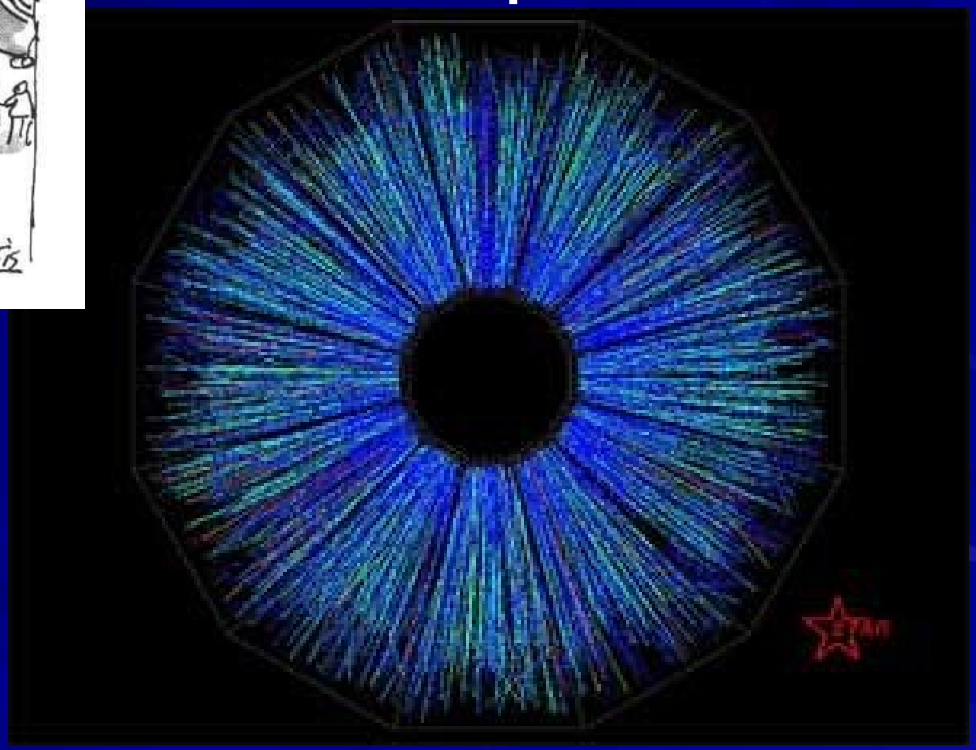
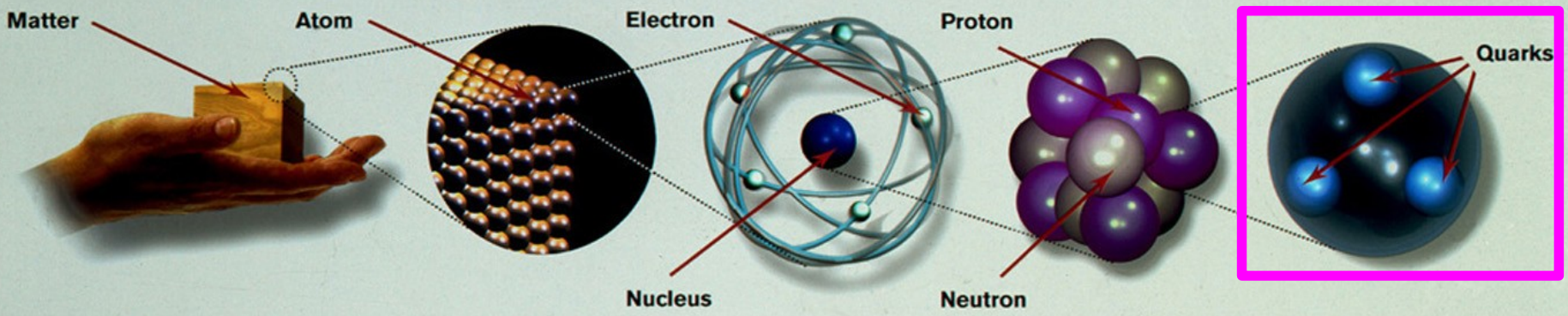
An introduction to high energy heavy ion physics

1 small bang in the STAR experiment





Matter particles
All ordinary particles belong to this group

These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators

LEPTONS

FIRST FAMILY	**Electron** Responsible for electricity and chemical reactions; it has a charge of -1	**Electron neutrino** Particle with no electric charge, and possibly no mass; billions fly through your body every second
SECOND FAMILY	**Muon** A heavier relative of the electron; it lives for two-millionths of a second	**Muon neutrino** Created along with muons when some particles decay
THIRD FAMILY	**Tau** Heavier still; it is extremely unstable. It was discovered in 1975	**Tau neutrino** not yet discovered but believed to exist

QUARKS

Up Has an electric charge of plus two-thirds; protons contain two, neutrons contain one	**Down** Has an electric charge of minus one-third; protons contain one, neutrons contain two
Charm A heavier relative of the up; found in 1974	**Strange** A heavier relative of the down; found in 1964
Top Heavier still	**Bottom** Heavier still; measuring bottom quarks is an important test of electroweak theory

Force particles
These particles transmit the four fundamental forces of nature although gravitons have so far not been discovered

Gluons
Carriers of the strong force between quarks

Felt by: quarks

The explosive release of nuclear energy is the result of the strong force

Photons
Particles that make up light; they carry the electromagnetic force

Felt by: quarks and charged leptons

Electricity, magnetism and chemistry are all the results of electro-magnetic force

Intermediate vector bosons
Carriers of the weak force

Felt by: quarks and leptons

Some forms of radio-activity are the result of the weak force

Gravitons
Carriers of gravity

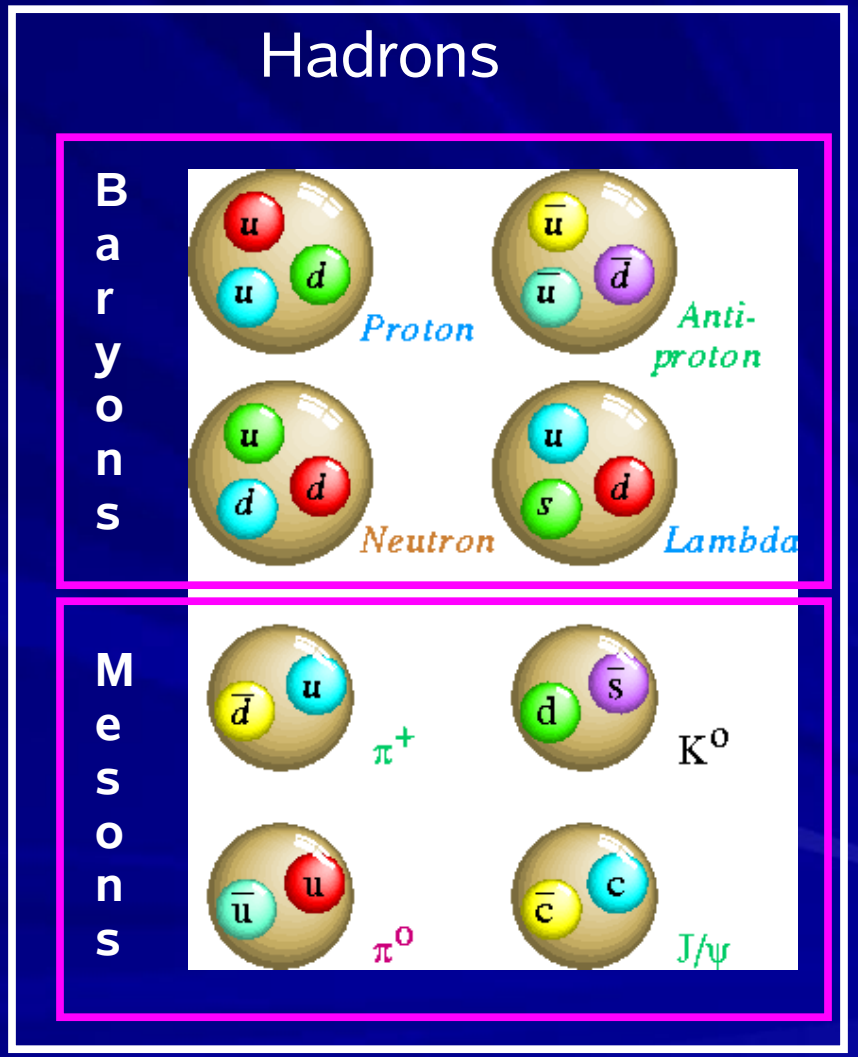
Felt by: all particles with mass

All the weight we experience is the result of the gravitational force

GRAPHICS: PETER CROWTHER

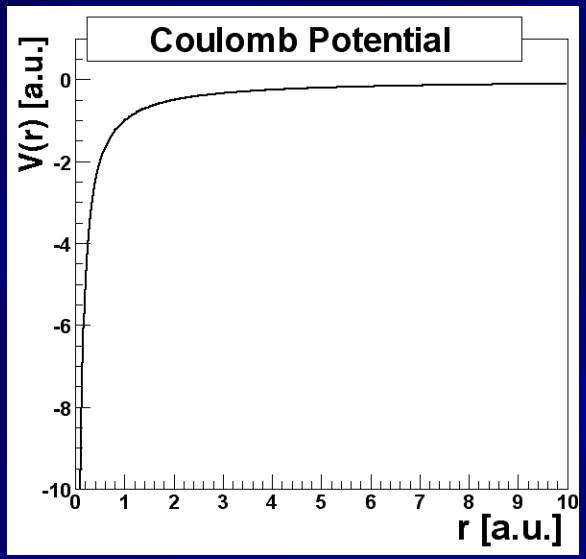
Quantum Chromo Dynamics (QCD)

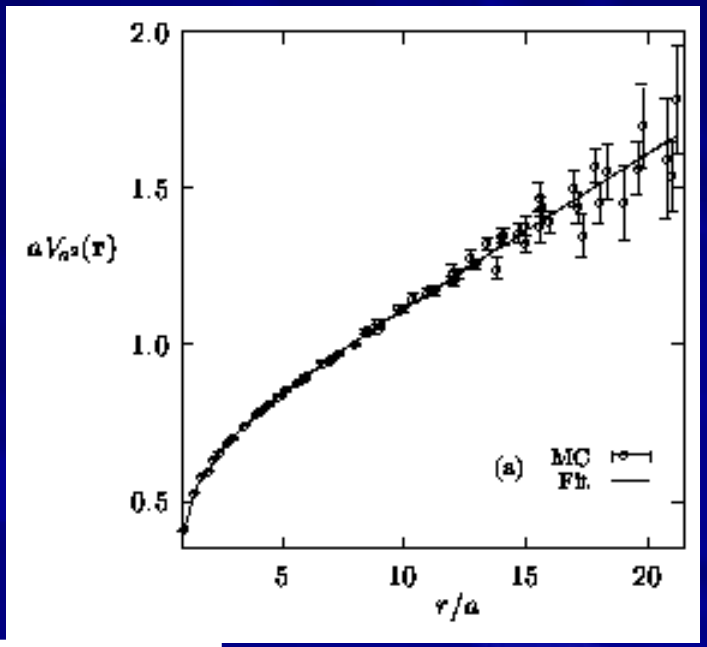
- 3 color charges (red, green, blue)
- Hadrons have to be colorless
- Baryons have all 3 colors
- Mesons has a color and an anti-color
- A single quark cannot be observed because it has color!
- The quarks are confined inside the hadrons!

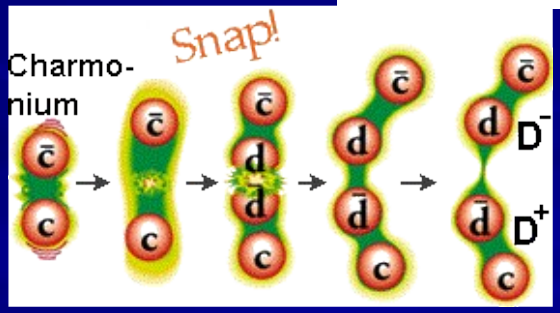


QCD potential

Gluons carries color ⇒ Gluons can interact with gluons (selfinteract)





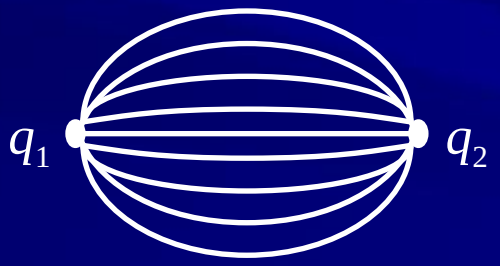


QCD & Confinement

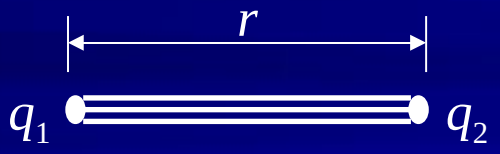
- The strong interaction potential
  - Compare the potential of the strong & e.m. interaction

$$V_{em} = -\frac{c}{r} \qquad V_s = -\frac{c'}{r} + kr \qquad c\,,\ c'\,,\ k \text{ constants}$$

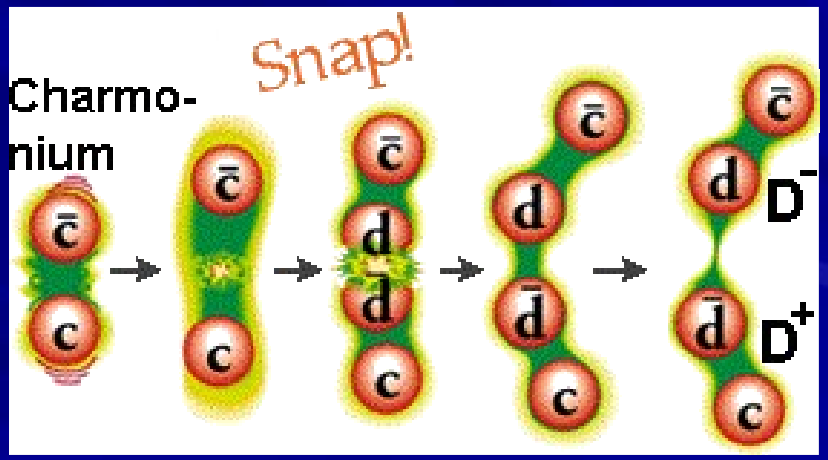
  - Confining term arises due to the self-interaction property of the colour field. k~1GeV/fm



a) QED or QCD ($r < 1$ fm)

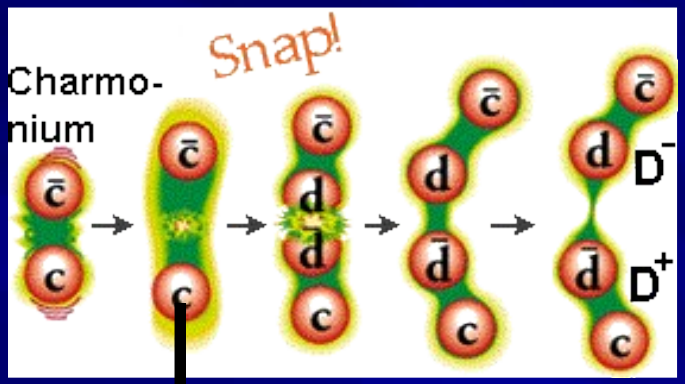


b) QCD ($r > 1$ fm)



Exercise: How big is k?

