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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  - What happens when I crash two gold nuclei together?

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RHIC

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- $ **Compelling question:**
  - ☞ What fundamental *thermal* properties of our gauge theories of nature can be investigated experimentally?

The Thermal Universe

- 10 GeV / fm^3
  ~ 10^{16} gm / cm^3

- T ~ 170 MeV
  ~ 2 x 10^{12} K

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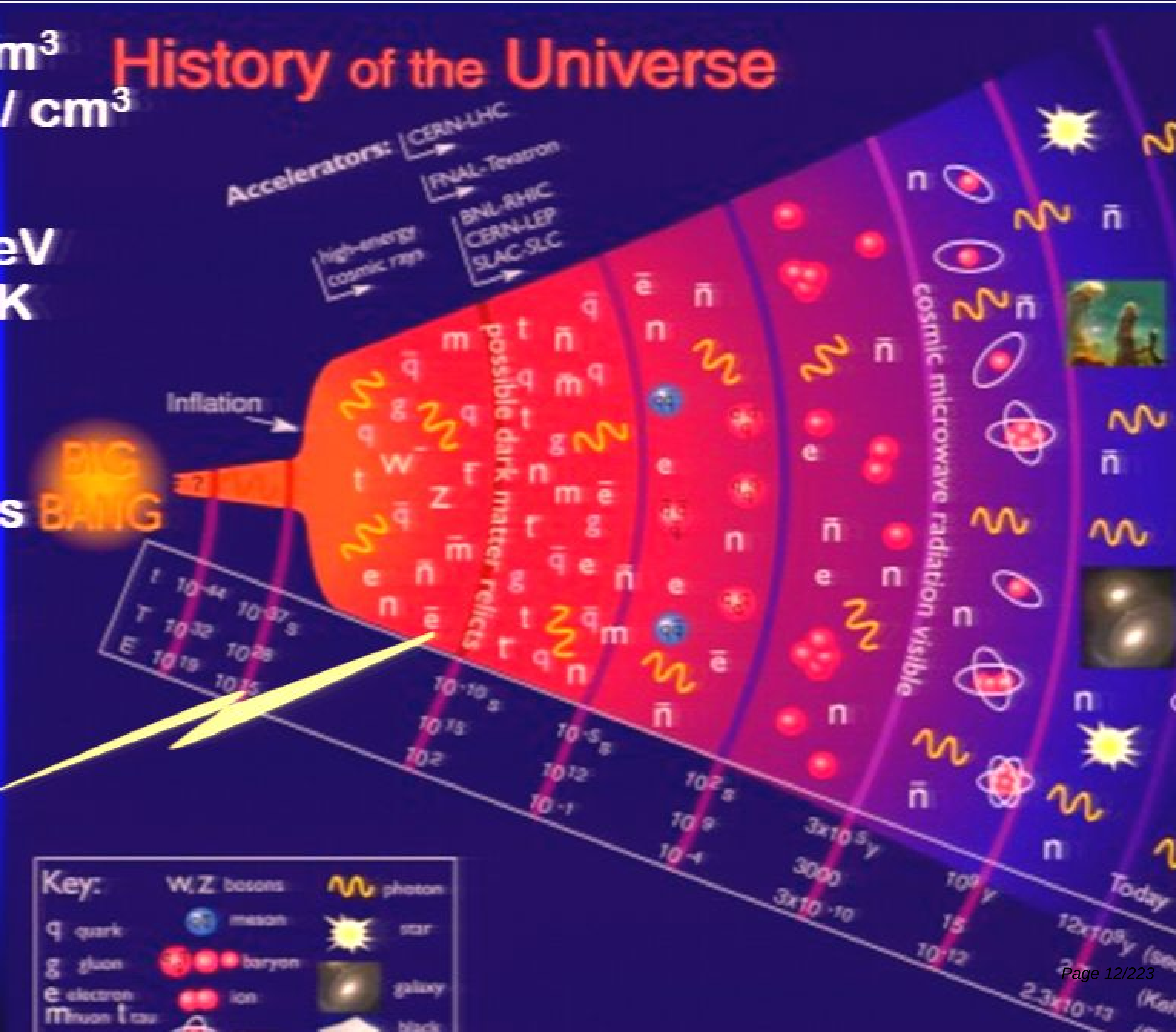

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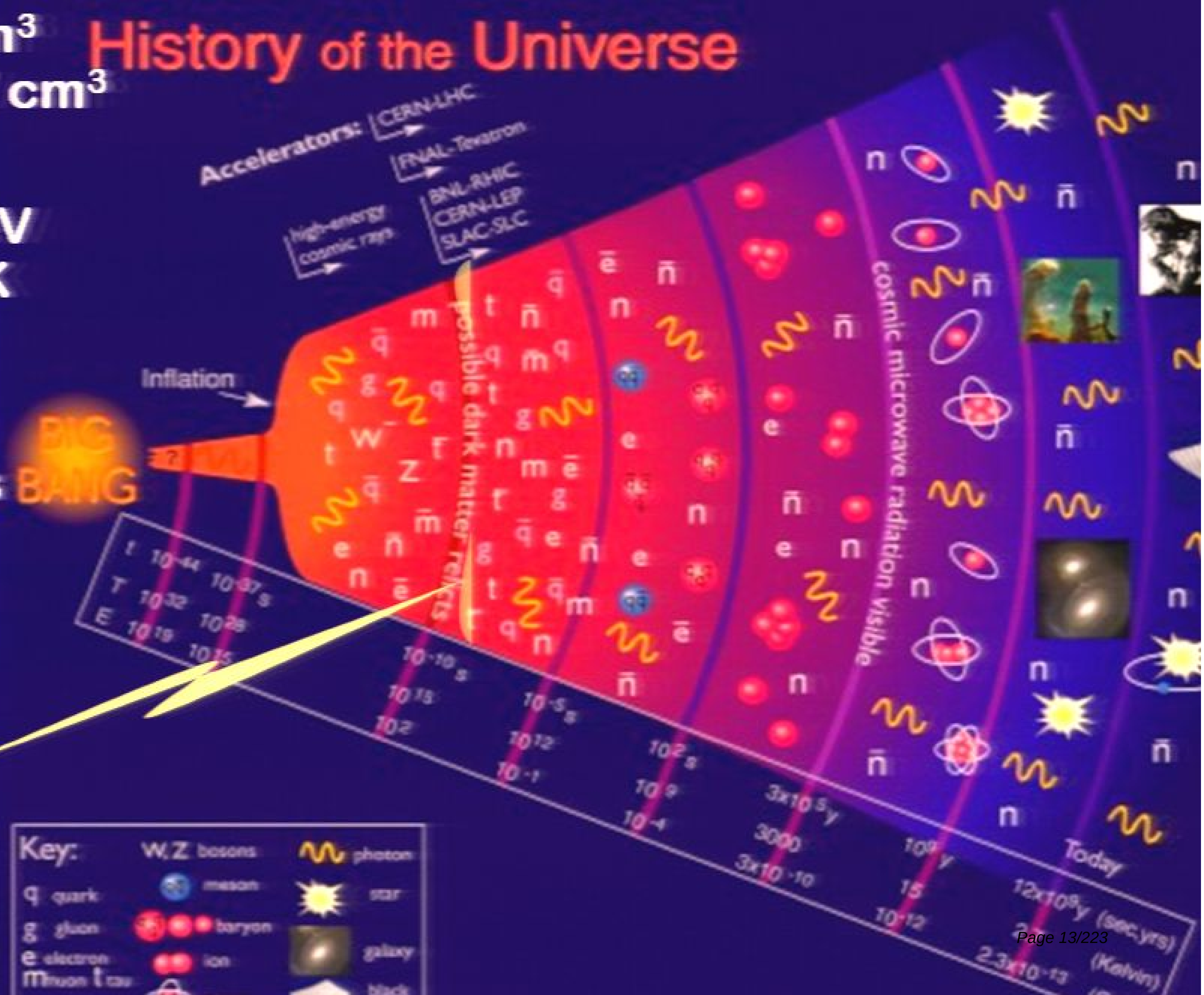

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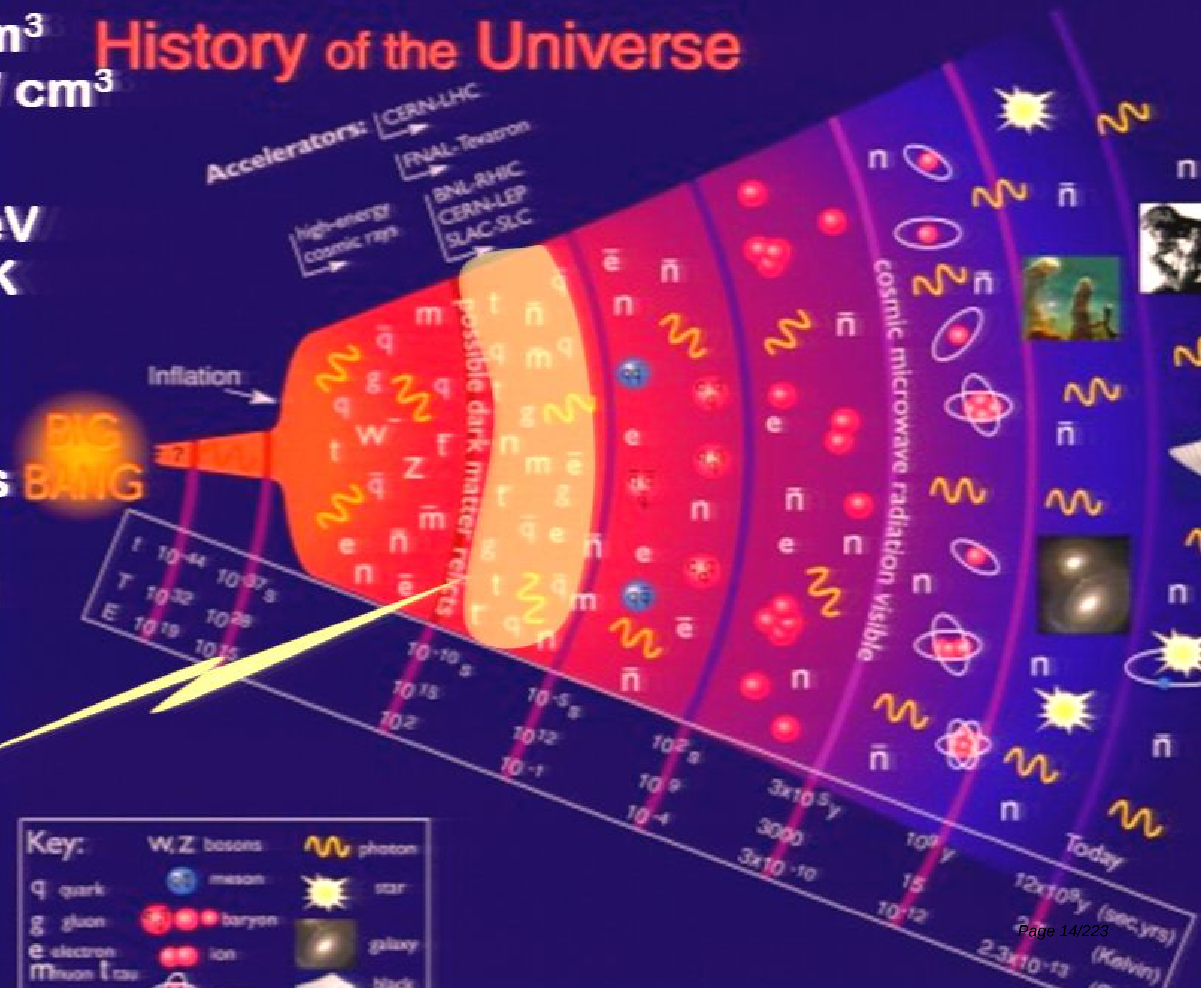
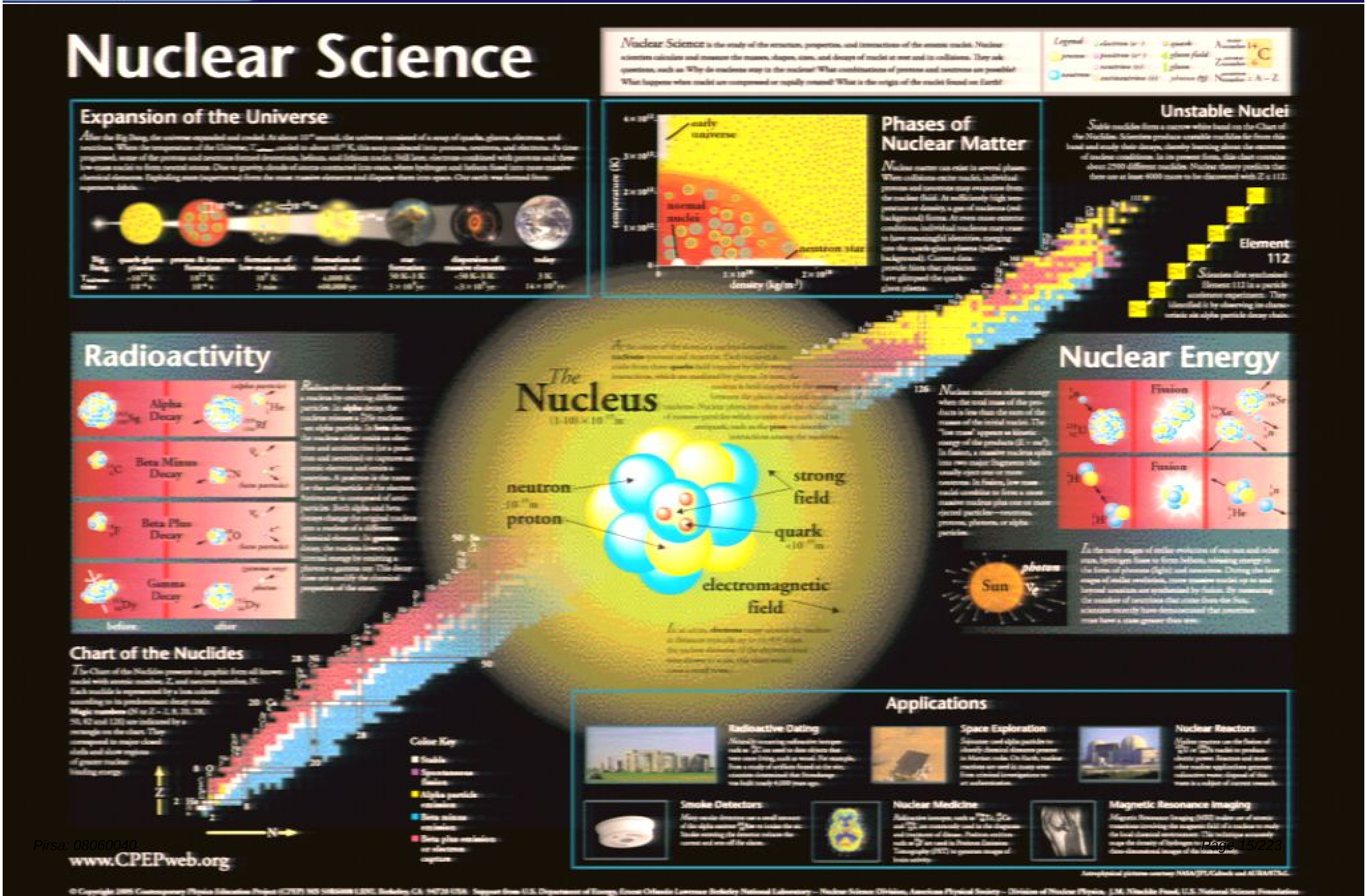


Expectations circa 2000



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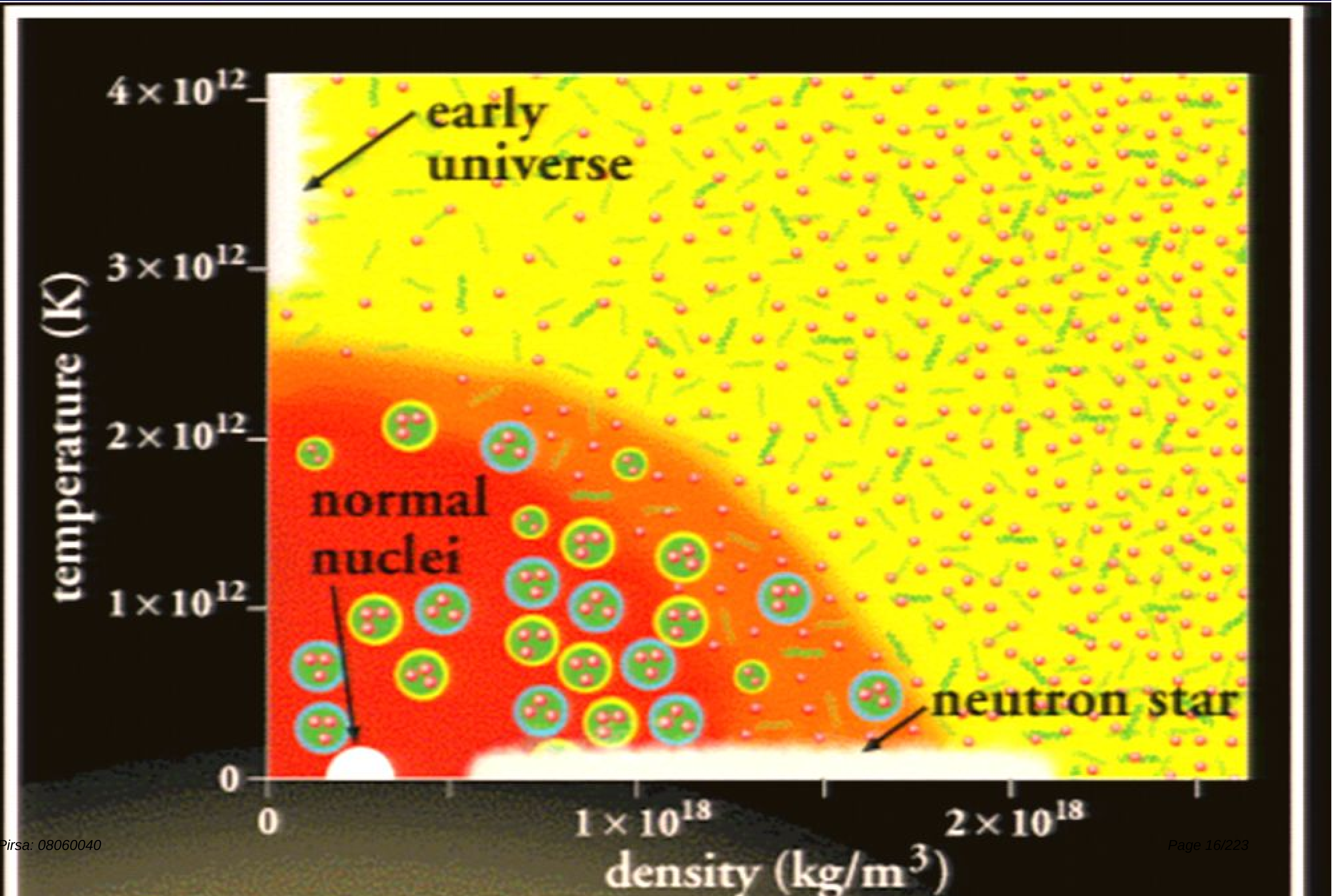

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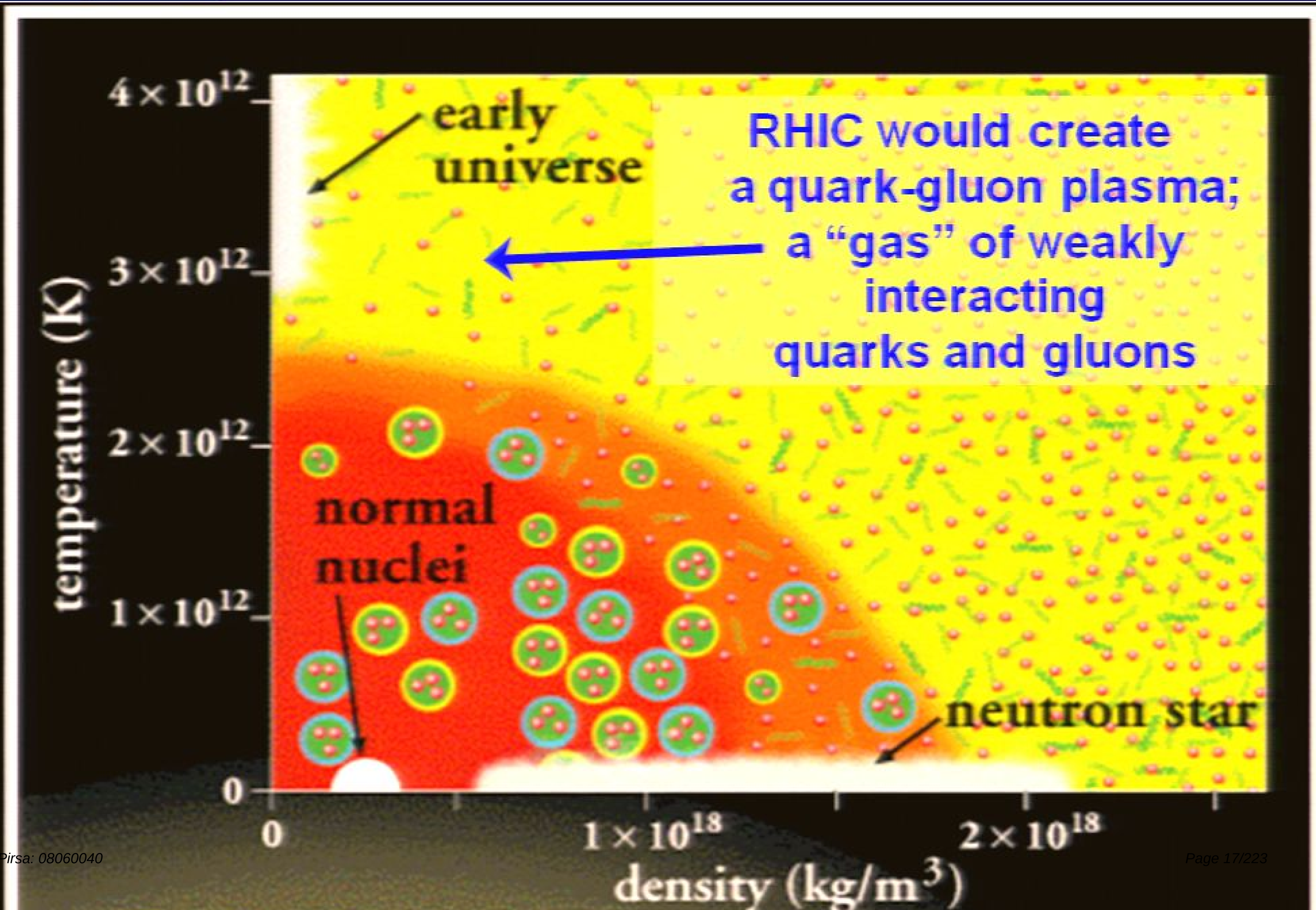

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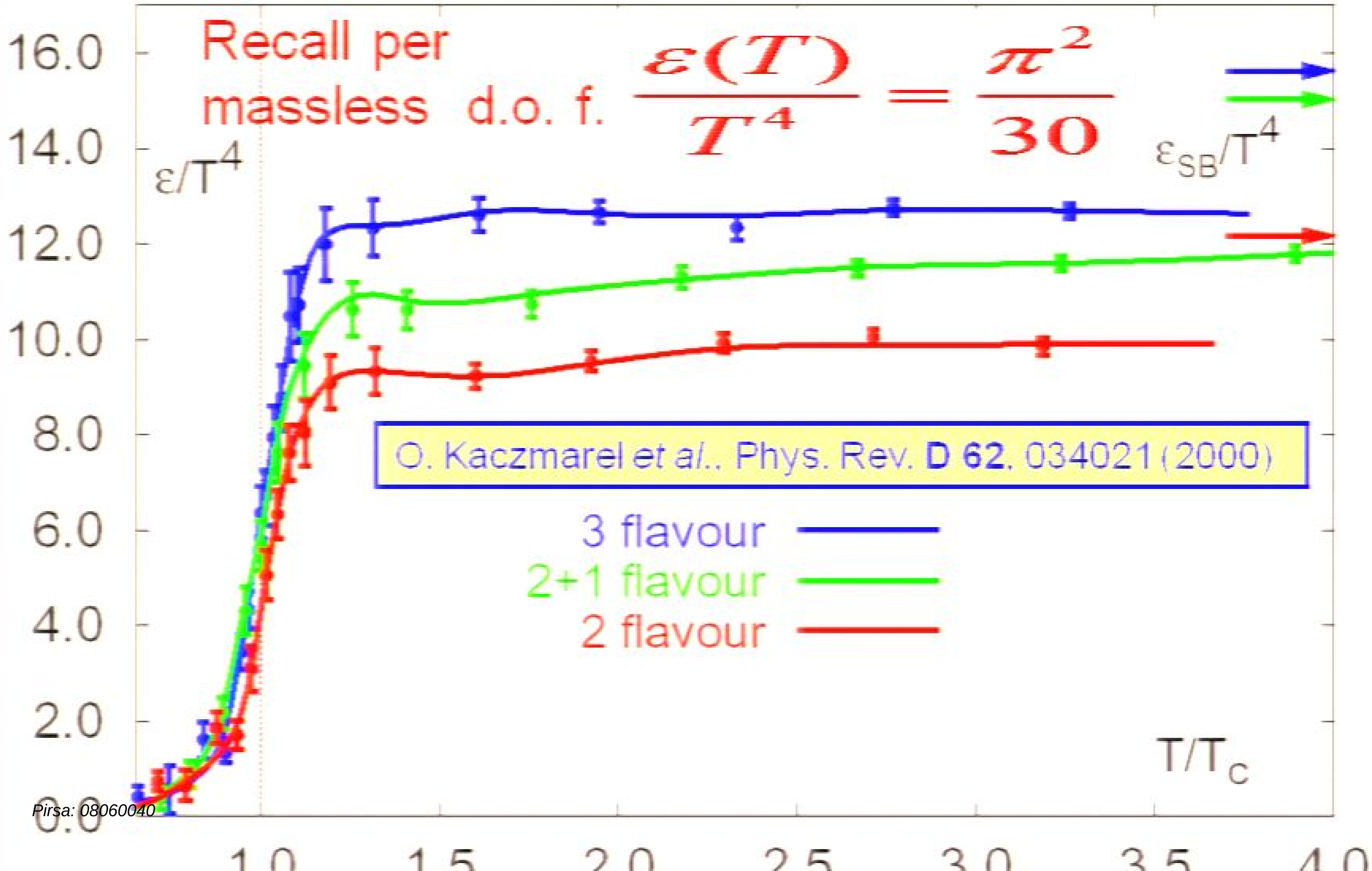
  - ⇨ Quark-Gluon Plasma is a weakly coupled ‘plasma’



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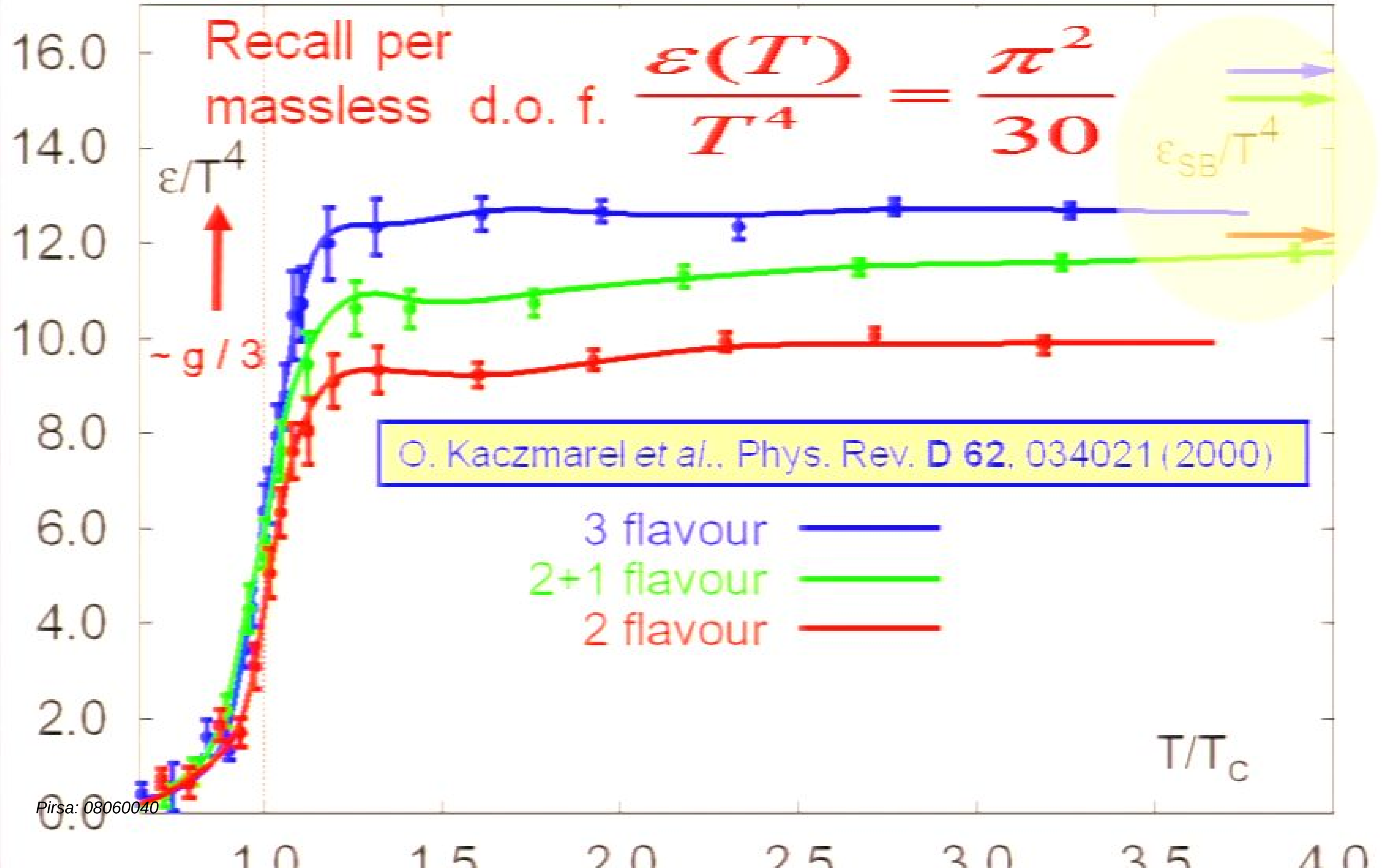

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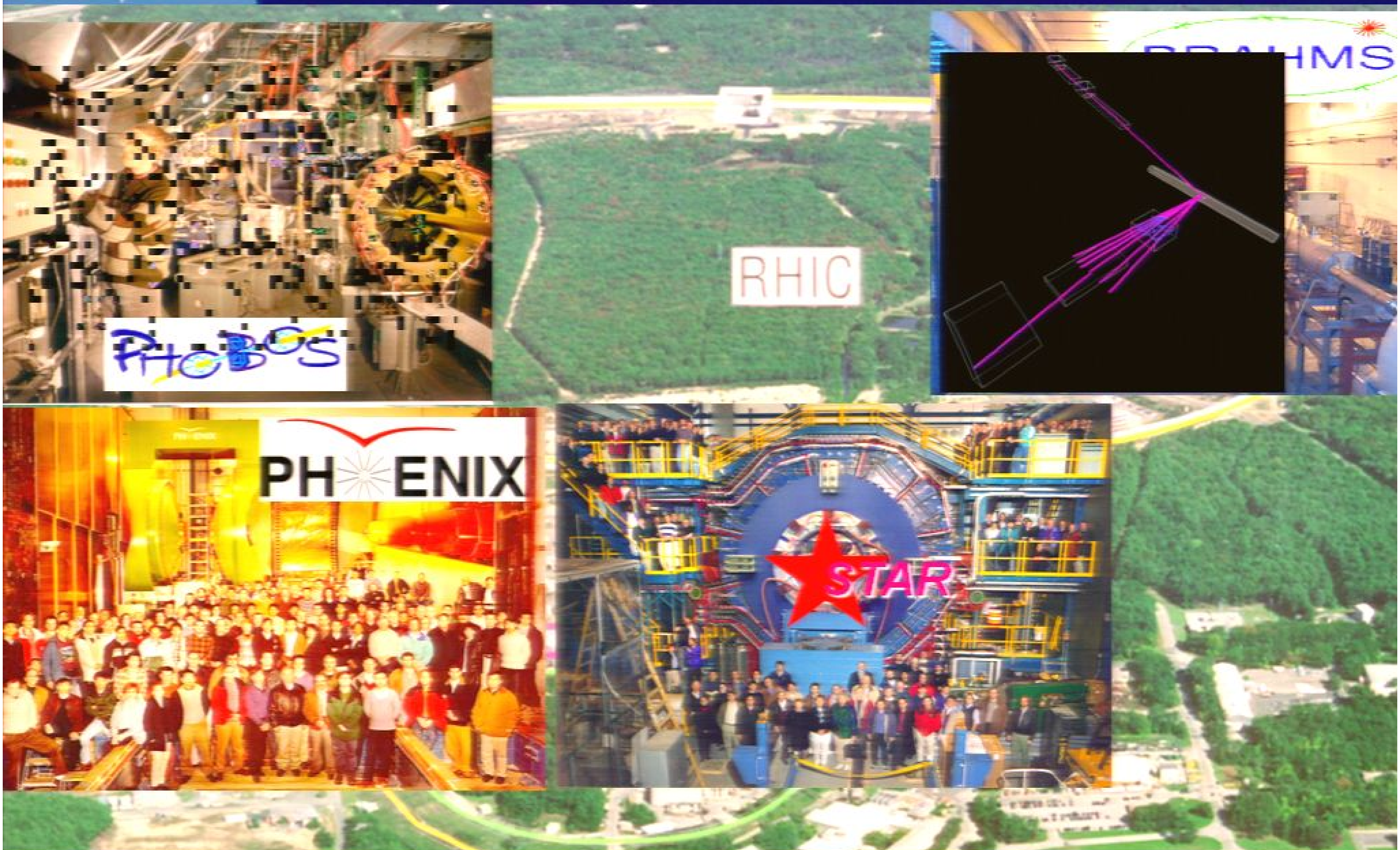

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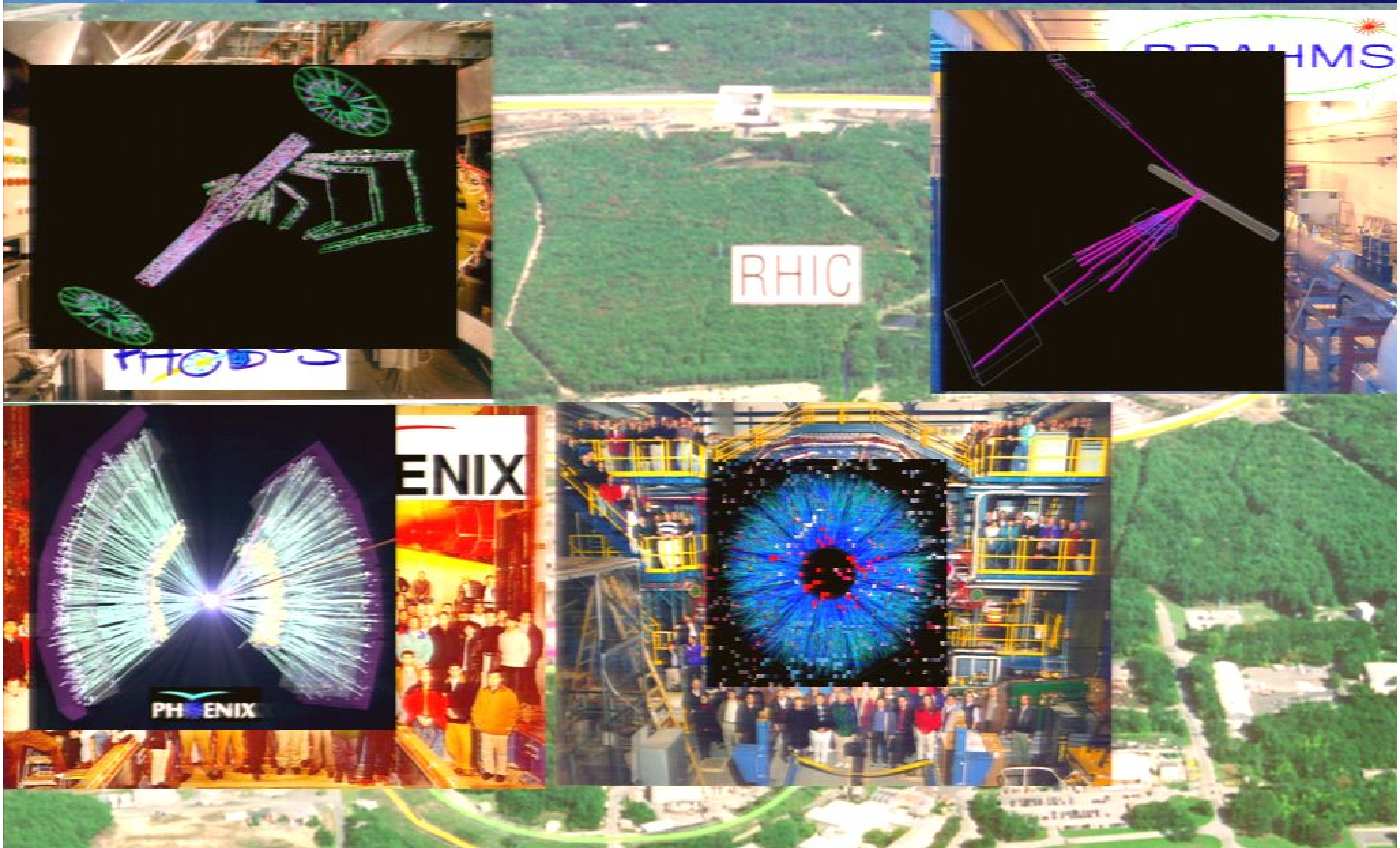

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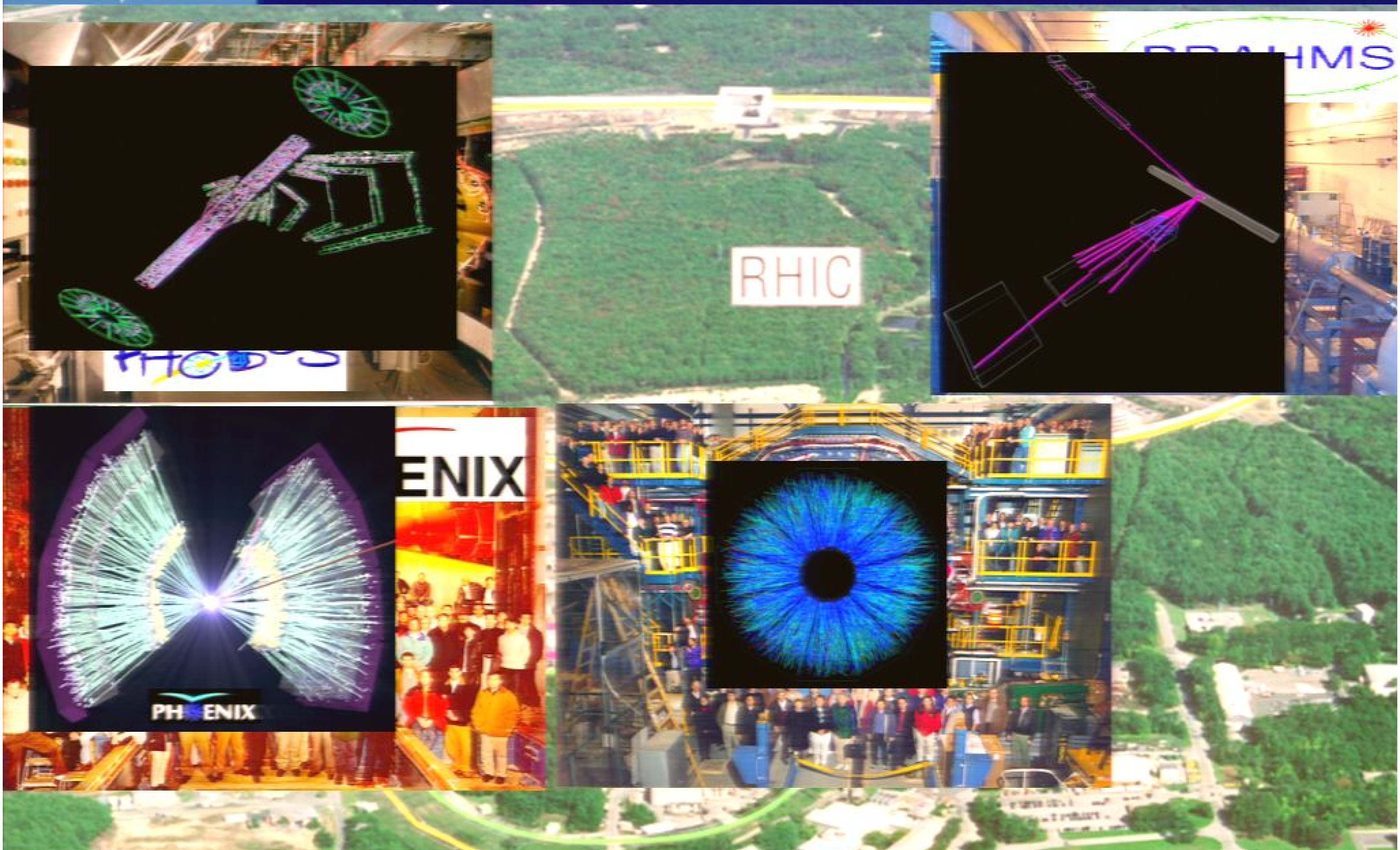

