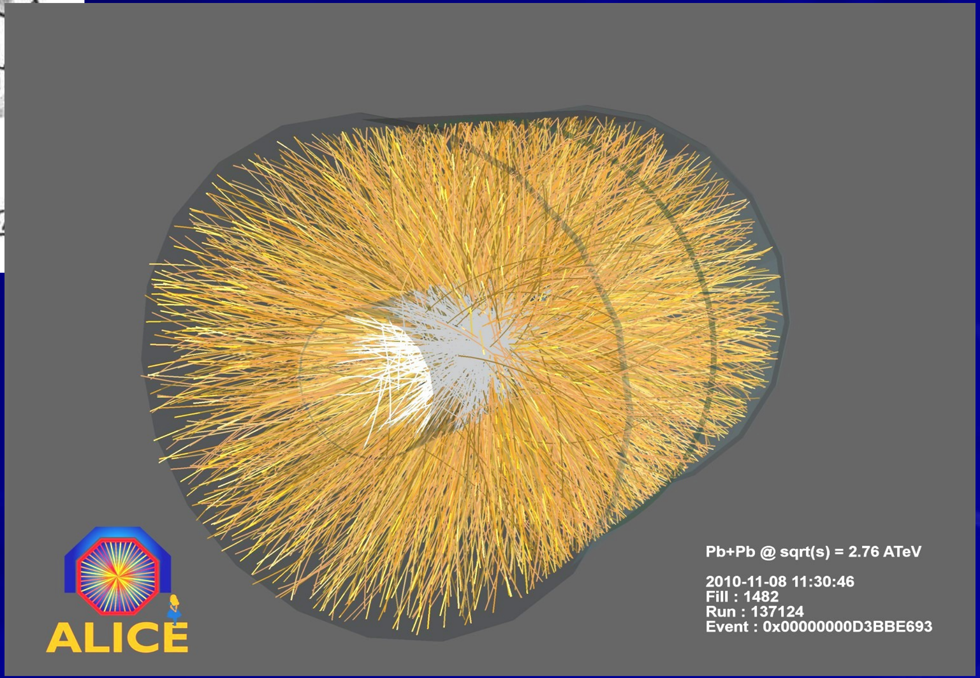
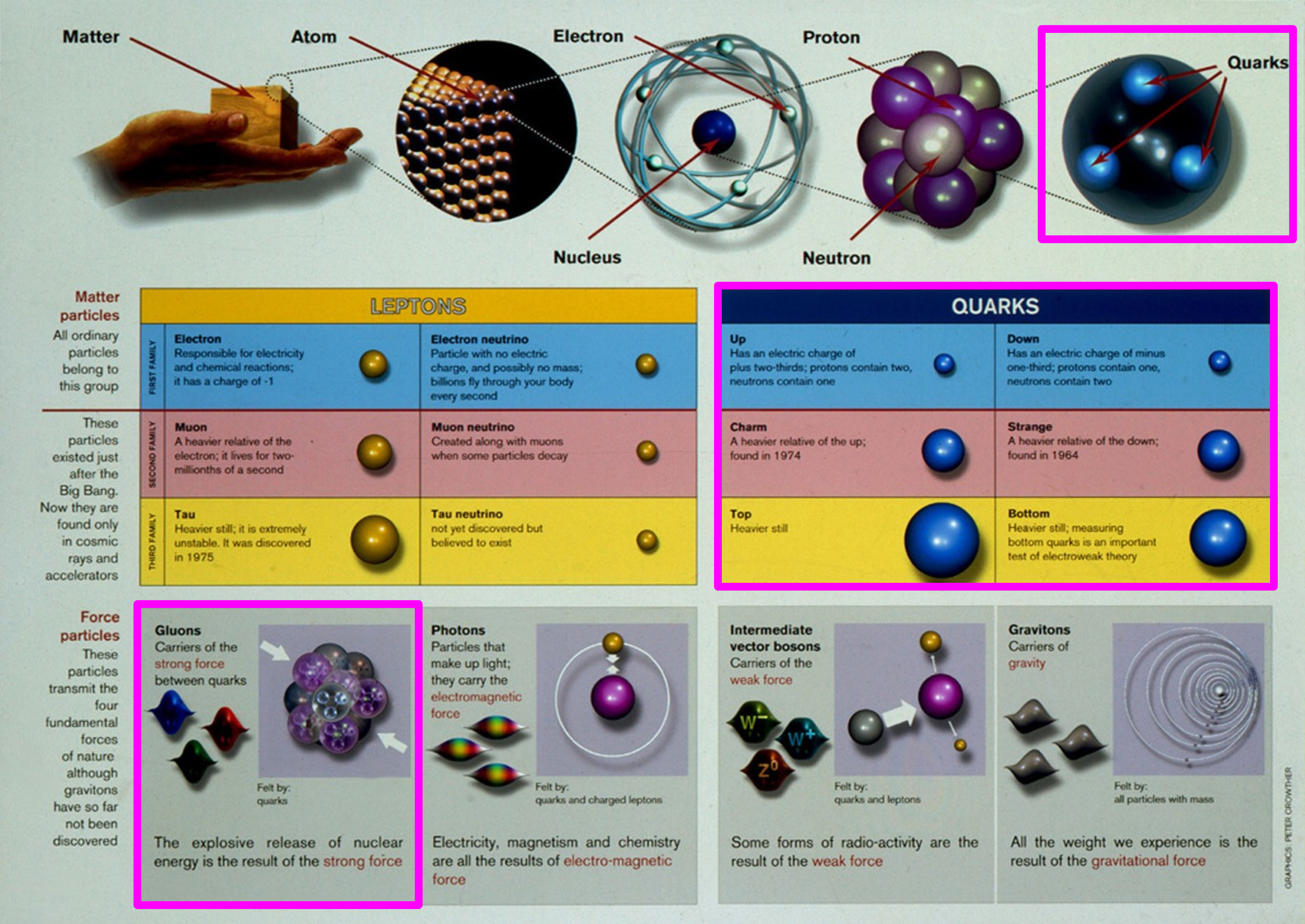
An introduction to high energy heavy ion physics

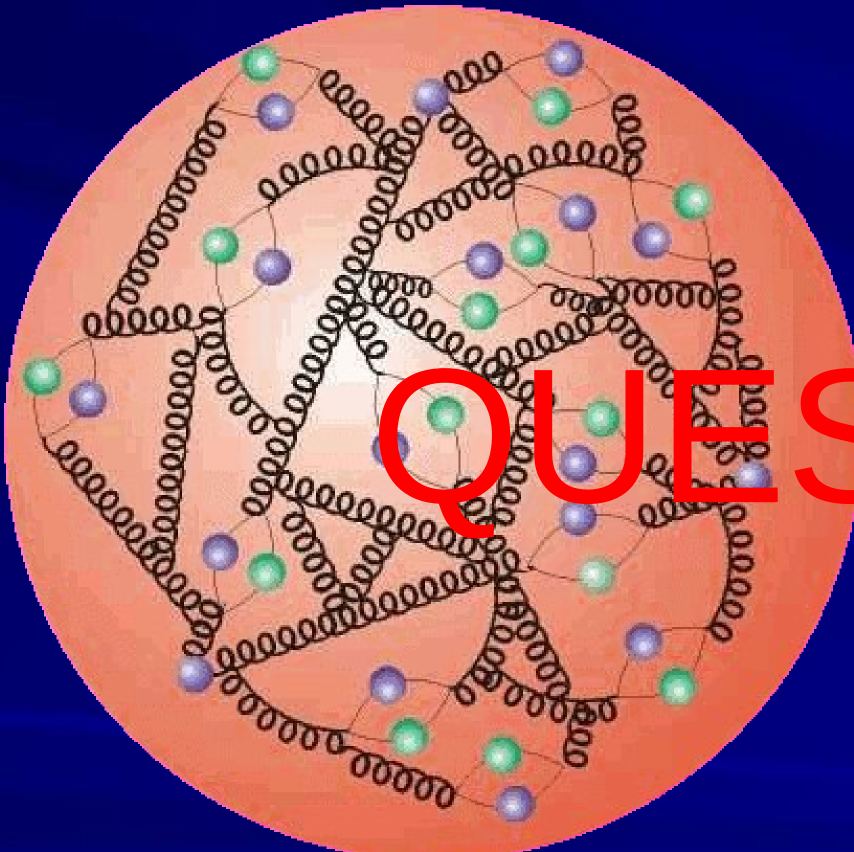
1 small bang in the ALICE experiment



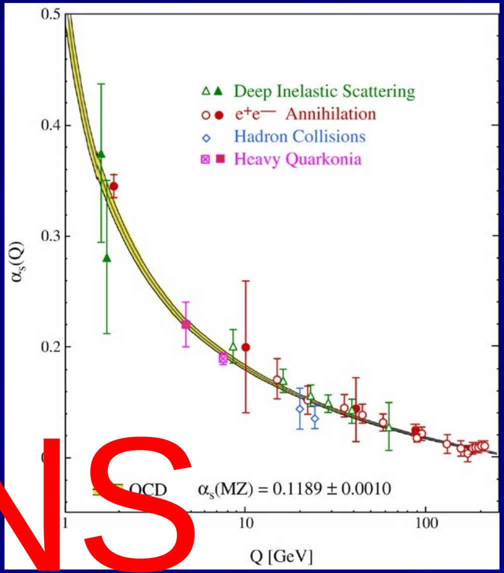

Matter
Atom
Electron
Proton
Quarks
Nucleus
Neutron
Matter particles
All ordinary particles belong to this group
These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators
LEPTONS
FIRST FAMILY
SECOND FAMILY
THIRD FAMILY
Electron
Responsible for electricity 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
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
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
W−
W+
Z0
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

The focus of this talks is quark and gluon physics

- The strong interaction is very complex!

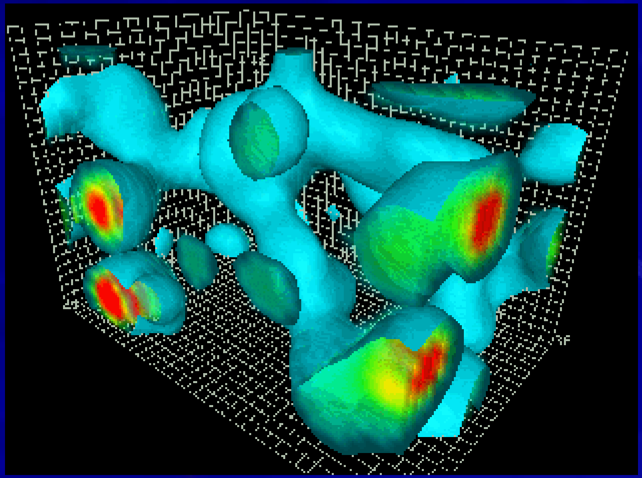


Quarks and gluons couples strong:



QUESTIONS

Complex vacuum:



CONFINEMENT

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

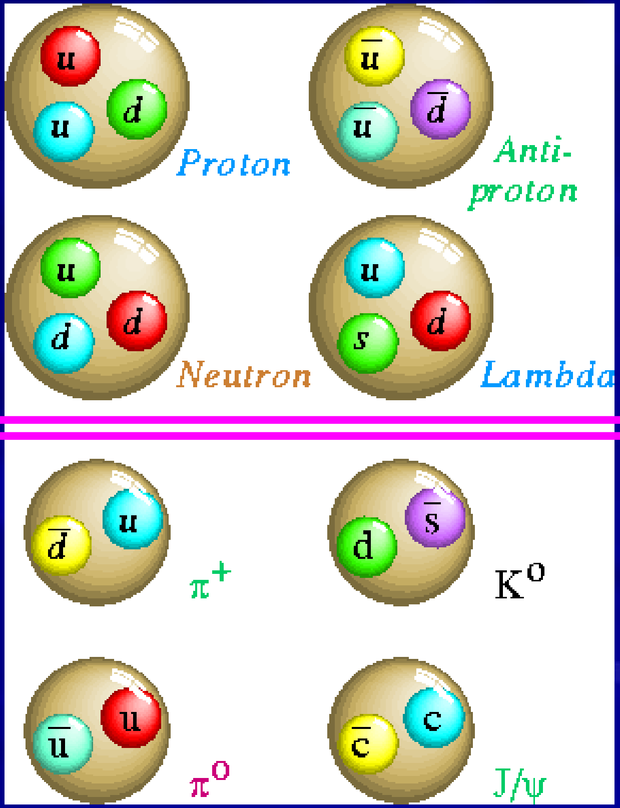
A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!

Hadrons

Baryons

Mesons

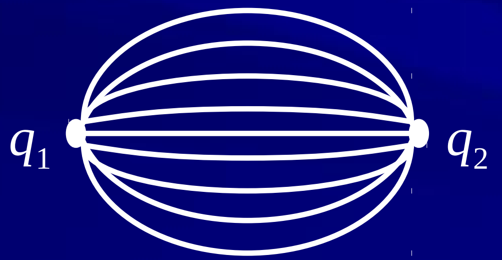


QCD & Confinement

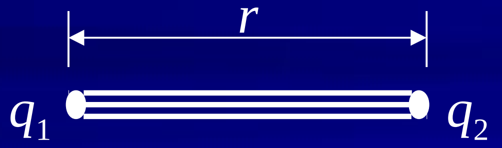
- The strong interaction potential
  - Compare the potential of the strong & e.m. interaction

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

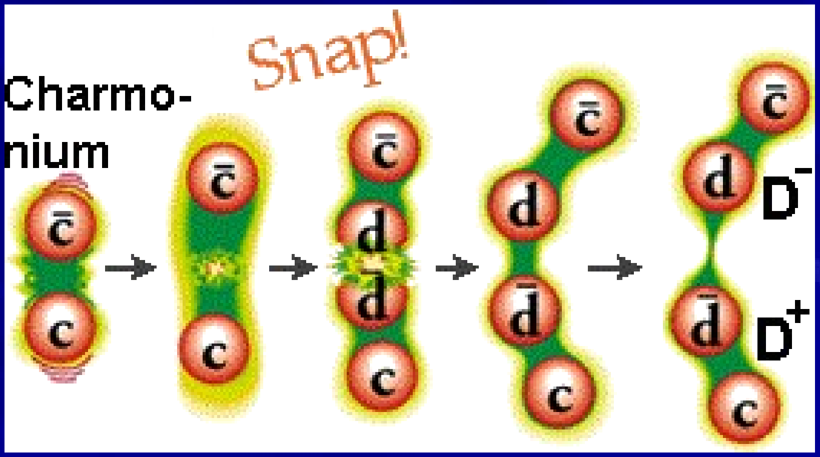
  - Confining term arises due to the self-interaction property of the colour field. k~1GeV/fm



a) QED or QCD (r < 1 fm)



b) QCD (r > 1 fm)

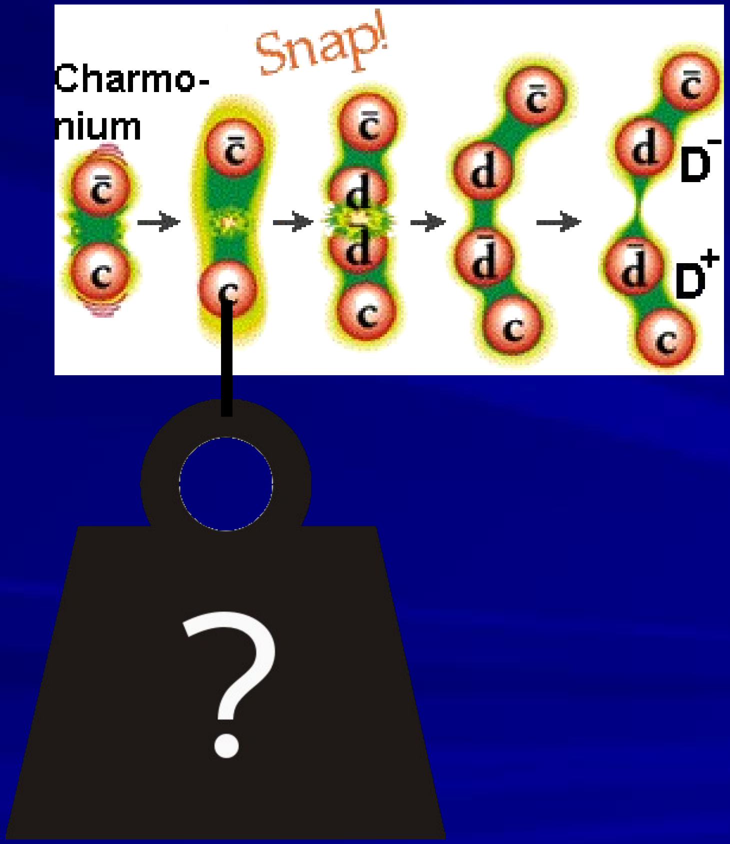


Question

- What is “the self-interaction property” of the strong force?

Exercise: How big is k?

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

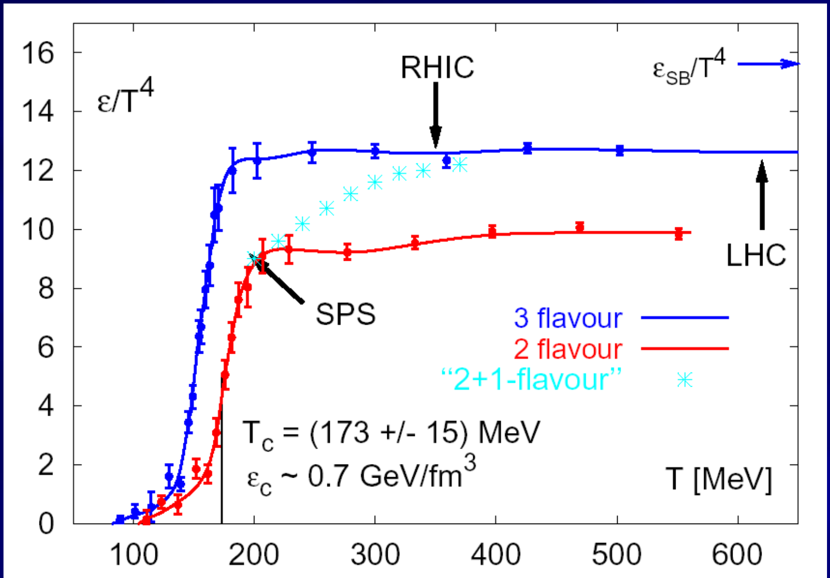


Consequences of 10 ton force!

