



华中师范大学
CENTRAL CHINA NORMAL UNIVERSITY



Institute of Particle Physics
粒子物理研究所

50 years of Quark-Gluon Plasma: Past, Present and Future

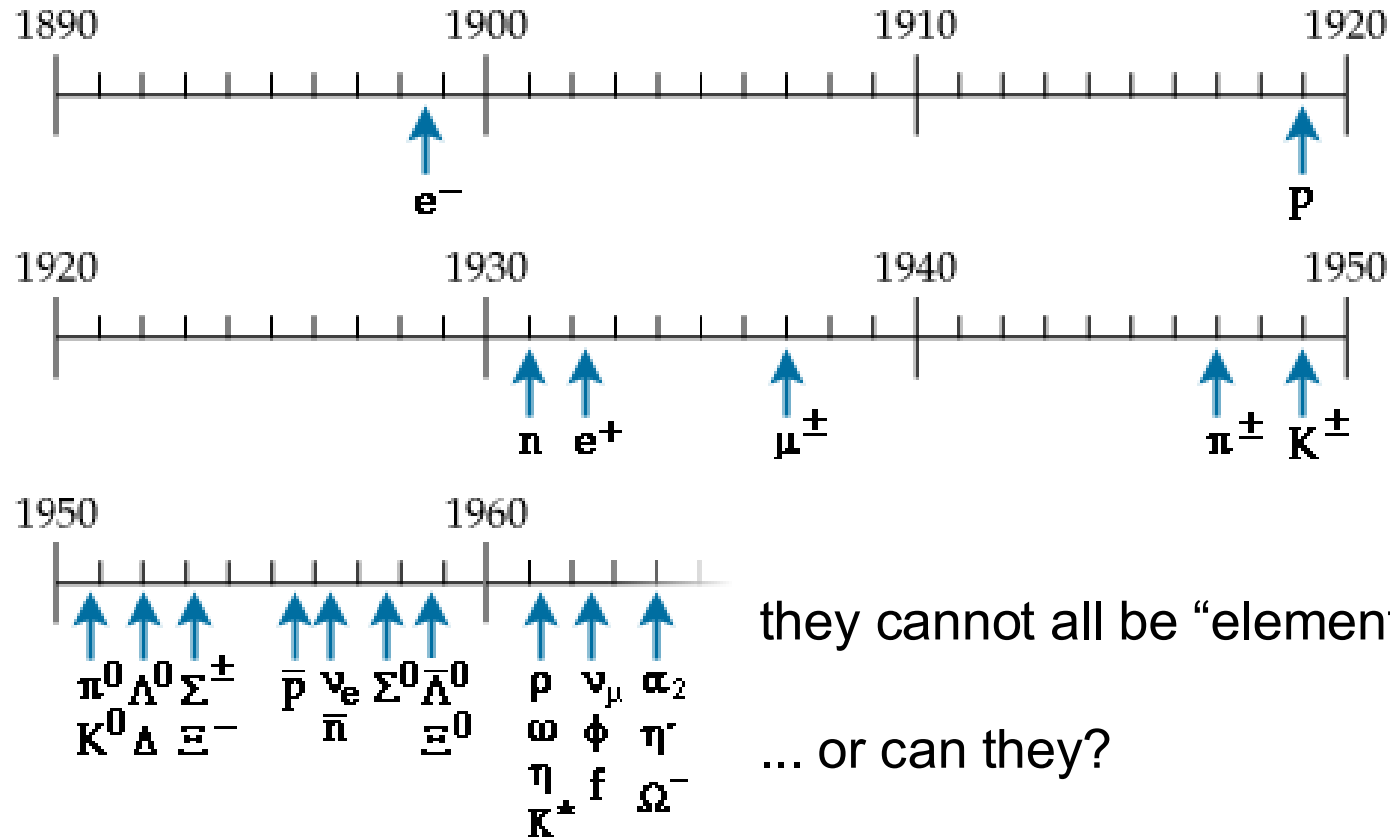


Federico Antinori
(INFN, Padova, Italy)



武汉, 华中师范大学, 2025年11月10日

A bit of history: discovery of subnuclear particles

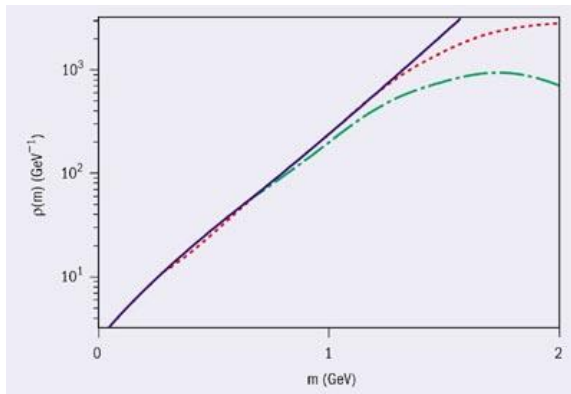


Statistical Bootstrap and Hagedorn Temperature

- very elegant idea:
 - hadrons are made of hadrons which in turn are made of hadrons which in turn...
 - no fundamental hadron (“nuclear democracy”)
 - very popular in the sixties (pre-quarks)
(very much “sixties”, in fact: F Capra takes the idea and runs away with it in “The Tao of Physics”)
- pioneered by Geoffrey Chew (UC Berkeley)
 - e.g.: G. Chew (1962). *S-Matrix theory of strong interactions*. New York: W A Benjamin
- developed by Rolf Hagedorn (CERN) into a full-fledged theory of strong interactions
 - e.g.: R Hagedorn: Statistical thermodynamics of strong interactions at high energies 1965 Nuovo Cim. Suppl. 3 147
- very successful in calculating hadronic collision cross sections
 - e.g.: H Grote, R Hagedorn and J Ranft, Atlas of particle spectra, CERN-report (1970)
 - calculated based on hadron exchange → need to know spectrum of all existing hadrons

Spectrum of hadron masses

- spectrum of hadrons from “bootstrap equation”: $\rho(m) \propto m^{-3} \exp(\frac{m}{T_H})$
 - exponential growth of number of hadrons at higher and higher masses!
 - controlled by “Hagedorn temperature”, $T_H \sim 150\text{-}160 \text{ MeV}$



green: states known in 1967

red: states known by mid-1990's

blue: expected spectrum for $T_H = 158 \text{ MeV}$

- btw, still holds: very similar results from lattice QCD
 - e.g.: A Majumder, B Müller, PRL 105:252002,2010
 - that's why bootstrap theory worked well for hadron interactions!
(the idea was very deep, even if the picture was not the correct fundamental one!)

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:

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

- interactions as resonance formation:
 - interacting system of pions $\leftrightarrow$ non-interacting gas of all possible resonances

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

- inserting Hagedorn's spectrum:

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

- 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!

... but Quarks enter the scene...

- the other main idea proposed in the 60's to explain the multitude of hadrons
 - 1961: “eightfold way” (SU(3) flavour symmetry, Murray Gell-Mann)
 - 1965: quark hypothesis (Murray Gell-Mann, George Zweig)
 - 1968: observation of “partons” in Deep Inelastic Scattering at SLAC
 - 1970: GIM mechanism (Sheldon Glashow, John Iliopoulos, Luciano Maiani)
 - to explain absence of flavour-changing neutral currents
 - proposal of fourth quark (charm) → cancellation of flavour-changing terms
 - 1974: discovery of charm (J/ψ) at Brookhaven and SLAC (+ Frascati 5 days later)
- quark hypothesis widely accepted, and in 1975...

1974: Lee and Wick: a key precursor!

PHYSICAL REVIEW D

VOLUME 9, NUMBER 8

15 APRIL 1974

Vacuum stability and vacuum excitation in a spin-0 field theory*

T. D. Lee and G. C. Wick

Columbia University, New York, New York 10027

(Received 17 January 1974)

The theoretical possibility that in a limited domain in space the expectation value $\langle \phi(x) \rangle$ of a neutral spin-0 field may be abnormal (that is to say quite different from its normal vacuum expectation value) is investigated. It is shown that if the ϕ^3 coupling is sufficiently large, then such a configuration can be metastable, and its physical size may become substantially greater than the usual microscopic dimension in particle physics. Furthermore, independent of the strength of the ϕ^3 coupling, if $\phi(x)$ has sufficiently strong scalar interaction with the nucleon field, the state that has an abnormal $\langle \phi(x) \rangle$ inside a very heavy nucleus can become the minimum-energy state, at least within the tree approximation; in such a state, the “effective” nucleon mass inside the nucleus may be much lower than the normal value. Both possibilities may lead to physical systems that have not yet been observed.

