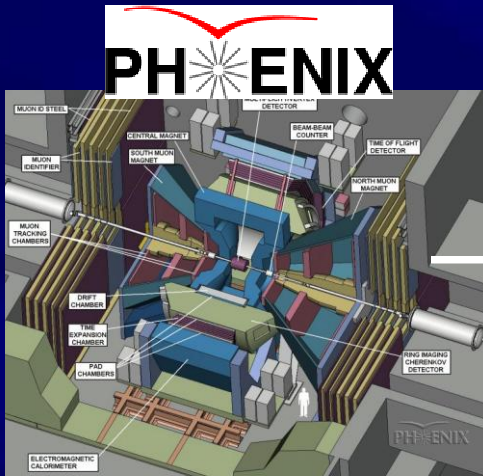
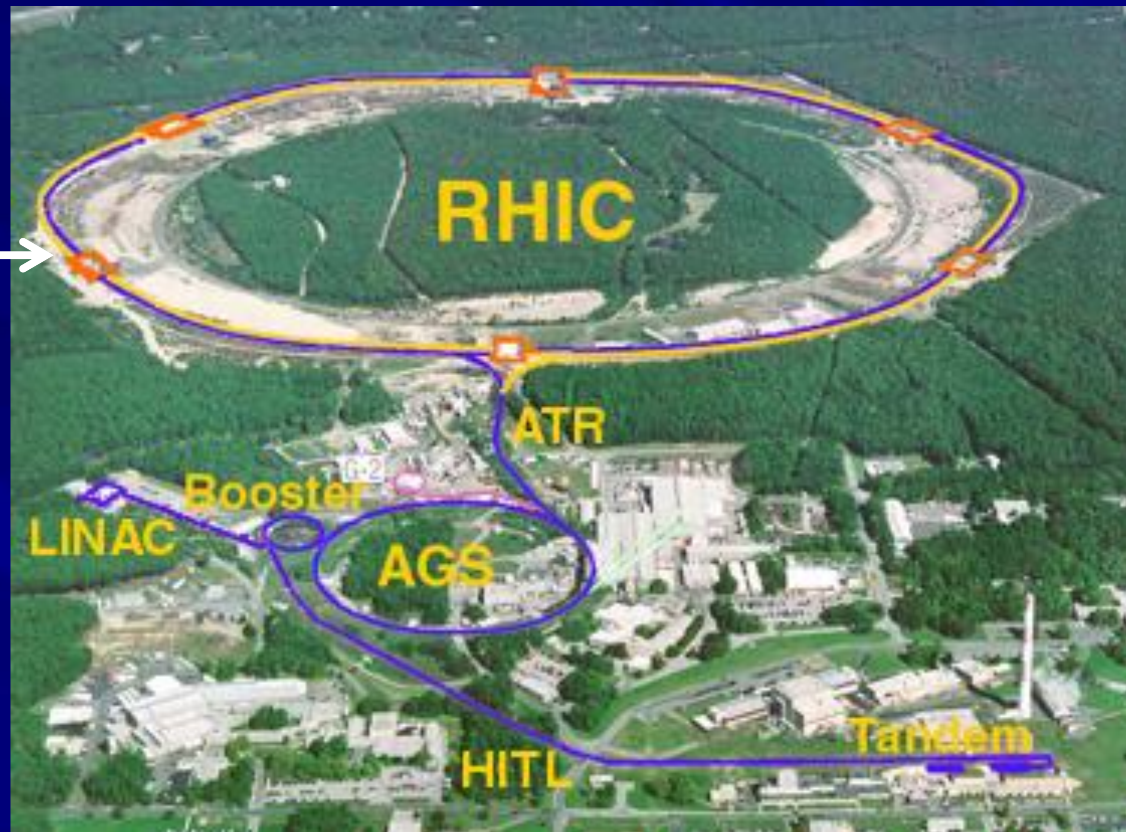
The highest man-made temperature

In February 2010, scientists at Brookhaven National Laboratory's Relativistic Heavy Ion Collider on Long Island, New York, USA, announced that they had smashed together gold ions at nearly the speed of light, briefly forming an exotic state of matter known as a quark-gluon plasma. This substance is believed to have filled the universe just a few microseconds after the Big Bang. During the experiment the plasma reached temperatures of around 4 trillionºC, some 250,000 times hotter than the centre of the Sun.

Brookhaven National Laboratory's Relativistic Heavy Ion Collider

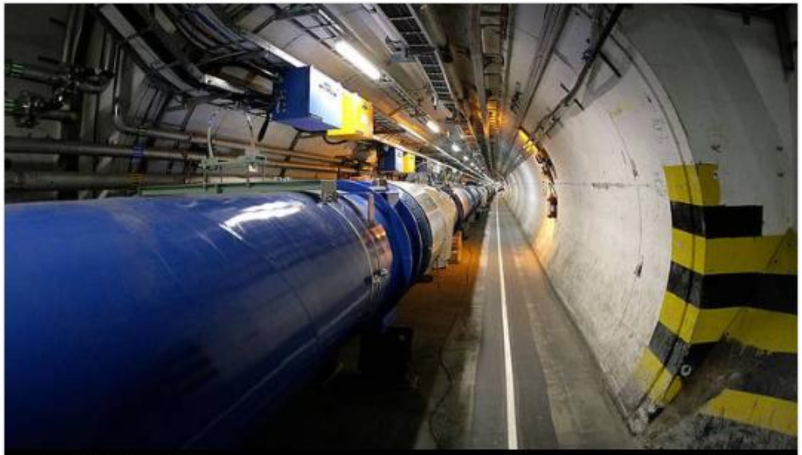




Lund – 10MSEK worth design, development and construction to the Pad Chambers

- **RHIC is the first heavy ion collider in the world. Operational since 2000 (program until 2020+). Max beam energy: $\sqrt{s_{NN}}$=200GeV**

Record broken at LHC



Partikelacceleratorn LHC	Foto: Scanpix

Hettan rekordhög vid experiment i Schweiz

5.000.000.000.000 grader Fem tusen miljarder grader. Det är numera den högsta temperatur som människor skapat.

PUBLICERAD 16 AUGUSTI 2012 - 09:51 – UPPDATERAD 17 AUGUSTI 2012 - 17:14

DELA VIA E-MAIL
SKRIV UT

Det är forskare vid Cern i Schweiz som slagit rerkord vid experiment i partikelacceleratorn LHC, rapporterar Sveriges Radios vetenskapsredaktion.

Fem tusen miljarder grader är ungefär som temperaturen vid Big Bang och hundra tusen gånger högre än i solens mitt.

Forskarna åstadkom den varmaste materien någonsin genom att låta blykärnor kollidera med hög energi i acceleratorn.

Genom experimentet vill man efterlikna processer vid universums allra tidigaste period. Framför allt vill forskarna se vad som händer när kvarkar övergår till vanlig materia.

Två år att mäta
Det har tagit två år att mäta hur hög temperaturen var under experimentet, vilket beror på att analyserna tar tid.

– Som vid annan upphettning ändrar materien tillstånd, som när vatten kokar och går från vätska till ånga. Temperaturen i vattnet ökar inte när man tillför energi, vattnet förångas i stället. På samma sätt har vi studerat processen när protoner delas upp i kvarkar. Och det är på den sida av den så kallade fasövergången, som vi mätt temperaturen, säger Anders Oskarsson, partikelfysiker vid Lunds universitet, till Sveriges Radio.

Ingen teoretisk gräns
Det nya rekordet är omkring 40 procent högre än det tidigare värmerekordet, vilket Anders Oskarsson för övrigt var med och satte.

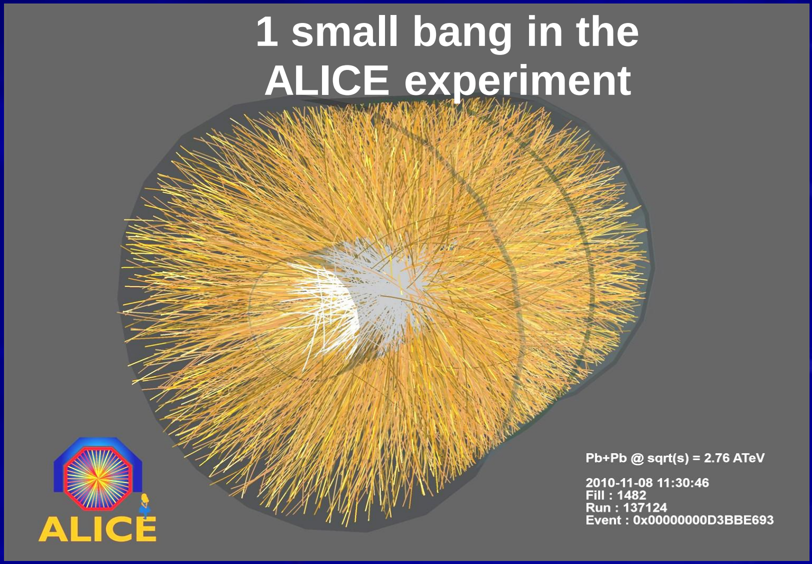
Enligt Anders Oskarsson finns det inte någon teoretisk gräns för hur varmt det kan bli.

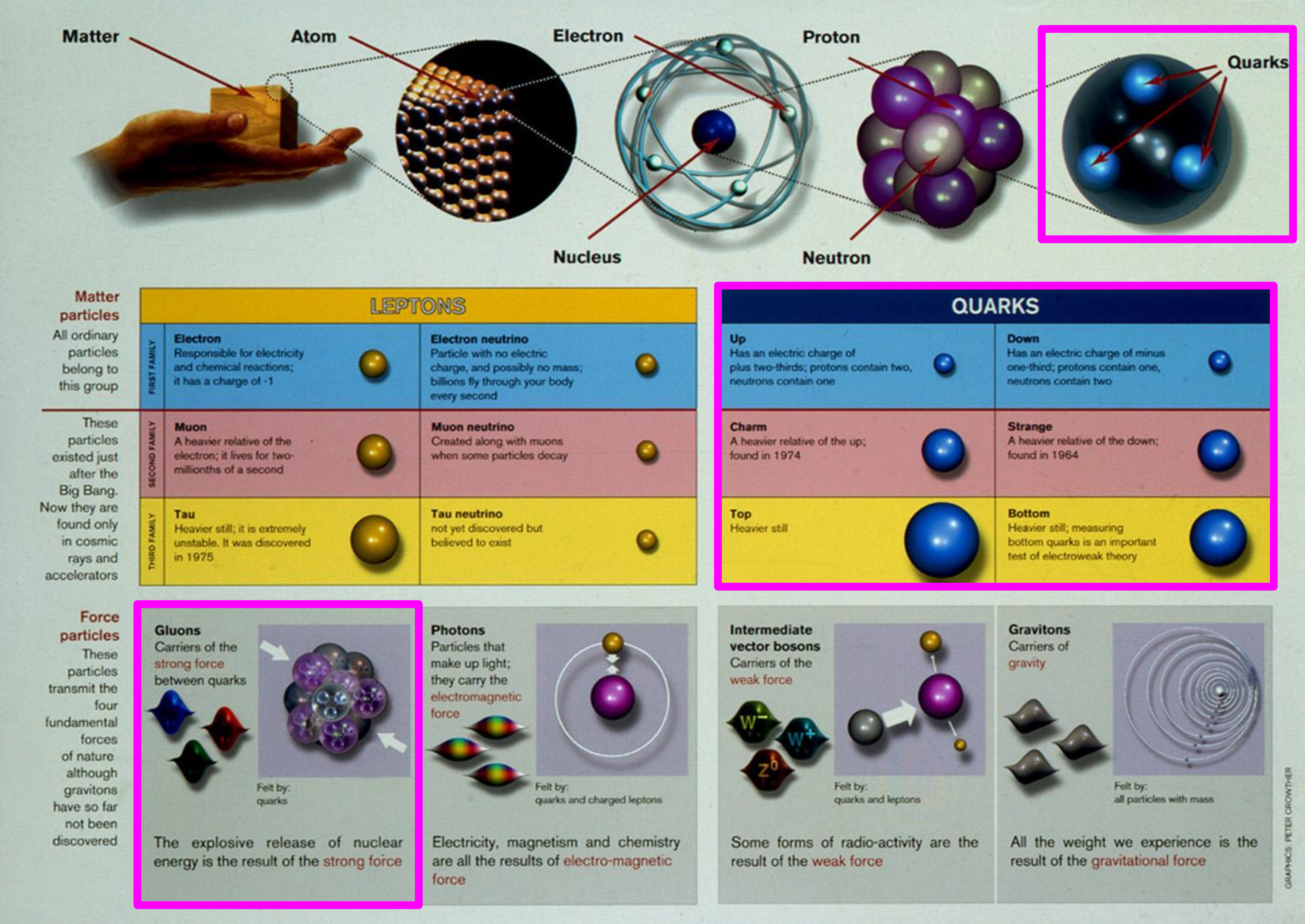
– Däremot finns det många andra gränser, som ekonomiska. Man måste ha en enorm partikelaccelererator för att pumpa in tillräckligt mycket energi i systemet, för att temperaturen ska bli så här hög. Så att vi skulle kunna komma särskilt mycket högre det tror jag knappast, säger han.

http://www.svt.se/nyheter/vetenskap/hettan-rekordhog-vid-experiment-i-schweiz

The highest man-made temperature

- QCD and hadron collisions
  - Soft and hard physics
- The medium created in heavy ion collisions
  - A nearly perfect liquid
- How we measure temperature




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
QUARKS
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
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
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
Charm
A heavier relative of the up; found in 1974
Strange
A heavier relative of the down; found in 1964
Tau
Heavier still; it is extremely unstable. It was discovered in 1975
Tau neutrino
not yet discovered but believed to exist
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

Quantum Chromo Dynamics (QCD)

3 color charges (red, green, blue)

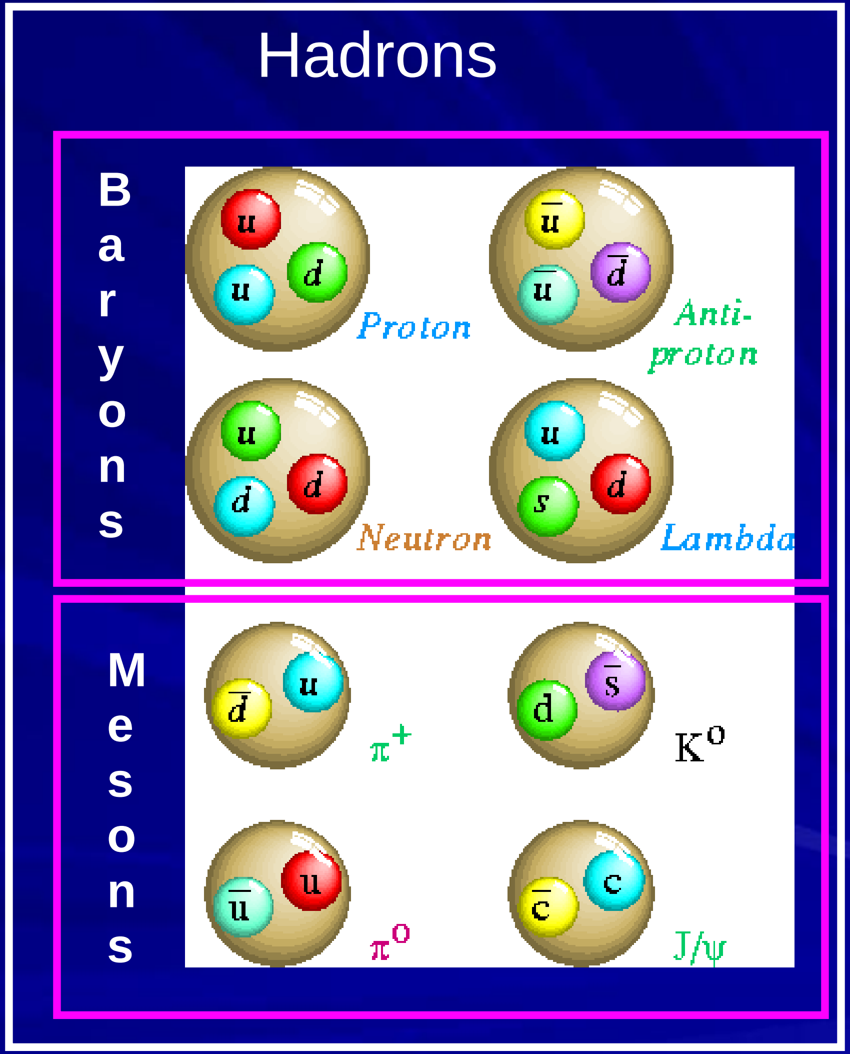
Hadrons have to be colorless

Baryons have all 3 colors

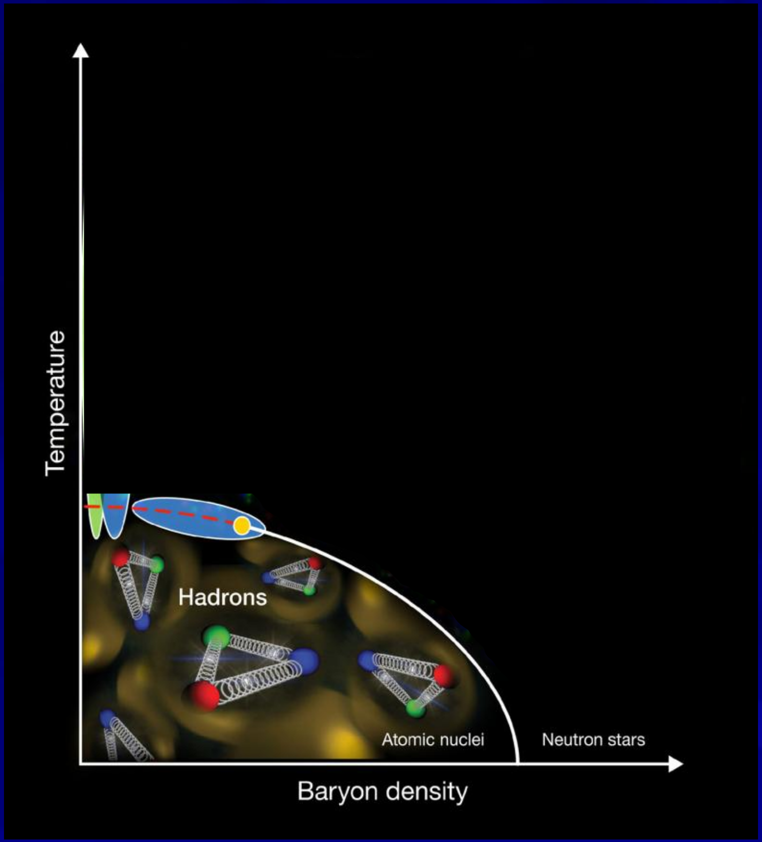
Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!



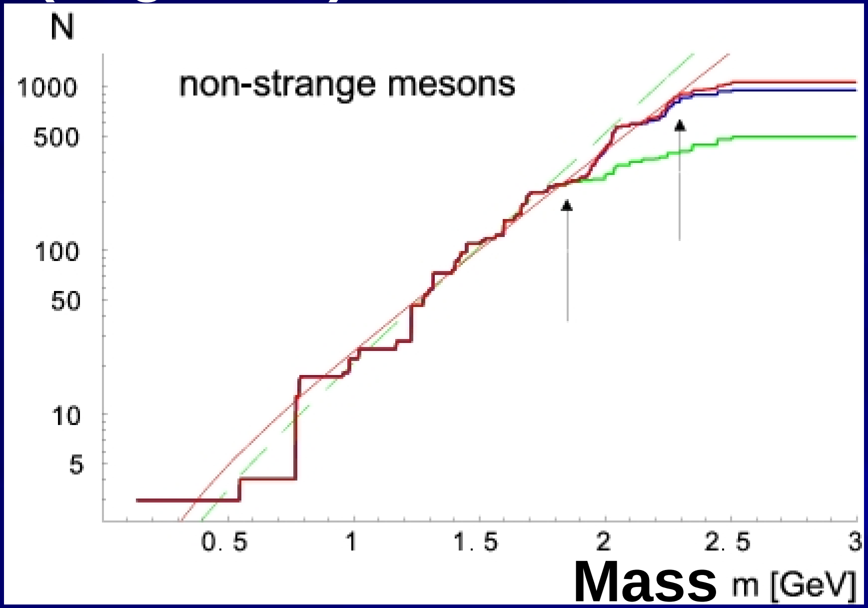
QCD phase diagram



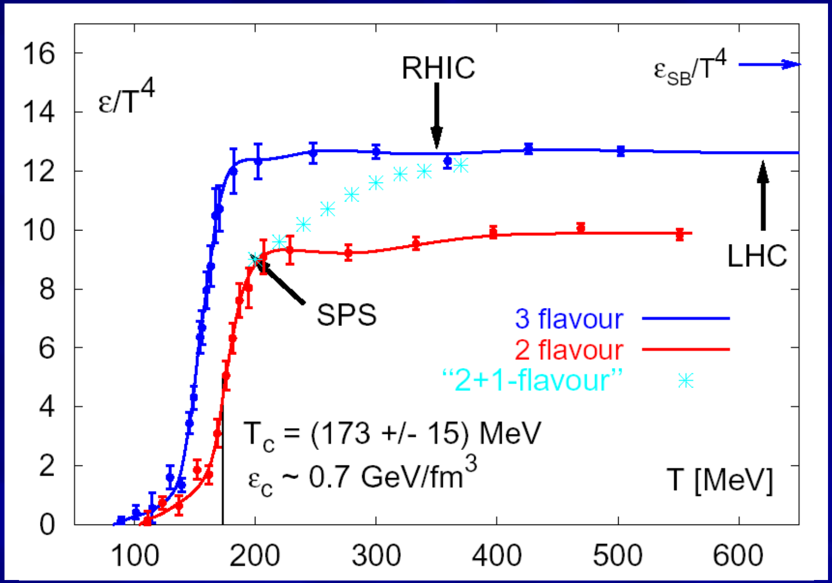
- Hadronic matter phase (quarks and gluons are confined)

What happens at higher energy densities?

Accumulated hadronic states (Hagedorn)



QCD energy denisty (Lattice QCD)



In a statistical model the hadronic states are populated proportional to: exp(-m/T)

Critical (Hagedorn) temperature ~ 200-300 MeV.

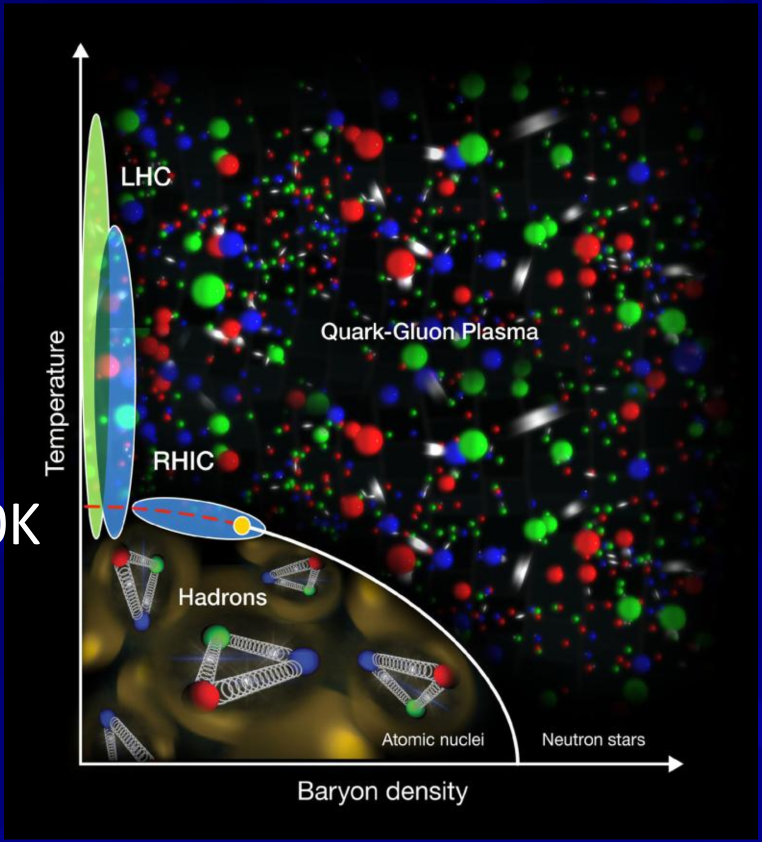
$$\varepsilon_{QCD} = \frac{\pi^2}{30}\left(2\times 8 + \frac{7}{8} 2\times 2\times 3\times 3\right) T^4$$