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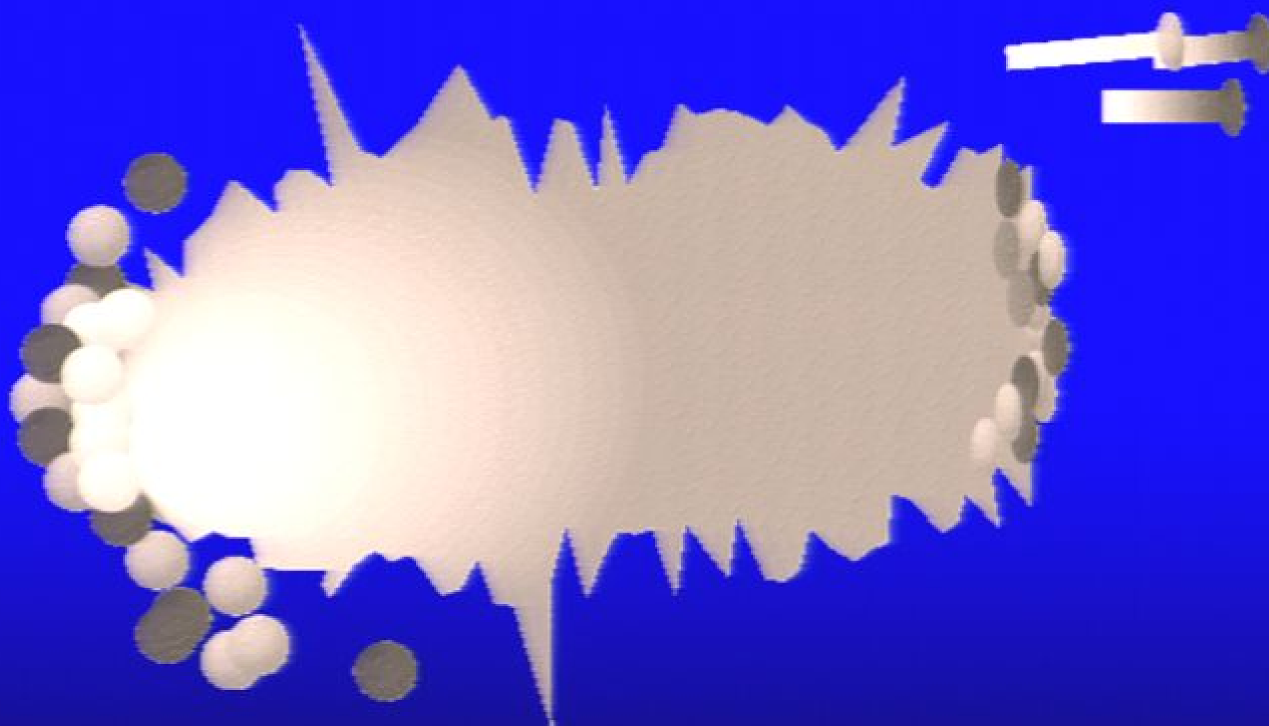
  - Demonstrated ability to upgrade
  - Key science questions identified
  - Accelerator and experimental upgrade program underway to perform that science

Approach

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



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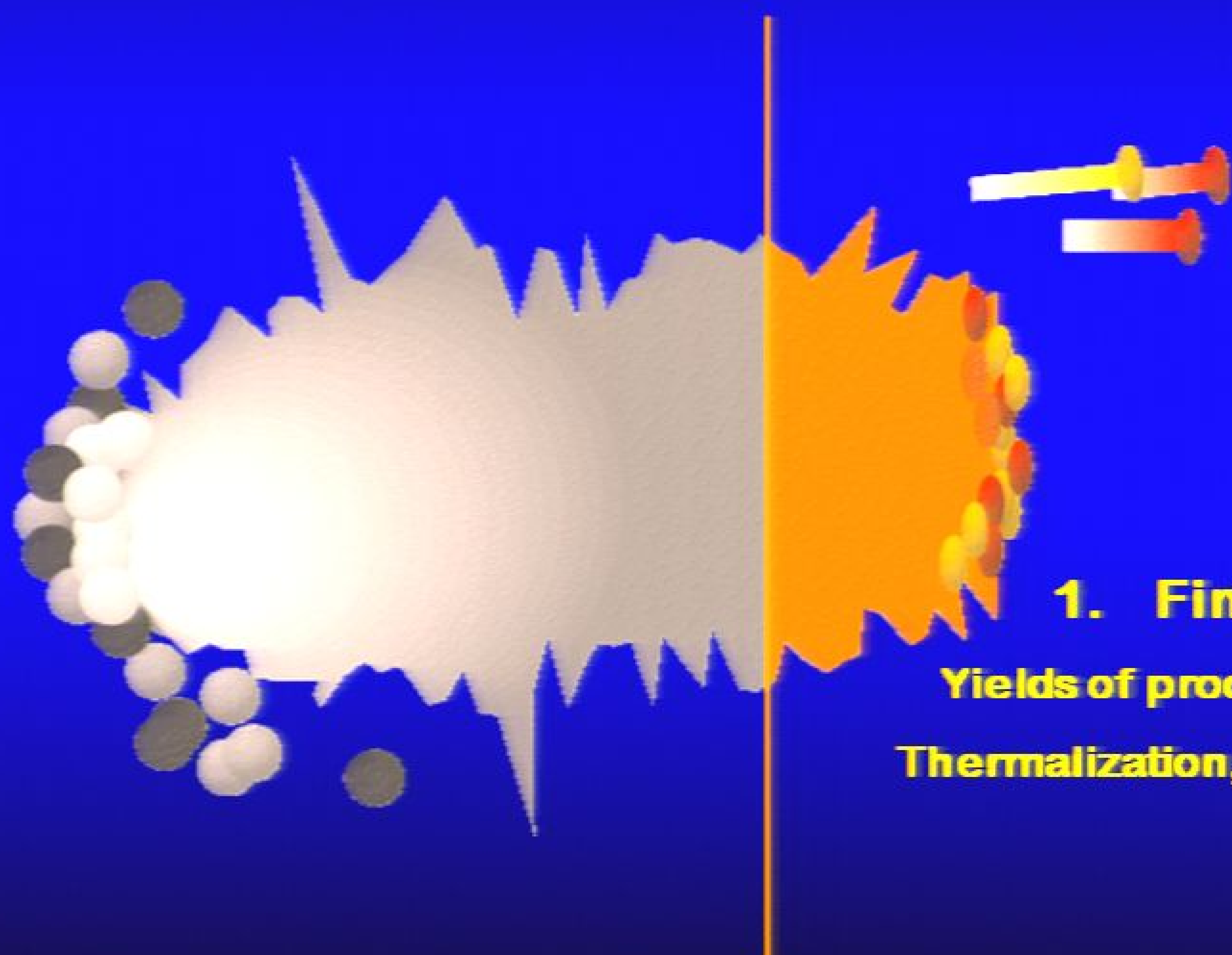

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Yields of produced particles

Thermalization, Hadrochemist

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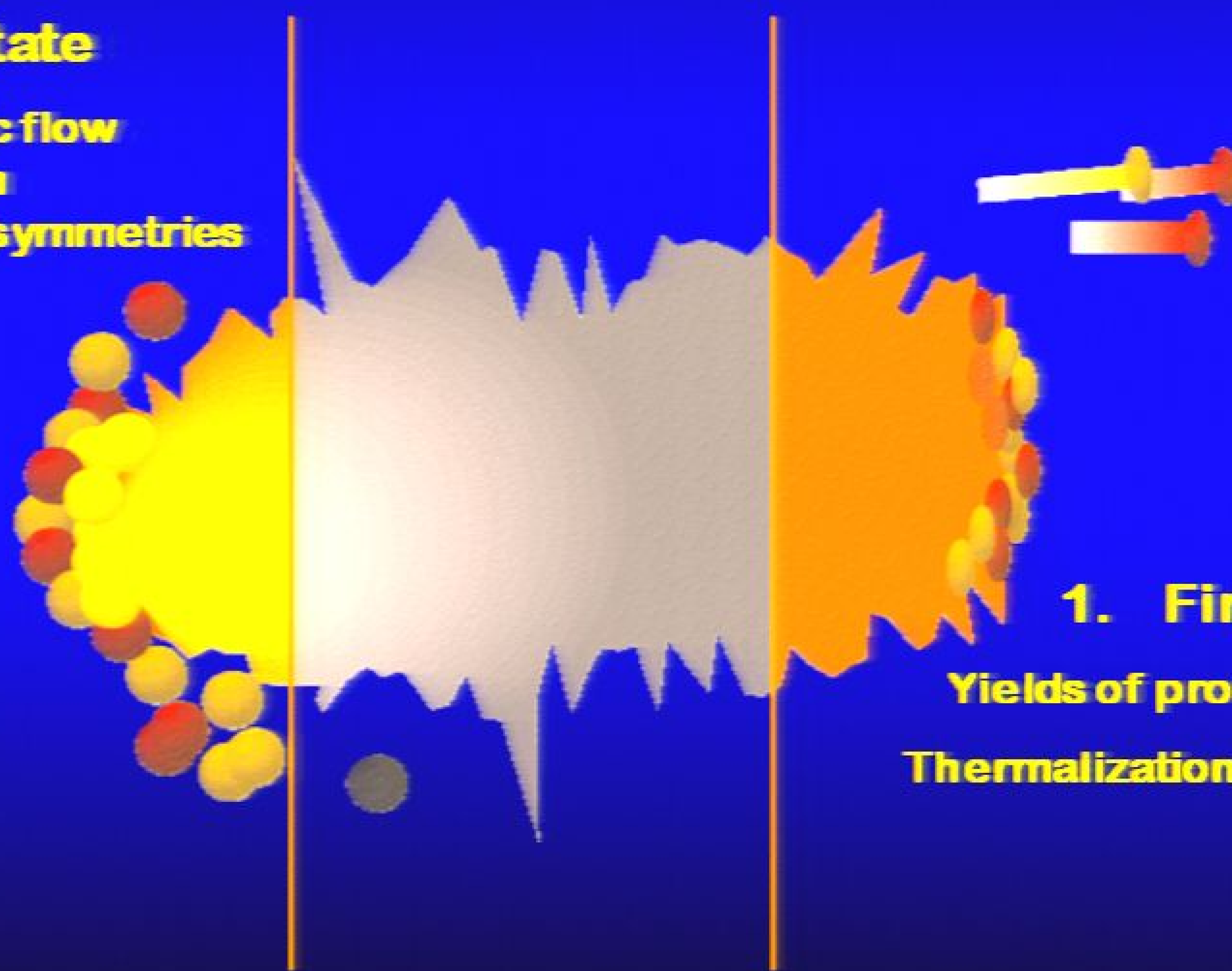

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Hydrodynamic flow
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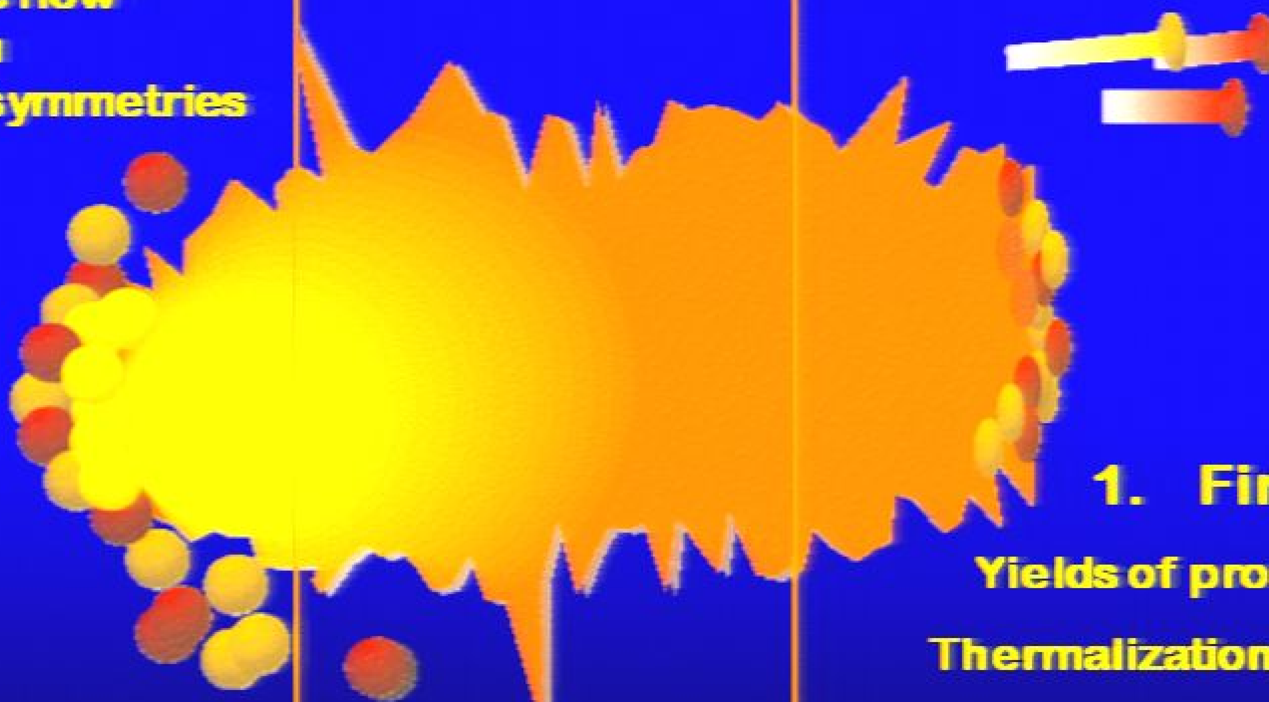

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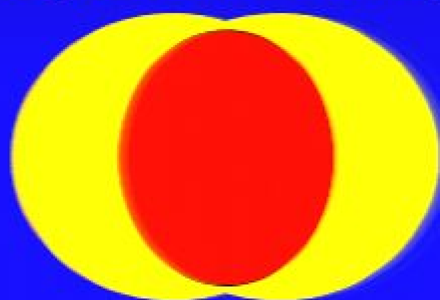
3. Probes of dense matter

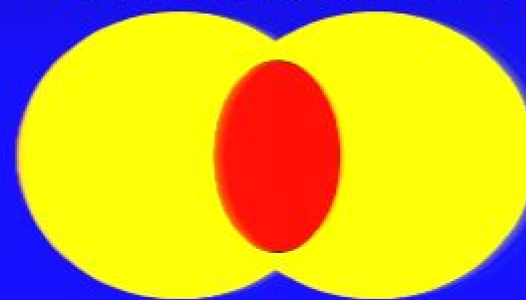
Assertion

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

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

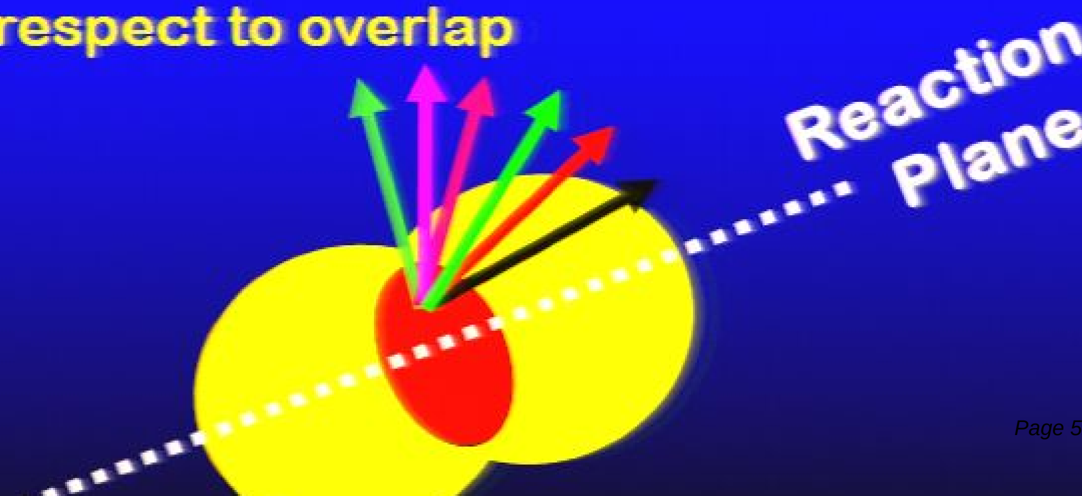


“Central”



“Peripheral”

  - Orientation with respect to overlap



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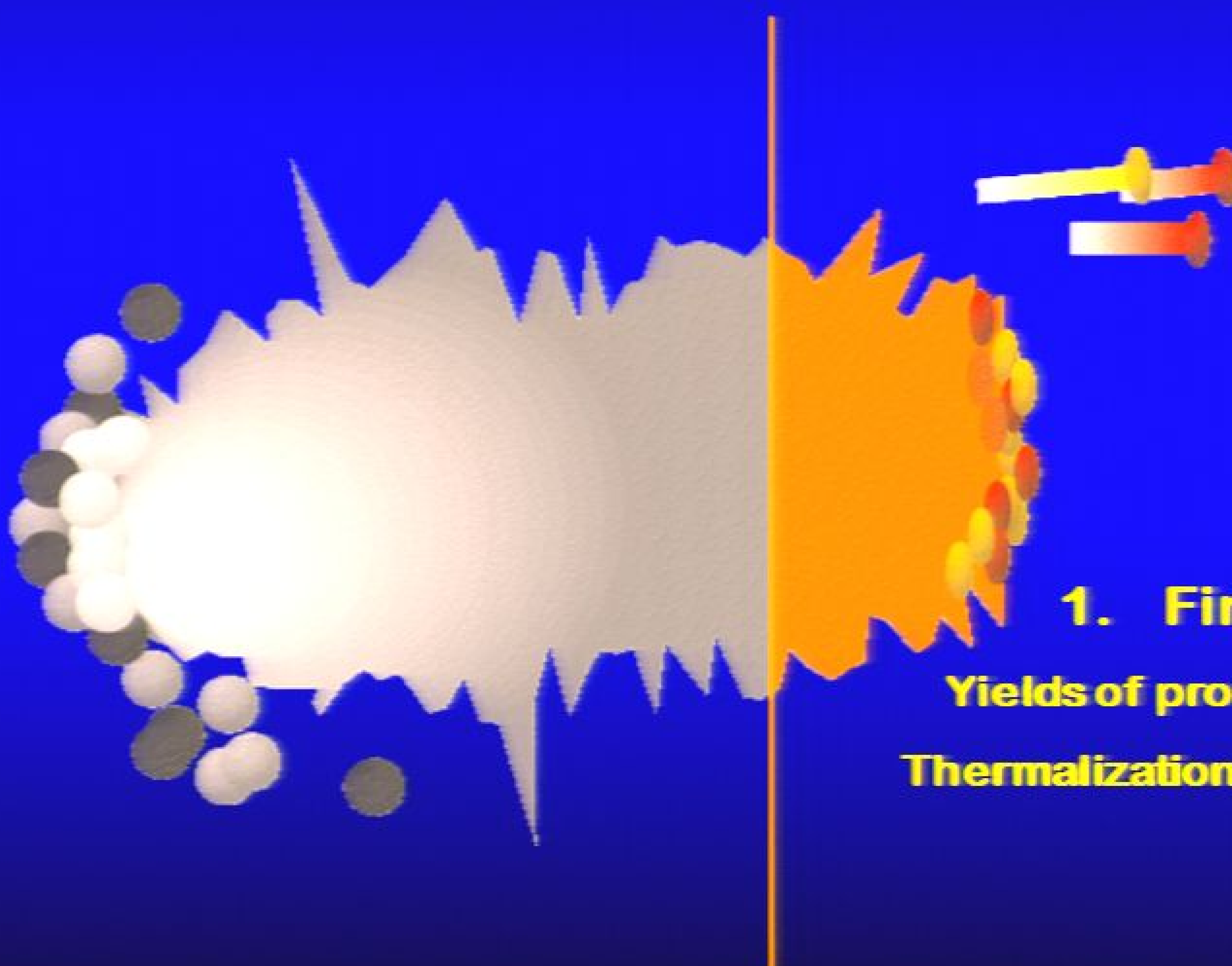

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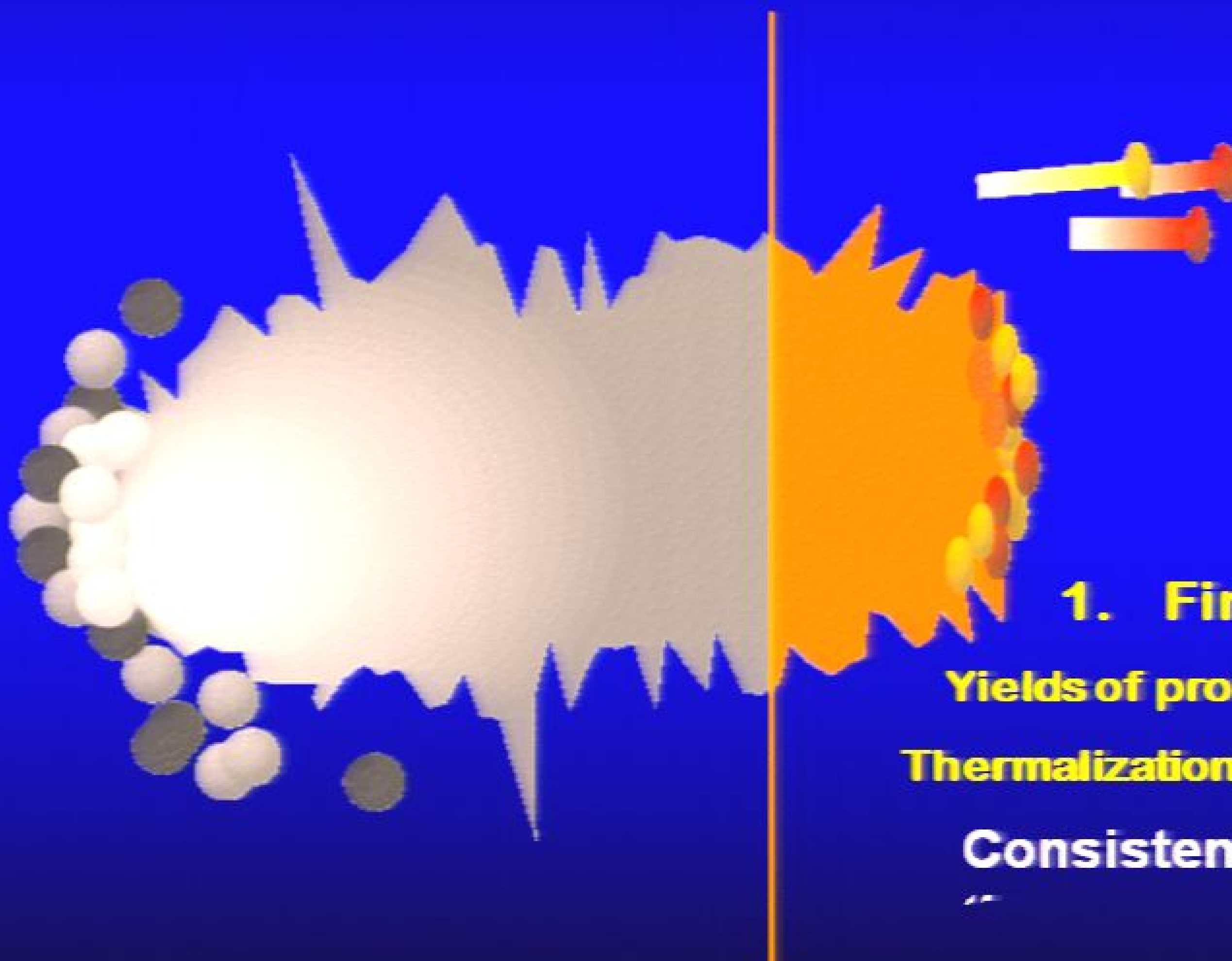

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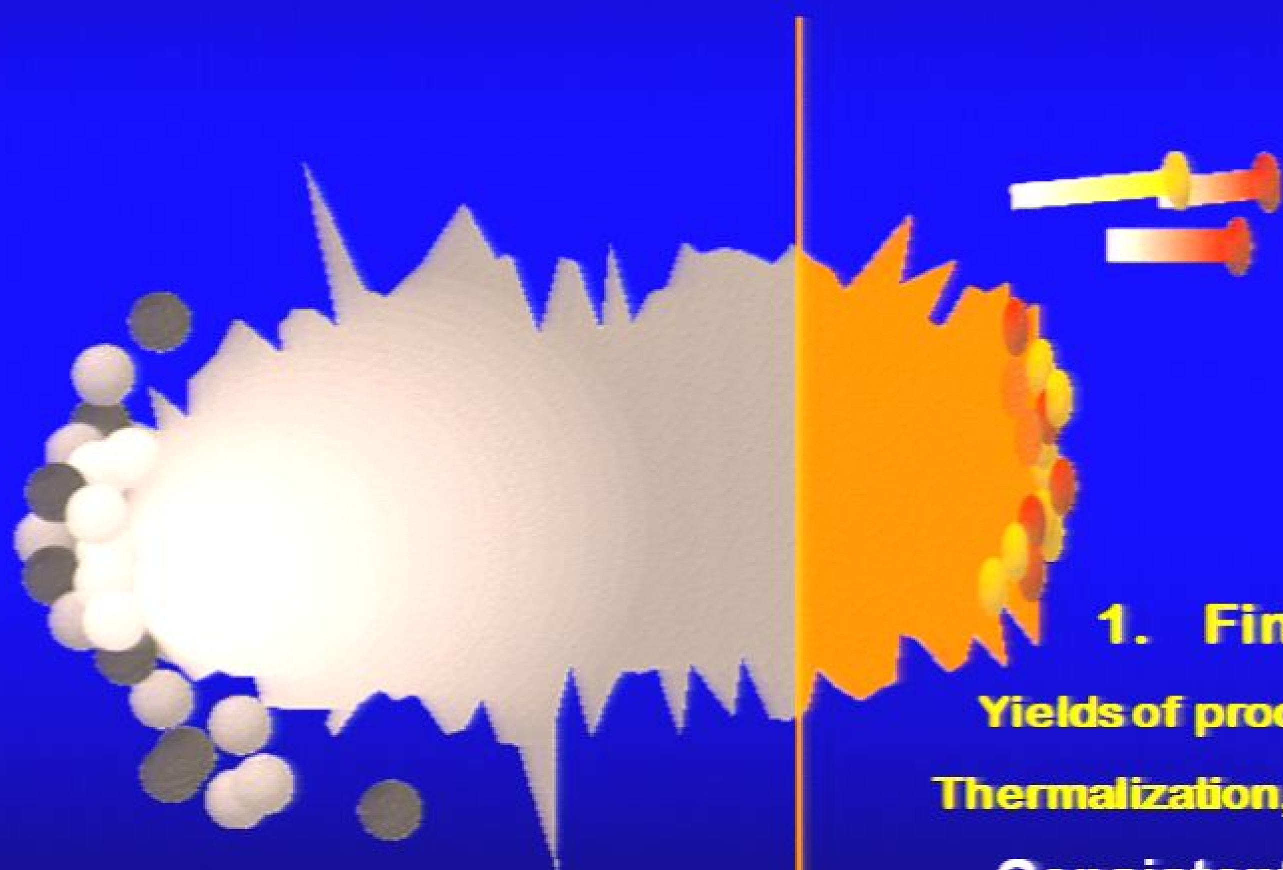

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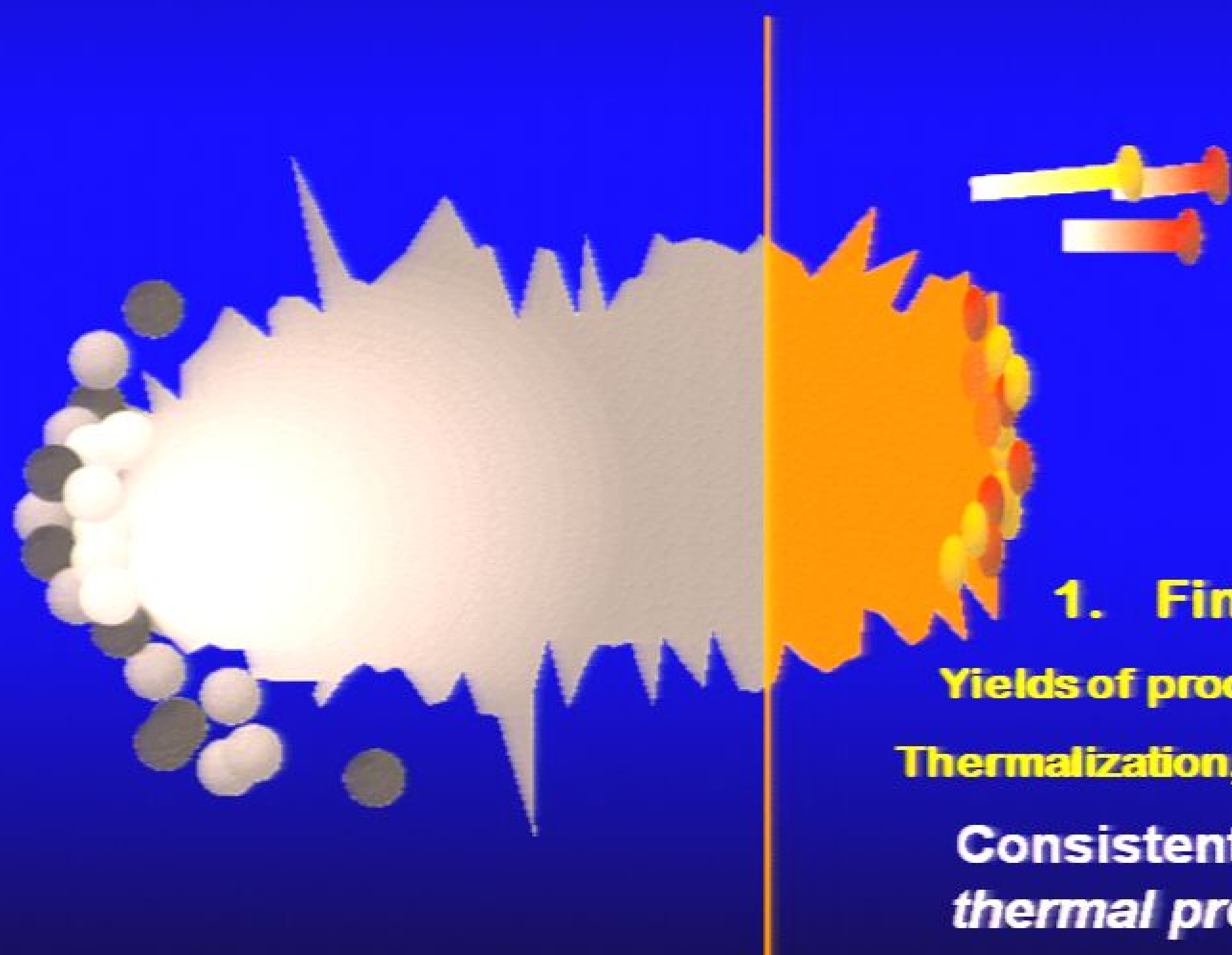

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$T \sim 170$ MeV, $\mu_B \sim 30$ MeV

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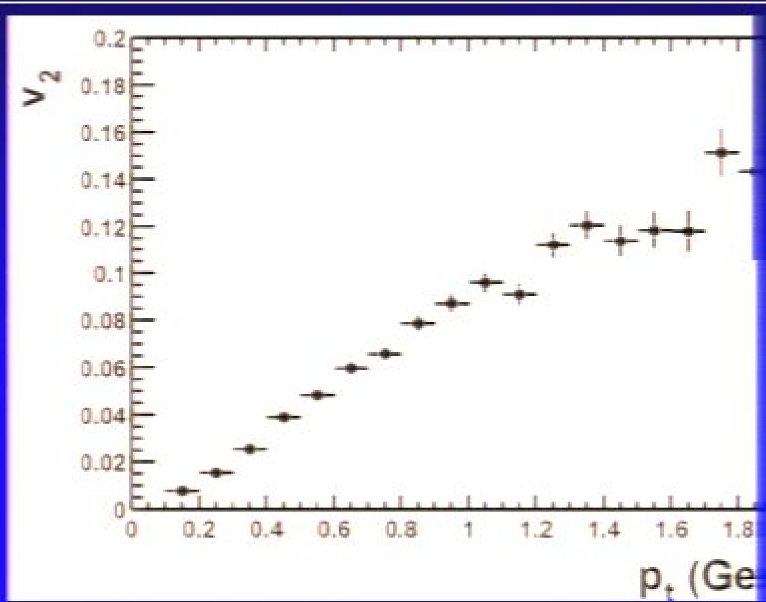

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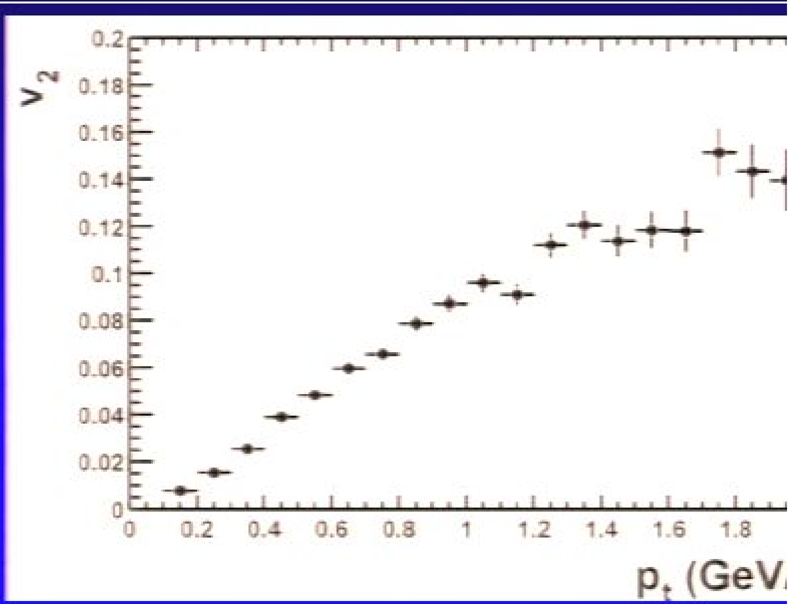

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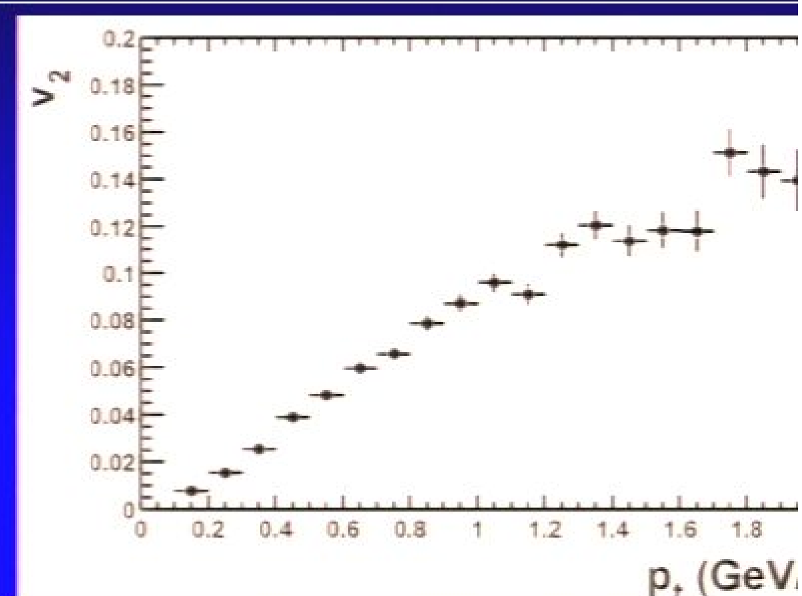

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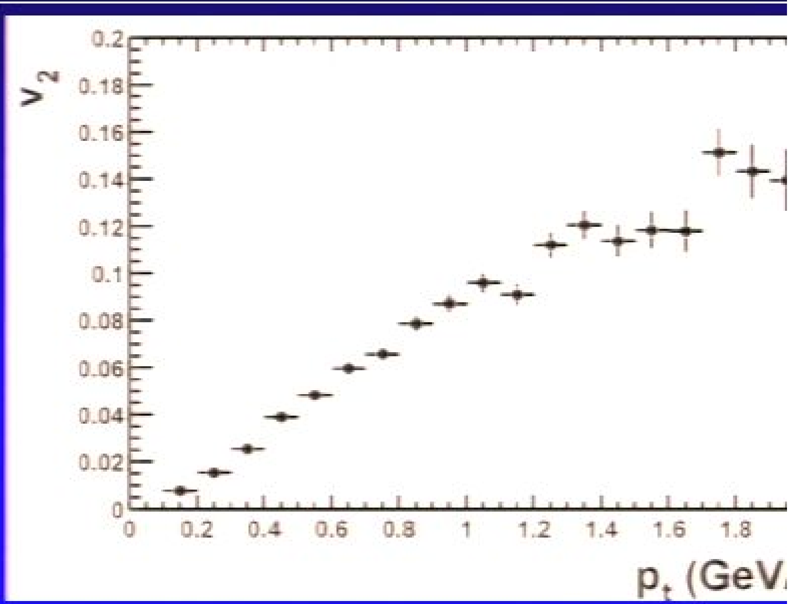

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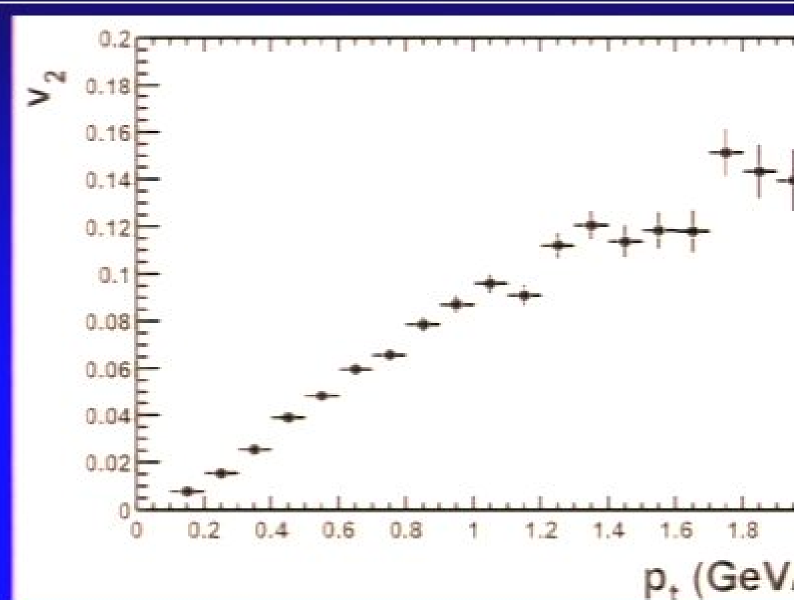

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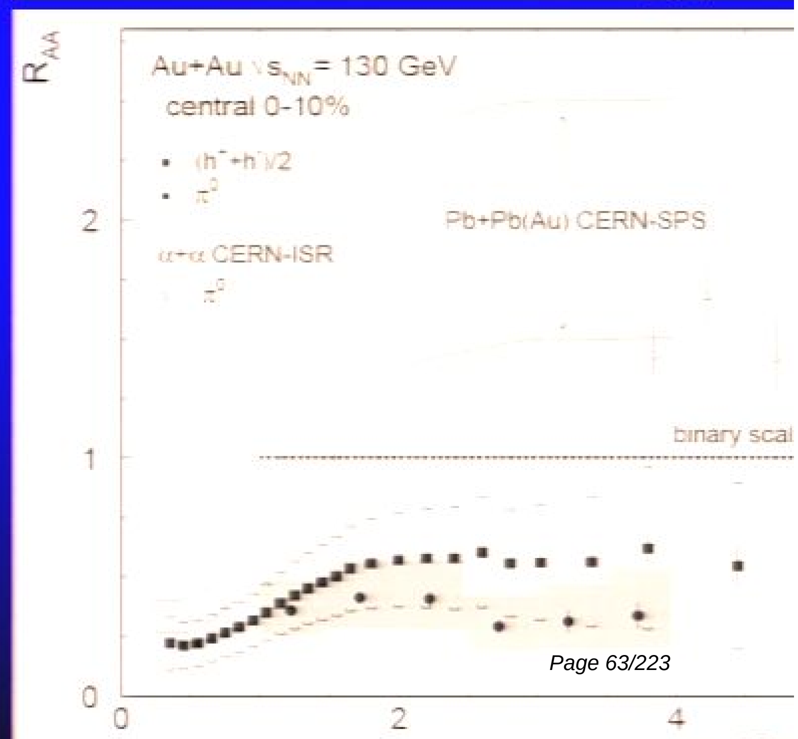

