Modern Experimental Particle Physics
FYST17

February 17 and 20, 2020

An introduction to the Quark Gluon Plasma and heavy-ion collisions

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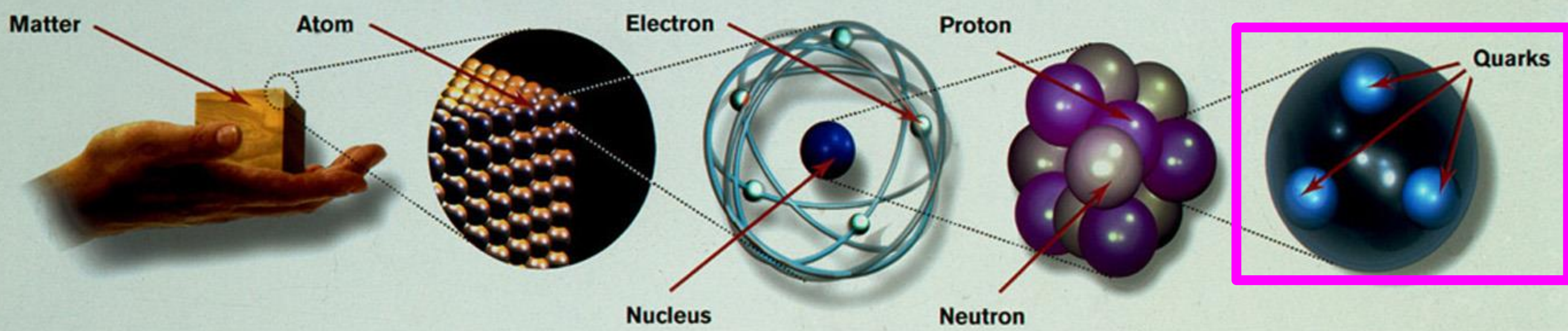
Outline

- 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?



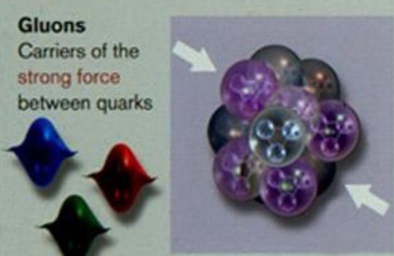
Matter particles
All ordinary particles belong to this group

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

	LEPTONS		QUARKS	
FIRST FAMILY	**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
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

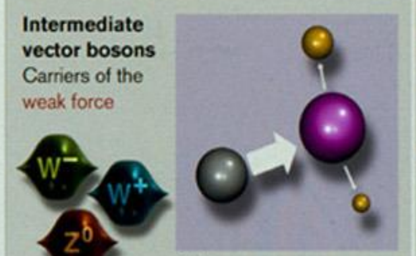
The explosive release of nuclear energy is the result of the strong force

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



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

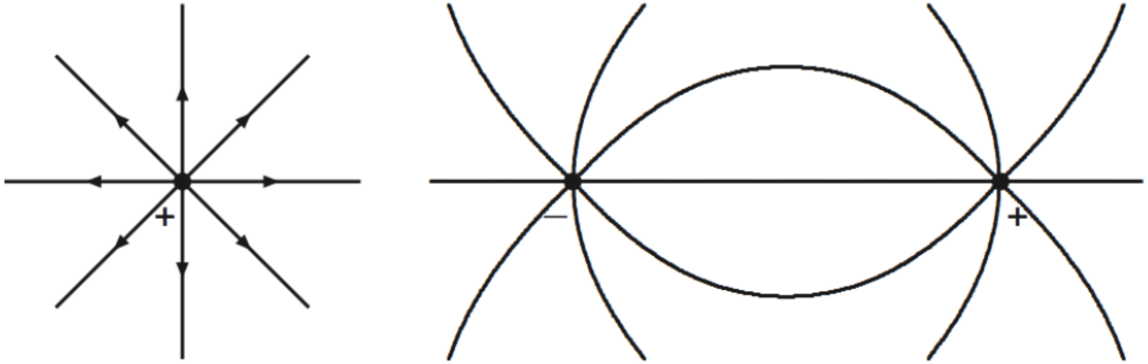
All the weight we experience is the result of the gravitational force

GRAPHICS: PETER CROWTHER

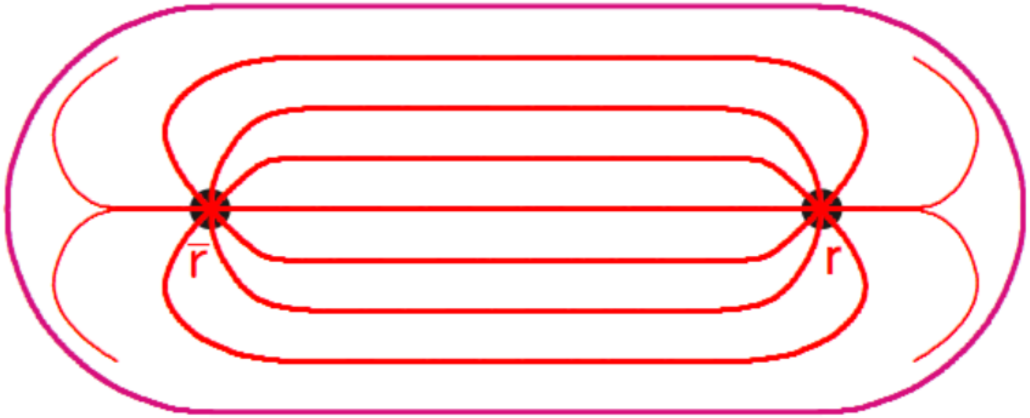
Let us recall what is special about QCD

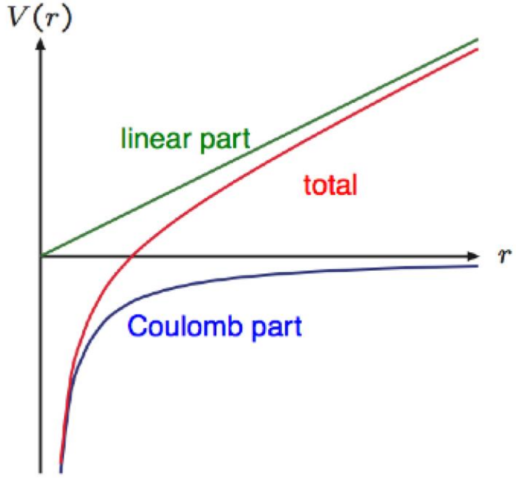
QED vs QCD

QED: superposition principle



QCD: color fields interact (form flux tube at long distance)

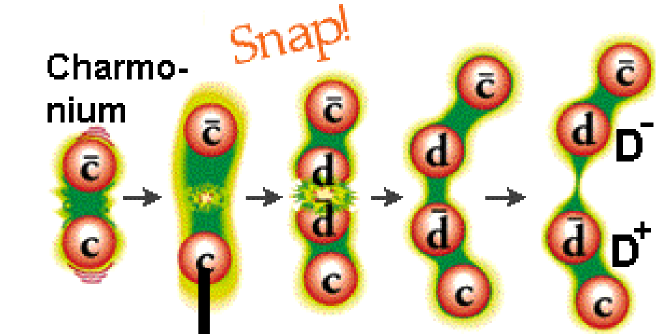




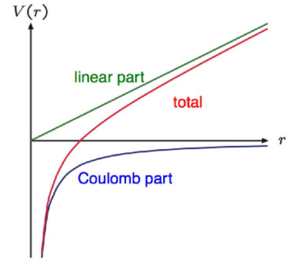
Basis of Lund string model

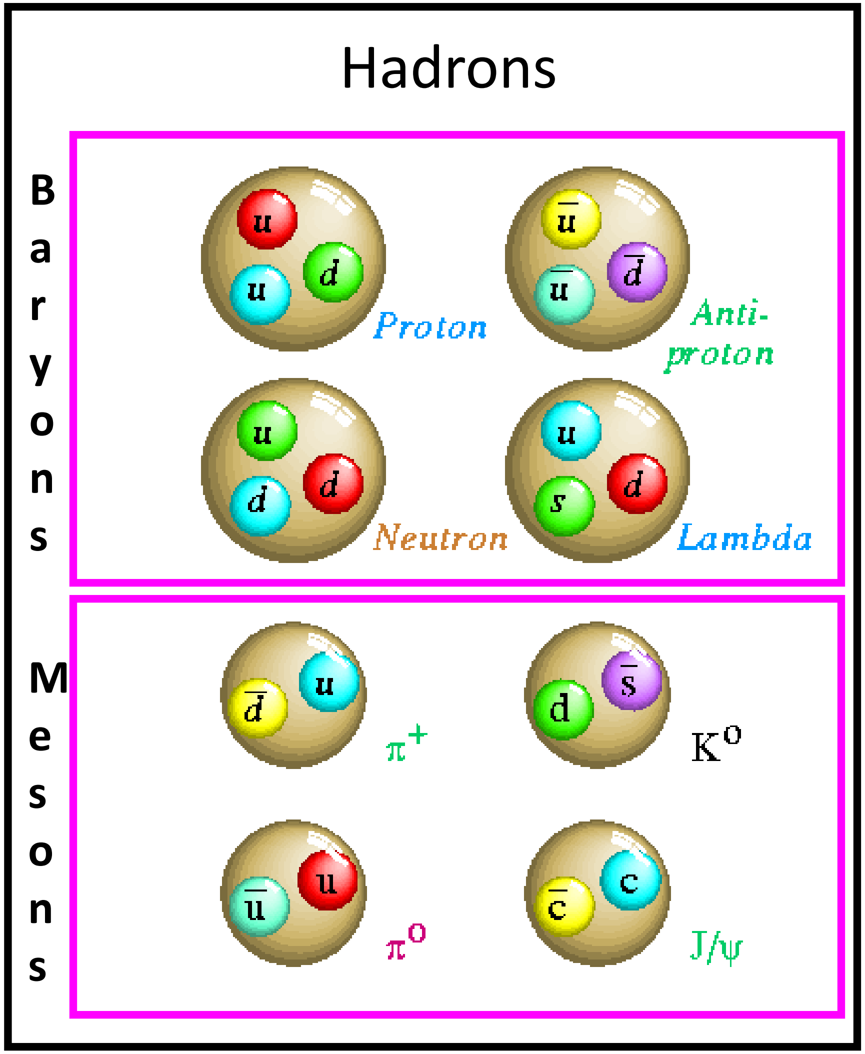
The strong interaction: Quantum Chromo Dynamics (QCD)

3 strong charges (red, green, blue)
Particles in nature are color neutral
Quarks are “confined”



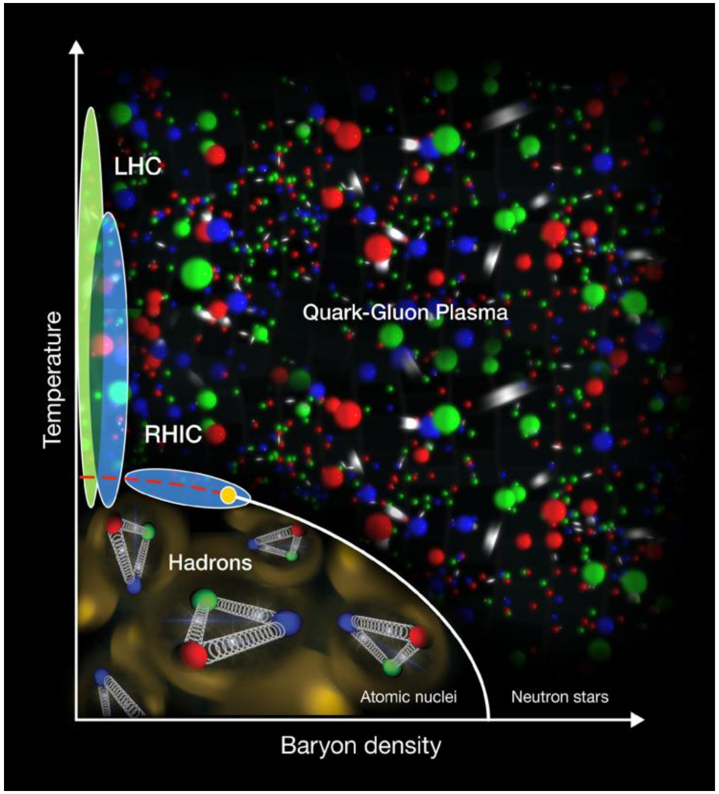
(Force ~ 1 GeV/fm)





Deconfinement at high energy densities

Tc ~ 160 MeV
(2.000.000.000.000 K)



At high energy densities a new form of matter exists: Quark-Gluon Plasma, where quarks&gluons are deconfined

We will only talk about the high temperature transition which is what we probe in heavy-ion collisions

What is the Quark Gluon Plasma?

"`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.

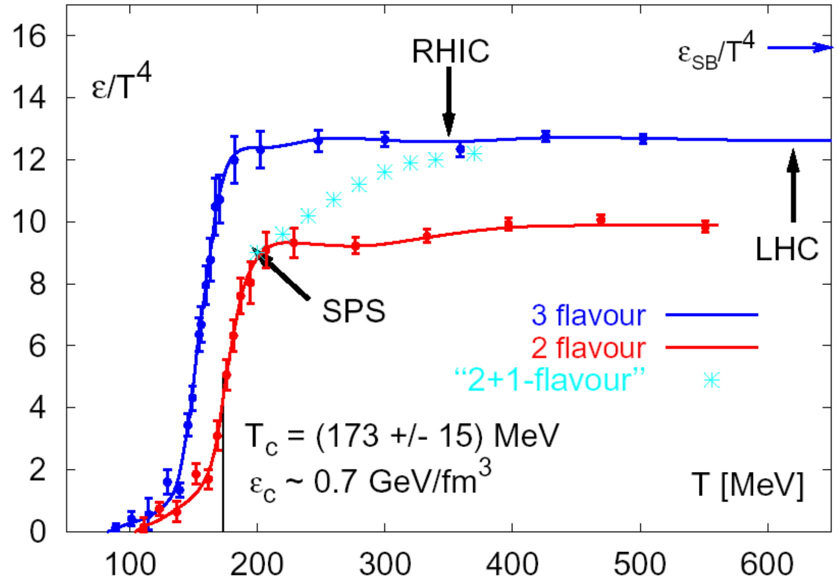
They point out a big problem: our main understanding is experimental and very little of the theory is on a firm basis.

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

Why do we study the QGP?

- New phase of matter predicted by QCD
  – Characterize its properties experimentally (and eventually be able to derive them)
- Cosmology: QGP phase transition in the early Universe (μs after Big Bang)
- New paradigm?
  – Circumvent traditional problem that while quarks and gluons are the fundamental degrees of freedom we observe hadrons to directly study the QCD dynamics of quarks and gluons

Lattice QCD calculation of the energy density



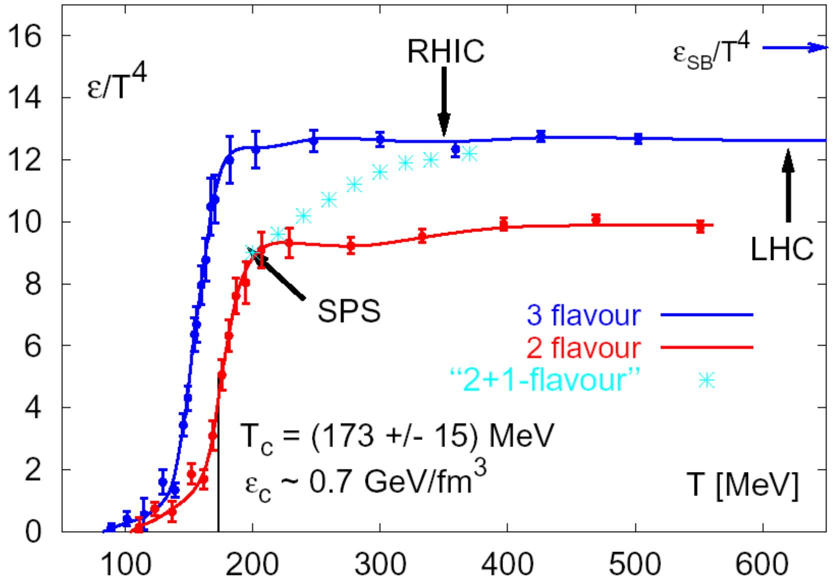
$$\varepsilon_{Quark-Gluon\ gas} = \frac{\pi^2}{30}\left(\text{bosonic dof} + \frac{7}{8}\ \text{fermionic dof}\right) T^4$$

?

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



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

Gluon spin and color

(Anti+)quark spin, color and flavor

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.

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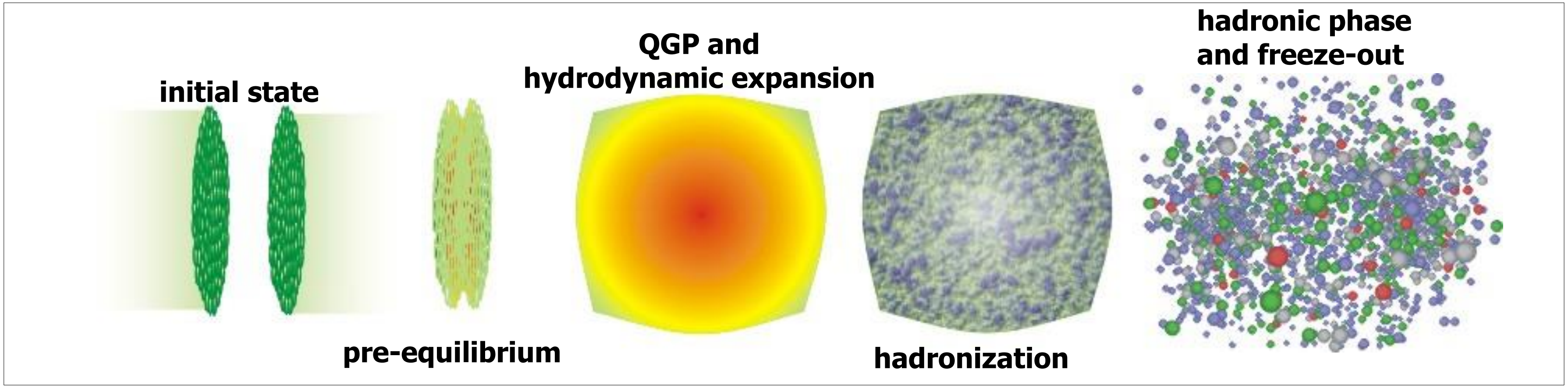
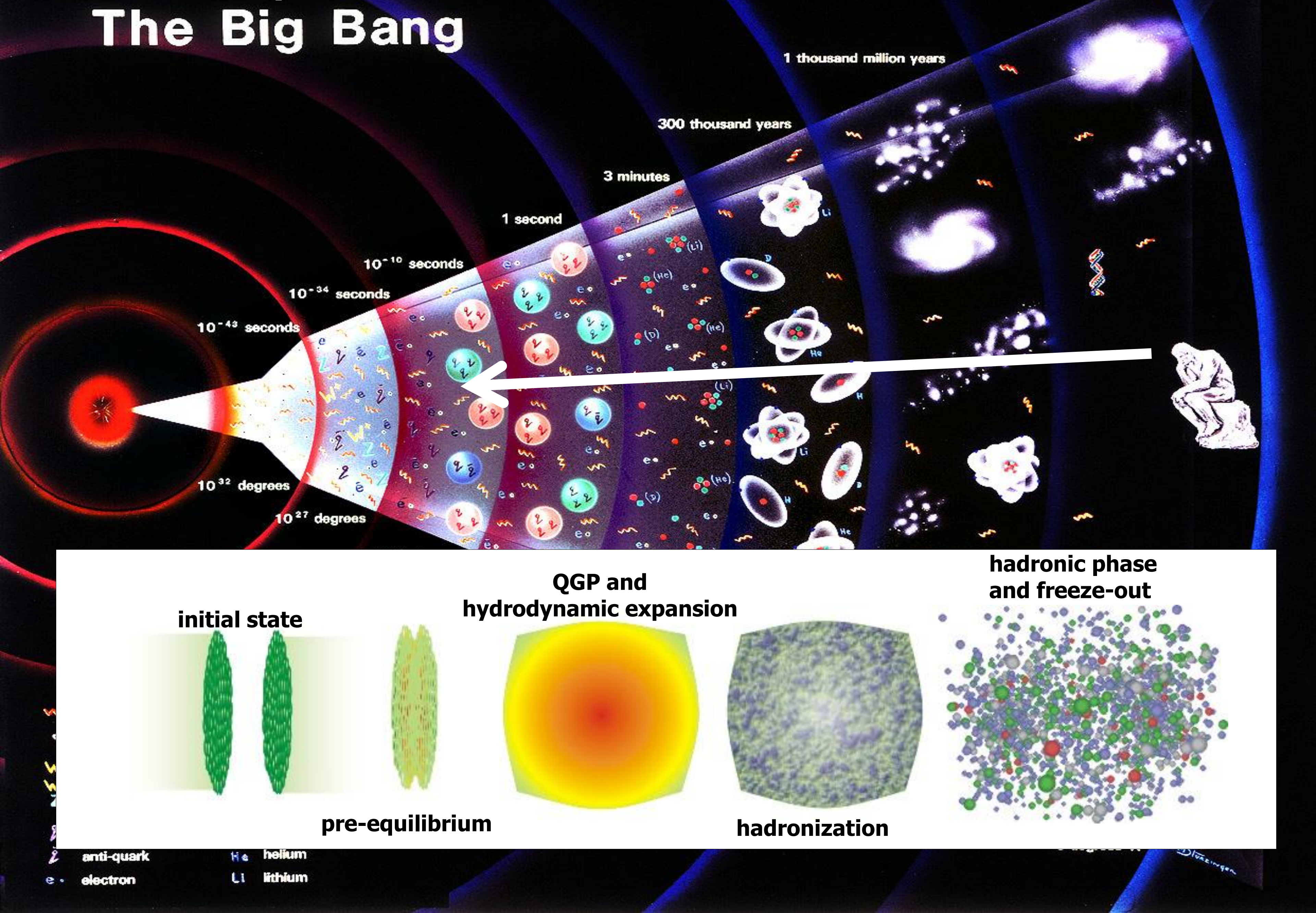
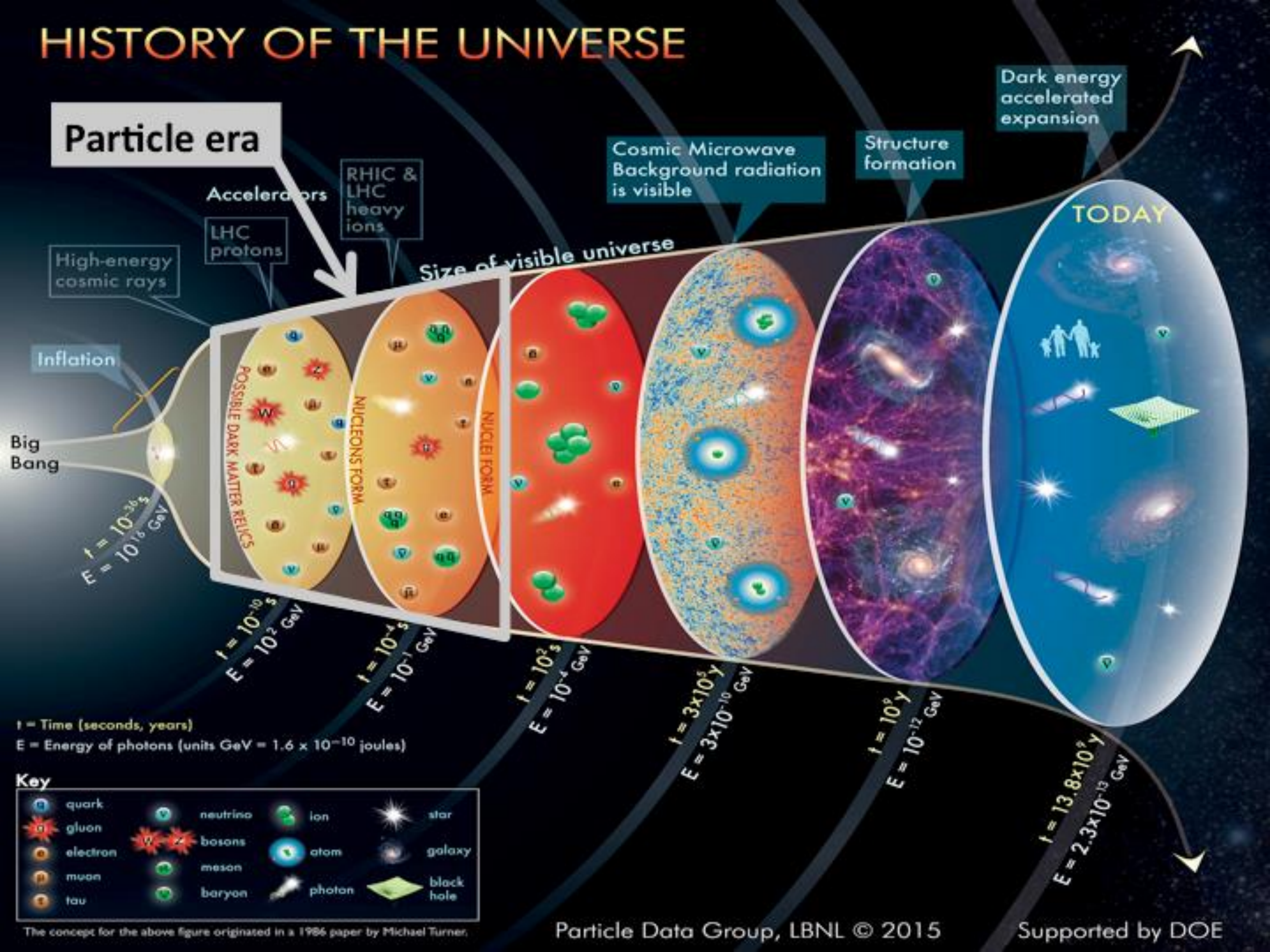
Heavy ion collisions



- The only way we can create the QGP in the laboratory!
- By colliding heavy ions it is possible to create a large (»1fm^3) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally 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





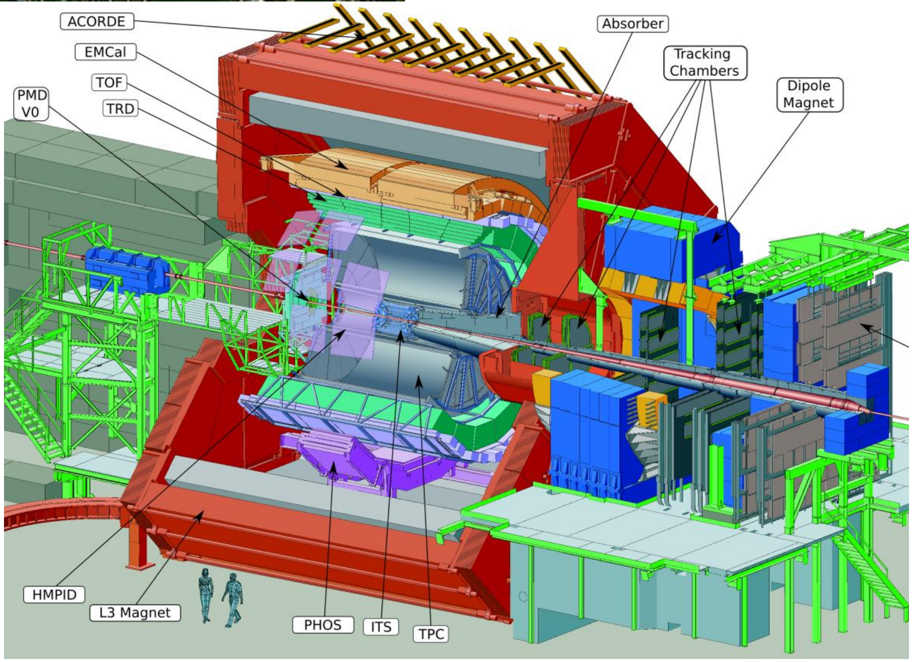
HISTORY OF THE UNIVERSE
Particle era
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ 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
$t = 3 \times 10^{5}$ y
$E = 3 \times 10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ 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

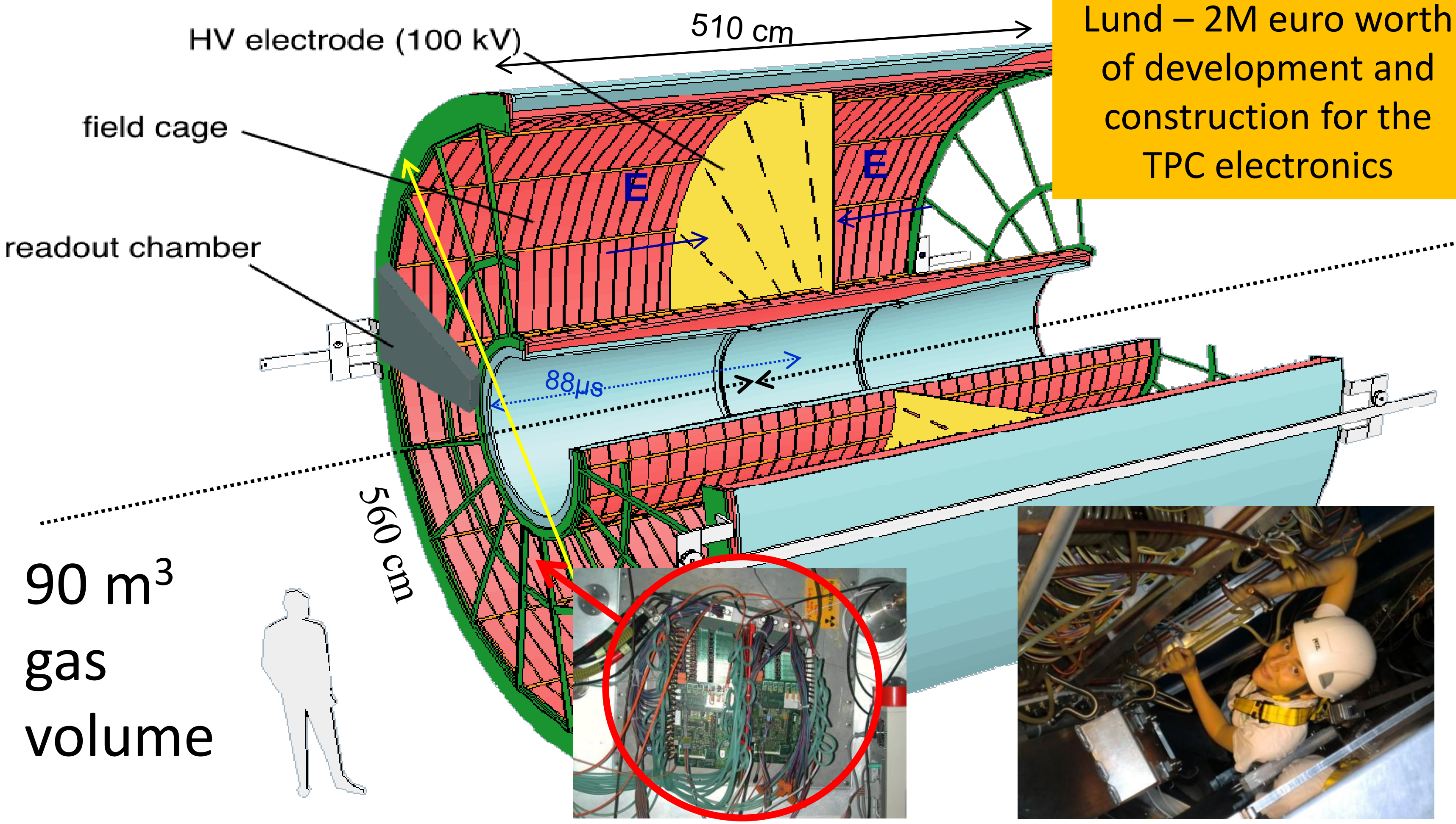
- 1st generation $\sqrt{s_{NN}}$<20GeV (fixed target)
AGS (BNL, US), SPS (CERN) late 80s and 90s
  - Experiments: NA61, NA49, NA60, NA50, NA44, ……
- 2nd generation $\sqrt{s_{NN}}$<200GeV (collider)
RHIC (BNL, US) 2000-Now
  - Experiments: PHENIX, STAR, PHOBOS, BRAHMS
- 3rd generation $\sqrt{s_{NN}}$=2760GeV 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 ALICE experiment at LHC: Detecting the QGP



The Time Projection Chamber: a 3D charged particle "camera"

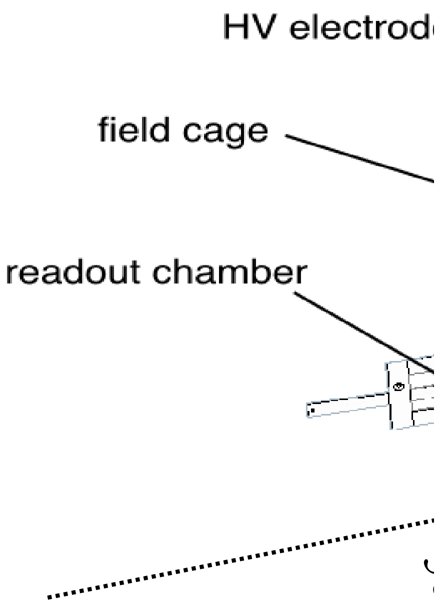


Lund – 2M euro worth of development and construction for the TPC electronics

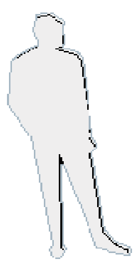
90 m^3 gas volume

Lund is active on both the hardware and software side

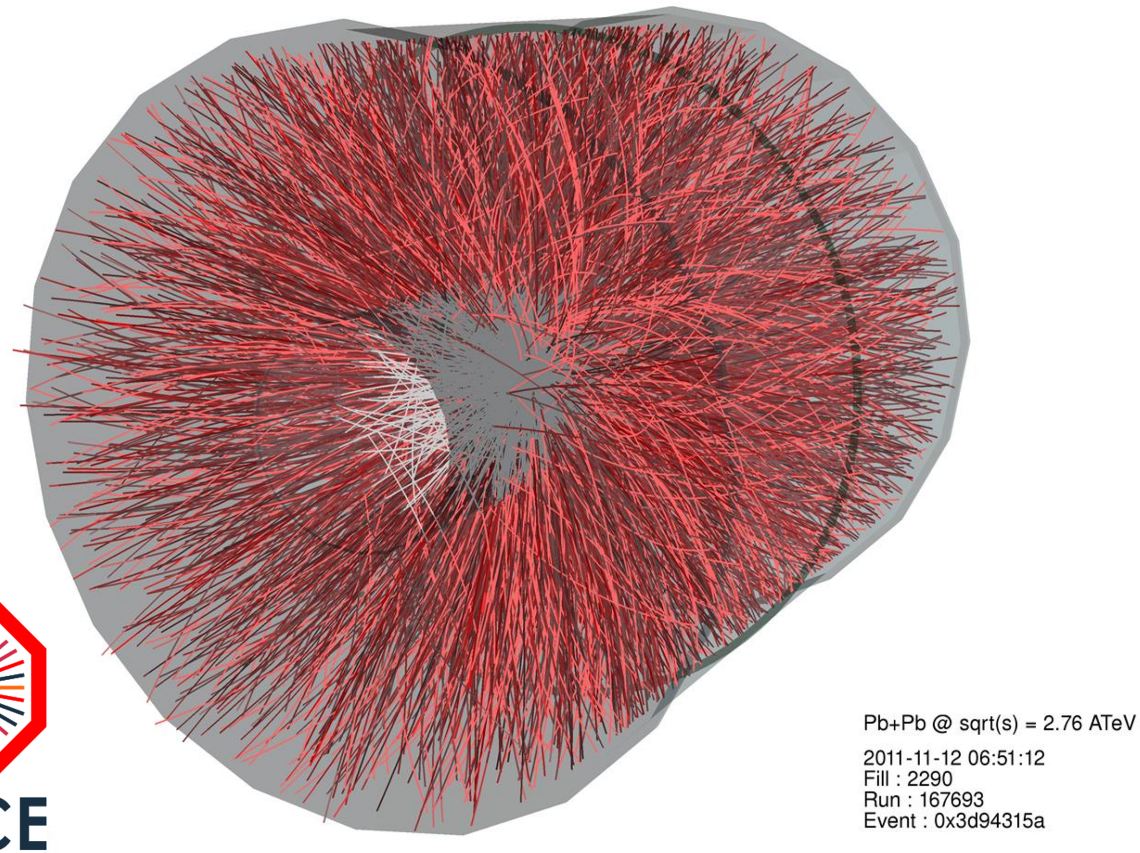
The Time Projection Chamber: a 3D charged particle "camera"



90 m^3 gas volume



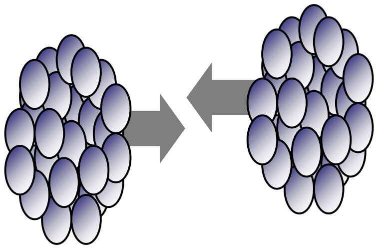
ALICE

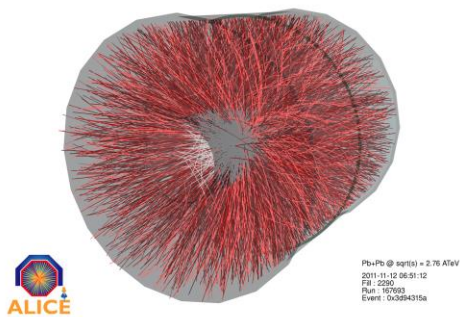


Lund is active on both the hardware and software side

The three systems (understanding before 2012)

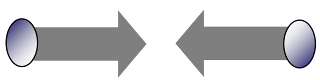
Pb-Pb

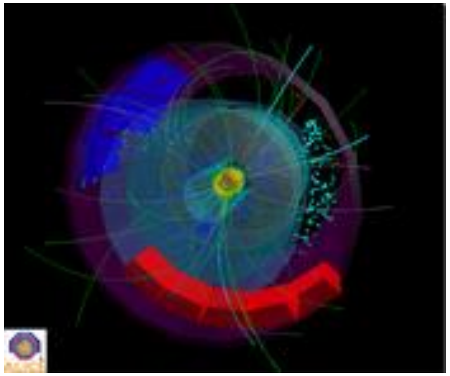




Hot QCD matter:
This is where we expect the QGP to be created in central collisions.

