Modern Experimental Particle Physics
FYST17
February 22 and 23, 2017

An introduction to the
Quark Gluon Plasma
and heavy-ion collisions
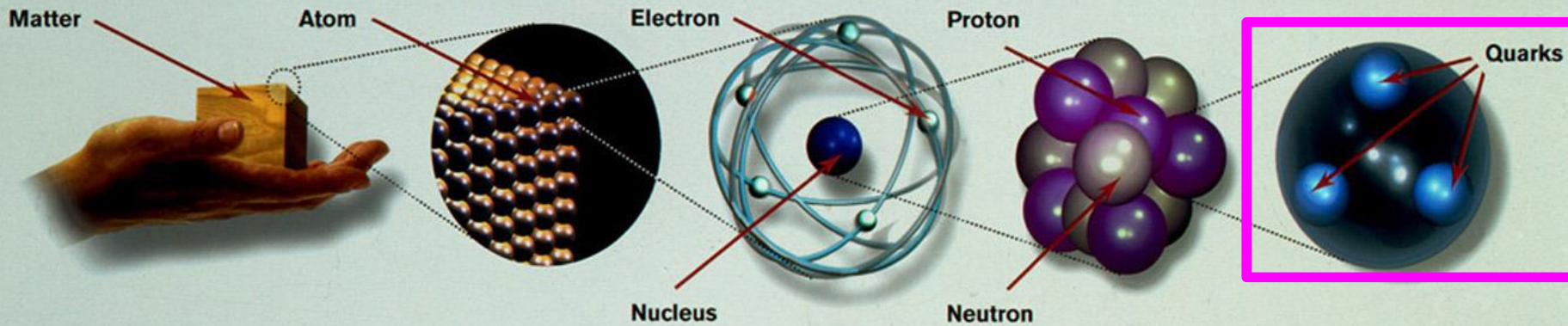
P. Christiansen (Lund University)

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Outline

- The medium temperature

- Hard probes

  - The standard candles

  - Quarkonium

  - Jets and high p_T particles

- Soft medium properties

  - Collective flow

- Quark Gluon Plasma (QGP) in small systems?

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Matter — Atom — Electron — Proton — Quarks

Nucleus — Neutron

Matter particles	LEPTONS				QUARKS			
All ordinary particles belong to this group	**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		**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	
These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators	**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		**Charm** A heavier relative of the up; found in 1974		**Strange** A heavier relative of the down; found in 1964	
	THIRD FAMILY	**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
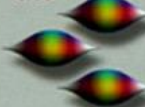
Felt by: quarks and charged leptons

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

The strong interaction: Quantum Chromo Dynamics (QCD)

Heavy-ion physics and the QGP (P. Christiansen, Lund)

3 strong charges (red, green, blue)

Particles in nature are color neutral

Quarks are "confined"

Charmo-nium   Snap!

10ton

(Force ~ 1 GeV/fm)

Hadrons

Baryons

Proton

Anti-proton

Neutron

Lambda

Mesons

π^+

K^0

π^0

J/ψ

Heavy-ion physics and the QGP (P. Christiansen, Lund)
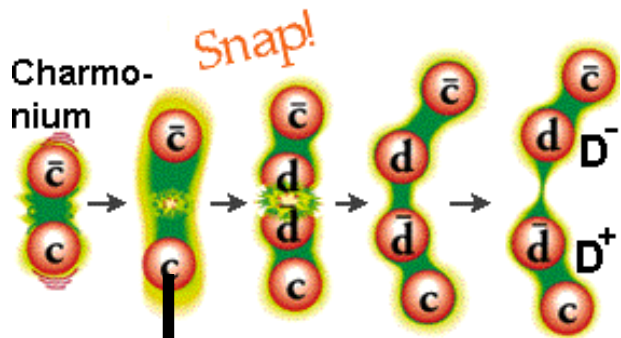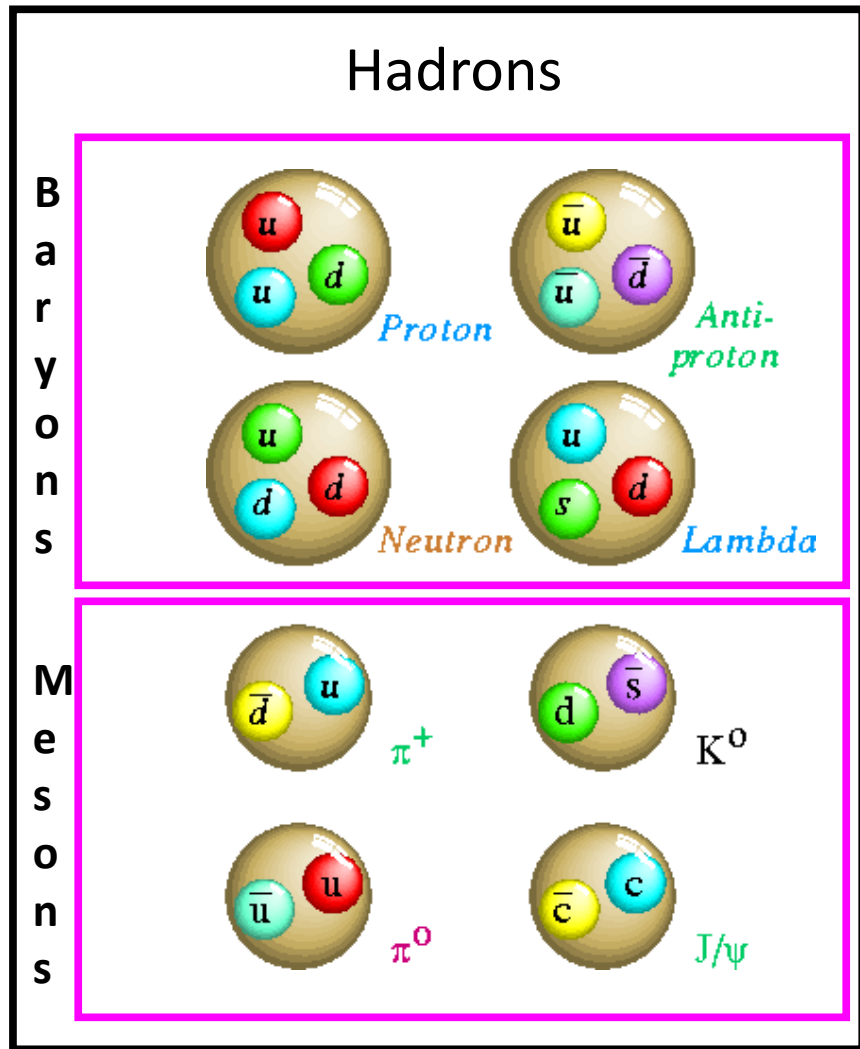
Let us recall why it is so

What is the Quark Gluon Plasma?

Heavy-ion physics and the QGP (P. Christiansen, Lund)

"`QGP' is not a new particle but a paradigm-shift of how we understand matter in extreme conditions. Thus there is no clear criterion by which one can claim an experimental discovery. For this reason QGP was rediscovered again with new experimental results obtained at the order of magnitude higher RHIC collision energies. In addition to confirming the CERN results, RHIC produced new puzzling phenomena; some will be discussed below. The circumstance repeats for the third time today: LHC data confirms SPS and RHIC results, and is offering another rich field of new experimental results.

Since no one plans to announce the QGP discovery at the LHC, we conclude that QGP has gained considerable acceptance as a new form of matter."

Johann Rafelski and Jeremey Birrell, arXiv:1311.0075.

They point out a big problem: our main understanding is experimental and very little of the theory is on a firm basis.

When we will have a better theoretical picture we can then really point out what the QGP properties are and when it was discovered.
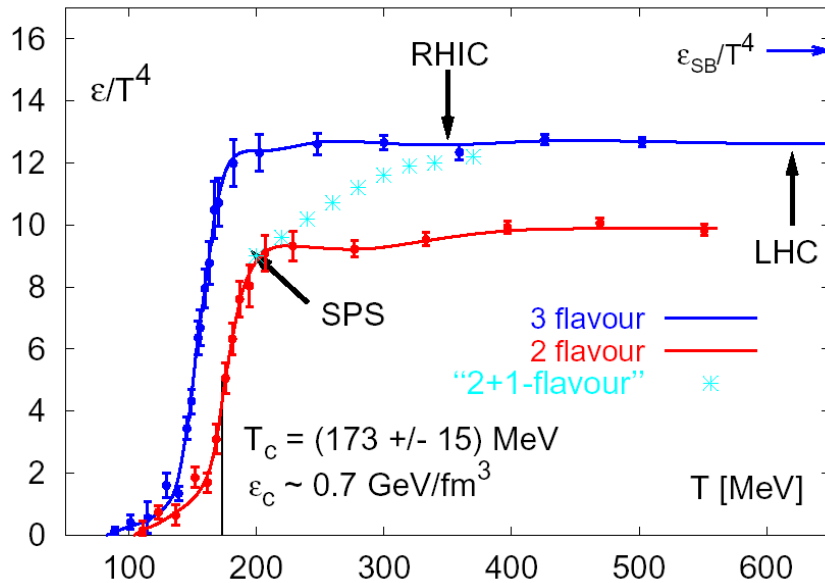
The quark-gluon phase diagram

Heavy-ion physics and the QGP (P. Christiansen, Lund)
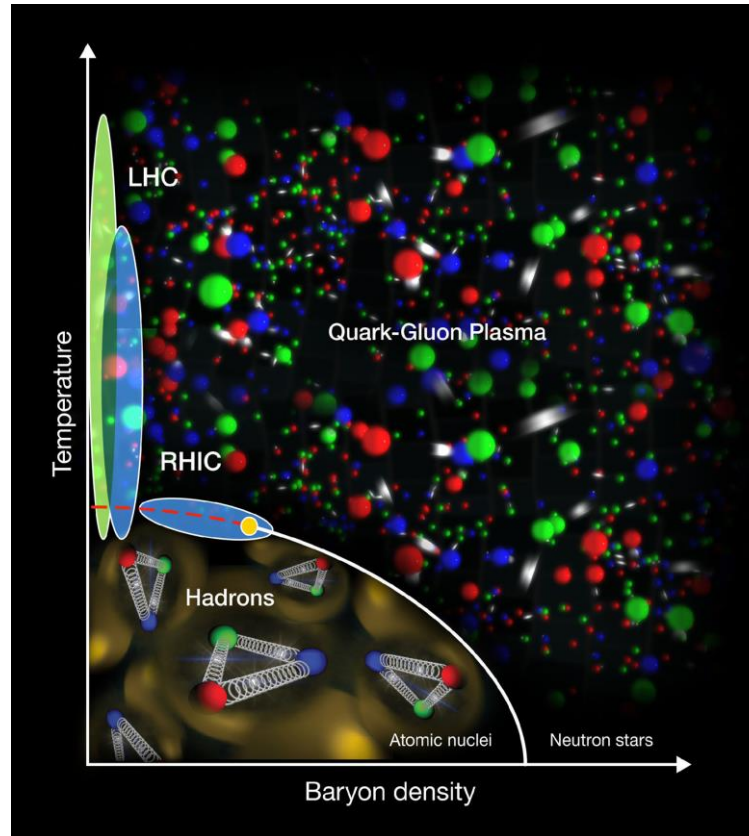
We will only talk about the high temperature transition which is what we probe in heavy-ion collisions

Lattice QCD calculation of the energy density

Heavy-ion physics and the QGP (P. Christiansen, Lund)

$$\epsilon_{Quark-Gluon\ gas} =$$
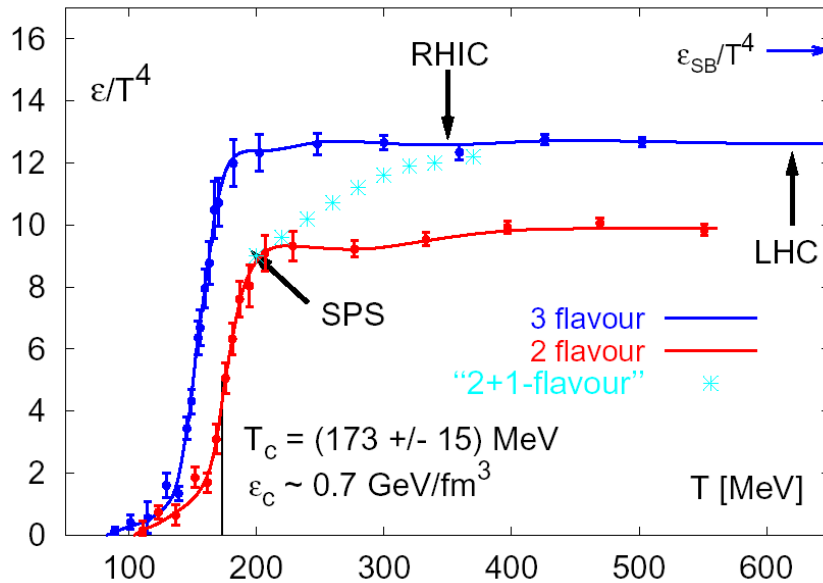$$\frac{\pi^2}{30}\left(\text{bosonic dof} + \frac{7}{8}\ \text{fermionic dof}\right) T^4$$

?

With lattice QCD one can study some aspects of QCD numerically. In this case the energy density shows that at a temperature of ~170 MeV there is a phase transition.
The phase transition is believed to be a Xover, meaning that for temperatures around Tc the hadronic and QGP phases coexist and that no entropy is produced in the phase transition.

Lattice QCD calculation of the energy density

$$\varepsilon_{Quark-Gluon\ gas} =$$

$$\frac{\pi^2}{30}(2 \times 8 + \frac{7}{8}2 \times 2 \times 3 \times 3)\,T^4$$
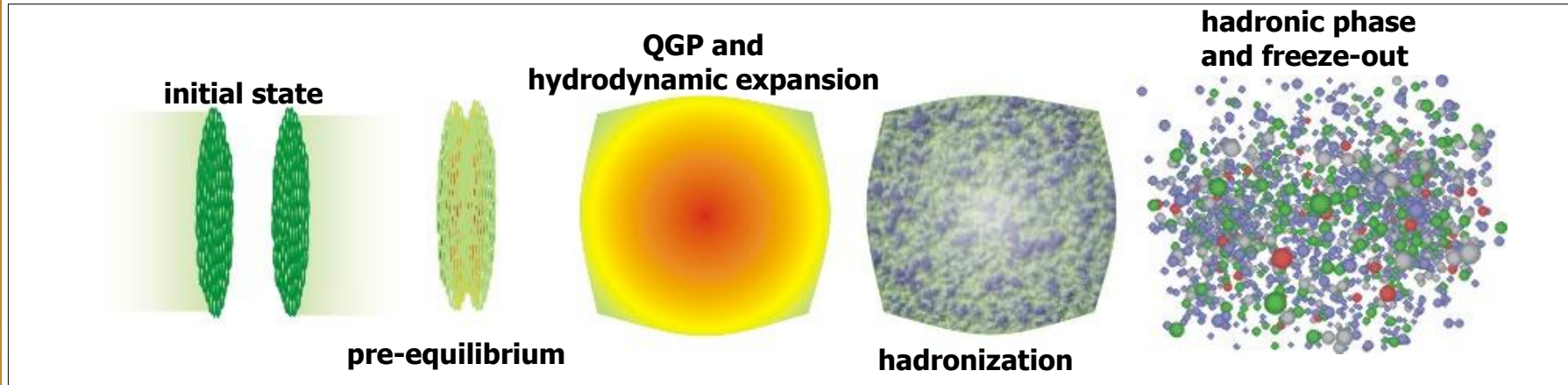
Gluon spin and color

(Anti+)quark spin, color and flavor

With lattice QCD one can study some aspects of QCD numerically. In this case the energy density shows that at a temperature of ~170 MeV there is a phase transition.
The phase transition is believed to be a Xover, meaning that for temperatures around Tc the hadronic and QGP phases coexist and that no entropy is produced in the phase transition.
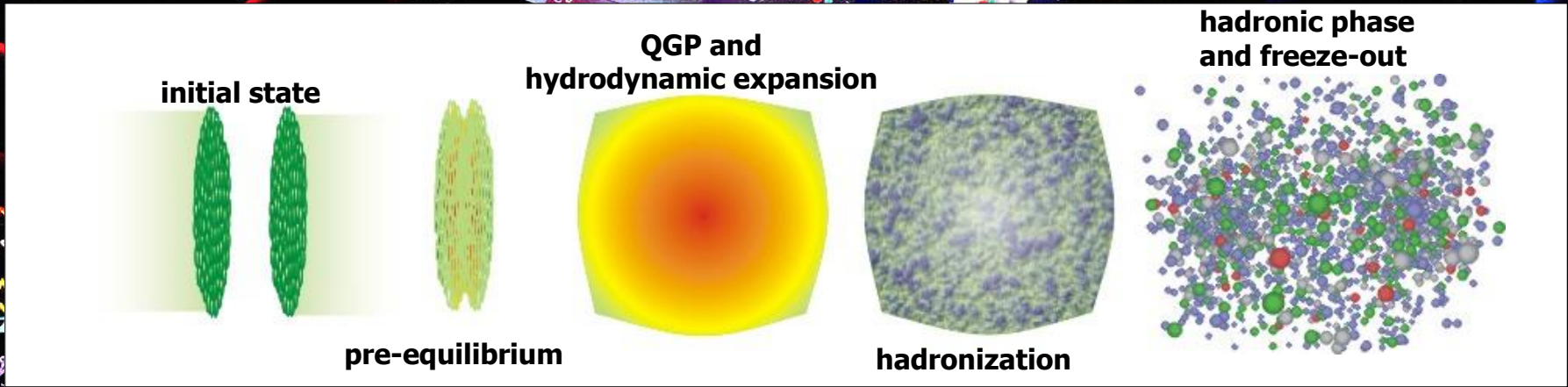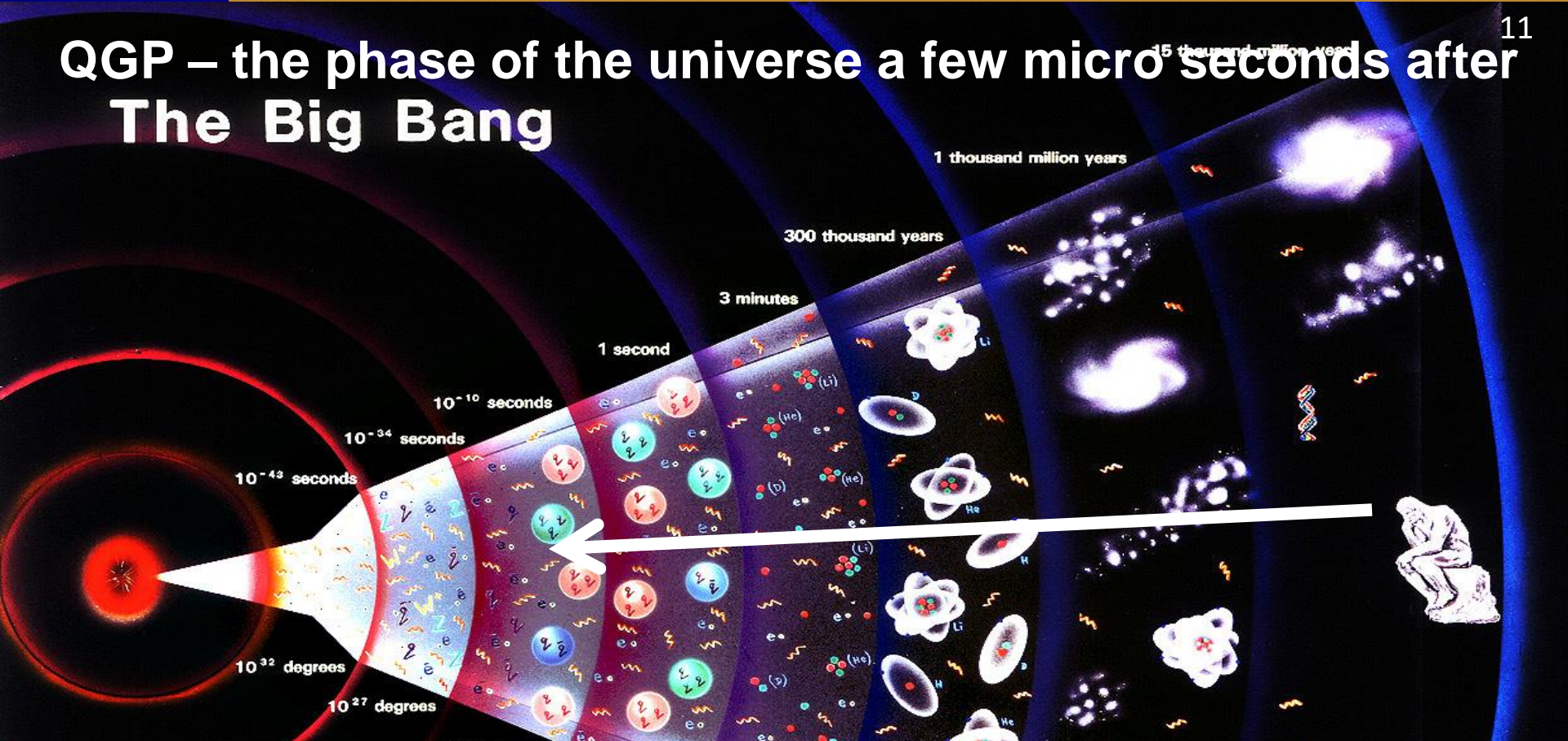
Heavy-ion physics and the QGP (P. Christiansen, Lund)

Heavy ion collisions

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- The only way we can create the QGP in the laboratory!

- By colliding heavy ions it is possible to create a large (»1fm³) zone of hot and dense QCD matter

- Goal is to create and study the properties of the Quark Gluon Plasma

- Experimentally mainly the final state particles are observed, so the conclusions have to be inferred via models
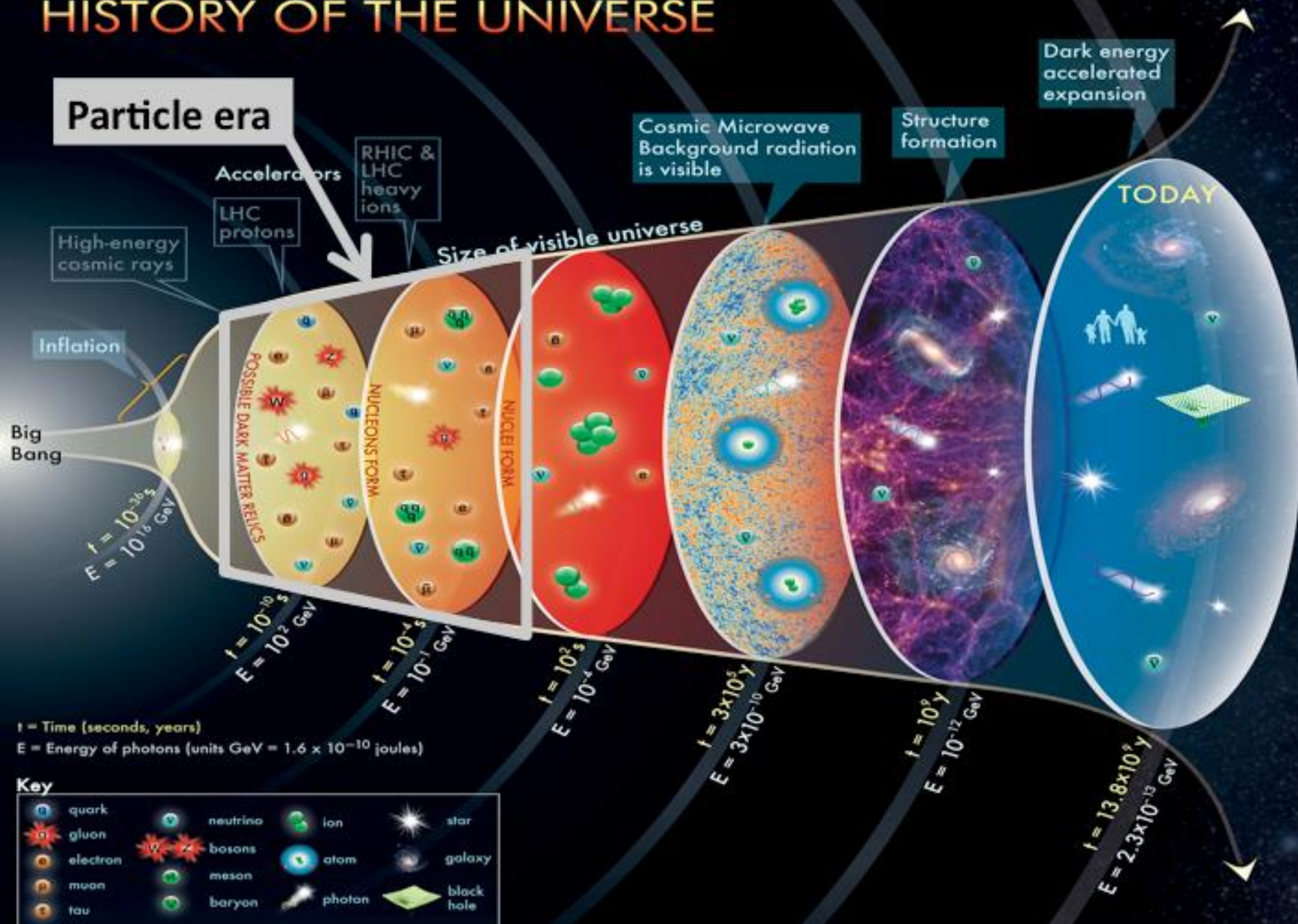
QGP – the phase of the universe a few micro seconds after

The Big Bang

15 thousand million years

1 thousand million years

300 thousand years

3 minutes

1 second

10^{-10} seconds

10^{-34} seconds

10^{-43} seconds

10^{32} degrees

10^{27} degrees

initial state

pre-equilibrium

QGP and
hydrodynamic expansion

hadronization

hadronic phase
and freeze-out

anti-quark   He helium
e⁻ electron   Li lithium

HISTORY OF THE UNIVERSE

Particle era

Dark energy accelerated expansion

Cosmic Microwave Background radiation is visible

Structure formation

RHIC & LHC heavy ions

Accelerators

LHC protons

High-energy cosmic rays

Size of visible universe

TODAY

Inflation

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

Big Bang

$t = 10^{-26}\ s$
$E = 10^{16}\ GeV$

$t = 10^{-10}\ s$
$E = 10^{2}\ GeV$

$t = 10^{-4}\ s$
$E = 10^{-1}\ GeV$

$t = 10^{2}\ s$
$E = 10^{-4}\ GeV$

$t = 3\times10^{5}\ y$
$E = 3\times10^{-10}\ GeV$

$t = 10^{9}\ y$
$E = 10^{-12}\ GeV$

$t = 13.8\times10^{9}\ y$
$E = 2.3\times10^{-13}\ GeV$

t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)

Key

- quark
- gluon
- electron
- muon
- tau
- neutrino
- bosons
- meson
- baryon
- ion
- atom
- photon
- star
- galaxy
- black hole

The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

History of ultra-relativistic heavy-ion physics

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- 1st generation $\sqrt{s_{NN}}$<20GeV (fixed target)
  AGS (BNL, US), SPS (CERN) late 80s and 90s

  - Experiments: NA61, NA49, NA60, NA50, NA44, ……

- 2nd generation $\sqrt{s_{NN}}$<200GeV (collider)
  RHIC (BNL, US) 2000-Now

  - Experiments: PHENIX, STAR, PHOBOS, BRAHMS

- 3rd generation $\sqrt{s_{NN}}$=2760GeV in run 1 (collider),
  $\sqrt{s_{NN}}$=5020GeV in run 2 (2015-)
  LHC (CERN) 2010-Now

  - Experiments: ALICE, CMS, and ATLAS.

I will mainly show results from LHC!

The three systems (understanding before 2012)

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Pb-Pb
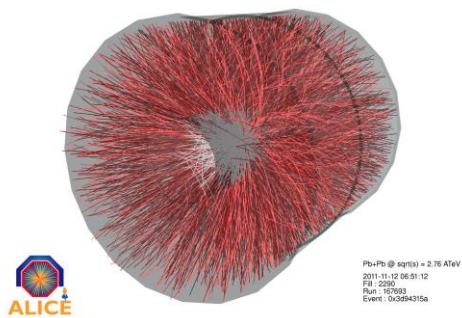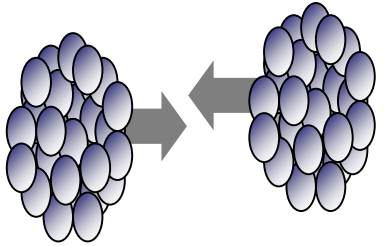
Hot QCD matter:
This is where we expect the QGP to be created in central collisions.

pp
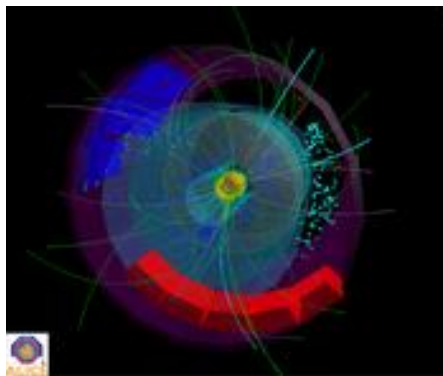
QCD baseline:
This is the baseline for "standard" QCD phenomena.

p-Pb
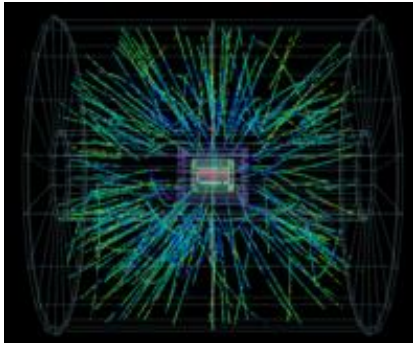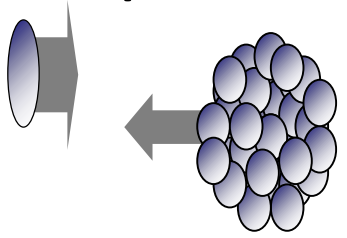
Cold QCD matter:
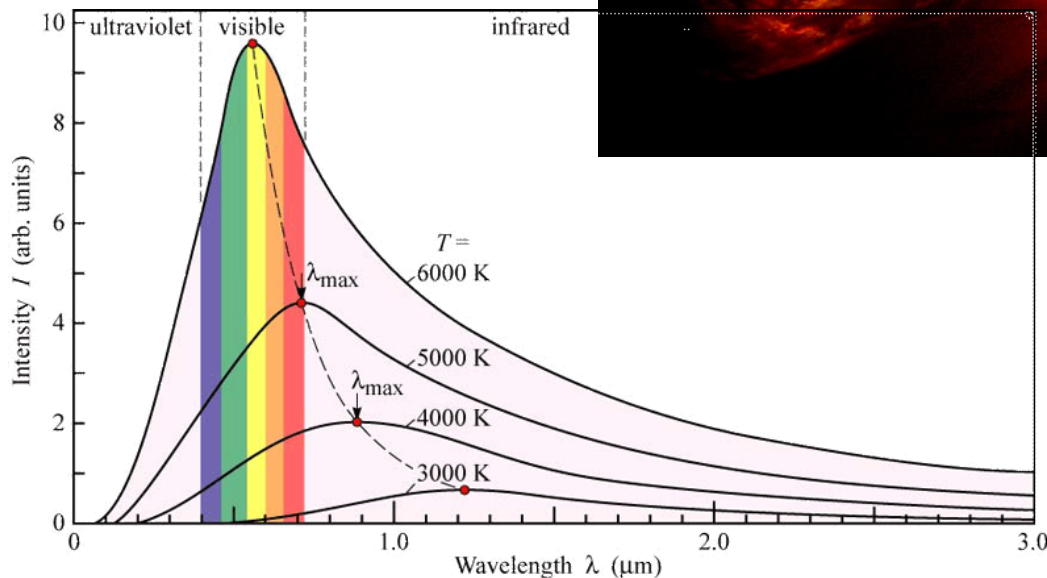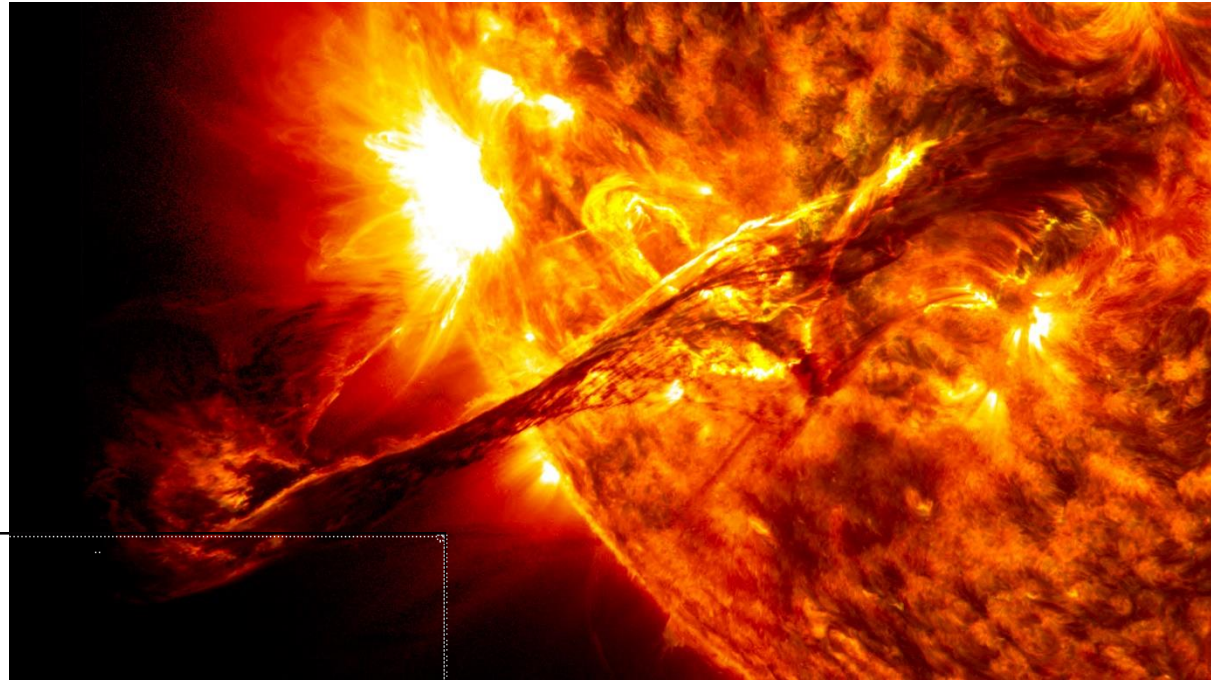This is to isolate nuclear effects, e.g. nuclear pdfs.

