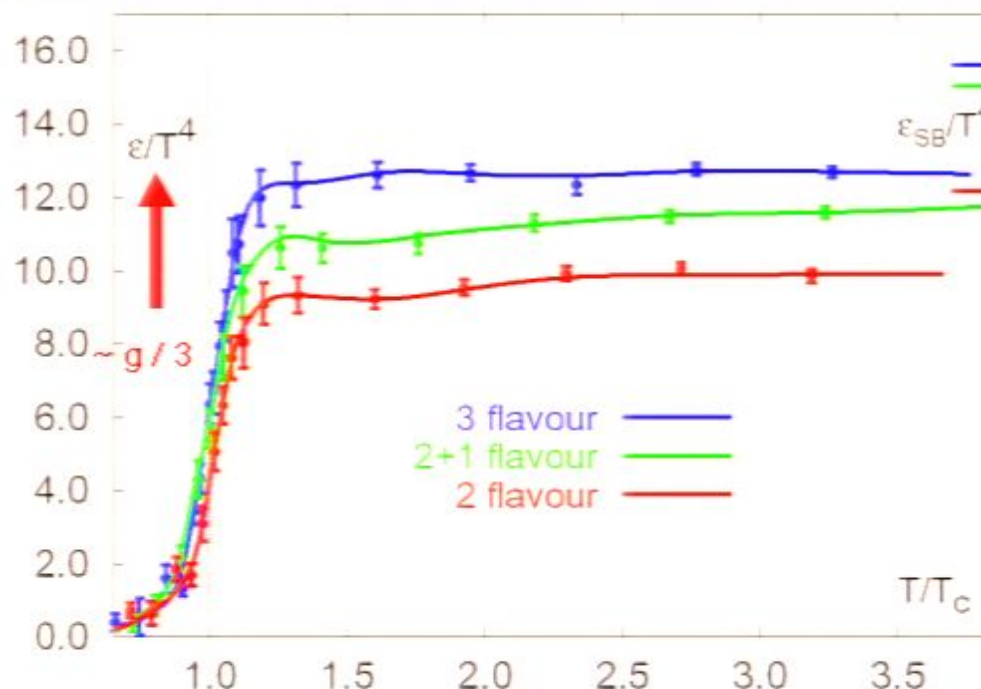
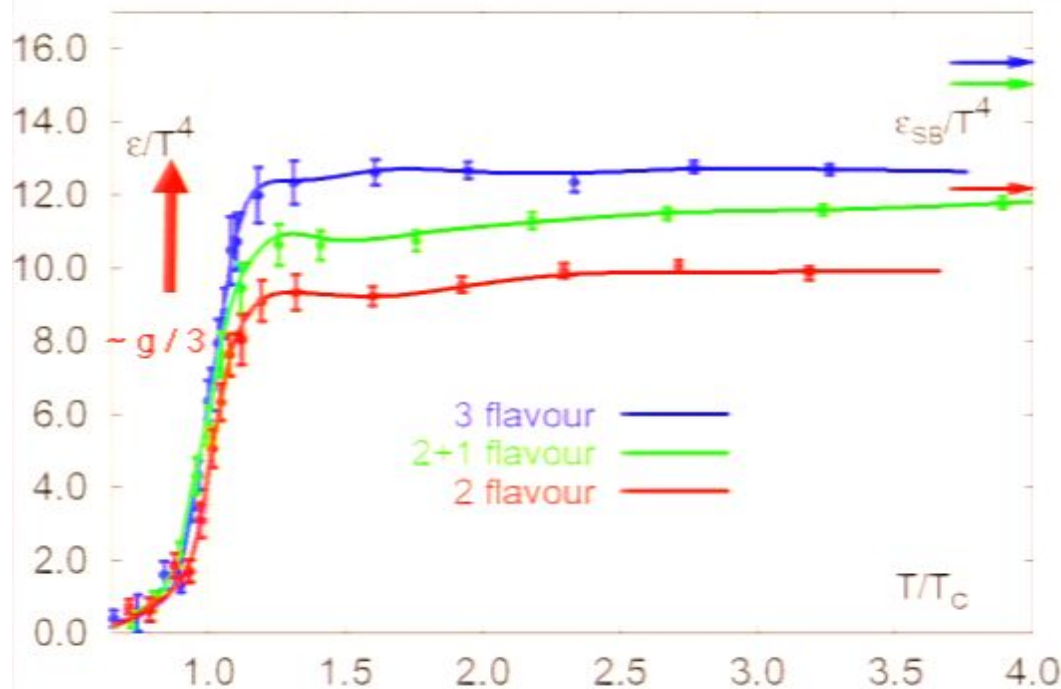
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# Visual Summary