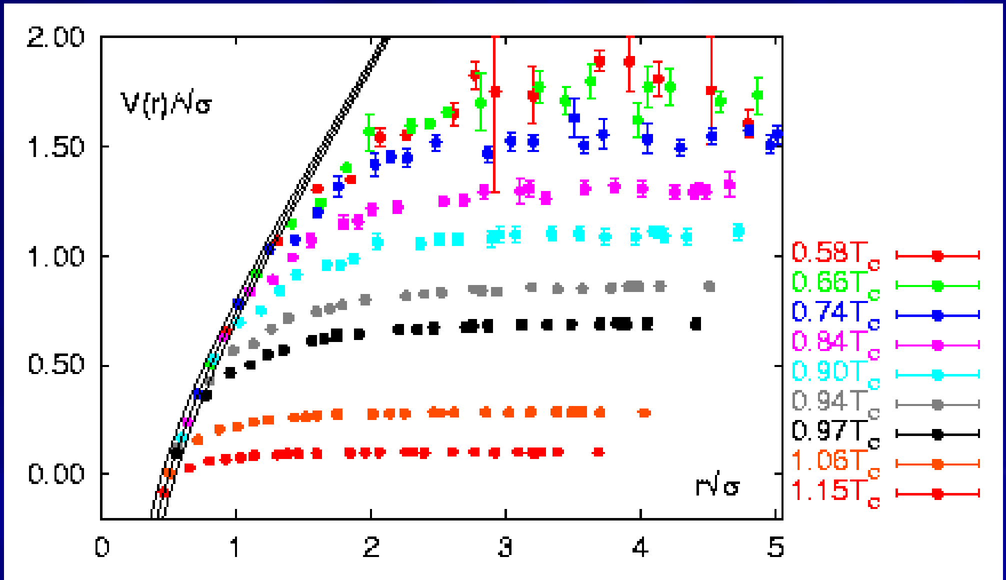
- This is why QCD is also called the strong interaction
  - QCD can bind together quarks even though they are EM repulsed
- QCD is for low energies non-perturbative
  - We know the theory but we cannot solve it!
  - We don't know how to describe hadronic properties with QCD
- But at high energies (small 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

Lattice QCD results (Numerical non-perturbative)

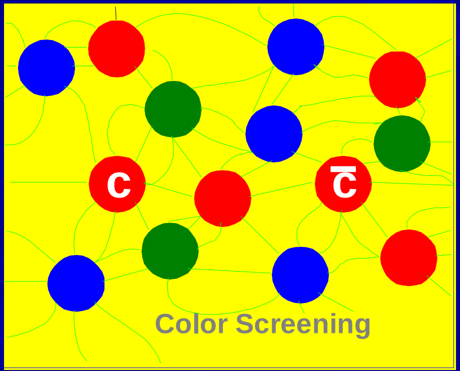
QCD energy denisty



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)

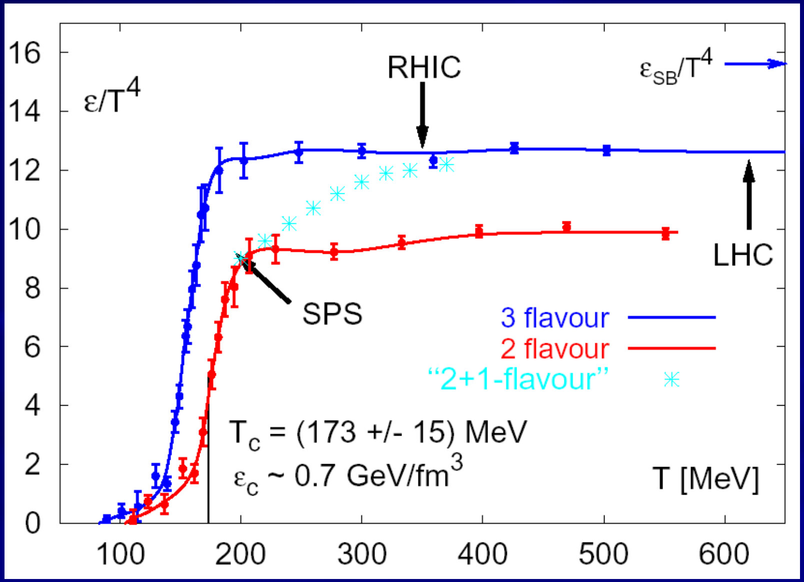
Fermionic degrees of freedom (quarks)

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

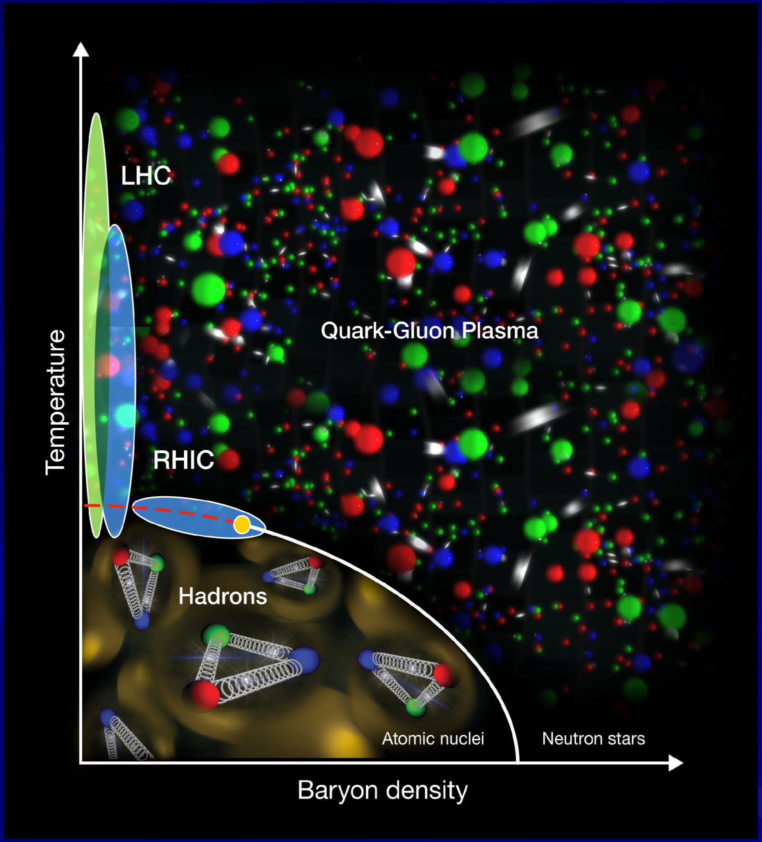
(Anti+)quark spin, color and flavor



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

QCD phase diagram

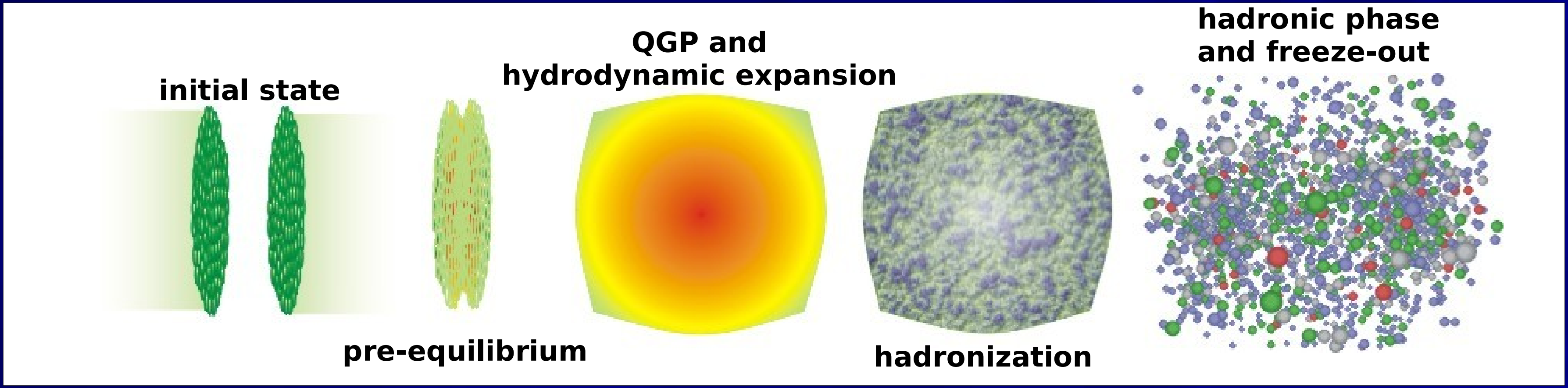
T~170MeV (~1GeV/fm^3)
1 eV = 11605K
T~2,000,000,000,000K
(T core sun: 16,000,000K)



- By colliding heavy ions we hope to create (and study the characteristics of) a new phase of matter called the Quark Gluon Plasma (where quarks and gluons are deconfined)

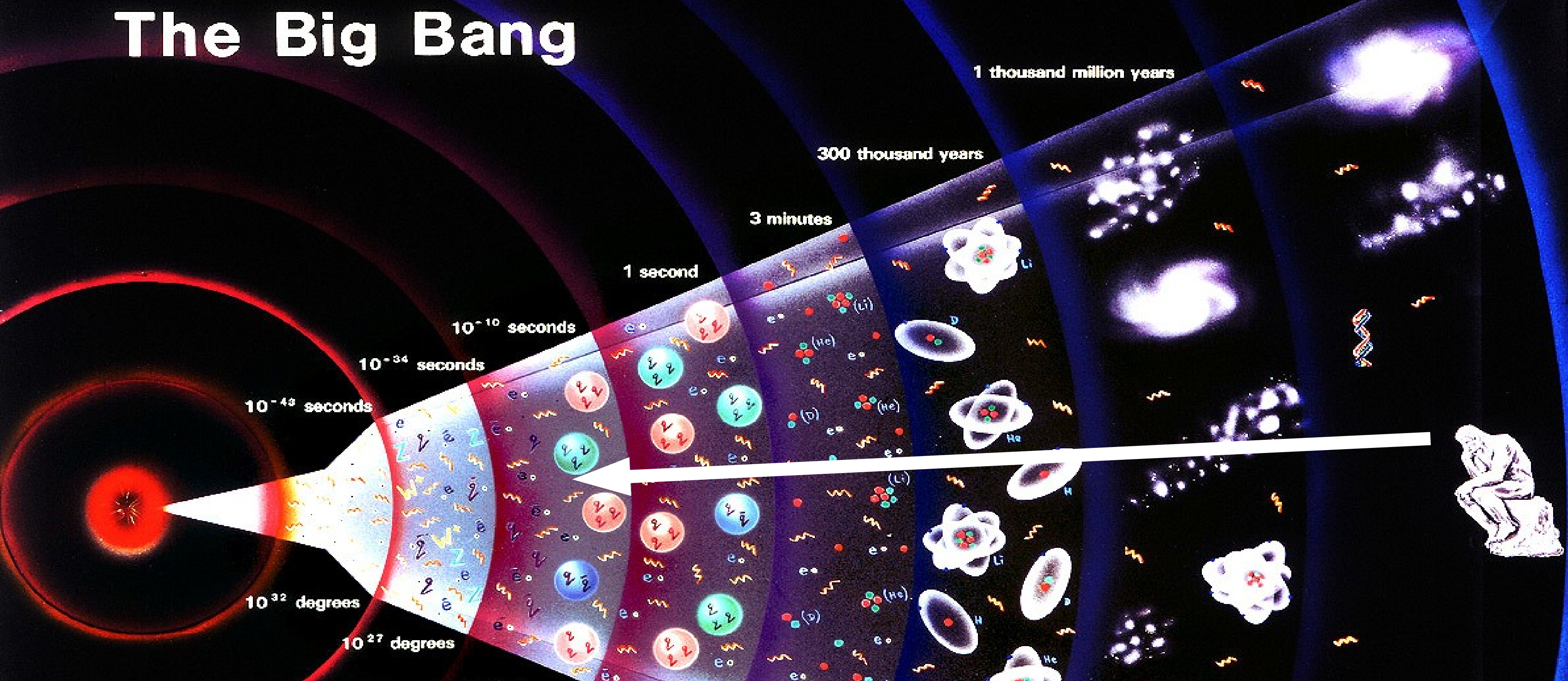
Heavy ion collisions: The study of high energy QCD

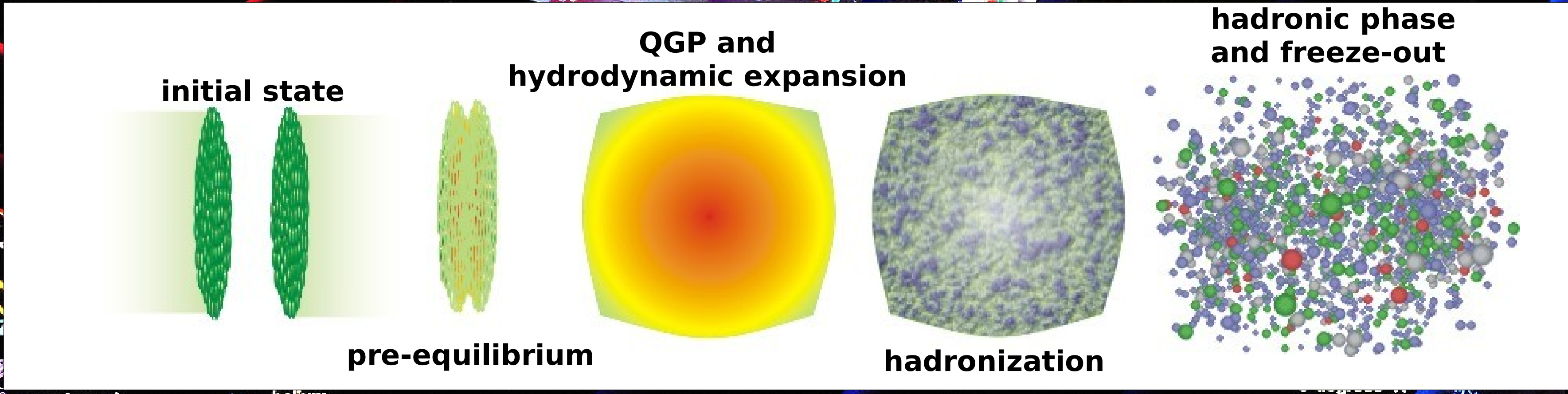
The evolution of a heavy ion collision



- 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

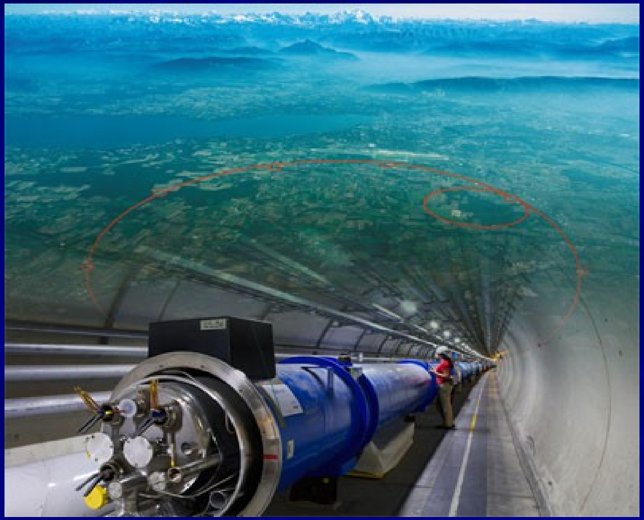
QGP – the phase of the universe 1 micro second after



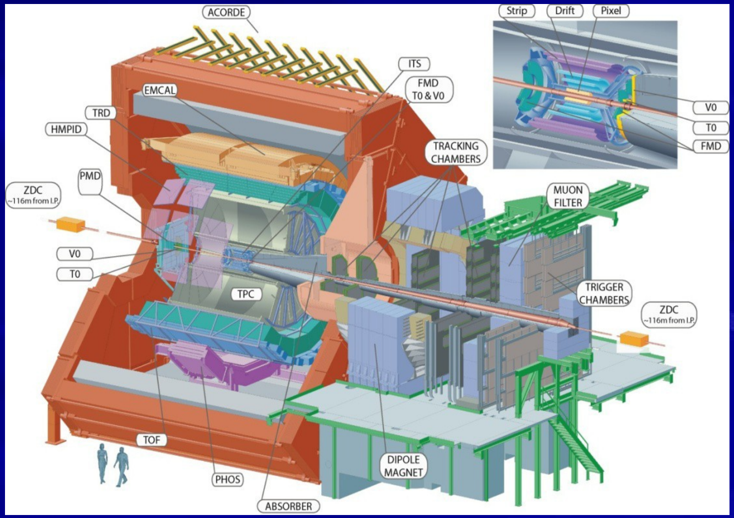


Assumed knowledge

- 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)

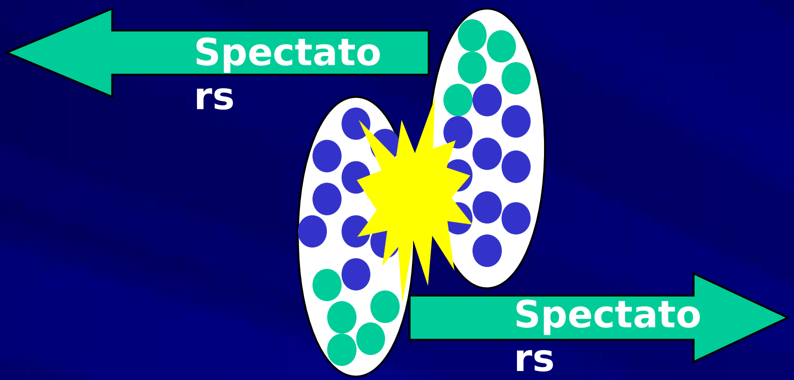


- Experiments to detect and reconstruct the final state particles
  - PHENIX and STAR at the Relativistic Heavy Ion Collider
  - ATLAS and ALICE at the Large Hadron Collide

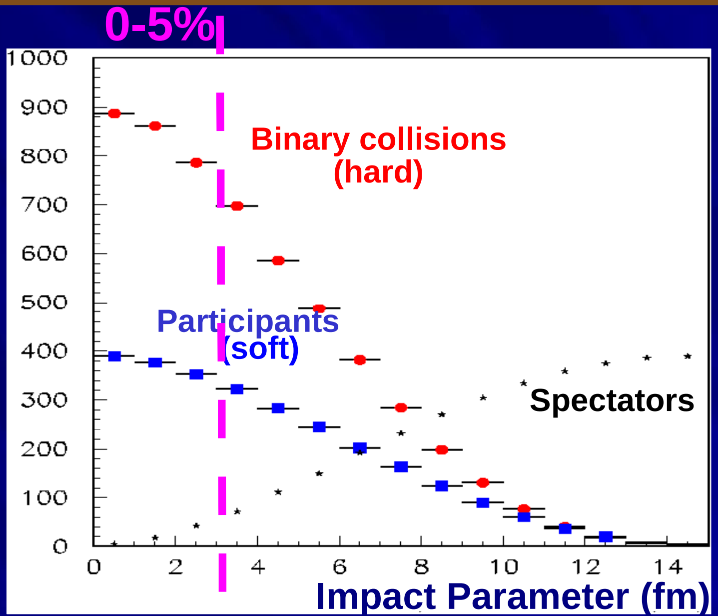


Heavy Ion Jargon

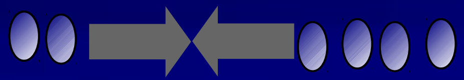
- Centrality (ex. for Au+Au):



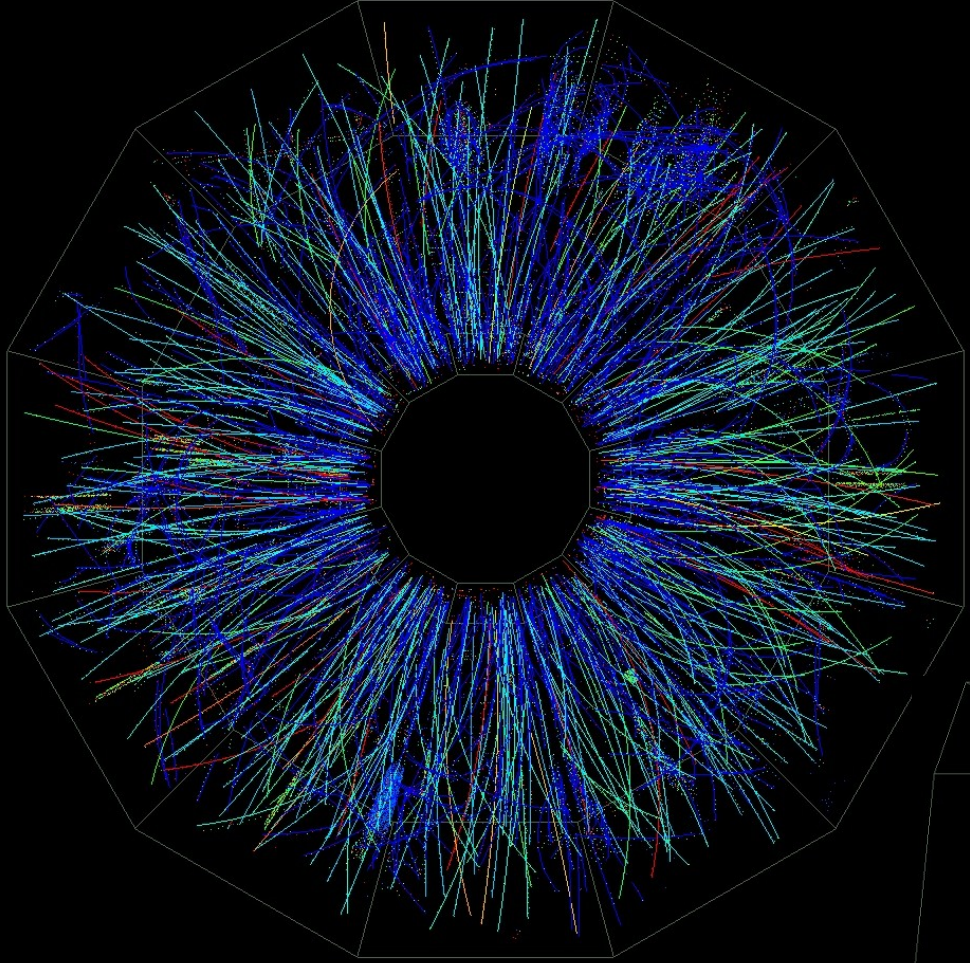
Participants = 2*197 - Spectators



- 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:

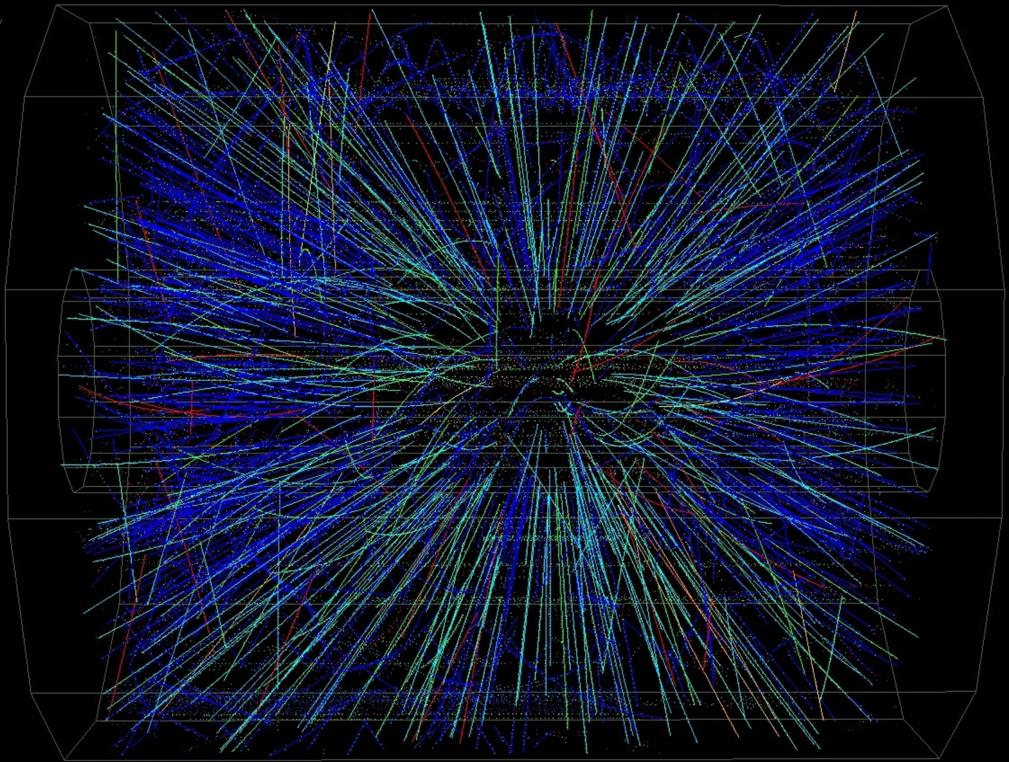


6 participant
8 binary collisions
(pp has 2 participant and 1 binary collision)



