XXXIV International School "Francesco Romano"
on Nuclear, Subnuclear and Astroparticle Physics

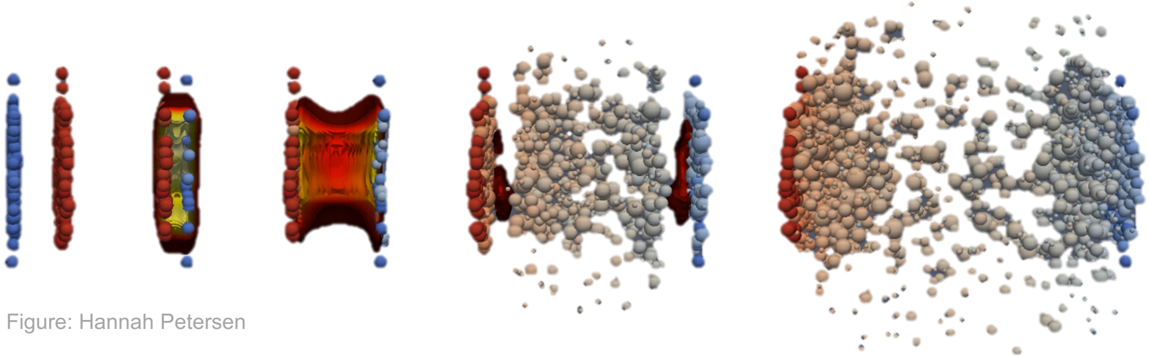

Figure: Hannah Petersen

Introduction to Ultrarelativistic Nuclear Collisions (2)

INFN PADOVA

Federico Antinori
(INFN, Padova, Italy)

Recap of Lecture 1...

Hagedorn temperature: a limiting value?

e.g. following K Redlich, H Satz in “Melting Hadrons, Boiling Quarks”, J Rafelski ed (Springer, 2016)

- partition function for a system of non-interacting pions:

$$\ln \mathcal{Z}(T,V) = \frac{VTm_0^2}{2\pi^2} K_2(\frac{m_0}{T})$$

- interactions as resonance formation:
  - interacting system of pions ←→ non-interacting gas of all possible resonances

$$\ln \mathcal{Z}(T,V) = \sum_i \frac{VTm_i^2}{2\pi^2} \rho(m_i) K_2(\frac{m_i}{T}) \approx \frac{VT}{2\pi^2} \int dm\, m^2 \rho(m) K_2(\frac{m}{T})$$

- inserting Hagedorn’s spectrum:

$$\ln \mathcal{Z}(T,V) \approx V \left[\frac{T}{2\pi}\right]^{3/2} \int \frac{dm}{m^{3/2}} e^{-\left[\frac{m}{T} - \frac{m}{T_H}\right]}$$ ← diverges for $T \to T_H$

  - energy pumped into such a system, goes to creating heavier and heavier resonances
  - asymptotically reaching T_H

→ T_H would then be the maximum possible temperature in the universe!

1975, Cabibbo and Parisi: “quark liberation” at high T

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

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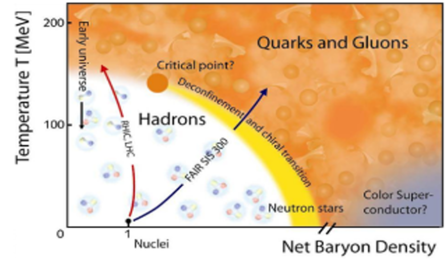
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the “observed” exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confine



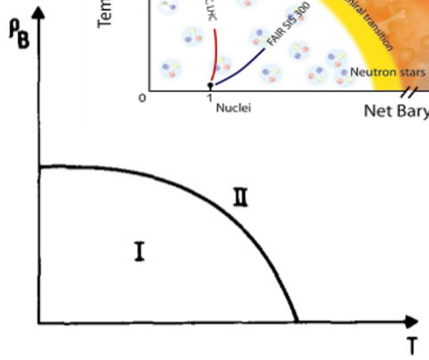


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

- T_H not maximum attainable, simply: for $T > T_H$ quarks not confined any more

The MIT Bag Model

- the essential phenomenology of confinement is described as follows:
  - assume quarks are confined within bubbles (bags) of perturbative (=empty) vacuum
  - on which the QCD vacuum ("liquid") exerts a confining pressure *B (*= bag constant*)*
  - B ~ Λ_{QCD}^4 → hadron size ~ 1/ $\boldsymbol{\Lambda_{QCD}}$

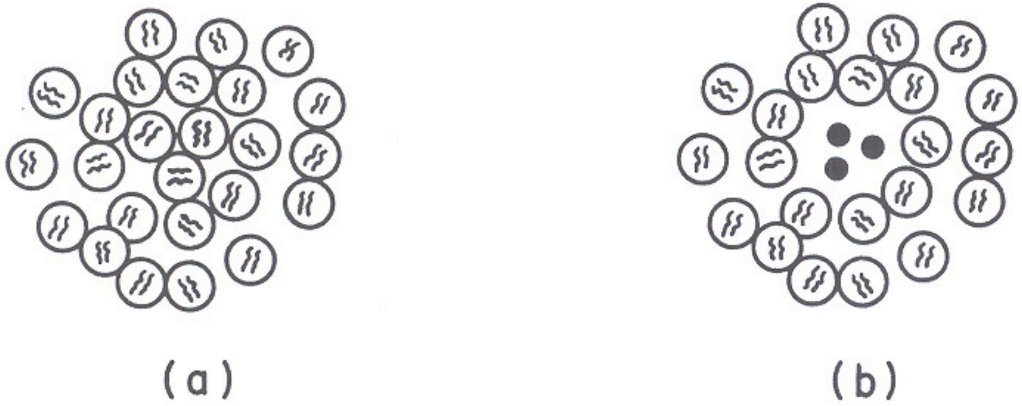
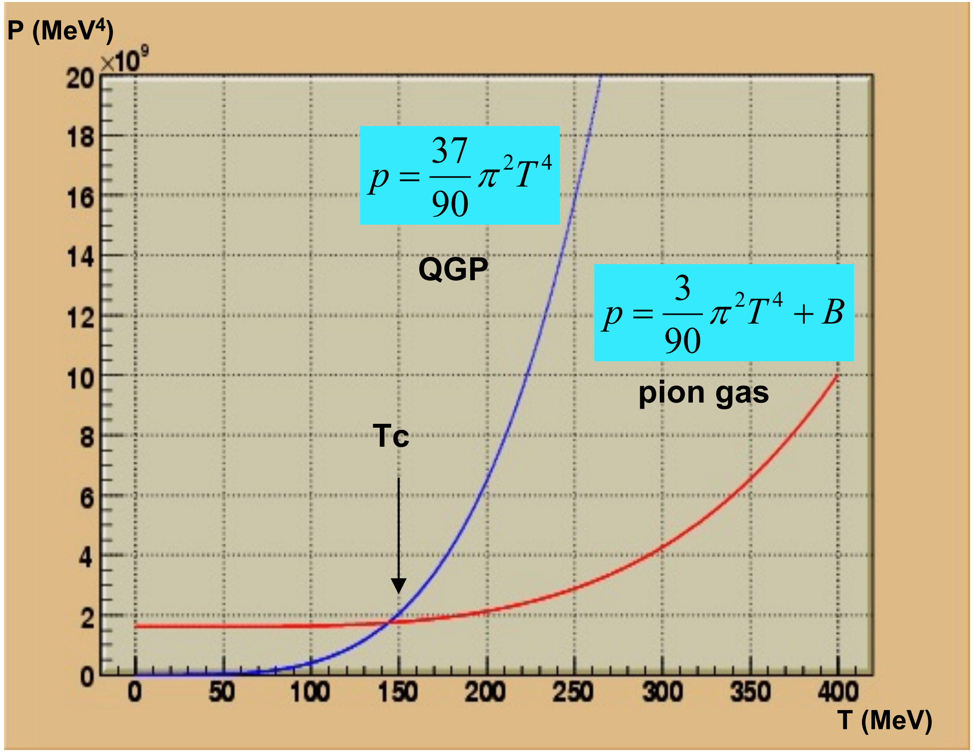


FIG. 9. The QCD vacuum state is depicted in (a). It is a random distribution of cells that contain a gluon pair in a color and spin singlet state. Quarks (in a color singlet configuration) displace these cells, creating a region (or "bag") of "empty" vacuum, as shown in (b).

(from: K Gottfried and V Weisskopf, "Concepts of Particle Physics", Vol. II, Oxford University Press, 1986)

- at low temperature the hadron gas is the stable phase
- but there is a temperature (T_C) above which the QGP "wins"
  - thanks to the larger number of degrees of freedom



one can easily derive:

$$T_C = \left[\frac{90}{34\pi^2}\right]^{1/4} B^{1/4}$$

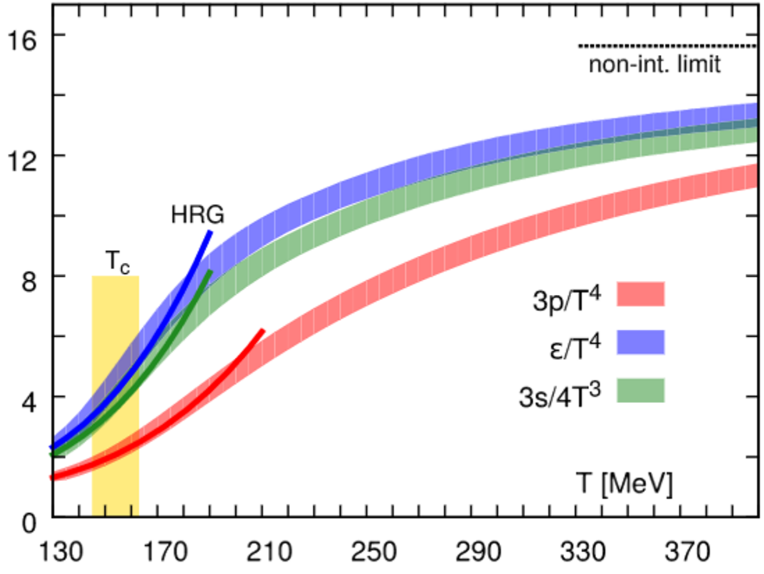
and plugging in $B^{1/4} \sim 200$ MeV
one gets:

$$T_C \sim 150\ \text{MeV}$$

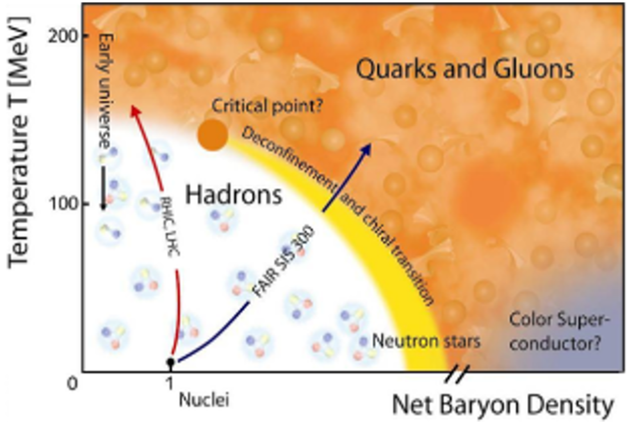
not too bad...
(latest lattice estimate: 156.5 ± 1.5 MeV)
[A Bazavov et al. Phys.Lett.B 795 (2019) 15]

Lattice QCD

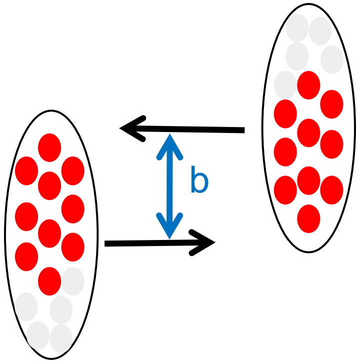
- the rigorous way of performing calculations in the non-perturbative regime of QCD
- discretisation on a space-time lattice
  - → ultraviolet (i.e. large-momentum scale) divergencies can be avoided
  - around critical temperature (T_C): rapid change of
    - energy density ε
    - entropy density s
    - pressure density p
  - <u>due to activation of partonic degrees of freedom</u>
  - at zero baryon density → smooth crossover
  - T_C = (156.5 ± 1.5) MeV [A Bazavov et al. Phys.Lett.B 795 (2019) 15]
  - ε ~ O(GeV/fm^3)



[A Bazavov et al. PRD 90 094503 (2014)]



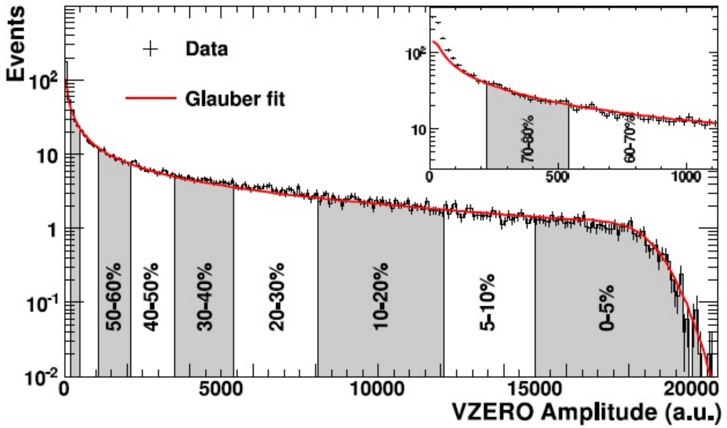
Centrality and geometry



- central collisions
  - small impact parameter b
  - high number of participants → high multiplicity
- peripheral collisions
  - large impact parameter b
  - low number of participants → low multiplicity

for example: sum of the amplitudes in the ALICE V0 scintillators reproduced by Glauber model fit (red):

- random relative position of nuclei in transverse plane
- Woods-Saxon distribution inside nucleus
- simple particle production model
- (deviation at very low amplitude expected due to non-nuclear (electromagnetic) processes)



Strangeness enhancement

- restoration of χ symmetry -> increased production of s
  - mass of strange quark in QGP expected to go back to current value
    - m_S ~ 150 MeV ~ Tc

  → copious production of $s\bar{s}$ pairs, mostly by gg fusion

  [J Rafelski: Phys. Rep. 88 (1982) 331]