• EACH



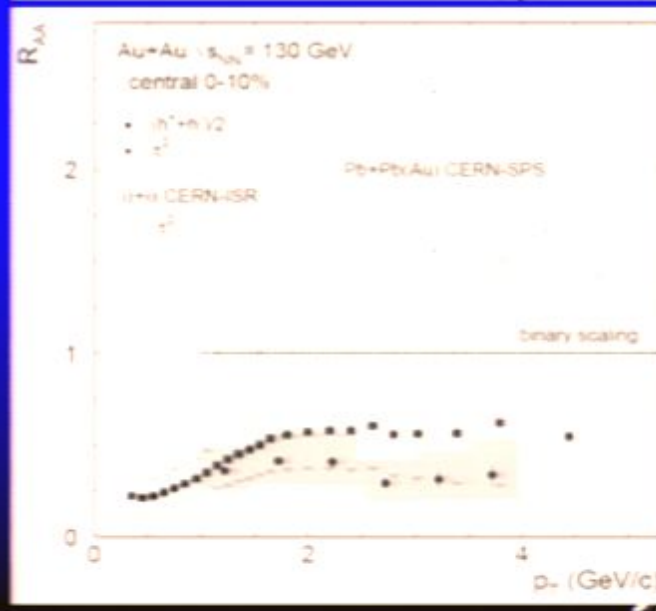
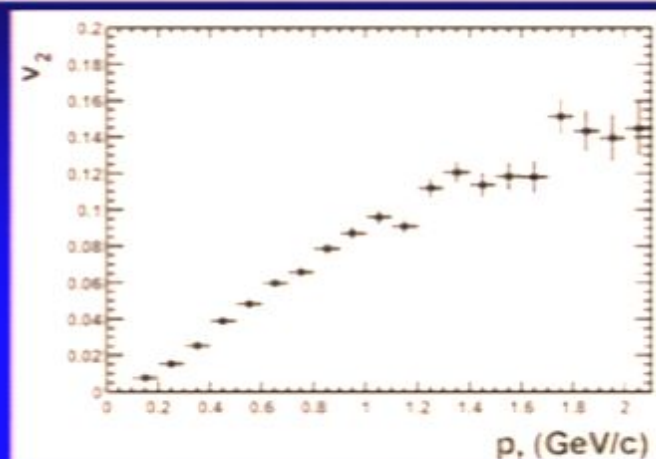
## RHIC's Two Major Discoveries

### • Discovery of strong “elliptic” flow:

- Elliptic flow in Au + Au collisions at  $\sqrt{s_{NN}} = 130$  GeV, STAR Collaboration, (K.H. Ackermann *et al.*), Phys.Rev.Lett.86:402-407,2001
- 345 citations

### • Discovery of “jet quenching”

- Suppression of hadrons with large transverse momentum in central Au+Au collisions at  $\sqrt{s_{NN}} = 130$  GeV, PHENIX Collaboration (K. Adcox *et al.*), Phys.Rev.Lett.88:022301,2002
- 429 citations



□ Indicative of strongly coupled “QGP”