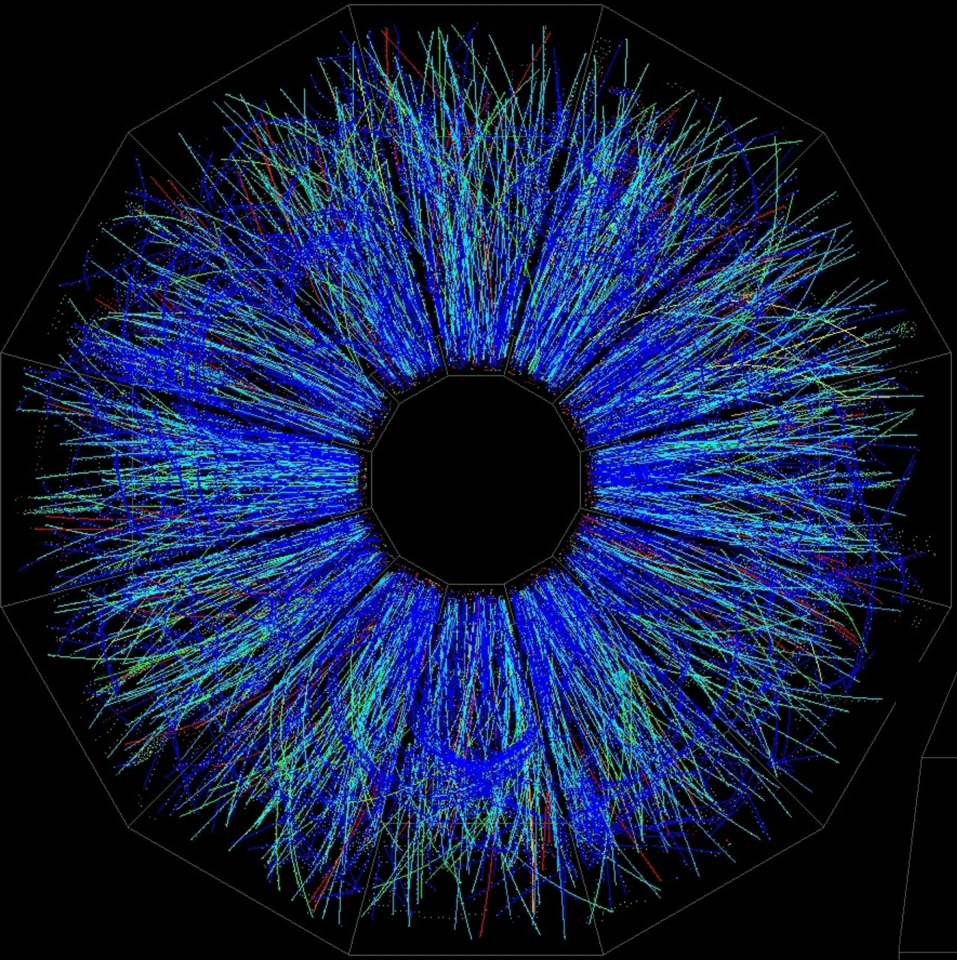
Peripheral Event

From real-time Level 3 display.



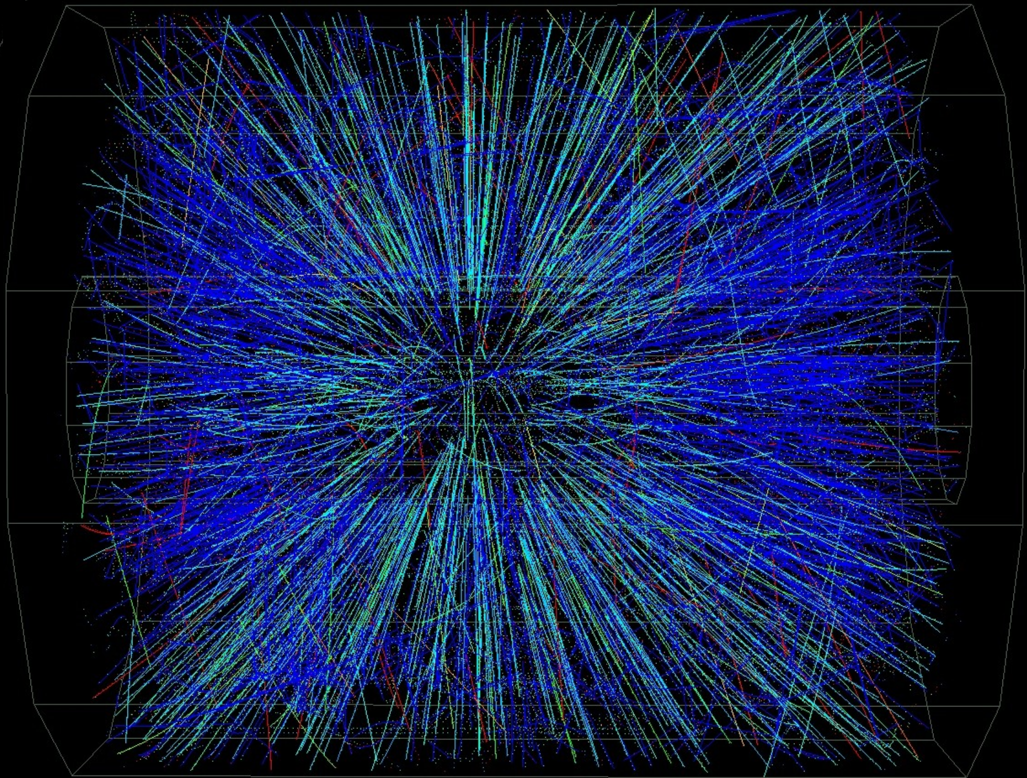
color code ⇒ energy loss

STAR

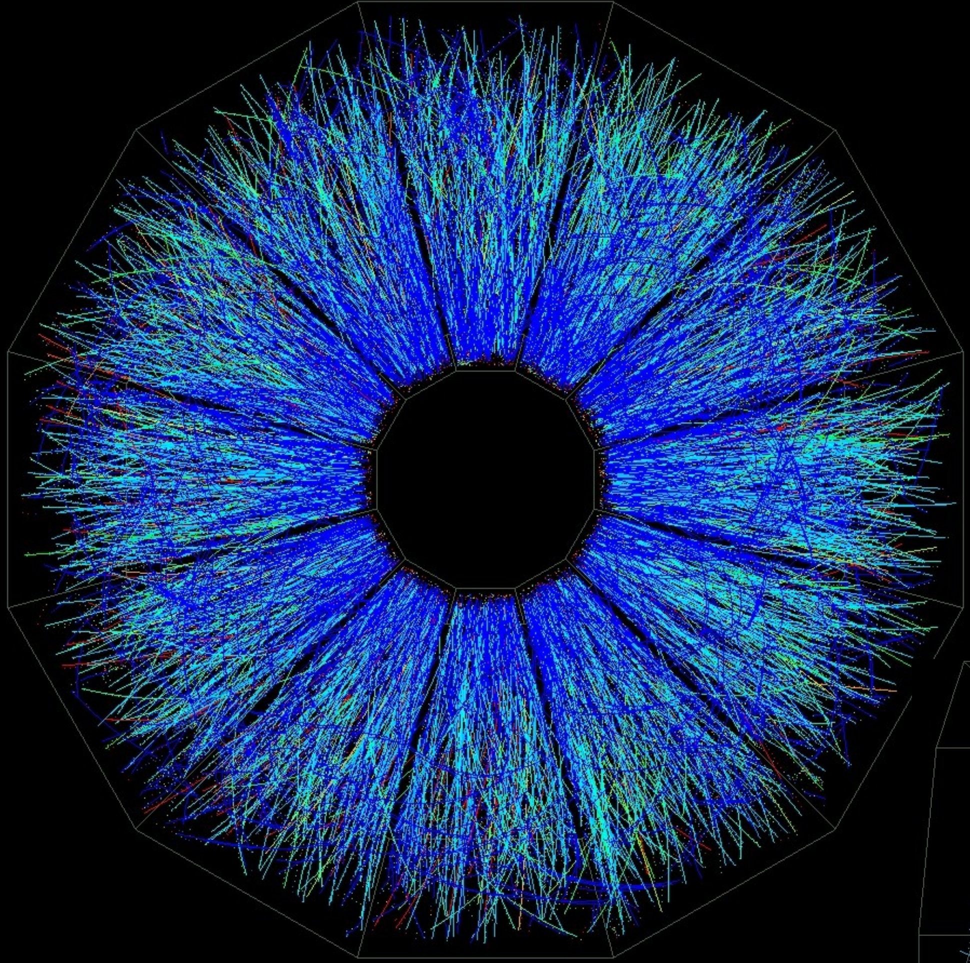


Mid-Central Event

From real-time Level 3 display.

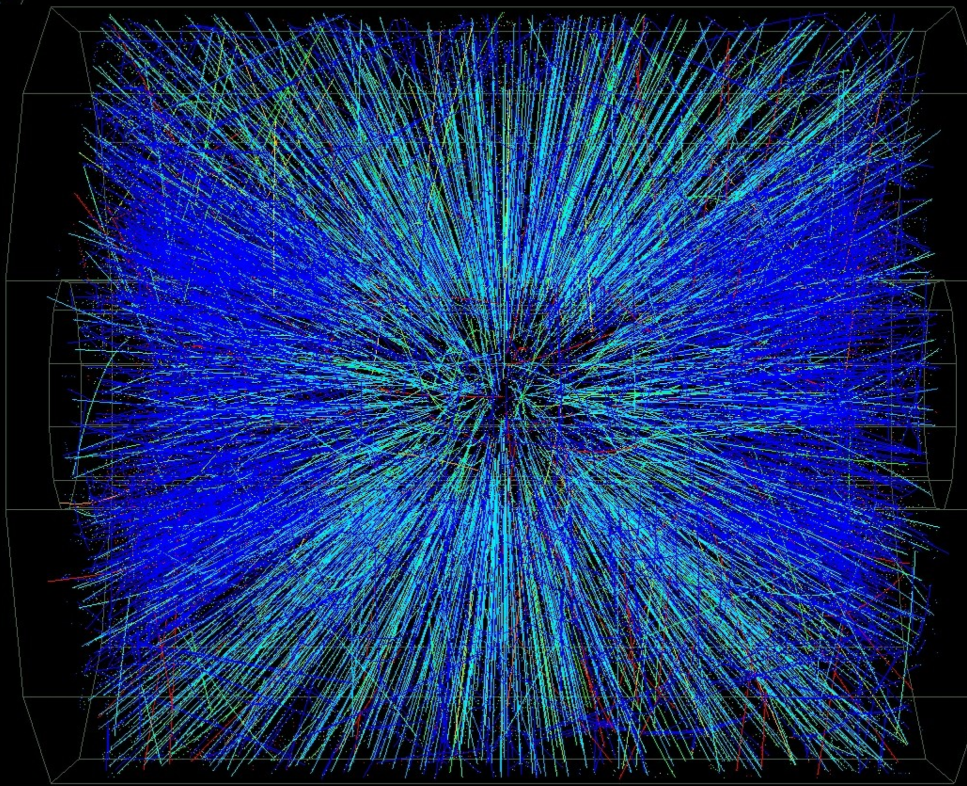


STAR



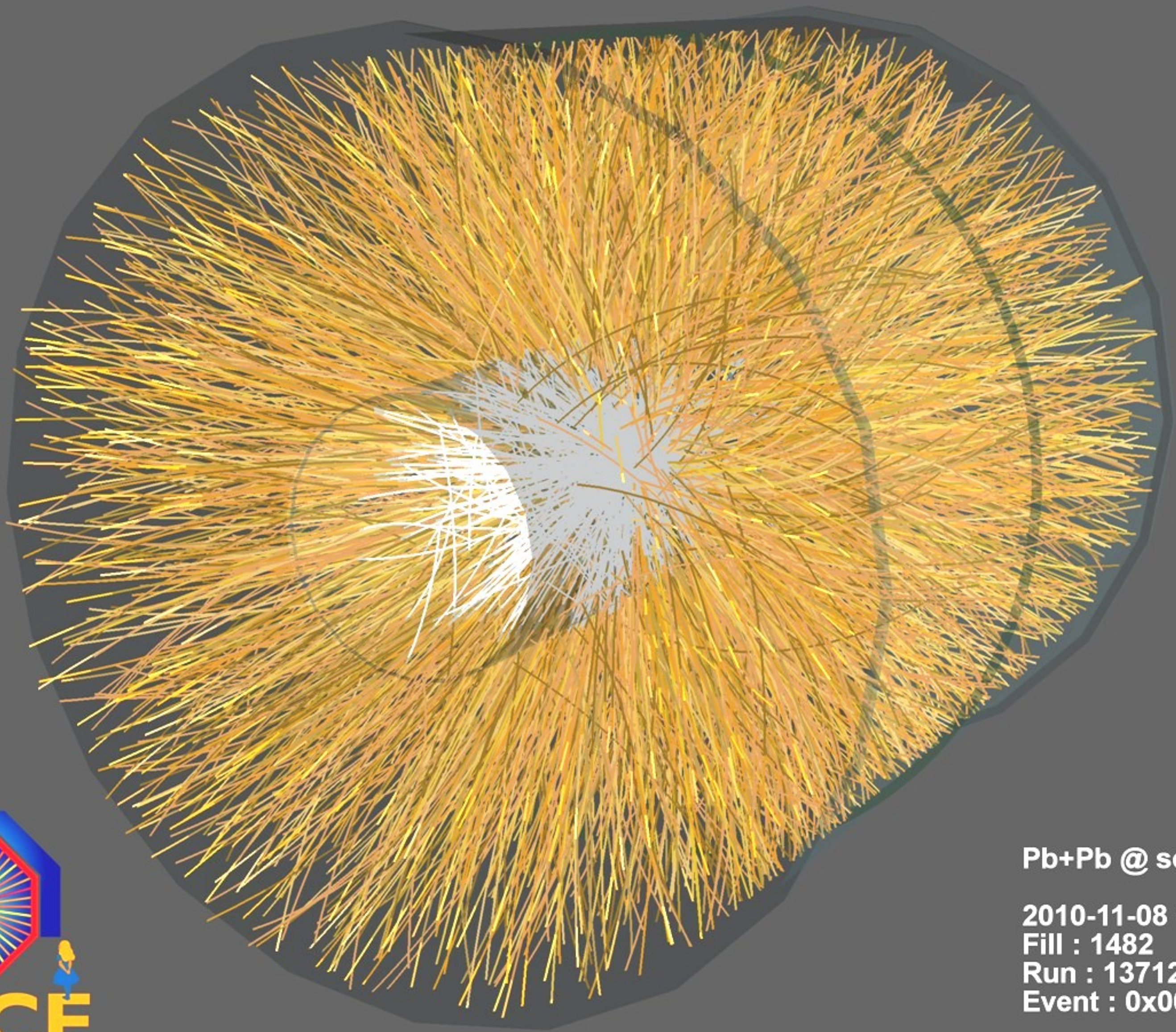
Central Event

From real-time Level 3 display.



STAR

ALICE first collisions: 8/11-2010
Factor 14 jump in energy!



Pb+Pb @ sqrt(s) = 2.76 ATeV

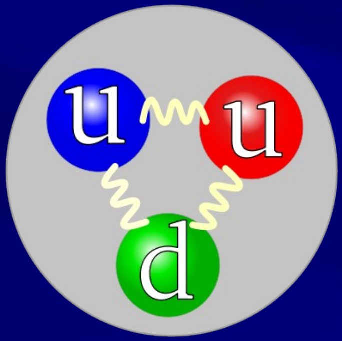
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

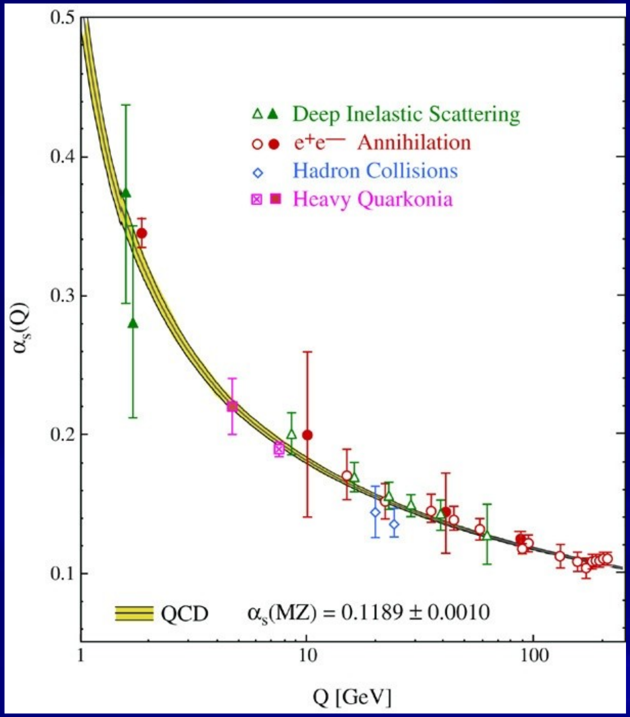
ALICE

What happens when we collide pp and Pb-Pb

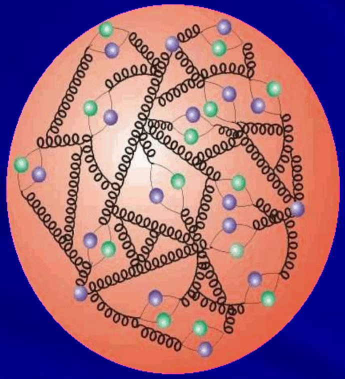
- 2 answers!