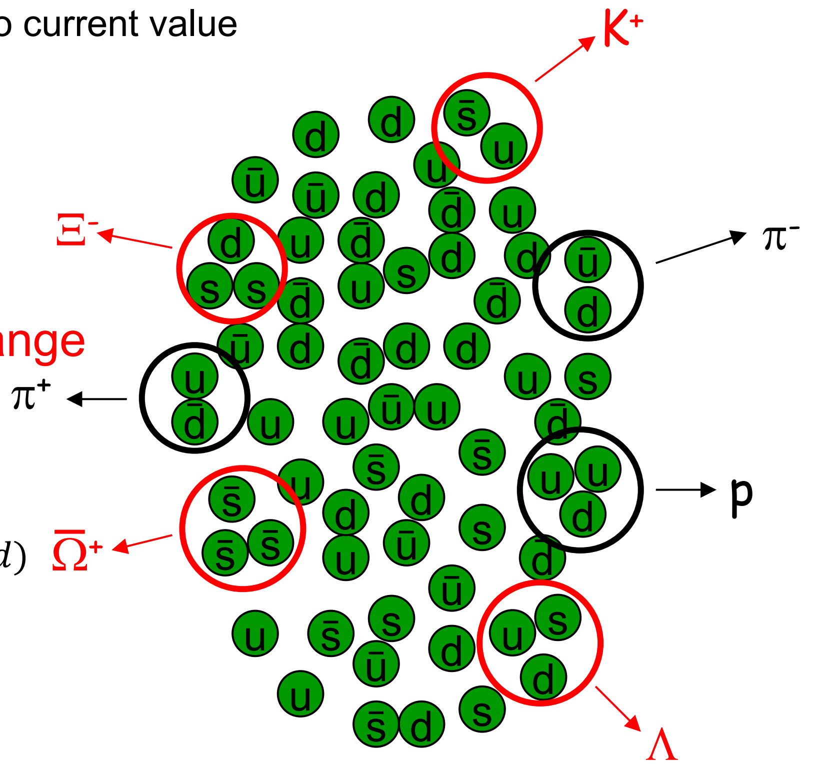
  [J Rafelski and B Müller: Phys. Rev. Lett. 48 (1982) 1066]

- deconfinement → stronger effect for multi-strange
  - can be built recombining s quarks

  → strangeness enhancement increasing with strangeness content

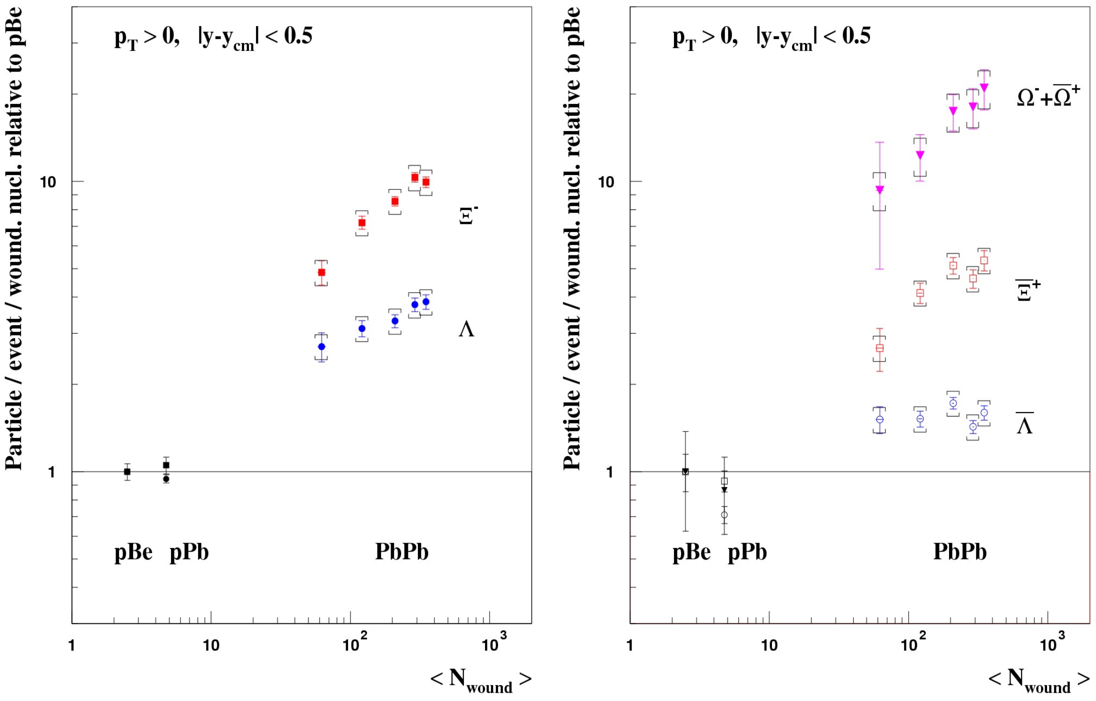
  → expect larger for $\Omega(sss)$ than for $\Xi(ssd)$ than for $\Lambda(sud)$

  [P Koch, B Müller and J Rafelski: Phys. Rep. 142 (1986) 167]



Strangeness enhancement at the SPS

- WA97/NA57



- enhancement relative to p-Be, p-Pb
- increasing with |S|
- up to ~ x 20 for the Ω

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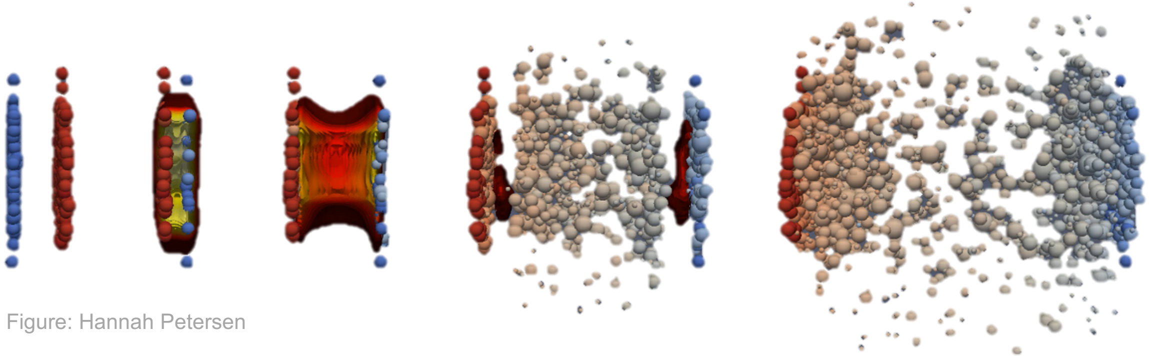

Figure: Hannah Petersen

Introduction to Ultrarelativistic Nuclear Collisions (2)

Federico Antinori
(INFN, Padova, Italy)

Quarkonium suppression

- QGP signature proposed by Matsui and Satz, 1986

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

creened

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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and

H. SATZ
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ind → suppressed

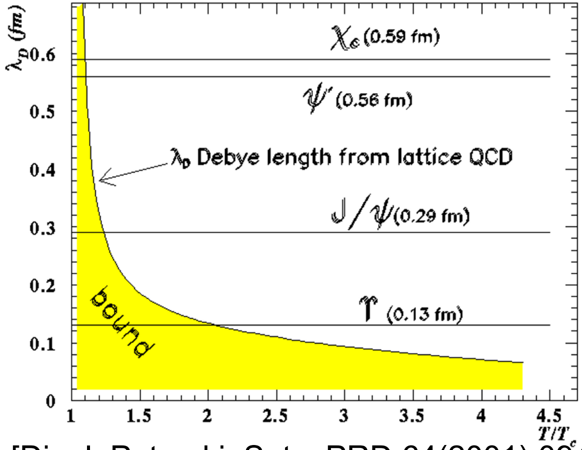
Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Quarkonium suppression

- QGP signature proposed by Matsui and Satz, 1986
- quarkonium: $c\bar{c}$ states (charmonium), $b\bar{b}$ states (bottomonium)
- in the plasma phase the interaction potential is expected to be screened
  - analogous to Debye screening in electromagnetic plasma
  - beyond the Debye screening length λ_D

λ_D depends on T

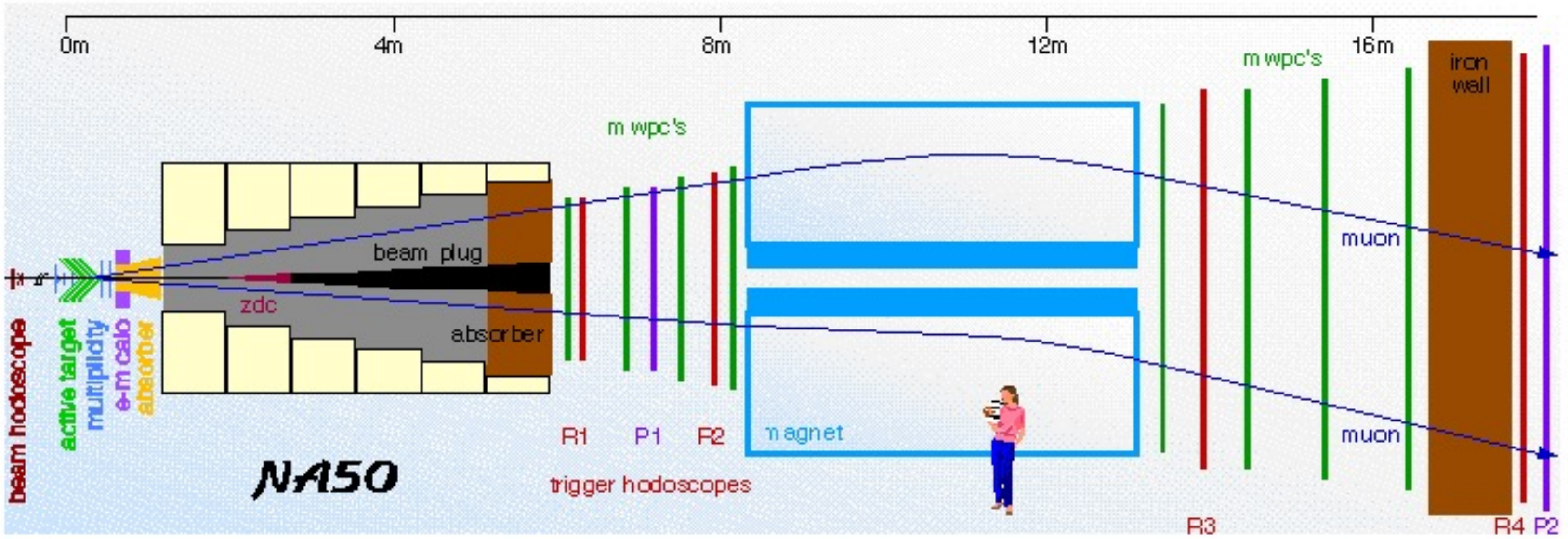


[Digal, Petrecki, Satz PRD 64(2001) 0940150]

→ states with radius > λ_D will not bind → suppressed

- J/ψ, ψ', χ_c → $c\bar{c}$ states
- Υ → $b\bar{b}$ states

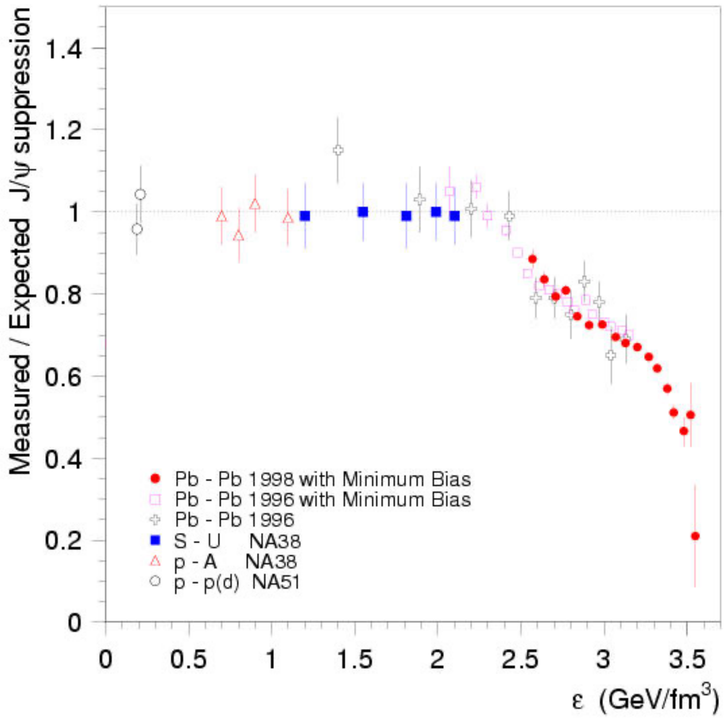
NA50 experiment



- muon spectrometer
  - high-mass lepton pairs
  - J/ψ production

J/ψ suppression at the SPS

- NA50: “anomalous” suppression



- nuclear suppression of J/ψ production
  - due to nuclear absorption effects
  - measured in pA, light ion collisions
  - scaled to Pb-Pb (= 1 in the plot)

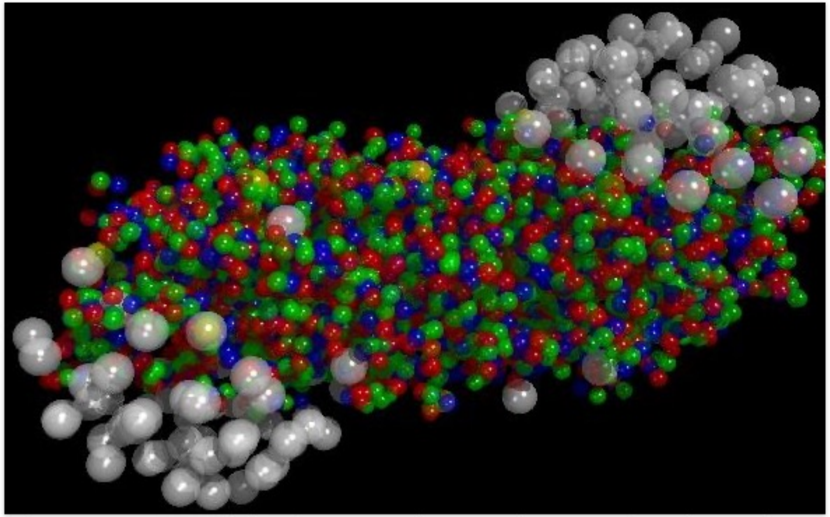
- “anomalous” suppression
  - measured/expected
  - sets in at $\varepsilon \sim 2.3$ GeV/fm^3 ($b \sim 8$ fm)

Two pillars of year 2000 announcement

- strangeness enhancement, J/ψ suppression

New State of Matter created at CERN

10 FEBRUARY, 2000



Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

C

SPECIAL SEMINAR

TITLE : A New State of Matter:
Results from the CERN Lead-Beam Programme

TIME : Thursday 10 February at 09.30 hrs

PLACE : Council Chamber, bldg 503

ABSTRACT

This special seminar aims at an assessment of the results from the heavy ion programme with lead ion beams at CERN which was started in 1994. A series of talks will cover the essential experimental findings and their interpretation in terms of the creation of a new state of matter at about 20 times the energy density inside atomic nuclei. The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma.

