Introduction to Relativistic Heavy Ion Physics

Lecture 2: Experimental Discoveries

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Reminder- From Lecture 1

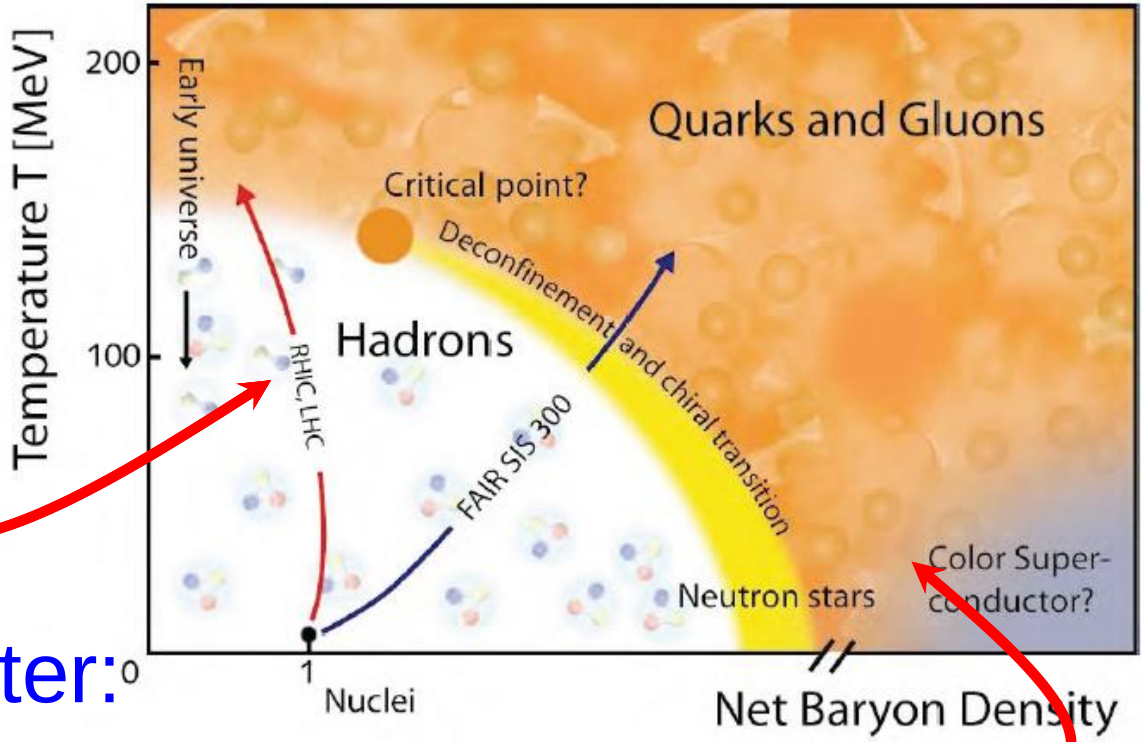
- General arguments suggest that for temperatures T ~ 200 MeV, nuclear matter will undergo a *deconfining* phase transition.
- Similar arguments suggest the required energy density is of order

$$\varepsilon \sim ndf\,\frac{\pi^2}{30}(200\,MeV)^4 \sim 37\,\frac{1}{3}\,\frac{(0.2\,GeV)}{fm^3} \sim 2.4\,GeV/\,fm^3$$

  - Note 1: normal nuclear density $\varepsilon_0 \sim 0.16$ GeV/fm^3
  - Note 2: Also true near T = 0, i.e., cold nuclear matter
- How to create study experimentally ?

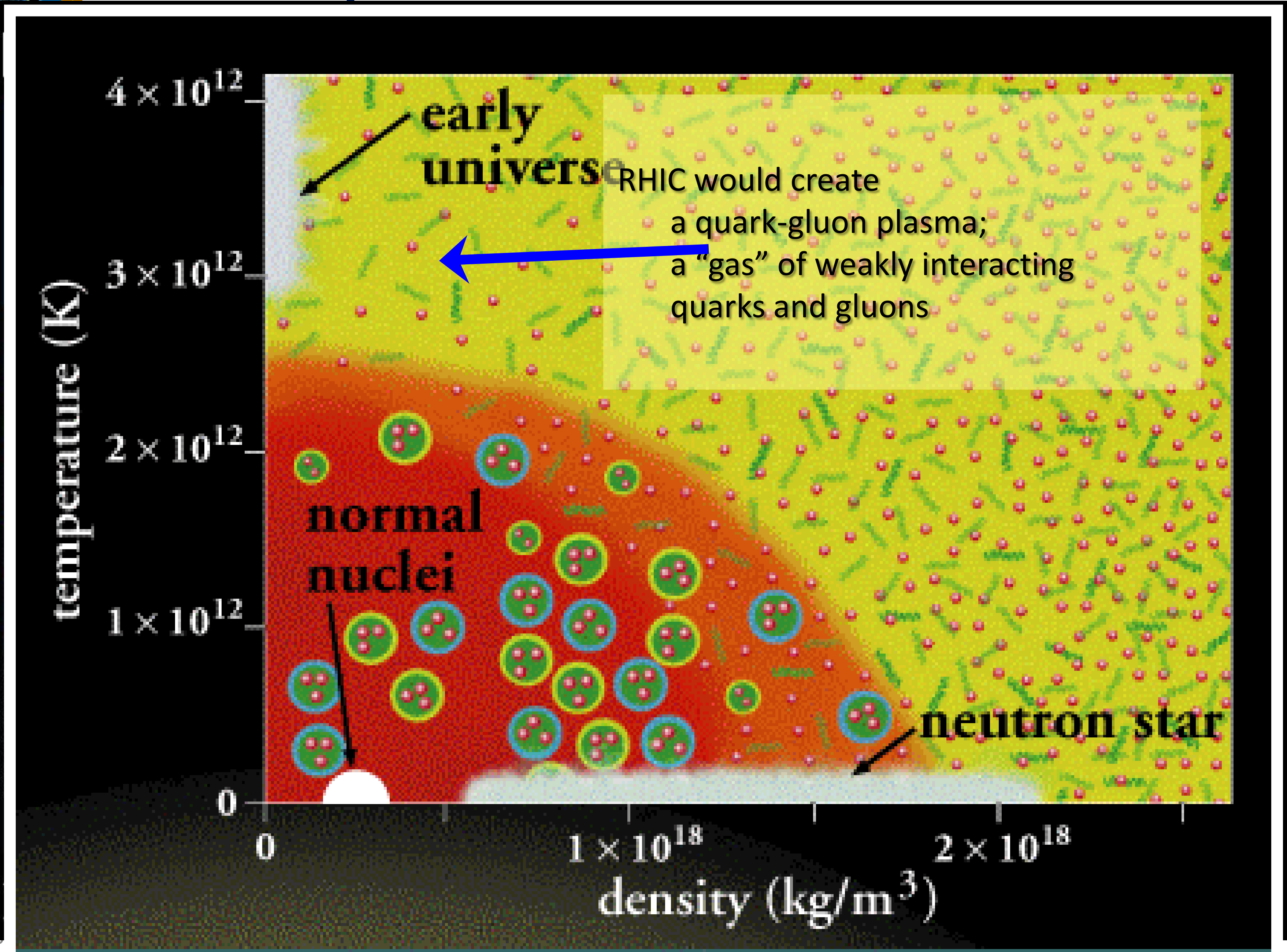
Exploring the QCD Phase Diagram

- Hot nuclear matter:
  - Study *experimentally* by colliding heaviest nuclei at highest energies:



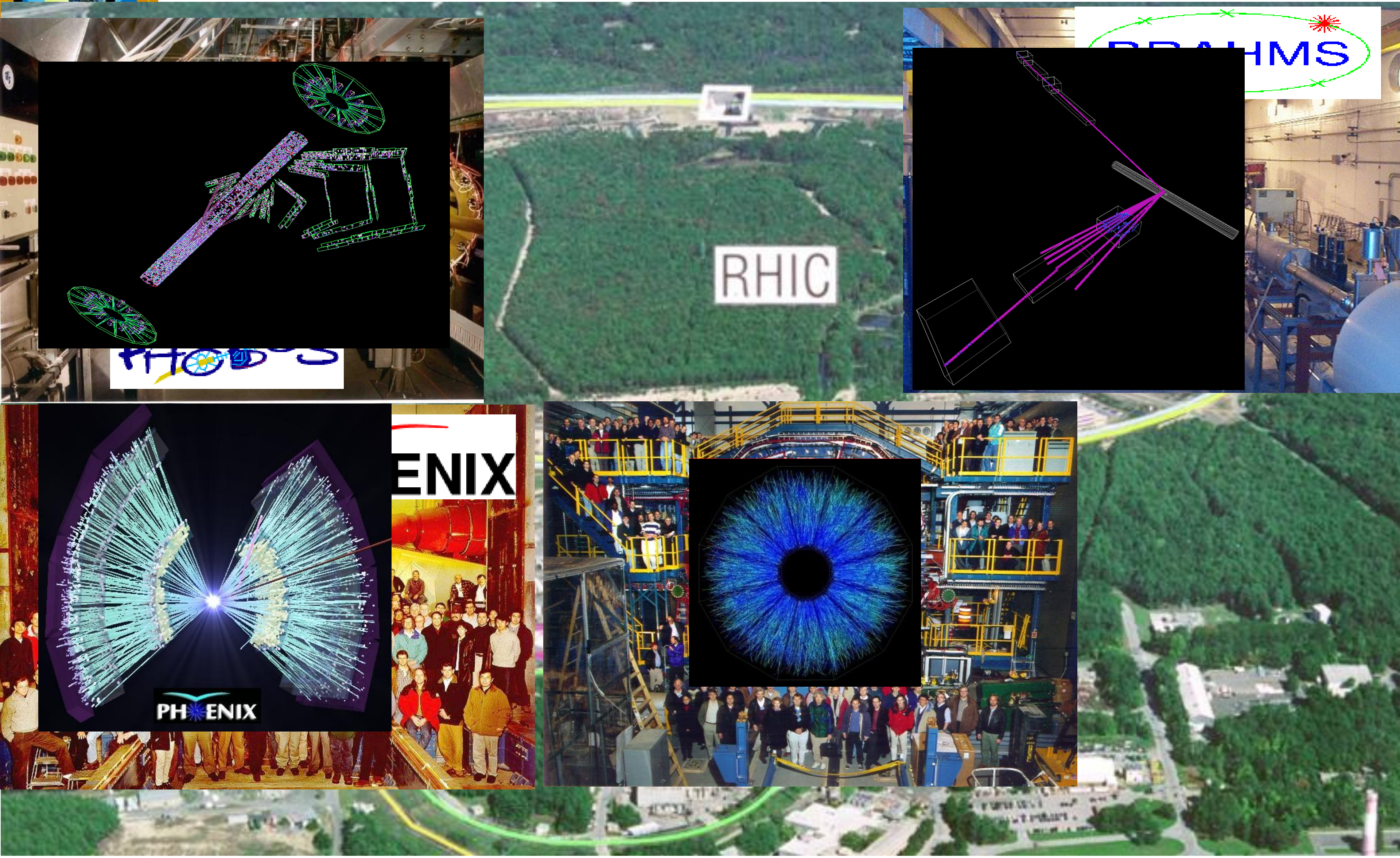
- Cold nuclear matter:
  - Study by *observation* of neutron stars and other exotic objects
  - (Not covered in these lectures)

Expectations circa 2000



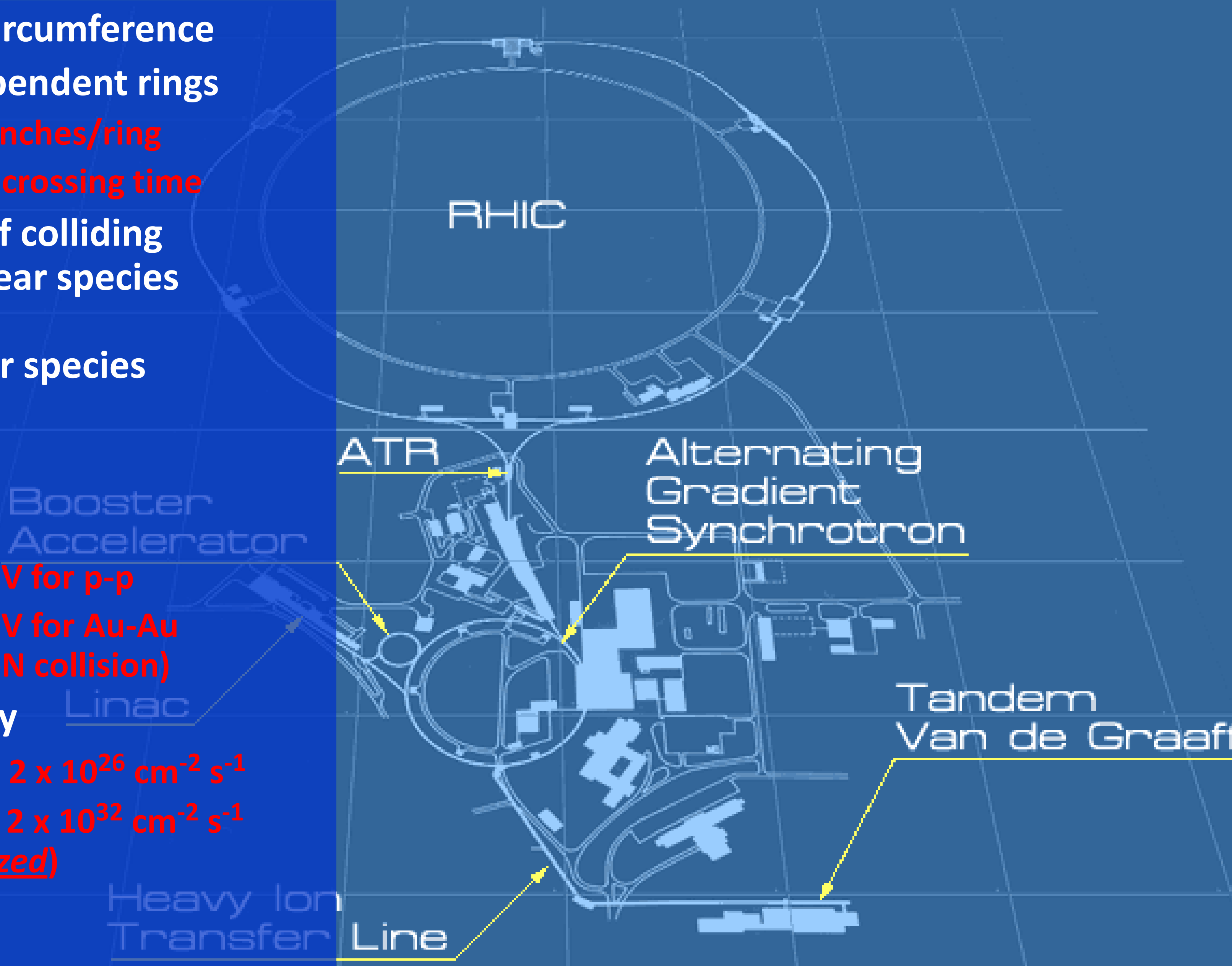
RHIC would create
a quark-gluon plasma;
a “gas” of weakly interacting
quarks and gluons

RHIC and Its Experiments



RHIC Specifications

- 3.83 km circumference
- Two independent rings
  - ❑ 120 bunches/ring
  - ❑ 106 ns crossing time
- Capable of colliding ~any nuclear species on ~any other species
- Energy:
  - ➔ 500 GeV for p-p
  - ➔ 200 GeV for Au-Au (per N-N collision)
- Luminosity
  - ❑ Au-Au: 2 x 10^{26} cm^{-2} s^{-1}
  - ❑ p-p : 2 x 10^{32} cm^{-2} s^{-1} (*polarized*)



How is RHIC Different?