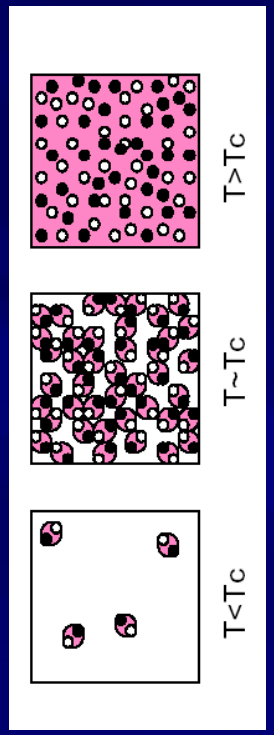
- k=1GeV/fm
- What force does that correspond to in kilograms?
  - mg= 1 GeV/fm => m=?

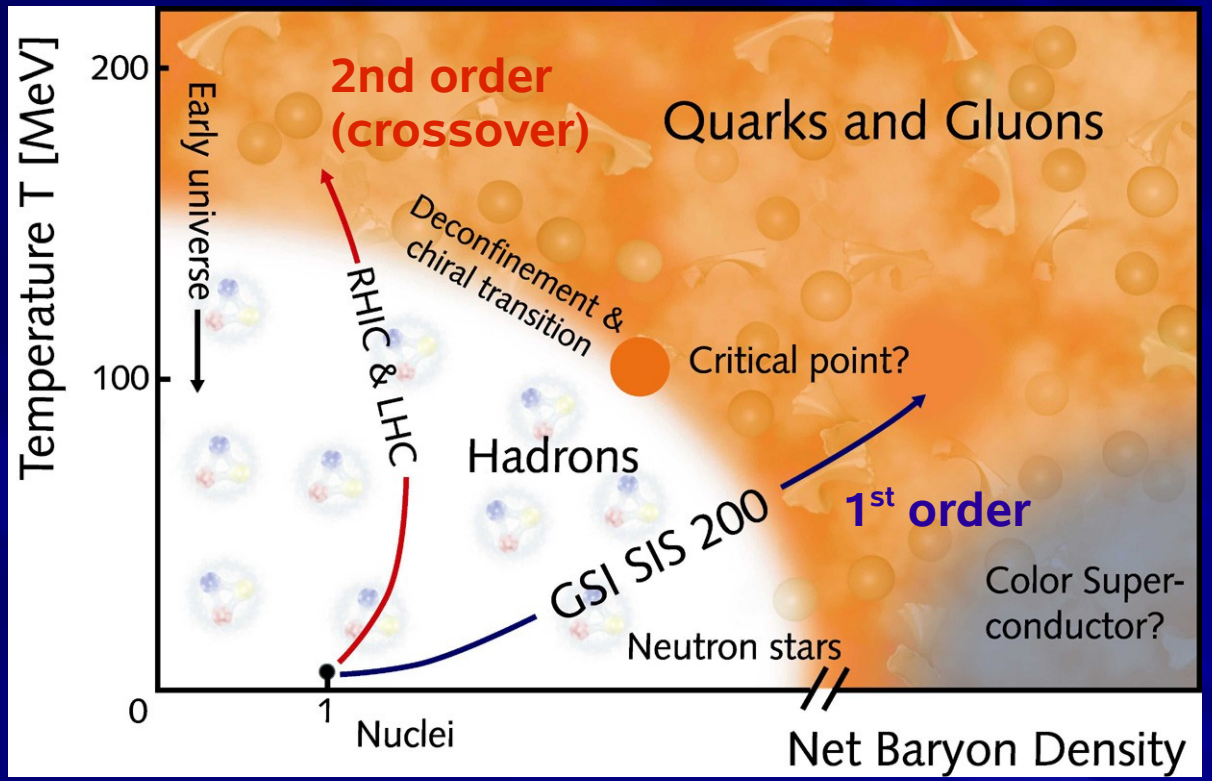


Consequences of 10 ton force!

- This is why QCD is also called the strong interaction
  - QCD can bind together quarks even though they are EM repulsed
- QCD is for low energies non-perturbative
  - We know the theory but we cannot solve it!
  - We don't know how to describe hadronic properties with QCD
- But at high energies (small distances << 1 fm) we can use perturbative QCD
- Idea: Can we create high energy matter where the quarks and gluons are the fundamental degrees of freedom
  - This is also the phase of matter in the universe around 1 micro second after the big bang!
  - It is first after this time that quarks and gluons “crystallize” into hadrons

Schematic QCD phase diagram

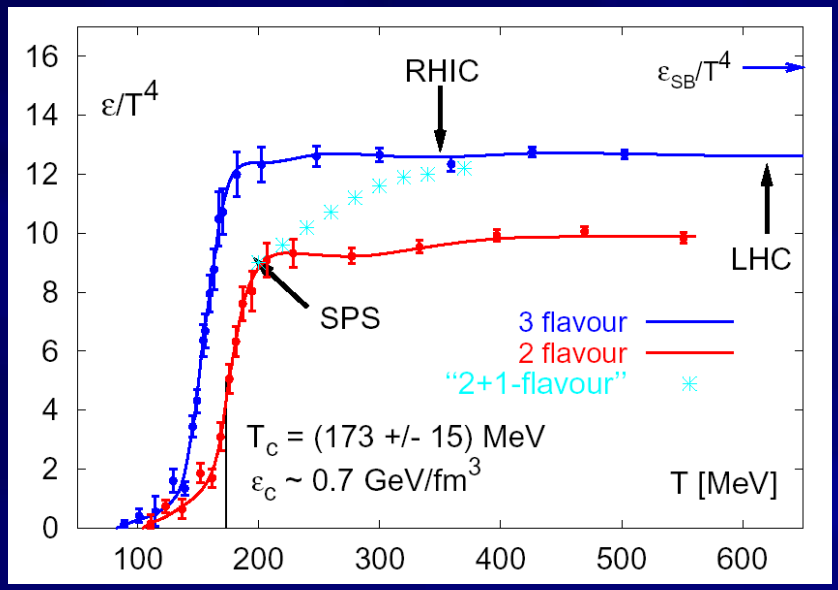




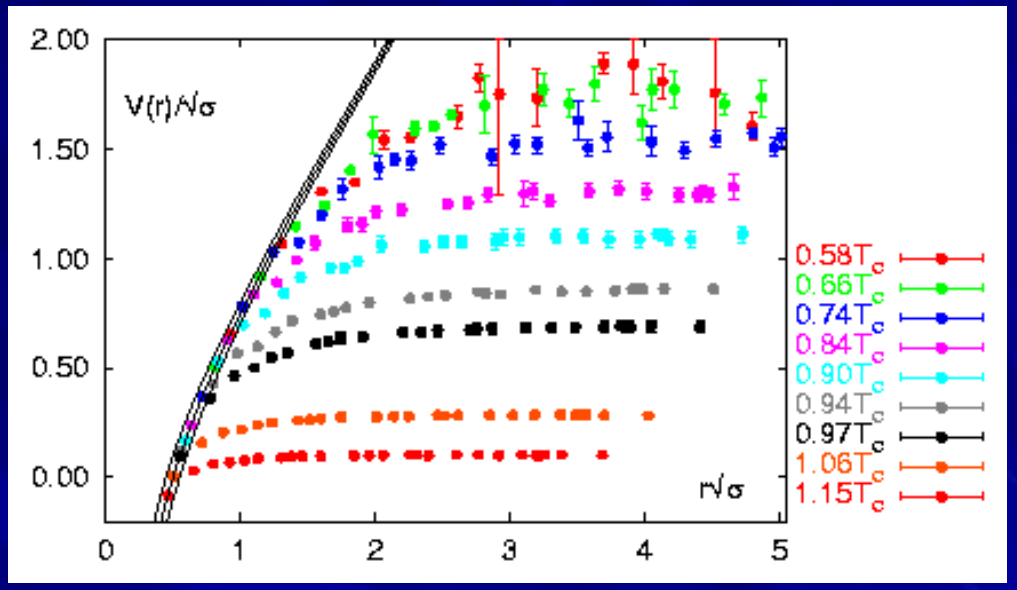
- At high temparures (T>170MeV) and/or energy densities (ε>1GeV/fm^3) we expect a phase transition to a phase where the quarks and gluons are deconfined:
  - The Quark Gluon Plasma (QGP)

Lattice QCD results (Numerical non-perturbative)

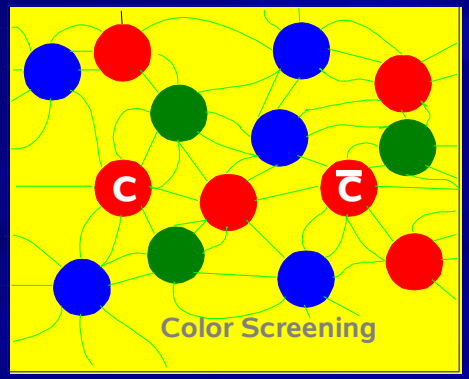
QCD energy denisty



Heavy quark potential



At T~Tc the strong potential is screened so e.g. c+c-bar states can disassociate.



Exercise: What is the high energy limit of QCD?

$$\epsilon_{QCD} = \frac{\pi^2}{30}\left(????? + \frac{7}{8} ????? \right) T^4$$

Bosonic degrees of freedom (gluons)

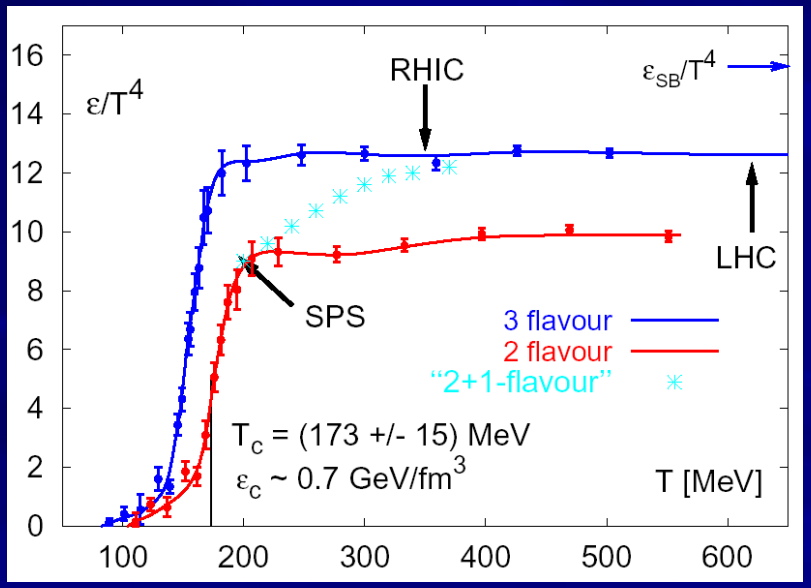
Fermionic degrees of freedom (quarks)

Answer:

$$\epsilon_{QCD} = \frac{\pi^2}{30}\left(2\times 8 + \frac{7}{8}2\times 2\times 3\times 3\right)T^4$$

Gluon spin and color

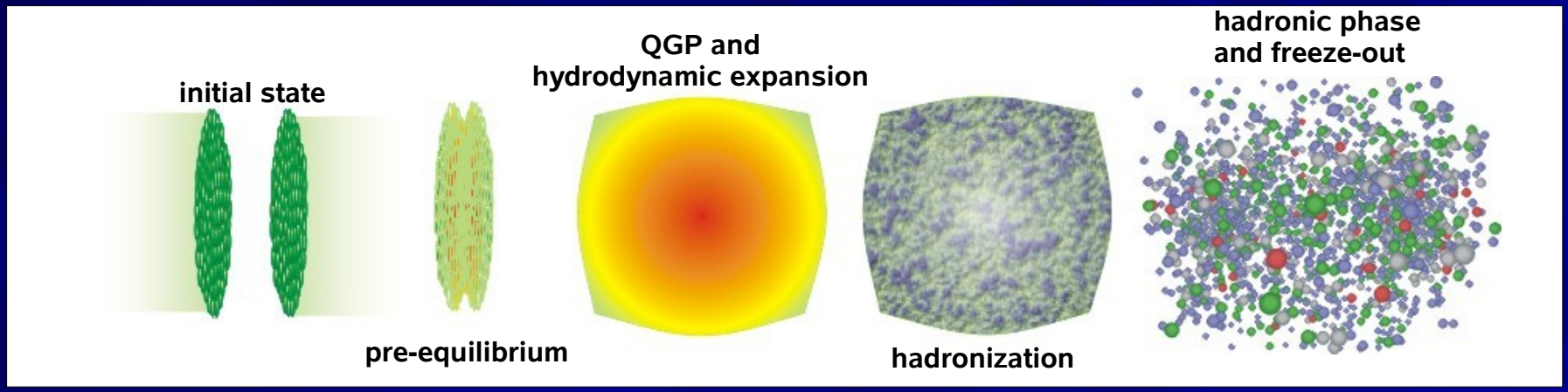
(Anti+)quark spin, color and flavor



This suggests that the Quark Gluon Plasma should behave as a gas of quarks and gluons!

Heavy ion collisions: The study of high energy QCD

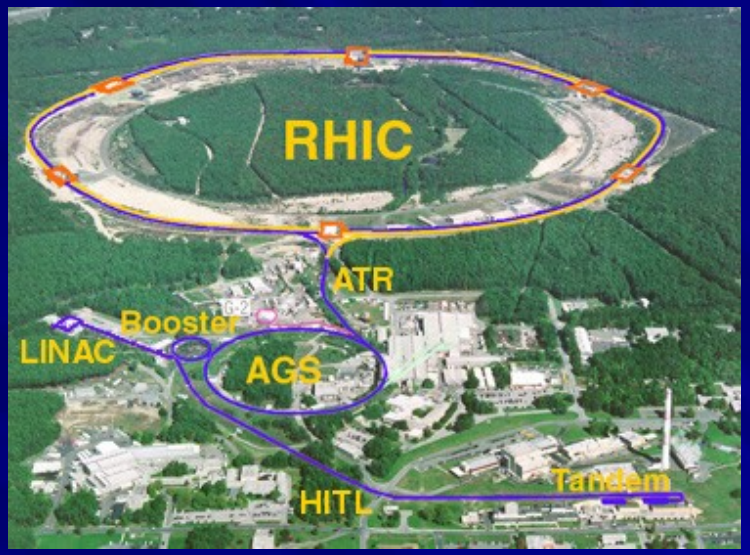
The evolution of a heavy ion collision



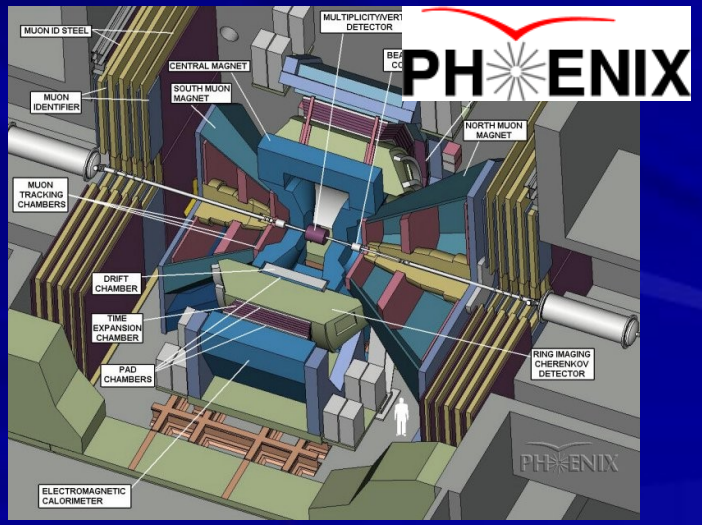
- By colliding heavy ions it is possible to create a large (»1fm^3) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally only the final state particles are observed, so the conclusions have to be inferred via models