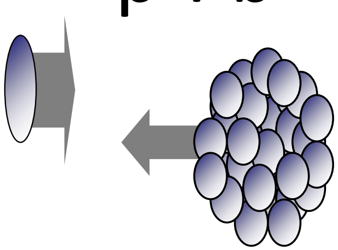
pp

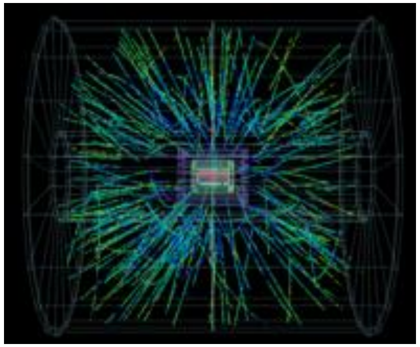




QCD baseline:
This is the baseline for “standard” QCD phenomena.

p-Pb





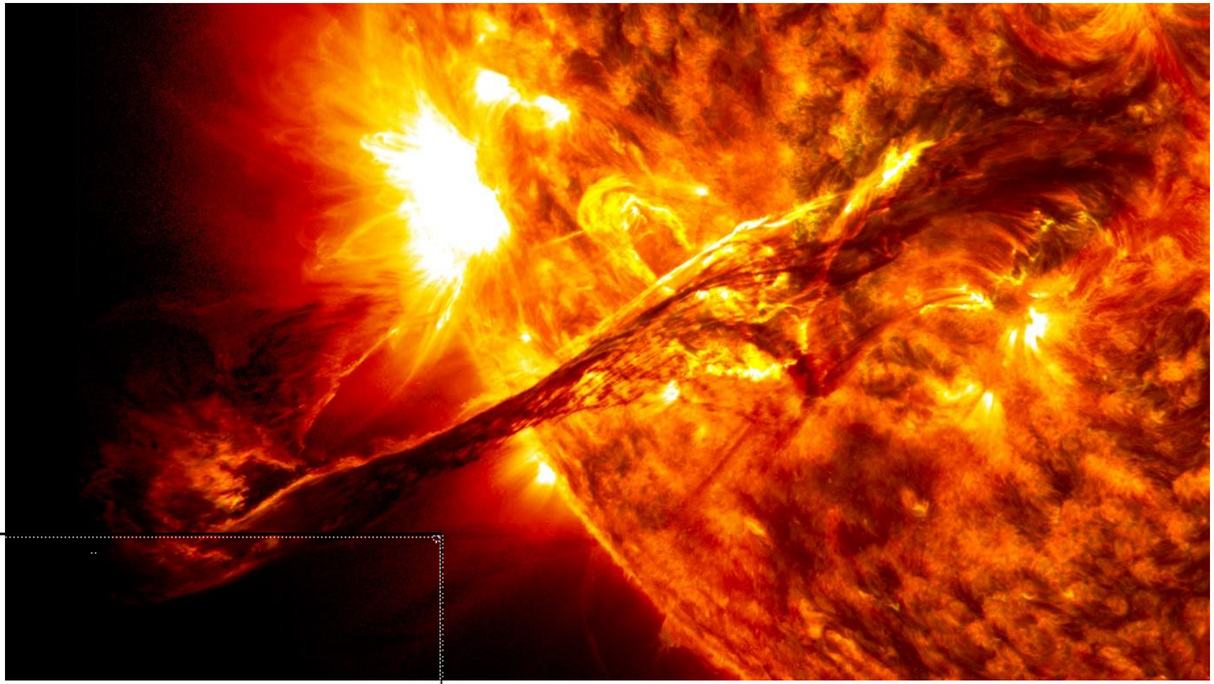
Cold QCD matter:
This is to isolate nuclear effects, e.g. nuclear pdfs.

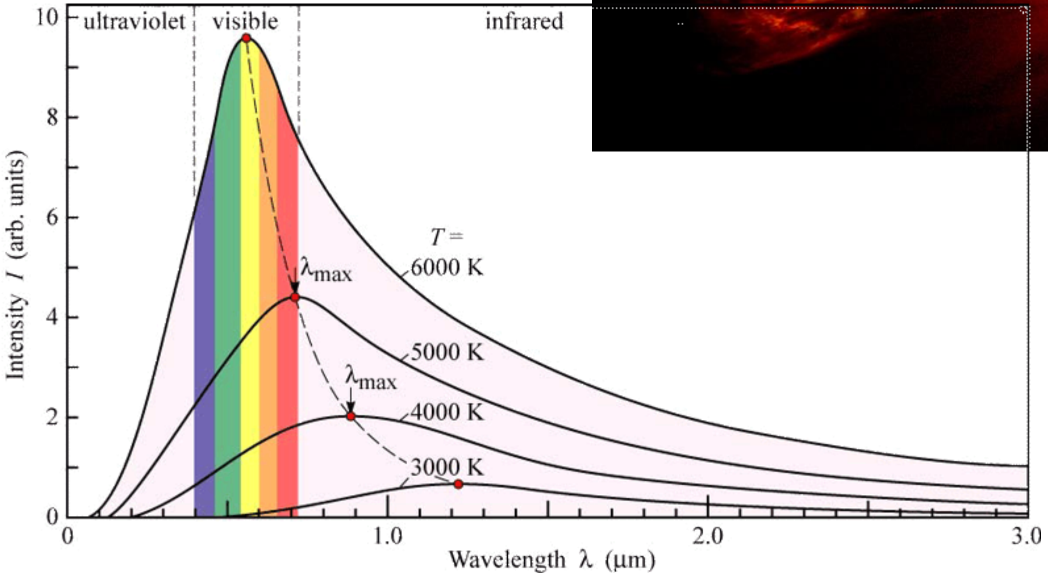
THERMAL PHOTONS

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…

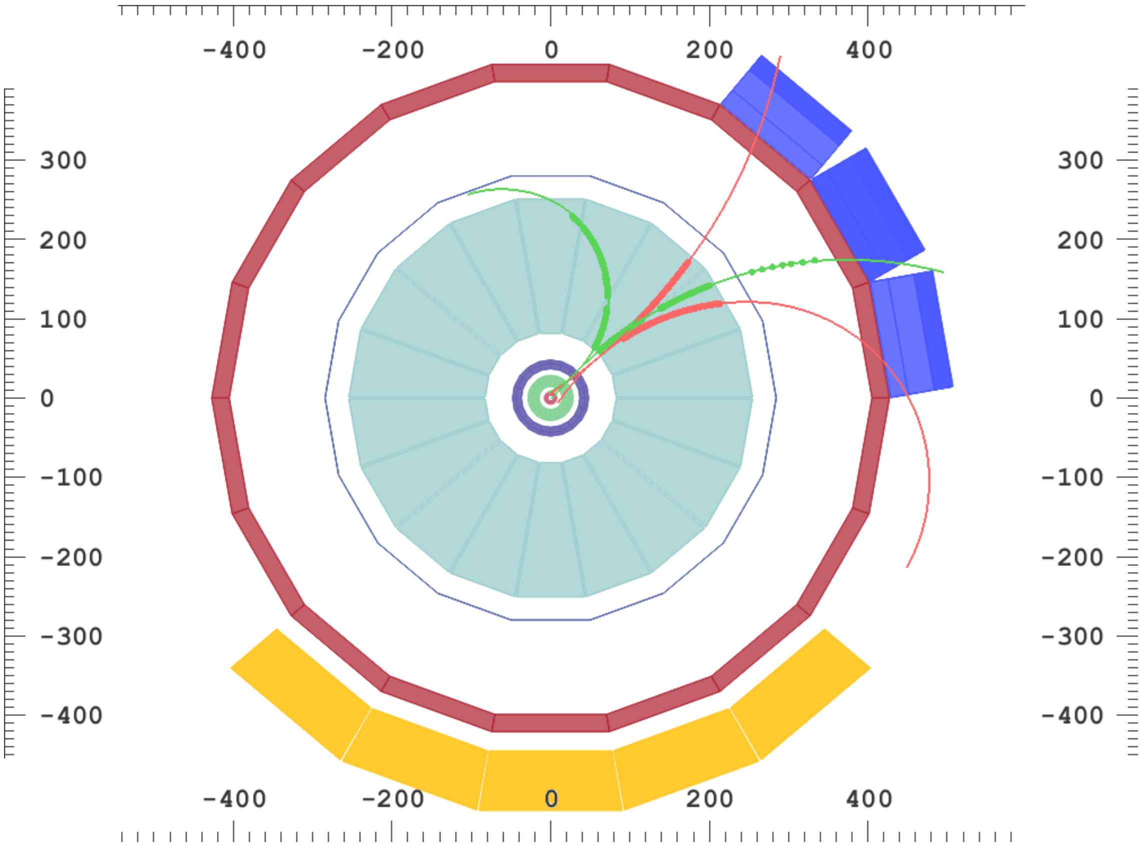


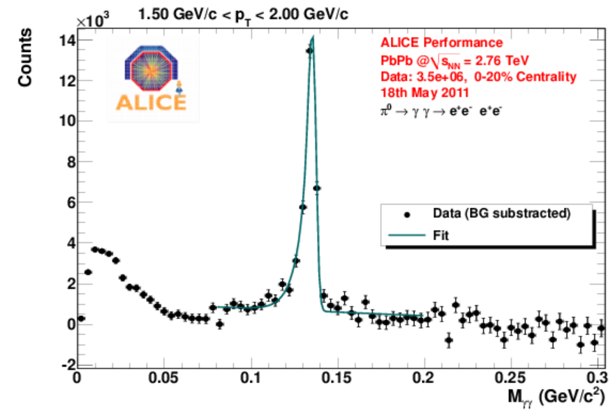


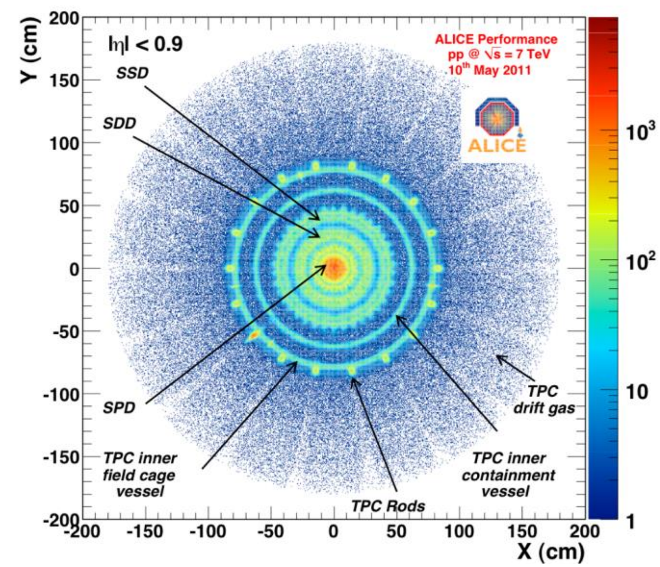
… we can measure the temperature of the QGP

Photon identification in the TPC via conversion

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



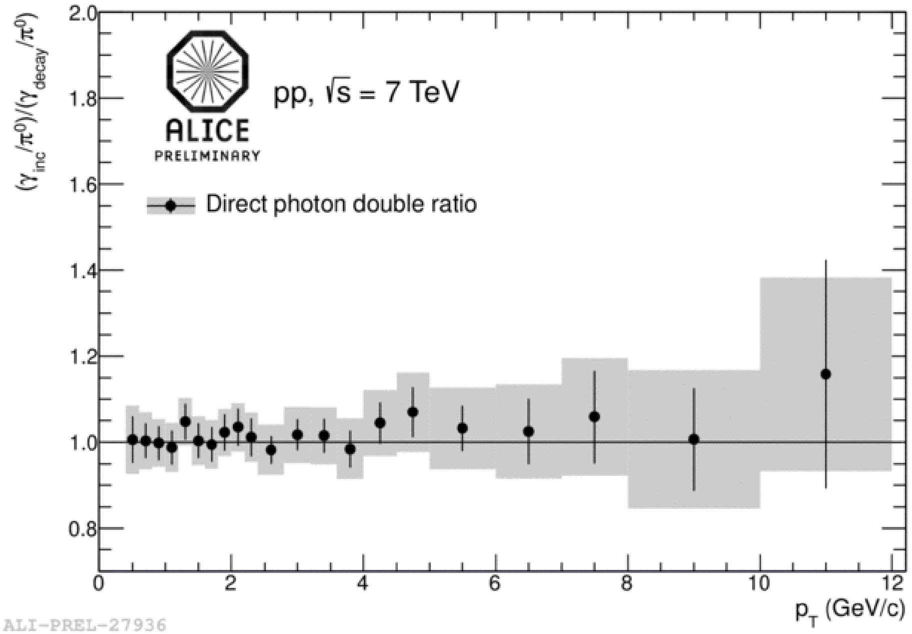




Direct photons in pp collisions

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

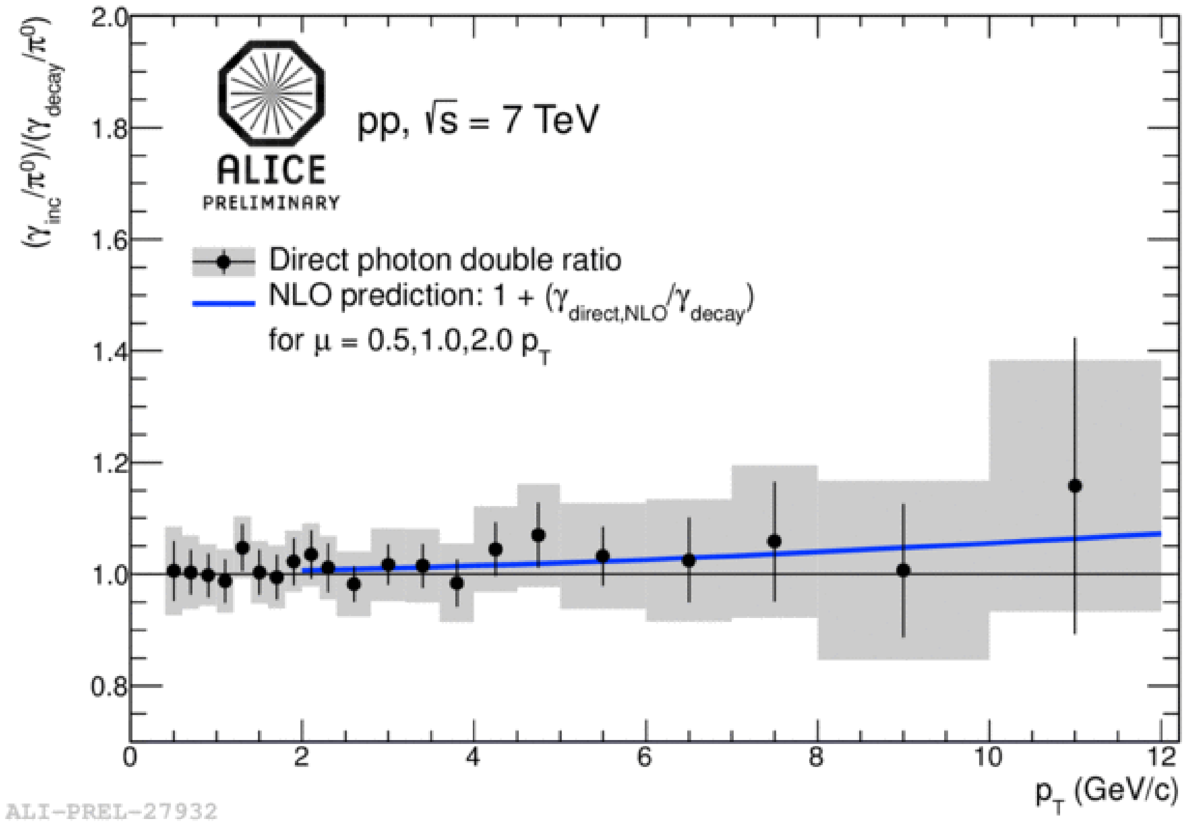
$\rightarrow$ cancellation of uncertainties

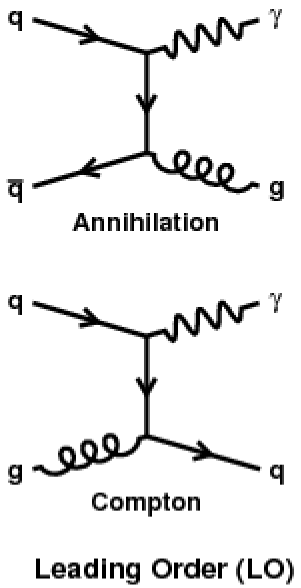


- Construct double ratio to eliminate/reduce systematics
- Numerator is the actual measurement
- Denominator is from a cocktail calculation

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

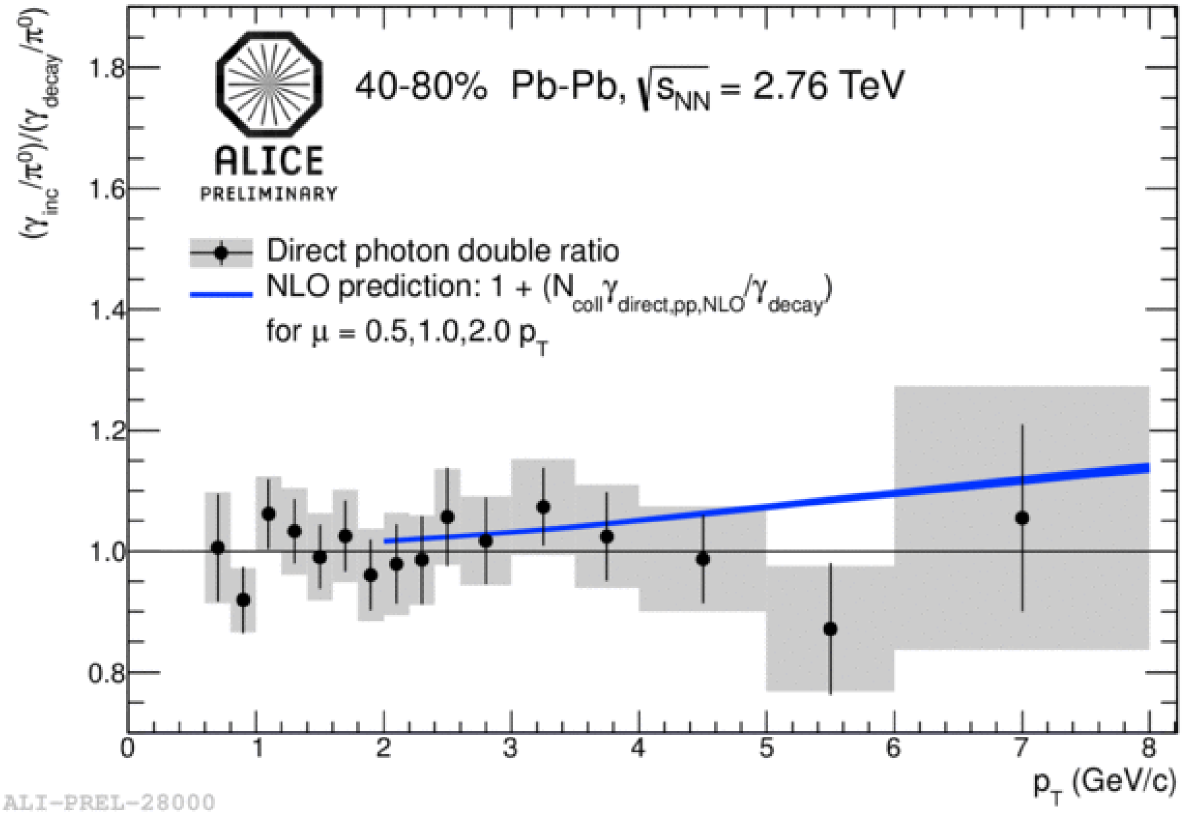
Direct photons in pp collisions





- Comparison to pQCD NLO calculation

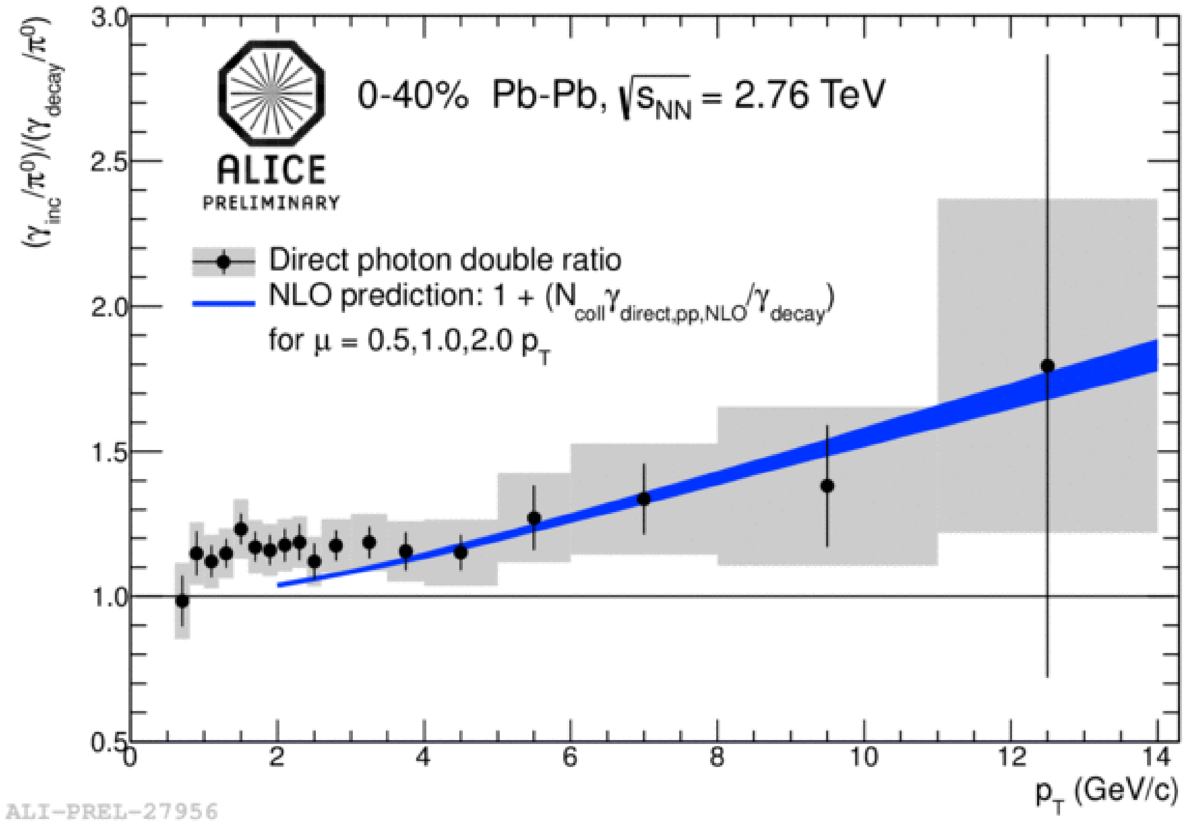
Direct photons in peripheral Pb-Pb collisions



- Peripheral Pb-Pb

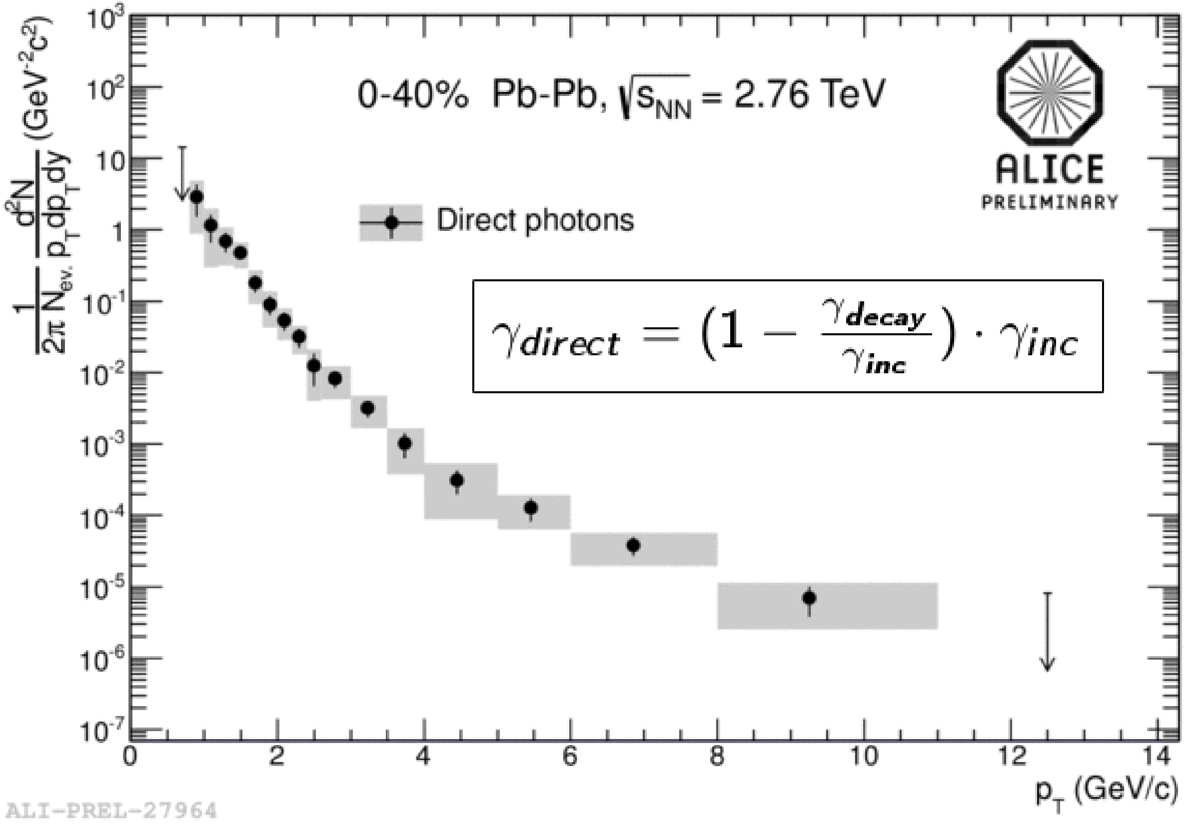
  Consistent with only direct and decay photons

Direct photons in central Pb-Pb collisions



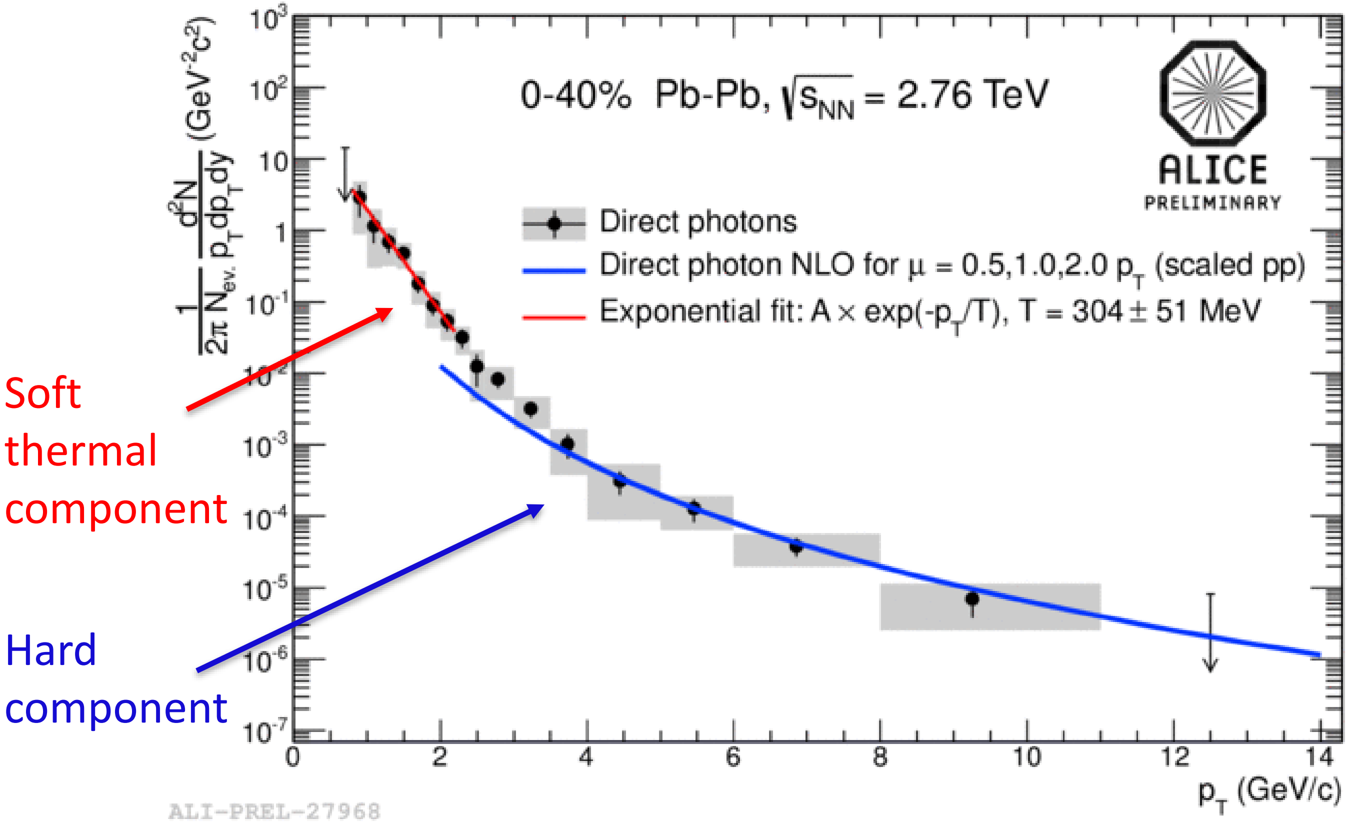
- Central Pb-Pb
  - Surplus of photons at high pT is expected from hard production
  - Surplus of photons at low pT are from thermal radiation from the QGP

Direct photon spectrum in central Pb-Pb



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

Direct photon spectrum in central Pb-Pb



- 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

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.

HARD PROBES

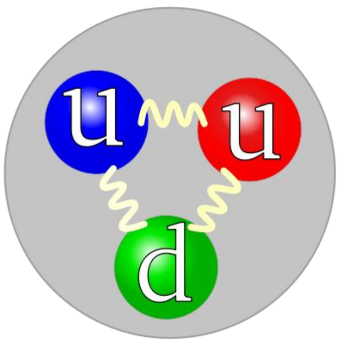
What happens when we collide pp and Pb-Pb?

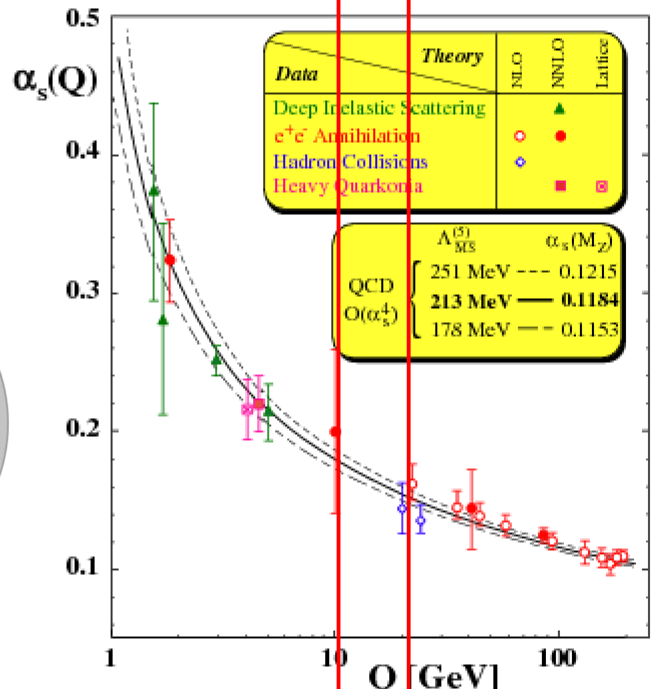
- Think for a few minutes
- Discuss with your neighbors for a few minutes

What happens in pp and Pb-Pb collisions – a simple picture

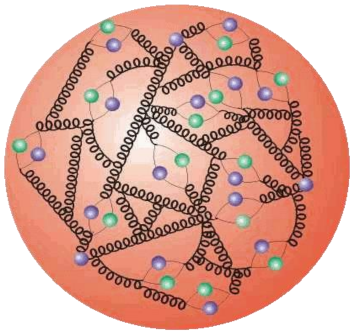
- 2 limits

SOFT





HARD



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

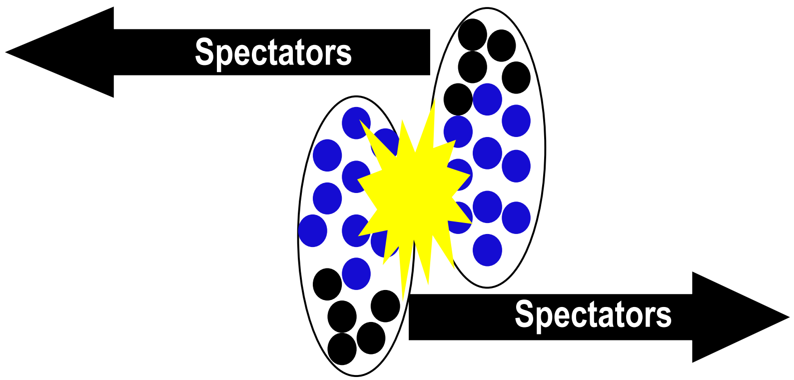
Perturbative physics
(theoretical predictions)
Rare jets (=probes)

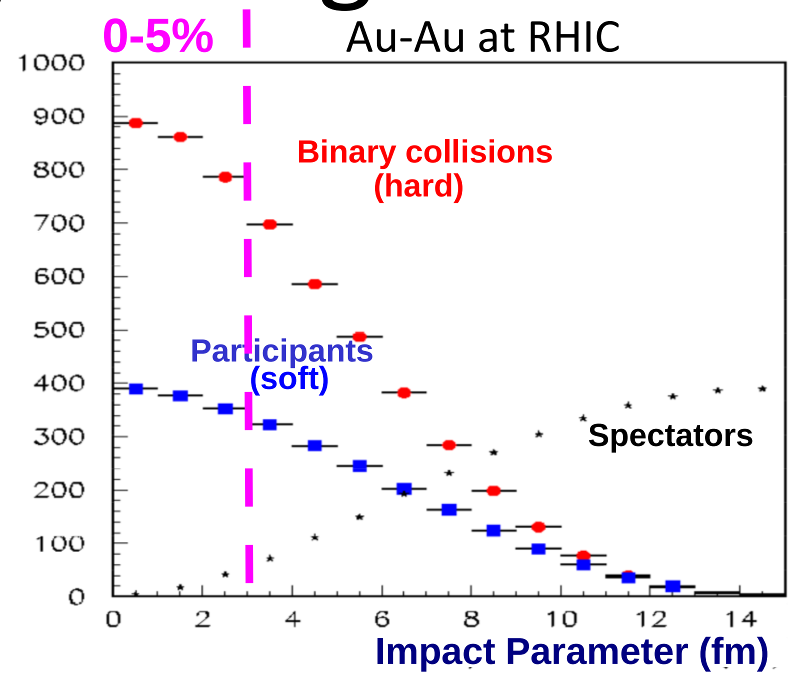
Hard probes in heavy-ion collisions

- 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

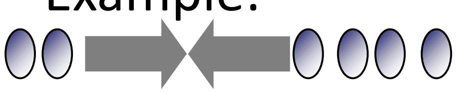
- Centrality (ex. for Au+Au):



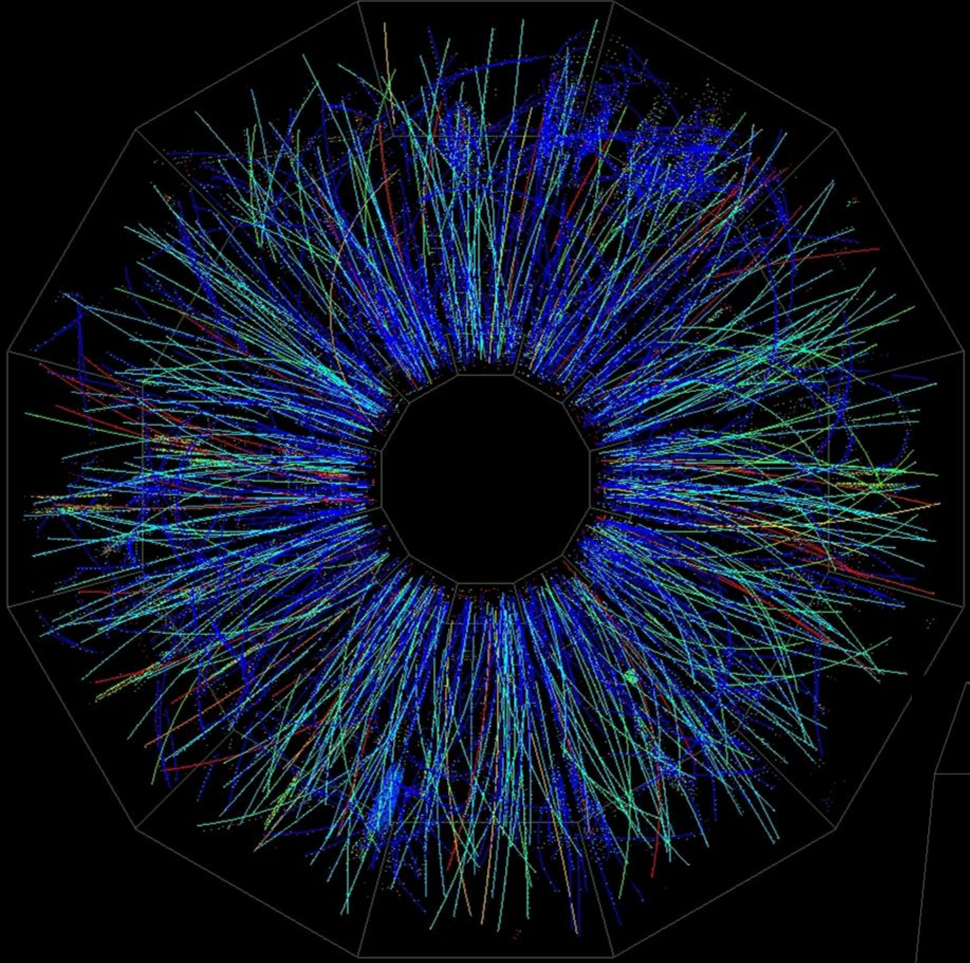


Participants = 2*197 - Spectators

- 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:

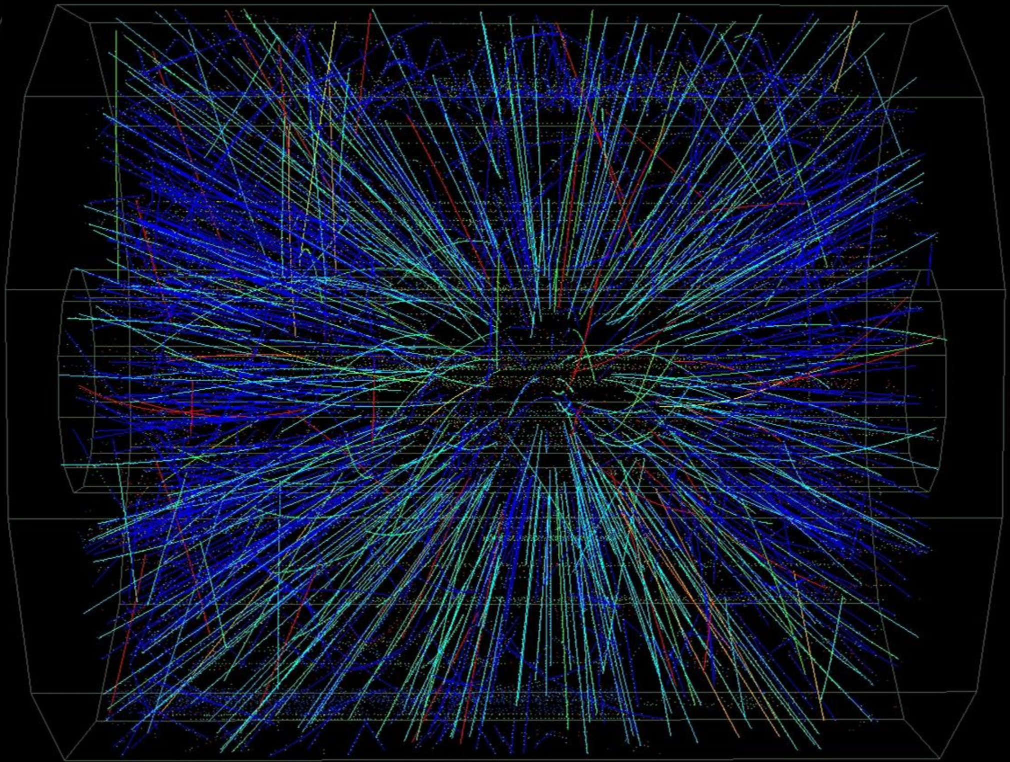


6 participant
8 binary collisions
(pp has 2 participant and 1 binary collision)



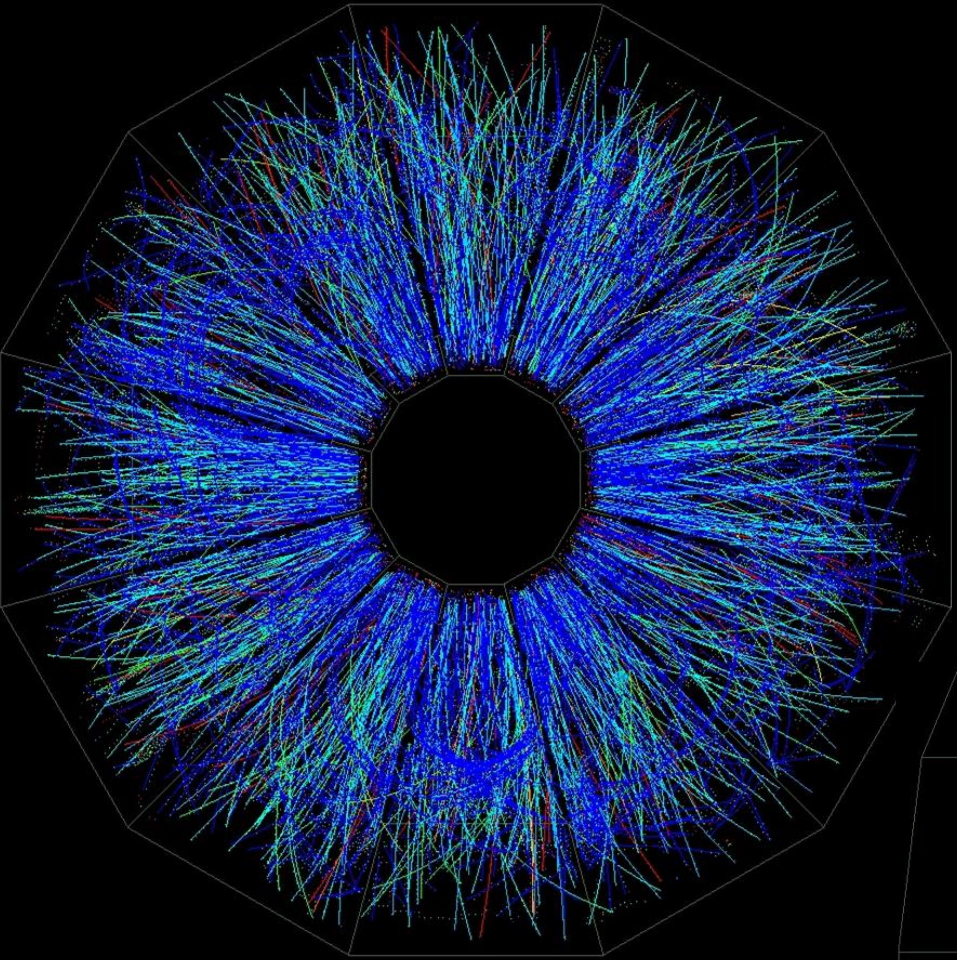
Peripheral Event

From real-time Level 3 display.