- Different from p-p, e-p colliders

  Atomic weight A introduces new scale $Q^2 \sim A^{1/3} Q_0^2$

- Different from previous (fixed target) heavy ion facilities
  - ❑ E_{CM} increased by order-of-magnitude
  - ➔Accessible x (parton momentum fraction) decreases by ~ same factor

$$x \sim \frac{2\,p_T}{\sqrt{s}}$$

  - ➔Access to perturbative phenomena
    - ♦ Jets
    - ♦ Non-linear dE/dx

Jargon Alert:
$\sqrt{s}$ = Center-of-mass energy (per nucleon collision)
p_T = transverse momentum = $|p| \sin\theta$
Q^2 = (momentum transfer)^2

- Its detectors are <u>comprehensive</u>
  - ➔~All final state species measured with a suite of detectors that nonetheless have significant overlap for comparisons

The Plan circa 2000

- Use RHIC’s unprecedented capabilities
    - Large $\sqrt{s}$ ⇨
        - Access to reliable pQCD probes
        - Clear separation of valence baryon number and glue
        - To provide definitive experimental evidence for/against Quark Gluon Plasma (QGP)
    - Polarized p+p collisions

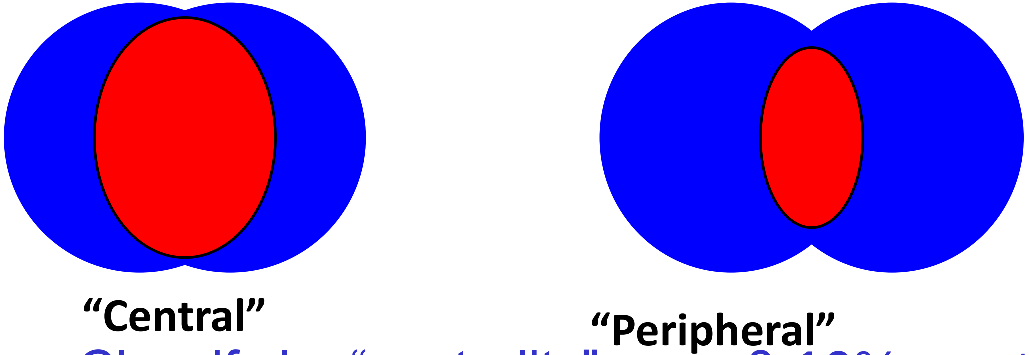
- Two small detectors, two large detectors
    - Complementary capabilities
    - Small detectors envisioned to have 3-5 year lifetime
    - Large detectors ~ facilities
        - Major capital investments
        - Longer lifetimes
        - Potential for upgrades in response to discoveries

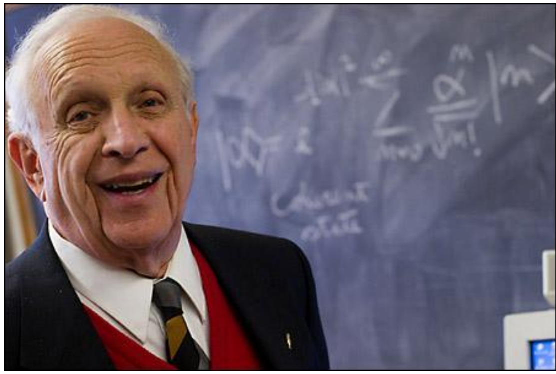
Since 2000…

- Accelerator complex
  - Routine operation at 2-4 x design luminosity (Au+Au)
  - Extraordinary variety of operational modes
    - Species: Au+Au, d+Au, Cu+Cu, p↑+p↑
    - Energies: 22 GeV (Au+Au, Cu+Cu, p↑), 56 GeV (Au+Au), 62 GeV (Au+Au,Cu+Cu, p↑+p↑) , 130 GeV (Au+Au), 200 GeV (Au+Au, Cu+Cu, d+Au, p↑+p↑), 410 GeV (p↑), 500 GeV (p↑)
- Experiments:
  - Worked !
- Science
  - More than 200 refereed publications, among them 100+ PRL's
  - *Major* discoveries
- Future
  - Demonstrated ability to upgrade
  - Key science questions identified
  - Accelerator and experimental upgrades underway for that science

Assertion

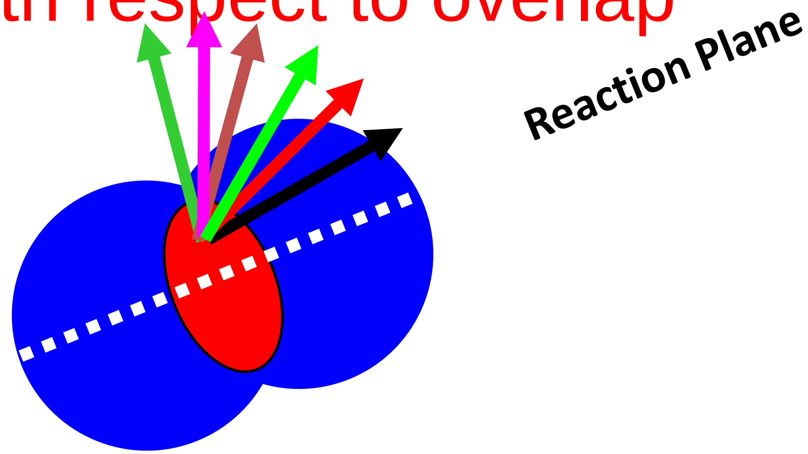
- In these complicated events, we have (*a posteriori*) control over the event geometry:
  - Degree of overlap





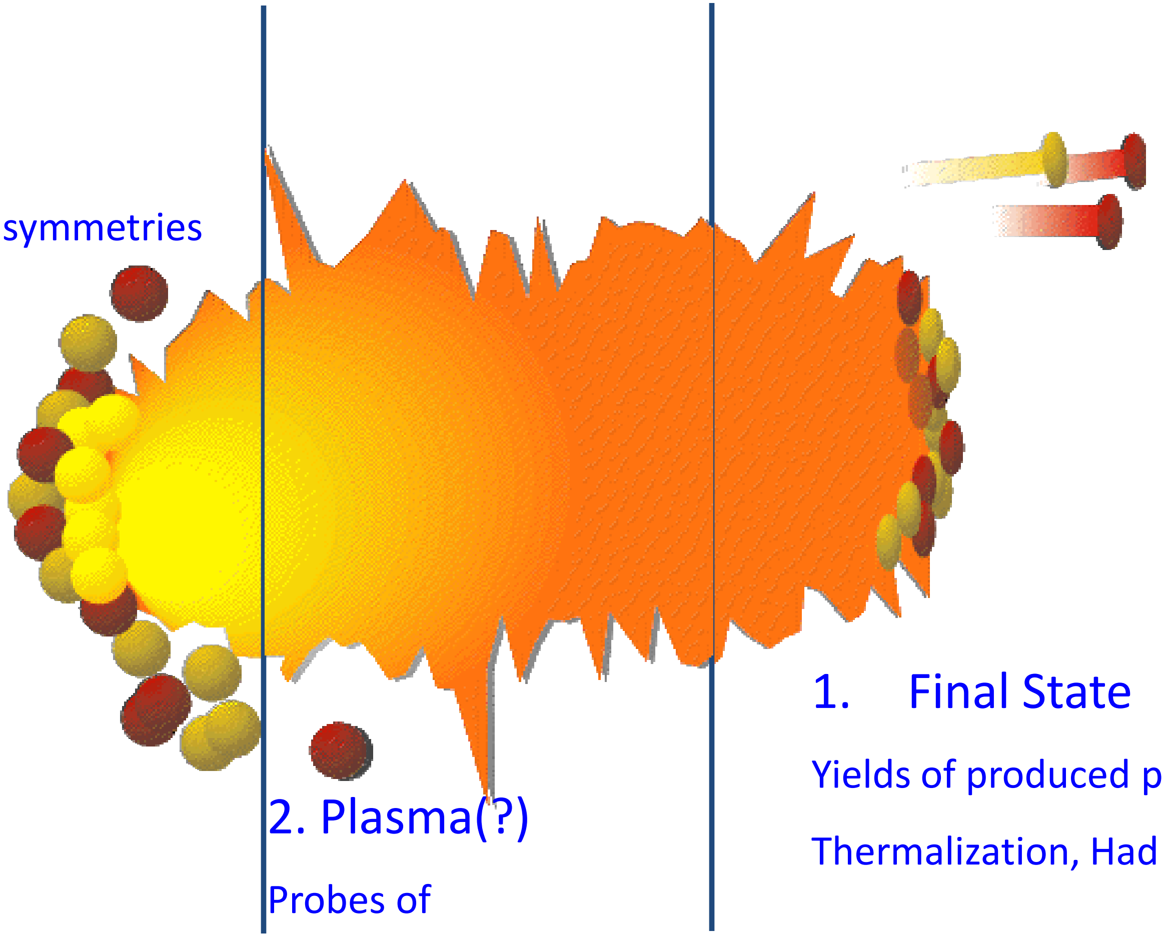
Classify by "centrality", e.g., 0-10% most central events

  - Orientation with respect to overlap



Outline

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



3. Initial State

Hydrodynamic flow
from
initial spatial asymmetries

2. Plasma(?)

Probes of
dense matter

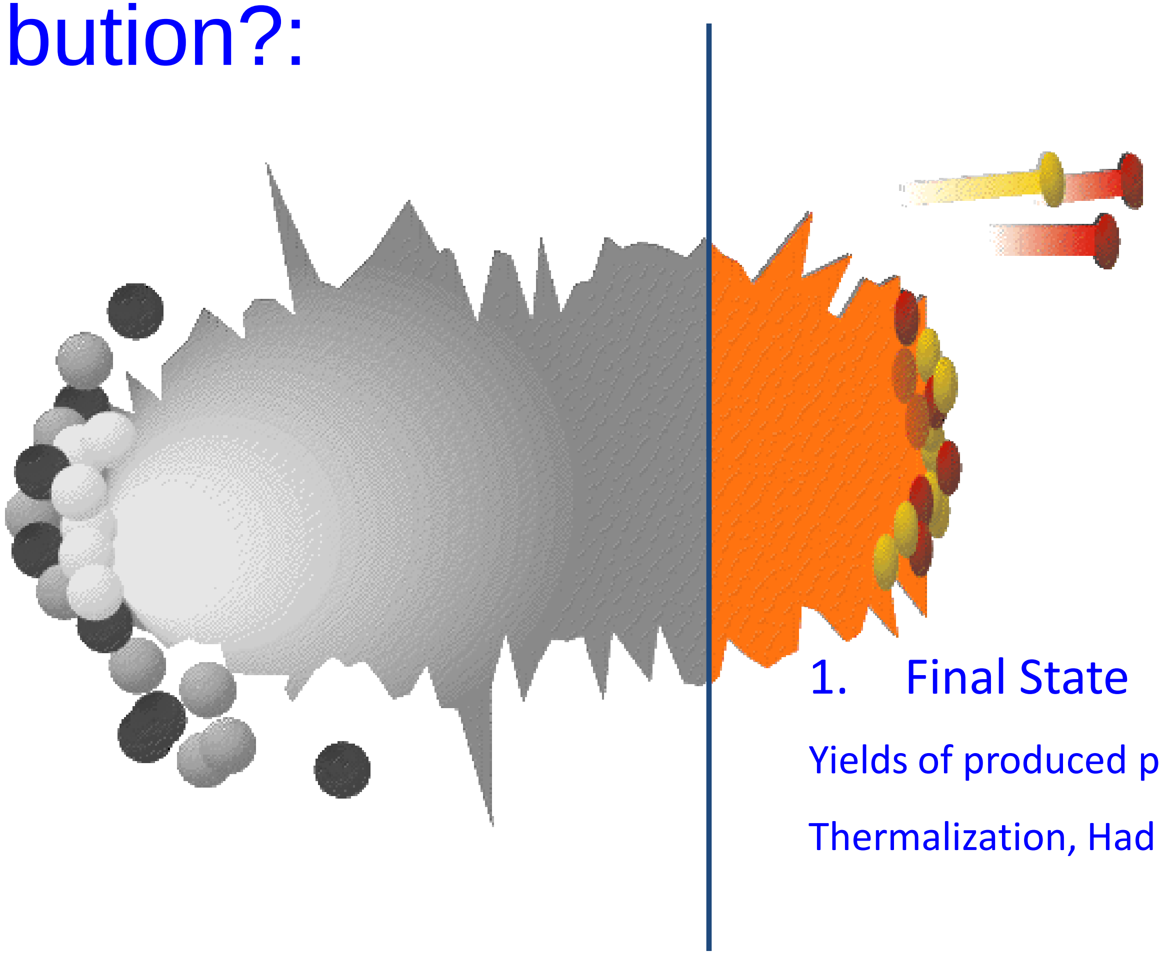
1. Final State

Yields of produced particles

Thermalization, Hadrochemistry

Final State

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



1. Final State

Yields of produced particles

Thermalization, Hadrochemistry

Origin of the (Hadronic) Species

- Thermal? Apparently:
  - Assume all distributions described by one temperature T and one (baryon) chemical potential μ :

$$dn \sim e^{-(E-\mu)/T} d^3p$$

  - One ratio (e.g., $\bar{p}$ / p) determines μ / T :

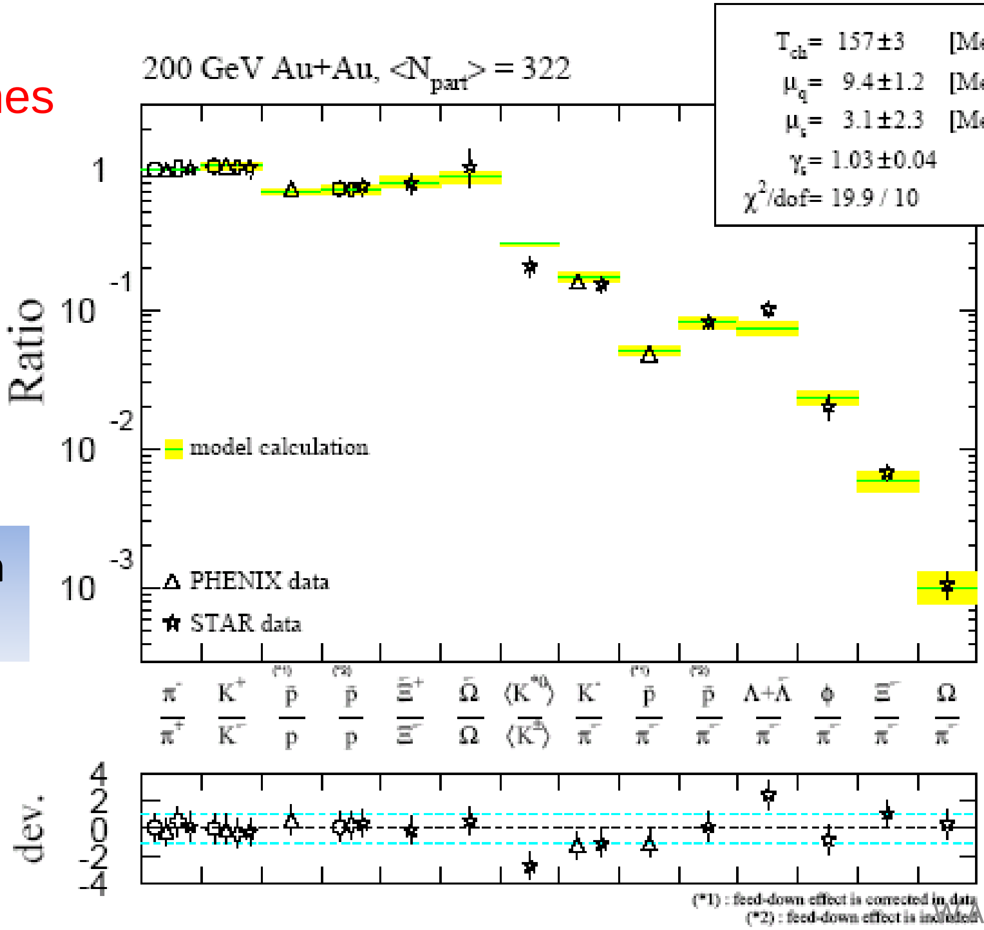
$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu)/T}}{e^{-(E-\mu)/T}} = e^{-2\mu/T}$$

  - A second ratio (e.g., K / π) provides T ➔ μ

Exercise 1: Find T and μ from data at right

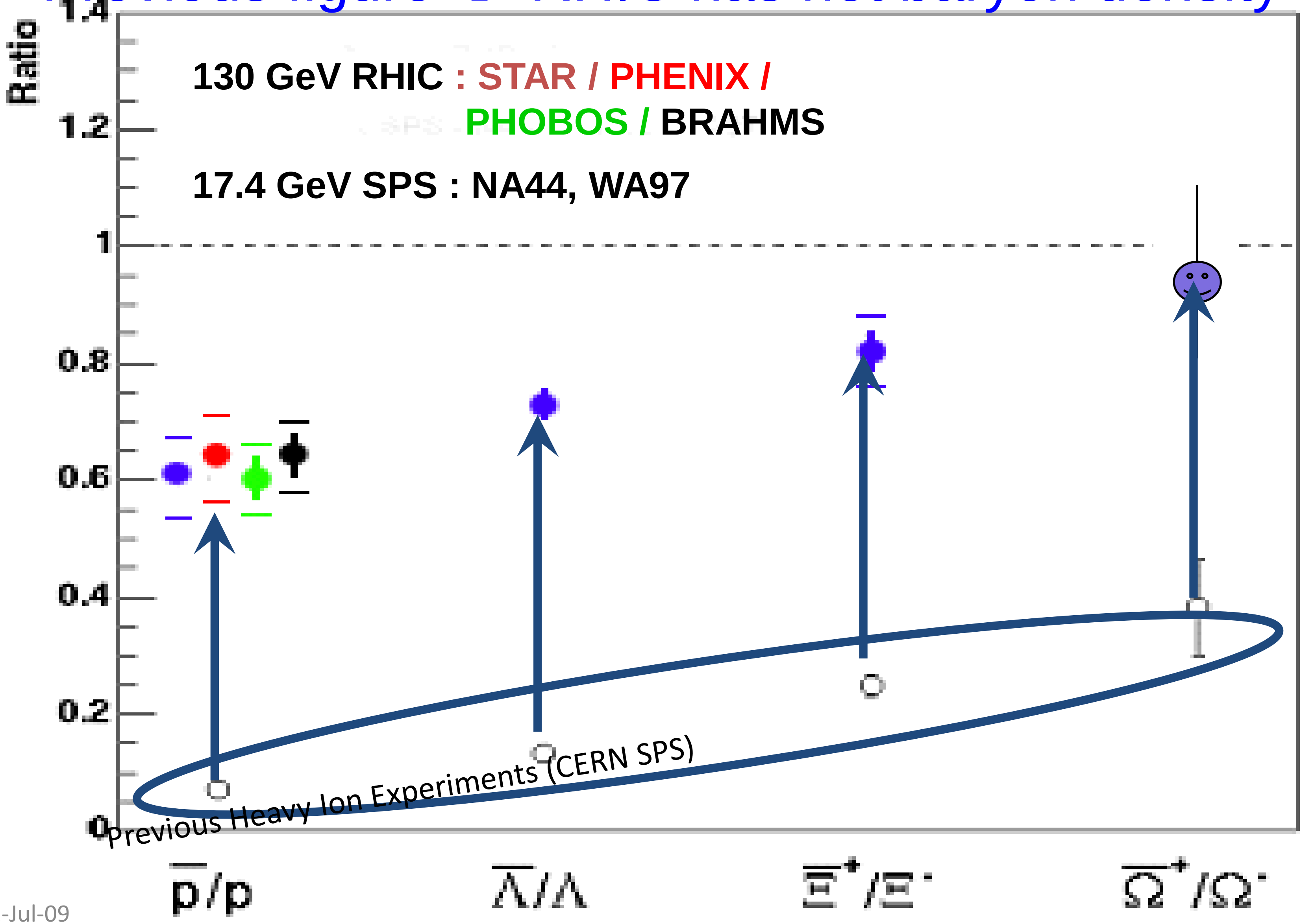
- Then predict all other hadronic yields and ratios:
- NOTE: Truly thermal implies *No memory (!)*