Assumed knowledge

- Accelerators to produce the high energy beams
  - Relativistic Heavy Ion Collider at Brookhaven National Laboratory (outside new York)
  - Large Hadron Collider at CERN (near Geneva)

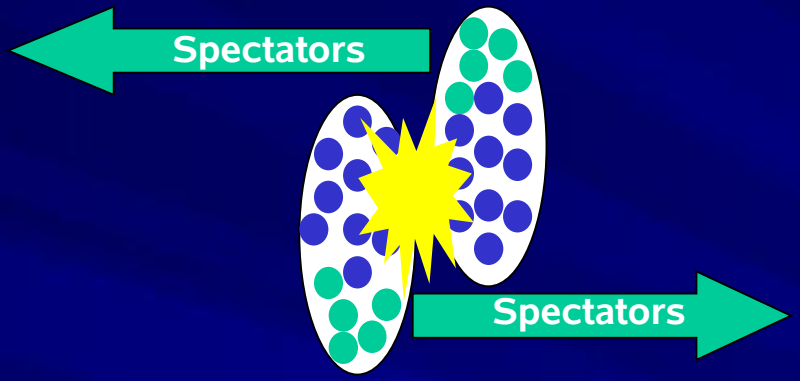


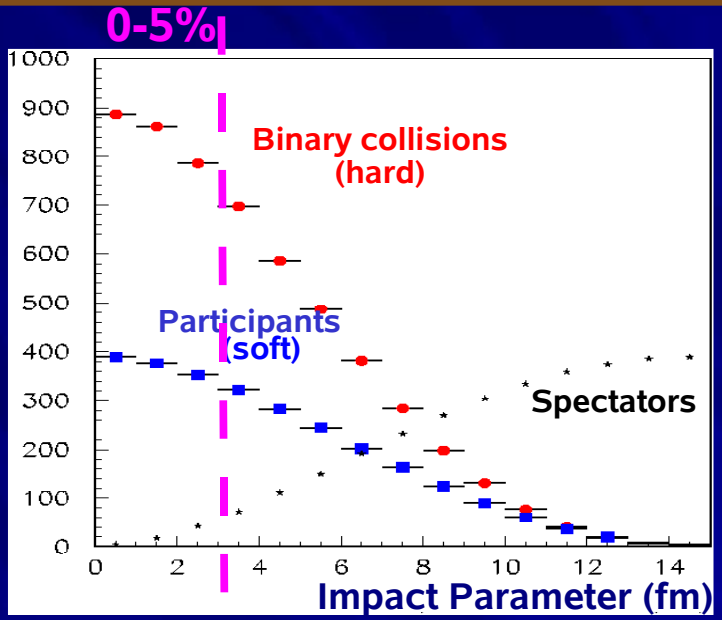
- Experiments to detect and reconstruct the final state particles
  - PHENIX and STAR at the Relativistic Heavy Ion Collider
  - ATLAS and ALICE at the Large Hadron Collide



Heavy Ion Jargon

- Centrality (ex. for Au+Au):

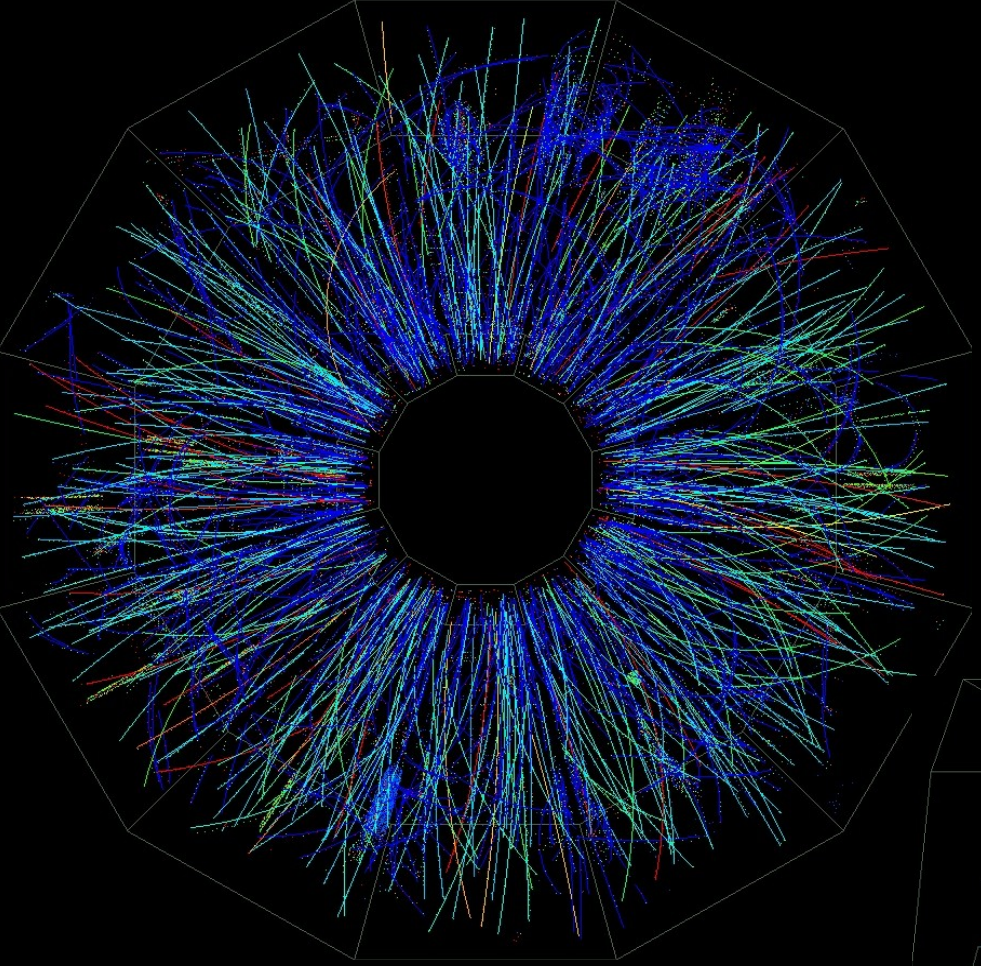




Participants = 2*197 - **Spectators**

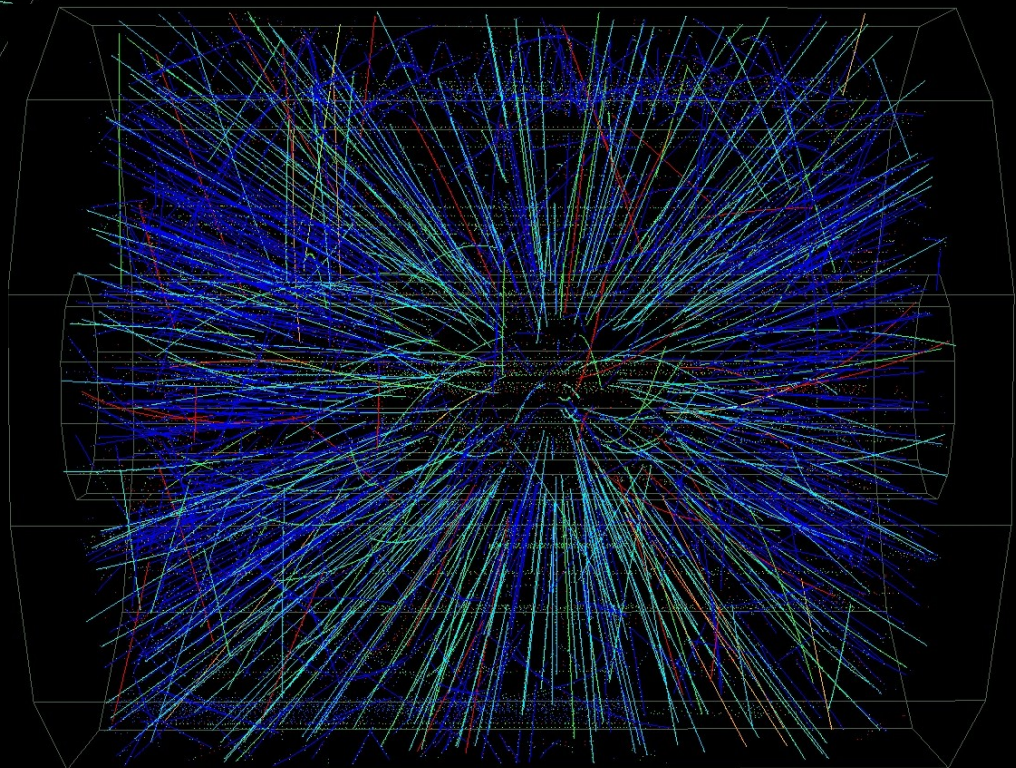
- The total energy is proportional to the participant
- The number of parton-parton (quark-quark, quark-gluon, gluon-gluon) is proportional to the binary collisions
- Example:

6 participant
8 binary collisions
(pp has 2 participant and 1 binary collision)



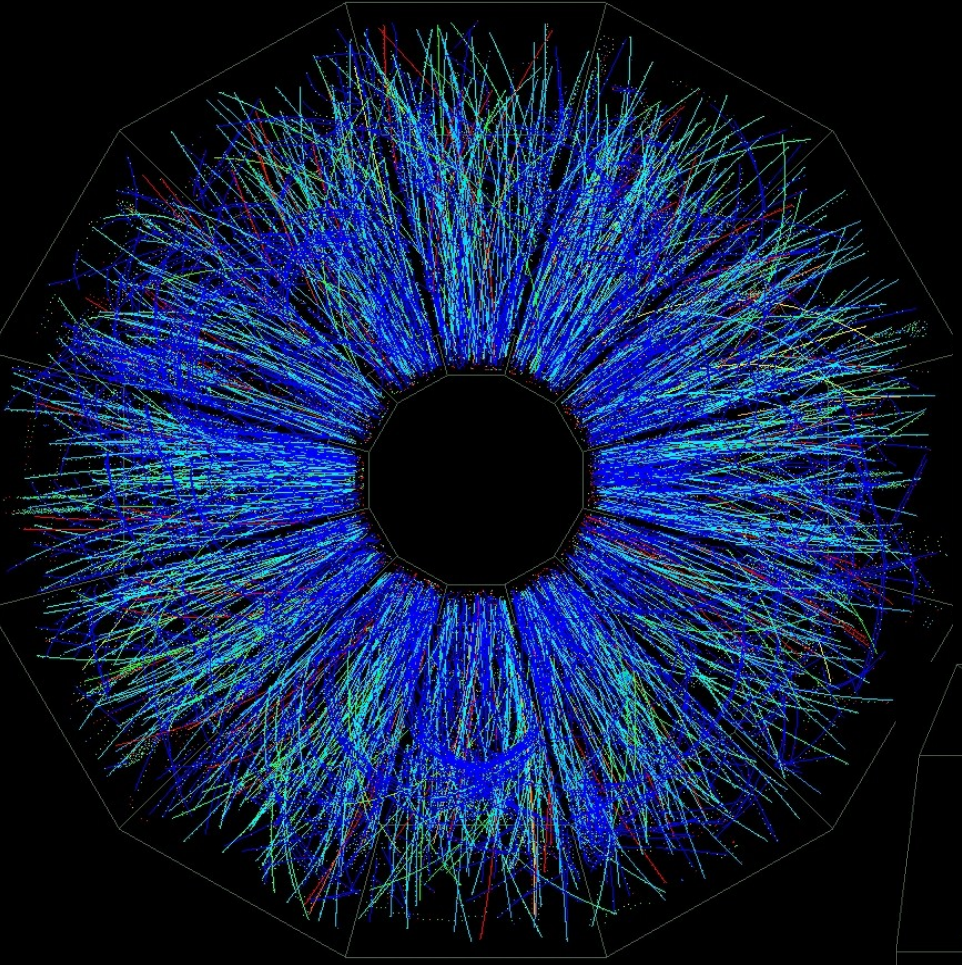
Peripheral Event

From real-time Level 3 display.



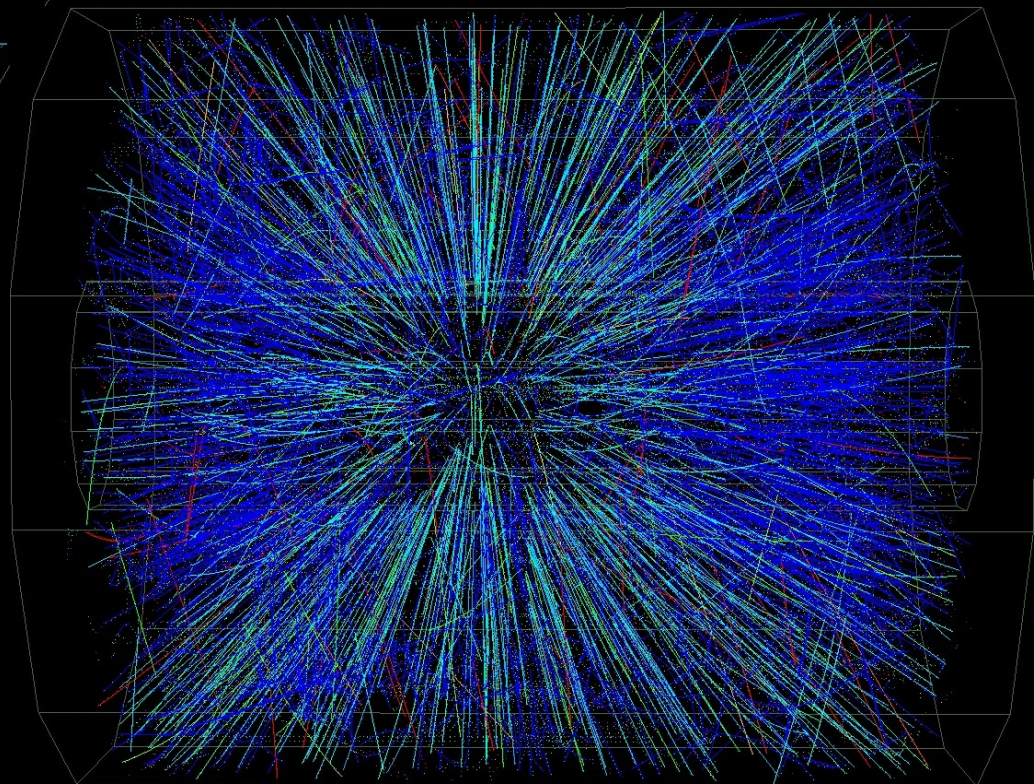
color code ⇒ energy loss

STAR

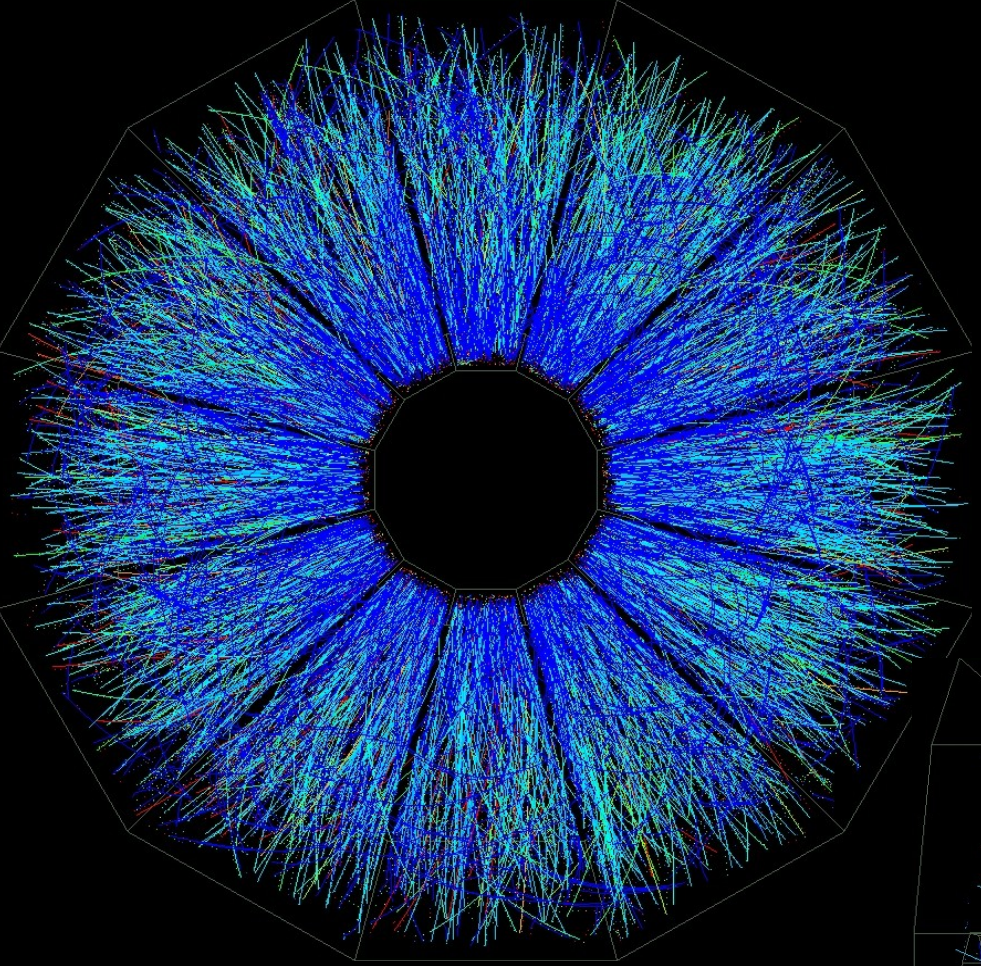


Mid-Central Event

From real-time Level 3 display.