SOFT





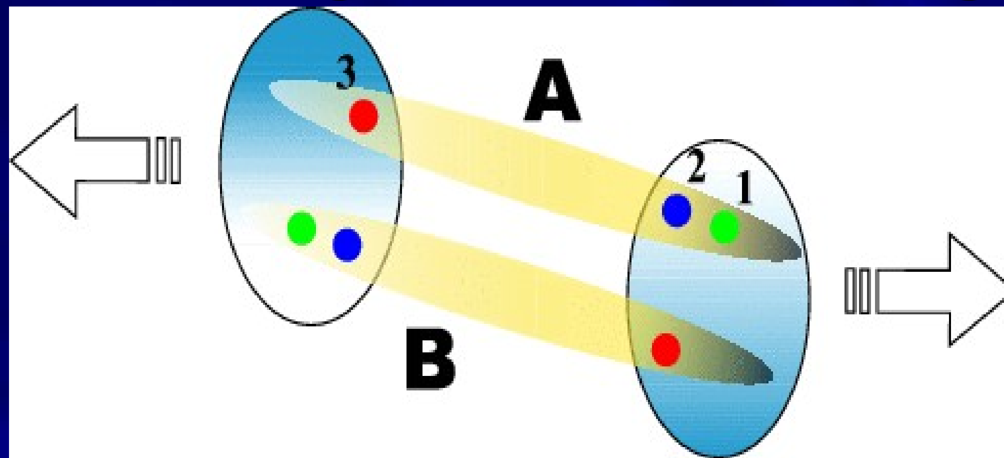
HARD



Non-perturbative physics
(know the equations but not how to solve them)
Bulk properties (=medium)

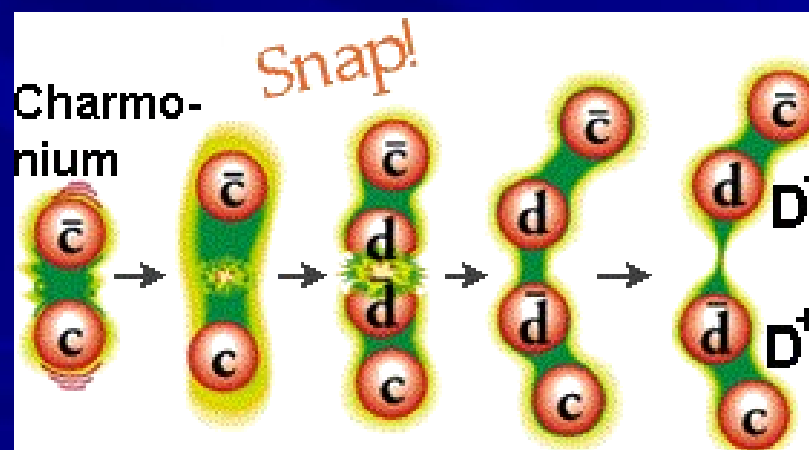
Perturbative physics
(theoretical predictions)
Rare processes
jets (=probes)

Phenomenological model of soft physics e.g. Lund string model

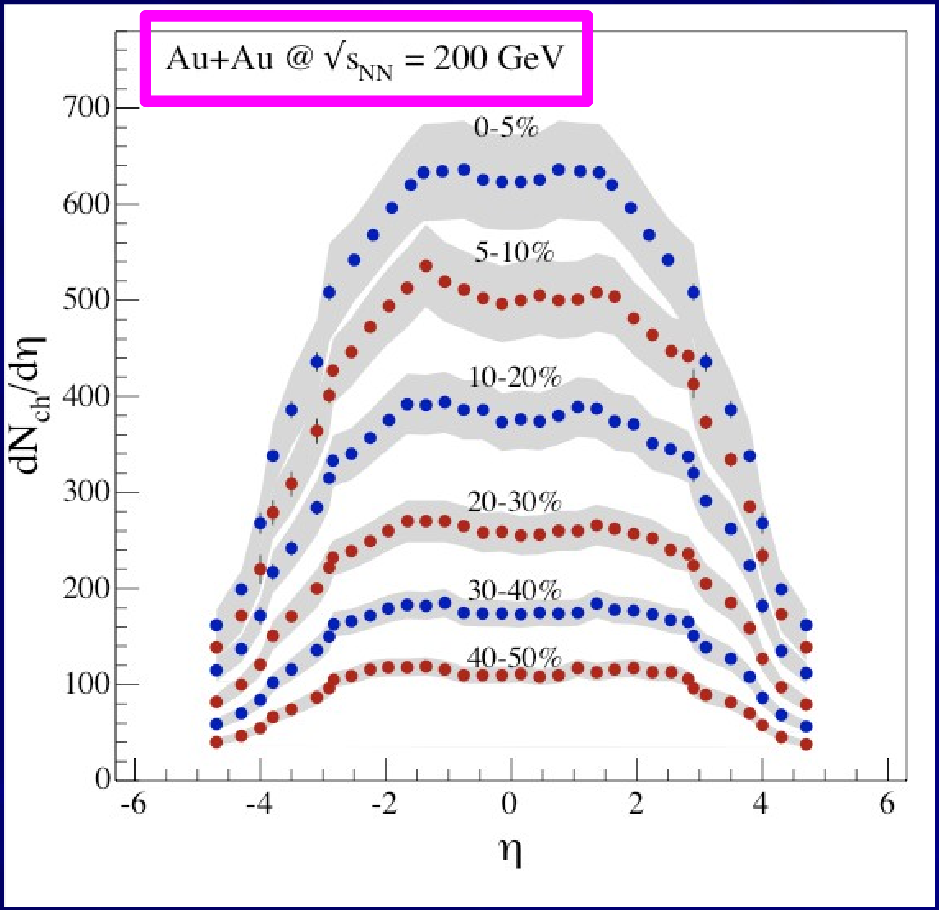


a) QED or QCD (r < 1 fm)

b) QCD (r > 1 fm)



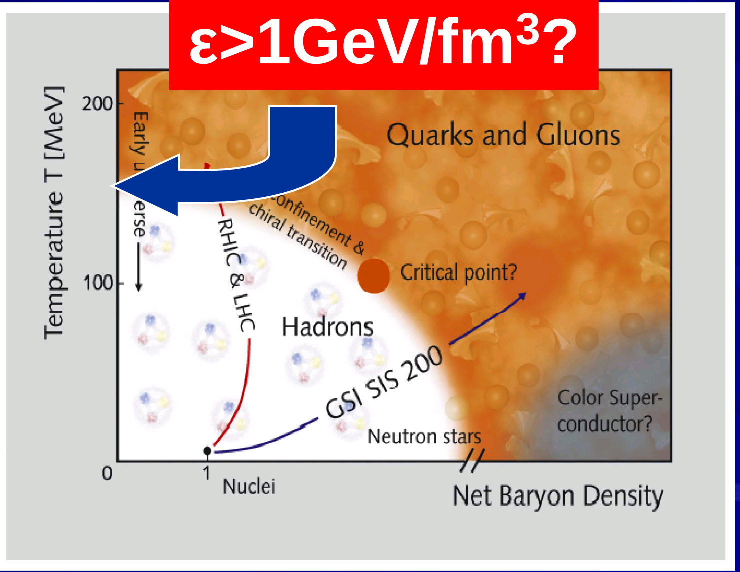
Charged Particle Multiplicity dN/dη



According to Bjorken:

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

ε>1GeV/fm³?

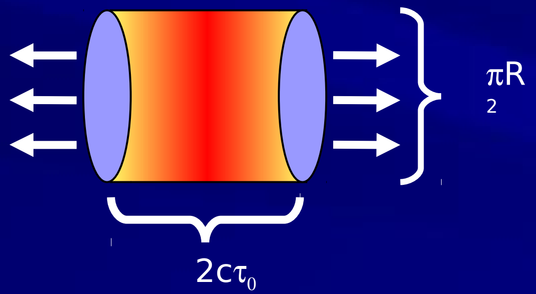


Estimate the energy density, assume <Et>~0.5GeV,

"Measured" initial energy density

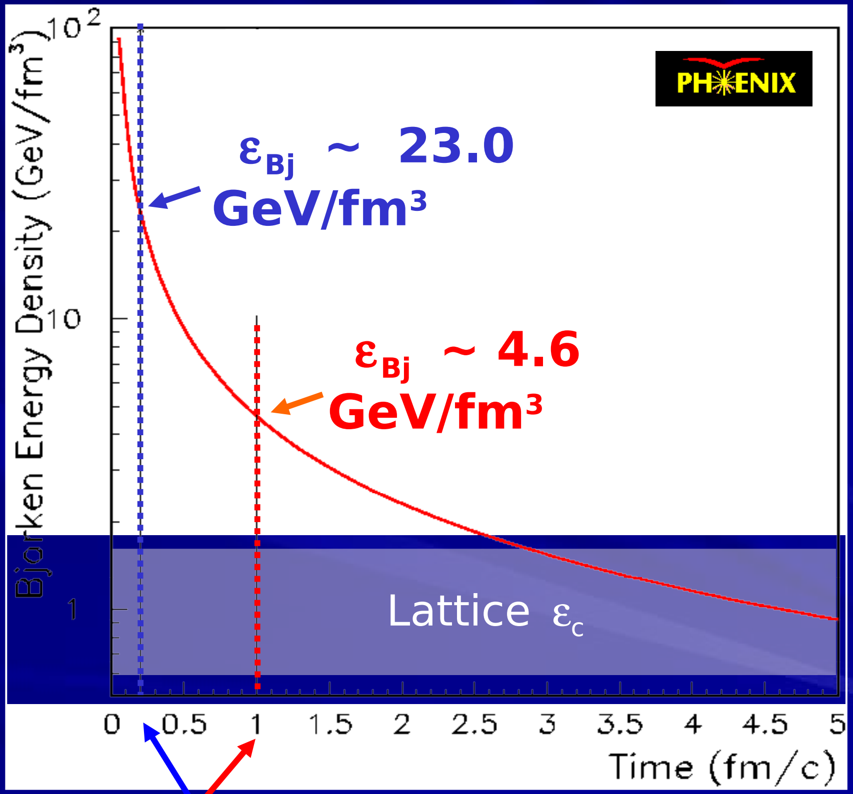
Bjorkens hydrodynamic formula for thermalized energy density in terms of measured transverse energy E_T

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



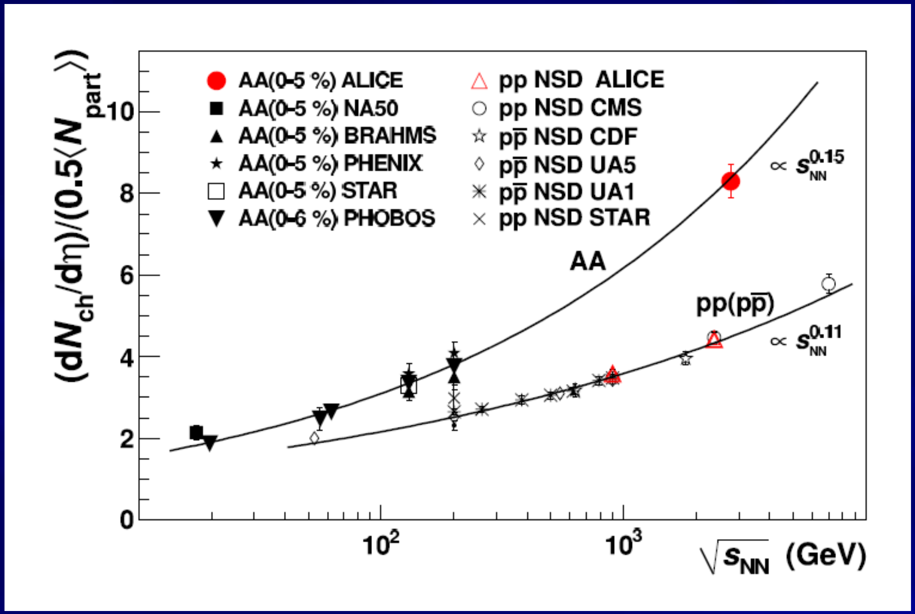
PHENIX: Central Au Au yields

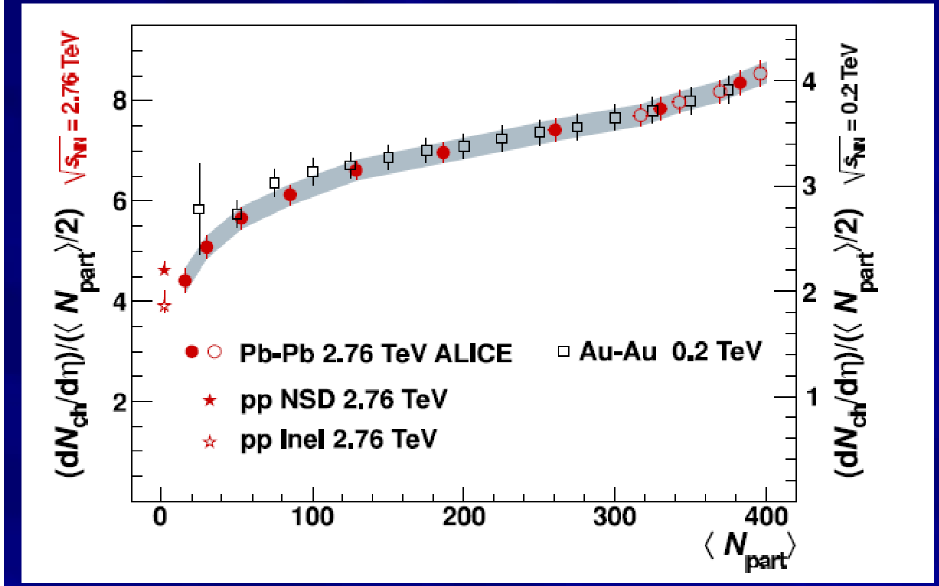
$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\, GeV$$



Formation(thermalization) time ?

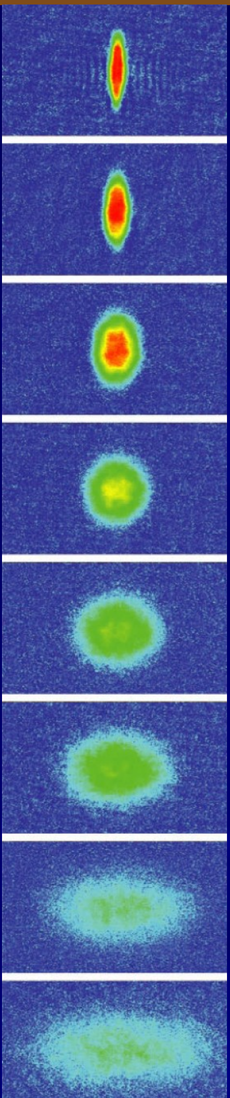
LHC first results from ALICE

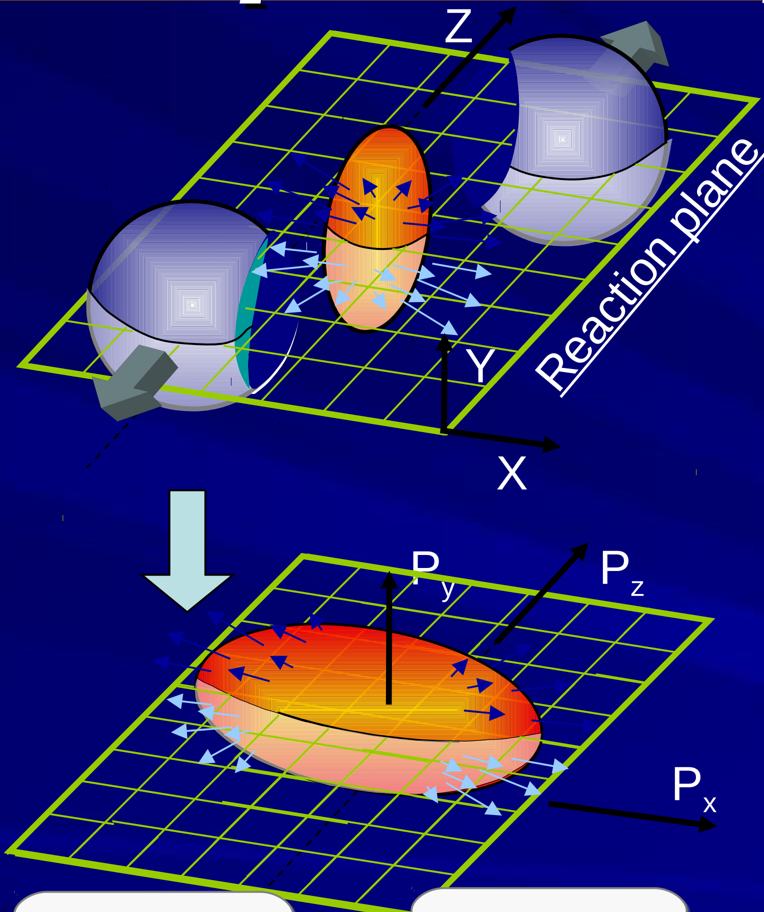




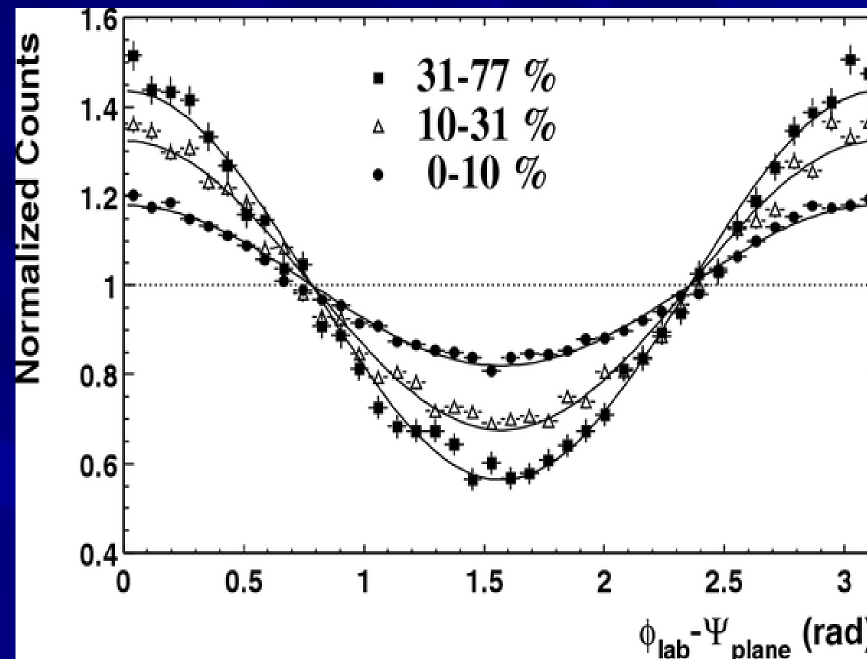
- Multiplicity *at mid-rapidity* increases a factor ~2 from RHIC to LHC (energy density a factor ~2) but most likely also widens significantly
- Centrality dependence is similar as at lower energy

Elliptic flow (v2) unique in heavy ion collisions



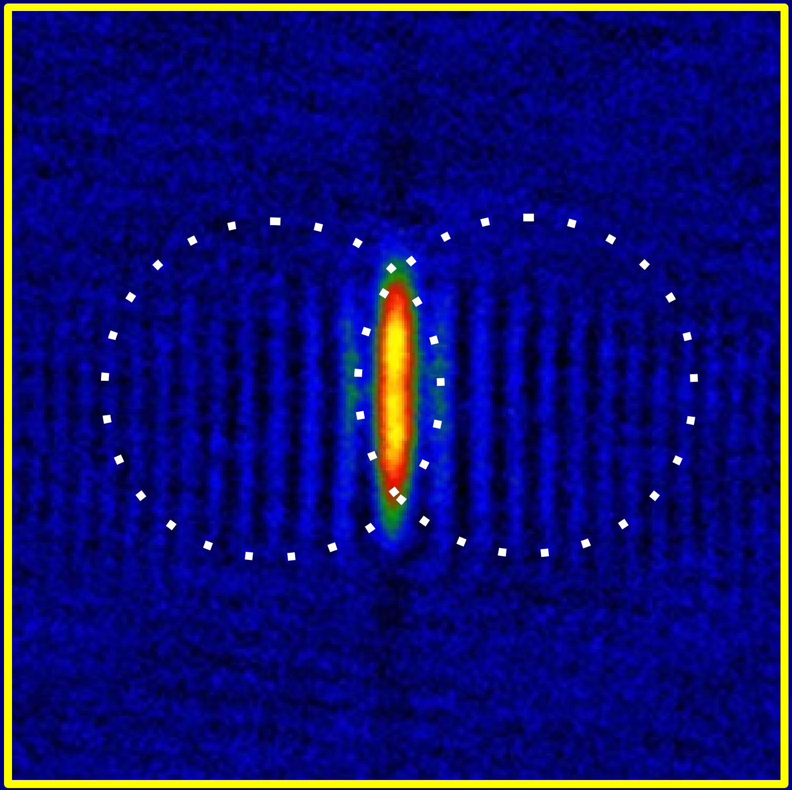


Fourier decomposition:
$dN/d\phi = 1 + 2\,V_2 \cos(2\,\Delta\phi)$



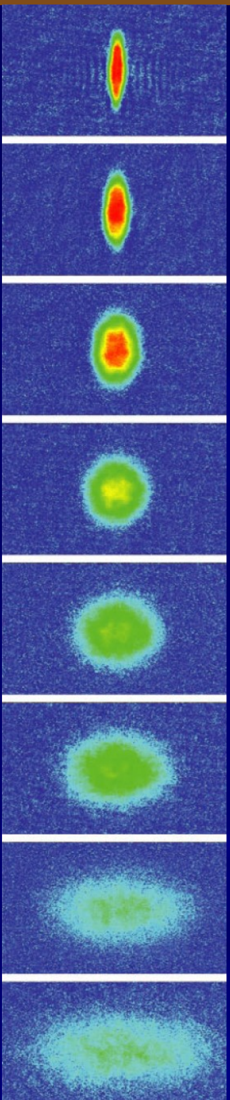
Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

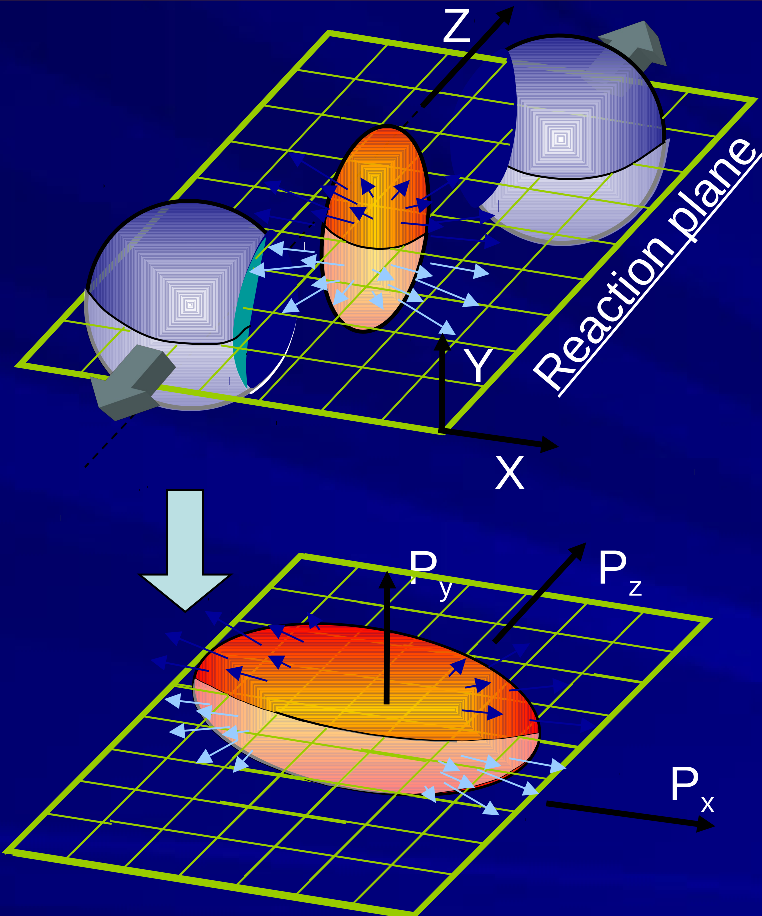
Example from atomic physics: Releasing Lithium atoms from a trap



http://www.physics.ncsu.edu/jet/index.html

Elliptic flow exercise(s)