$\pi^{\pm}$, π^0, $K^{\pm}$, $K^{*0}(892)$, K_S^0, η, p, d, ρ^0, ϕ, Δ, Λ, Σ*(1385), Λ*(1520), $\Xi^{\pm}$, Ω, D^0, $D^{\pm}$, J/Ψ's, (+ anti-particles) … ➡T ~ 170 MeV ~ 2 x 10^{12} K



Locating RHIC on Phase Diagram

- Previous figure ➔ RHIC has net baryon density ~ 0:



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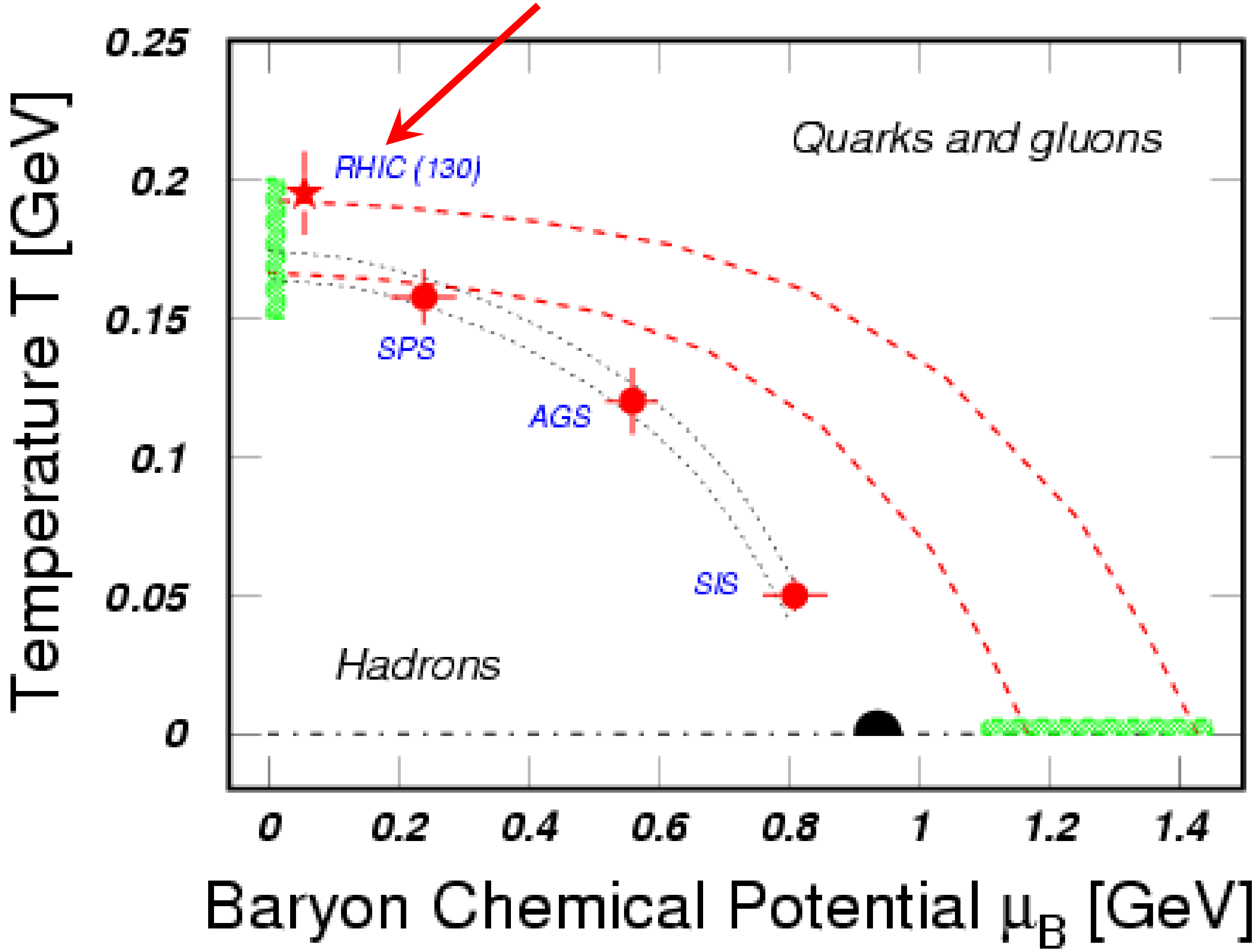
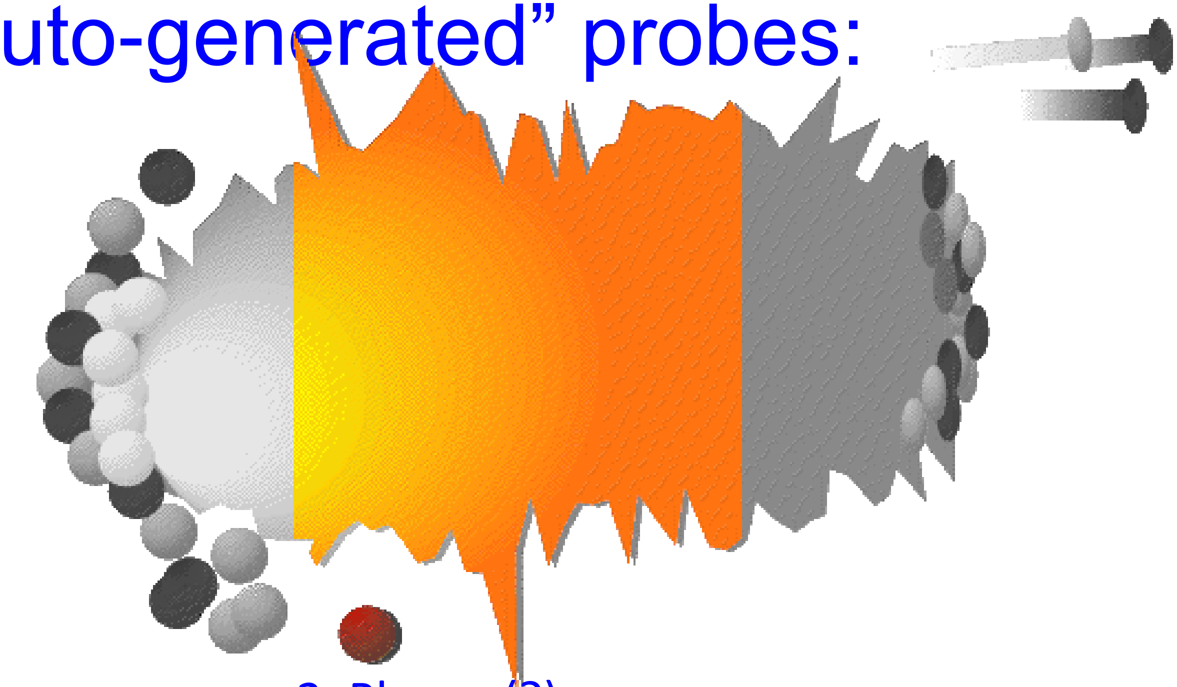


➔RHIC is as close as we’ll get to the early universe for some time (until next year ☺)

Probes of the Plasma(?) State

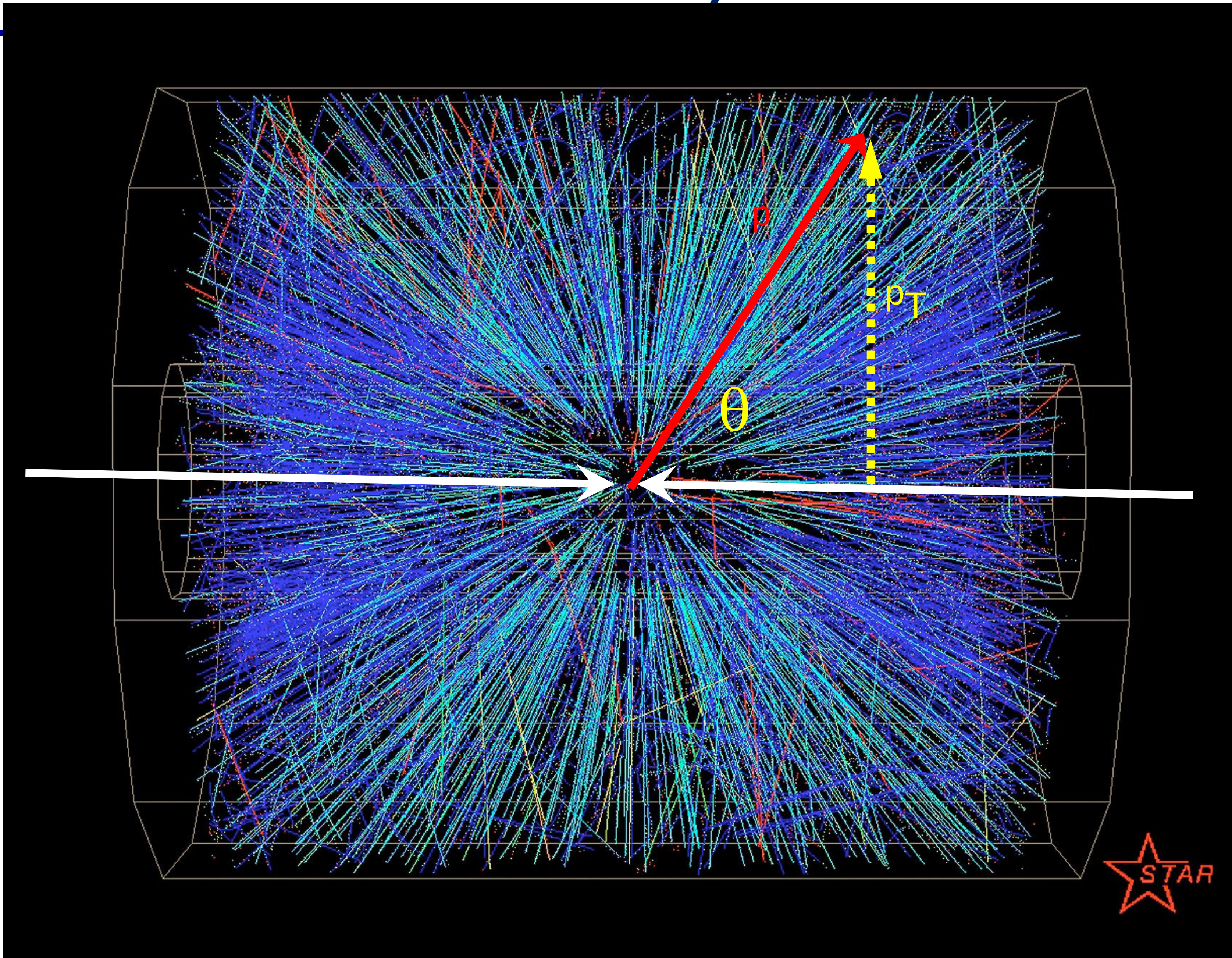
Q. How dense is the matter?

A. Do Rutherford scattering on deep interior using "auto-generated" probes:



Probes of
dense matter

Transverse Dynamics



Kinematics 101

Fundamental single-particle observable:

Momentum Spectrum

$$E\frac{d^3\sigma}{dp^3}$$

Exercise 2: Remind yourself why this is invariant

Kinematics

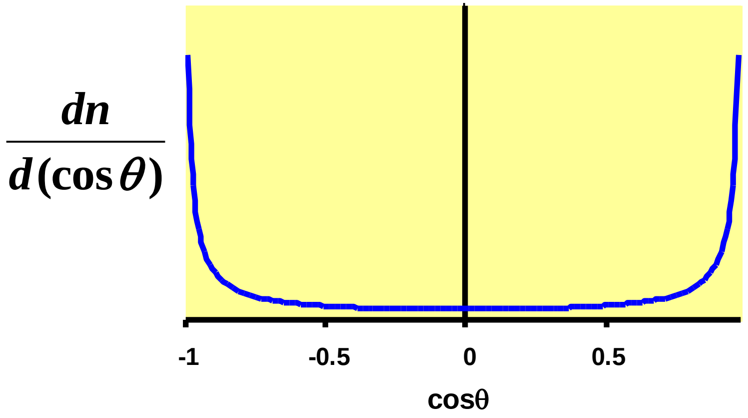
$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \Rightarrow \frac{d^3\sigma}{d^2p_T\,dy}$$

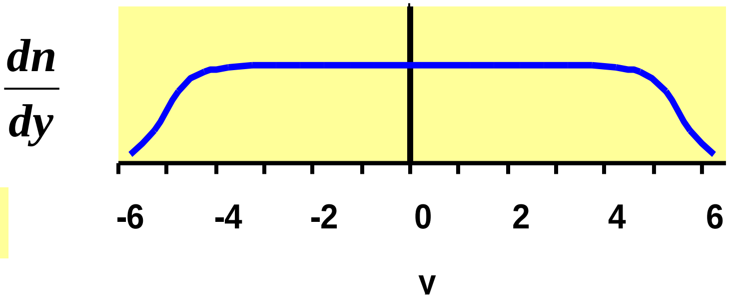
Exercise 3: Show that y is *additive* under Lorentz transformations.
Use this to show dy = dβ .

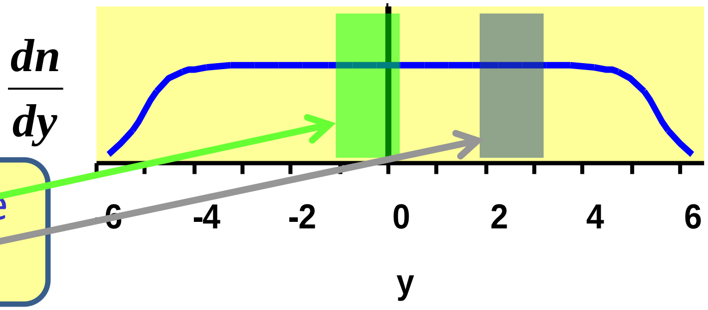
Dynamics

$$\sim \frac{d^2\sigma}{d^2p_T}\cdot\frac{dn}{dy}$$

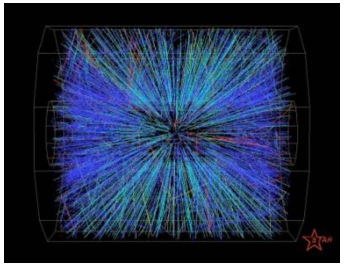
Observation: *Roughly* the same pT spectra here and here





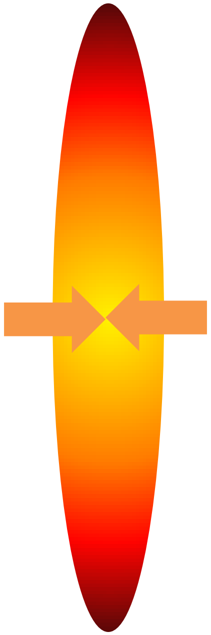


Aside- Estimating Energy Density



- This will be an incredibly crude (wrong) estimate:
  - Take all ~10,000 particles produced in Au+Au collision at RHIC
  - Assume the ~constant $<p_T>$ ~ 0.4 GeV represents “thermalized” energy
  - Initial volume
    - R_{Au} ~ 6.5 fm
    - Δz ~ 1/T ~ 1 fm
  - Energy density

    $\varepsilon \sim (10^4 \text{ x } 0.4 \text{ GeV}) / (\pi R_{Au}^2 \text{ x } 1 \text{ fm}) \sim 30 \text{ GeV/fm}^3$