- scalar field $\Phi(x)$
- extreme conditions (e.g. high T) $\rightarrow$ vacuum expectation value $\langle \Phi \rangle$ may vanish
- $\rightarrow$ nucleons become effectively massless!

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

Volume 59B, number 1

PHYSICS LETTERS

13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO

*Istituto di Fisica, Università di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Roma, 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

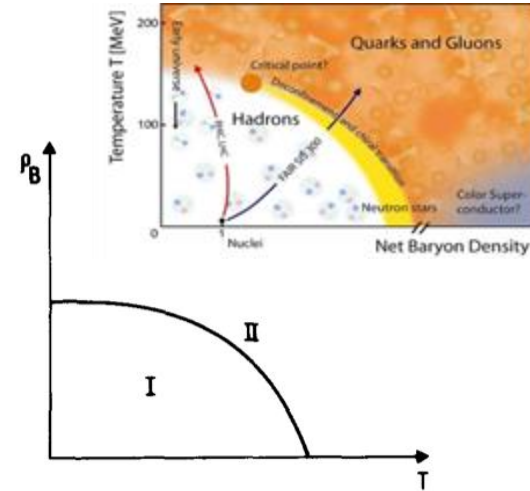


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

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

1975, Collins and Perry: “quark soup” in neutron stars?

VOLUME 34, NUMBER 21

PHYSICAL REVIEW LETTERS

26 MAY 1975

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry

*Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Cambridge CB3 9EW, England*

(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

the basic argument is contained in only a few lines...

A neutron has a radius¹⁰ of about 0.5–1 fm, and so has a density of about $8 \times 10^{14} \text{ g cm}^{-3}$, whereas the central density of a neutron star^{1,2} can be as much as 10^{16} – $10^{17} \text{ g cm}^{-3}$. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

1978, the name is coined

ЯДЕРНАЯ ФИЗИКА
JOURNAL OF NUCLEAR PHYSICS
т. 28, вып. 3(9), 1978

by E V Shuryak in Yadernaya Fizika 28 (1978) 403: "Kvark-Glyuonnaya Plazma"

**КВАРК-ГЛЮОННАЯ ПЛАЗМА И РОЖДЕНИЕ ЛЕПТОНОВ,
ФОТОНОВ И ПСИОНОВ В АДРОННЫХ СОУДАРЕНИЯХ**

Э. В. ШУРЯК

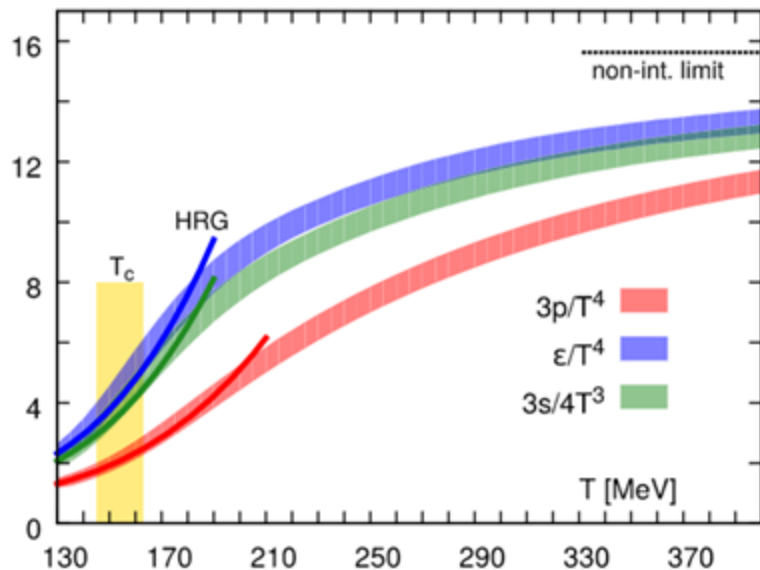
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

(Поступила в редакцию 14 марта 1978 г.)

Предлагается теория явлений, связанных с массами M и поперечными импульсами $p_{\perp}$, такими, что $1 \text{ Гэв} \lesssim M$, $p_{\perp} \ll \sqrt{s}$. Для их описания применяется модель локально-равновесной кварк-глюонной плазмы, разлетающейся по определенному закону. Применение квантовой хромодинамики для вычисления скоростей ряда реакций в такой плазме позволяет вычислить спектры масс дилептонов, распределение по $p_{\perp}$ лептонов, фотонов, пионов и адронных струй, сечения рождения пар очарованных кварков и различных состояний чармония (псионов): J/ψ -, χ -, ψ' -мезонов. Результаты согласуются с экспериментальными данными.

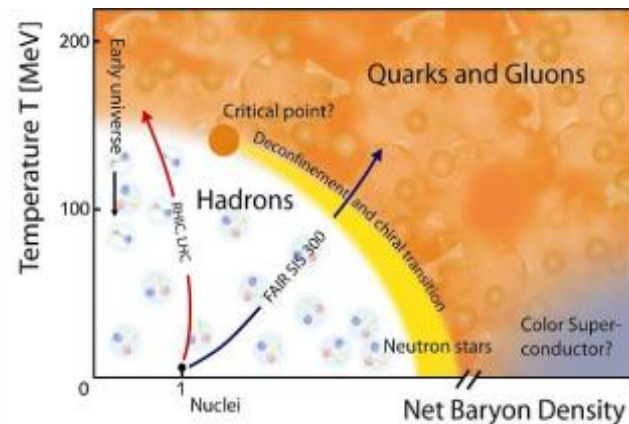
Lattice QCD

- 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

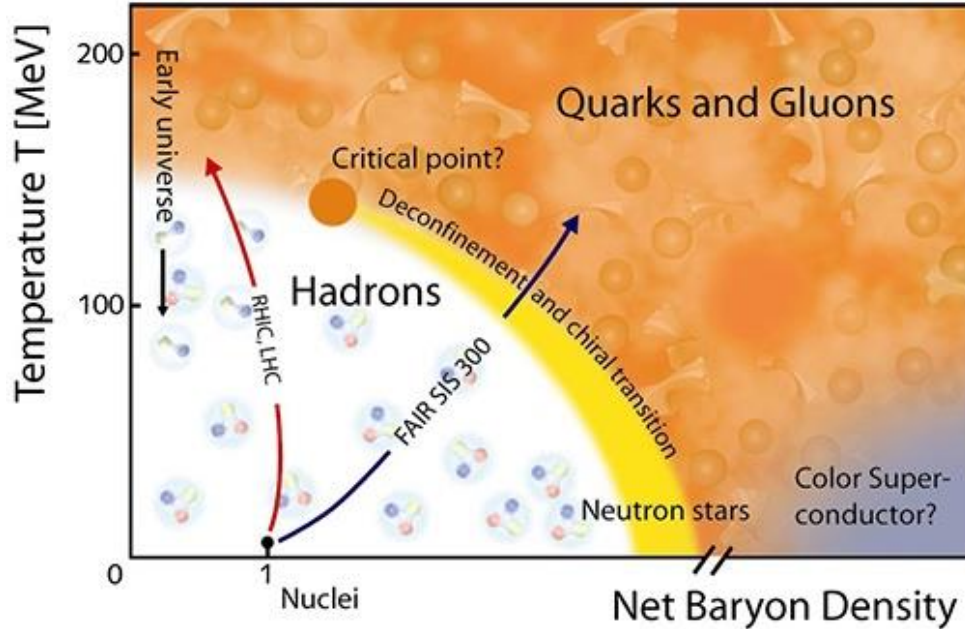


[A Bazavov et al. PRD 90 094503 (2014)]

- around critical temperature (T_c): rapid change of
 - energy density ϵ
 - entropy density s
 - pressure p
- due to activation of partonic degrees of freedom
- at zero baryon density → smooth crossover
- $T_c = (156.5 \pm 1.5) \text{ MeV}$ [A Bazavov et al. Phys.Lett.B 795 (2019) 15]
- $\epsilon \sim O(\text{GeV}/\text{fm}^3)$