Heavy-ion physics and the QGP (P. Christiansen, Lund)

THERMAL PHOTONS

Measuring the medium temperature

- To establish the necessary conditions for a medium one would like to measure the temperature/energy density

- There are in general three possibilities

  - Extracting the final temperature from the p_T slope and particle yields (this is the final temperature)

  - Bjorken has made a famous relation between the initial energy density and the final transverse energy (using hydrodynamics and assumptions on when a medium is formed) Phys. Rev. D27 (1983) 140-151 (2300 citations)

  - Measuring the thermal photon spectrum

    – Photons only interacts weakly with the QGP and so one can probe the early times directly (one measures the time integrated spectrum)

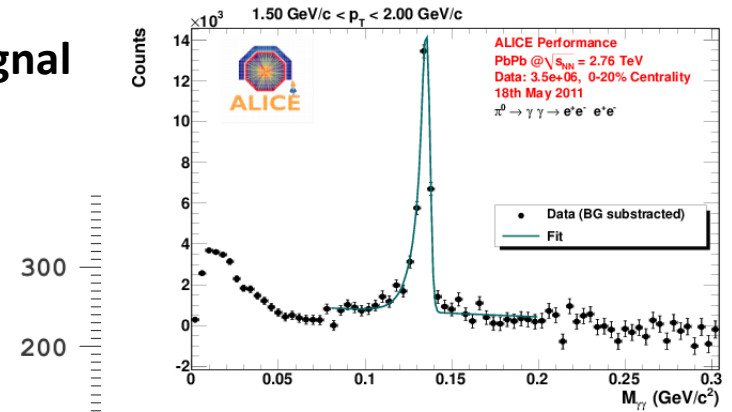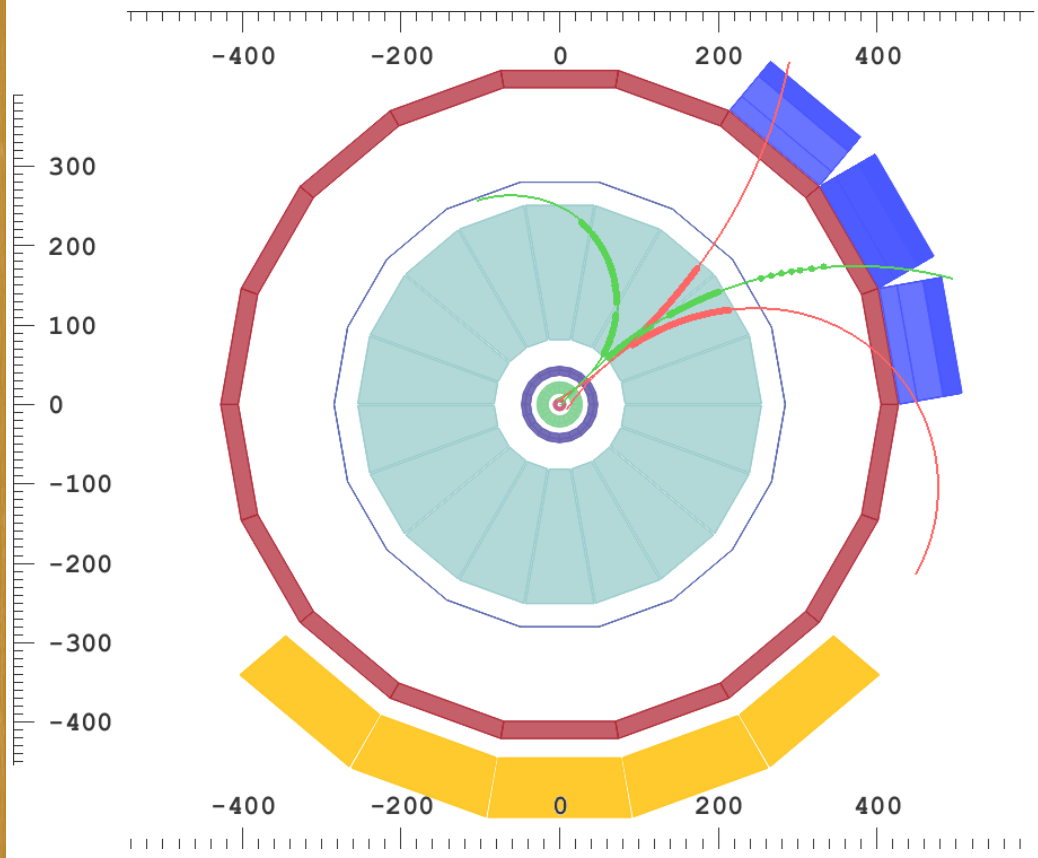# In a similar way as we measure the surface temperature of the sun…


… we can measure the temperature of the QGP

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Photon identification in the TPC via conversion

Heavy-ion physics and the QGP (P. Christiansen, Lund)

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

Direct photons in pp collisions

Heavy-ion physics and the QGP (P. Christiansen, Lund)
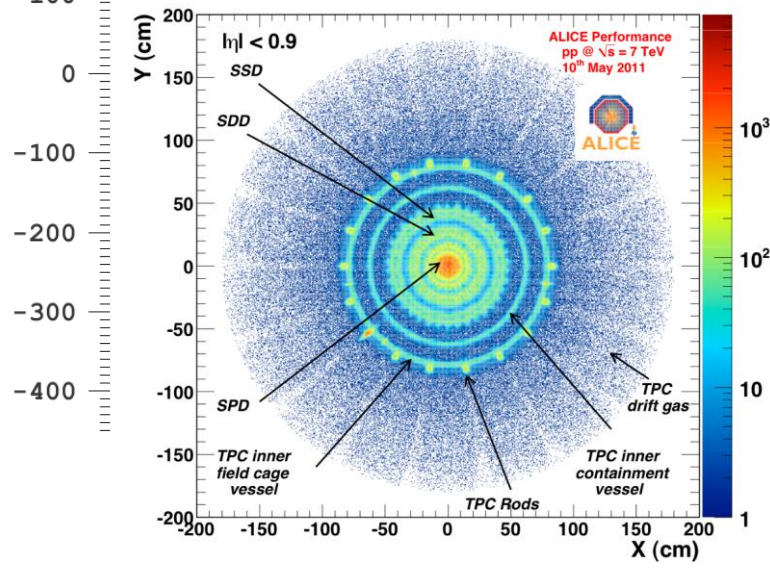
Double Ratio: $\frac{\gamma_{inc}}{\pi^0} / \frac{\gamma_{decay}}{\pi^0_{param}} \approx \frac{\gamma_{inc}}{\gamma_{decay}}$

$\rightarrow$ cancellation of uncertainties

ALI-PREL-27936
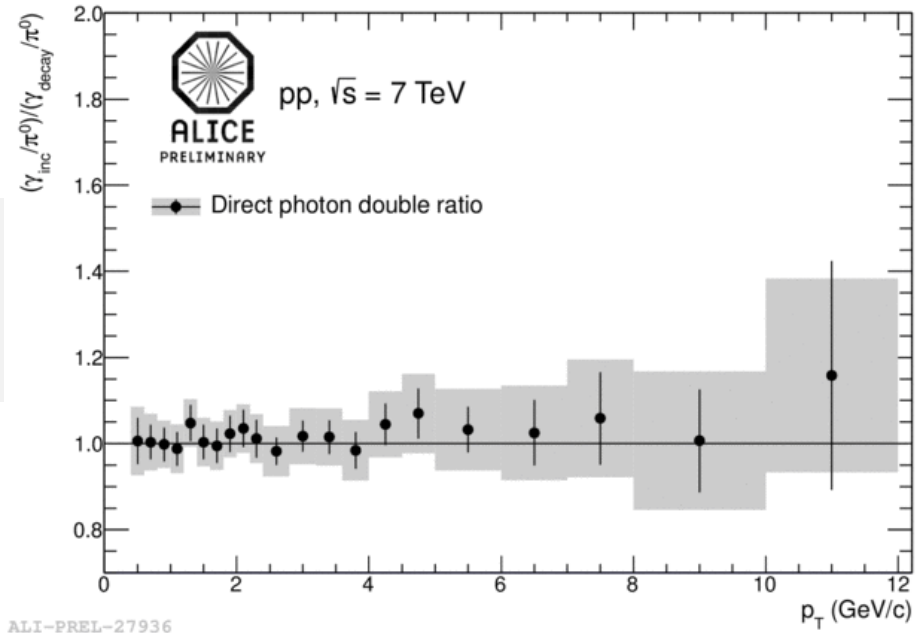
- Construct double ratio to eliminate/reduce systematics
- Numerator is the actual measurement
- Denominator is from a cocktail calculation

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

Direct photons in pp collisions
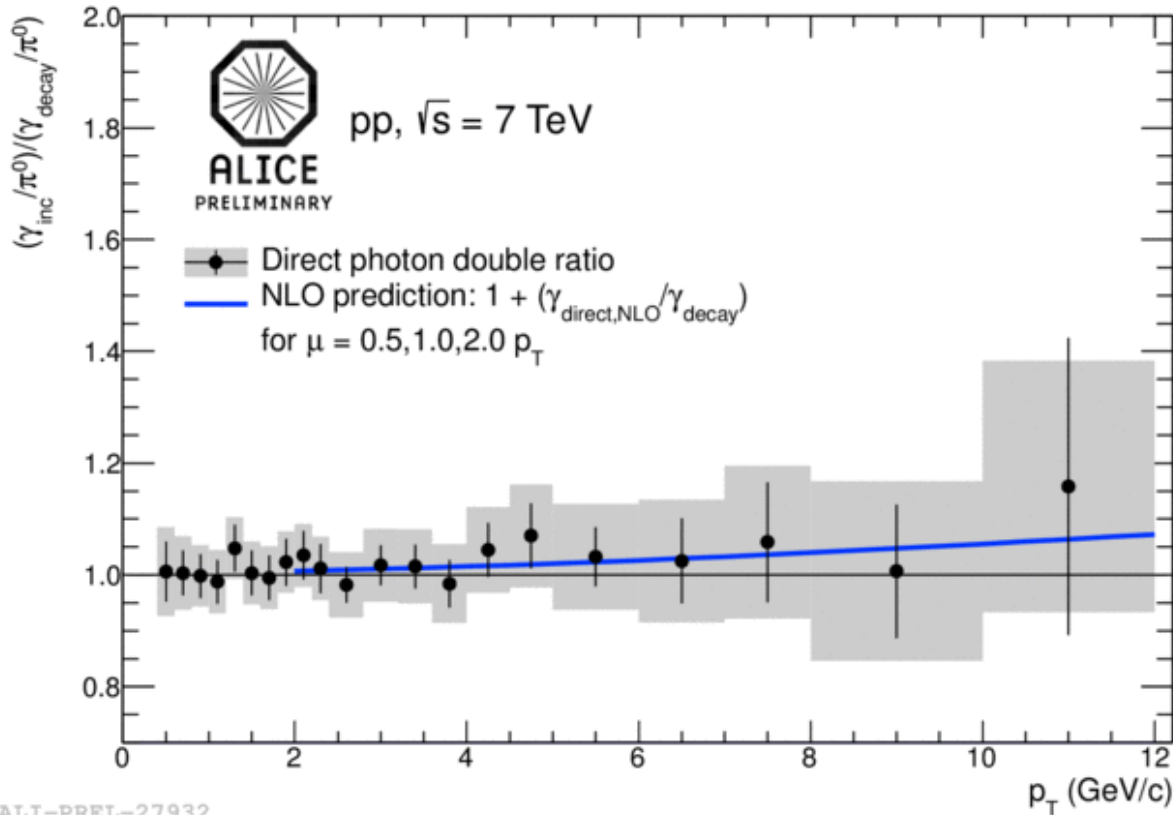
- Comparison to pQCD NLO calculation

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Direct photons in peripheral Pb-Pb collisions
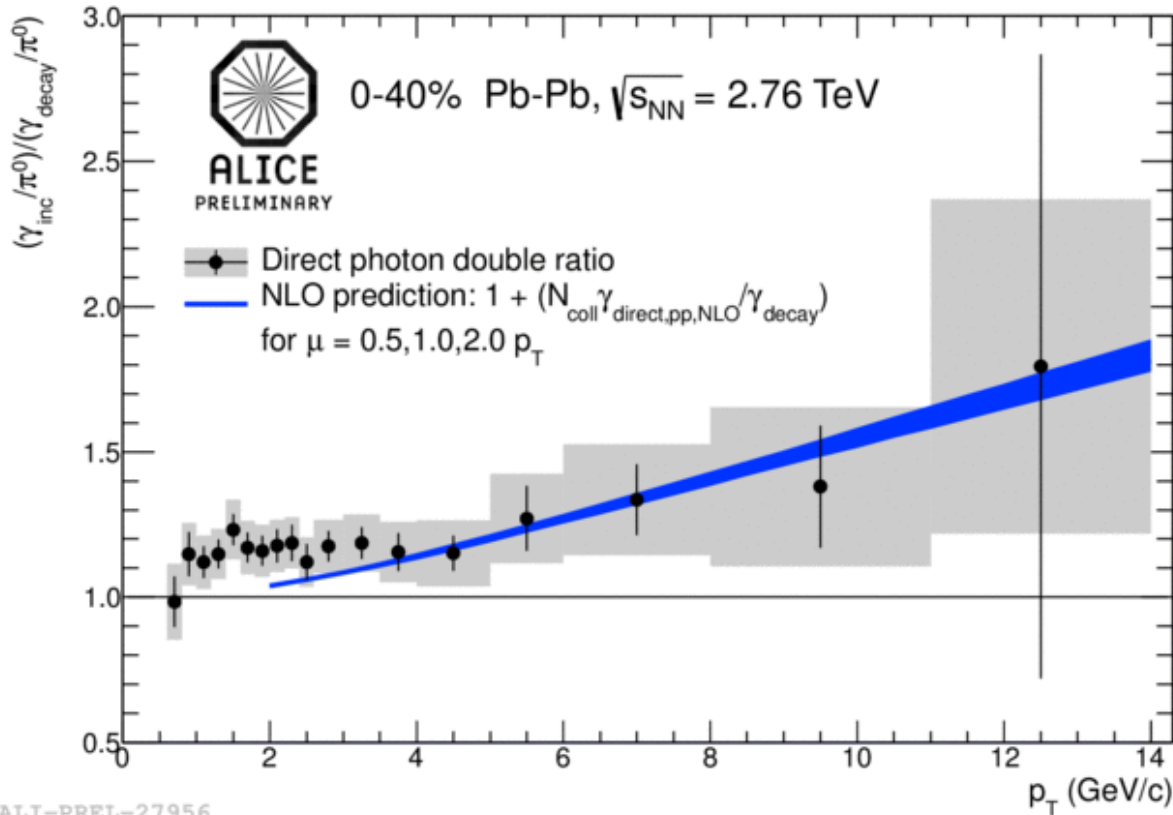
Heavy-ion physics and the QGP (P. Christiansen, Lund)

ALI-PREL-28000
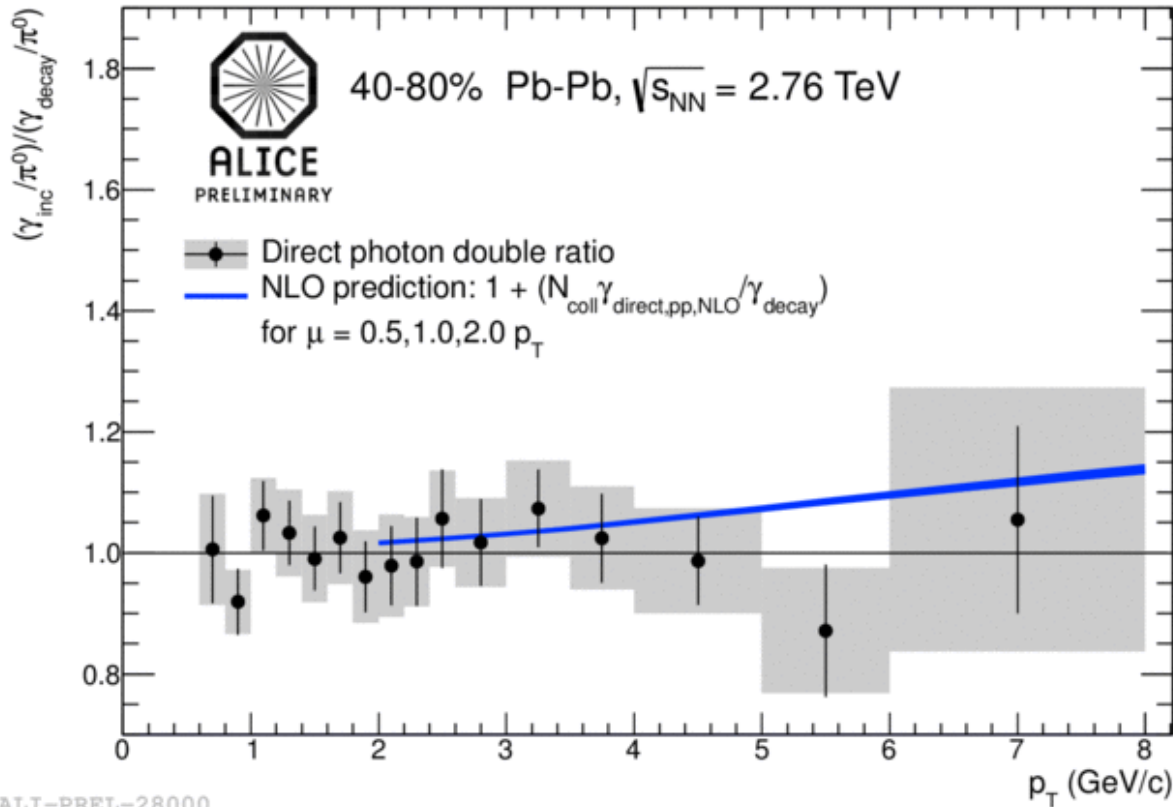
- Peripheral Pb-Pb

   Consistent with only direct and decay photons
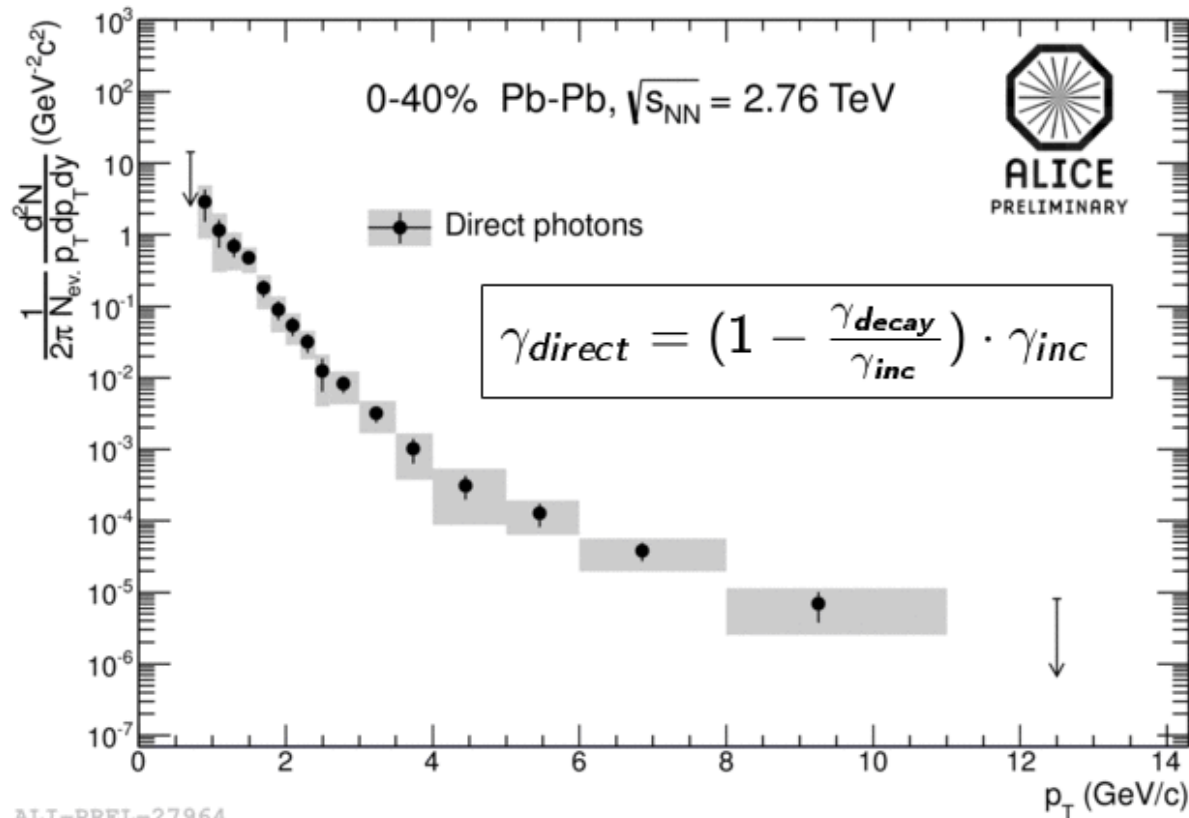
Direct photons in central Pb-Pb collisions

Heavy-ion physics and the QGP (P. Christiansen, Lund)

ALI-PREL-27956

• Central Pb-Pb

Surplus of photons at high pT is expected from hard production

Surplus of photons at low pT are from thermal radiation from the QGP

Direct photon spectrum in central Pb-Pb

0-40% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

ALICE PRELIMINARY

Direct photons

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

ALI-PREL-27964

- Obtain the direct γ spectrum by scaling with the inclusive γ spectrum

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Direct photon spectrum in central Pb-Pb

Heavy-ion physics and the QGP (P. Christiansen, Lund)

ALI-PREL-27968
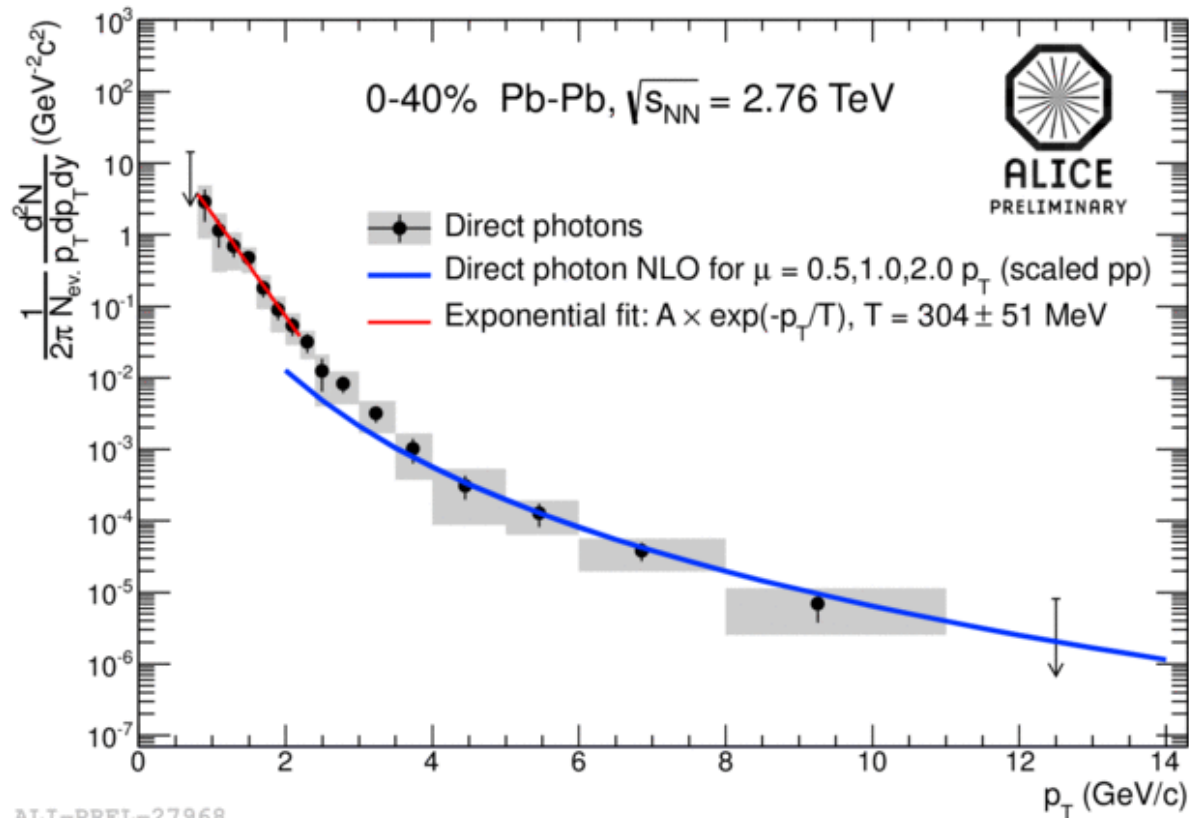
- The temperature of the low p_T direct γ spectrum is of order 300 MeV (recall that this is a time average over the lifetime of the medium)

The highest man-made temperature

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Highest man-made temperature

Share

Who

CERN, LARGE HADRON COLLIDER

What

5X10^12 DEGREE(S) KELVIN

Where

SWITZERLAND

When

13 AUGUST 2012

On 13 August 2012 scientists at CERN's Large Hadron Collider, Geneva, Switzerland, announced that they had achieved temperatures of over 5 trillion K and perhaps as high as 5.5 trillion K. The team had been using the ALICE experiment to smash together lead ions at 99% of the speed of light to create a quark gluon plasma – an exotic state of matter believed to have filled the universe just after the Big Bang.

Heavy-ion physics and the QGP (P. Christiansen, Lund)

HARD PROBES

What happens when we collide pp and Pb-Pb?

- Think for a few minutes

- Discuss with your neighbors for a few minutes

Heavy-ion physics and the QGP (P. Christiansen, Lund)

What happens when we collide pp and Pb-Pb

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- 2 answers!
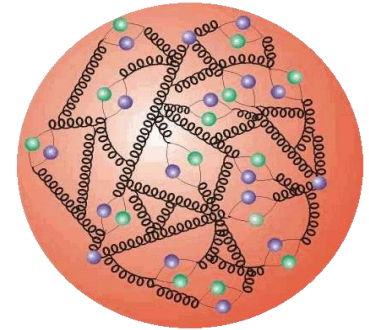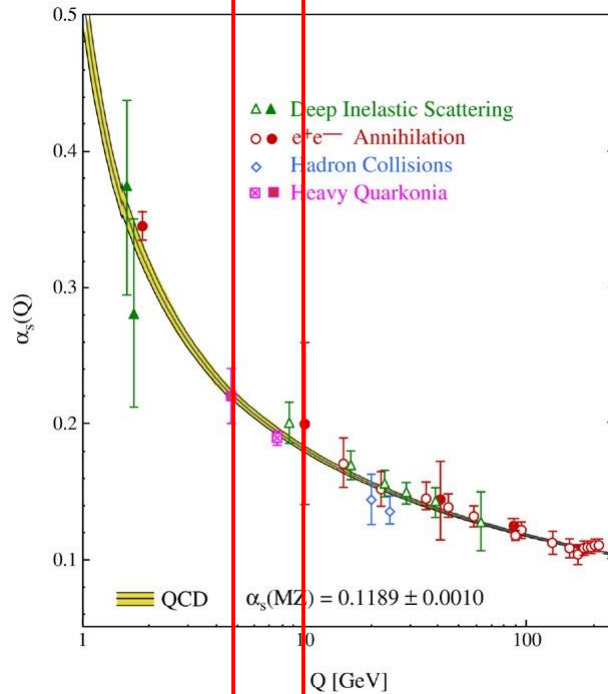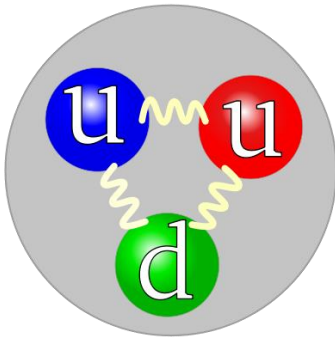
Non-perturbative physics
(knows the equations but not how to
Solve them)
Bulk properties (=medium)

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

Hard probes in heavy-ion collisions

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- The cross sections for Hard probes (HP) can in principle be calculated using pQCD (+ pdfs and FFs). In practice they need to be measured to achieve the best systematic precision.
- The cross sections can easily be extrapolated from pp to Pb-Pb collisions using binary scaling (next slide) unless there are "nuclear" effects
  - HP allow the precise study of nuclear effects
- Penetrating probes
- Strongly interacting probes
  - Heavy quarks (quarkonia), jets

The collision geometry and binary scaling

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- Centrality (ex. for Au+Au):

Spectators

Spectators

0-5% Au-Au at RHIC

Binary collisions (hard)

Participants (soft)

Spectators

Impact Parameter (fm)
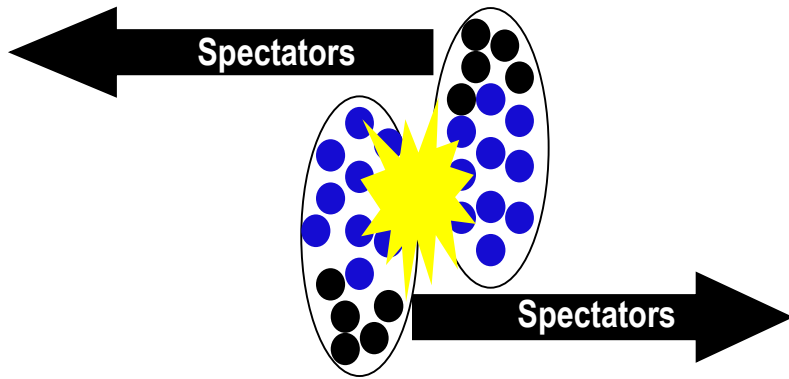
Participants = 2*197 - Spectators
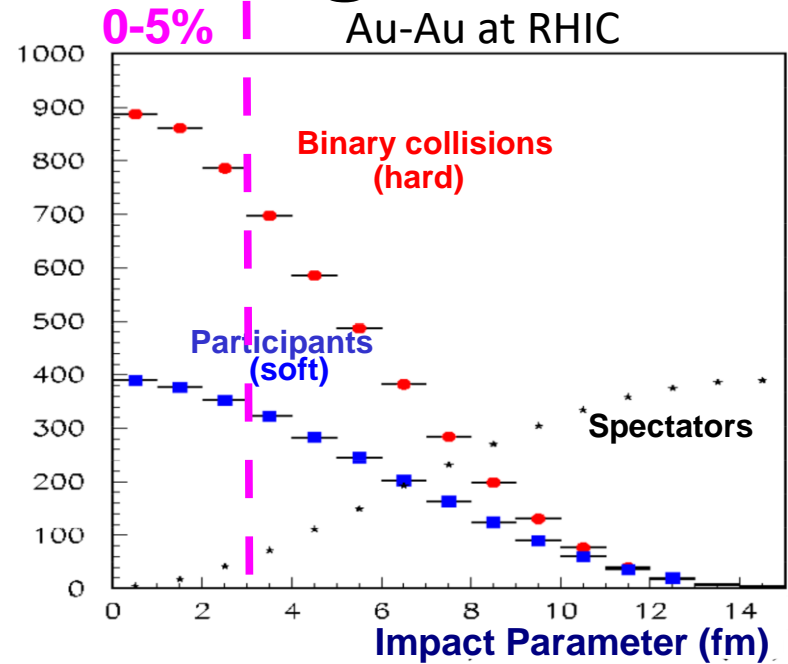
- The "medium" energy is proportional to the # of participant (Npart)
- The number of parton-parton (quark-quark, quark-gluon, gluon-gluon) is proportional to the # of binary collisions (Nbin)
- Example:

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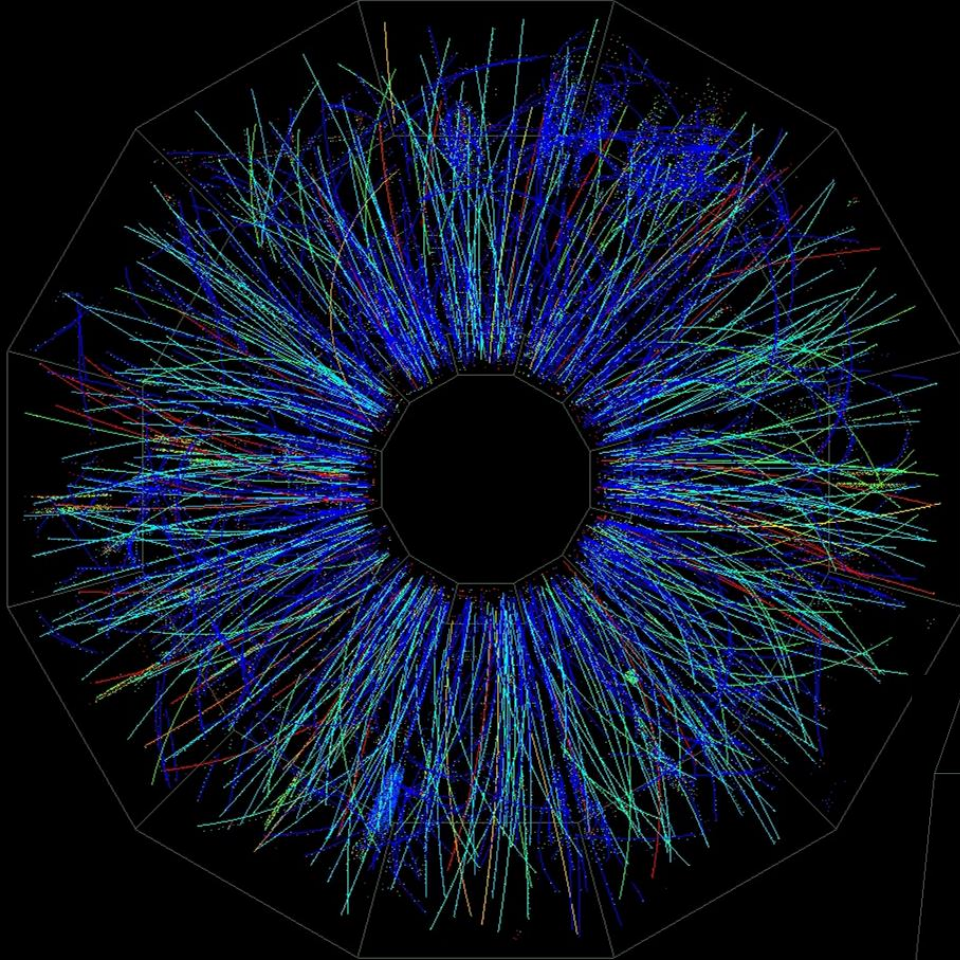
Peripheral Event

From real-time Level 3 display.

color code ⇒ energy loss

STAR
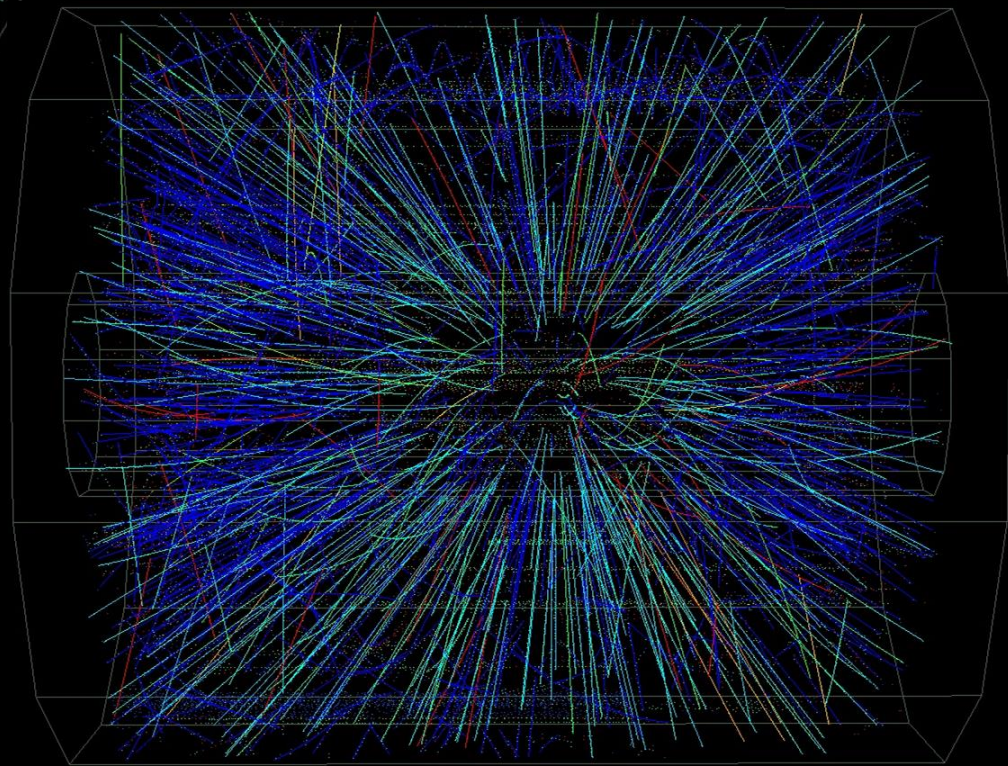
Mid-Central Event

From real-time Level 3 display.