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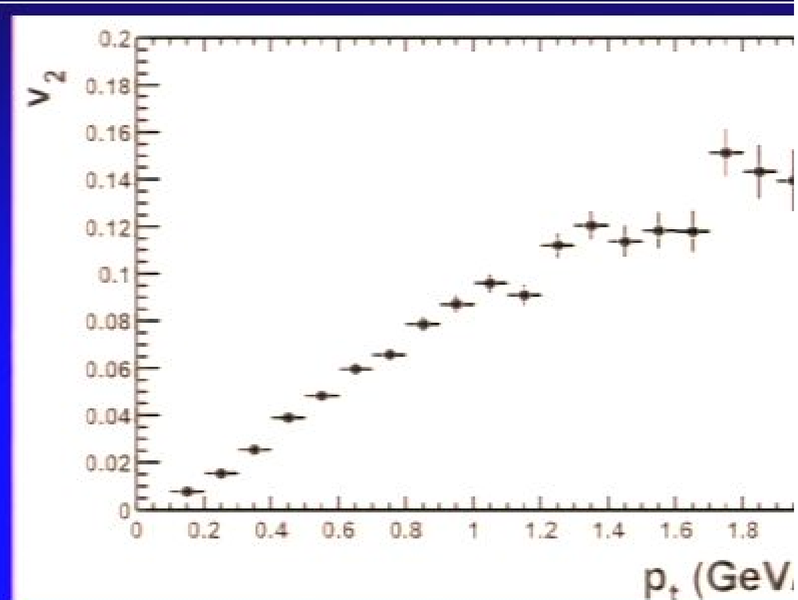

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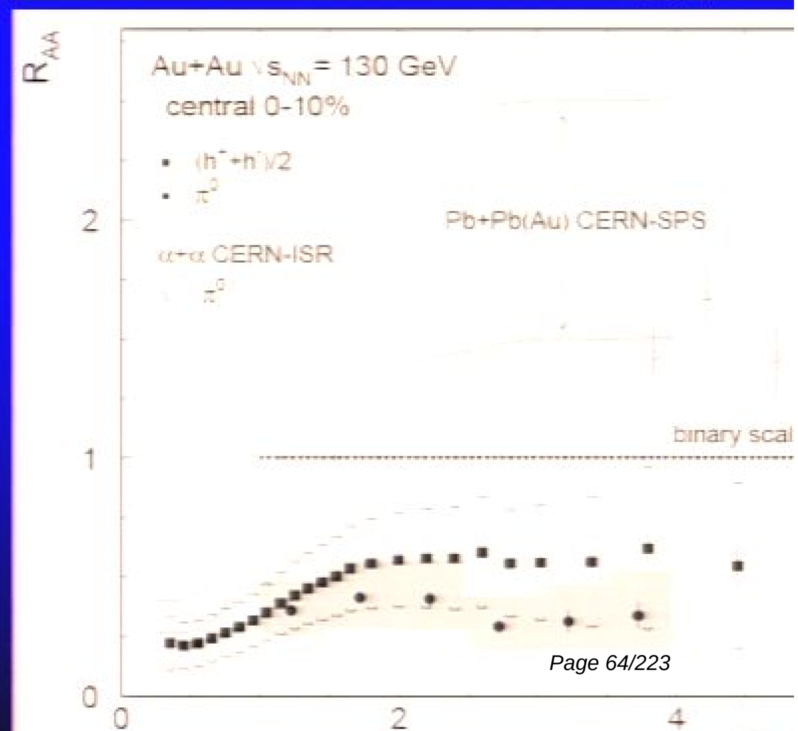

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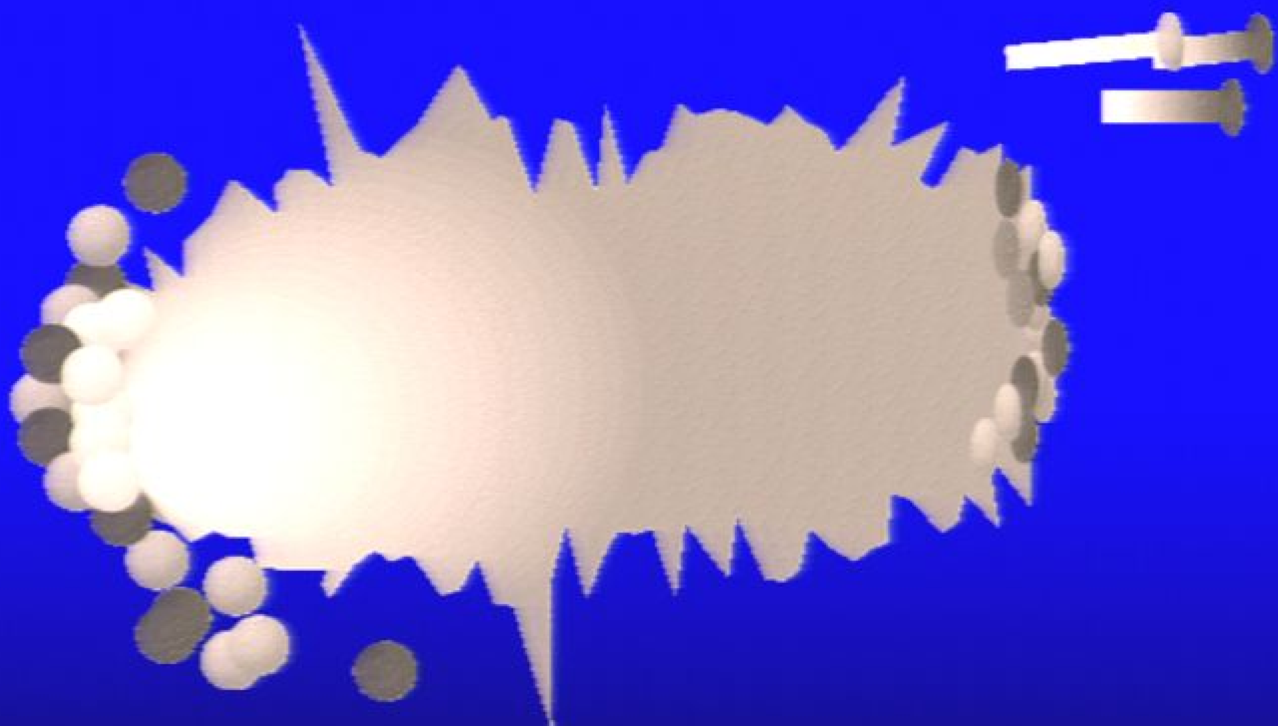

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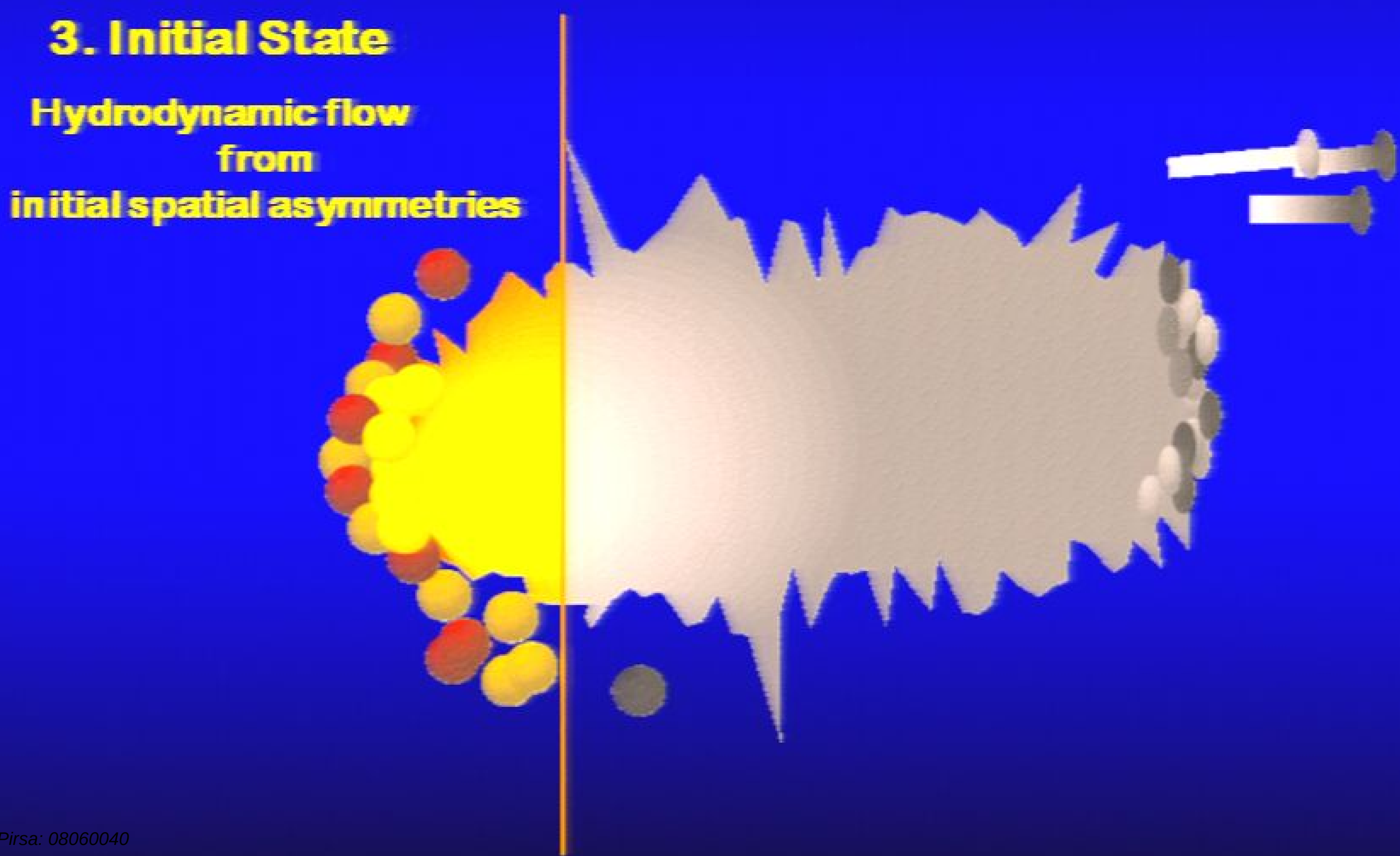

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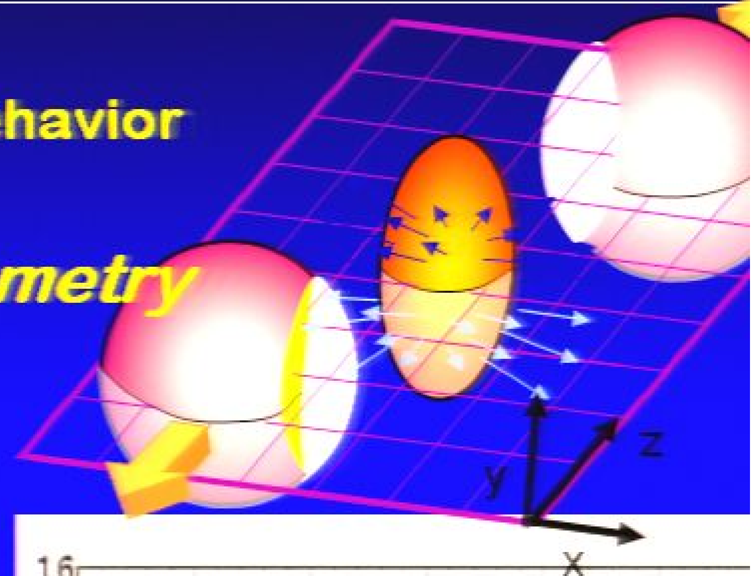

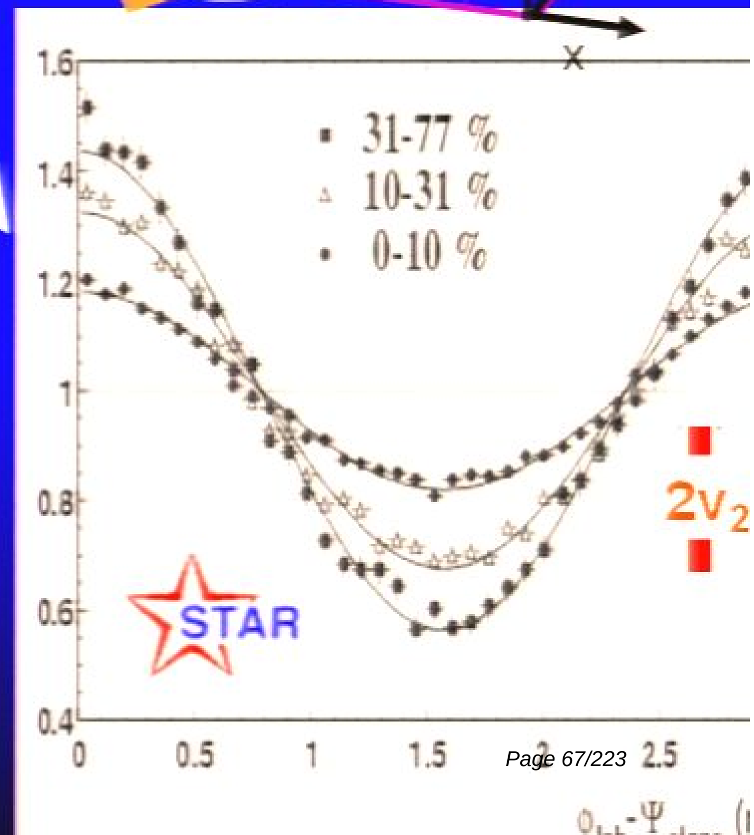

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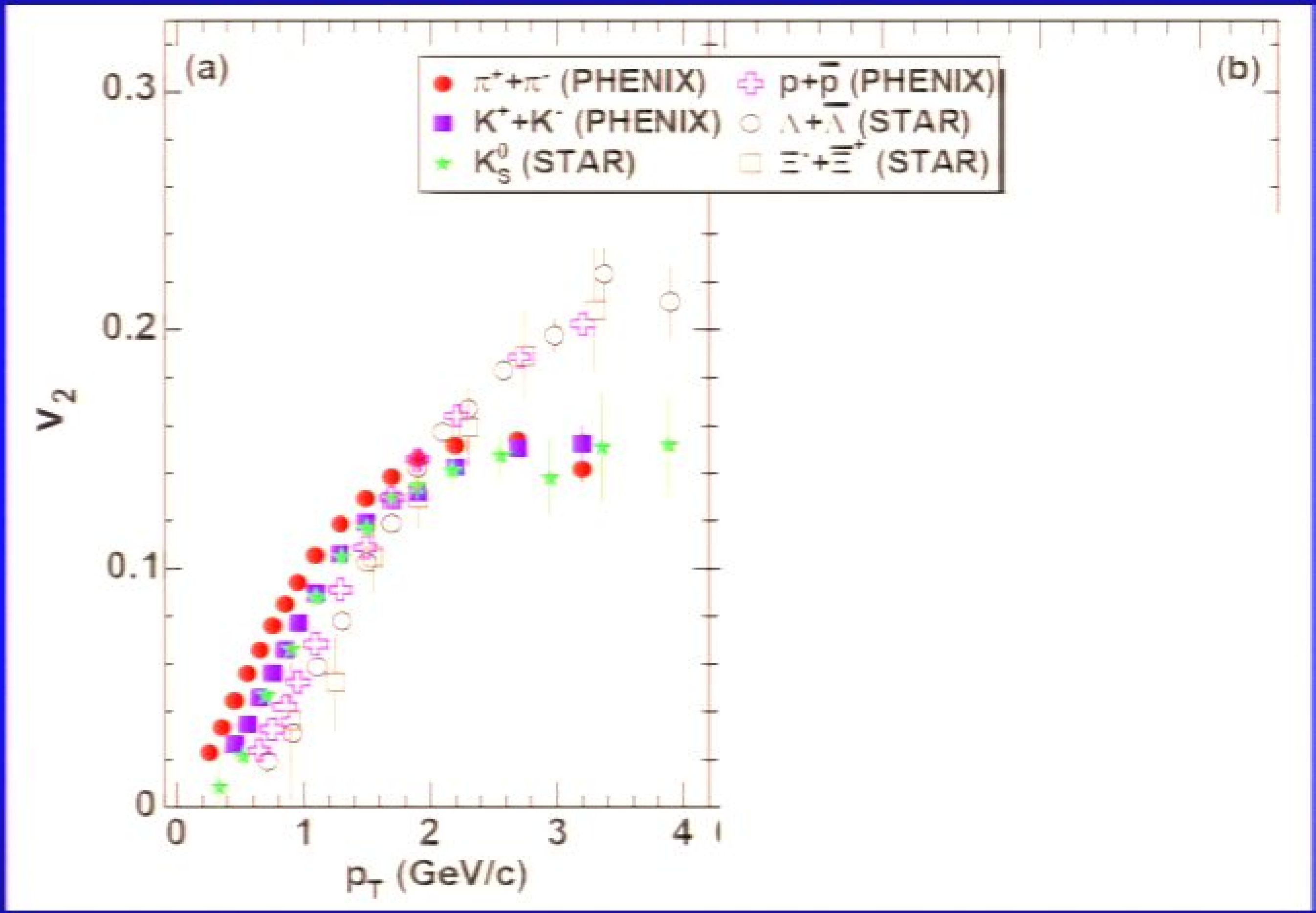

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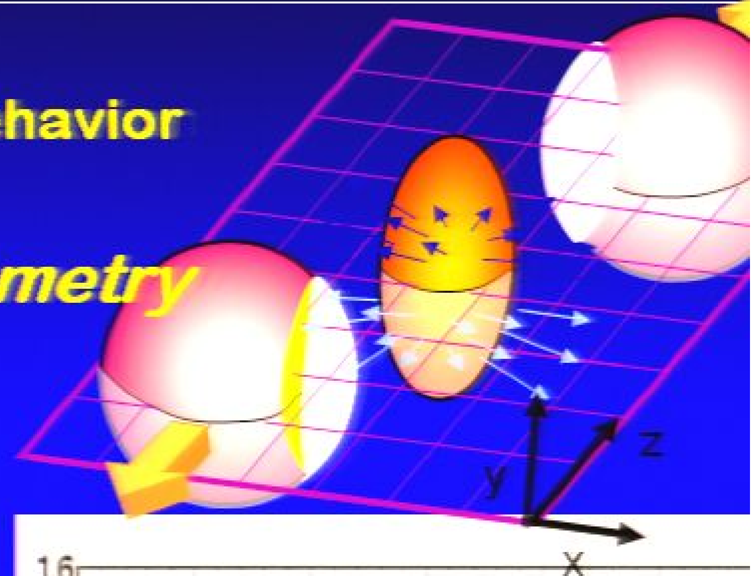

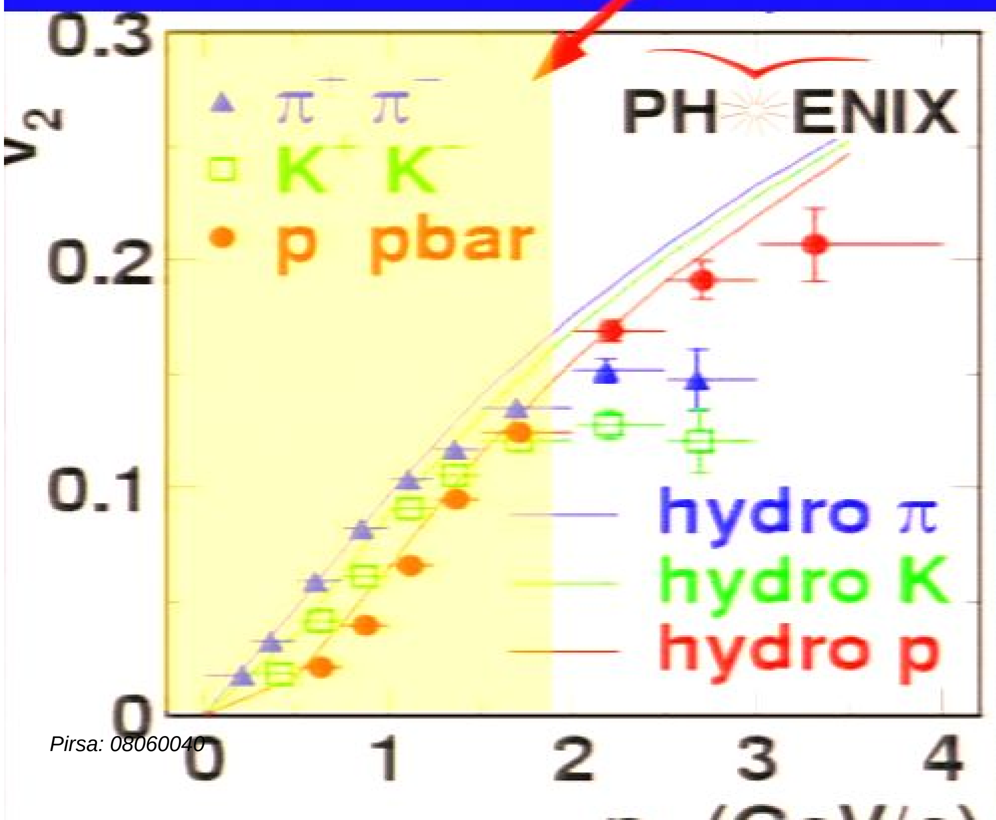

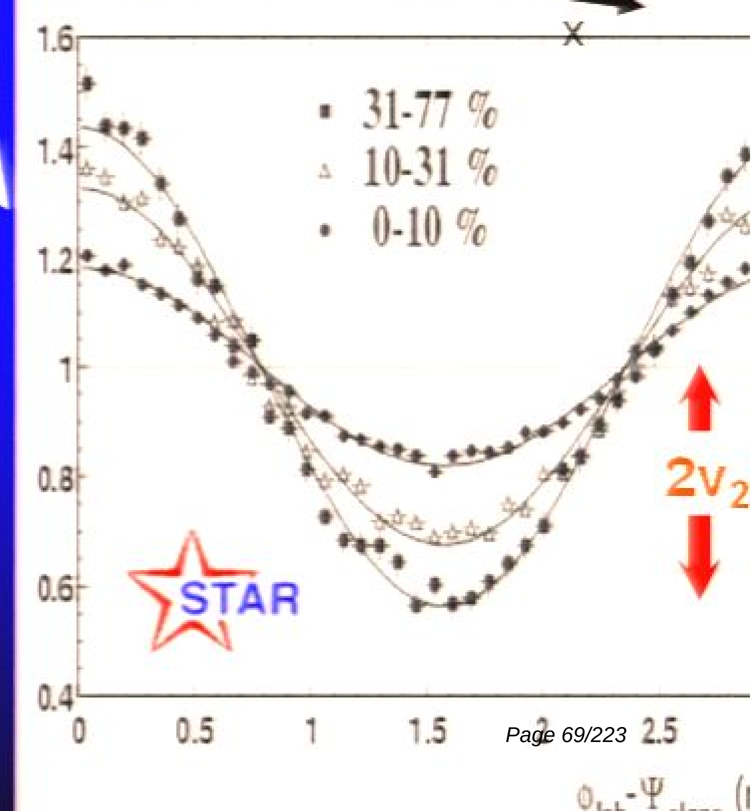

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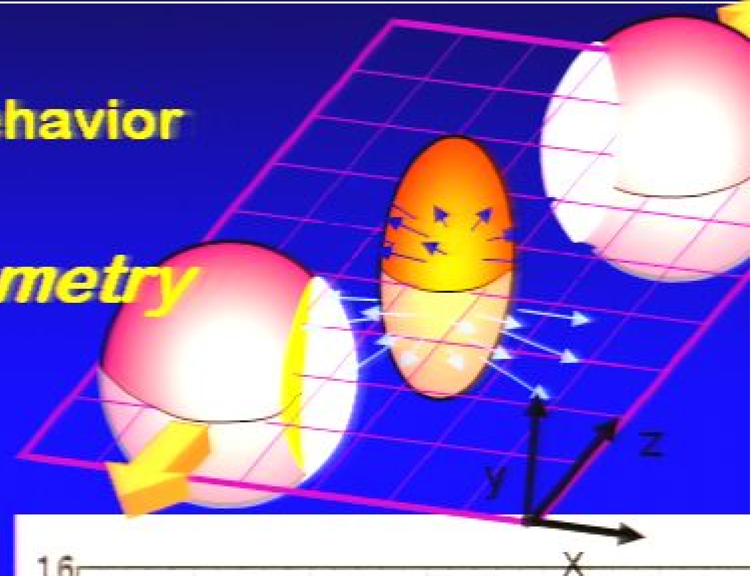

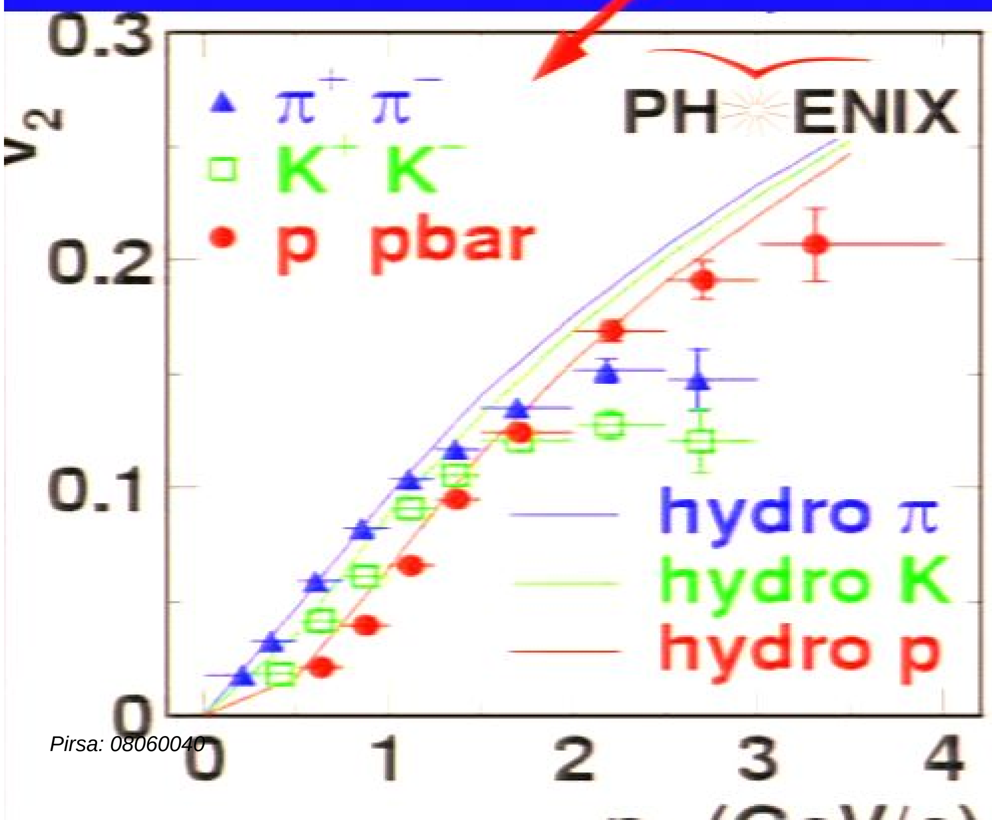

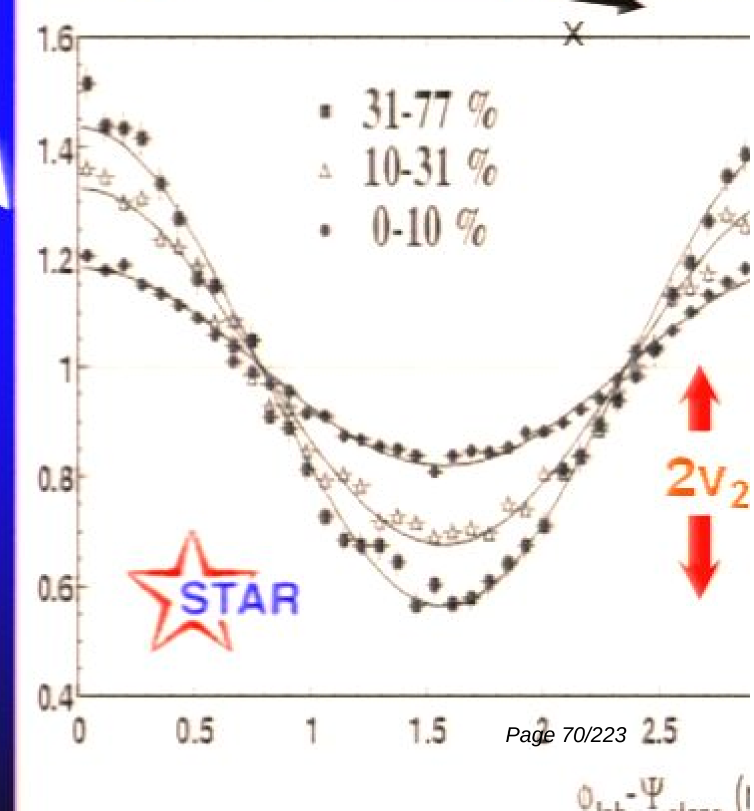

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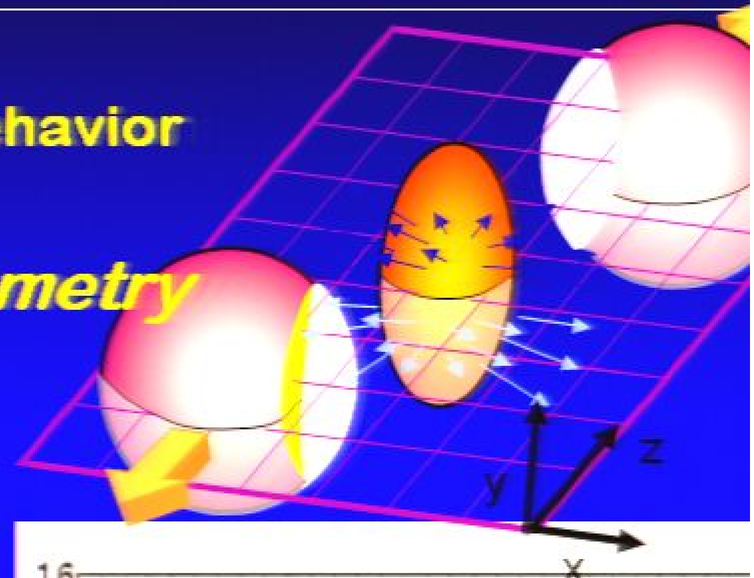

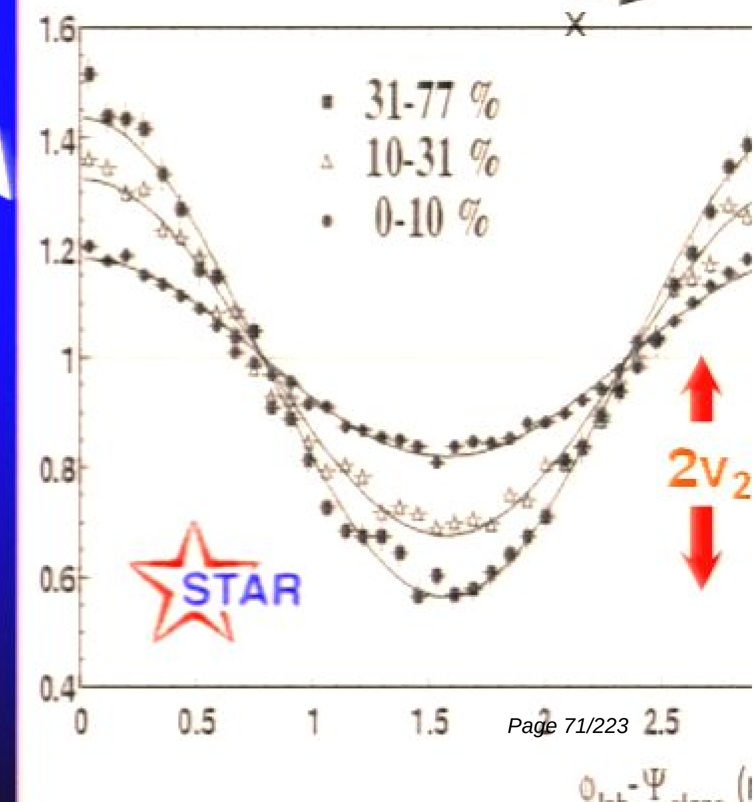

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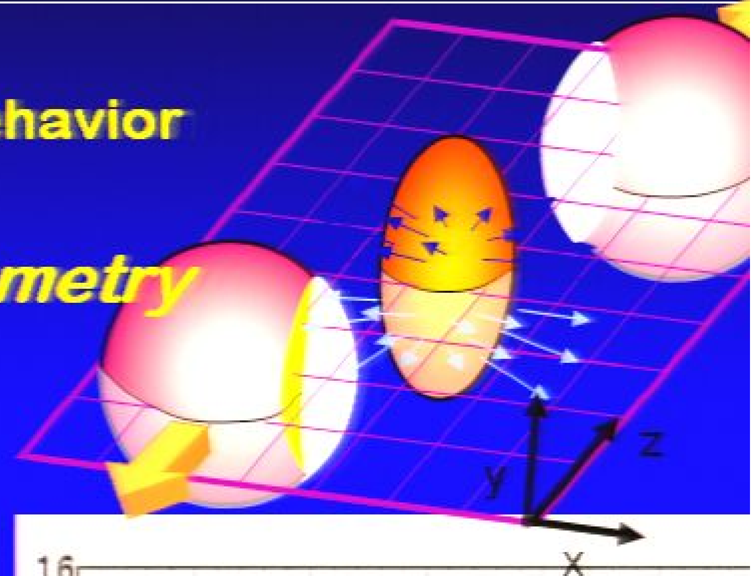

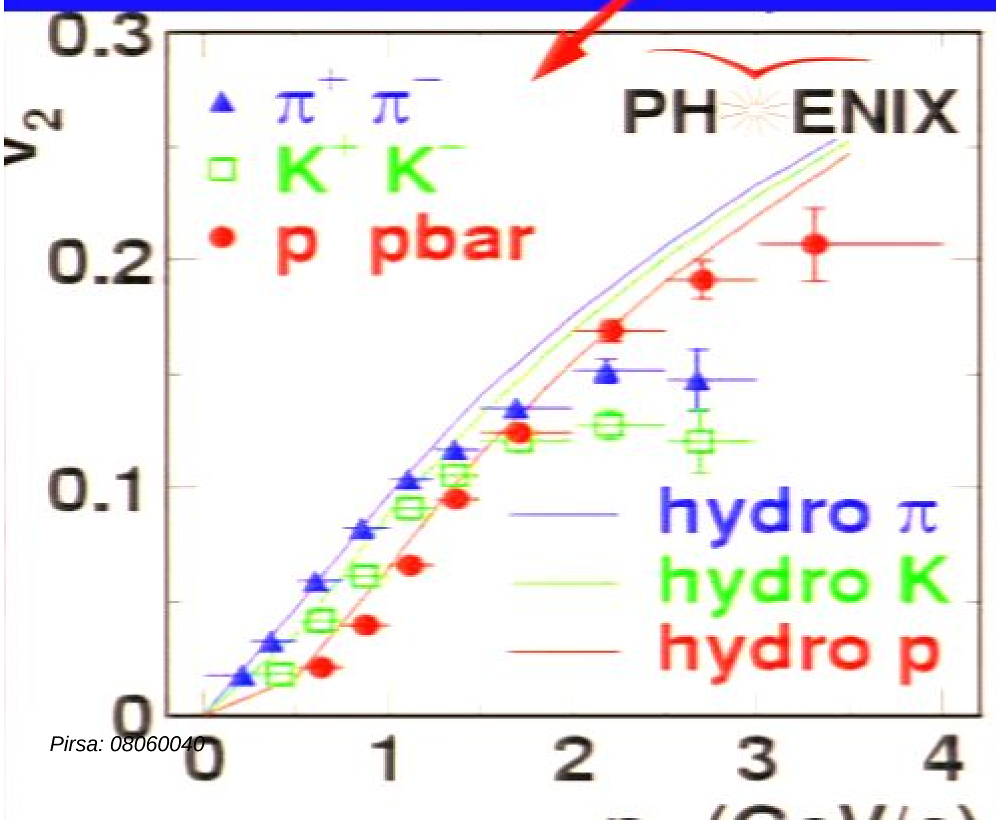

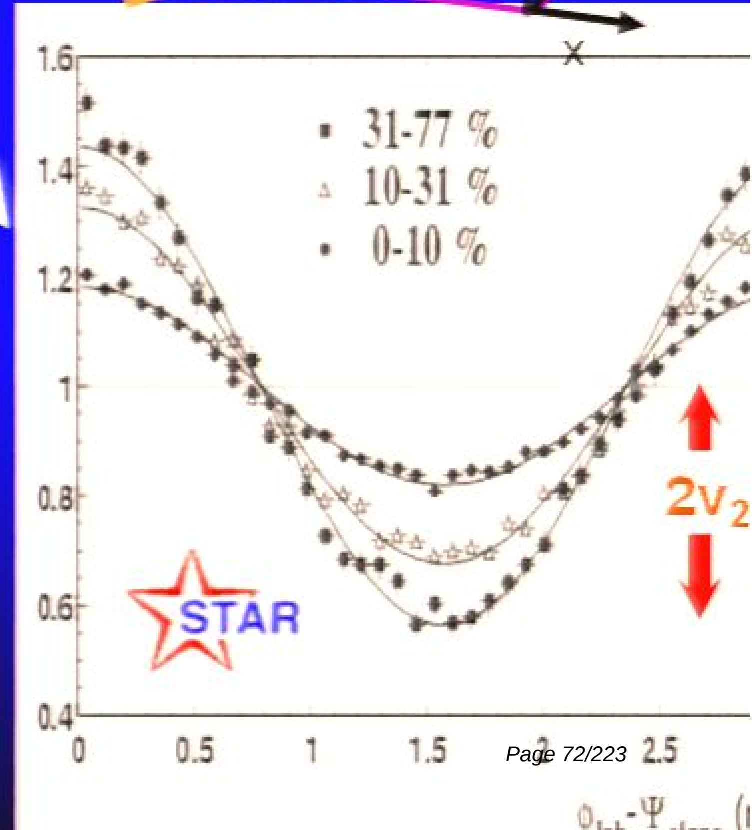

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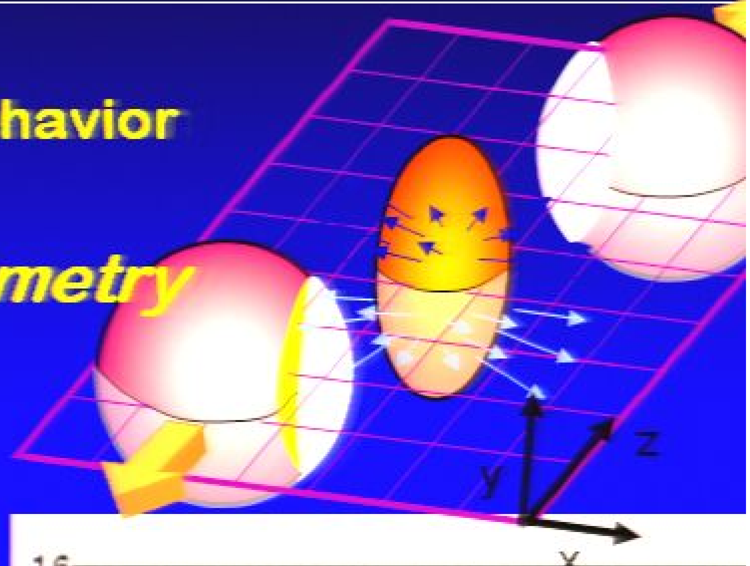