The QCD (de-)confinement phase transition



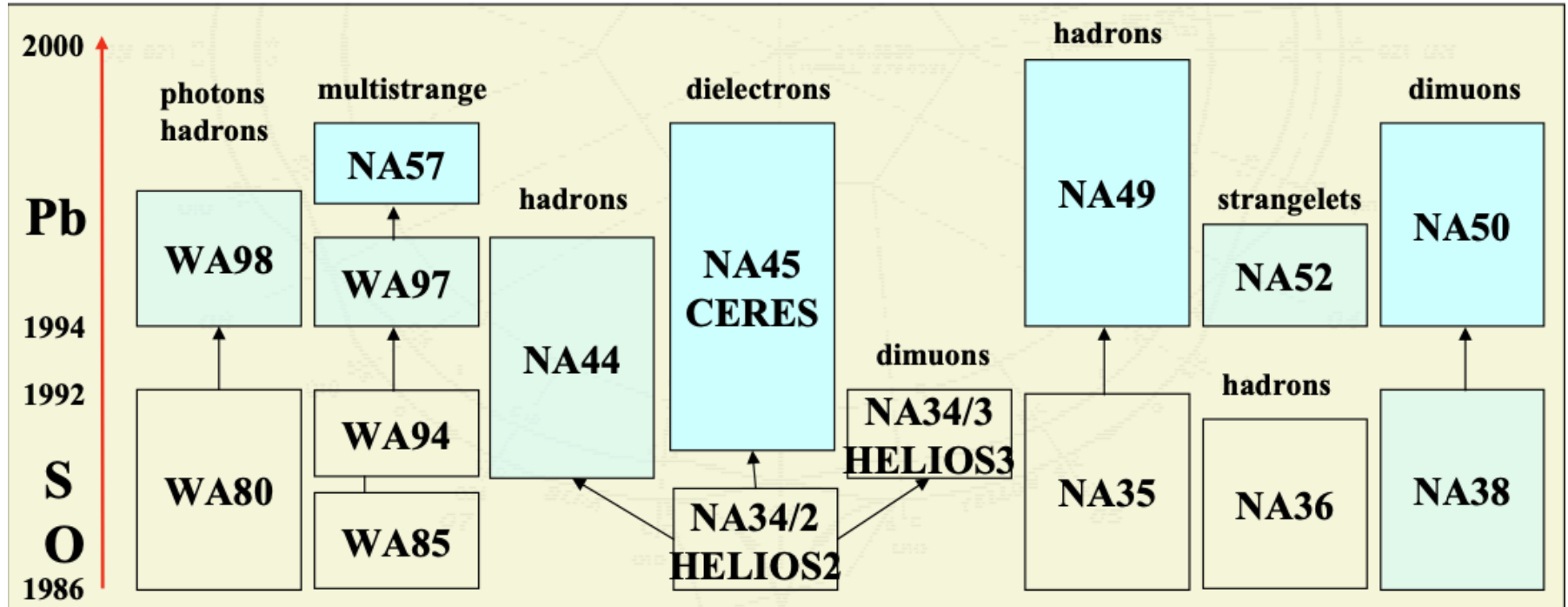
- origin of nucleon masses
 - $2 m_u + m_d \sim 10 \text{ MeV!}$
- phase transition in QFT
 - the only experimentally accessible one!
- Big Bang evolution
 - QGP $\rightarrow$ hadrons at $t \sim 10 \mu\text{s}$
- structure of compact stars

1980's: the hunt is on ...

- how to access this physics experimentally? high-energy nuclear collisions!
 - since the 70's nuclear physicists were already colliding heavy ions
 - Coulomb barrier, shock waves...
 - UNILAC (GSI), Super-Hilac and Bevalac (Berkeley), Synchrophasotron (Dubna)
 - it was realised that nuclear collisions could provide the conditions for QGP formation
 - but to reach T_c higher-energy accelerators were needed → ultrarelativistic AA collisions
- starting from the mid-80's: high-energy beams of nuclei on fixed target
 - at the Alternating Gradient Synchrotron (AGS)
 - at Brookhaven National Laboratory (New York)
 - $\sqrt{s_{NN}} \sim 5 \text{ GeV}$
 - O (1986), Si (1987), Au (1993)
 - at the Super-Proton Synchrotron (SPS)
 - at CERN (Geneva)
 - $\sqrt{s_{NN}} \sim 17 \text{ GeV}$
 - O (1987), S (1987), Pb (1994)

Nuclear beam experiments at the SPS (1986 – 2000)

- a wide spectrum of observables (and technologies!)



(from F Fleuret)

Two historic predictions...

- QGP phase, if existed, would obviously be very short-lived, how to observe it?
 - is there a memory of the passage through the QGP phase?
 - are there “signatures” of the QGP that we can look for in the final state?

two major proposals made in the 80's:

- strangeness enhancement (Johann Rafelski and Berndt Müller)
 - enhanced production of strange quarks in the QGP
 - enhancement of strange particles in the final state
- J/ψ suppression (Tetsuo Matsui and Helmut Satz)
 - colour field screened at short distances in QGP
 - suppression of production of tightly-bound quarkonium states

Strangeness enhancement

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller

Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany

(Received 11 January 1982)

Rates are calculated for the processes $gg \rightarrow s\bar{s}$ and $u\bar{u}, d\bar{d} \rightarrow s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \geq 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec.

PACS numbers: 12.35.Ht, 21.65.+f

Given the present knowledge about the interactions between constituents (quarks and gluons), it appears almost unavoidable that, at sufficiently high energy density caused by compression and/or excitation, the individual hadrons dissolve in a new phase consisting of almost-free quarks and gluons.¹ This quark-gluon plasma is a highly excited state of hadronic matter that occupies a volume large as compared with all characteristic length scales. Within this volume individual color charges exist and propagate in the same manner as they do inside elementary particles as described, e.g., within the Massachusetts Institute of Technology (MIT) bag model.²

It is generally agreed that the best way to create a quark-gluon plasma in the laboratory is with collisions of heavy nuclei at sufficiently high energy. We investigate the abundance of strangeness as function of the lifetime and excitation of the plasma state. This investigation was motivated by the observation that significant changes in relative and absolute abundance of strange particles, such as $\bar{\Lambda}$,³ could serve as a probe for quark-gluon plasma formation. Another interesting signature may be the possible creation of exotic

multistrange hadrons.⁴ After identifying the strangeness-producing mechanisms we compute the relevant rates as functions of the energy density ("temperature") of the plasma state and compare them with those for light u and d quarks.

In lowest order in perturbative QCD $s\bar{s}$ -quark pairs can be created by annihilation of light quark-antiquark pairs [Fig. 1(a)] and in collisions of two gluons [Fig. 1(b)]. The averaged total cross sections for these processes were calculated by

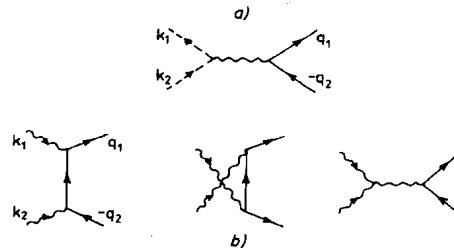
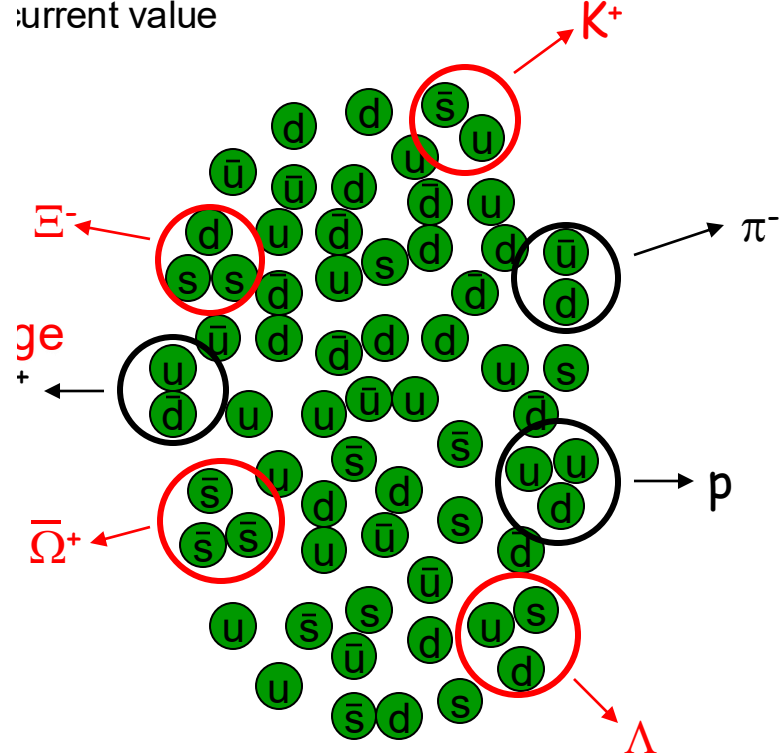


FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q} \rightarrow s\bar{s}$, (b) $gg \rightarrow s\bar{s}$.

on of s
current value



Strangeness enhancement

- **restoration of χ symmetry -> increased production of s**

- mass of strange quark in QGP expected to go back to current value

- $m_s \sim 150 \text{ MeV} \sim T_c$

- 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]

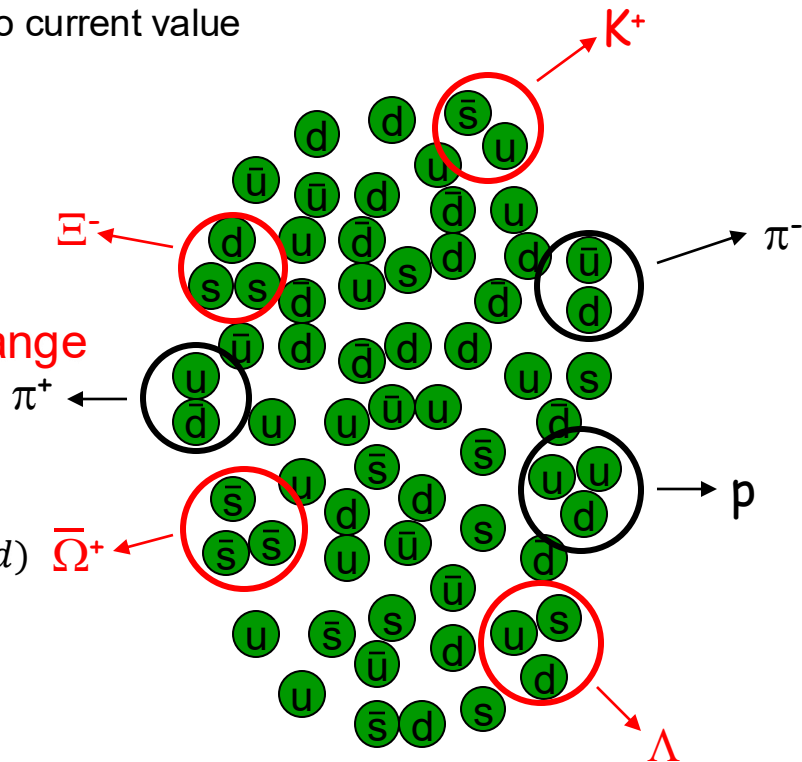
- **deconfinement → stronger effect for multi-strange**

- can be built recombining s quarks

- strangeness enhancement increasing with strangeness content

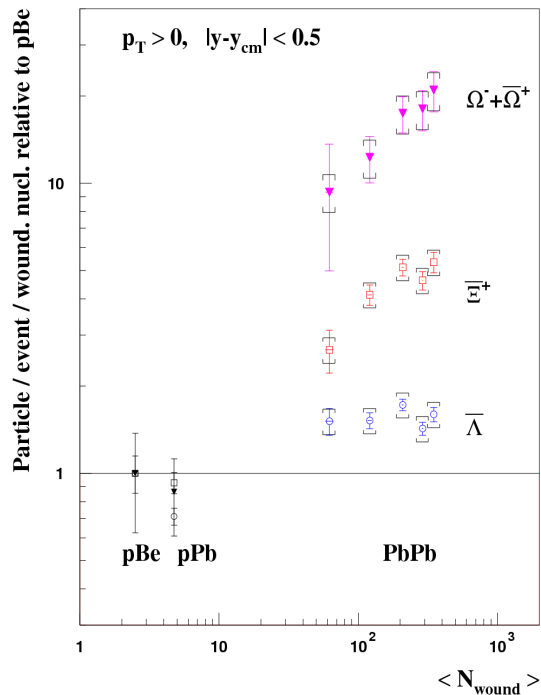
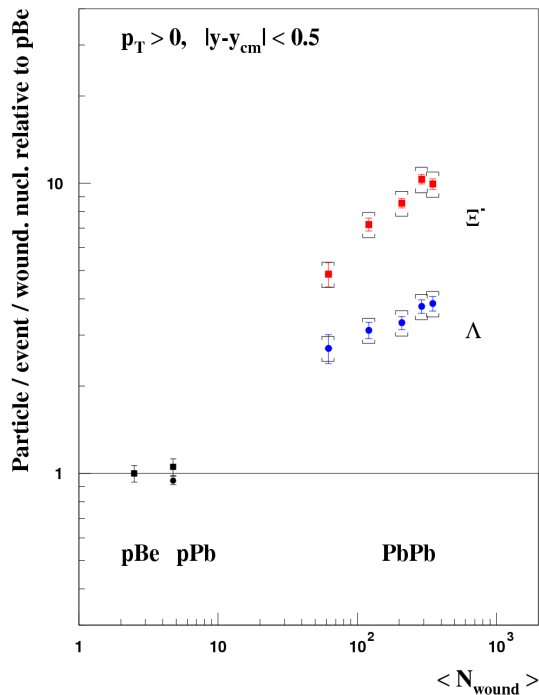
- expect larger for $\Omega(sss)$ than for $\Xi(ssd)$ than for $\Lambda(sud)$

[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 $\sim \times 20$ for the Ω

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 ☆

T. MATSUI

*Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology,
Cambridge, MA 02139, USA*

and

H. SATZ

*Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany
and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*

Received 17 July 1986

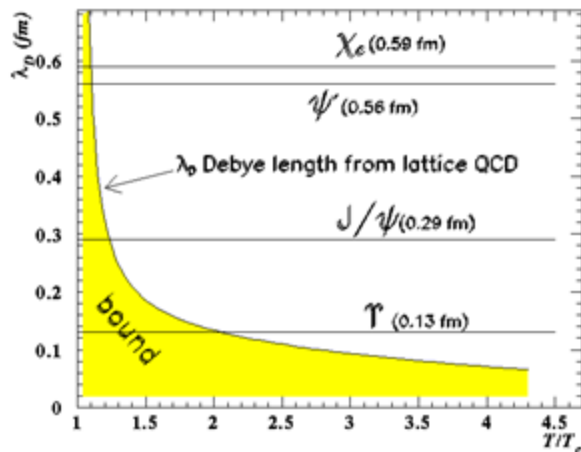
ind $\rightarrow$ suppressed

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

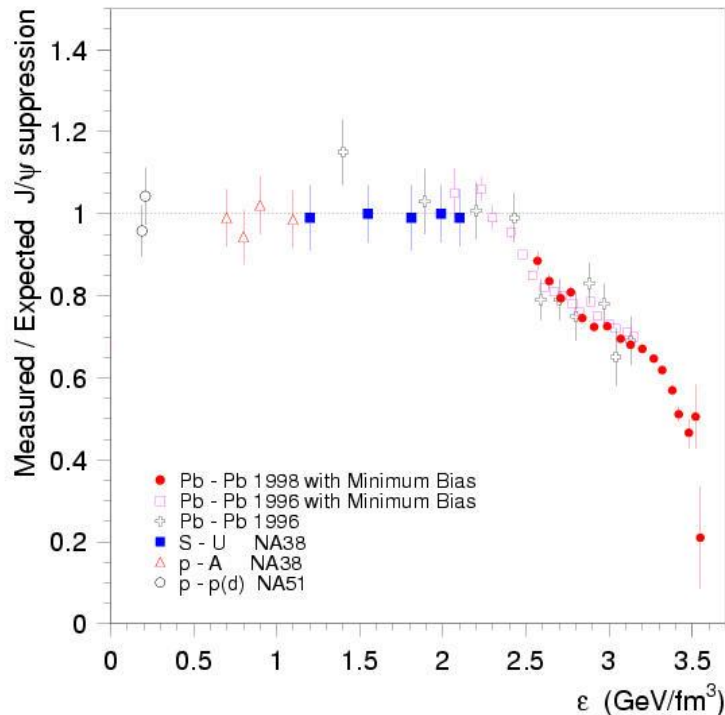


→ states with radius $> \lambda_D$ will not bind → suppressed

- $J/\psi, \psi', \chi_c \rightarrow c\bar{c}$ states
- $\Upsilon \rightarrow b\bar{b}$ states