STAR
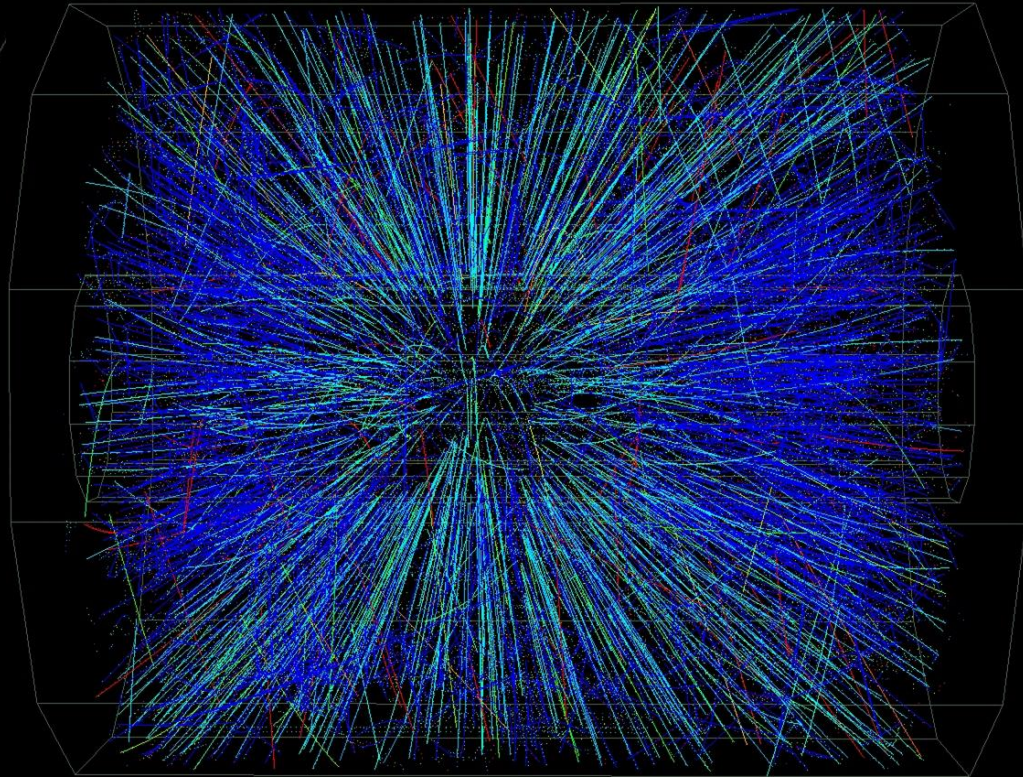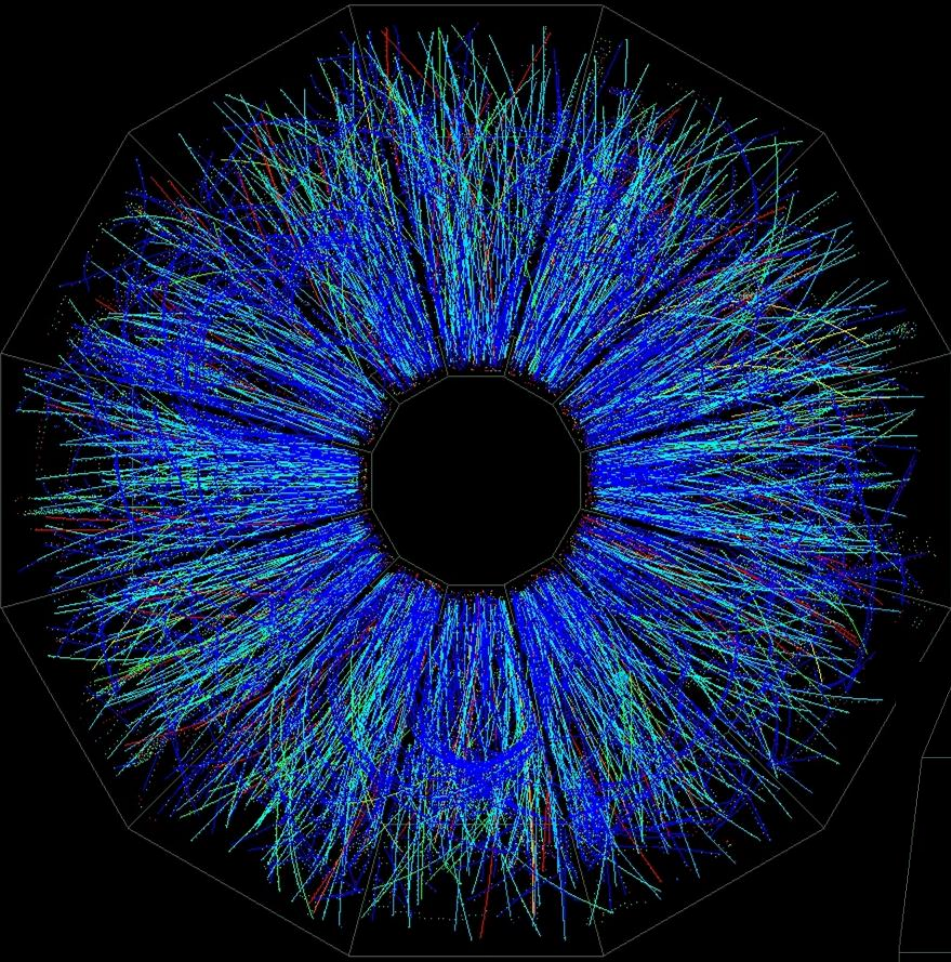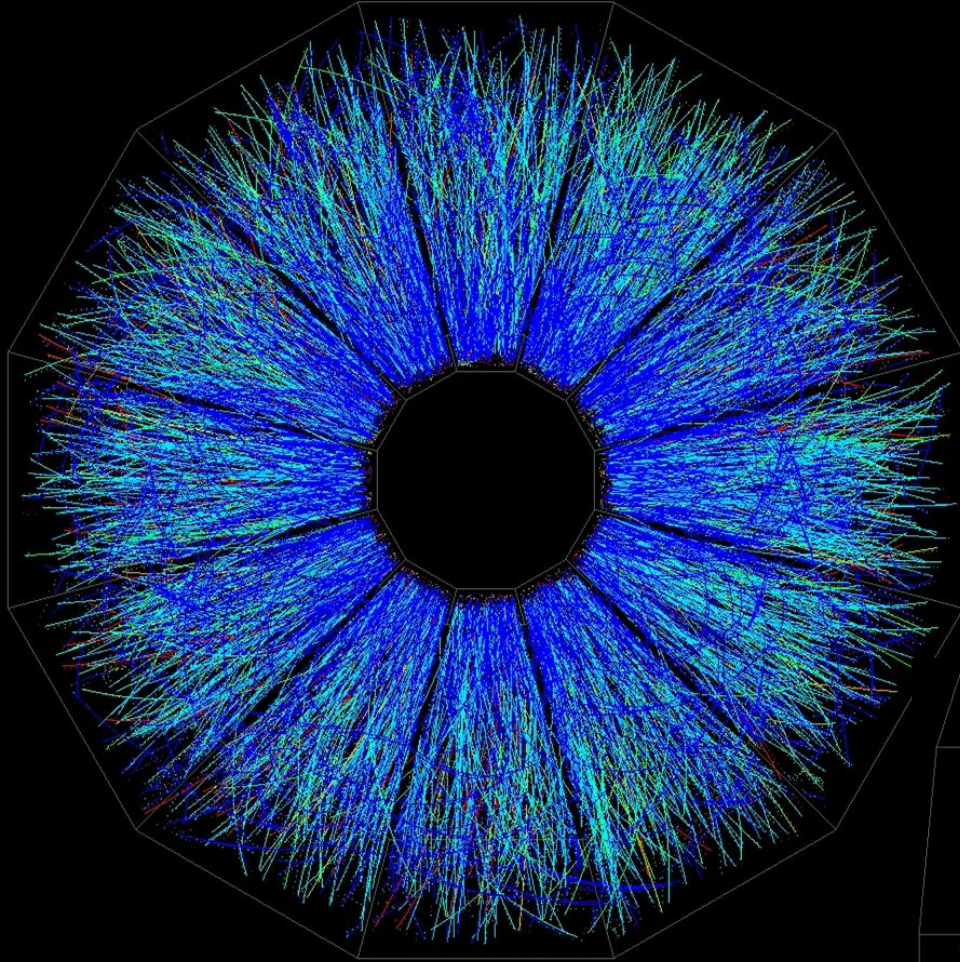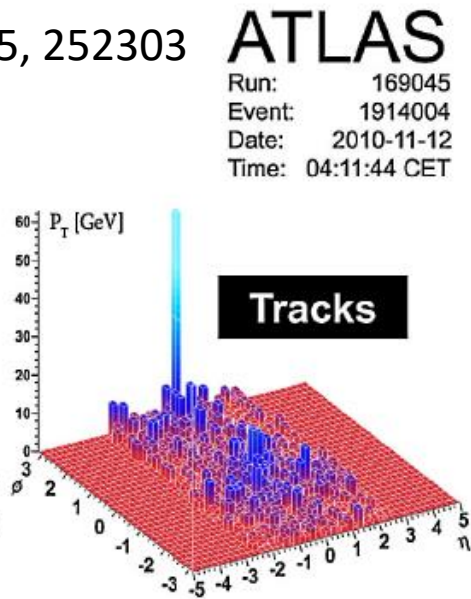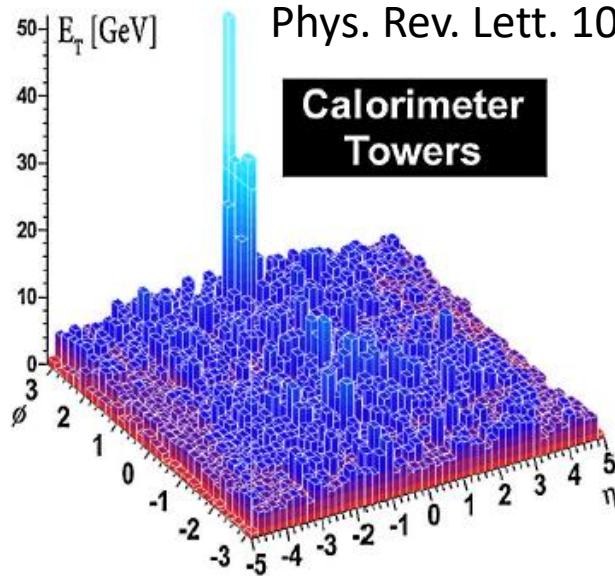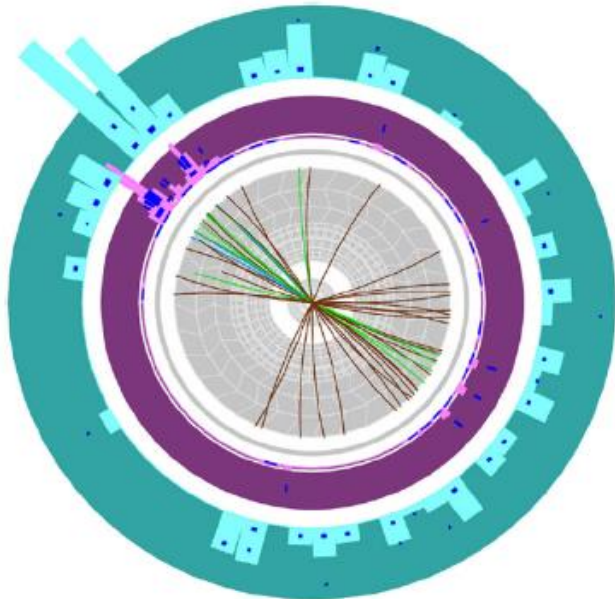
Central Event

From real-time Level 3 display.
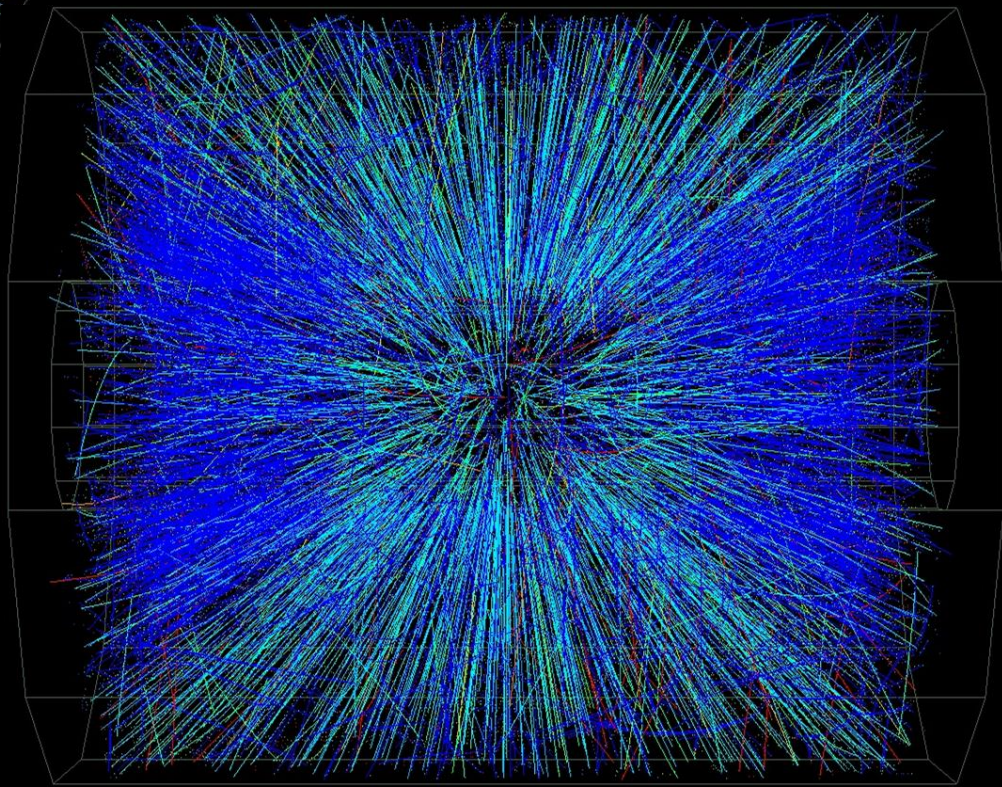
Jet quenching in the QGP
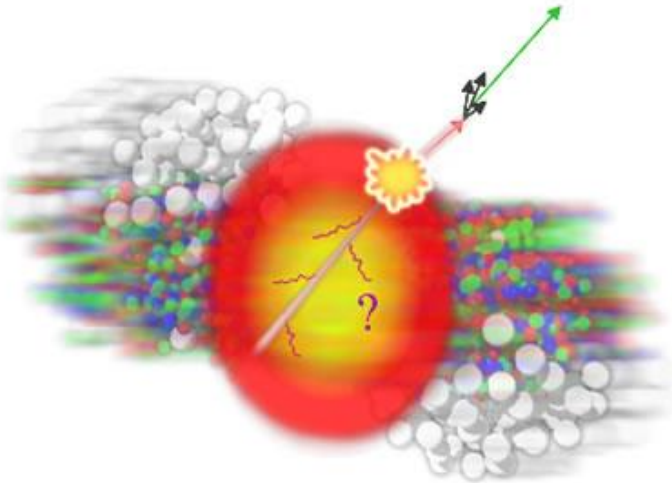
For color charges one expects energy losses of GeV/fm vs MeV/cm for electric charges in normal atomic matter. 10,000,000,000,000,000 (10^{16}) times larger energy loss.

Phys. Rev. Lett. 105, 252303

The nuclear modification factor R_{AA} (1/2)

Heavy-ion physics and the QGP (P. Christiansen, Lund)

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

$<T_{AA}>\sigma^{pp} = <N_{coll}>$
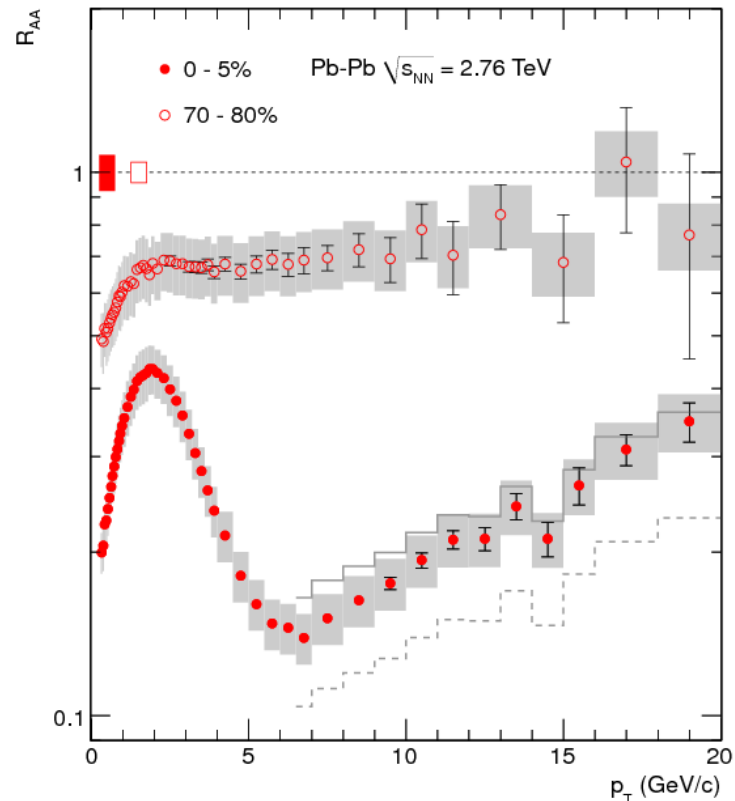N_{coll} is the number of binary collisions

For perturbative QCD processes:
R_{AA}<1: suppression
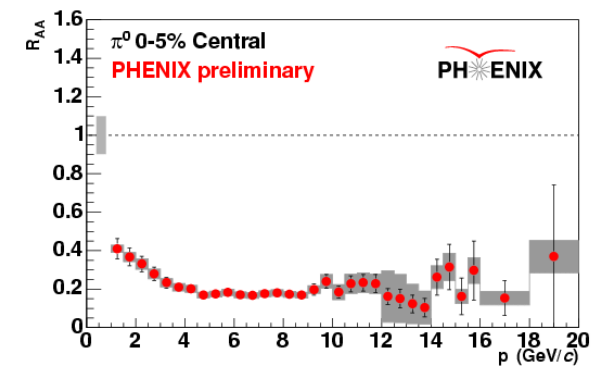R_{AA}=1: no nuclear effects
R_{AA}>1: enhancement
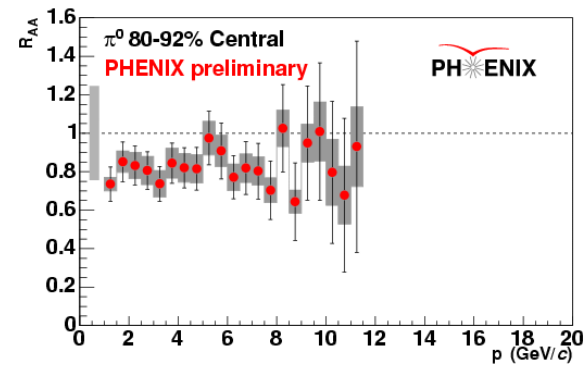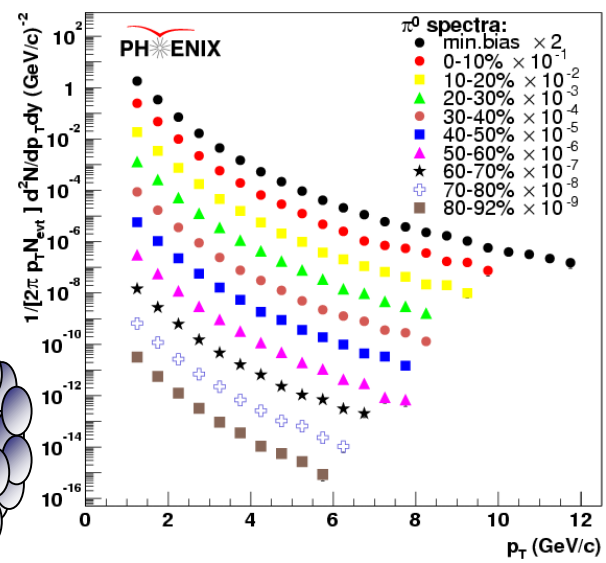

Phys. Lett. B 696 (2011)
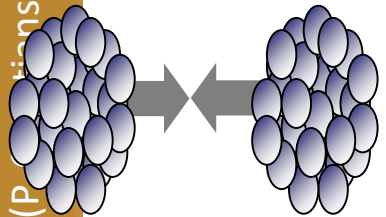
So R_{AA} is a way to quantify the nuclear effects!

The nuclear modification factor R$_{AA}$ (2/2)

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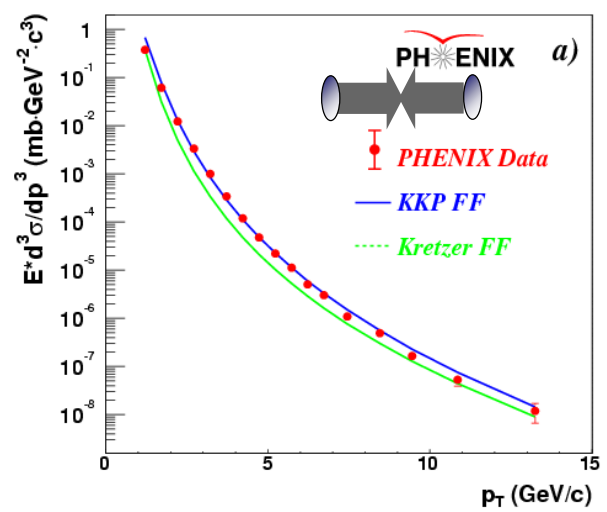
Ncoll

Standard candles

We need penetrating hard probes to validate the binary scaling

What could that be?

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Ncoll scaling for direct photons
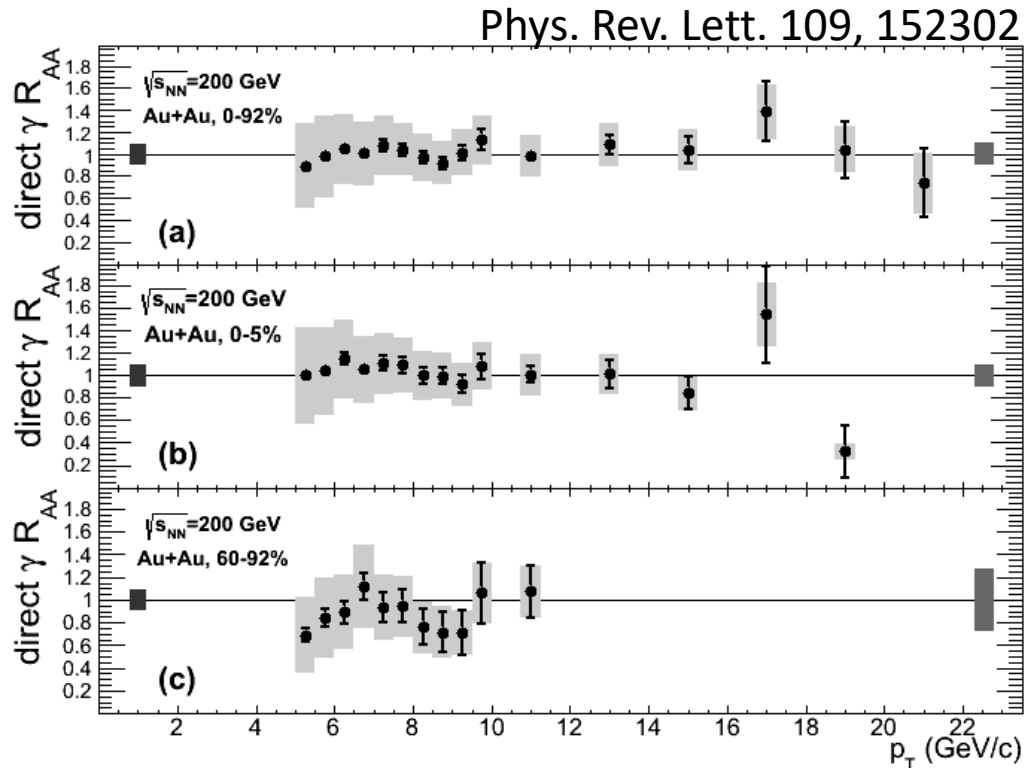
Source of direct photons

Annihilation   Compton Scattering
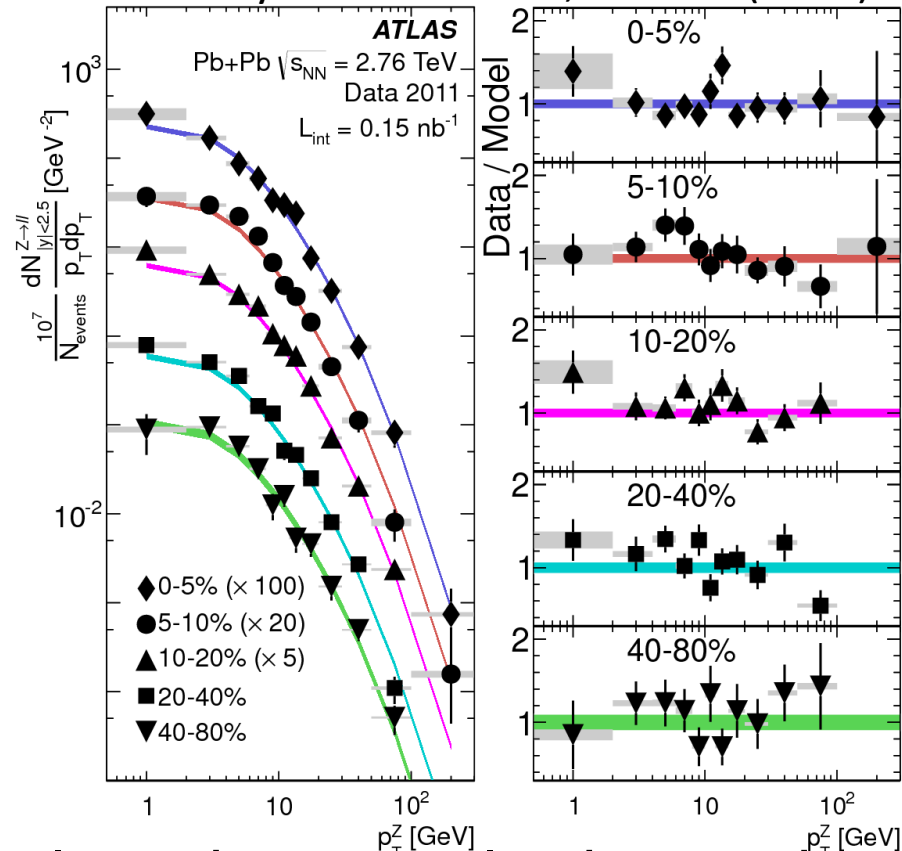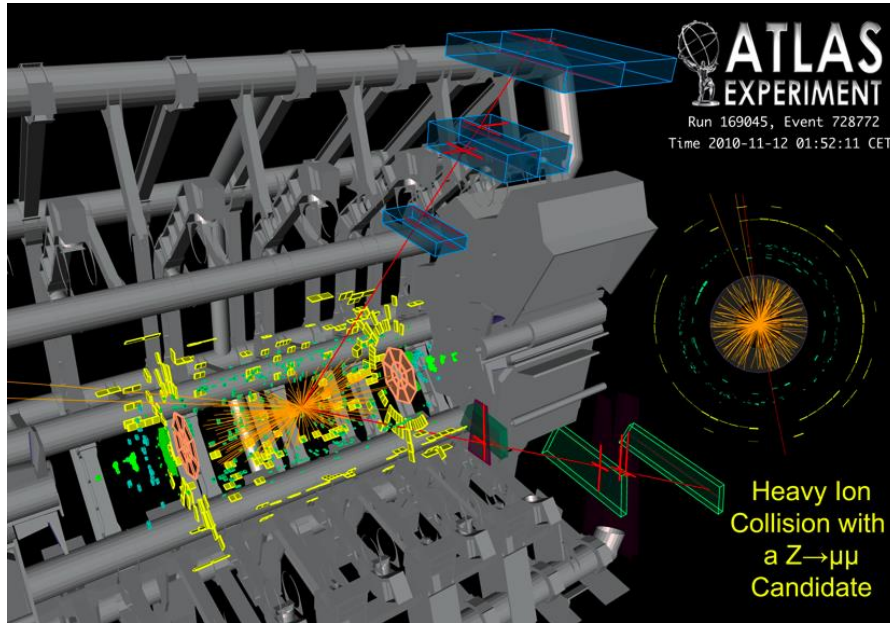
Heavy-ion physics and the QGP (P. Christiansen, Lund)
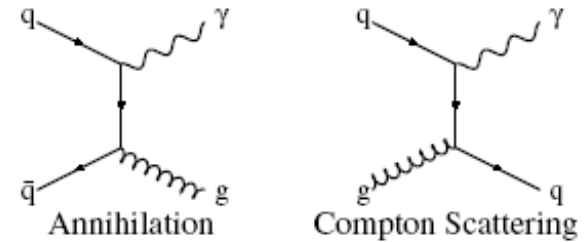
- Direct photons does not interact with final state hadronic matter and the results confirm binary scaling of hard processes!
- The best standard candle at RHIC

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

Heavy-ion physics and the QGP (P. Christiansen, Lund)

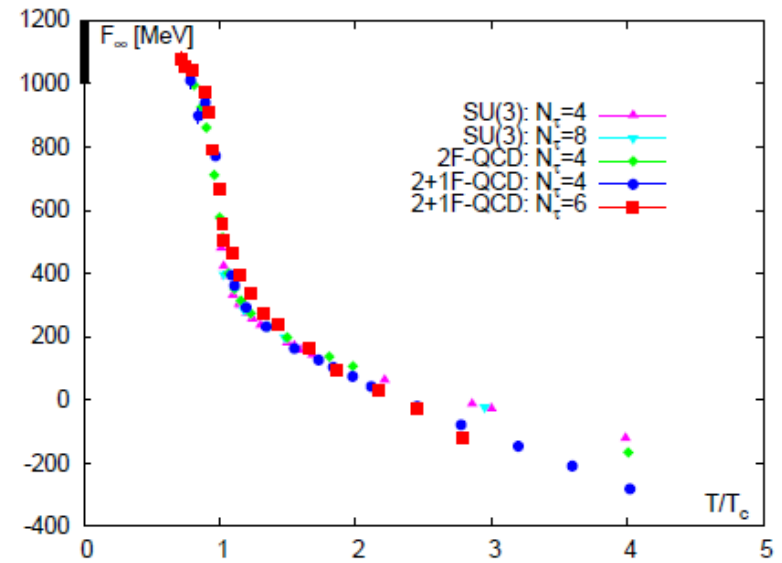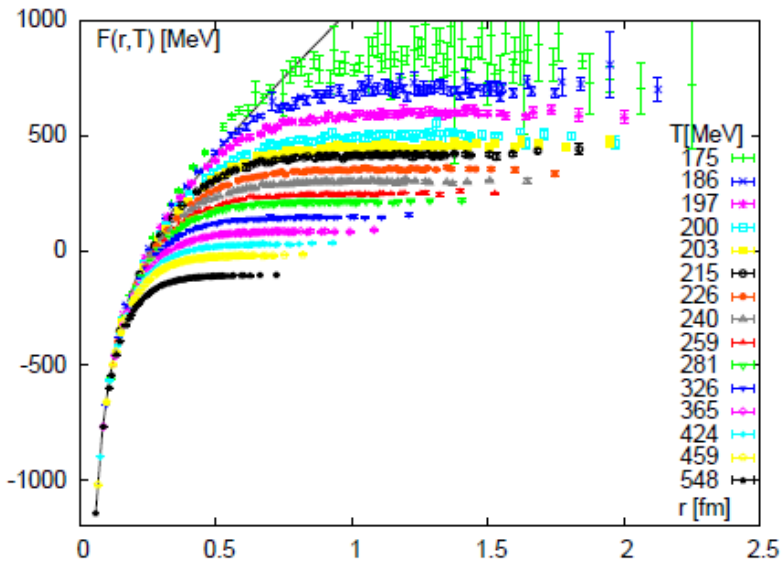Phys. Rev. Lett 110, 022301 (2013)

- The Z does not interact strongly and so can also be used to check binary scaling at LHC
- Also the W have been used at LHC

Heavy quarks:
I will only focus on Quarkonia

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Lattice QCD results for the heavy quark potential (free energy): arXiv:0710.0498

Lattice QCD predicts that the long range force will be screened in the plasma
Bound state properties will change and some states will disappear / melt

Original idea:
"J/ψ Suppression by Quark-Gluon Plasma Formation" by T. Matsui and H. Satz
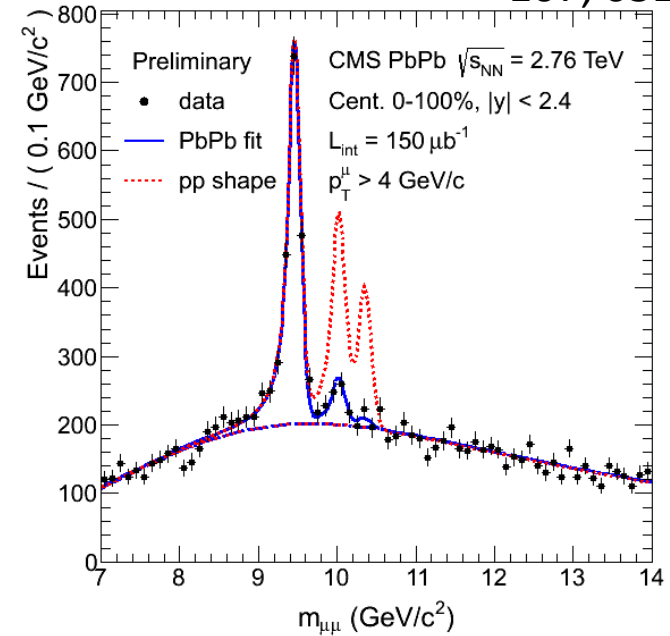Phys.Lett. B178 (1986) 416
Cited by 2108 records

LHC has delivered

Heavy-ion physics and the QGP (P. Christiansen, Lund)

ϒ: 1S 2S 3S   Published in PRL 107, 052302
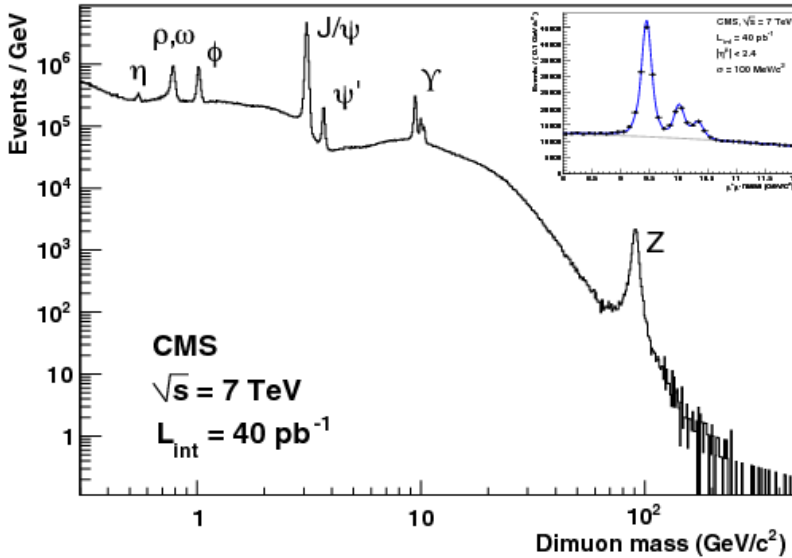
CMS has proven to be a marvelous detector for bottomonium
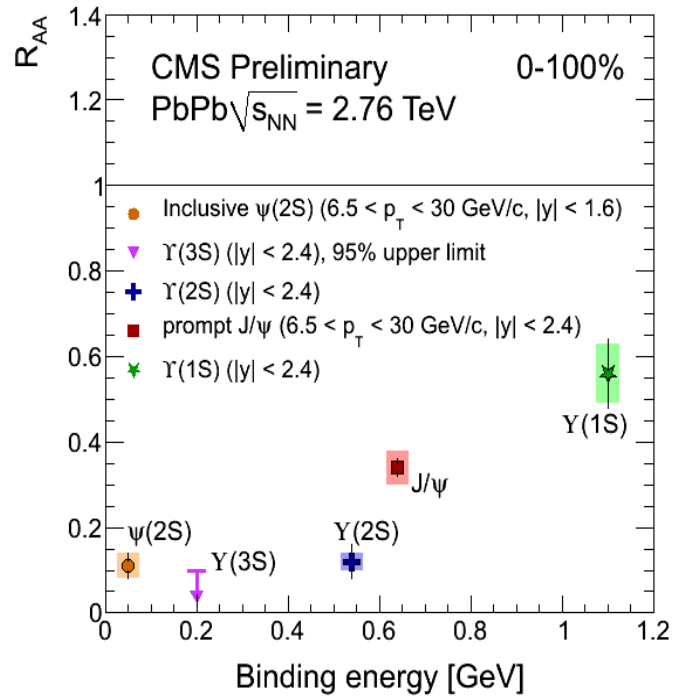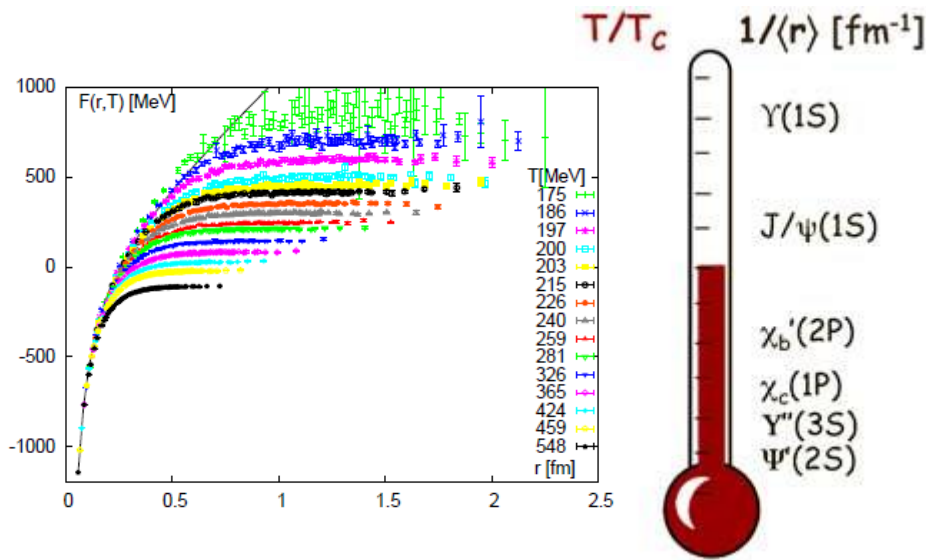ALICE can complement by going to lower p_T for charmonium

These textbook results demonstrate the amazing capabilities of LHC detectors

Suppression of heavy quarkonia can work as a thermometer

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

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Suppression qualitatively depends on binding energy as predicted

J/ψ results from ALICE: Evidence for regeneration

Heavy-ion physics and the QGP (P. Christiansen, Lund)
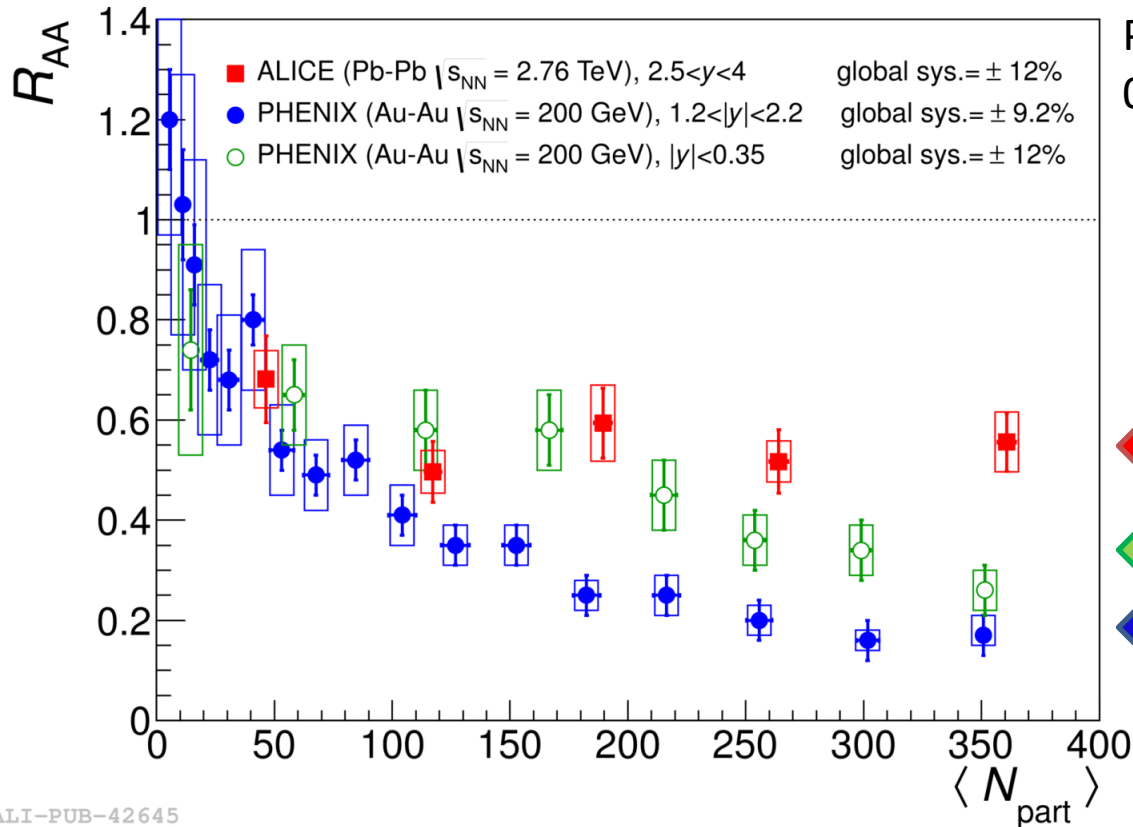
Phys. Rev. Lett. 109, 072301 (2012)

ALICE can go down to p_T~0.