Gluon spin and color

(Anti+)quark spin, color and flavor

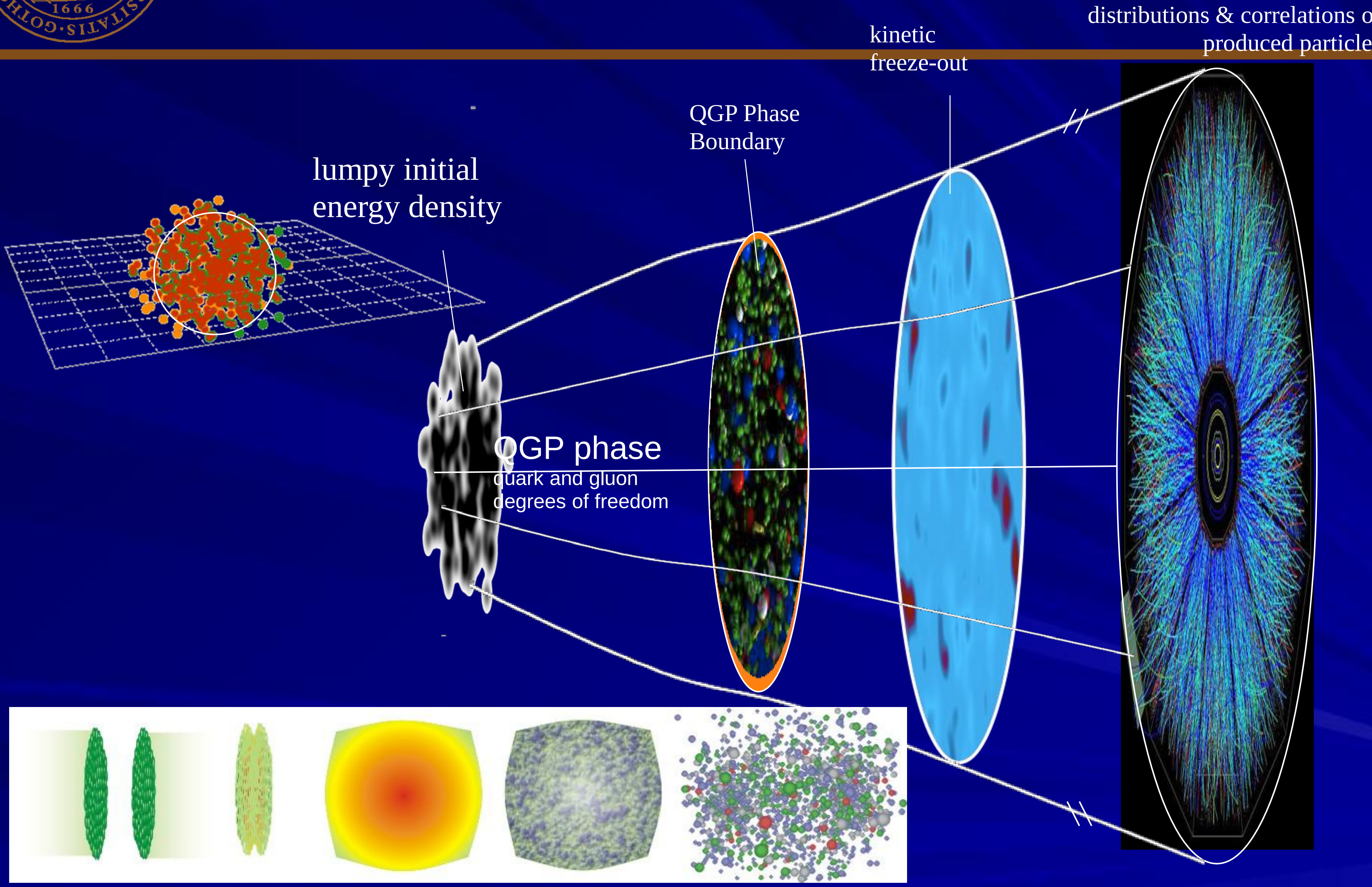
QCD phase diagram

T~170MeV
1 eV = 11605K
T~2,000,000,000,000K
(T core sun:
16,000,000K)

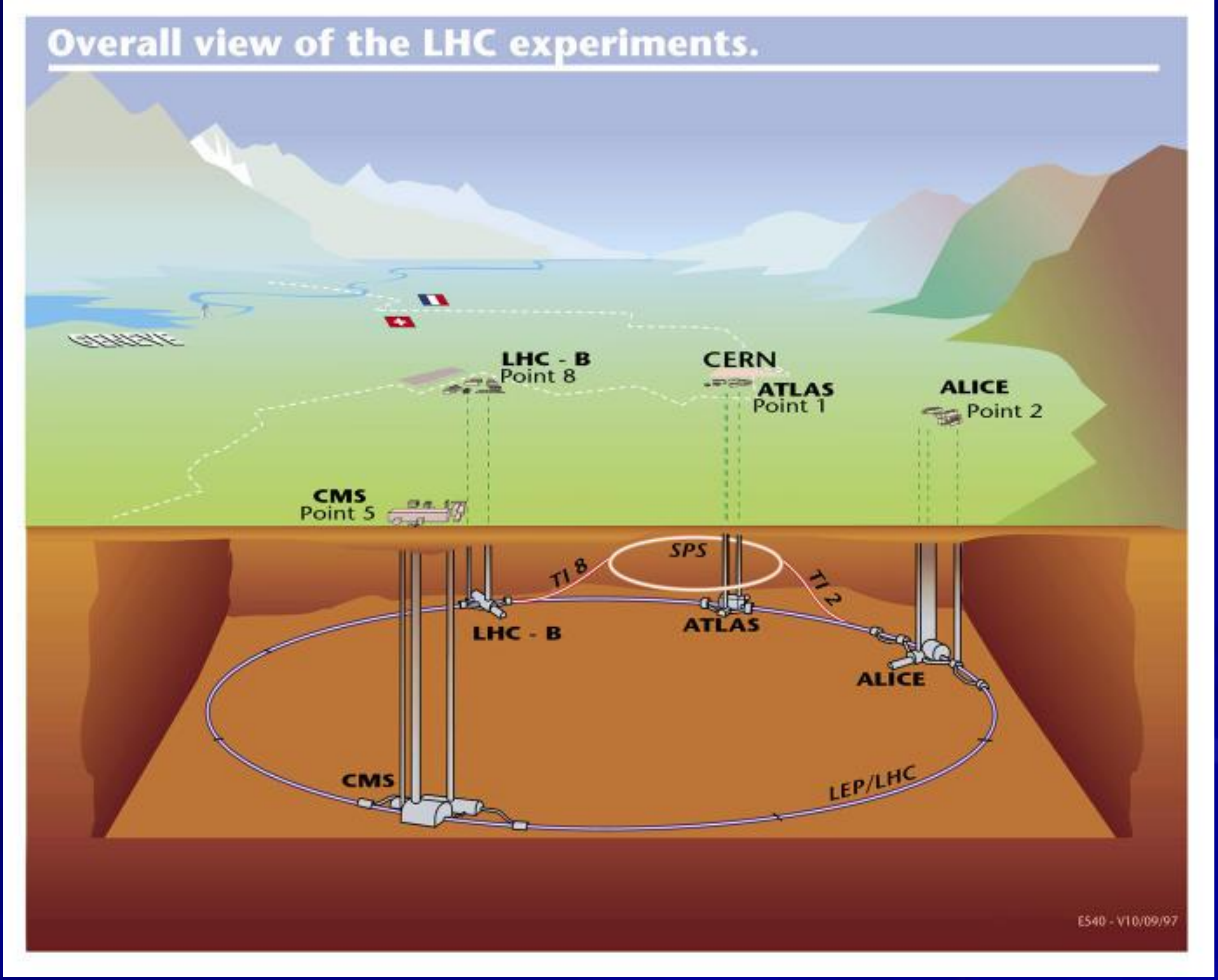


- By colliding heavy ions we hope to create (and study the characteristics of) a new phase of matter called the Quark Gluon Plasma (where quarks and gluons are deconfined)

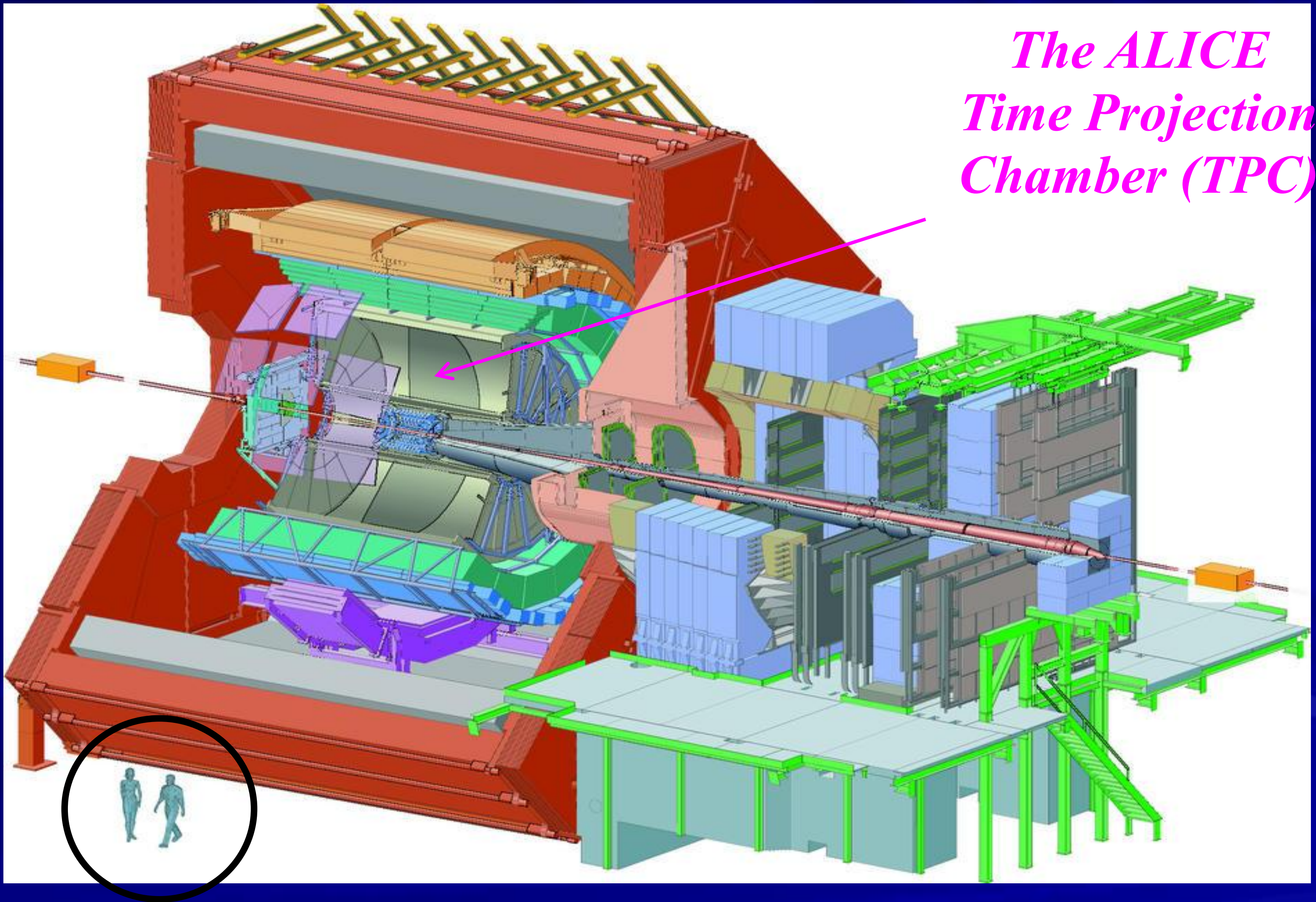
QGP in the laboratory



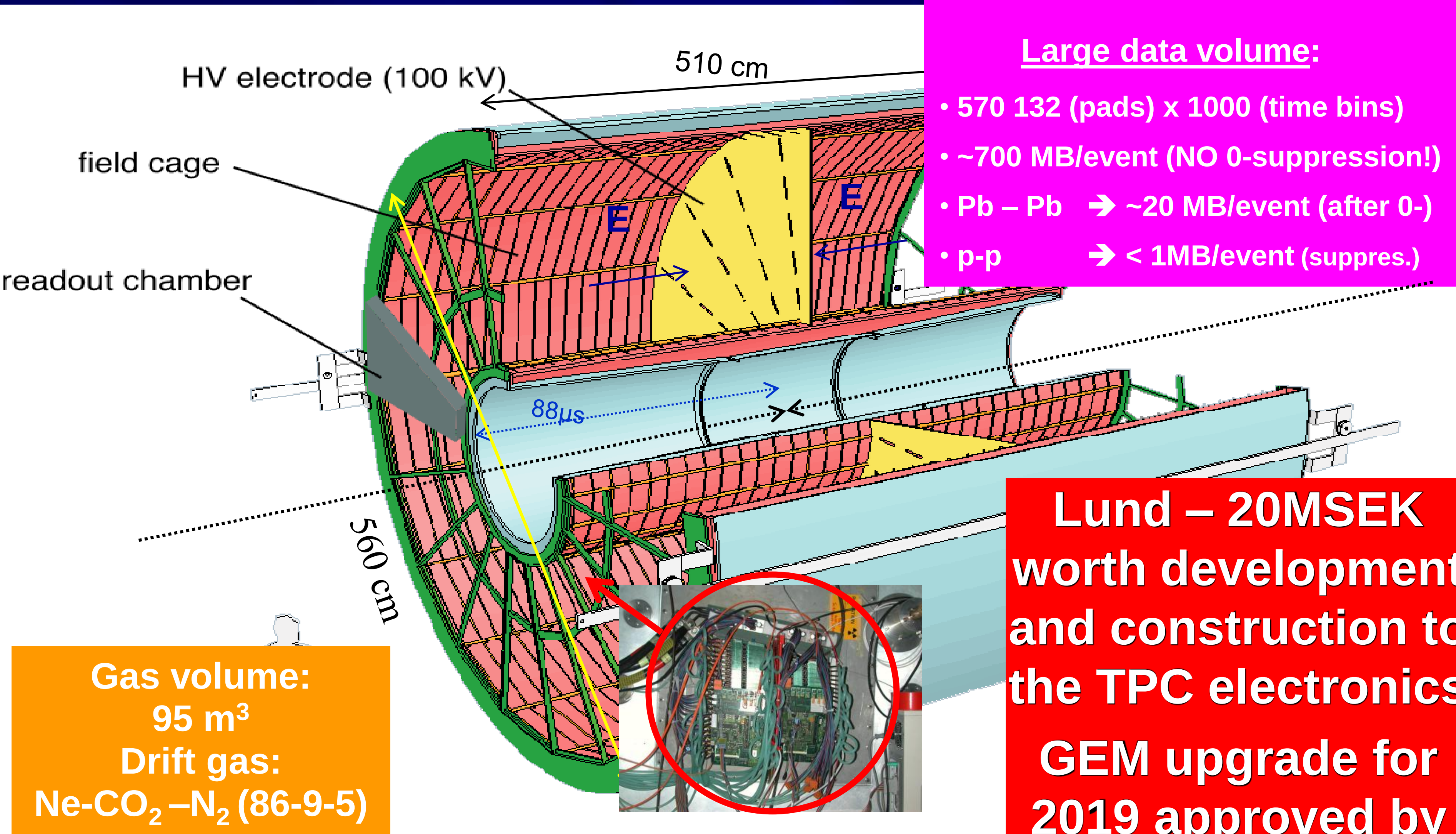
The LHC accelerator at CERN



The ALICE experiment at LHC



The ALICE TPC



Large data volume:

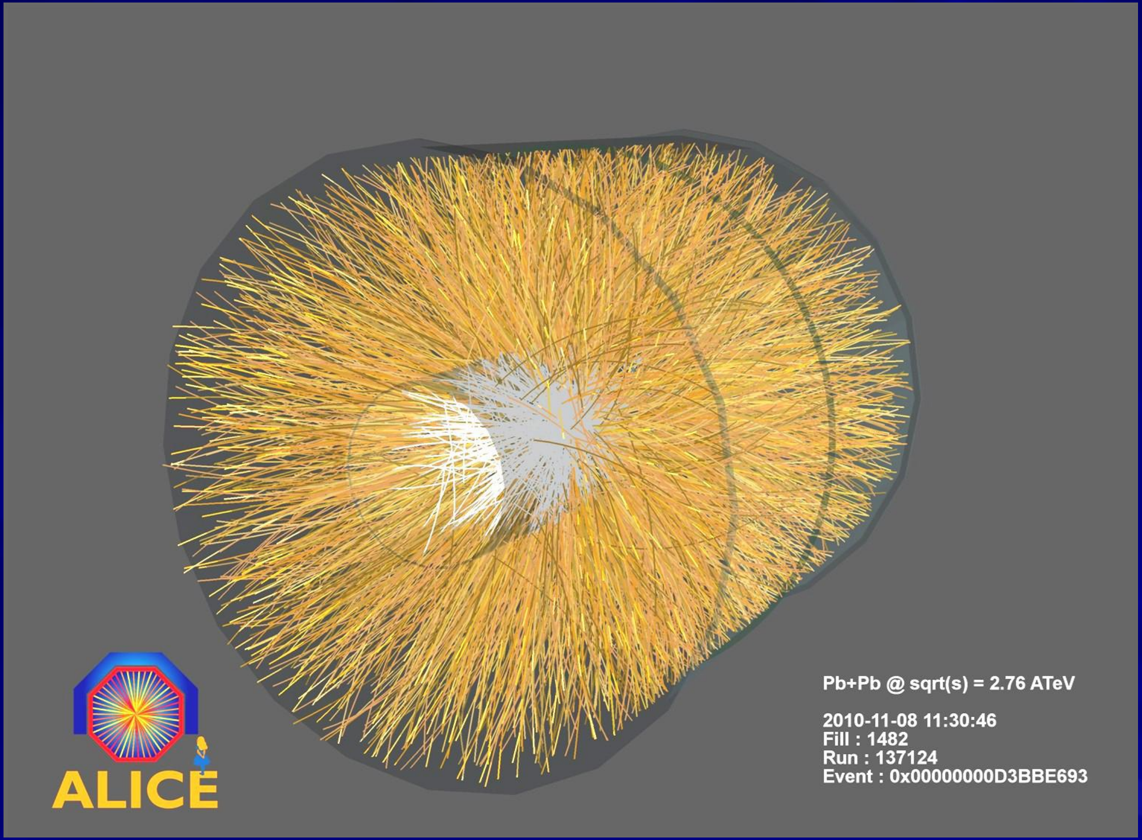
- 570 132 (pads) x 1000 (time bins)
- ~700 MB/event (NO 0-suppression!)
- Pb – Pb ➔ ~20 MB/event (after 0-)
- p-p ➔ < 1MB/event (suppres.)

Gas volume:
95 m^3
Drift gas:
Ne-CO_2 –N_2 (86-9-5)

Lund – 20MSEK worth development and construction to the TPC electronics

GEM upgrade for 2019 approved by LHCC

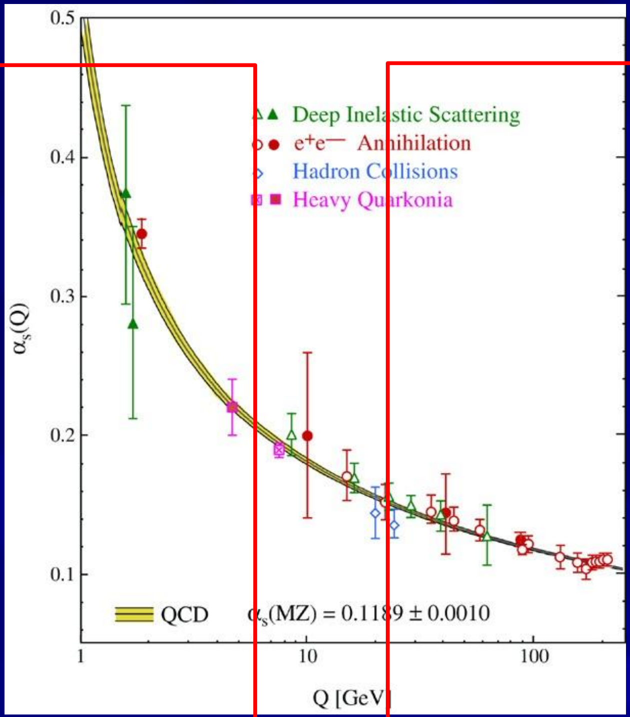
One collision in the ALICE TPC



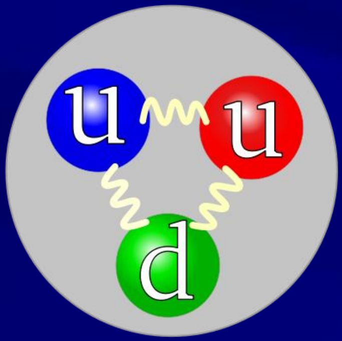
- ALICE first PbPb collisions: 8/11-2010
- Factor 14 jump in energy!

What happens when we collide pp and Pb-Pb

- 2 answers!

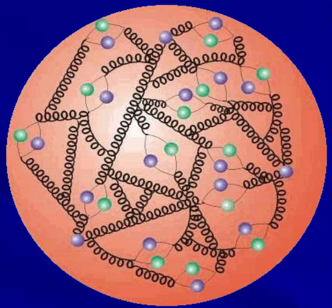


SOFT



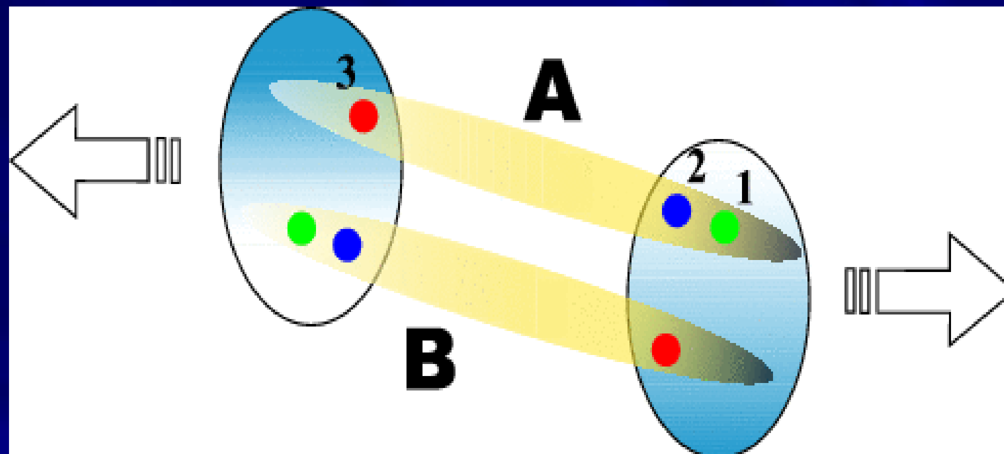
Non-perturbative physics
(know the equations but not how to solve them)
Bulk properties (=medium)

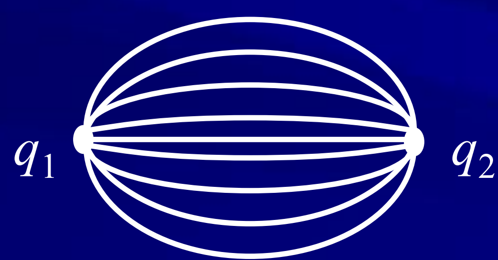
HARD



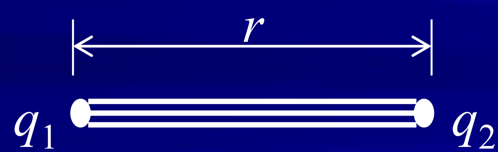
Perturbative physics
(theoretical predictions)
Rare processes
jets (=probes)

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

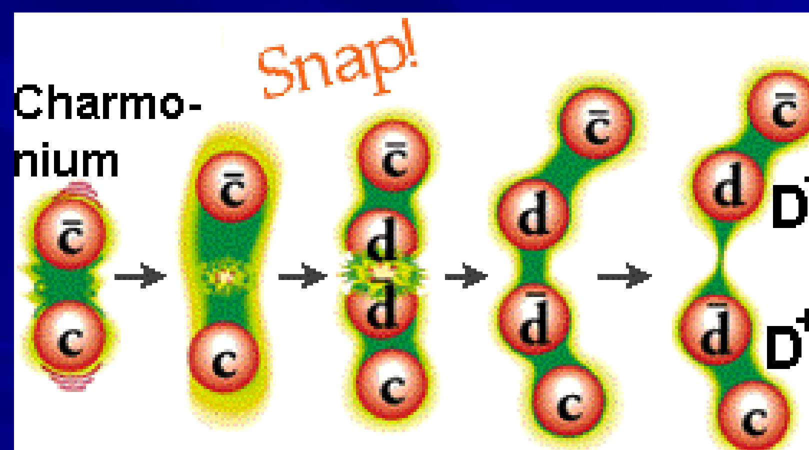




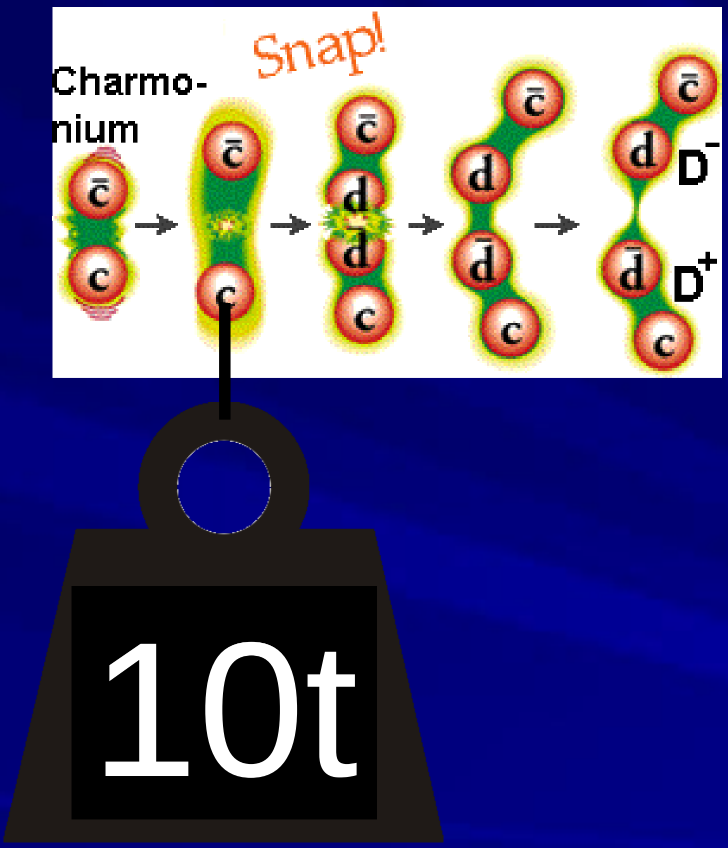
a) QED or QCD ($r < 1$ fm)



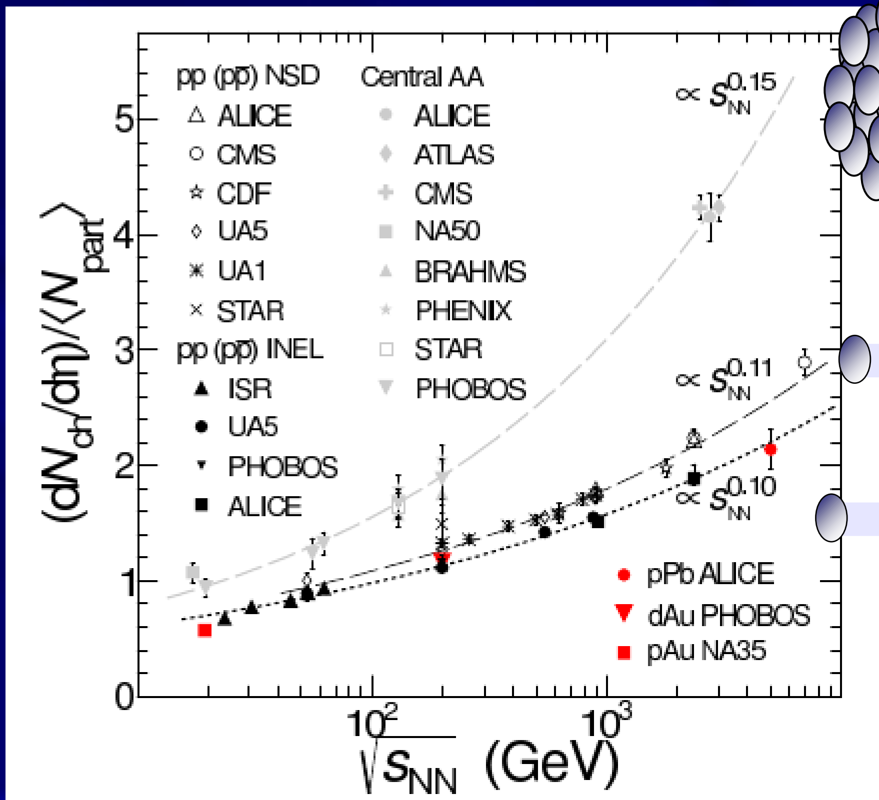
b) QCD ($r > 1$ fm) – constant string-like force ~ 1GeV/fm

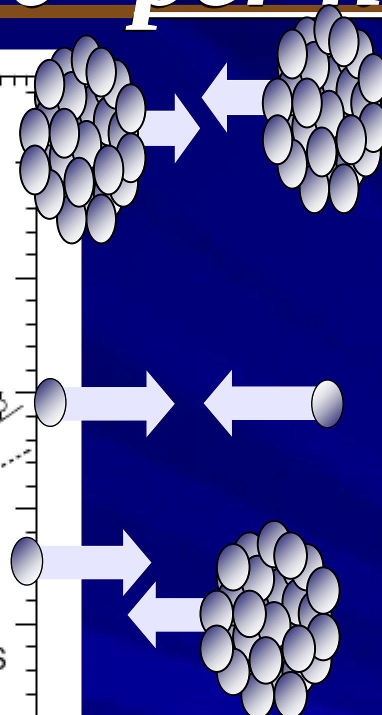


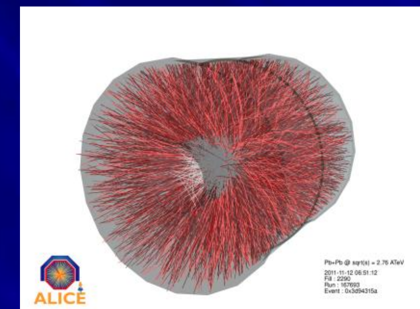
What is 1 GeV/fm for a macroscopic force?