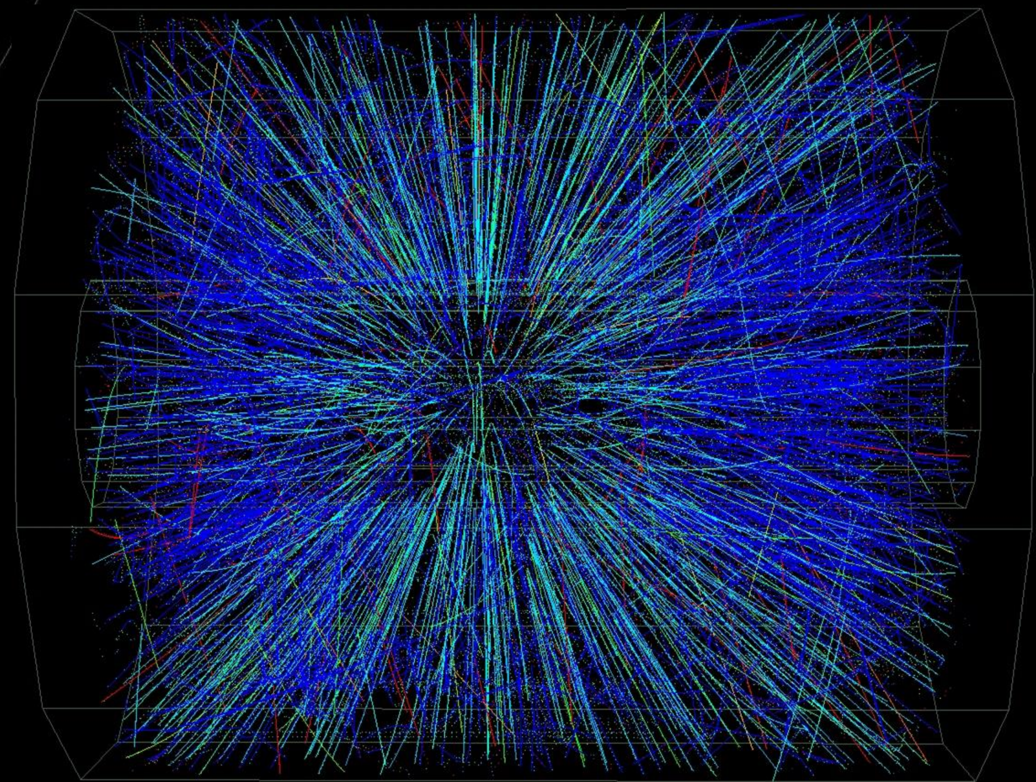
color code ⇒ energy loss

STAR

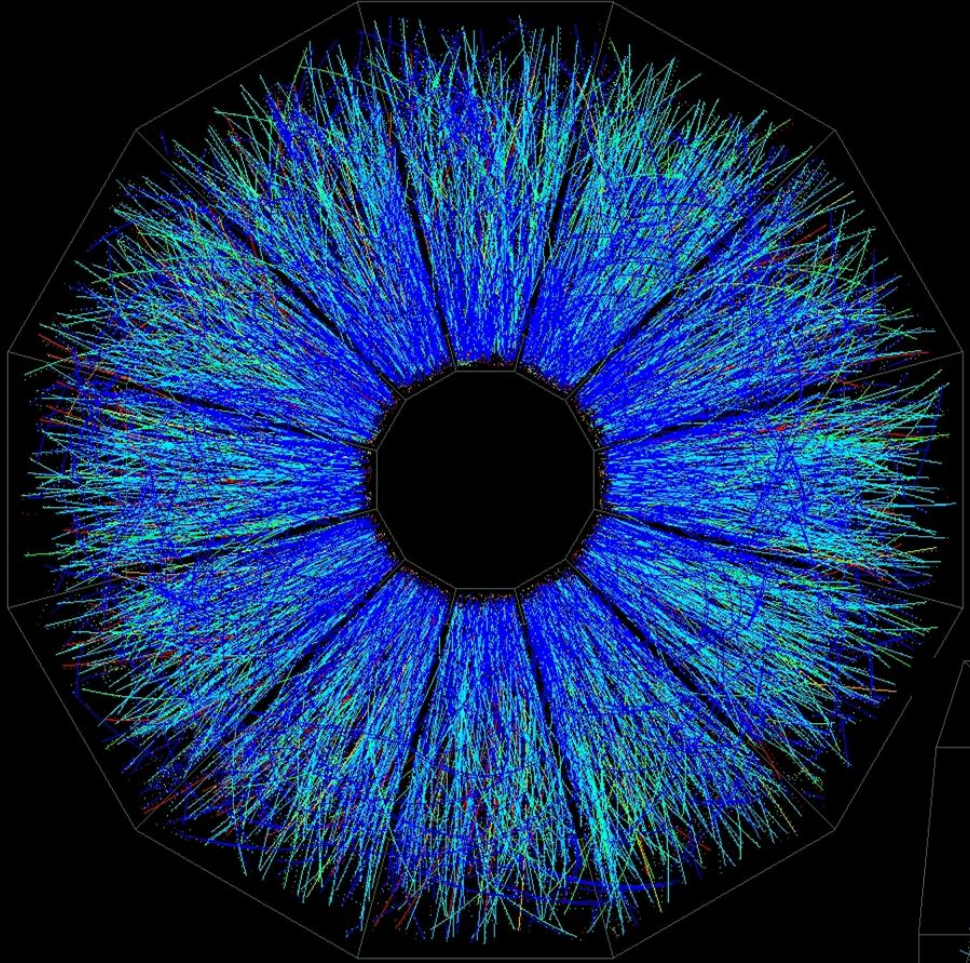


Mid-Central Event

From real-time Level 3 display.

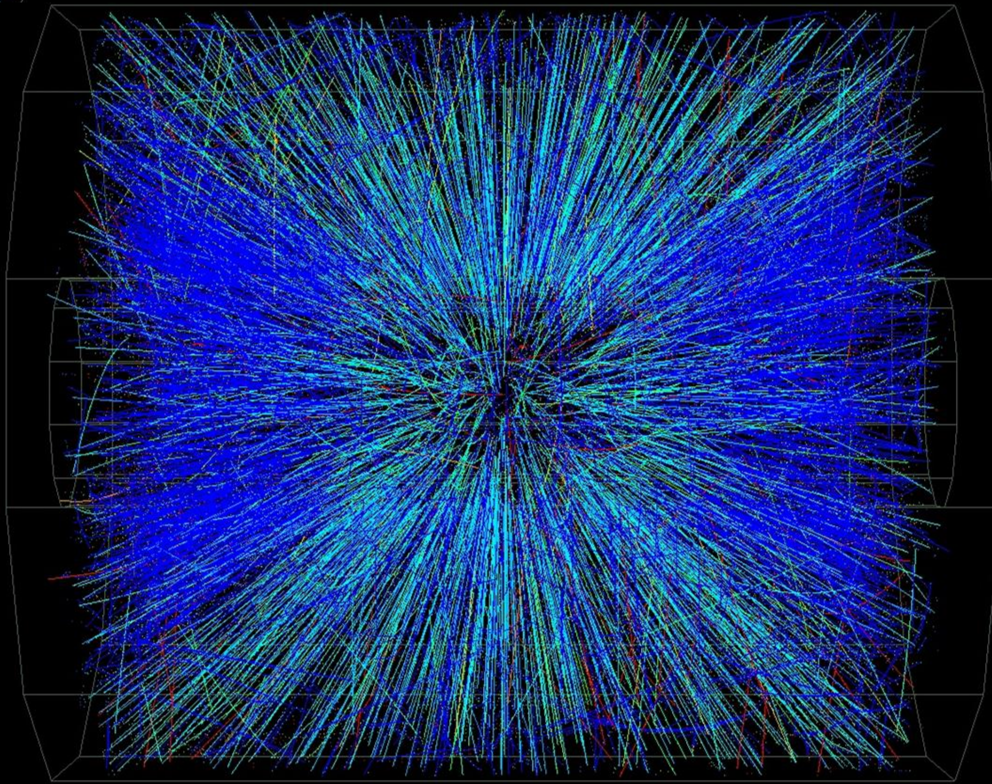


STAR



Central Event

From real-time Level 3 display.



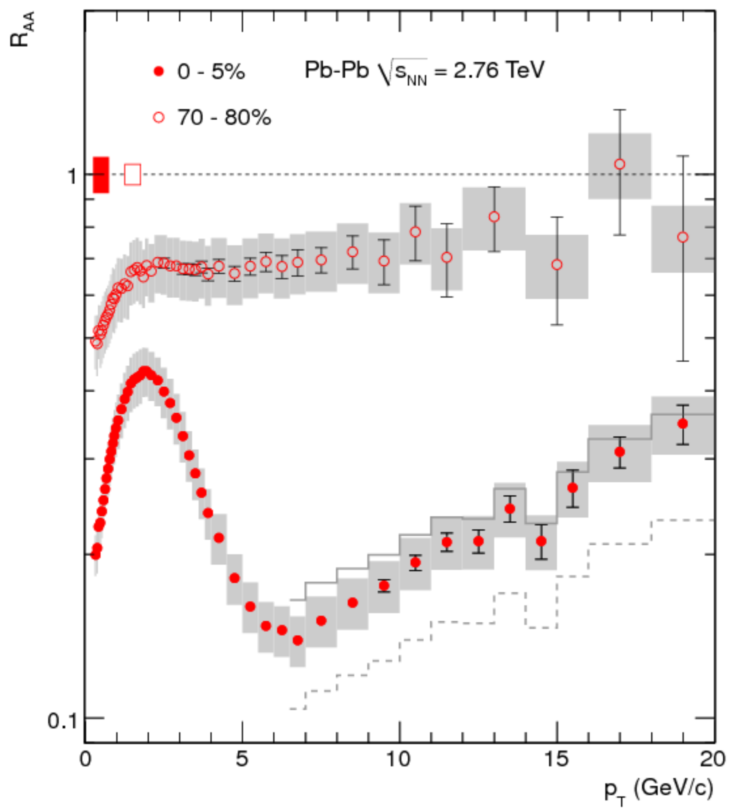
STAR

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

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

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

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

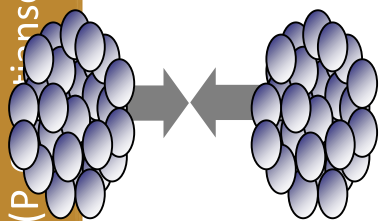


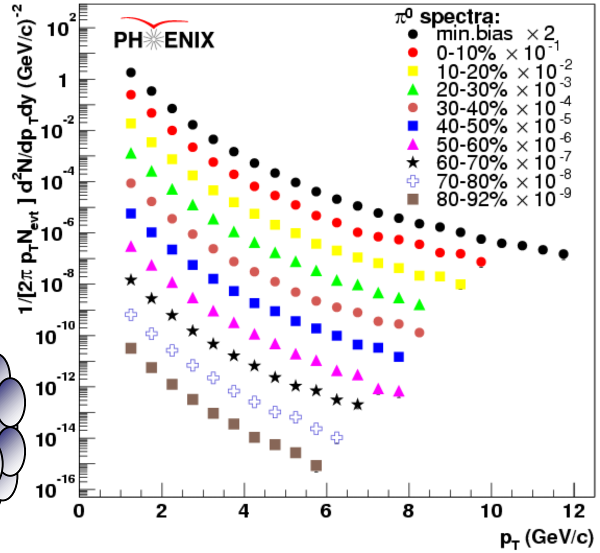
Phys. Lett. B 696 (2011)

So R_{AA} is a way to quantify the nuclear effects!

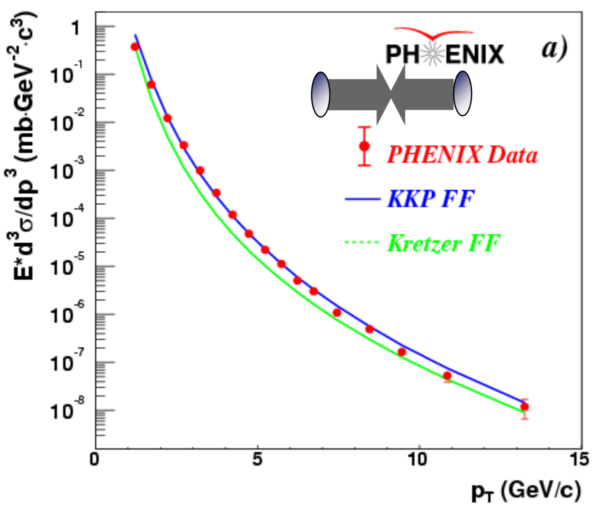
The nuclear modification factor R_{AA} (2/2)

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





Ncoll



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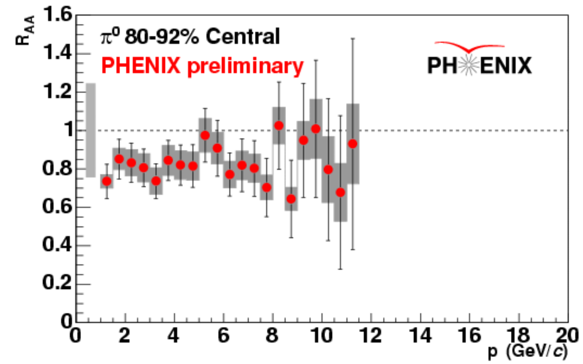
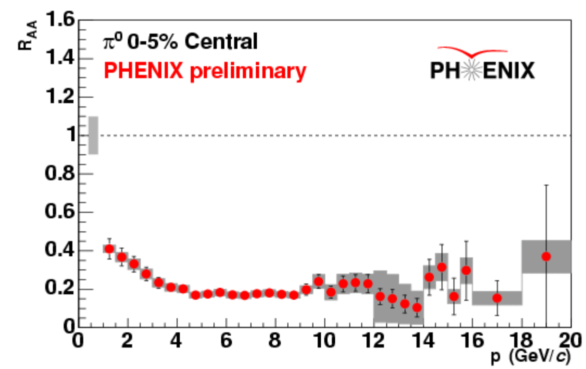




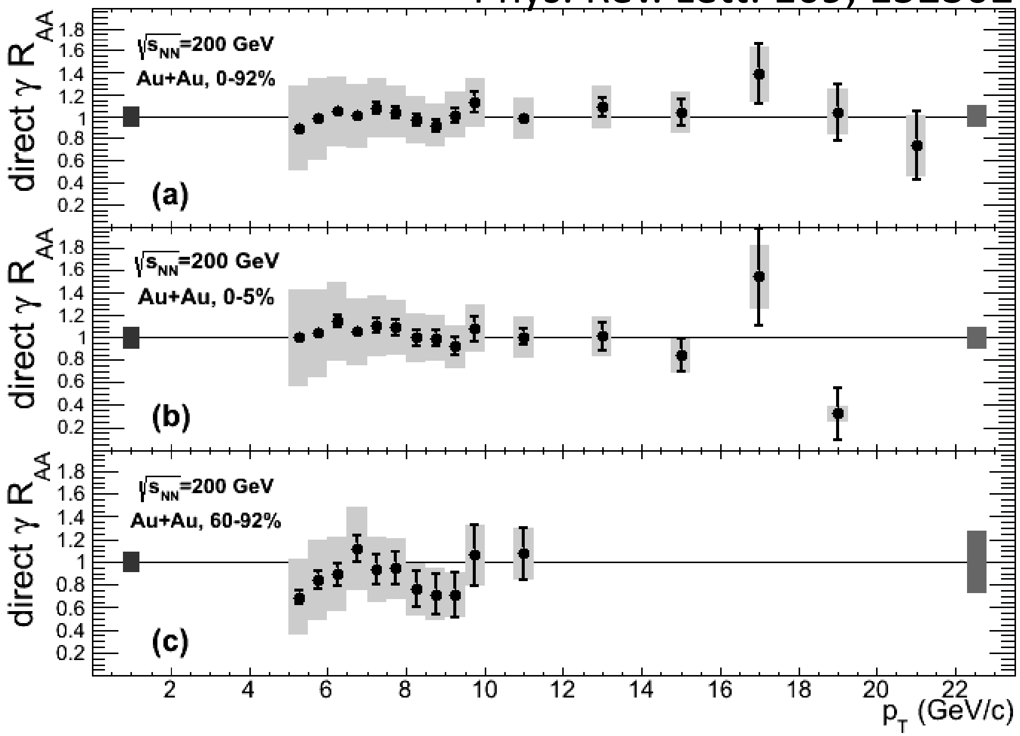
Hard Probes: Standard candles

We need penetrating hard probes to validate the binary scaling

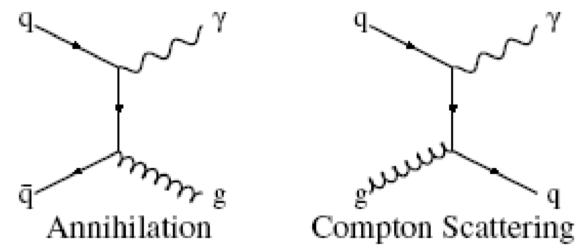
What could that be?

Ncoll scaling for direct photons

Phys. Rev. Lett. 109, 152302



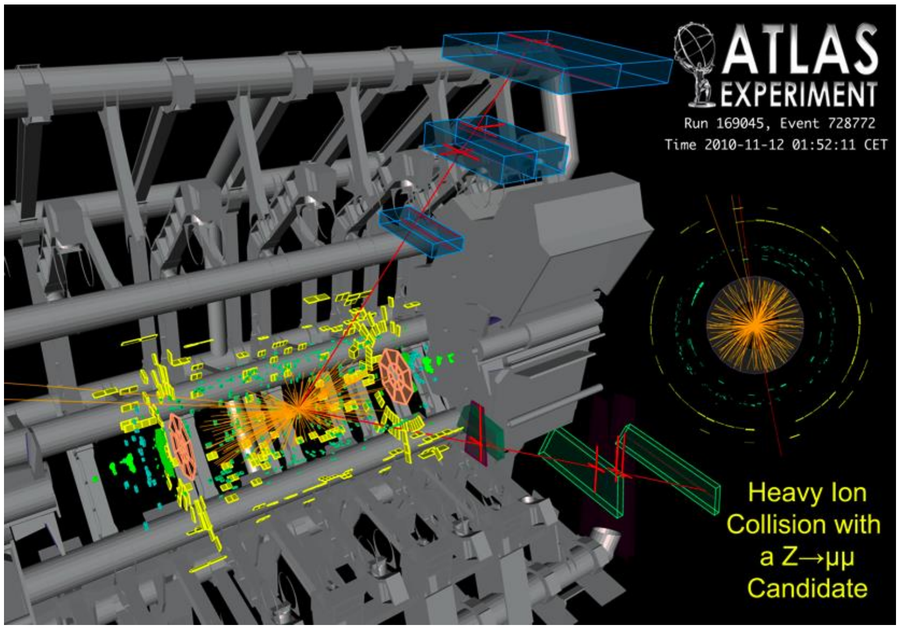
Source of direct photons

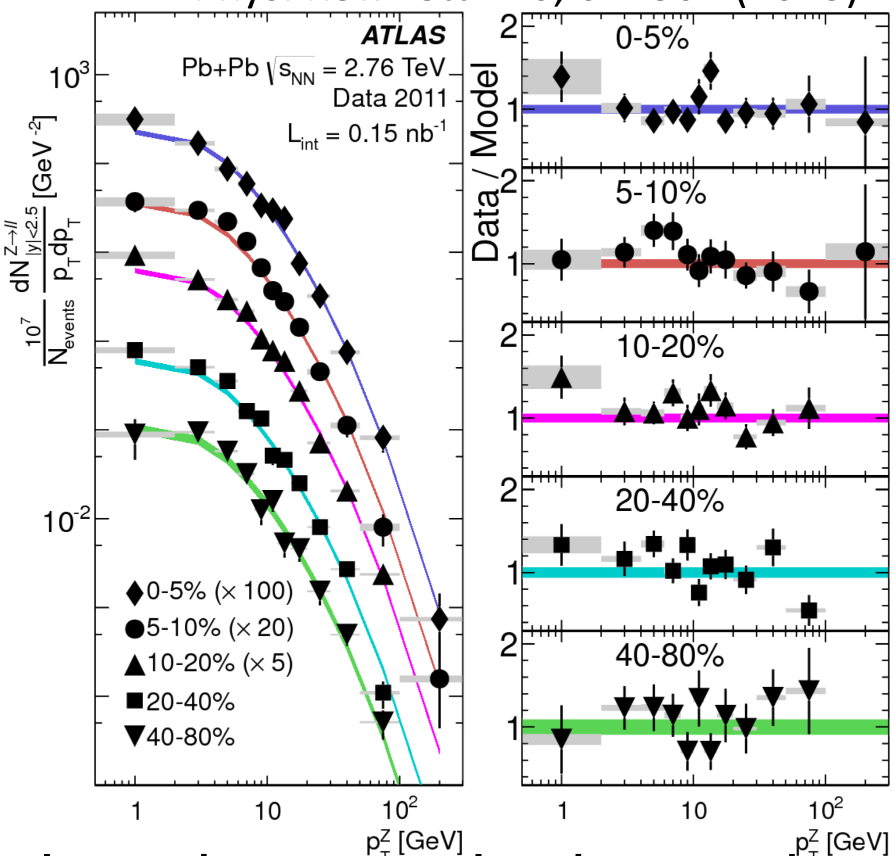


- Direct photons does not interact with final state hadronic matter and the results confirm binary scaling of hard processes!
- The best standard candle at RHIC

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

Phys. Rev. Lett 110, 022301 (2013)



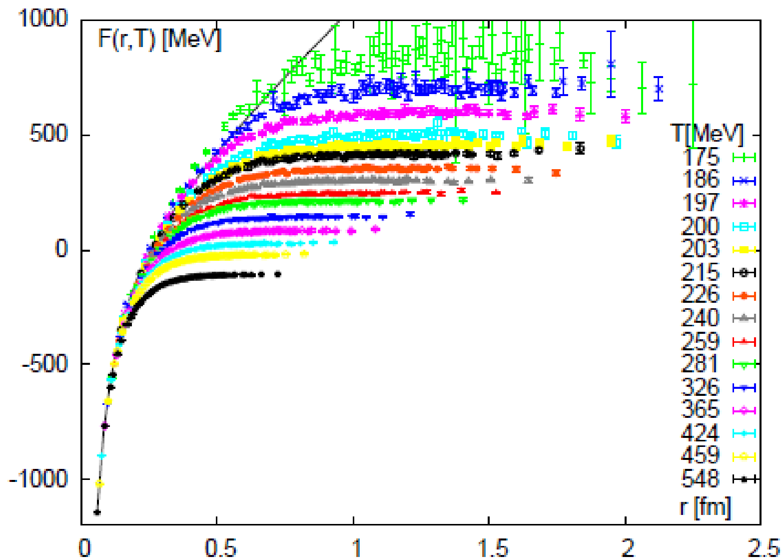


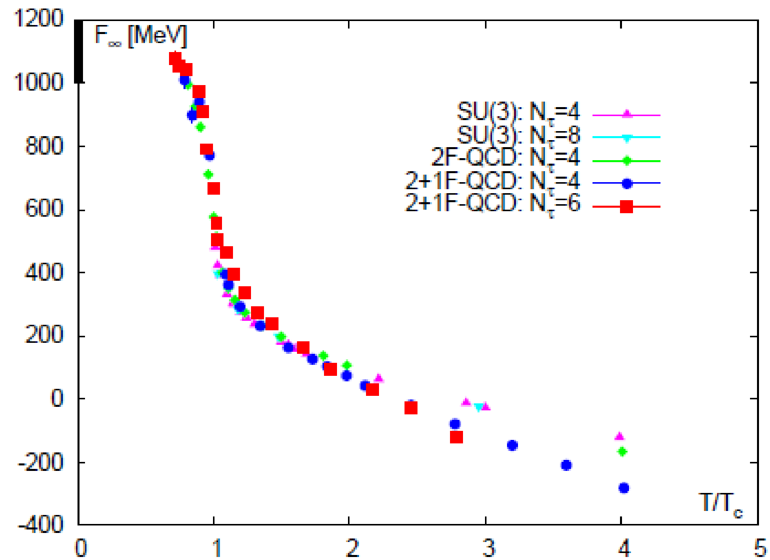
- The Z does not interact strongly and so can also be used to check binary scaling at LHC
- Also the W have been used at LHC

HARD PROBES: HEAVY QUARKS

Heavy quarks: I will only focus on Quarkonia

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





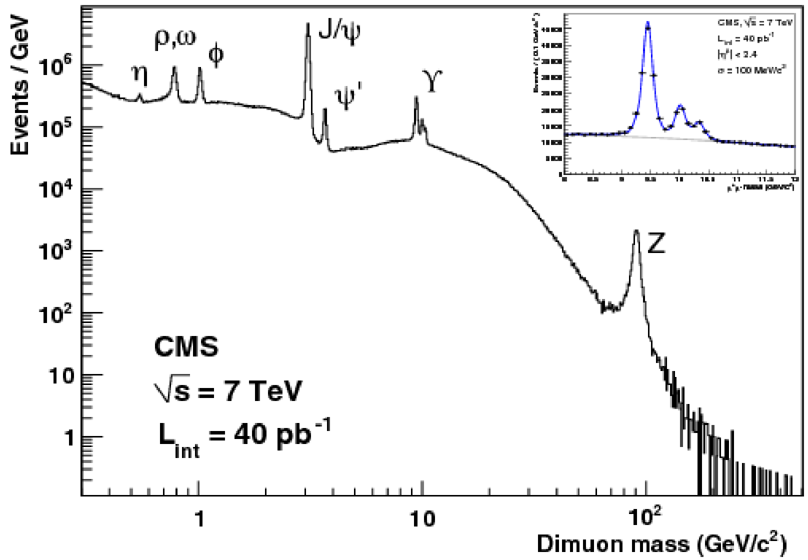
Lattice QCD predicts that the long range force will be screened in the plasma
Bound state properties will change and some states will disappear / melt

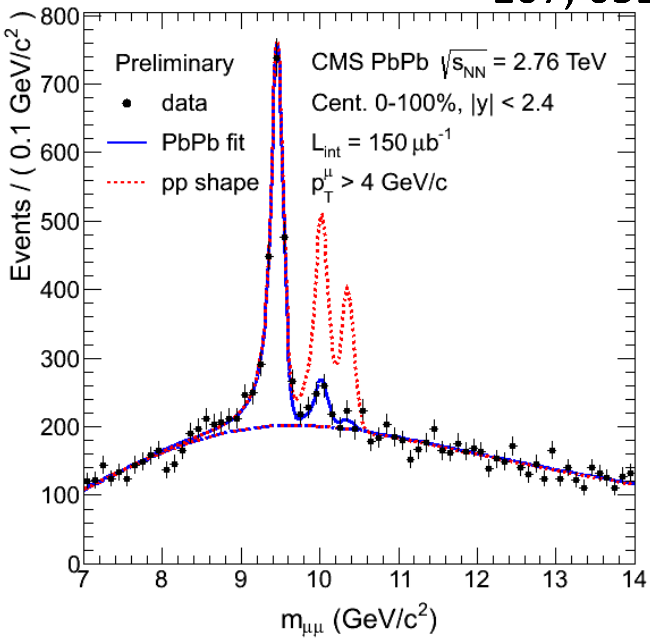
Original idea:
"J/ψ Suppression by Quark-Gluon Plasma Formation" by T. Matsui and H. Satz
Phys.Lett. B178 (1986) 416
Cited by 2108 records

LHC has delivered

ϒ: 1S 2S 3S

Published in PRL 107, 052302



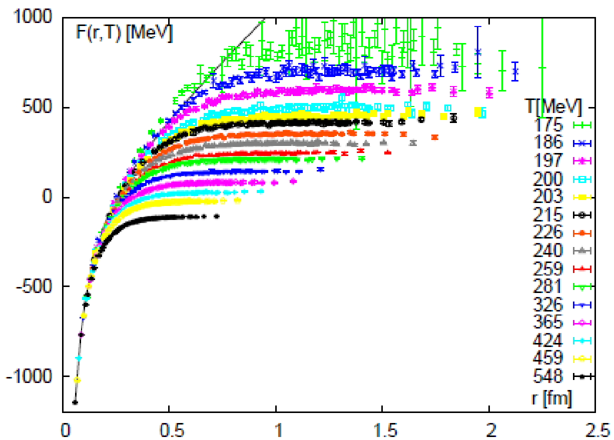


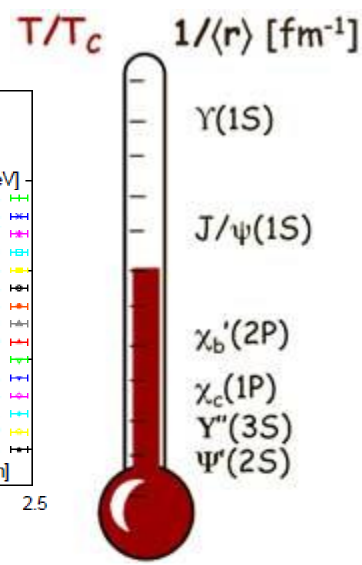
CMS has proven to be a marvelous detector for bottomonium
ALICE can complement by going to lower p_T for charmonium

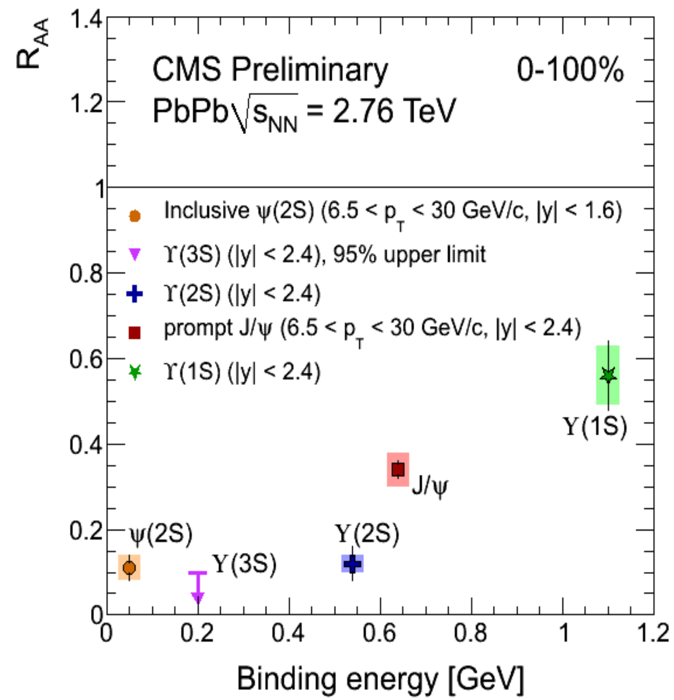
These textbook results demonstrate the amazing capabilities of LHC detectors

Suppression of heavy quarkonia can work as a thermometer

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

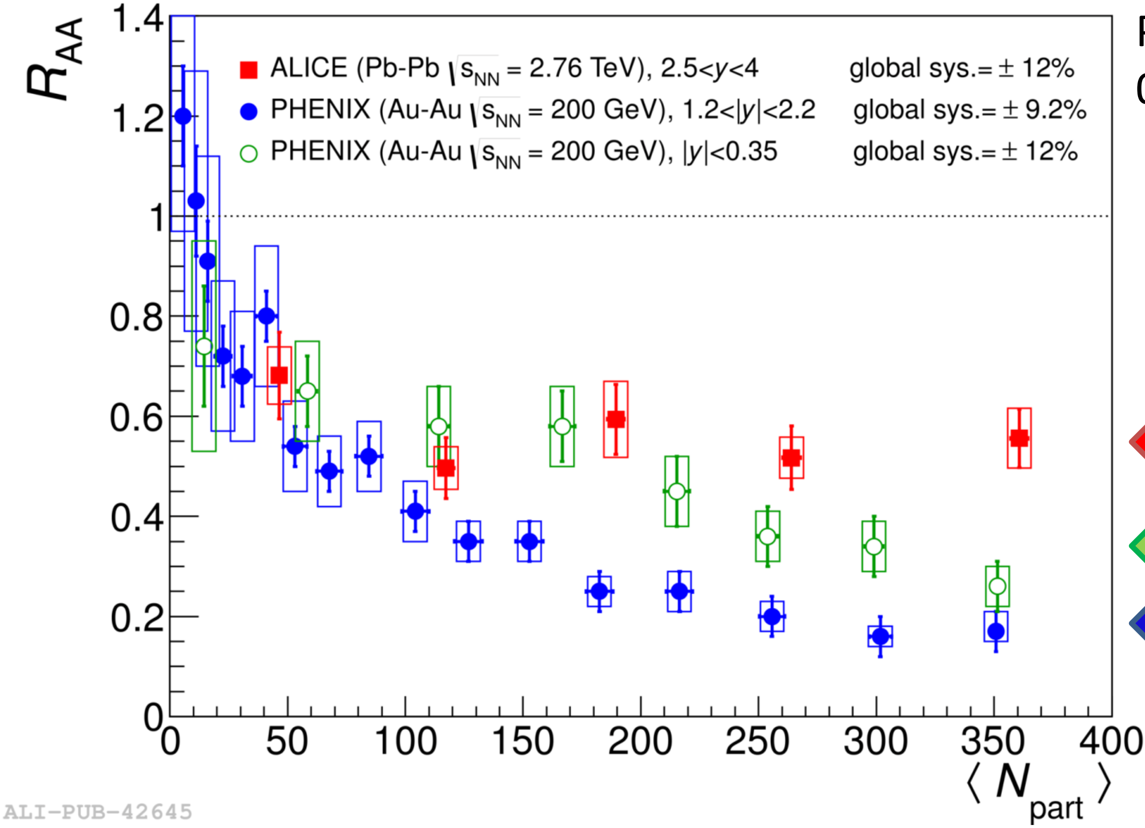






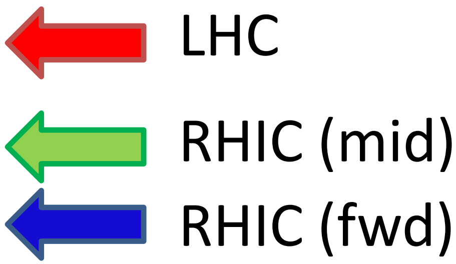
Suppression qualitatively depends on binding energy as predicted

J/ψ results from ALICE: Evidence for regeneration



Phys. Rev. Lett. 109, 072301 (2012)

ALICE can go down to p_T~0.

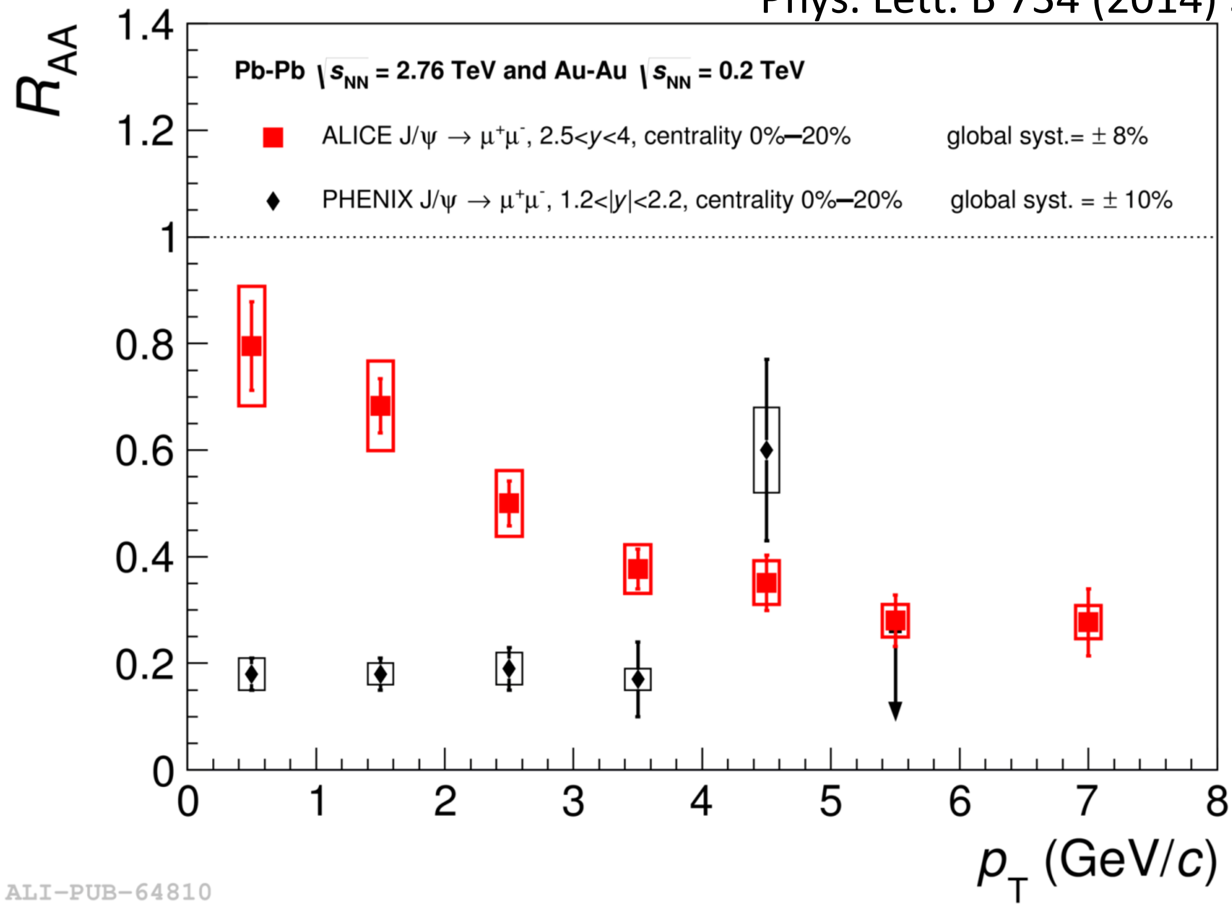


The suppression of J/ψ at LHC is less than at RHIC!