Ulrich Heinz (CERN)
Making Quark-Gluon Matter in Relativistic Nuclear Collisions

Louis Kluberg (IN^2P^3)
The J/ψ suppression pattern observed in Pb-Pb collisions ions: a signature for the production of a new state of matter.

Johanna Stachel (University of Heidelberg)
Virtual and real photons radiated by the cooling and hadronizing fireball.

Reinhard Stock (University of Frankfurt)
Hadron Signals of the Little Bang.

Emanuele Quercigh (CERN)
Strange signals of a new state of matter from nuclear collisions at SPS.

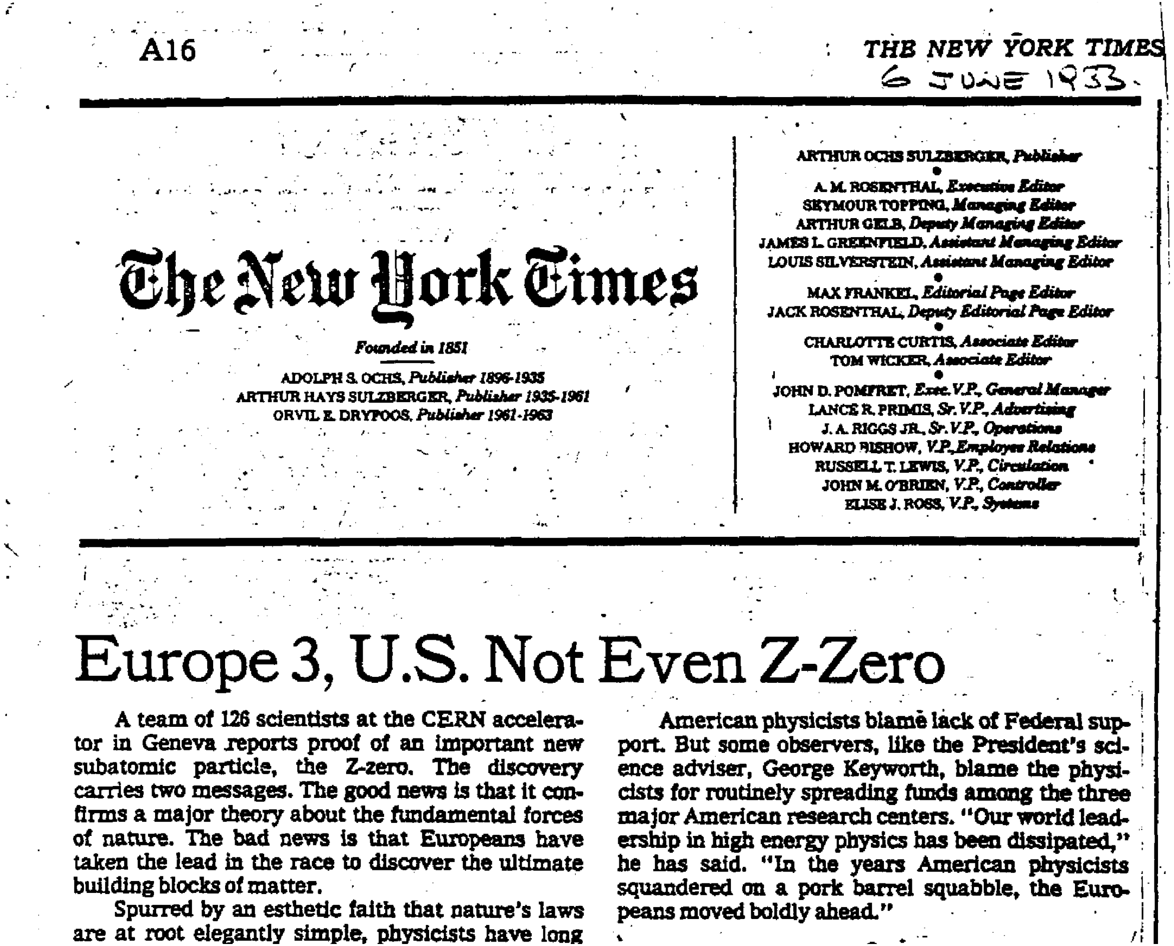
Luciano Maiani (Director General, CERN)
Summary.

... meanwhile, in the US...

- 1978: start of construction of ISABELLE pp collider at Brookhaven (400 GeV)
- *1978: approval of transformation of SPS into $p\bar{p}$ collider at CERN (630 GeV)*
- 1981-82: problems in production of ISABELLE magnets
- *1983: discovery of $W^{\pm}$ (January) and Z^0 (May) bosons at SPS collider*

... meanwhile, in the US...

- 1978: st GeV)
- *1978: ap GeV)*
- 1981-82
- *1983: di*



A16 THE NEW YORK TIMES

6 JUNE 1983.

The New York Times

Founded in 1851

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ORVIL E. DRYFOOS, *Publisher 1961-1963*

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Europe 3, U.S. Not Even Z-Zero

A team of 126 scientists at the CERN accelerator in Geneva reports proof of an important new subatomic particle, the Z-zero. The discovery carries two messages. The good news is that it confirms a major theory about the fundamental forces of nature. The bad news is that Europeans have taken the lead in the race to discover the ultimate building blocks of matter.

Spurred by an esthetic faith that nature's laws are at root elegantly simple, physicists have long

American physicists blame lack of Federal support. But some observers, like the President's science adviser, George Keyworth, blame the physicists for routinely spreading funds among the three major American research centers. "Our world leadership in high energy physics has been dissipated," he has said. "In the years American physicists squandered on a pork barrel squabble, the Europeans moved boldly ahead."

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- July 1983: construction of ISABELLE stopped, project cancelled
- July 1983: NSAC town meeting in Aurora: ISABELLE infrastructure to build a RHIC
  - Relativistic Heavy-Ion Collider
  - (that was quick, but already in 1981, at an ISABELLE workshop in Brookhaven...)

... m

- 1978 /)
- *1978*)
- 198
- *198*

- July
- July a RHIC
  -
  - .)

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... meanwhile, in the US...

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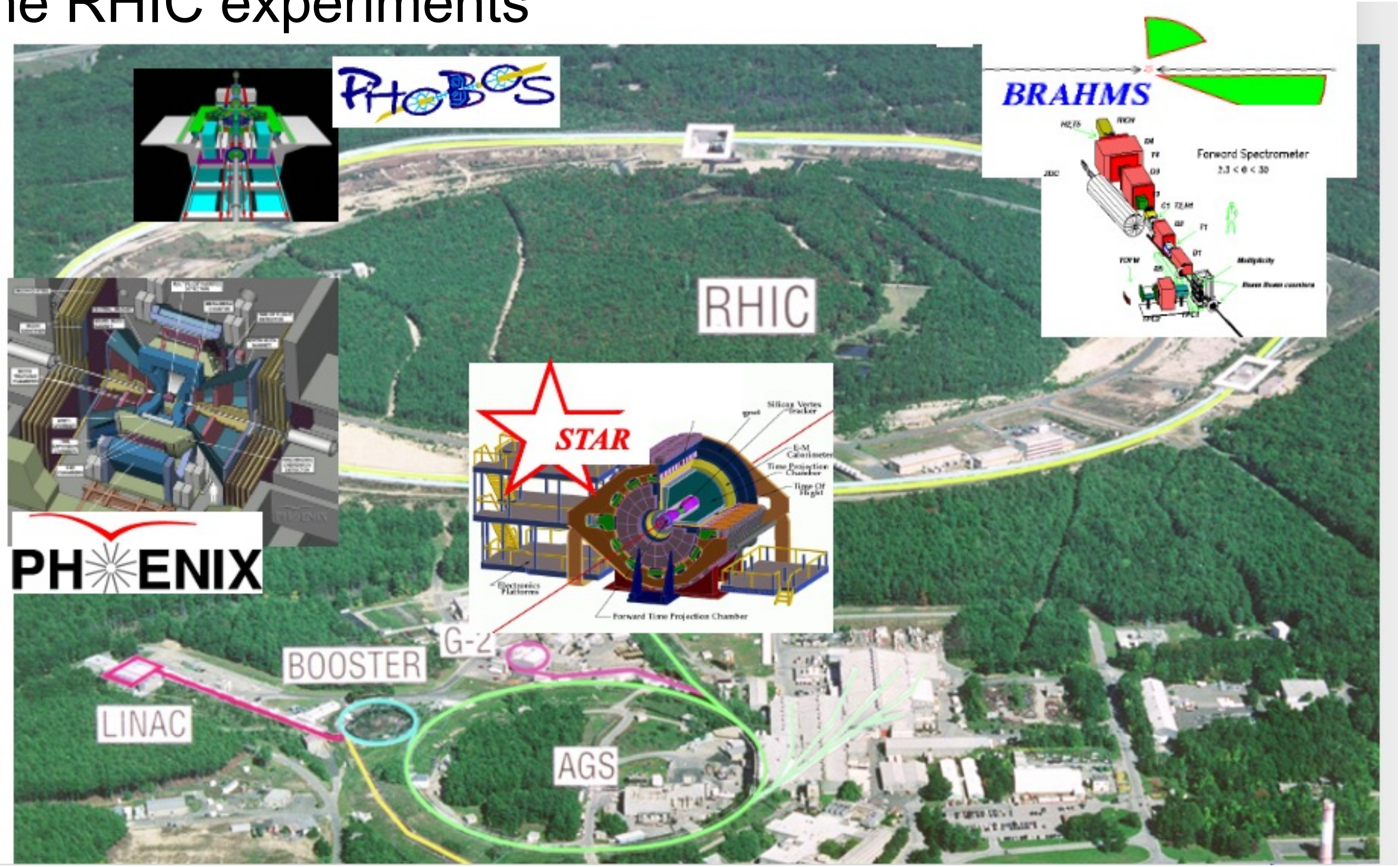
- *1986: start of heavy-ion collisions at CERN/SPS and Brookhaven/AGS*
- 1987: start of RHIC R&D
- 1991: start of construction
- 2000: first collisions

The RHIC experiments

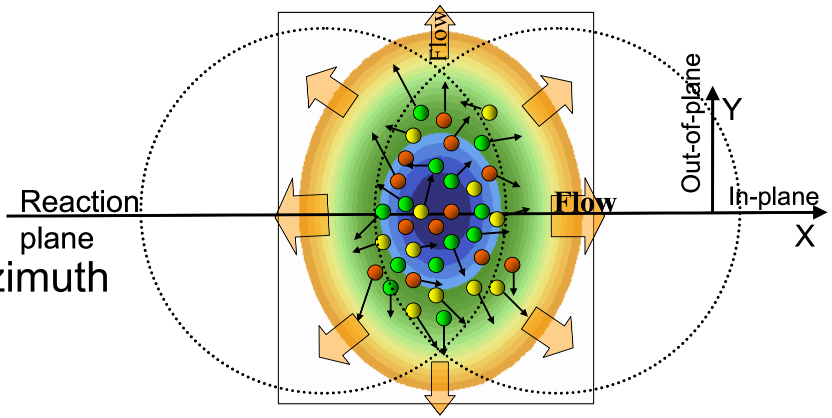


Azimuthal asymmetry

… in the transverse momentum distribution of produced particles

- why is it important?
- non-central collisions are asymmetric in azimuth

  azimuth = angle in the plane of the screen



→ transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena

- large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- small mean free path
  - larger density gradient -> larger pressure gradient -> larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)

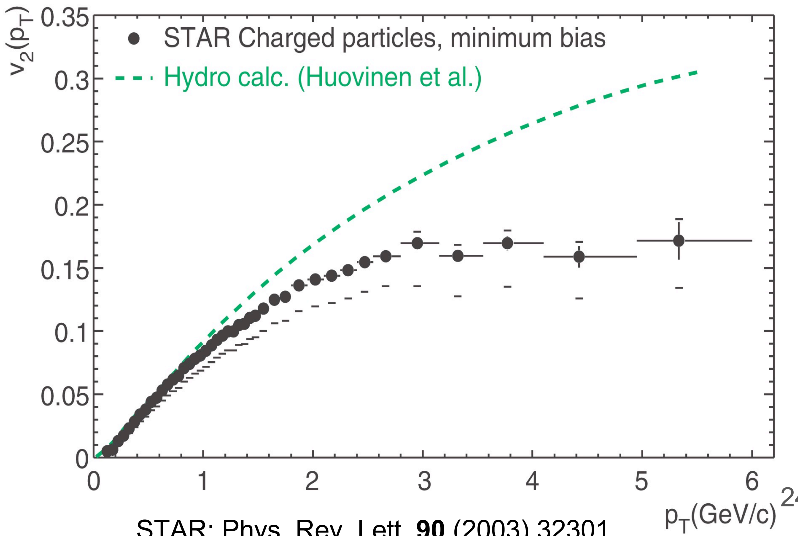
v_2 at RHIC

- to quantify the asymmetry:
  → Fourier expansion of the angular distribution:
  $$\propto 1 + 2v_1\cos(\varphi - \psi_1) + 2v_2\cos(2[\varphi - \psi_2]) + \ldots$$
  - in the central detector region (ϑ ~ 90º) → v_1 ~ 0 → asymmetry quantified with v_2
  - v_2: "elliptic flow coefficient"
- experimentally: low-p_T v_2 ~ as large as expected by hydrodynamics
  - mean free path ~ 0
  - i.e. η/s at minimum

→ "almost-perfect liquid"
  - very efficient transfer of asymmetry from coordinate to momentum space

  → "hard" equation of state

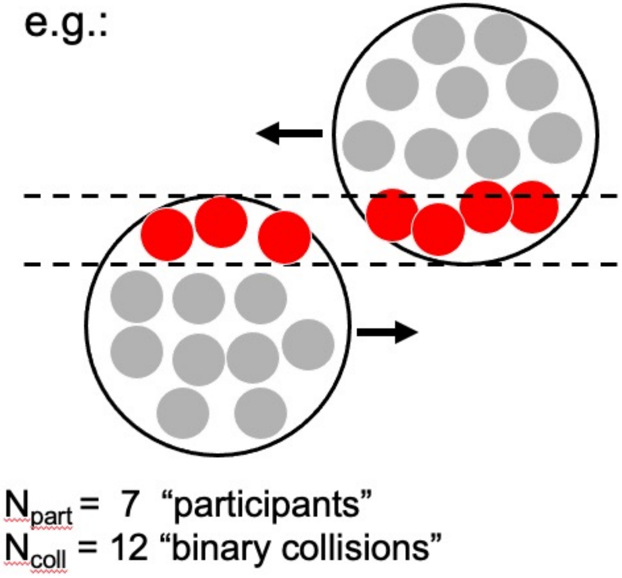
  → crucial support for QGP picture!