⟸ LHC

⟸ RHIC (mid)

⟸ RHIC (fwd)

The suppression of J/ψ at LHC is less than at RHIC!
Understanding: due to the large cross section "random" charm and anti-charm quarks combine (see next slides)

J/Psi differential results

Heavy-ion physics and the QGP (P. Christiansen, Lund)

ALI-PUB-64810
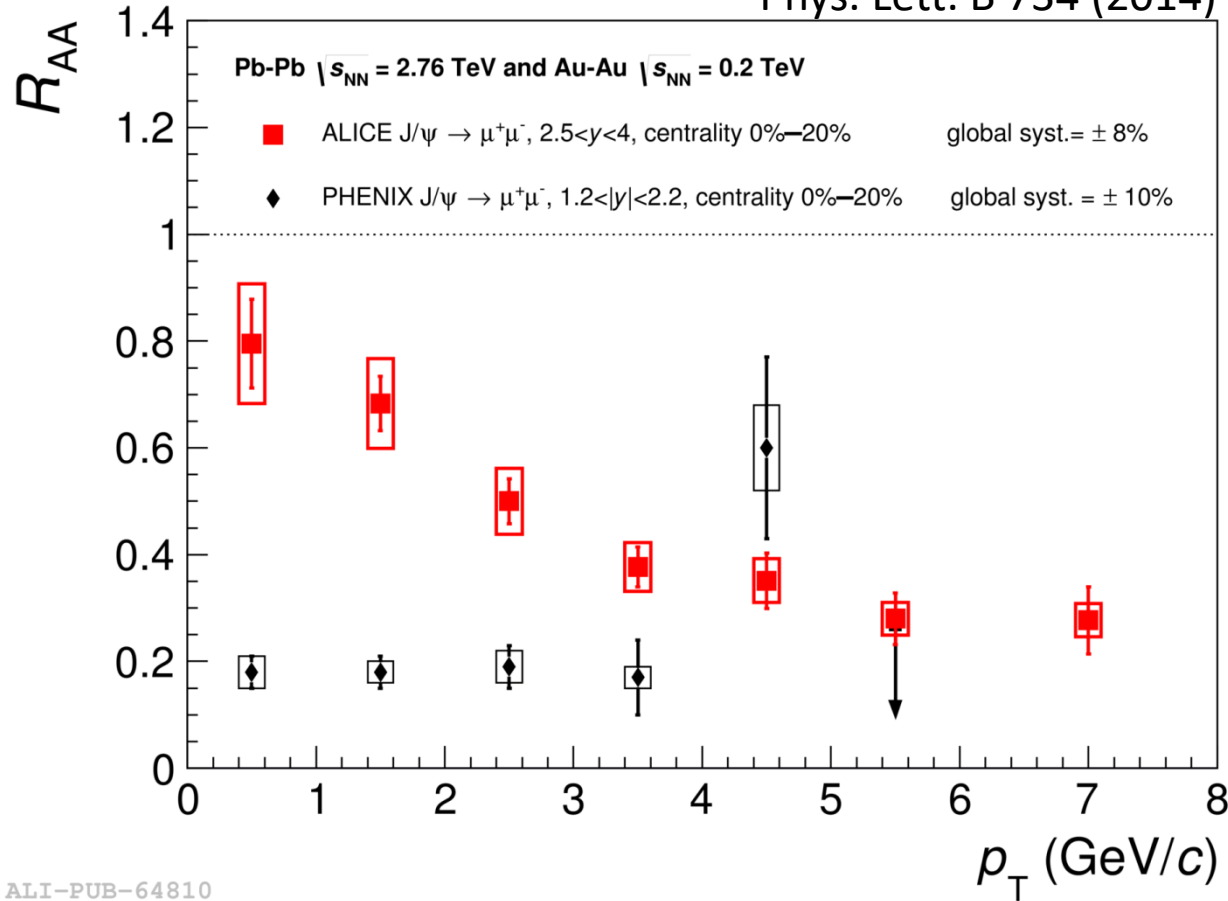
The difference in suppression is visible at low p_T

J/Psi differential results

Heavy-ion physics and the QGP (P. Christiansen, Lund)

ALI-DER-65286
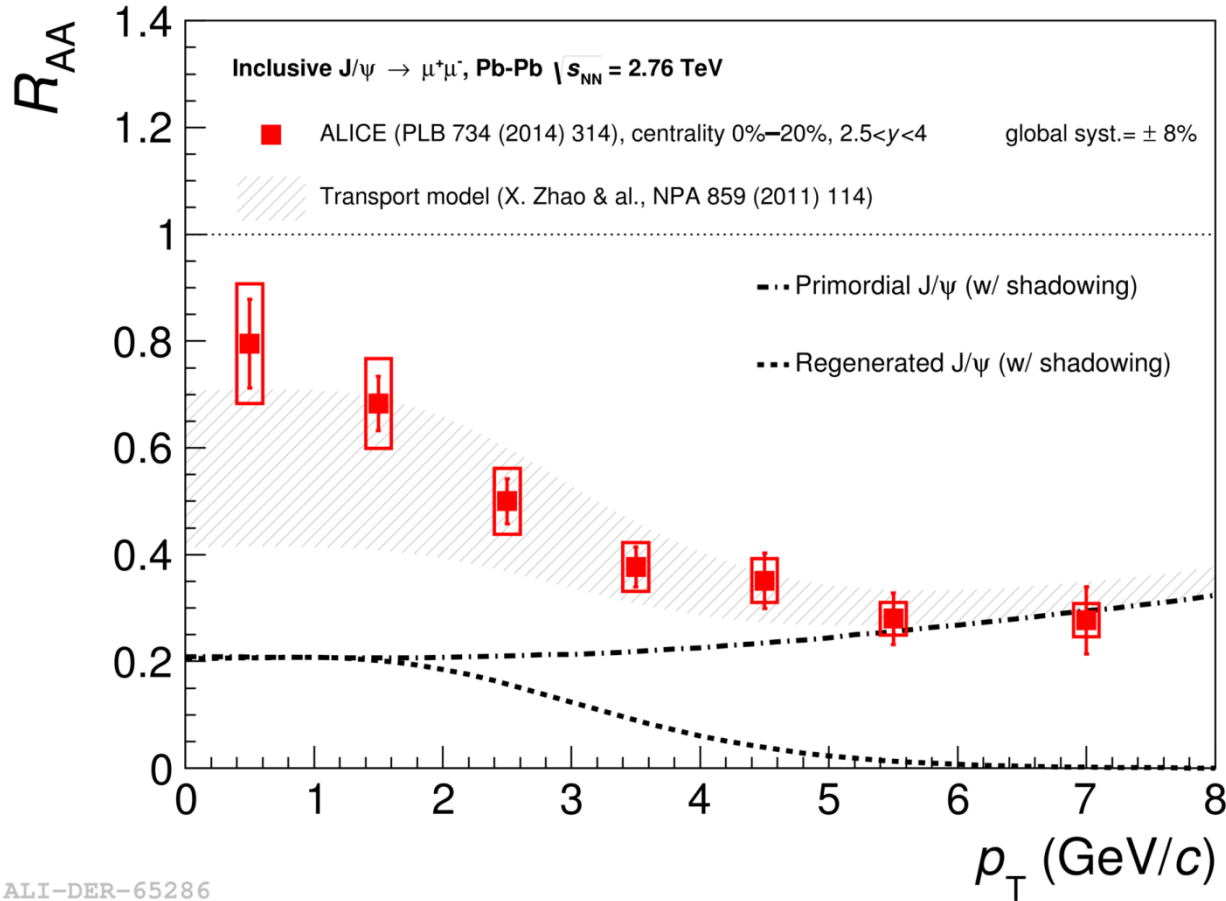
The difference can be explained by J/ψ regeneration (much larger charm Xsection at LHC)

(This effect was already proposed before the RHIC results came out.)

Caveat: cold nuclear matter effects are not understood

Heavy-ion physics and the QGP (P. Christiansen, Lund)

JHEP12(2014)073

lead rapidity

proton rapidity

ALICE, p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV, inclusive J/ψ, ψ(2S)→μ$^+$μ$^-$
▲ J/ψ
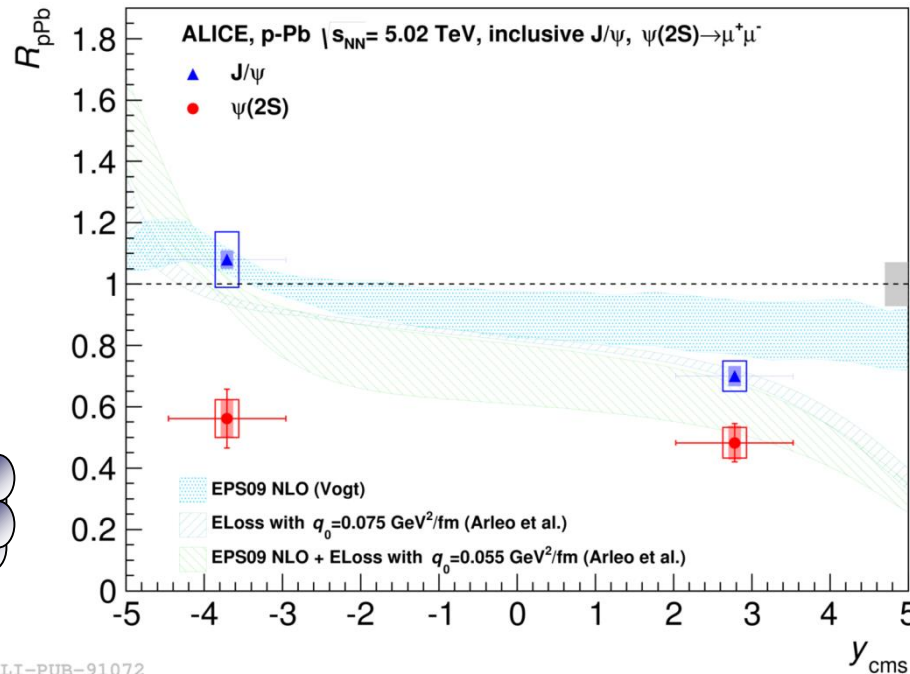● ψ(2S)

R_{pPb}

EPS09 NLO (Vogt)
ELoss with q_0=0.075 GeV^2/fm (Arleo et al.)
EPS09 NLO + ELoss with q_0=0.055 GeV^2/fm (Arleo et al.)

y_{cms}
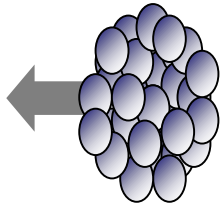
ALI-PUB-91072

For J/ψ we have reasonable good description: energy loss really just means that due to collisions with other nucleons the rapidity of the J/ψ is shifted towards the Pb-nuclei.
But why is the 2S state extremely suppressed in p-Pb (at the rapidity) where the 1S state is a bit enhanced?

The relative production of ϒ states is affected by event activity (?)

JHEP04(2014)103

Heavy-ion physics and the QGP (P. Christiansen, Lund)
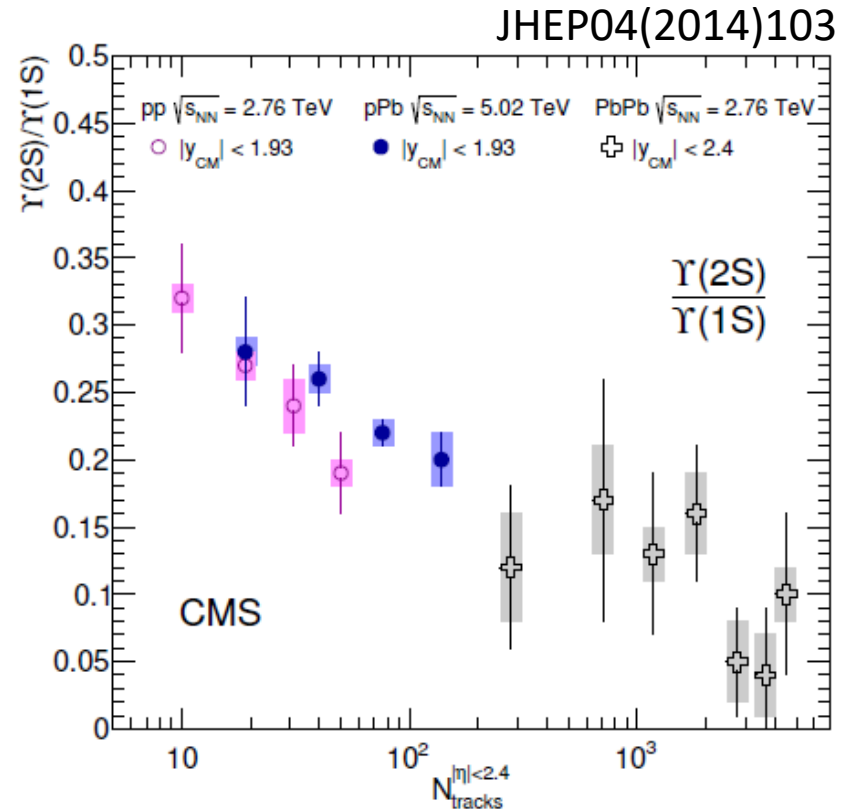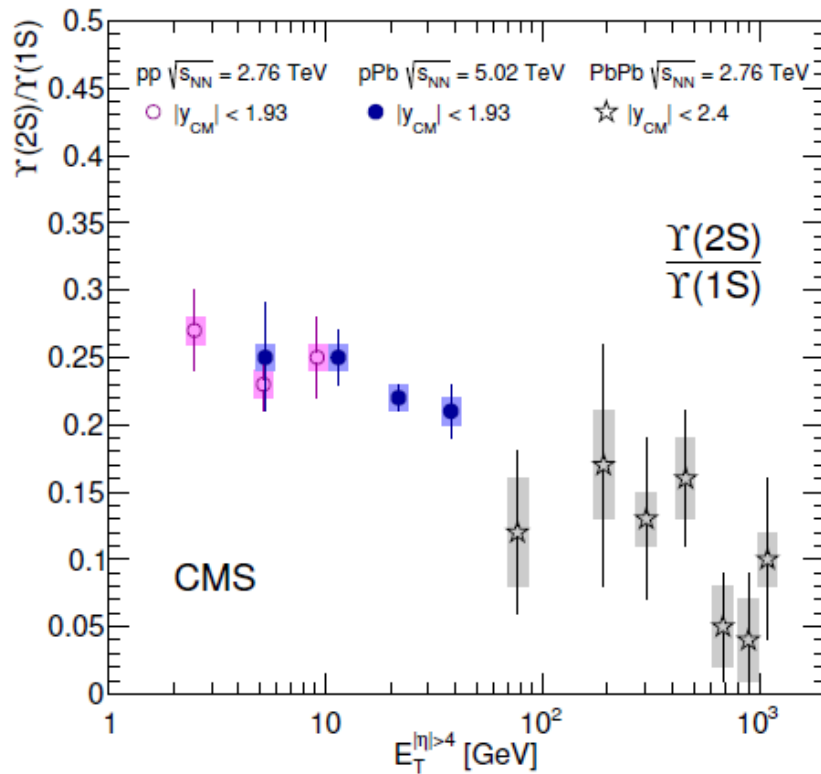
Also for ϒ we observe varying trends for the different states even for pp collisions!
(More info on next slide)

In small systems we observe enhancement with event activity

JHEP04 (2014)103

Heavy-ion physics and the QGP (P. Christiansen, Lund)

In this case we observe different trends with event activity
Caveat: should study binary scaling (but this does not work for pp)
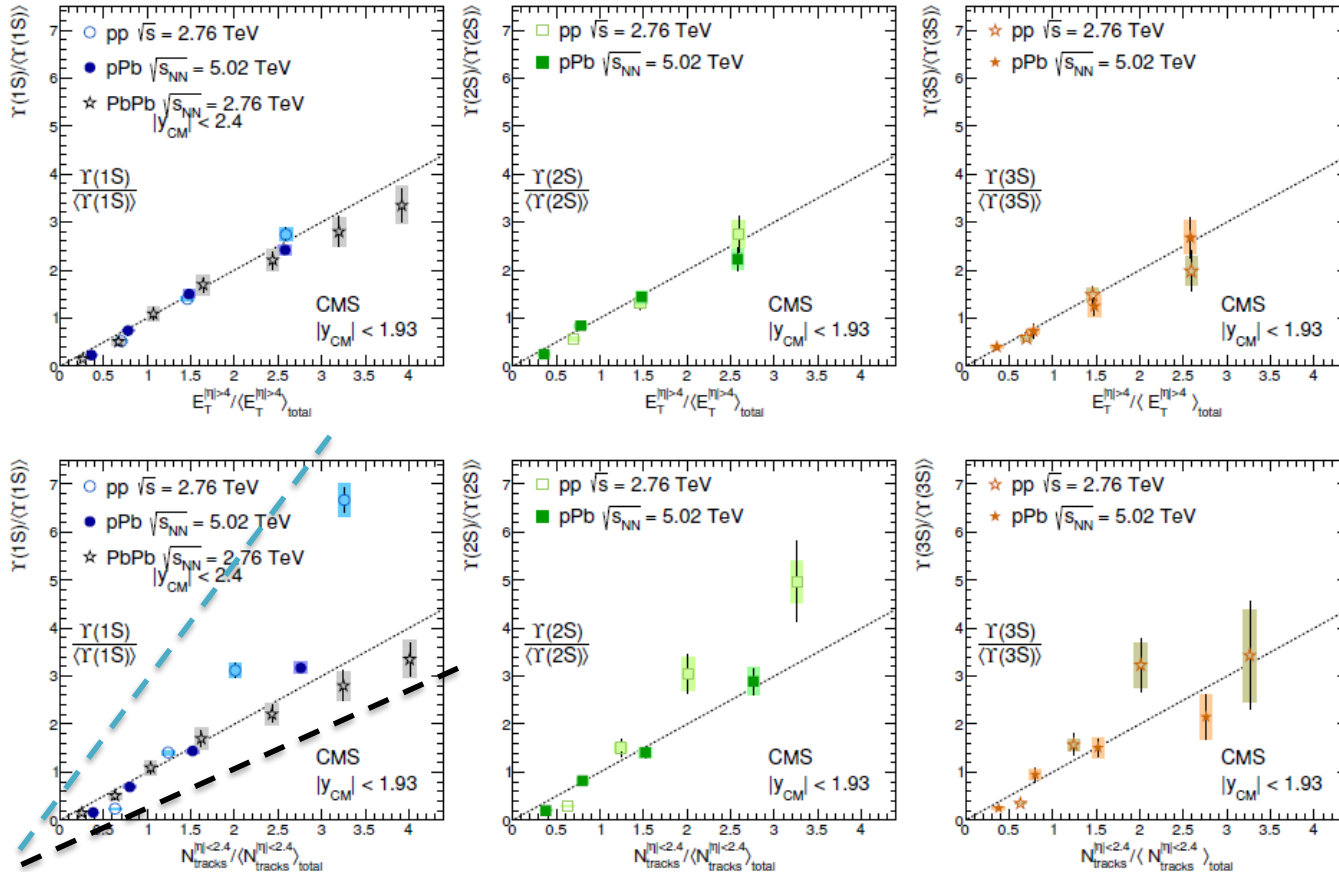
Summary of quarkonia results

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- The qualitative results are in agreement with what one expects for a Quark Gluon Plasma

- The advantage of LHC is that all quarkonia states have been measured making the measurements less sensitive to assumptions about feed-down corrections

- The quantitative picture is complicated and there are many issues that are even interesting for pp phenomenology

Heavy-ion physics and the QGP (P. Christiansen, Lund)

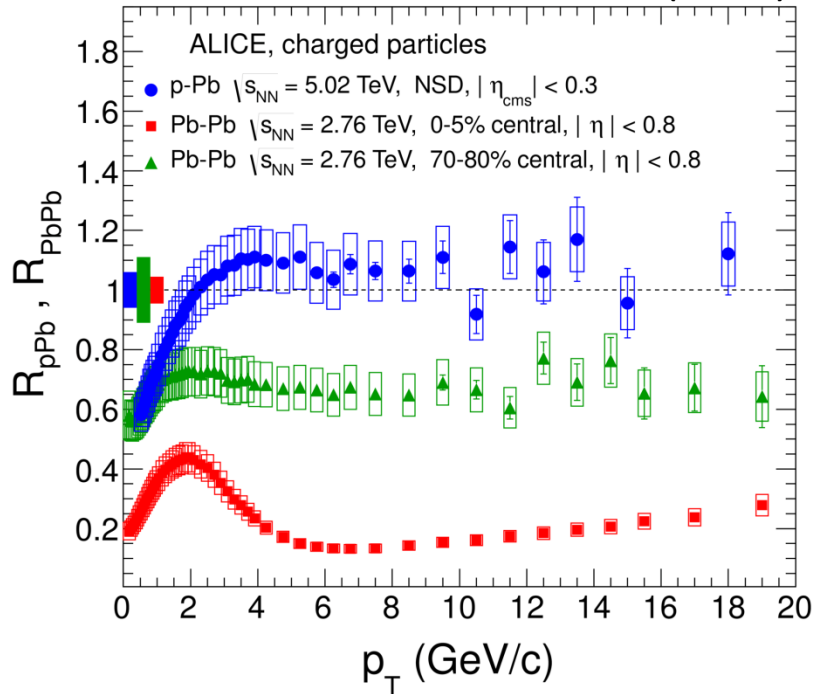# JETS

Jets as probes of the QGP
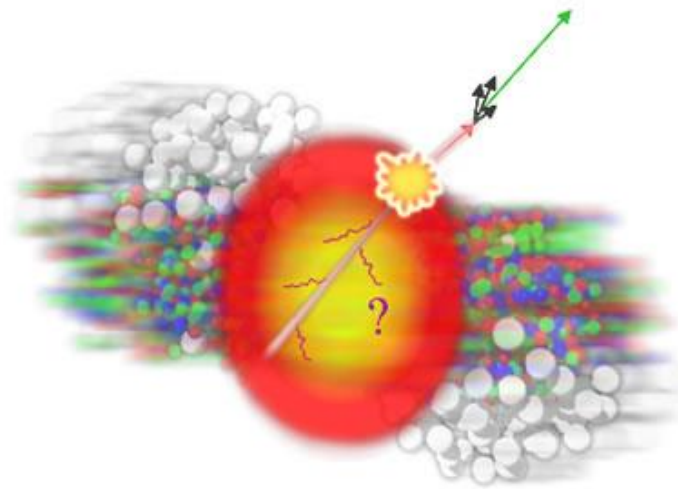
- The idea to use jets to probe the QGP goes back to Bjorken. He made a first study of collisional energy loss but never published this as he realized that radiative energy loss was much more important

- The phenomenology is quite difficult and has many variants so I focus on the experimental results

High p_T particles: a proxy for jets

ALICE, PRL 110, 082302 (2013)

At RHIC very few studies have been done with jets. Instead high p_T particles have been used to study jet quenching.

At LHC high p_T results are also used but additionally there are many jet studies.

Results at LHC are qualitatively similar to results from RHIC with a large suppression in central collisions
New things were the clear rise with p_T
LHC has huge advantage due to the larger jet Xsection.

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Jets in pp

hadrons from jet fragmentation

parton

parton

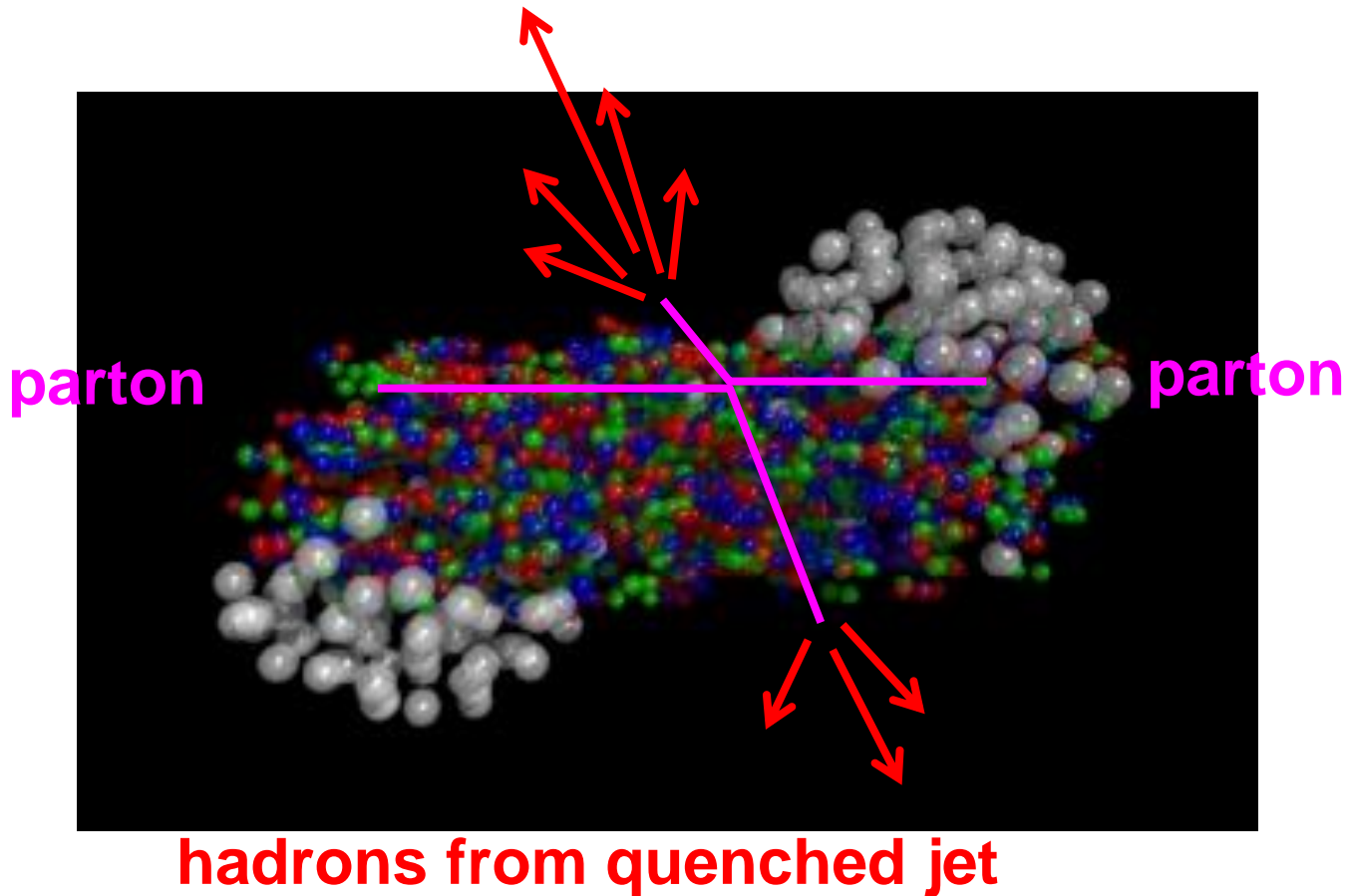**hadrons from jet fragmentation**

Heavy-ion physics and the QGP (P. Christiansen, Lund)
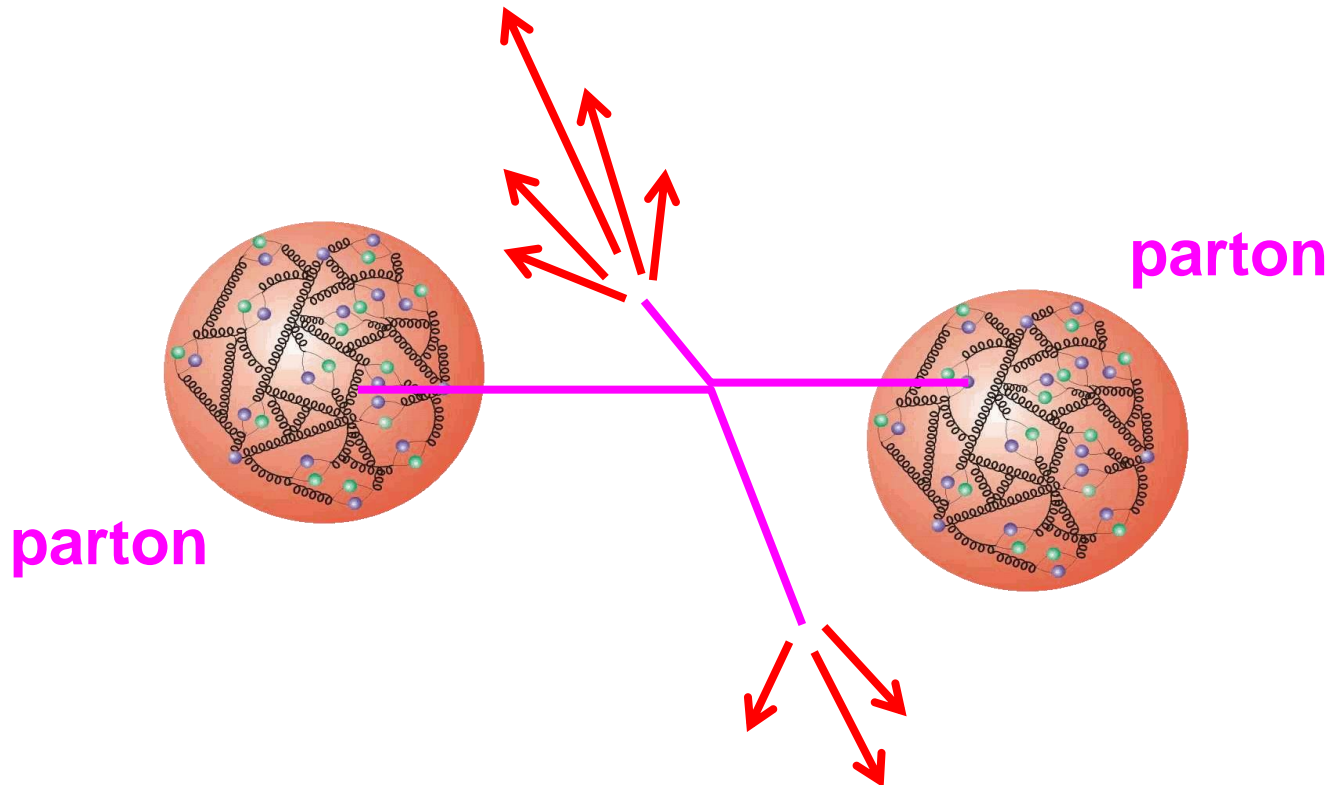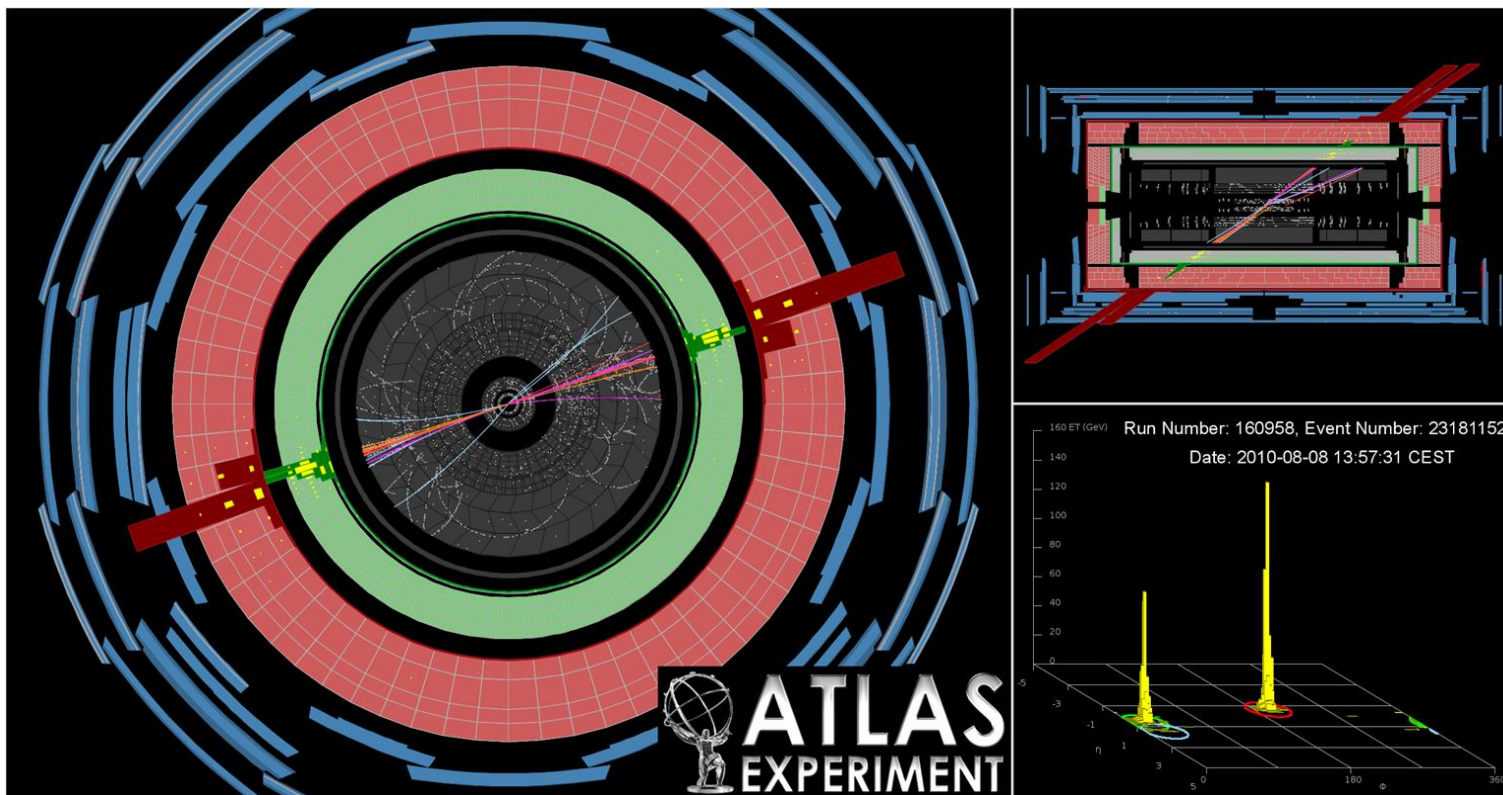
Jets in pp

Jets in Pb-Pb

hadrons from leading jet

parton   **parton**

hadrons from quenched jet

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Jets in Pb-Pb (ATLAS)

Phys. Rev. Lett. 105, 252303

Heavy-ion physics and the QGP (P. Christiansen, Lund)
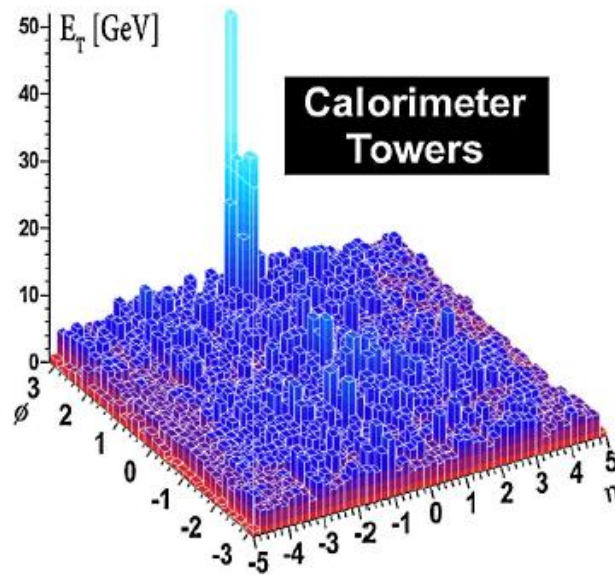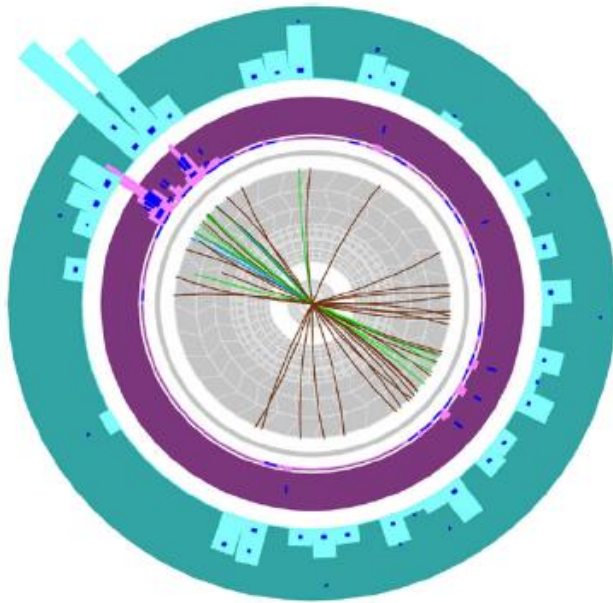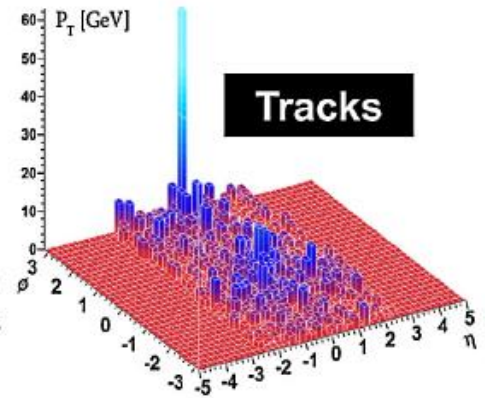
- Jet asymmetry – away side jet is absorbed/modified by the medium

  Advantage of jets is that they "map" onto the QCD degrees of freedoms: quarks and gluons (more complicated in heavy ion collisions)

  Advantage of ATLAS and CMS is larger acceptance

Jets in Pb-Pb (CMS)