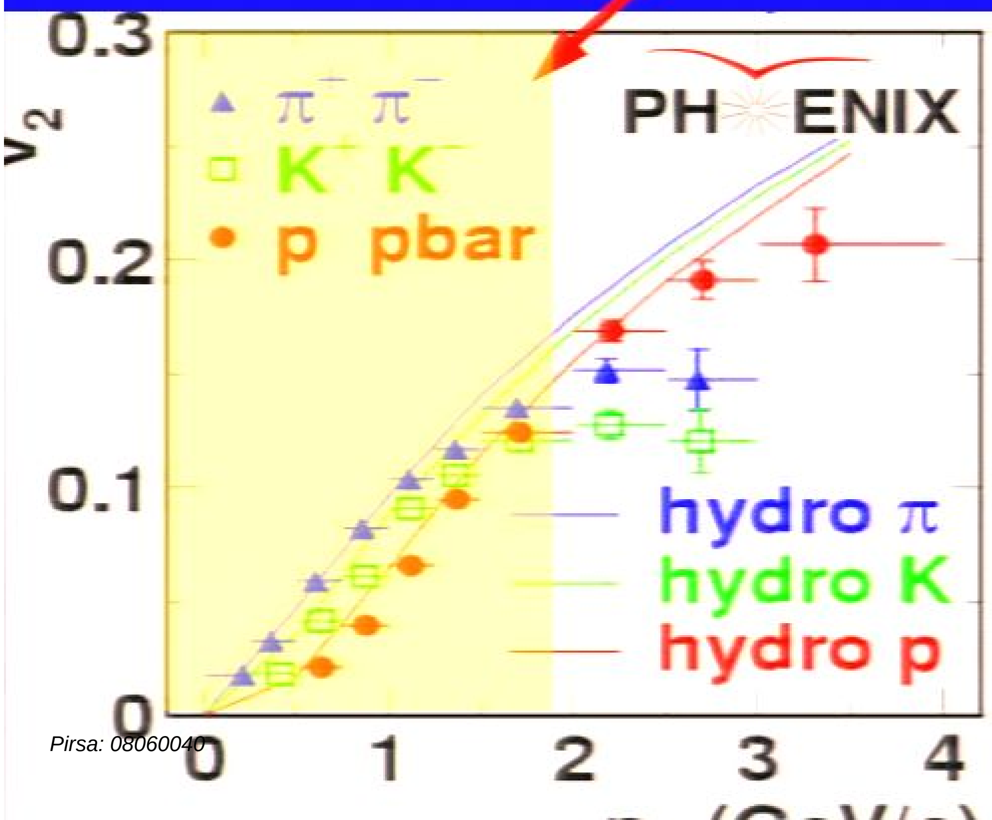

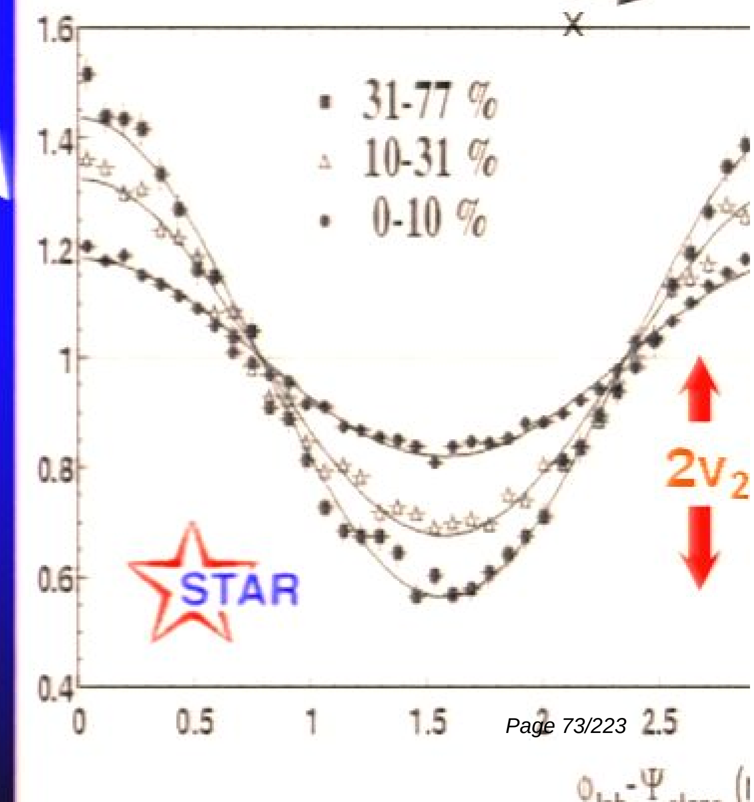

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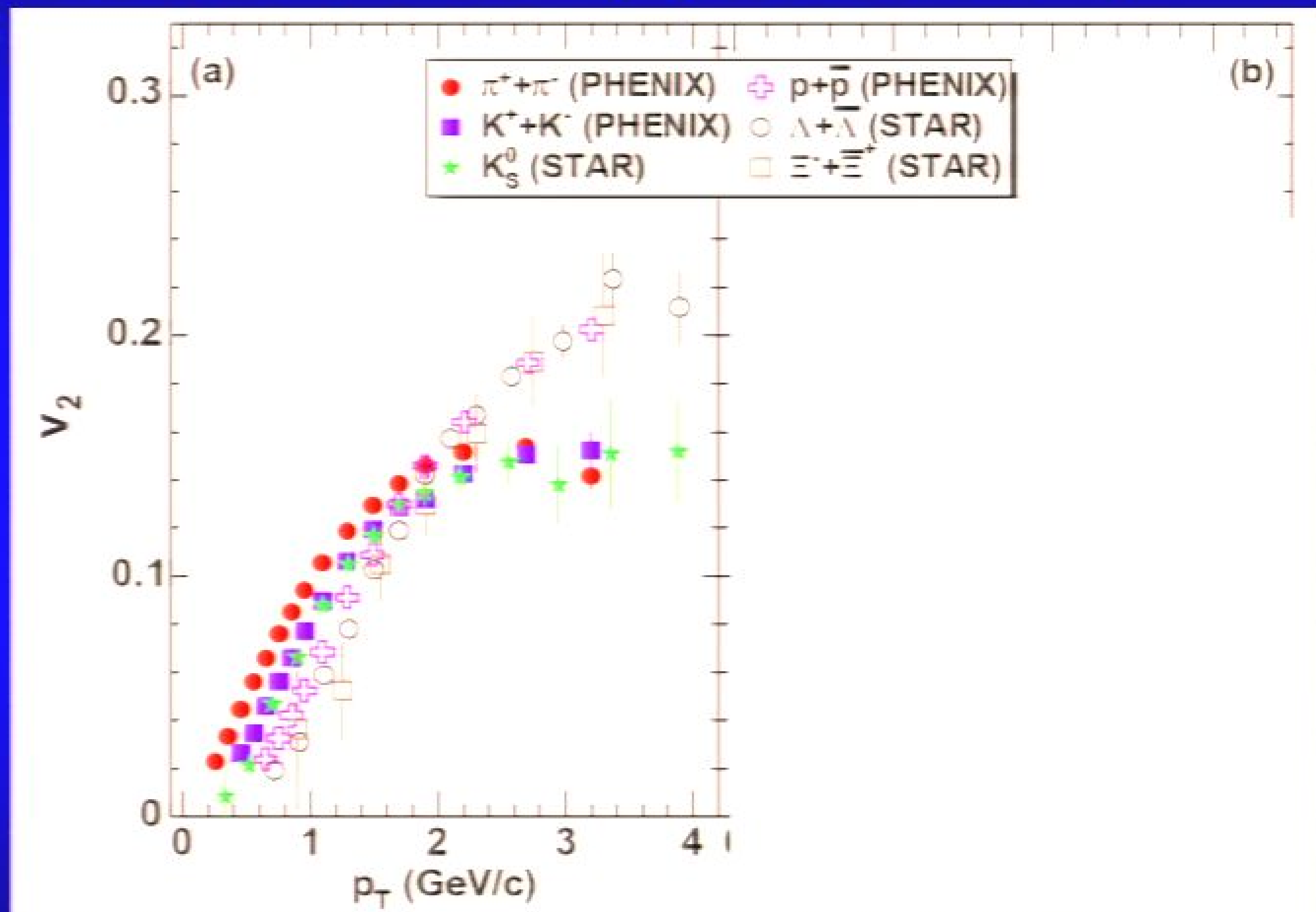

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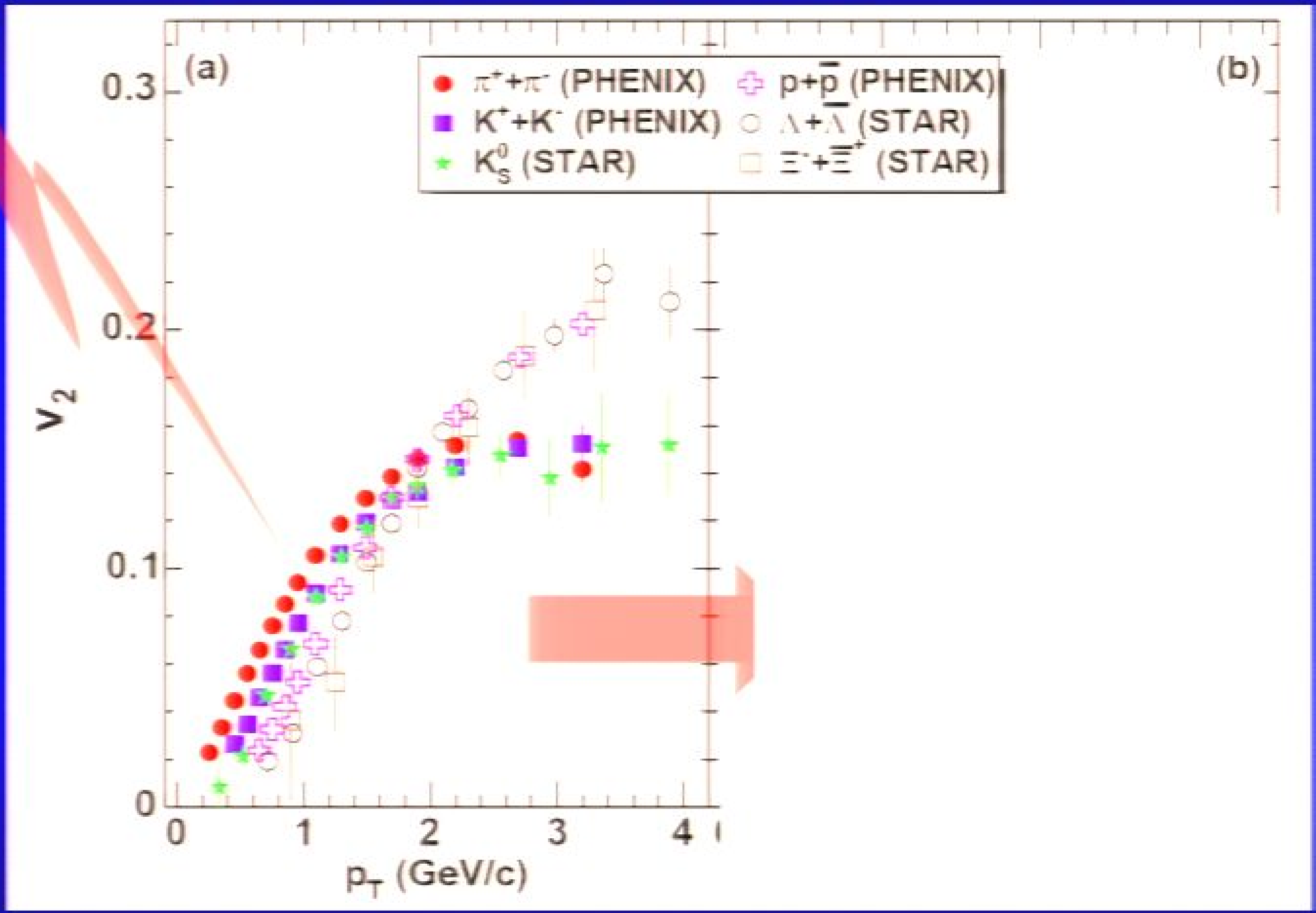

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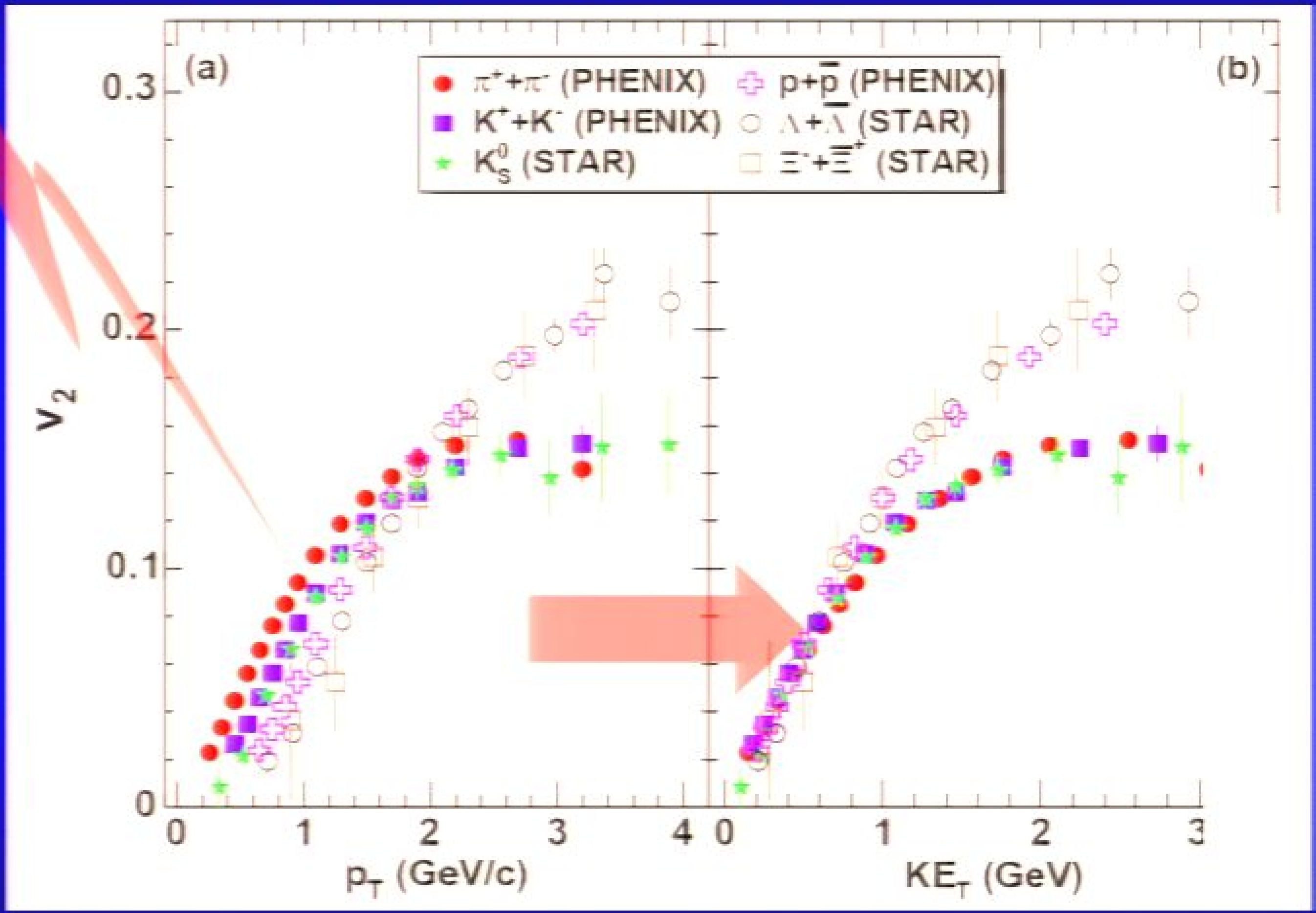

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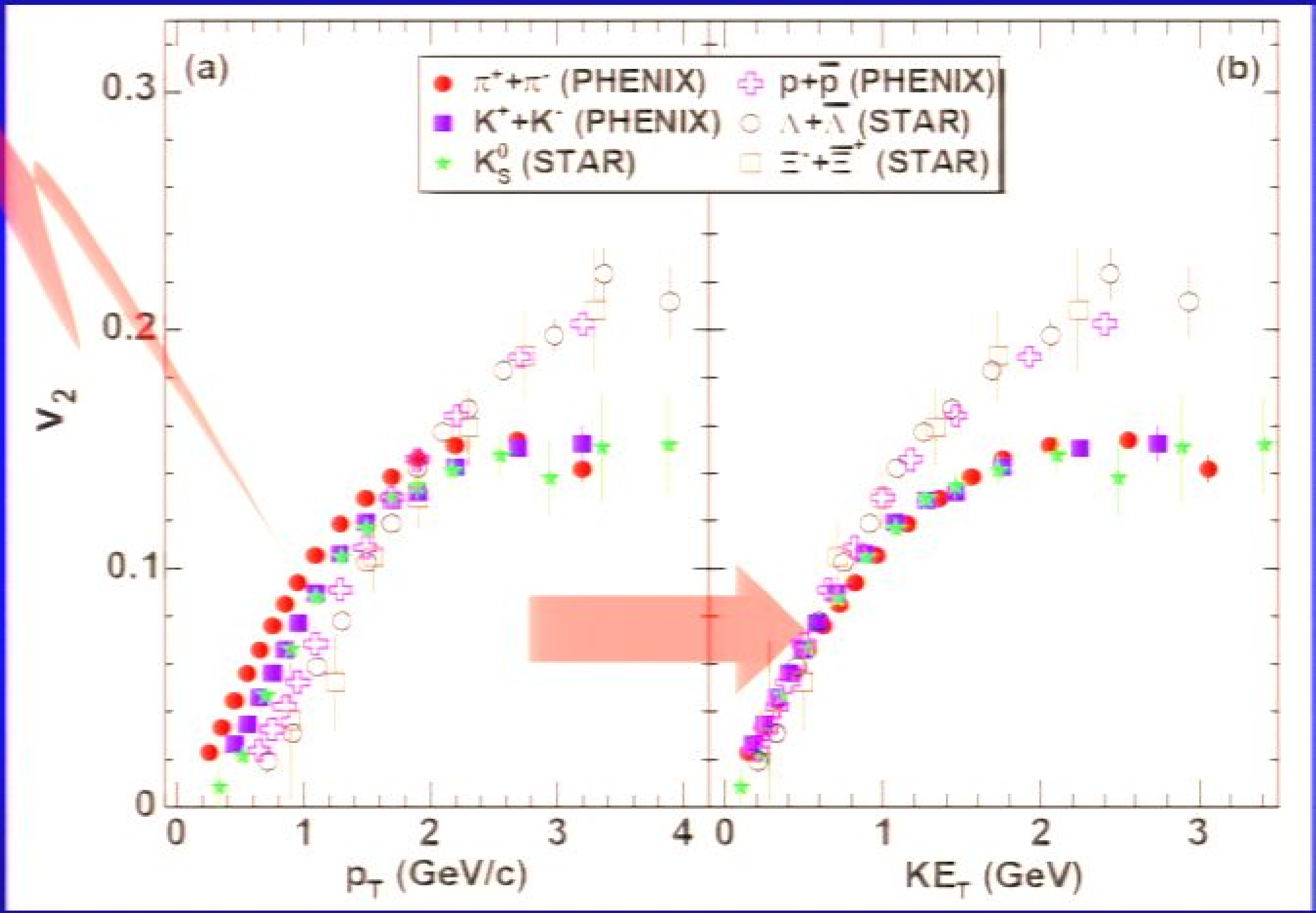

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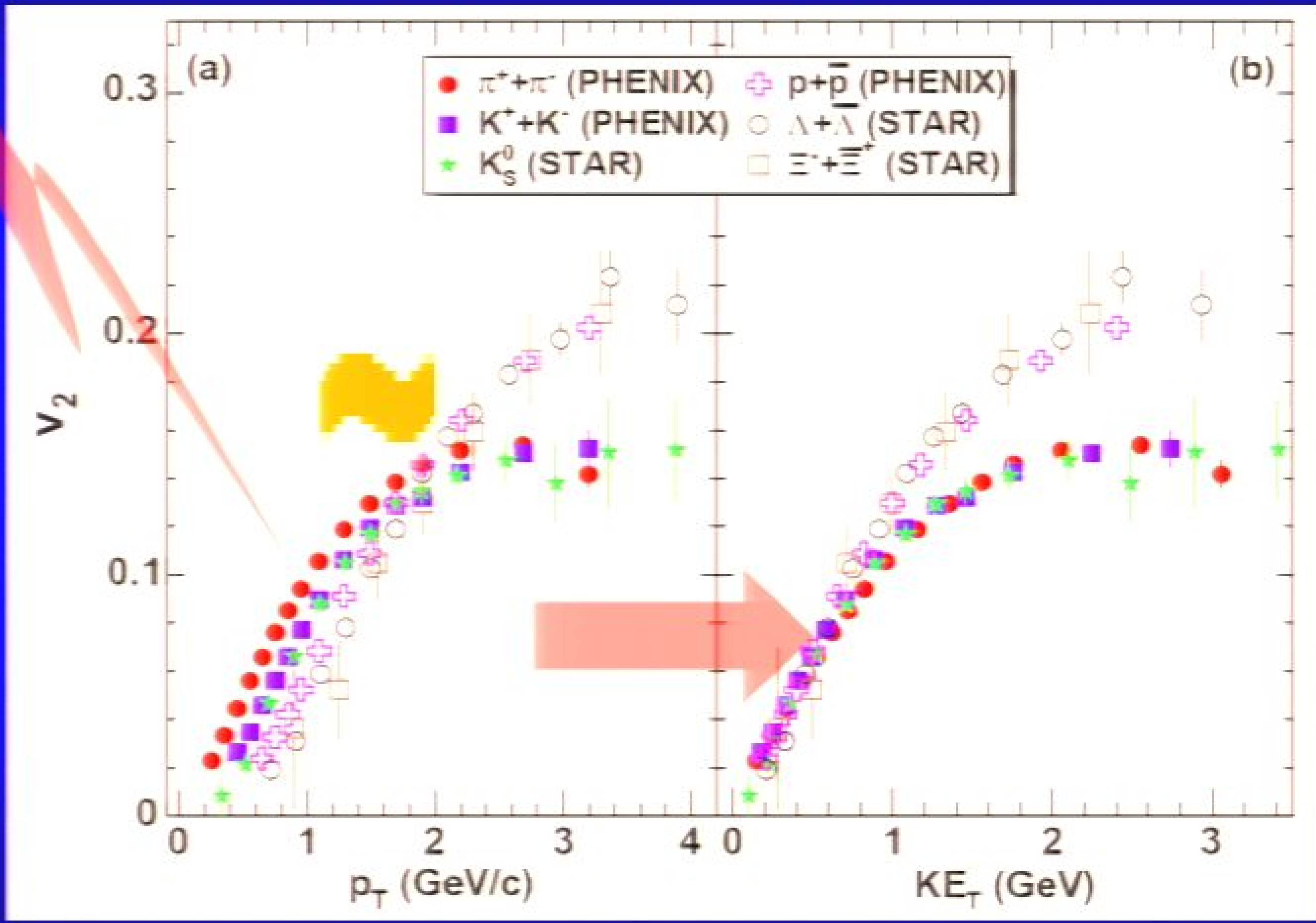

- Roughly: $\partial_\nu T^{\mu\nu} = 0 \rightarrow$ Work-energy theorem

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

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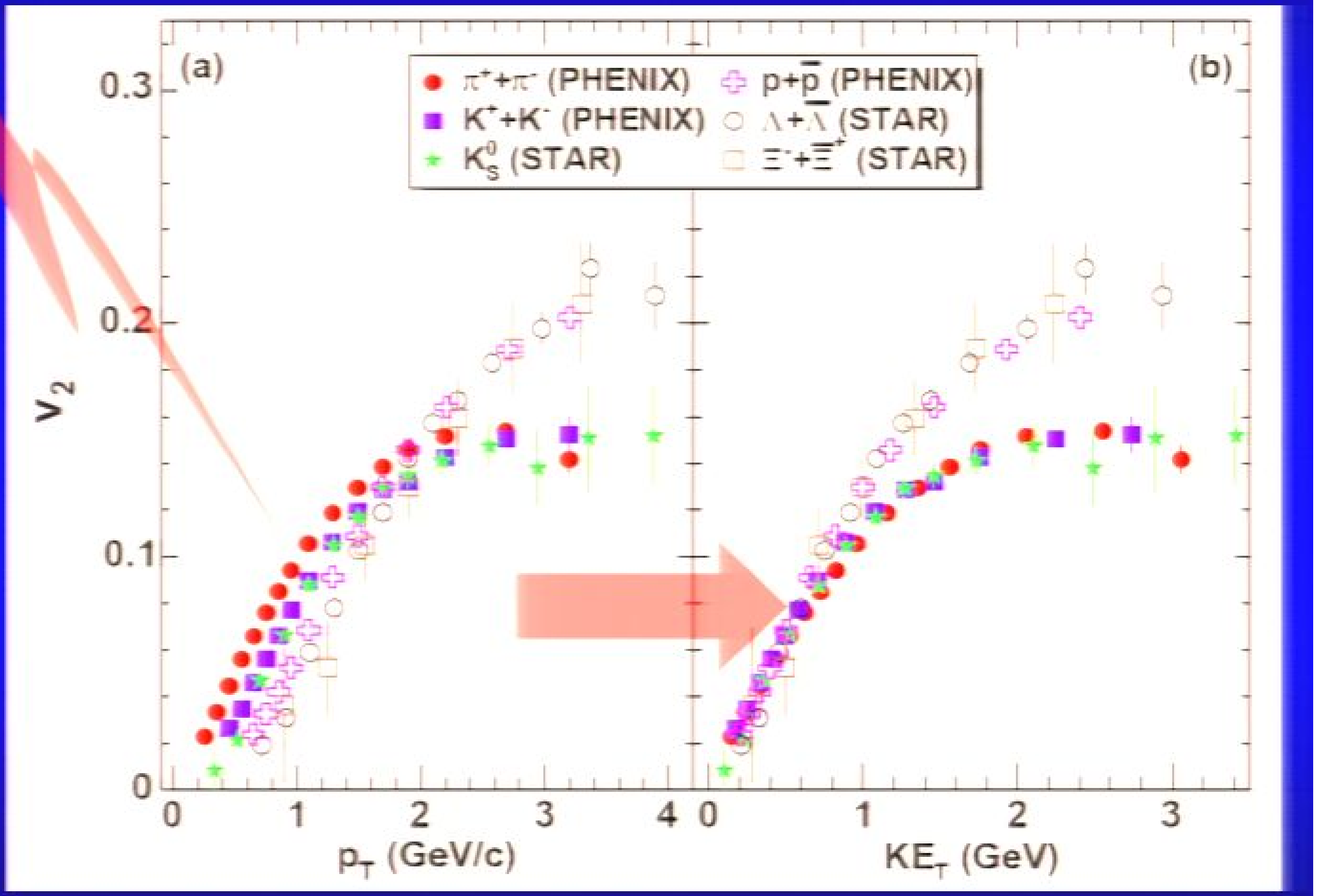

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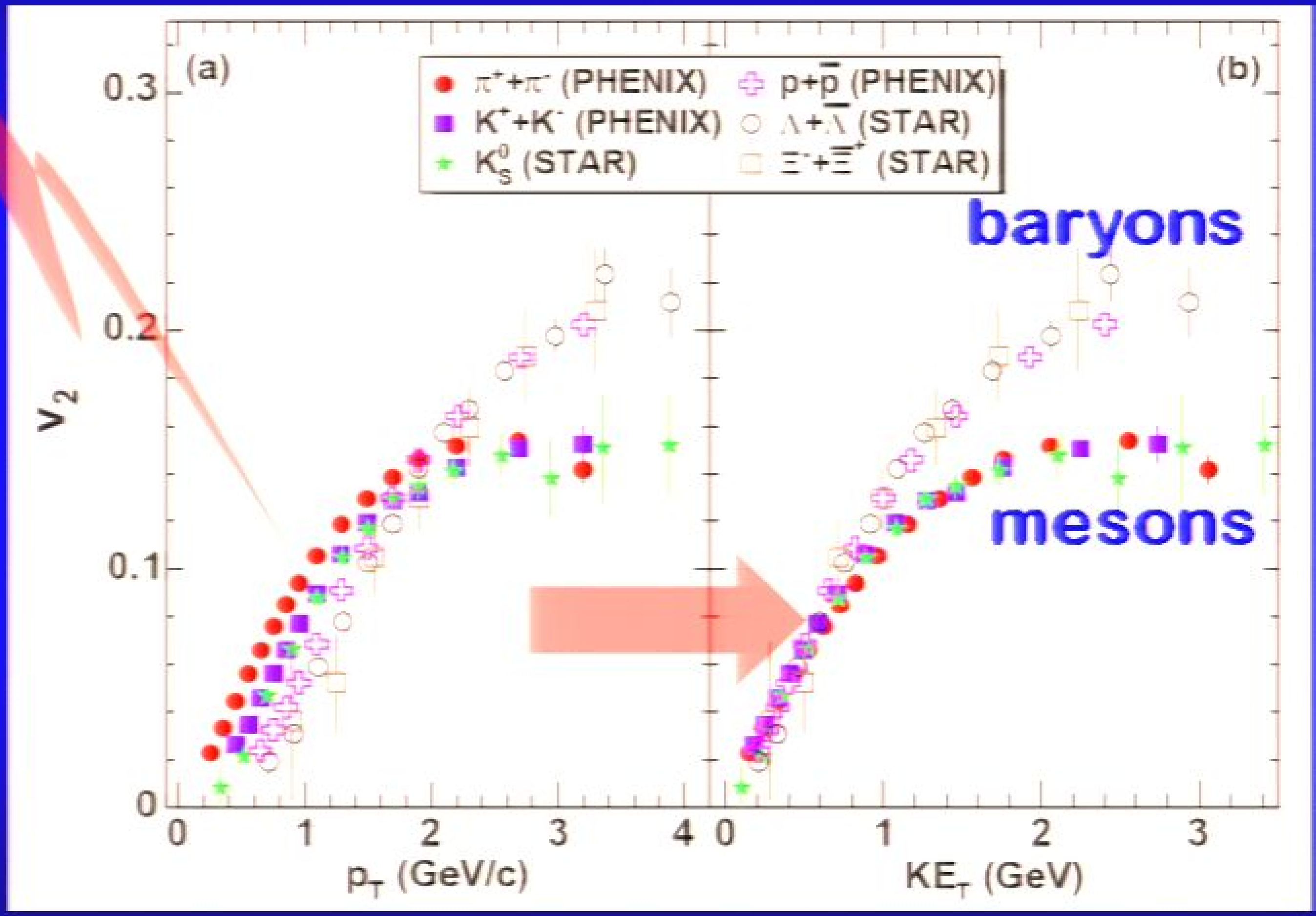

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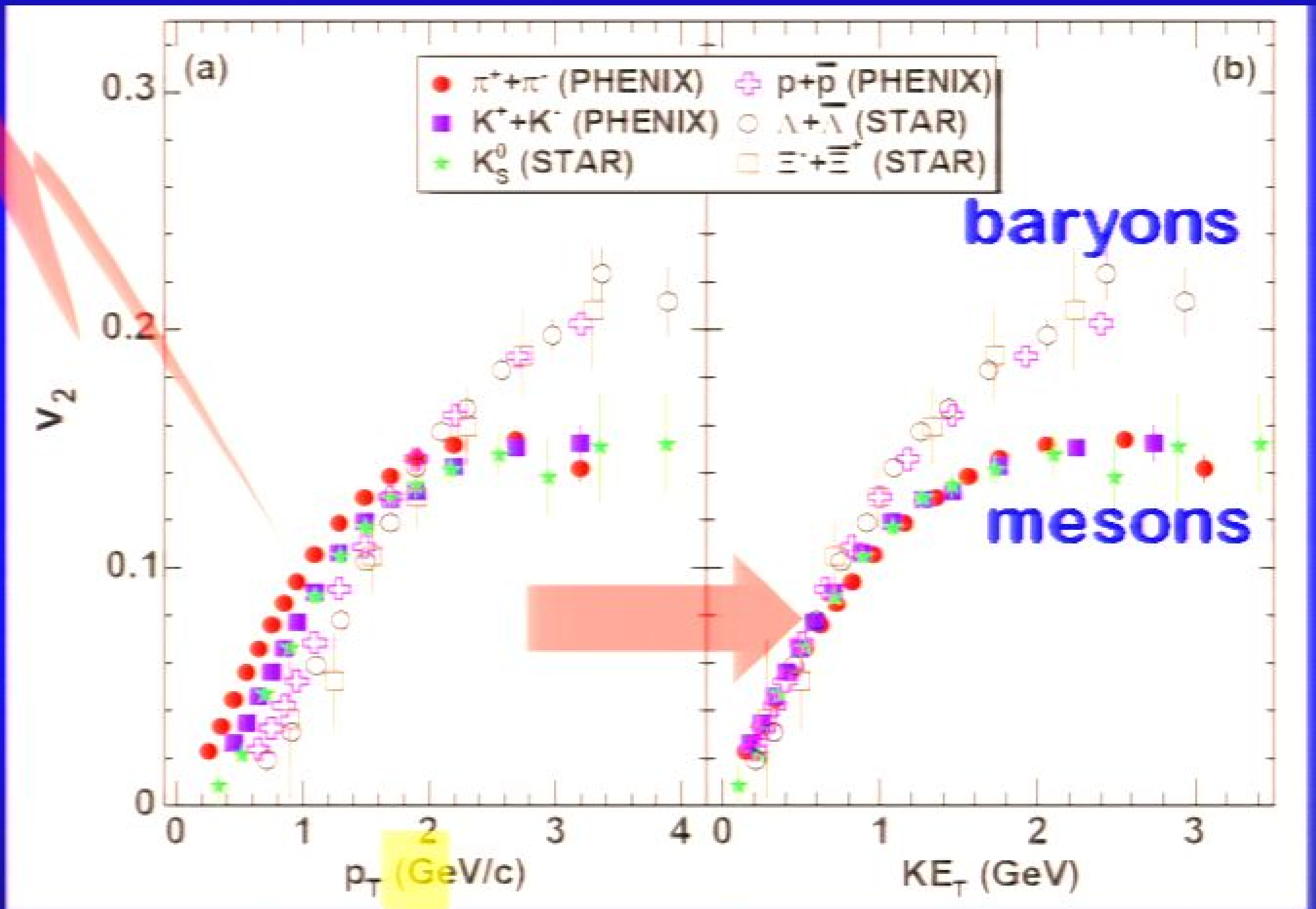

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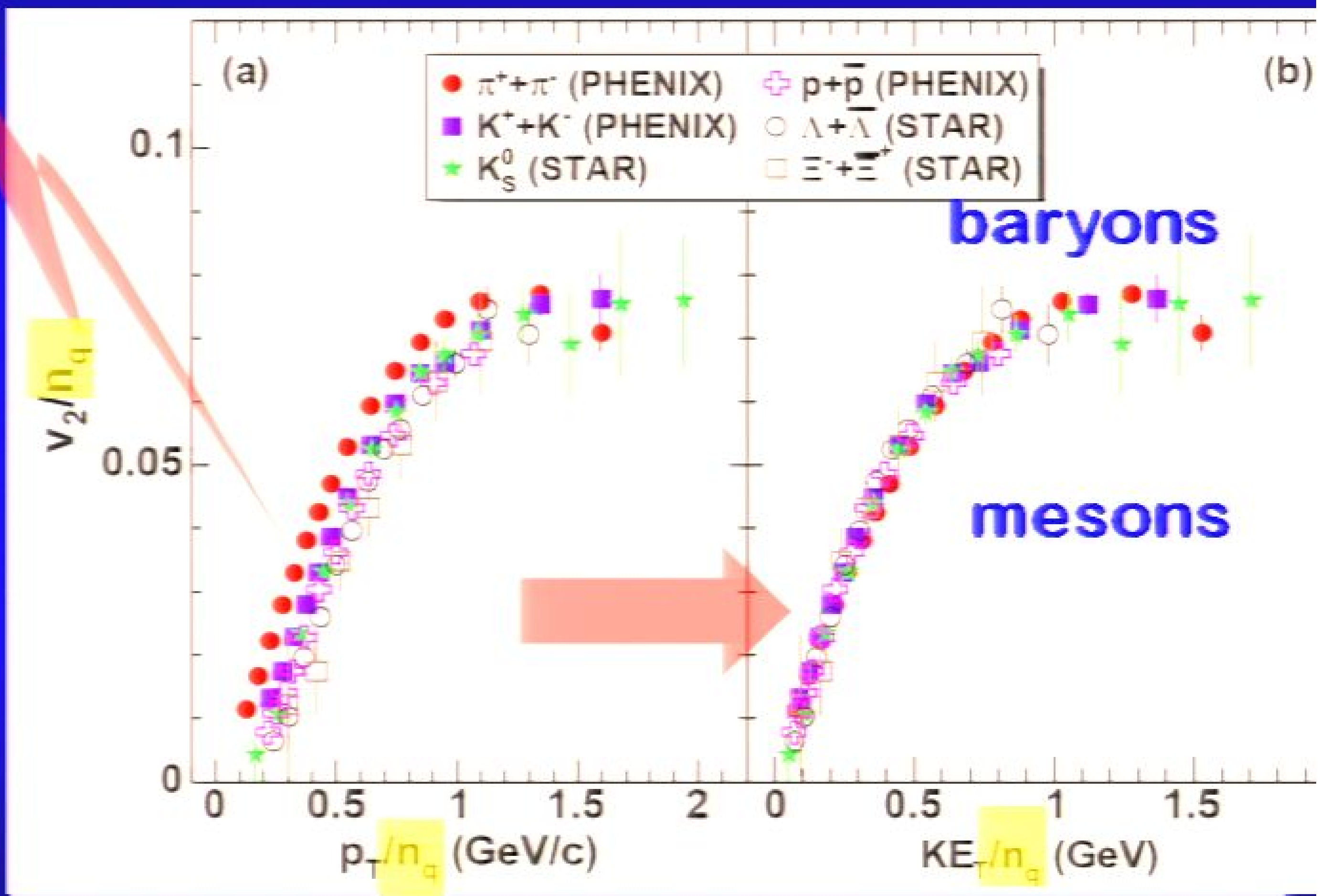

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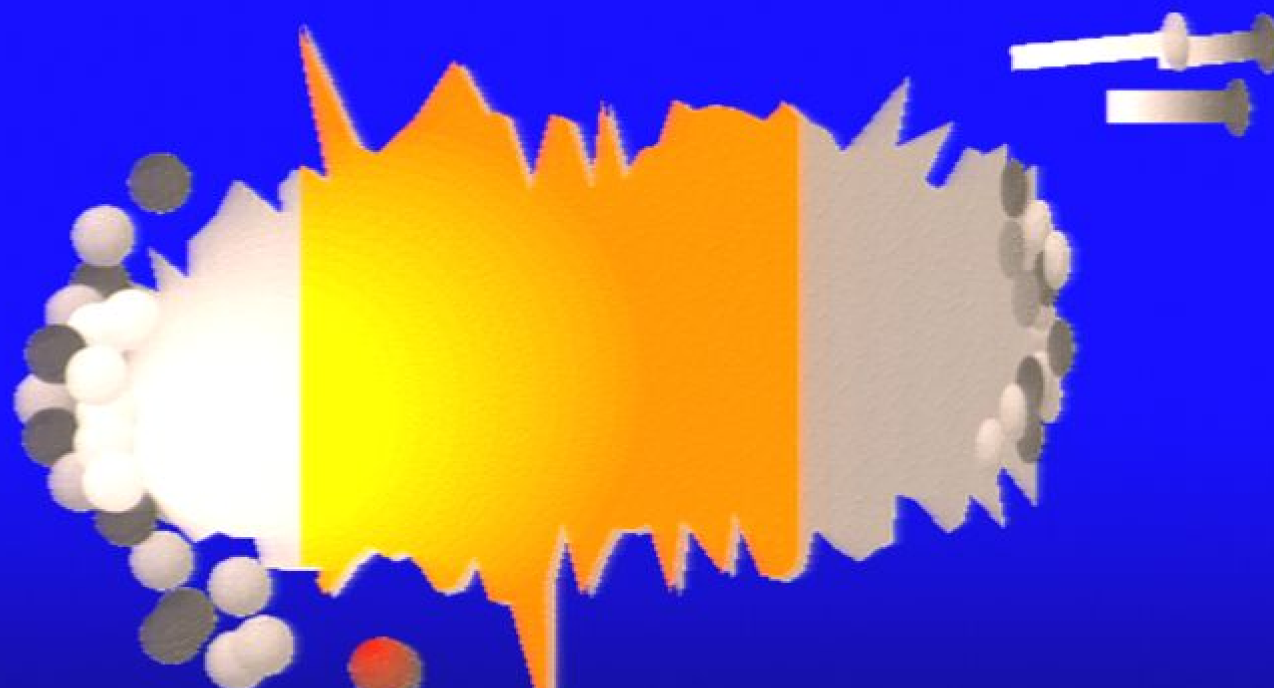
Probes of Dense Matter