STAR: Phys. Rev. Lett. **90** (2003) 32301

Nuclear modification factor

- participant vs collisions

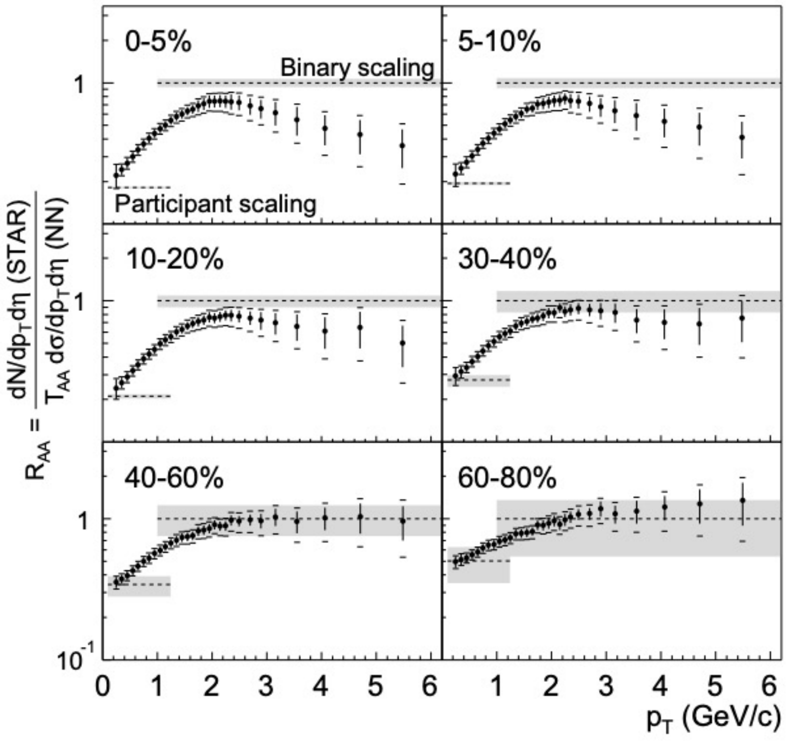


$$R_{AA} = \frac{(dN/dp_T)_{AA}}{\langle N_{coll} \rangle (dN/dp_T)_{pp}}$$

- R_{AA}: “nuclear modification factor”
  - quantifies deviation from Ncoll scaling

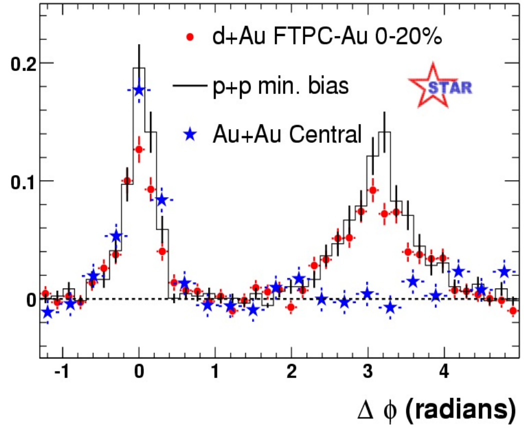
- “soft”, large cross-section processes expected to scale like N_{part}
- “hard”, low cross-section processes expected to scale like N_{coll}

Nuclear modification factor at RHIC



STAR: Phys.Rev.Lett. 89 (2002) 202301

- high-p_T should follow Ncoll
  - if no nuclear/medium effects
- clearly violated for central collisions
- indication of energy loss of partons in the QGP!
  - not due to initial-state effects
  - (checked with pA, dA collisions)
- coherent with picture from azimuthal correlations



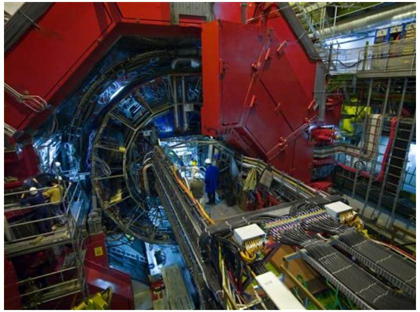
... meanwhile, in Europe...

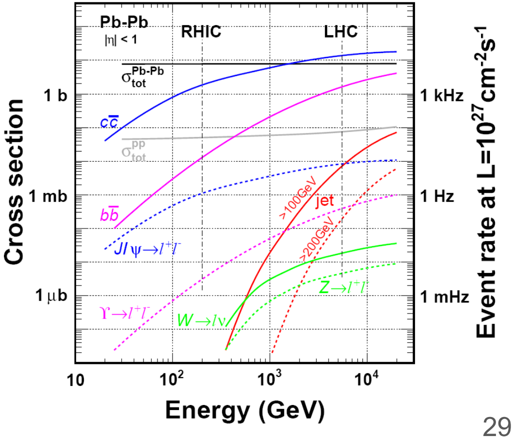
- 1984: ECFA meeting in Lausanne: pp machine in LEP tunnel
    - (n.b.: first collisions in LEP only in 1989!)
- 1986 start of heavy-ion collisions at CERN/SPS and Brookhaven/AGS
- capability to collide heavy ions in LHC quickly realised
    - mentioned at a workshop on Physics at Future Accelerators in La Thuile in 1987
- 1989 LHC workshop in Aachen
    - physics case for heavy-ion programme, start of organisation of experimental community
- 1992 Expression of Interest (Heavy-Ion Proto-Collaboration)
- 1993 Letter of Intent (A Large Ion Collider Experiment)
    - reusing the magnet of LEP experiment L3 at Interaction Point 2
- 1995 ALICE Technical Proposal
- 1997 ALICE approved by CERN Research Board
- 2000’s construction, installation, commissioning
- 2009 first collisions
- 2010 first Pb-Pb collisions!


CMS
LHCb
ALICE
ATLAS

Nuclear collisions at the Large Hadron Collider

- ideal conditions: net baryon density = 0
  - close to conditions at Big Bang
  - theoretical calculations more reliable
- LHC is an excellent collider of nuclei!
  - excellent luminosity
  - even asymmetric collisions (p-Pb) in spite of 2-in-1 design!
- abundance of hard, “calibrated” probes
  - heavy flavour, jets, …
- very high multiplicity
  - key for precision studies of collectivity
- state-of-the-art detectors

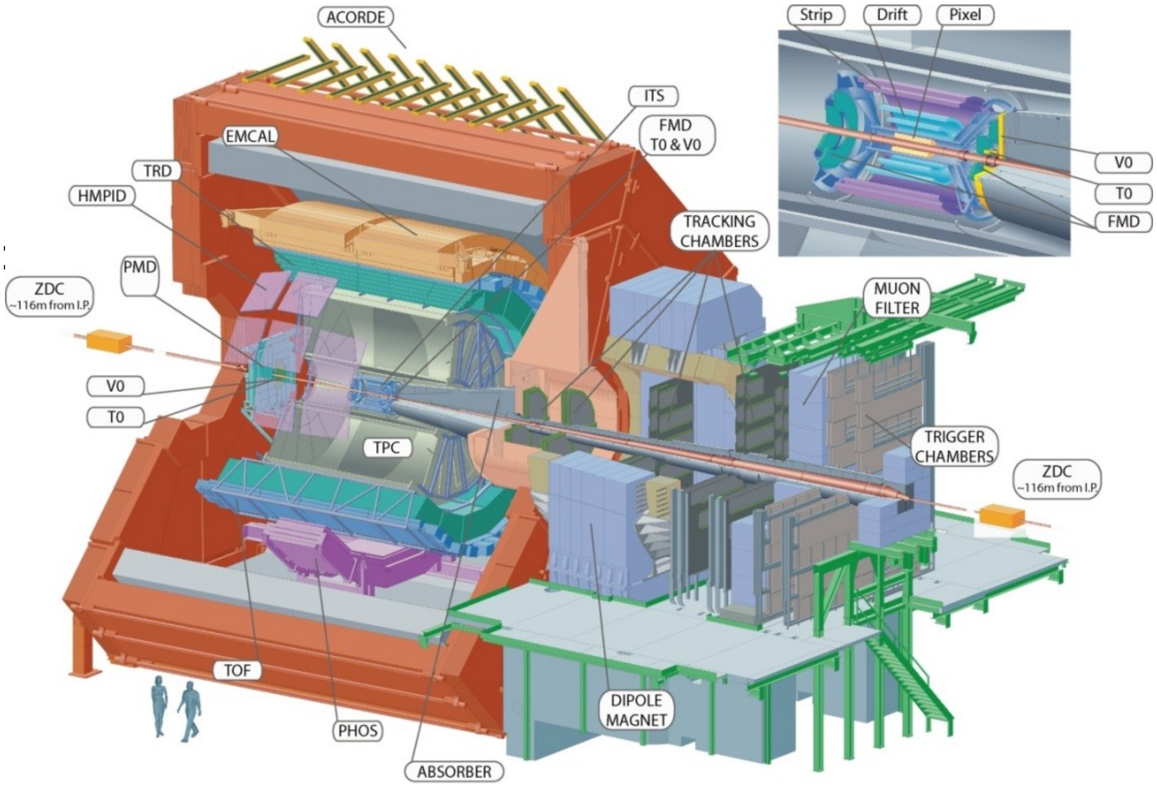




- ALICE
  - dedicated experiment
  - 1030 authors, 171 institutions, 40 countries
- ATLAS, CMS, LHCb also participating in programme

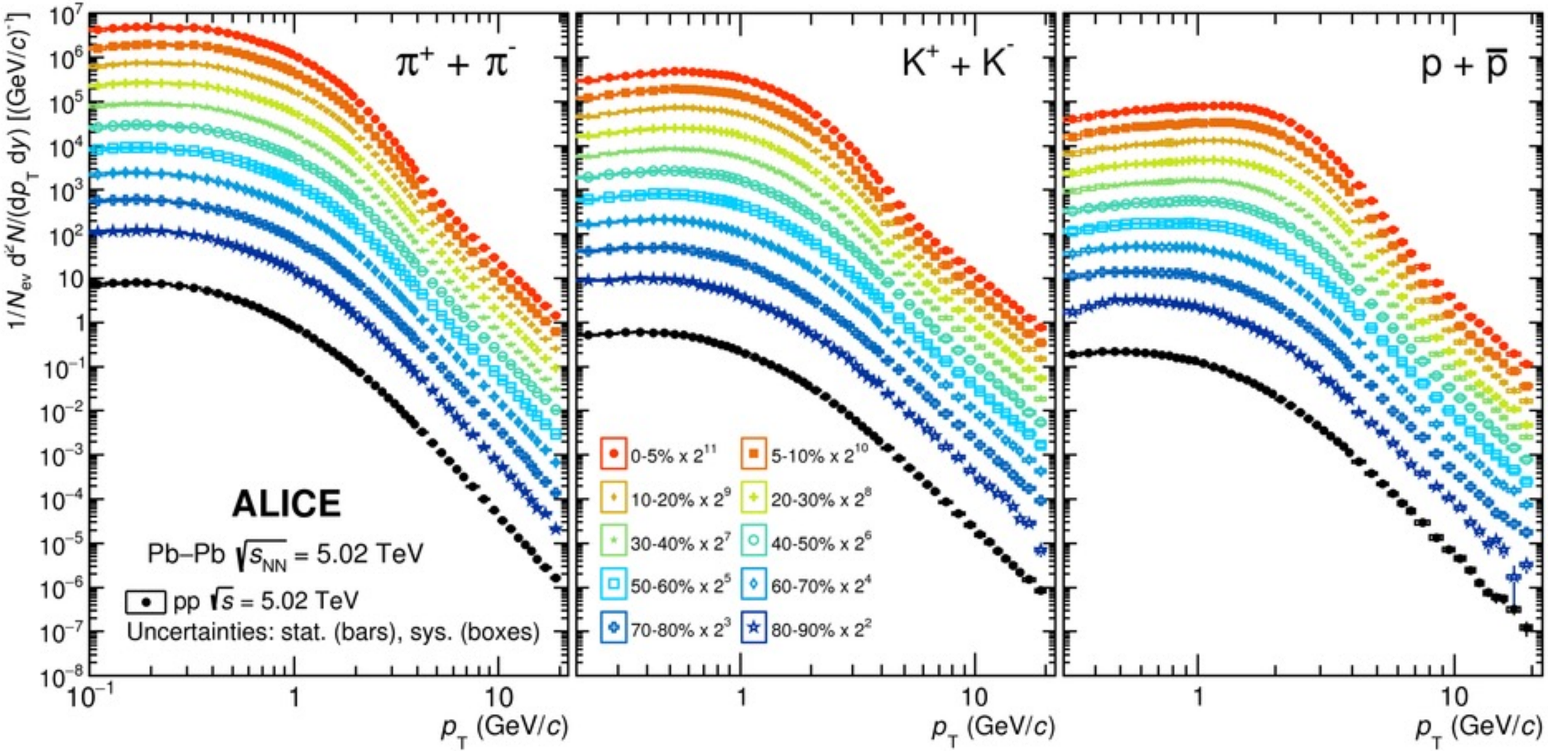
The ALICE experiment

- two main parts:
  - barrel ($|\eta|<0.9$), B = 0.5 Tesla
  - muon spectrometer, $-4<\eta<-2.5$
- high-precision reconstruction:
  - low material tracking
  - high-resolultion vertexing
  - hadron and lepton ID
- triggers:
  - minimum-bias (MB)
    - or centrality, in Pb-Pb
  - single and di-muon
  - EMCAL, high-mult., UPC
  - TRD