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Jet 1, pt: 70.0 GeV

Jet 0, pt: 205.1 GeV
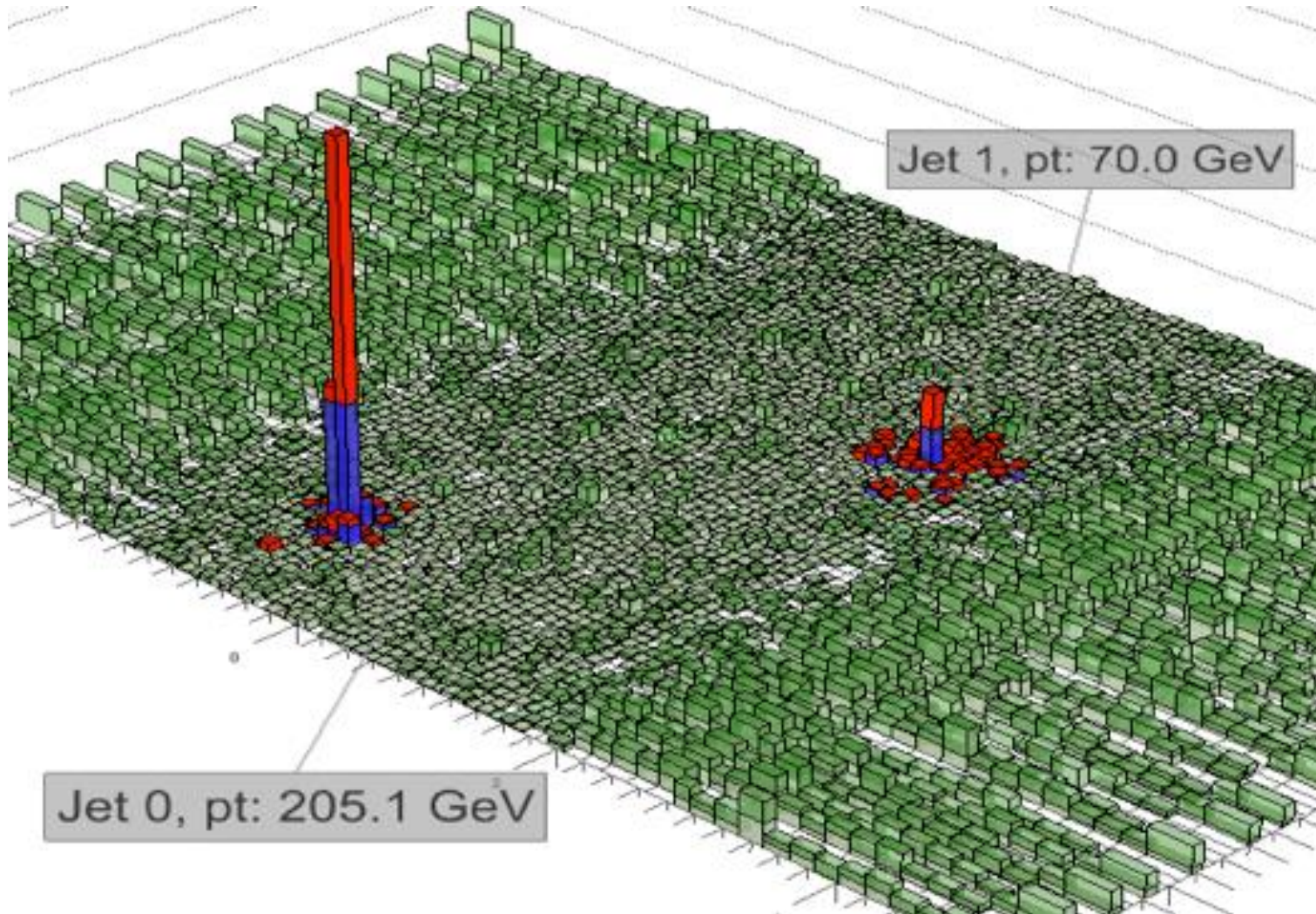
Quantifying the dijet asymmetry

Phys. Rev. Lett. 105, 252303
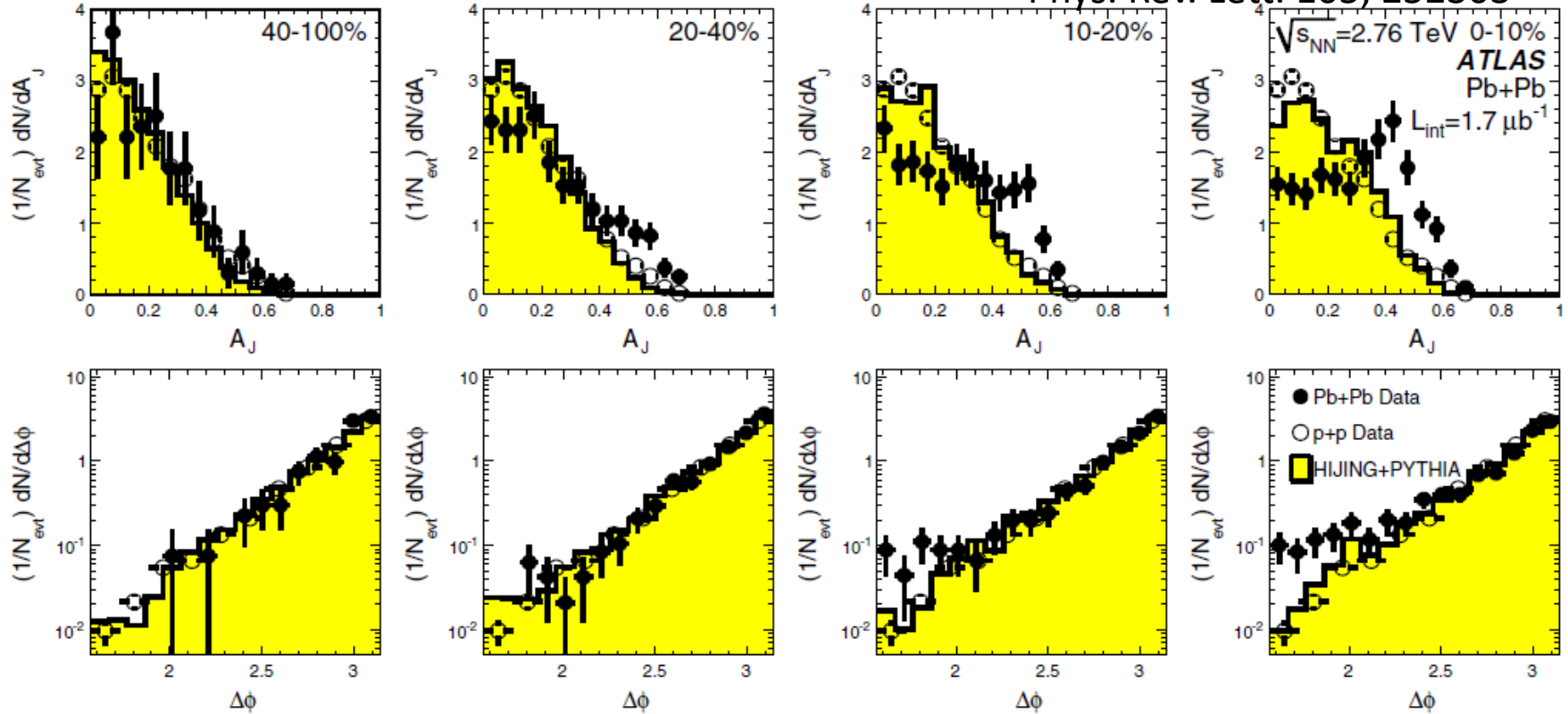
$$A_{\mathrm{J}} = \frac{E_{\mathrm{T}1} - E_{\mathrm{T}2}}{E_{\mathrm{T}1} + E_{\mathrm{T}2}}$$

Where $E_{\mathrm{T}1}$ ($E_{\mathrm{T}2}$) is the transverse energy of the leading (subleading) jet ($E_{\mathrm{T}1}$>100 GeV and $E_{\mathrm{T}2}$>25 GeV).

Notice that the jets are still back-to-back!

Looking into the jet structure

Heavy-ion physics and the QGP (P. Christiansen, Lund)
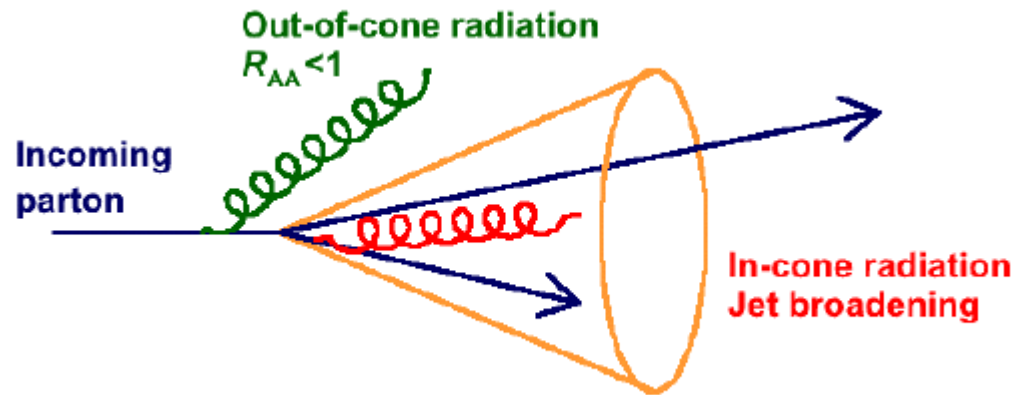
The motivation for these studies was:
- to recover some of the radiated energy
(in principle jets did not have to suppressed!)
- to study how the FF is modified

Two examples of ideas for modified FFs

Direct interaction with medium

(a) Fragmentation in vacuum

Projectile gluon

(b) Medium−modified fragmentation

Projectile gluon

Target parton
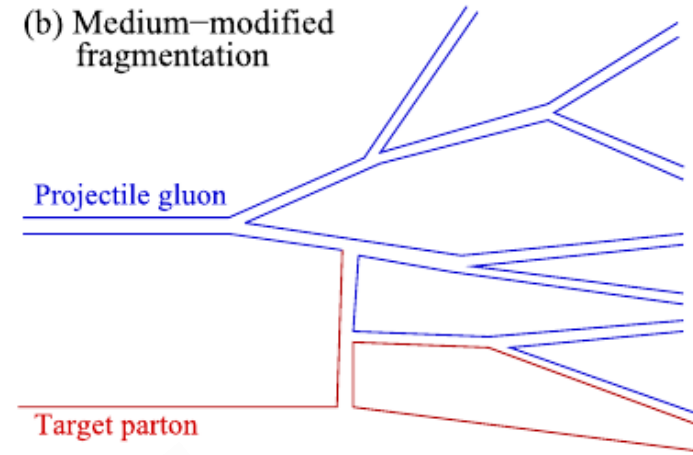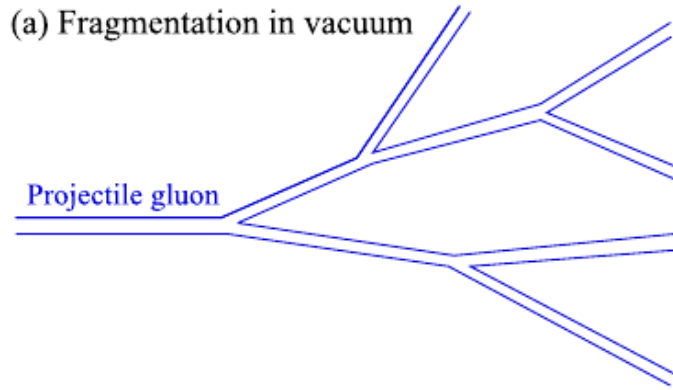
Fragments are quenched differently

Projectile gluon
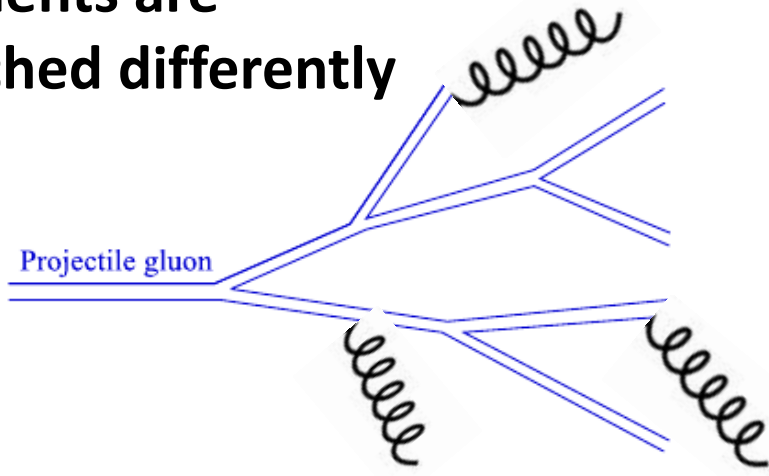
Selecting dijet events and comparing to pp
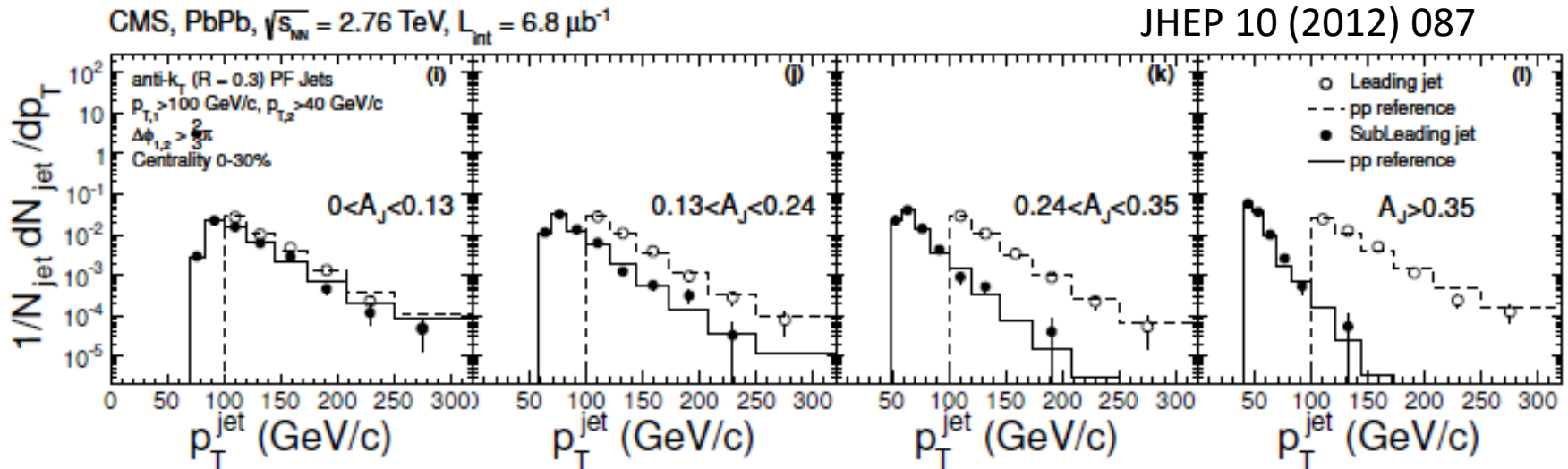
JHEP 10 (2012) 087

The A$_J$ selection introduces the same bias on the dijet samples

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Surprisingly the jet structure is the same! (tracks with p_T>4GeV/c)

JHEP 10 (2012) 087

Heavy-ion physics and the QGP (P. Christiansen, Lund)
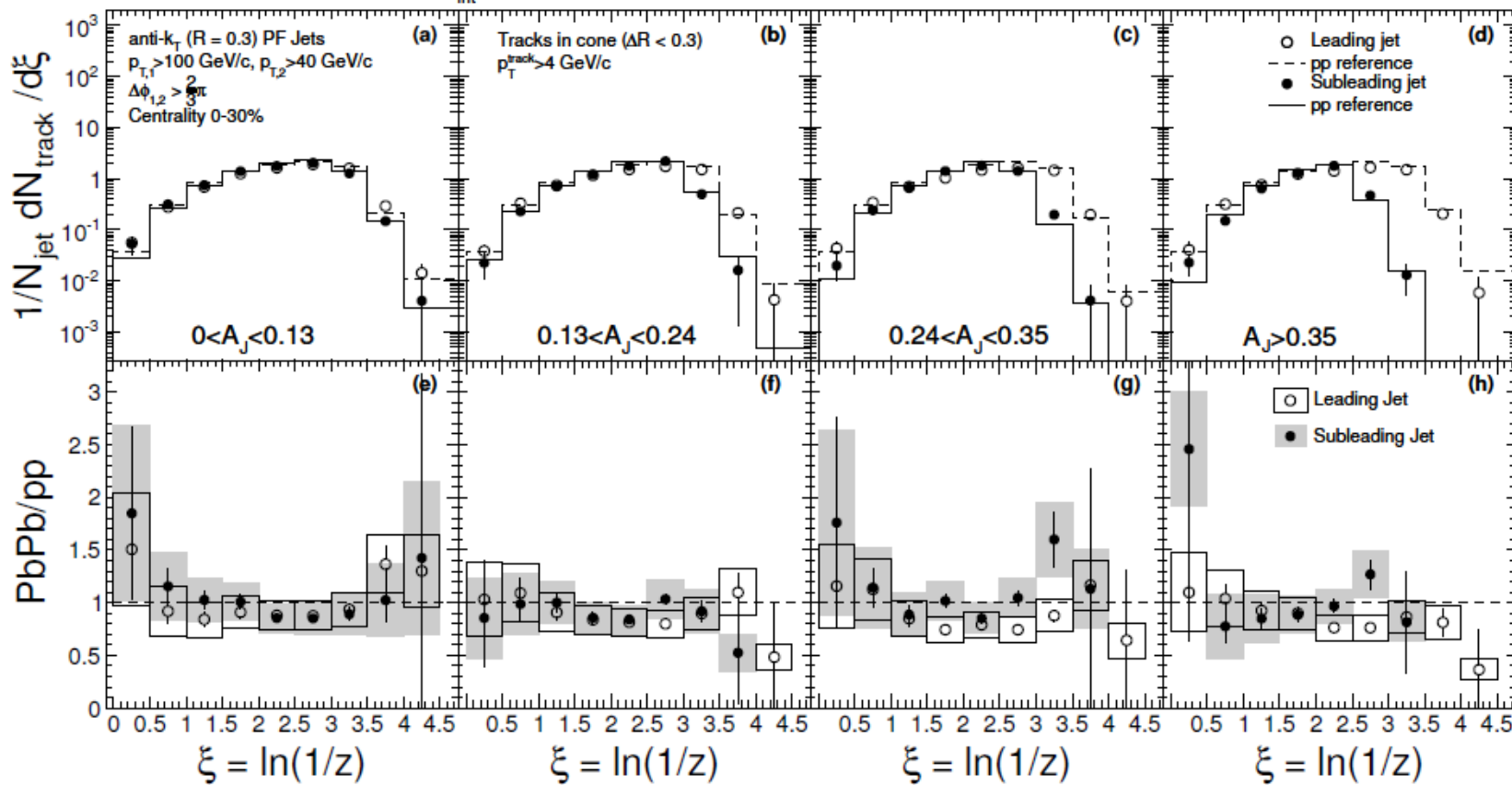
The result shows that quenched jets looks like pp (vacuum) jets! Even in the case where A_J is large and for the subleading jet!

The results show that quenching is coherent!?

Projectile gluon

wavelength
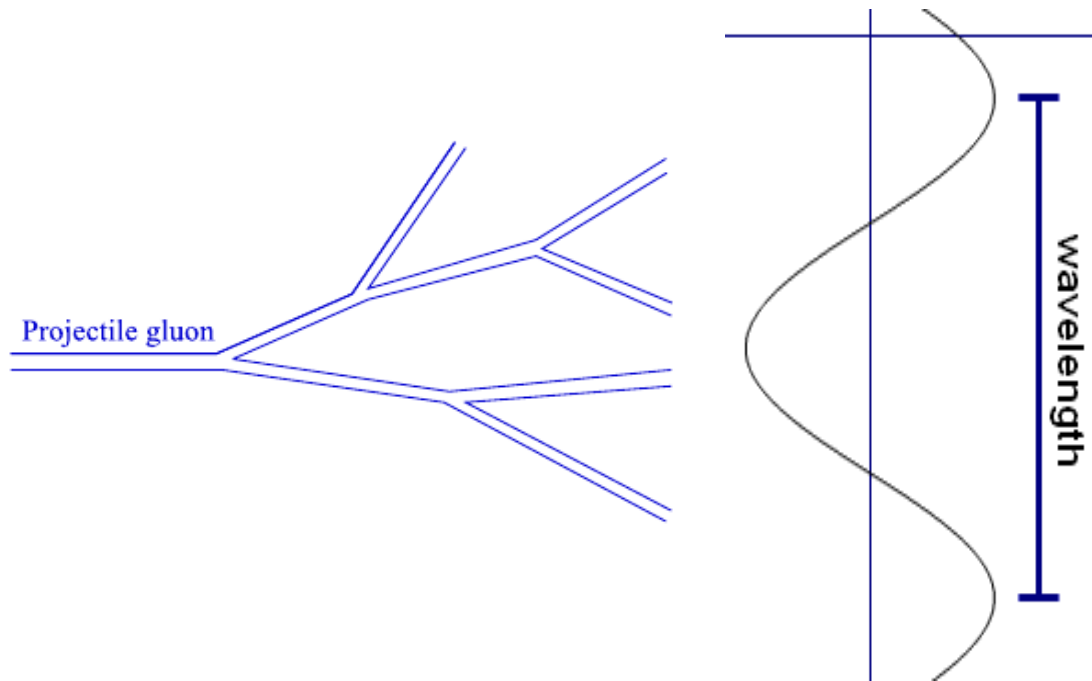
One proposed solution is that the medium cannot resolve the jet constituents (Phys.Lett. B725 (2013) 357-360).
So for the medium the jet will look essentially as a single parton and so all fragments are quenched coherently!

The finer structure of the fragmentation function

Phys. Rev. C 90, 024908

Heavy-ion physics and the QGP (P. Christiansen, Lund)
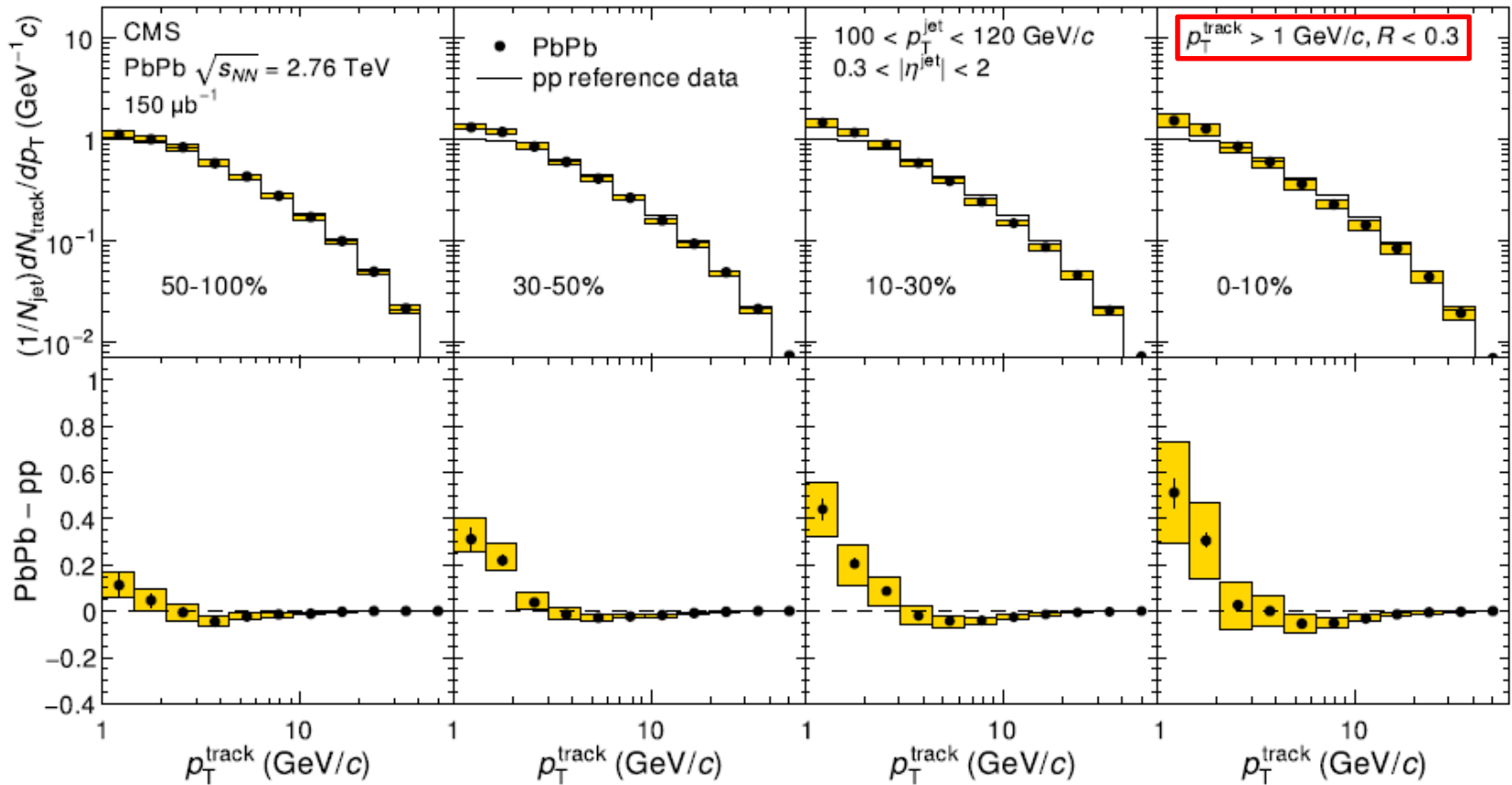
This analysis considers tracks down to p_T = 1 GeV/c

The modifications are sitting at low p_T, mainly p_T<3GeV/c

Tracking the energy loss

CMS-HIN-14-016

Heavy-ion physics and the QGP (P. Christiansen, Lund)
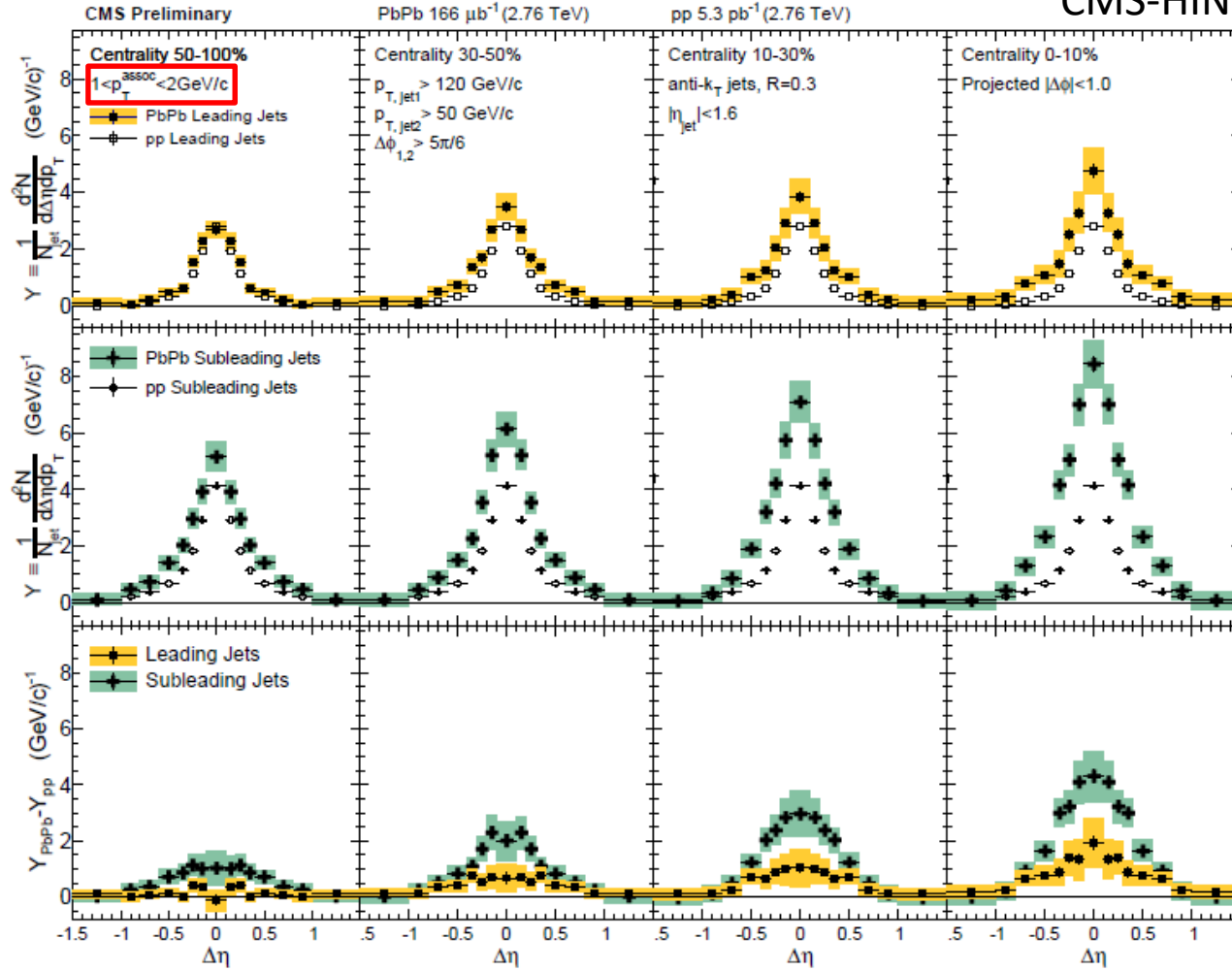
CMS have shown that the energy loss can be recovered at low p_T at large $\Delta\eta$ and large $\Delta\phi$

Extending the R_{AA} to identified particles

Heavy-ion physics and the QGP (P. Christiansen, Lund)

ALICE, PRL 110, 082302 (2013)

ALICE, Int. J of Mod. Phys. A 29, 1430044 (2014)

ALICE , PLB 736, 196 (2014)
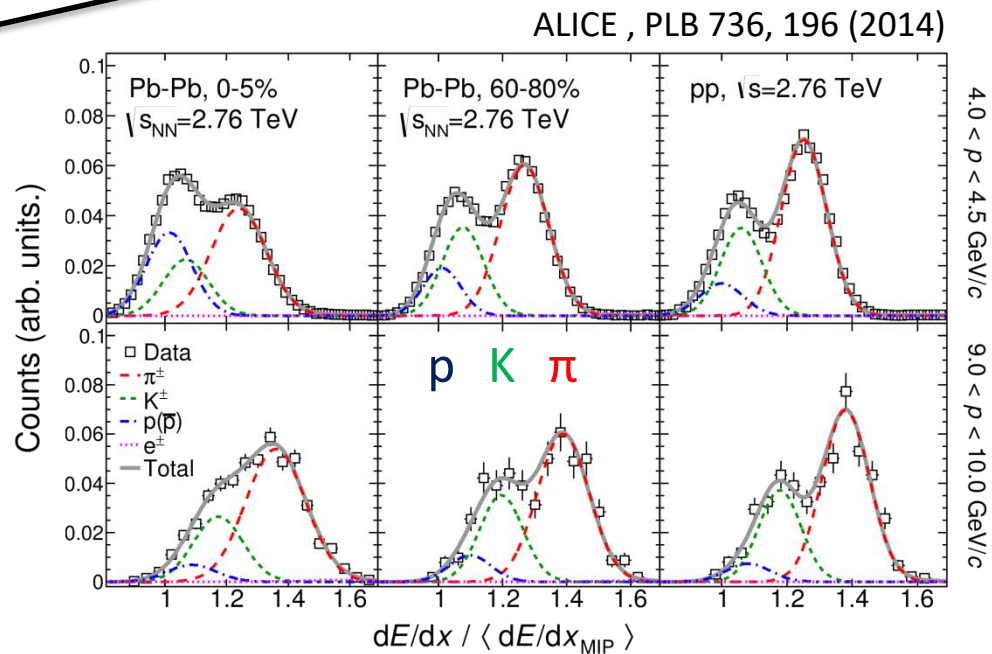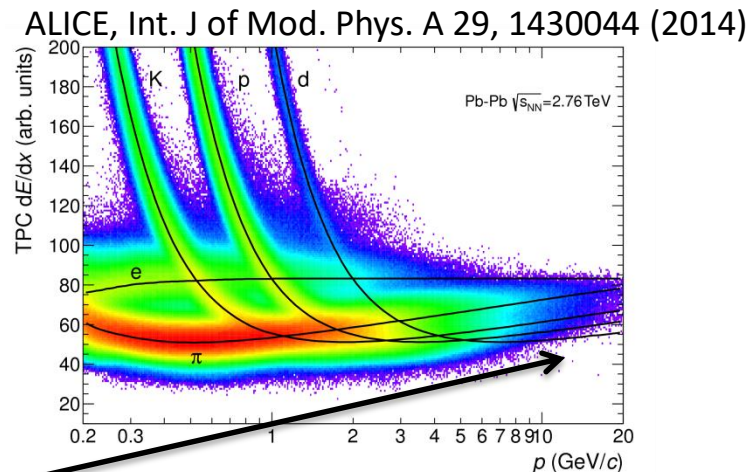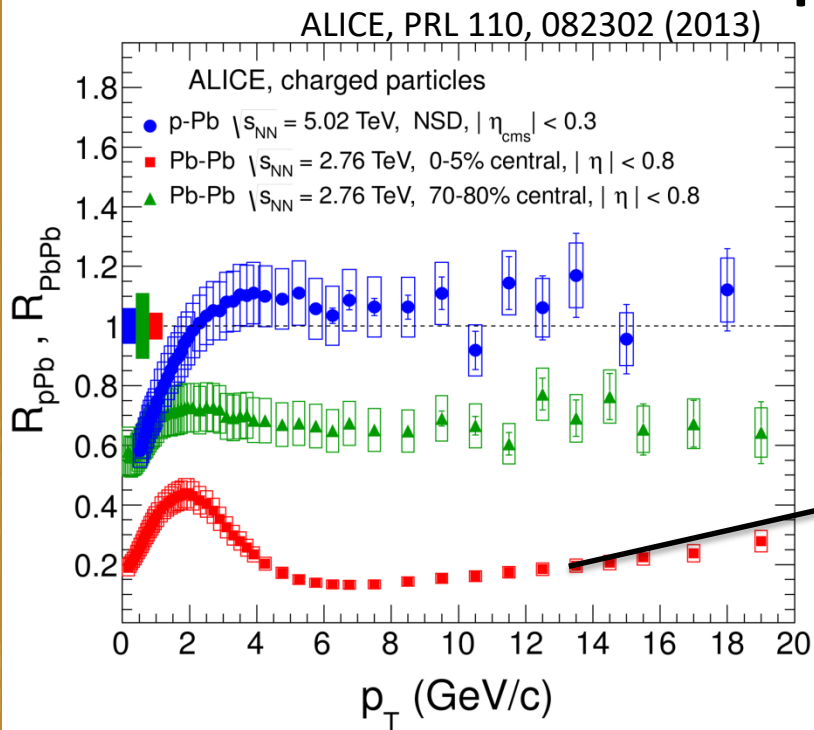
Each TPC track also has an associated dE/dx that can be used for ID on the relativistic rise

Charged π, K, and p spectra in pp and Pb-Pb collisions

ALICE , PLB 736, 196 (2014)

Heavy-ion physics and the QGP (P. Christiansen, Lund)
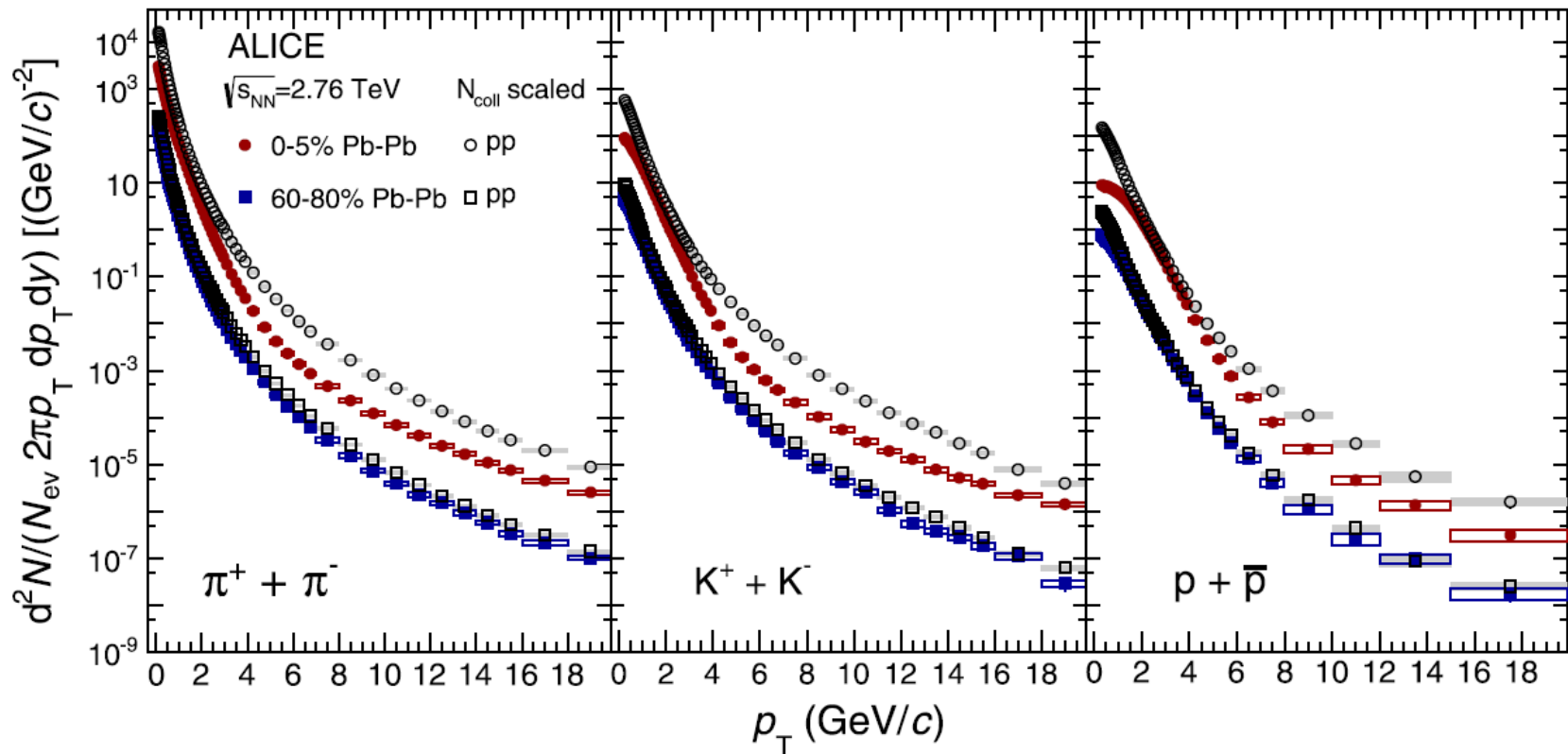
High p_T p/π ratio in pp and central Au-Au collisions at √s_{NN}=200 GeV

Heavy-ion physics and the QGP (P. Christiansen, Lund)

STAR, PRL 108, 072302 (2012)

FFs:
DSS
AKK2008
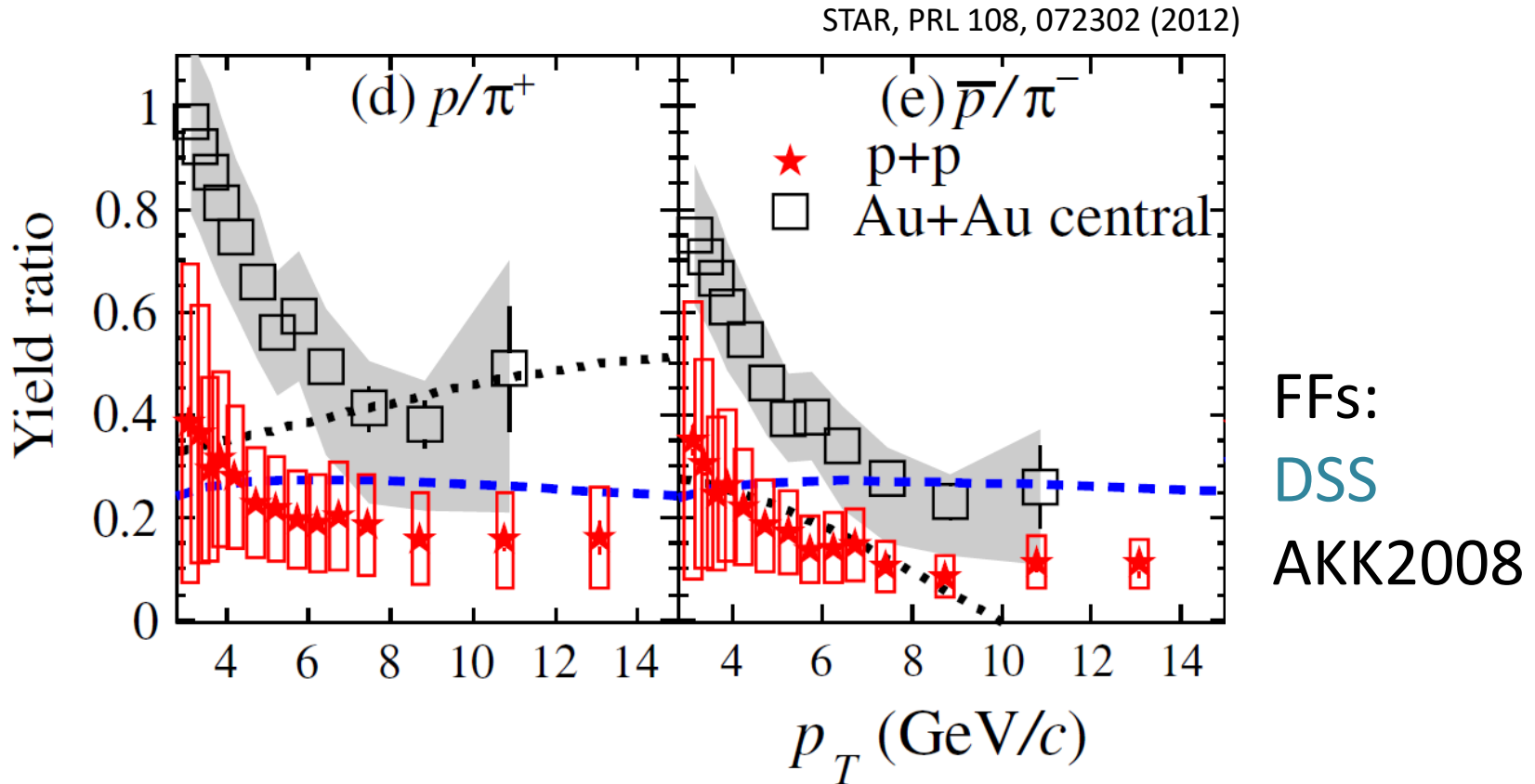
NB! At this low energy there is significant difference between baryon and anti-baryon production.