Understanding: due to the large cross section ”random” charm and anti-charm quarks combine (see next slides)

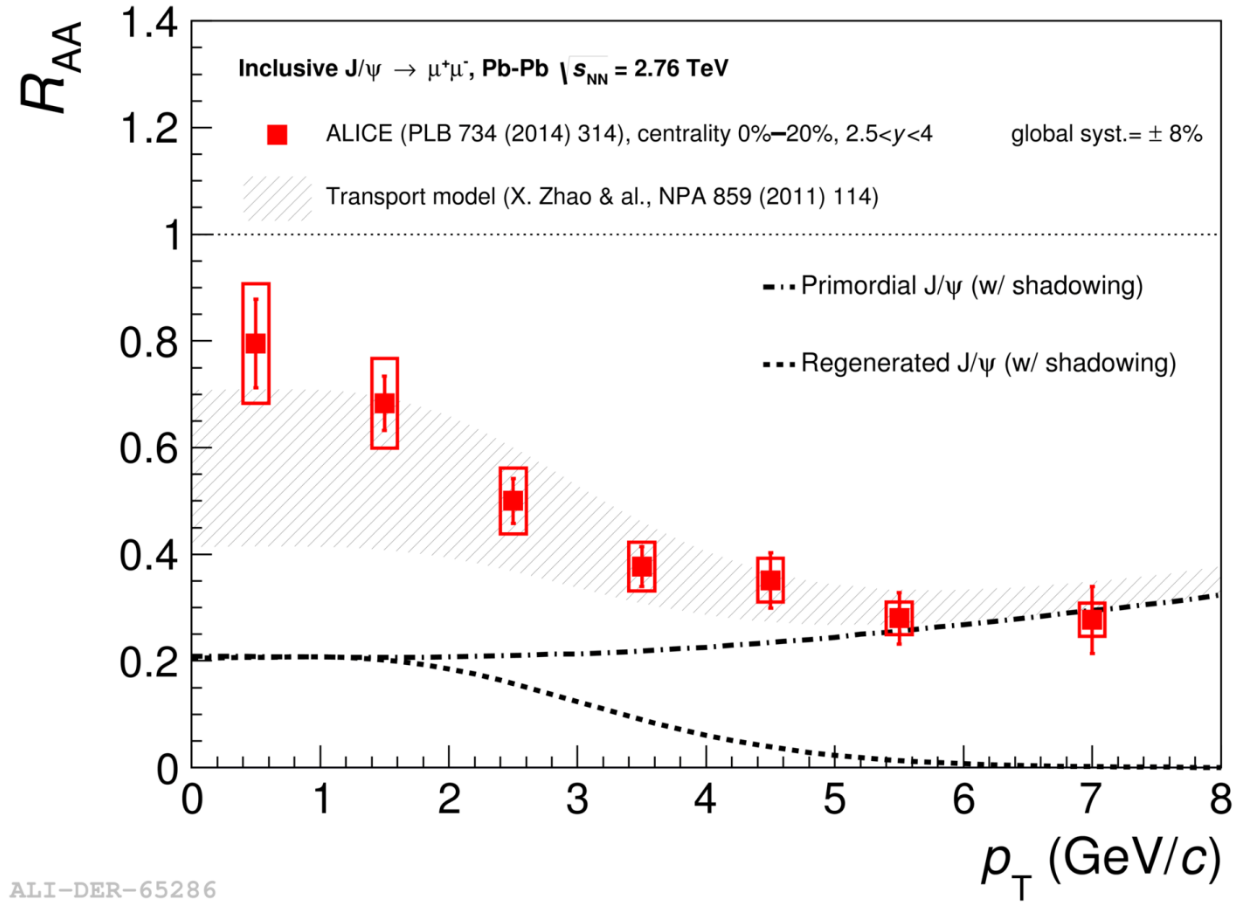
J/Psi differential results

Phys. Lett. B 734 (2014) 314-327



The difference in suppression is visible at low p_T

J/Psi differential results



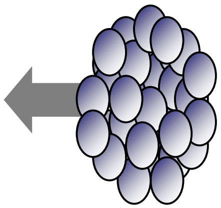
The difference can be explained by J/ψ regeneration (much larger charm Xsection at LHC)

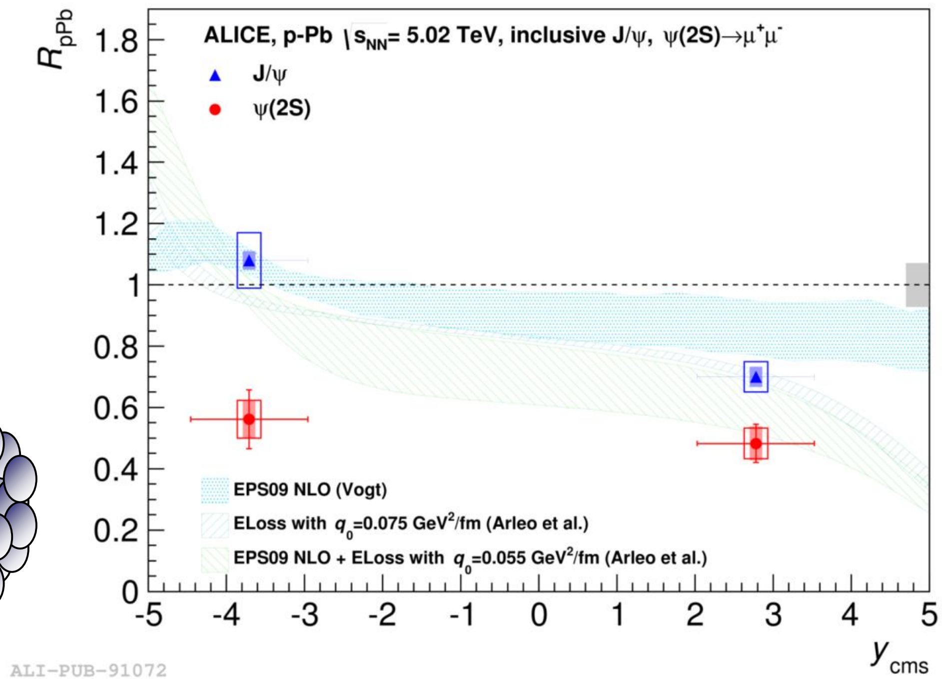
(This effect was already proposed before the RHIC results came out.)

Caveat: cold nuclear matter effects are not understood

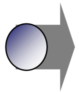
JHEP12(2014)073

lead rapidity





proton rapidity

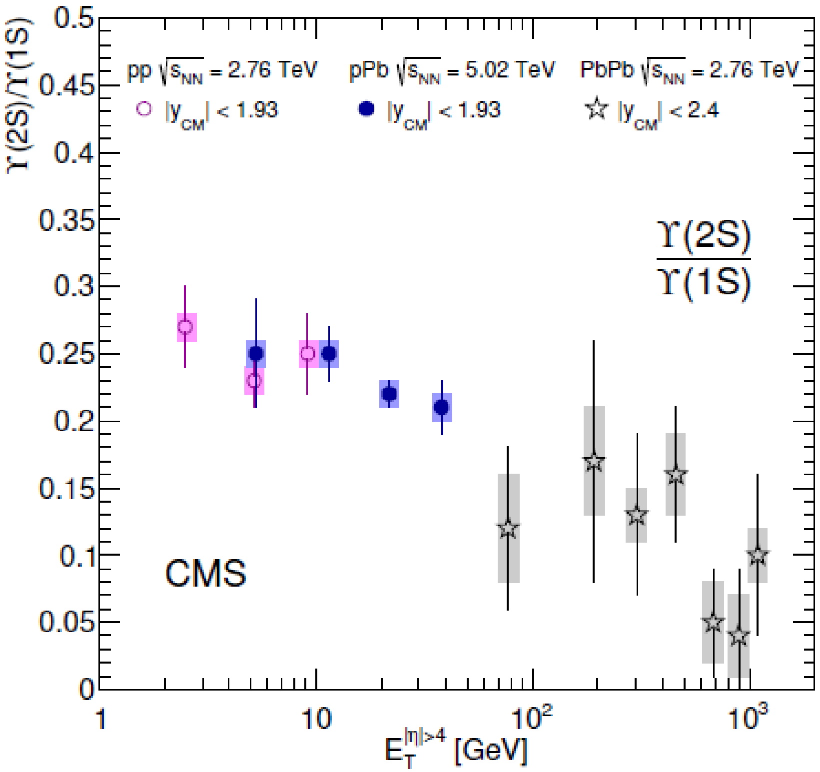


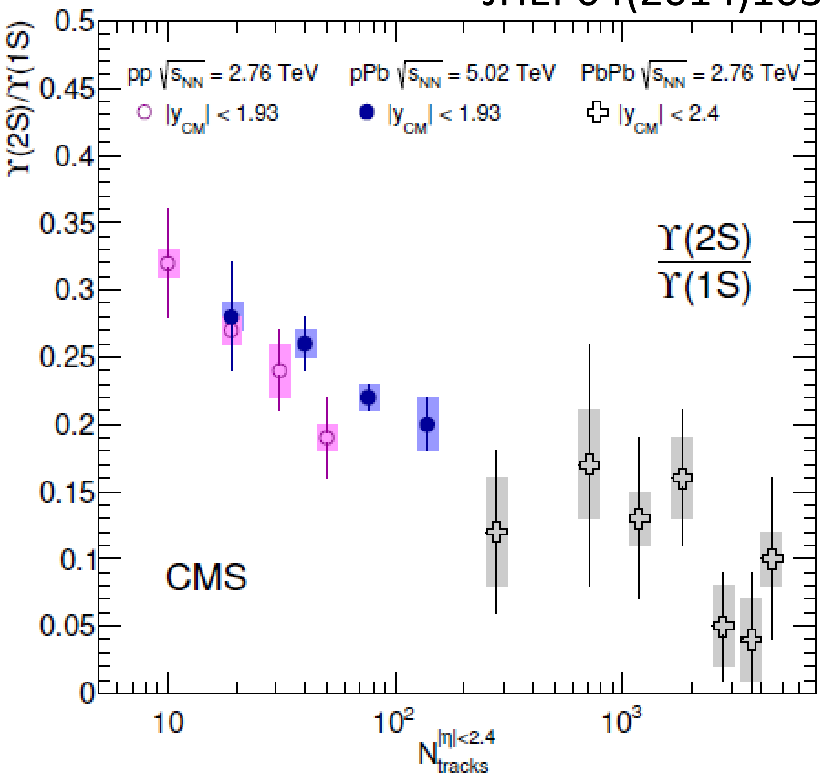
For J/ψ we have reasonable good description: energy loss really just means that due to collisions with other nucleons the rapidity of the J/ψ is shifted towards the Pb-nuclei.

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 (?)

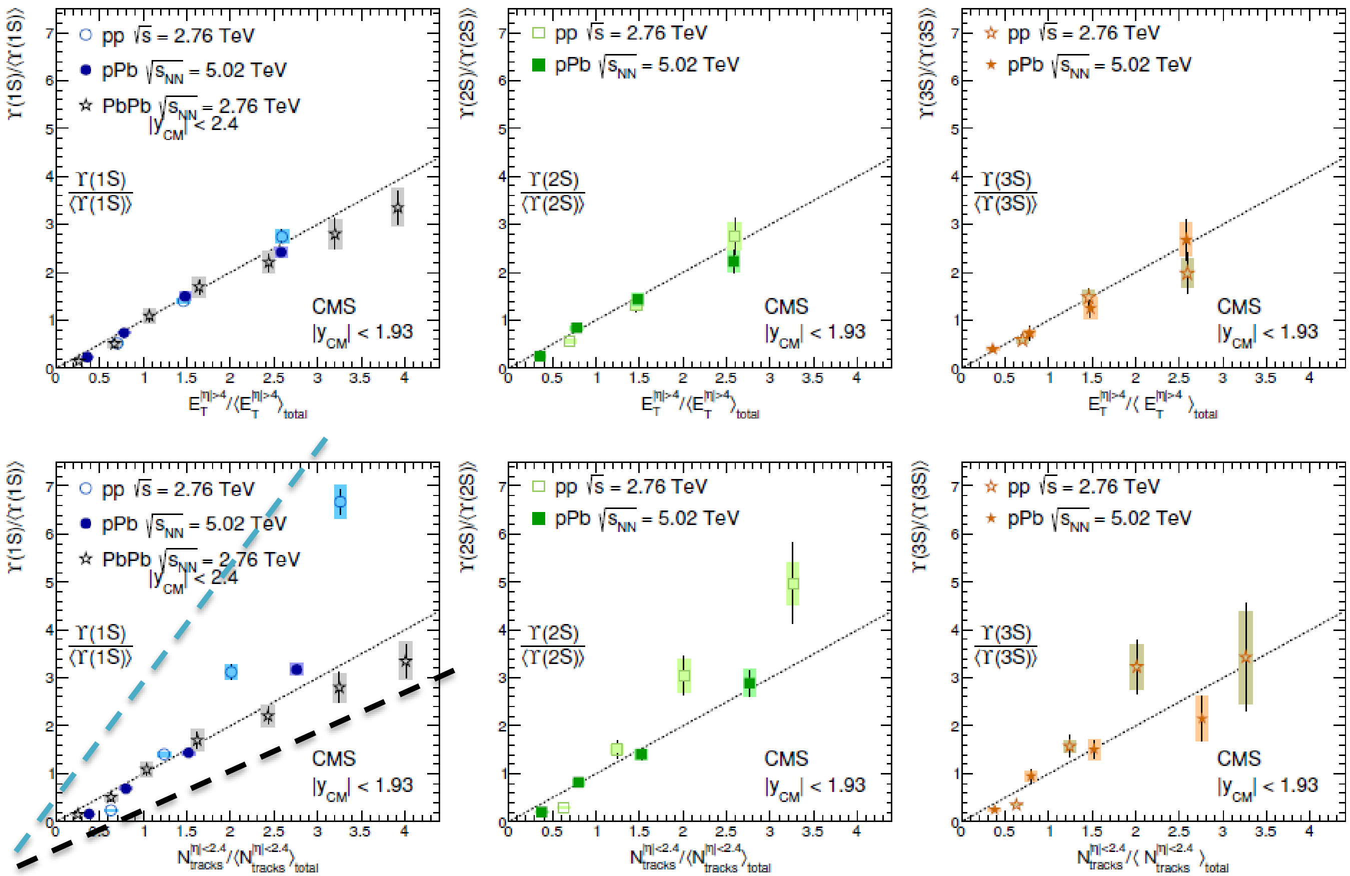
JHEP04(2014)103





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

In this case we observe different trends with event activity

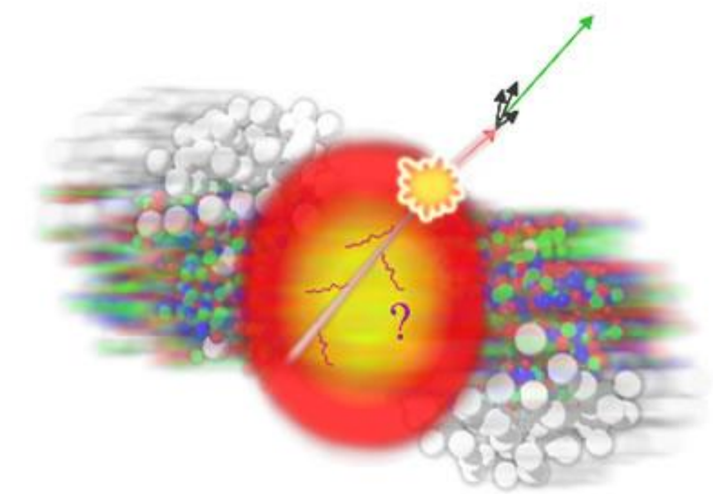
Caveat: should study binary scaling (but this does not work for pp)

Summary of quarkonia results

- 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

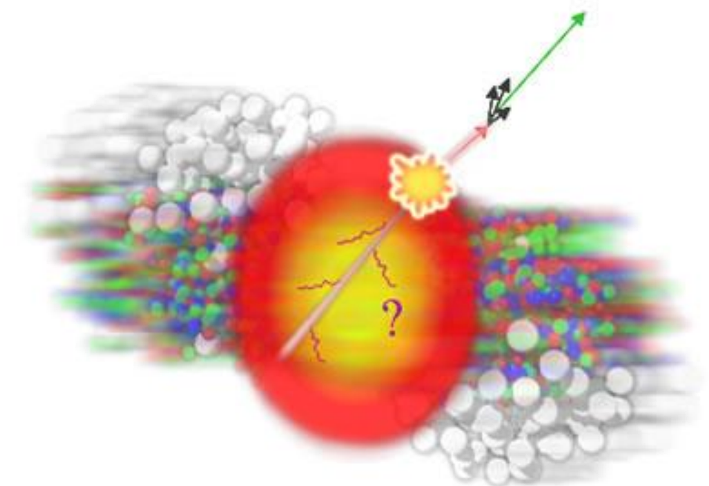
HARD PROBES: JETS

Jets as probes of the QGP



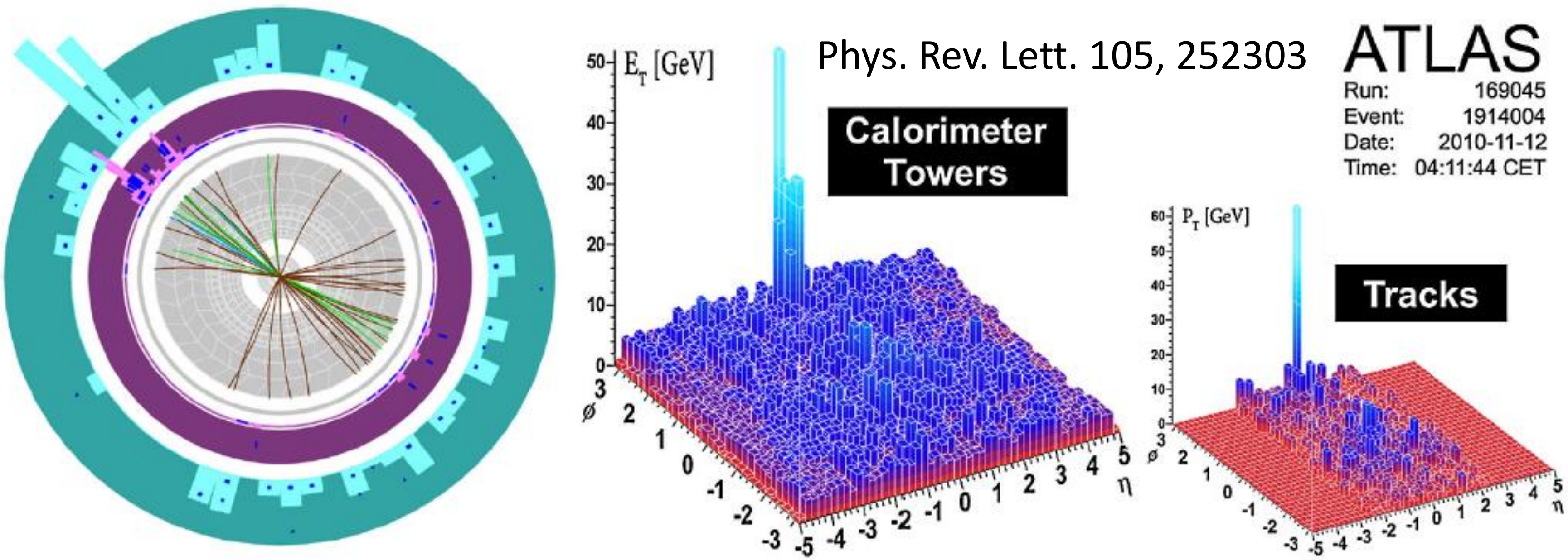
- The idea to use jets to probe the QGP goes back to Bjorken. He made a first study of collisional energy loss but never published this as he realized that radiative energy loss was much more important
- The phenomenology is quite difficult and has many variants so I focus on the experimental results

Jet quenching in the QGP



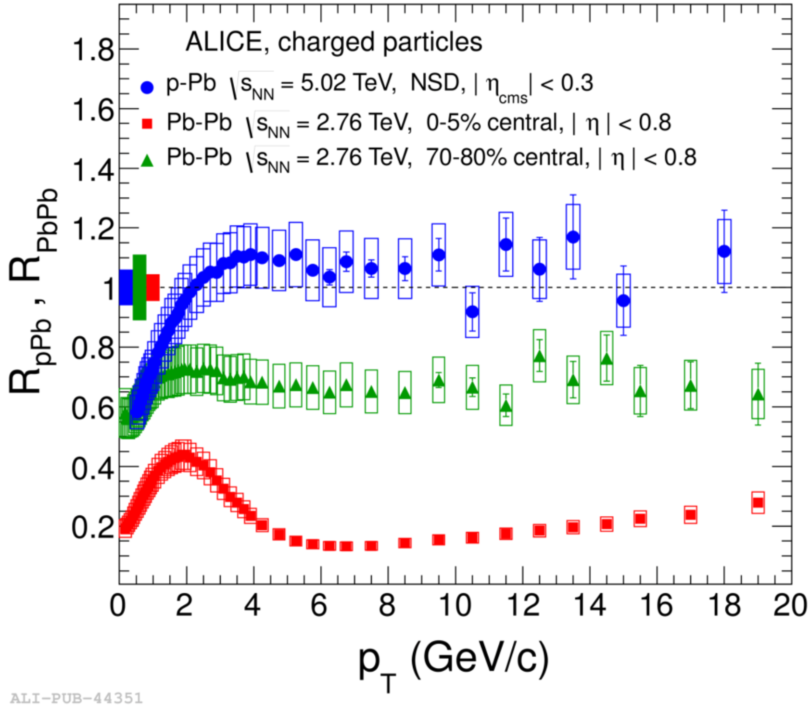
For color charges one expects energy losses of GeV/fm vs MeV/cm for electric charges in normal atomic matter. 10,000,000,000,000,000 (10^{16}) times larger energy loss.

Phys. Rev. Lett. 105, 252303



High p_T particles: a proxy for jets

ALICE, PRL 110, 082302 (2013)

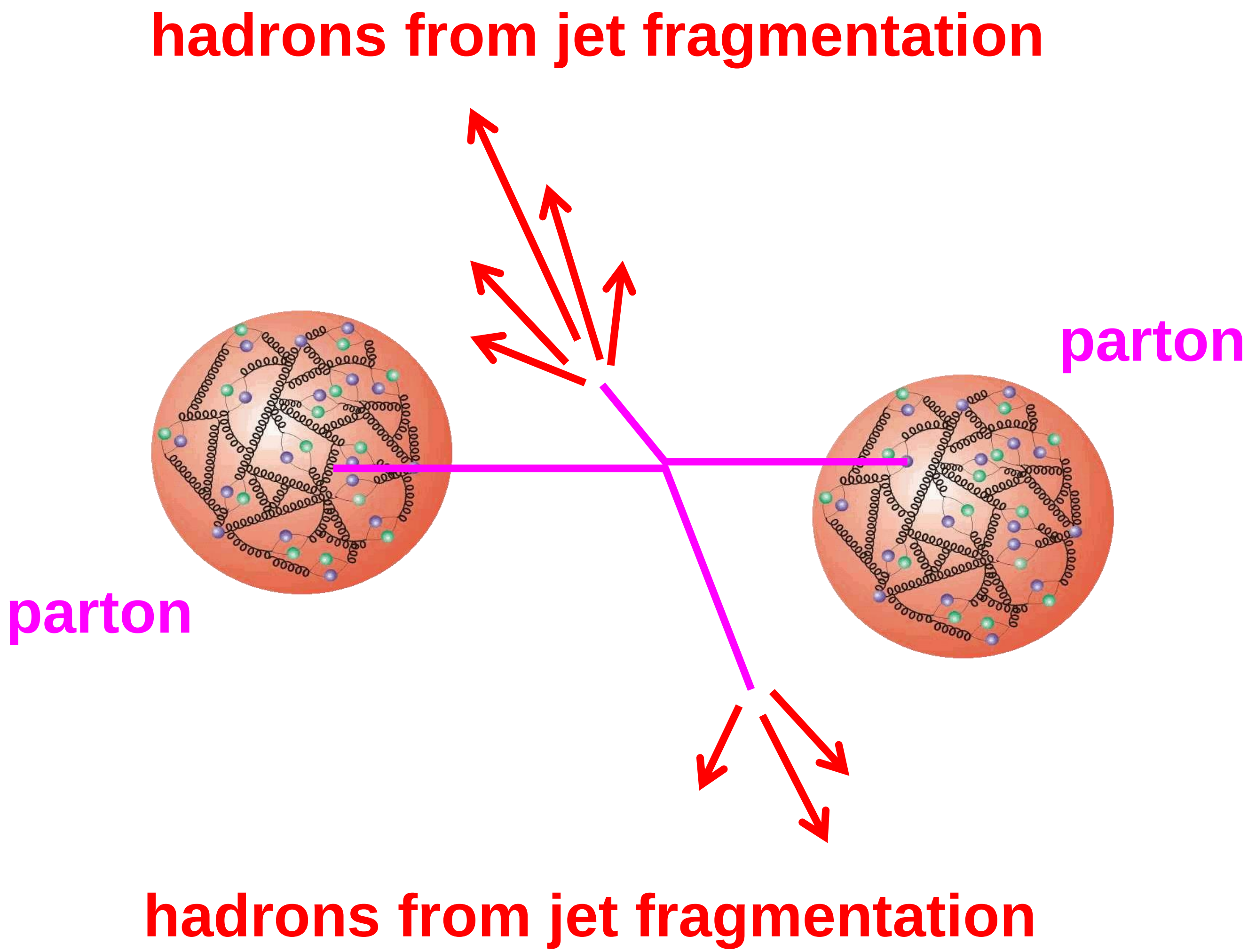


At RHIC very few studies have been done with jets. Instead high p_T particles have been used to study jet quenching.

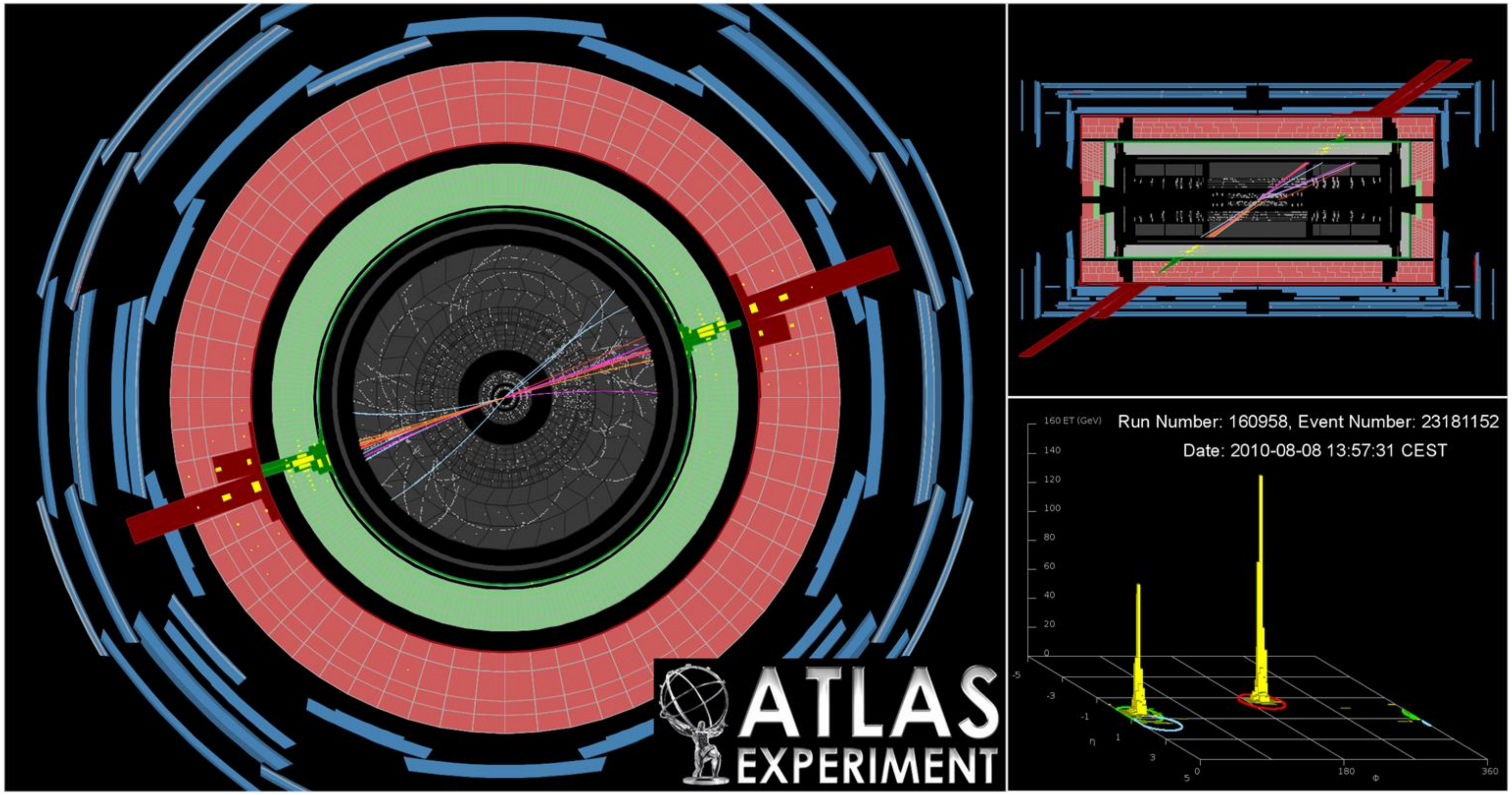
At LHC high p_T results are also used but additionally there are many jet studies.

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.

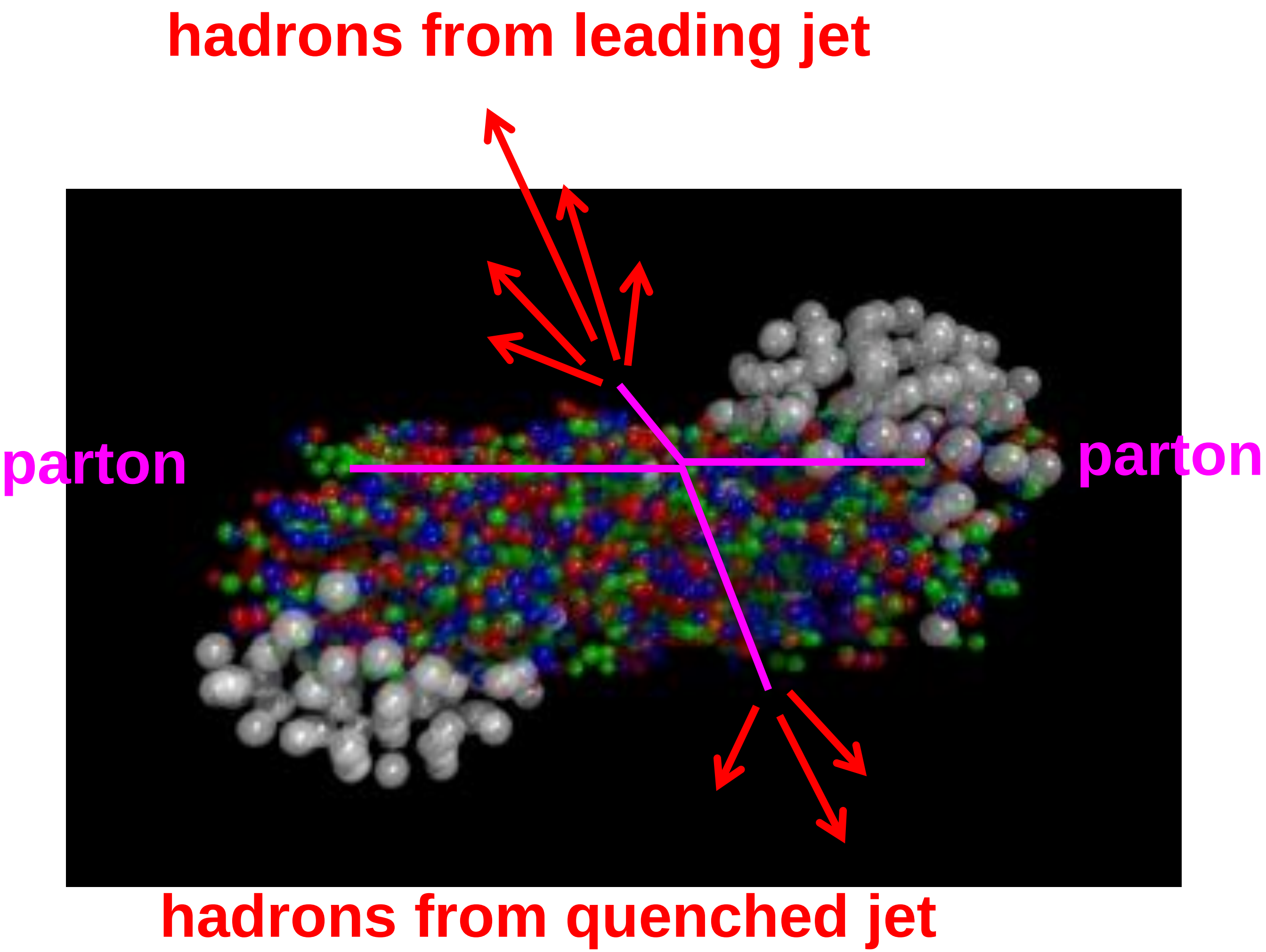
Jets in pp


hadrons from jet fragmentation
parton
parton
hadrons from jet fragmentation

Jets in pp

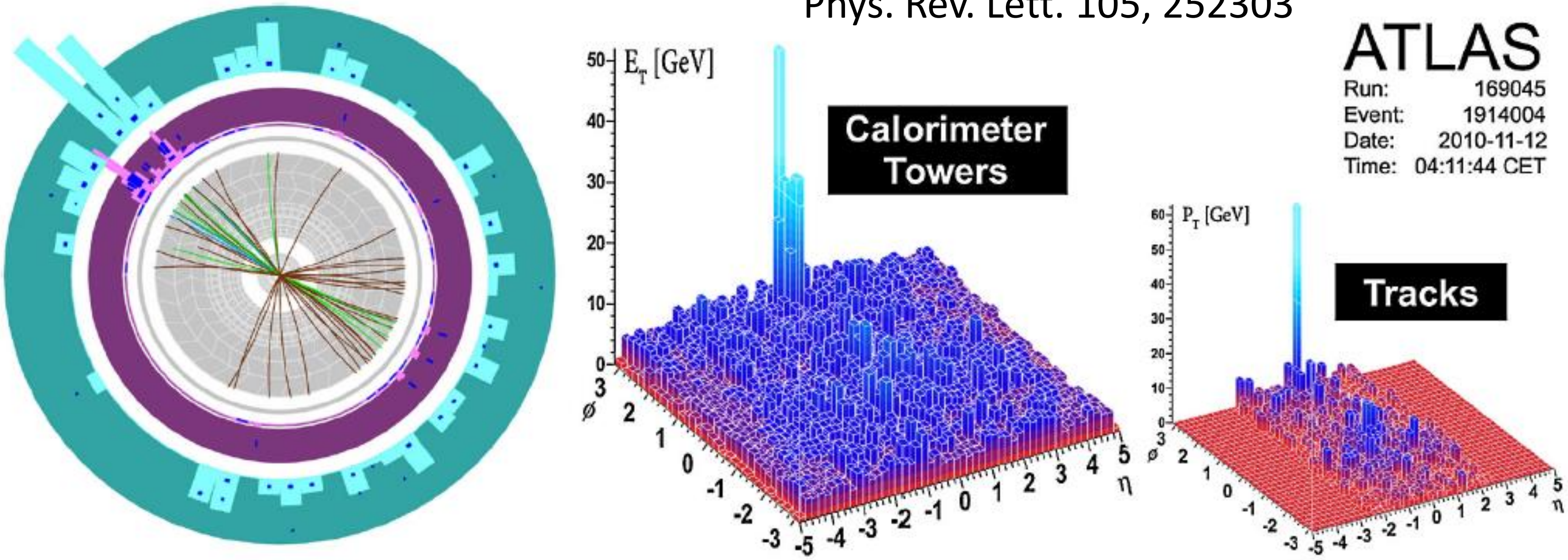

Run Number: 160958, Event Number: 23181152
Date: 2010-08-08 13:57:31 CEST
ATLAS
EXPERIMENT

Jets in Pb-Pb


hadrons from leading jet
parton
parton
hadrons from quenched jet

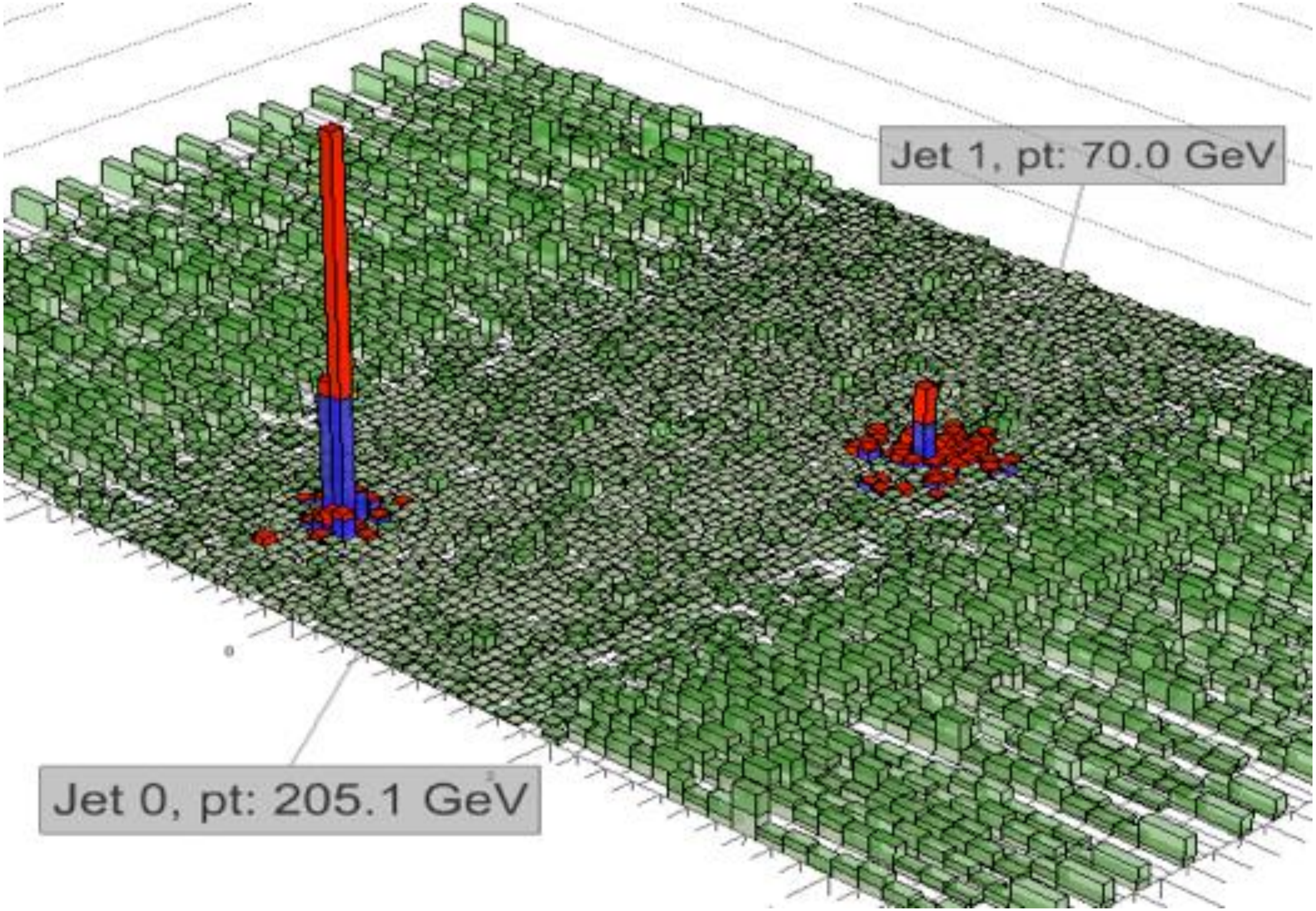
Jets in Pb-Pb (ATLAS)