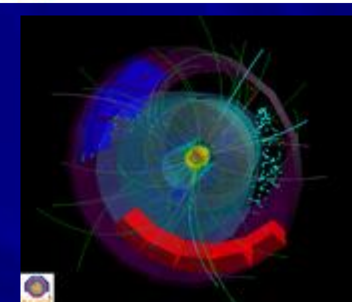


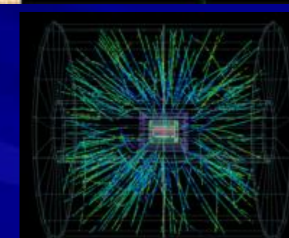
Bulk observables – multiplicity dN/dη at 90º per nucleon







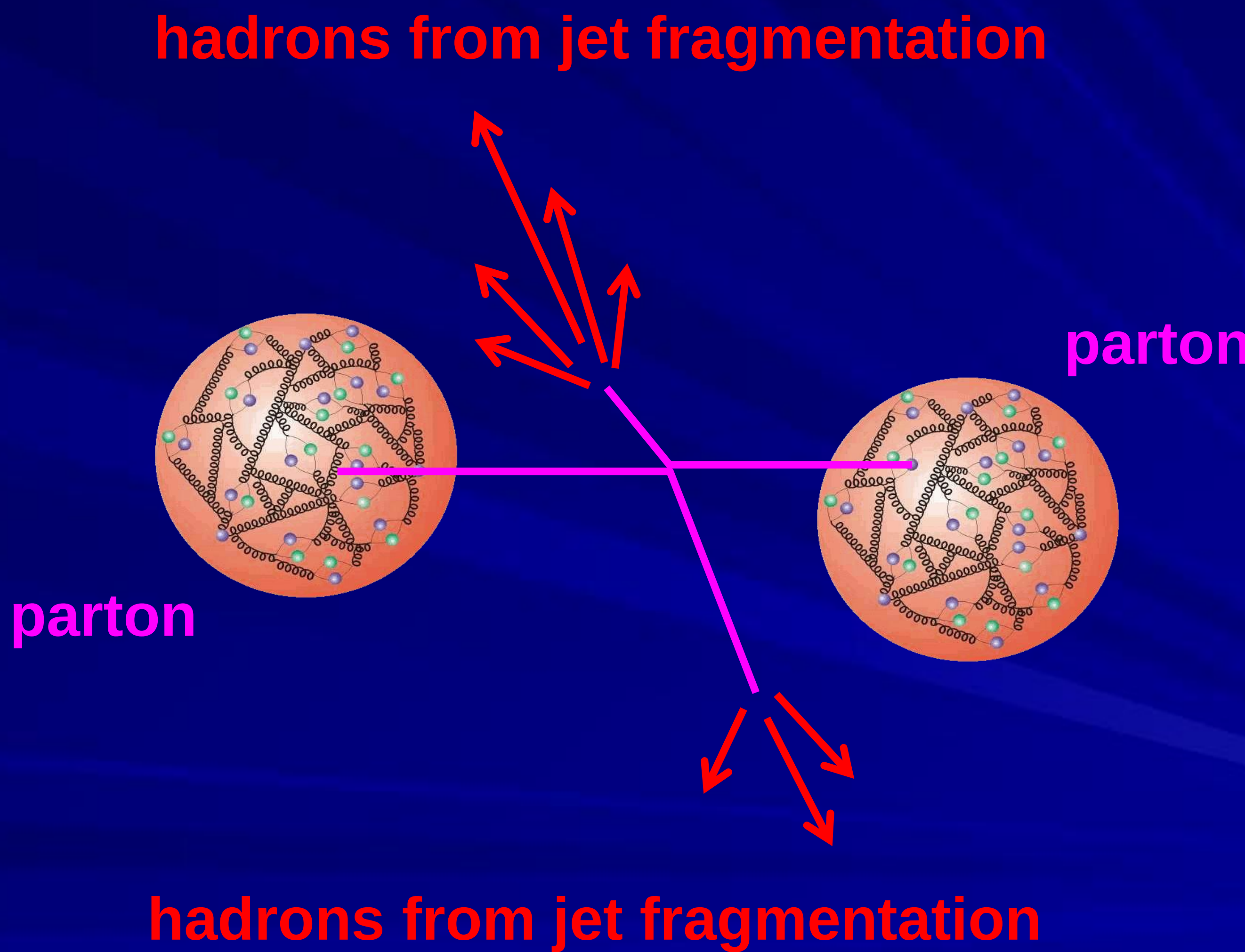




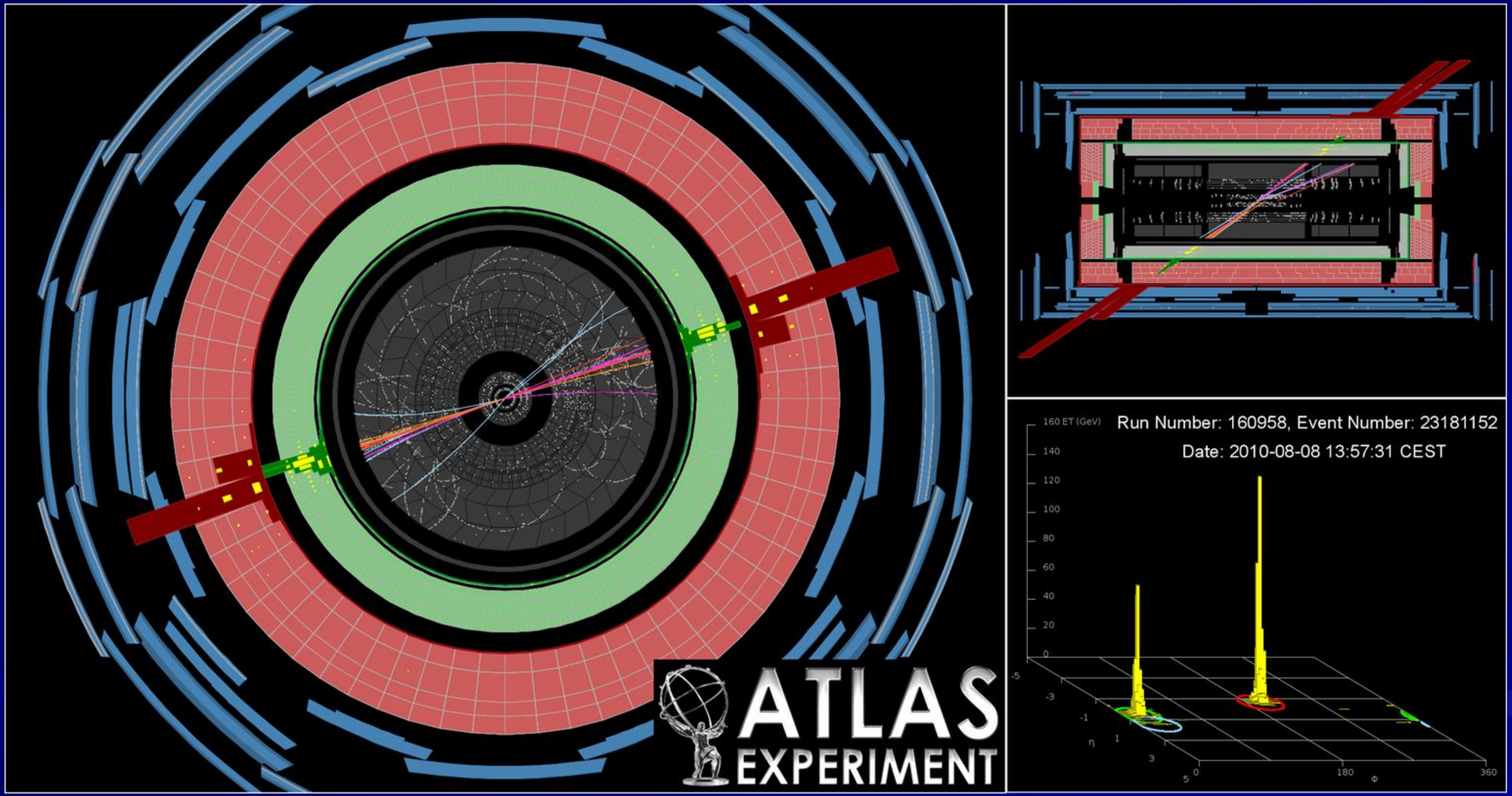
ALICE Collaboration:
Submitted to PRL.
http://arxiv.org/abs/1210.3615

Total integrated number of charged particles: ~17,000 for most central 0-5% collisions

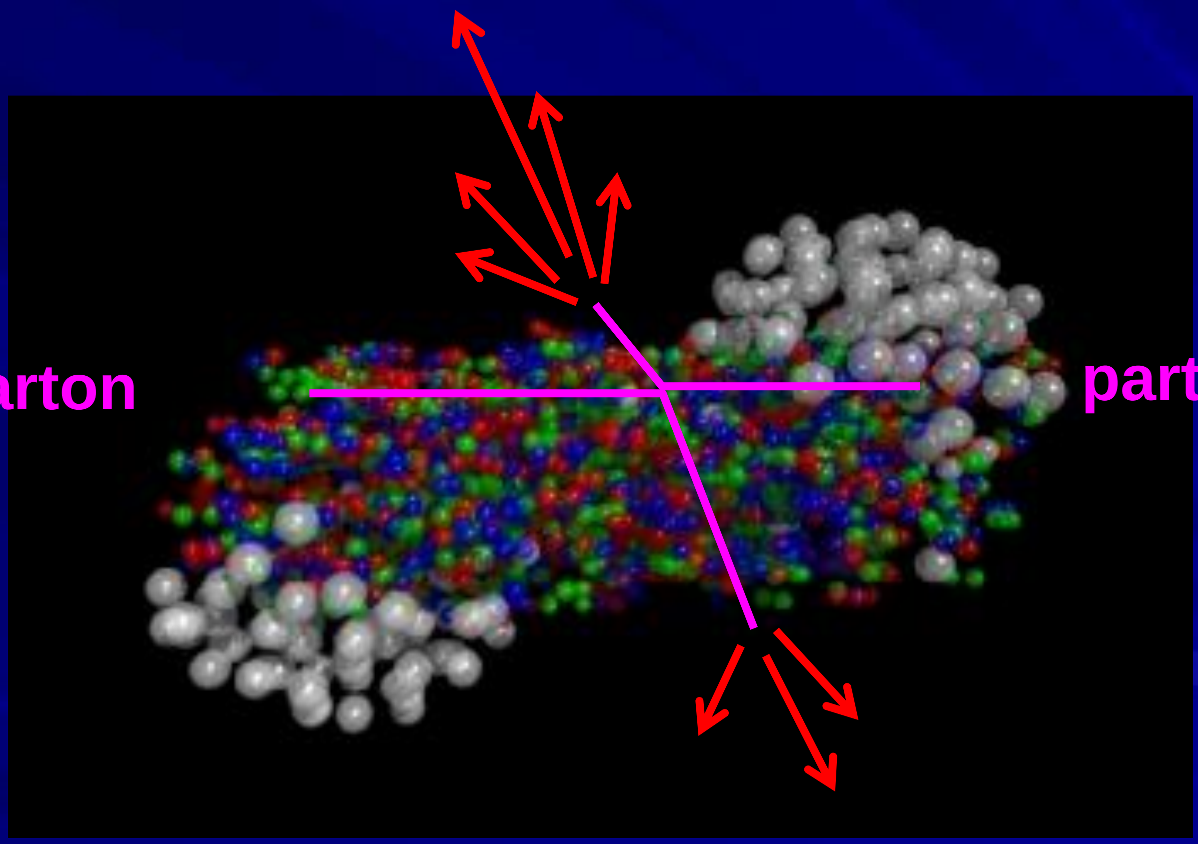
Jets in pp


hadrons from jet fragmentation
parton
parton
hadrons from jet fragmentation

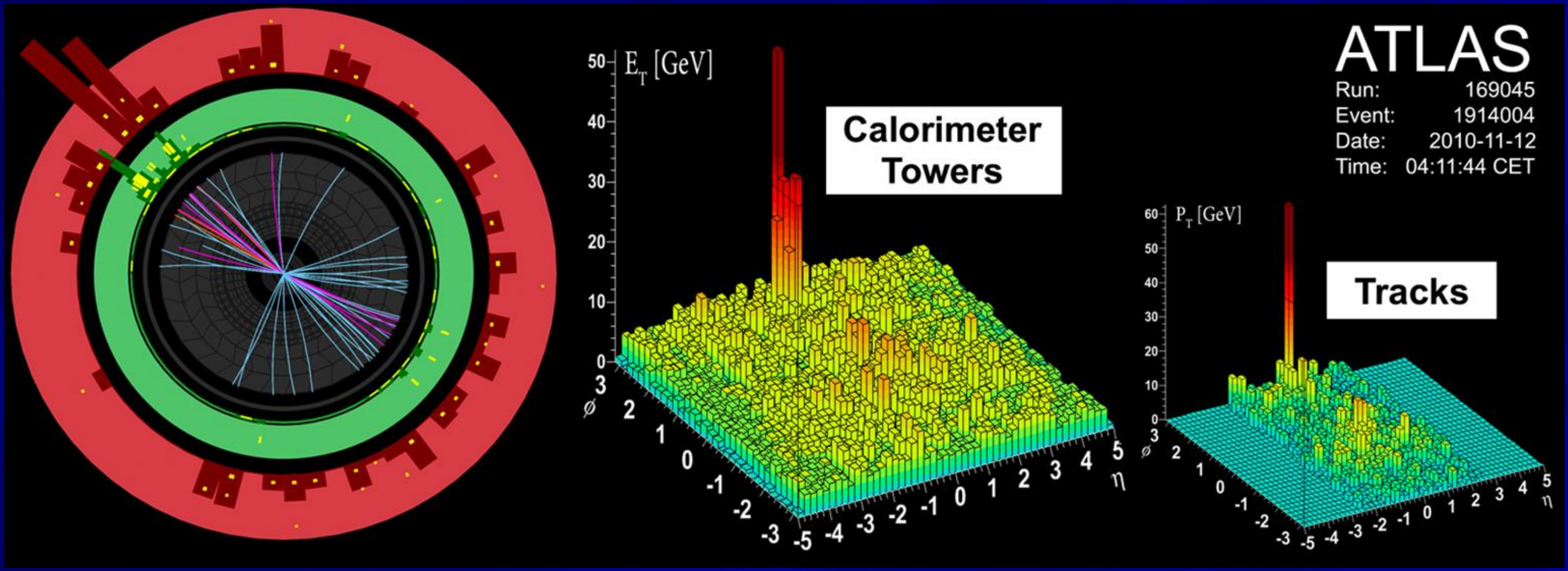
Jets in pp


Run Number: 160958, Event Number: 23181152
Date: 2010-08-08 13:57:31 CEST
ATLAS
EXPERIMENT

Jets in Pb-Pb


hadrons from leading jet
parton
parton
hadrons from quenched jet

Jets in Pb-Pb



- Jet asymmetry – away side jet is absorbed/modified by the medium

The nuclear modification factor R_{AA} for unidentified hadrons

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}/dp_T d\eta}$$

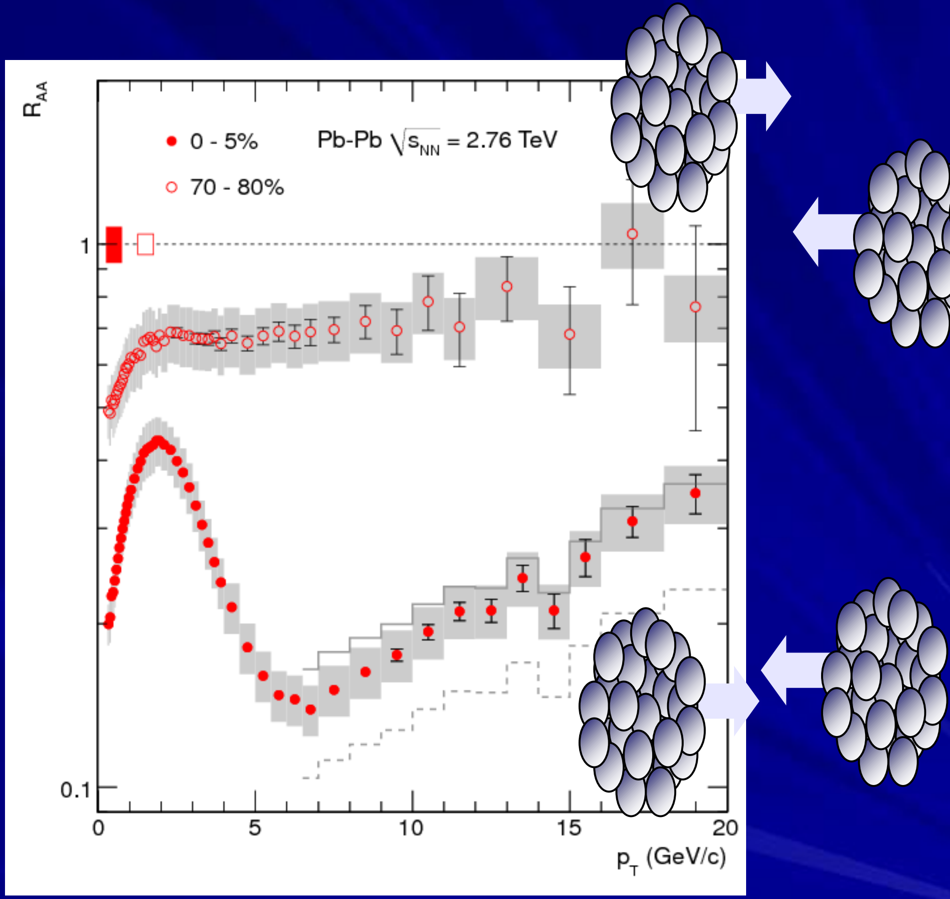
$\langle T_{AA}\rangle\sigma^{pp} = \langle N_{coll}\rangle$

N_{coll} is the number of binary collisions

$R_{AA}<1$: suppresion

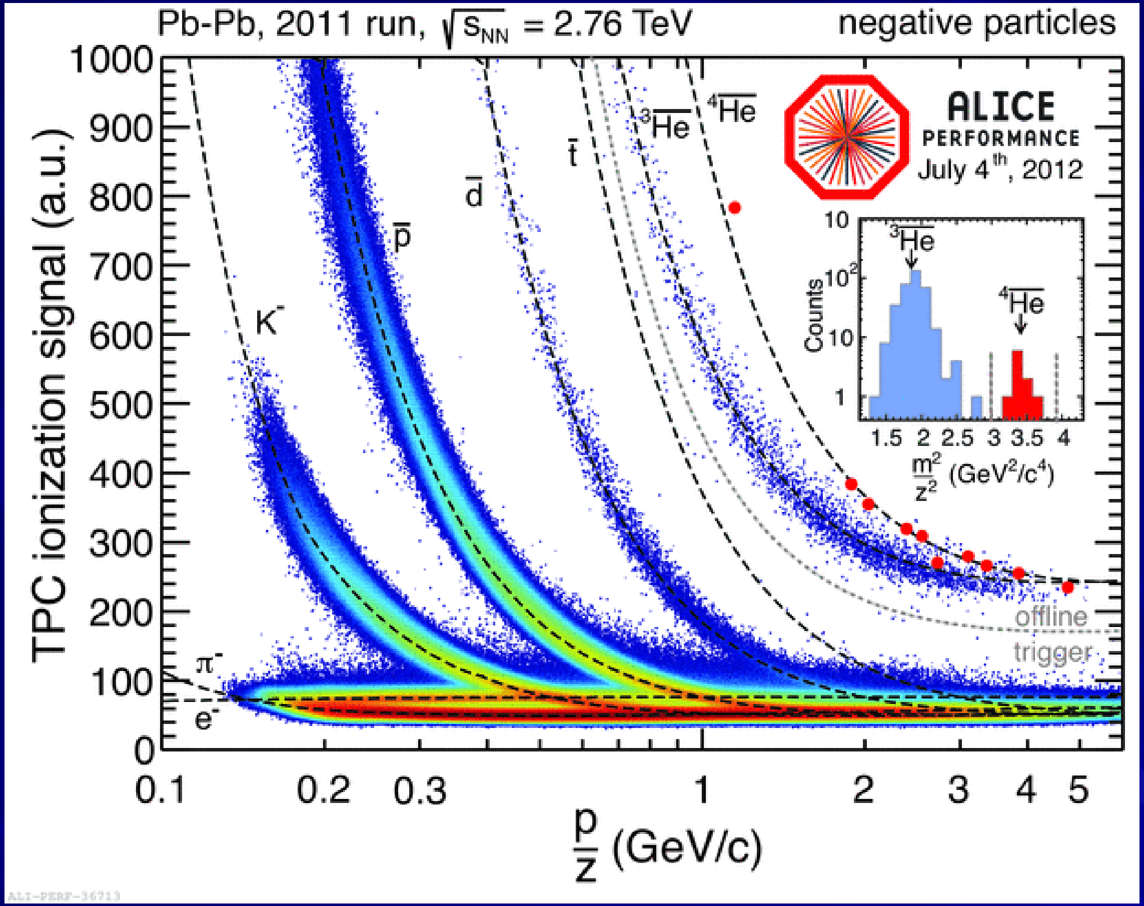
$R_{AA}=1$: no nuclear effects

$R_{AA}>1$: enhancement



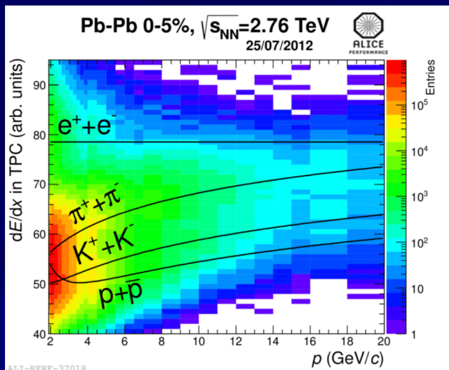
- Jet quenching on the track level
  - 65-85% less high p_T tracks than expected from binary scaling

R_{AA} for identified charged hadrons

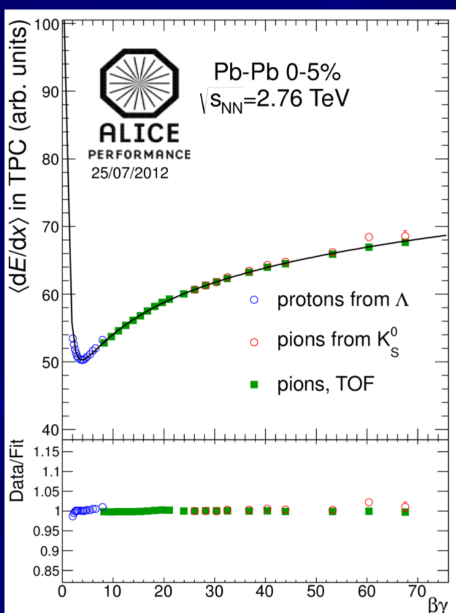


- Use the additional information for each track encoded in the TPC dE/dx ("Bethe-Bloch")

R_{AA} for identified charged hadrons (Lund)



Pushing the separation to the relativistic rise



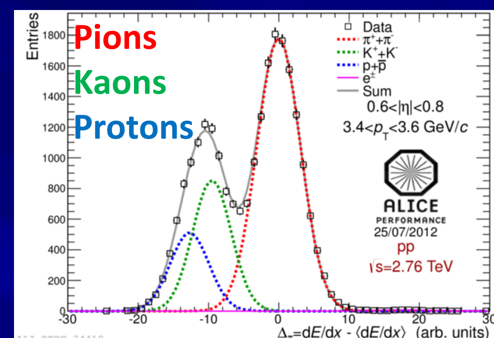
Baryon anomaly in central PbPb. Quark recombination?