Dynamics 101

Q. How to really (?) estimate initial energy density?

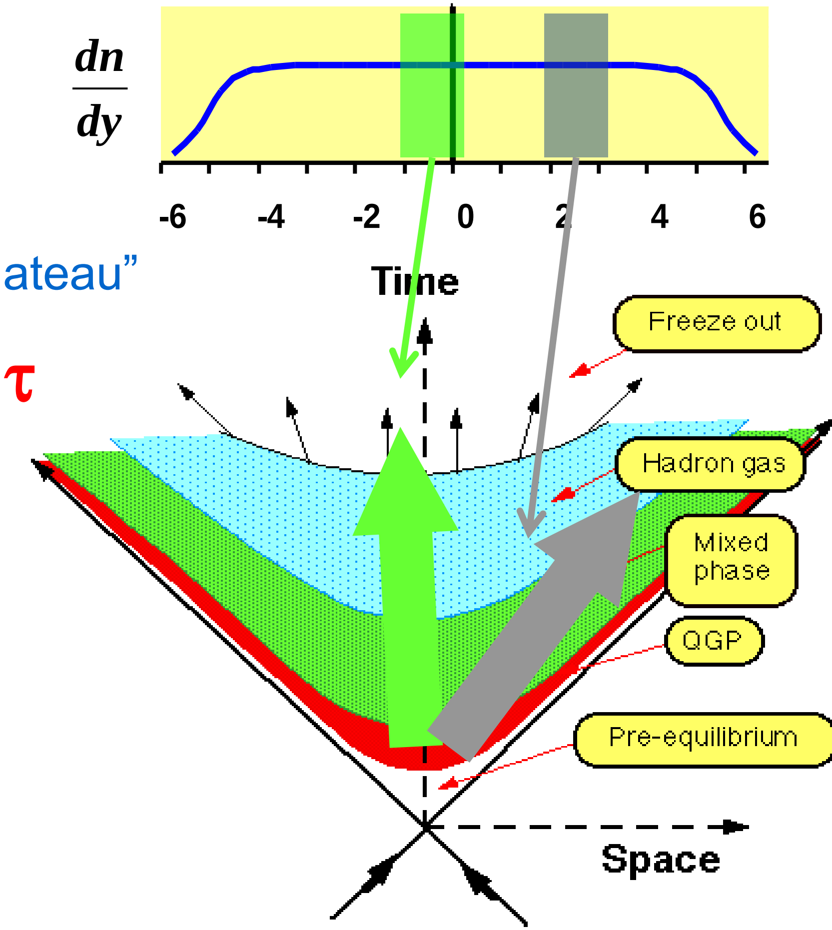
A. From *rapidity density* of transverse energy $E_T \equiv \Sigma_i E_i \sin\theta_i$

- "*Highly relativistic nucleus-nucleus collisions: The central rapidity region*", J.D. Bjorken, Phys. Rev. D27, 140 (1983).
- Assumes
  - ~ 1-d hydrodynamic expansion
  - *Invariance* in y along "central rapidity plateau" (I.e., flat rapidity distribution)
  - Then

$$\varepsilon = \frac{E}{V} \sim \frac{dE_T}{\pi R_T^{\,2} \cdot dz} = \frac{1}{\pi R_T^{\,2} \cdot \tau} \frac{dE_T}{dy}$$

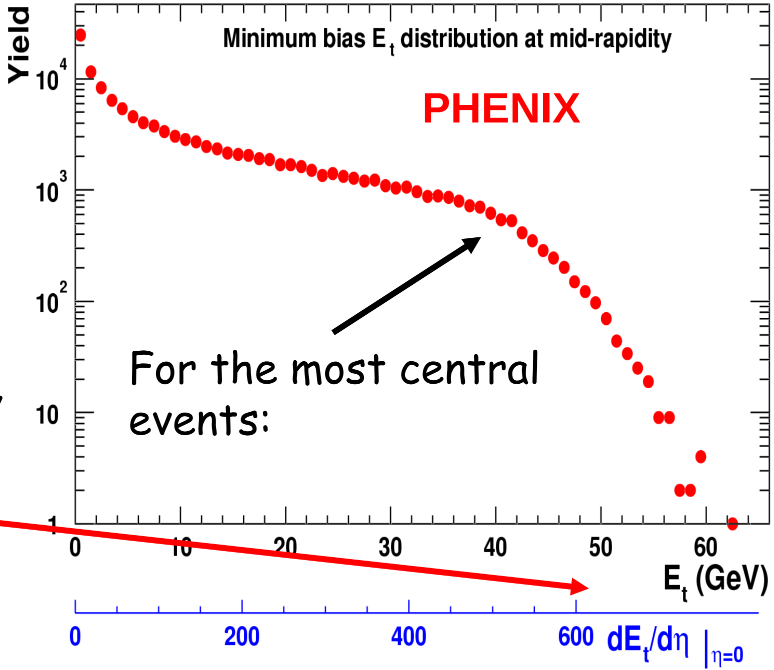
since boost-invariance of matter

$\Rightarrow$ $dz = \tau\, dy$ where $\tau \sim 1$ fm/c



Determining Energy *Density*

- What is the energy density achieved?
- How does it compare to the expected phase transition value ?



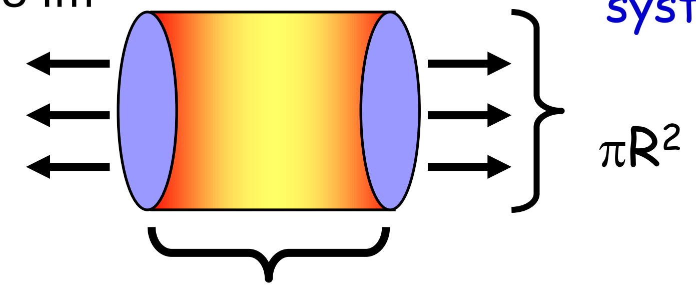
For the most central events:

Bjorken formula for thermalized energy density

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

~6.5 fm

time to thermalize the system (τ_0 ~ 1 fm/c)



$$dz = \tau_0 dy$$

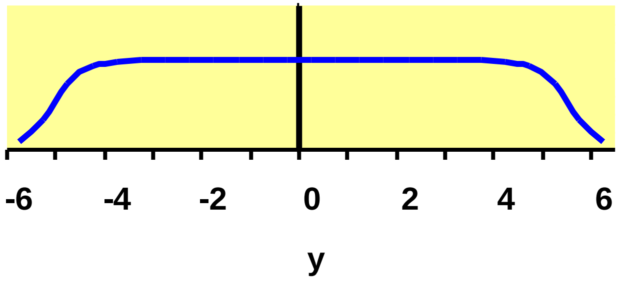
$\varepsilon_{Bjorken}$ ~ 4.6 GeV/fm^3

~30 times normal nuclear density
~1.5 to 2 times higher than any previous experiments

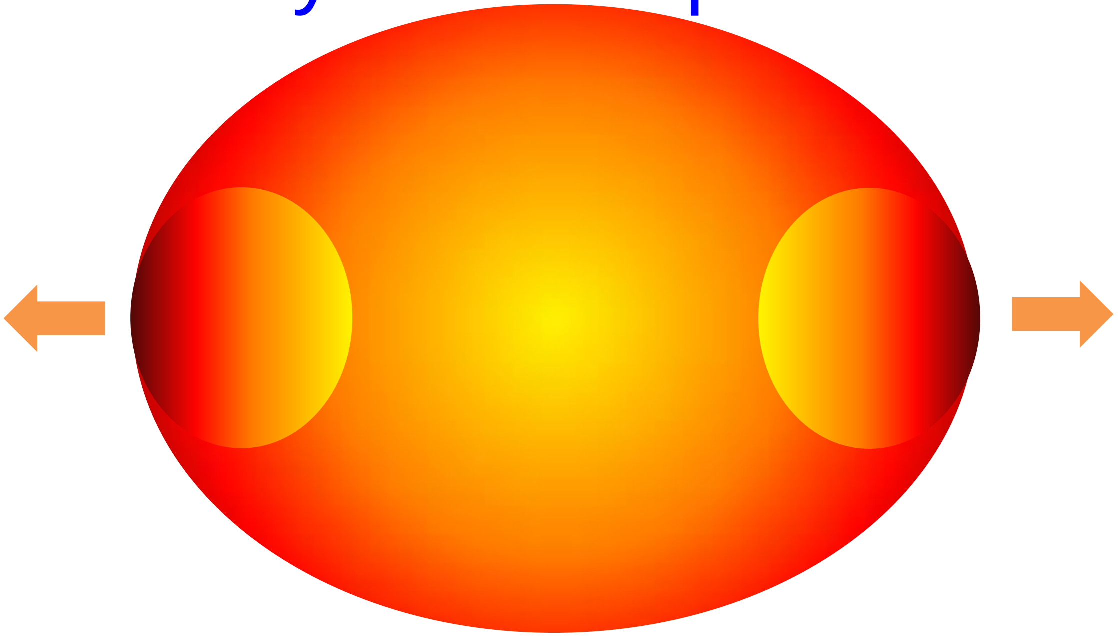
The Danger in Cartoons

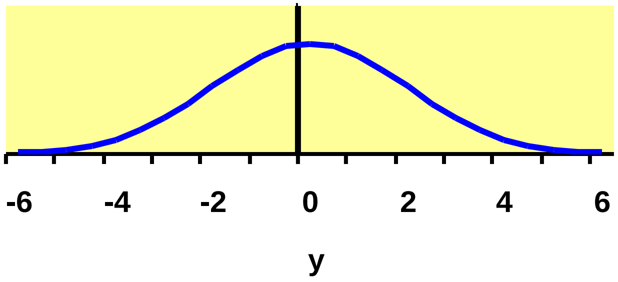
- What is this thing ??

?

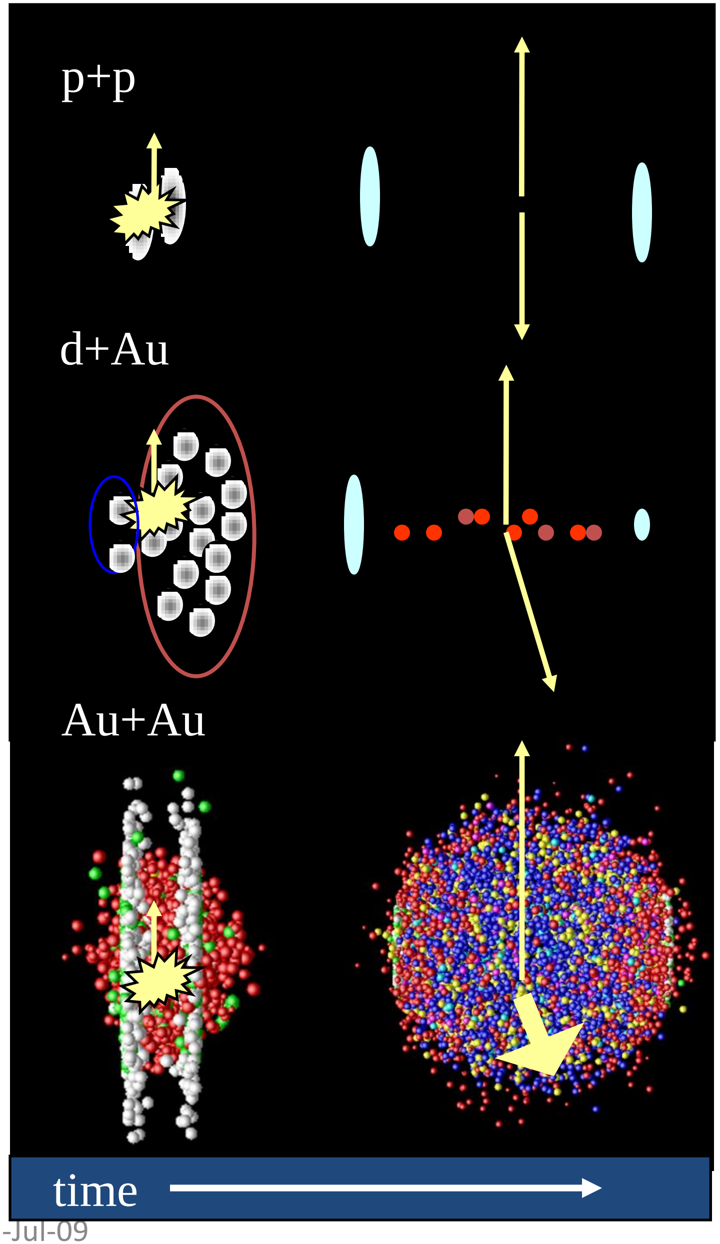


- Surely not the space-time development:





Using “Hard Probes”



Systematic approach essential:

- ❑ p+p: BASELINE
- ❑ d+Au: CONTROL
- ❑ Au+Au: NEW EFFECT

Baseline p+p Measurements with pQCD

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

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

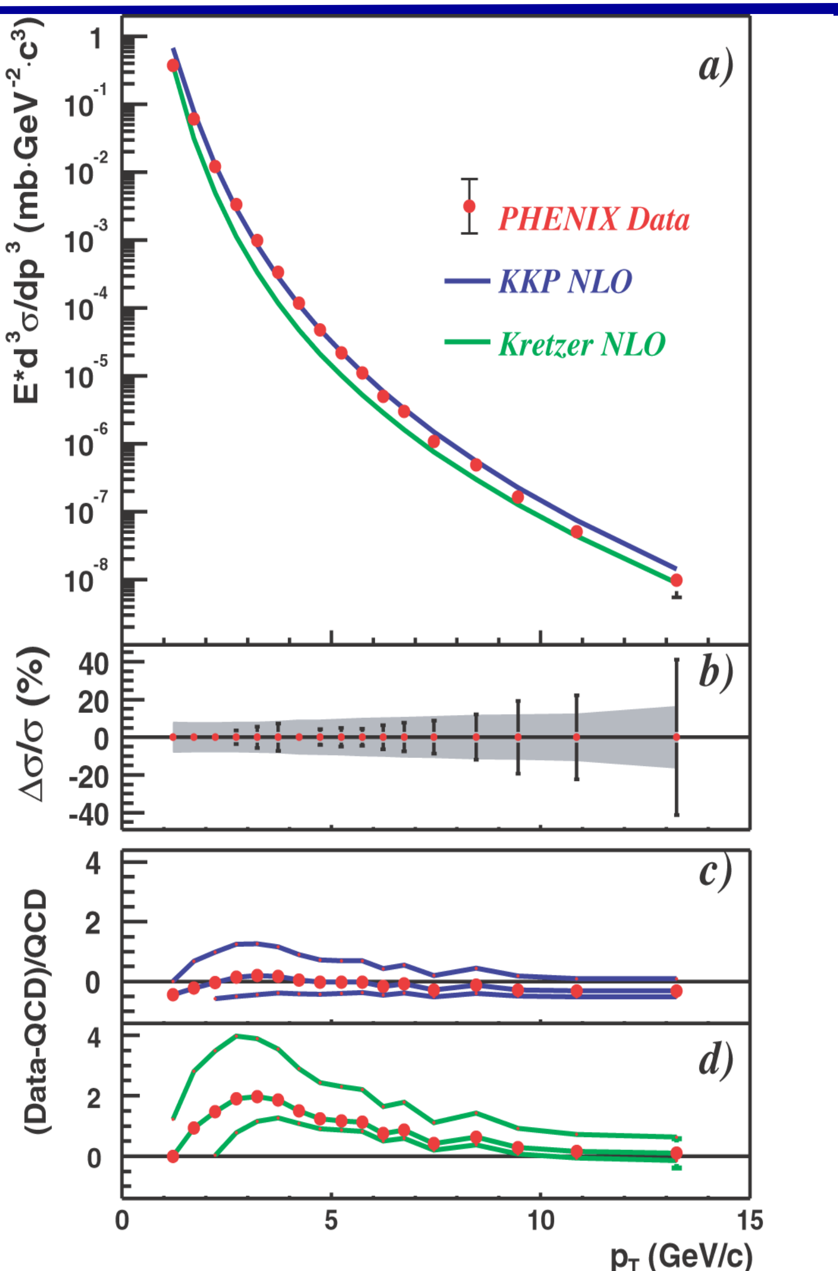
- parton distribution functions, for partons a and b
- measured in DIS, universality