Phys. Rev. Lett. 105, 252303



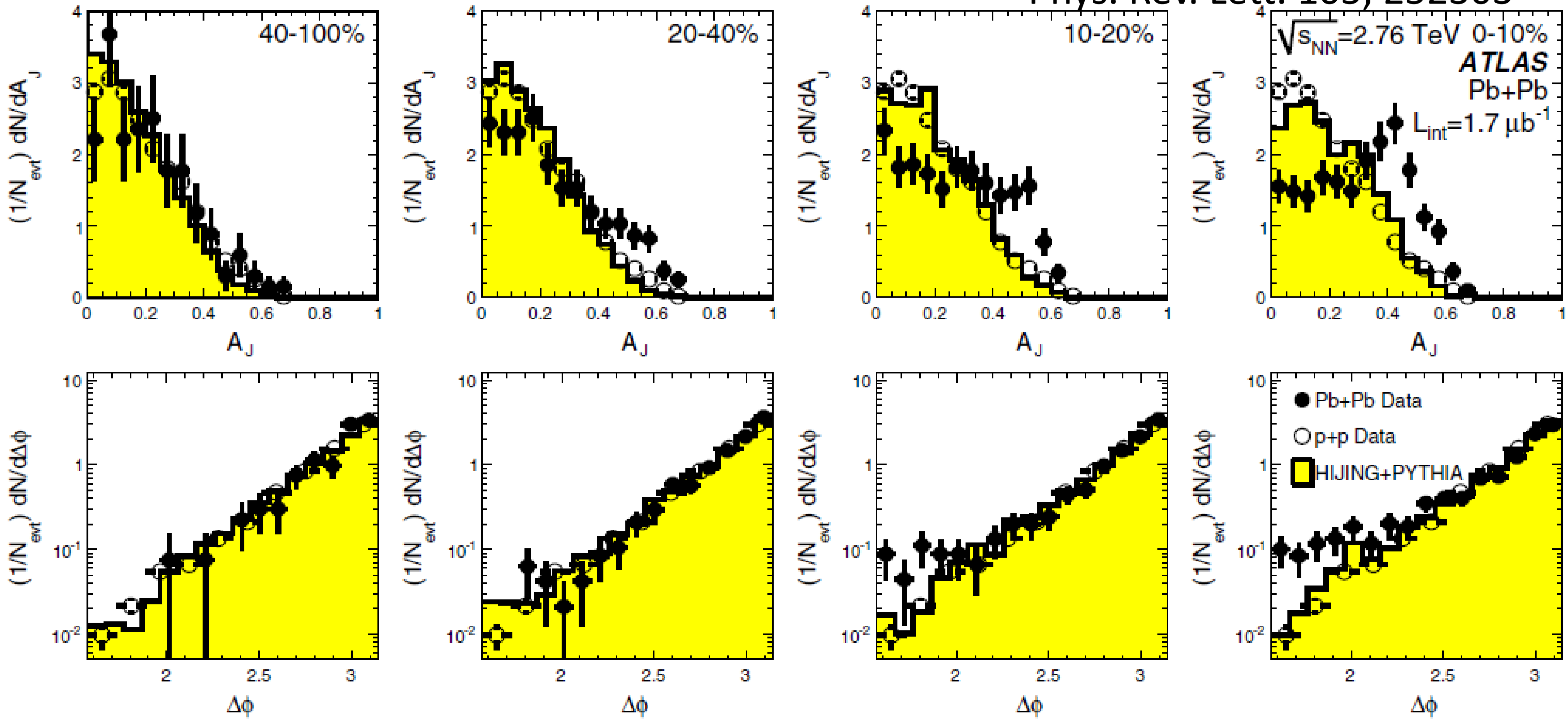
- Jet asymmetry – away side jet is absorbed/modified by the medium
  - Advantage of jets is that they “map” onto the QCD degrees of freedoms: quarks and gluons (more complicated in heavy ion collisions)
  - Advantage of ATLAS and CMS is larger acceptance

Jets in Pb-Pb (CMS)



Quantifying the dijet asymmetry

Phys. Rev. Lett. 105, 252303

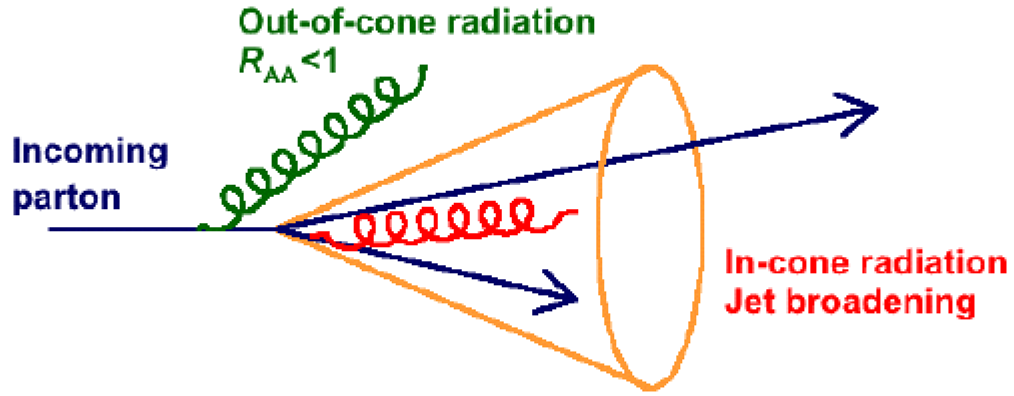


$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

Where E_{T1} (E_{T2}) is the transverse energy of the leading (subleading) jet (E_{T1}>100 GeV and E_{T2}>25 GeV).

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

Looking into the jet structure

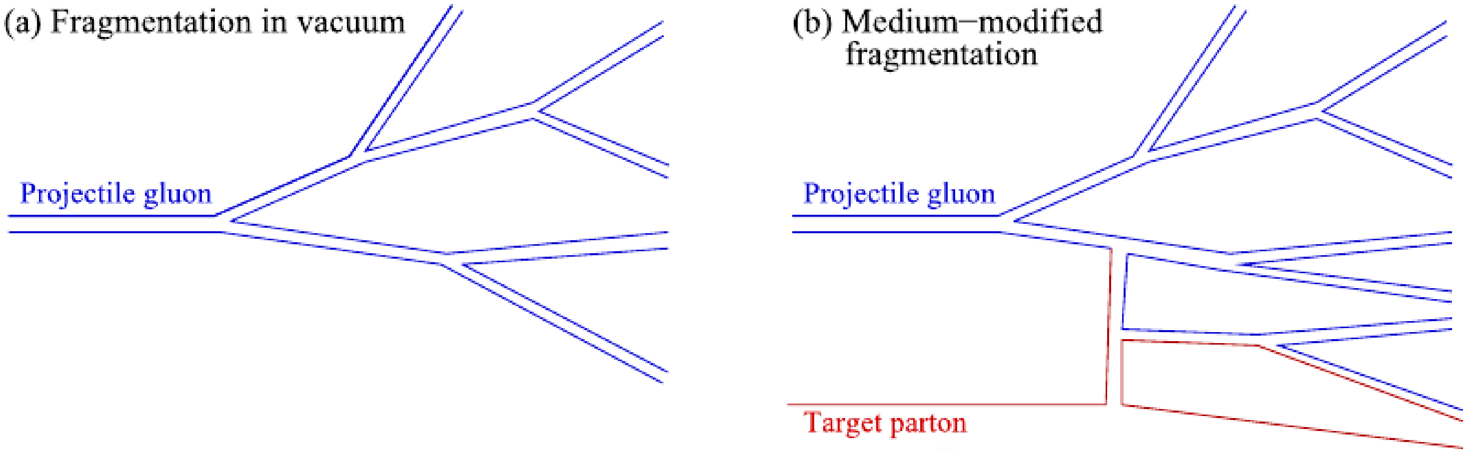


The motivation for these studies was:

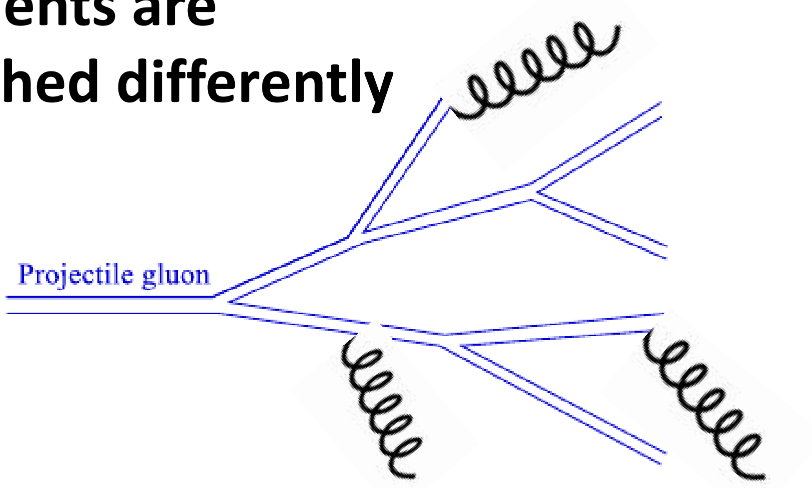
- to recover some of the radiated energy
  (in principle jets did not have to suppressed!)
- to study how the FF is modified

Two examples of ideas for modified FFs

Direct interaction with medium

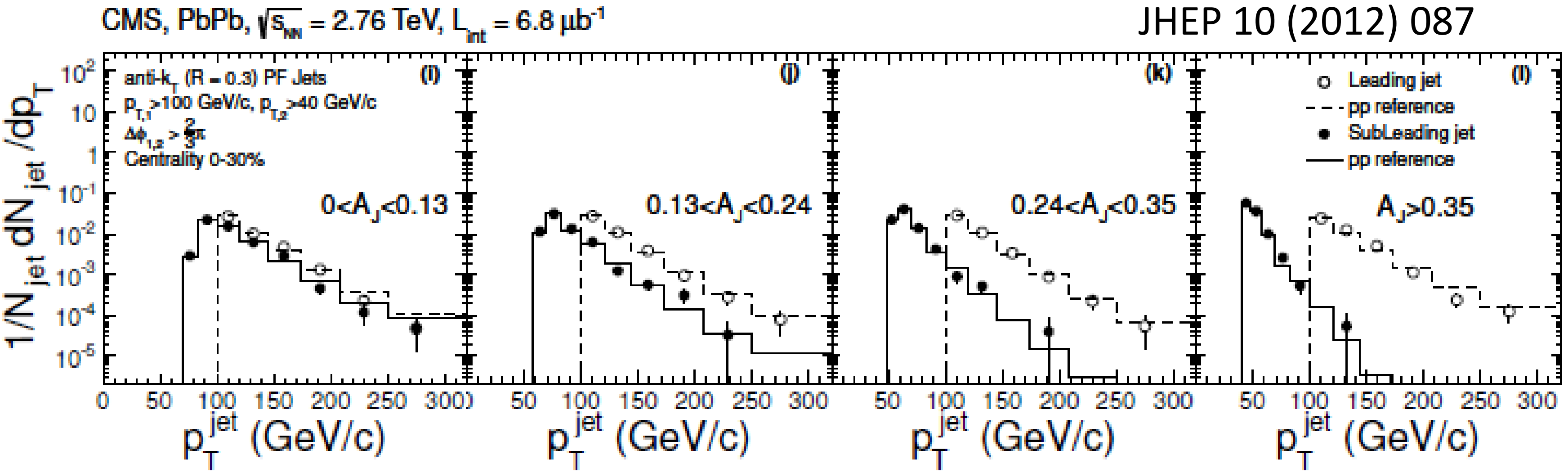


Fragments are quenched differently



Selecting dijet events and comparing to pp

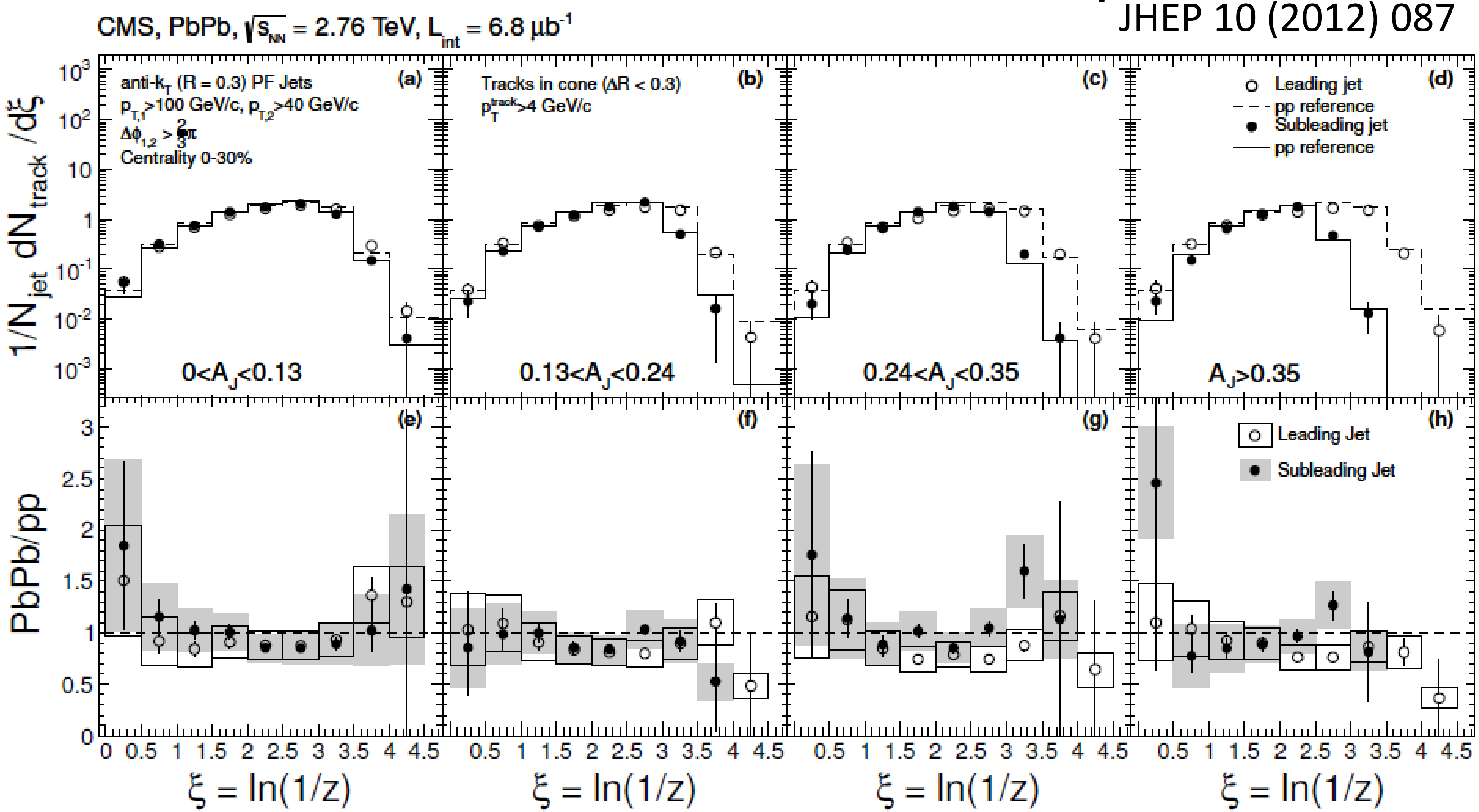
JHEP 10 (2012) 087



The A_J selection introduces the same bias on the dijet samples

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

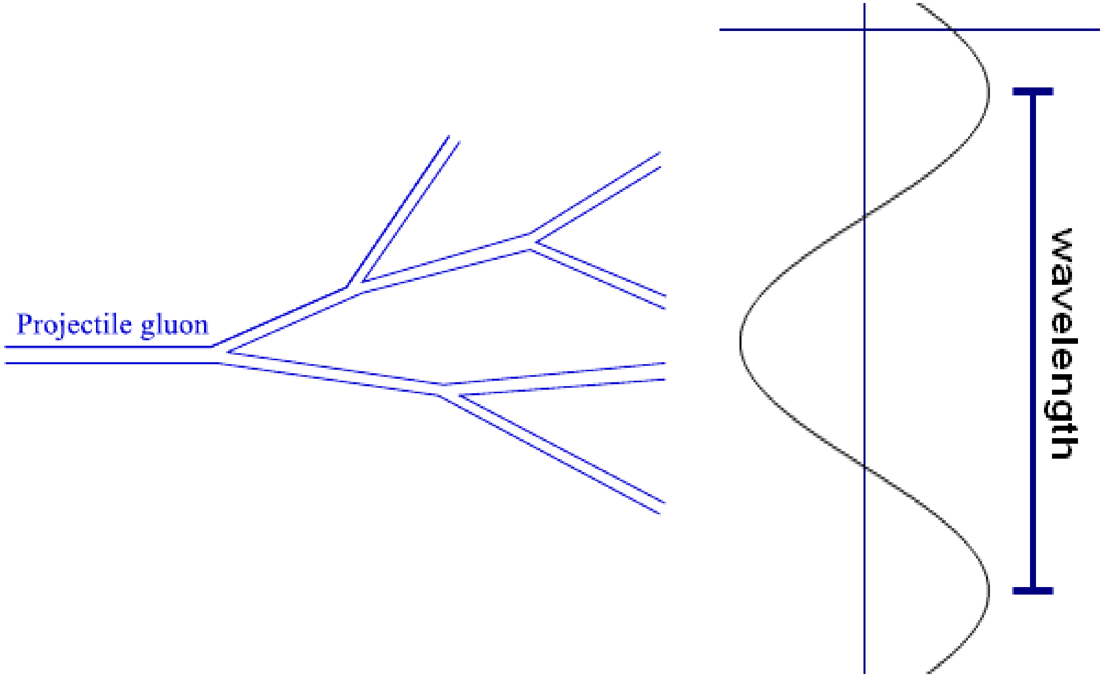
JHEP 10 (2012) 087



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!

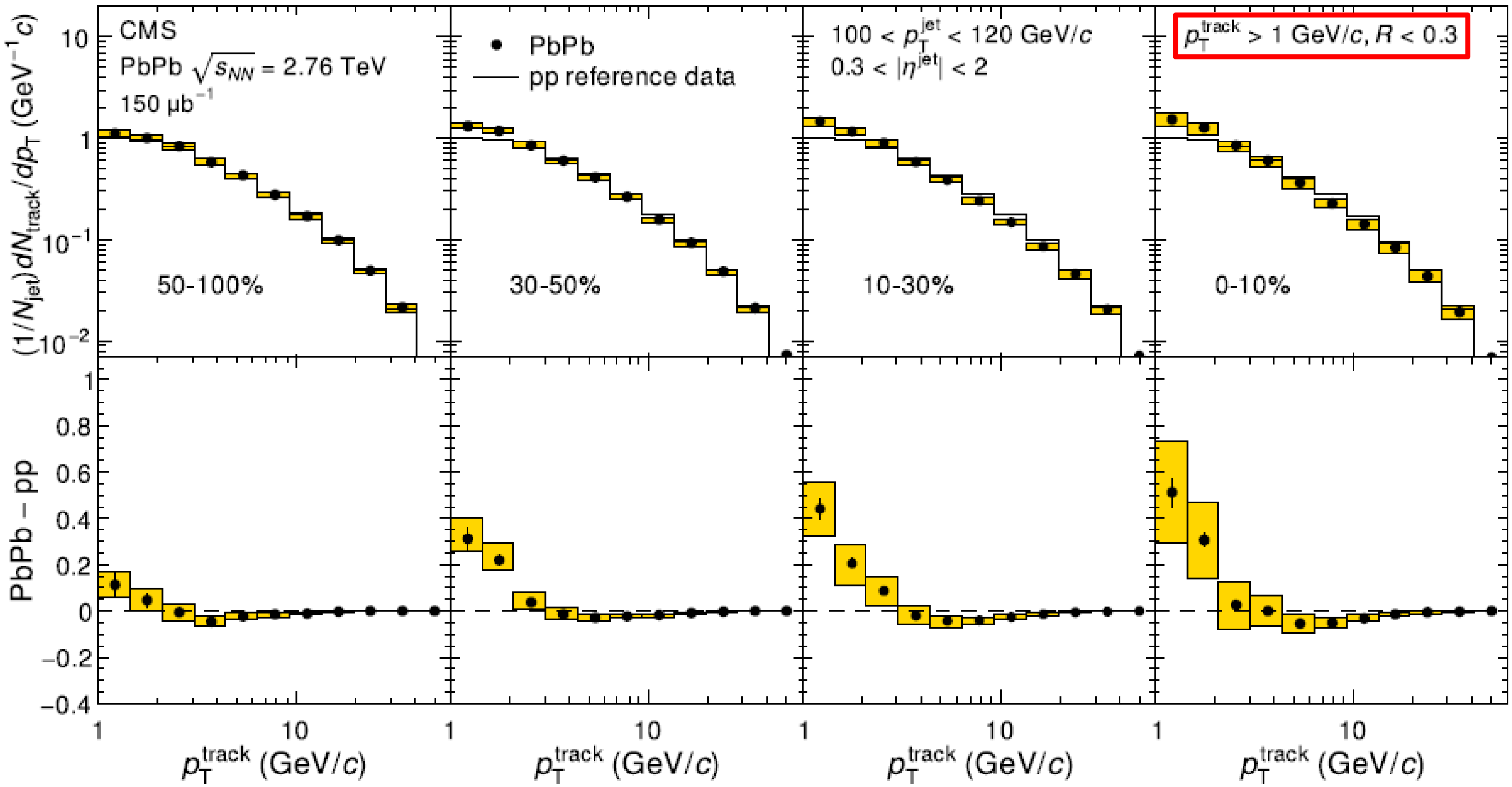
The results show that quenching is coherent!?



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

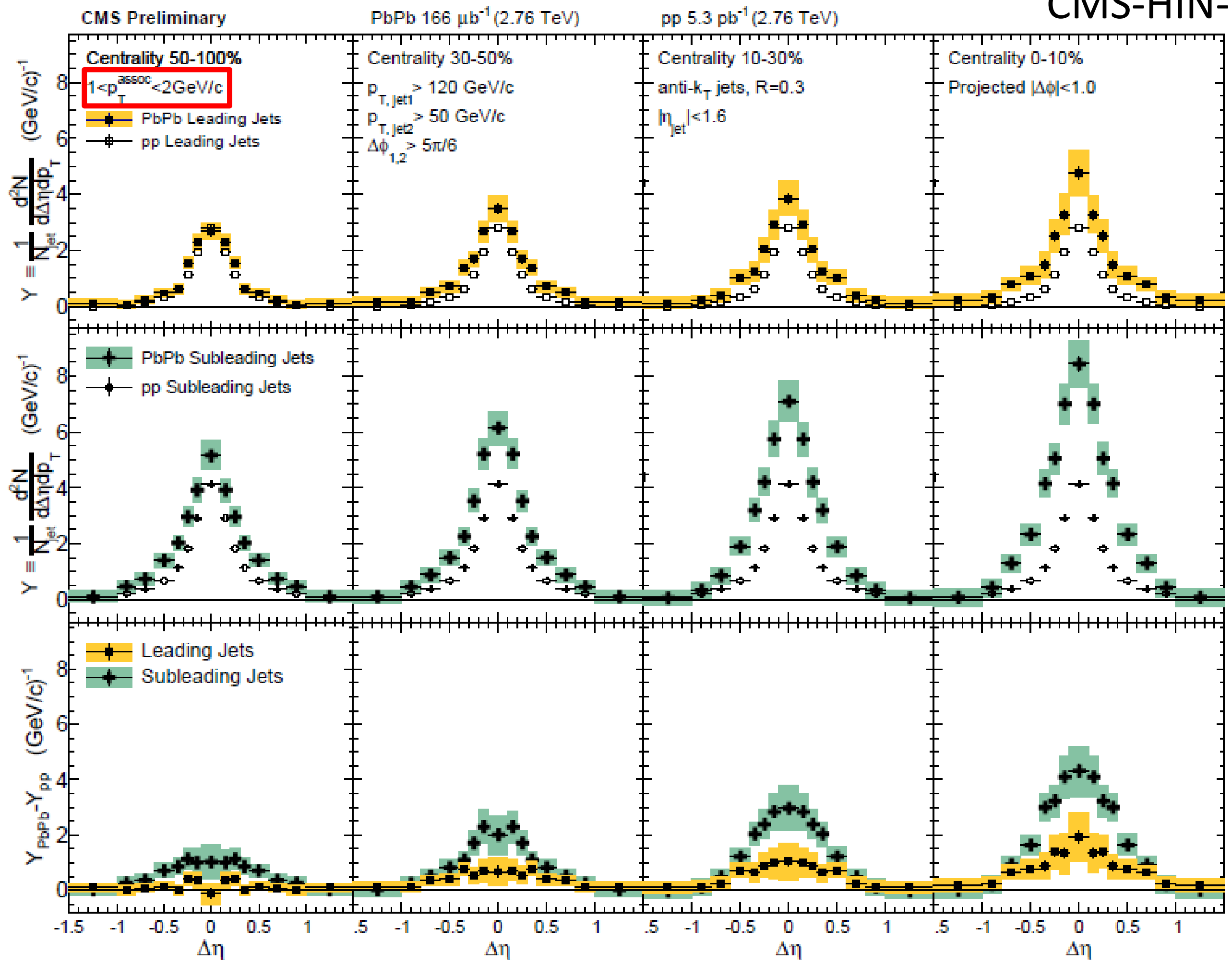


This analysis considers tracks down to p_T = 1 GeV/c

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

Tracking the energy loss

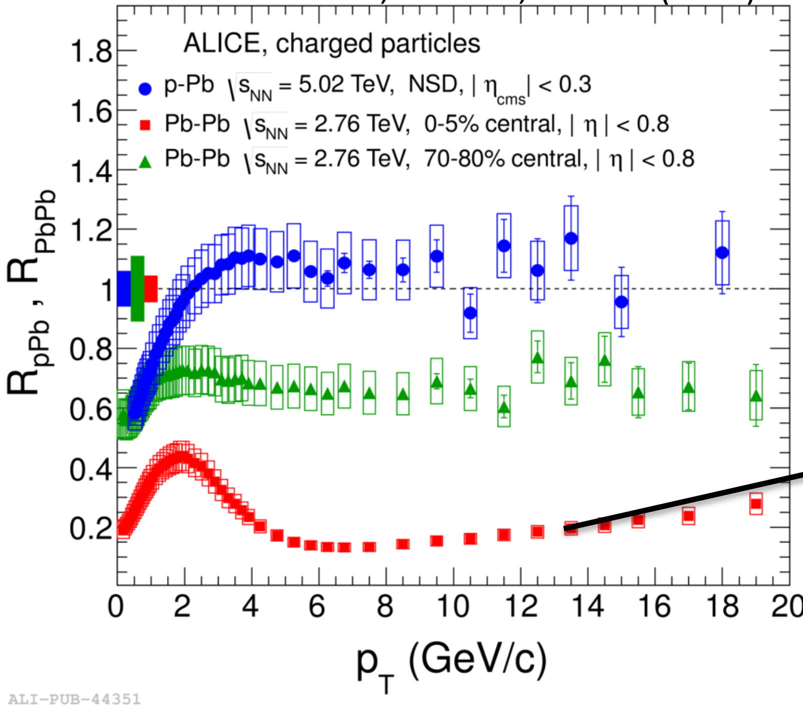
CMS-HIN-14-016



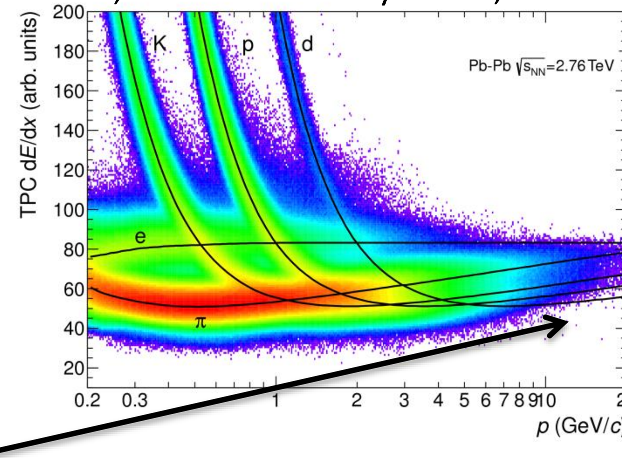
CMS have shown that the energy loss can be recovered at low p_T at large Δη and large Δϕ

Extending the R_{AA} to identified particles

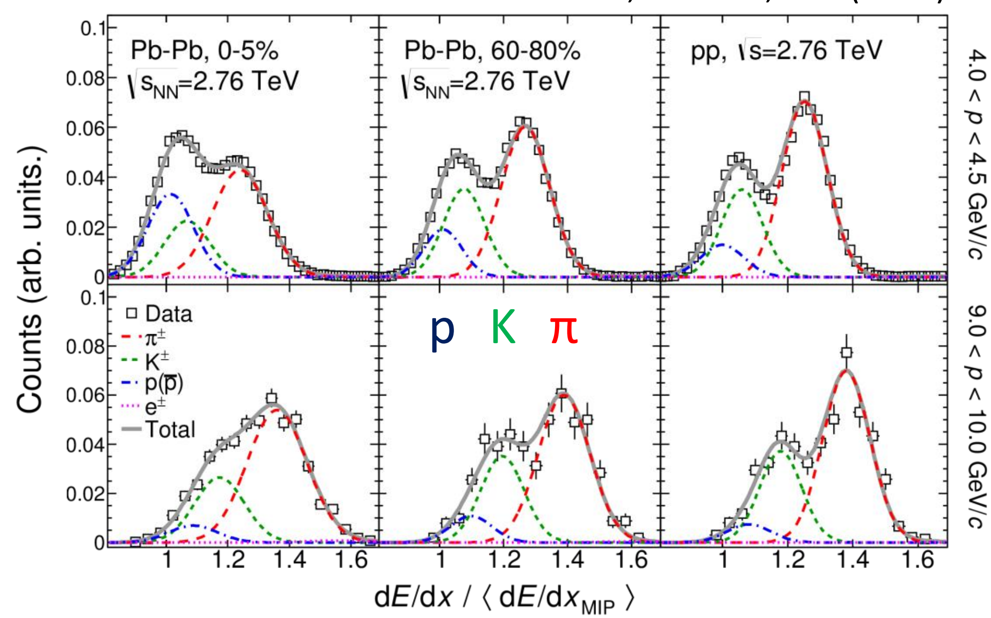
ALICE, PRL 110, 082302 (2013)



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



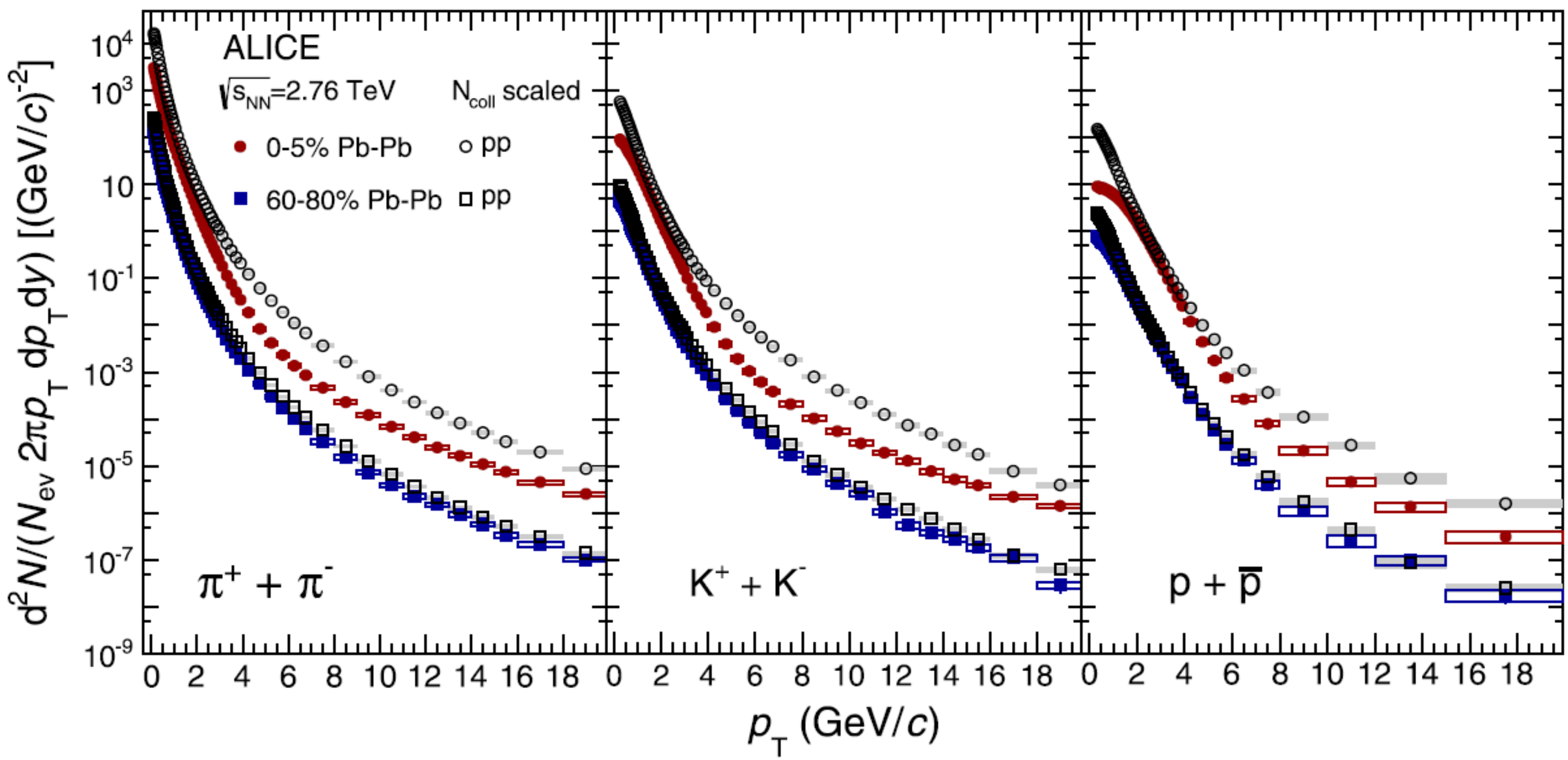
ALICE , PLB 736, 196 (2014)



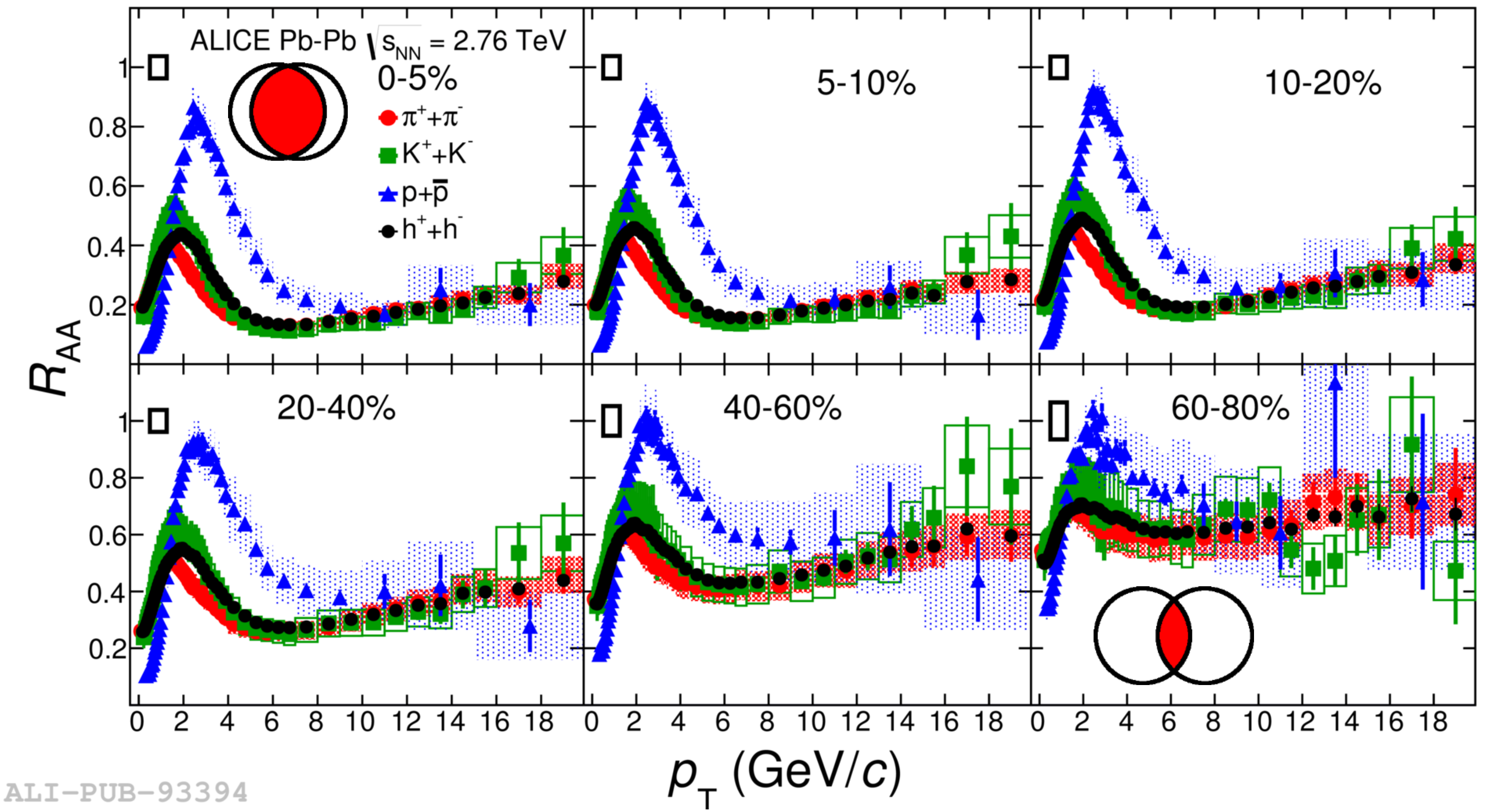
Each TPC track also has an associated dE/dx that can be used for ID on the relativistic rise

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

ALICE , PLB 736, 196 (2014)

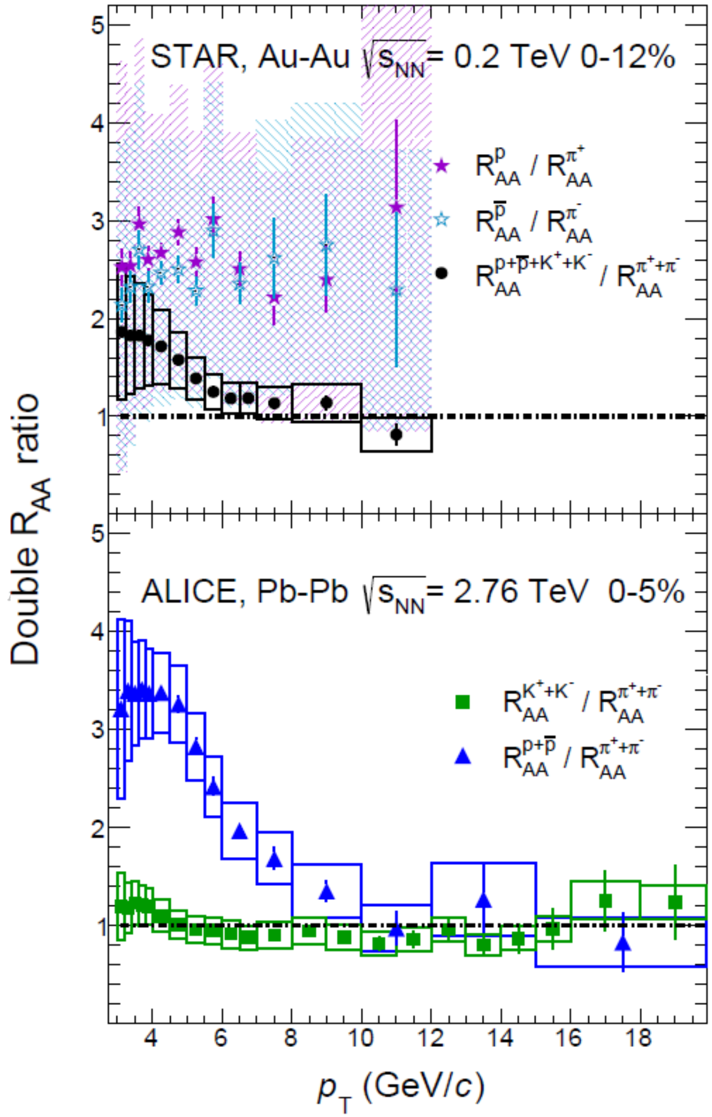


The nuclear modification factor



For p_T < 8 GeV/c: R_{AA} for π and K compatible and smaller than R_{AA} for p.
At high p_T above 10 GeV/c the R_{AA} for π, K and p are compatible.