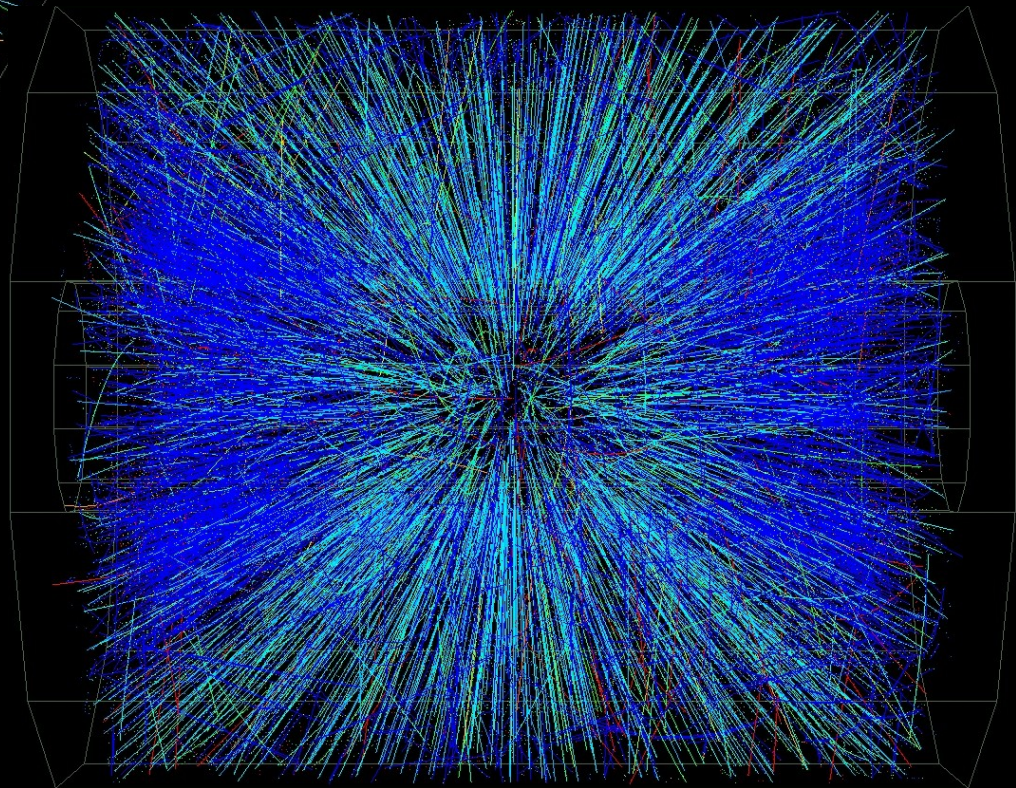


STAR

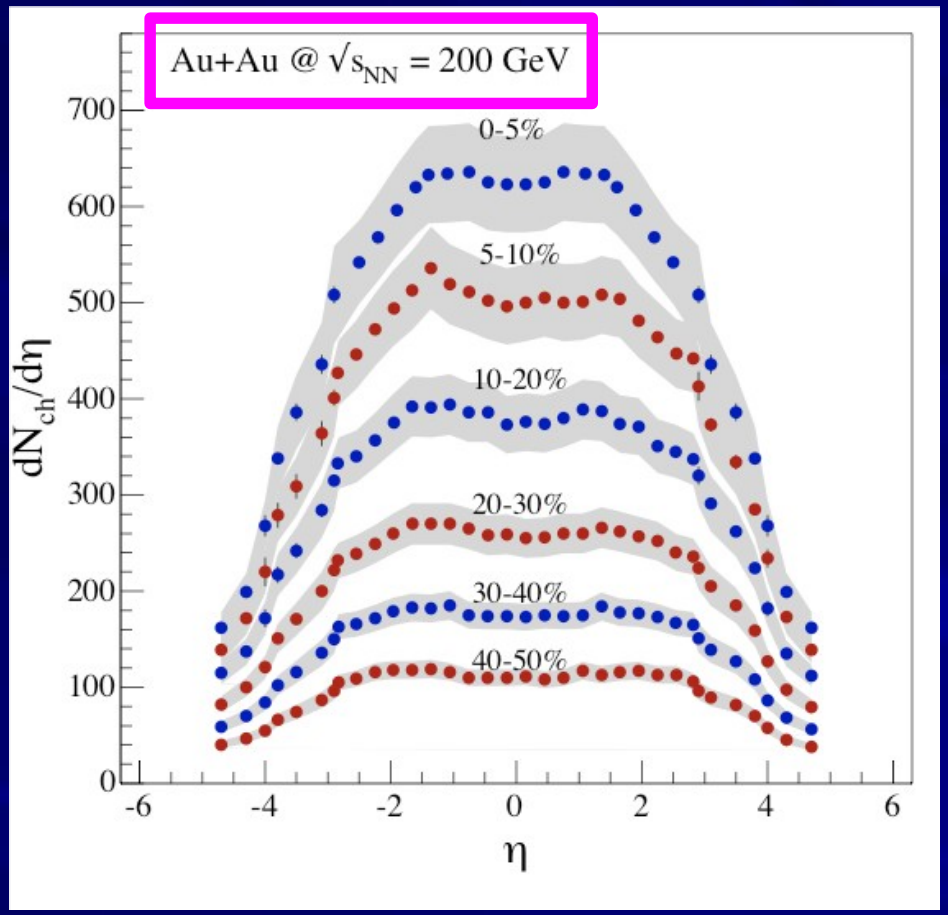


Central Event

From real-time Level 3 display.

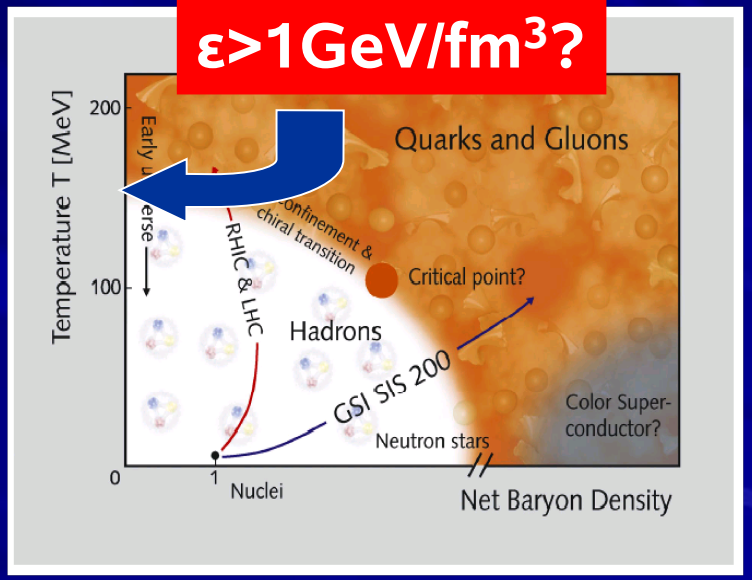


Charged Particle Multiplicity dN/dη



According to Bjorken:

$$\epsilon \approx \frac{1}{A_t}\frac{dN}{d\eta}\frac{1}{\tau} < E_t >$$

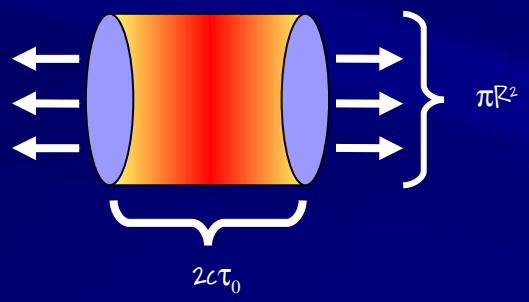


Estimate the energy density, assume <Et>~0.5GeV,

"Measured" initial energy density

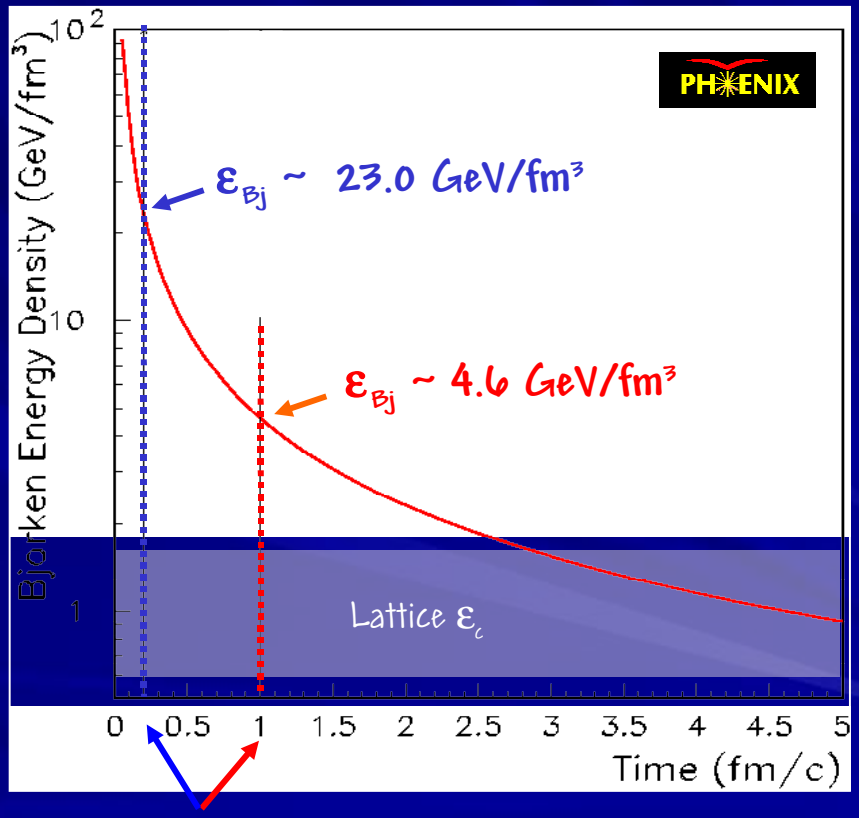
Bjorkens hydrodynamic formula for thermalized energy density in terms of measured transverse energy E_T

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\left(\frac{dE_T}{dy}\right)$$



PHENIX: Central Au Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\, GeV$$



Formation(thermalization) time ?

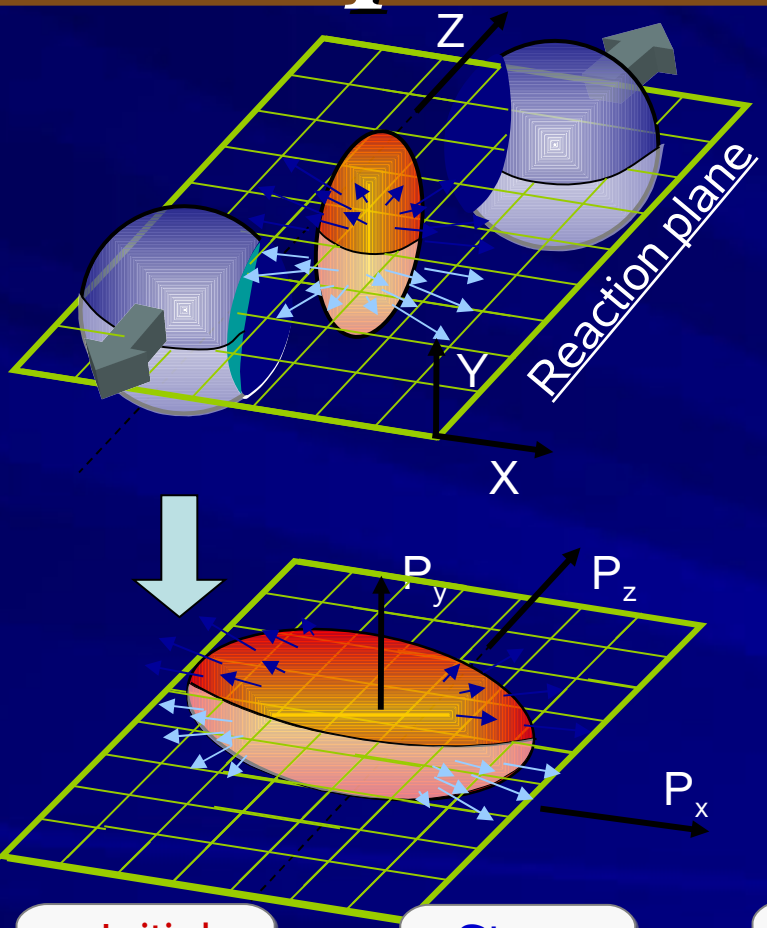
Break

- Please take 1 minute to write down on a piece of paper what the muddiest point so far has been