- collisions systems (so far) : Pb-Pb, pp, p-Pb, Pb-p, Xe-Xe

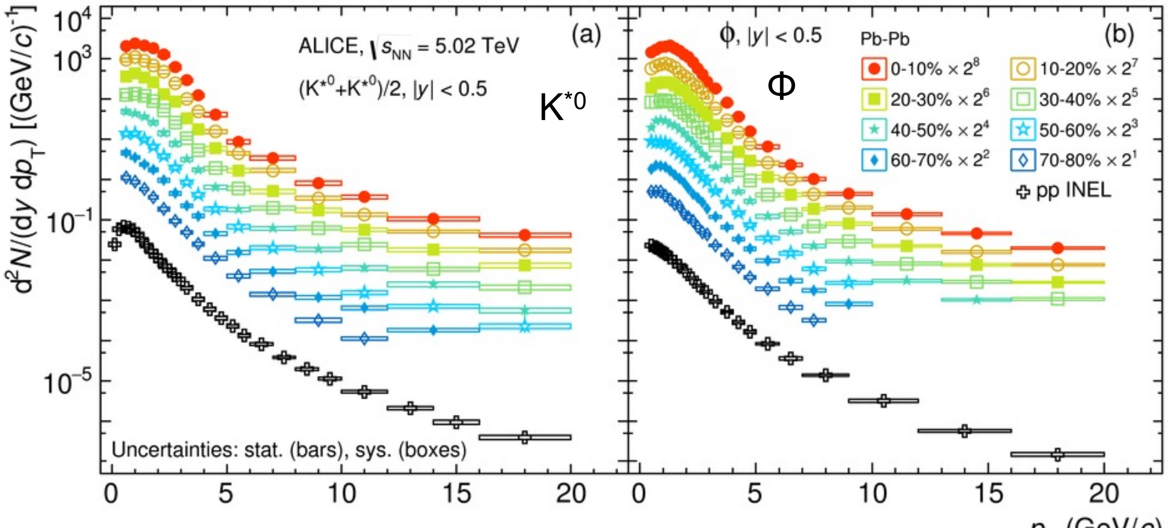
Identified particles



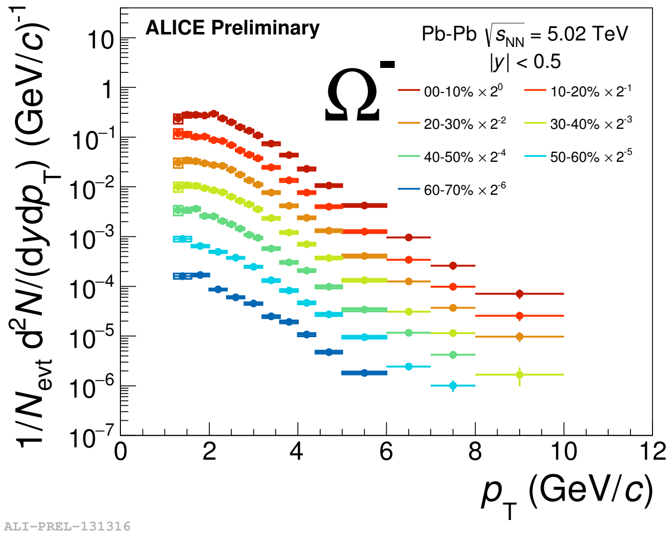
ALICE, arXiv:1910.07678

More and more species

- Resonances, hyperons,…

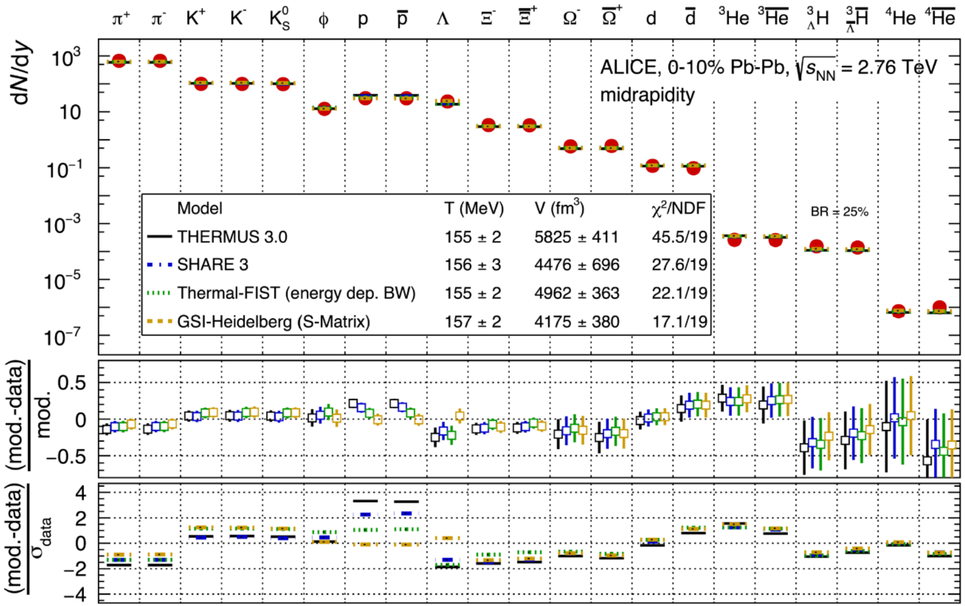


ALICE, arXiv:1910.14419



→ QGP hadronisation, radial expansion, freeze-out, …

Integrated yields

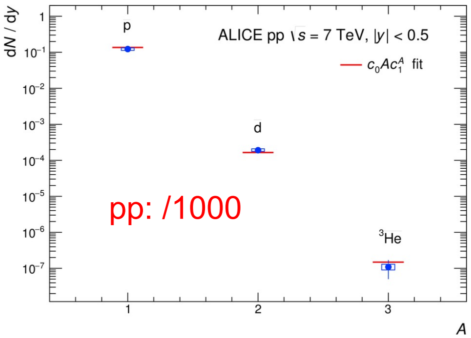


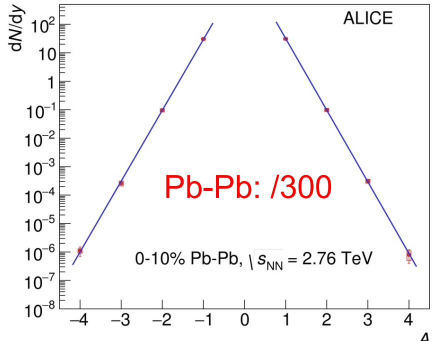
arXiv:2211.04384

$T_{chem} \approx T_C \approx 156$ MeV

→ hadronisation very close to the phase transition

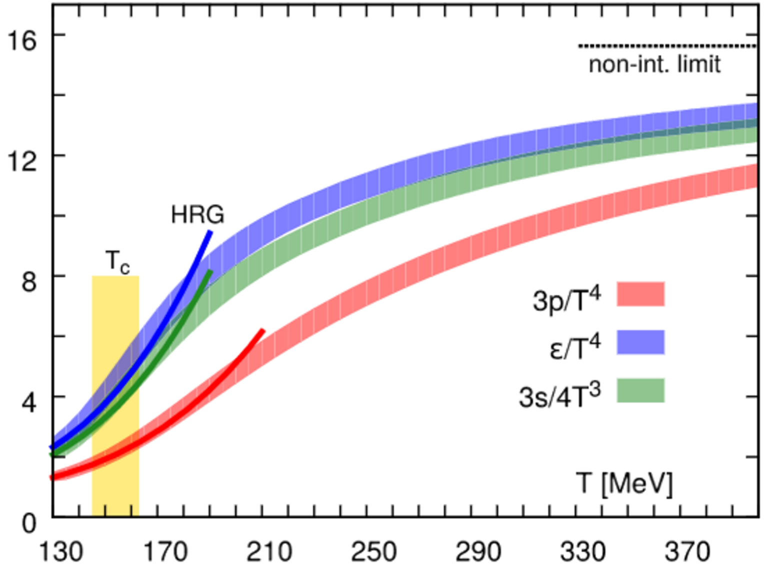
- hadron chemistry in central Pb-Pb
  - ~at thermodynamic equilibrium
  - → very different from pp!
  - → strangeness enhancement!
  - looking at the fine print: some deviations
    - a few σ: K*, p/Λ/Ξ
    - → key window on interactions in hadronic final state
- … even for nuclei, hypernuclei
  - in spite of very low binding energy!
  - substantial enhancement wrt pp
  - → AA is a (hyper-)nuclei factory
  - for each additional nucleon:





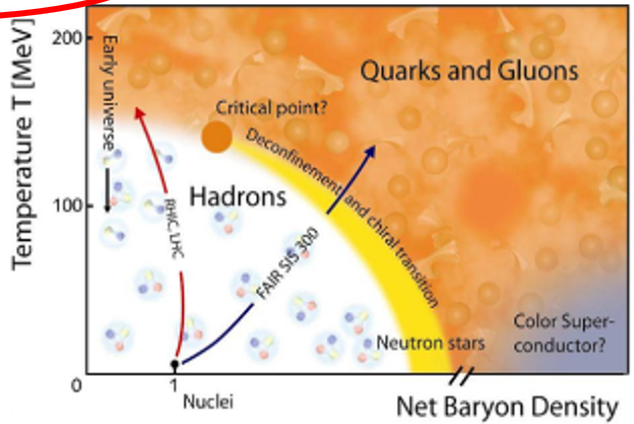
Lattice QCD

- the rigorous way of performing calculations in the non-perturbative regime of QCD
- discretisation on a space-time lattice
  - → ultraviolet (i.e. large-momentum scale) divergencies can be avoided



[A Bazavov et al. PRD 90 094503 (2014)]

- around critical temperature (T_C): rapid change of
  - energy density ε
  - entropy density s
  - pressure density p
- due to activation of partonic degrees of freedom
- at zero baryon density → smooth crossover
- T_C = (156.5 ± 1.5) MeV [A Bazavov et al. Phys.Lett.B 795 (2019) 15]
- ε ~ O(GeV/fm³)

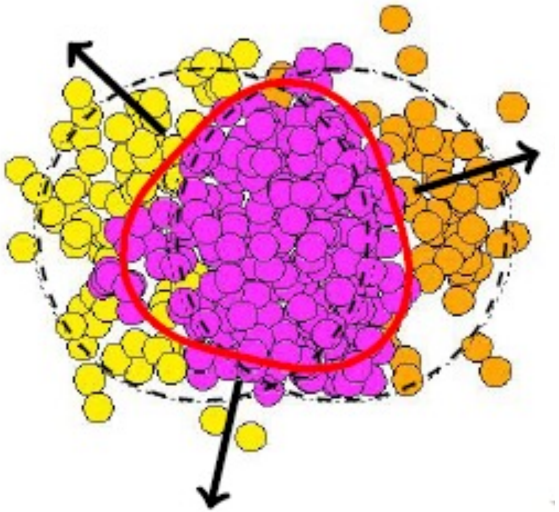


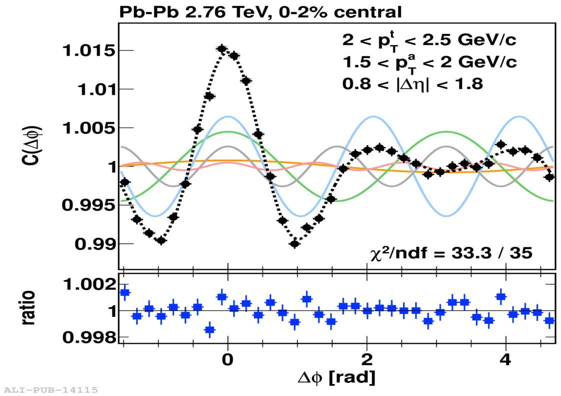
ALICE

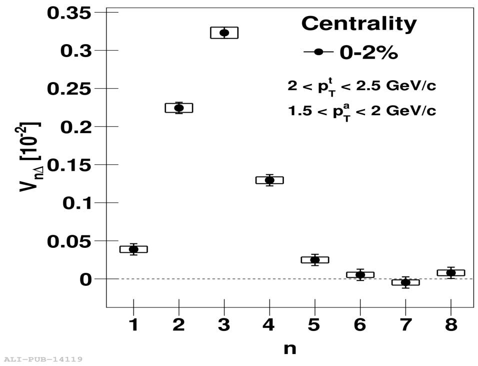
Higher harmonics: a beautiful tool…

initial-state geometrical asymmetries → final state momentum asymmetries

- dynamic response of QCD medium
- interaction of hard probes with QCD medium





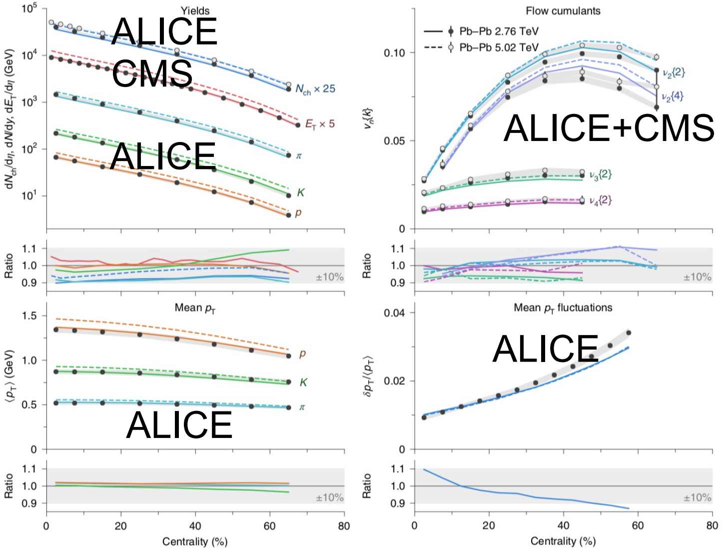


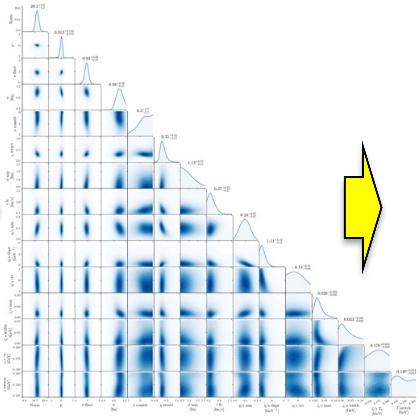
→ Fourier decomposition of azimuthal distribution

- "flow harmonics"
- sensitive to transport parameters of medium

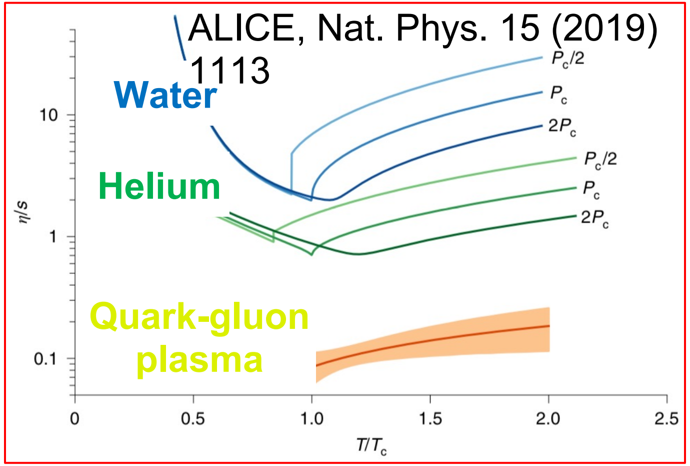
Entering precision era!