R_{AA} double ratios



To obtain the best estimate for the similarity between the R_{AA} of π, K, and p we computed the double ratio of R_{AA}.
This cancels the most of the common systematic uncertainties.

Similarity between R_{AA} at high p_T:
π/K: ≈10% (1σ)
π/p: ≈20% (1σ)

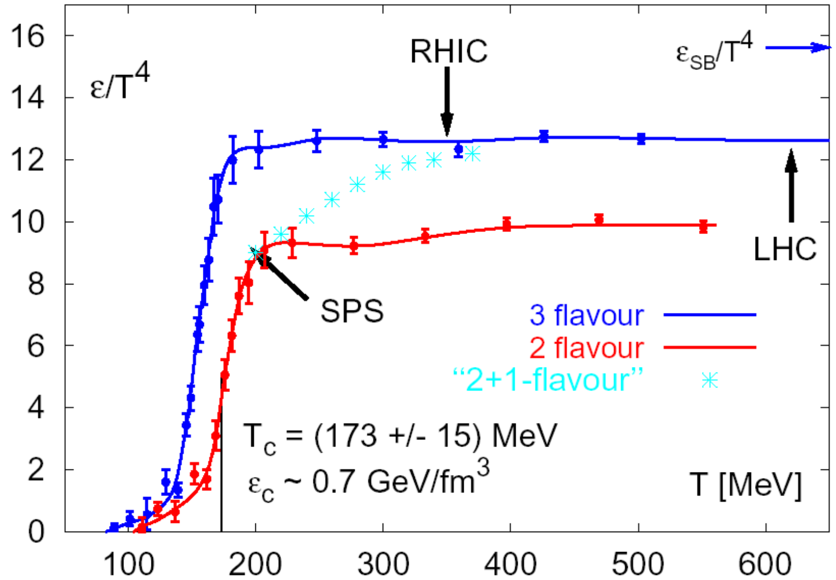
The improvement in systematic precision is almost an order of magnitude, compared to lower energy STAR results.

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

SOFT MEDIUM PROPERTIES

Lattice QCD calculation of the energy density



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

Gluon spin and color

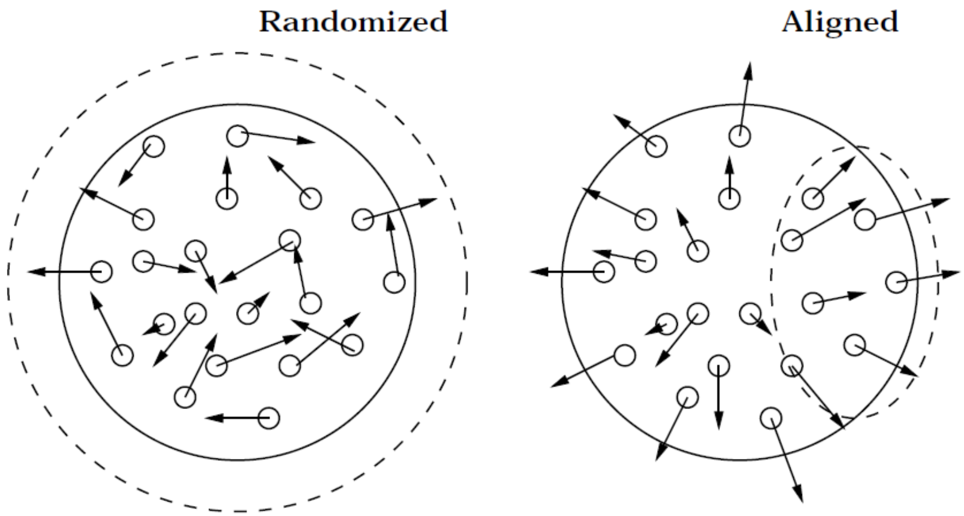
(Anti+)quark spin, color and flavor

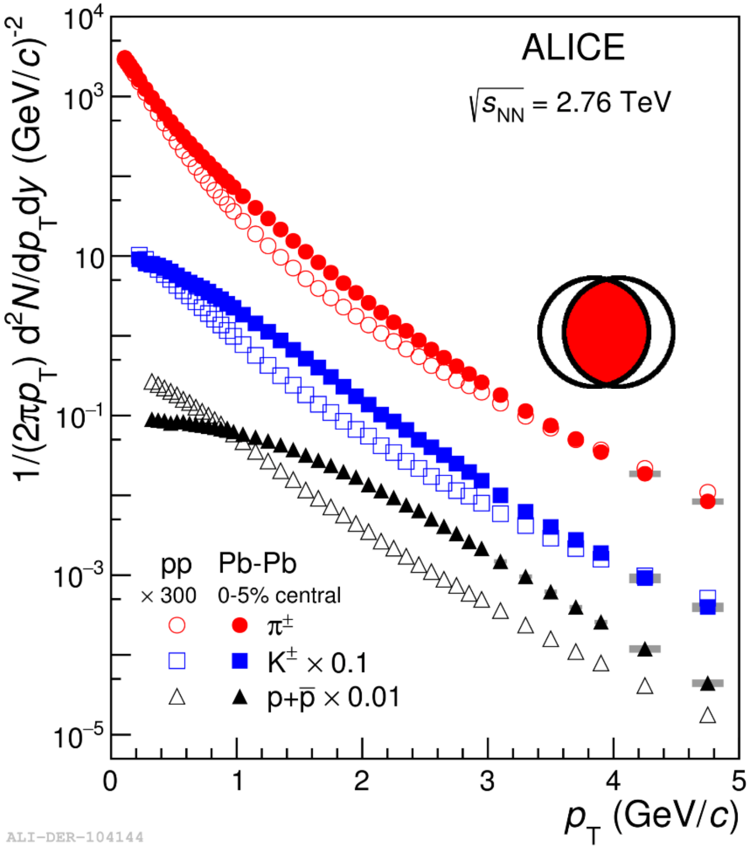
Because of the similarity with Stefan-Boltzmann energy density for a quark-gluon gas:

QGP should be weakly coupled

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

Radial flow



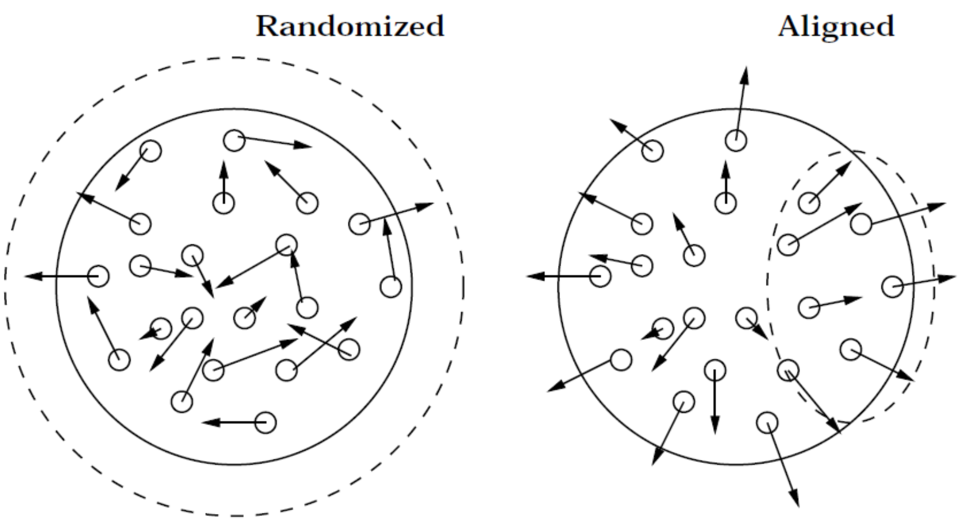


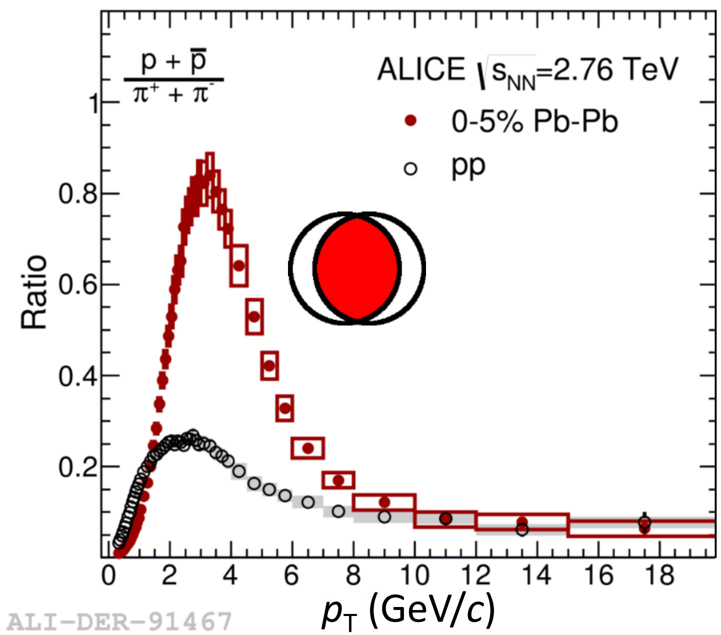
- Flow in general plays a very important role in heavy-ion collisions.
- We believe that flow in the partonic phase is imprinted on the final state hadrons at freeze out.

Flow velocity β_r → mass dependent boost:

$p_T \sim \gamma\beta_r m$ (for particle initially at rest)

Radial flow





- Flow in general plays a very important role in heavy-ion collisions.
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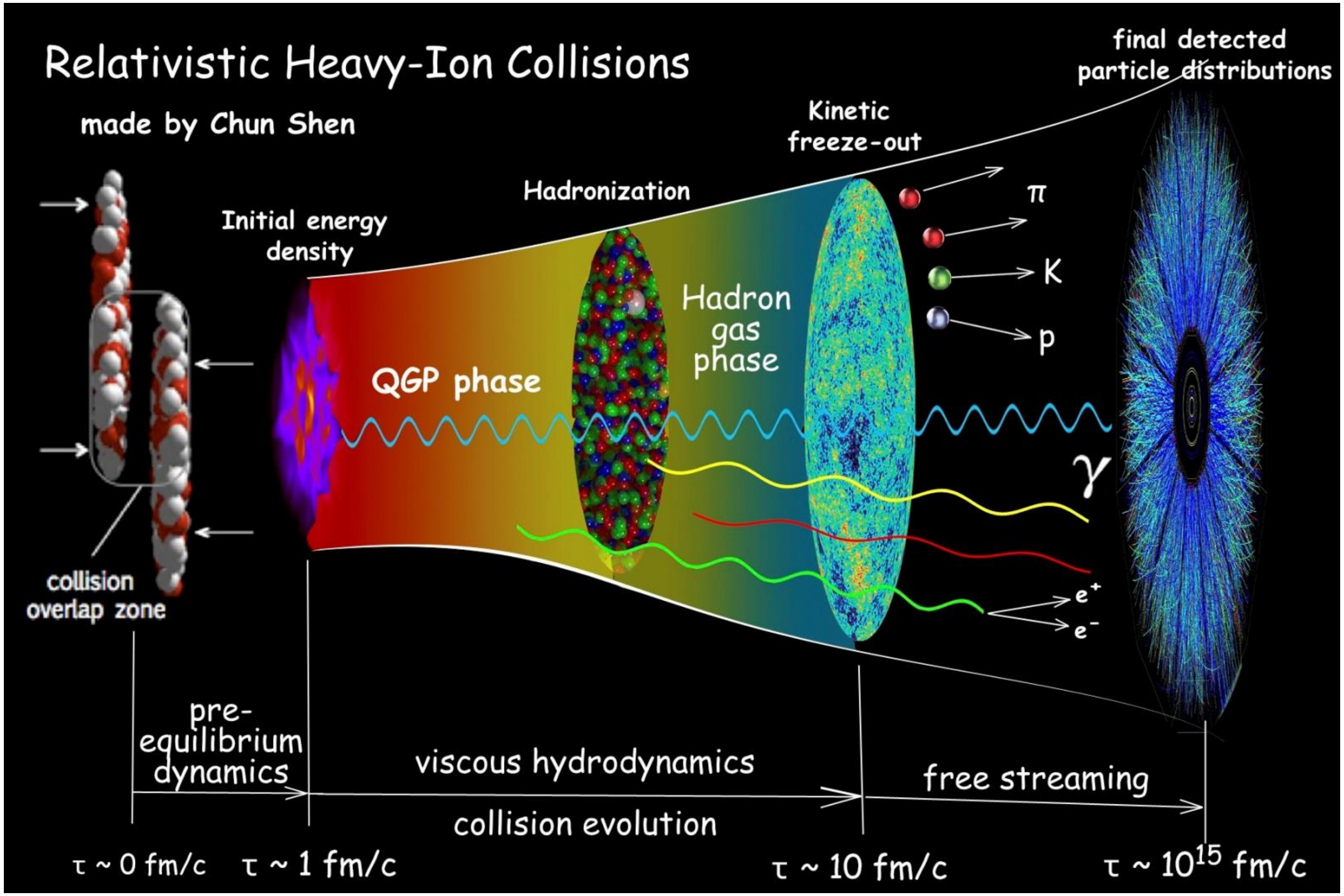
Flow velocity β_r → mass dependent boost:

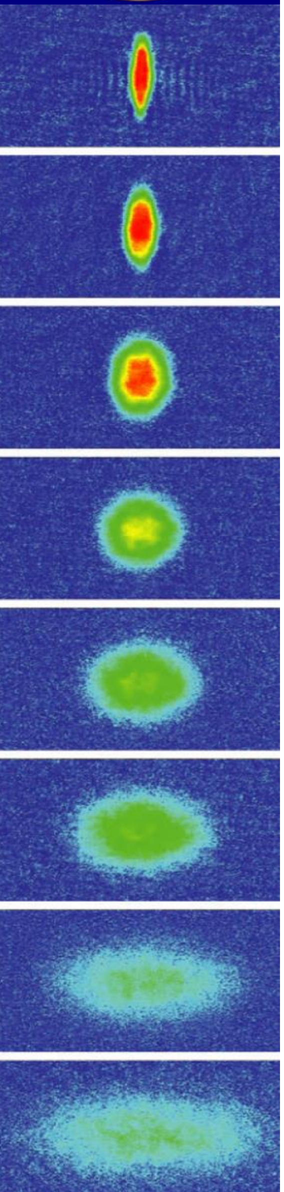
$p_T \sim \gamma\beta_r m$ (for particle initially at rest)

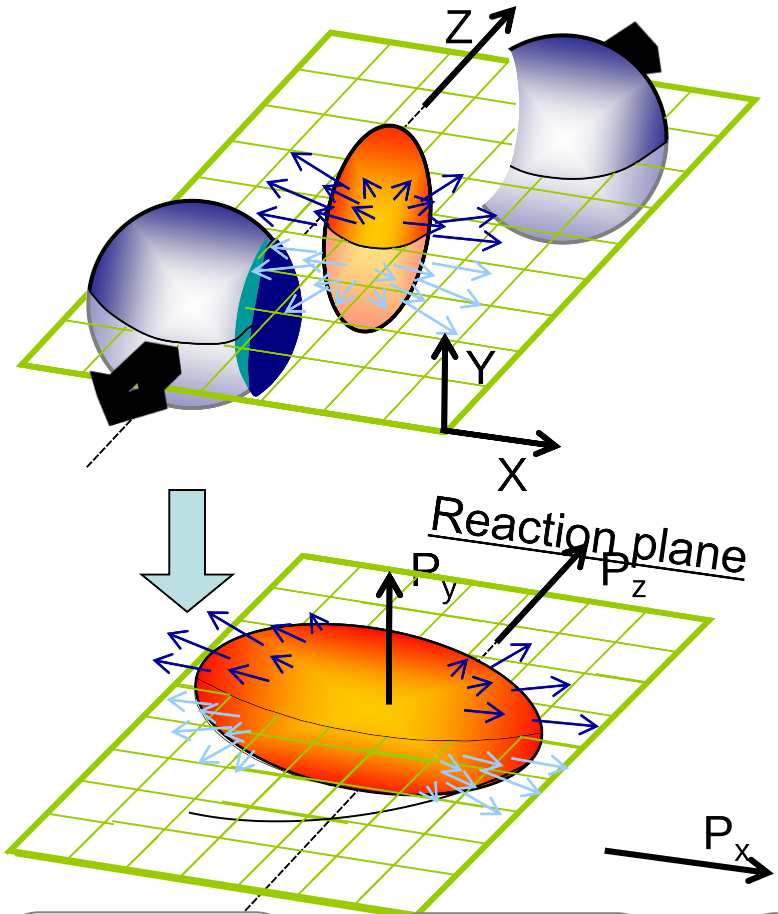
Evolution of the heavy-ion collision



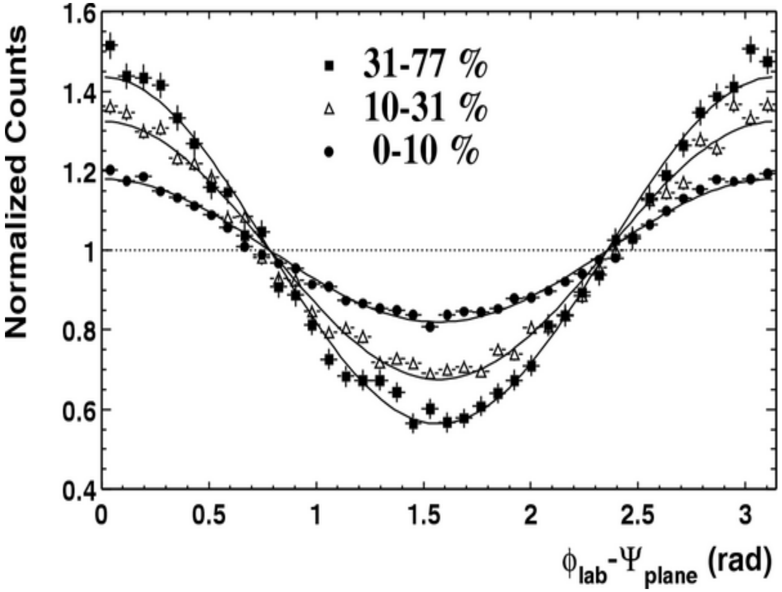
Mainly this period where flow build up

Elliptic flow (v_2)



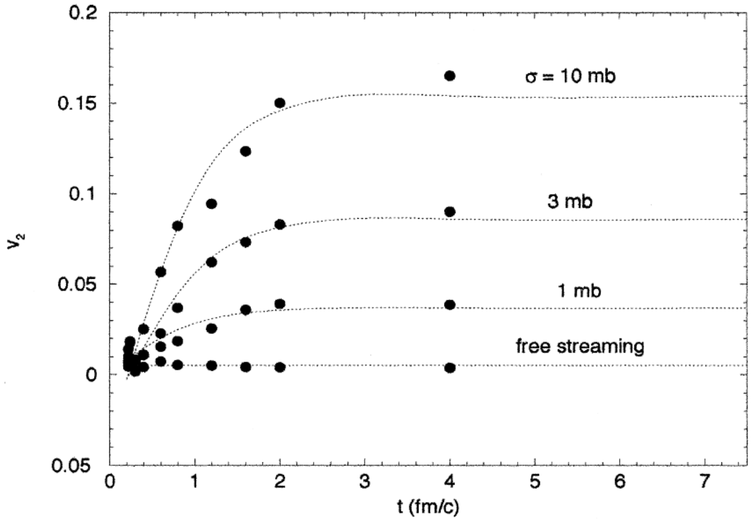


Fourier decomposition:
$dN/d\Delta\phi = 1 + 2\, v_2 \cos(2\,\Delta\phi)$



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

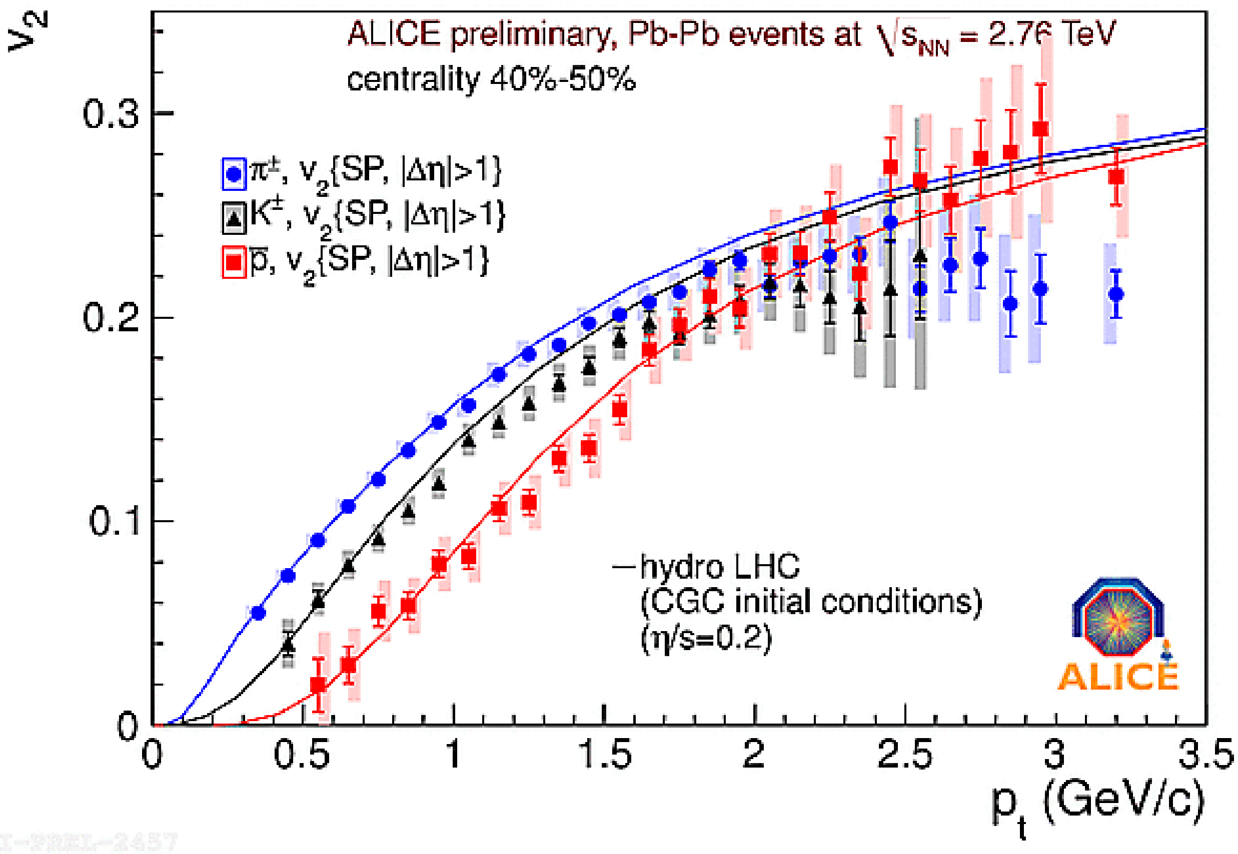
Elliptic flow requires early strong interactions to form



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

Mass ordering of the elliptic flow



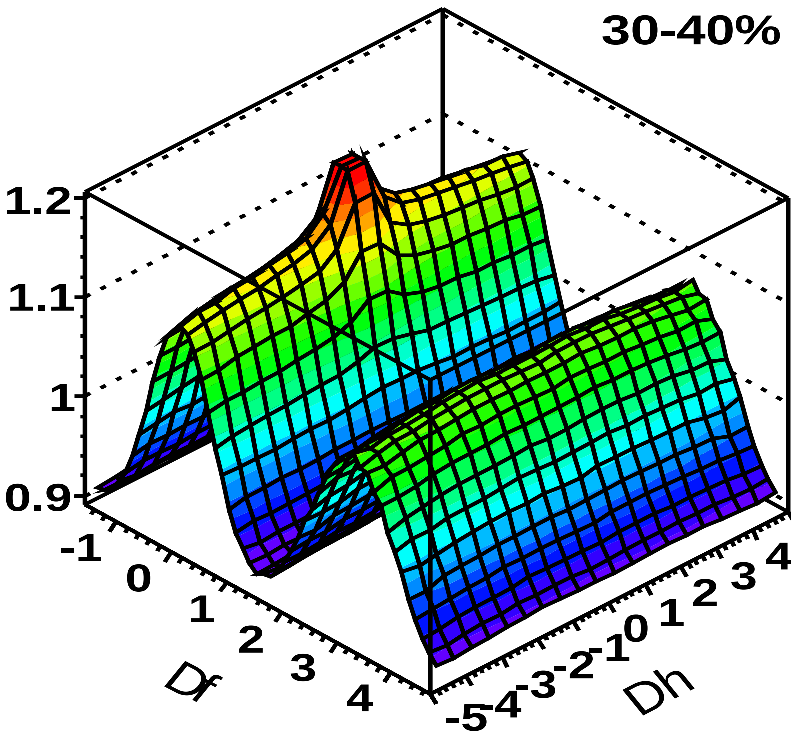
The mass ordering is characteristic of flow since heavier particles are pushed out to higher p_T

Surprisingly this is well described by nearly ideal hydrodynamics

Some simulation movies of hydrodynamics

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

Ridge (ATLAS)



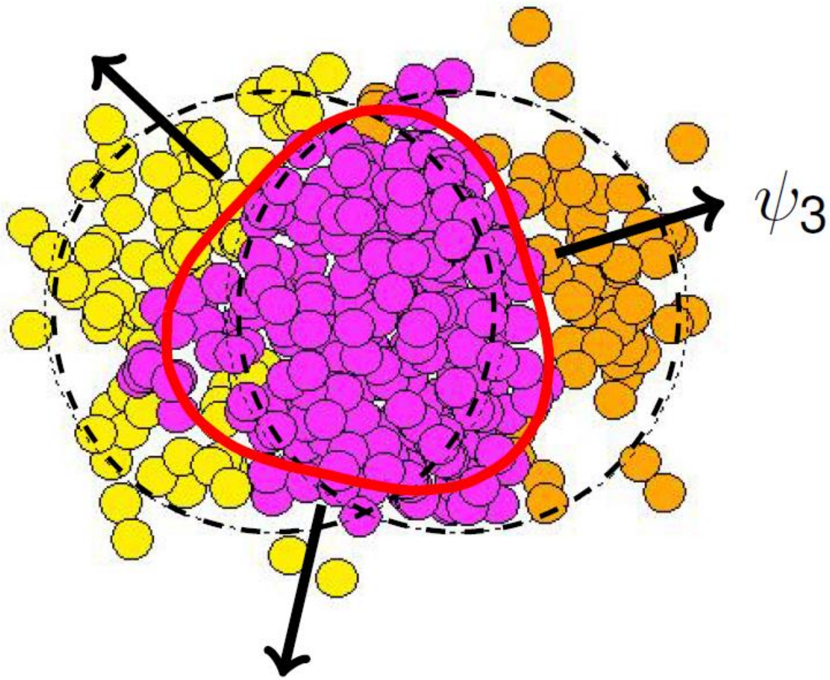
One can study flow using two particle correlations. Here $2 < p_{T1}, p_{T2} < 3$ GeV/c

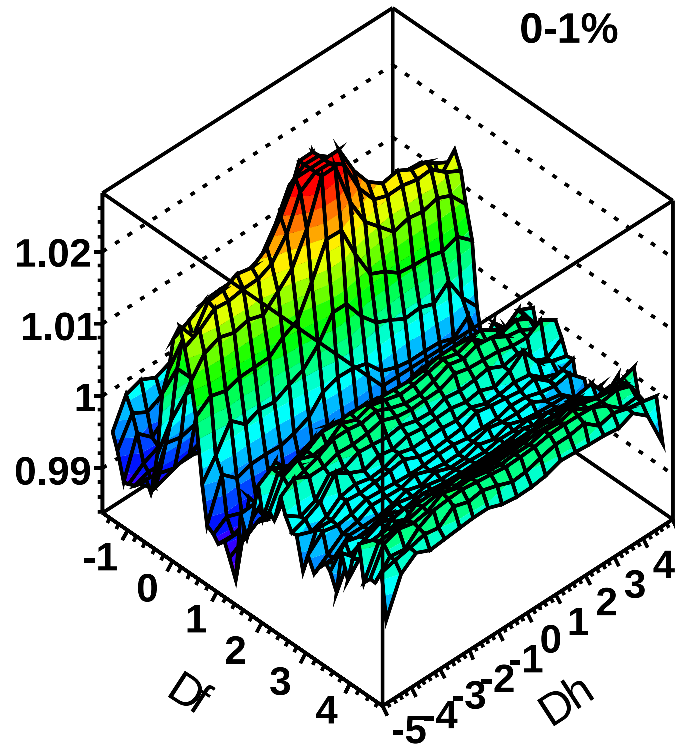
The long range correlations are imprinted by the flow because **the initial elliptic overlap is a global property of a collision!**

For completeness:

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

Flow fluctuations

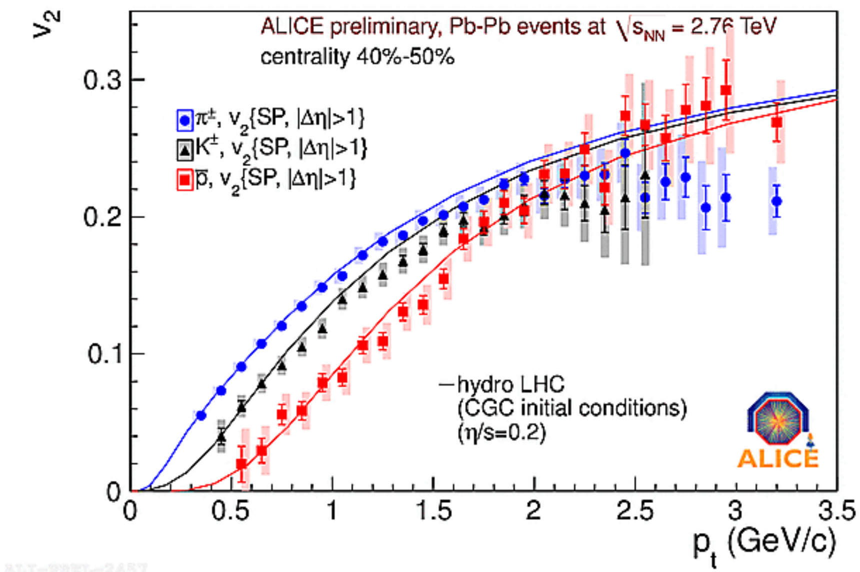


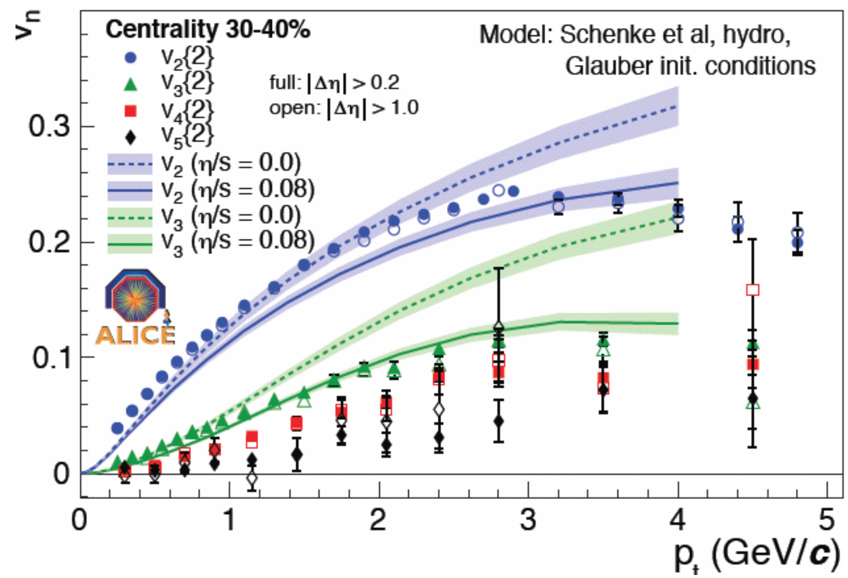


Because the nuclei are not homogenous the initial state can be quite asymmetric giving rise to e.g. triangular flow!

Famous paper: B. Alver, G. Roland, Phys.Rev. C81 (2010) 054905 (420 citations)

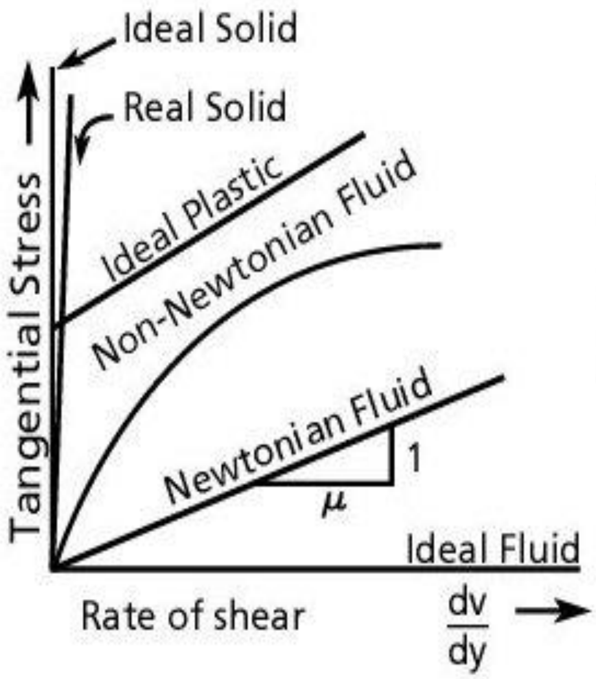
Elliptic flow and triangular flow is almost ideal!





- 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



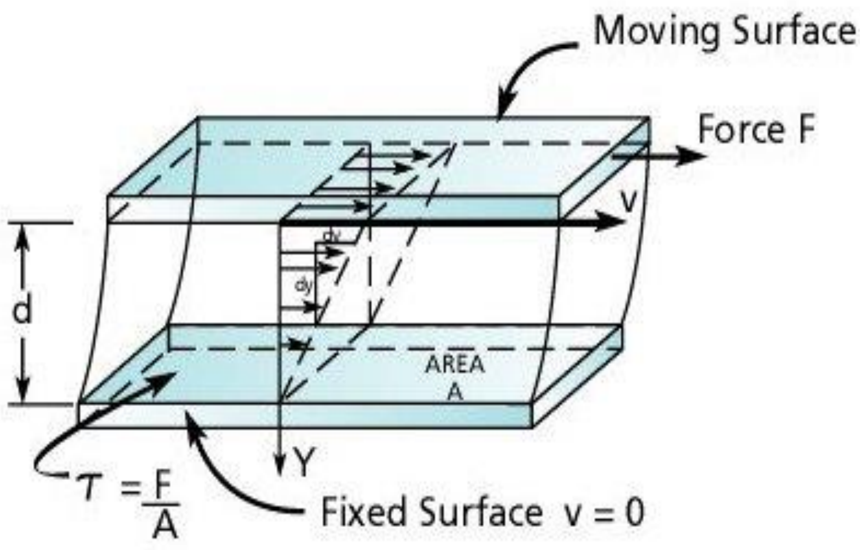


Figure taken from
http://www.pumpfundamentals.com/about_fluids.htm

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.
For the QGP, η/s is extremely small!