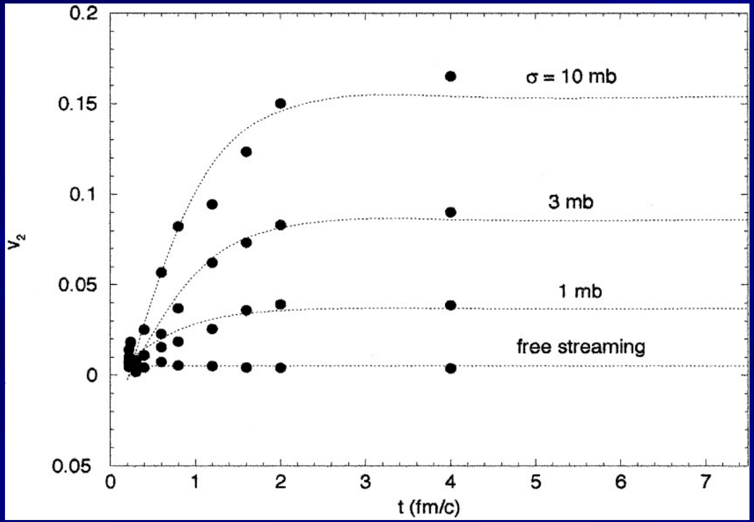


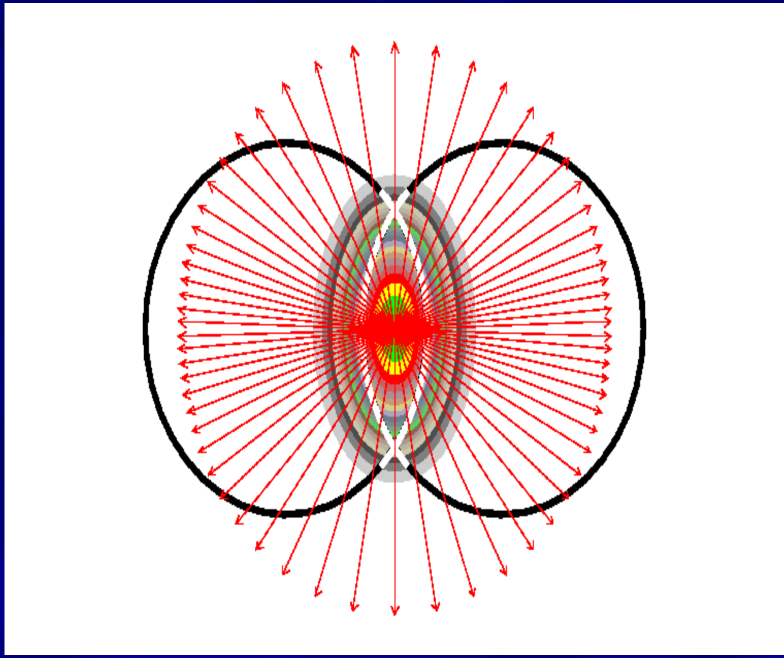
- Why is the elliptic flow sensitive to early interactions after the hot and dense matter has been formed?
  - Hint: How would the phi distribution look if there were no interactions
- Bonus question: Why is the flow generated in the event plane and not transverse to that
  - Hint: How is the matter density distributed in the overlap region

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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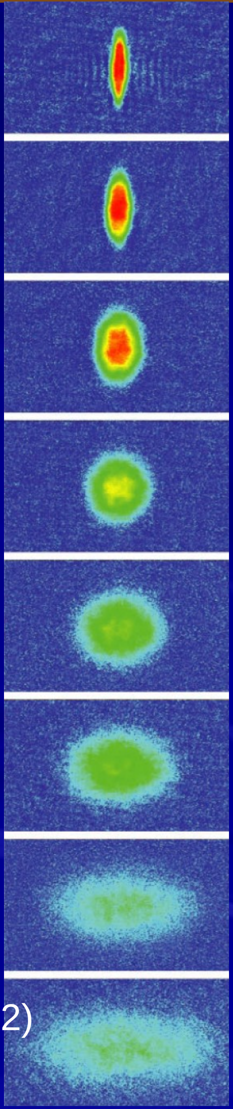
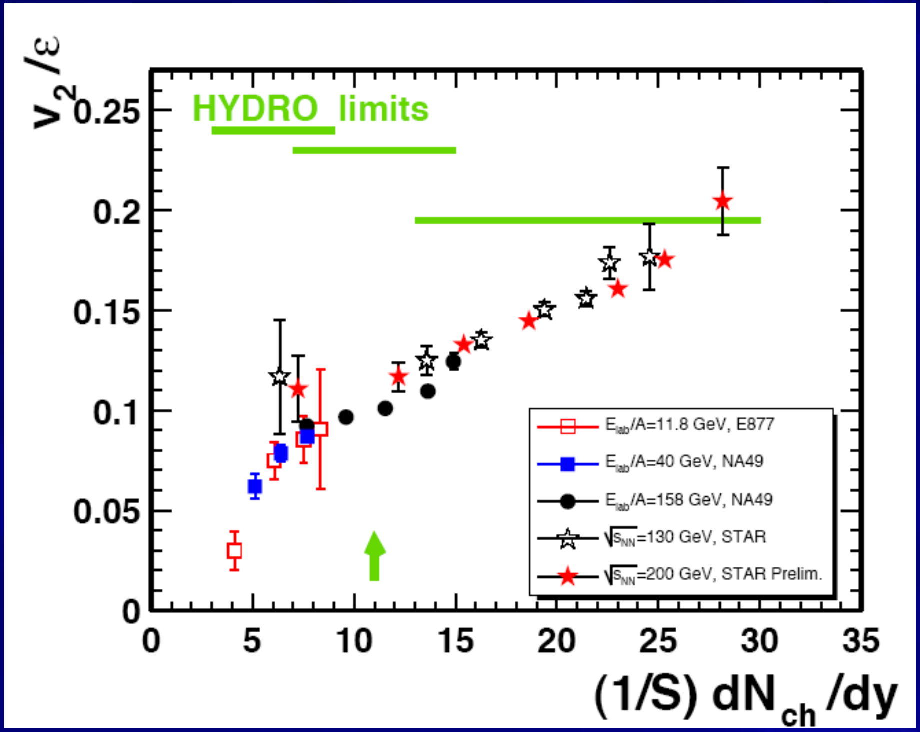


Elliptic flow at RHIC is "Maximal"

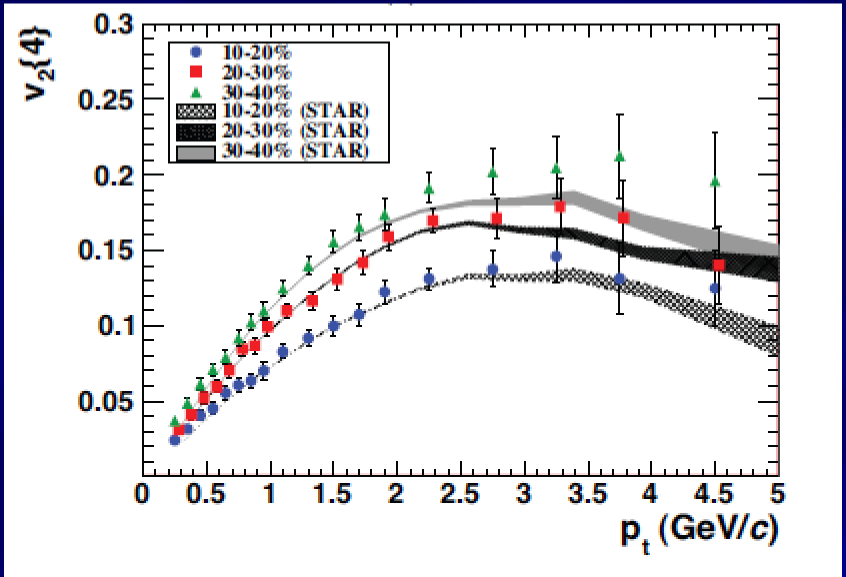


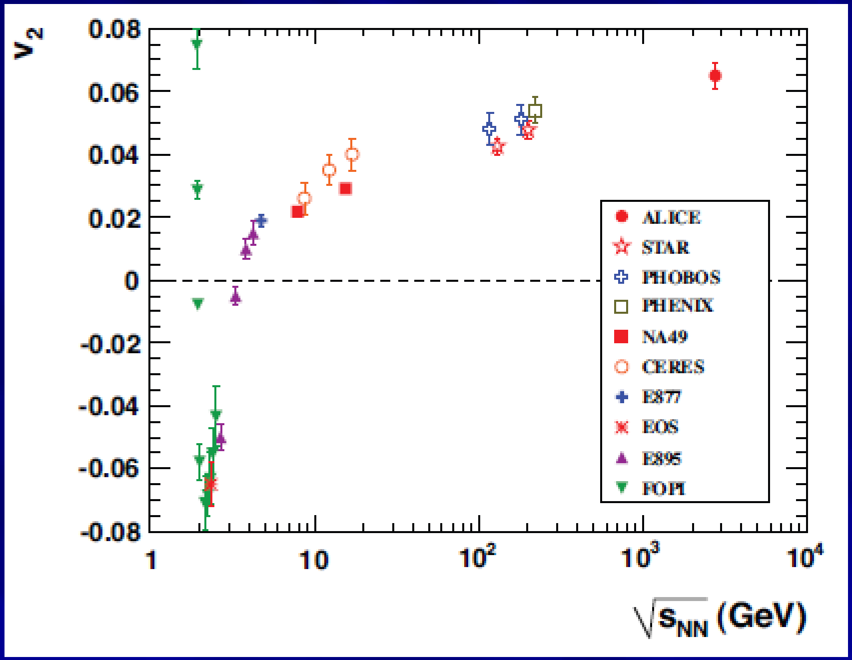
- Relativistic hydrodynamic predicts elliptic flow
  - The high energy medium interacts very strongly immediately after being formed
  - Medium does not behave as a gas, but an almost perfect fluid!

The QGP is less like a crowd and more like a synchro team

- Big theoretical challenge:
  - how to go from initial random collisions to organized state in a VERY short time (<1fm/c~10-23s)
  - Remains to be understood

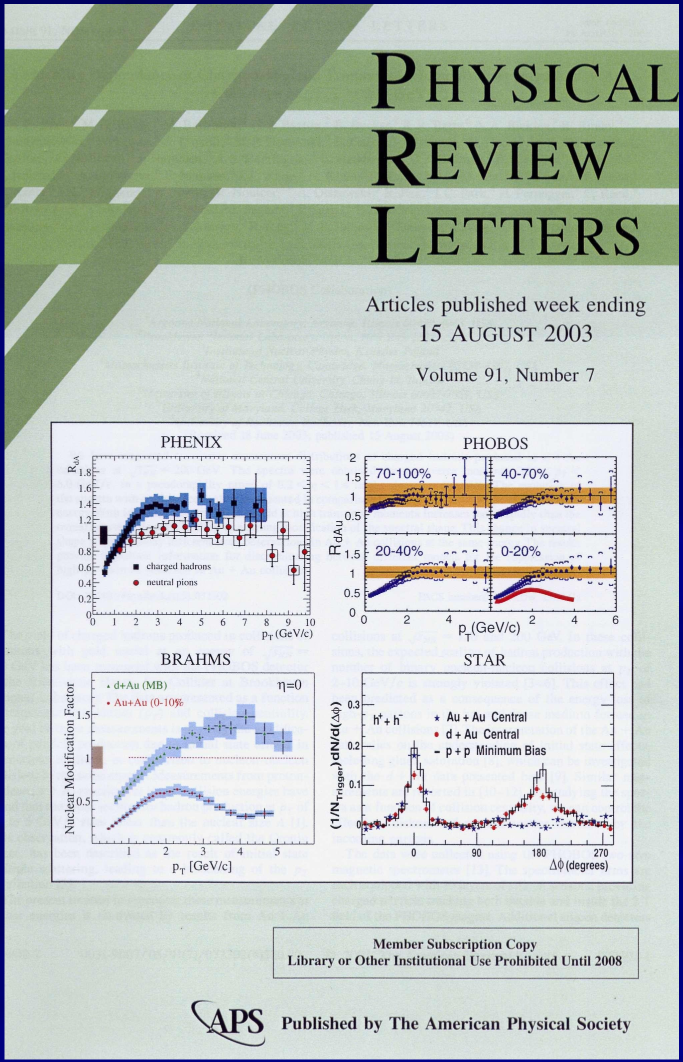
LHC first results from ALICE

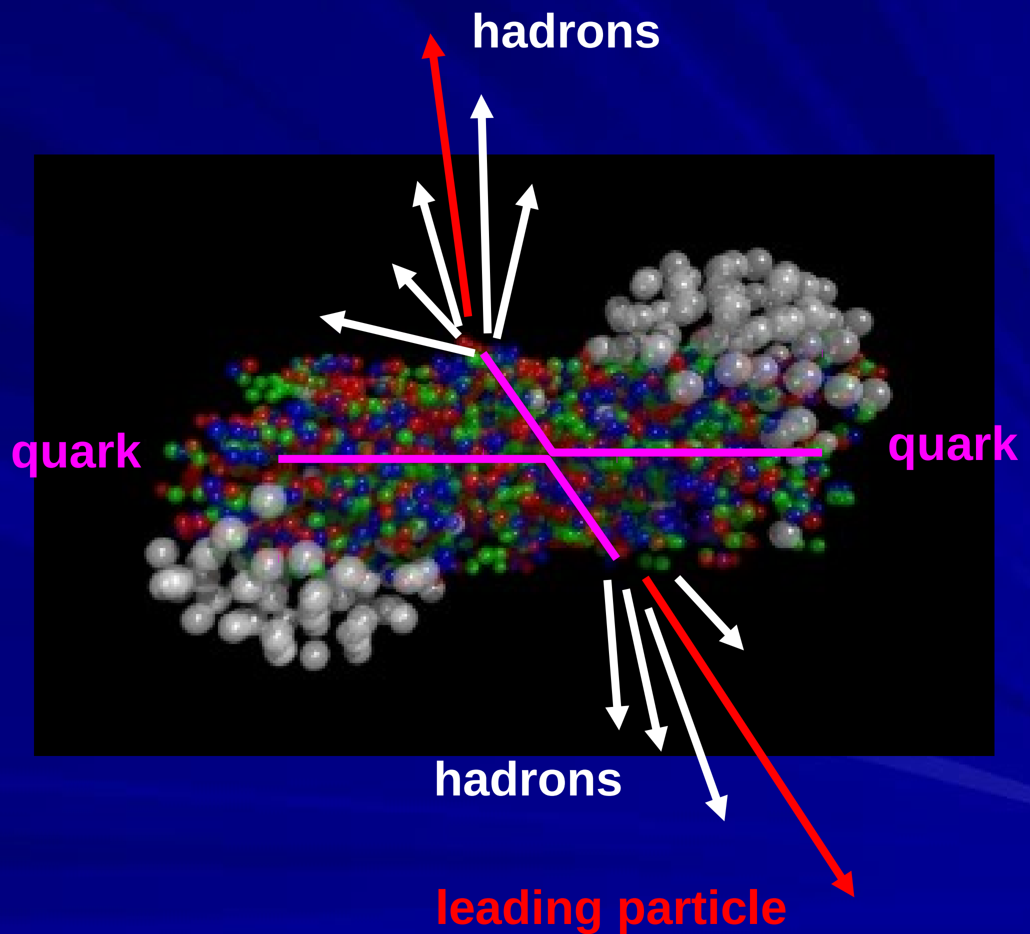




- *Differential* flow at LHC is very similar to RHIC!
  - Hydrodynamic limit?
- The total magnitude is larger because system is harder!
- Question: Where is QCD dynamics?

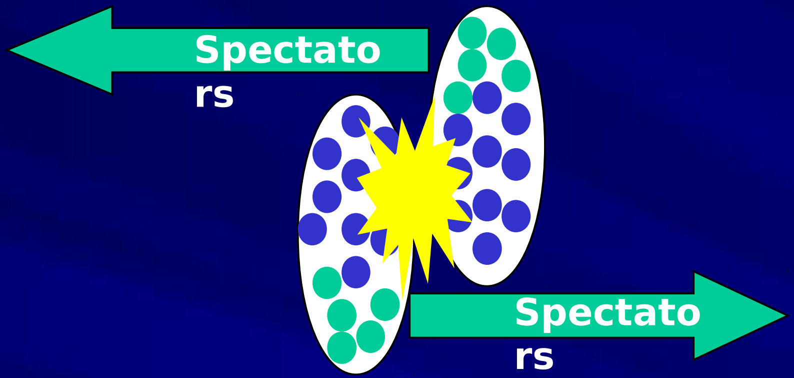
Hard probes (pQCD): parton-parton interactions



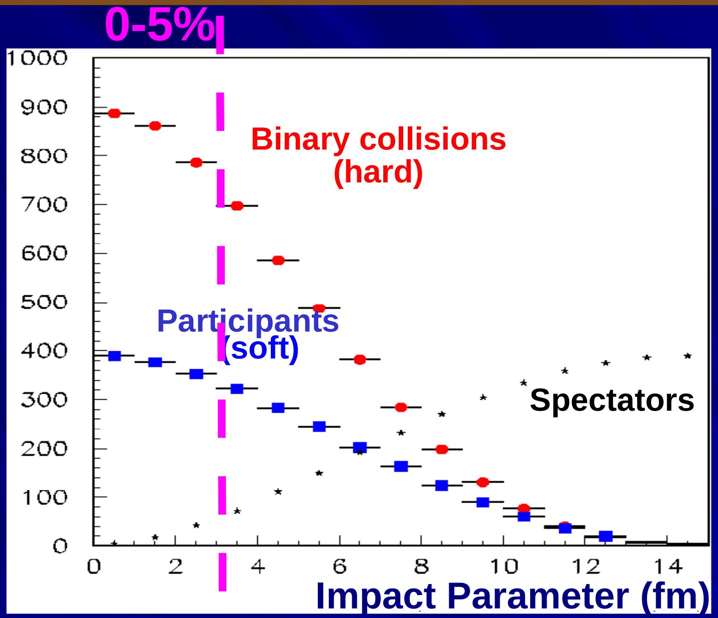


Heavy Ion Jargon Revisited

- Centrality (ex. for Au+Au):

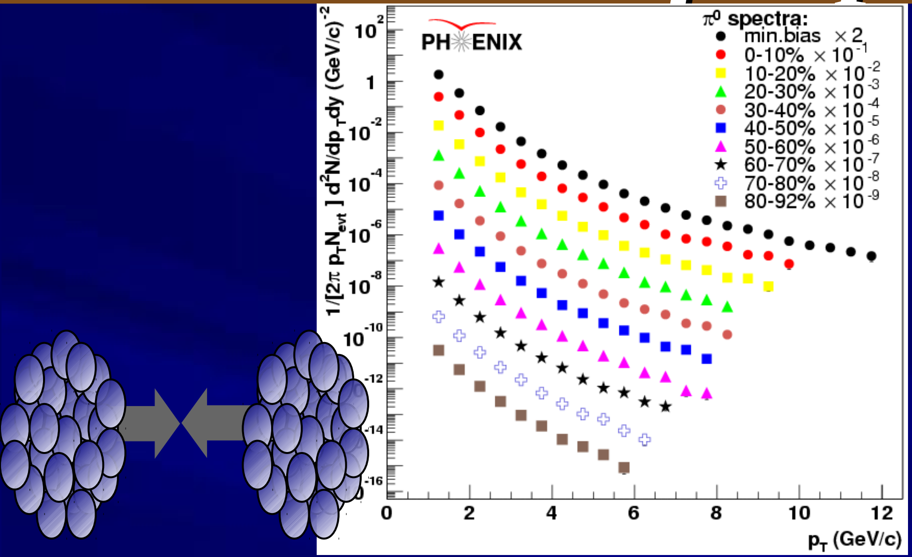


Participants = 2*197 - Spectators



- 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?