- High data quality enables quantitative extraction of medium parameters
  - e.g.: Bayesian parameter estimation from ALICE (mainly) data (Duke group)
  - → extraction of temperature dependence of medium bulk and shear viscosity





QGP shear viscosity vs. temperature

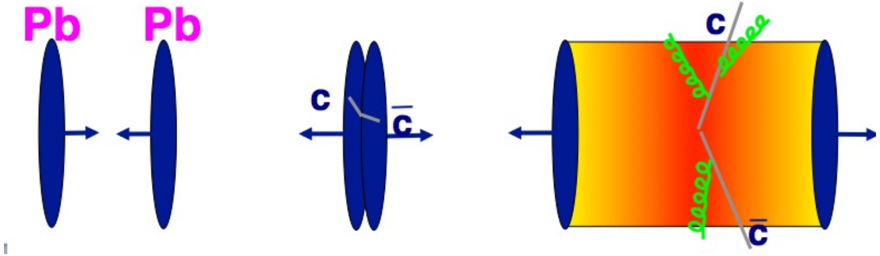


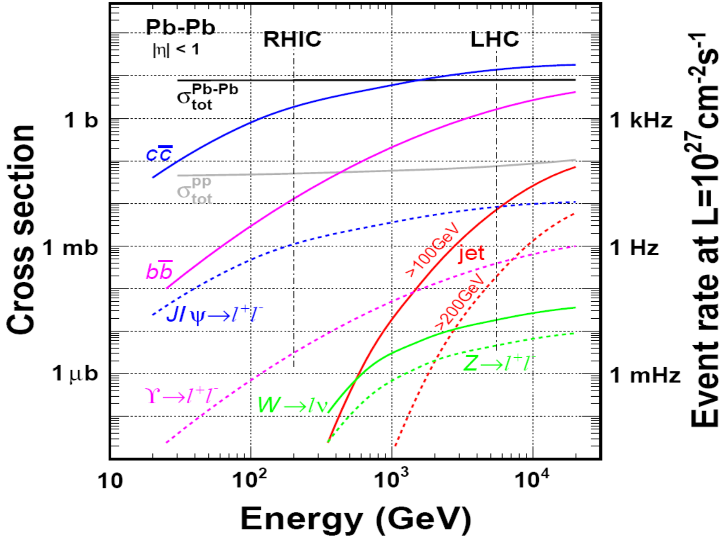
→ QGP viscosity with ~20% precision

→ QGP ~10 times less viscous than any other form of matter

Heavy Flavour

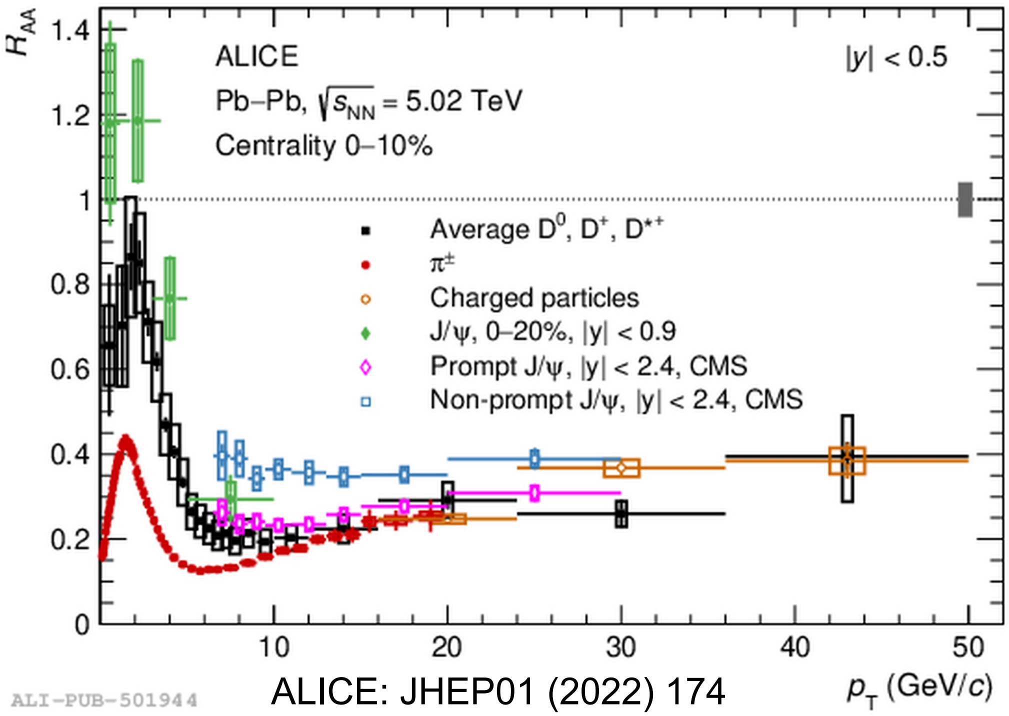
- ideal probes of QGP at LHC
  - large cross sections
  - generated in initial hard parton scatterings
  - controlled values of mass and colour charge of propagating parton
  - large value of mass → “brownian” probes
  - sensitive to QGP hadronisation





Beautiful data from the LHC!

a gold mine!



ALICE: JHEP01 (2022) 174

- controlled probe
  - mass
  - colour charge
  - pQCD
- generated in initial parton scattering
- conserved throughout evolution
- large mass → "Brownian" probe
- powerful probe of hadronisation

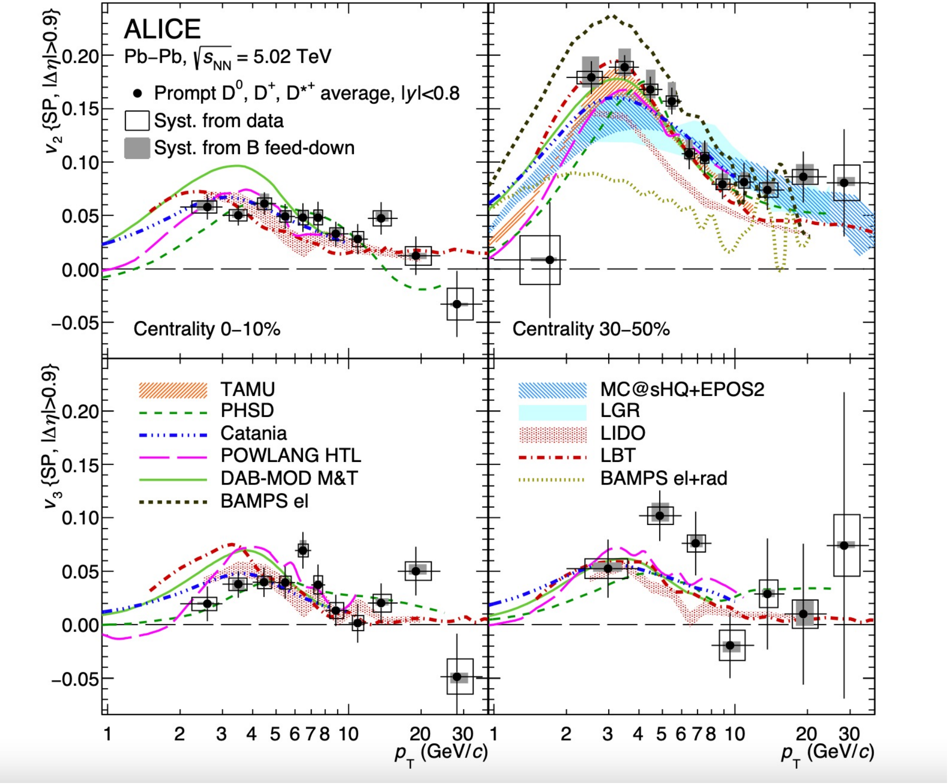
experimentally:

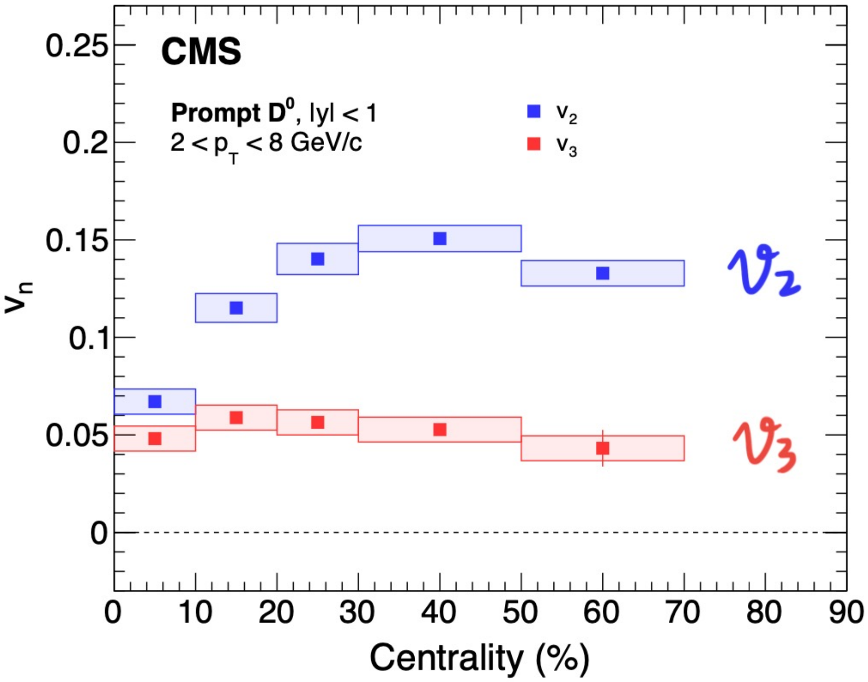
- strongly coupled to medium
- clear hierarchy at low p_T

Strongly involved in the flow

v_2

and v_3!

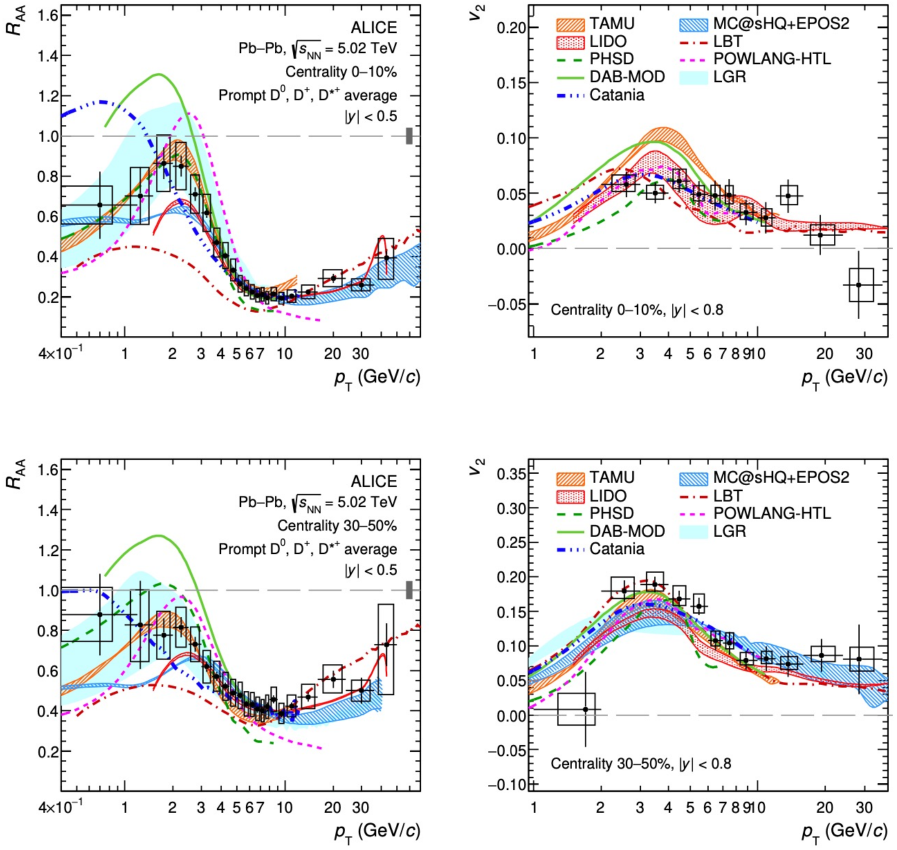




ALICE: Phys. Lett. B 813 (2021) 136054

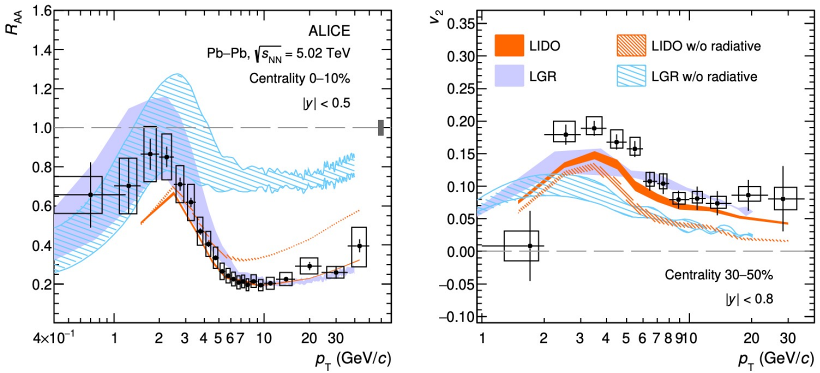
CMS: Phys. Lett. B 816 (2021) 136253

State-of-the-art...