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 π^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

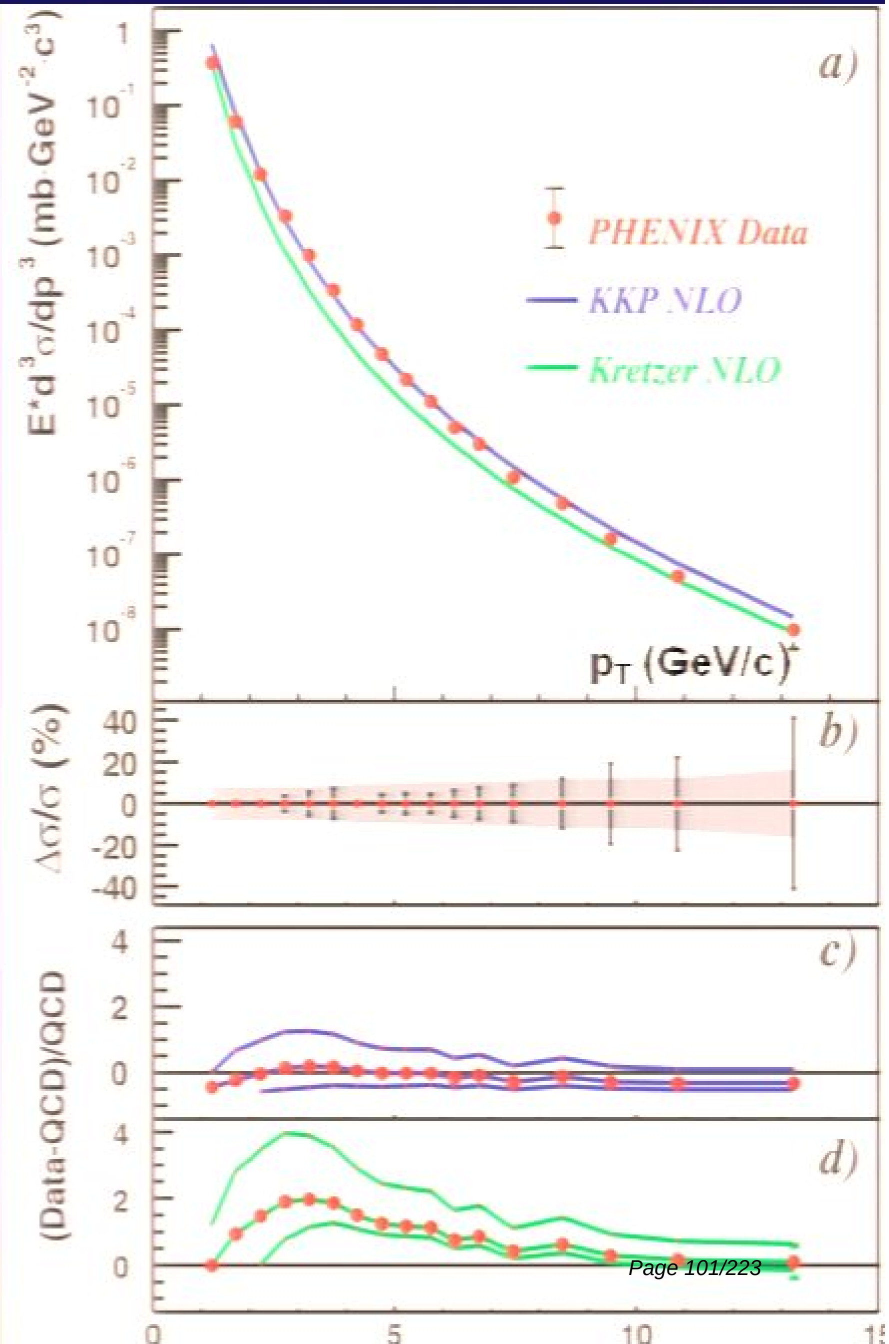
$$\otimes\, d\hat{\sigma}(a+b\rightarrow c+d)$$

•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-

- Phys. Rev. Lett. 91, 241803 (2003)



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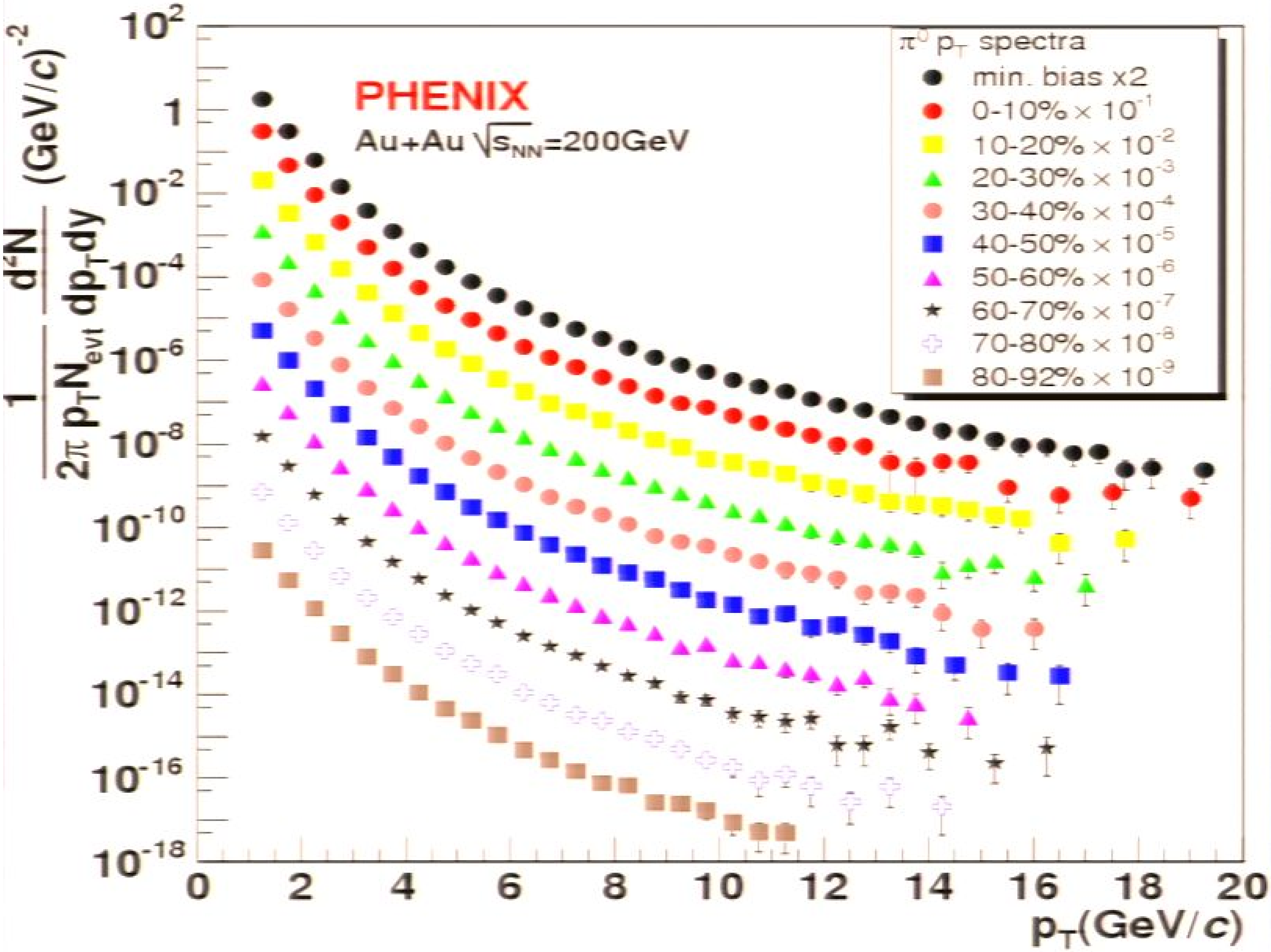

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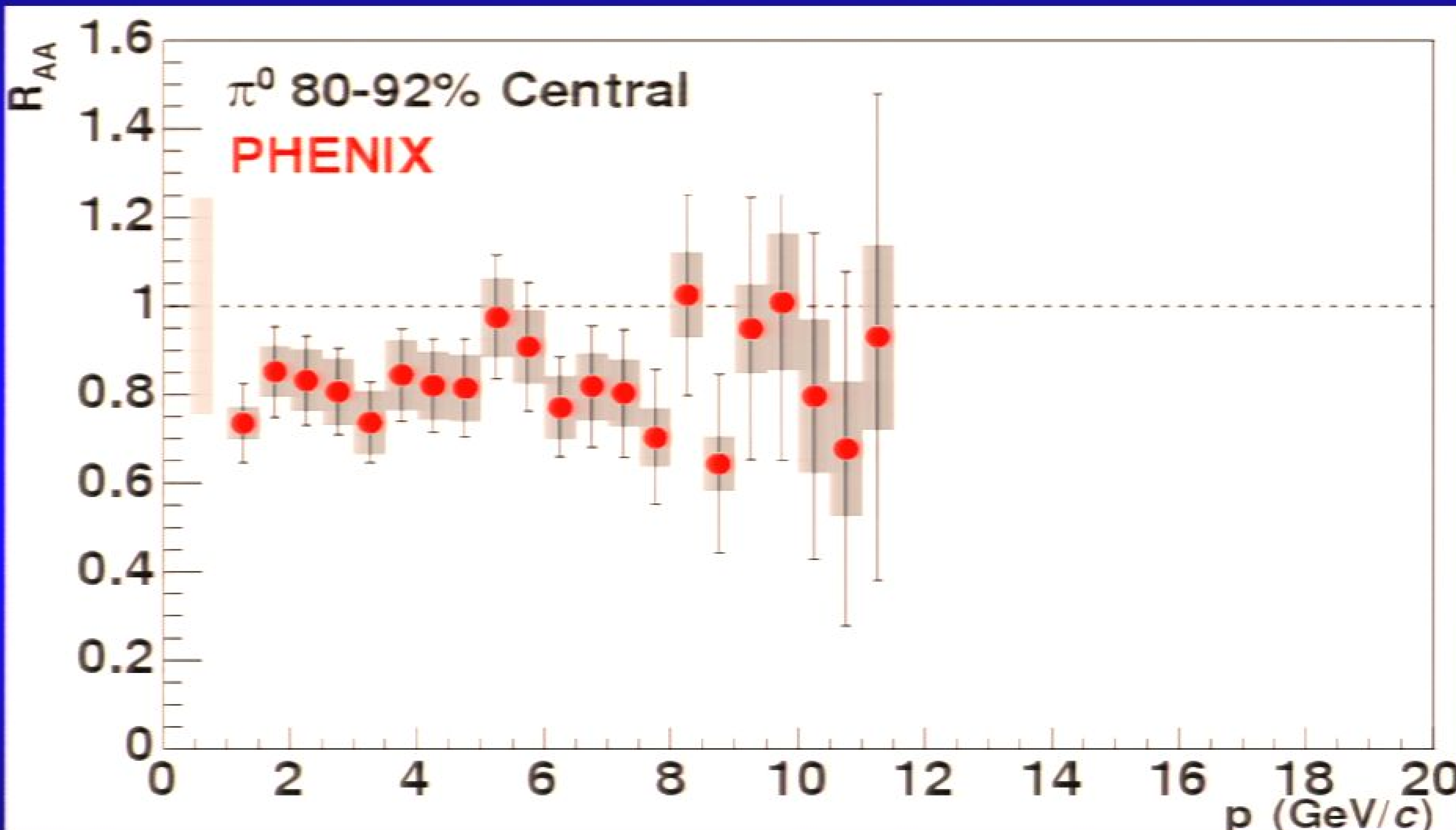

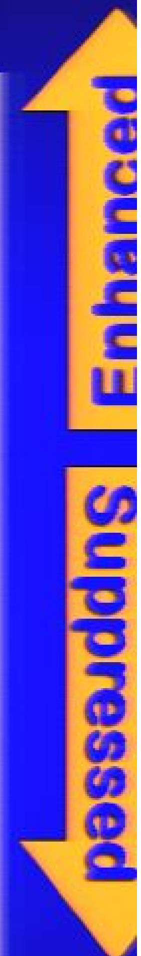

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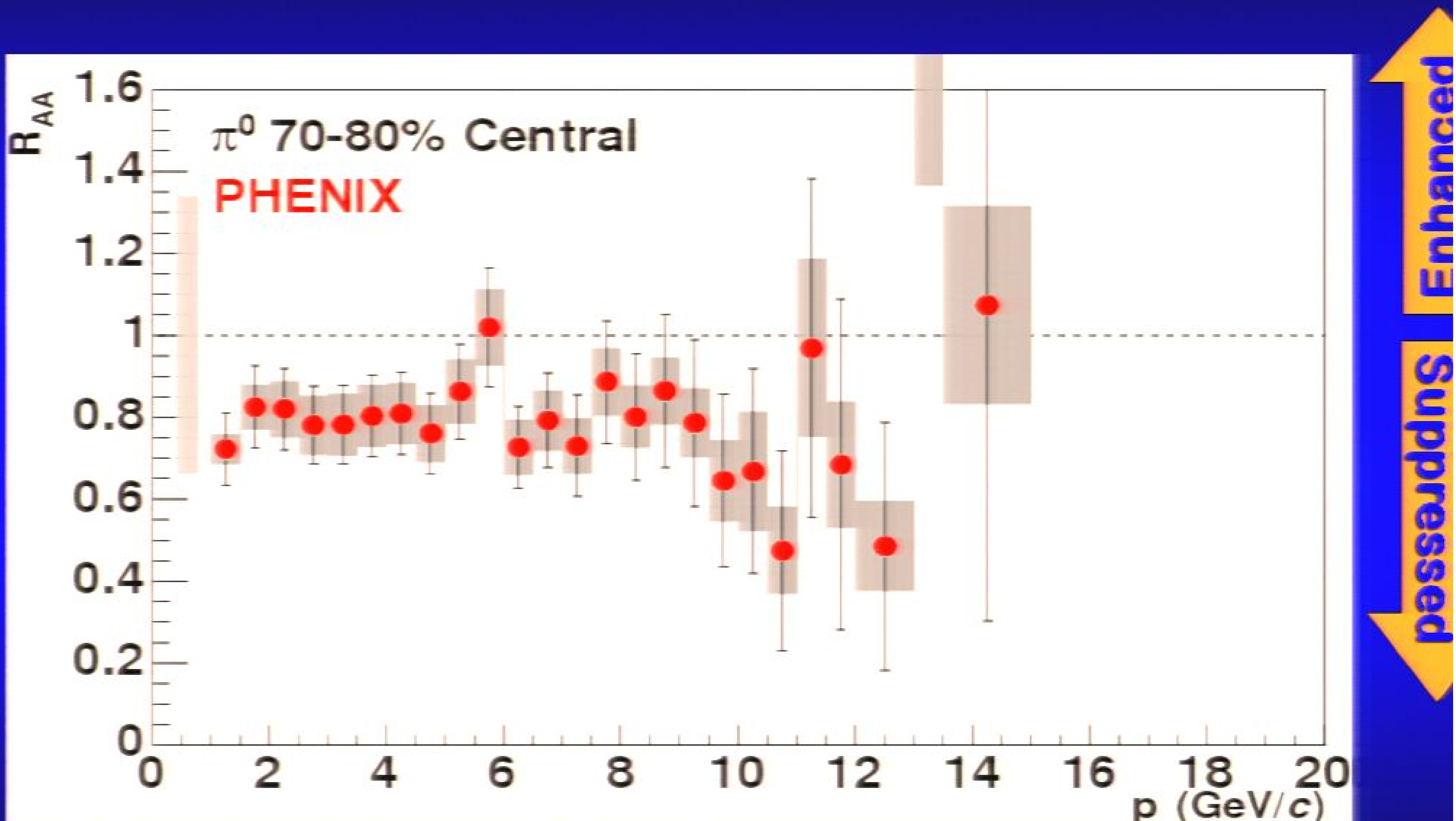

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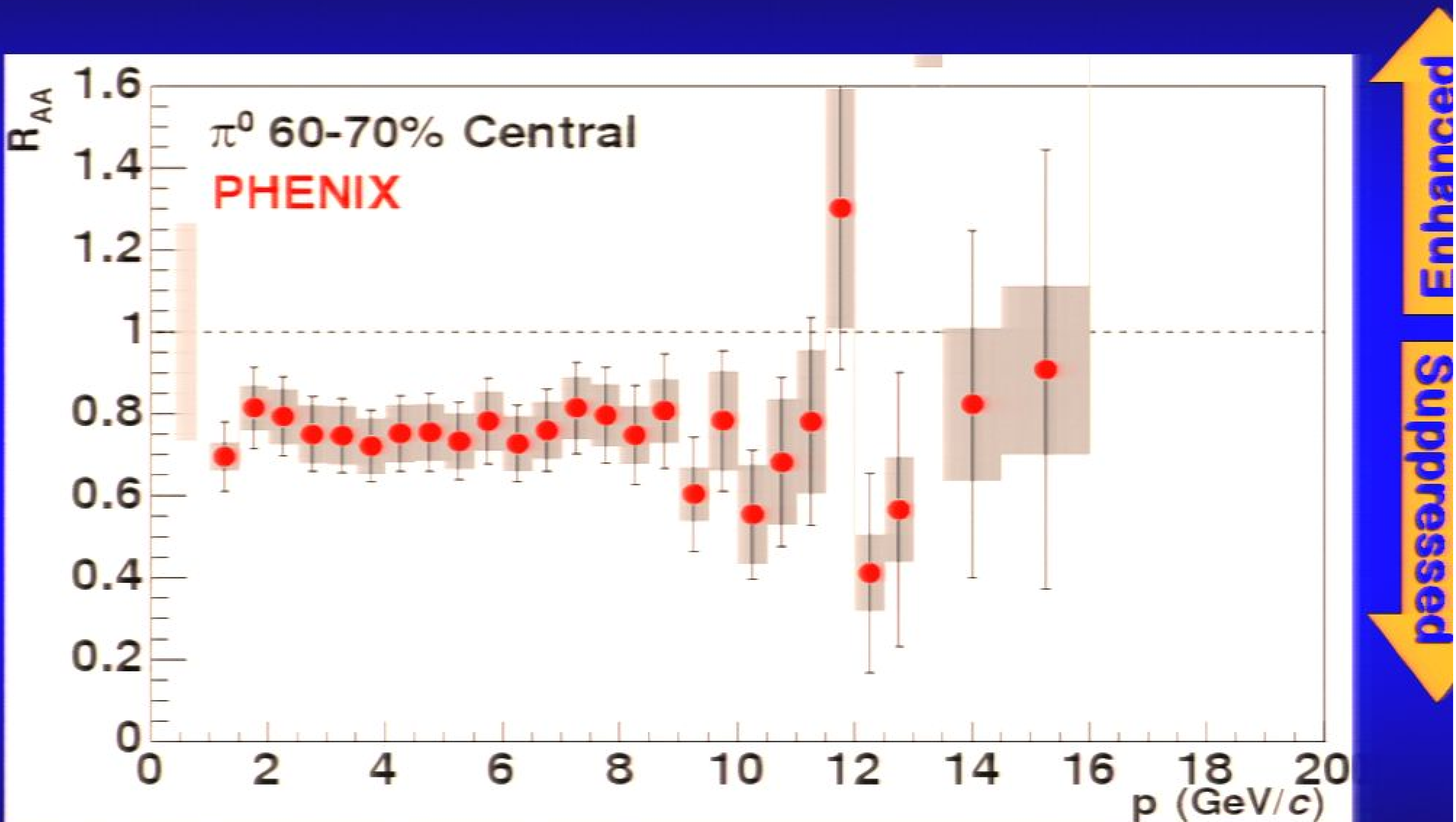

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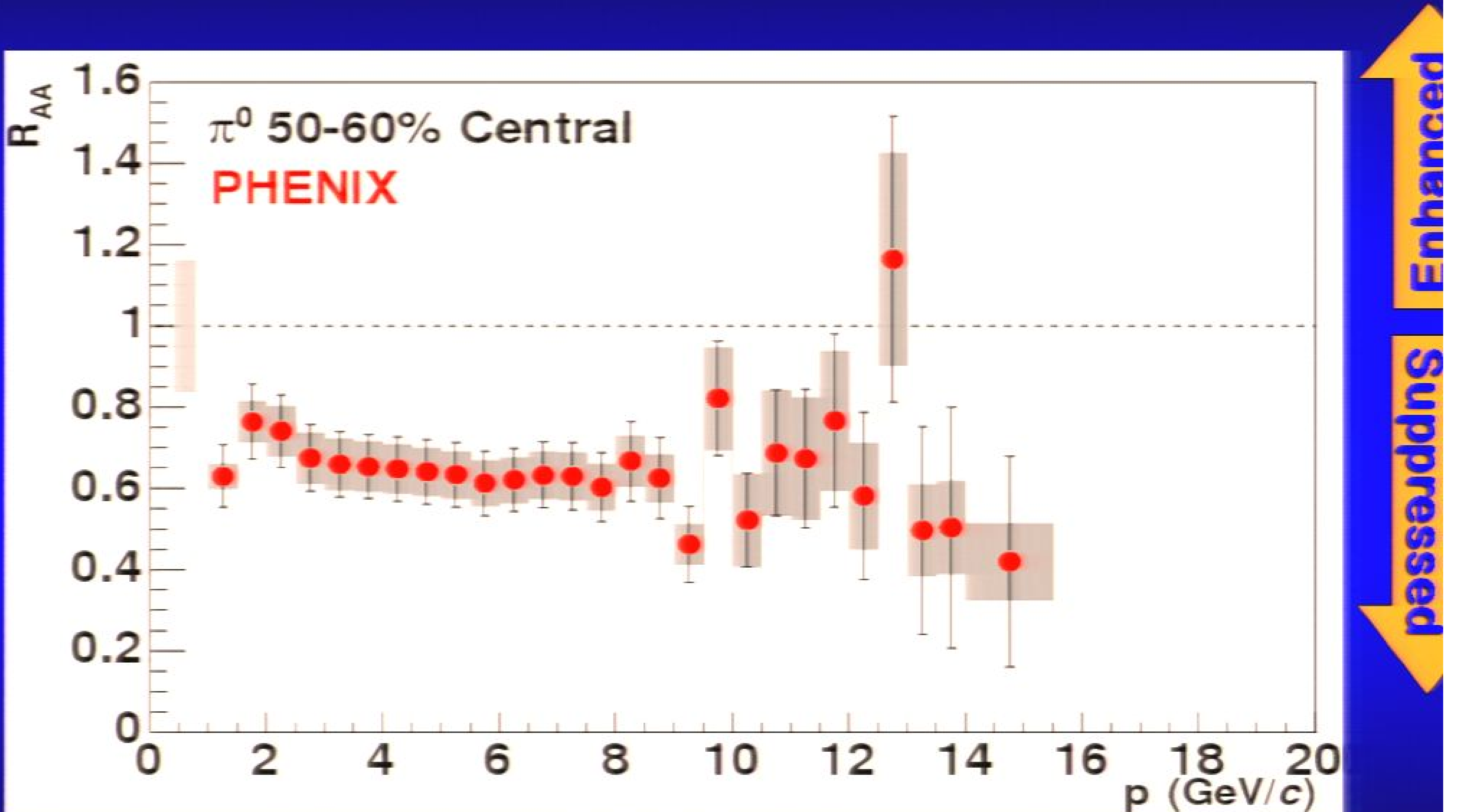

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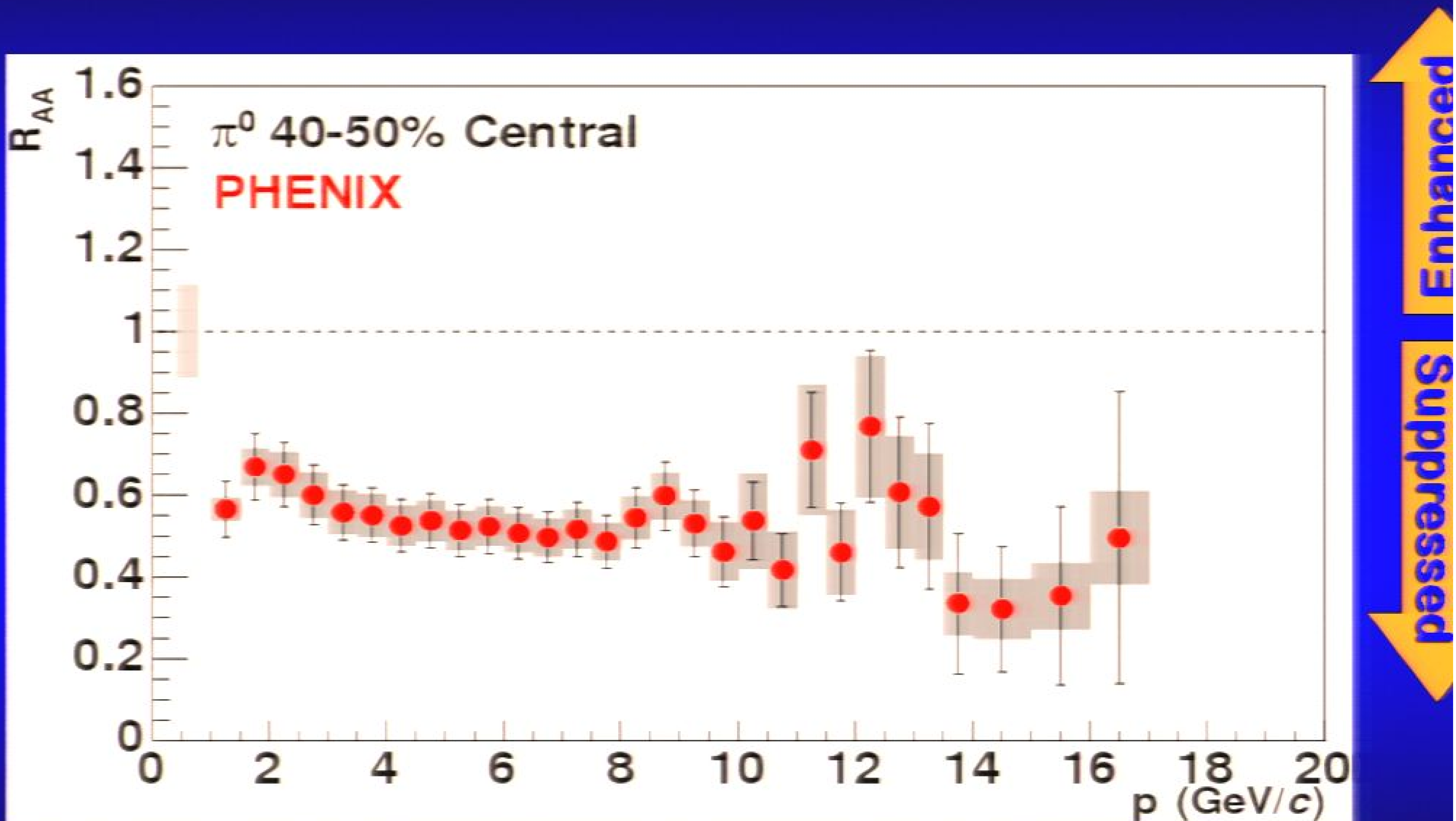

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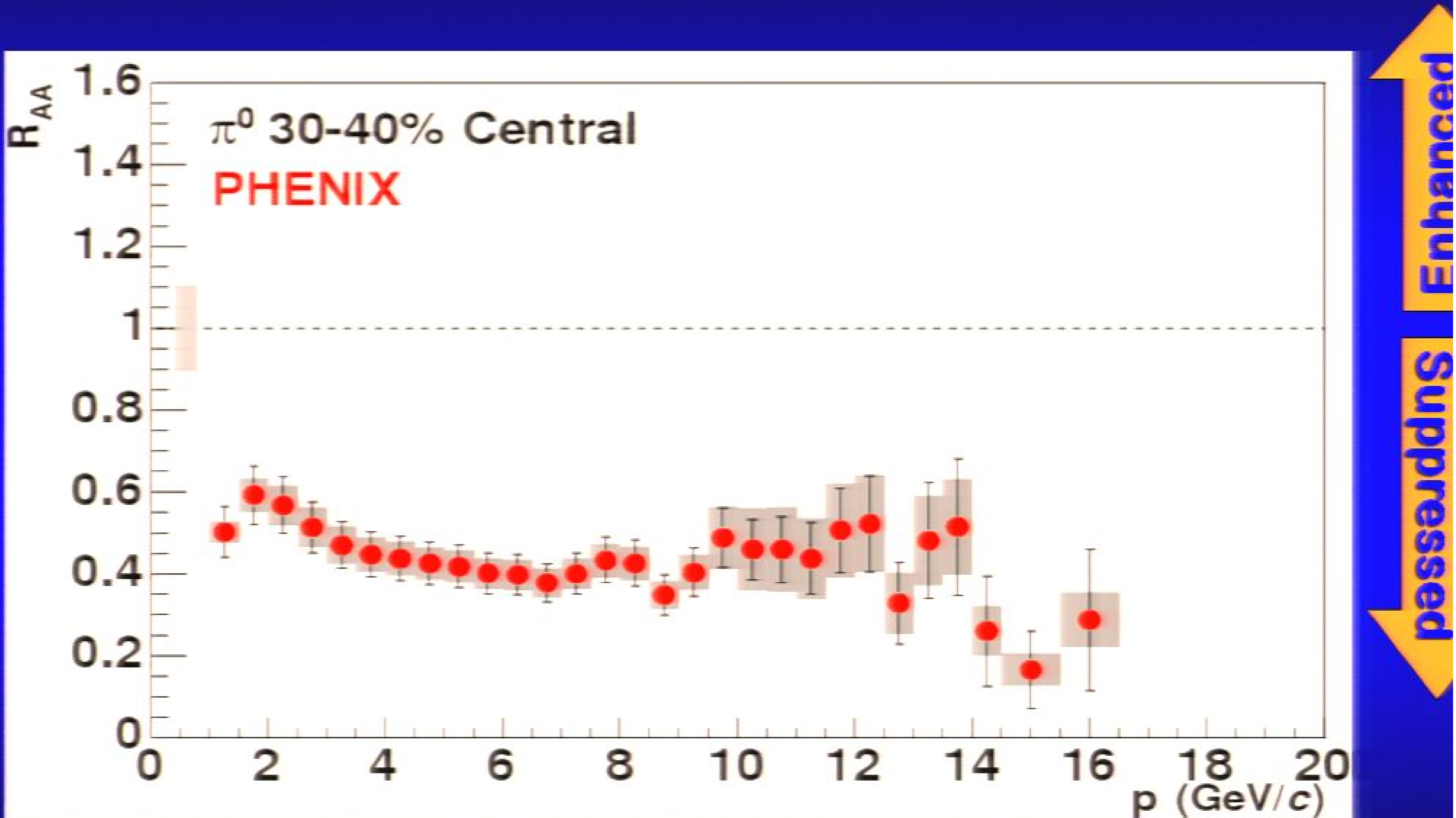

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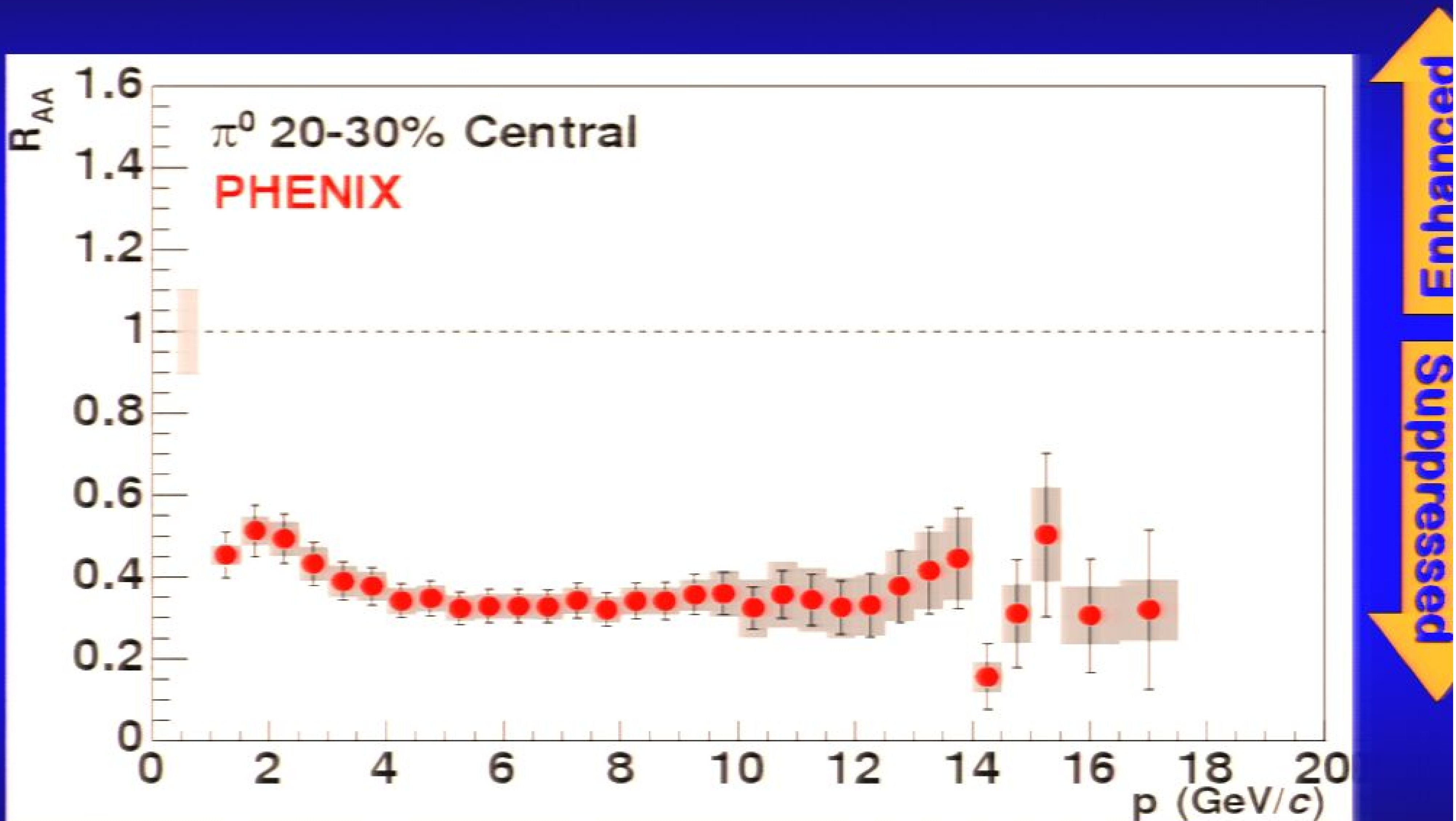

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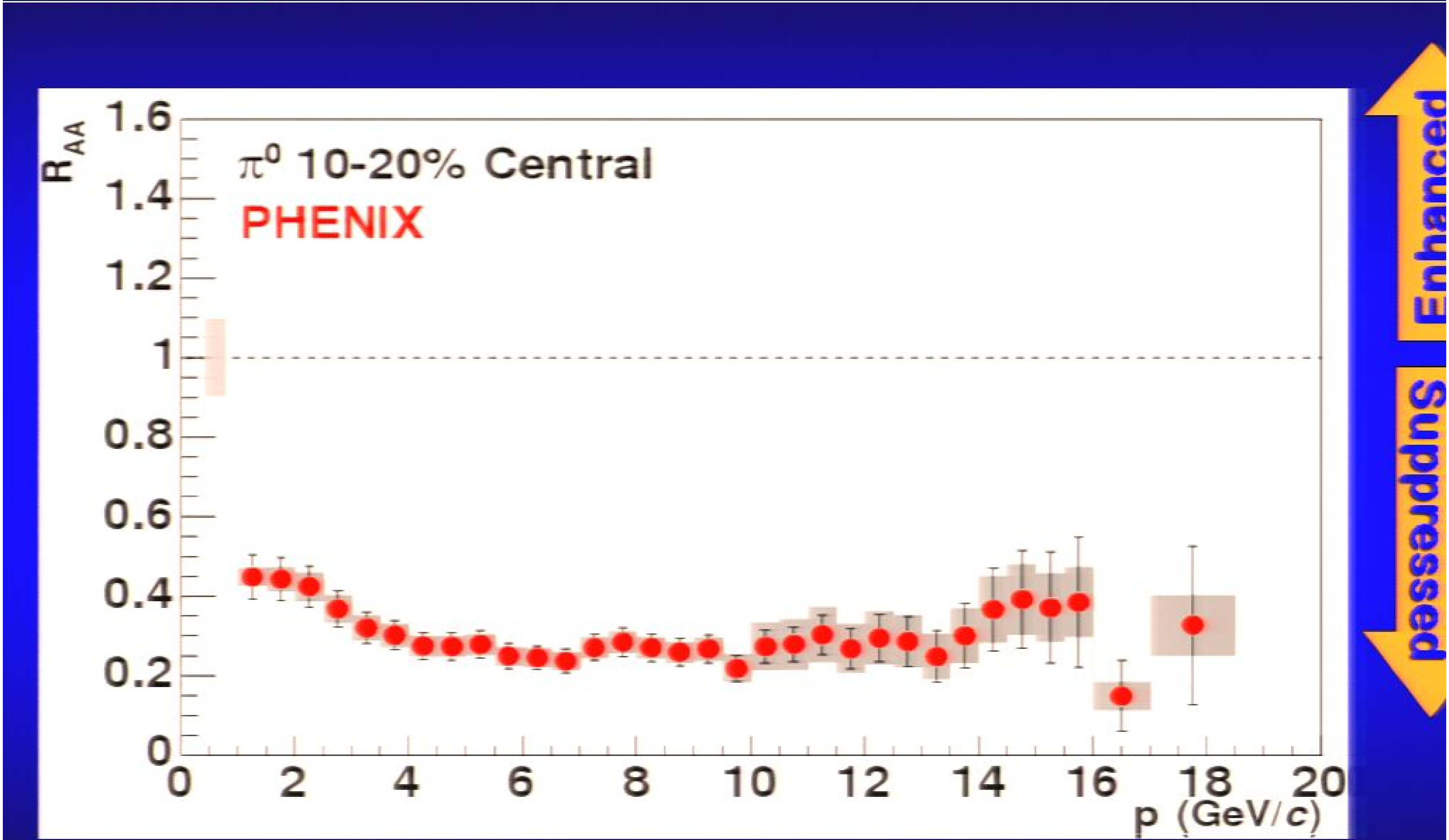

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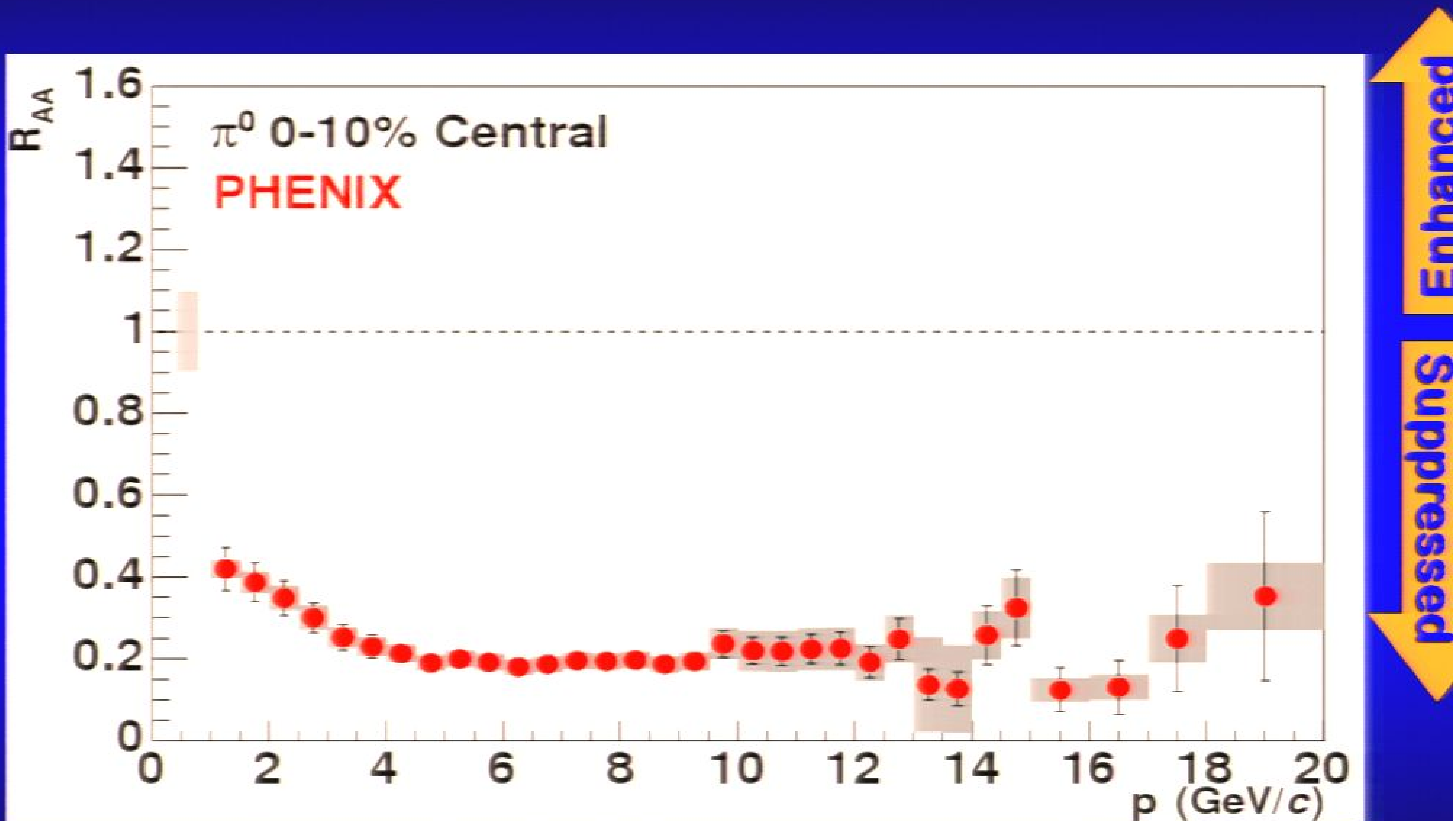