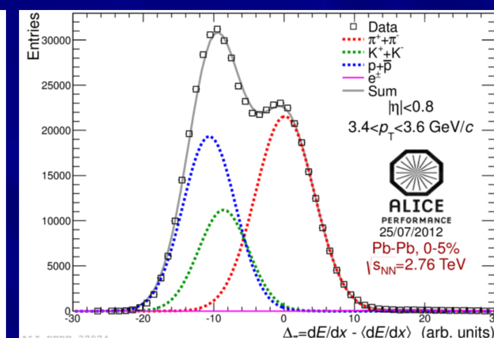
p_T

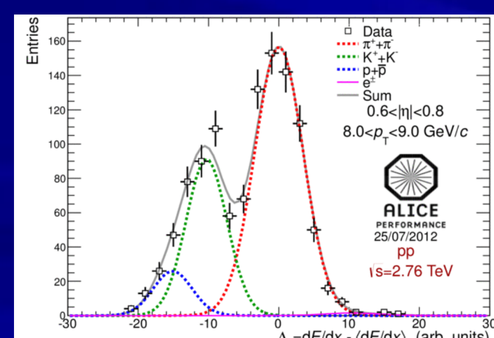
Baryon anomaly not observed at high p_T as speculated pre-LHC.

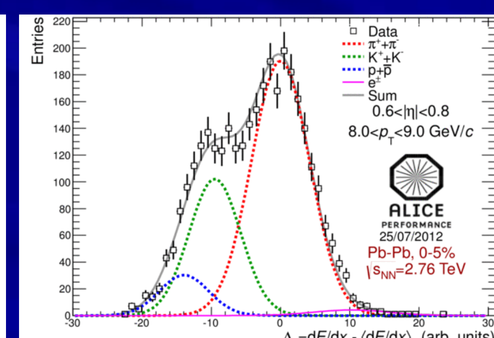
pp

central PbPb

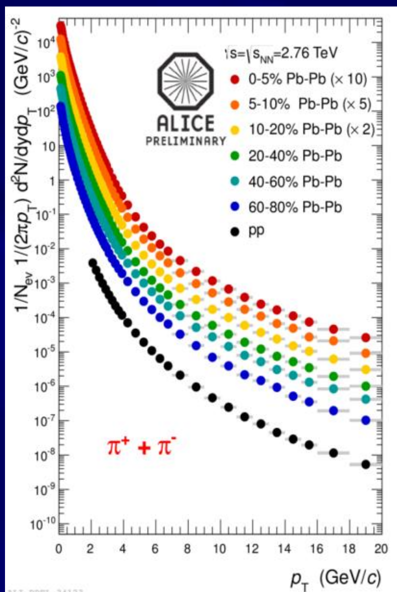


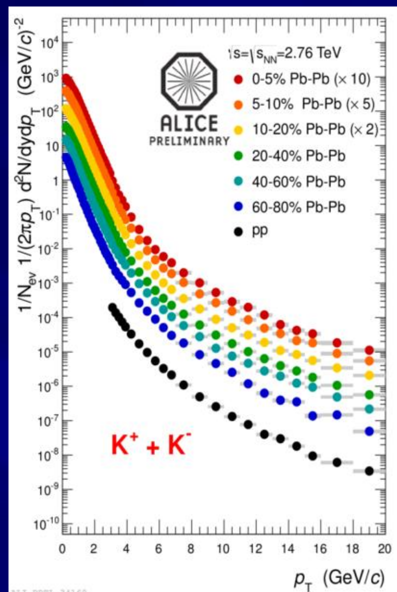


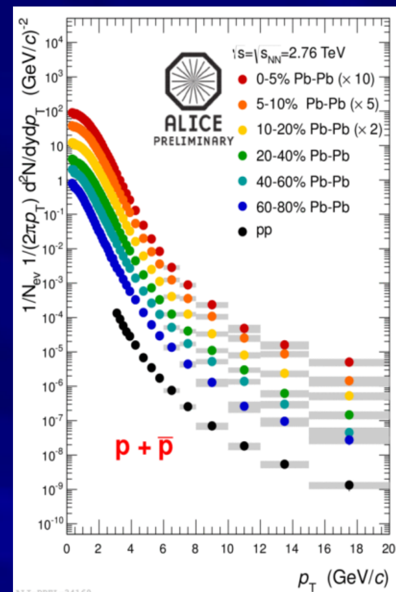


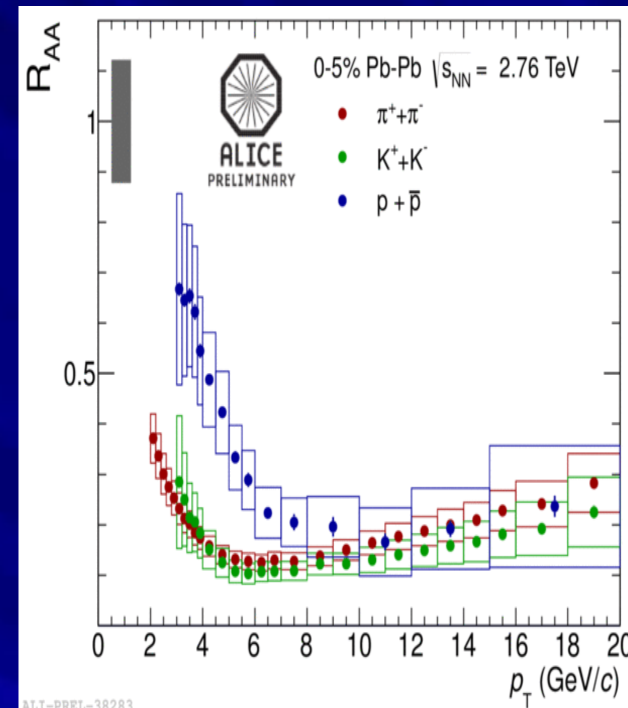


R_{AA} identified hadrons







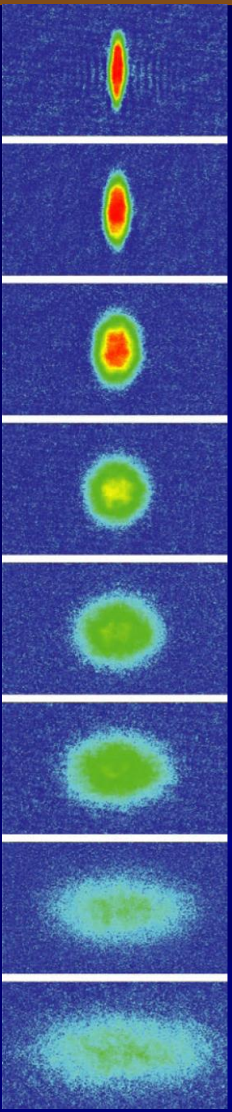


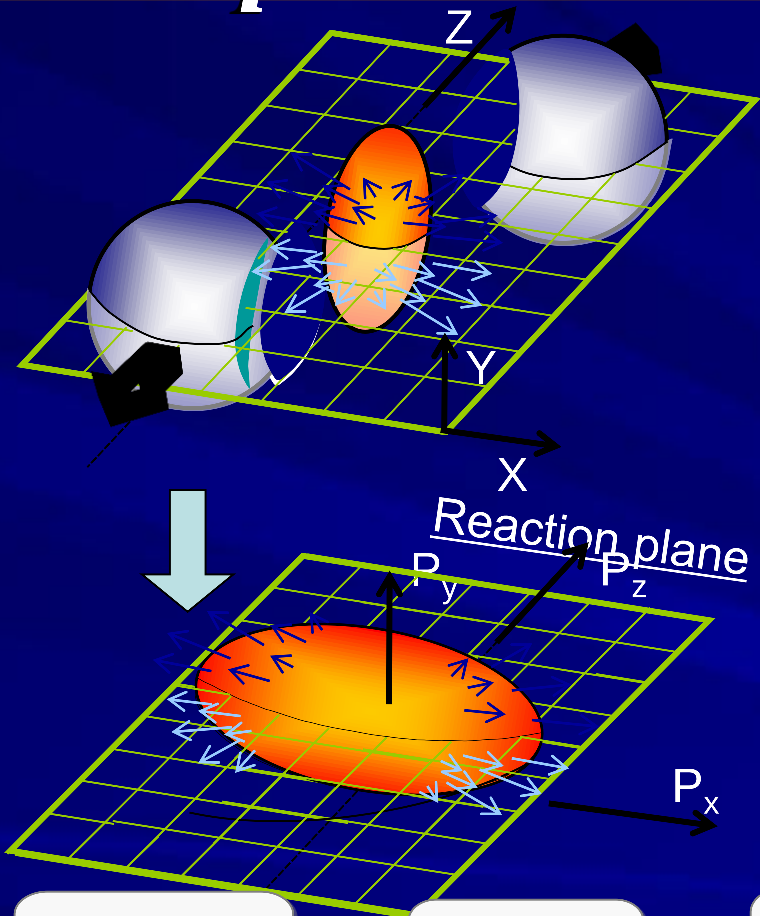
- Identified spectra from 2-3 < p_T < 20 GeV/c from Lund analysis. First time presented by Antonio Ortiz Velasquez (Lund) at Quark Matter 2012, August 12-18, Washington.
- Extends ALICE unique PID capabilities to the hard regime

What is the medium formed in the collisions?

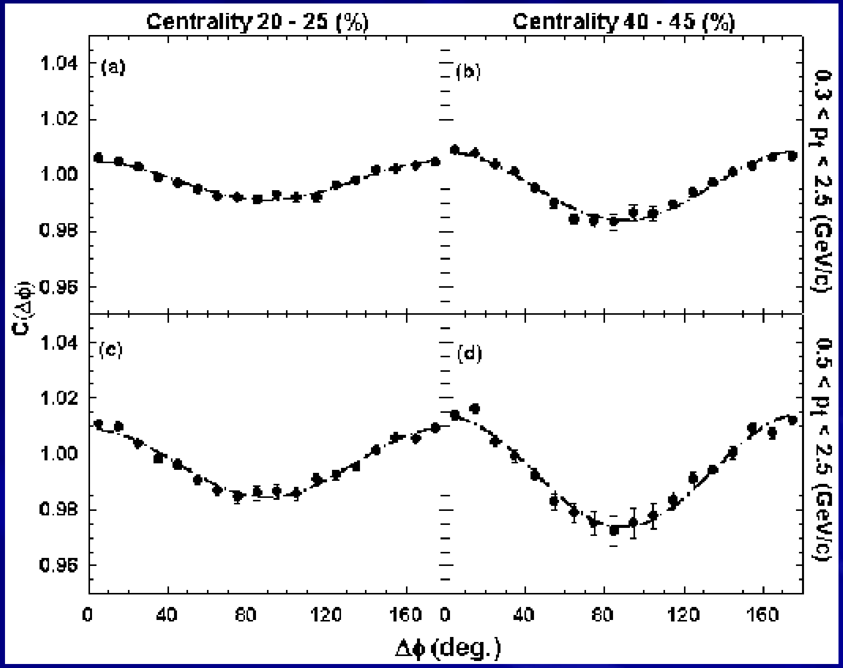
- To talk about temperature we need to establish that a medium is formed e.g. collective effect = communication
- Jet quenching still not well understood theoretically
  – Need that to extract properties

Elliptic flow (v2) unique in heavy ion collisions



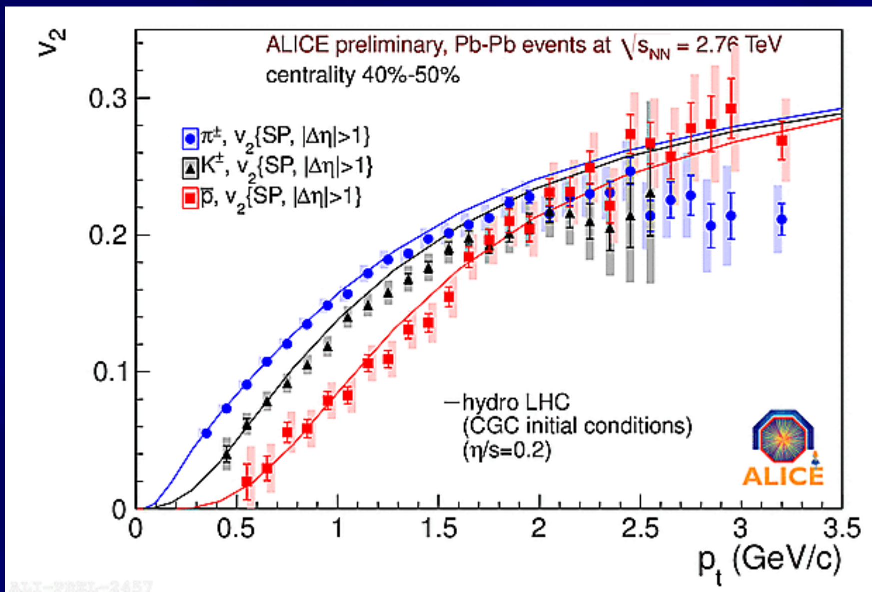


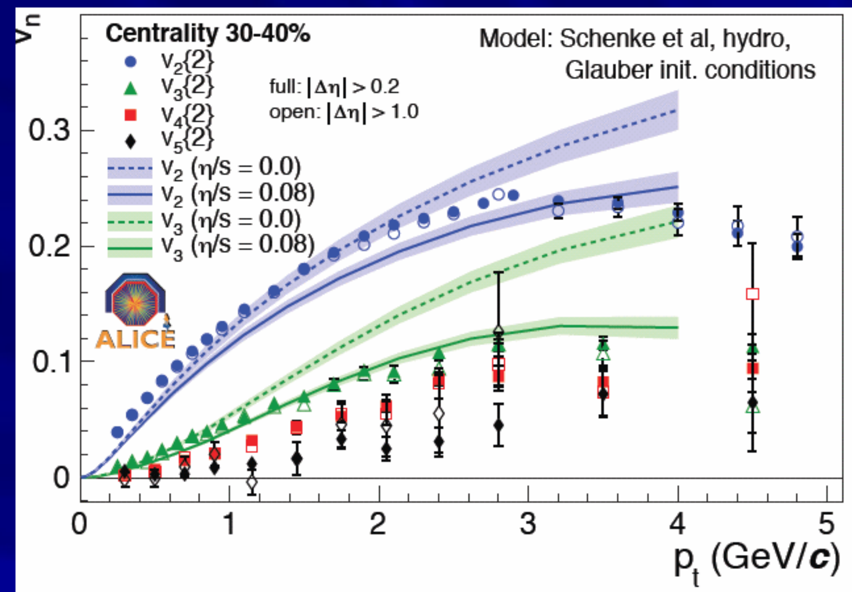
Fourier decomposition:
$dN/d\phi = 1 + 2\ V_2\cos(2\ \Delta\phi\ )$



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

Elliptic flow and triangular flow is almost ideal

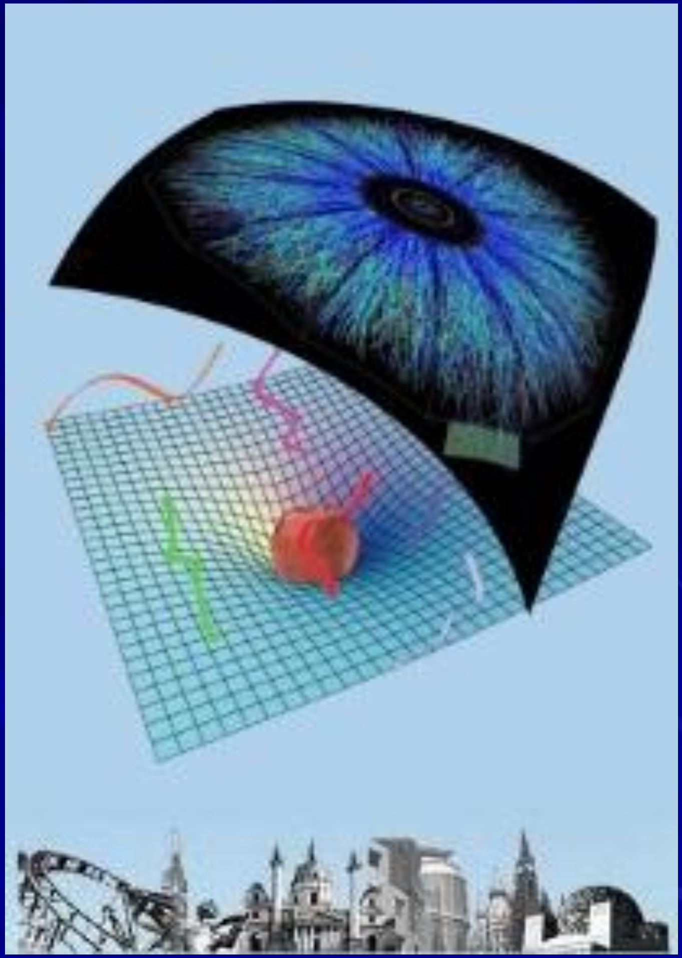




- Huge flow at intermediate pT:
  - 2 times more particles in plane than out
  - Nearly ideal fluid
- Significant higher order flow caused by fluctuations – also described by nearly ideal hydro + initial state

AdS-CFT

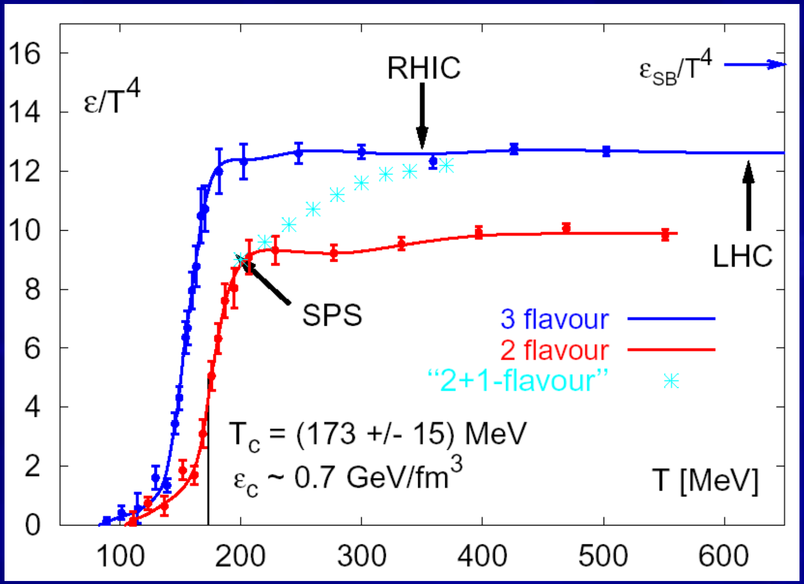
- How to reconcile nearly ideal fluid with energy density like a relativistic gas?
- AdS-CFT correspondence (conjecture)
  - J.M. Maldacena, Adv.Theor.Math.Phys.2:231-252, 1998, 8595 citations on inspire=most cited
- Duality between ***weakly*** coupled gravity like theory (AdS) and ***strongly*** coupled QCD like theory (CFT)
- QCD like theory, but
  - conformal (no confinement, no running coupling)
  - infinite Ncolors
  - SUSY



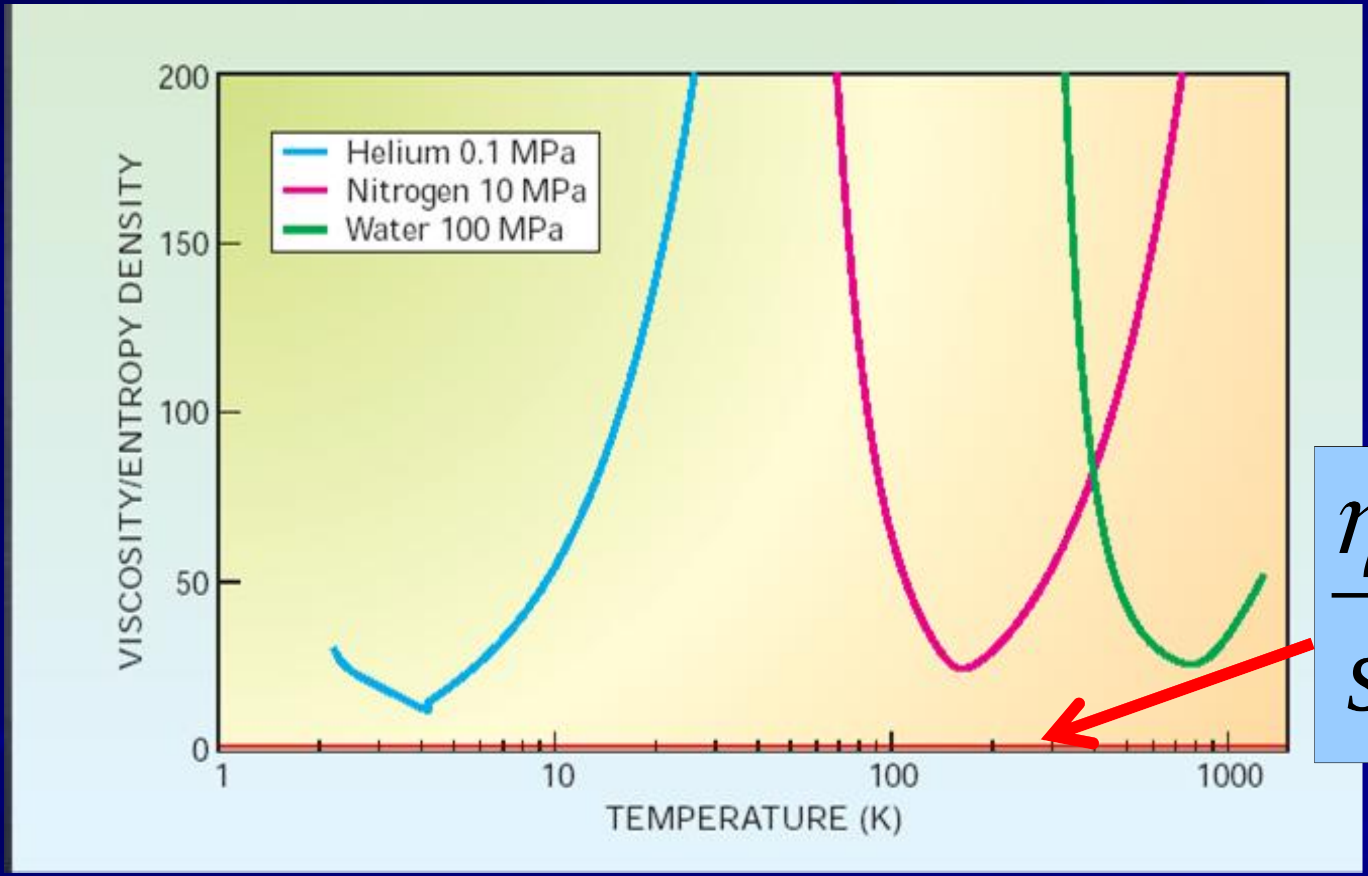
From: http://quark.itp.tuwien.ac.at/~ads/

AdS-CFT

- Two very important results:
  - Conjectured bound on shear viscosity: $\eta/s \geq 1/(4\pi) \sim 0.08$
    - **Viscosity in strongly interacting quantum field theories from black hole physics, P. Kovtun, D.T. Son, A.O. Starinets (Washington U., Seattle), Phys.Rev.Lett. 94 (2005) 111601. (989 citations on inspire.)**
  - Possibility of infinitely strong coupling at energy density of ¾ SB gas



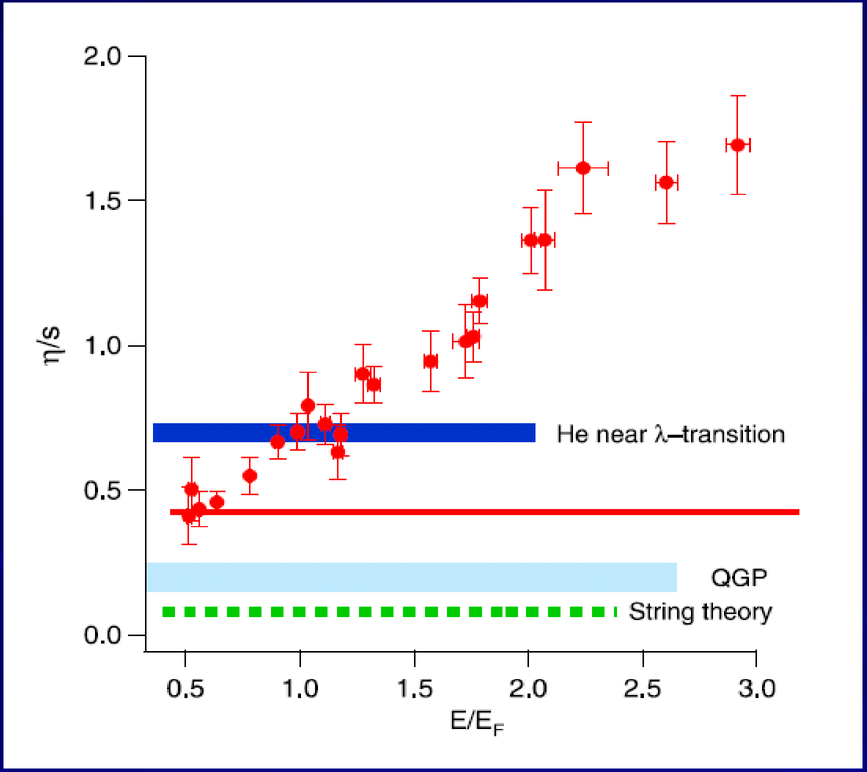
The QGP fluid compared to other fluids

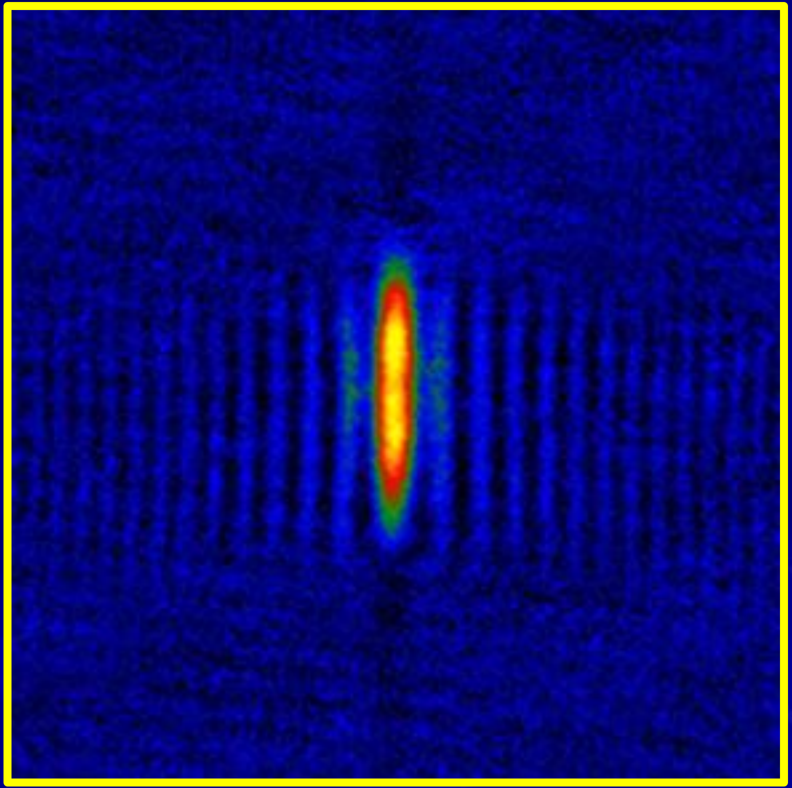


$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi}\frac{1}{k_\mathbf{B}}$$

The QGP fluid compared to other fluids

Strongly interacting Li atoms released from a trap





$\eta/s \sim 7 \times 1/4\pi$

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

The QGP fluid compared to other fluids

PRL 103, 025301 (2009)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
10 JULY 2009

Graphene: A Nearly Perfect Fluid

Markus Müller,[1] Jörg Schmalian,[2] and Lars Fritz[3]

[1]*The Abdus Salam International Center for Theoretical Physics, Strada Costiera 11, 34014 Trieste, Italy*
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(Received 24 March 2009; revised manuscript received 18 May 2009; published 6 July 2009)

Hydrodynamics and collision-dominated transport are crucial to understand the slow dynamics of many correlated quantum liquids. The ratio η/s of the shear viscosity η to the entropy density s is uniquely suited to determine how strongly the excitations in a quantum fluid interact. We determine η/s in clean undoped graphene using a quantum kinetic theory. As a result of the quantum criticality of this system the ratio is smaller than in many other correlated quantum liquids and, interestingly, comes close to a lower bound conjectured in the context of the quark gluon plasma. We discuss possible consequences of the low viscosity, including preturbulent current flow.