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

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

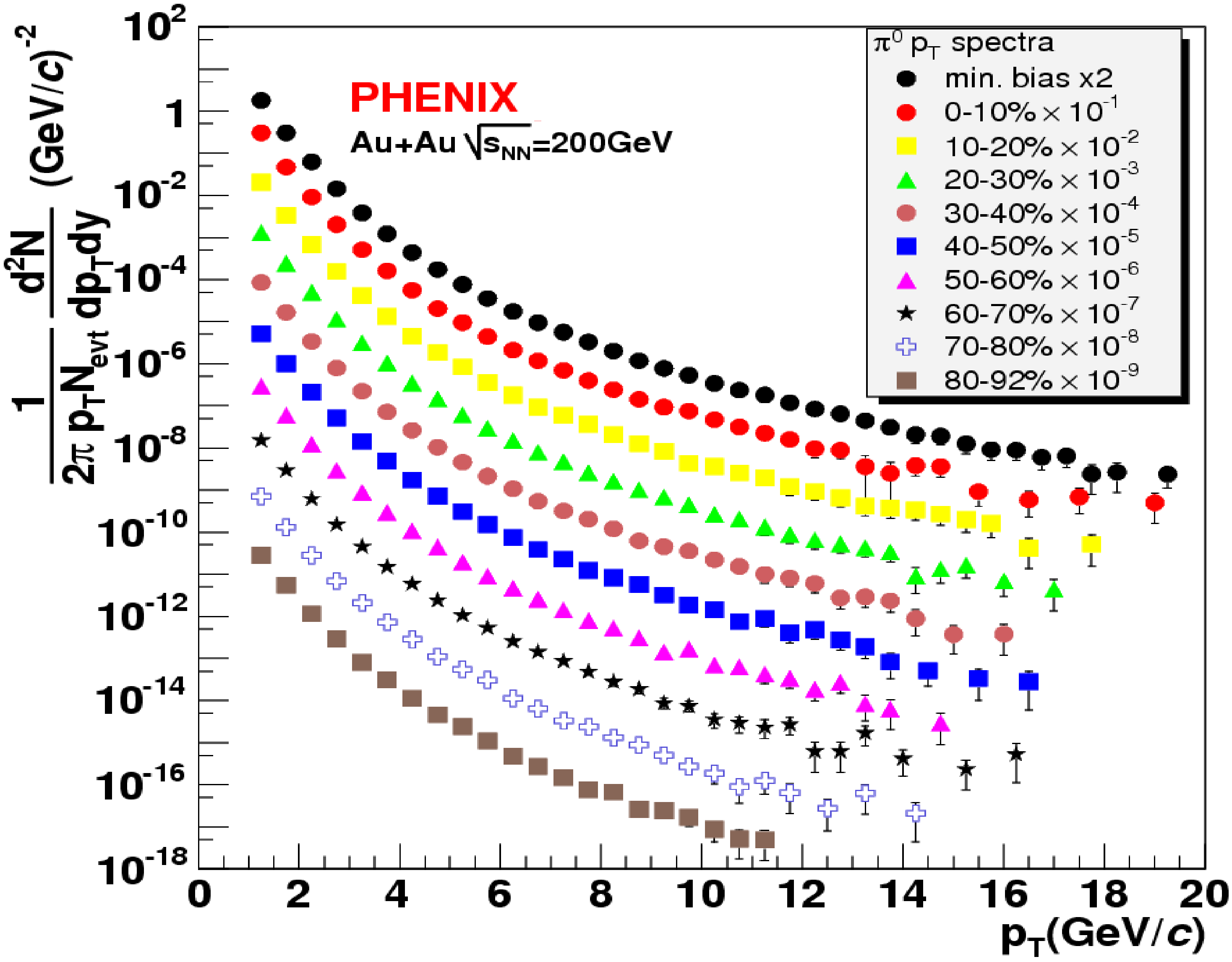
$$\otimes\, D_{h/c}(z_h,\mu^2)$$

- fragmentation function
- measured in e+e-



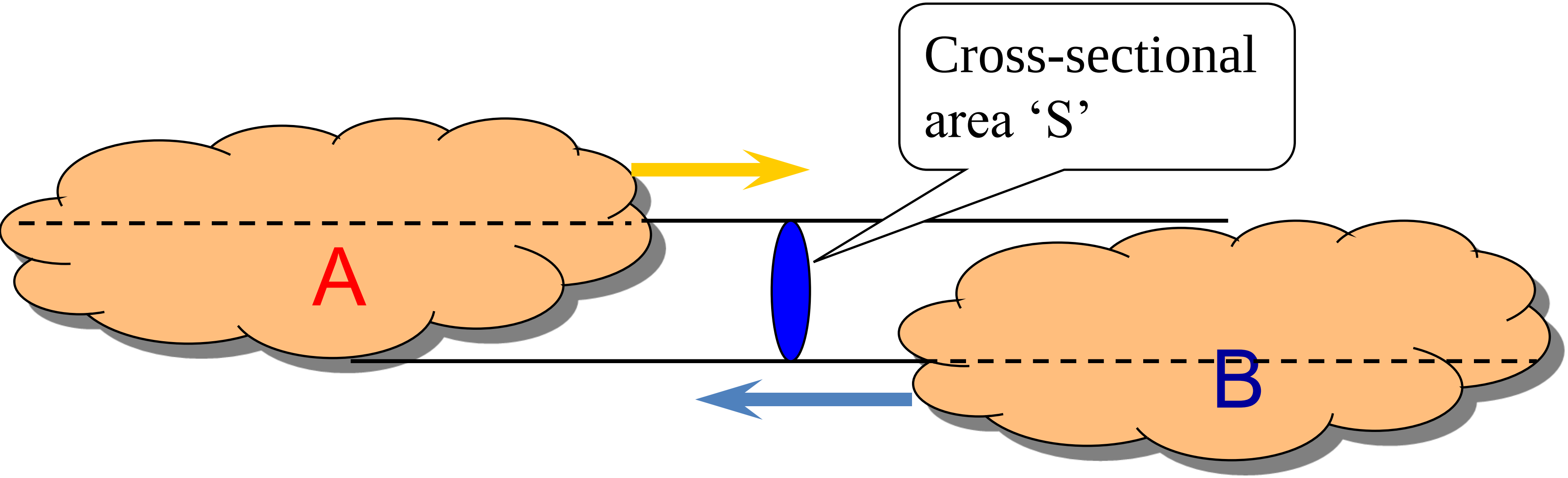
- [Phys. Rev. Lett. 91, 241803 (2003)]

Systematic Measurement in Au+Au



Luminosity

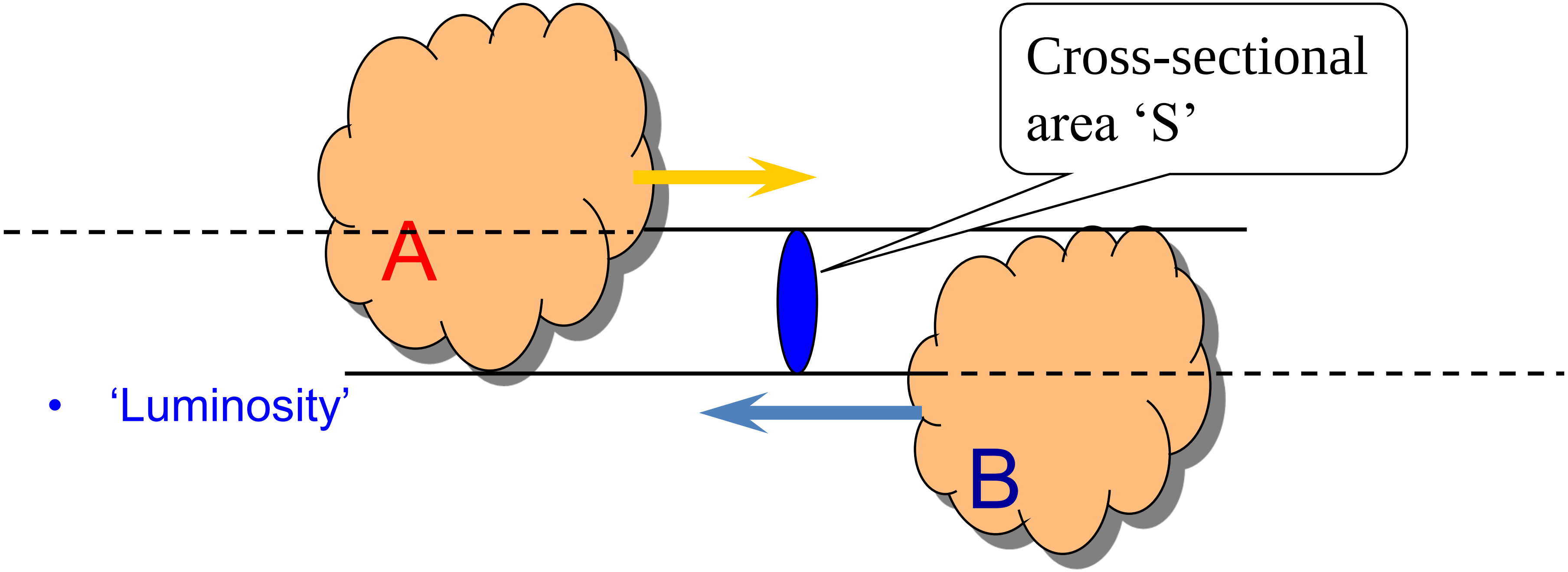
- Consider collision of ‘A’ ions per bunch
  with ‘B’ ions per bunch:


Cross-sectional area ‘S’

$$L \sim \frac{A \cdot B}{S}$$

Change scale by ~ 10^9

- Consider collision of 'A' nucleons per nucleus
  with 'B' nucleons per nucleus:



- 'Luminosity'

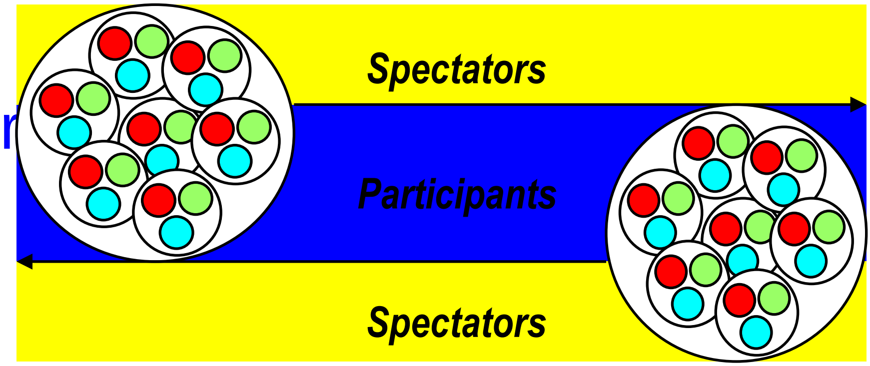
$$L \sim \frac{A \cdot B}{S} \sim N_{Coll} \propto A \cdot B$$

$$\textit{not} \quad N_{Part} \propto A + B$$

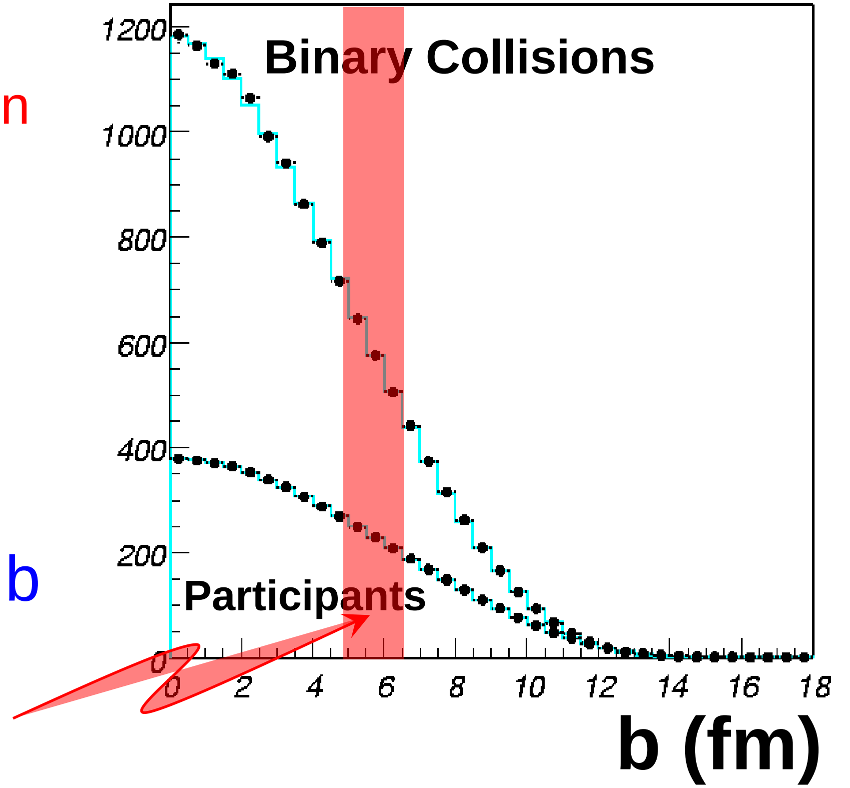
Provided:

No shadowing
→Small cross-sections

Systematizing our Knowledge

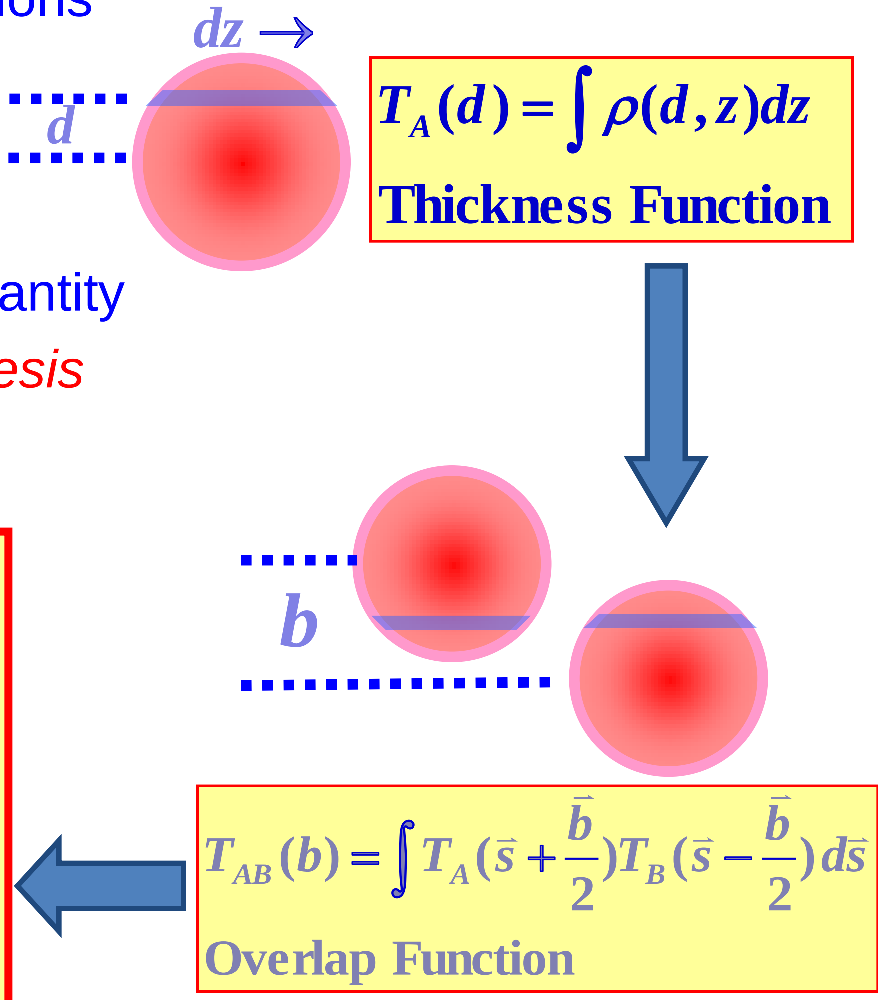


- All four RHIC experiments have carefully developed techniques for determining
  - the number of participating nucleons N_{PART} in each collision (and thus the impact parameter)
  - The number of binary nucleon-nucleon collisions N_{COLL} as a function of impact parameter
- This effort has been essential in making the QCD connection
  - Soft physics ~ N_{PART}
  - Hard physics ~ N_{COLL}
- Often express impact parameter b in terms of "centrality", e.g., 10-20% most central collisions



Rare Processes

- Particle production via *rare processes* should scale with N_{coll}, the number of underlying binary nucleon-nucleon collisions
- Roughly: Small σ ➔ no shadowing
  ➔ *per nucleon* luminosity is relevant quantity
- Take scaling with N_{coll} as our *null hypothesis* for hard processes



$$T_A(d) = \int \rho(d,z)\,dz$$

Thickness Function

$$T_{AB}(b) = \int T_A(\vec{s}+\frac{\vec{b}}{2})\,T_B(\vec{s}-\frac{\vec{b}}{2})\,d\vec{s}$$

Overlap Function

If Nucleus "A" has A constituents
and Nucleus "B" has B constituents
which interact with cross section σ_{INT}
the TOTAL cross section σ_{AB} is then

$$\sigma_{AB} = \int d^2b\left[1-e^{-\sigma_{INT}T_{AB}(b)}\right]$$

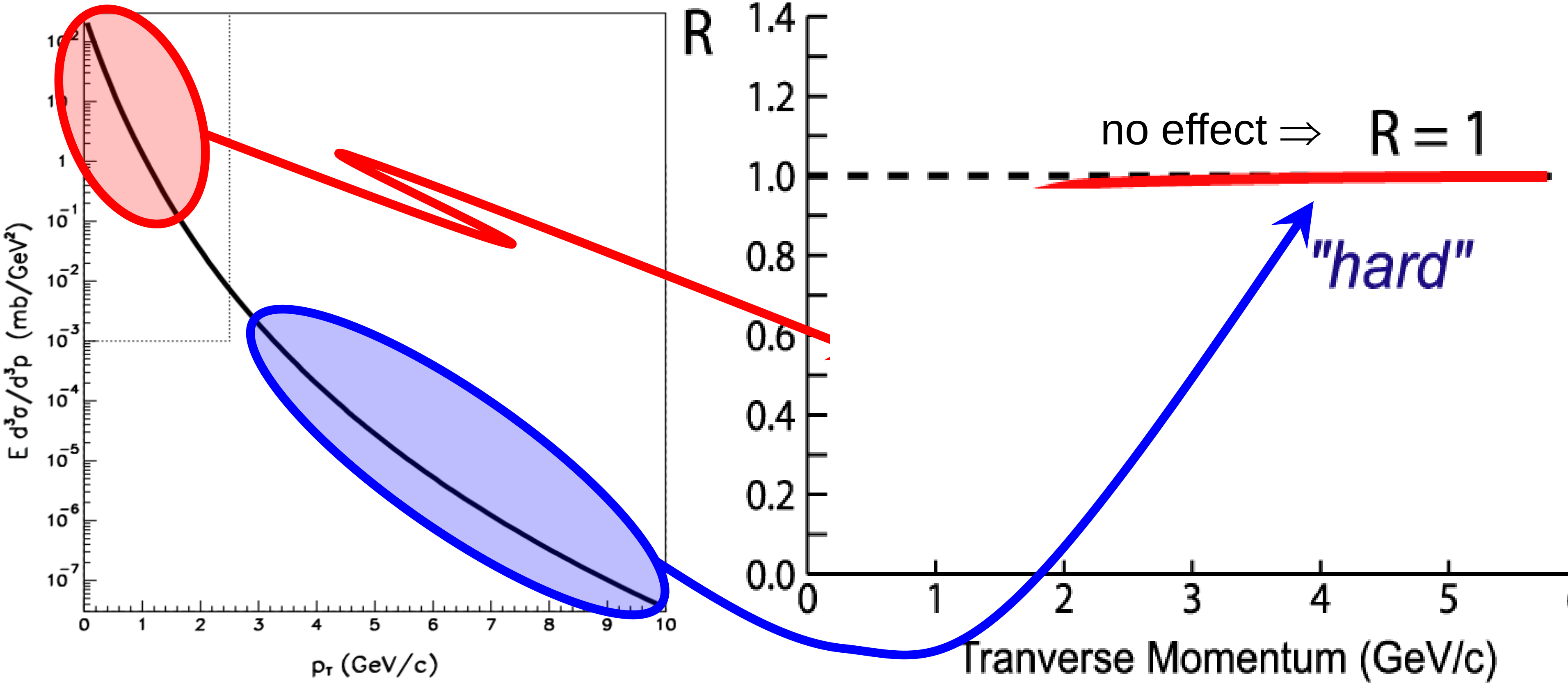
$$\rightarrow \approx A\cdot B\times\sigma_{INT} \text{ for "small" } \sigma_{INT}$$

Exercise 4: Make a plausibility argument for σ_{AB} formula, and verify approximation.