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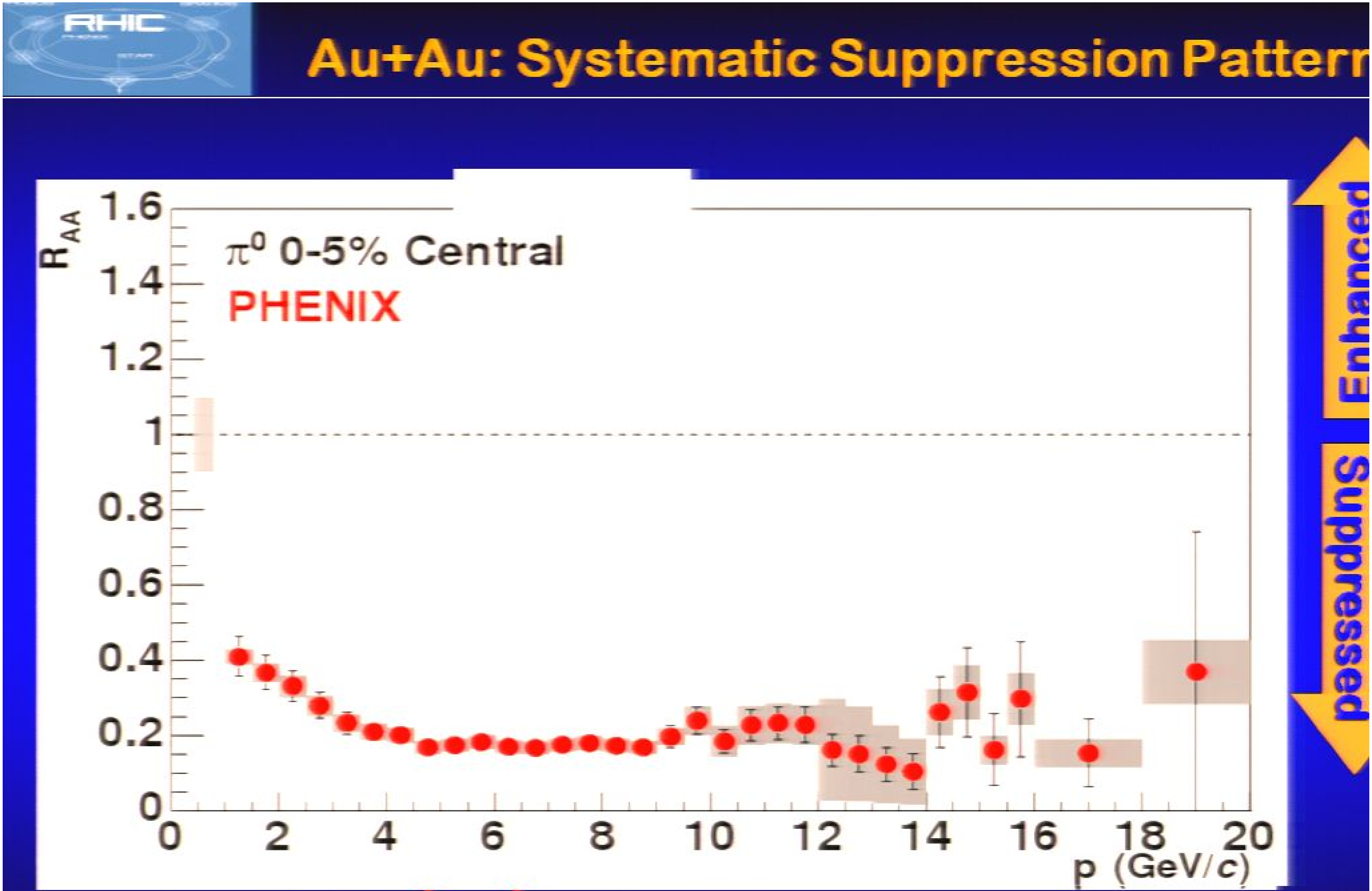
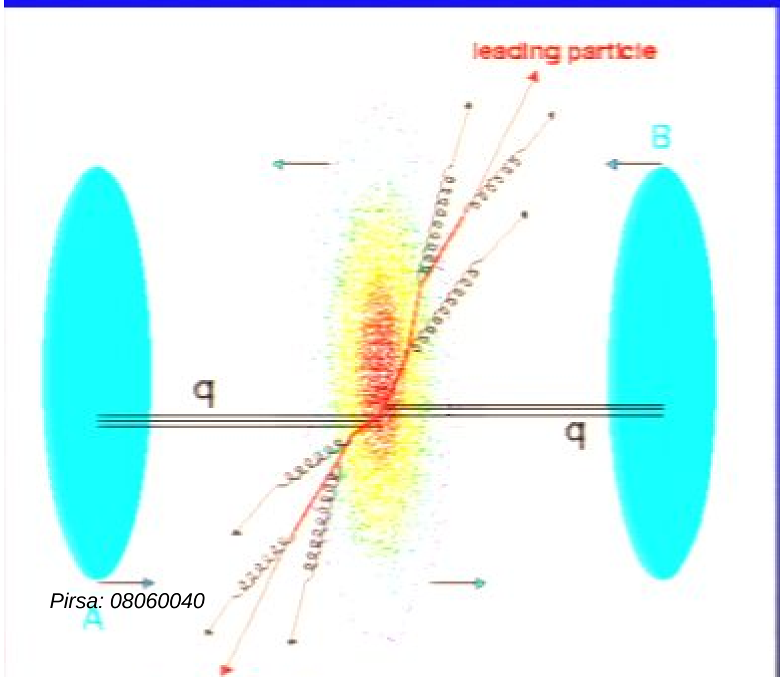


The Matter is Opaque

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



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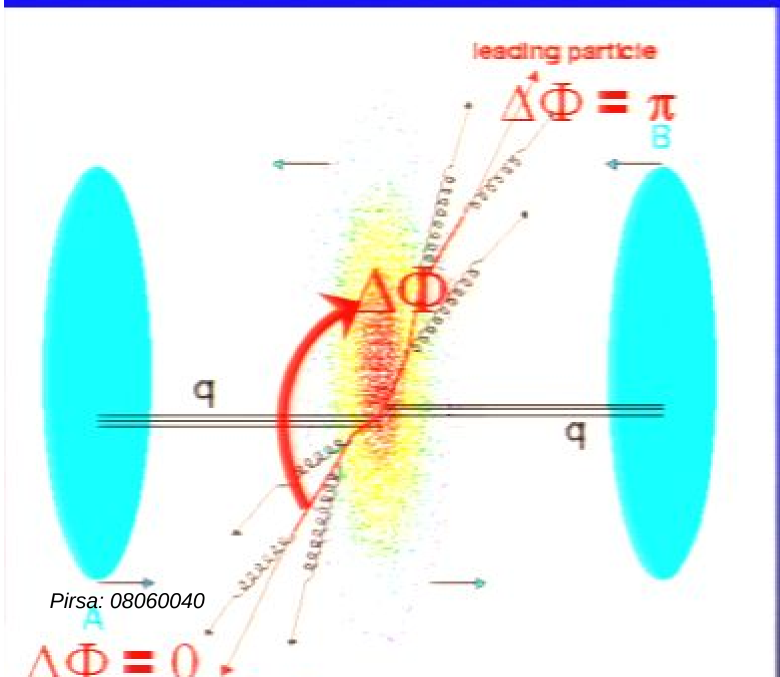

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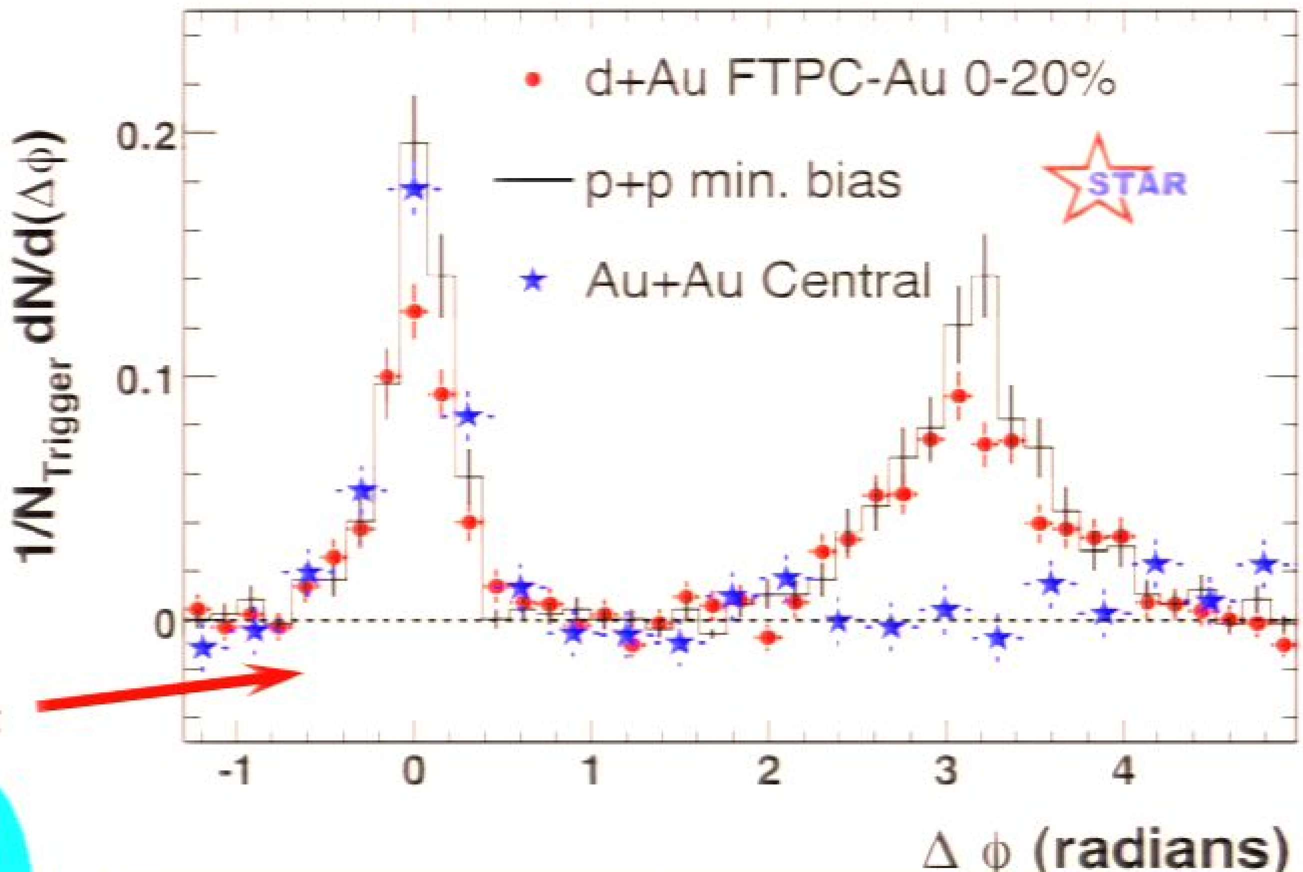

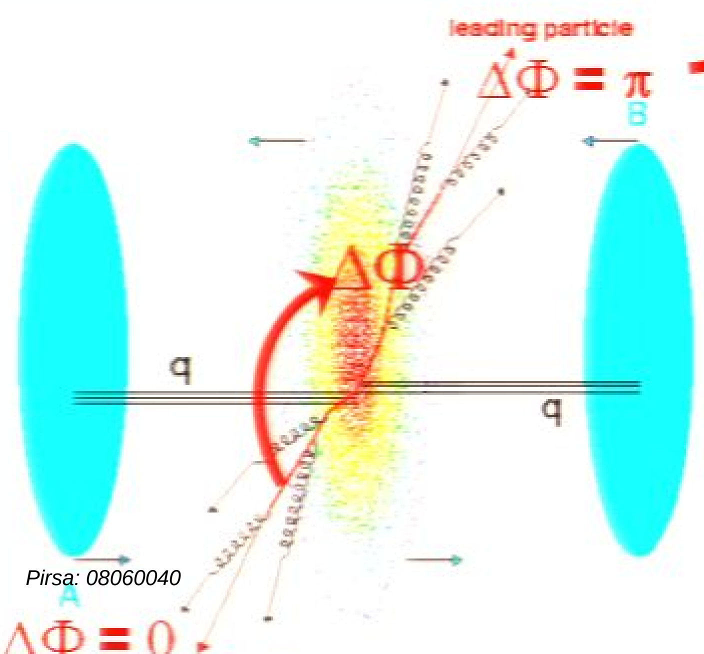

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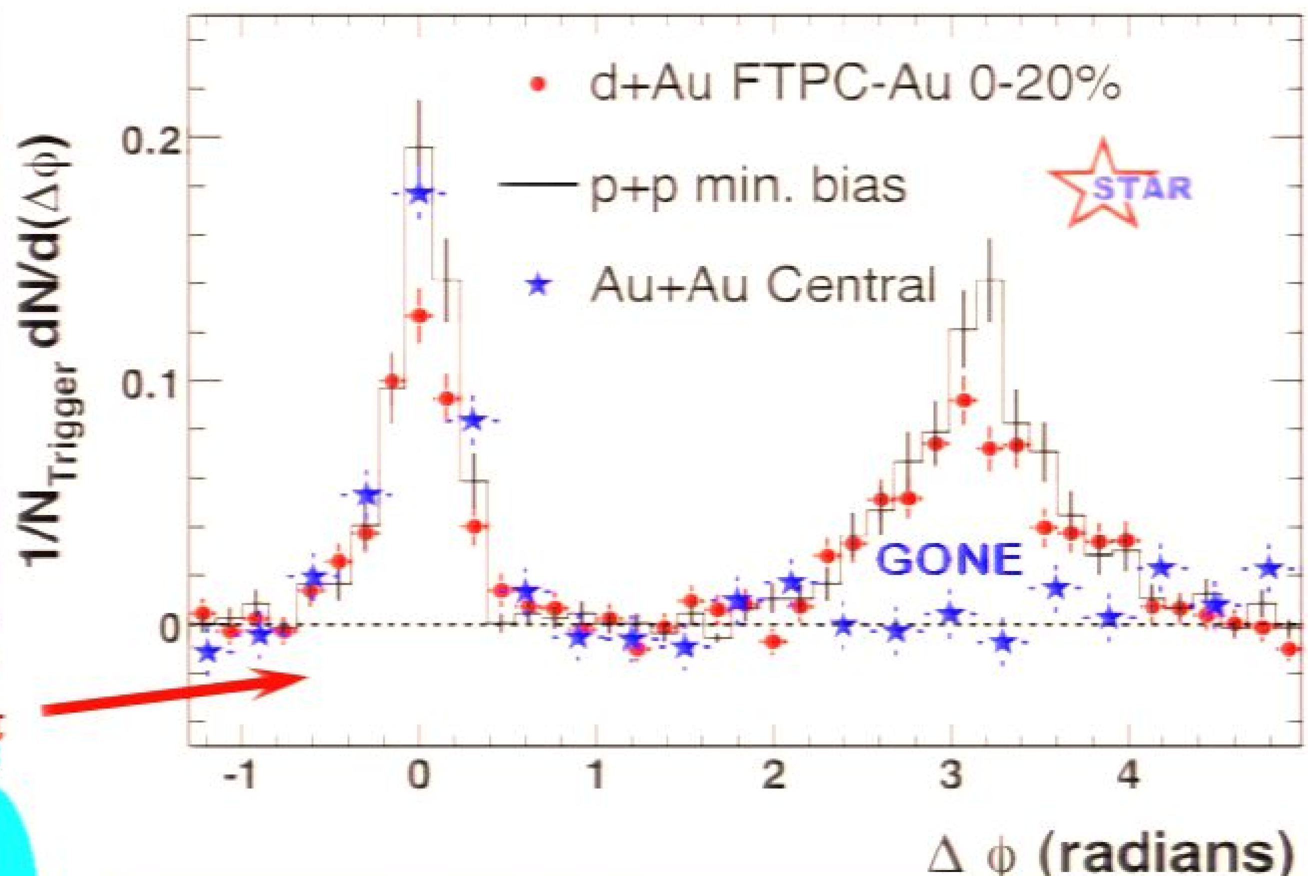
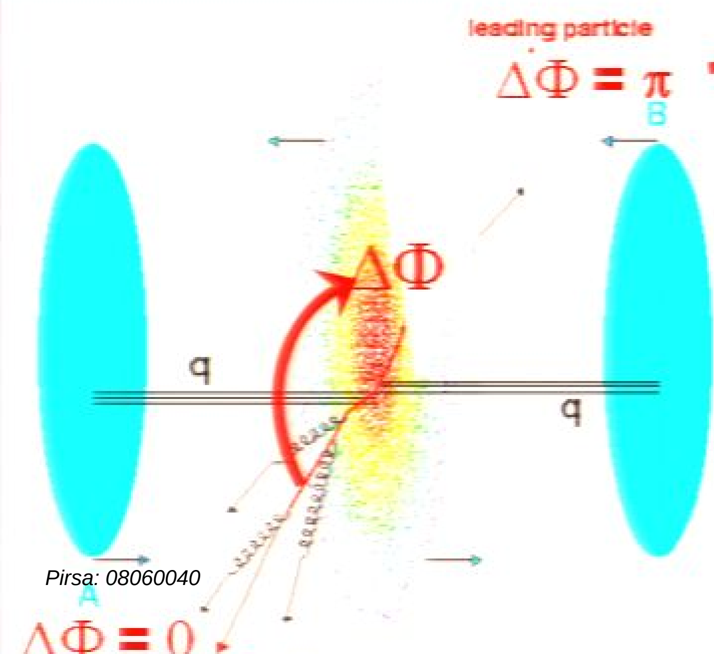
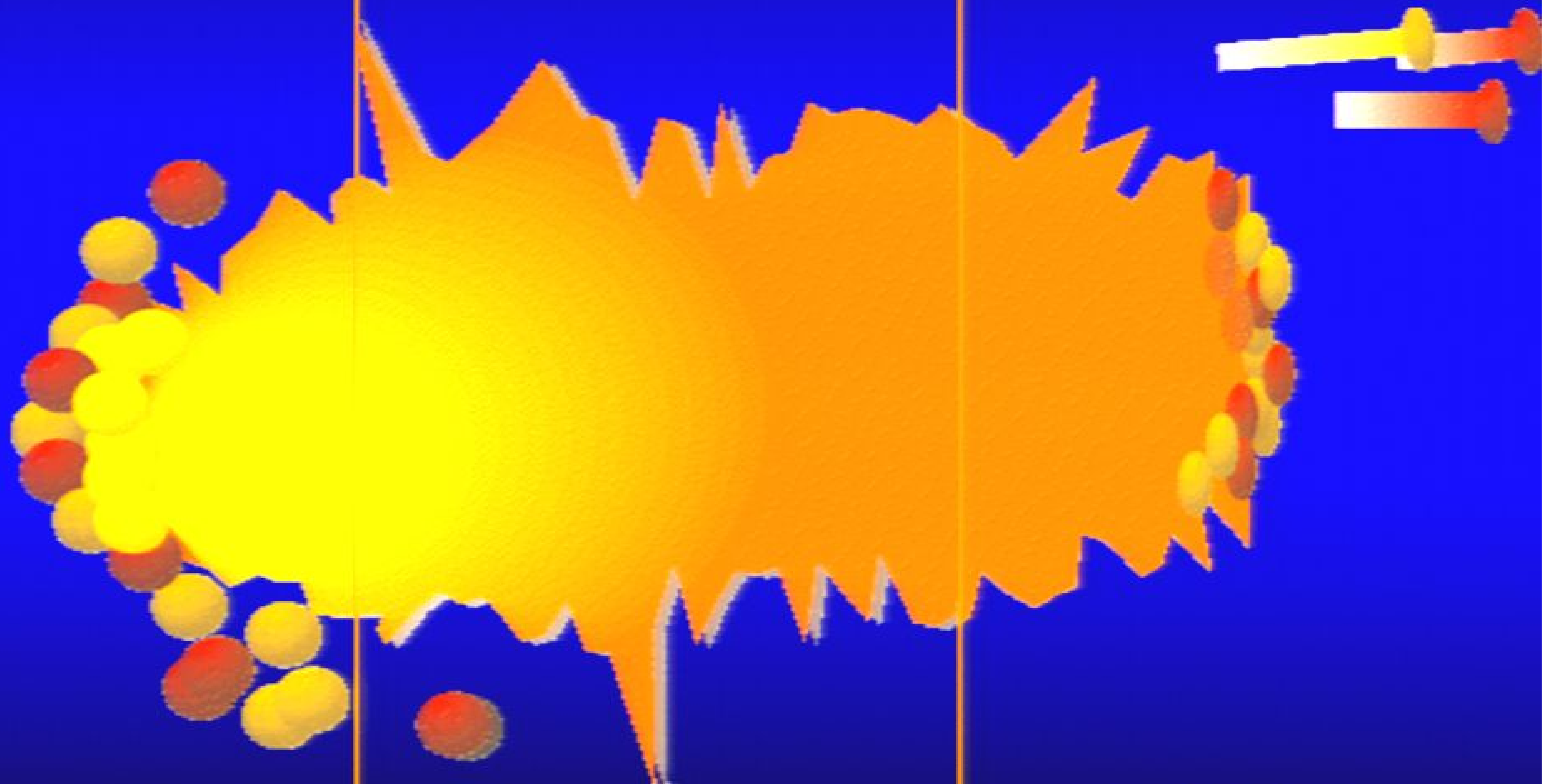




☞ **Partner in hard scatter is *completely absorbed* in the dense medium**

Schematically (Partons)

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



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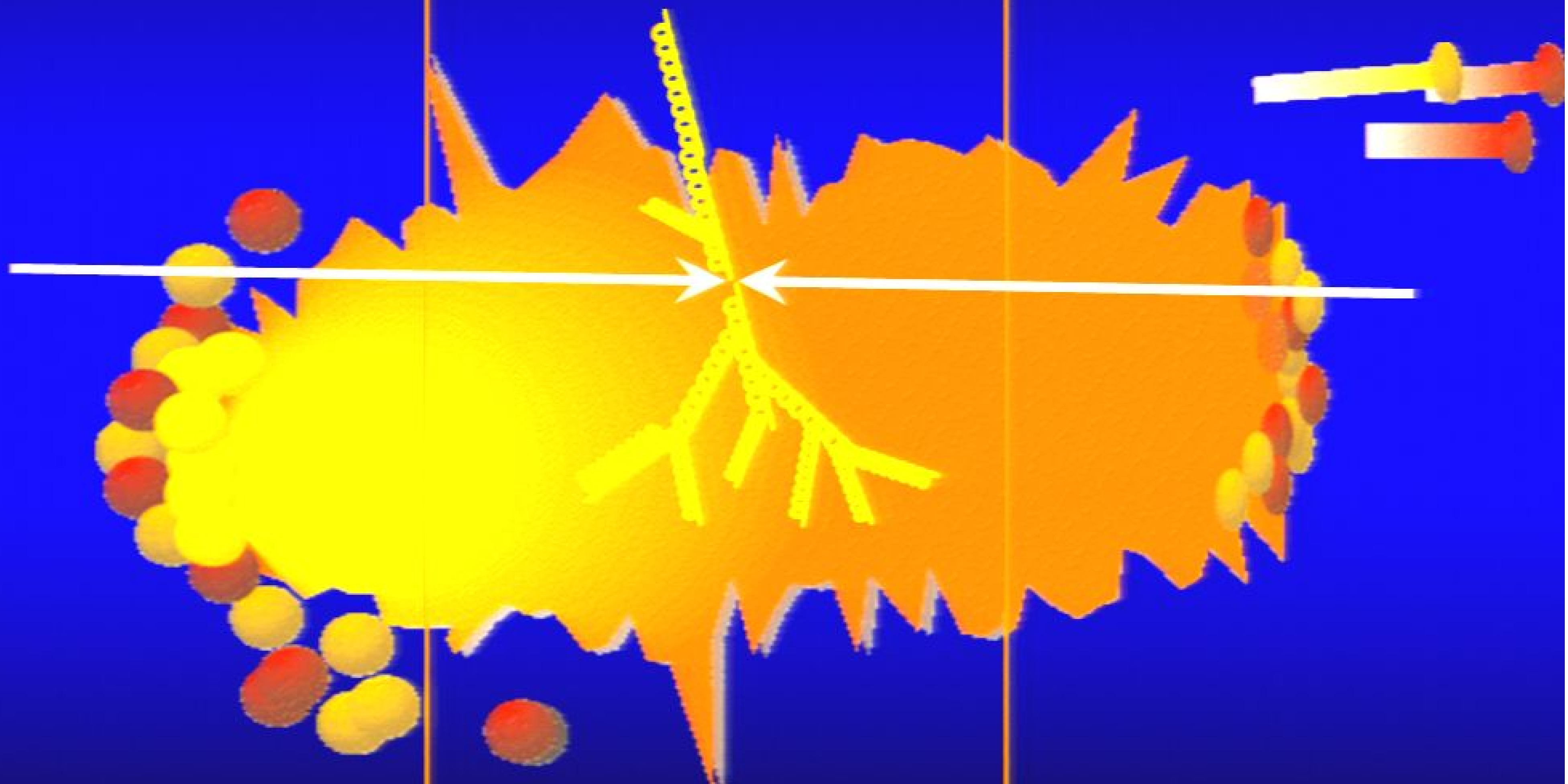

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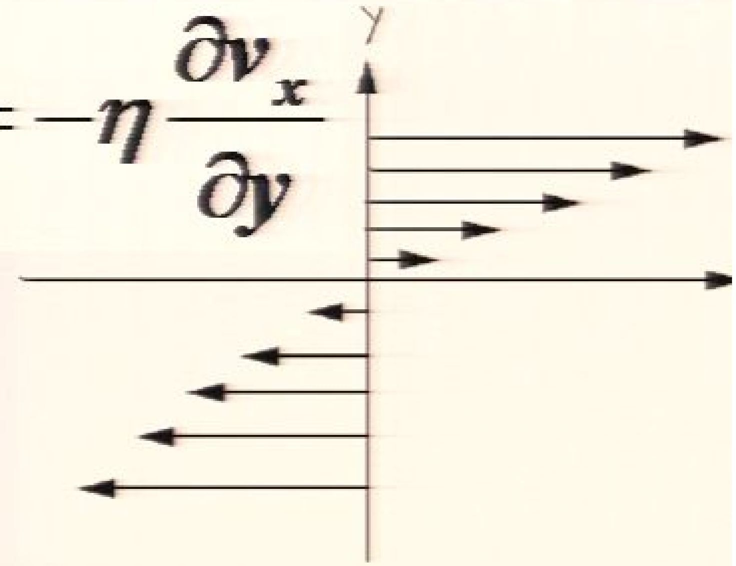
- How to quantify these statements?

Viscosity 101

- Parameterizes momentum transport between "layers"

$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



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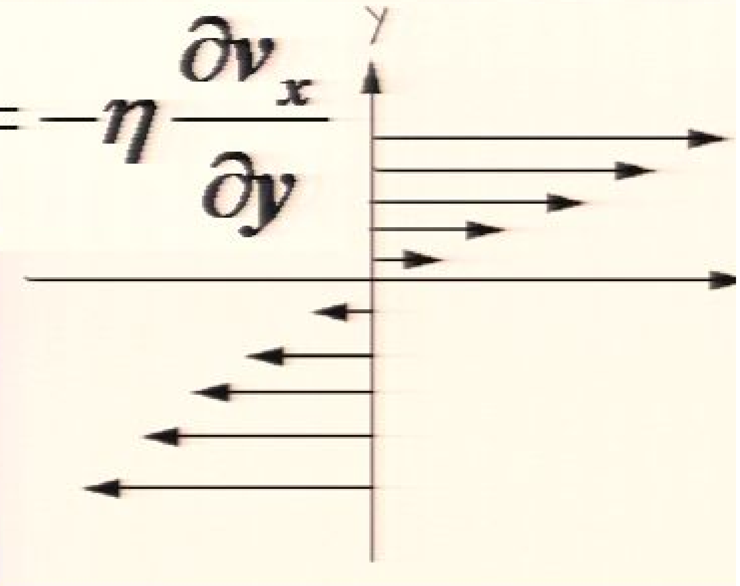

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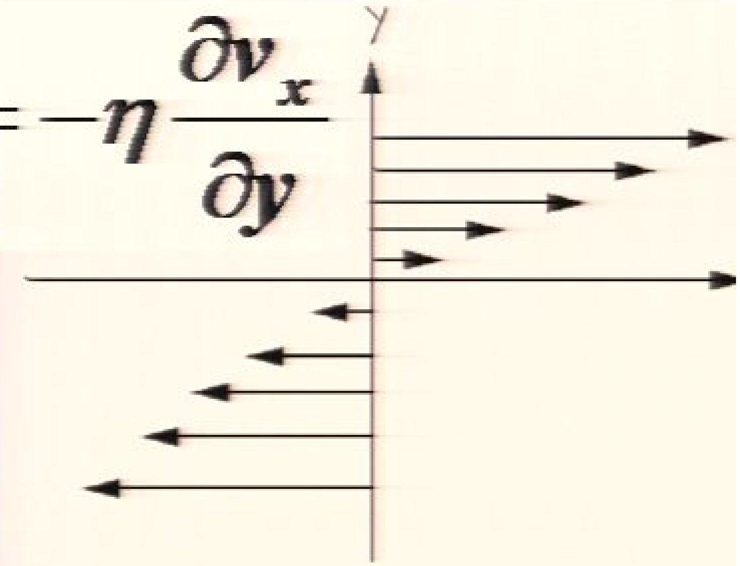

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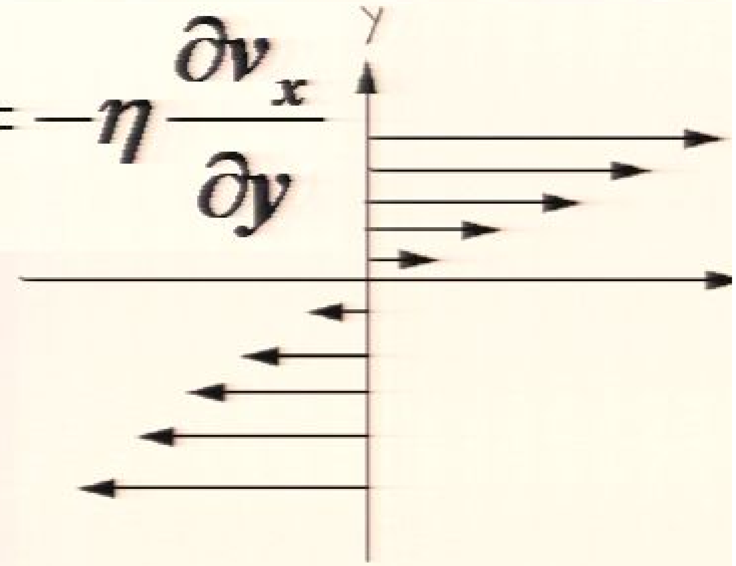

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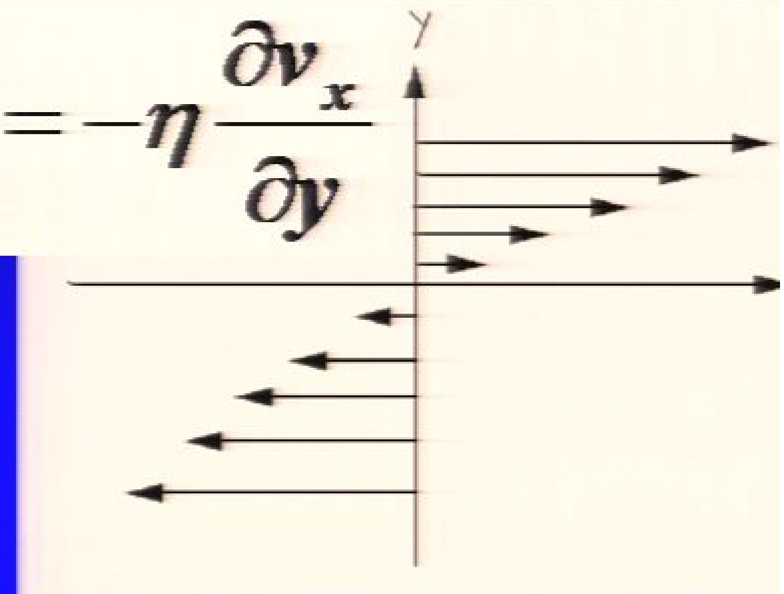

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- ☐Small viscosity ➔ Small λ_{mfp}
- ☐ *"Ideal hydro"* ➔ $\lambda_{mfp} \to 0$ ➔ $\eta \to 0$

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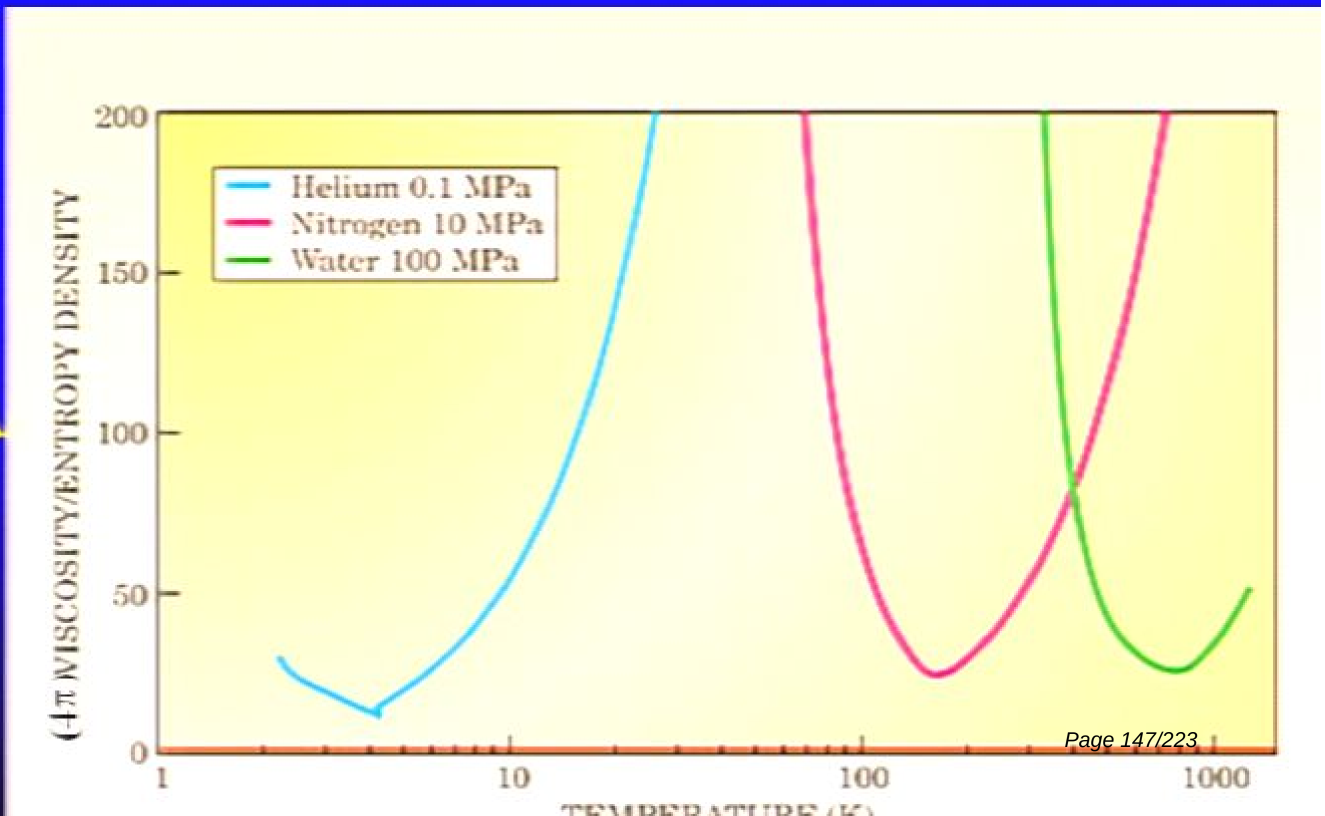

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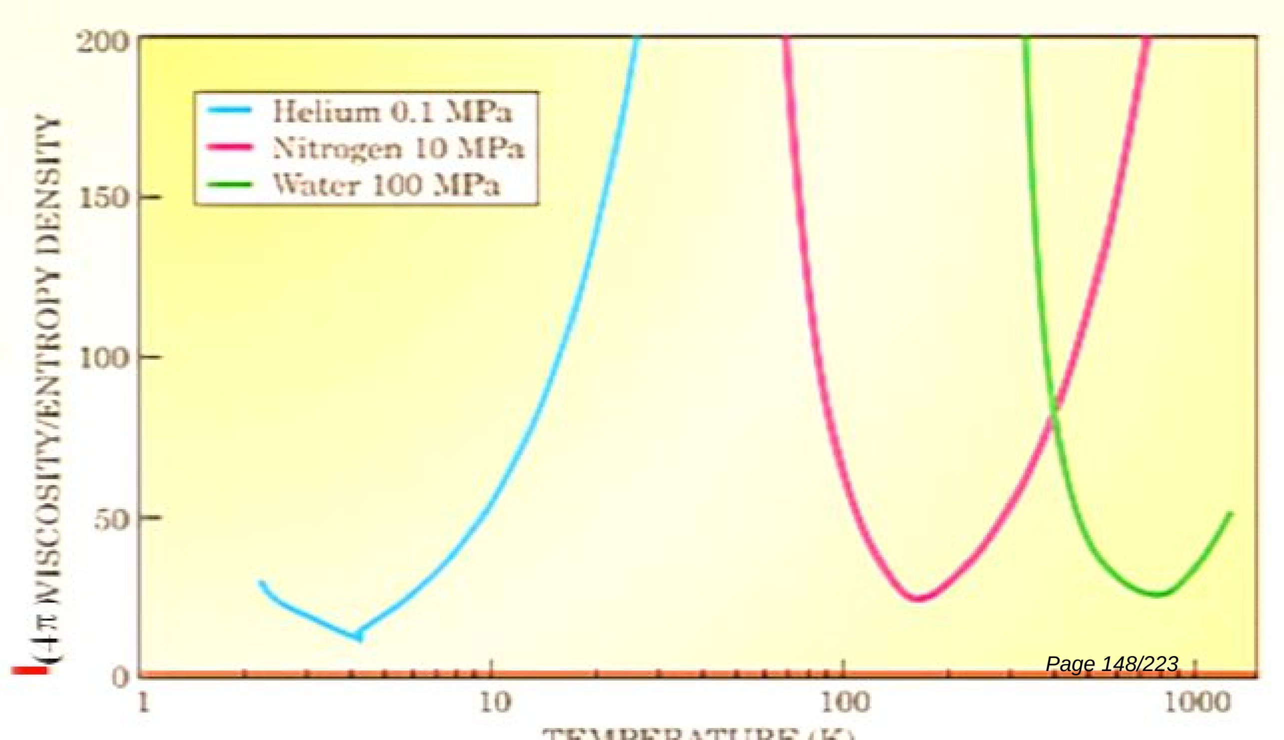