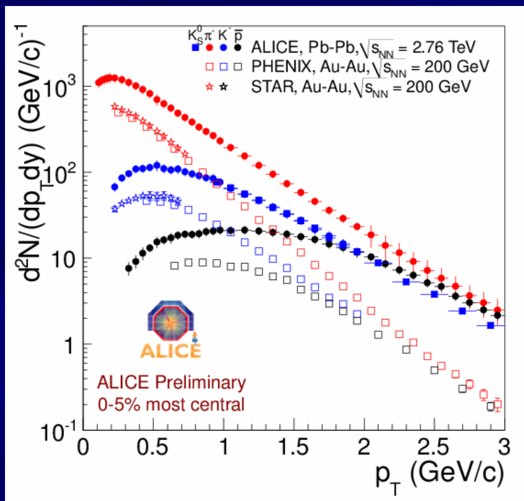
DOI: 10.1103/PhysRevLett.103.025301 PACS numbers: 05.60.Gg, 71.10.−w, 73.23.−b, 81.05.Uw

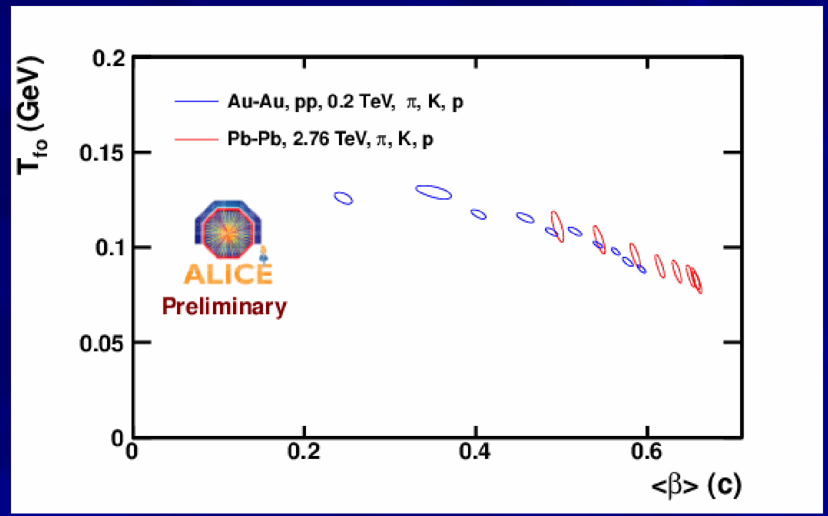
The QGP is less like a crowd and more like a synchro team

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

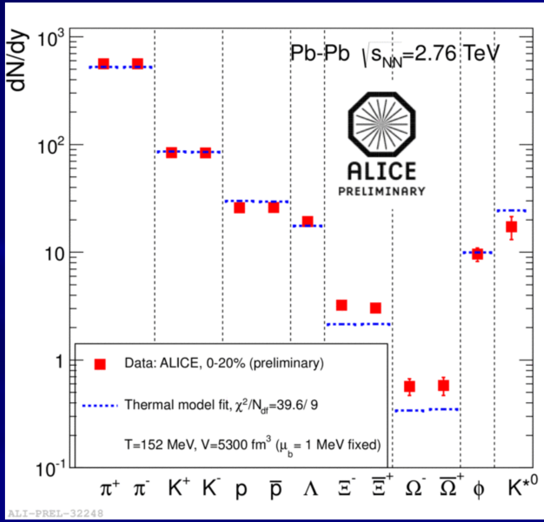
How hot is the medium?

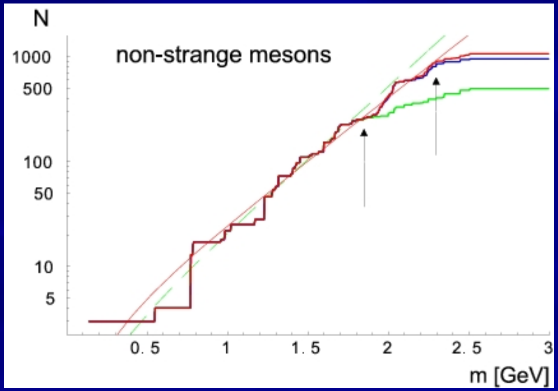
Temperature at freeze-out





Results from blast wave analysis.
RHIC analysis from STAR Nuclear Physics A 757 (2005) .

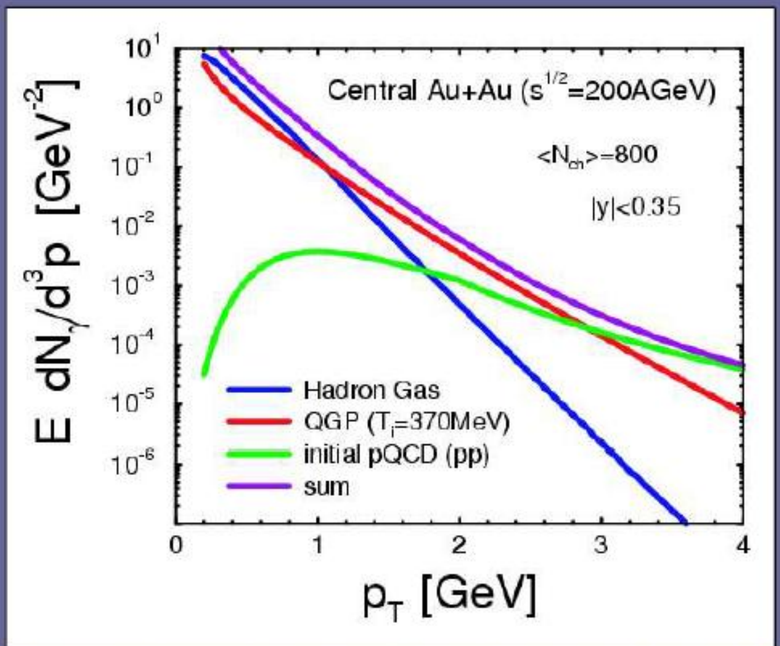




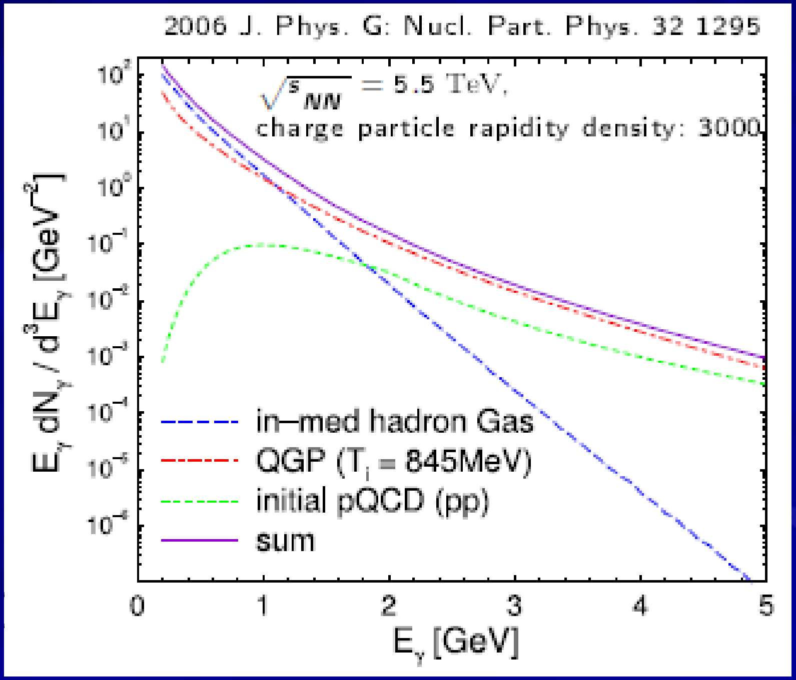
1. Generate hadrons with weights: $\exp(-(m+\mu_B)/T)$
2. Decay strongly
3. Compare to data

How to measure T at earlier times

- Need a probe that does not freezeout at the end of the collision
  - Direct photons (photons that are not from decays which is the major background)

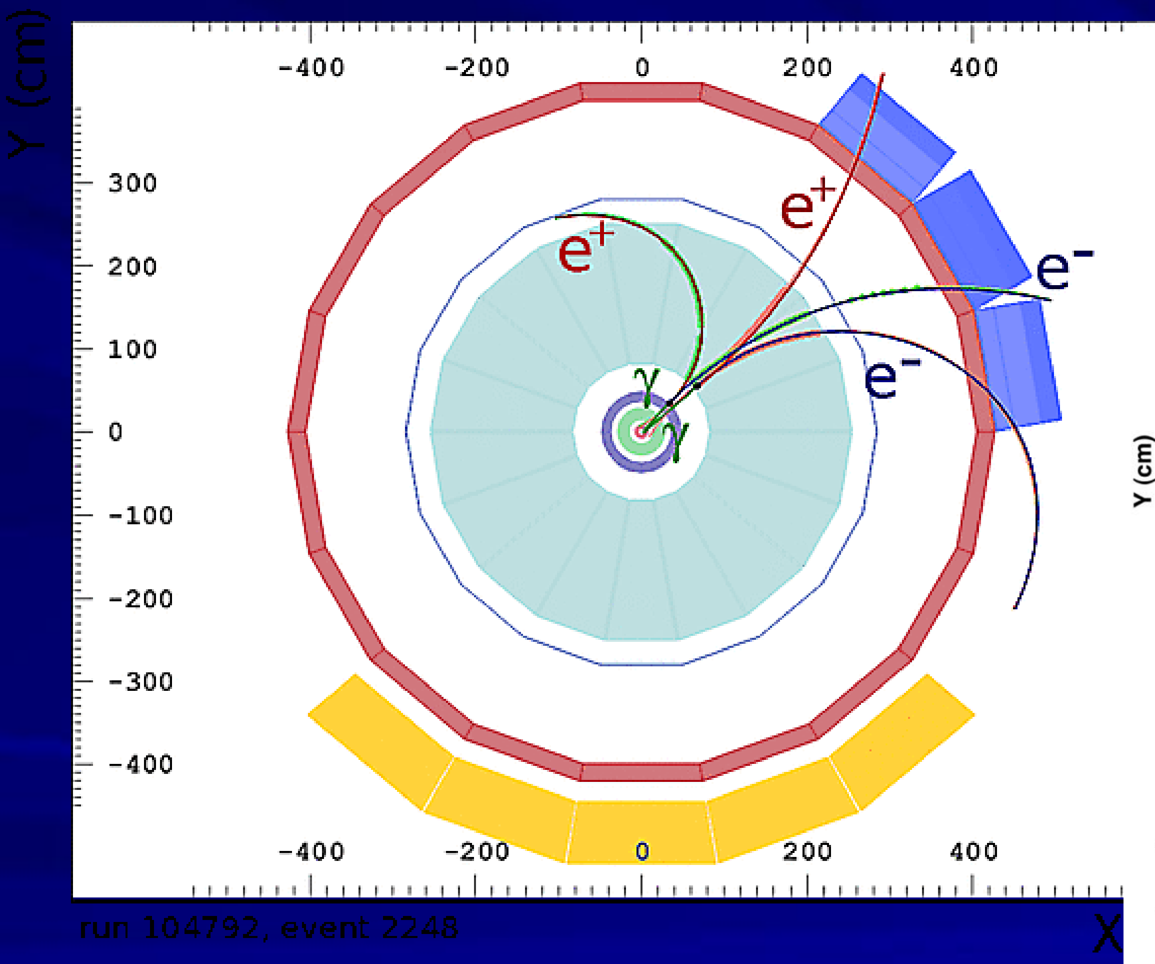


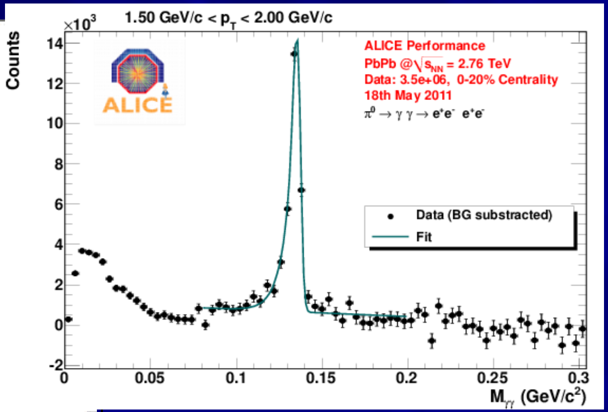
Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

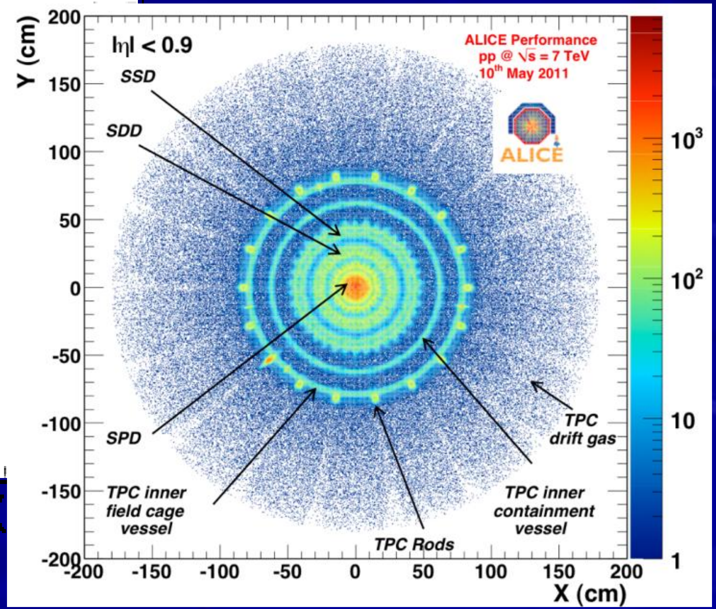


Photon identification in the TPC via conversion

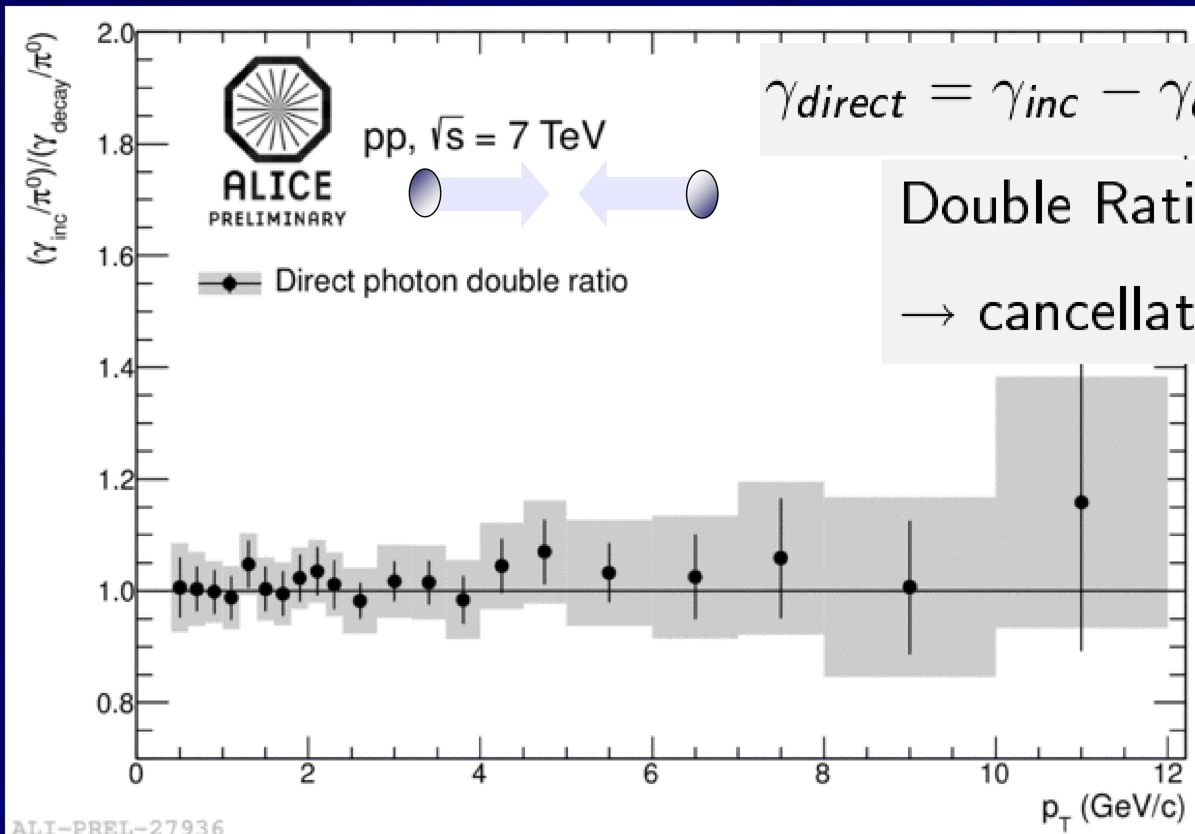
$\pi^0 \rightarrow 2\gamma$ converts to $2*(e^- + e^+)$ = background for signal







Direct photons in pp



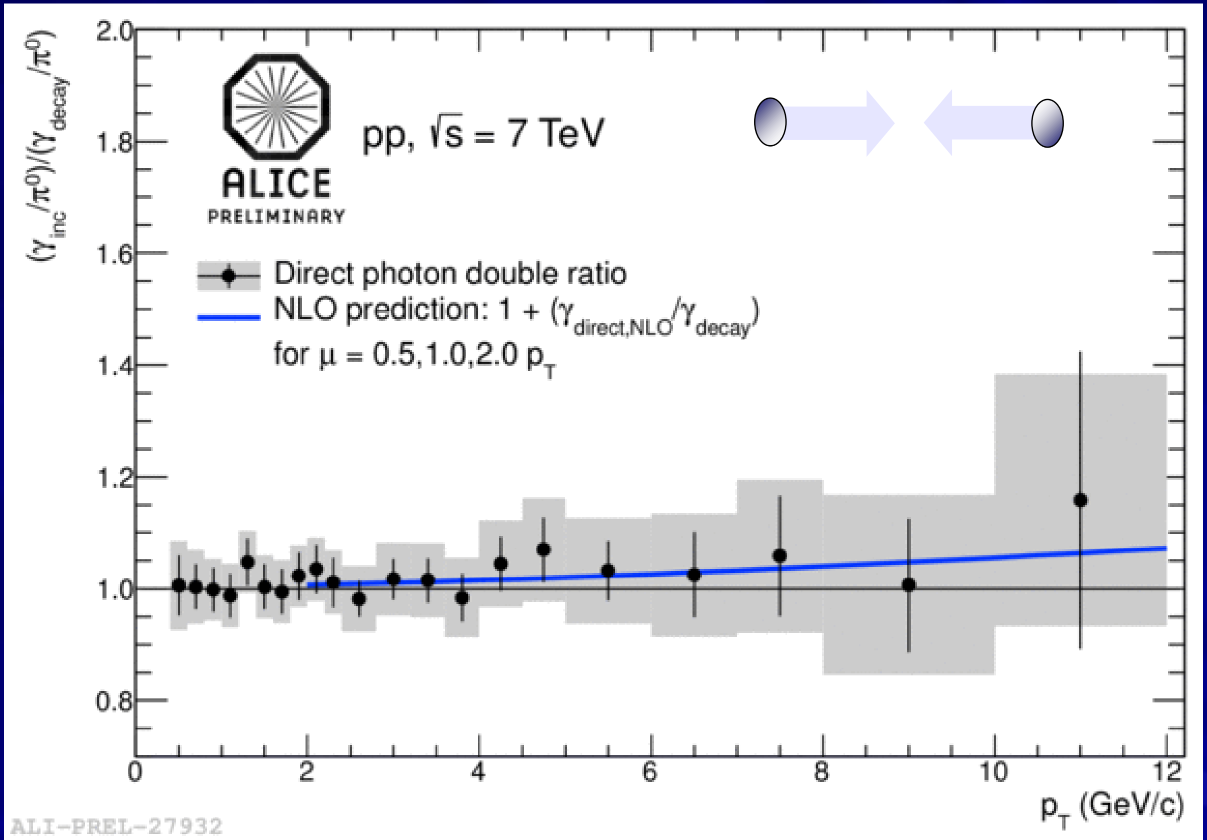
$$\gamma_{direct} = \gamma_{inc} - \gamma_{decay} = \left(1 - \frac{\gamma_{decay}}{\gamma_{inc}}\right) \cdot \gamma_{inc}$$

Double Ratio: $\frac{\gamma_{inc}}{\pi^0} / \frac{\gamma_{decay}}{\pi^0_{param}} \approx \frac{\gamma_{inc}}{\gamma_{decay}}$

$\rightarrow$ cancellation of uncertainties

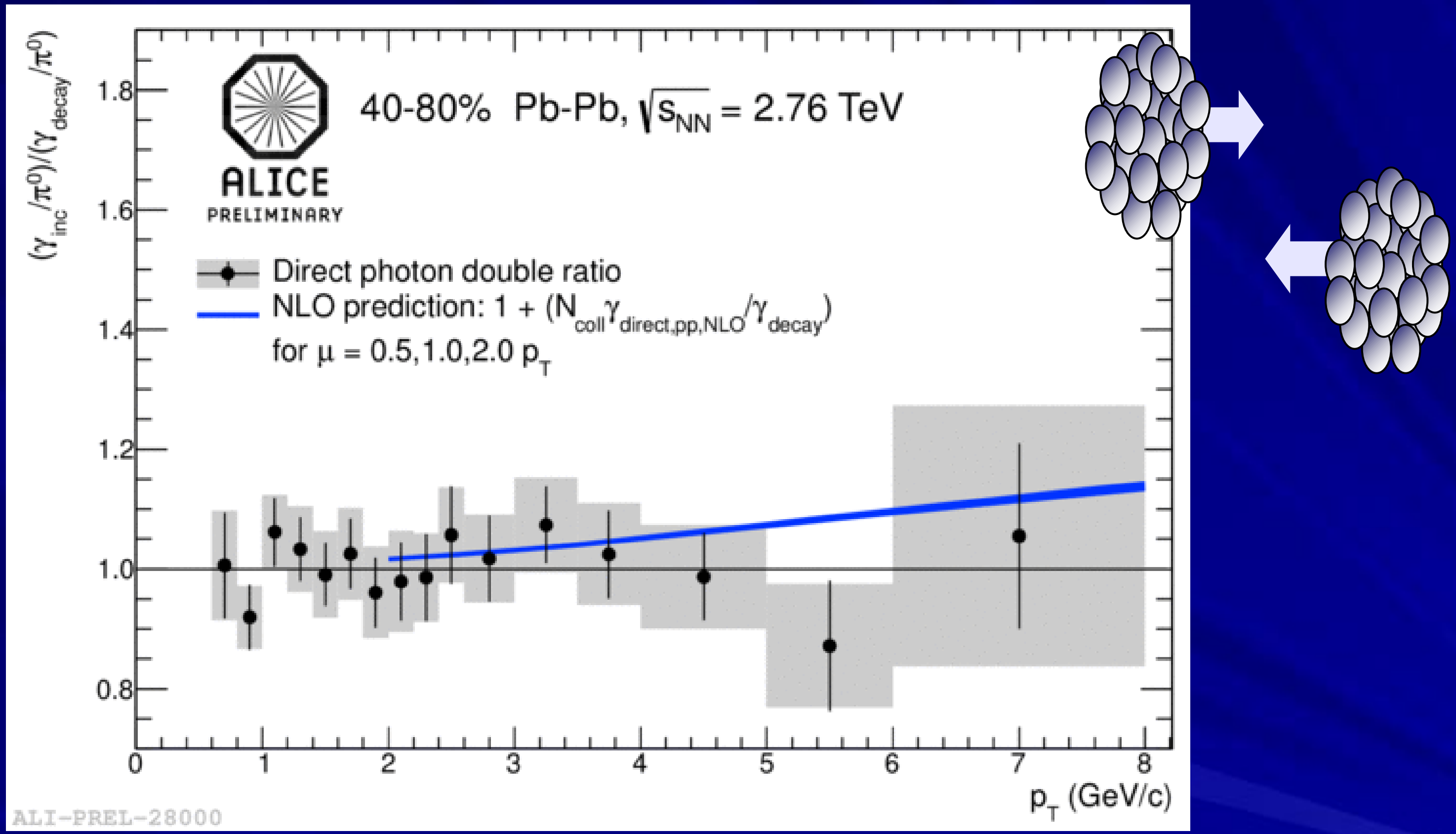
- Construct double ratio to elliminate/reduce systematics
- Numerator is the actual measurement
- Denominator is from a cocktail calculation