J/ ψ suppression at the SPS

- **NA50**: “anomalous” suppression



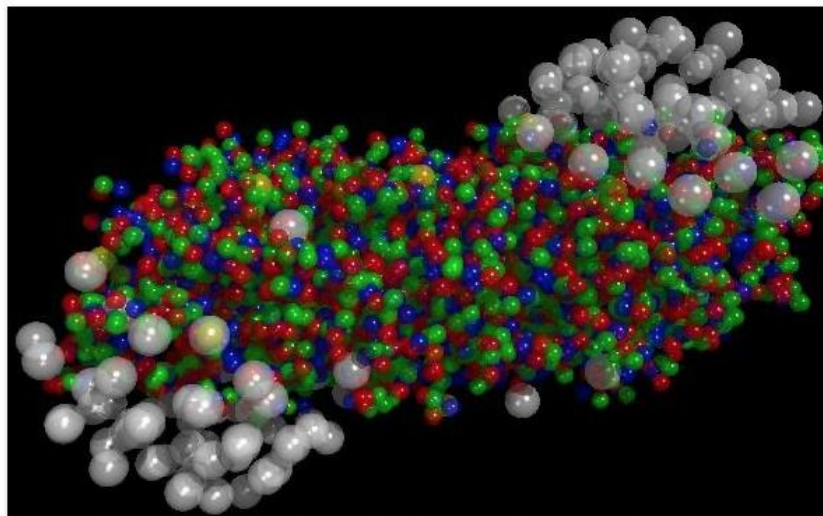
- measured/expected
- sets in at $\epsilon \sim 2.3$ GeV/fm³ ($b \sim 8$ fm)
- (on top of nuclear suppression)
 - due to nuclear absorption effects
 - measured in pA, light ion collisions
 - scaled to Pb-Pb (= 1 in the plot)

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 CERN¹'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 (IN²P³)

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: sta
- 1978: ap
- 1981-82
- 1983: di

A16

THE NEW YORK TIMES

6 JUNE 1983

The New York Times

Founded in 1851

ADOLPH S. OCHS, *Publisher 1896-1935*
ARTHUR HAYS SULZBERGER, *Publisher 1935-1961*
ORVIL E. DRYFOOS, *Publisher 1961-1963*

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GeV)
3eV)

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."

... meanwhile, in the US...

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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...)

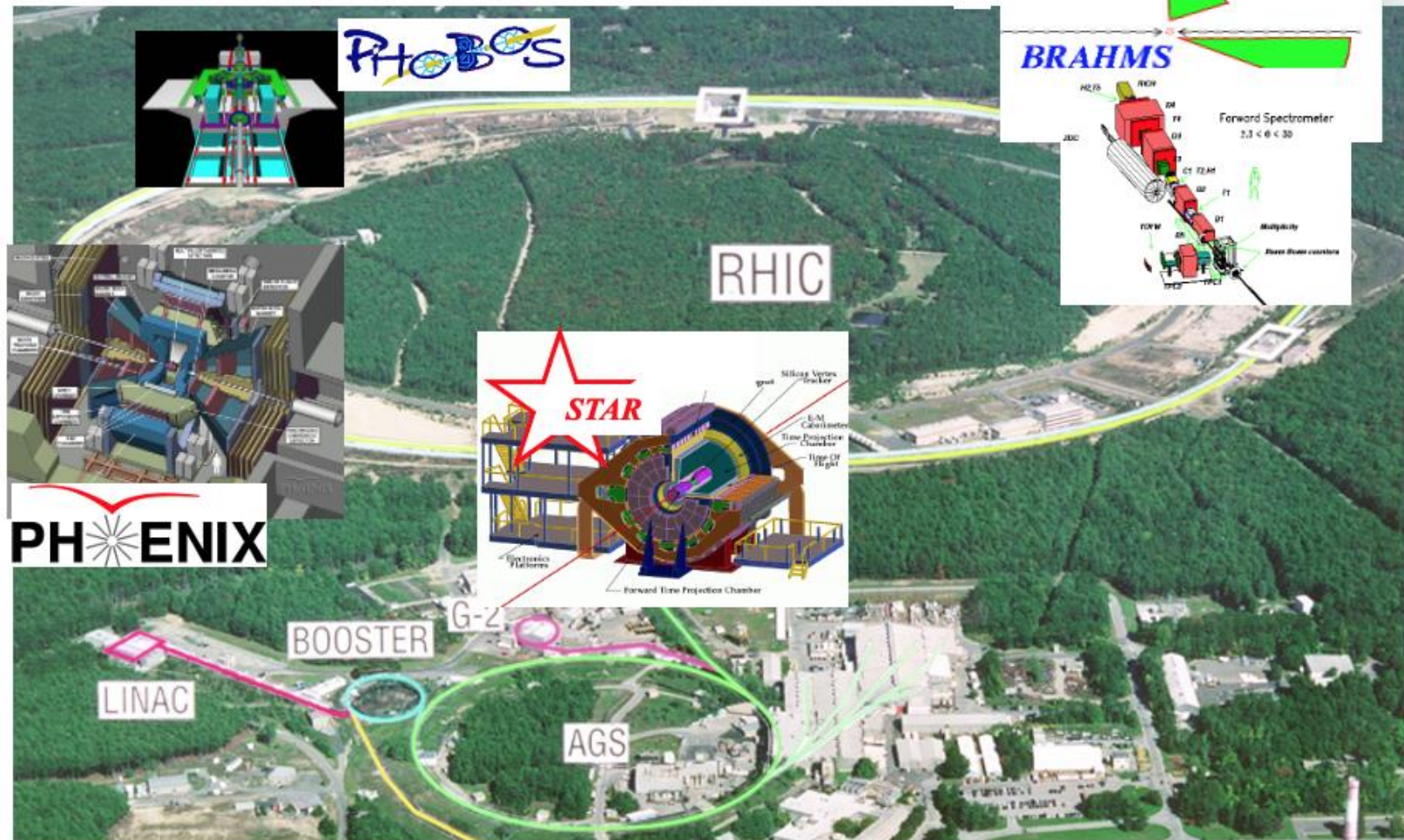
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... meanwhile, in the US...

- 1978: start of construction of ISABELLE pp collider at Brookhaven (400 GeV)
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 - Relativistic Heavy-Ion Collider
 - (that was quick, but already in 1981, at an ISABELLE workshop in Brookhaven...)
- *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

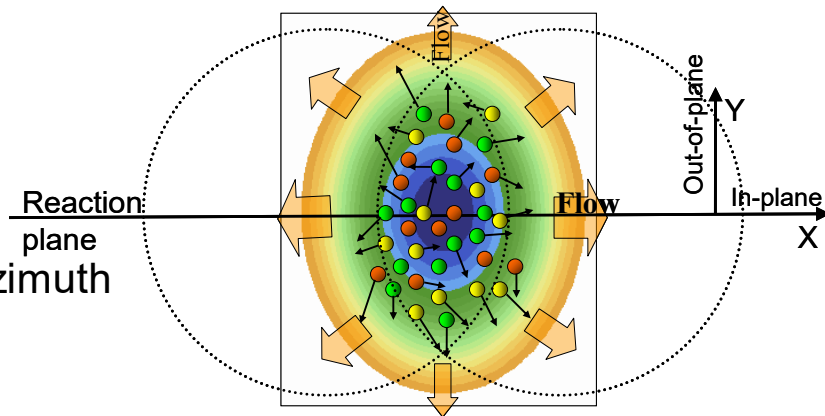
The RHIC experiments



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 $\rightarrow$ larger pressure gradient $\rightarrow$ larger momentum
 - extreme: ideal liquid (zero mean free path, hydrodynamic limit)