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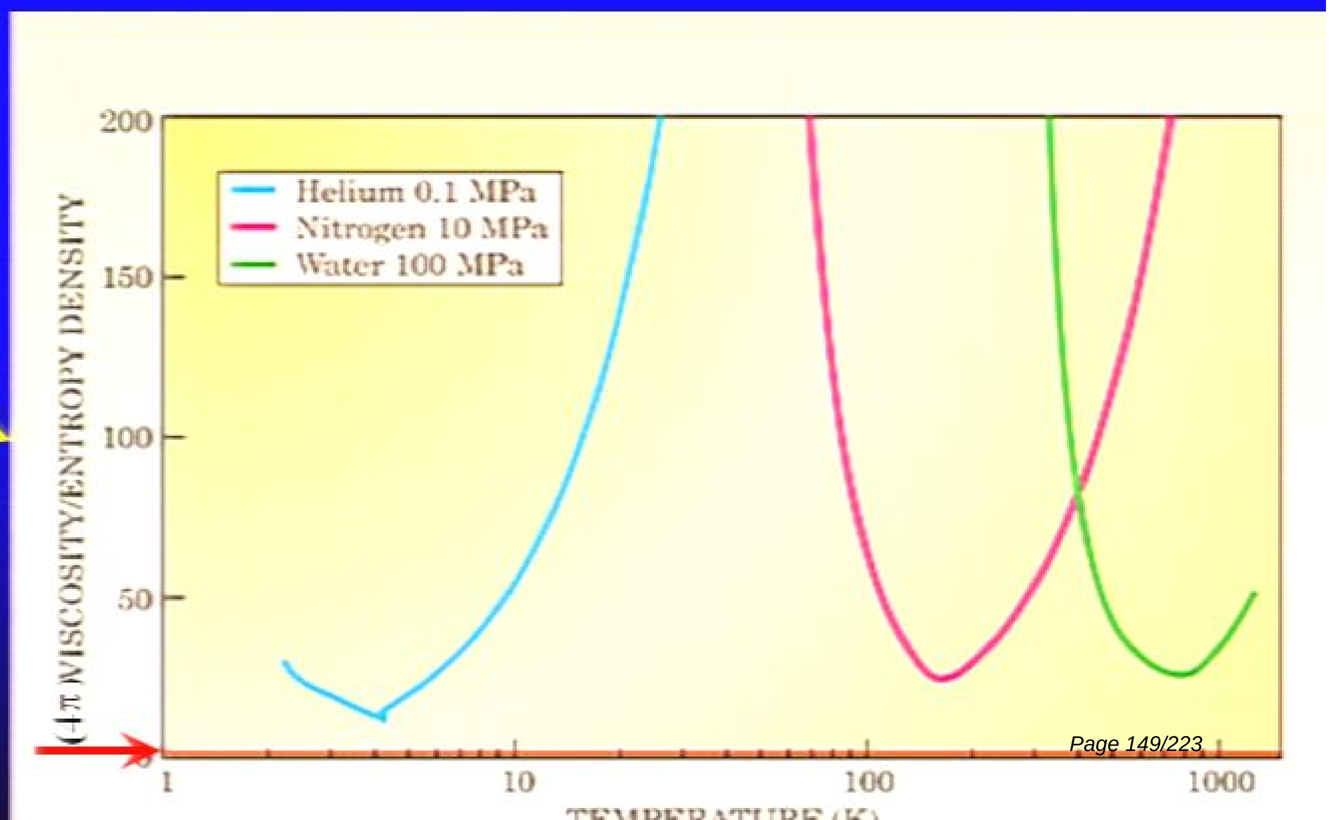

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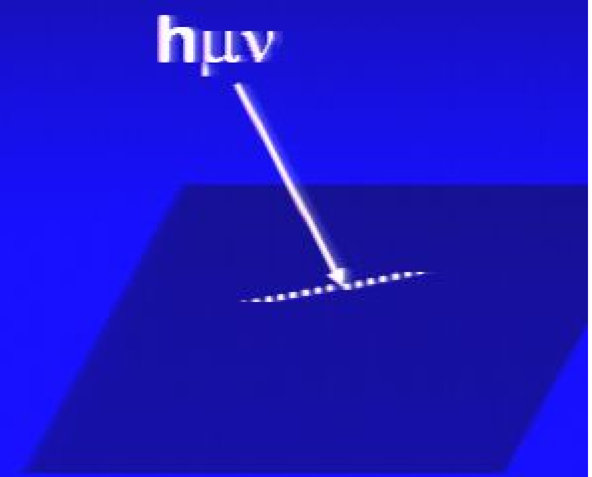

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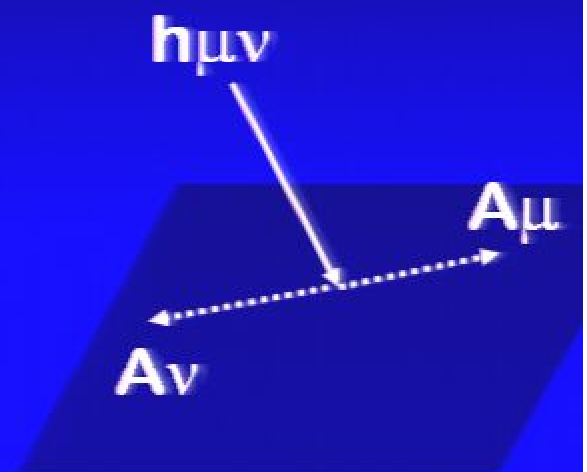

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See next talk: K. Rajagopal

- ***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**

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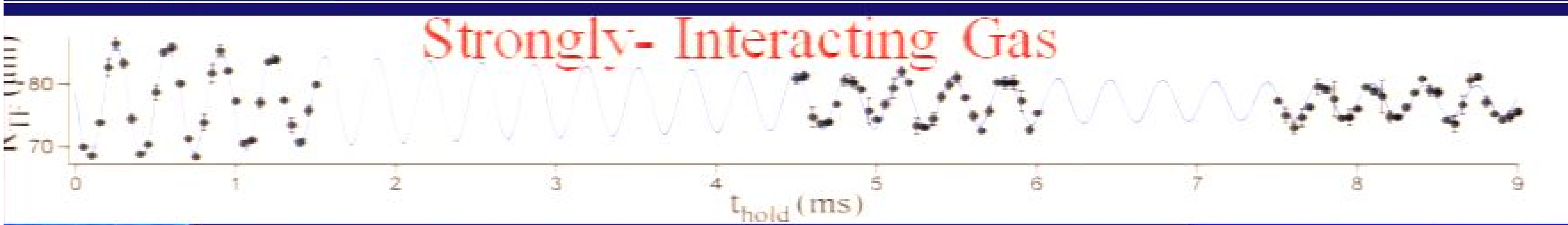
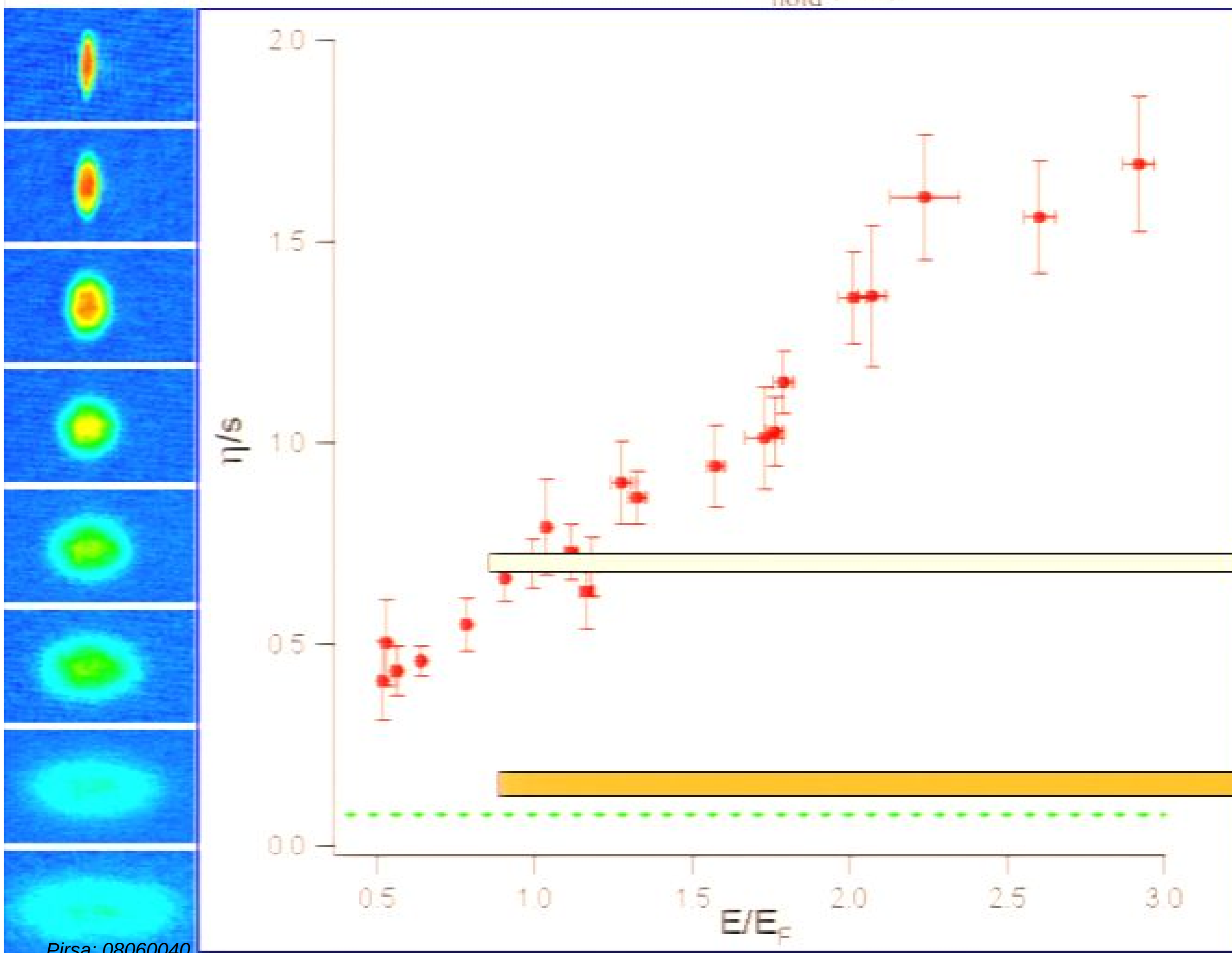
Compare to the Competition





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

^3He, ^4He near λ–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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- **Neglect various terms at your own risk:**
  - Natsuume and Okamura, Comment on "Viscous hydrodynamics relaxation time from AdS/CFT correspondence"

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, $<p_T>$
- **Calculation:** 2^{nd} order causal viscous hydro:

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

(Glauber IC's)

- **Payoff Plots:**

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

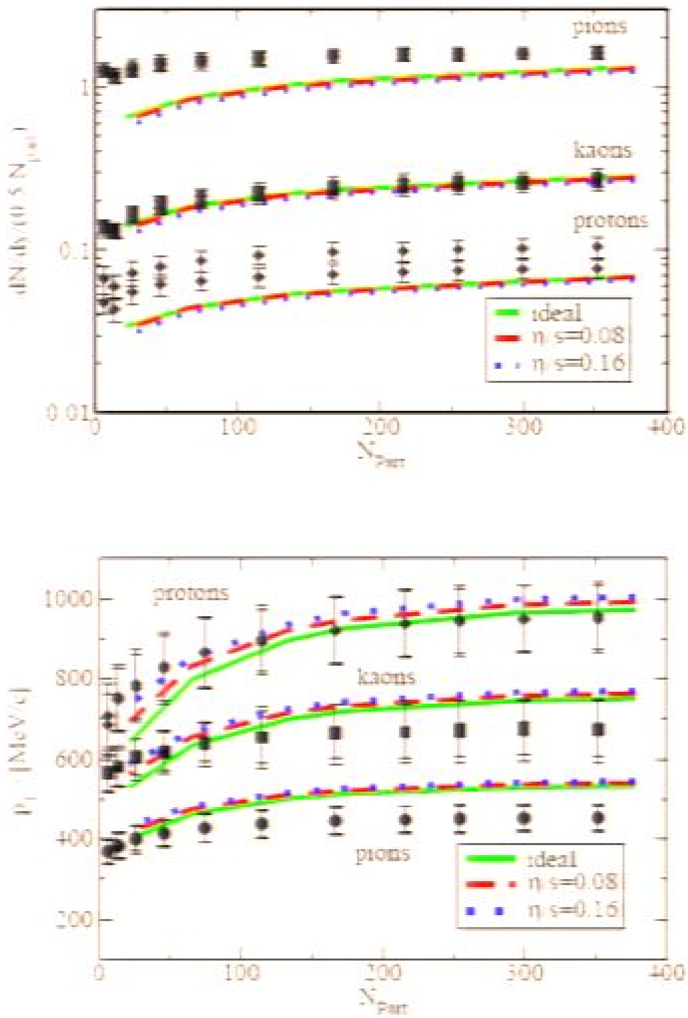
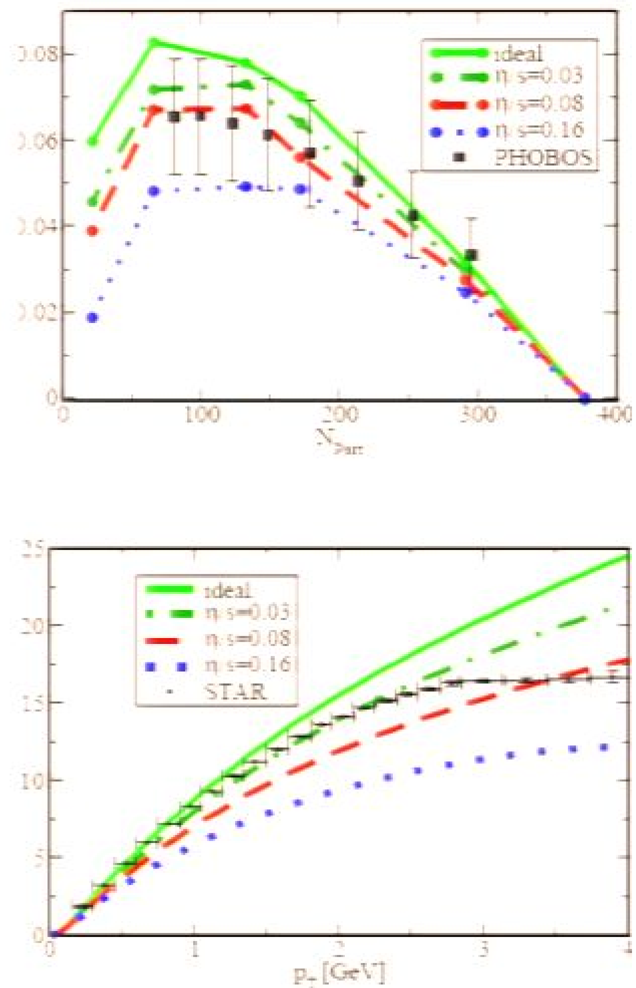


FIG. 2: Total multiplicity dN/dy and mean momentum for π^+,π^-,K^+,K^-,p and $\bar{p}$ from PHENIX [23] for Au+Au collisions at $\sqrt{s}=200$ GeV, compared to our hydrodynamic model for various viscosity ratios η/s.



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

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  - PHENIX: arXiv:0801.166

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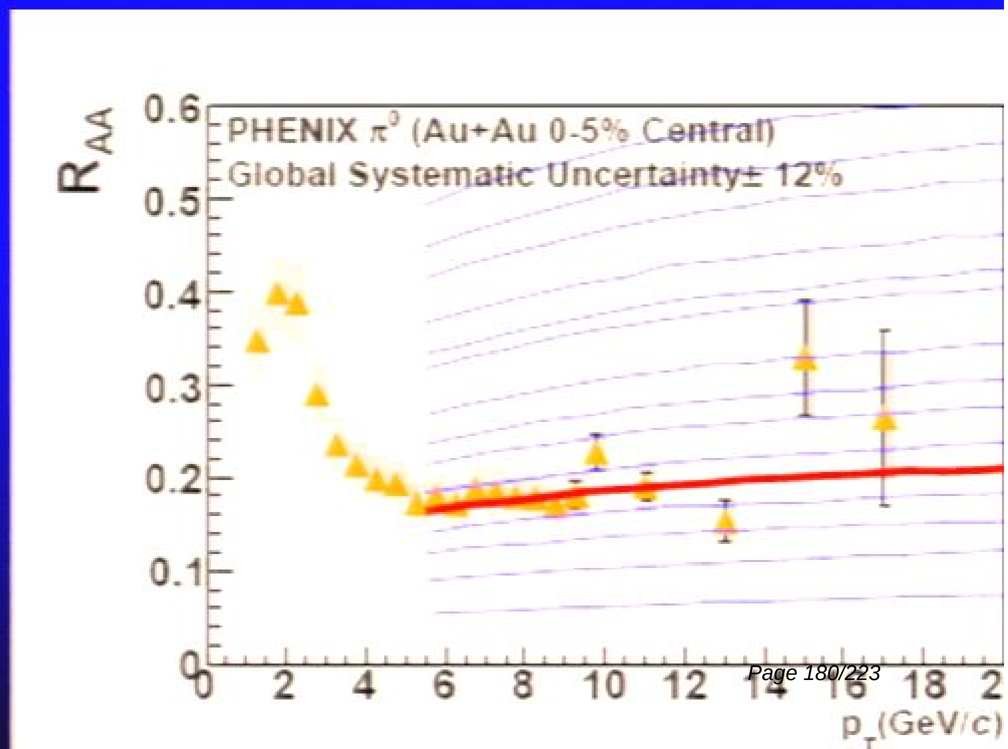

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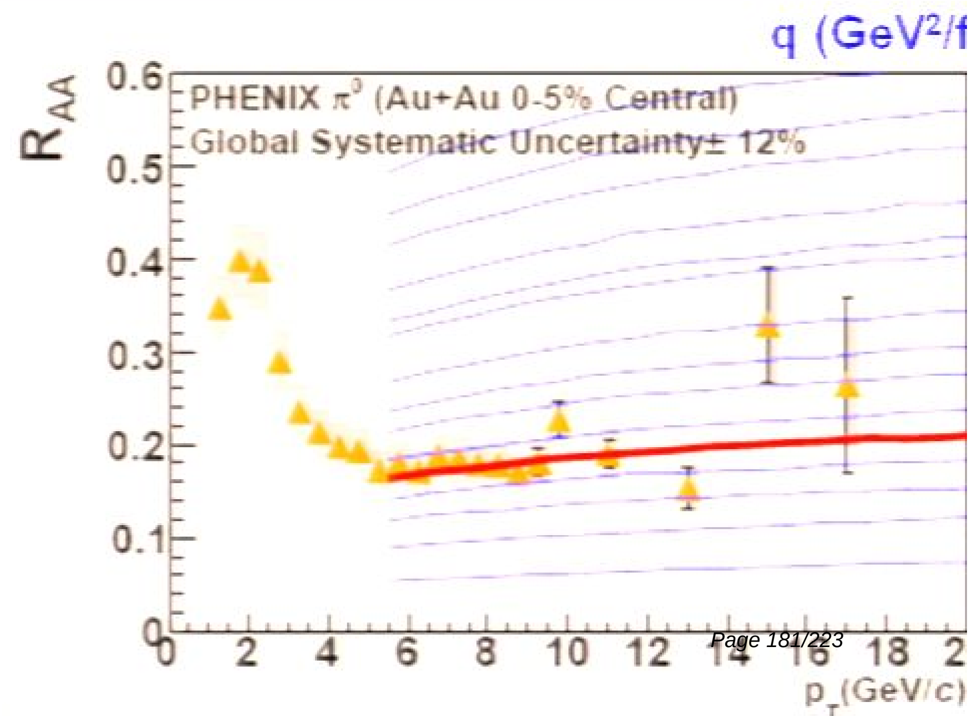

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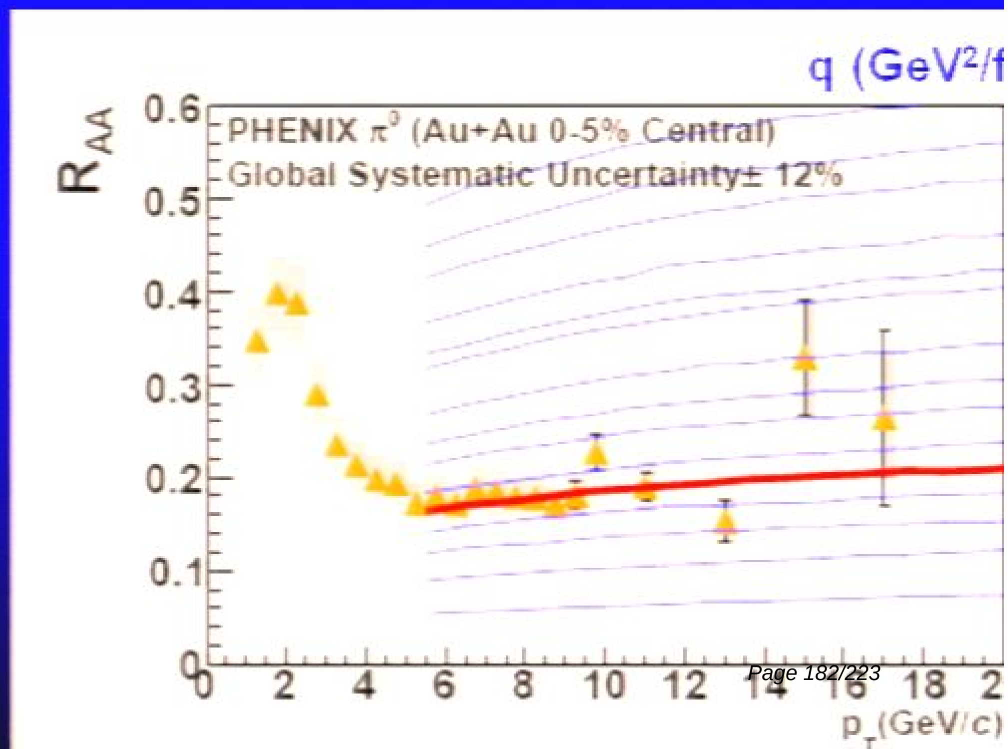

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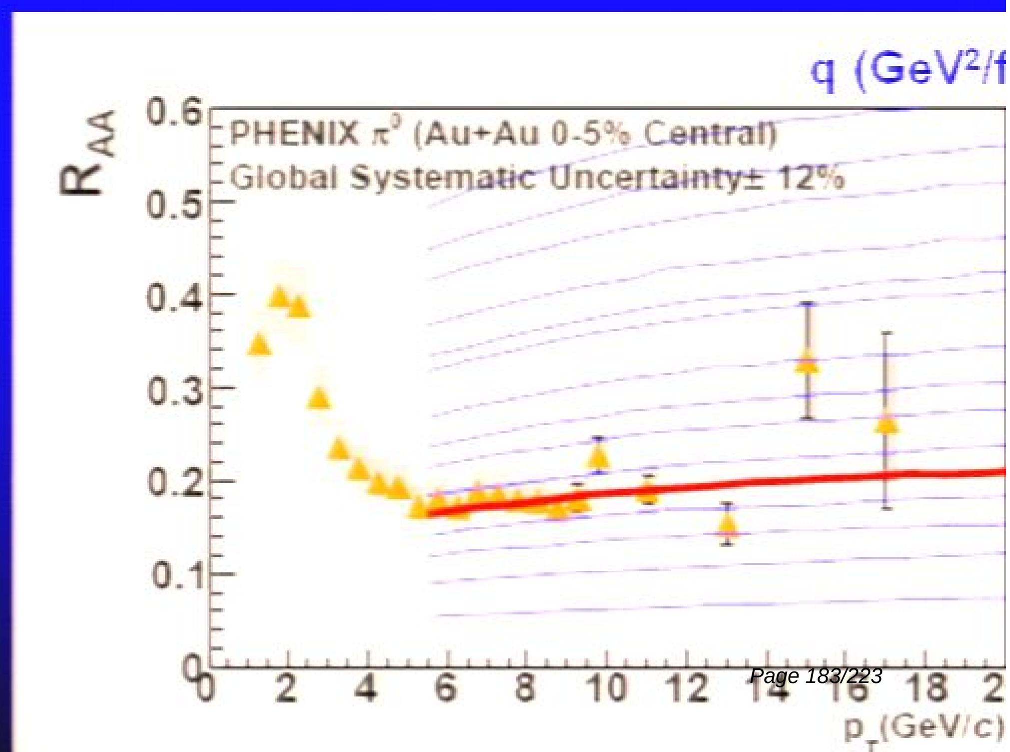

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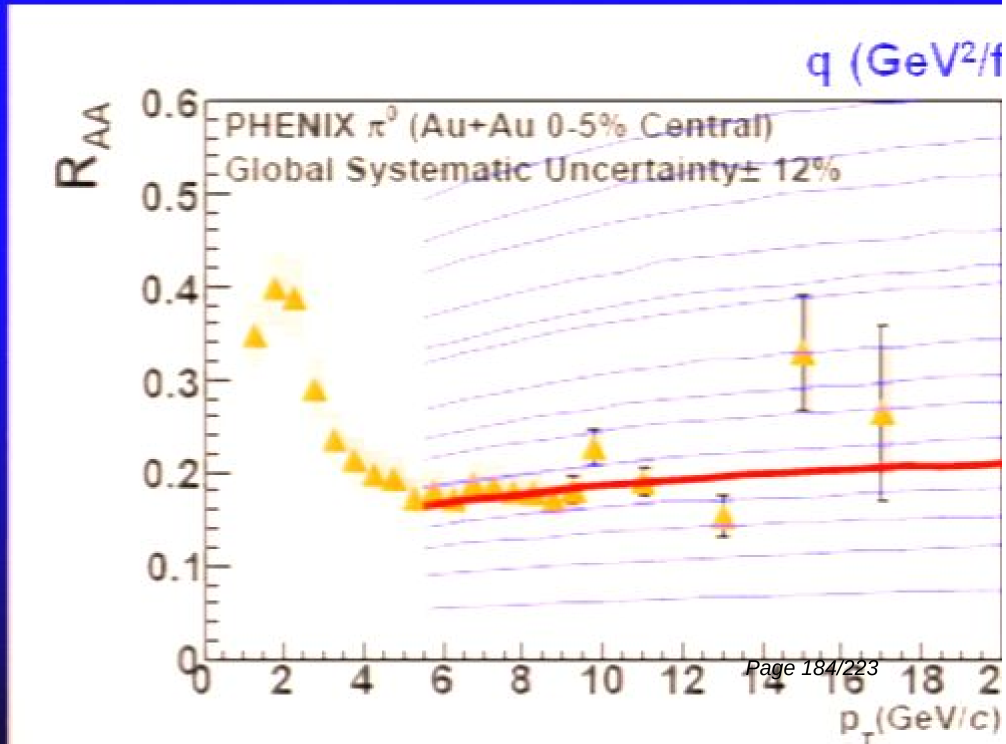

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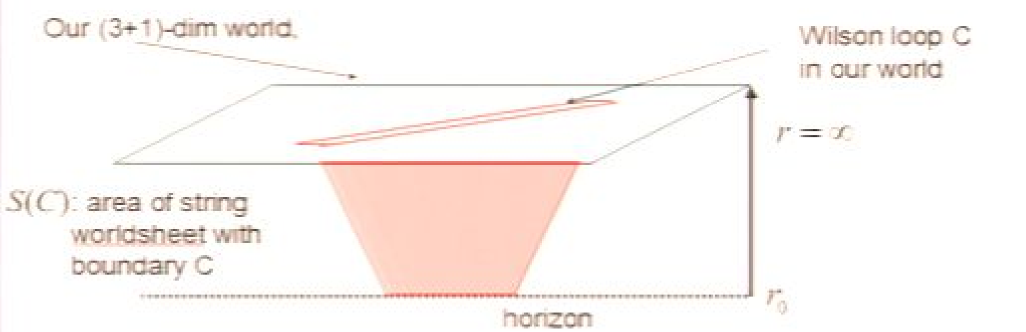
- AdS/CFT ?:

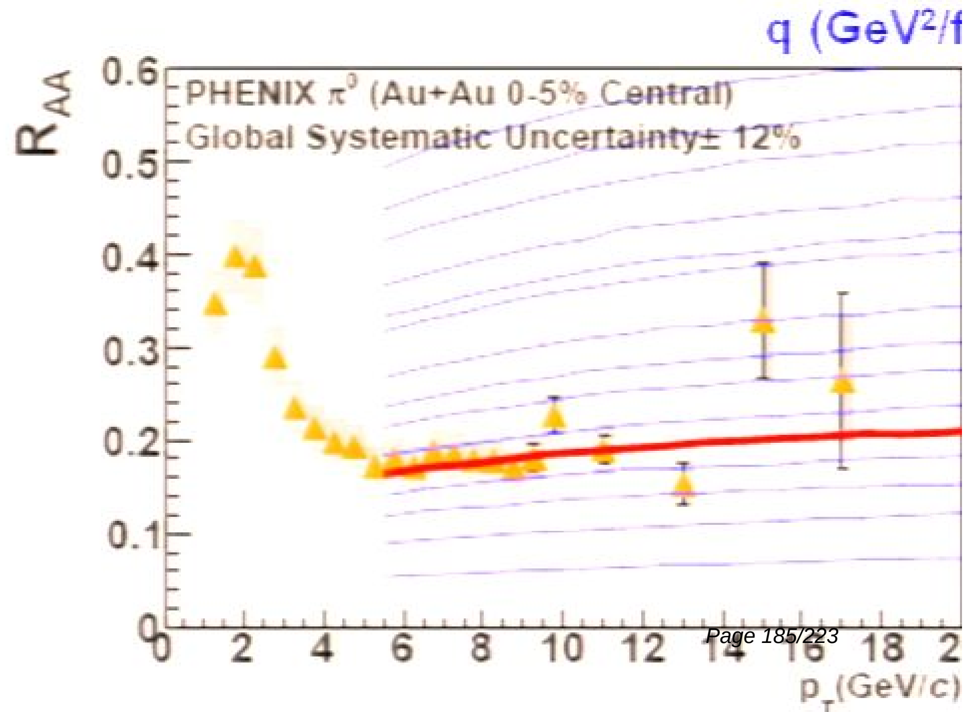
Wilson loop from AdS/CFT

Maldacena (1998); Rey and Yee (1998)

Recipe: $\langle W(\mathcal{C})\rangle = \exp\left[iS(\mathcal{C})\right]$



Black hole in AdS spacetime:
- radial coordinate r,
- horizon: r=r...



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  - Liu, Rajagopal, Wiedemann: hep-ph/0605178

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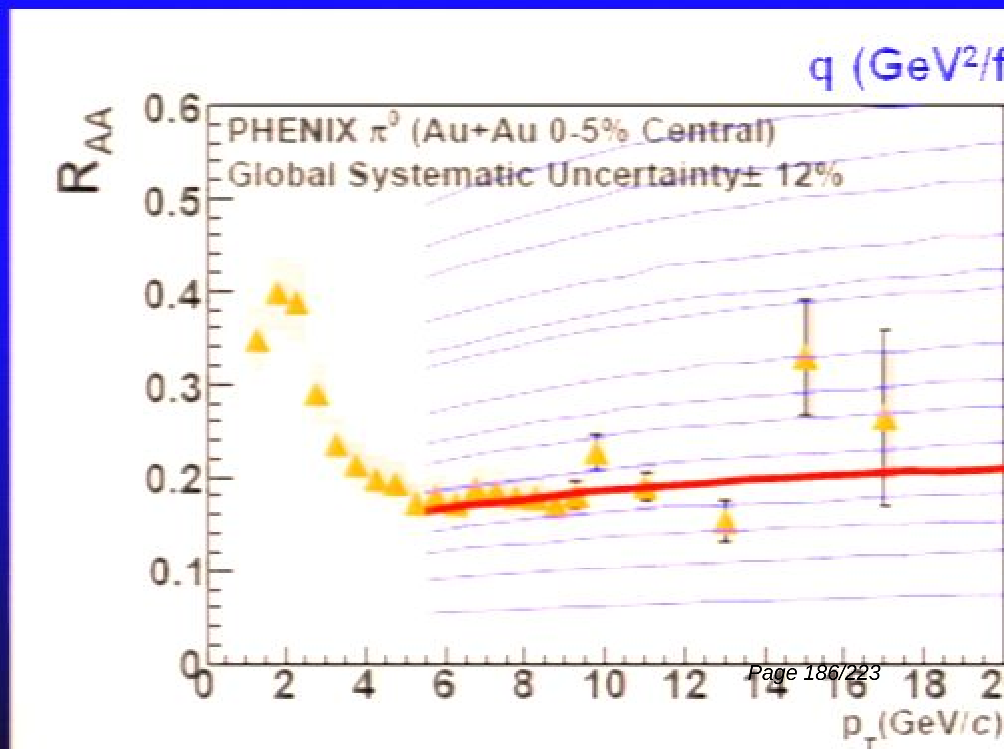

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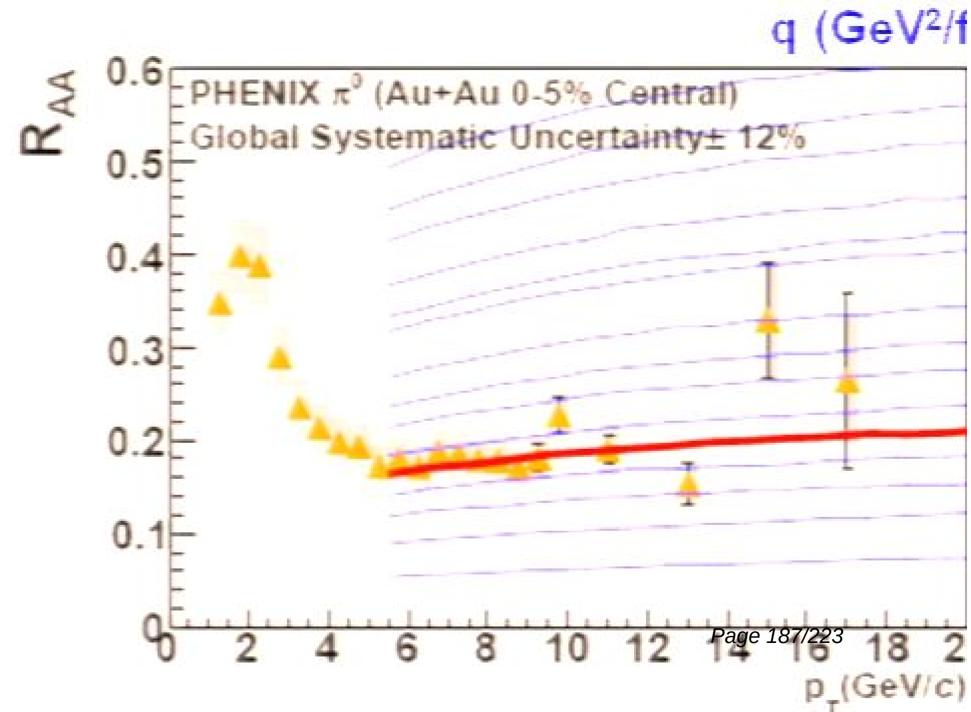
- Factor of ~3 di



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- So- RHIC flow data within factors 1-4 of the bound on η/s calculated via AdS/CFT
- Can AdS/CFT also be applied to the strong energy loss in the fluid?

$$\hat{q} \sim \frac{\langle p_T^{\,2} \rangle}{\lambda} \rightarrow \Delta E_{rad} \approx \alpha_s \hat{q}$$

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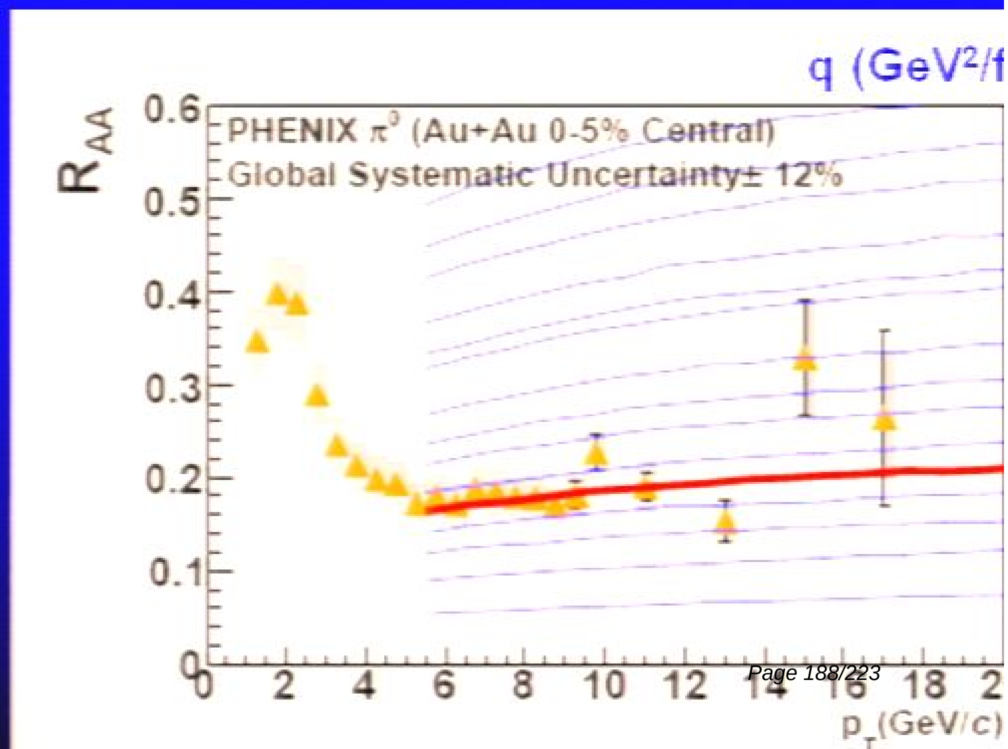

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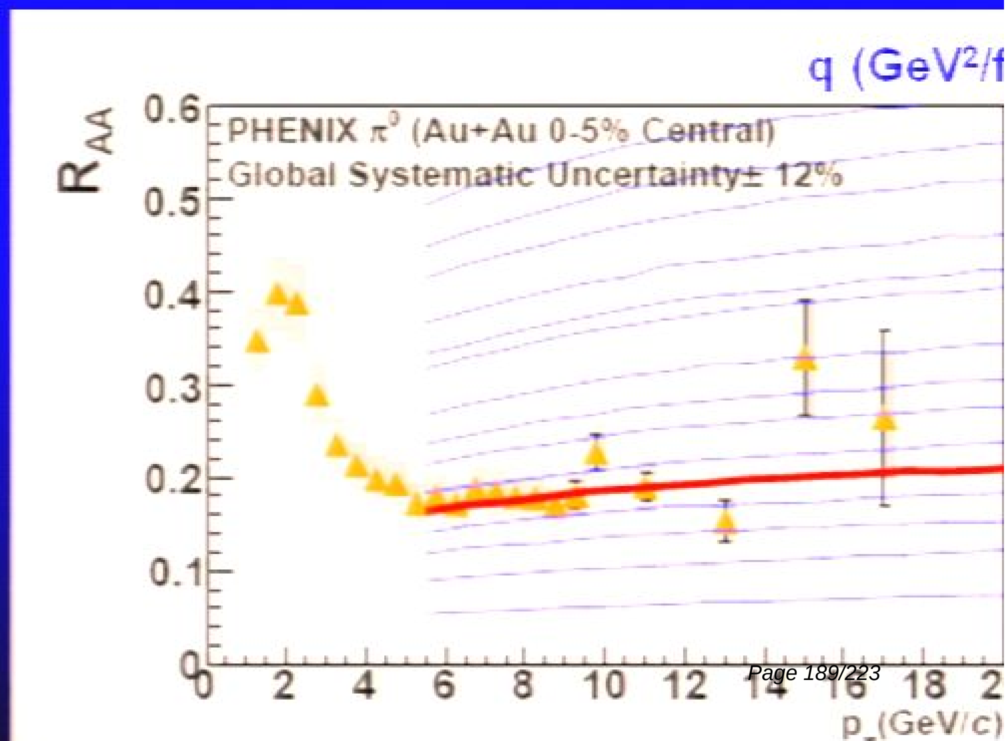