Direct photons in pp



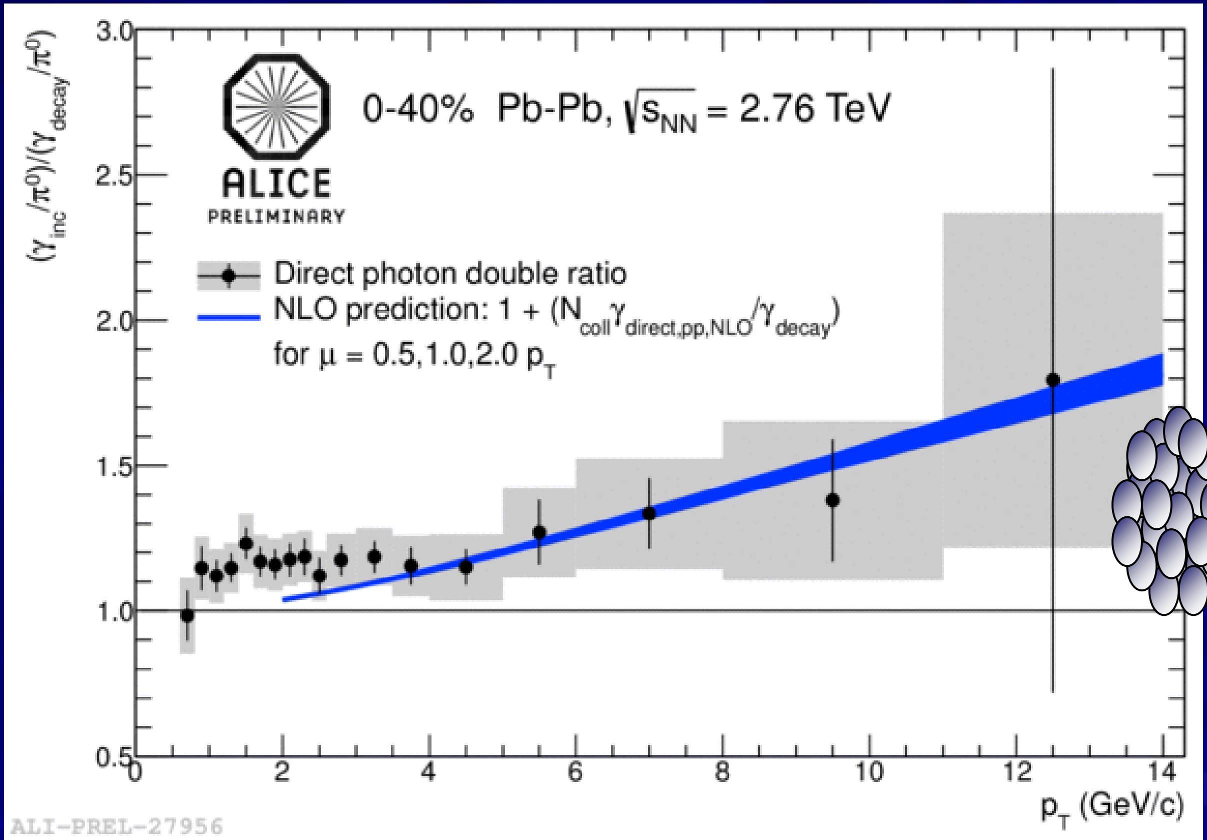
- Comparison to pQCD NLO calculation

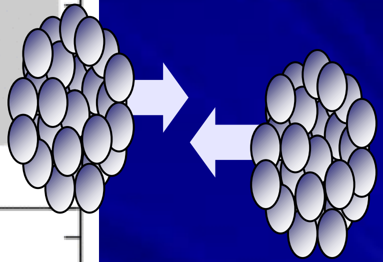
Direct photons in peripheral Pb-Pb



- Peripheral Pb-Pb
  - Consistent with only direct and decay photons

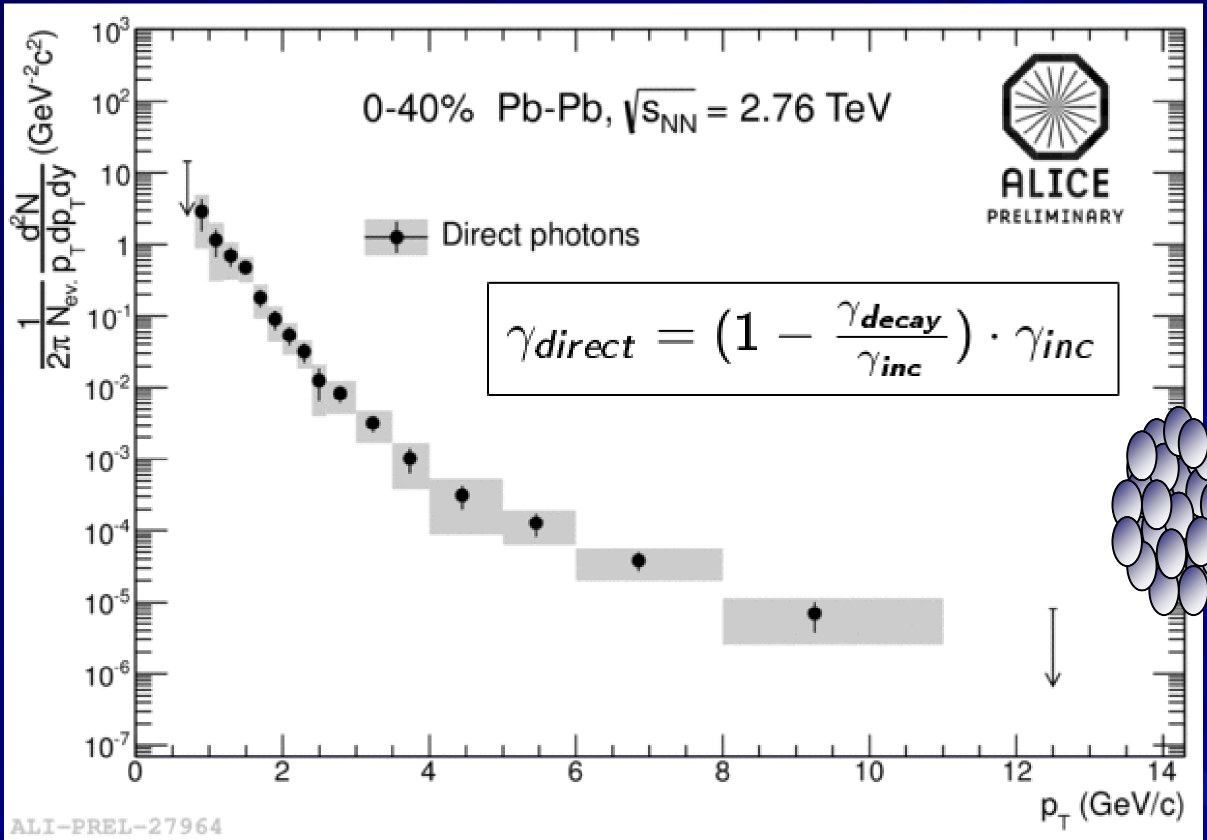
Direct photons in central Pb-Pb

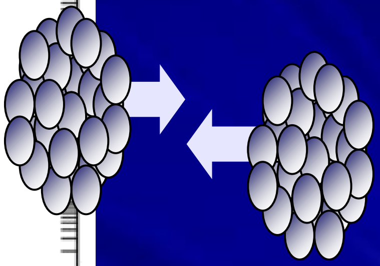




- Central Pb-Pb
  - p_T < 2 GeV/c: ~20% excess of direct photons
  - p_T > 4 GeV/c: agreement with N_{coll}-scaled NLO

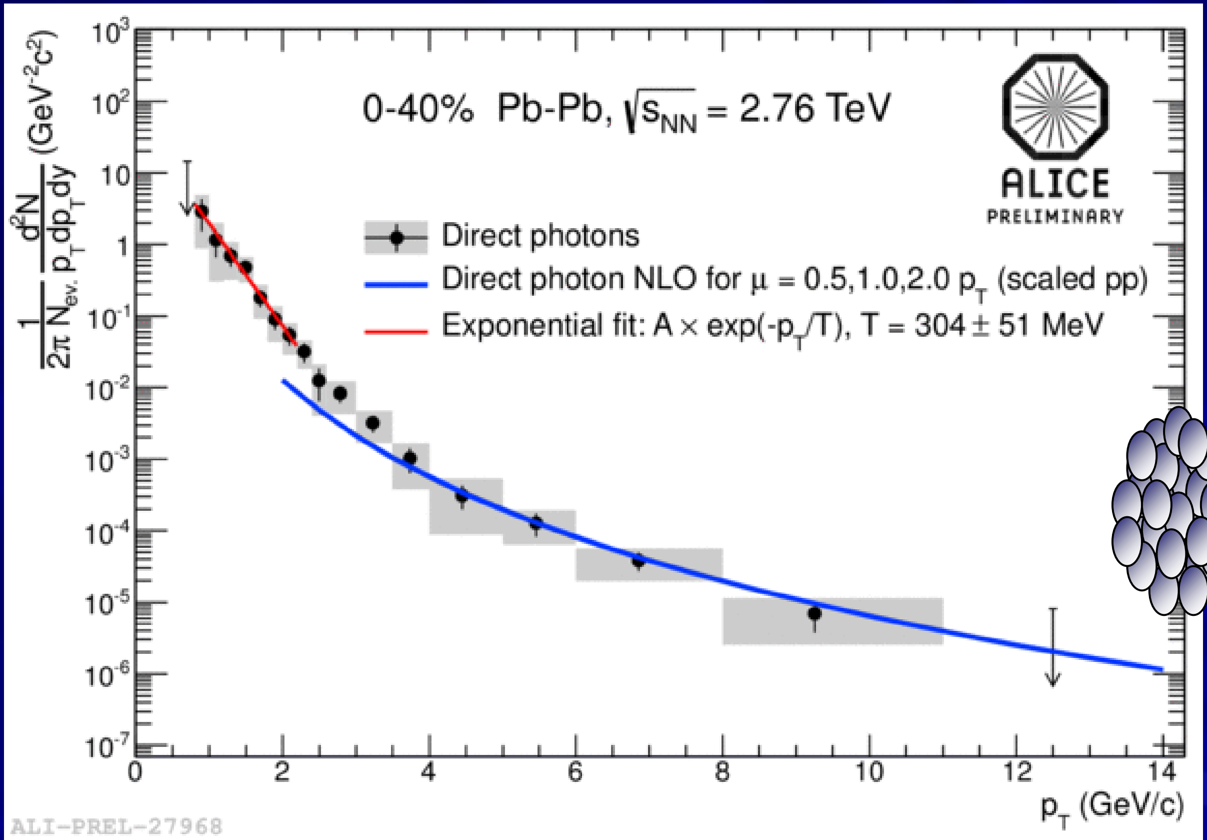
Direct photon spectrum in central Pb-Pb

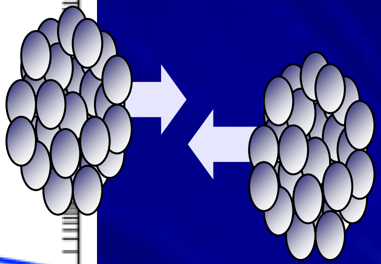




- Obtain spectrum by scaling

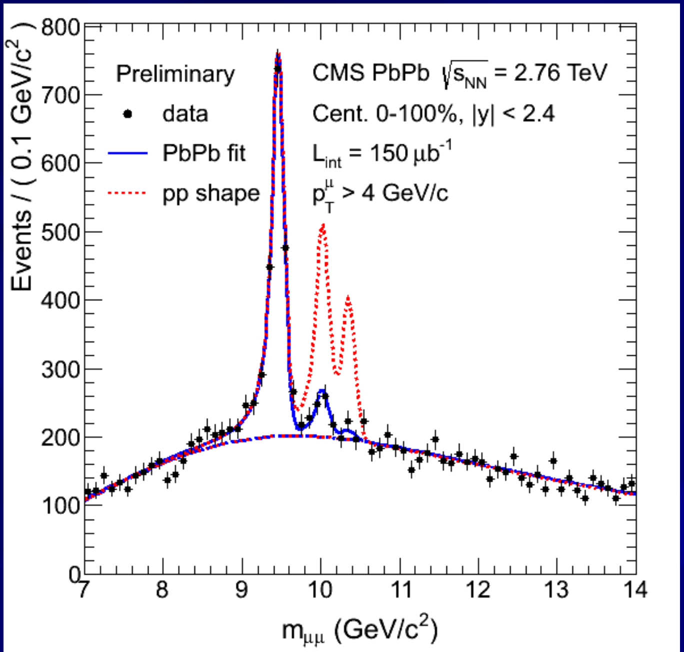
Direct photon spectrum in central Pb-Pb with fit

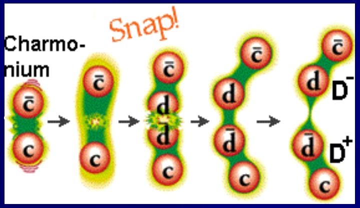


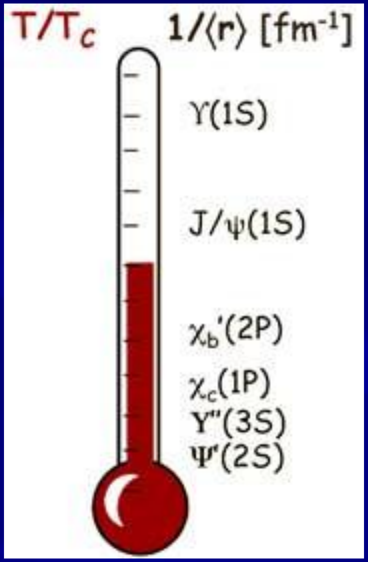


- Exponential fit for p_T < 2.2 GeV/c
  - inv. slope T = 304±51 MeV for 0–40% Pb–Pb at $\sqrt{s}$=2.76 TeV
  - PHENIX: T = 221±19±19 MeV for 0–20% Au–Au at $\sqrt{s}$=200 GeV

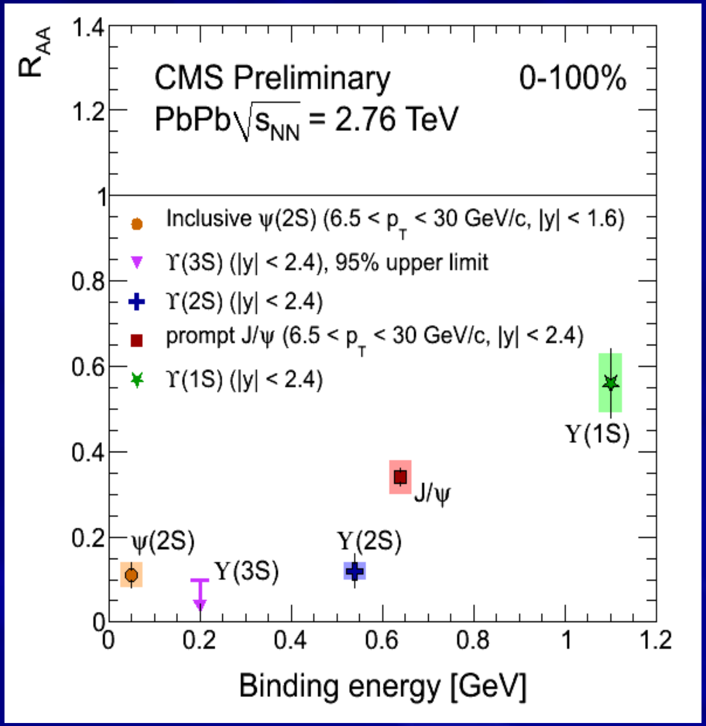
Heavy quark thermometer







Note: 6.5<p_T<30 GeV for J/ψ and ψ(2s)



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

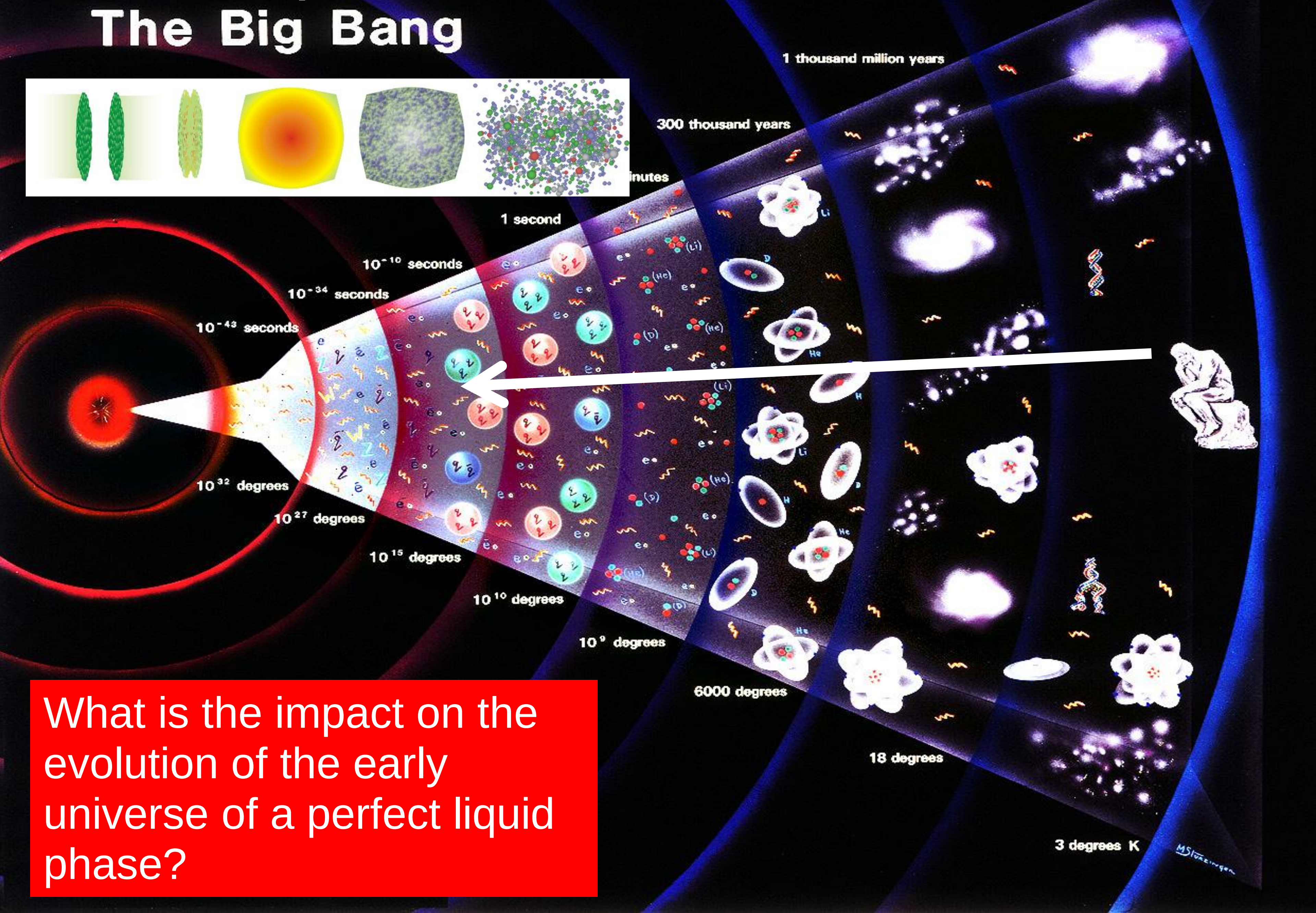
Expected in terms of binding energy

Unfortunately heavy quark results are more complex when systematically studied!

Summary

- In heavy ion collisions at ultra-relativistic energies the hadronic matter melts forming a hot (T>200 MeV) nearly perfect quark-gluon fluid
- The description of this fluid is governed almost entirely by ideal hydrodynamics and it seems it is insensitive to specific constants (light quark masses)
- Even the viscosity seems to be common for QCD like theories
- This new state of matter thus seems to be a very fundamental property of QCD (as apposed to nuclear and atomic matter which is very sensitive to SM constants)

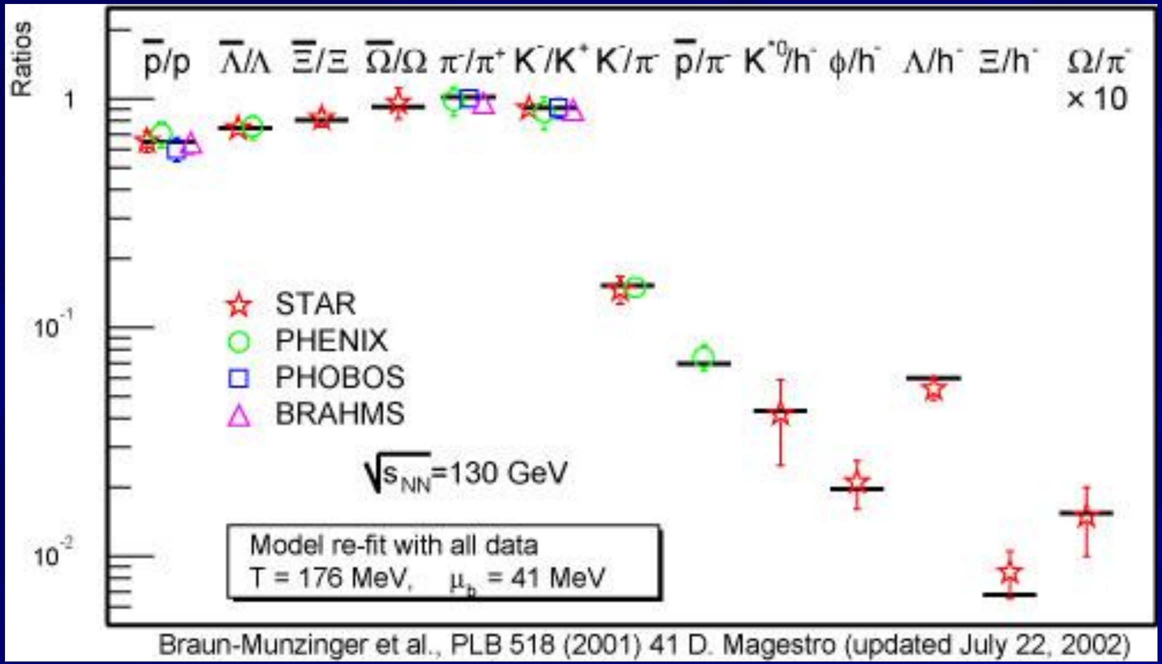
QGP – the phase of the universe 1 micro second after

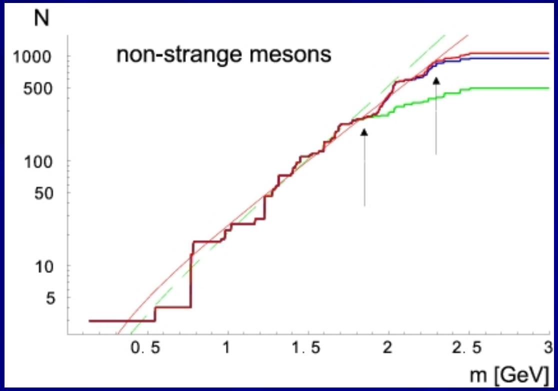


What is the impact on the evolution of the early universe of a perfect liquid phase?