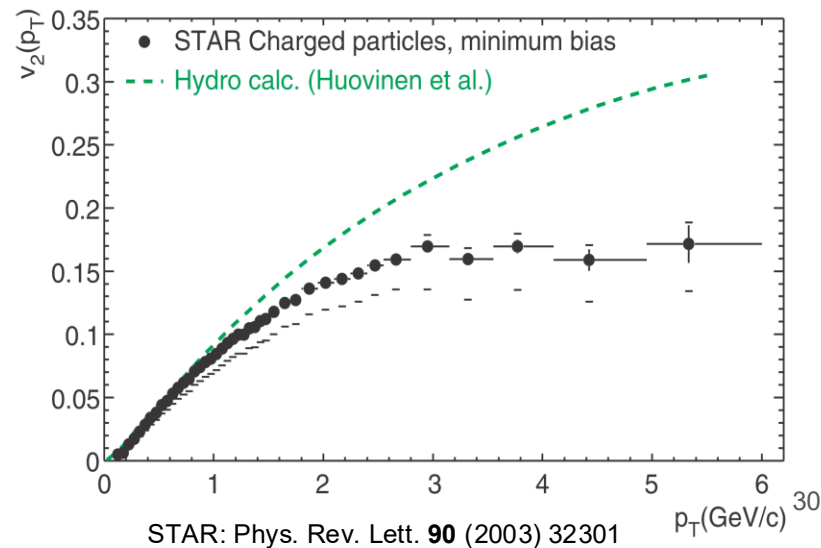
v_2 at RHIC

- to quantify the asymmetry:
 - Fourier expansion of the angular distribution:
 $\propto 1 + 2v_1 \cos(\varphi - \psi_1) + 2v_2 \cos(2[\varphi - \psi_2]) + \dots$
 - in the central detector region ($\vartheta \sim 90^\circ$) $\rightarrow v_1 \sim 0 \rightarrow$ asymmetry quantified with v_2
 - v_2 : “elliptic flow coefficient”
- experimentally: low- p_T $v_2 \sim$ as large as expected by hydrodynamics

- mean free path ~ 0
- i.e. η/s at minimum

→ “almost-perfect liquid”

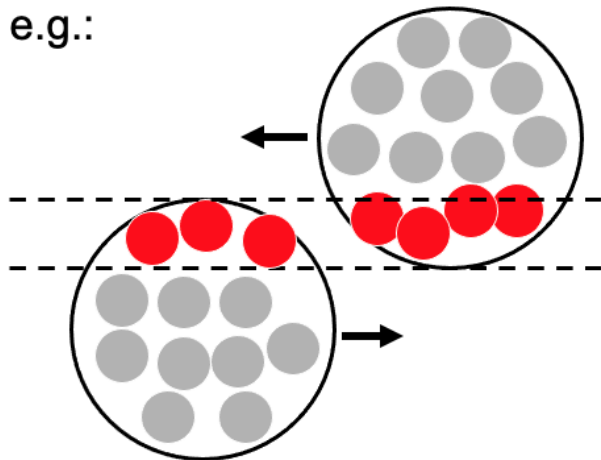
- very efficient transfer of asymmetry from coordinate to momentum space
- “hard” equation of state
- crucial support for QGP picture!



Nuclear modification factor

- participant vs collisions

e.g.:



$N_{\text{part}} = 7$ “participants”

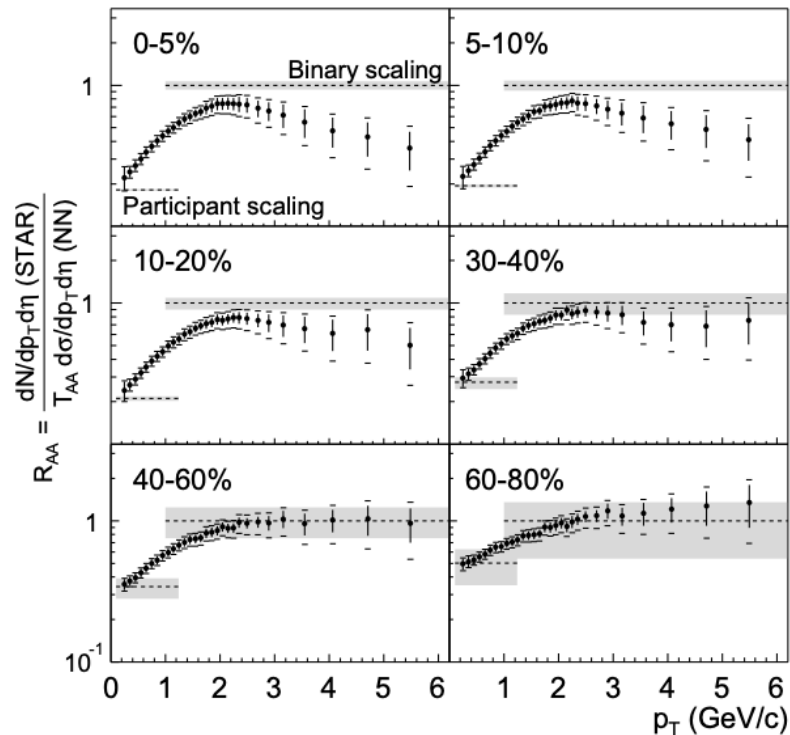
$N_{\text{coll}} = 12$ “binary collisions”

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

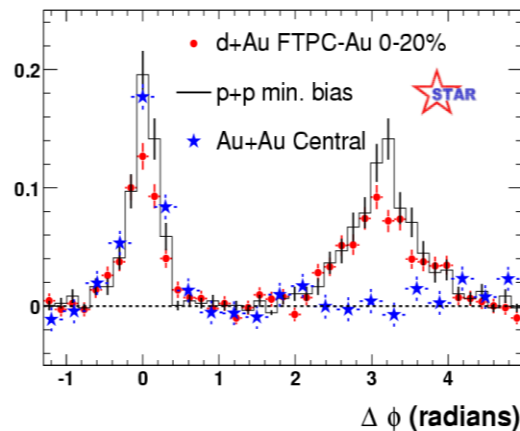
- R_{AA} : “nuclear modification factor”
 - quantifies deviation from N_{coll} scaling

- “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

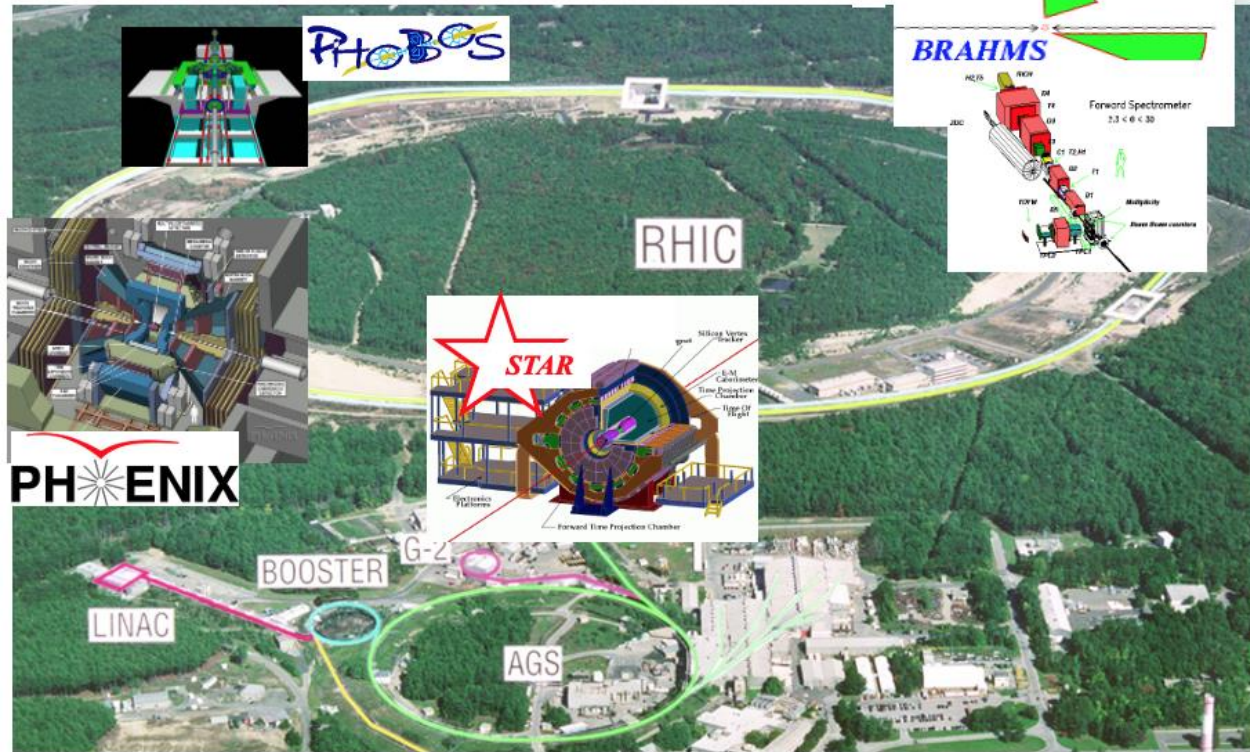


- high- p_T should follow Ncoll
 - if no nuclear/medium effects
- clearly violated for central collisions
- indication of energy loss of partons in the QGP!
 - not due to initial-state effects
 - (checked with pA, dA collisions)
- coherent with picture from azimuthal correlations