Systematizing Our Expectations

Describe in terms of *scaled ratio* R_{AA} $\equiv \dfrac{\text{Yield in Au+Au Events}}{(A \bullet B)(\text{Yield in p+p Events})}$

= 1 for “baseline expectations”
> 1 “Cronin” enhancements (as in proton-nucleus)
< 1 (at high p_T) “anomalous” suppression



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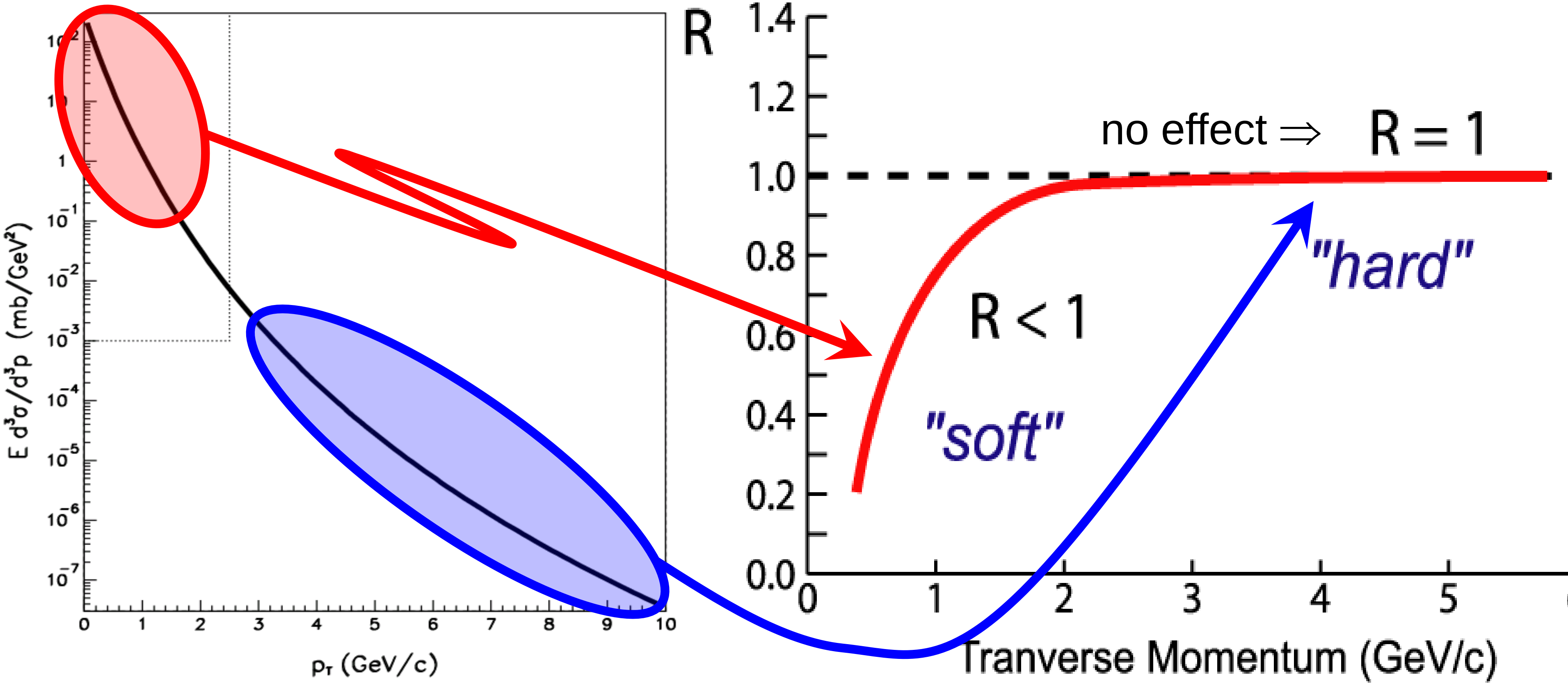
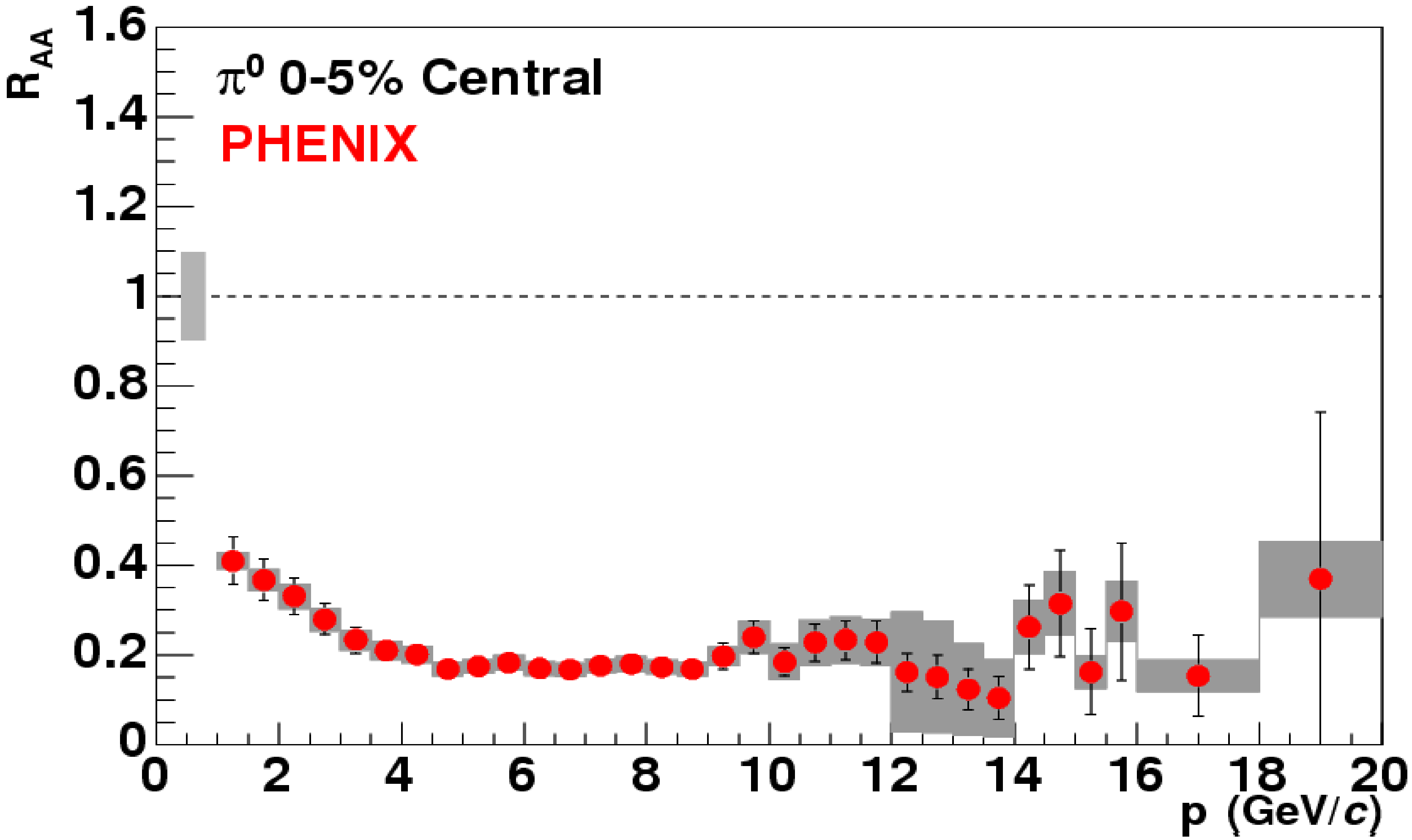
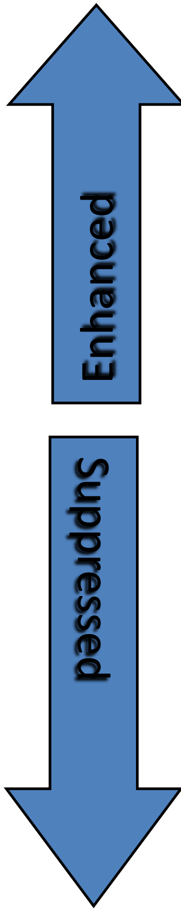


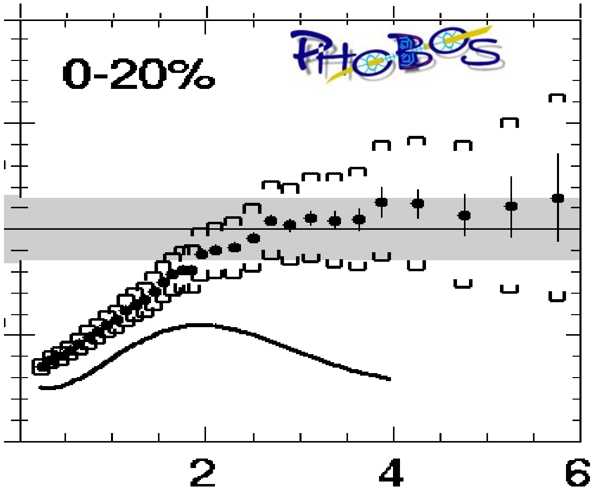
Systematic Suppression Pattern

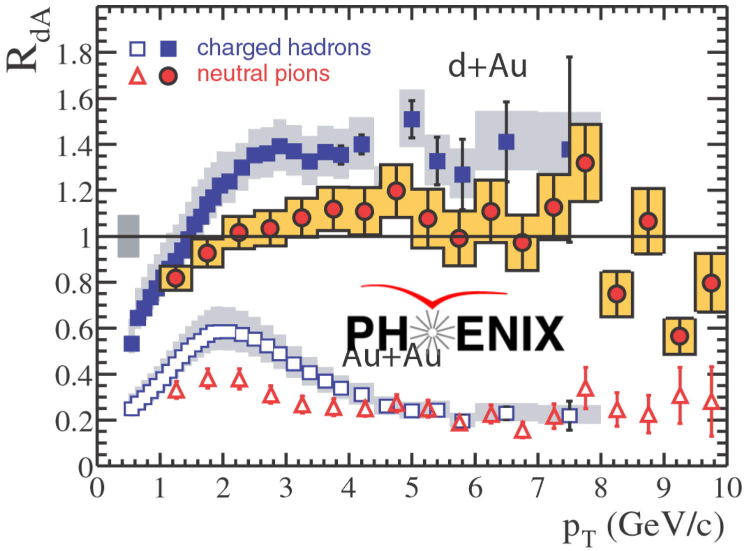


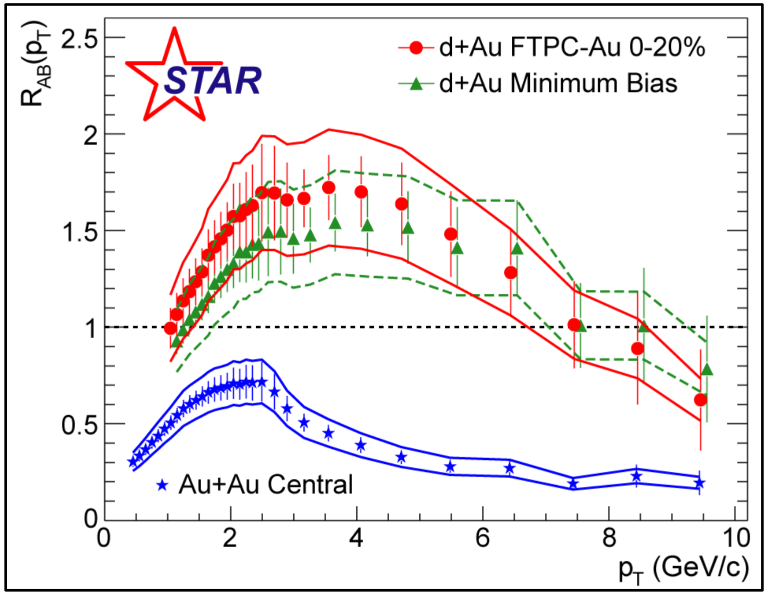


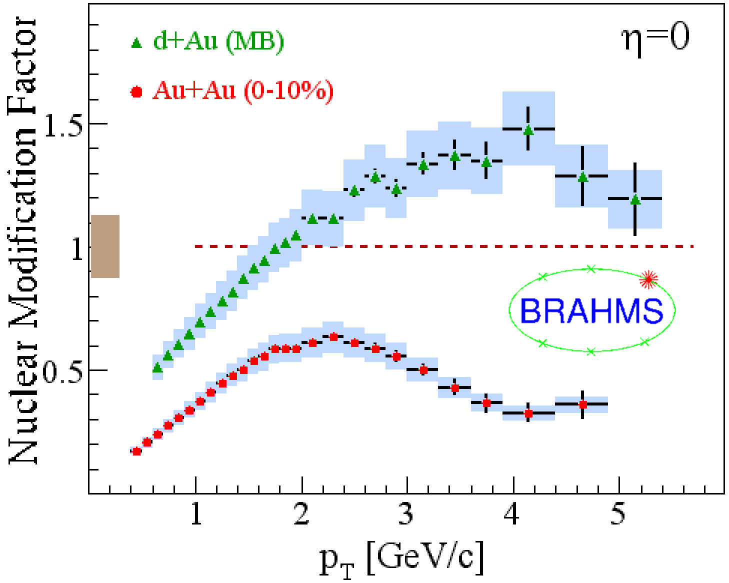
Unique to Heavy Ion Collisions?