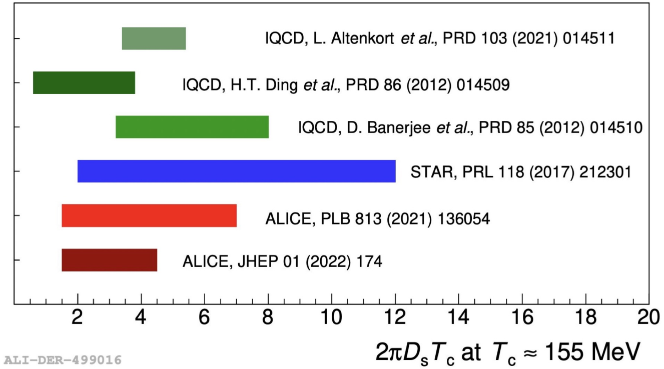


ALICE: JHEP01 (2022) 174

- substantial model constraints...

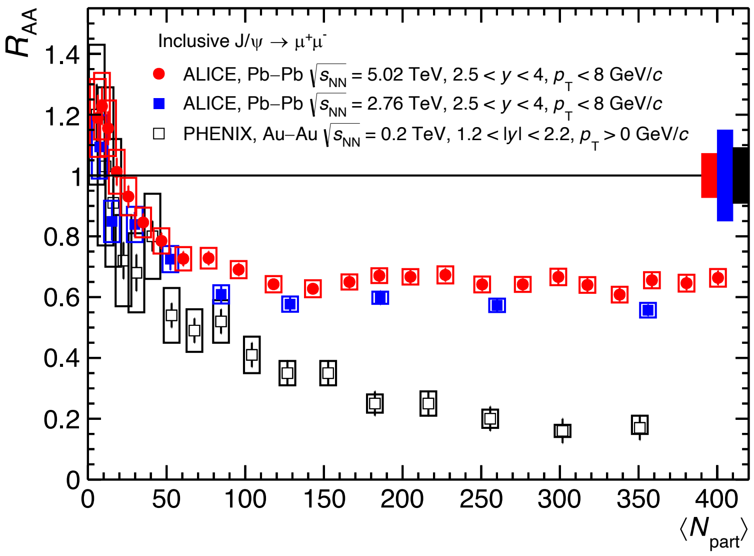


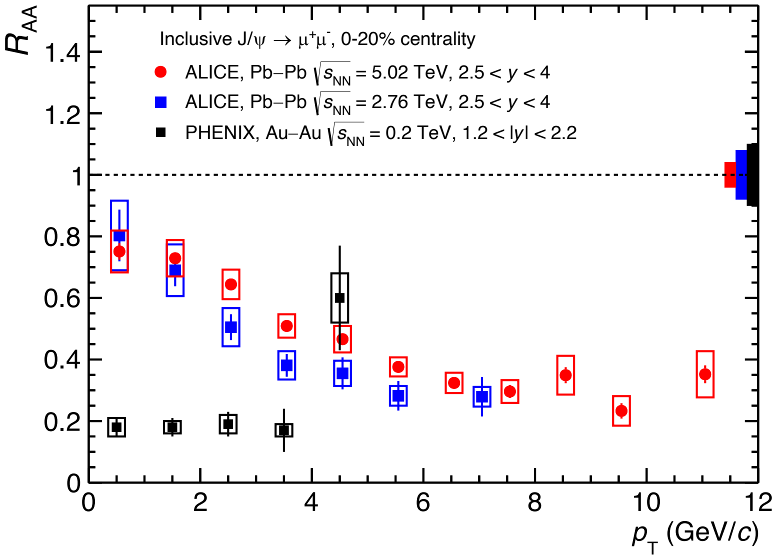
- 50% uncertainty on diffusion coefficient
  - it starts to be a measurement!



A new regime for J/ψ production!

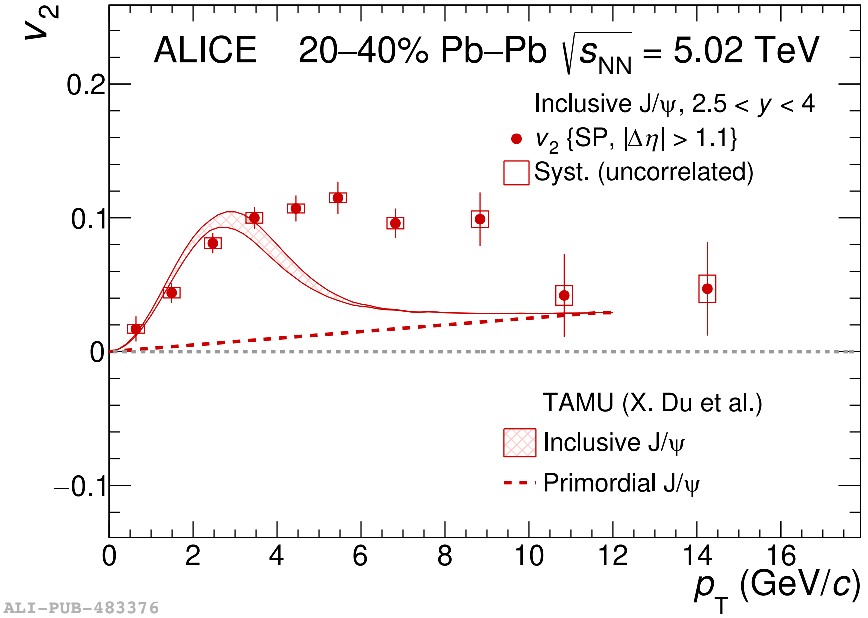
- a remarkable change of behaviour from SPS/RHIC!

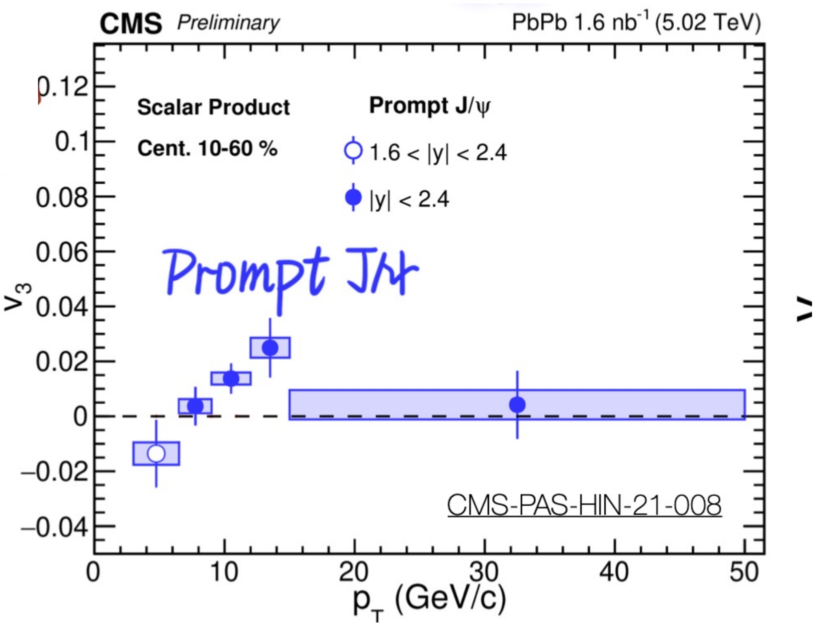




- in both the centrality and the p_T dependence
- evidence for production by recombination of exogamous $c\bar{c}$ pairs!

Charm quarks themselves flow

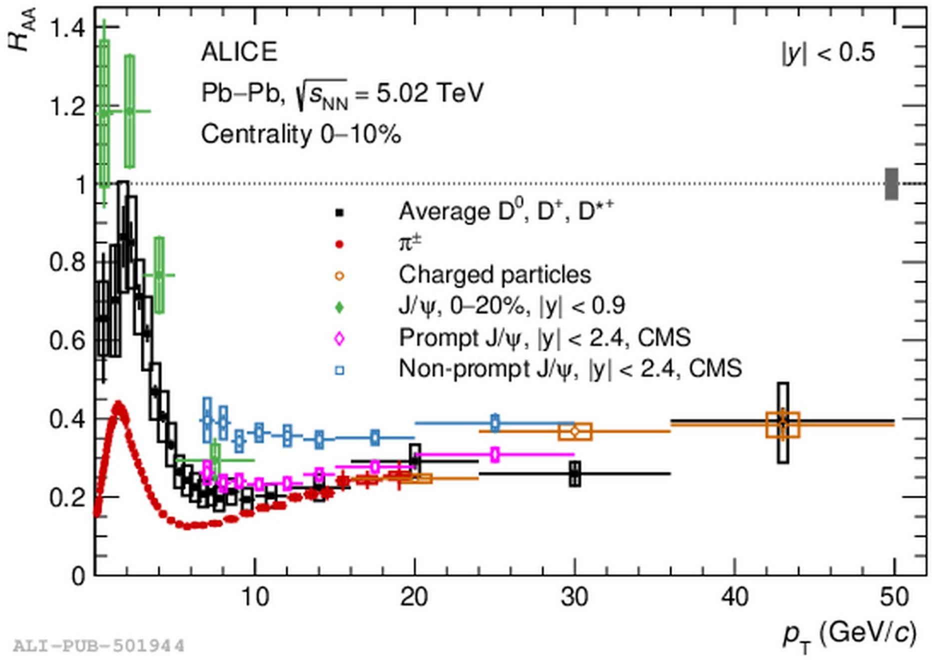


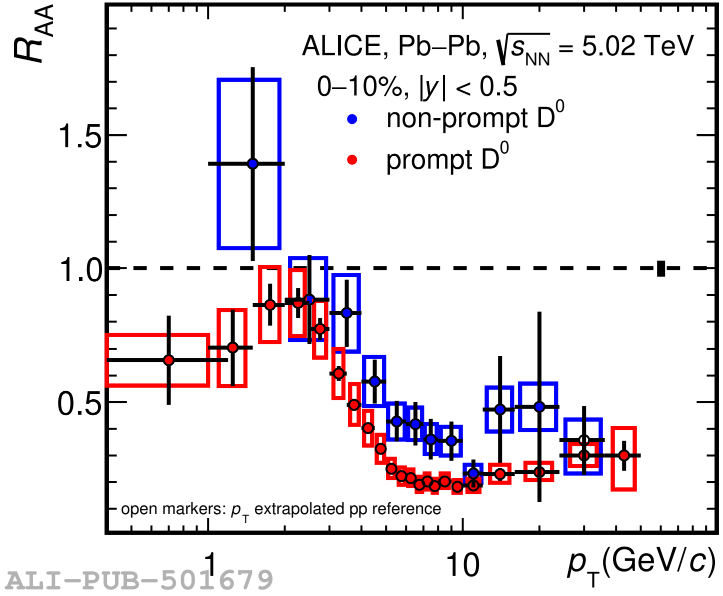


ALICE: JHEP 10 (2020) 141

CMS: PAS-HIN-21-008

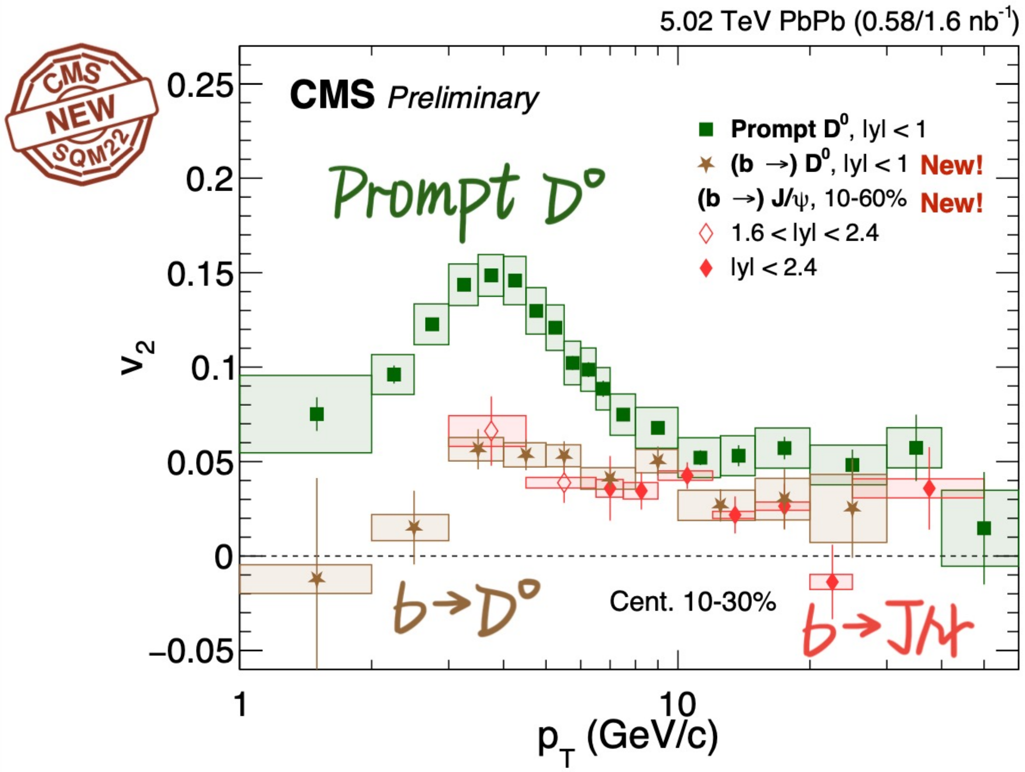
Beauty is quenched, too...