Short recap

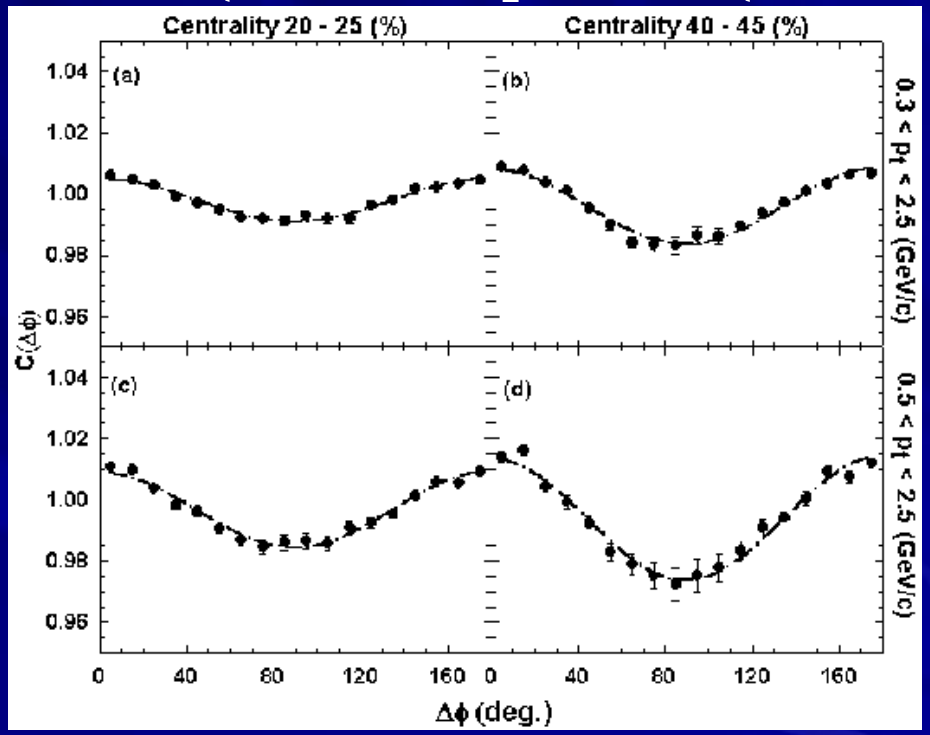
- We want to prove that the matter formed in heavy ion collisions is the expected Quark Gluon Plasma predicted by theory
  - a high energy gas/phase of quarks and gluons
- Problem: We have to derive this from the final state particles that are emitted after the system has cooled of
- We have shown that the energy density derived from the charged particle density is larger than the energy density required from QCD numerical simulations
  - Necessary condition, but not sufficient condition
- We want now to show that the matter formed is strongly interacting and that it shows quark and gluon degrees of freedom

Elliptic flow (v2) unique in heavy ion collisions



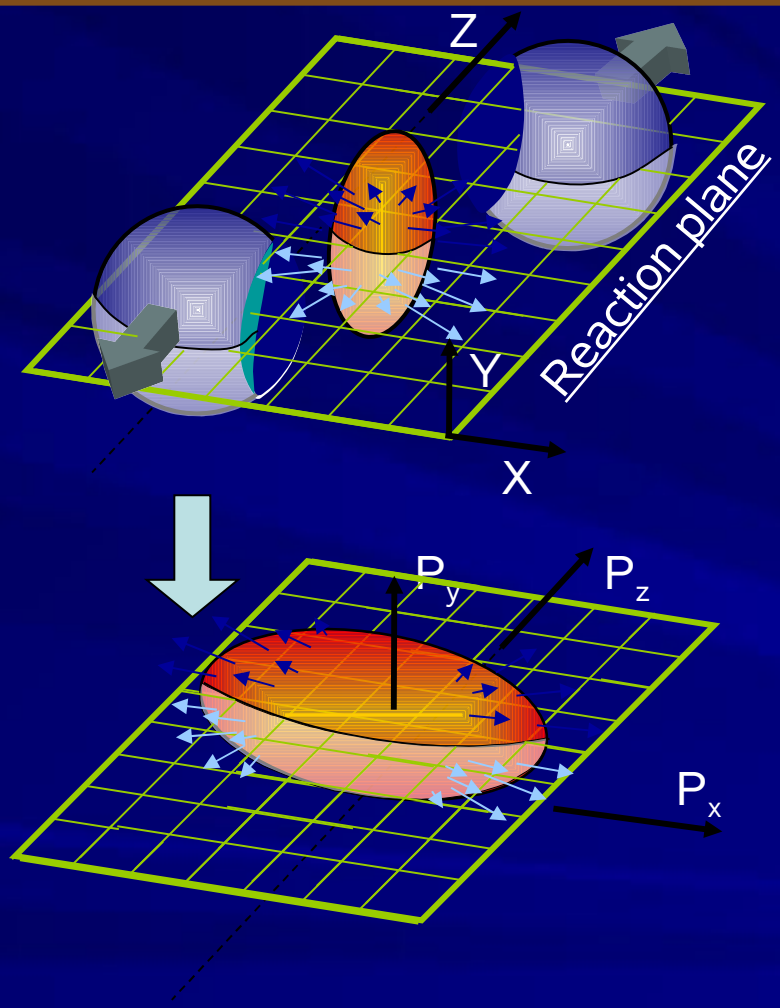
Fourier decomposition:

$dN/d\phi = 1 + 2\,V_2\cos(2\,\Delta\phi)$



Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

Elliptic flow exercise(s)

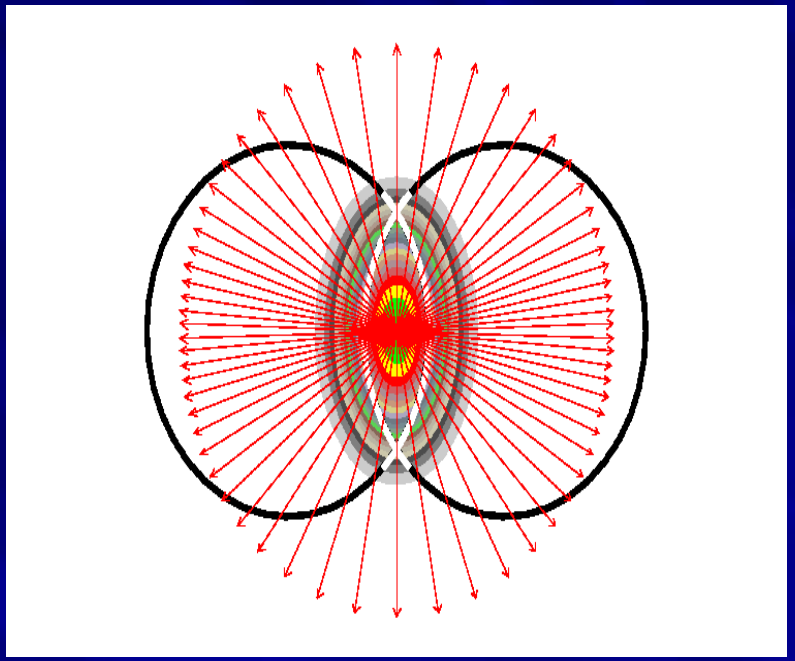


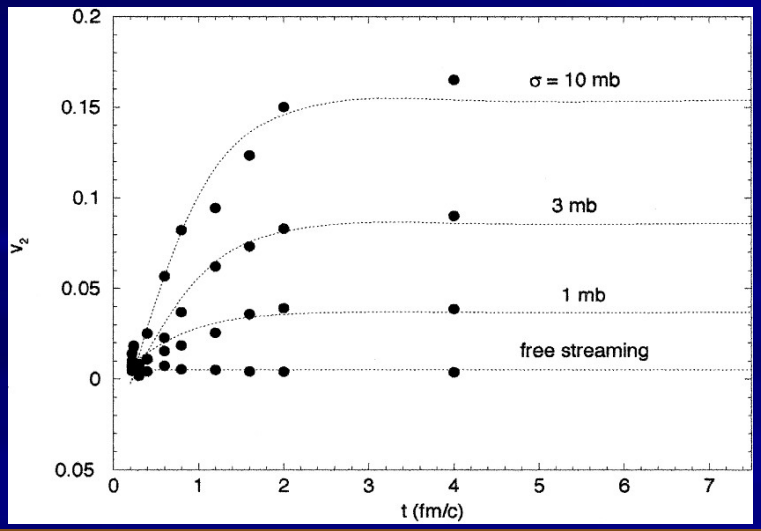
- Why is the elliptic flow sensitive to early interactions after the hot and dense matter has been formed?
  - Hint: The individual nucleon-nucleon collisions don't know the event plane
- Bonus question: Why is the flow generated in the event plane and not transverse to that
  - Hint: Think of the matter density contours

Answers

- Each nucleon-nucleon interaction produces on average a spherical symmetric distribution. Only by interacting elliptic flow is generated

  Zhang, Gyulassy, Ko, Phys. Lett. B455 (1999) 45





- Flow is strongest in the event plane because of the stronger matter gradient
  - hydrodynamic explanation

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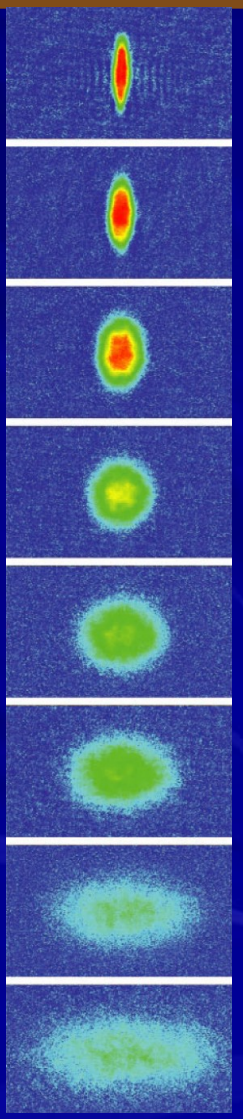
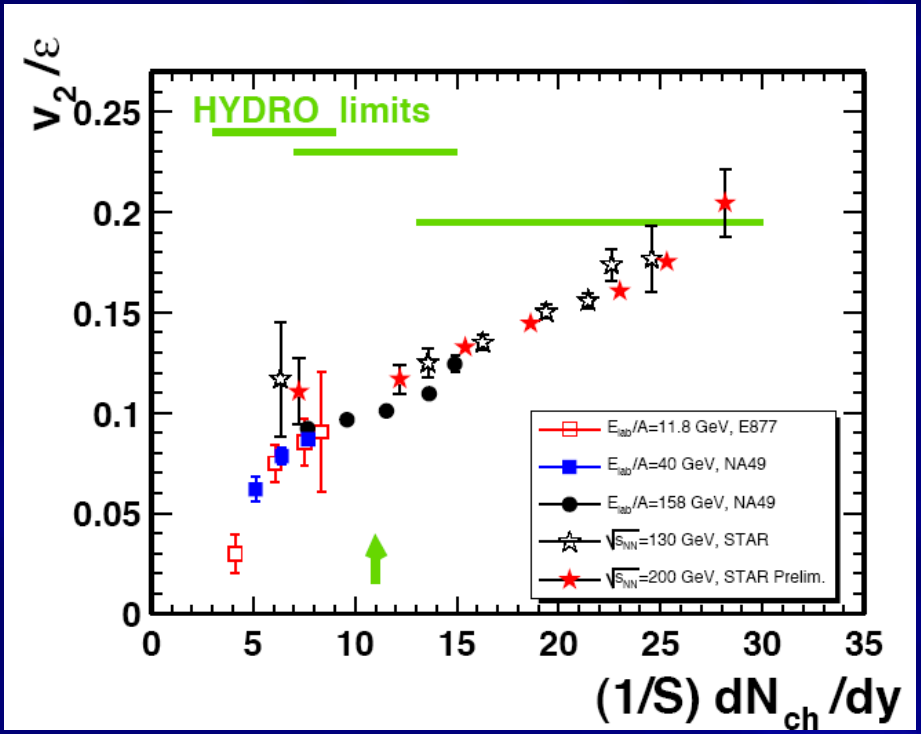
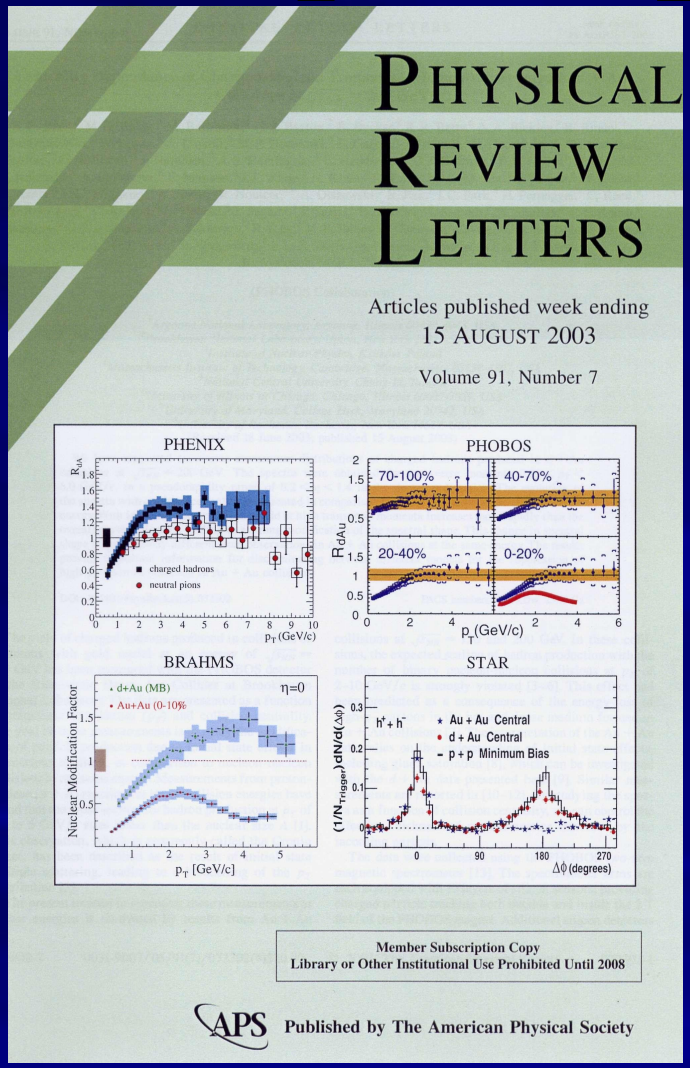


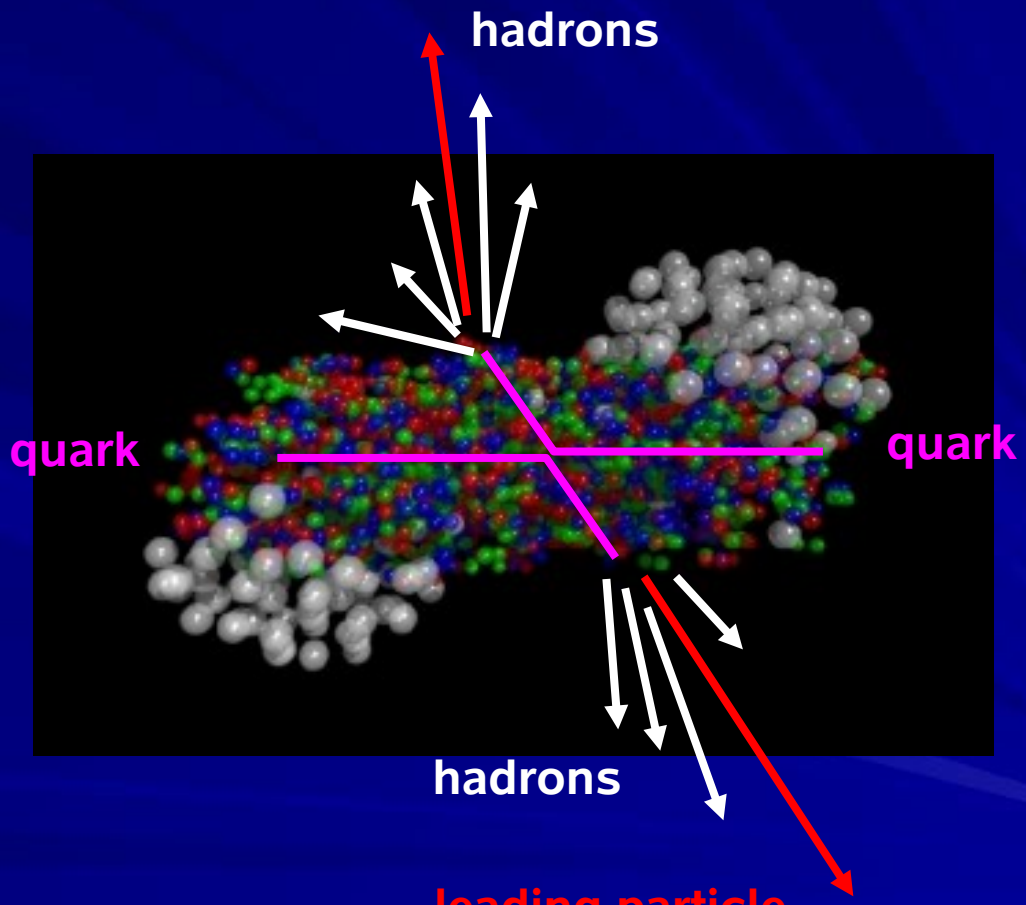
Elliptic flow at RHIC is "Maximal"



- Relativistic hydrodynamic predicts elliptic flow
  - The high energy medium interacts very strongly immediately after being formed
  - Medium does not behave as a gas, but an almost perfect fluid!
- Question: Where is QCD dynamics?