Backup

Identified particle ratios: T and μ_B at freezeout

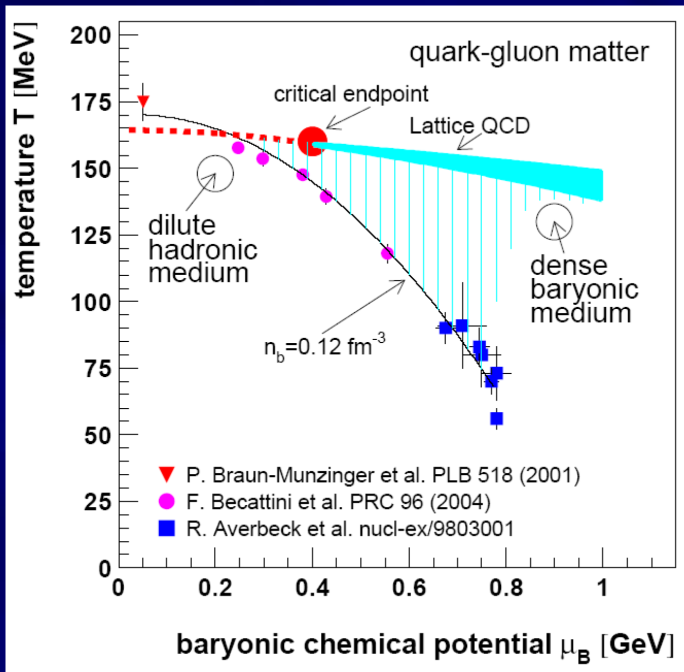


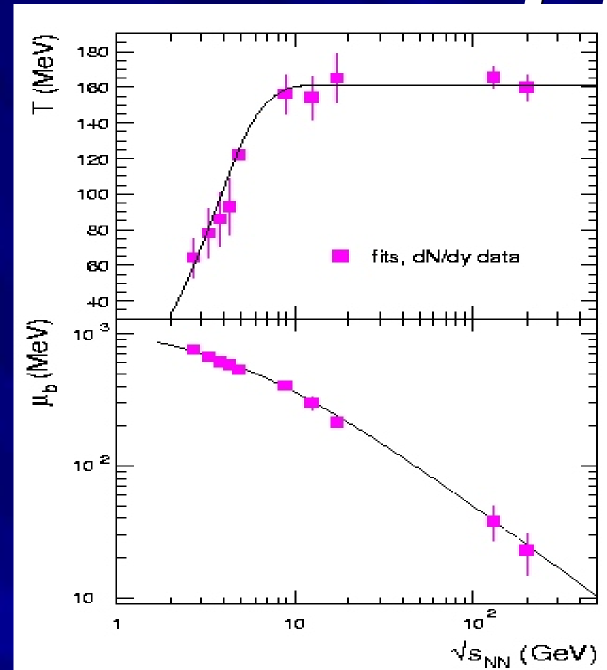


1. Generate hadrons with w
2. Decay strongly
3. Compare to data

- Particle ratios are well described by statistical models when decay from hadronic resonances are taken into account (only QCD input are the masses and decays)
- The temperature is consistent with what we expect from Lattice QCD calculations for the transition temperature

The QCD phase diagram with the measured T and μ_B





T ... = 161 ± 4

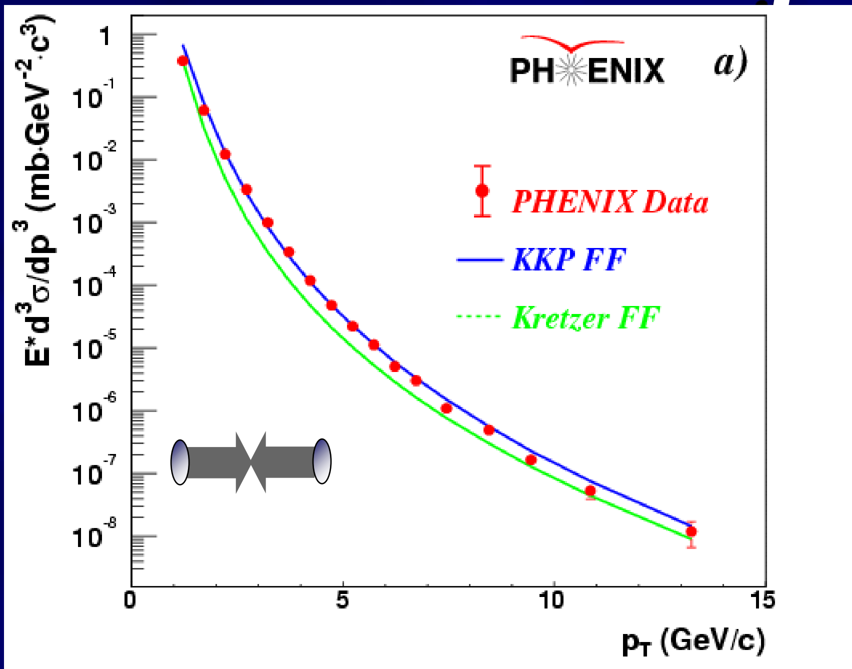
M

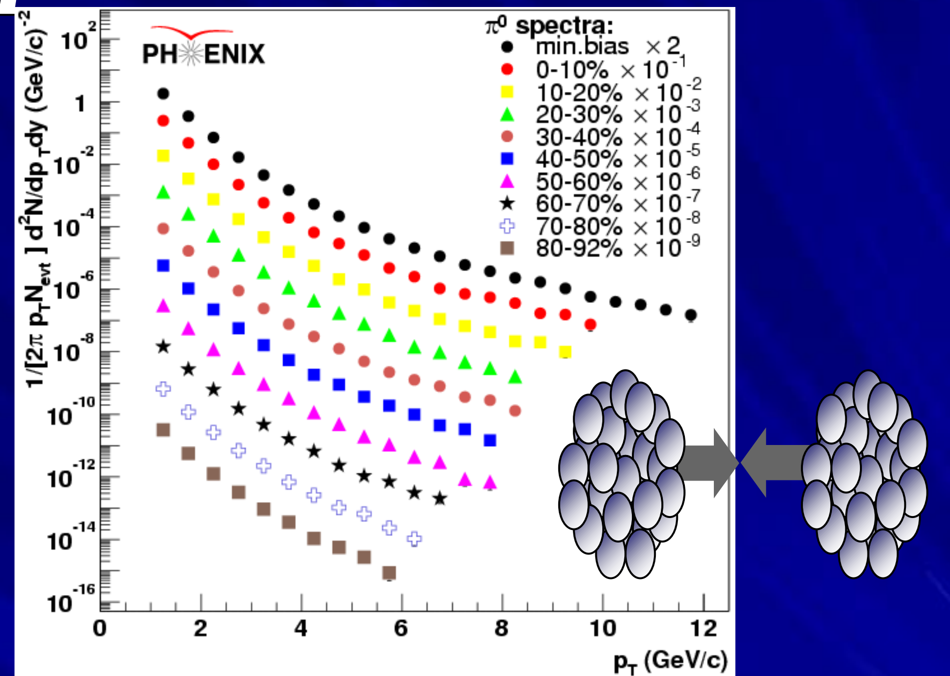
A. Andronic,
P. Braun-Munzinger,
J. Stachel,
nucl-th/0511071

Because of the sin

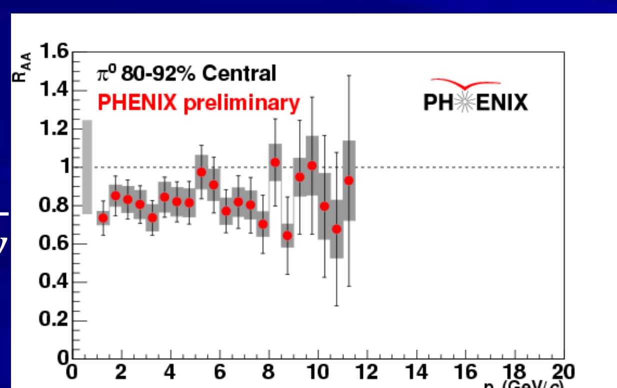
- The statistical description of particle rations is also good for lower energies: AGS and SPS
- The temperature saturates at T~160 MeV indicating that the system has crossed the phase boundary
- But p+p ratios can be described with a similar (canonical) formalism and T! So it is a hadronization attribute.

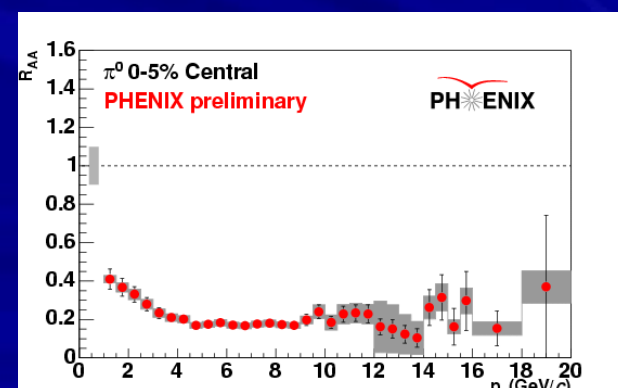
The nuclear modification factor for pions



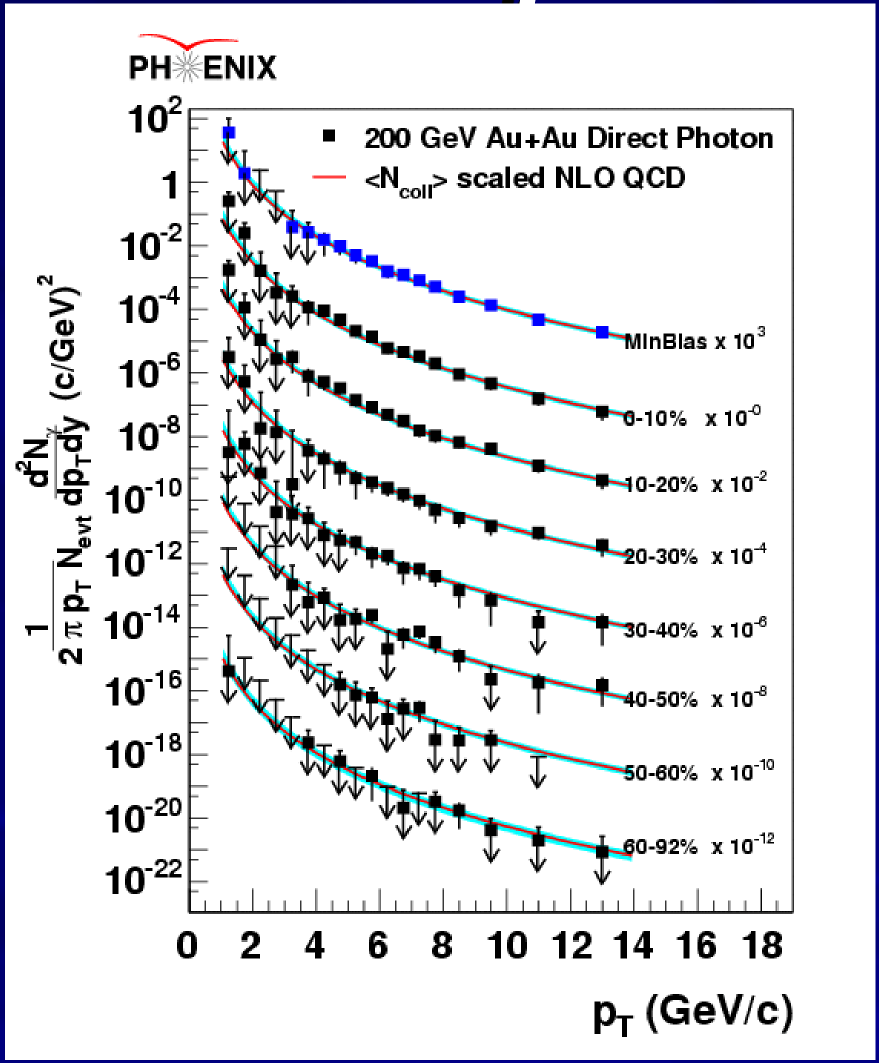


$$R_{AA} = \frac{d^2 N^{AA}/d\,p_T dy}{\langle N_{bin}\rangle d^2 N^{NN}/d\,p_T dy}$$

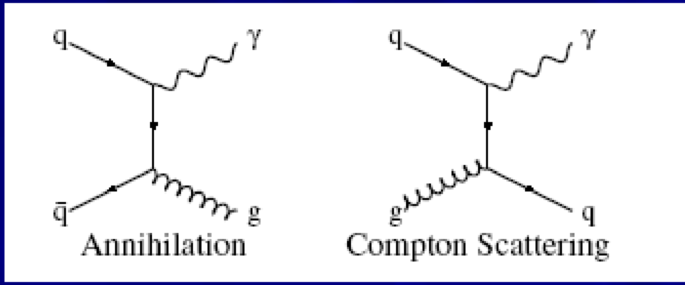




The nuclear modification factor for direct photons

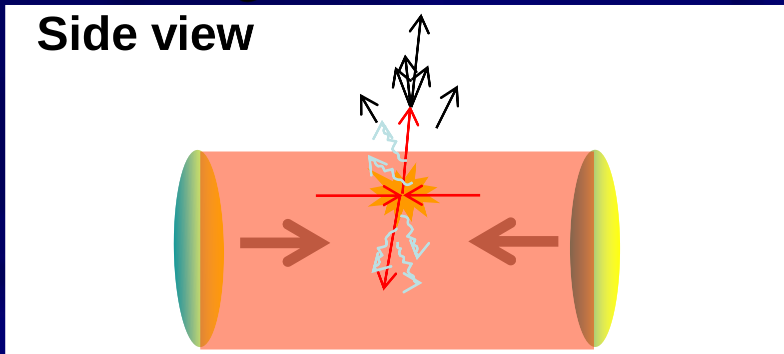


Source of direct photons

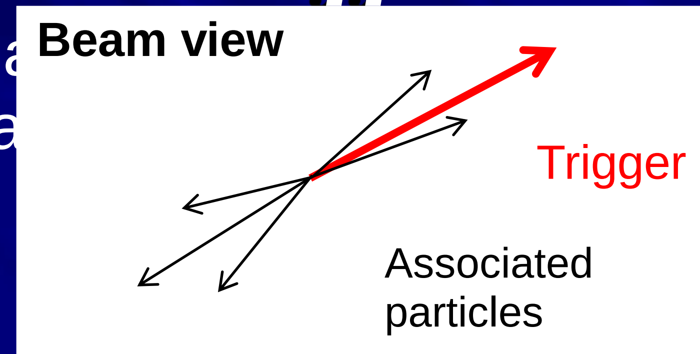


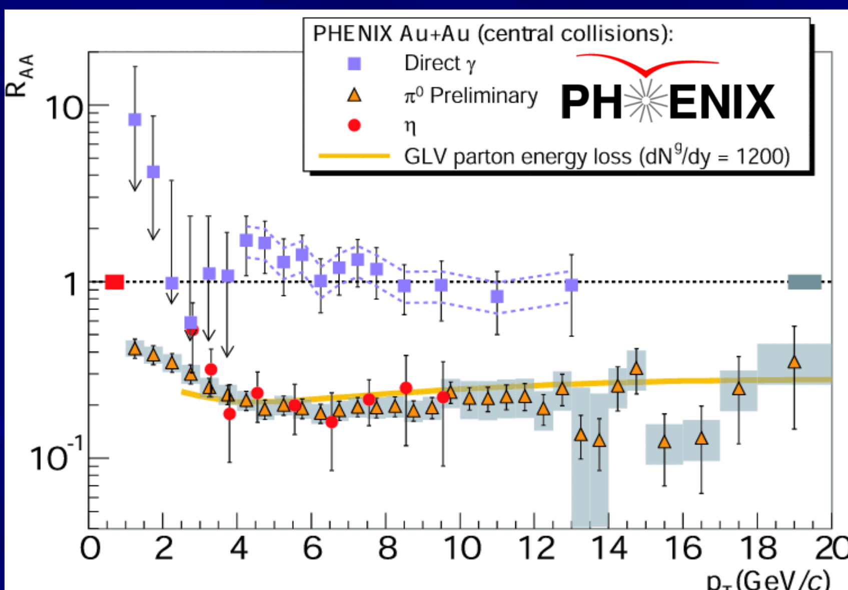
- Direct photons does not interact with final state hadronic matter!
- At low pT photons are dominantly decay photons e.g. $\pi^0 \rightarrow 2\gamma$
- Direct photons confirm binary scaling of hard processes!

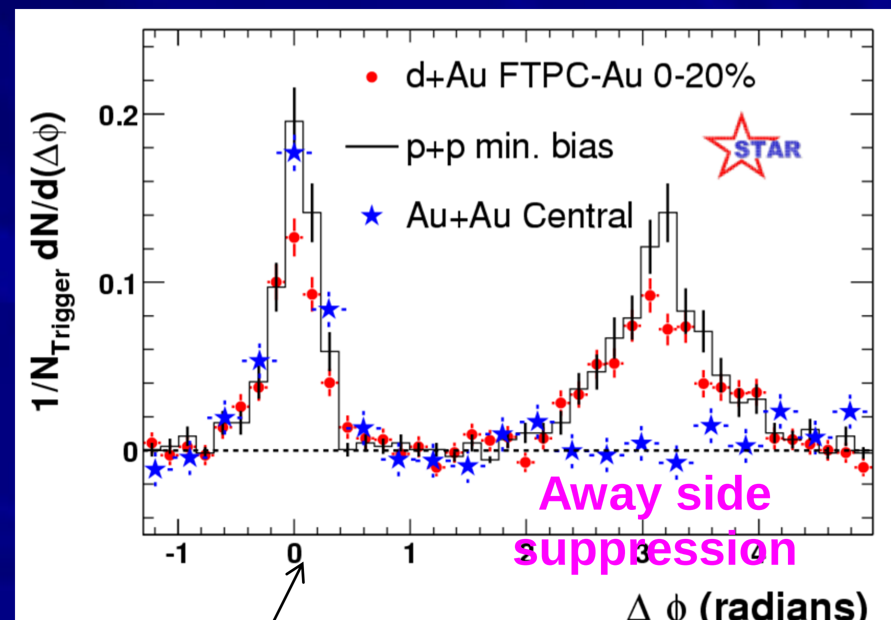
Disappearance of the away side jet indicates final state effect



Most jets a
back to ba



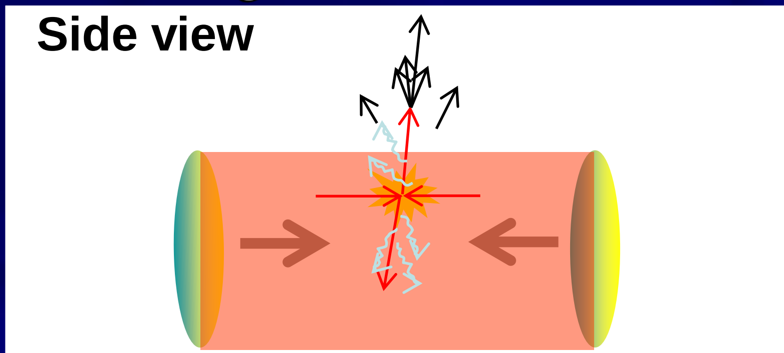




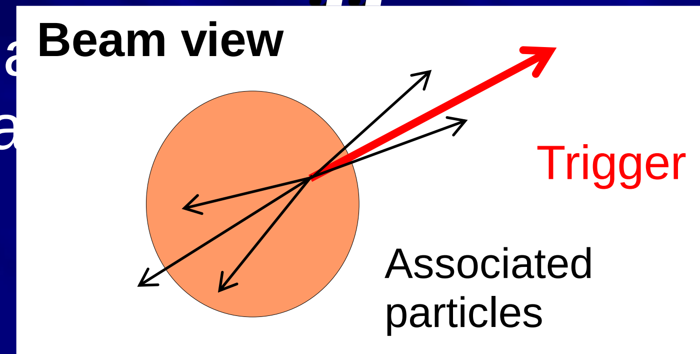
$4 < p_T(trig) < 6$ GeV/c

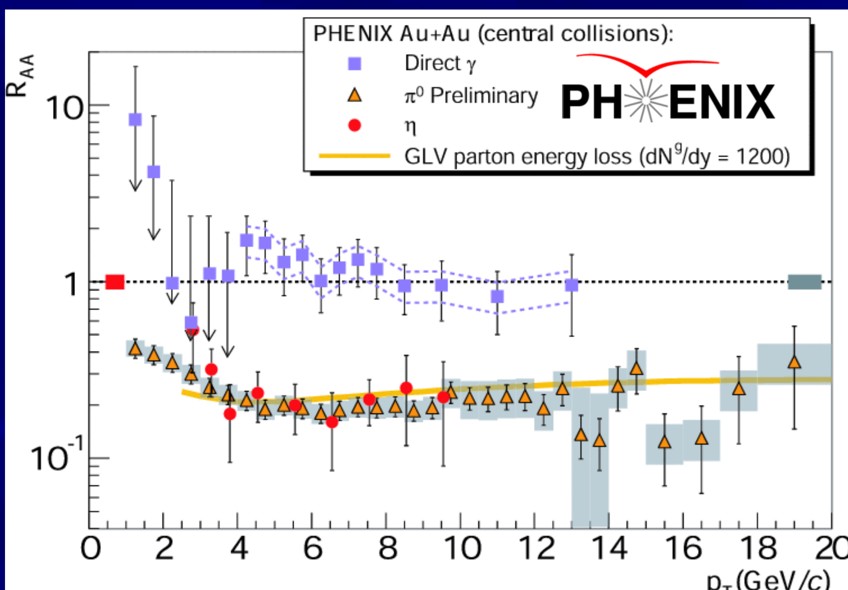
$p_T(assoc) > 2$ GeV/c

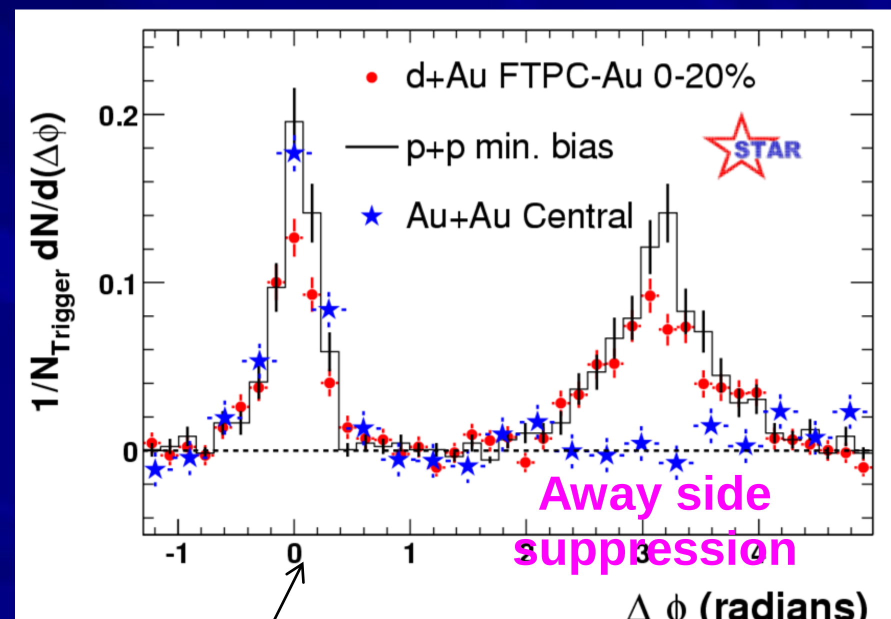
Disappearance of the away side jet indicates final state effect



Most jets a
back to ba



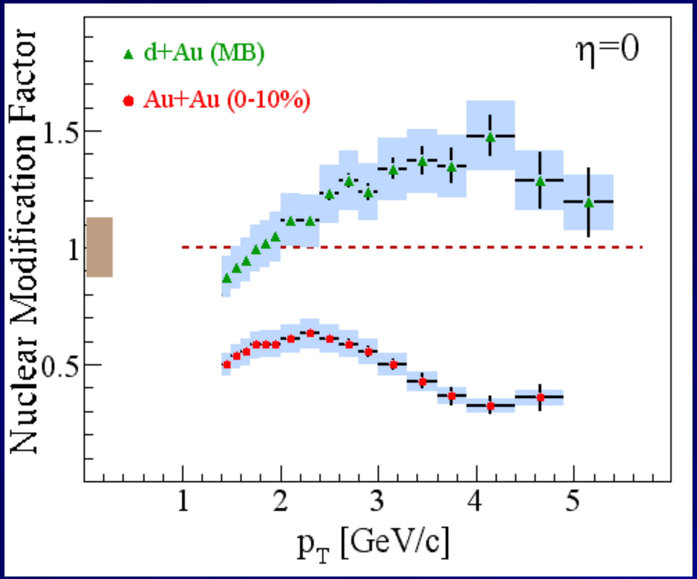


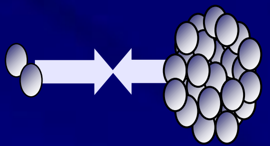


4 < p_T(trig) < 6 GeV/c

p_T(assoc) > 2 GeV/c

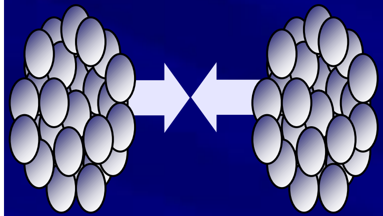
Au+Au vs d+Au
Hot vs cold nuclear matter



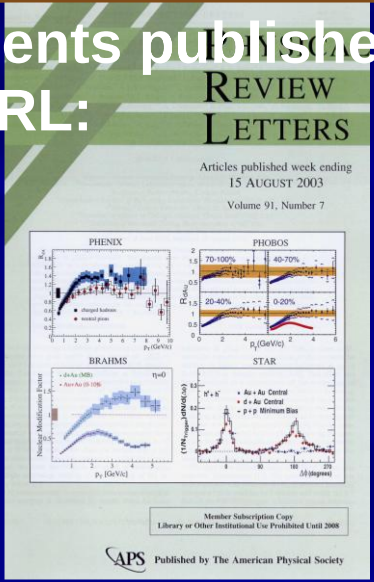


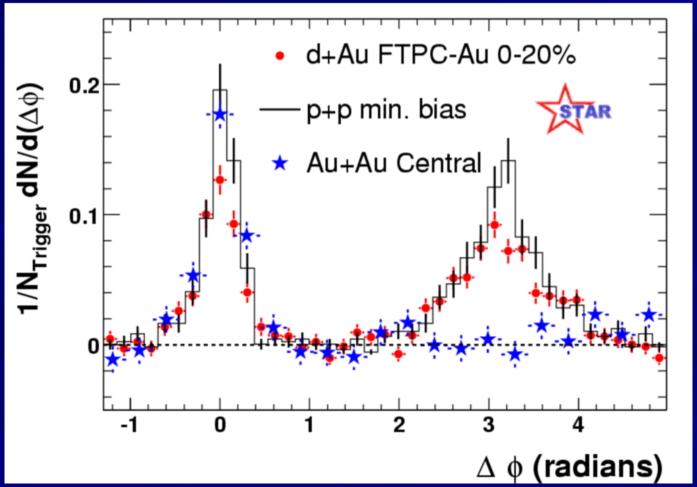
d+Au

Au+Au



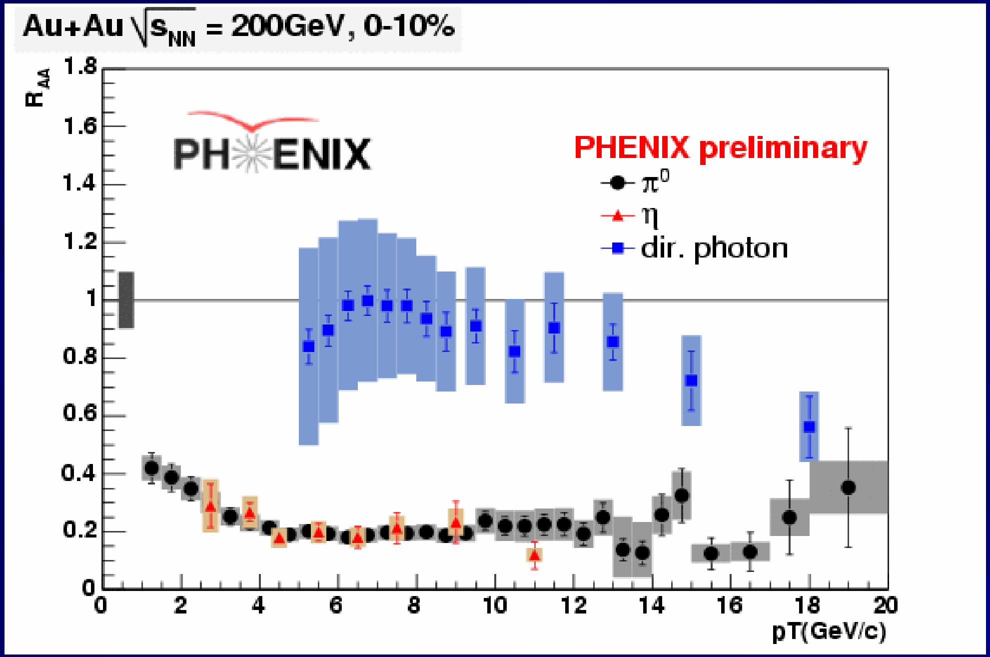
All 4 experiments published together in PRL:



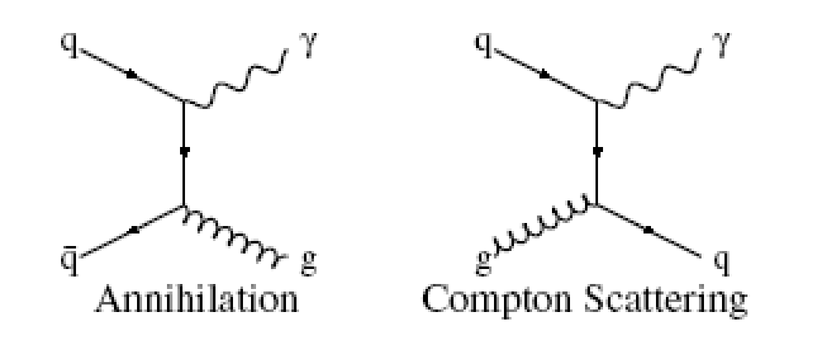


No suppression seen in d+Au
→Final state effect not seen at lower er
Quarks and gluons loose/radiate energ
They probe the created matter

Could the binary scaling be wrong?