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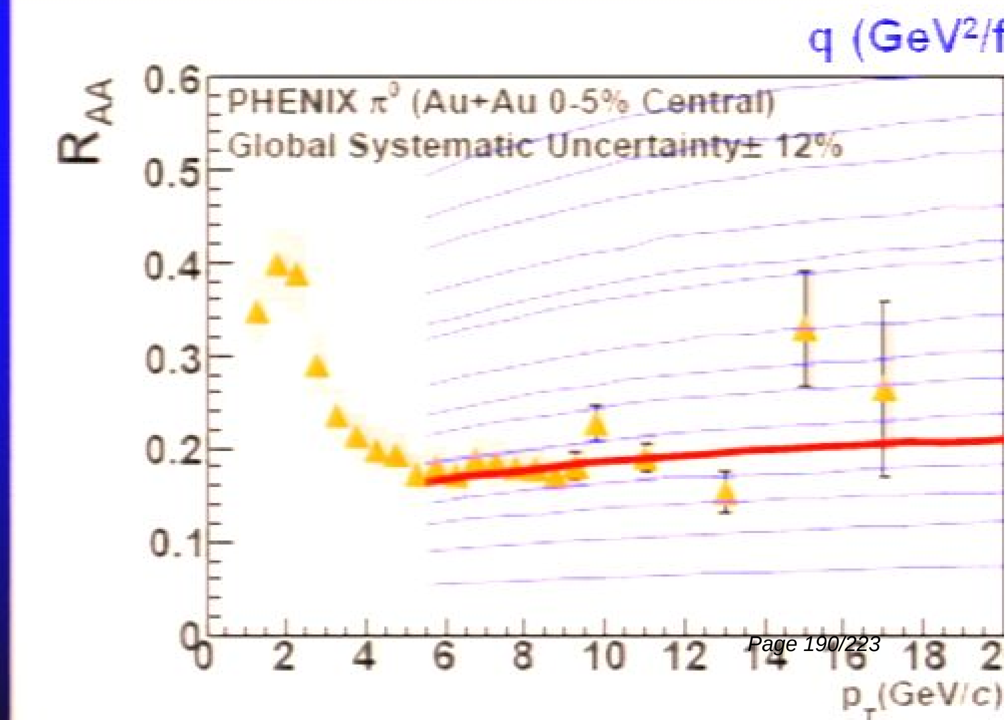

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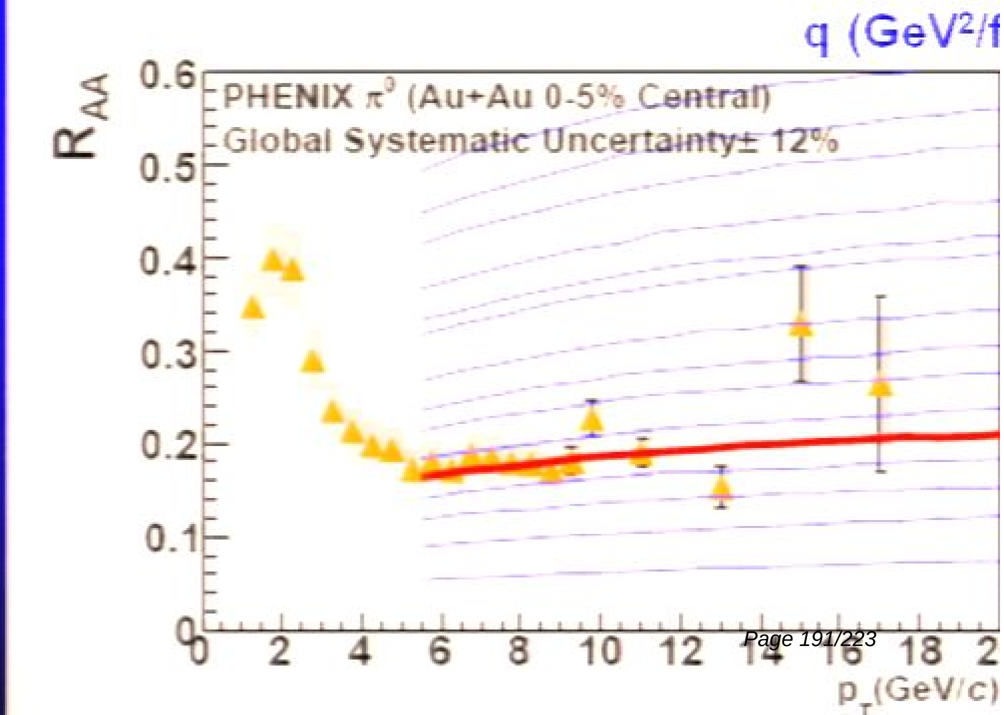

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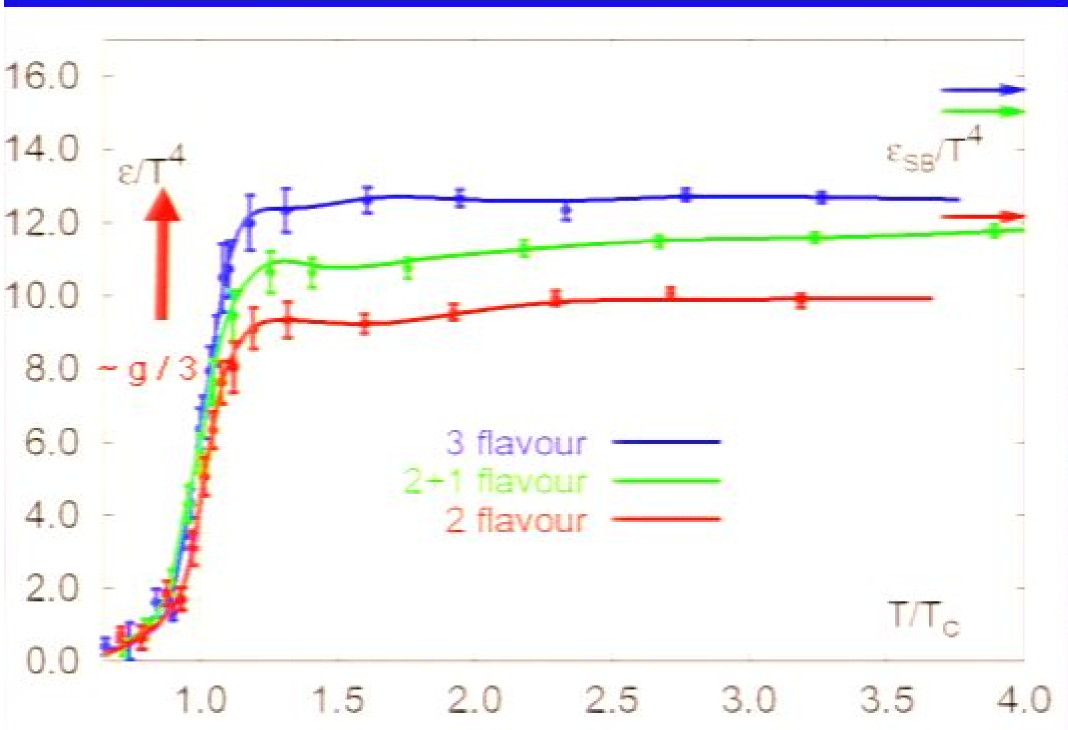
$$\frac{\varepsilon(T > T_c)}{\varepsilon_{Stefan-Boltzmann}} = 80\% \Rightarrow \text{almost asymptotically free}$$



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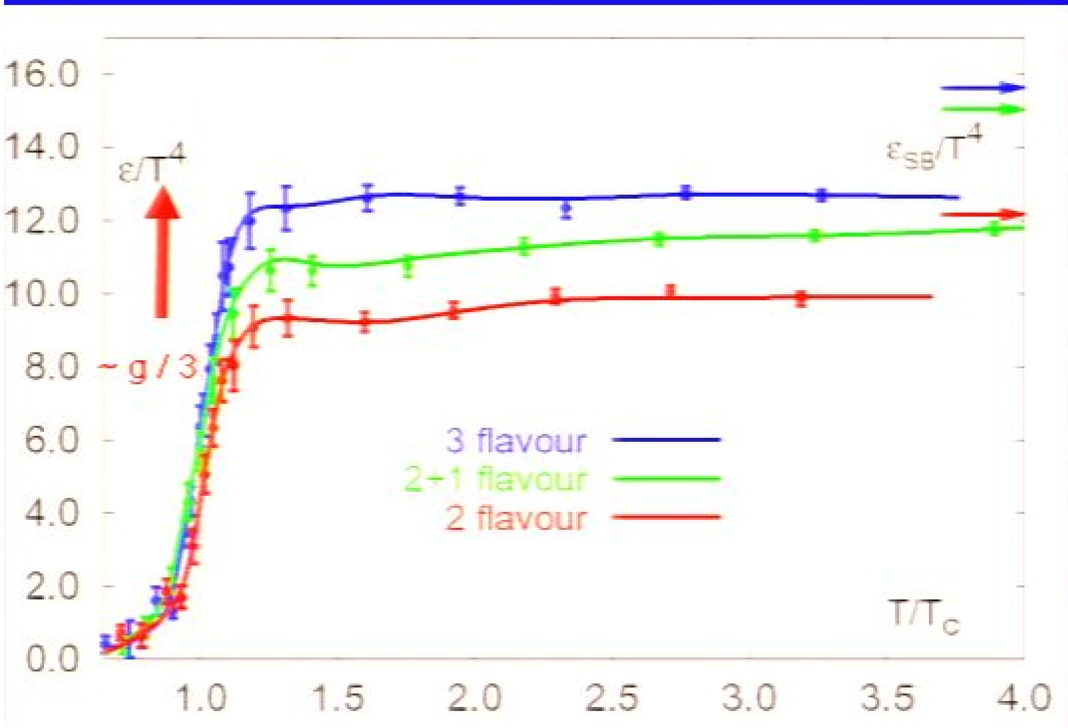

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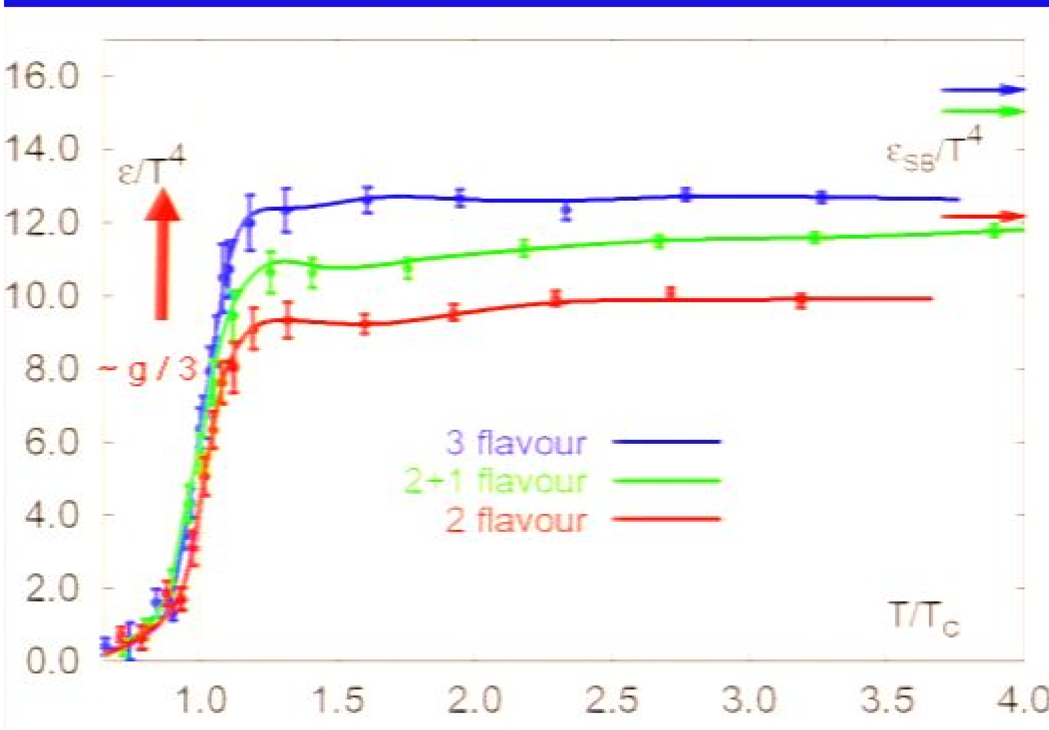

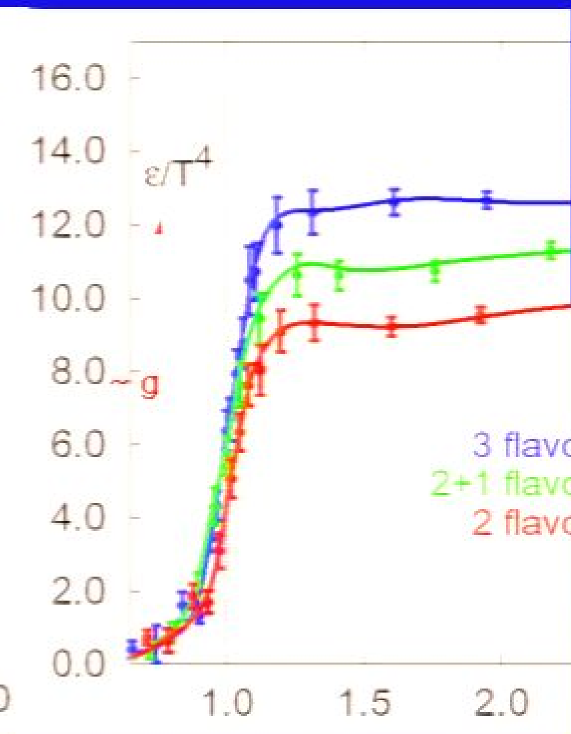

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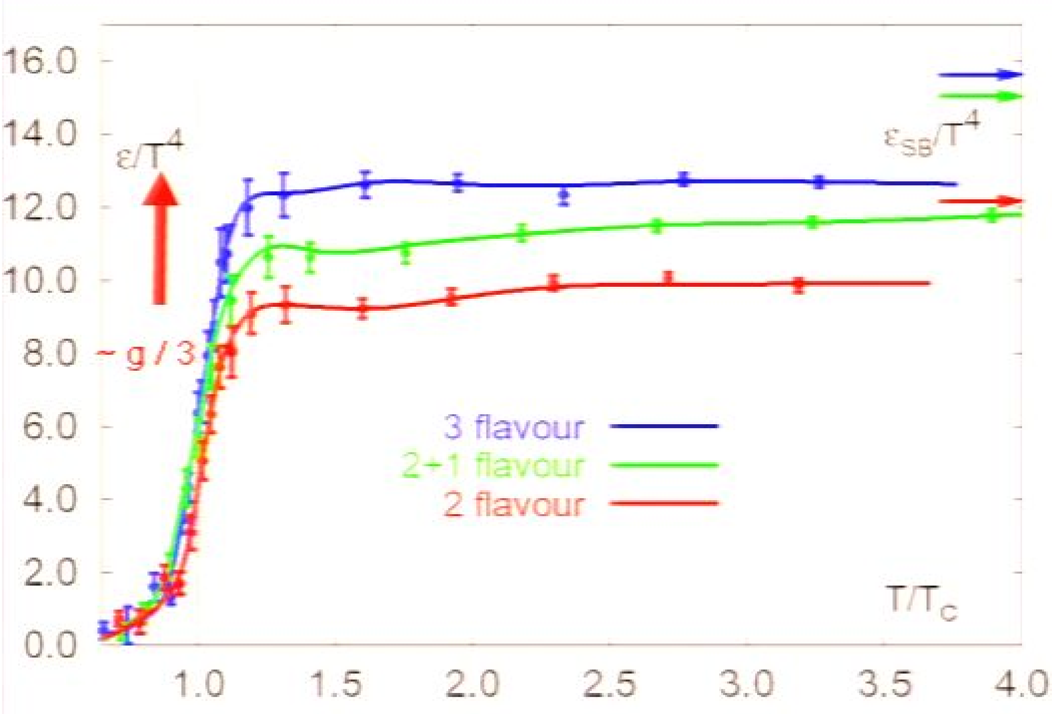

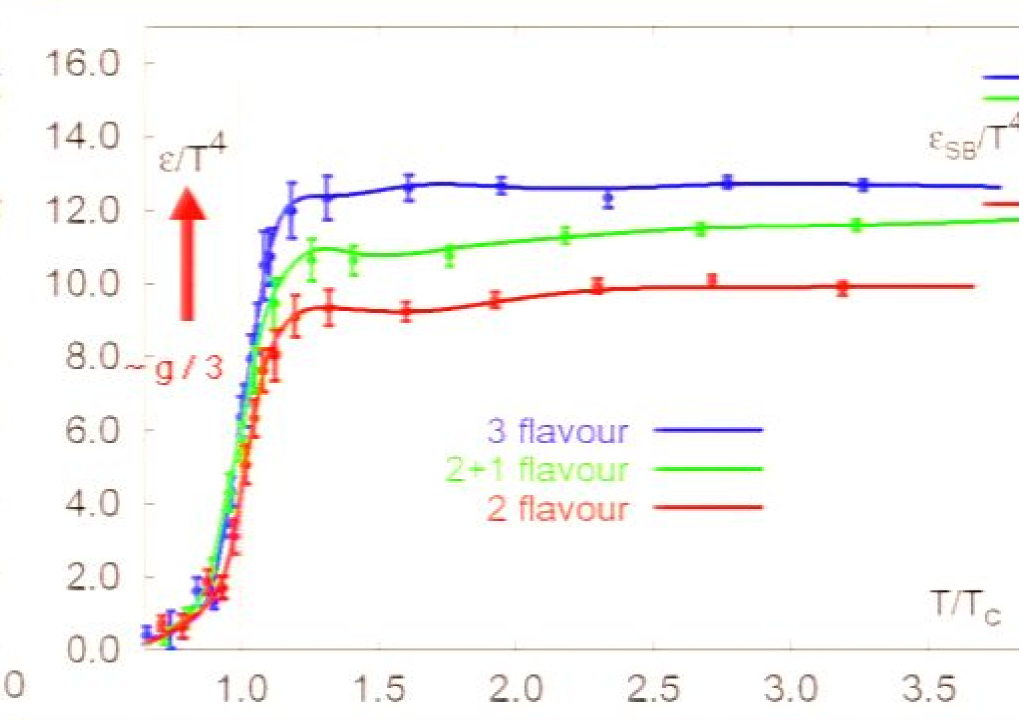

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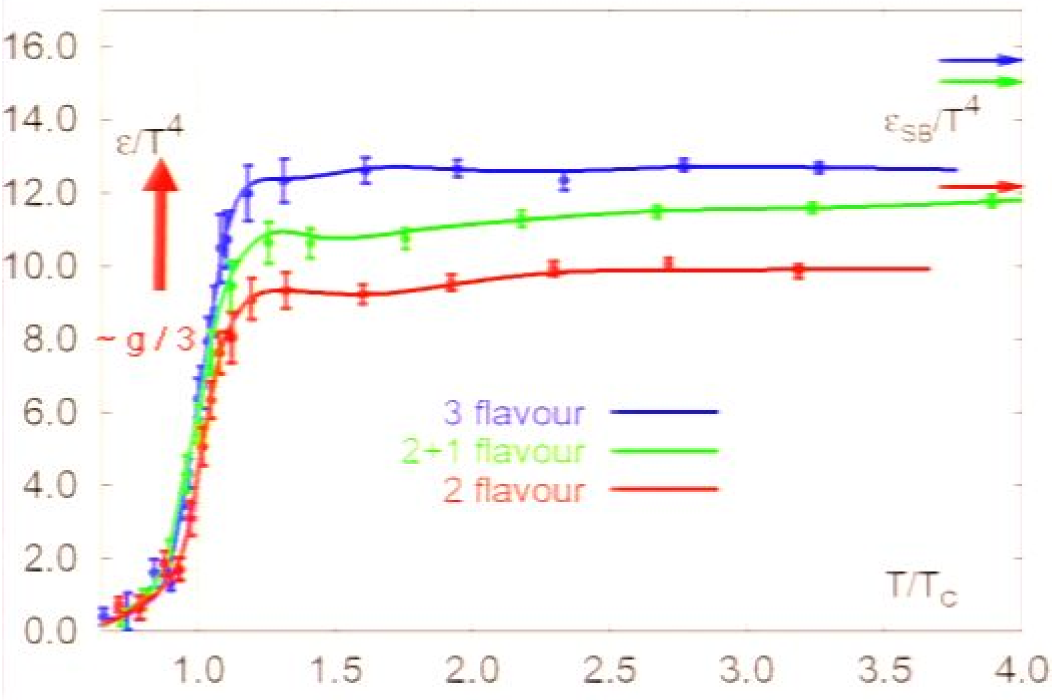

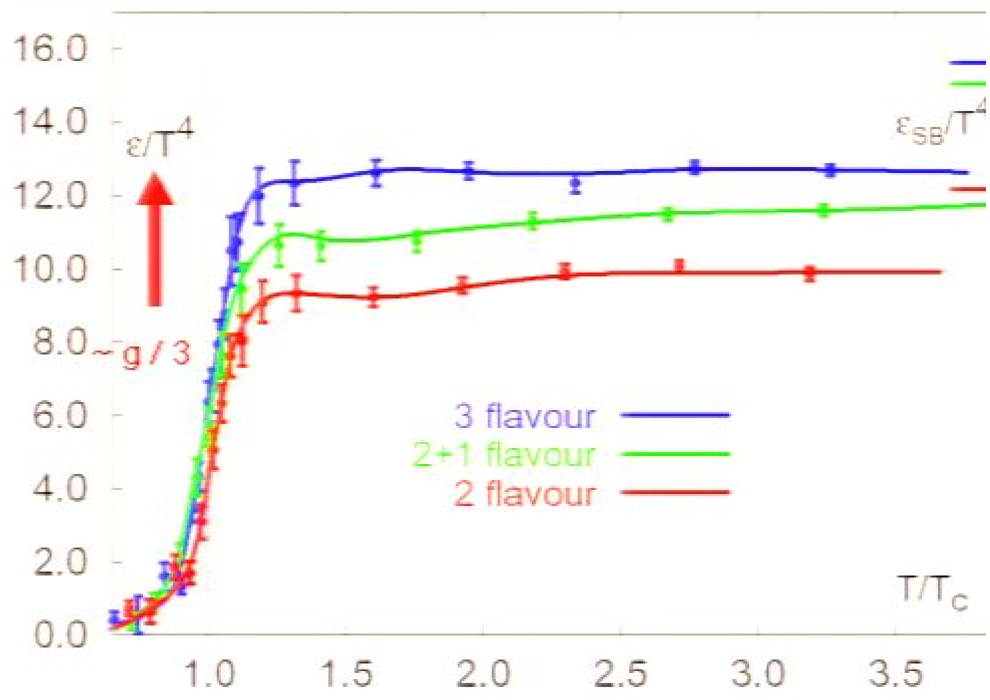

- 'Strongly' motivated by famous Gubser, Klebanov, Peet result

$$\frac{s(\lambda=\infty)}{s(\lambda=0)}$$

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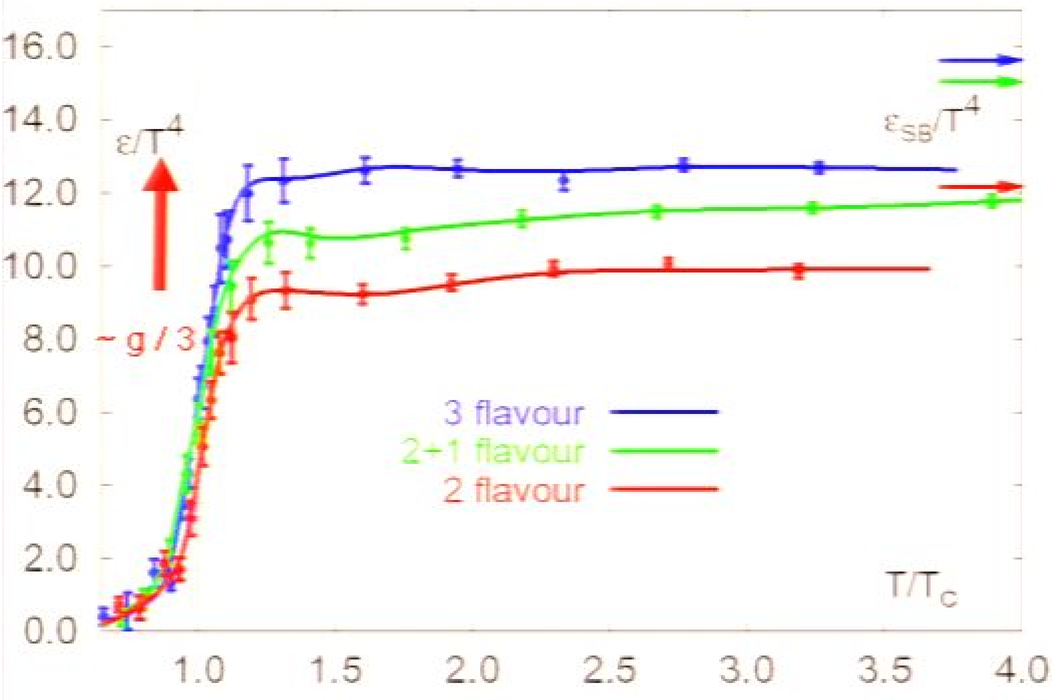

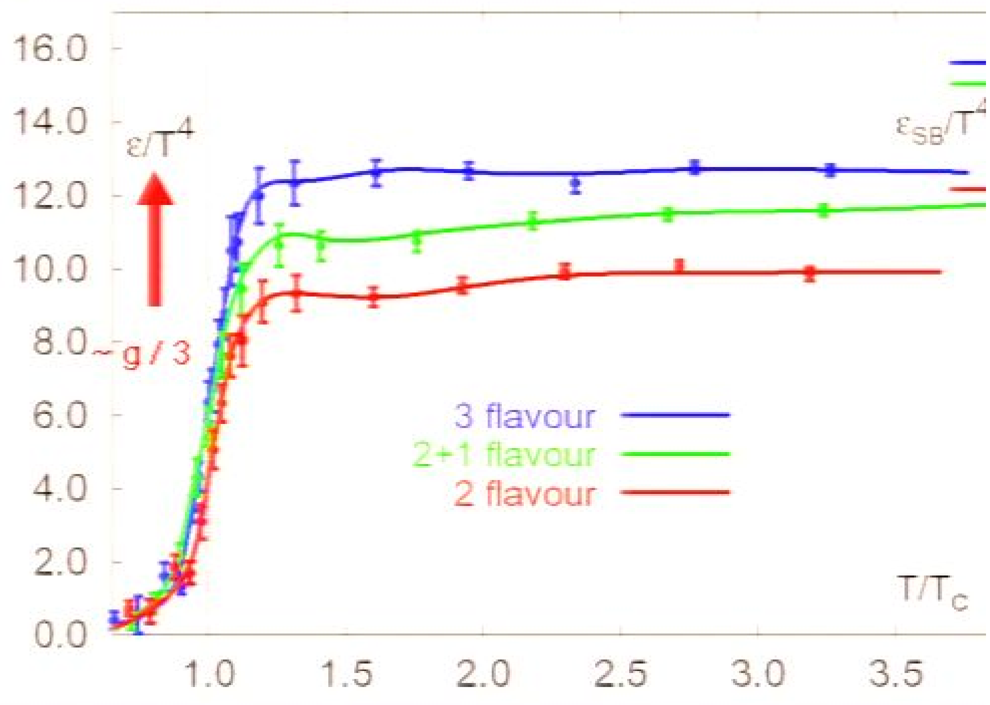

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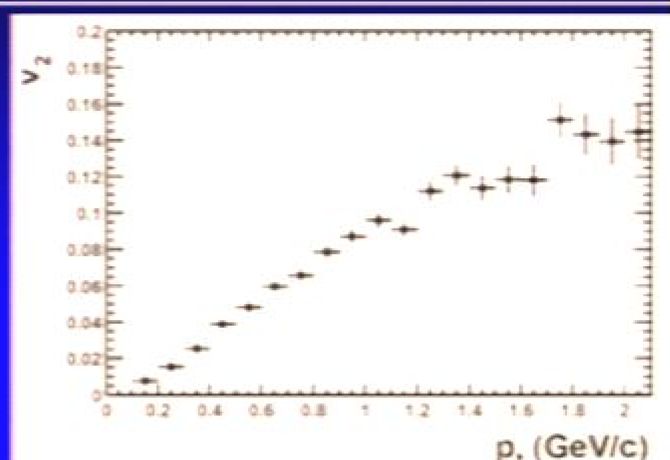
$$\frac{s(\lambda=\infty)}{s(\lambda=0)} = \frac{3}{4} = 75\%$$

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*



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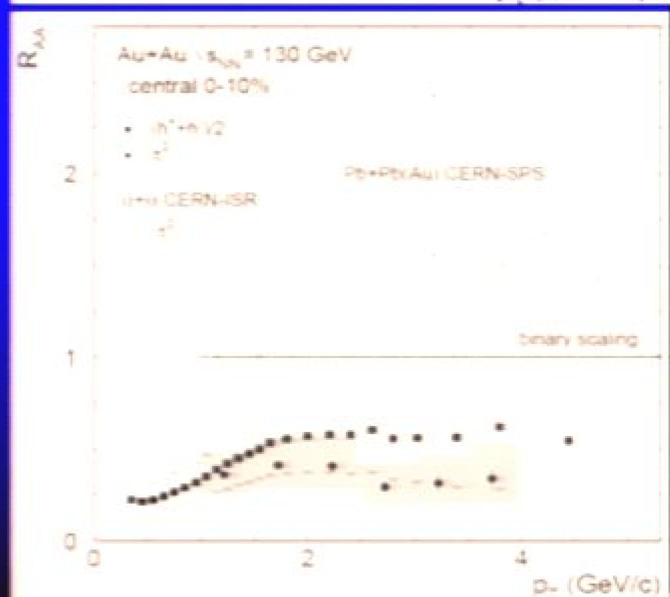

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04-Jun-08

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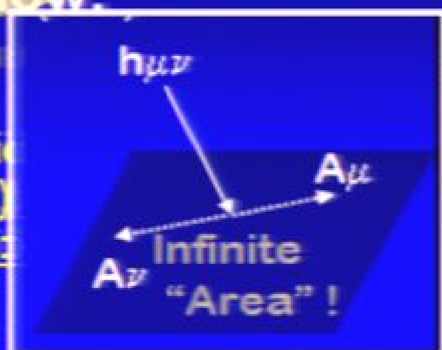

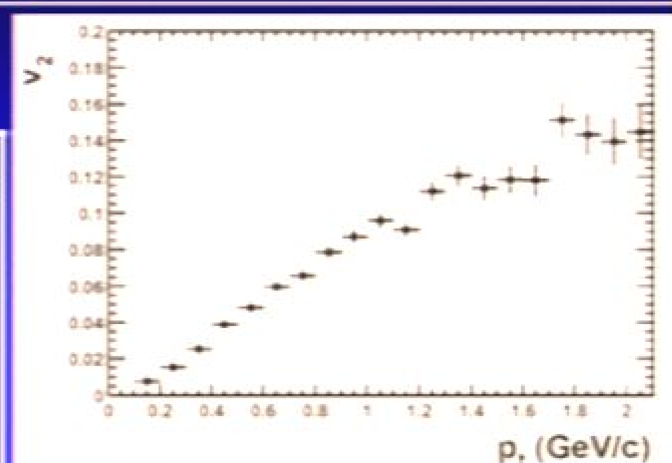

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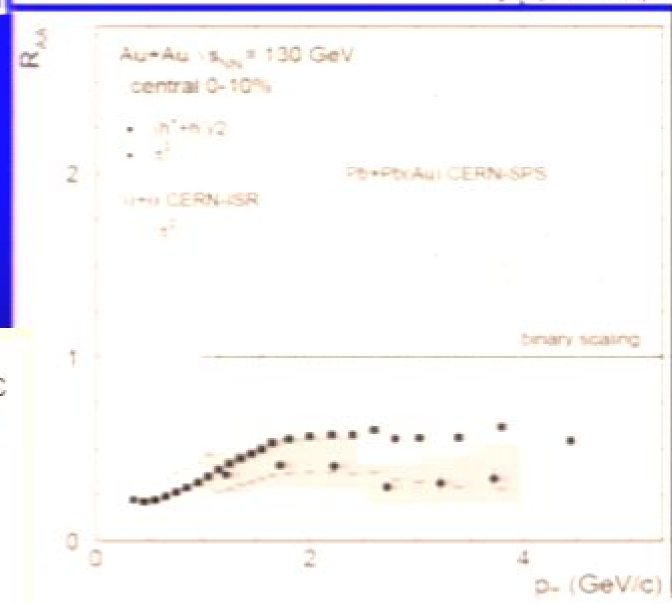

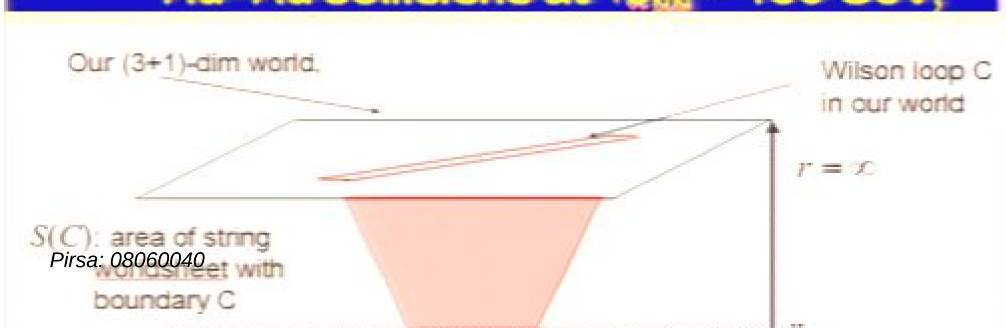

- Indicative of strongly coupled "QGP"
- Consistent to within factors of 2-3 with AdS/CFT results

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- The near-simultaneous development of
  - RHIC Discoveries
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☞ See next talk by Krishna Rajagopal for the theoretical details

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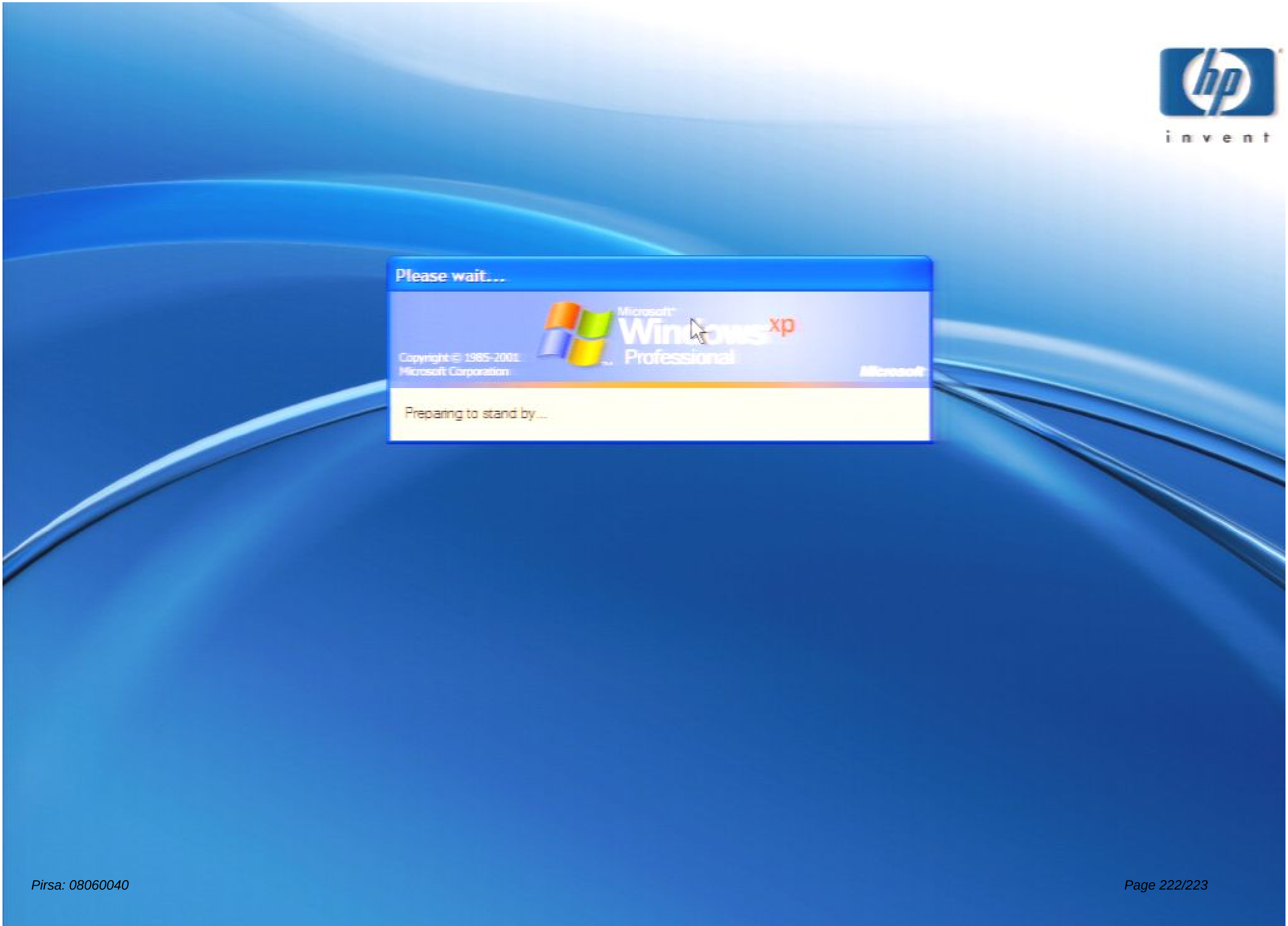
represents a true *paradigm shift*

in our understanding of thermal QCD

☞ See next talk by Krishna Rajagopal for the theoretical details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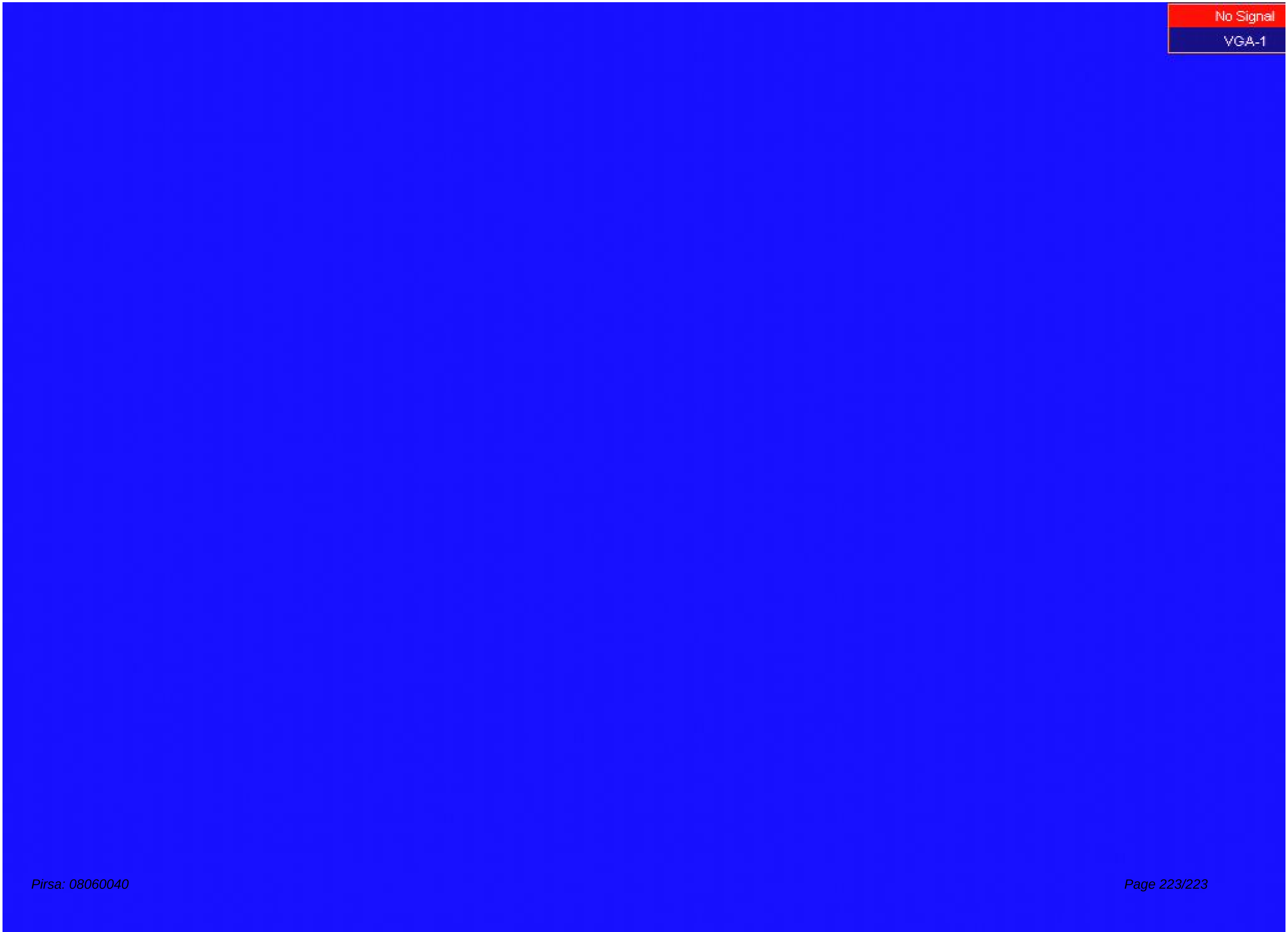
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