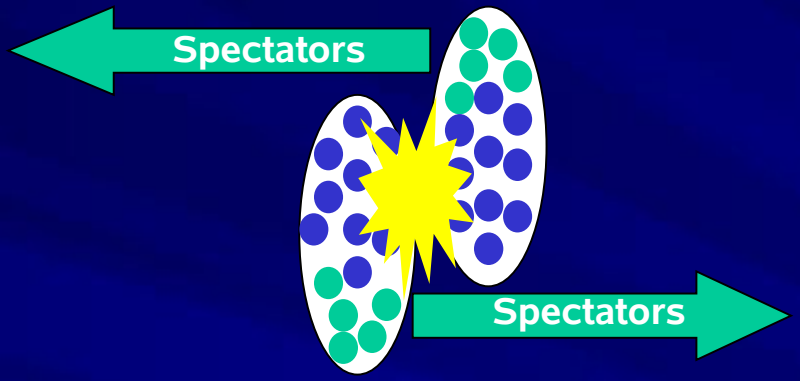
Hard probes (pQCD): parton-parton interactions

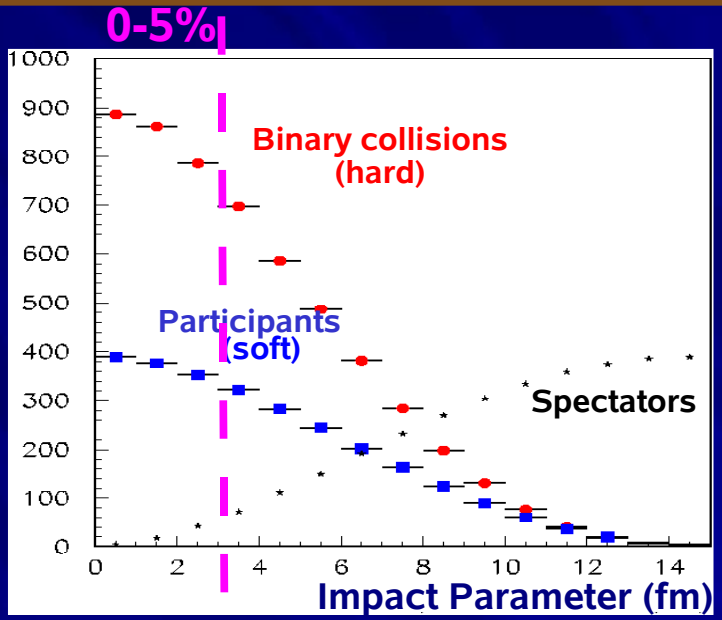




Heavy Ion Jargon Revisited

- Centrality (ex. for Au+Au):

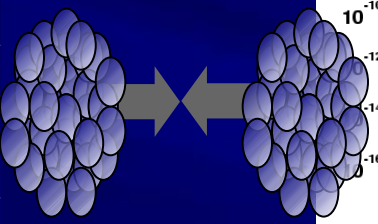


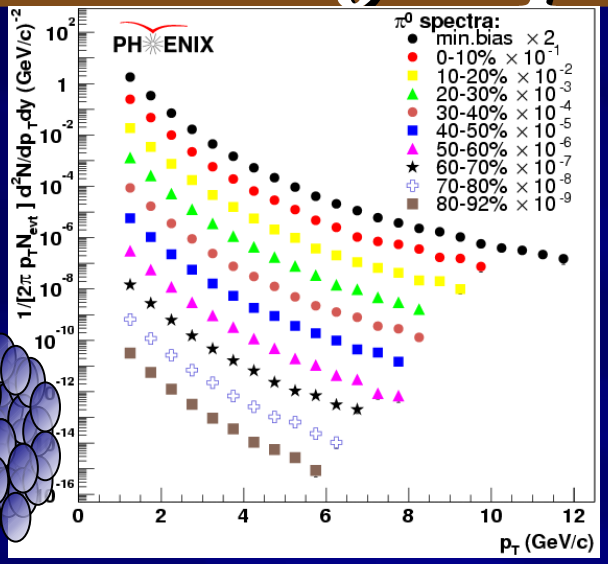


Participants = 2*197 - Spectators

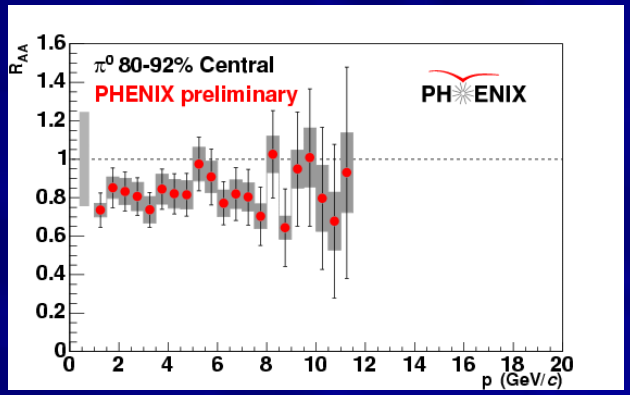
- parton-parton collisions are proportional to binary collisions
- Exercise: Why is the number of binary collisions in central collisions proportional to $A^{4/3}$ while the number of participants is A?
  - Hint: What is the average amount of nuclear matter covered in the "target" nuclei?

The nuclear modification factor for pions (1/2)

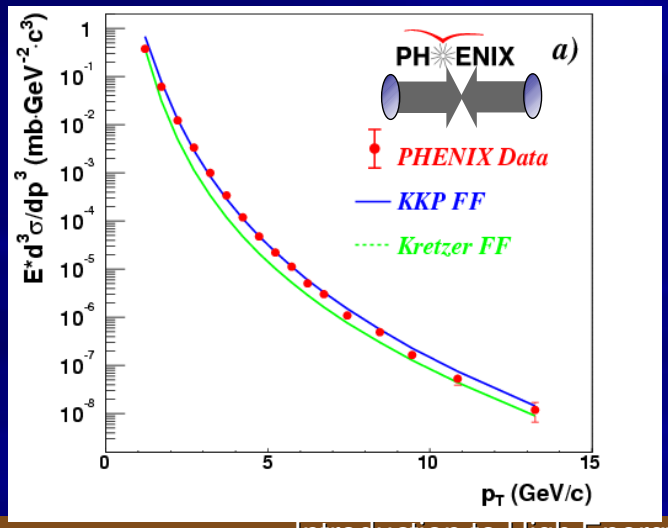


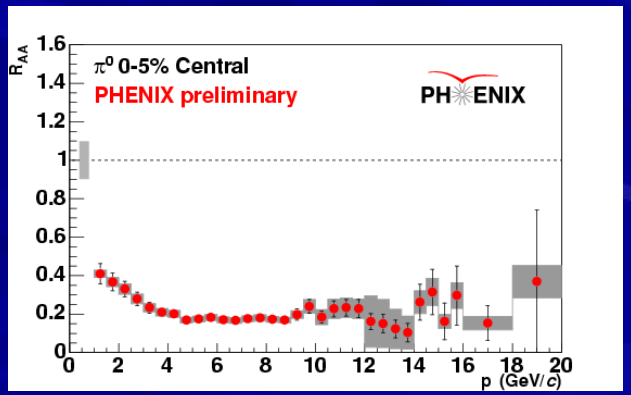


$$R_{AA} = \frac{d^2 N^{AA}/d\,p_T dy}{\langle N_{bin} \rangle d^2 N^{NN}/d\,p_T dy}$$

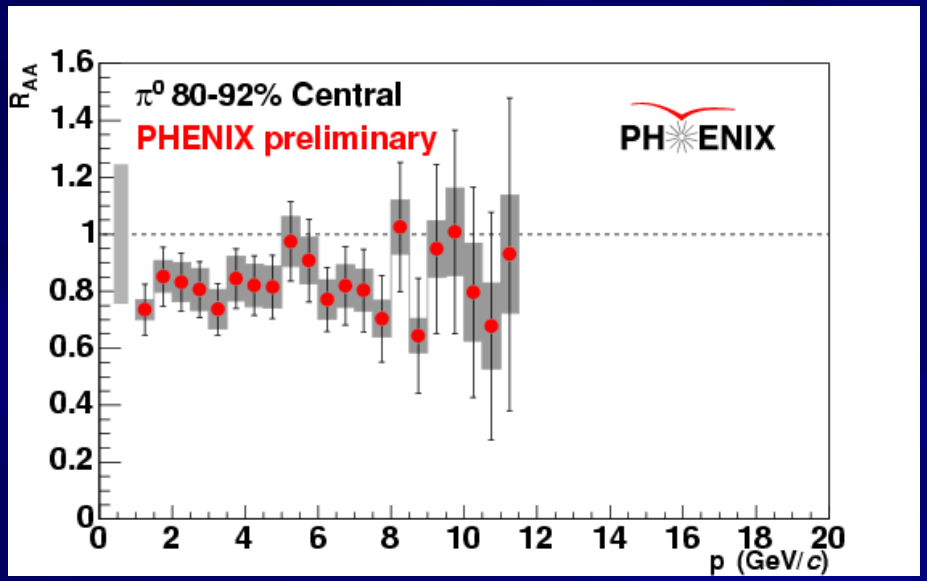


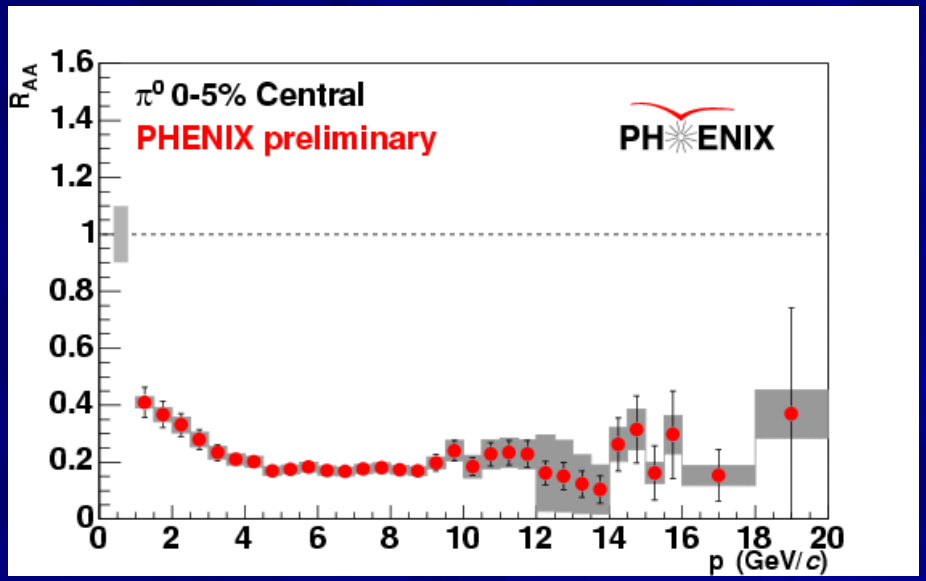
Nbin





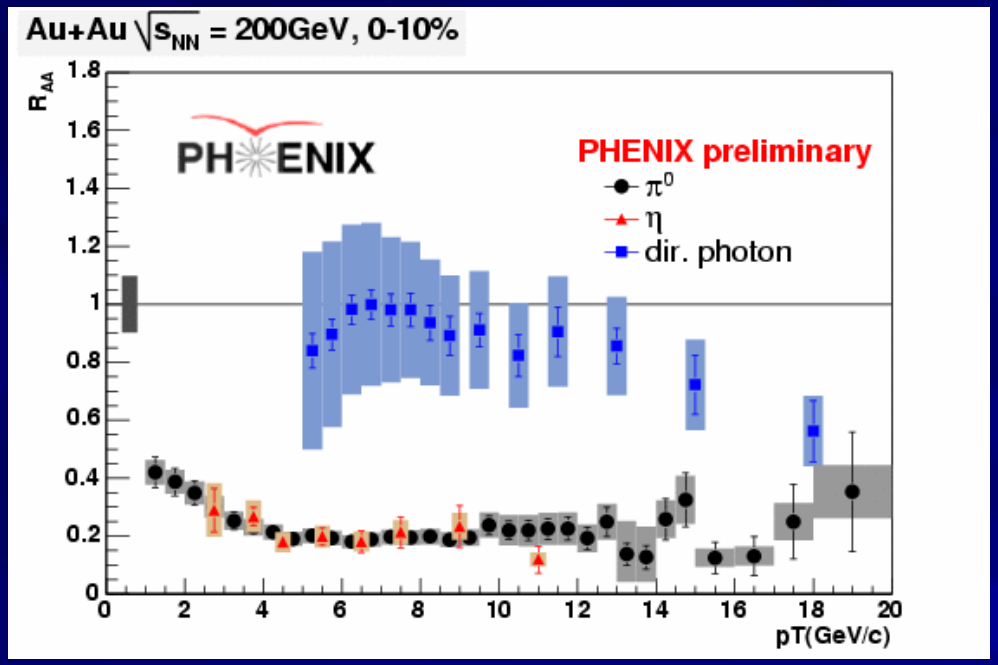
The nuclear modification factor for pions (2/2)



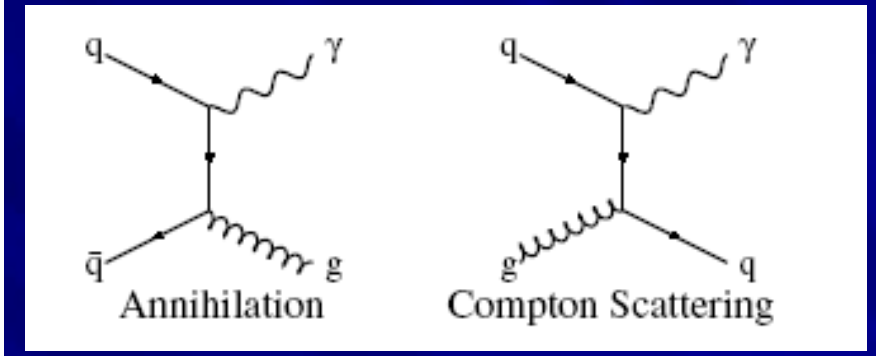


- In central collisions we observe only 20% of the remnants from parton-parton collisions that we expected to observe!
- What happens to the rest?
  - They loose energy as they go through the high energy matter!
  - This is the QCD signature we looked for!
- But first let us consider other alternatives!

Could the binary scaling be wrong?