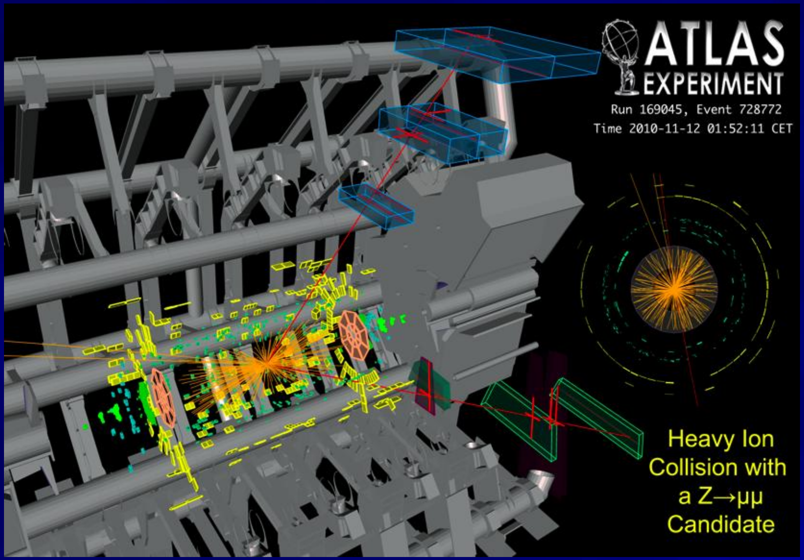


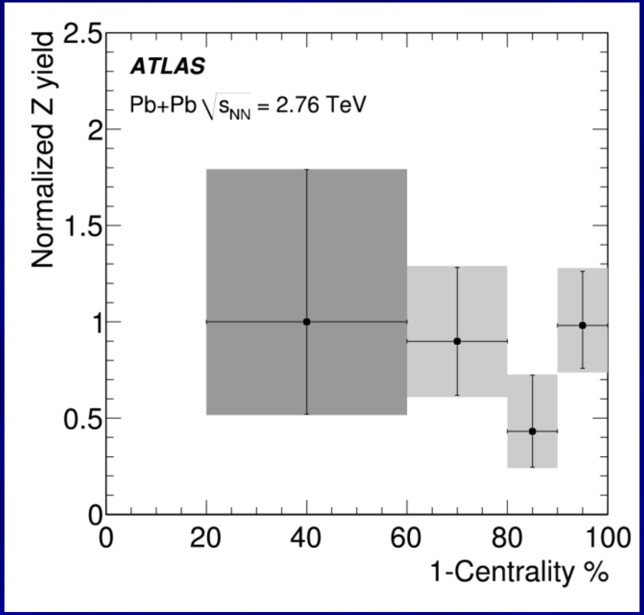
Source of direct photons



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

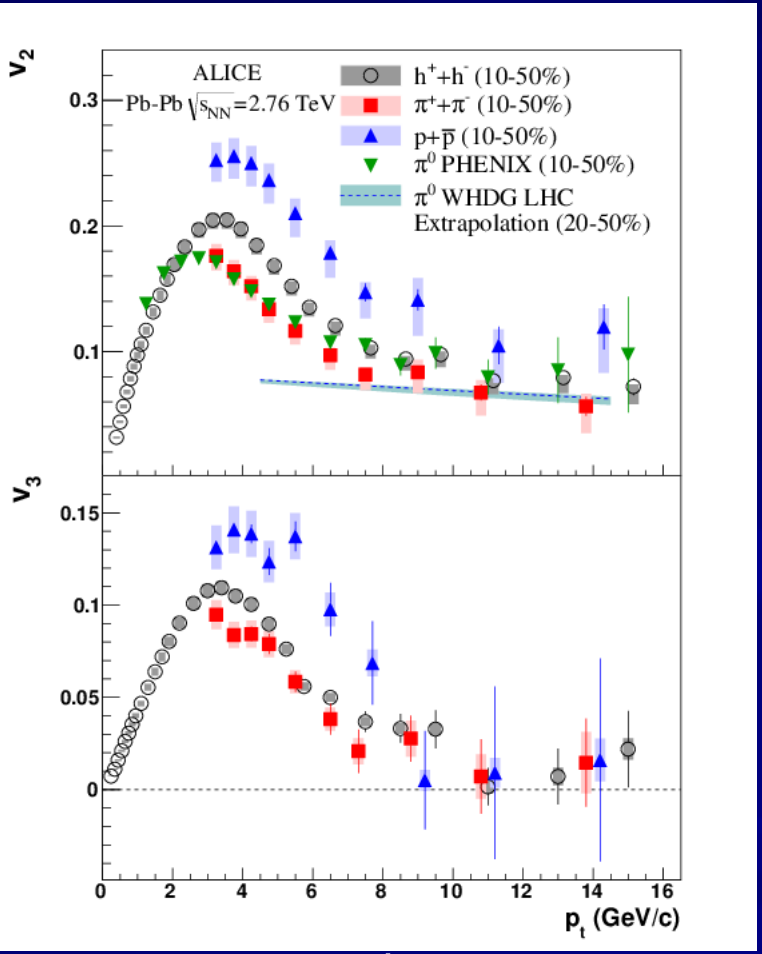
New "standard candle" at LHC: ATLAS measures Z bosons





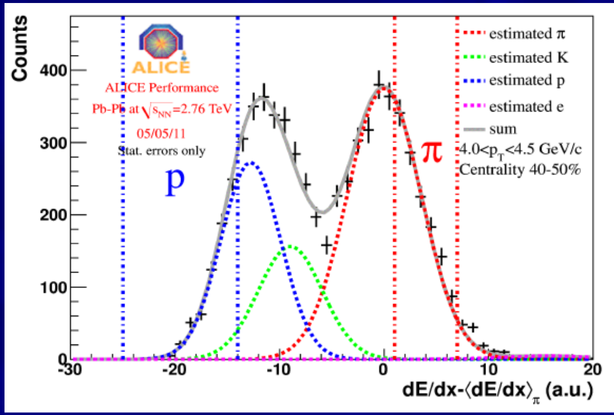
- The Z does not interact strongly and so can also be used to check binary scaling at LHC

Elliptic and triangular flow for identified particles at high p_T



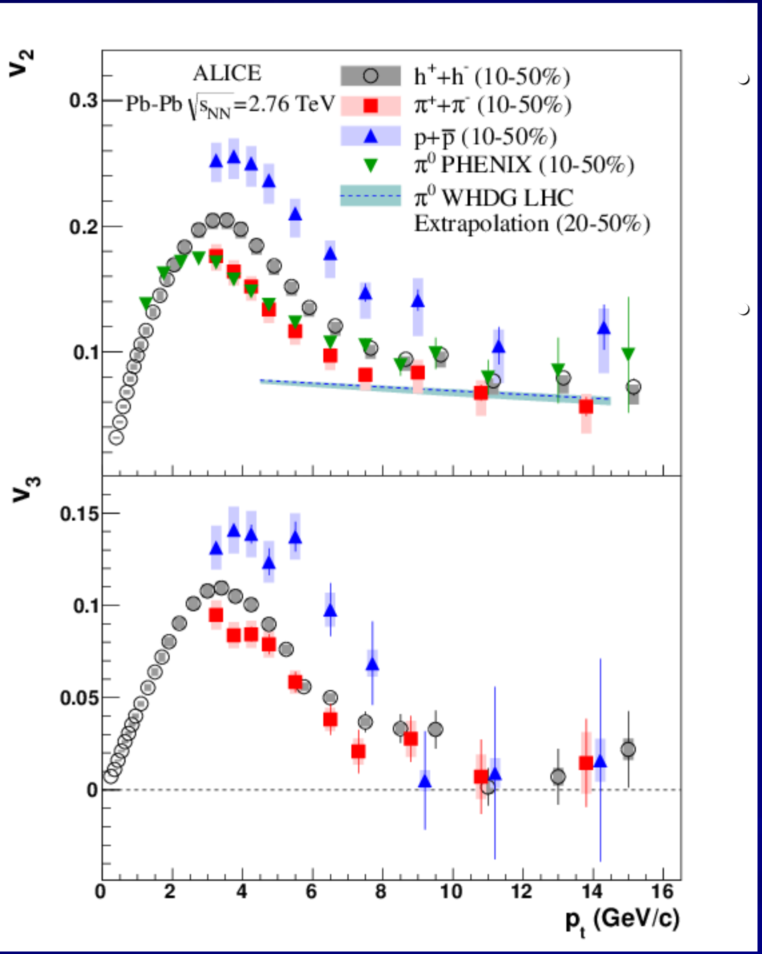
arXiv: 1205.5761

PID using TPC: dE/dx - <dE/dx>$_\pi$
4.5 < p_T < 5.0 GeV/c

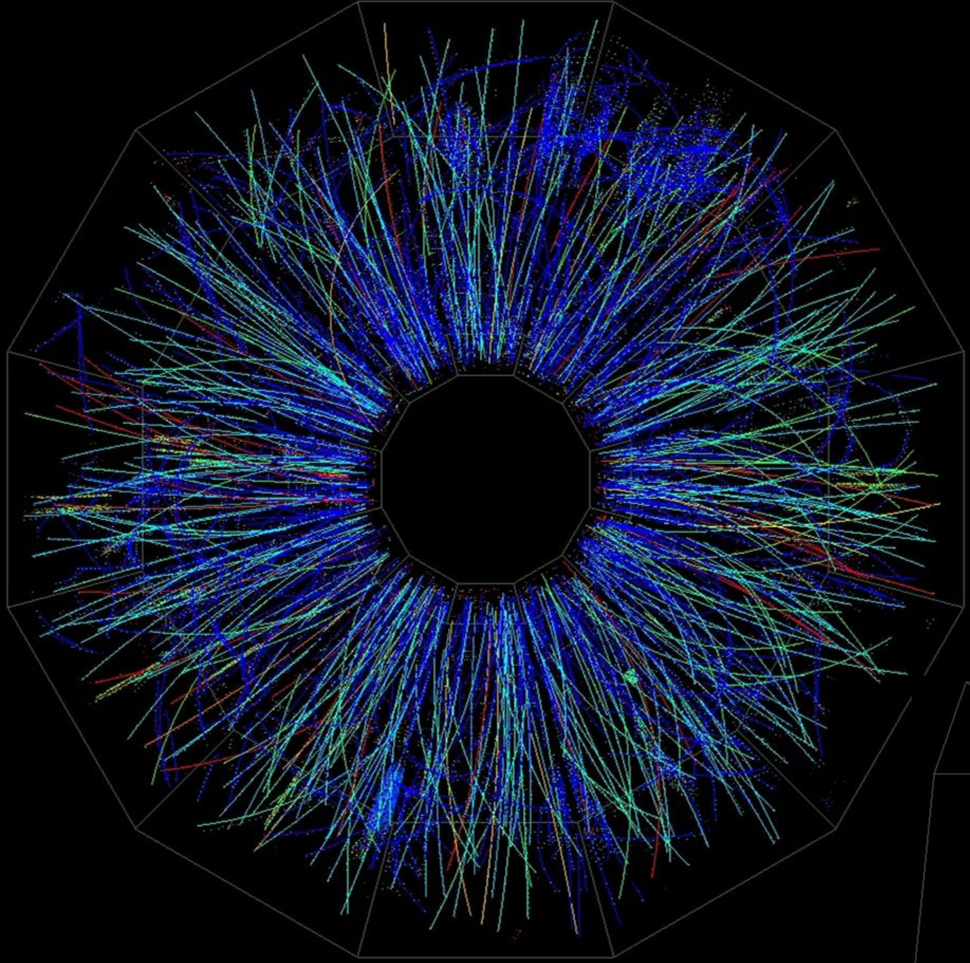


- PID using "clean" regions of dE/dx on the relativistic rise

Elliptic and triangular flow for identified particles at high p_T

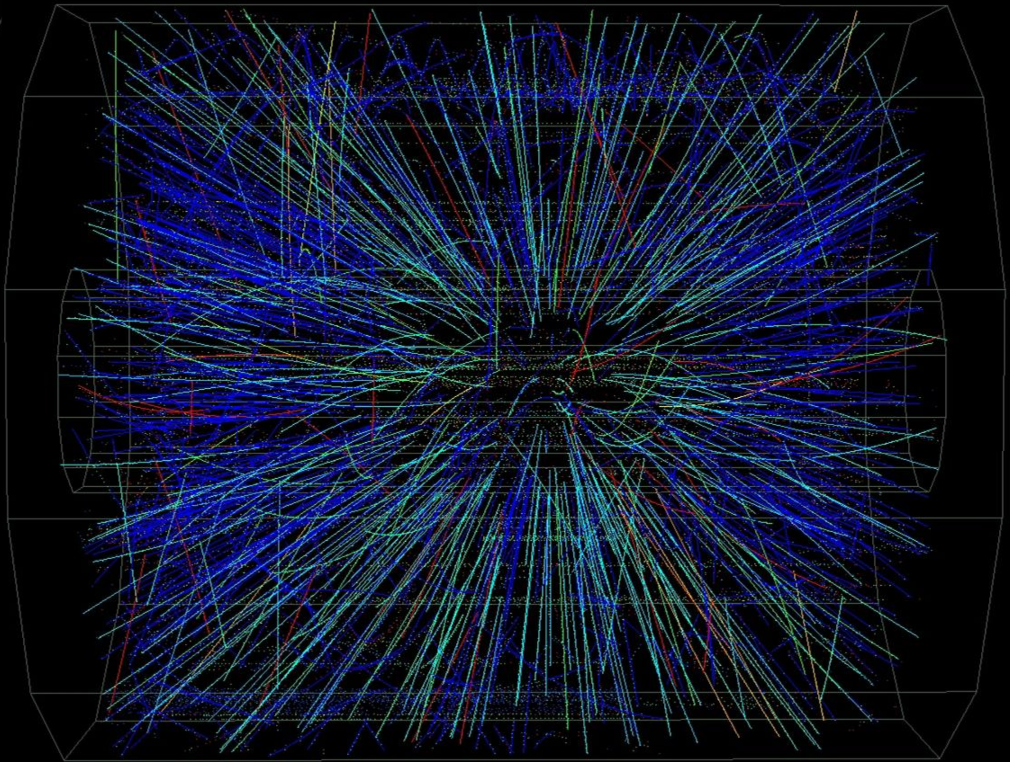


- The v_2 and v_3 also peaks in the intermediate p_T region
  - Large particle species dependence
- End of hydrodynamic flow for $p_T \geq$ 9-10 GeV/c ?
  - Triangular flow which is not sensitive to collision geometry becomes small
  - No or small particle species dependence for v_2 (little mass dependence)
  - And pion v_2 is well described by jet quenching prediction



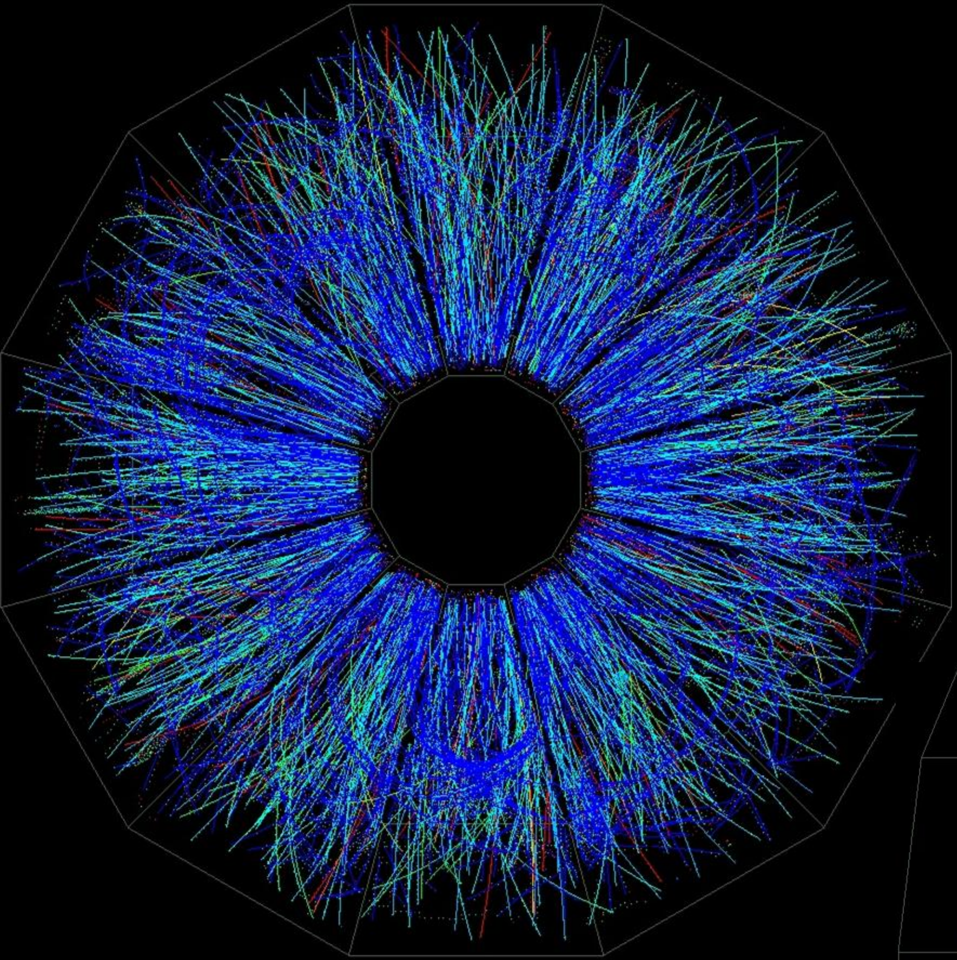
Peripheral Event

From real-time Level 3 display.



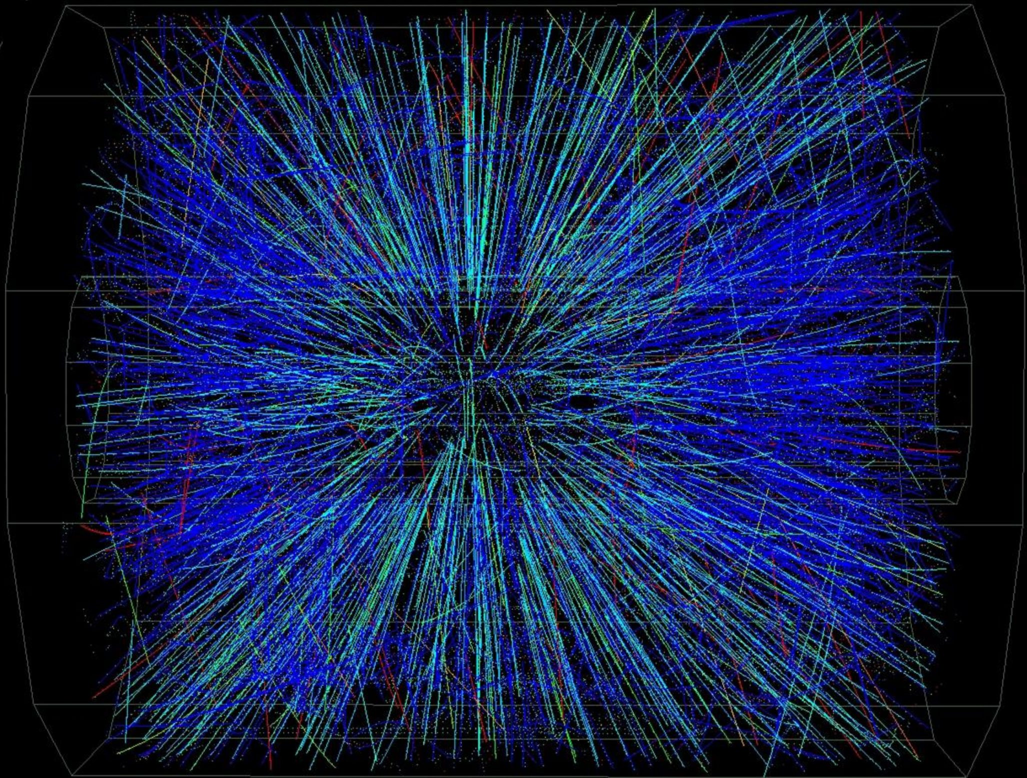
color code ⇒ energy loss

STAR



Mid-Central Event

From real-time Level 3 display.



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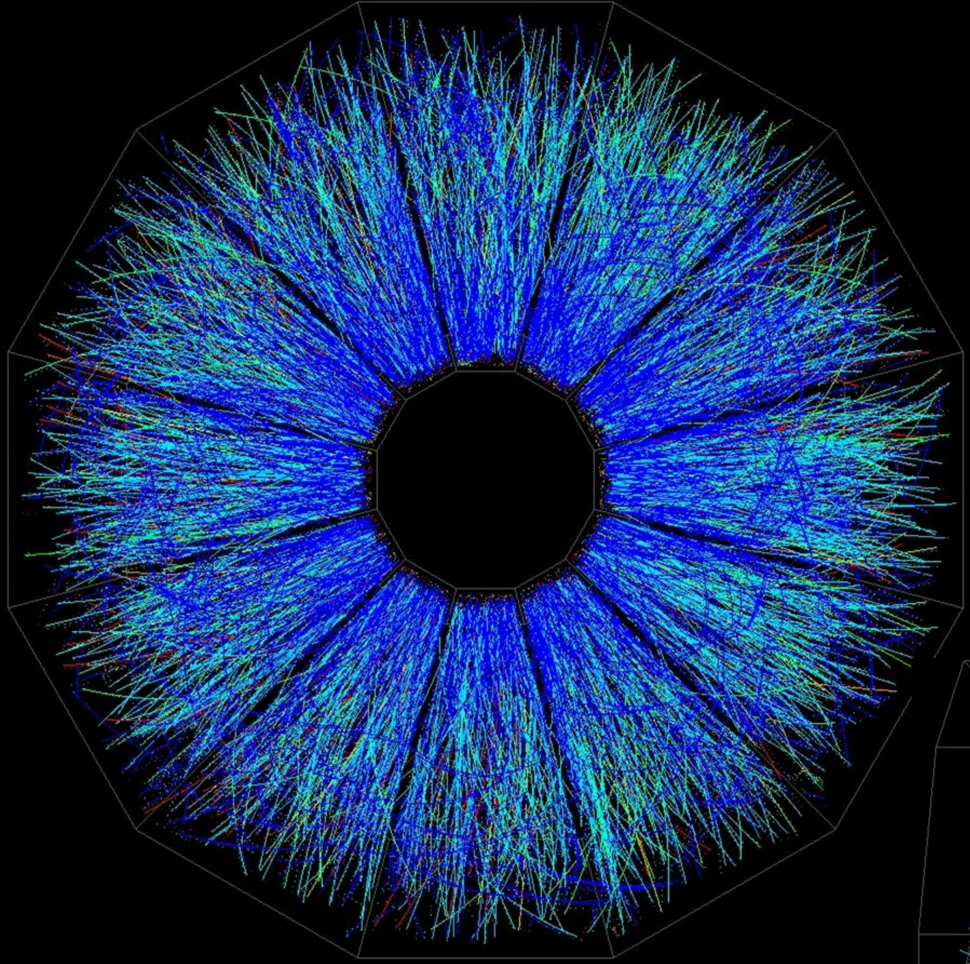
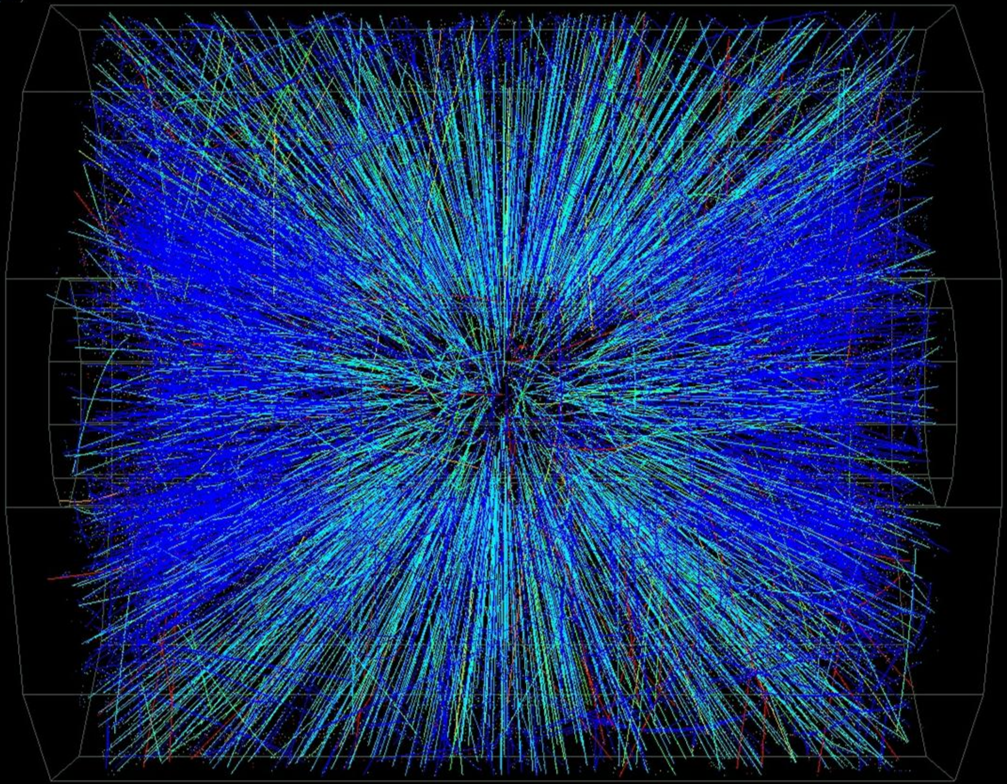


Central Event

From real-time Level 3 display.



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