- YES! : Run-3: *a crucial control measurement* via d+Au collisions









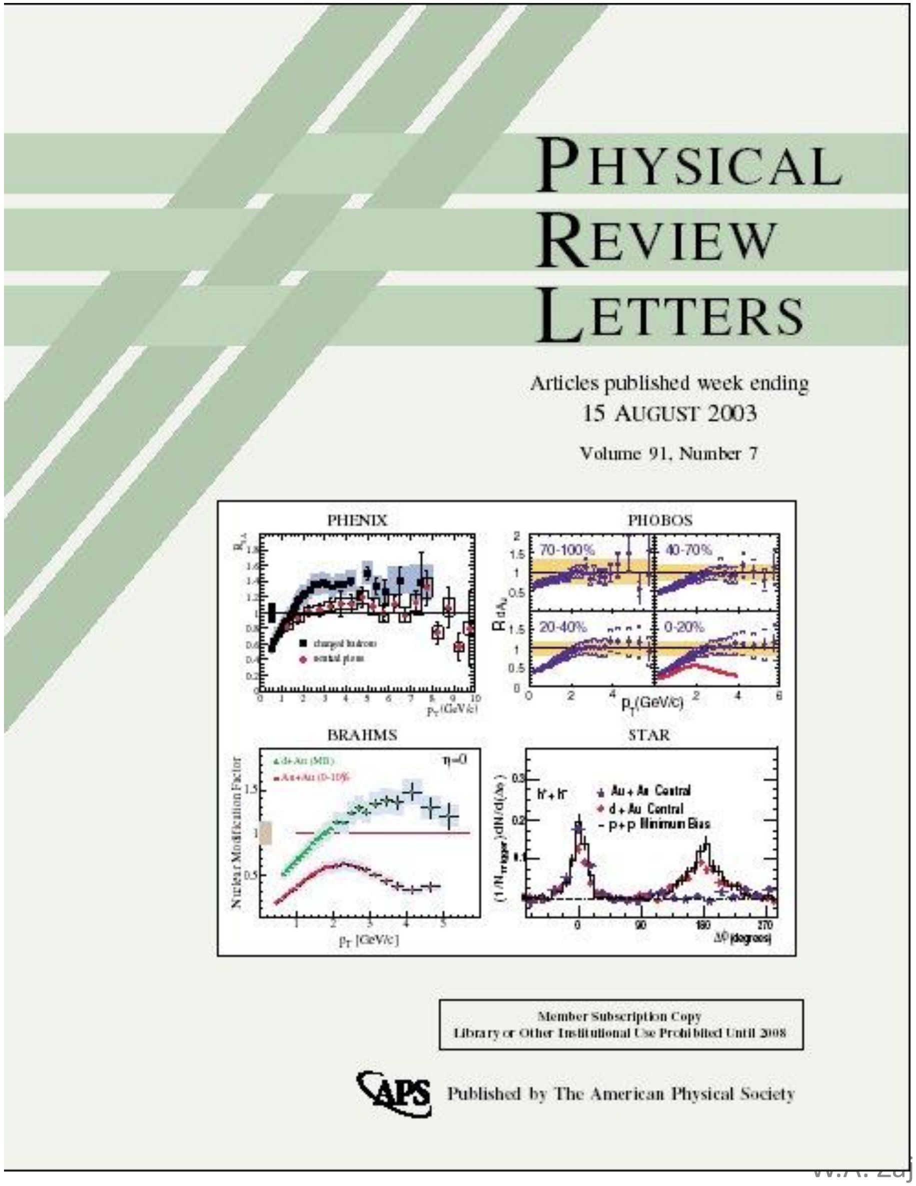
Unique to Heavy Ion Collisions?

- YES! : Run-3: *a crucial control measurement* via d+Au collisions

d+Au results from

BRAHMS PHENIX PHOBOS STAR

presented at a press conference
at BNL on June, 18th, 2003



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Energy Loss of Fast Partons

- Many approaches
  - 1983: Bjorken

$$-\frac{dE}{dx} = \frac{3\sqrt{30}}{4}\alpha_S^{2}\sqrt{\varepsilon}\ln\left(\frac{4ET}{M^2}\right) \sim \alpha_S^{2}T^2\ln\left(\frac{4ET}{M^2}\right)$$

  - 1991: Thoma and Gyulassy (1991)

$$-\frac{dE}{dx} \approx \frac{4\pi}{3}C_F\alpha_S^{2}T^2\ln\left(\frac{E}{\mu_D}\right)$$

  - 1993: Brodsky and Hoyer (1993)

$$-\frac{dE}{dx} \approx \frac{\left\langle \Delta k_T^{2}\right\rangle}{2}$$

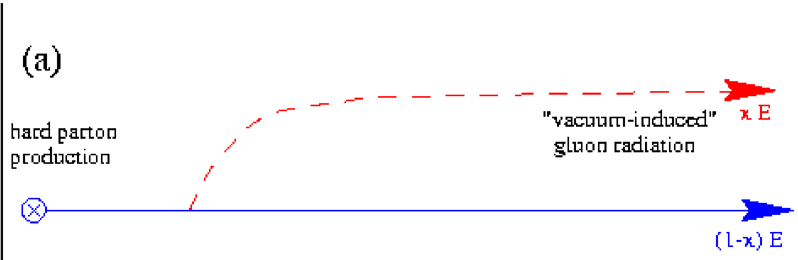
  - 1997: BDMPS- depends on path length(!)

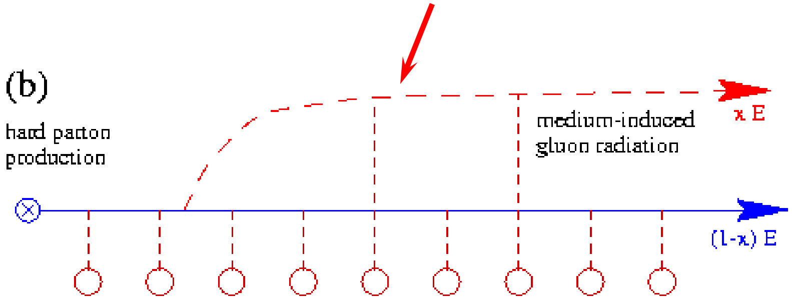
$$-\frac{dE}{dx} \approx \alpha_S\frac{C_R}{8}\frac{\mu_D^{2}}{\lambda_g}L\ln\left(\frac{L}{\lambda_g}\right)$$

  - 1998: BDMS

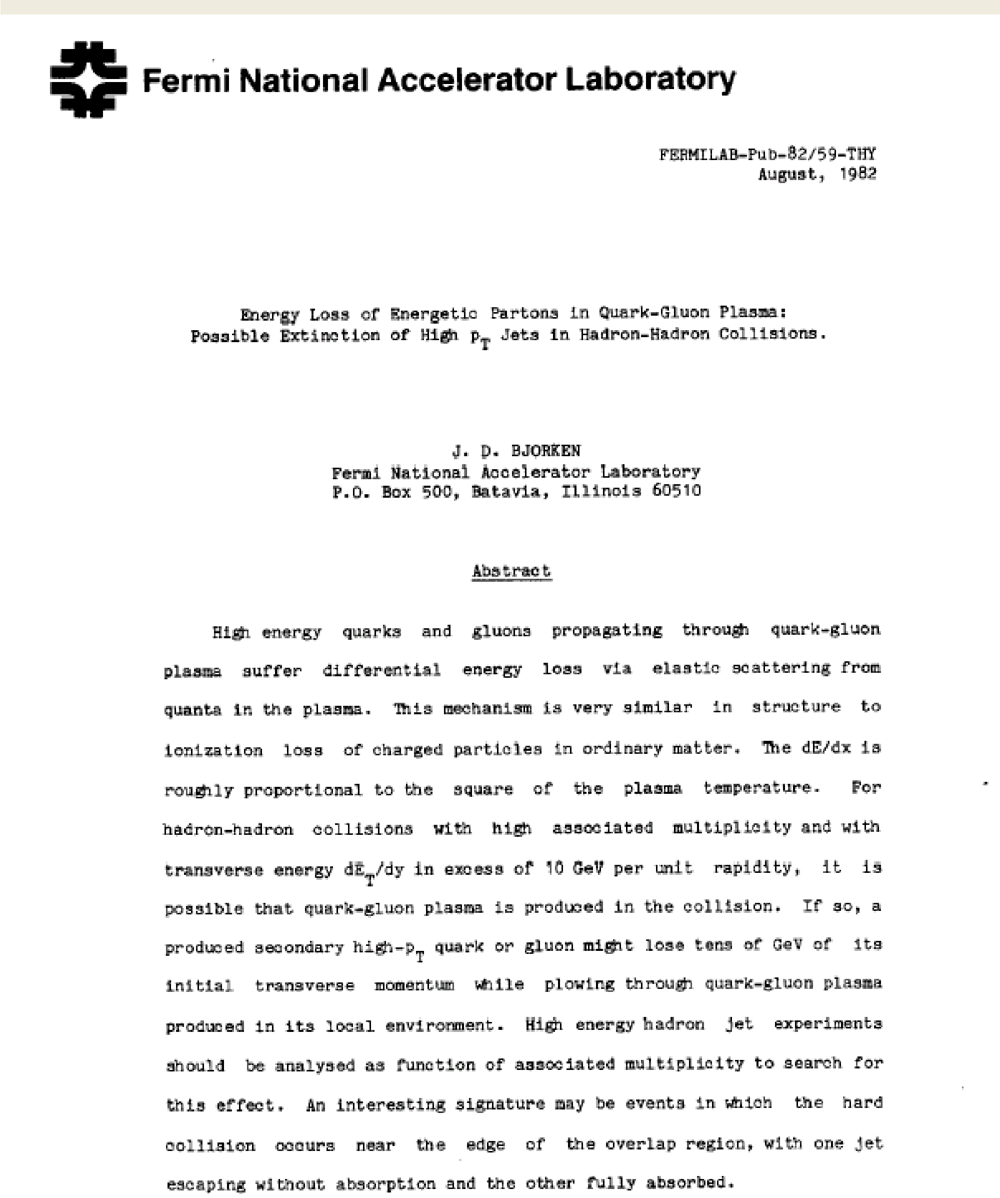
$$-\frac{dE}{dx} \approx \alpha_s\frac{N_C}{4}\frac{\left\langle \Delta k_T^{2}\right\rangle}{2}$$

- Numerical values range from
  - ~ 0.1 GeV / fm (Bj, elastic scattering of partons)
  - ~several GeV / fm (BDMPS, non-linear interactions of gluons)





The One That Started It All…



Fermi National Accelerator Laboratory

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Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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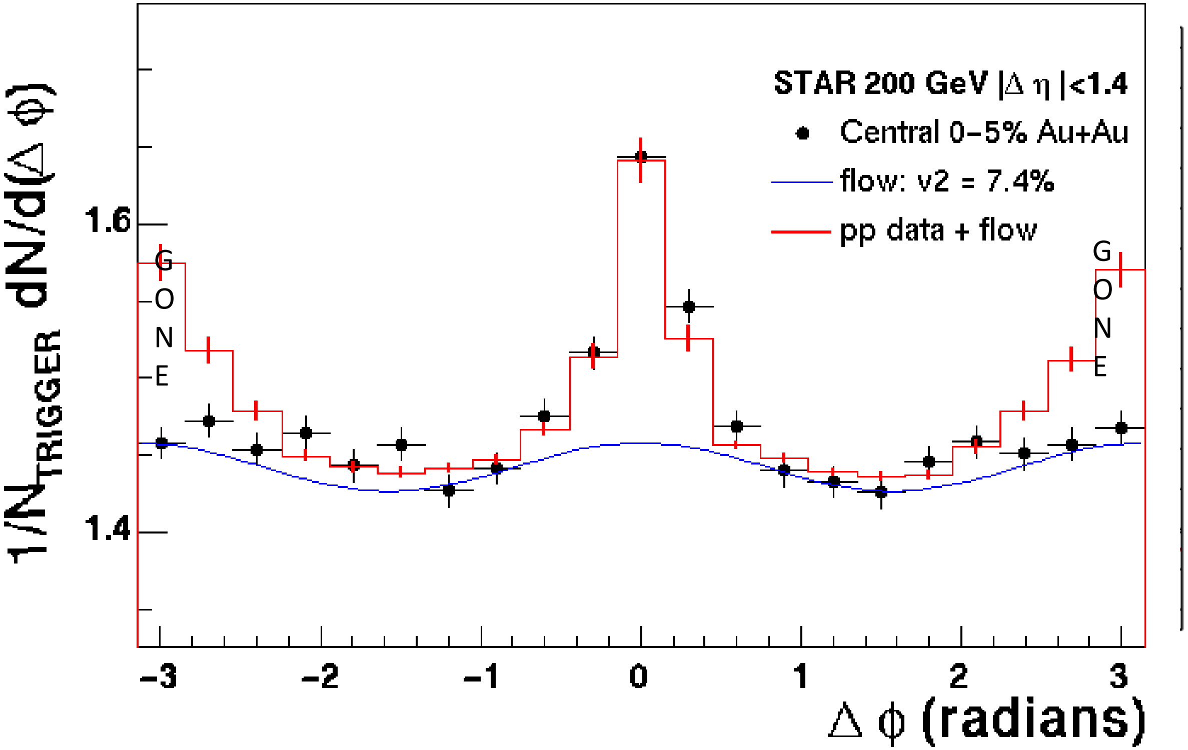
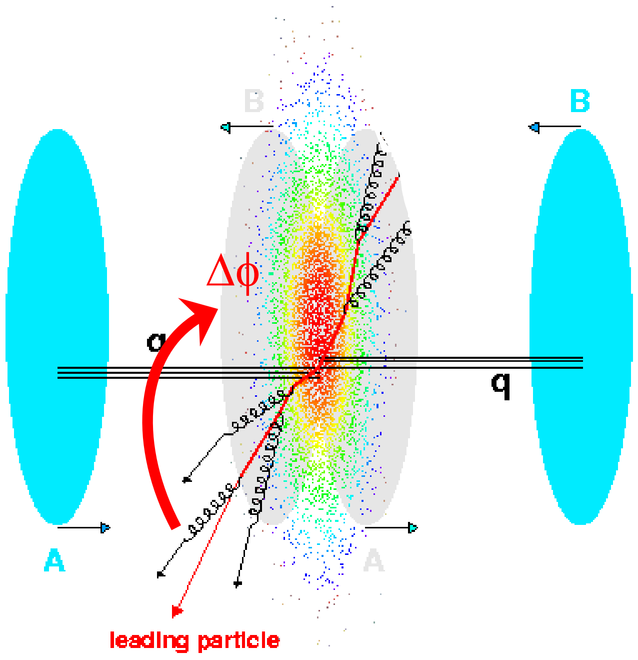
Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

The Matter is Opaque

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



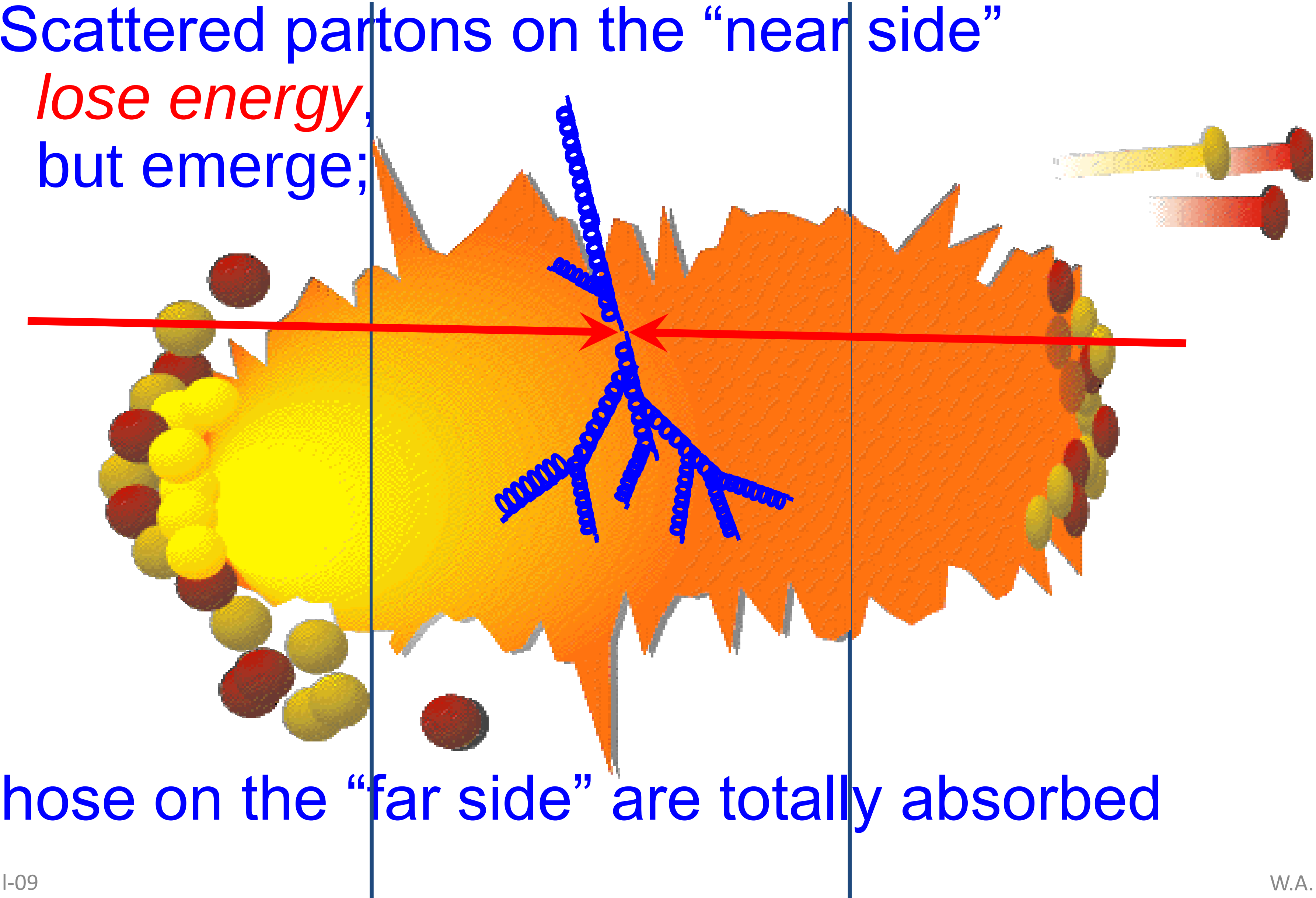


$$C_2(Au+Au)=C_2(p+p)+A*(1+2v_2^2\cos(2\Delta\phi))$$

That is, "partner" in hard scatter is *absorbed* in the *dense* medium

⇒Density ~ 50 x normal nuclear ε_0

Schematically (Partons)