Source of direct photons

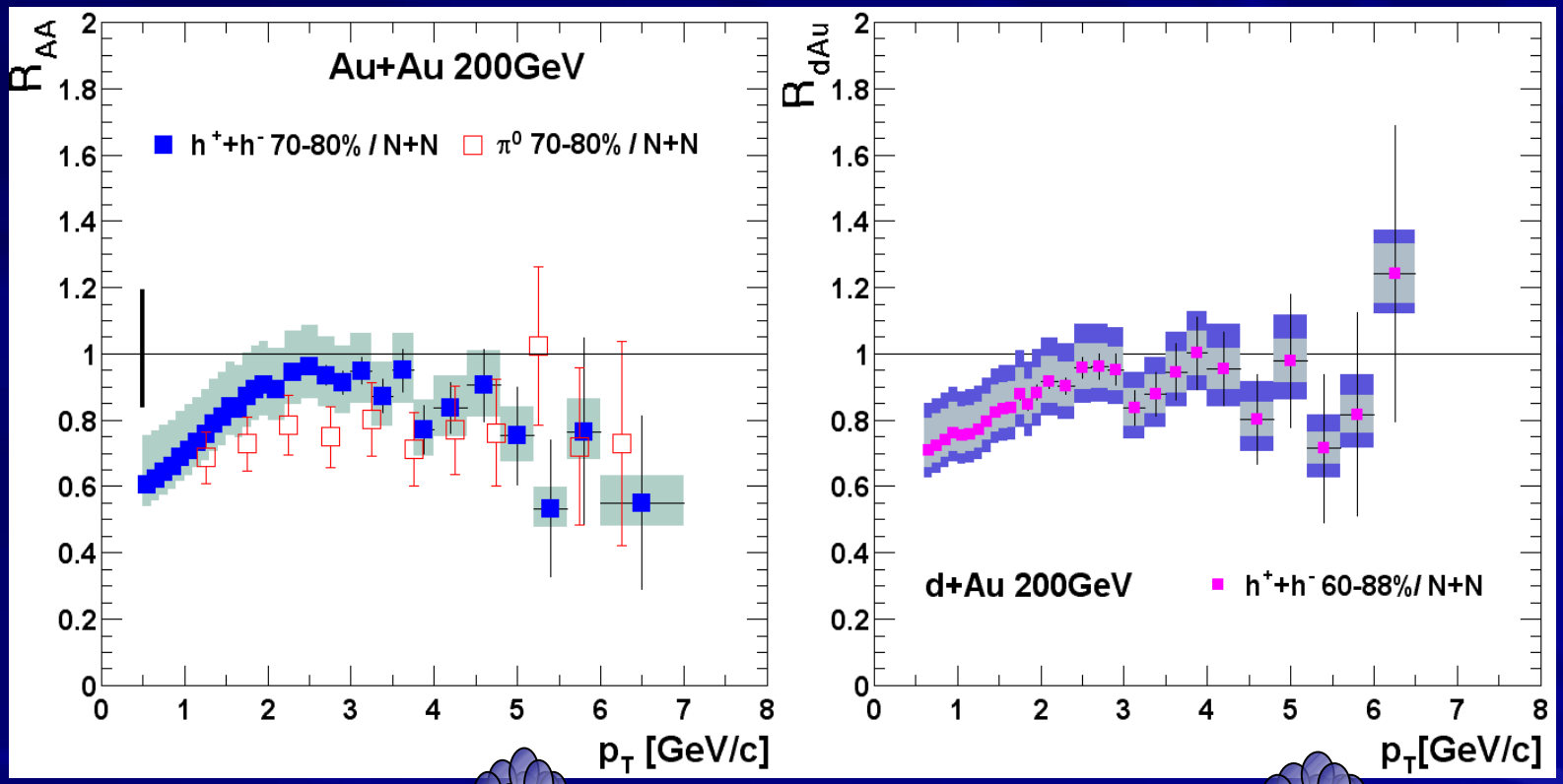


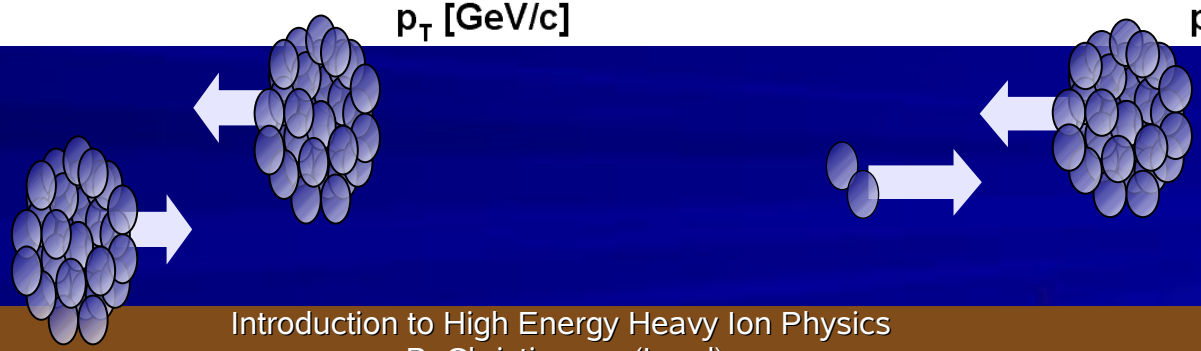
- Direct photons does not interact with final state hadronic matter!
- Direct photons shows no nuclear modification and therefore confirm binary scaling of hard processes!

Could it be an initial state effects? Au+Au vs d+Au

Au + Au Experiment

d + Au Control





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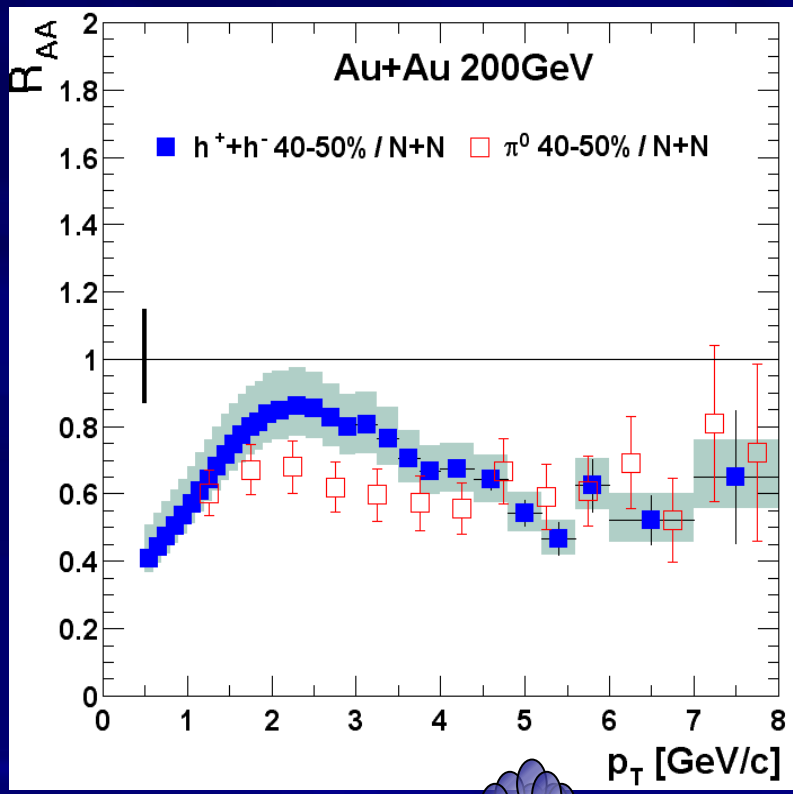
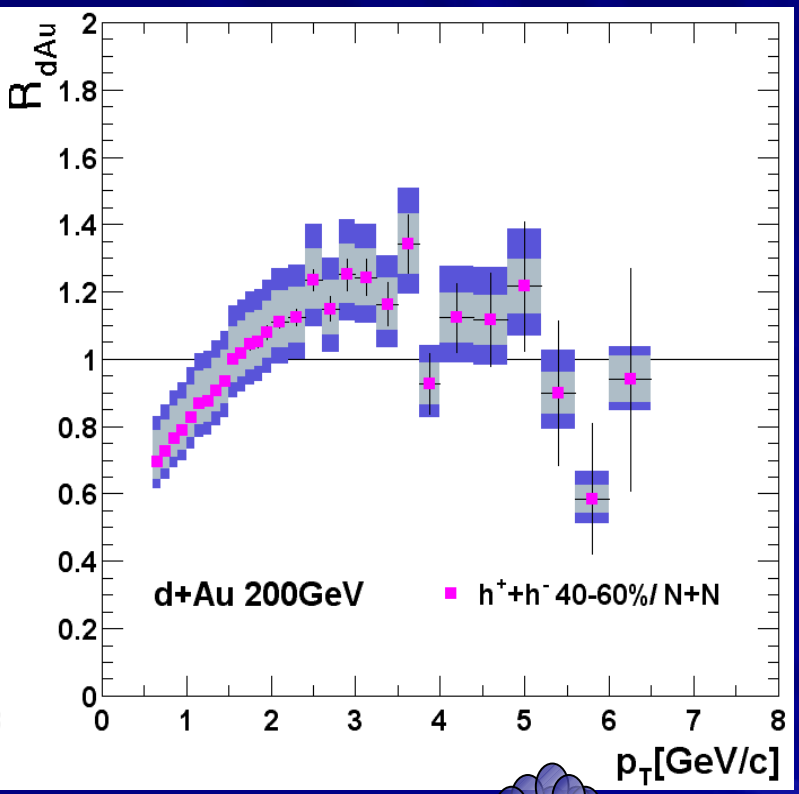
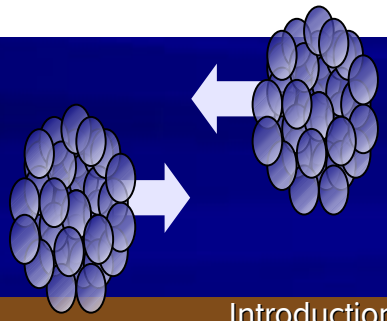
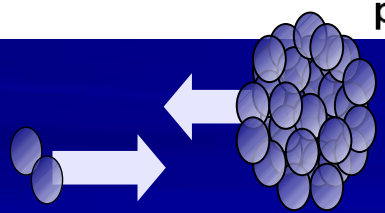
Au + Au Experiment



d + Au Control

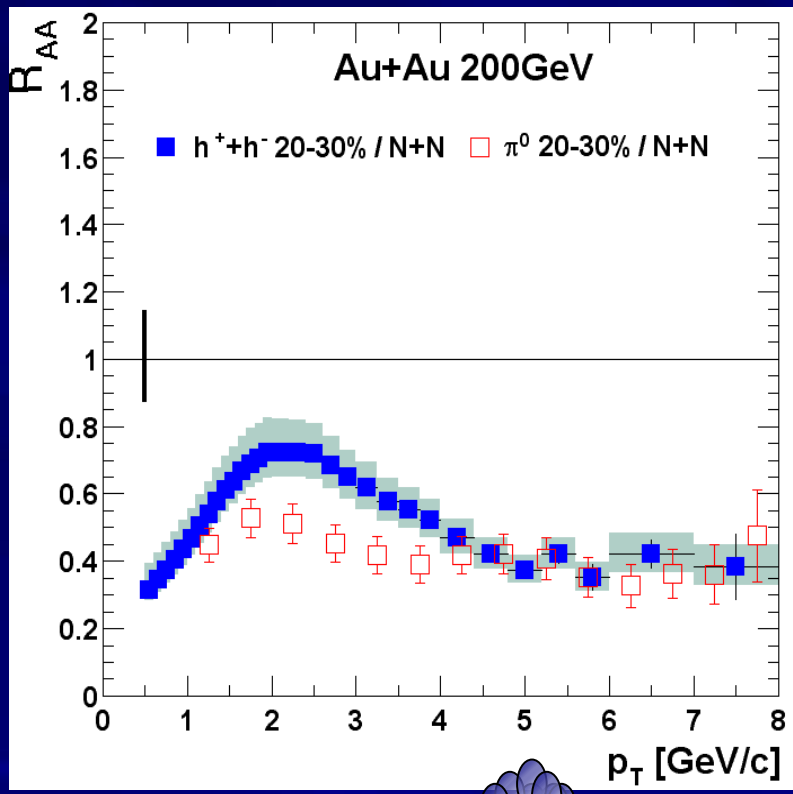




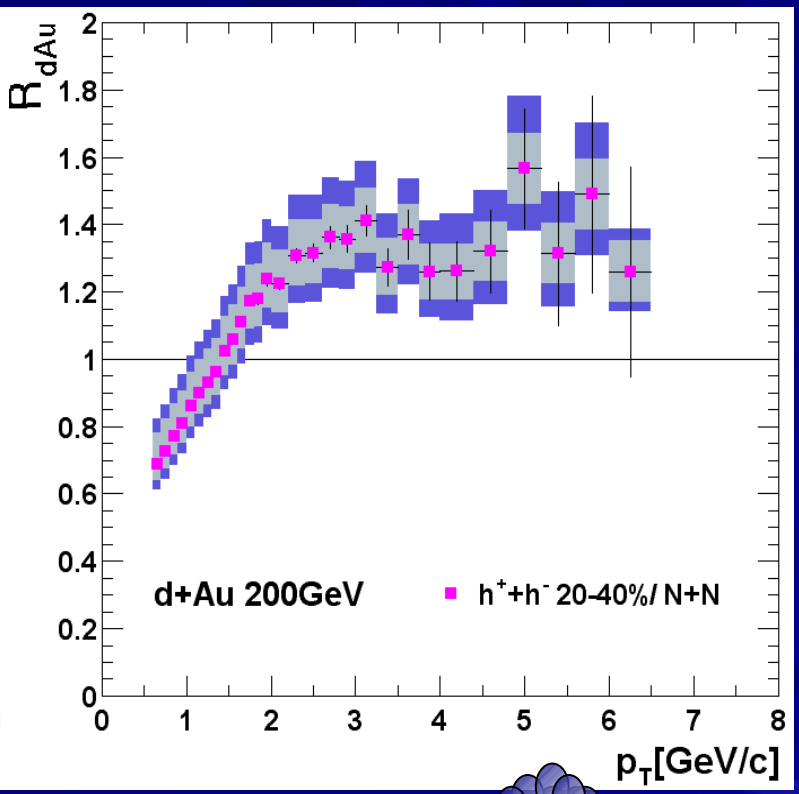


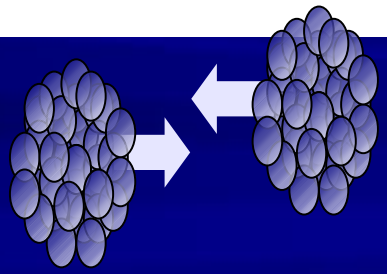
Could it be an initial state effects? Au+Au vs d+Au