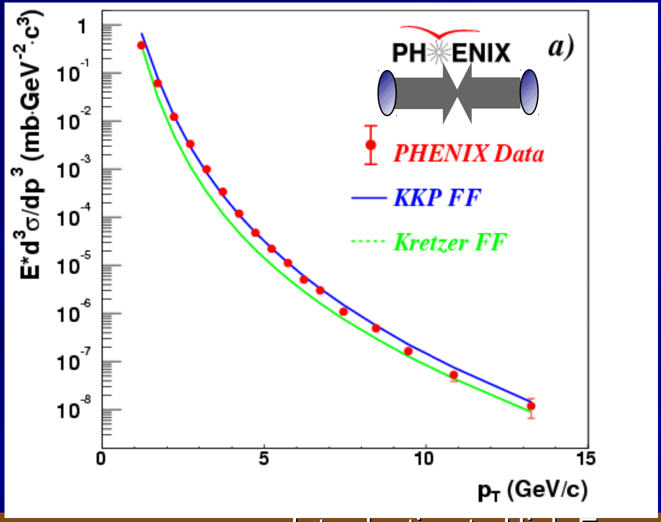
The nuclear modification factor for pions (1/2)

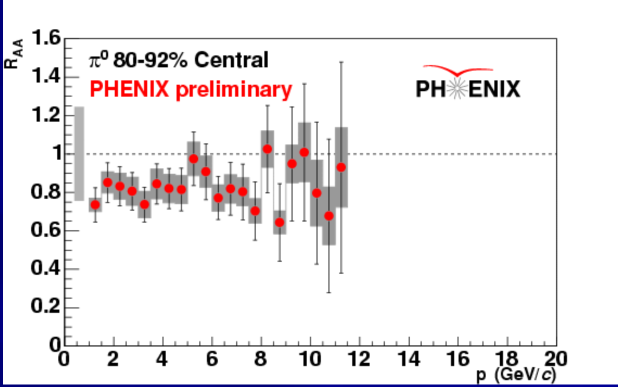


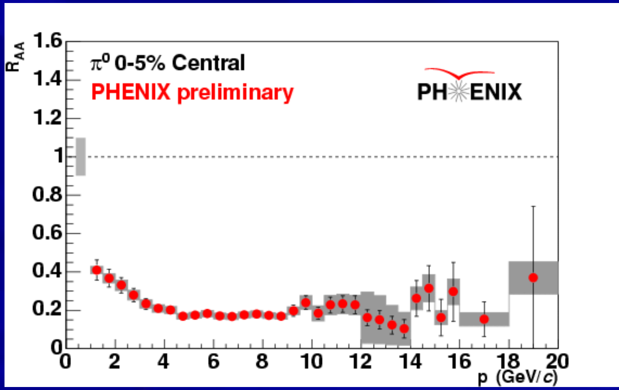
$$R_{AA} = \frac{d^2 N^{AA} / d\, p_T\, dy}{\langle N_{bin} \rangle d^2 N^{NN} / d\, p_T\, dy}$$

=

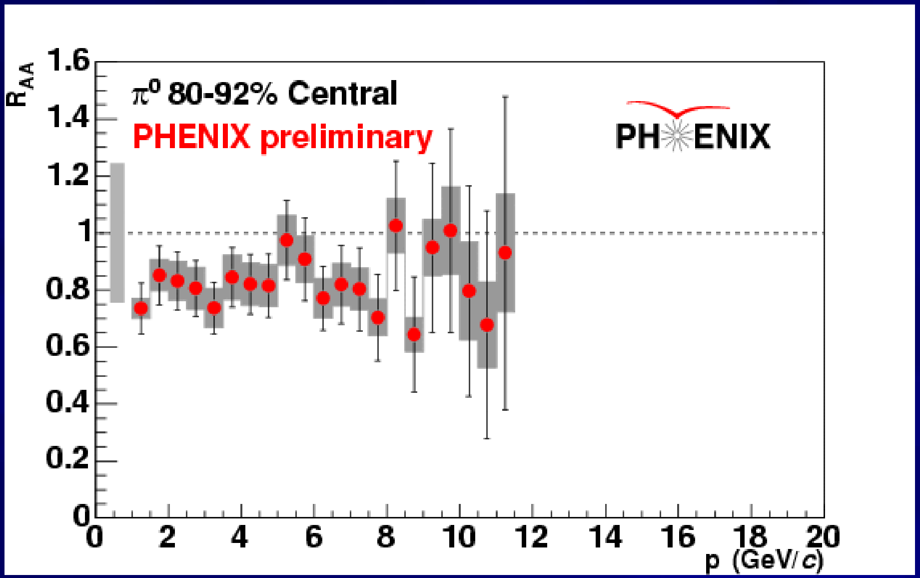
Nbin

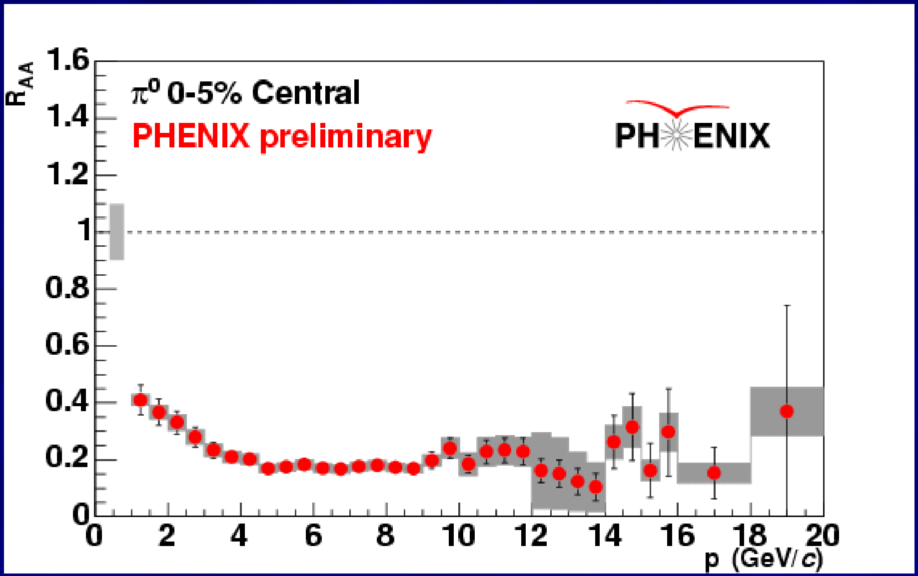






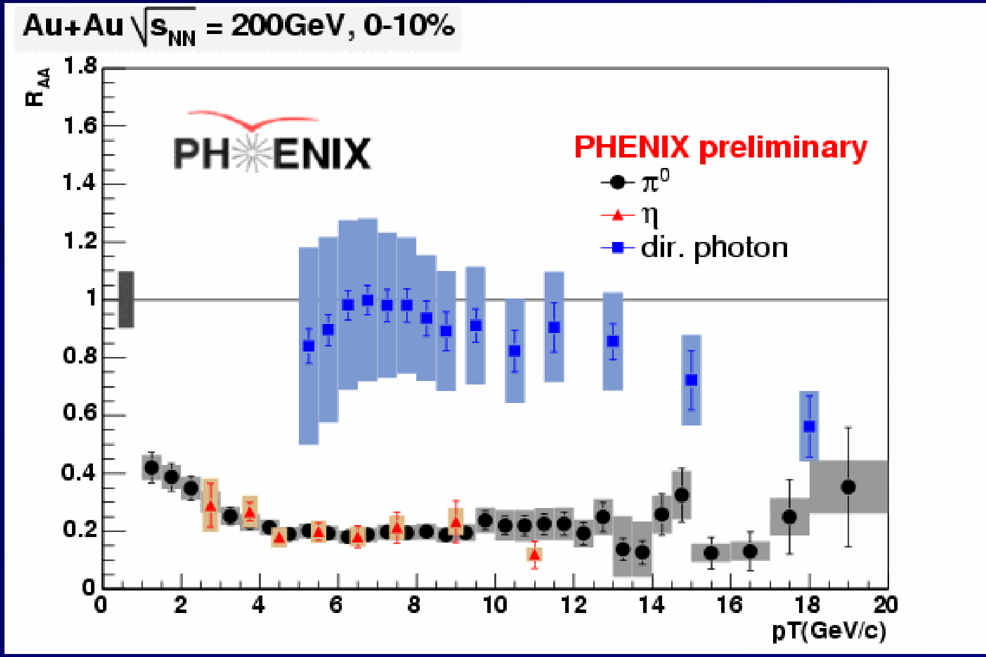
The nuclear modification factor for pions (2/2)



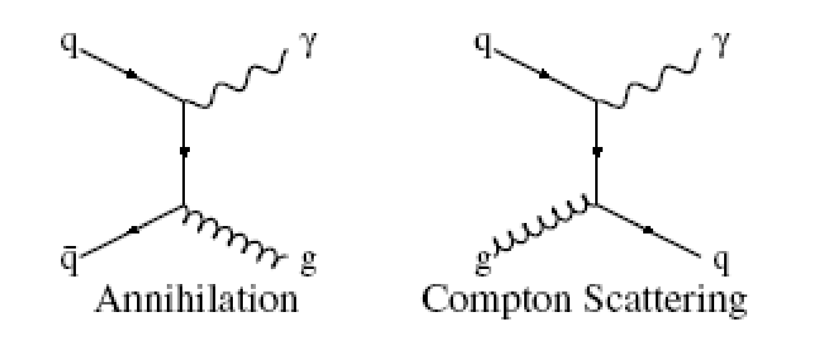


- In central collisions we observe only 20% of the remnants from parton-parton collisions that we expected to observe!
- What happens to the rest?
  - They loose energy as they go through the high energy matter!
  - This is the QCD signature we looked for!
- But first let us consider other alternatives!

Could the binary scaling be wrong?

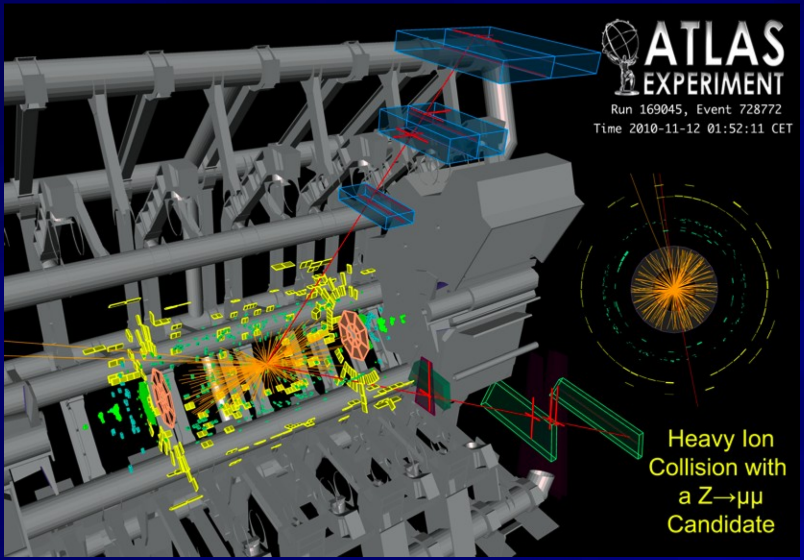


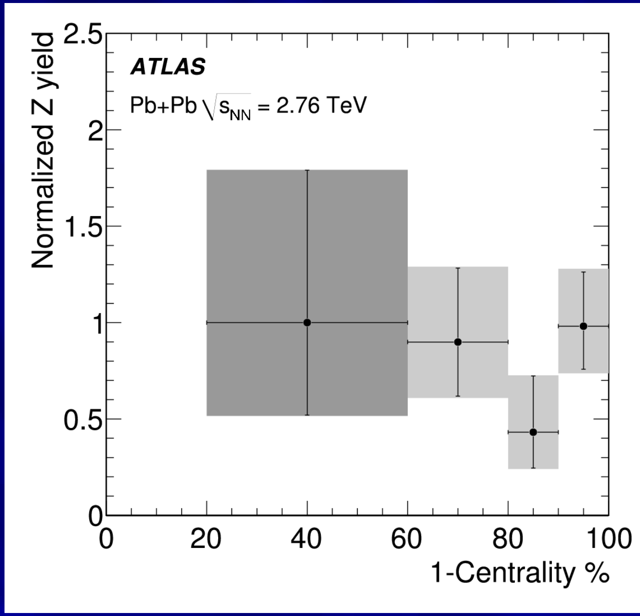
Source of direct photons



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

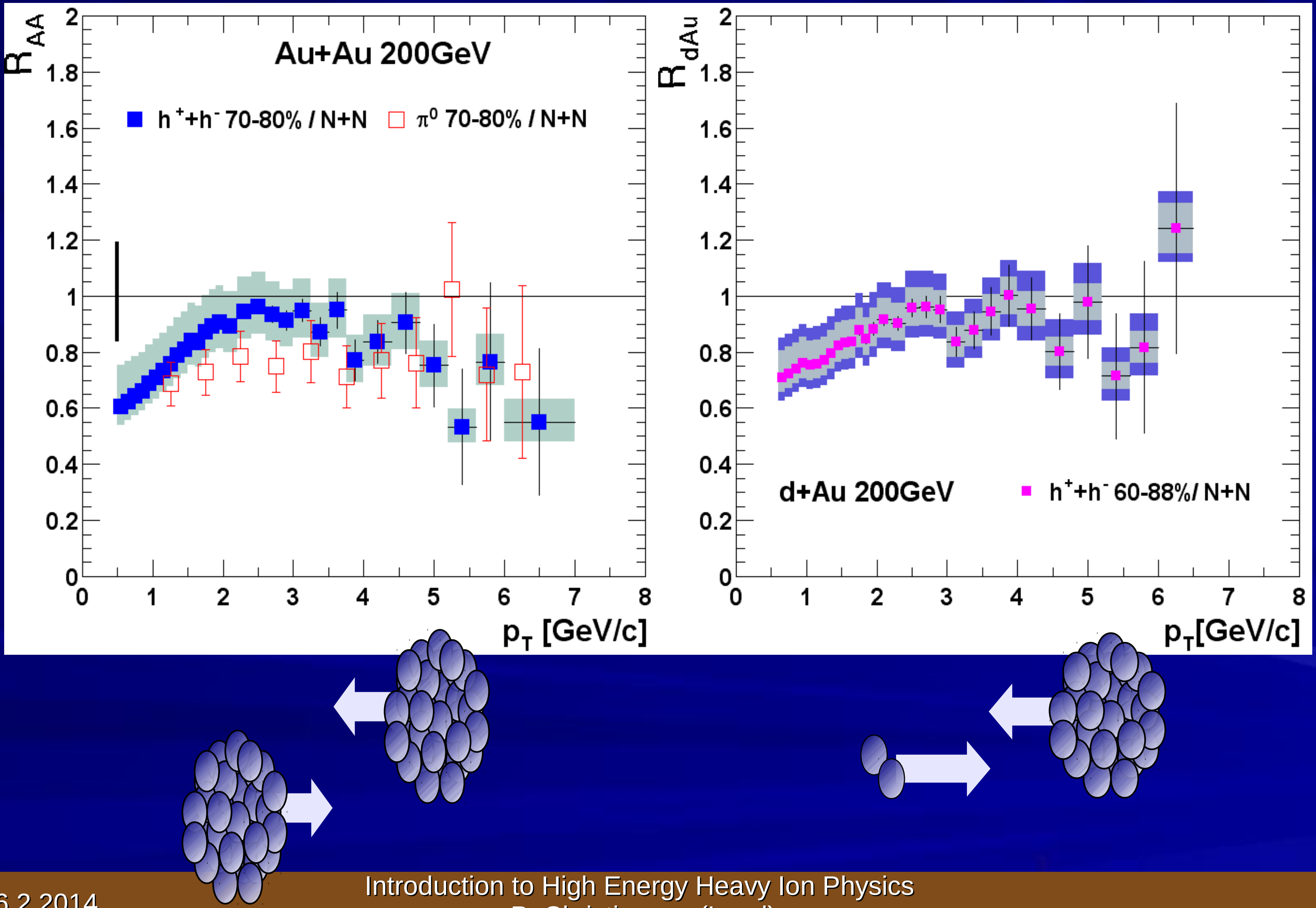
New "standard candle" at LHC: ATLAS measures Z bosons





- The Z does not interact strongly and so can also be used to check binary scaling at LHC

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



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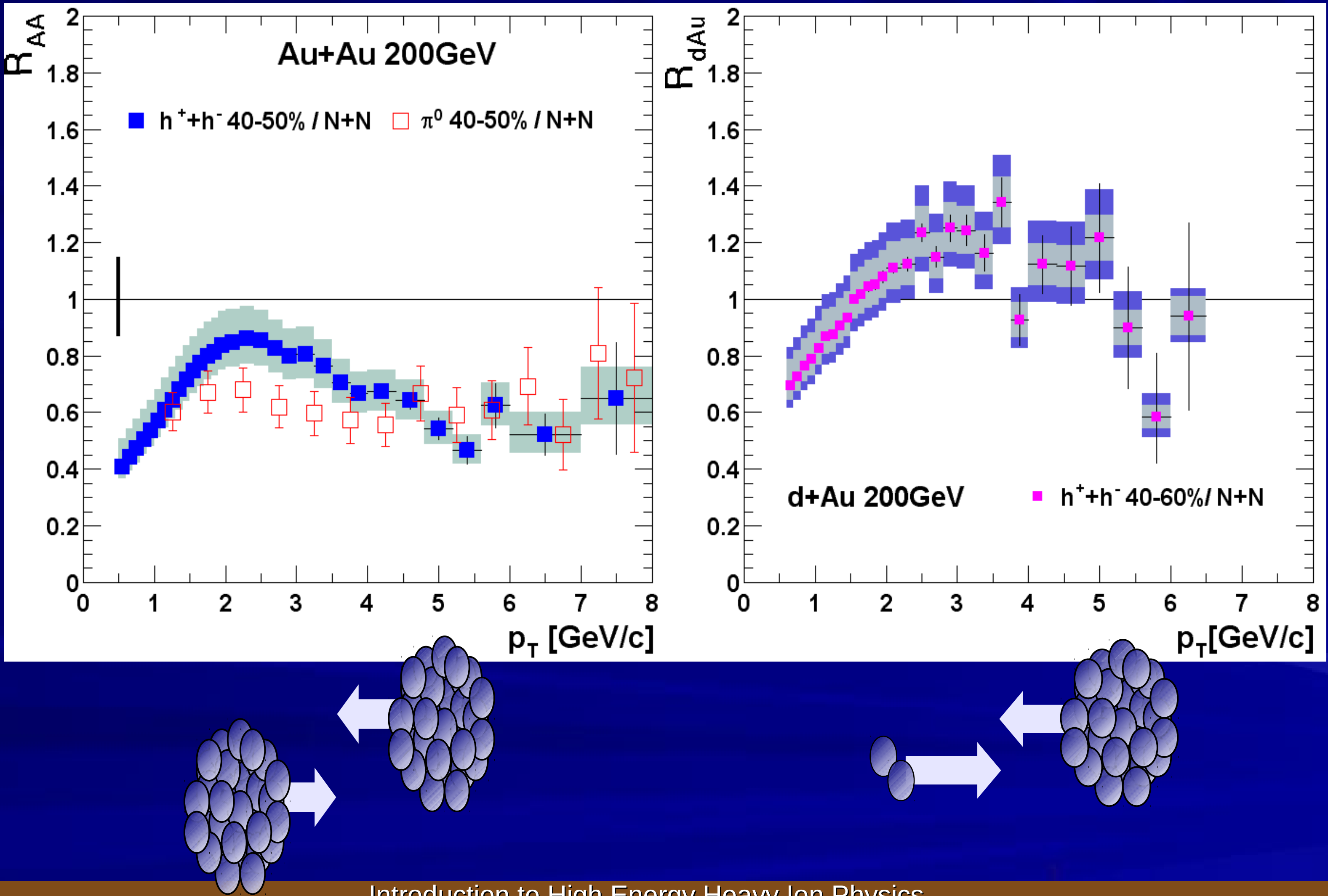
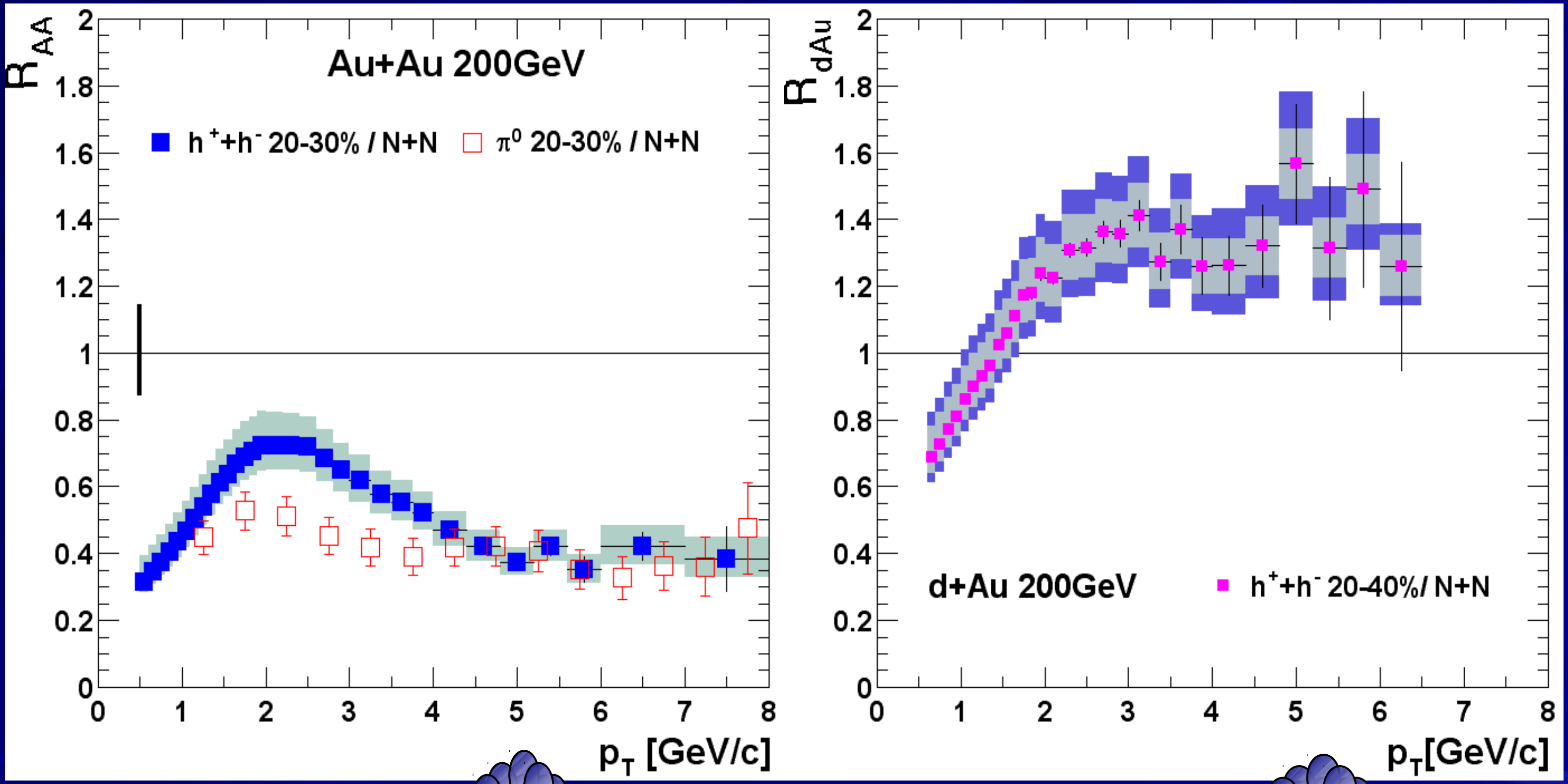
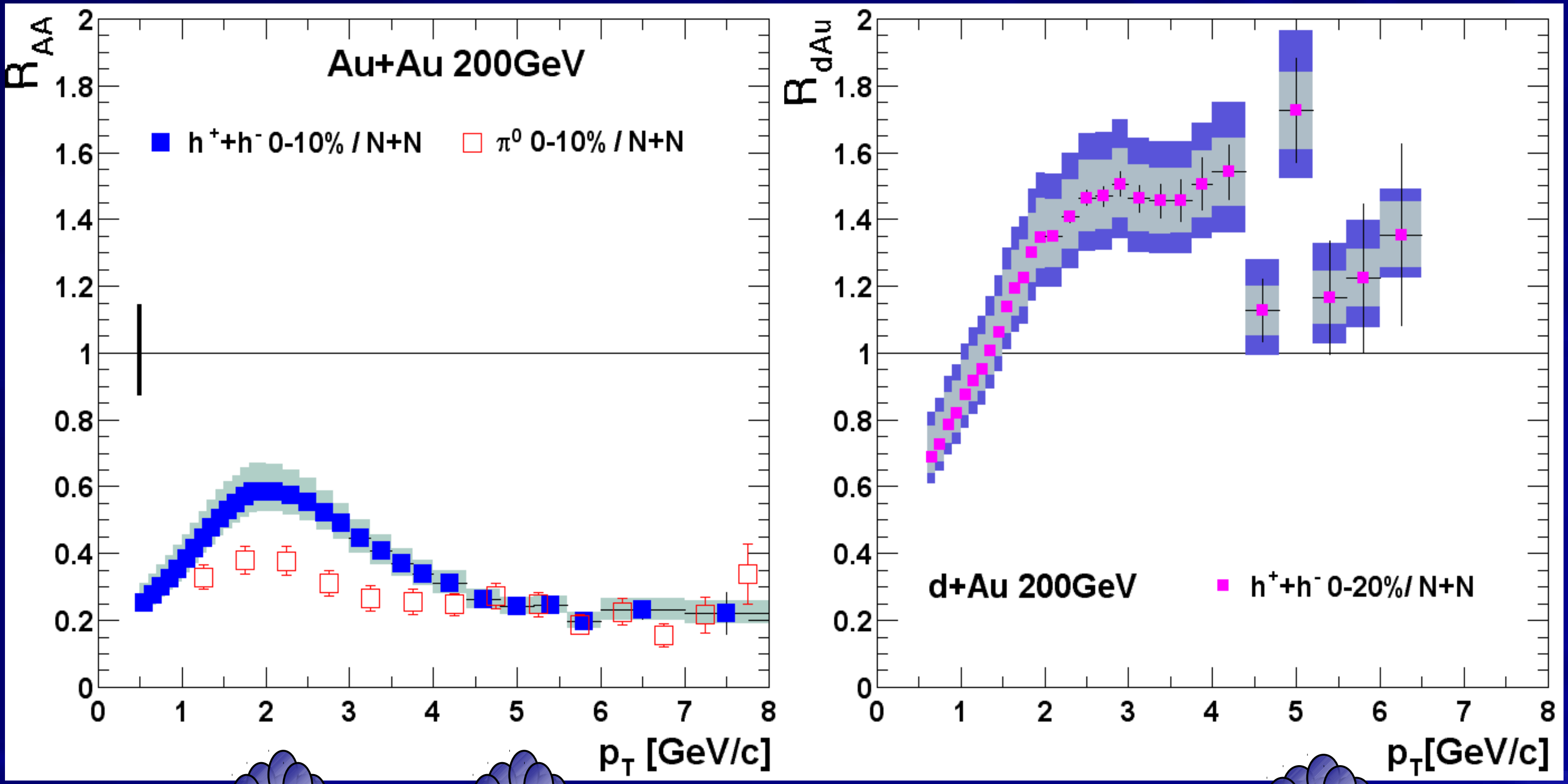
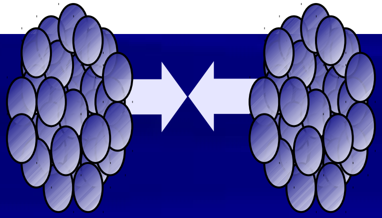