The nuclear modification factor R_{AA} for charged π, K, and p

Heavy-ion physics and the QGP (P. Christiansen, Lund)

PLB 736, 196 (2014)
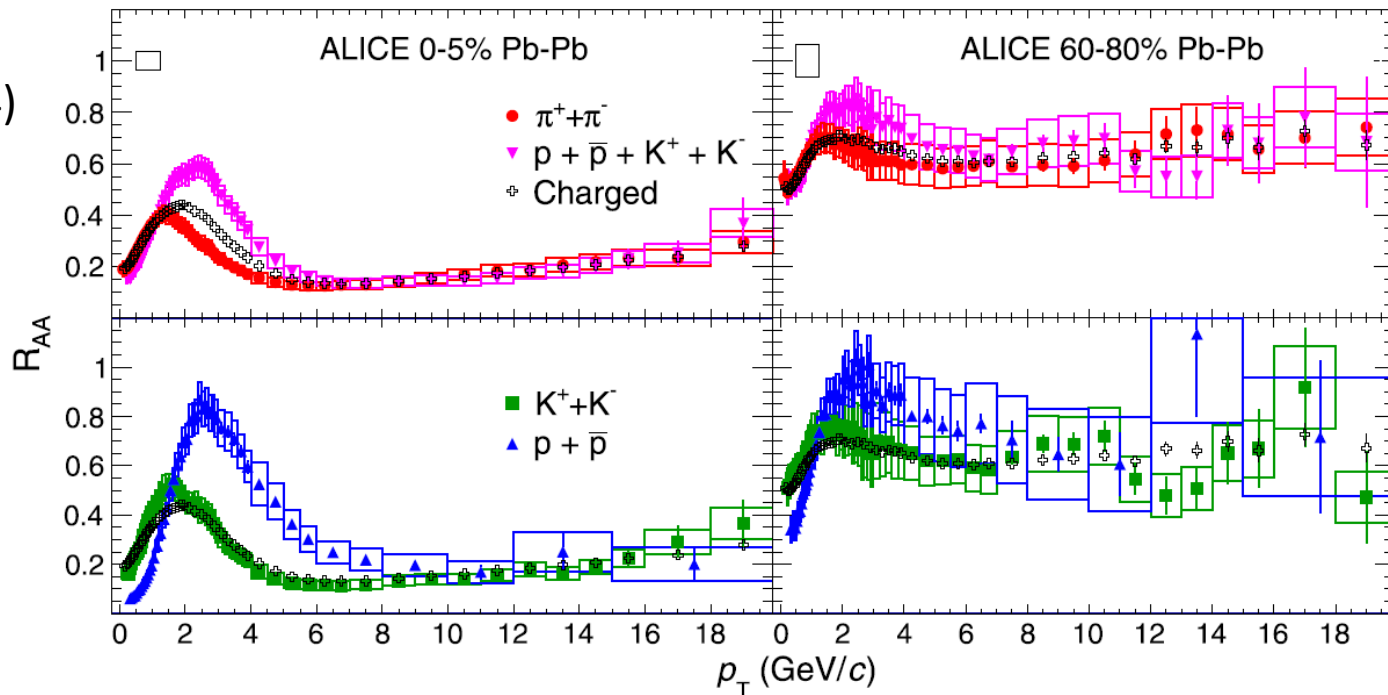
The nuclear modification factors are consistent for π, K, p for $p_T > 10$ GeV/c. For 0-5% Pb-Pb collisions: K and π to within ~10% (syst), p and π to within ~20% (syst)

The results rules out popular ideas of jet quenching where the large energy loss is coupled to large leading order particle species dependent effects.

Conclusions on jets

- High p_T particles (and jets) were one of the hottest topics at RHIC where they were difficult to measure
  - And it seemed at RHIC that jets were modified in a spectacular way giving rise to exotic effects
- At LHC the picture we have of jet quenching has turned out to be surprisingly simple
  - Experimentally the jets seem to first loose energy in the QGP and then afterwards to fragment as vacuum jets
    The energy loss is observed as soft particles at large angles

Heavy-ion physics and the QGP (P. Christiansen, Lund)

SOFT MEDIUM PROPERTIES

Lattice QCD calculation of the energy density

Heavy-ion physics and the QGP (P. Christiansen, Lund)
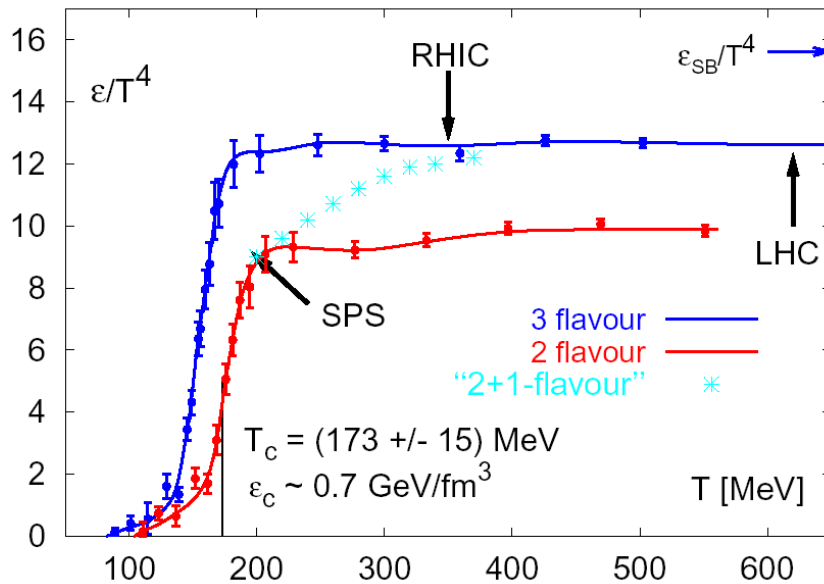
$$\varepsilon_{Quark-Gluon\ gas} =$$

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

Gluon spin and color

(Anti+)quark spin, color and flavor

Because of the similarity with Stefan-Boltzmann energy density for a quark-gluon gas:

QGP should be weakly coupled

At a deeper level this is also what we expect from asymptotic freedom

Radial flow

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Aligned   Randomized
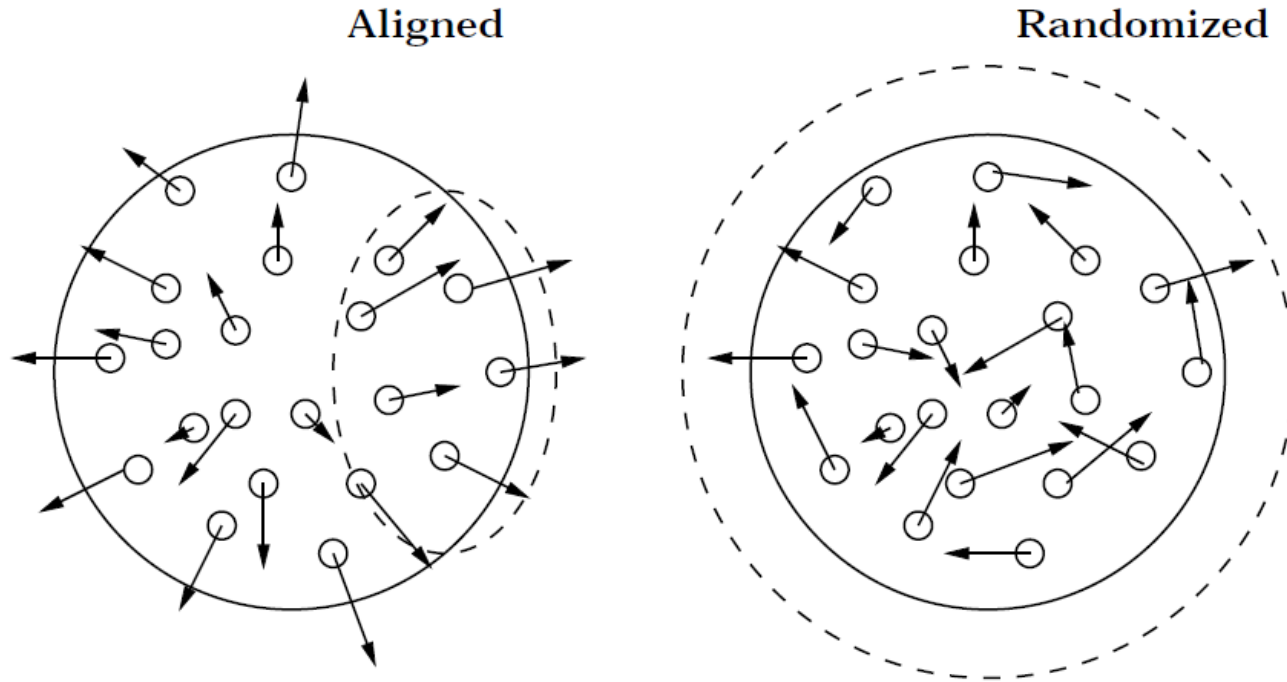
Flow in general plays a very important role in heavy ion collisions.
Flow means that there are strong correlation between position
and momentum in the source.
We believe that flow in the partonic phase is imprinted on the
final state hadrons at freeze out.

Evolution of the heavy-ion collision

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Mainly this period where flow build up

Radial flow pushes heavier particles out to larger p_T
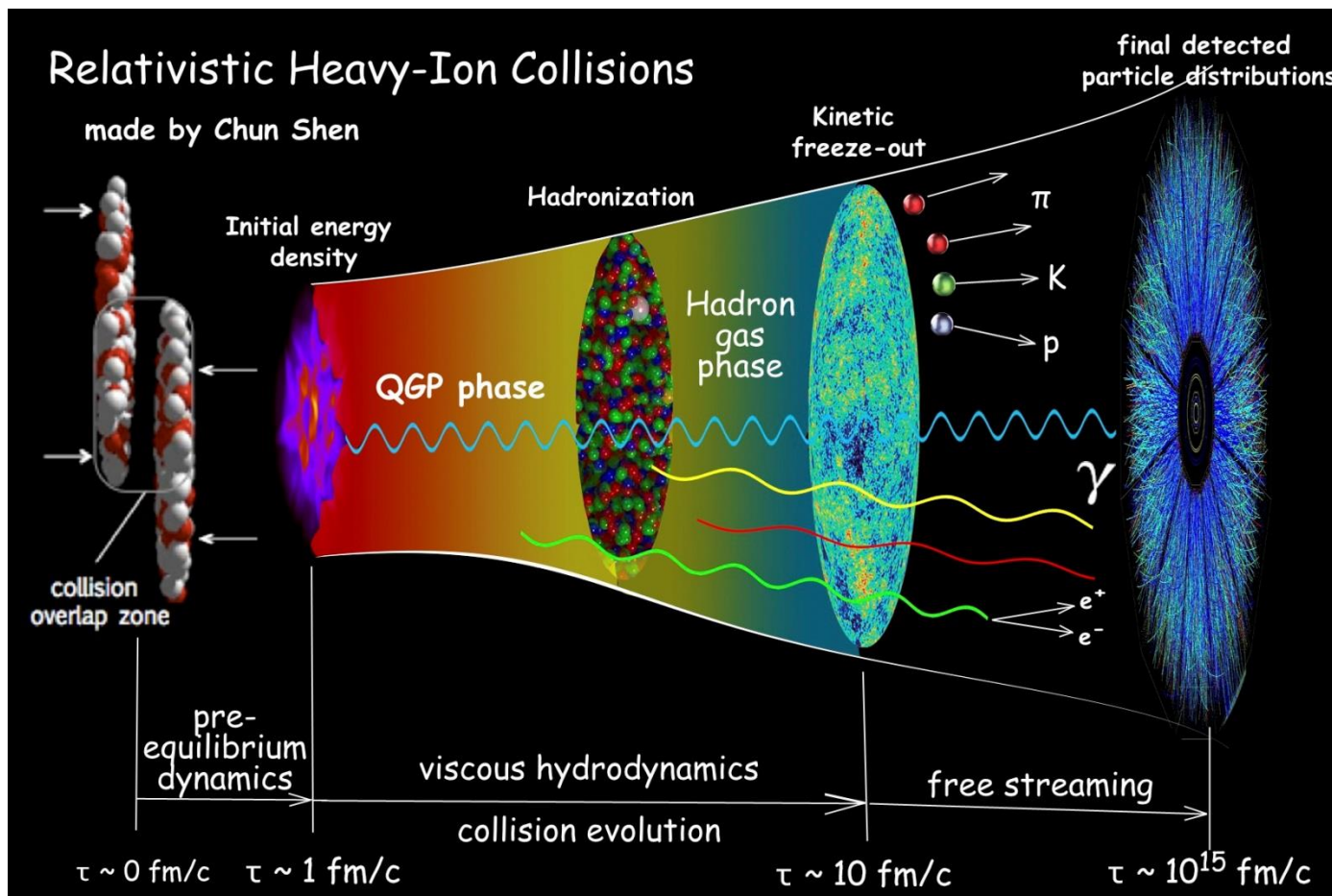

ALI-DER-91467
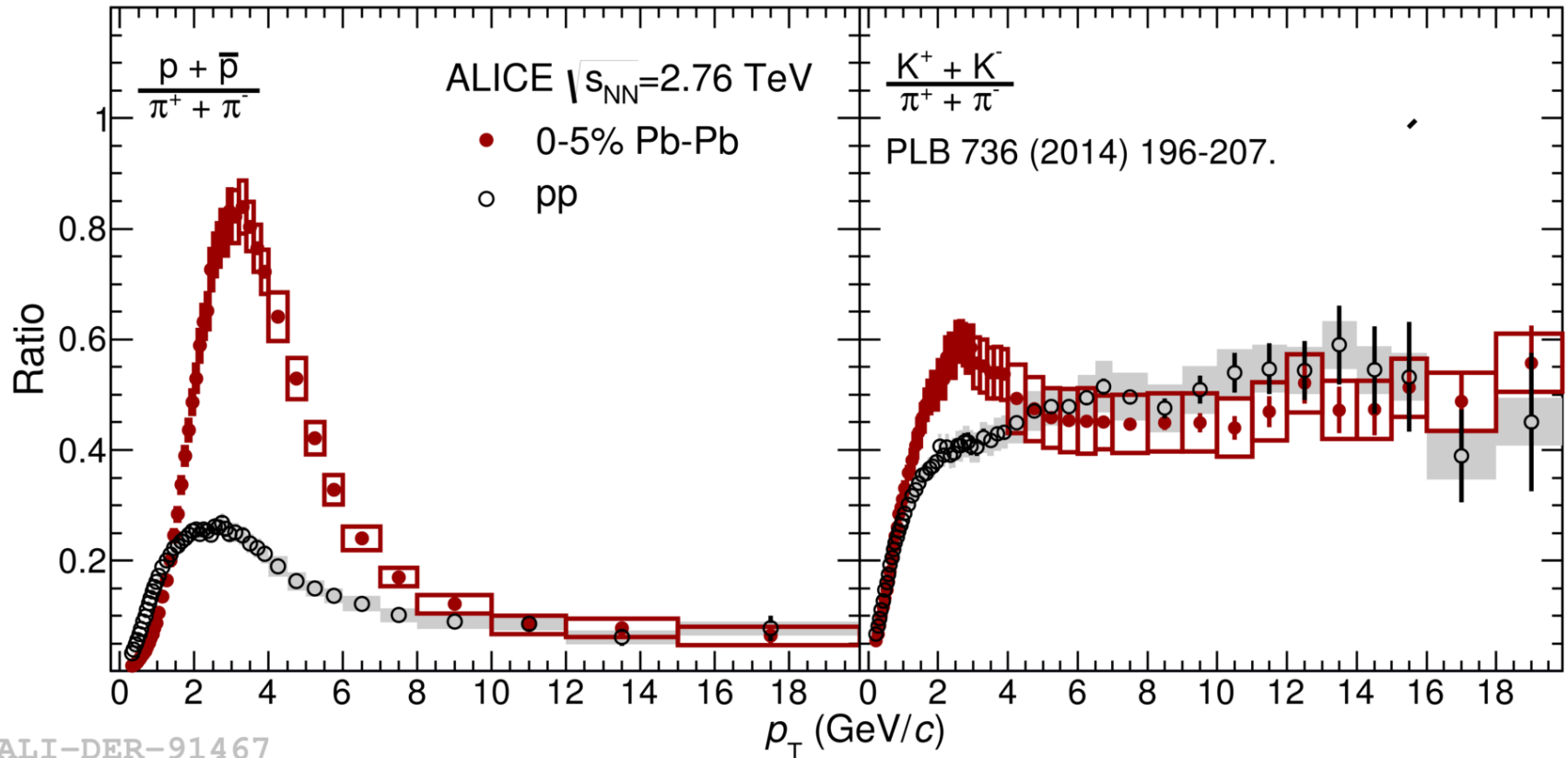
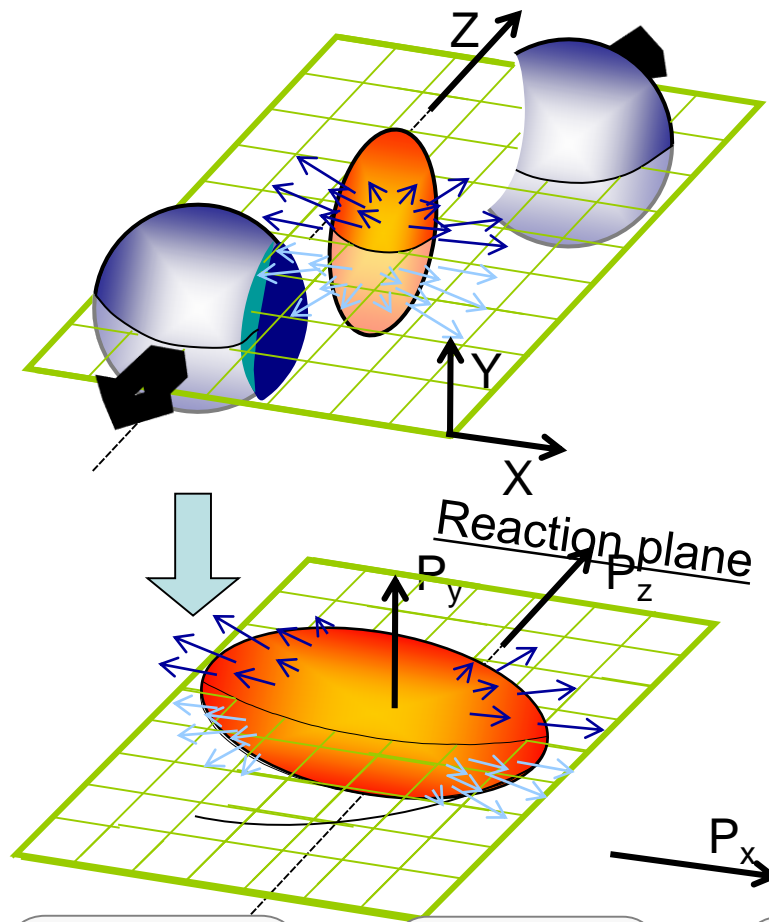If the source has a radial flow velocity β_r then particles <u>at rest</u> in the flowing frame are boosted in the lab as: $p_T \sim \gamma\beta_r m$
So they get a mass dependent boost!

Elliptic flow (v$_2$)
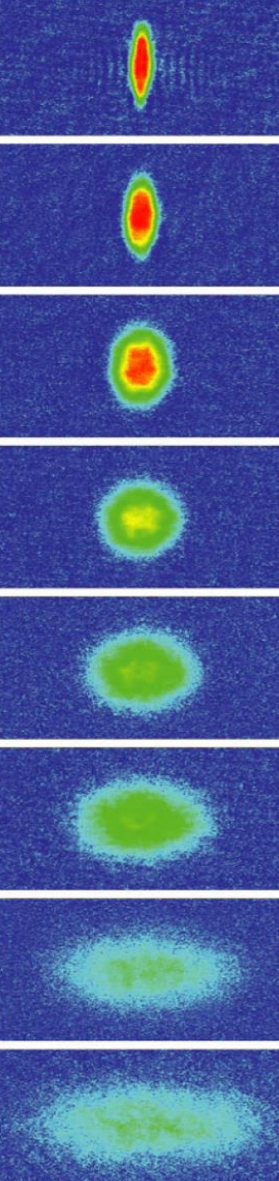
Fourier decomposition:

dN/dΔϕ = 1 + 2 v$_2$cos(2 Δϕ)

| Initial spatial anisotropy | ▶ | Strong pressure gradients | ▶ | **v$_2$** Azimuthal anisotropy | ▶ | **Sensitivity to early expansion** |
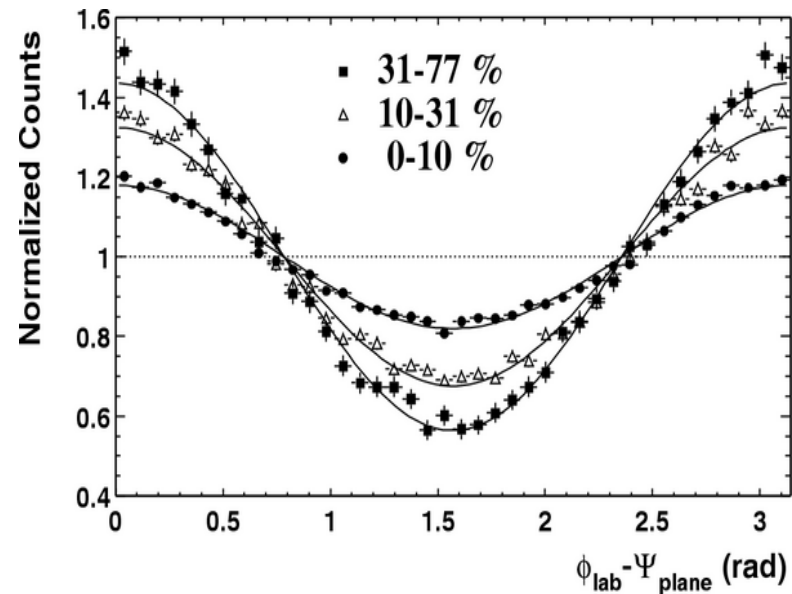
Elliptic flow requires early strong interactions to form
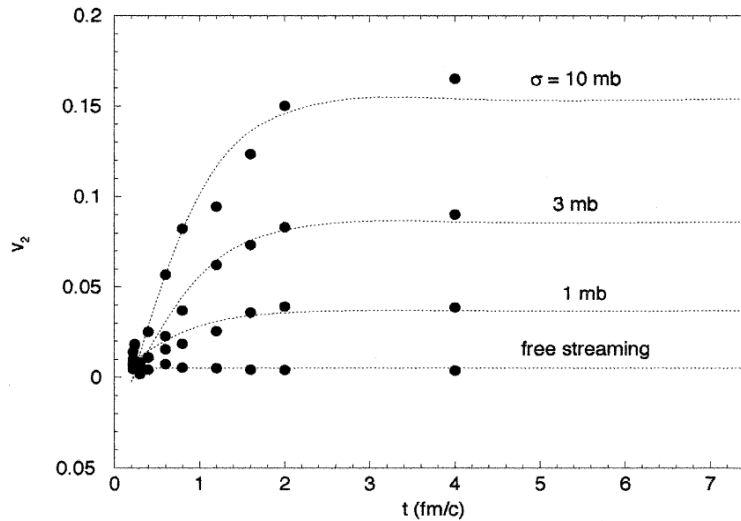
Zhang, Gyulassy, Ko,
Phys. Lett. B455 (1999) 45

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

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Mass ordering of the elliptic flow

Heavy-ion physics and the QGP (P. Christiansen, Lund)
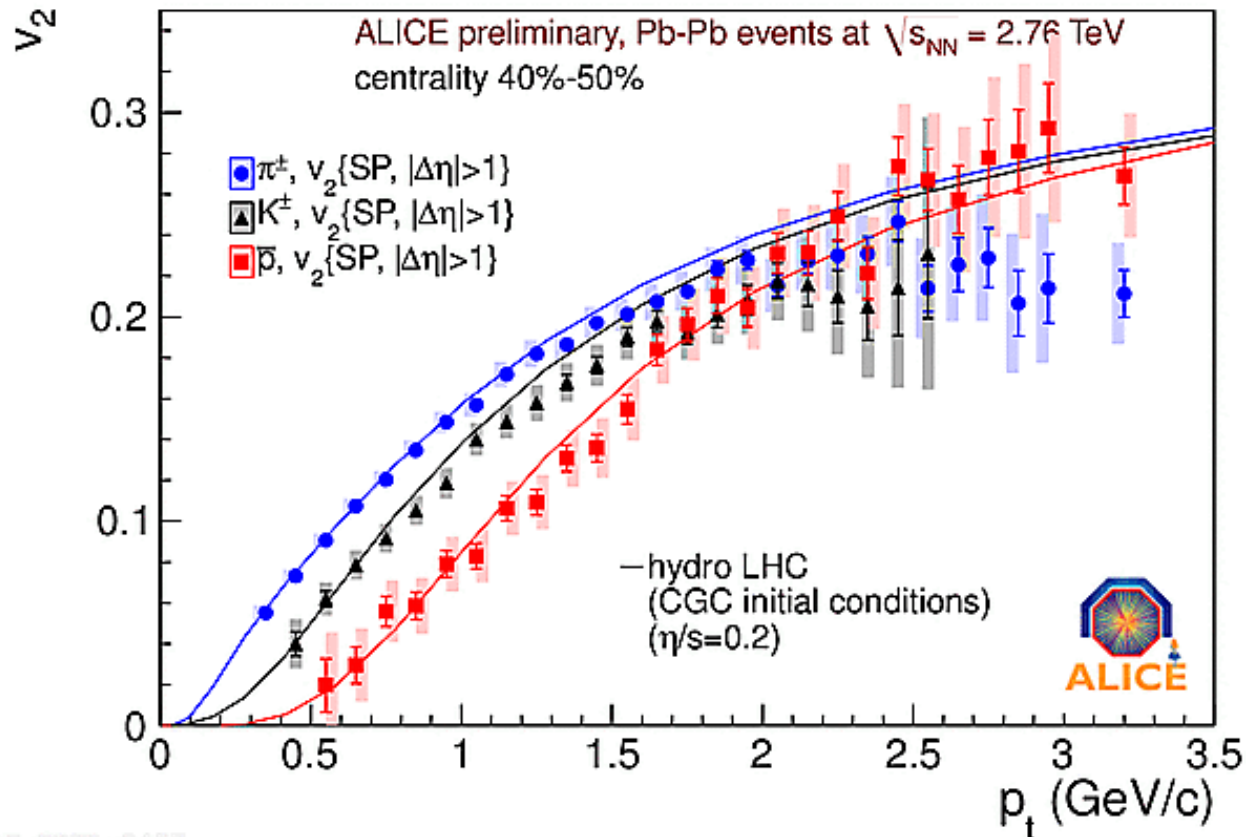
The mass ordering is characteristic of flow since heavier particles are pushed out to higher p_T
Surprisingly this is well described by nearly ideal hydrodynamics

Ridge (ATLAS)

30-40%
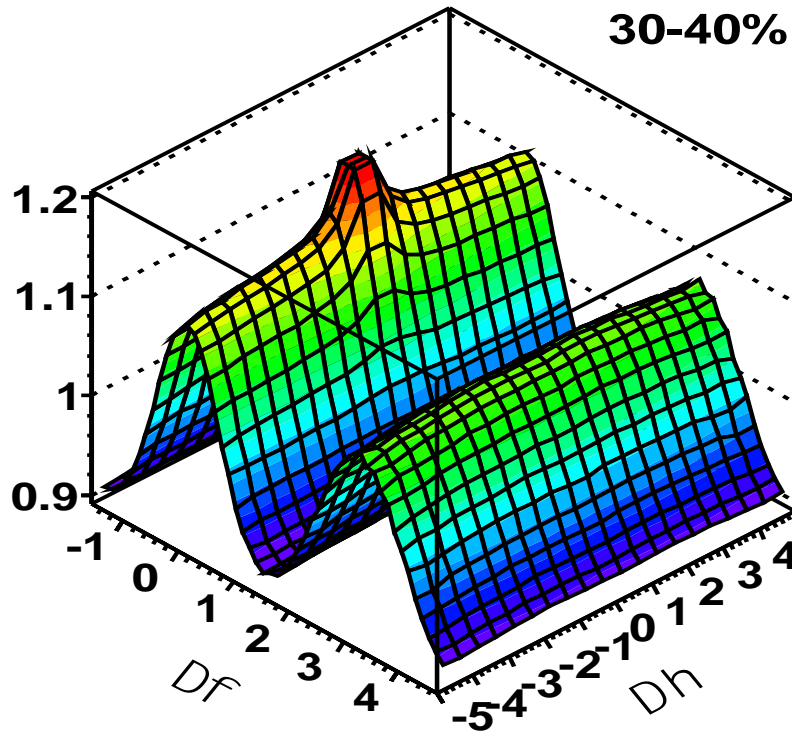
One can study flow using two particle correlations. Here 2 < p_{T1}, p_{T2} < 3 GeV/c

The long range correlations are imprinted by the flow because **the initial elliptic overlap is a global property of a collision!**

Heavy-ion physics and the QGP (P. Christiansen, Lund)

For completeness:

Singles: $\dfrac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n\left(\phi - \Psi_n\right)$ **EP method**

Pairs: $\dfrac{dN}{d\Delta\phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos\left(n\Delta\phi\right)$ **2PC method**

Some simulation movies of hydrodynamics

- https://www.youtube.com/watch?v=G18pyVOmSRw

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Flow fluctuations

Heavy-ion physics and the QGP (P. Christiansen, Lund)
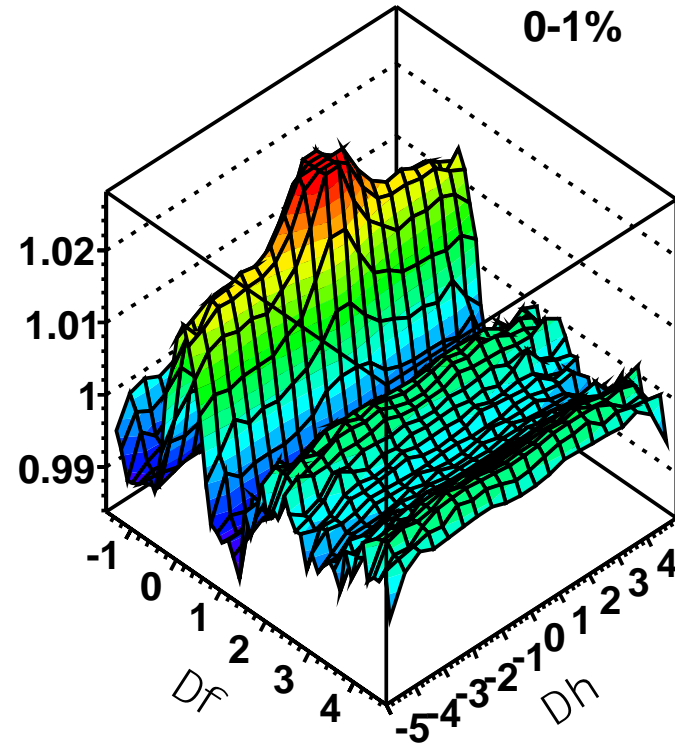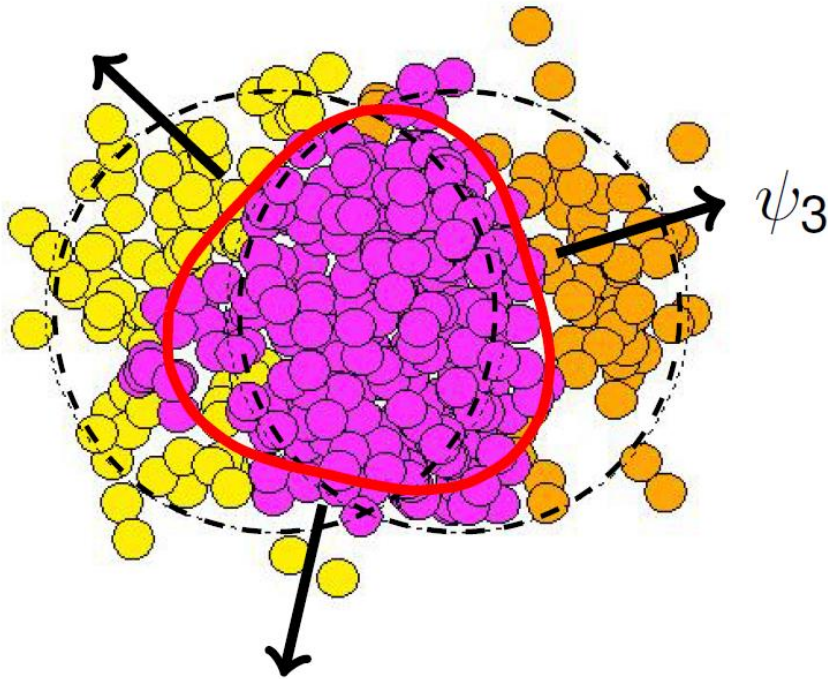
Because the nuclei are not homogenous the initial state can be quite asymmetric giving rise to e.g. triangular flow!
Famous paper: B. Alver, G. Roland, Phys.Rev. C81 (2010) 054905 (420 citations)

Elliptic flow and triangular flow is almost ideal!