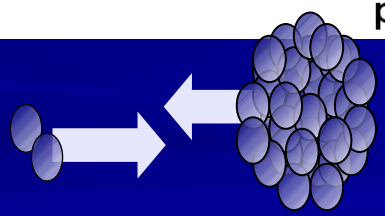
Au + Au Experiment



d + Au Control

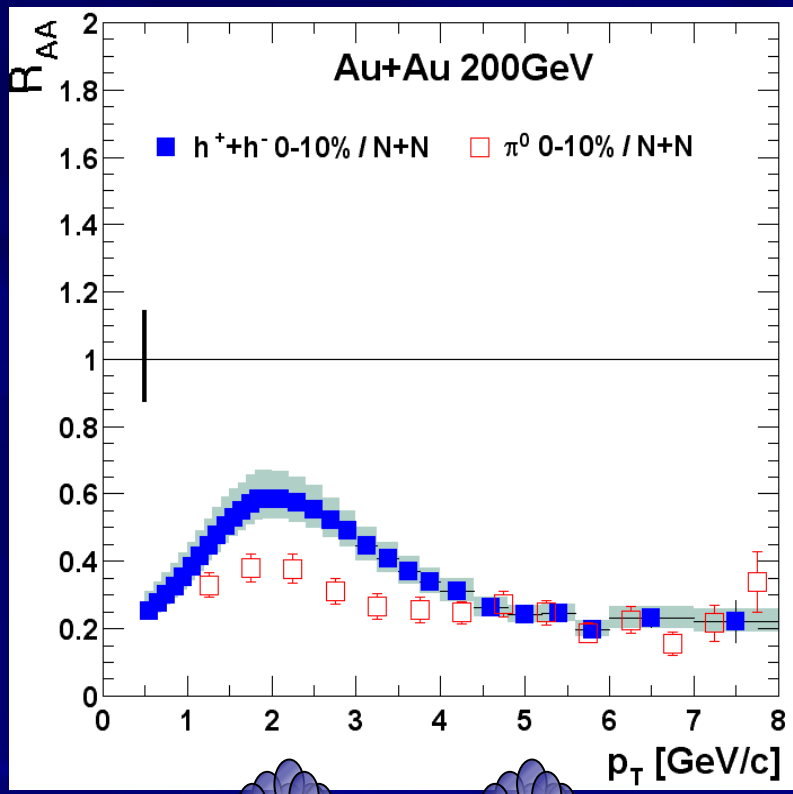




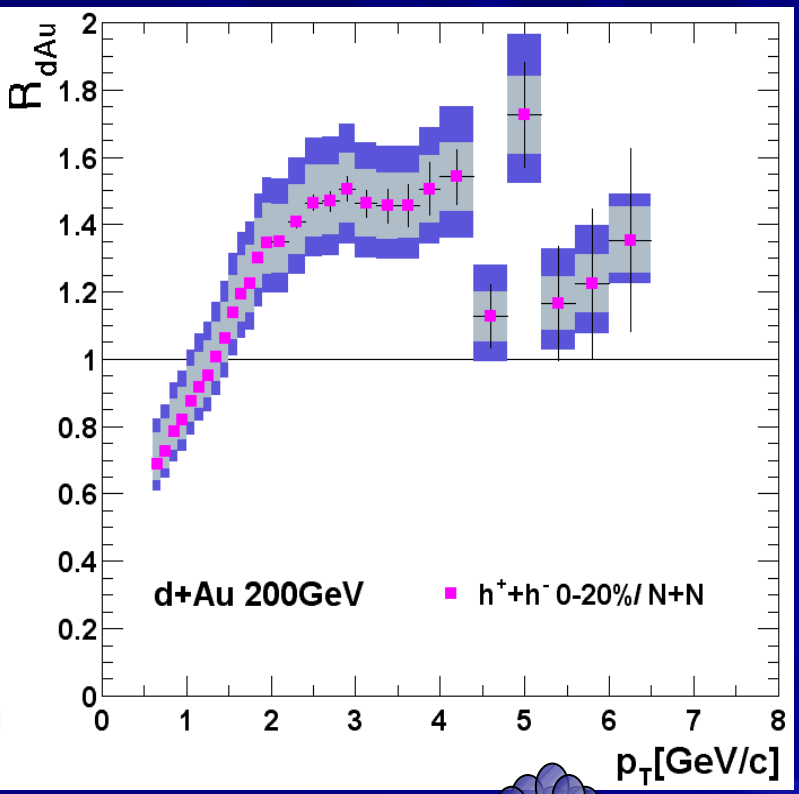


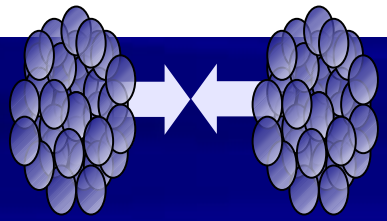
Could it be an initial state effects? Au+Au vs d+Au

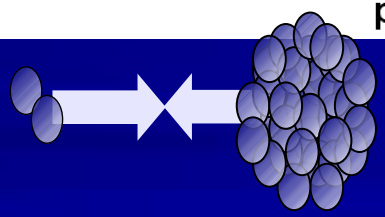
Au + Au Experiment



d + Au Control



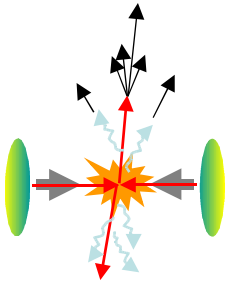




So it must be a final state effect!

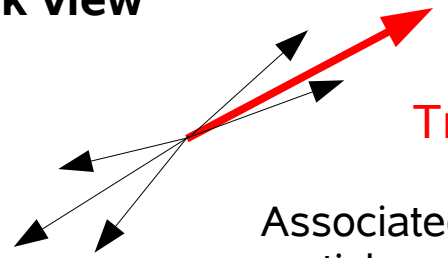
The suppression is due to energy loss in the medium

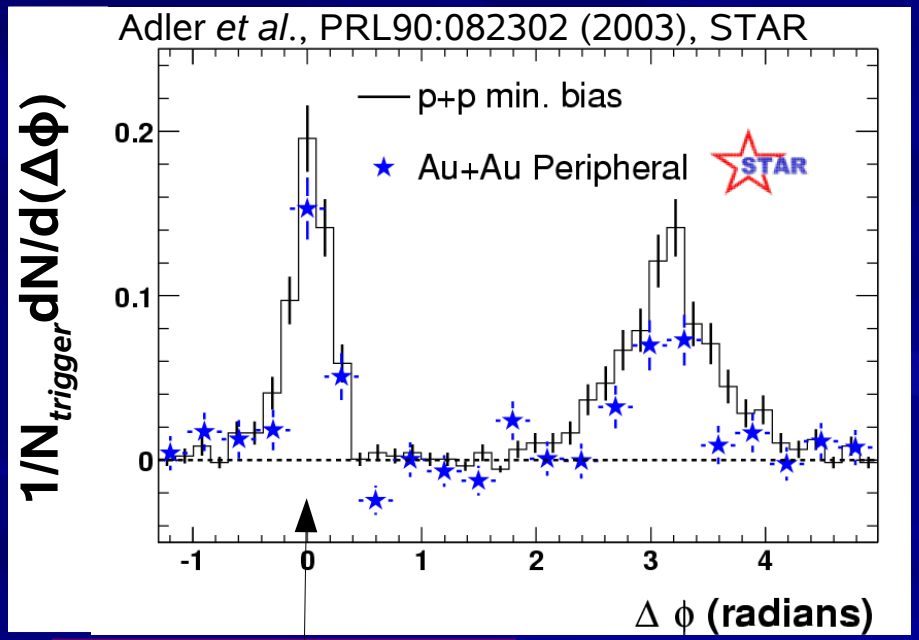
Side view



Most jets are created back to back!

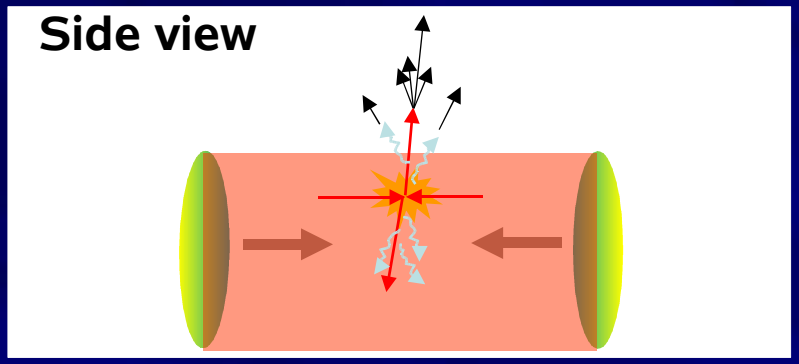
Back view



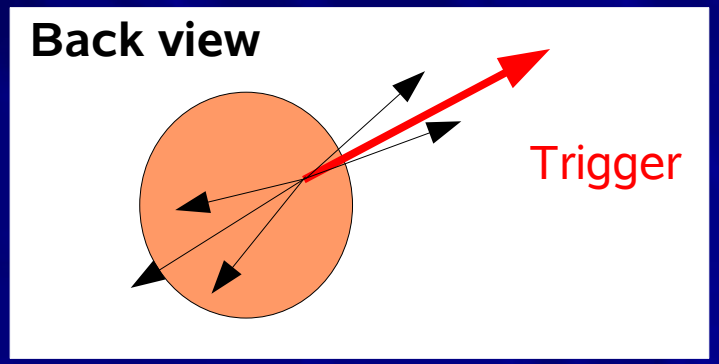


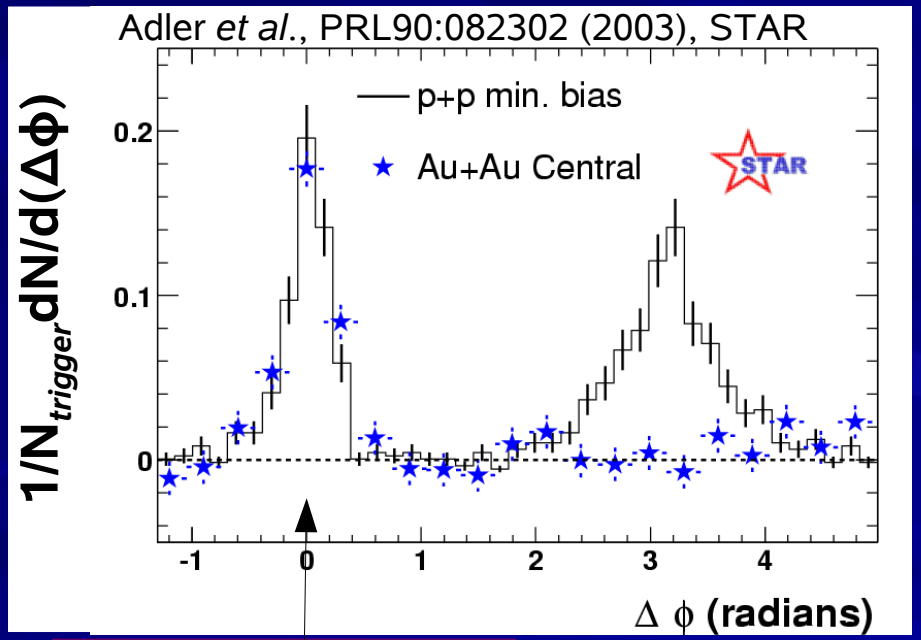
$4 < p_T(\text{trig}) < 6$ GeV/c **$p_T(\text{assoc}) > 2$ GeV/c**

The suppression is due to energy loss in the medium



Most jets are created back to back!



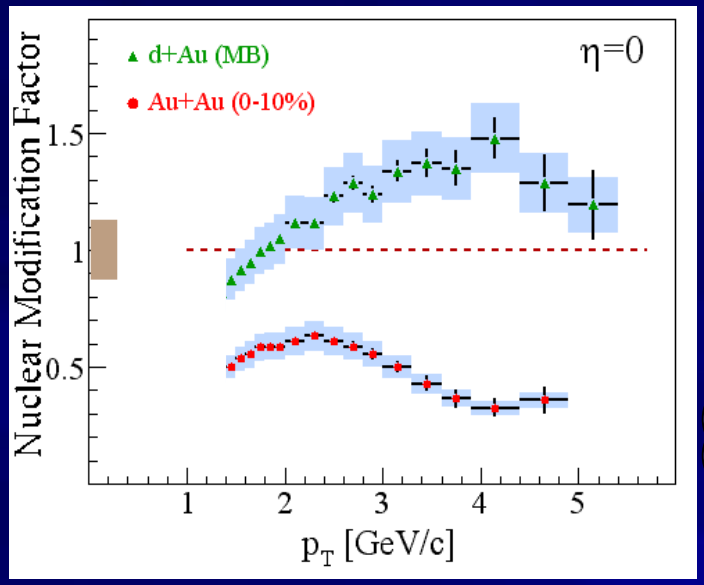


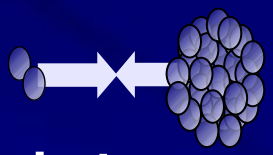
$4 < p_T(\text{trig}) < 6$ GeV/c

$p_T(\text{assoc}) > 2$ GeV/c

A large energy loss requires a QCD interacting medium, i.e., a colored medium!

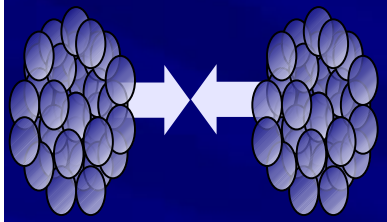
Au+Au vs d+Au
Hot vs cold nuclear matter



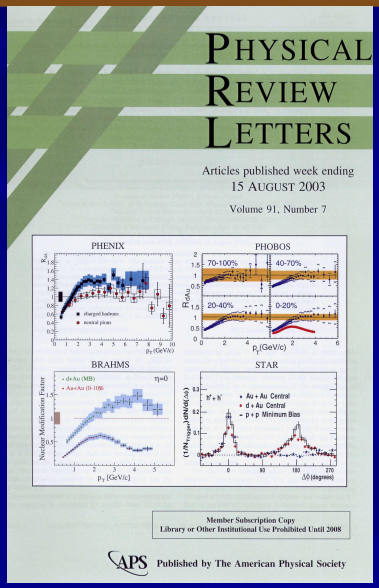


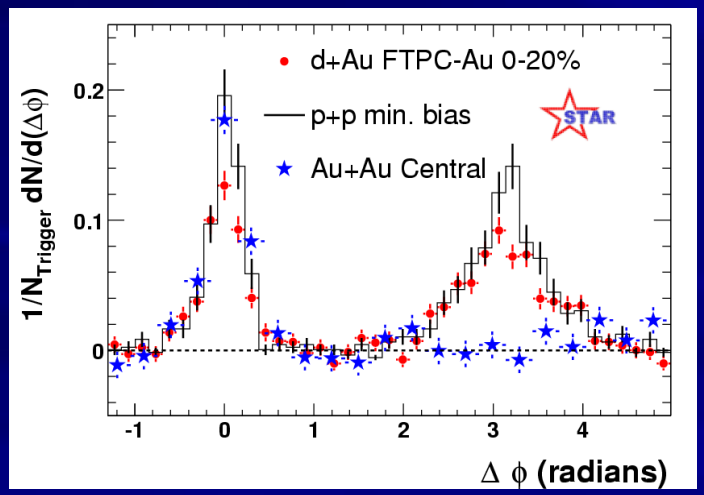
d+Au

Au+Au



All 4 experiments published together in PRL:





No suppression seen in d+Au
→ Quarks and gluons loose/radiate energy as they interact with the colored quarks and gluons of the created matter.
This suggests that the quark gluon plasma has been discovered!

Summary:

- Hard experimental work at RHIC has lead to the conclusion that a Quark Gluon Plasma is most likely produced in central collisions of gold on gold! BUT
- Theoretical models are not very constrained by the data as they use many phenomenological inputs
  - New excitement: Can string theory describe non-perturbative QCD?
- Many observations suggests that the picture is more complicated (Quark Gluon Plasma is not like we expected)
  - Particularly heavy quark data challenges many models
- One expects that all these effects should grow as one goes up in energy

What will we see at LHC?!