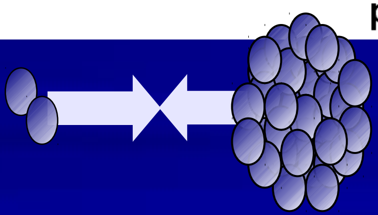
Could it be an initial state effects? Au+Au vs d+Au



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

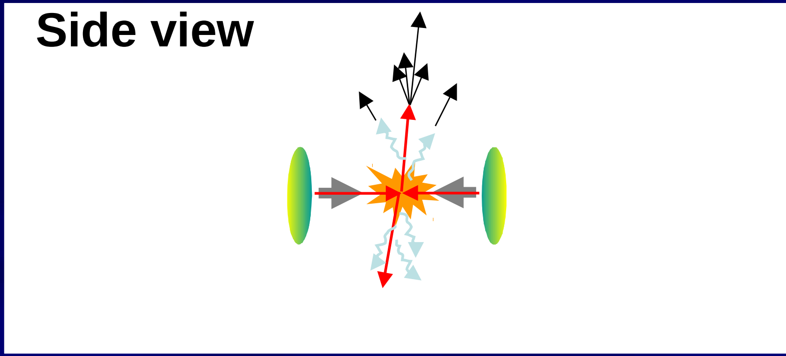




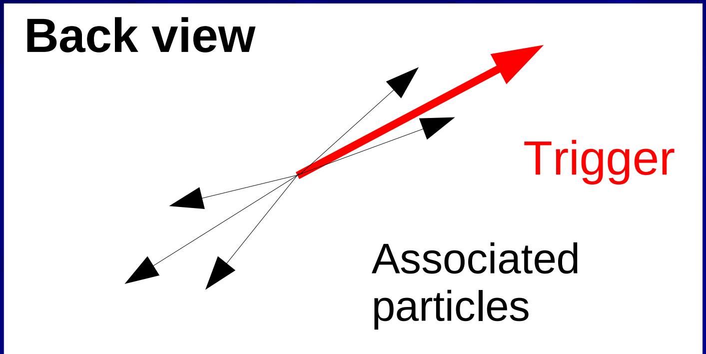


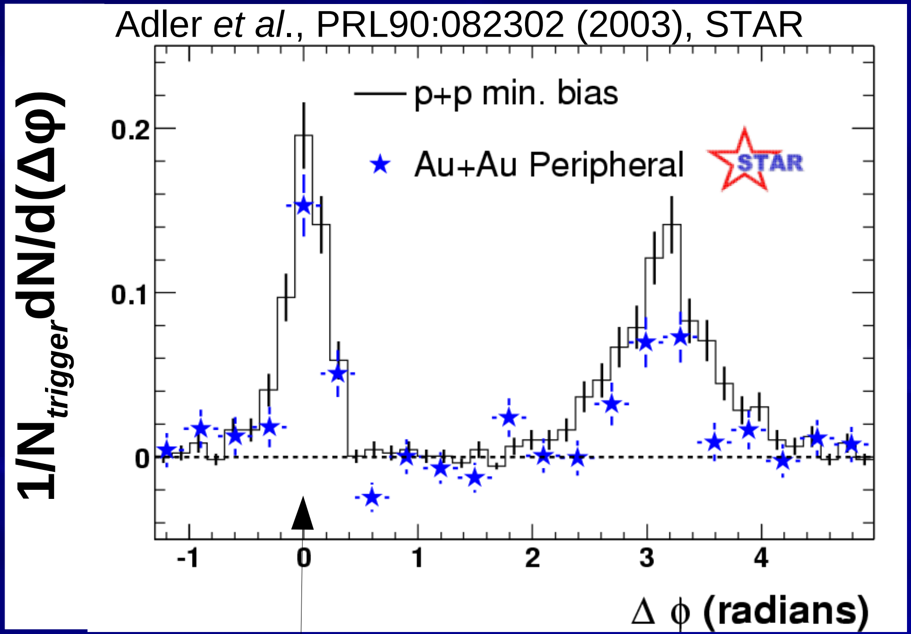
So it must be a final state effect!

The suppression is due to energy loss in the medium



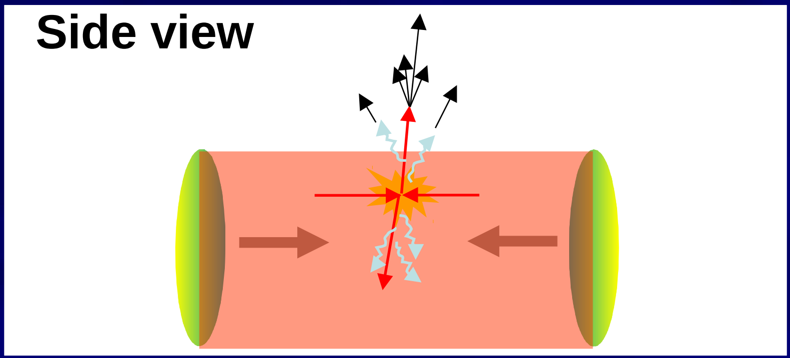
Most jets are created back to back!





4 < p_T(trig) < 6 GeV/c **p_T(assoc) > 2 GeV/c**

The suppression is due to energy loss in the medium



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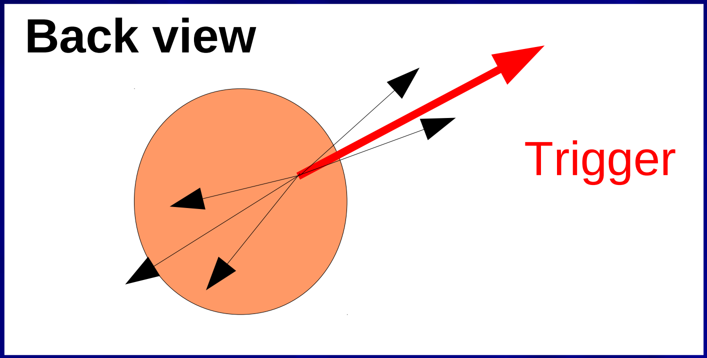
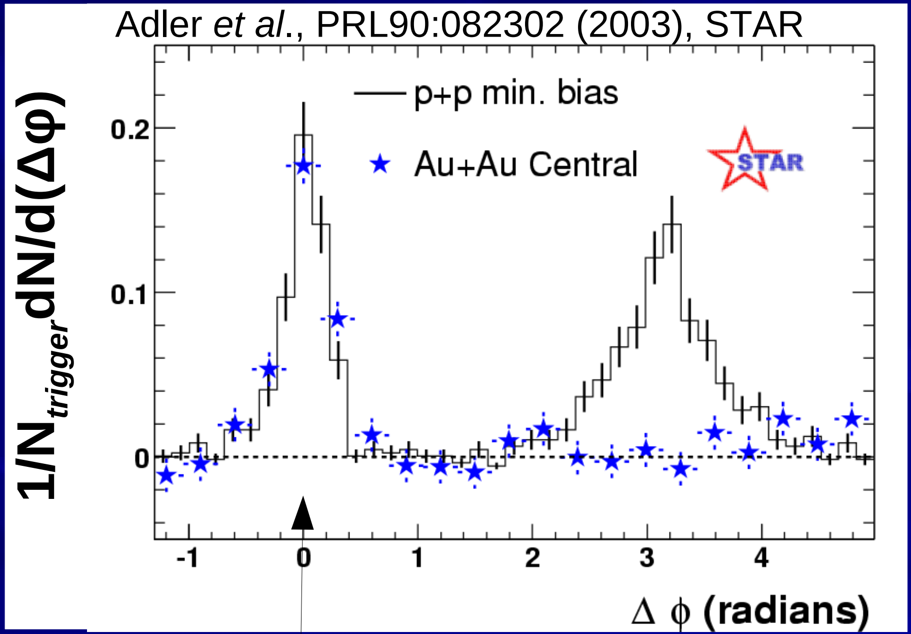
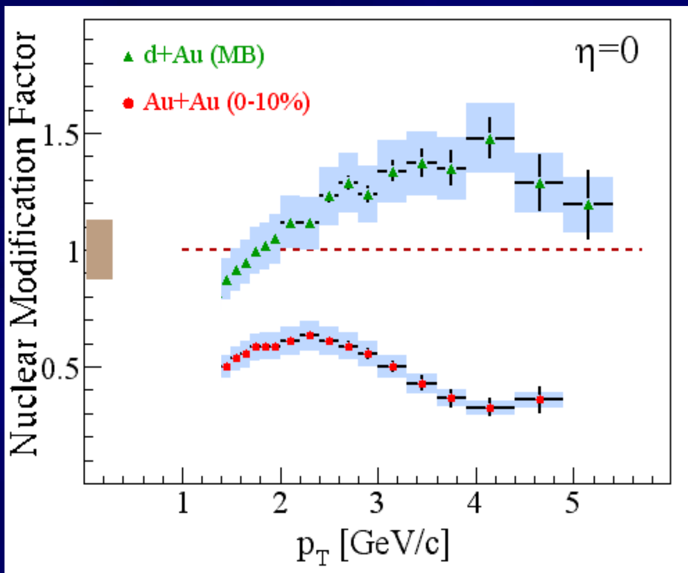


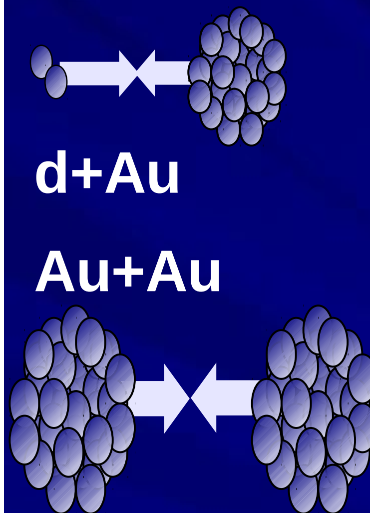


4 < p_T(trig) < 6 GeV/c p_T(assoc) > 2 GeV/c

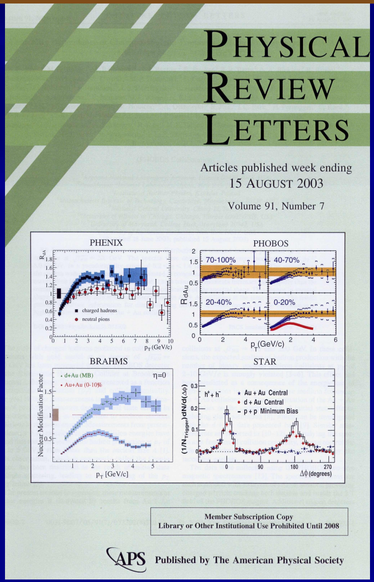
A large energy loss requires a QCD interacting medium, i.e., a colored medium!

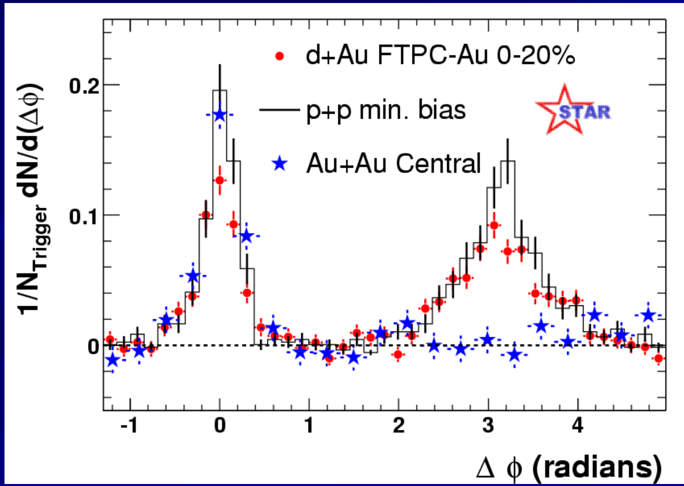
Au+Au vs d+Au
Hot vs cold nuclear matter





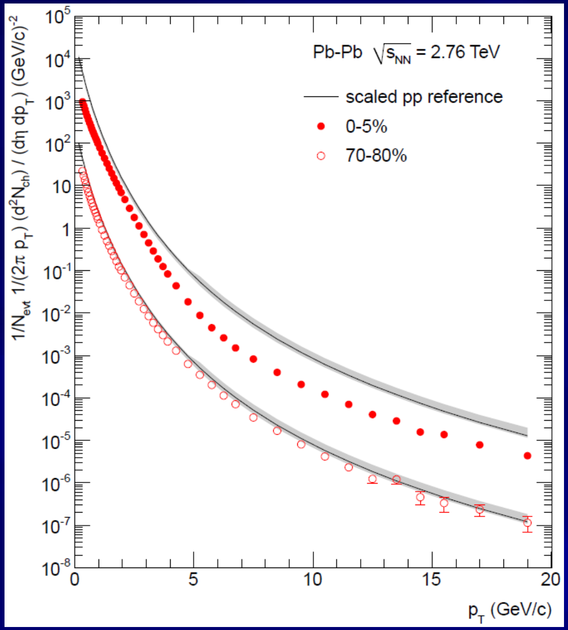
All 4 experiments published together in PRL:

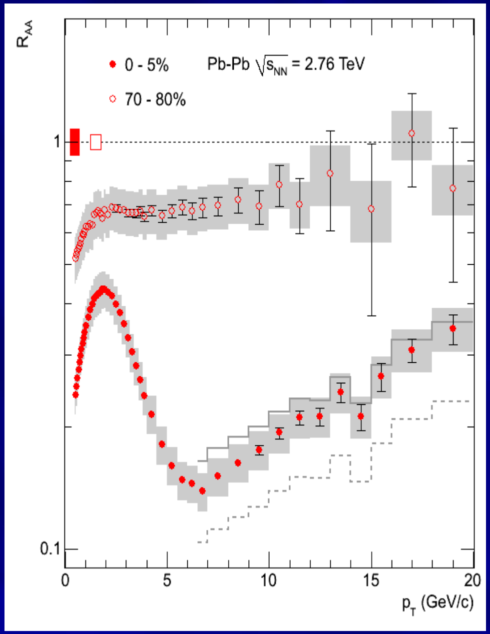




No suppression seen in d+Au
→ Quarks and gluons loose/radiate energy as they interact with the colored quarks and gluons of the created matter.
This suggests that the quark gluon plasma has been discovered!