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

The RHIC experiments



→ strongly-coupled QGP (sQGP)

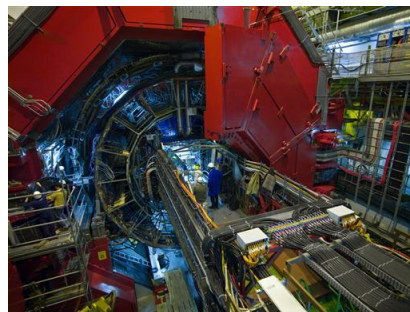
much more in the “RHIC White Papers” (NPA 757, 2005)

... meanwhile, in Europe...

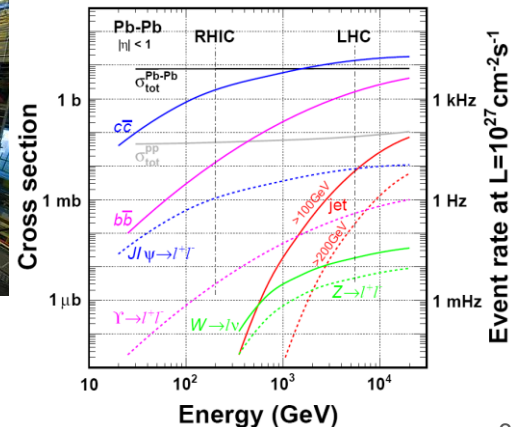
- 1984: ECFA meeting in Lausanne: pp machine in LEP tunnel
 - (n.b.: first collisions in LEP only in 1989!)
- 1986 start of heavy-ion collisions at CERN/SPS and Brookhaven/AGS
- capability to collide heavy ions in LHC quickly realised
 - mentioned at a workshop on Physics at Future Accelerators in La 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!

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

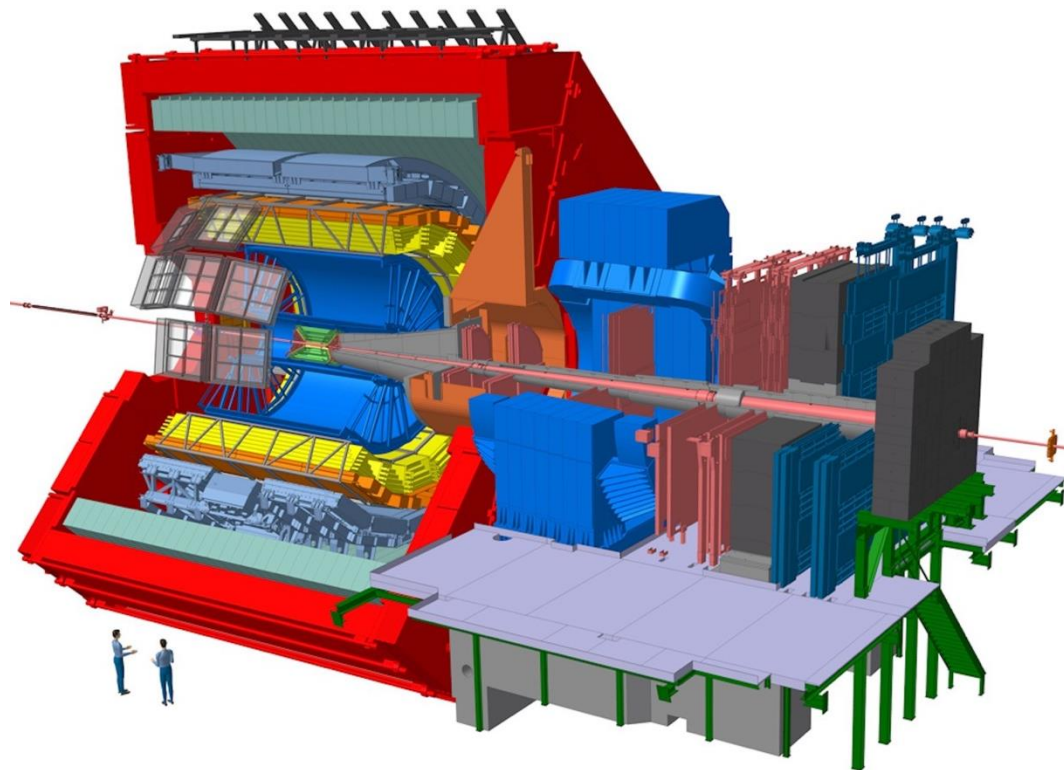


- ALICE
 - dedicated experiment
 - ~1070 authors, ~ 170 institutions, 40 countries
- ATLAS, CMS, LHCb also participating in programme