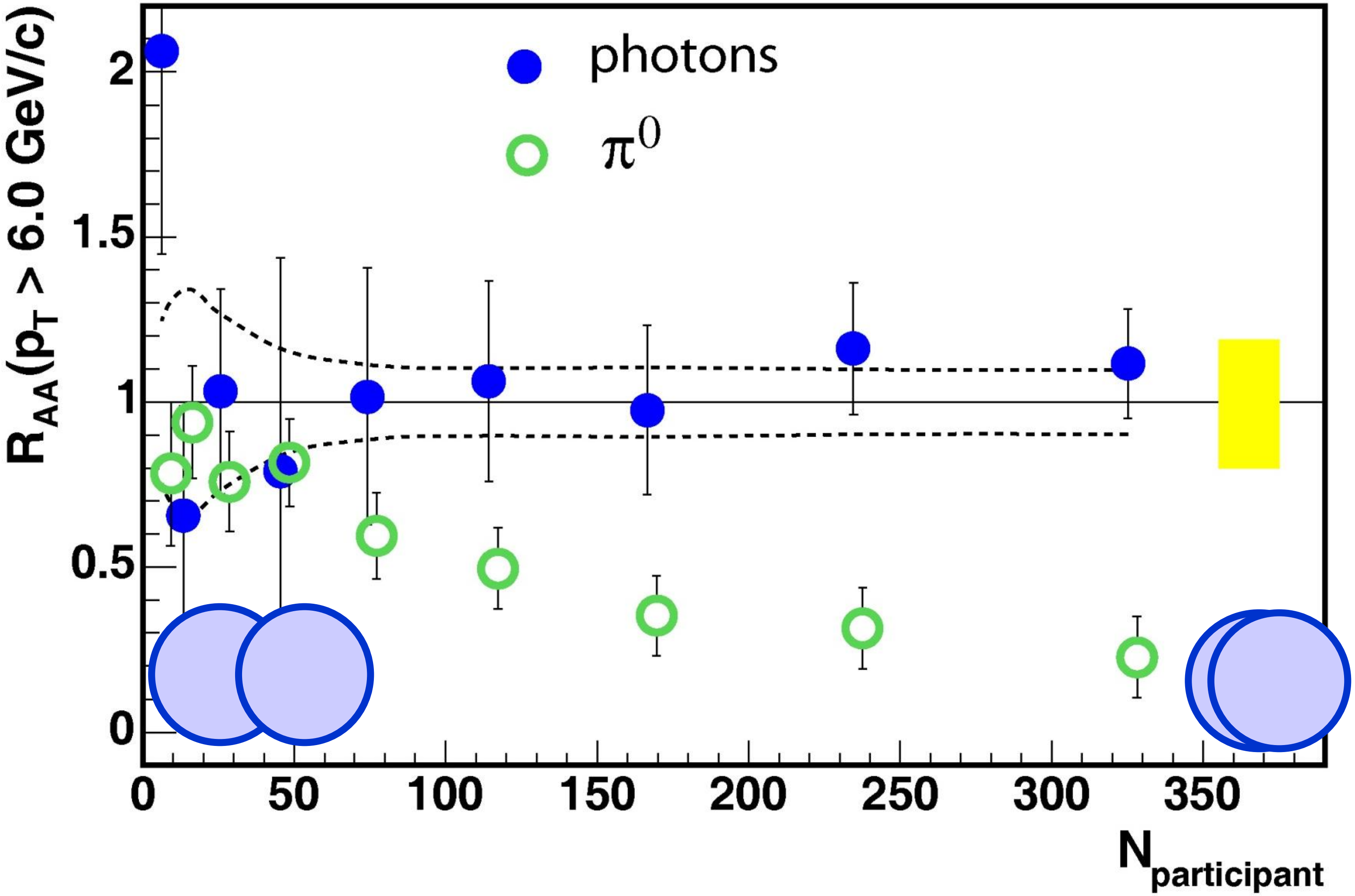
Scattered partons on the "near side"

lose energy,

but emerge;

those on the "far side" are totally absorbed

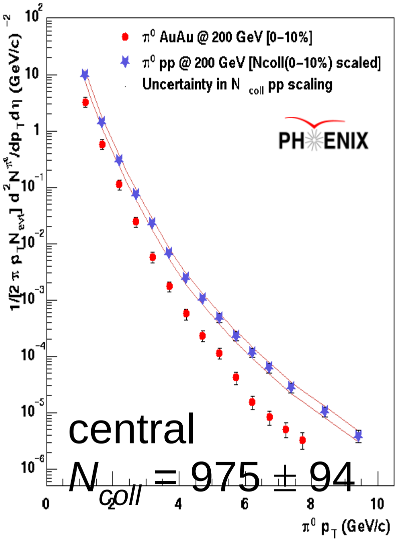
Photons shine, Pions don't



- Direct photons are *not* inhibited by hot/dense medium
- Rather: *shine* through consistent with pQCD

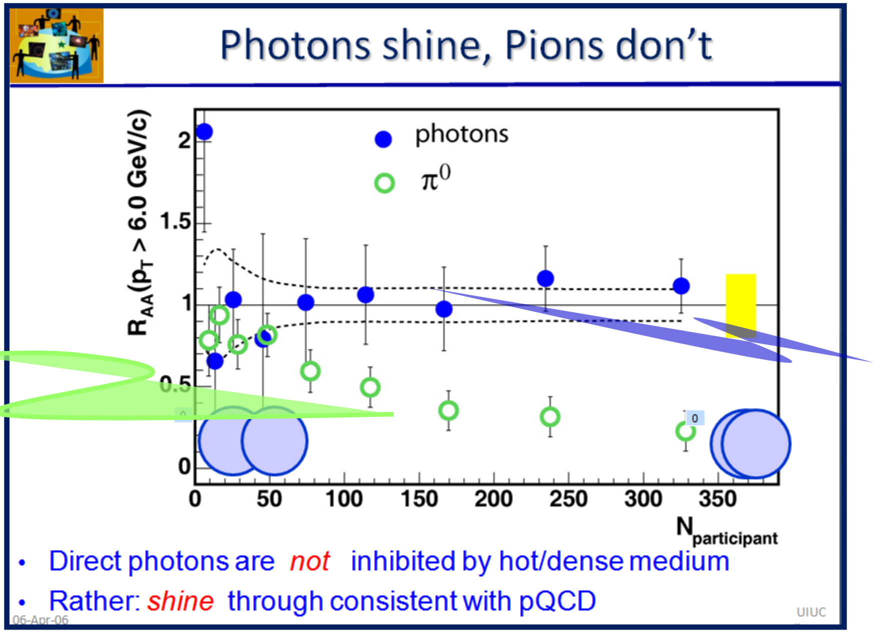
Precision Probes

- This one figure encodes rigorous control of systematics



central

$N_{coll} = 975 \pm 94$



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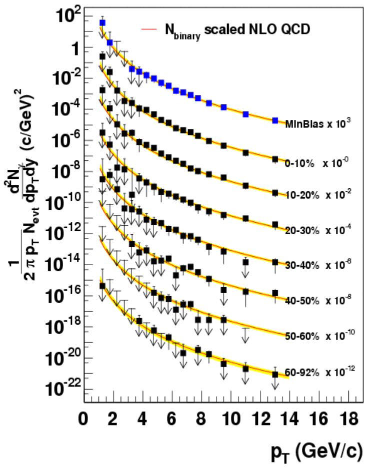
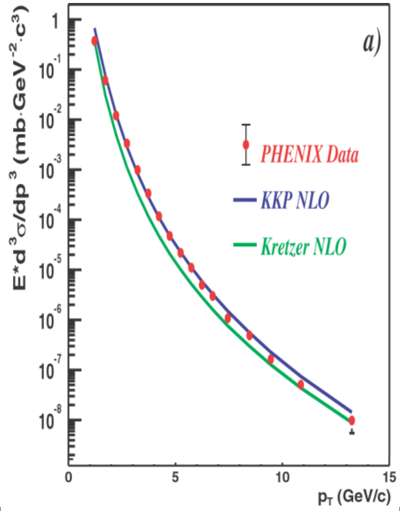
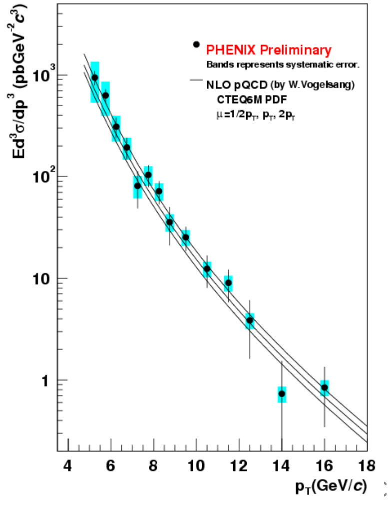




- in four different measurements over many orders of magnitude



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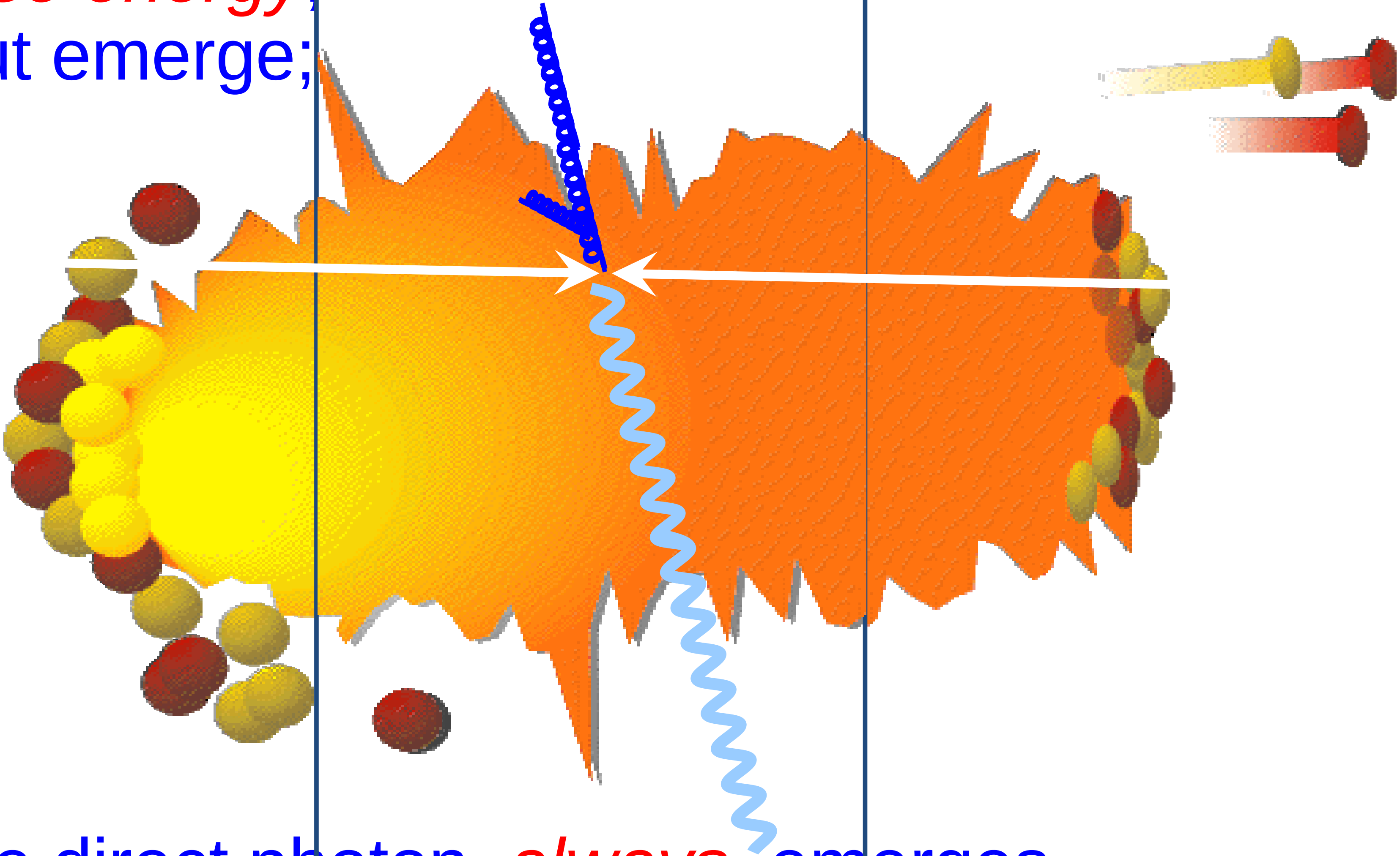
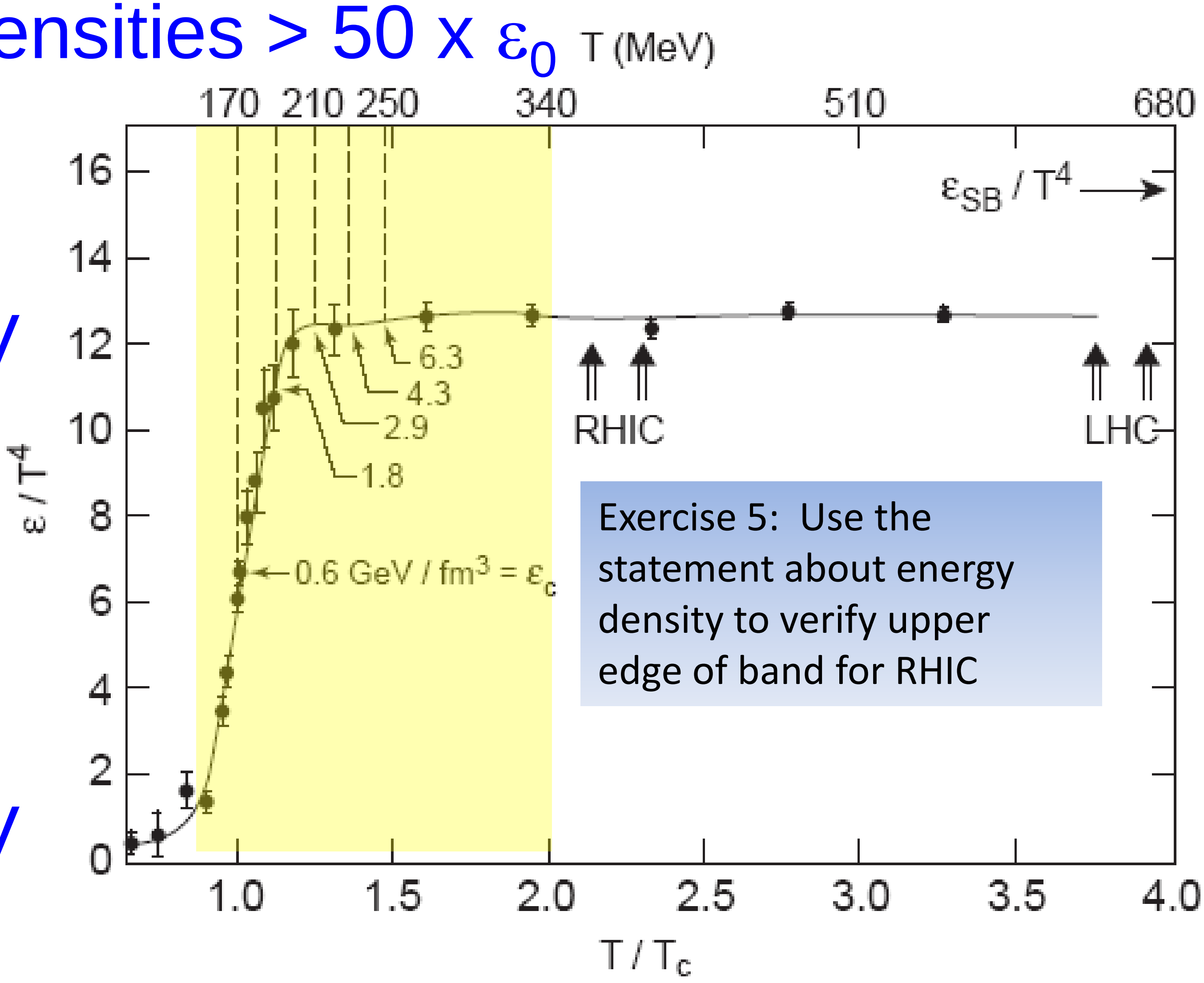


the direct photon *always* emerges

RHIC and the Phase “Transition”

- Suppression of high momentum probes requires densities > 50 x ε_0



Exercise 5: Use the statement about energy density to verify upper edge of band for RHIC

- High T_{init} ~ 300 MeV

  to

- Low T_{final} ~ 100 MeV

Summary- Lecture 2

- Au+Au collisions at top RHIC energy produces *thermal* matter with energy density

$$\varepsilon >> \varepsilon_0 \quad \textit{and} \quad \varepsilon >> \varepsilon_{QGP}$$

  - ☐ From simple estimates
  - ☐ From detailed pQCD probes
- Suppression not seen in
  - ☐ d+Au control
  - ☐ Photons
- Results consistent with the formation of QGP with a temperature $T \sim 2T_C$
- Next time: How fluid is the densest matter ever studied ?