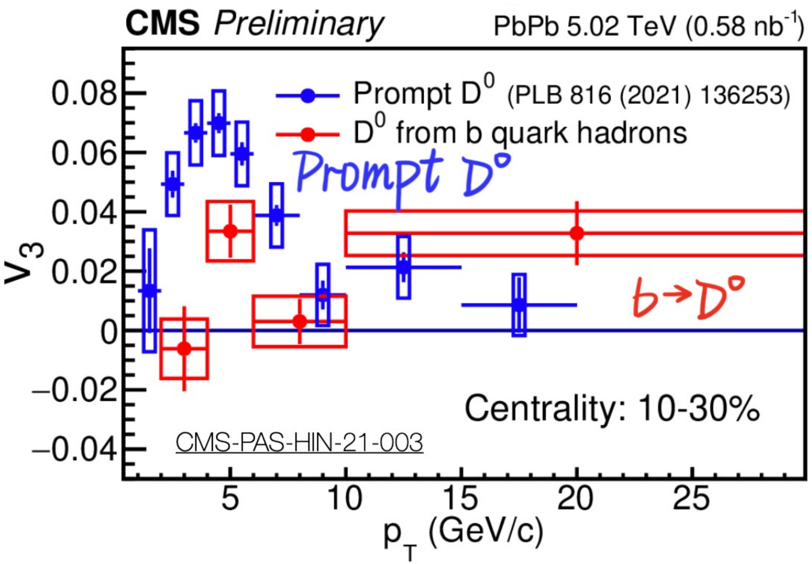


- less so than charm...

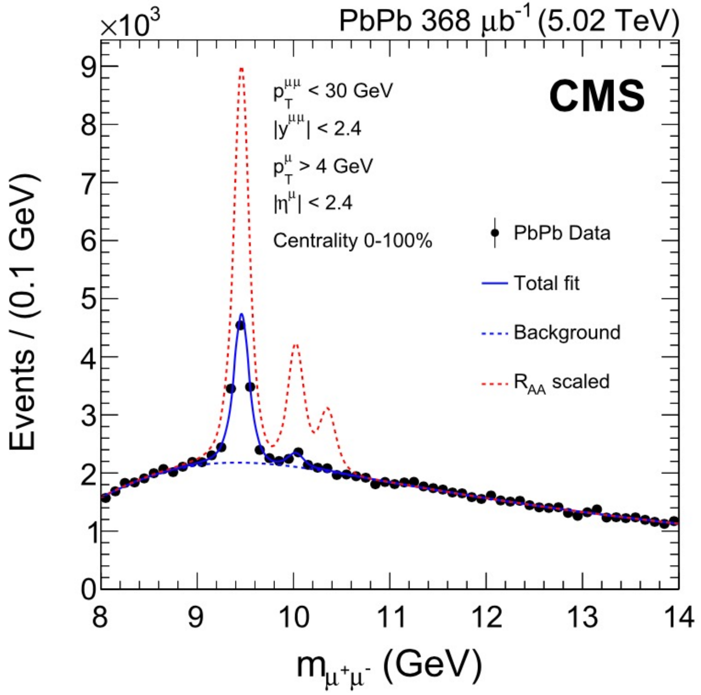
... and it flows, too...



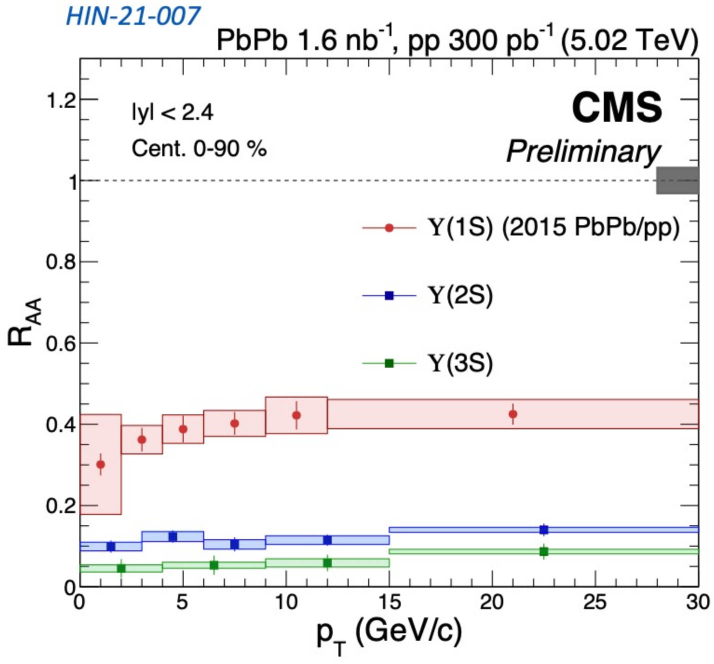
- less so than charm...
- similar trend for v_3:



Υ states seem to follow a sequential suppression pattern

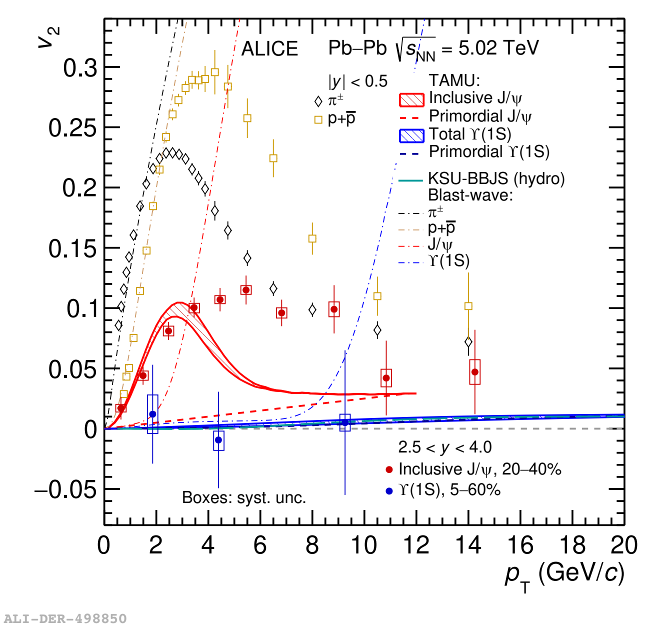


CMS: PLB 790 (2019) 270

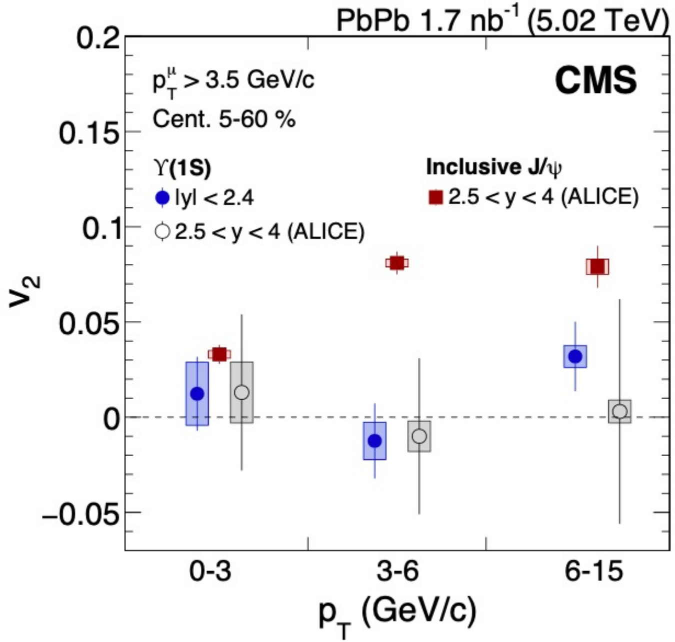


CMS: PAS-HIN-21-007

... but the ϒ doesn't seem to flow much...

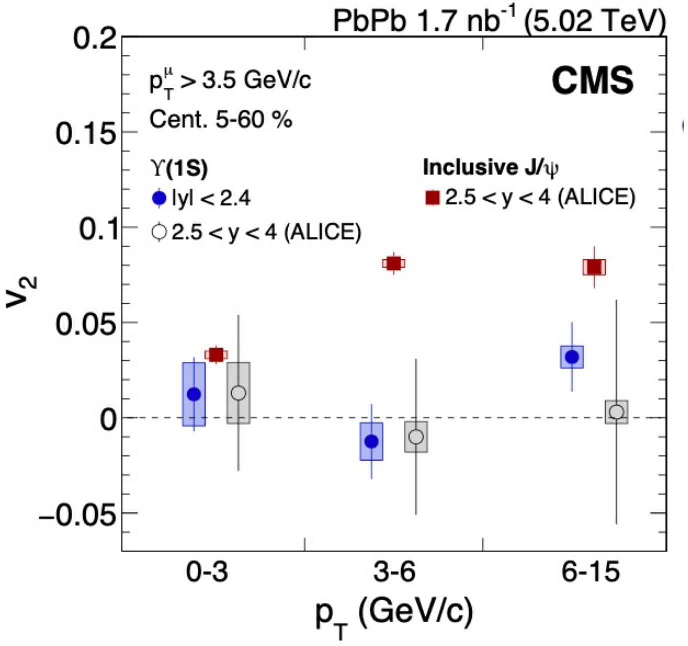


ALICE: PRL 123 (2019) 192301



CMS: PLB 819 (2021) 136385

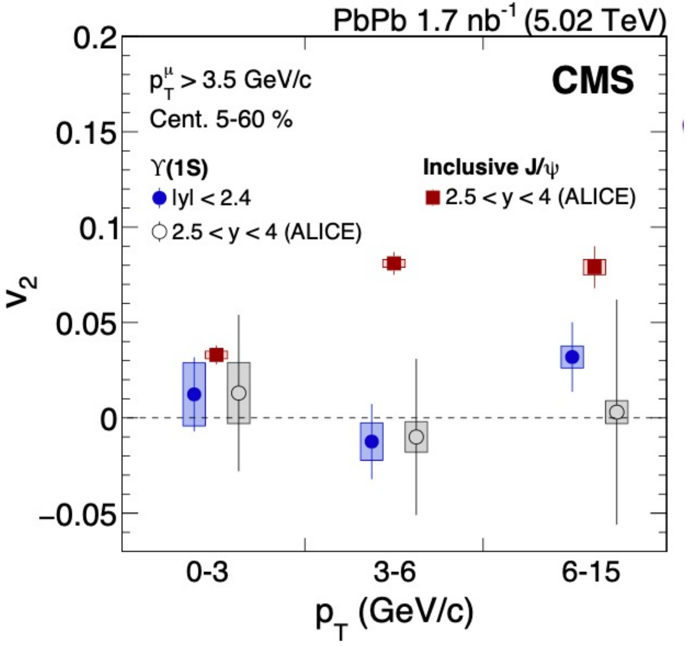
... but the Υ doesn't seem to flow much...



CMS: PLB 819 (2021) 136385

- could it be that b quarks don't flow?
  - and B get their flow from light quarks?

... but the ϒ doesn't seem to flow much...



CMS: PLB 819 (2021) 136385

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  - recombination component should be small

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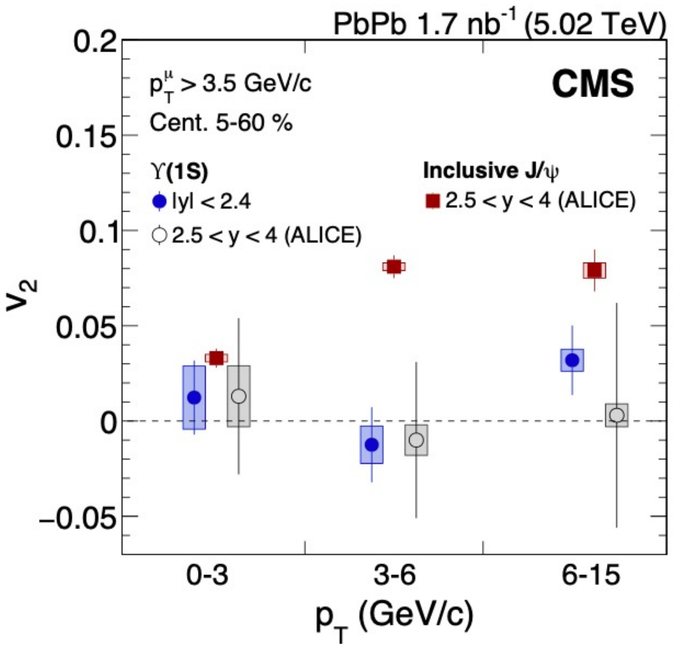

CMS: PLB 819 (2021) 136385

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  - shouldn't that asymmetry be there, at least?

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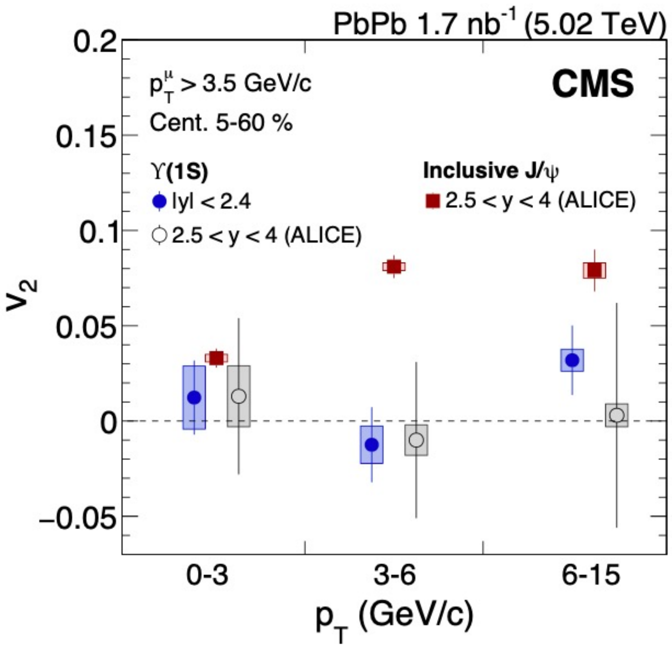

CMS: PLB 819 (2021) 136385

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  - and B get their flow from light quarks?
- but should ϒ flow reflect b quark flow?
  - recombination component should be small
- shouldn't ϒ suppression feel the geometry?
  - shouldn't that asymmetry be there, at least?
- perhaps two populations?
  - e.g.: colour octet and colour singlet?
  - colour octet disappears?
  - colour singlet goes through ~ isotropically?
- 🤔...