# Visual Summary

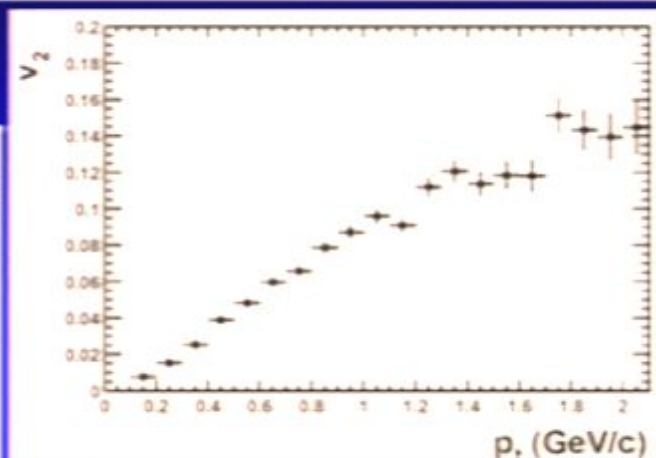
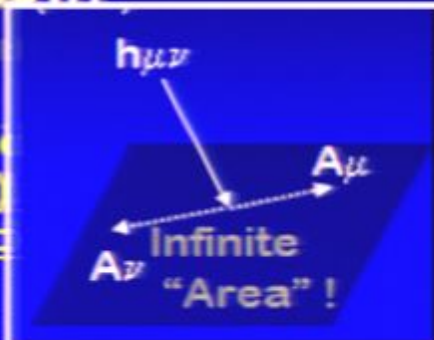
• EACH



## RHIC's Two Major Discoveries

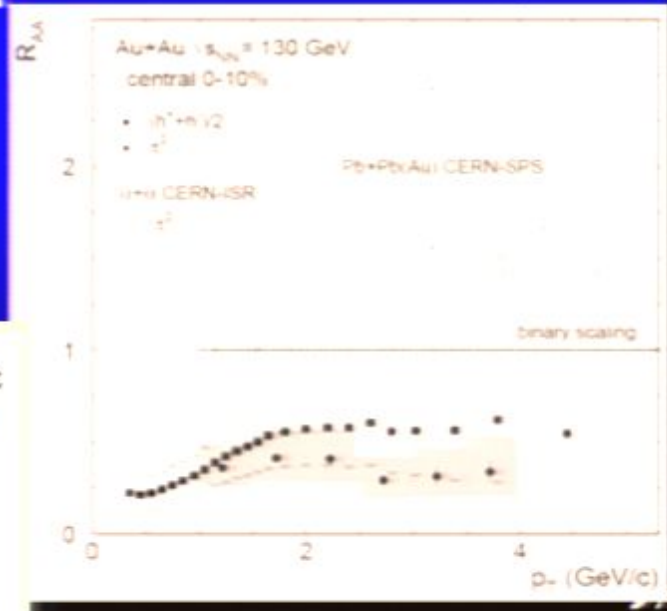
### Discovery of strong "elliptic" flow:

- Elliptic flow in Au+Au collisions at  $\sqrt{s_{NN}} = 130$  GeV, STAR Collaboration (Ackermann *et al.*) Phys.Rev.Lett.86:1975-1978, 1991
- 345 citations



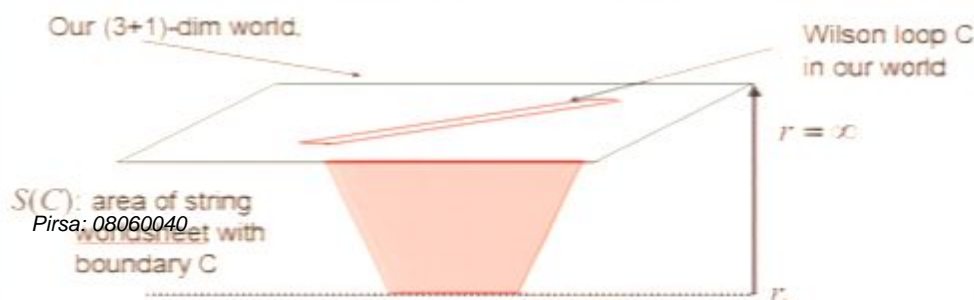
### Discovery of "jet quenching"

- Suppression of hadrons with large transverse momentum in central Au+Au collisions at  $\sqrt{s_{NN}} = 130$  GeV,



□ Indicative of strongly coupled "QGP"

□ Consistent to within factors of 2-3 with AdS/CFT results







# Summary

- The near-simultaneous development of
  - RHIC Discoveries
  - Theoretical Synthesis
  - Overthrow of “classical” QGP
  - Emergence of AdS/CFT connections



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➡ See next talk by Krishna Rajagopal  
for the theoretical details



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No Signal

VGA-1