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

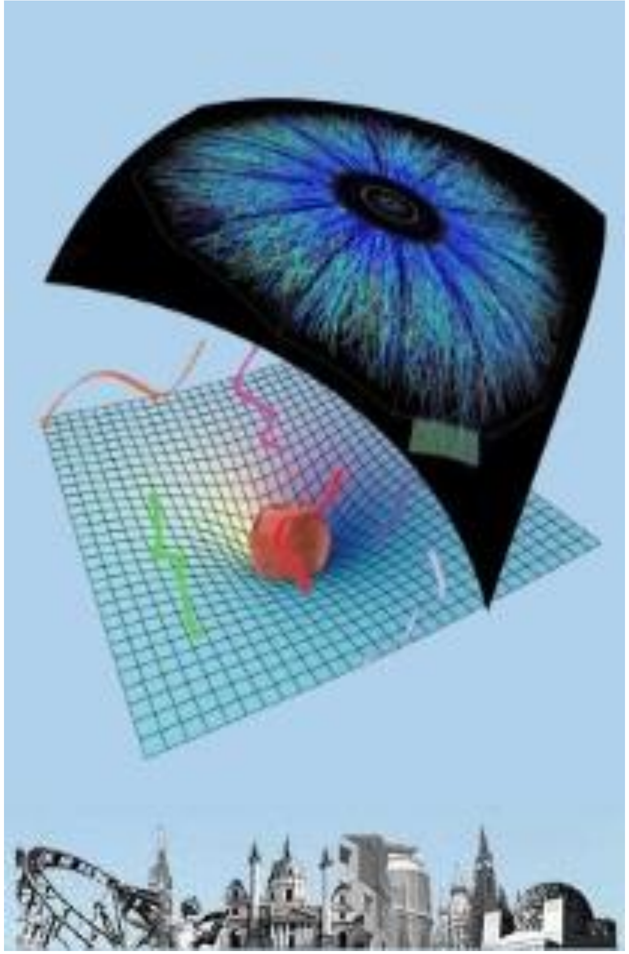
- Big theoretical challenges:

  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~10^{-23}s). This remains to be understood

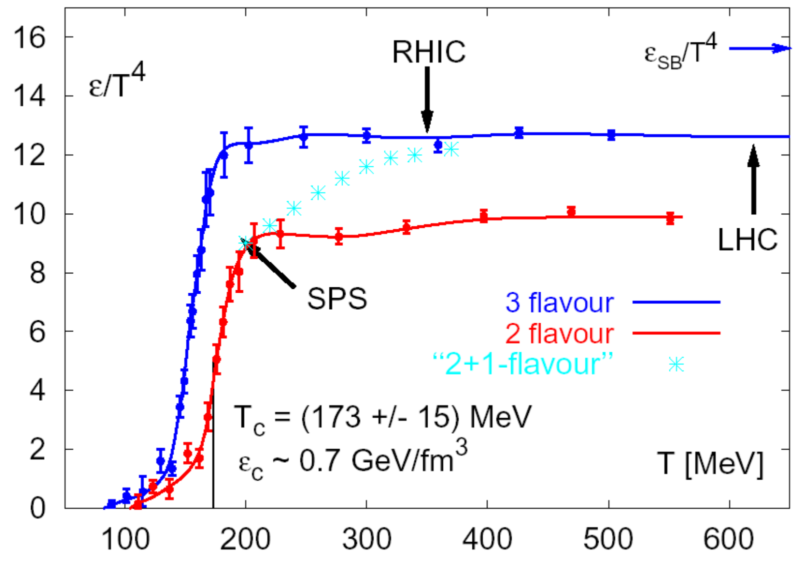
How to understand this? AdS-CFT

- 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

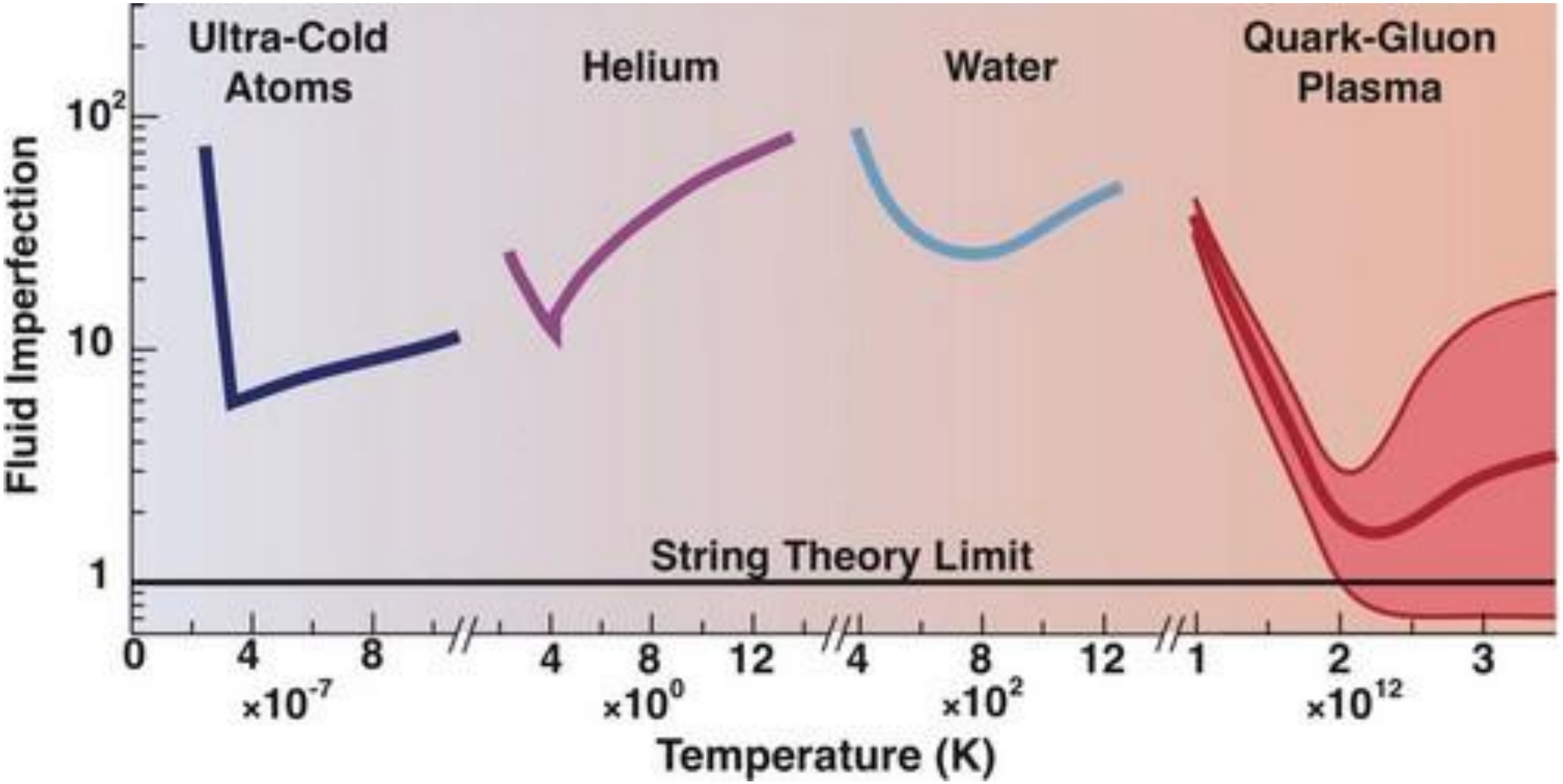


AdS-CFT

- Two very important results:
  - Conjectured bound on shear viscosity: $\eta/s \geq 1/(4\pi) \sim 0.08$
    - **Viscosity in strongly interacting quantum field theories from black hole physics, P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett. 94 (2005) 111601. (~1400 citations on inspire.)**
  - Possibility of infinitely strong coupling at energy density of ¾ SB gas

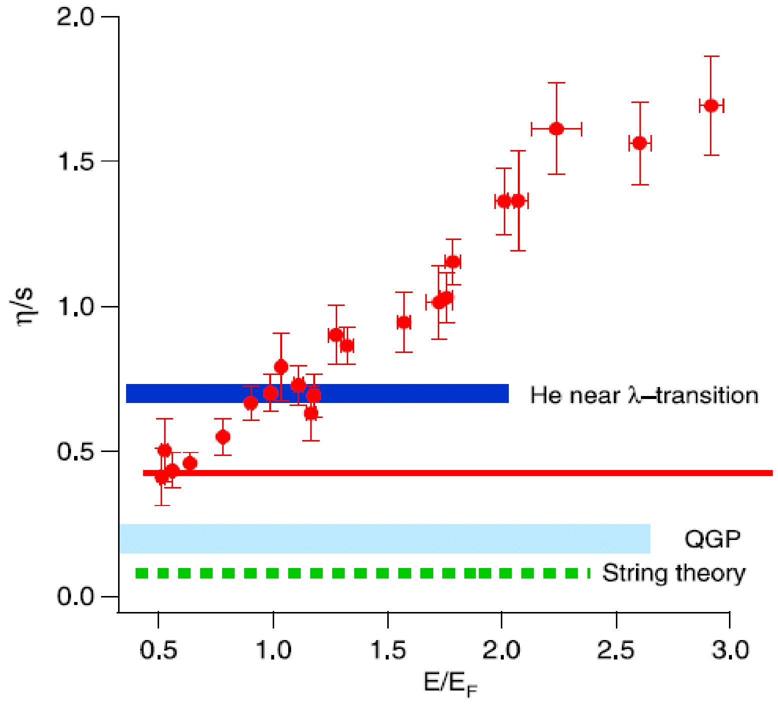


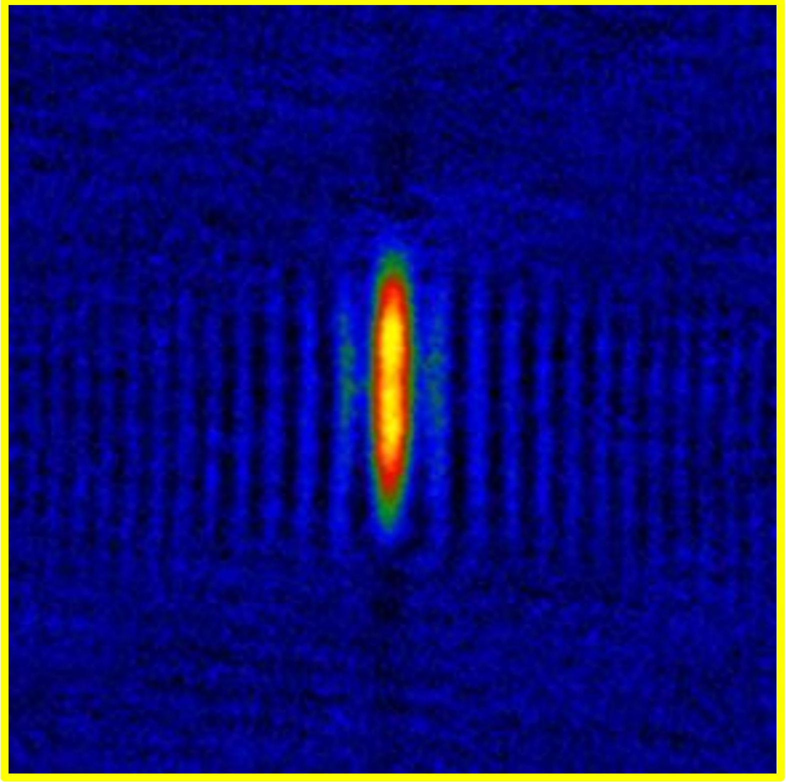
The QGP fluid compared to other fluids



The QGP fluid compared to other fluids

Strongly interacting ultra-cold Li atoms released from a trap





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

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

Conclusions about soft physics

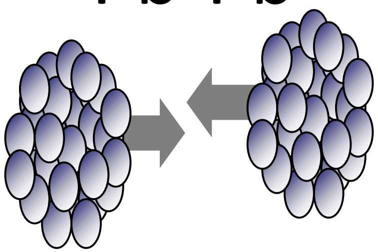
- The medium produced in heavy-ion collisions behaves like a nearly perfect liquid. In fact like the most perfect liquid we know!
- This was completely unexpected based on lattice QCD results
- We can get some insight into the liquid nature from AdS-CFT but so far this does not give a full picture e.g. it does not yet describe jet quenching

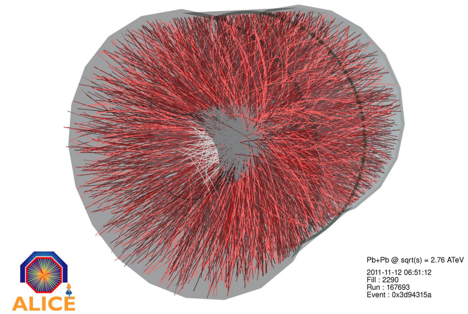
COLLECTIVITY IN SMALL SYSTEMS

The effect of system size:

Macroscopic effects in small systems?

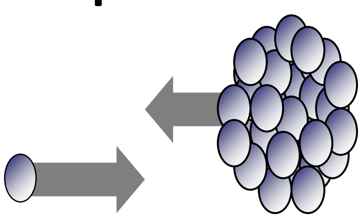
Pb-Pb

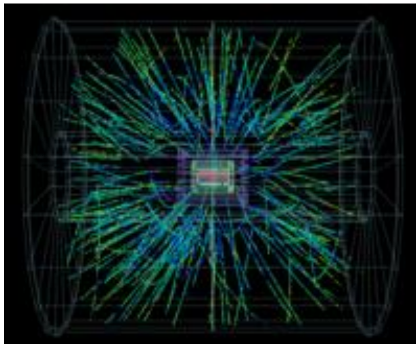




Hot nuclear matter

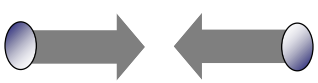
p-Pb

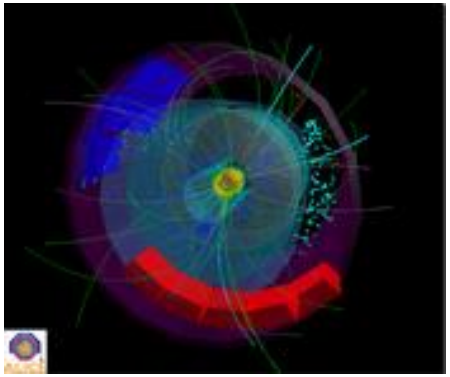




Cold nuclear matter

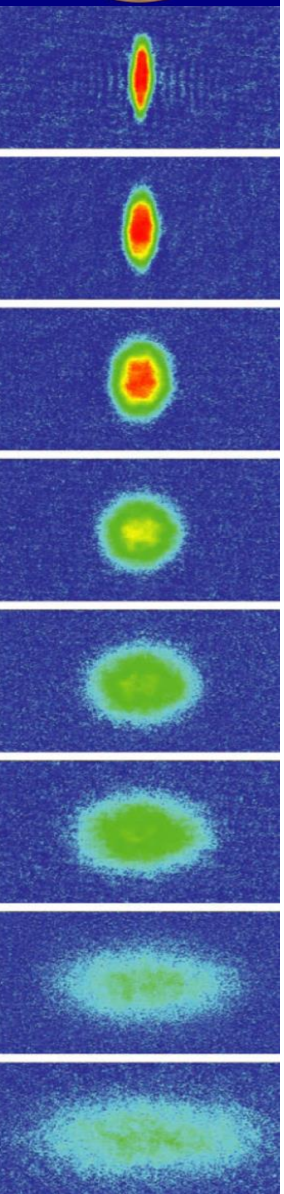
pp

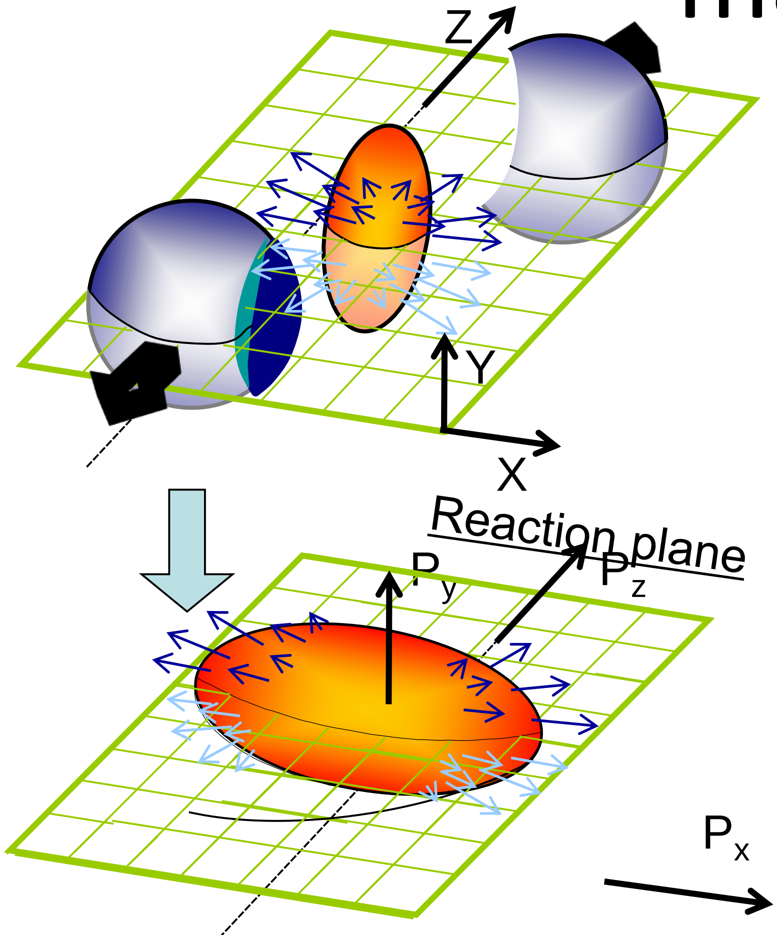


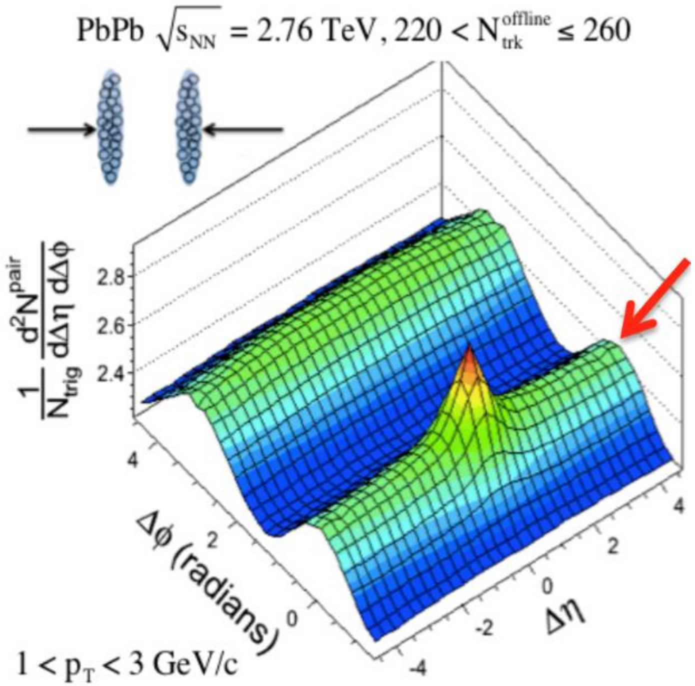


QCD baseline

The ridge: a fingerprint of the macroscopic QGP

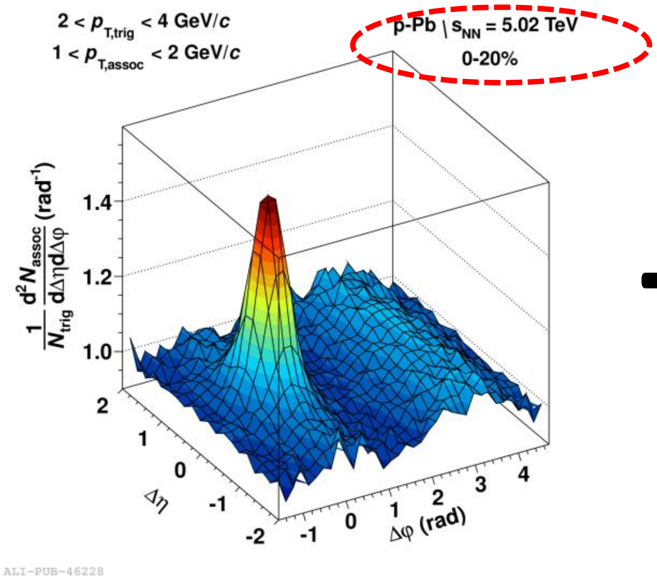






Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

The rise of the double ridge



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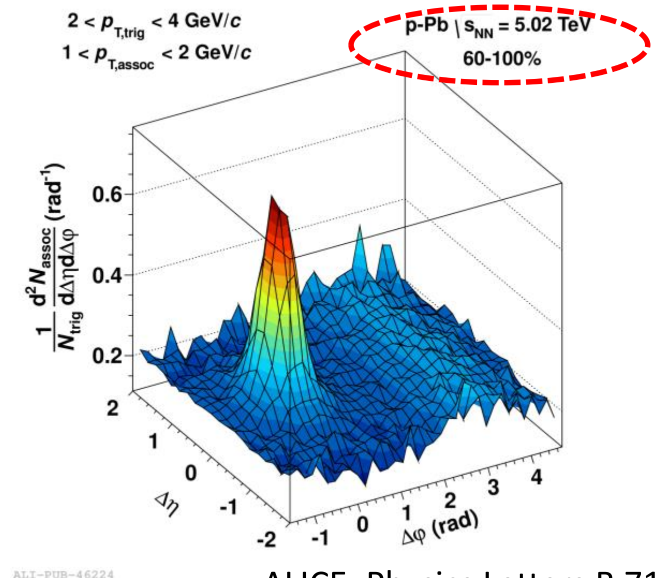

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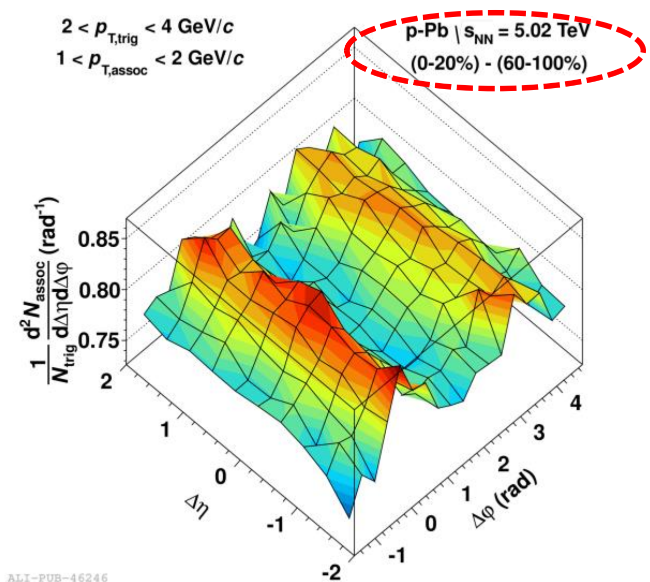
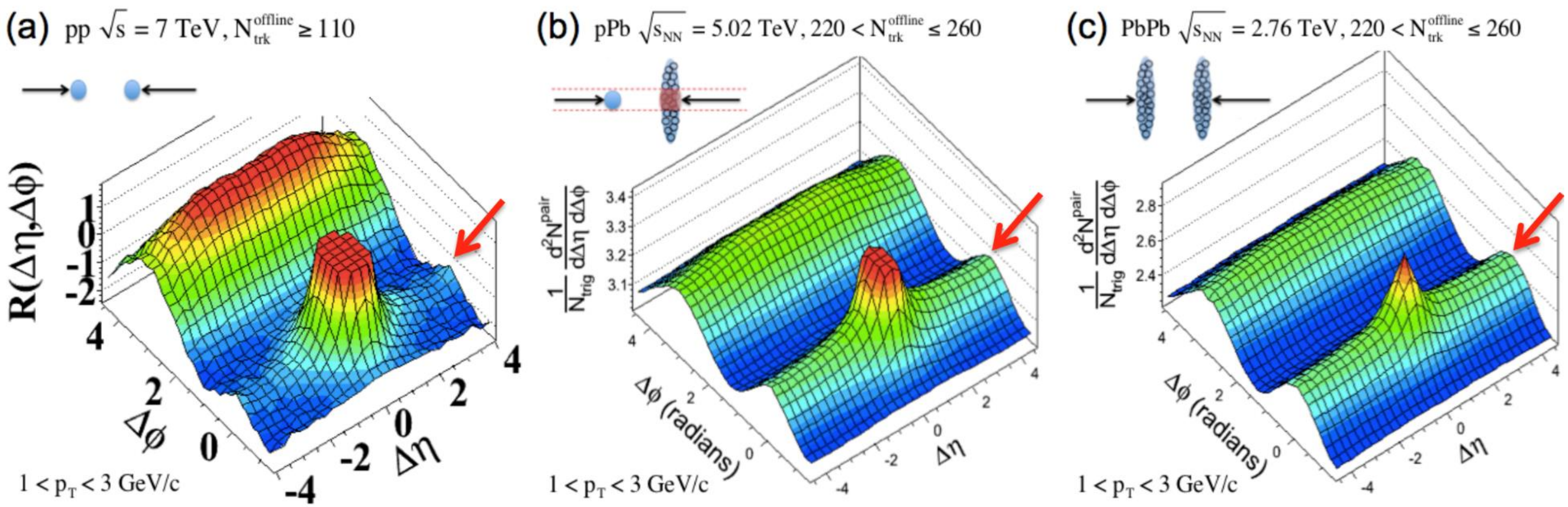
ALICE: Physics Letters B 719 (2013)



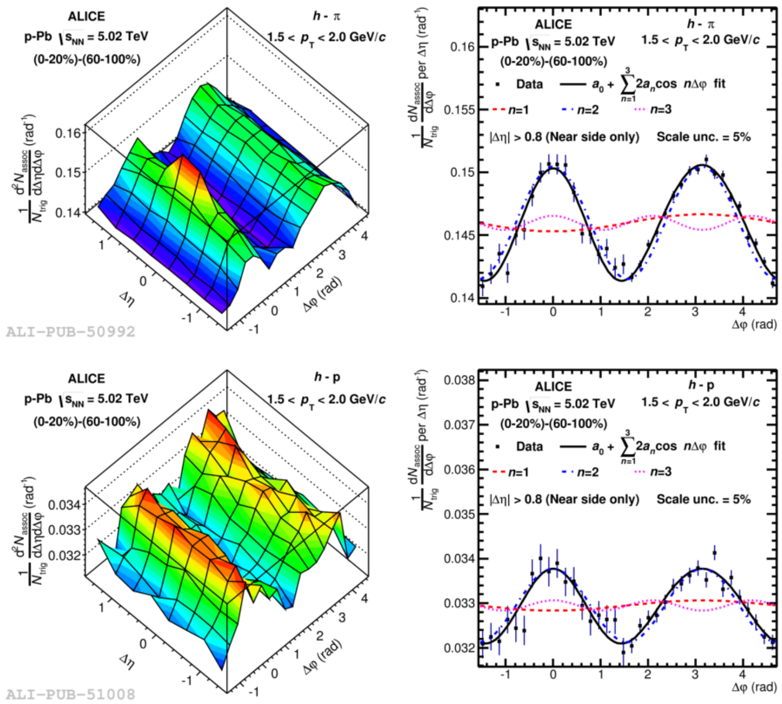
- Double ridge structure reminiscent of azimuthal flow in Pb-Pb collisions

Ridges in all systems

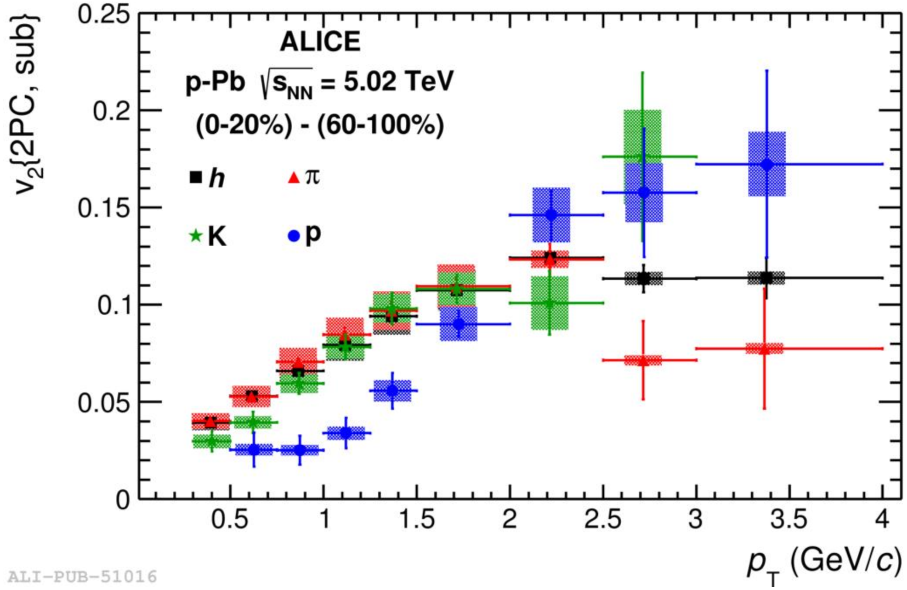


The perfect liquid is produced in all systems suggesting that small QCD systems produce “macroscopic” matter

Using Particle IDentification to study the double ridge



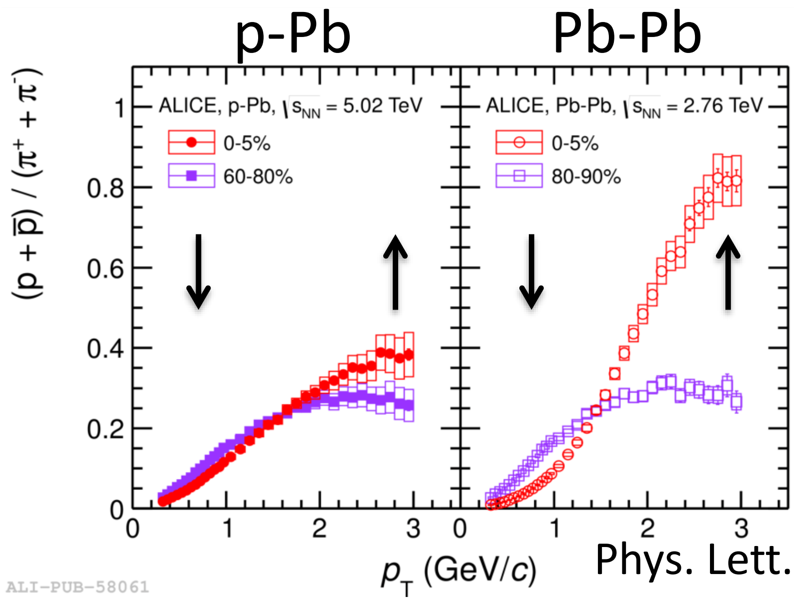
Fourier coefficients:

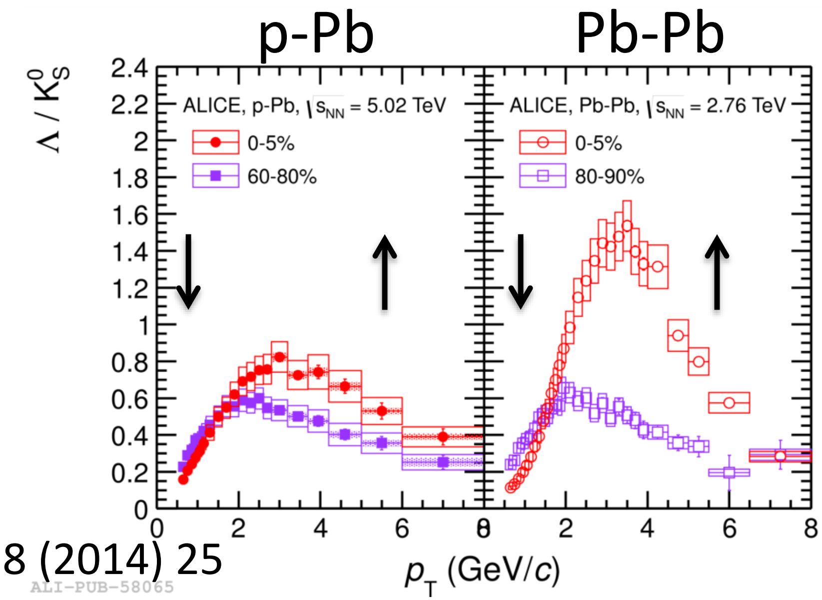


Phys. Lett. B 726 (2013) 164–177

- Clear mass ordering suggests flow

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





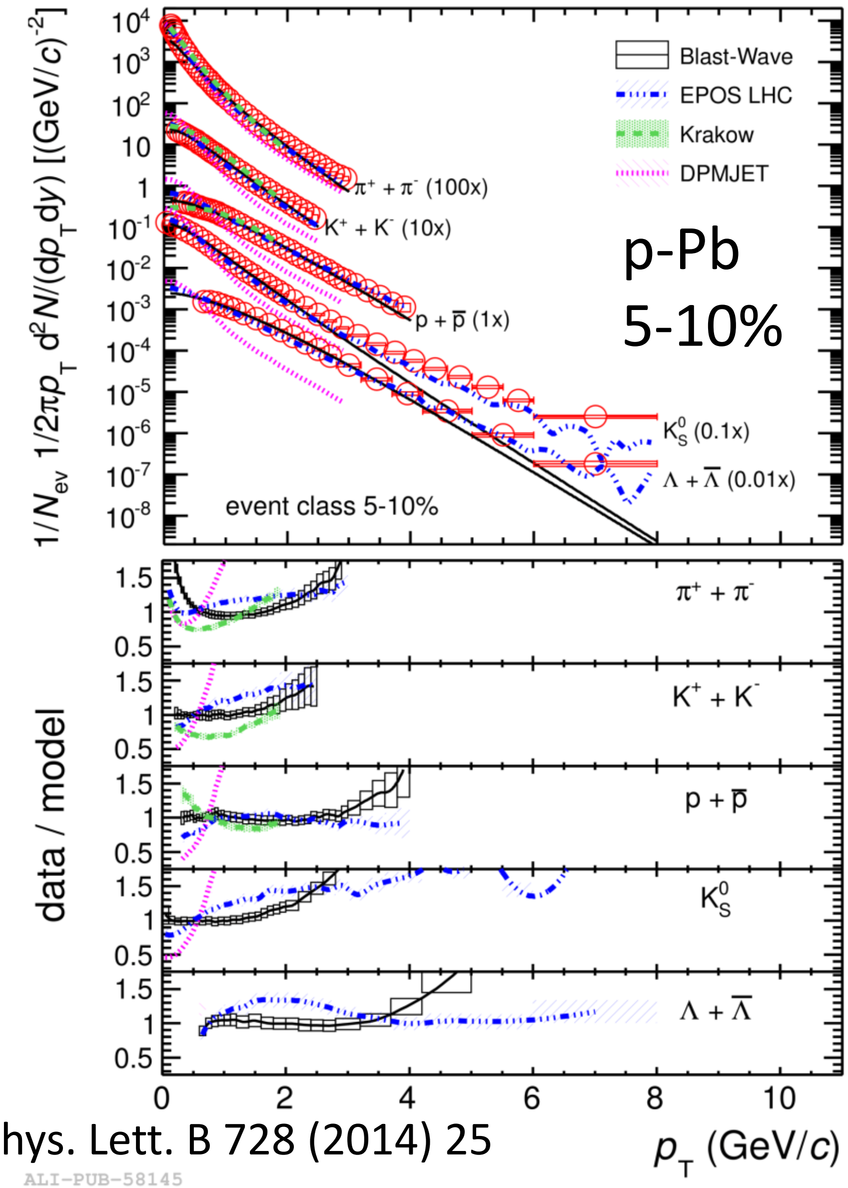
Phys. Lett. B 728 (2014) 25

- 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
  ⇒ 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)

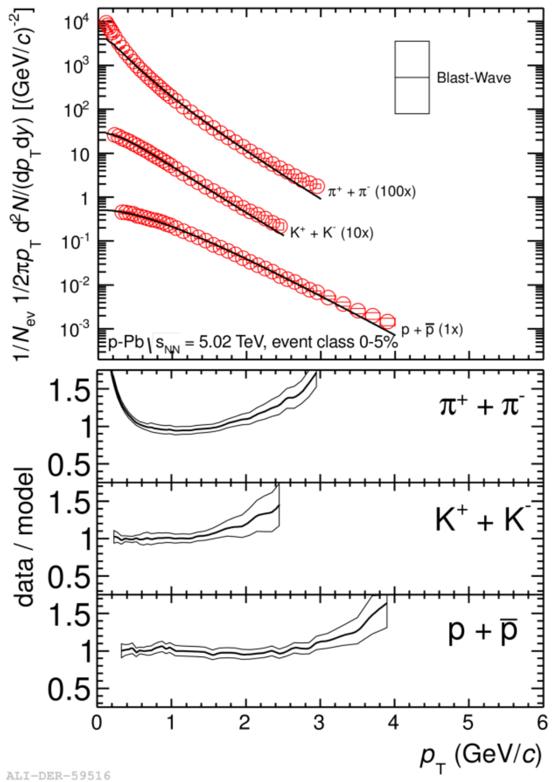
- Only models which employ hydrodynamics can describe the p_T spectra



Phys. Lett. B 728 (2014) 25

A blast wave study of the data

p-Pb 0-5%



- 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)

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

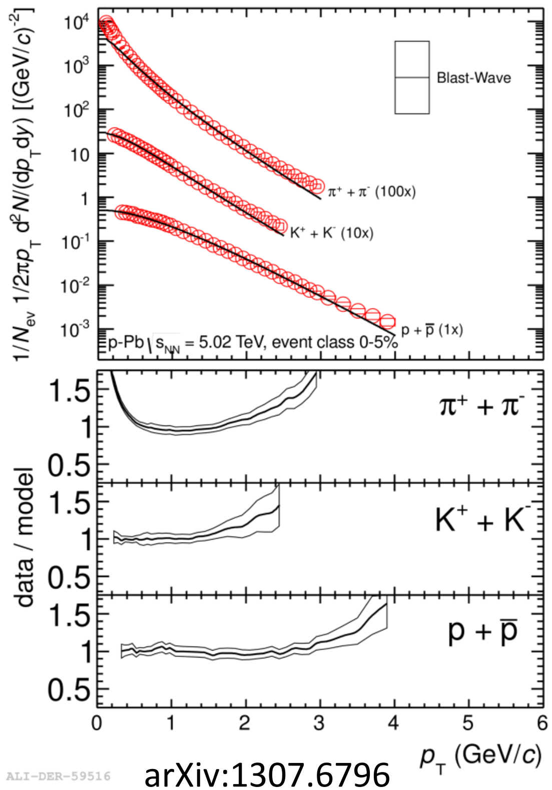
$$\rho = \tanh^{-1}\beta_T$$

$$\beta_T = \beta_S (r/R)^n$$

$$\langle\beta_T\rangle = \frac{2}{2+n}\beta_S.$$

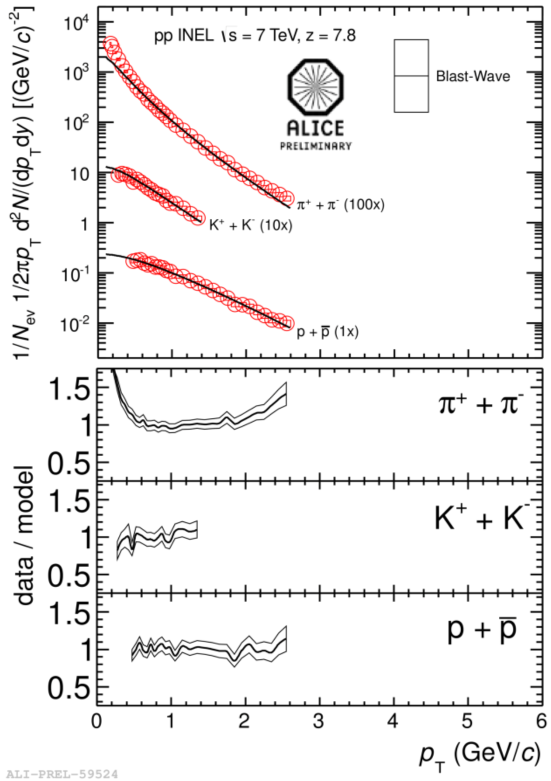
A blast wave study of the data

p-Pb 0-5%



arXiv:1307.6796

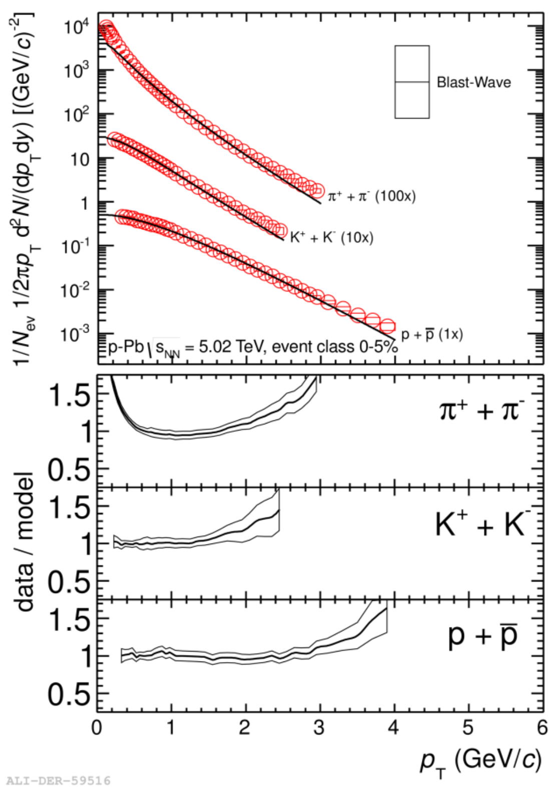
pp highest mult √s = 7 TeV



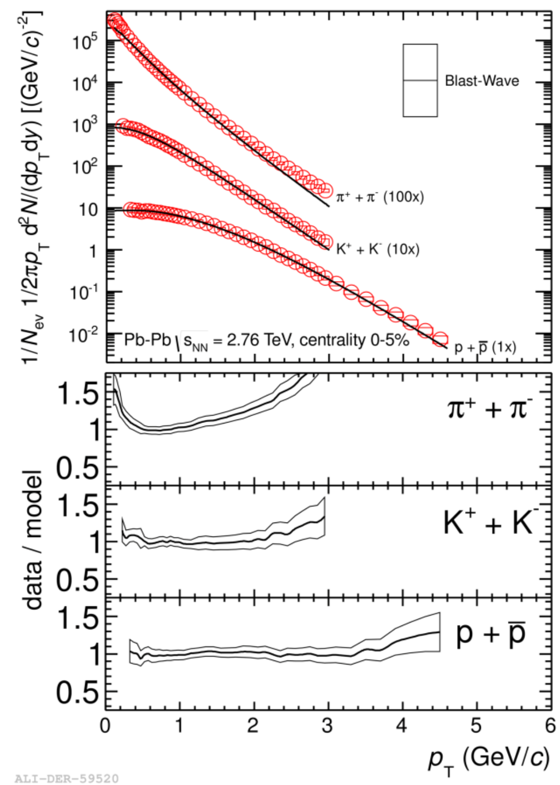
The description of p-Pb and pp data by the blast-wave fit is reasonable without being excellent