Heavy-ion physics and the QGP (P. Christiansen, Lund)
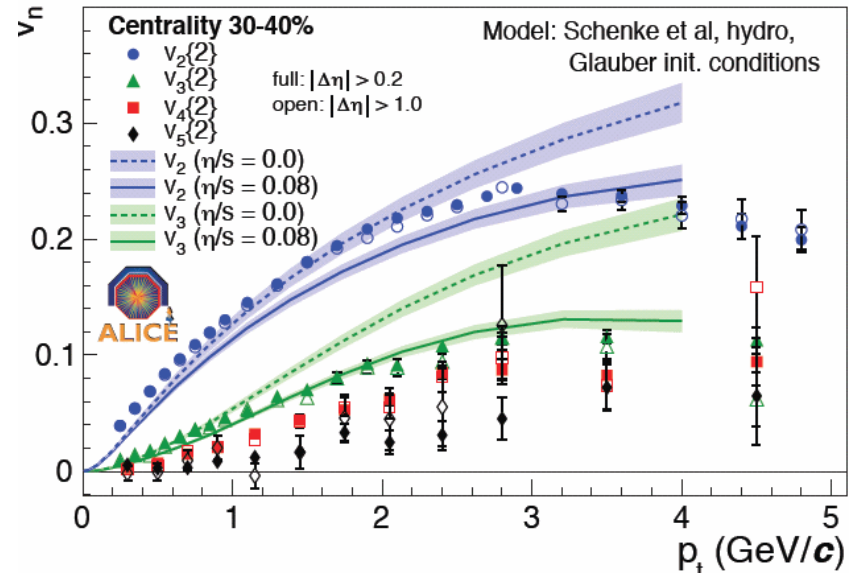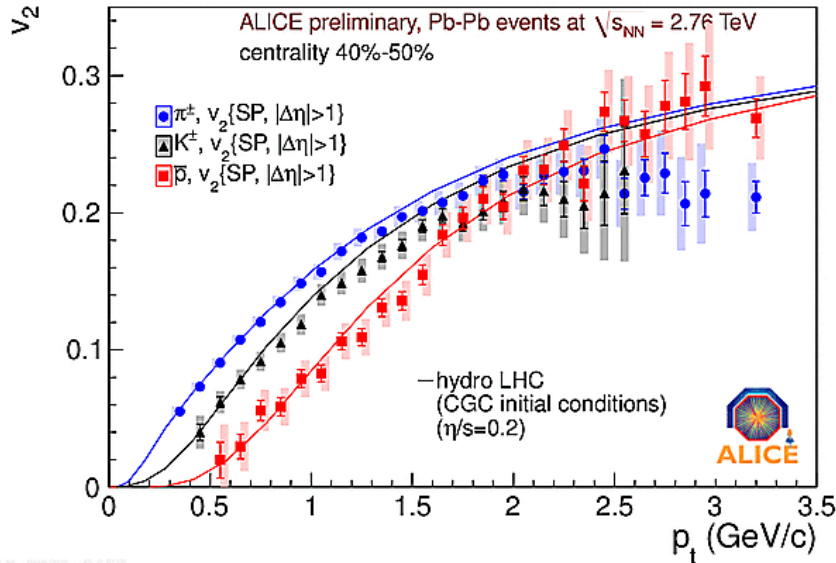
- ## Huge flow at intermediate p_T:
  - 2 times more particles in plane than out
  - Nearly ideal fluid
- ## Significant higher order flow caused by fluctuations – also described by nearly ideal hydro + initial state

Shear viscosity

Figure taken from
http://www.pumpfundamentals.com/about_fluids.htm
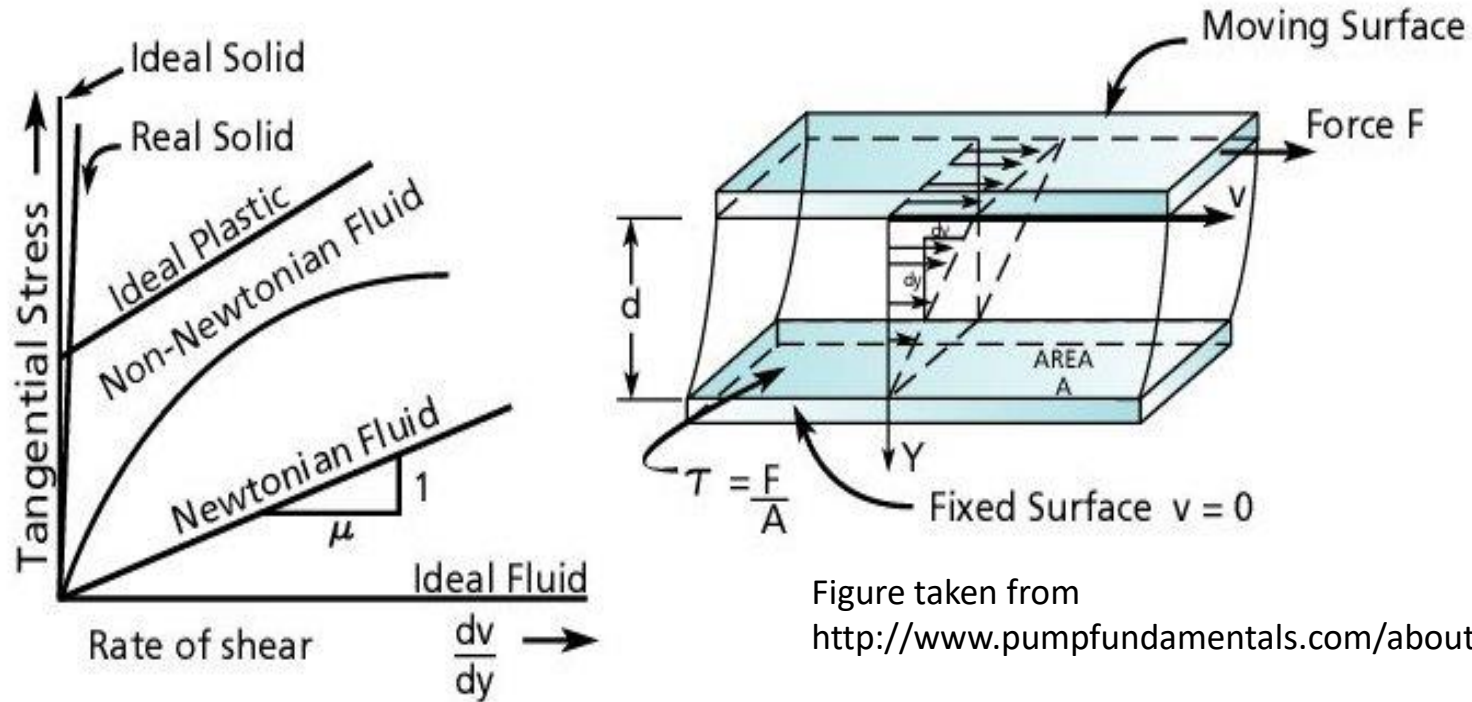
The shear force is given as F=ηAv/d
The shear vicosity-to-entropy density ratio, η/s, is a unitless
quantity for characterizing fluids

How ideal is it? (1/2)
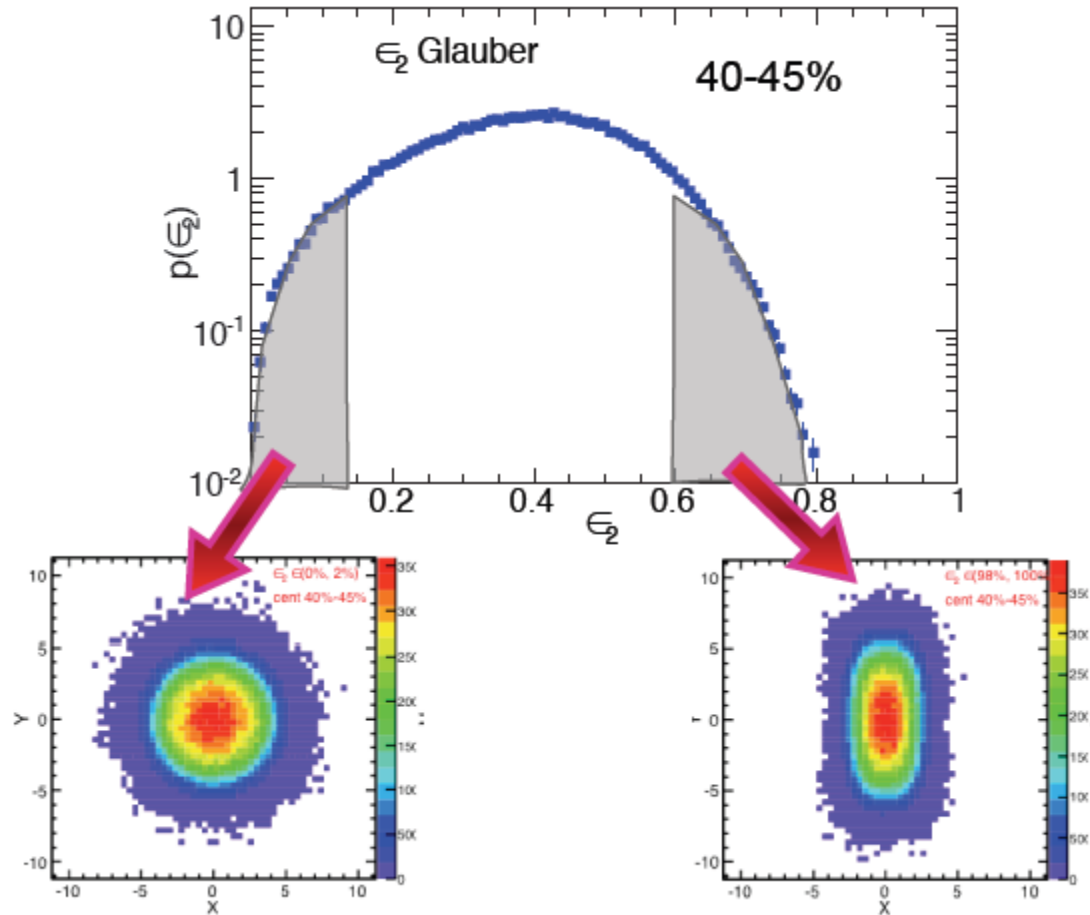
Ideal = reversible => linear response to initial state ($v_2 \sim k*\varepsilon_2$) => fluctuations should be equal to geometrical

Heavy-ion physics and the QGP (P. Christiansen, Lund)

How ideal is it? (2/2)
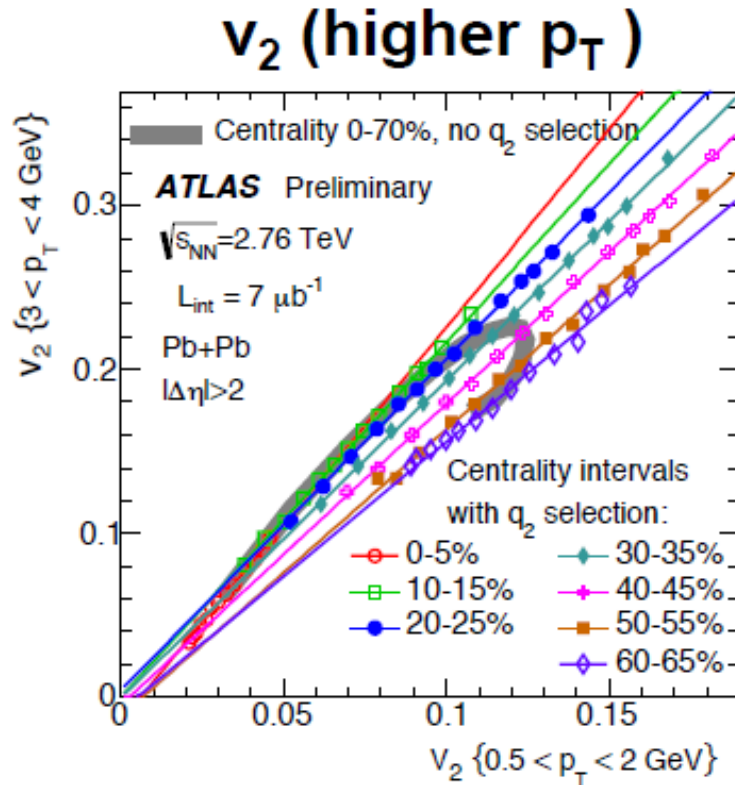
Left: v2 response is linear at low and high p_T (=global property)
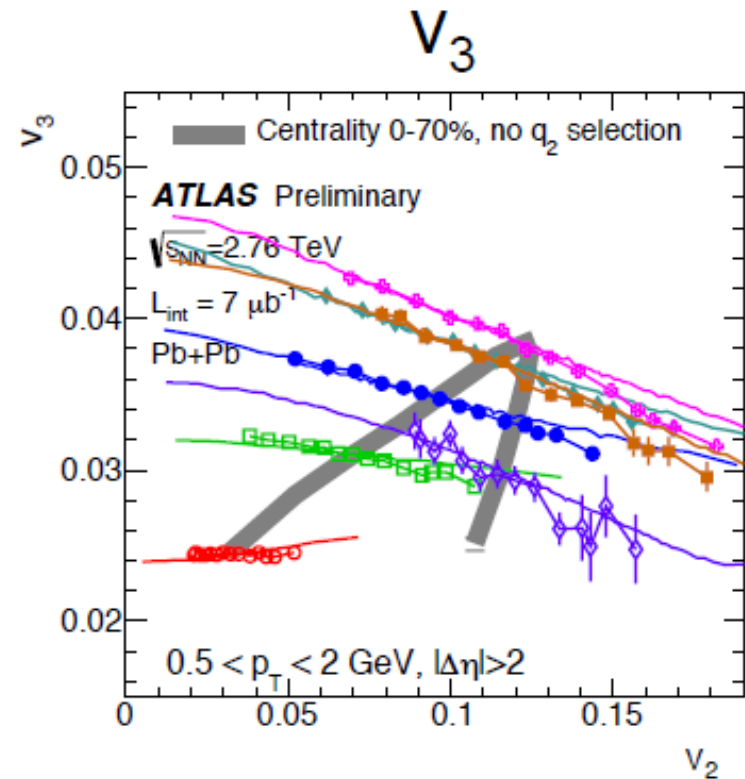
Right: v2 and v3 correlations are given by pure Glauber model!
(solid curves)

Heavy-ion physics and the QGP (P. Christiansen, Lund)

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

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- Big theoretical challenges:

    Why is the QGP behaving like a liquid? (next slide)

    how to go from initial random collisions to organized state in a VERY short time ($<1fm/c \sim 10^{-23}$s). This remains to be understood

How to understand this? 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,
    ~10,000 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)   (like QGP!)

    infinite Ncolors

    SUSY
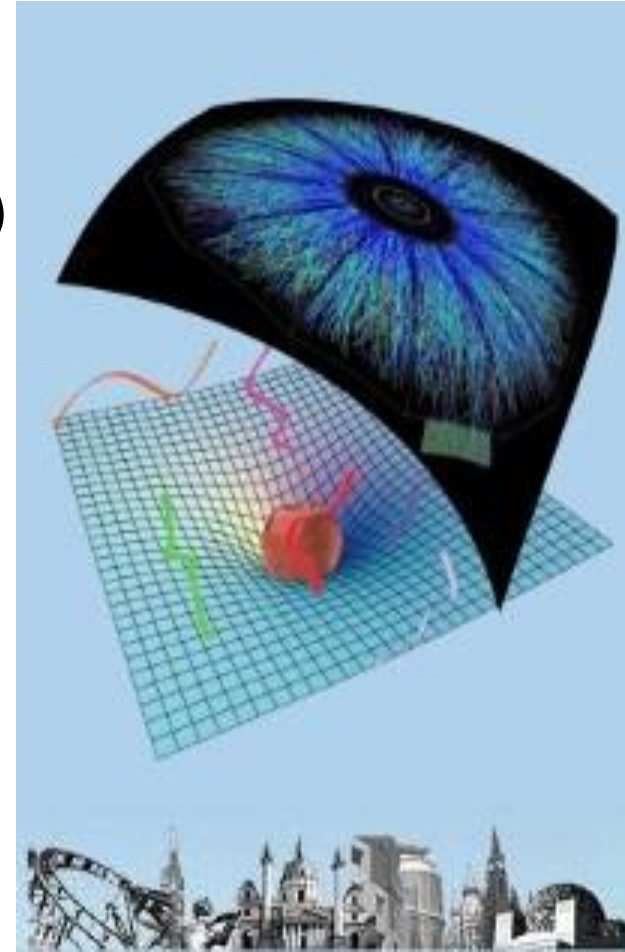
AdS-CFT

- Two very important results:

  Conjectured bound on shear viscosity: η/s≥1/(4π)~0.08
  - **Viscosity in strongly interacting quantum field theories from black hole physics, P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett. 94 (2005) 111601. (~1400 citations on inspire.)**

  Possibility of infinitely strong coupling at energy density of ¾ SB gas

Heavy-ion physics and the QGP (P. Christiansen, Lund)

The QGP fluid compared to other fluids

Heavy-ion physics and the QGP (P. Christiansen, Lund)
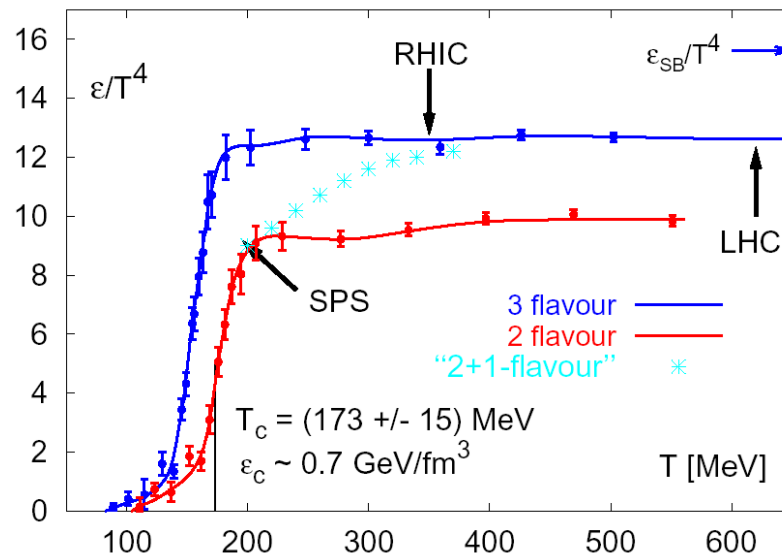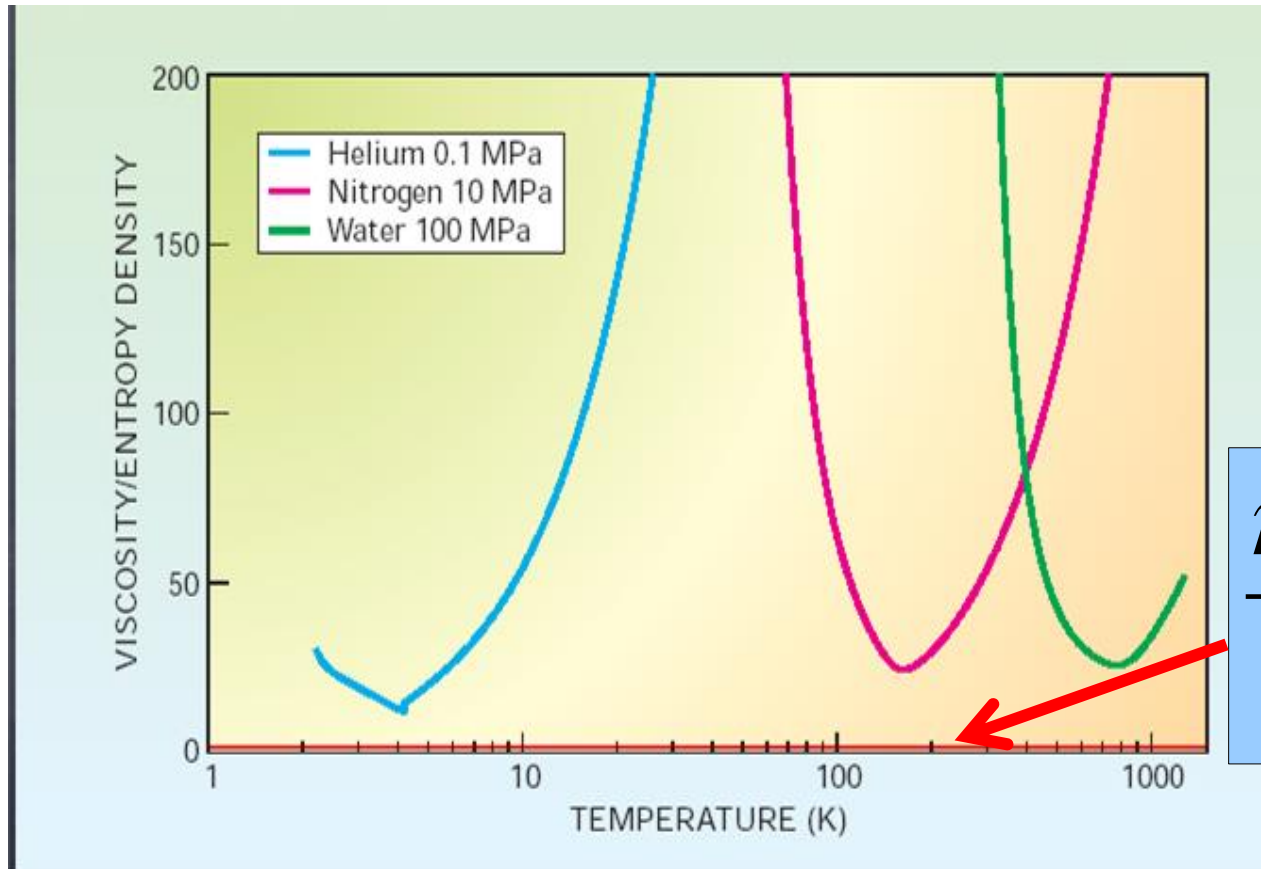
$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi} \frac{1}{k_{\mathbf{B}}}$$

The QGP fluid compared to other fluids

Strongly interacting ultra-cold Li atoms released from a trap

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

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

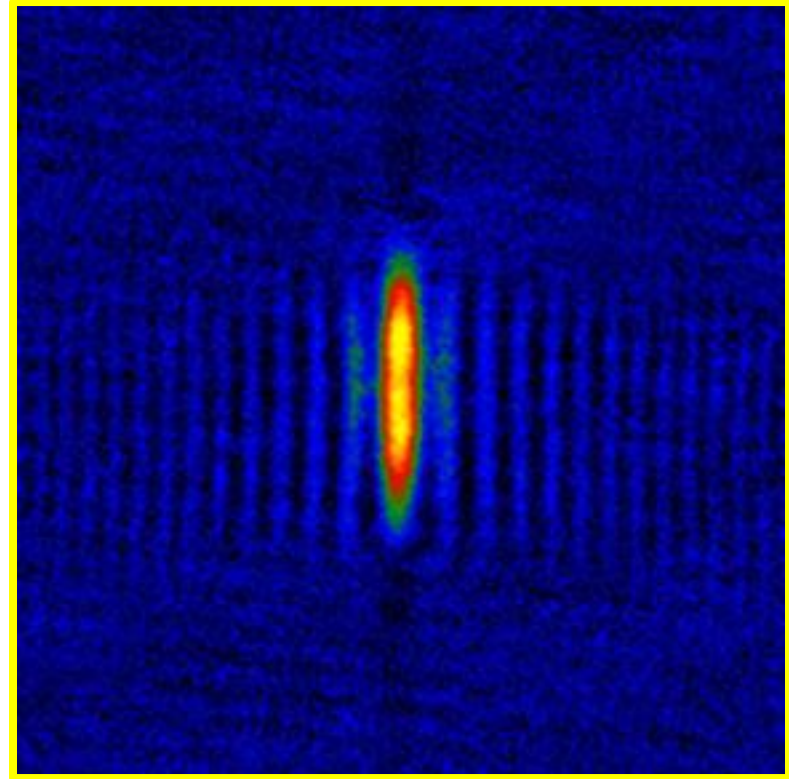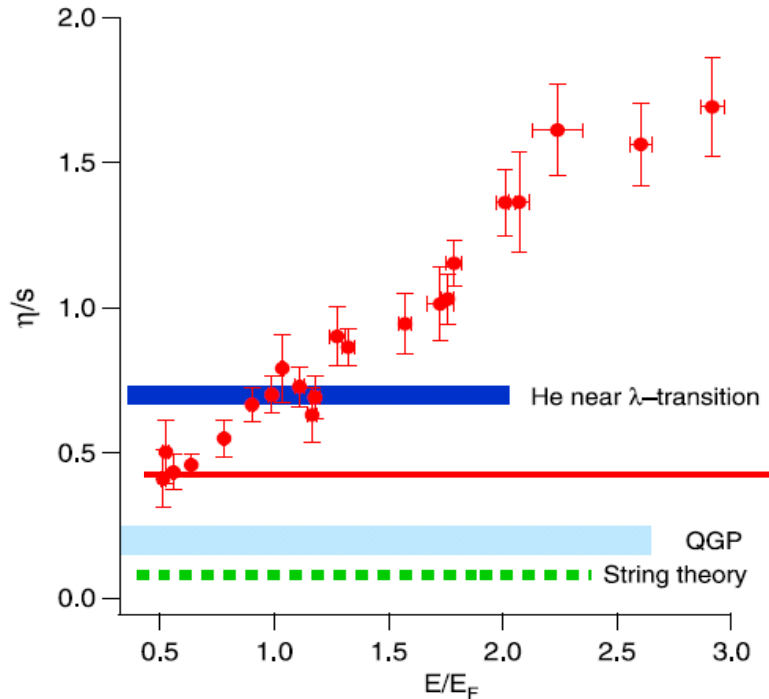Heavy-ion physics and the QGP (P. Christiansen, Lund)

The QGP fluid compared to other fluids

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*
[2]*Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*
[3]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
(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.

Conclusions about soft physics

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- The medium produced in heavy-ion collisions behaves like a nearly perfect liquid. In fact like the most perfect liquid we know!

- This was completely unexpected based on lattice QCD results

- We can get some insight into the liquid nature from AdS-CFT but so far this does not give a full picture e.g. it does not yet describe jet quenching

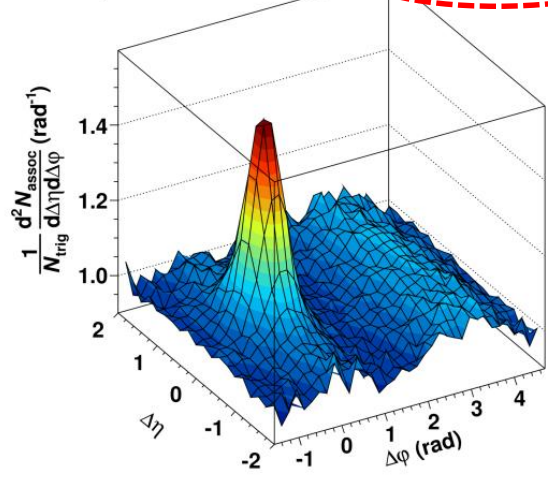Heavy-ion physics and the QGP (P. Christiansen, Lund)

COLLECTIVITY IN SMALL SYSTEMS

Collectivity in p-Pb collisions?
The rise of the double ridge
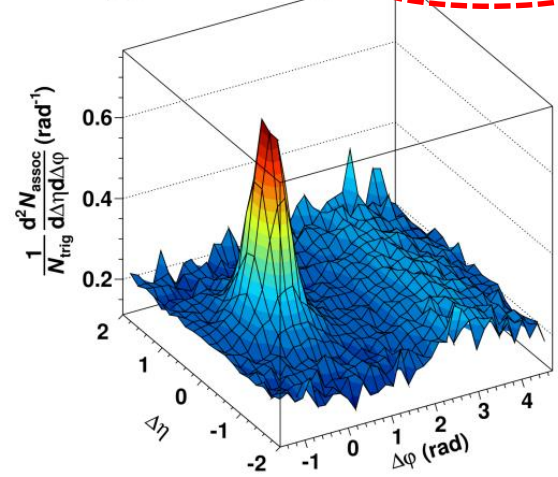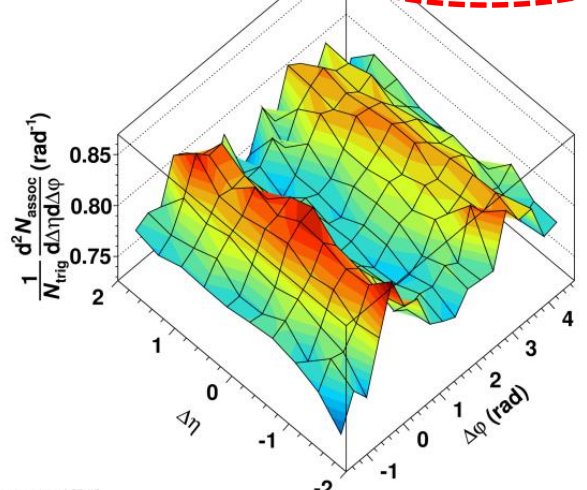
ALICE: Physics Letters B 719 (2013)

- Double ridge structure reminiscent of azimuthal flow in Pb-Pb collisions

Using Particle IDentification to study the double ridge

Heavy-ion physics and the QGP (P. Christiansen, Lund)
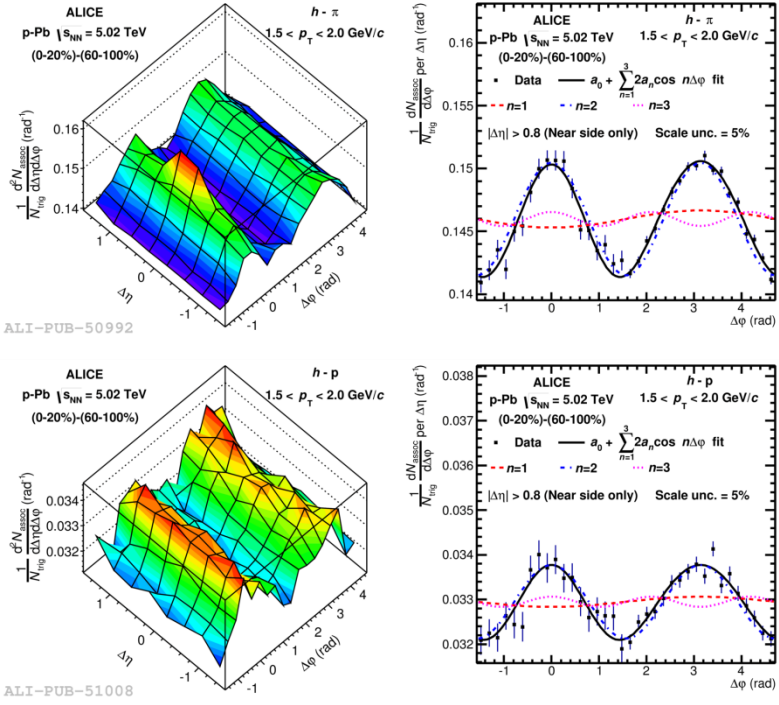
Fourier coefficients:
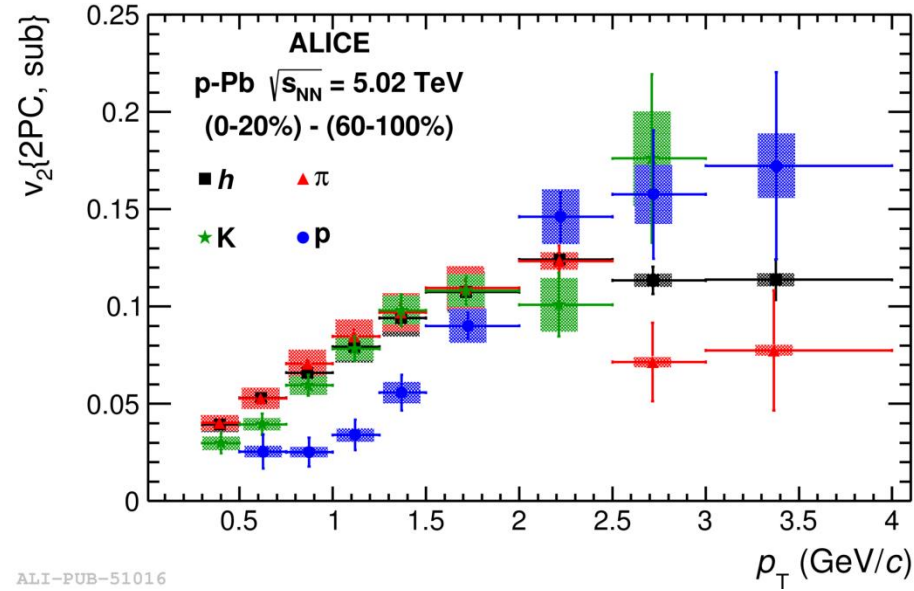
Phys. Lett. B 726 (2013) 164–177

• Clear mass ordering suggests flow

Particle ratios in p-Pb and Pb-Pb show similar features

Heavy-ion physics and the QGP (P. Christiansen, Lund)

p-Pb   Pb-Pb   p-Pb   Pb-Pb

Phys. Lett. B 728 (2014) 25
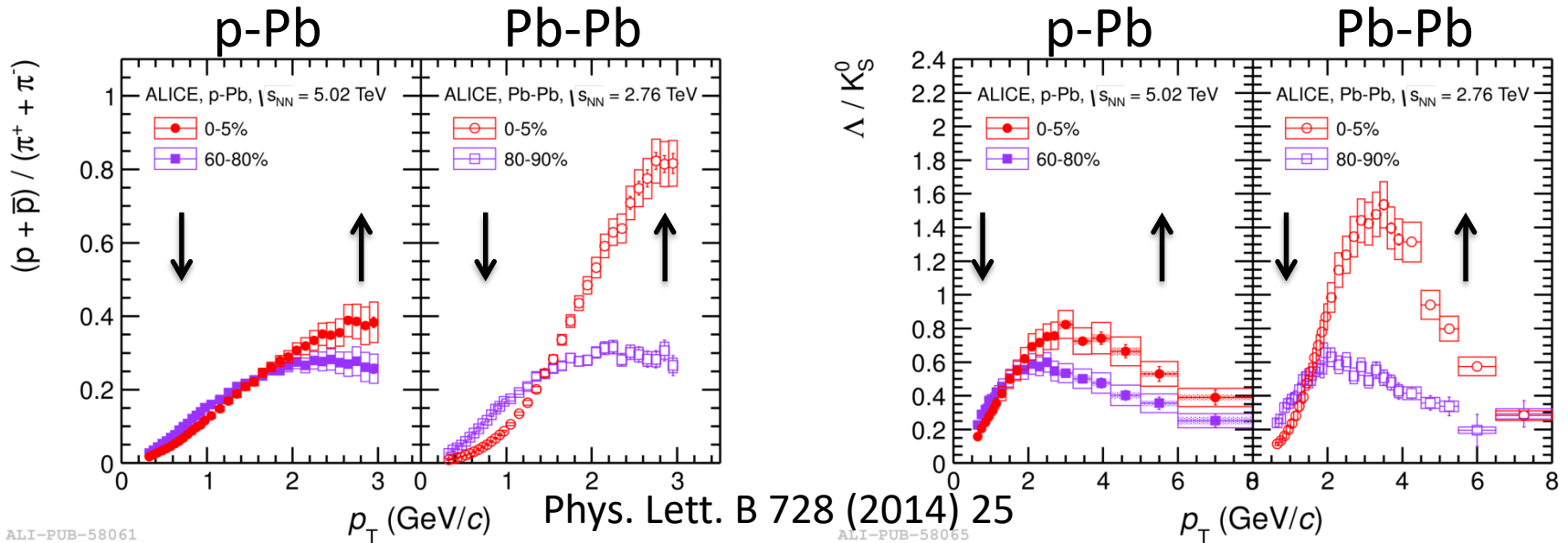
- Characteristic evolution of p/π and Λ/ K^0_S with multiplicity is reminiscent of Pb-Pb where it is believed to be due to radial flow

- NB! The solid boxes for p-Pb ratios indicate the uncorrelated systematic error
  $\Rightarrow$ the relative trend can be measured rather precisely

Which models can capture these features?