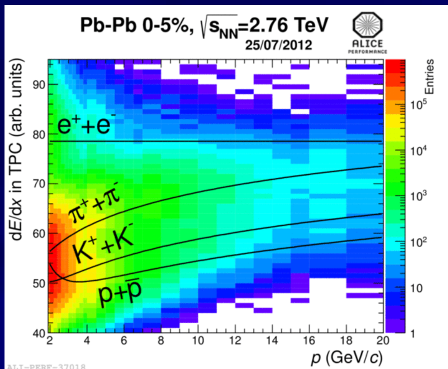
LHC first results from ALICE



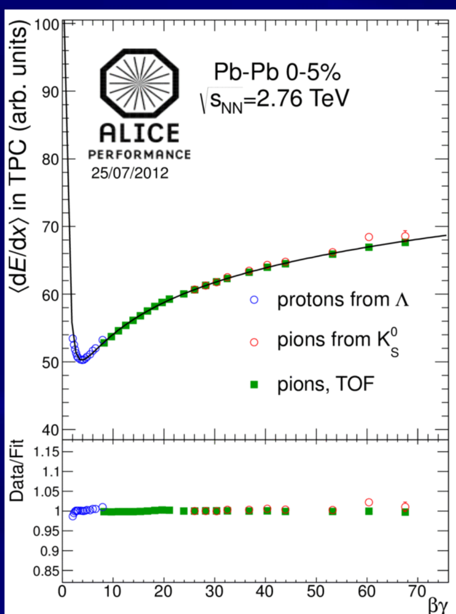


- The nuclear modification factor is lower than at RHIC suggesting that the energy loss is larger.
- The rise with pT was not observed at RHIC and could give new insight into the energy loss mechanism

RAA for identified charged hadrons (Lund)



Pushing the separation to the relativistic rise

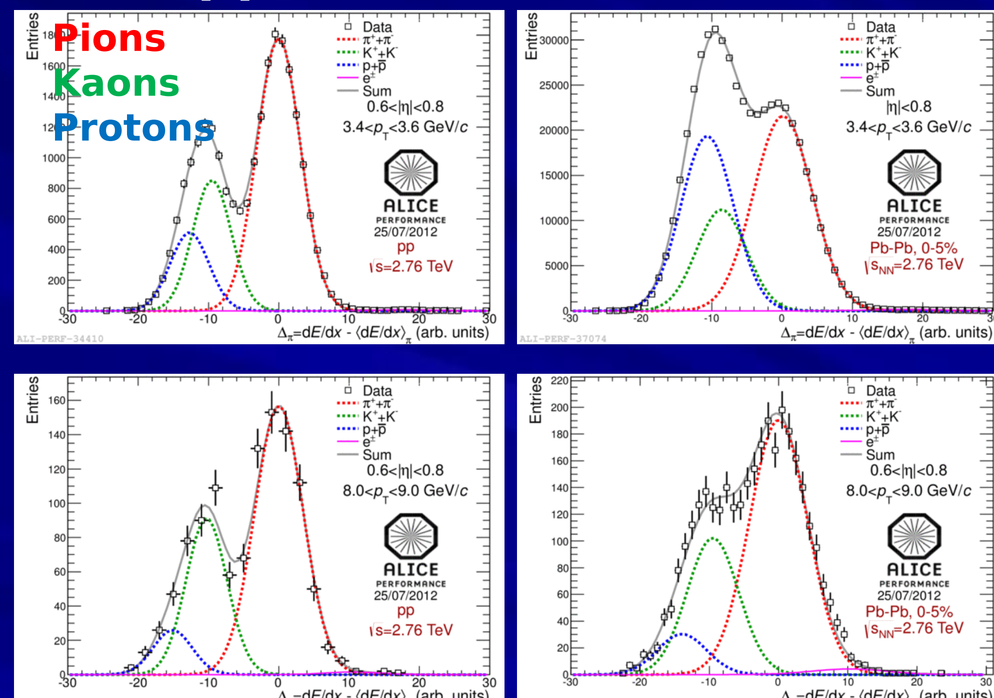


Baryon anomaly in central PbPb. Quark recombination?

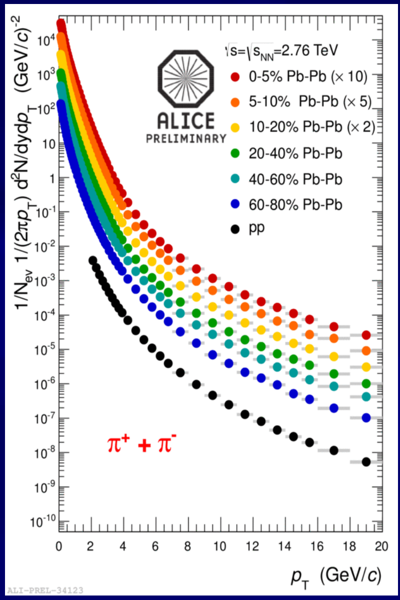
pT ↓

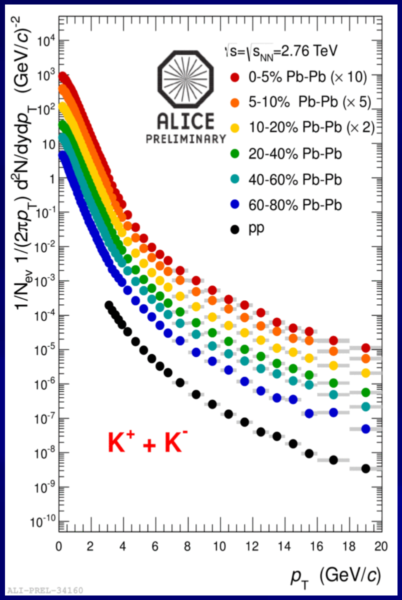
Baryon anomaly not observed at high pT as speculated pre-LHC.

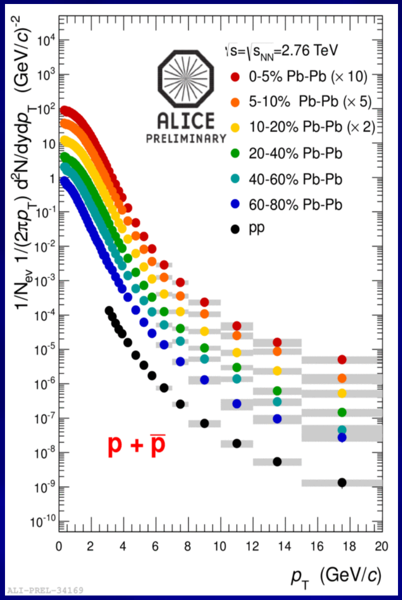
pp **central PbPb**

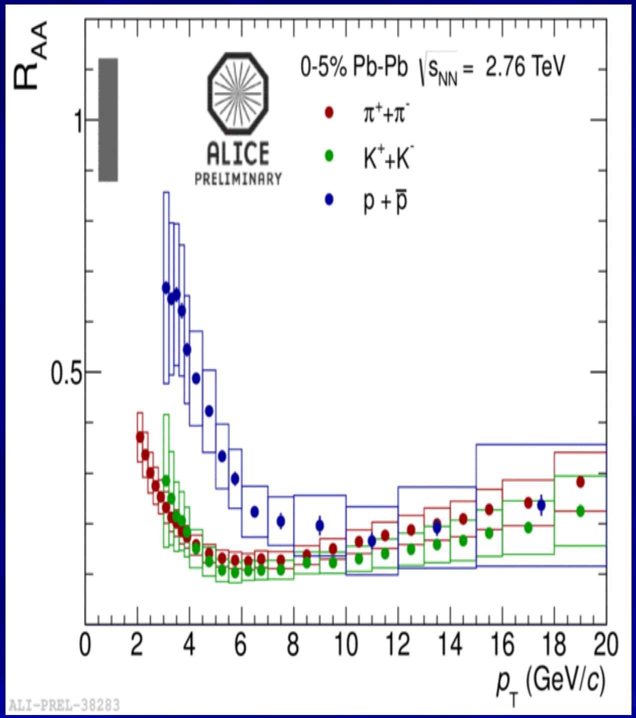


RAA identified hadrons



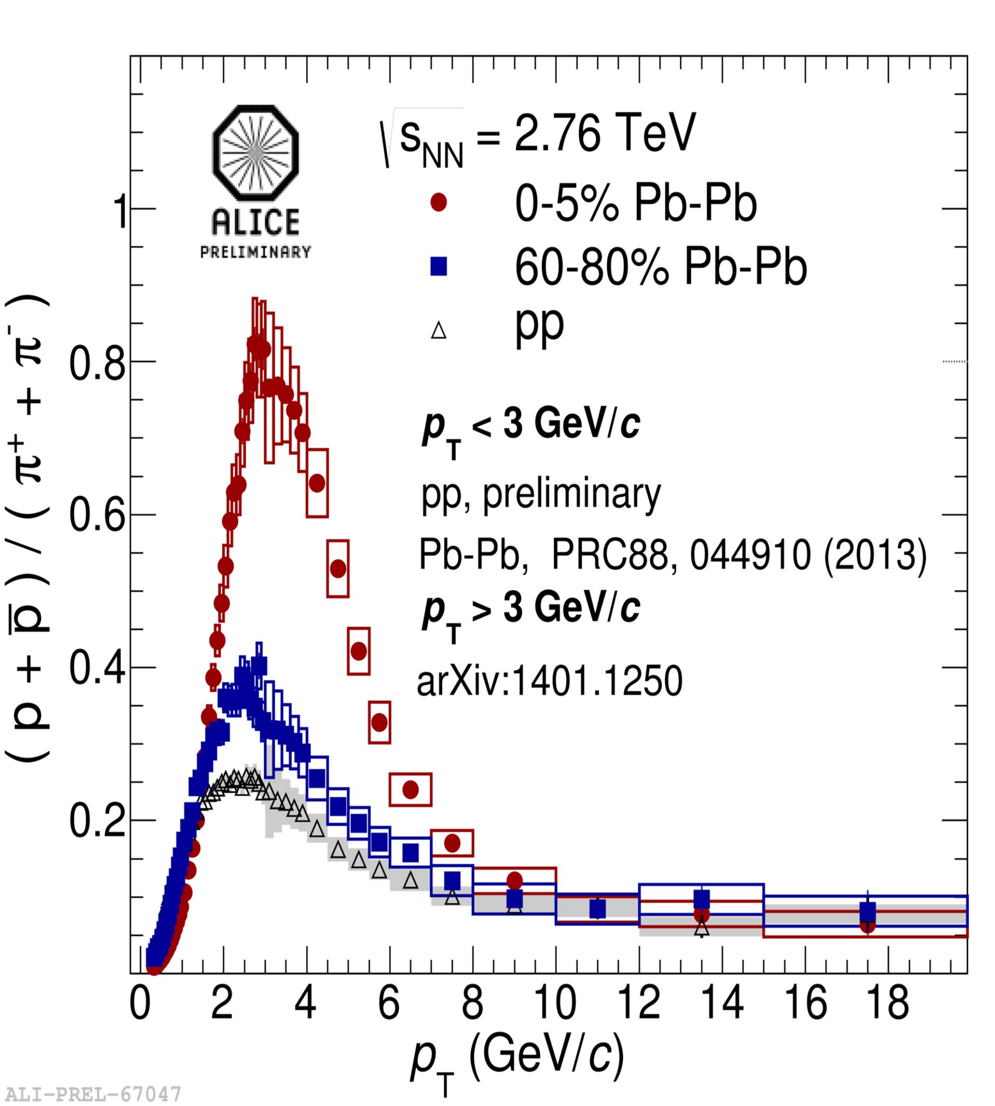




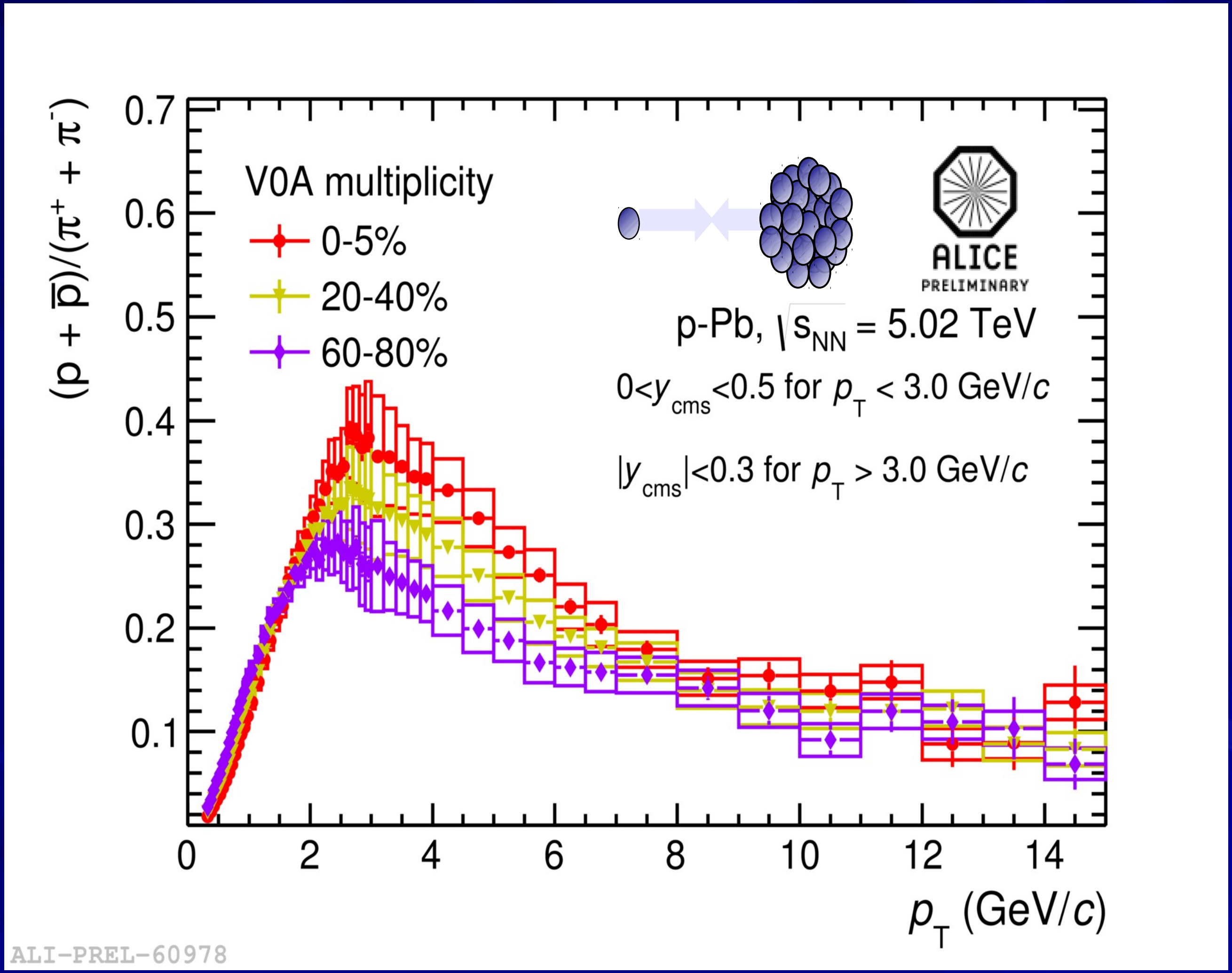


- Identified spectra from 2-3 < pT < 20 GeV/c from Lund analysis. First time presented by Antonio Ortiz Velasquez (Lund) at Quark Matter 2012, August 12-18, Washington.
- Extends ALICE unique PID capabilities to the hard regime

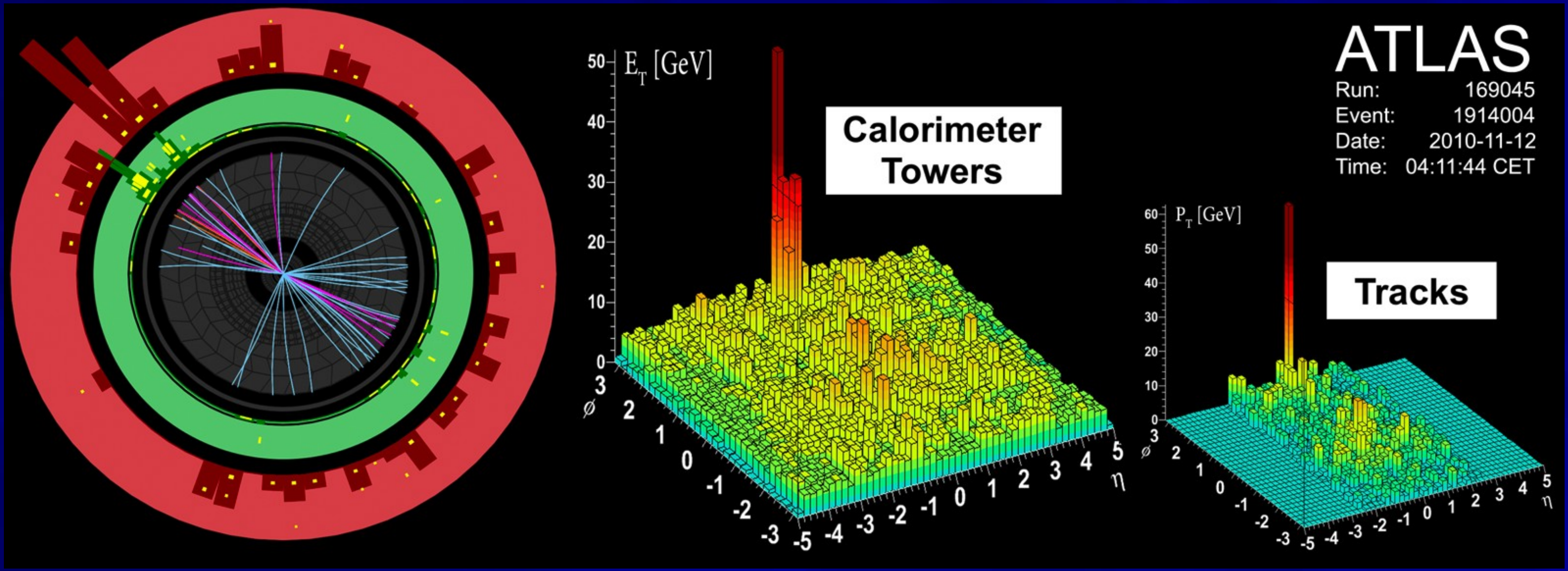
From low pT to high pT: The full picture



Similar behavior in p-Pb: Collectivity/flow in small systems?



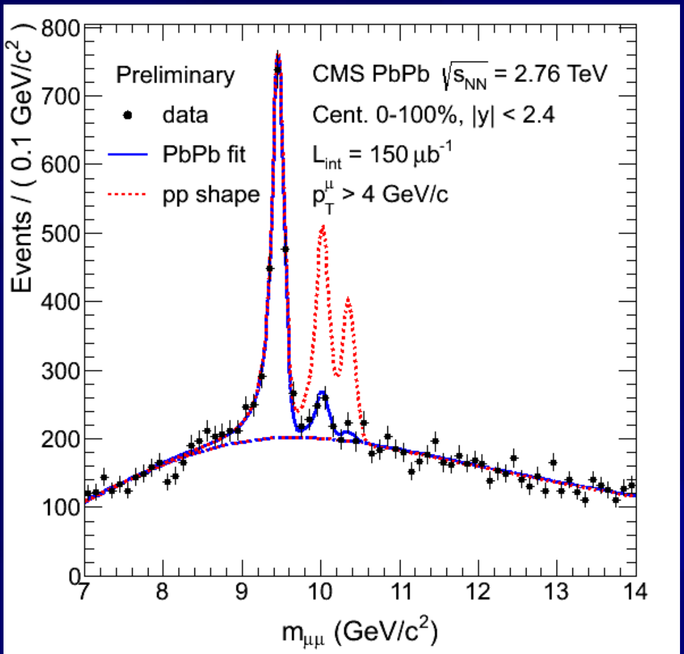
New realm at LHC: ATLAS measures very high pT jets

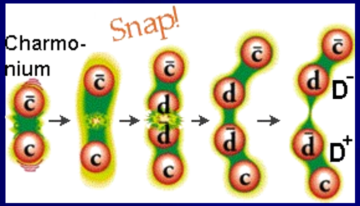


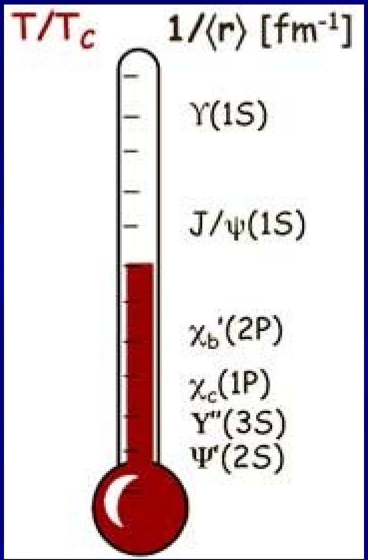
- Jet asymmetry confirms picture frtom RHIC – away side jet is absorbed/modified by the medium
  - Advantage of jets is that they “map” onto the QCD degrees of freedoms: quarks and gluons

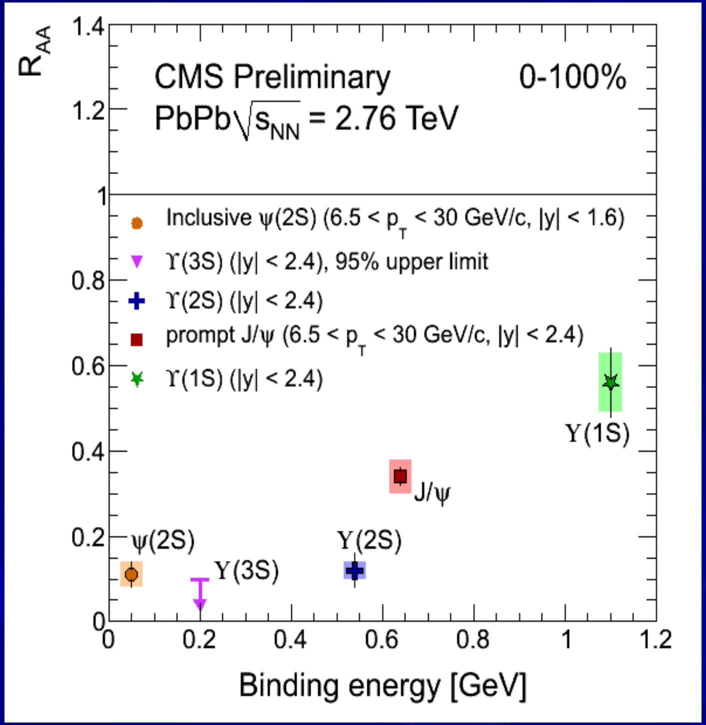
Heavy quark thermometer

Note: 6.5<pT<30 GeV for J/ψ and ψ(2s)









Observation of sequential suppression of Υ (b+b-bar) family

Expected in terms of binding energy

Unfortunately heavy quark results are more complex when systematically studied!

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
- A lot of new results from LHC has to be digested by the community. This will hopefully help constrain the models.