A blast wave study of the data

p-Pb 0-5%

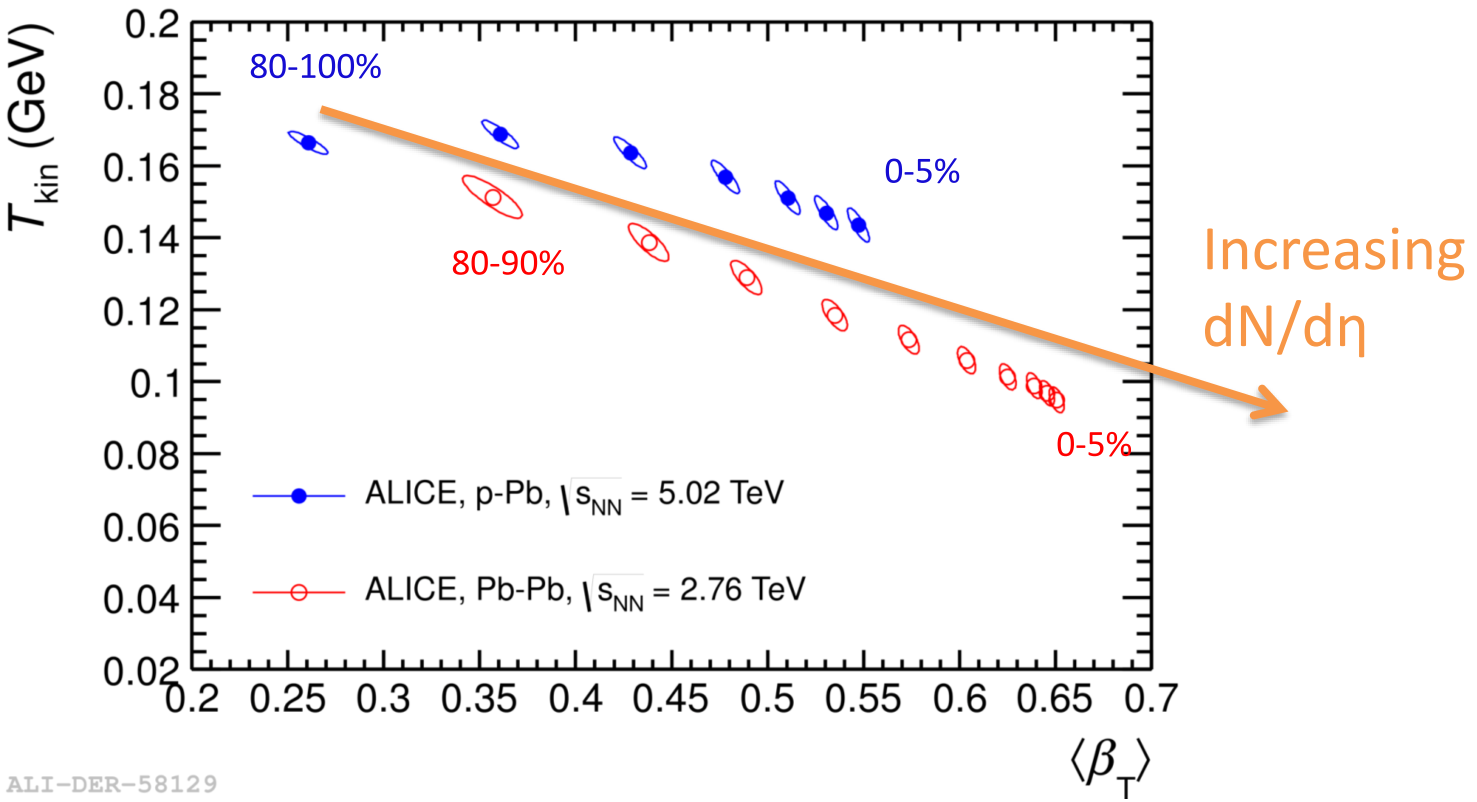


Pb-Pb 0-5% $\sqrt{s_{NN}}$ = 2.76 TeV



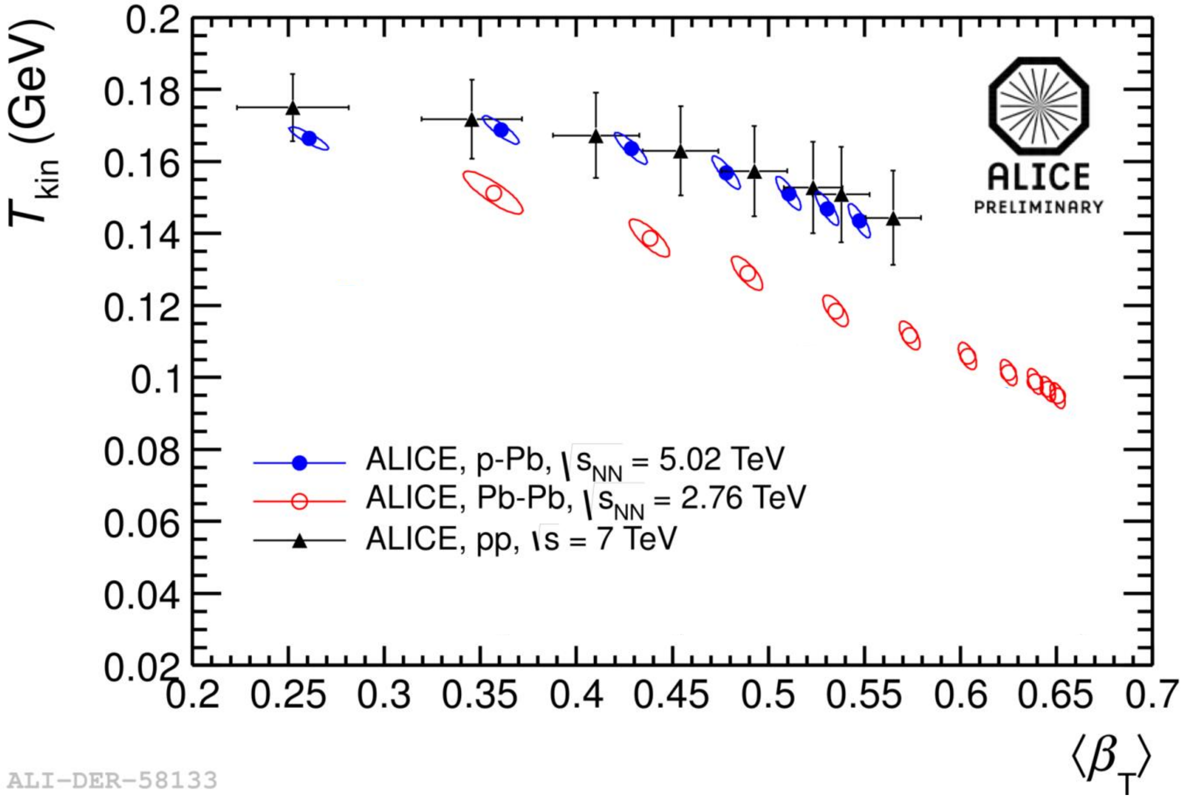
The p_T region where the blast-wave fit describes the data is in general broader for Pb-Pb

Summarizing the results from the blast-wave studies



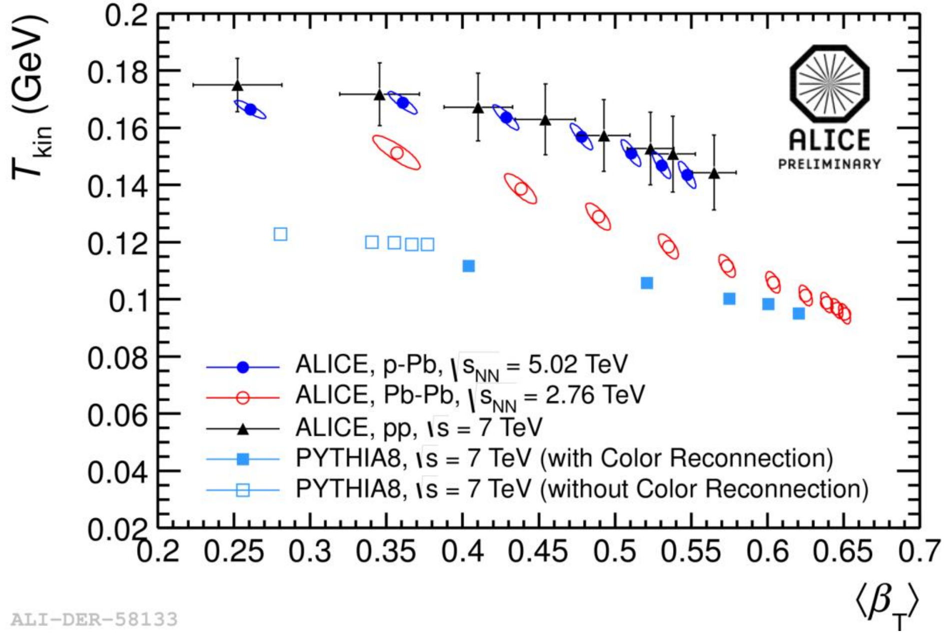
There is a strong common trend between the parameters extracted from Pb-Pb and p-Pb

Summarizing the results from the blast-wave studies



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

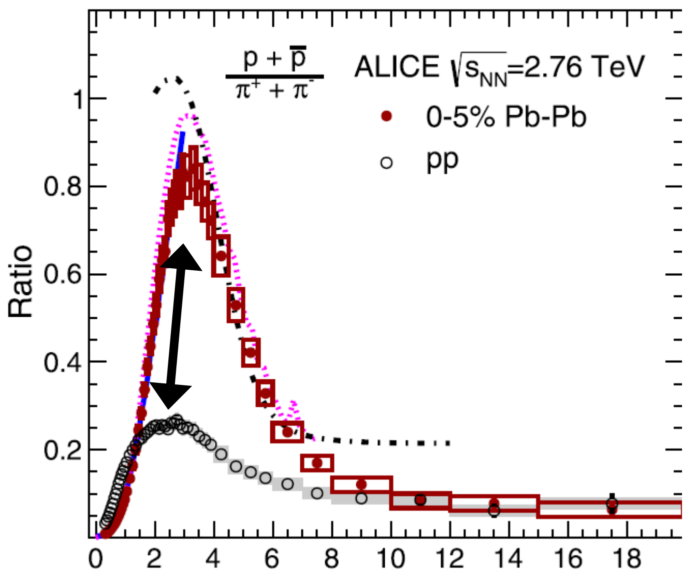


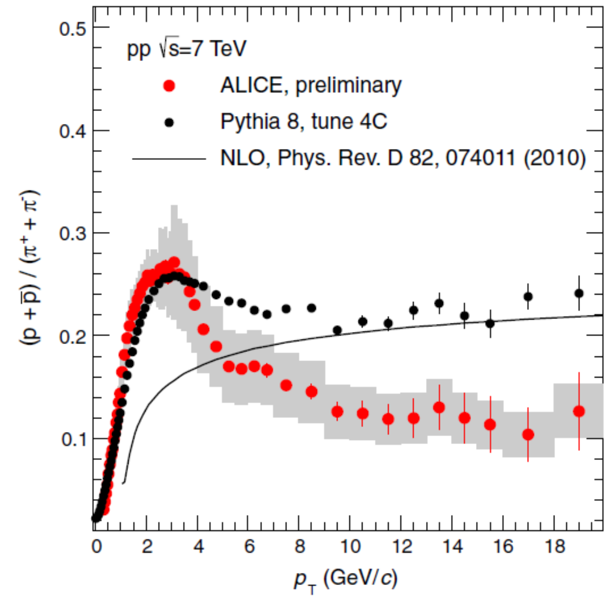
BUT also simulated PYTHIA8 pp events follow a <u>qualitatively</u> similar trend when Color Reconnection (CR) is enabled

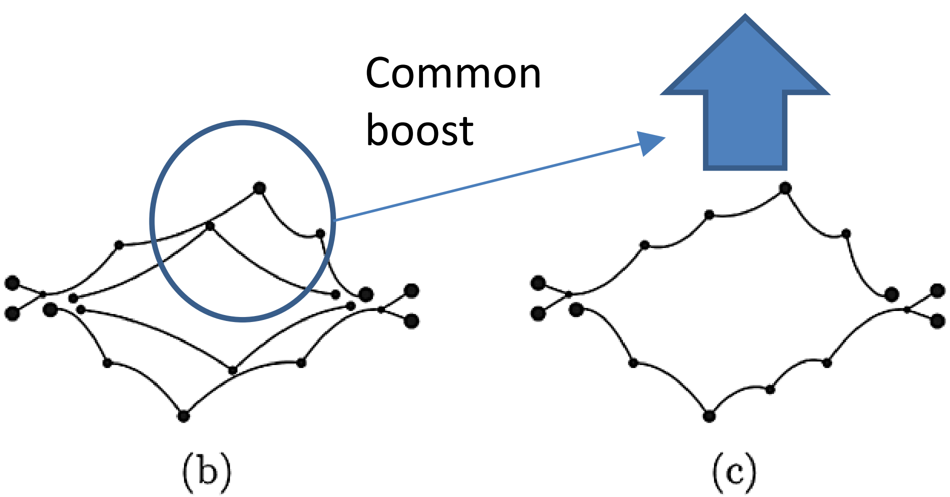
CR has been shown to mimic radial flow but without requiring the formation of a medium

The "flow peak" in pp

ALICE , PLB 736, 196 (2014)







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.

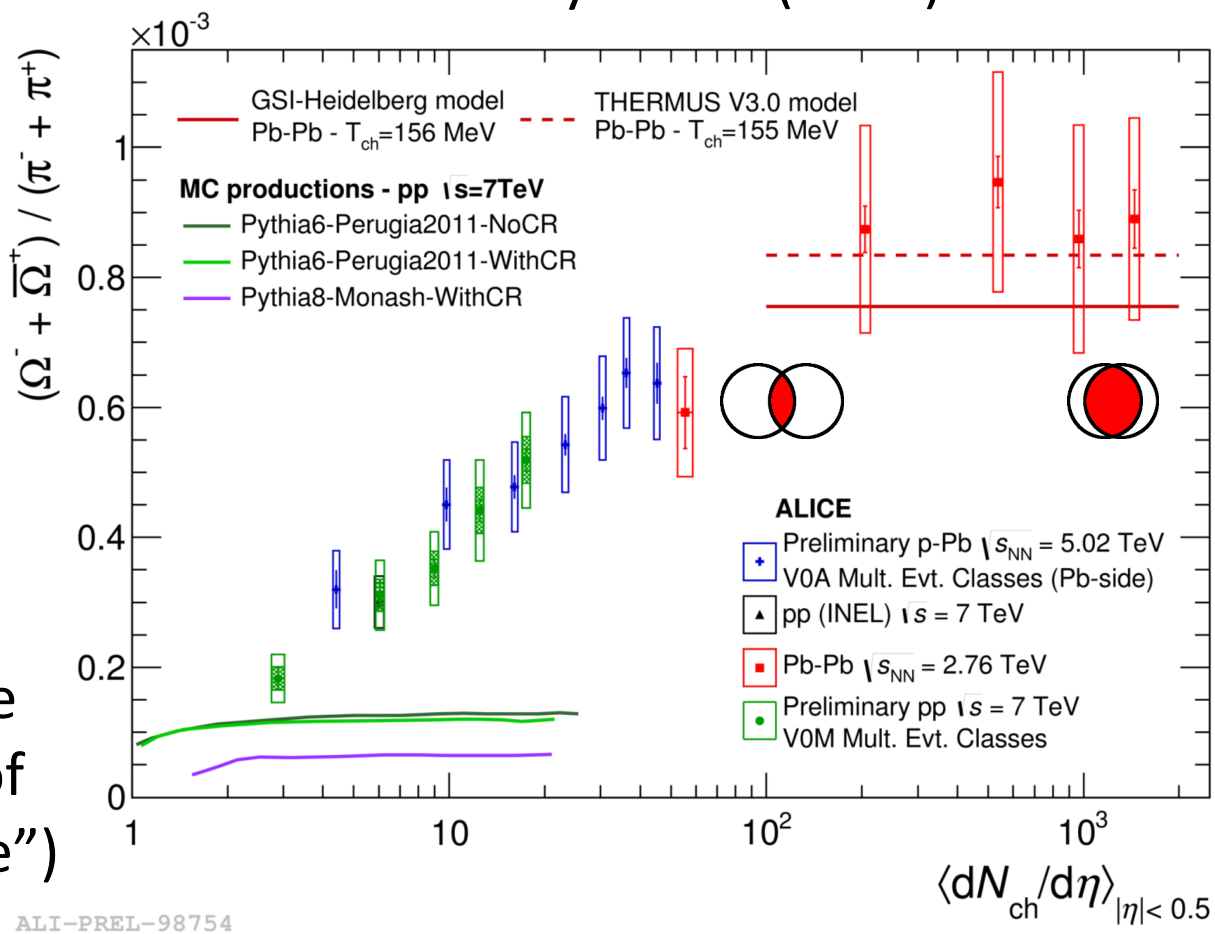
Can be interpreted different ways: CR as microscopic model of flow or one needs (hydro) flow in pp.

pp phenomenologists' favorite figure from ICHEP 2016

Nature Physics 13 (2017) 535

(sss)

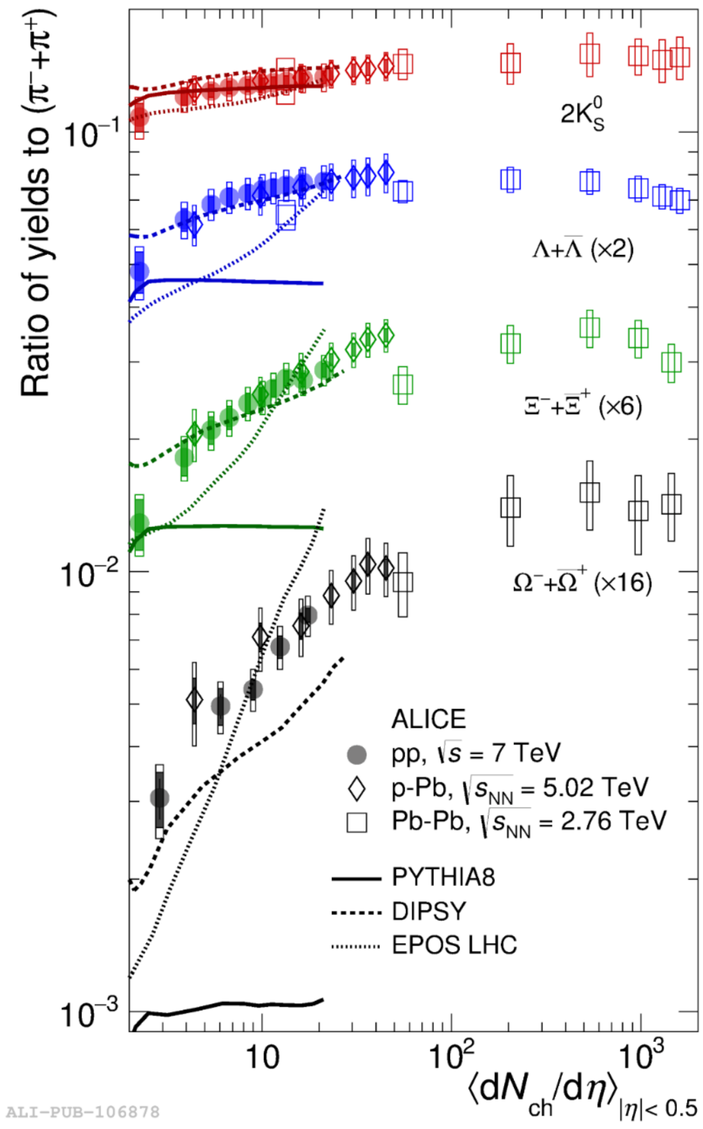
AA limit



$e^+ + e^-$ like ("more of the same")

Need bulk physics (medium) to describe increase!

Integrated particle ratios



DIPSY Color rope model:
C. Bierlich, G. Gustafson, L. Lönnblad, A. Tarasov (Jefferson Lab), JHEP 1503 (2015) 148

Nature Physics 13 (2017) 535

Macroscopic (top-down) vs microscopic (bottom up) models

- Stat. thermal model
  - Canonical
  - Grand-canonical
- Hydrodynamics
  - Radial flow
  - Azimuthal anisotropic
- Tunneling of $q\bar{q}$-pairs
  - Strings
  - Ropes
- String interactions
  - Color reconnection
  - Shoving

Project: “**Pinning down the origin of collective effects in small collision systems**”

Grant: SEK 26 200 000 over five years

Principal investigator: **Associate Professor Peter Christiansen, Lund University**

P. Christiansen (Partikelfysik)

L. Lönnblad (Teoretisk högenergifysik)

Knut and Alice Wallenberg Foundation

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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!

What I did not cover

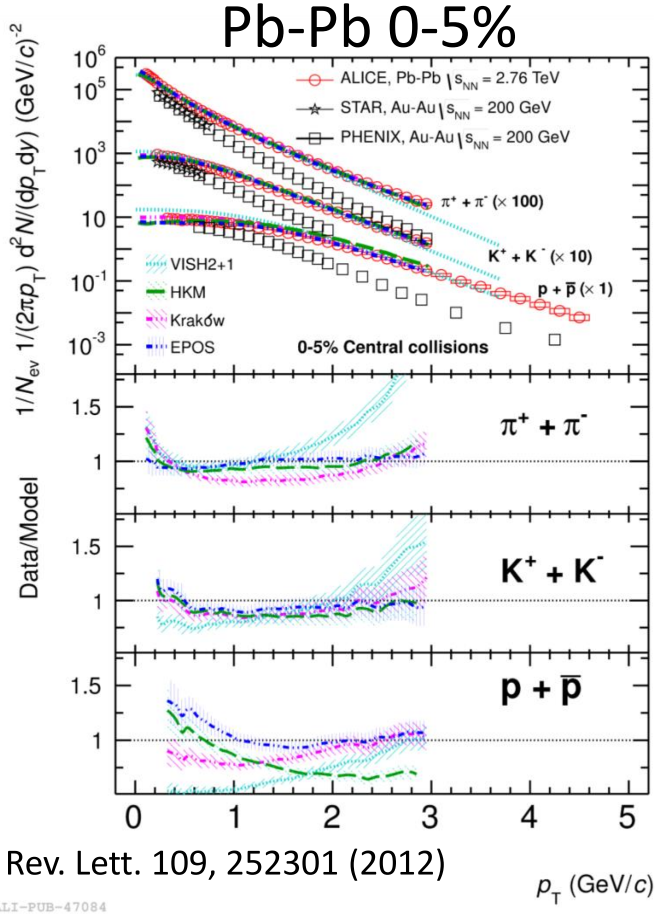
- Charged multiplicity and hadronization
  - Color Glass Condensate and Statistical Model
- Quark scaling of elliptic flow
  - Recombination of quark like degrees of freedom (picture is more complicated at LHC)
- Quenching and flow of heavy quarks
  - Suggests that there are also large collisional energy loss

Why are the small systems so critical to understand

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

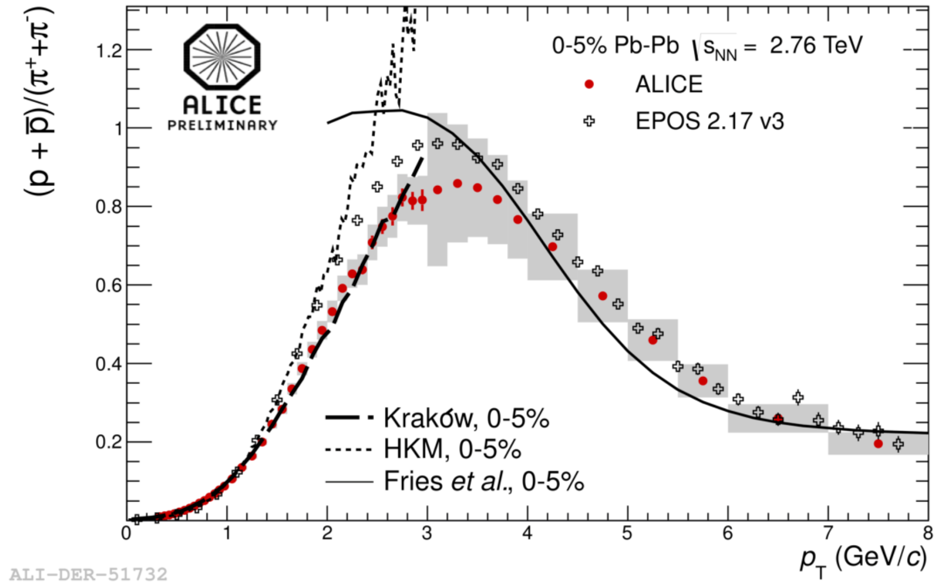
Geometry: is the Pb-Pb centrality evolution described by hydro?

Pb-Pb 0-5%



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

Pb-Pb 0-5%

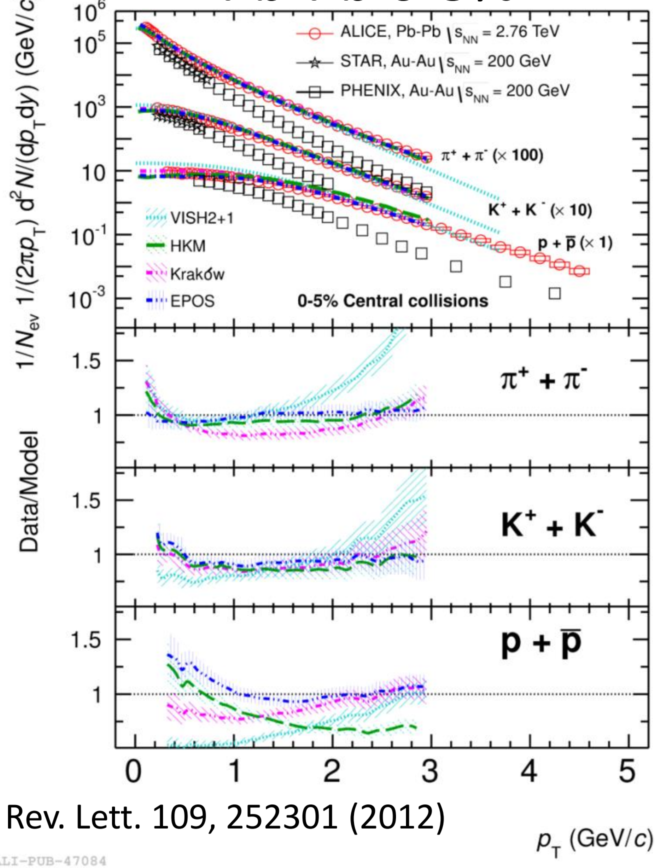


Krakow: PRC85, 064915 (2012)
HKM: PRC87, 024914 (2013)
Fries: PRL90, 202303 (2003) and private communication
EPOS: PRL109, 102301 (2012) and private communications

- Near ideal hydrodynamics with some implementation of the hadronic phase describes well p_T spectra in central collisions

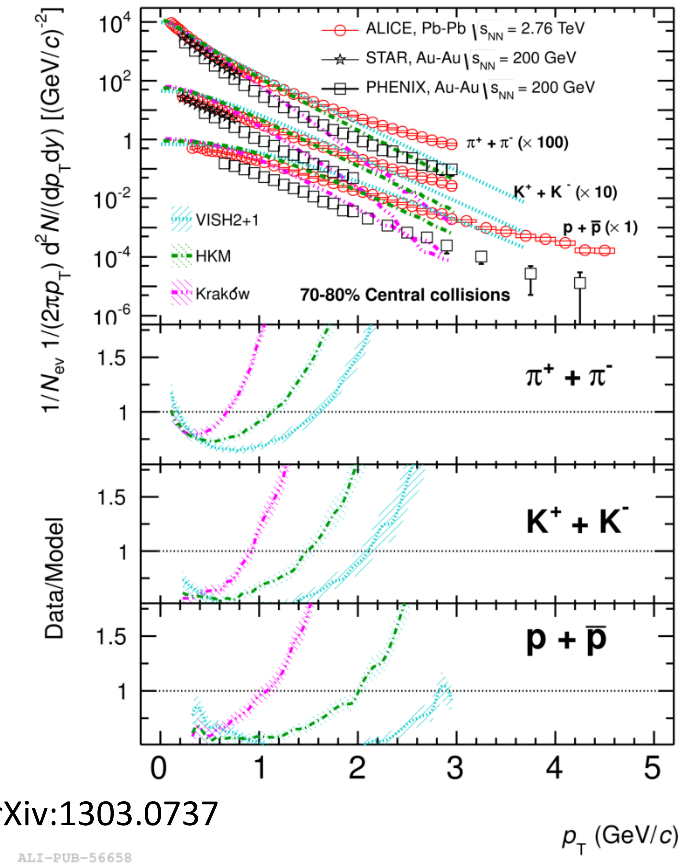
Geometry: is the Pb-Pb centrality evolution described by hydro?

Pb-Pb 0-5%



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

Pb-Pb 70-80%



arXiv:1303.0737

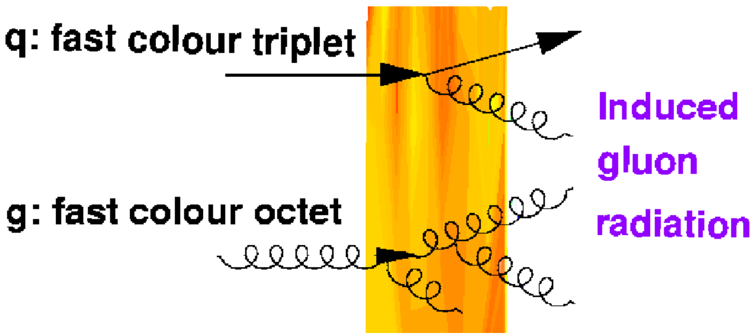
- The same models fail to describe the p_T spectra in peripheral collisions
- Typically hydro has not been expected to work in peripheral collisions but if it is at work in p-Pb and pp collisions should it not work there?

Why is this a problem

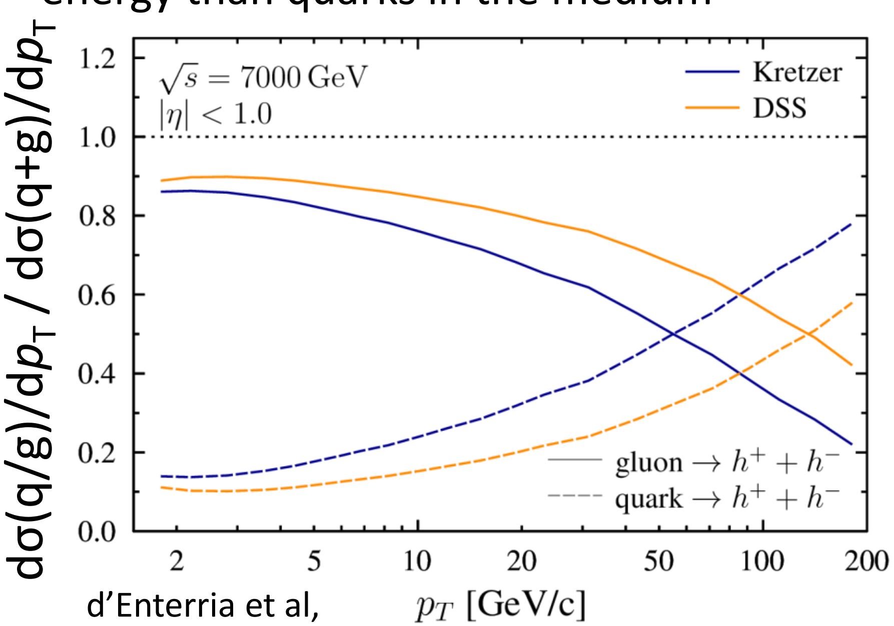
- Our description of the medium is not only critical for the low p_T observables, the jet quenching also relies on our medium properties
- If we cannot resolve this issue then we are a bit stuck
- Need to understand if a medium is also created in small systems!
  - My own view: need to look for energy loss in small systems

Backup slides

Motivation: searching for "footprints" of the energy loss

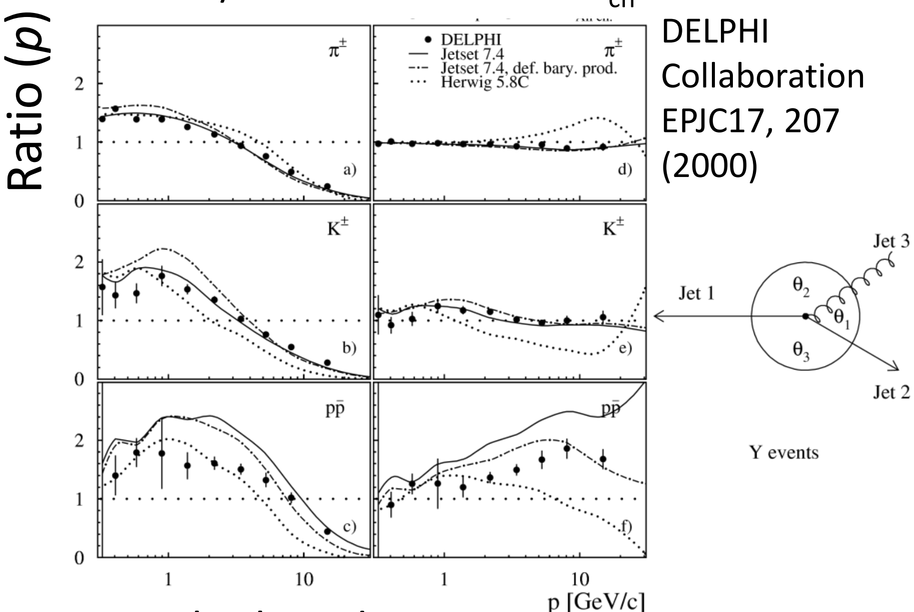


Gluons lose 2 times (color factor) more energy than quarks in the medium



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

Gluon / duscb Relative to N_{ch}



DELPHI Collaboration EPJC17, 207 (2000)

Several other ideas:

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

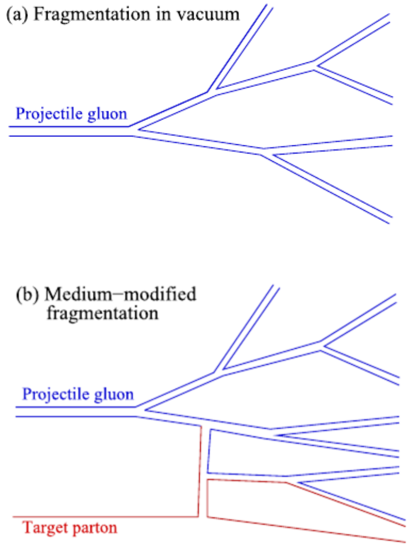
Color structure (Aurenche, Zakharov, EPJC71, 1829, 2011)

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

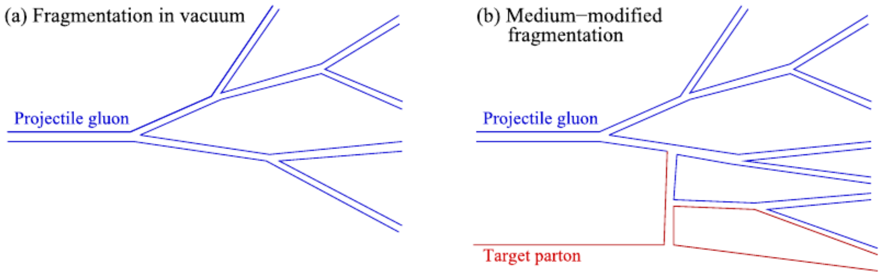


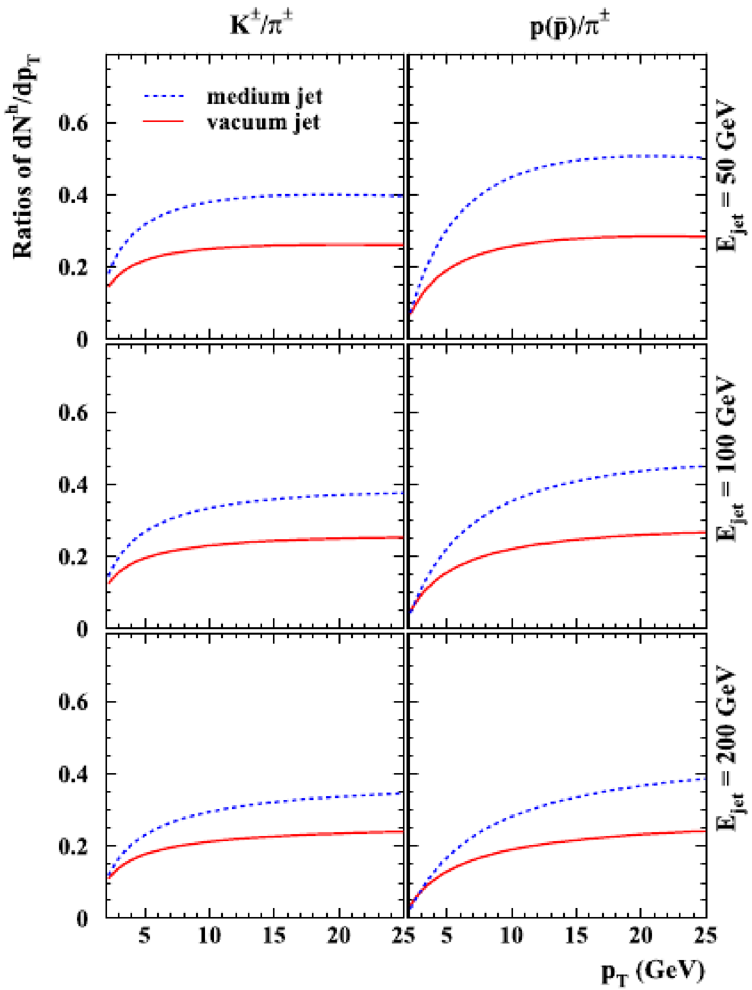
S. Sapeta and U.A. Wiedemann, Eur.Phys.J. C55 (2008) 293:

- 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

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





- Effect <u>inside jet</u>
- But for p_T >> 8 GeV/*c* we expect all hadrons to belong to jets