- Models
  - Blast-wave (next slides)
  - EPOS LHC (full event generator including hydro)
  - Krakow (hydro calculation focused on low p_T)
  - DPMJet (PHOJET pp + nuclei via Glauber-Gribov theory)

- Only models which employ hydrodynamics can describe the p_T spectra

p-Pb
5-10%

Phys. Lett. B 728 (2014) 25

ALI-PUB-58145

A blast wave study of the data

Heavy-ion physics and the QGP (P. Christiansen, Lund)

p-Pb 0-5%
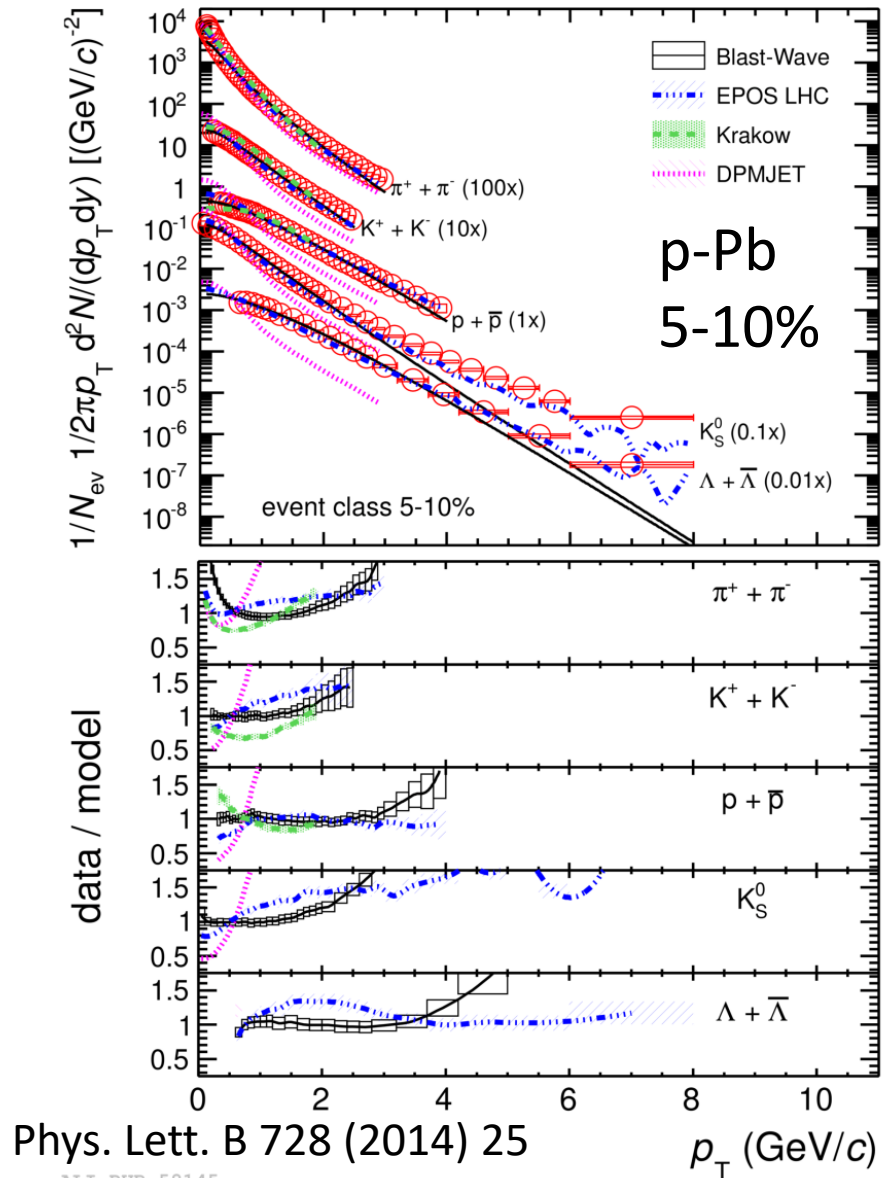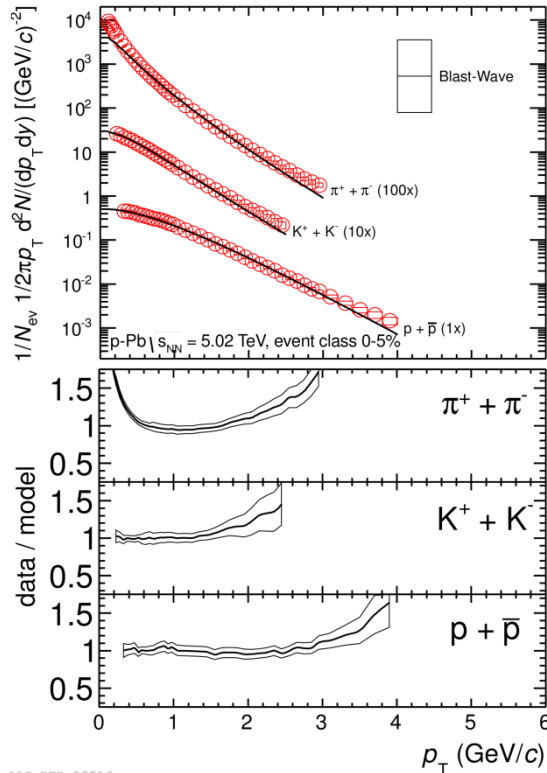

ALI-DER-59516

- Simultaneous fits
  π: $0.5 < p_T < 1.0$ GeV/c
  K: $0.2 < p_T < 1.5$ GeV/c
          pp: $0.3 < p_T < 1.5$ GeV/c
  p: $0.3 < p_T < 3.0$ GeV/c
          pp: $0.5 < p_T < 2.5$ GeV/c

- Adding
  K^0_S ($0.0 < p_T < 1.5$ GeV/c)
  and
  Λ ($0.6 < p_T < 2.0$ GeV/c)
  does not significantly change
  extracted parameters

Schnedermann et al, Phys. Rev. C 48, 2462 (1993)

$$\frac{dN}{p_\perp dp_\perp} \propto \int_0^R r\, dr\, m_\perp I_0 \left(\frac{p_\perp \sinh \rho}{T_{kin}} \right) K_1 \left(\frac{m_\perp \cosh \rho}{T_{kin}} \right)$$

$$\rho = \tanh^{-1} \beta_T$$
$$\beta_T = \beta_S (r/R)^n$$
$$\langle \beta_T \rangle = \frac{2}{2+n} \beta_S.$$

A blast wave study of the data

Heavy-ion physics and the QGP (P. Christiansen, Lund)

p-Pb 0-5%

pp highest mult √s = 7 TeV

arXiv:1307.6796
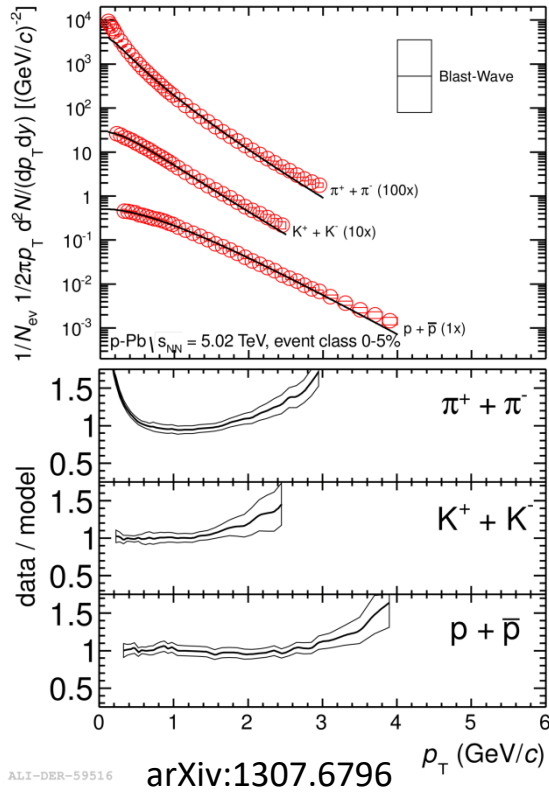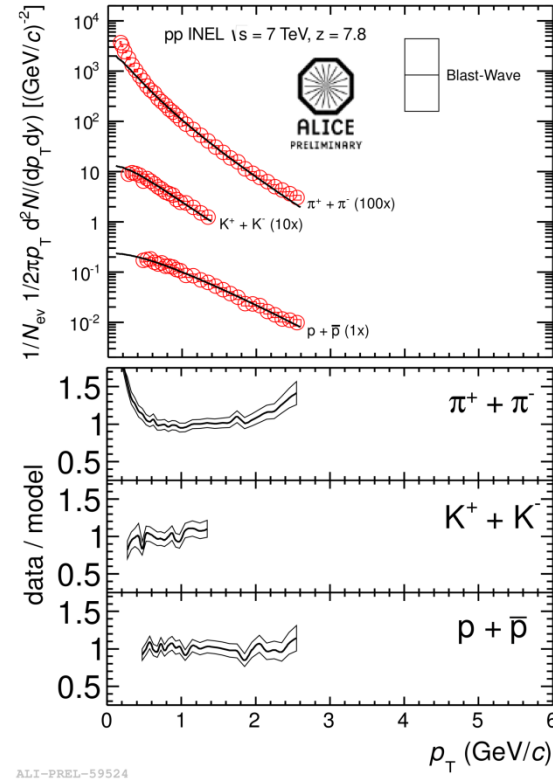
The description of p-Pb and pp data by the blast-wave fit is reasonable without being excellent

A blast wave study of the data

Heavy-ion physics and the QGP (P. Christiansen, Lund)

p-Pb 0-5%
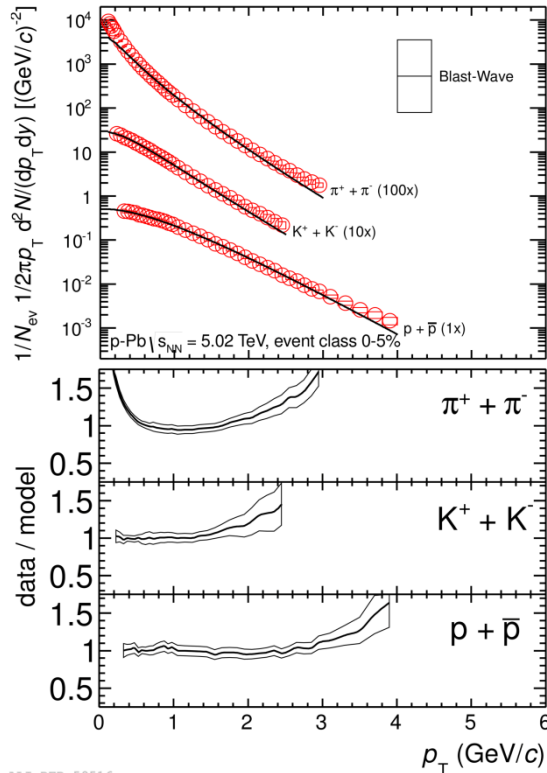
Pb-Pb 0-5% √s$_{NN}$ = 2.76 TeV
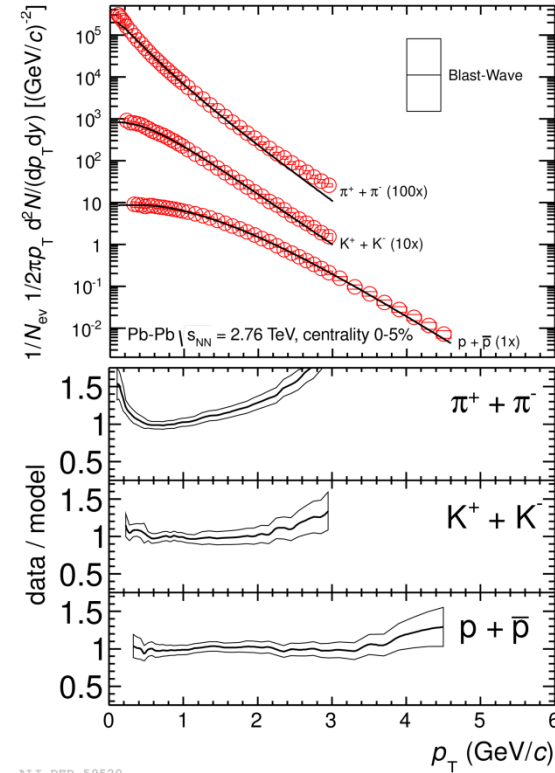
The p_T region where the blast-wave fit describes the data is in general broader for Pb-Pb

Summarizing the results from the blast-wave studies

Heavy-ion physics and the QGP (P. Christiansen, Lund)
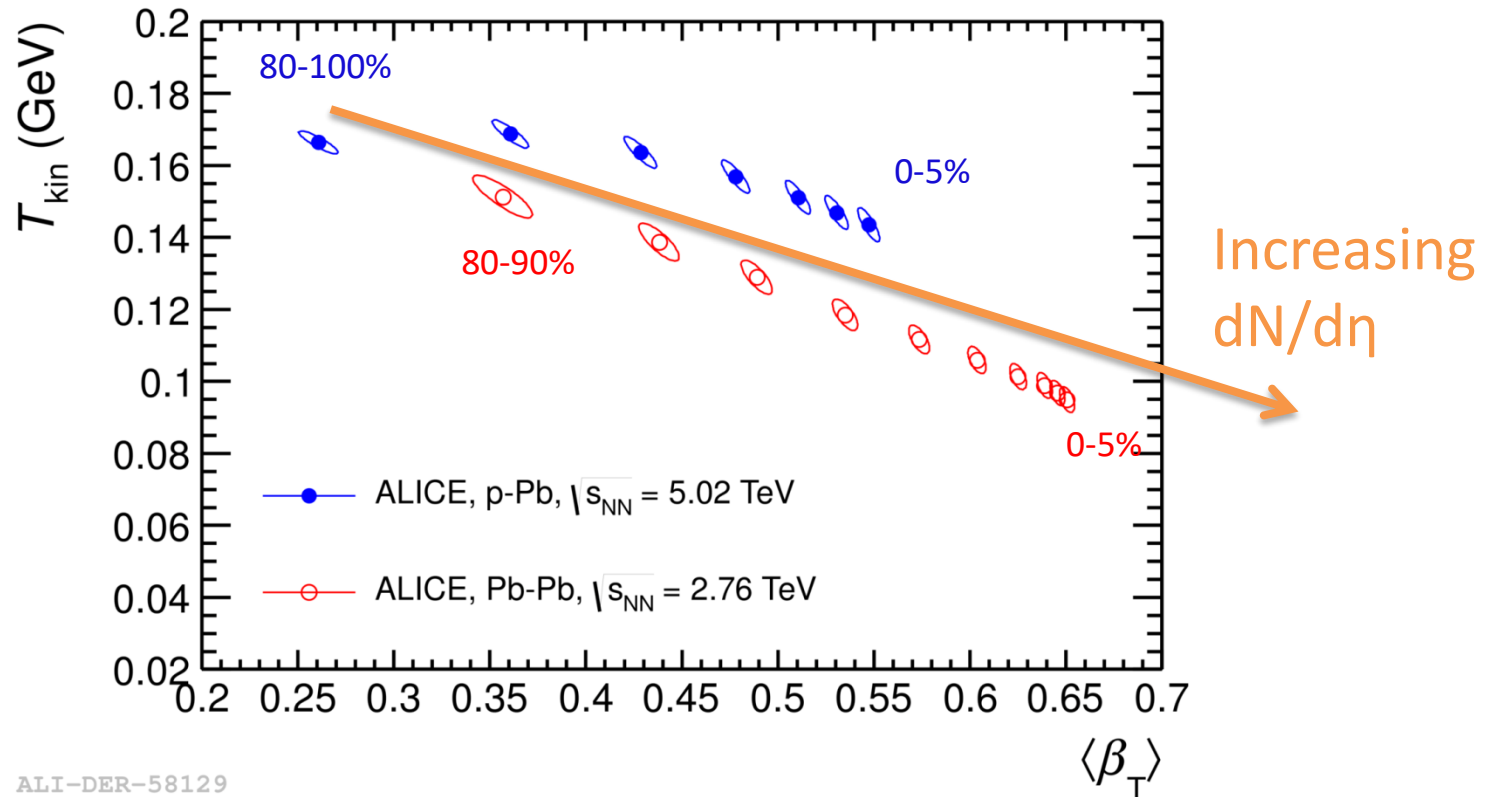
There is a strong common trend between the parameters extracted from Pb-Pb and p-Pb

Summarizing the results from the blast-wave studies

Heavy-ion physics and the QGP (P. Christiansen, Lund)

ALI−DER−58133
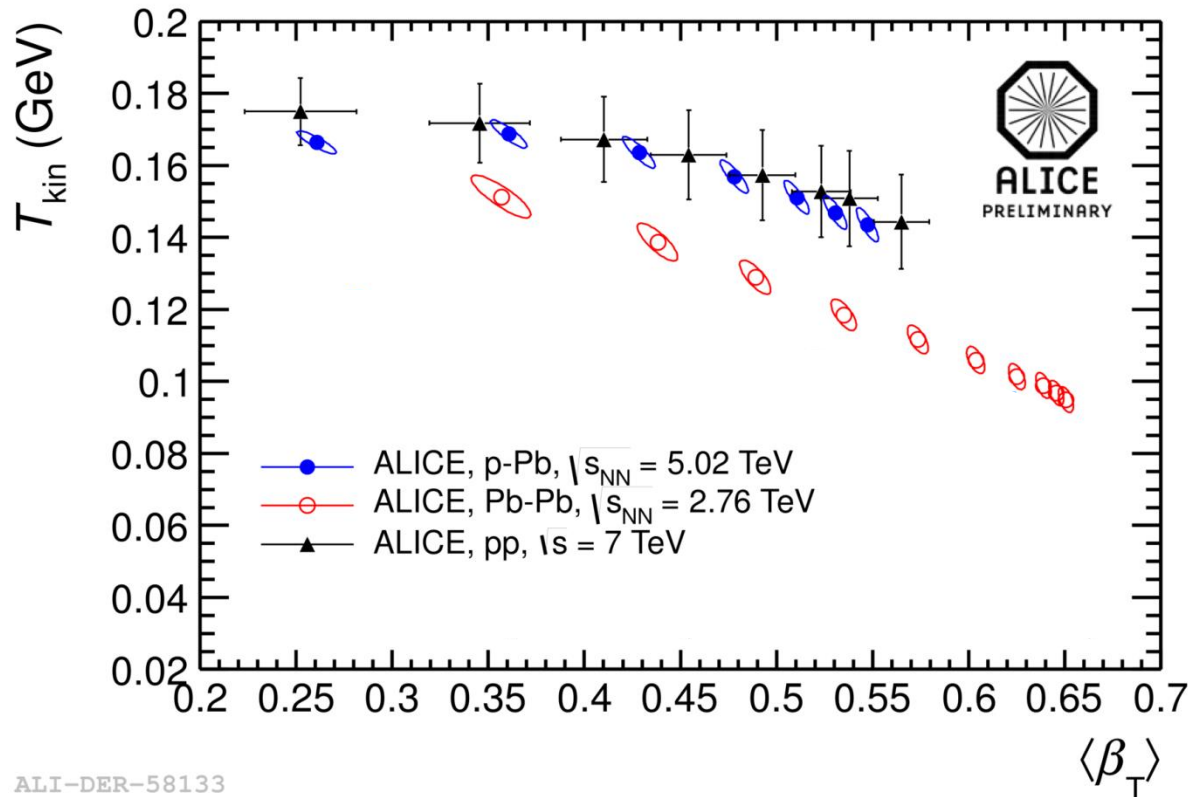
Even the pp data seems to follow the same trend!
It seems that if we ascribe the change in spectral shape
to radial flow in p-Pb then the same can be done in pp

Summarizing the results from the blast-wave studies

Heavy-ion physics and the QGP (P. Christiansen, Lund)
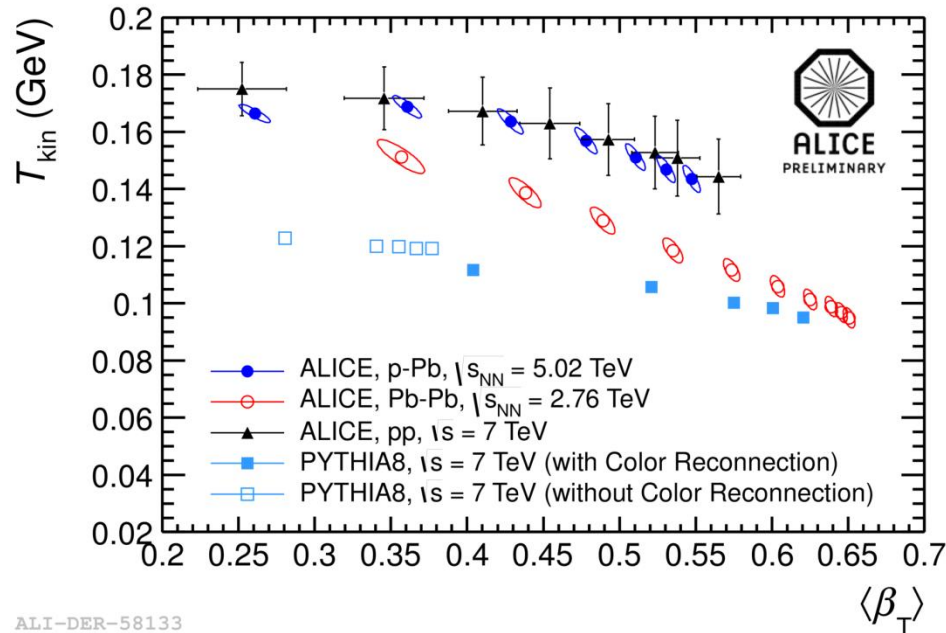
BUT also simulated PYTHIA8 pp events follow a <u>qualitatively</u> similar trend when Color Reconnection (CR) is enabled
CR has been shown to mimic radial flow but without requiring the formation of a medium

The "flow peak" in pp

Heavy-ion physics and the QGP (P. Christiansen, Lund)

ALICE , PLB 736, 196 (2014)

Common boost

(b)   (c)
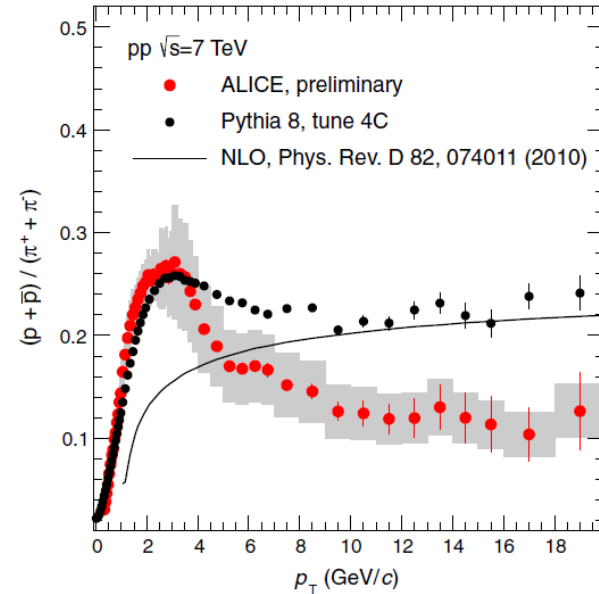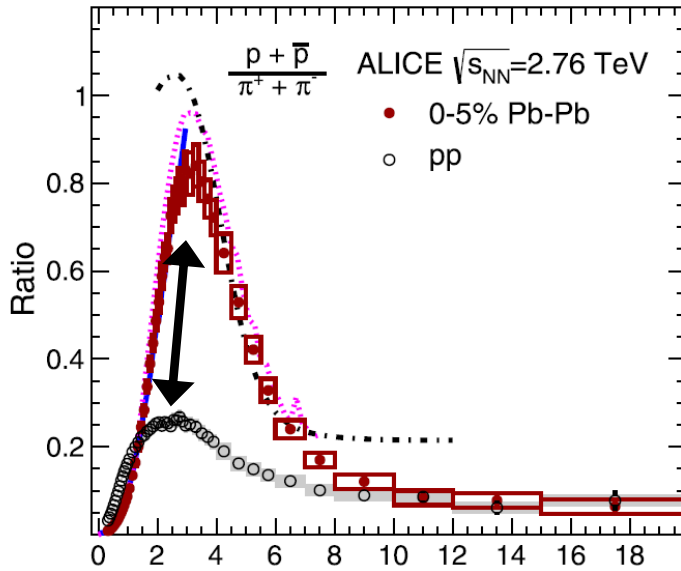
Realized that Color Reconnection in PYTHIA gives rise to flow like boosts, A. O. Velasquez, P. Christiansen, et al, PRL 111, 042001 (2013).
For details, see T. Sjöstrand, arXiv:1310.8073.
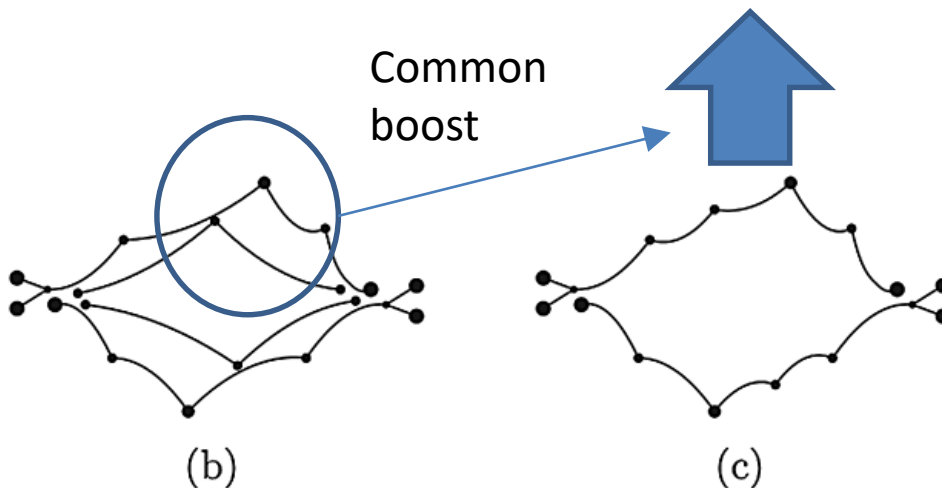
Can be interpreted different ways: CR as microscopic model of flow or one needs (hydro) flow in pp.

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Conclusions

- The reason we believe in a QGP
  - We clearly form a medium that behaves as a nearly ideal fluid with a temperature in the range given by LQCD
  - It dissolves quarkonia as expected indicating that there are strong screening effects = high density of colored objects
  - It quenches jets and gives rise to energy losses of order GeV/fm which is as expected from color fields
- The challenge to this paradigm is that we now observe medium like effects in small systems
  - We need to understand this better!

Heavy-ion physics and the QGP (P. Christiansen, Lund)

What I did not cover

- Charged multiplicity and hadronization
  - Color Glass Condensate and Statistical Model

- Quark scaling of elliptic flow
  - Recombination of quark like degrees of freedom (picture is more complicated at LHC)

- Quenching and flow of heavy quarks
  - Suggests that there are also large collisional energy loss

Why are the small systems so critical to understand

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- Before we were happy to have
  - Small systems = QCD
    - Phenomenology: PYTHIA
  - Large systems = QGP
    - Phenomenology: Glauber + hydro + stat. model + some hadronic rescattering

Geometry: is the Pb-Pb centrality evolution described by hydro?

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Pb-Pb 0-5%   Pb-Pb 0-5%

Phys. Rev. Lett. 109, 252301 (2012)

Krakow: PRC85, 064915 (2012)
HKM: PRC87, 024914 (2013)
Fries: PRL90, 202303 (2003) and private communication
EPOS: PRL109, 102301 (2012) and private communications
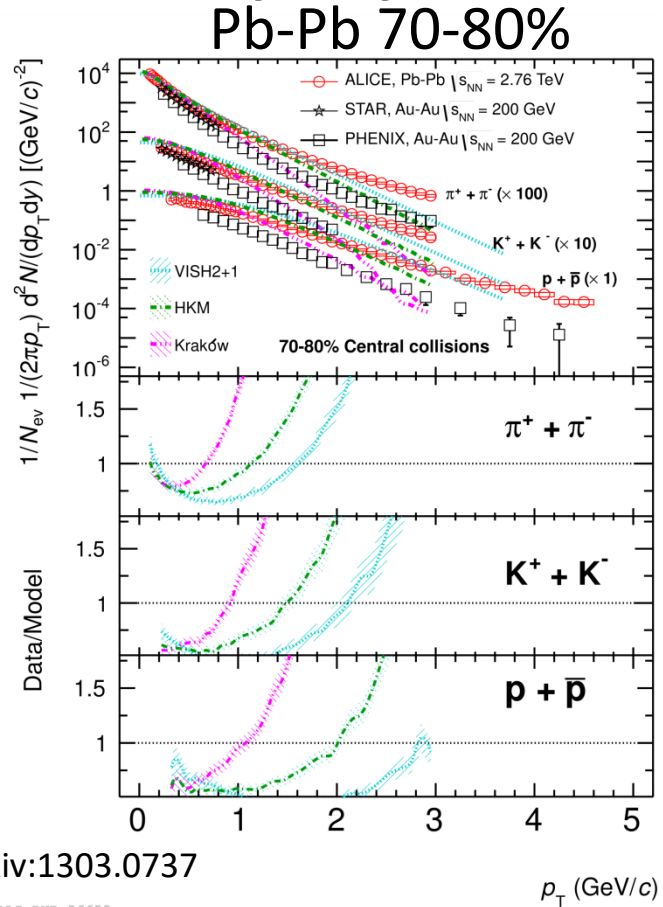
- Near ideal hydrodynamics with some implementation of the hadronic phase describes well p_T spectra in central collisions

Geometry: is the Pb-Pb centrality evolution described by hydro?

Heavy-ion physics and the QGP (P. Christiansen, Lund)

Pb-Pb 0-5%   Pb-Pb 70-80%
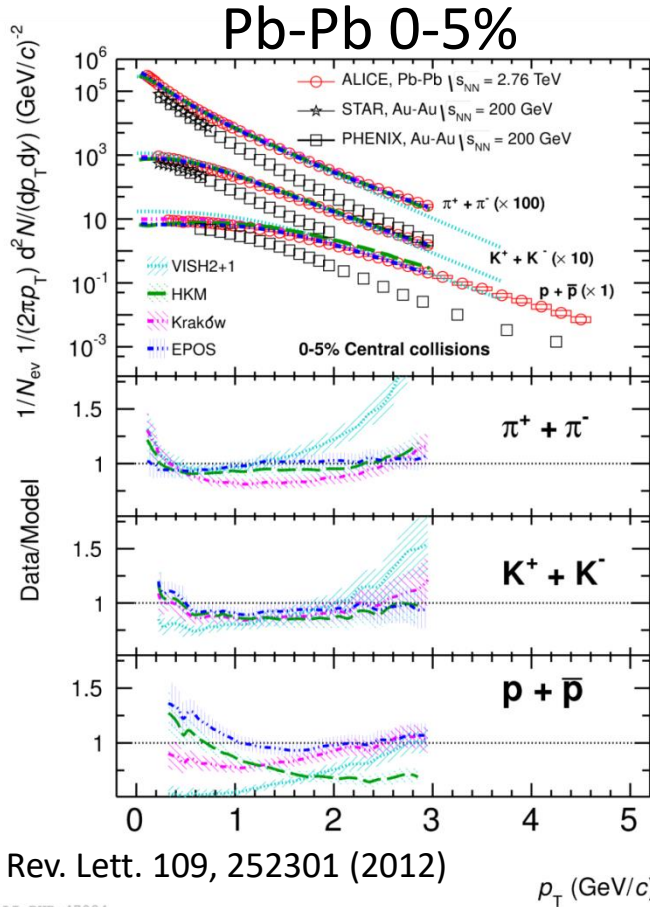
Phys. Rev. Lett. 109, 252301 (2012)   arXiv:1303.0737

- The same models fail to describe the p_T spectra in peripheral collisions
- Typically hydro has not been expected to work in peripheral collisions but if it is at work in p-Pb and pp collisions should it not work there?

Why is this a problem

Heavy-ion physics and the QGP (P. Christiansen, Lund)

- Our description of the medium is not only critical for the low p_T observables, the jet quenching also relies on our medium properties

- If we cannot resolve this issue then we are a bit stuck

- Need to understand if a medium is also created in small systems!
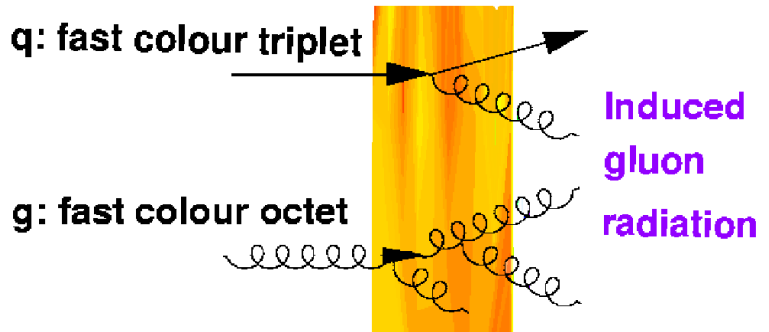 - My own view: need to look for energy loss in small systems
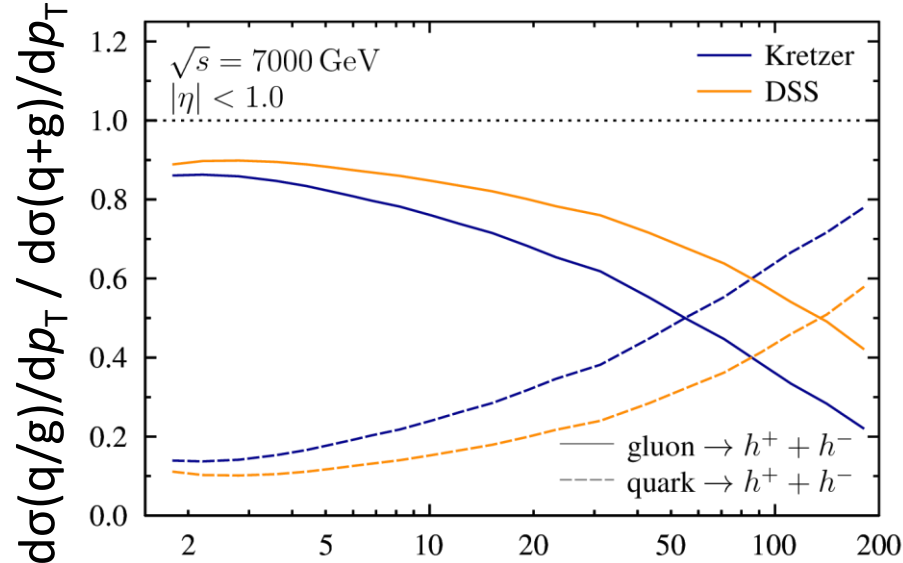
Backup slides

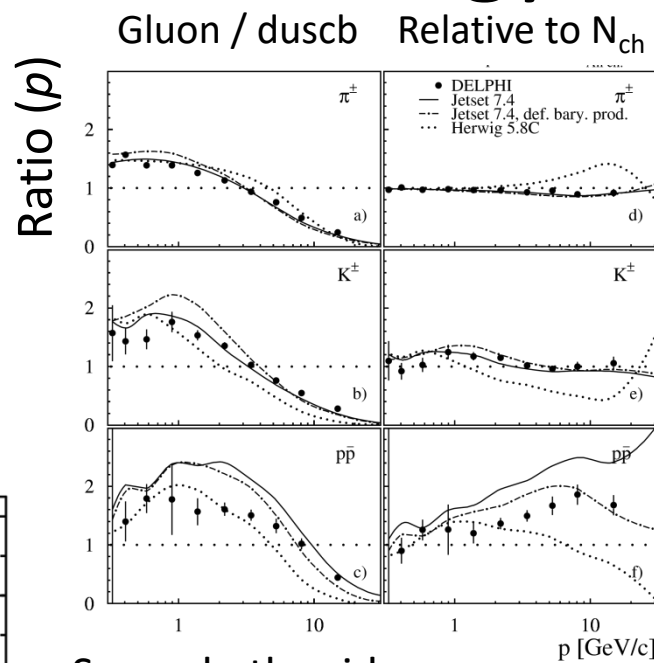# Motivation: searching for "footprints" of the energy loss
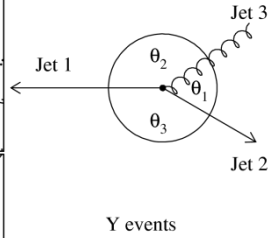
Heavy-ion physics and the QGP (P. Christiansen, Lund)

q: fast colour triplet

g: fast colour octet

Induced gluon radiation

Gluon / duscb   Relative to N_{ch}

Ratio (p)

DELPHI Collaboration EPJC17, 207 (2000)

Gluons lose 2 times (color factor) more energy than quarks in the medium

$\frac{d\sigma(q/g)/dp_T}{d\sigma(q+g)/dp_T}$

$\sqrt{s} = 7000\,\text{GeV}$
$|\eta| < 1.0$

Kretzer
DSS

gluon $\to h^+ + h^-$
quark $\to h^+ + h^-$

p_T [GeV/c]

d'Enterria et al, Nucl.Phys. B883, 615 (2014)

Several other ideas:

Color flow (Sapeta, Wiedemann, EPJC55, 293, 2008)

Color structure (Aurenche, Zakharov, EPJC71, 1829, 2011)

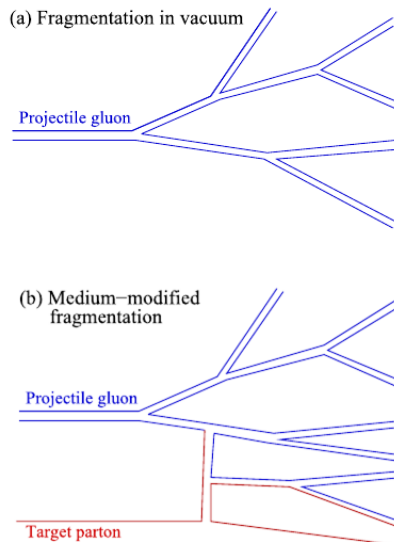In medium formation time effects (Bellwied, Markert, PLB691, 208, 2010)

Magnitude of the effects are large (50+%) since it is linked to the large energy loss

Why expect particle species dependent R_{AA} at high p_T?

- Large effects at intermediate p_T – does this effect just disappear?

- The low value of R_{AA} suggests that most hard partons interacts strongly with the medium
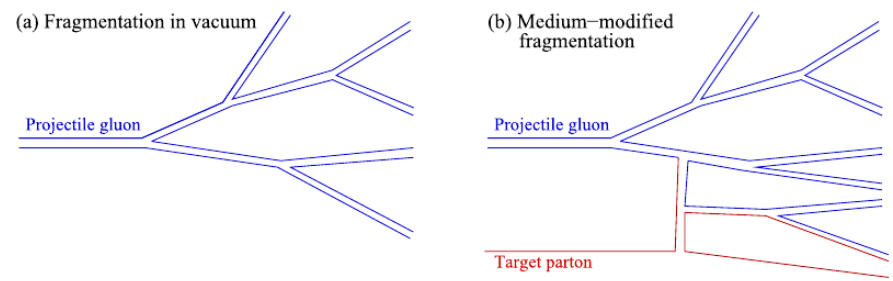
(a) Fragmentation in vacuum

Projectile gluon

(b) Medium−modified fragmentation

Projectile gluon

Target parton

S. Sapeta and U.A. Wiedemann, Eur.Phys.J. C55 (2008) 293:

- Indirect
  - "in all models of radiative parton energy loss, the interaction of a parent parton with the QCD medium transfers color between partonic projectile and target. This changes the color flow in the parton shower and is thus likely to affect hadronization."
- Direct
  - "In addition, flavor or baryon number could be exchanged between medium and projectile."

A general model with particle species dependent modifications

Heavy-ion physics and the QGP (P. Christiansen, Lund)

S. Sapeta and U.A. Wiedemann, Eur.Phys.J. C55 (2008) 293

(a) Fragmentation in vacuum

Projectile gluon

(b) Medium−modified fragmentation

Projectile gluon

Target parton

- Effect <u>inside jet</u>

- But for p_T >> 8 GeV/c we expect all hadrons to belong to jets