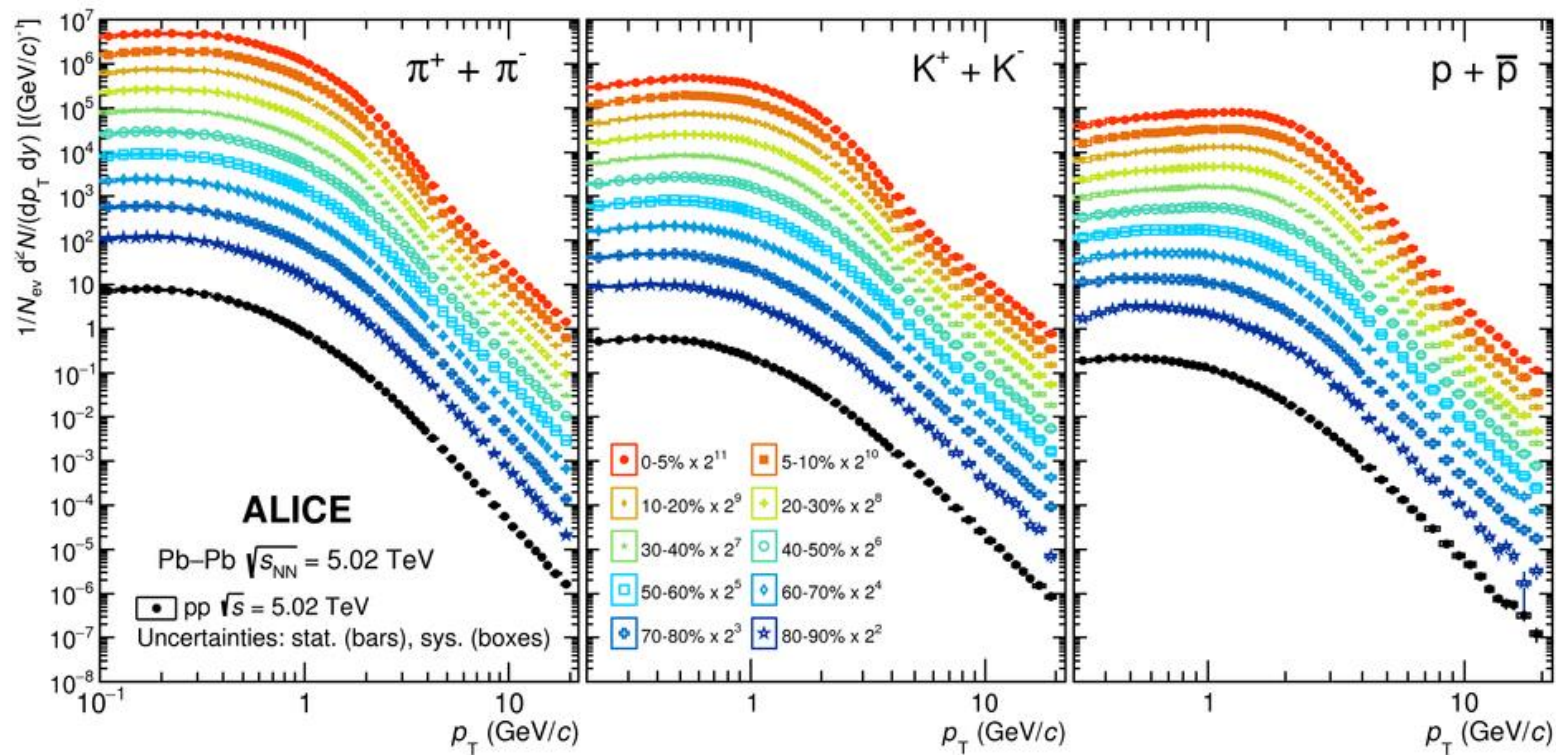
The ALICE experiment

- two main parts
 - barrel ($|\eta| < 0.9$), $B = 0.5$ Tesla
 - muon spectrometer, $-4 < \eta < -2.5$
- high-precision reconstruction
 - low material tracking
 - high-resolution vertexing
 - hadron and lepton ID
- trigger-less readout
 - for the main detectors
 - up to 50 kHz for Pb-Pb
- collisions systems (so far) : Pb-Pb, pp, p-Pb, Pb-p, Xe-Xe, OO, pO, Ne-Ne



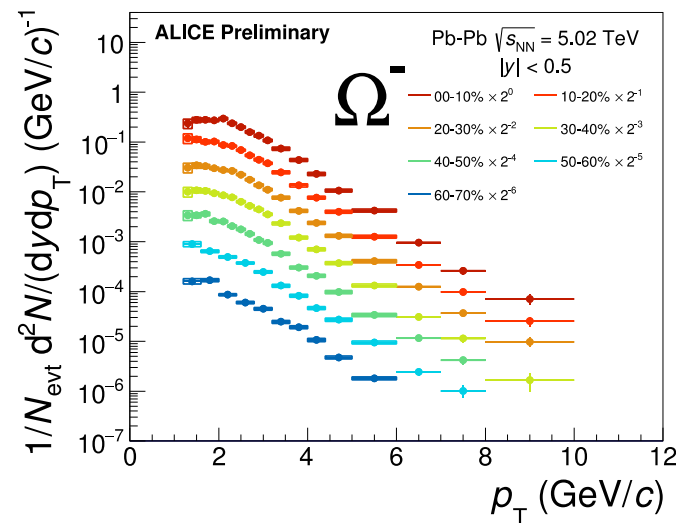
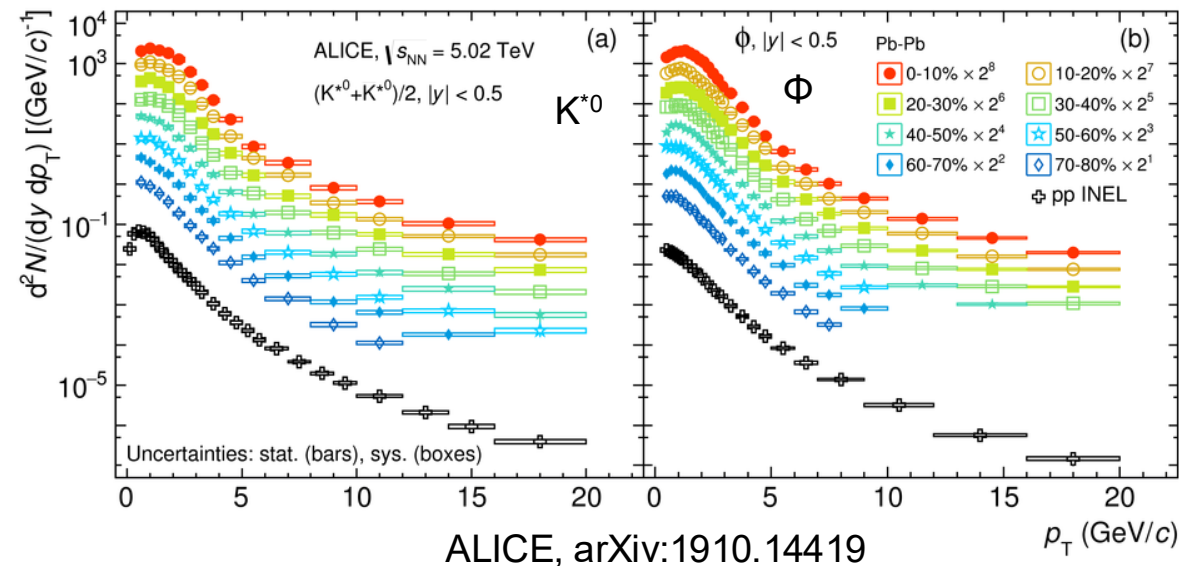
this July!

Identified particles



More and more species

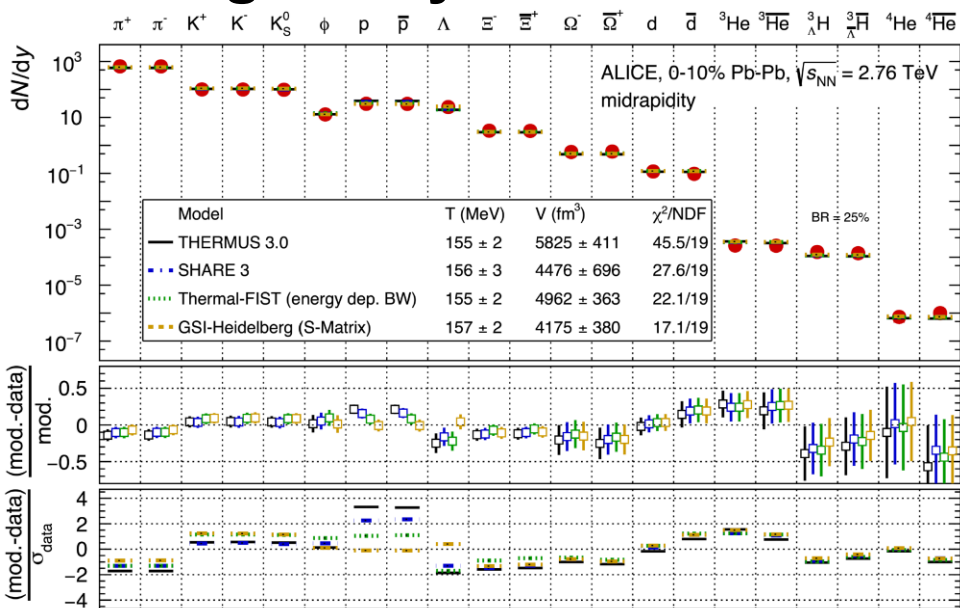
- Resonances, hyperons, ...



ALI-PREL-131316

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

Integrated yields

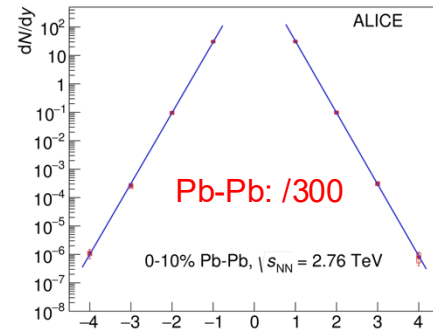
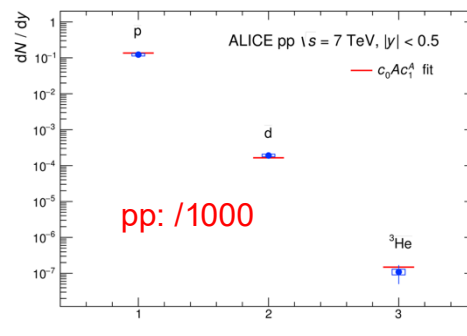


$$T_{\text{chem}} \approx T_C \approx 156 \text{ MeV}$$

arXiv:2211.04384

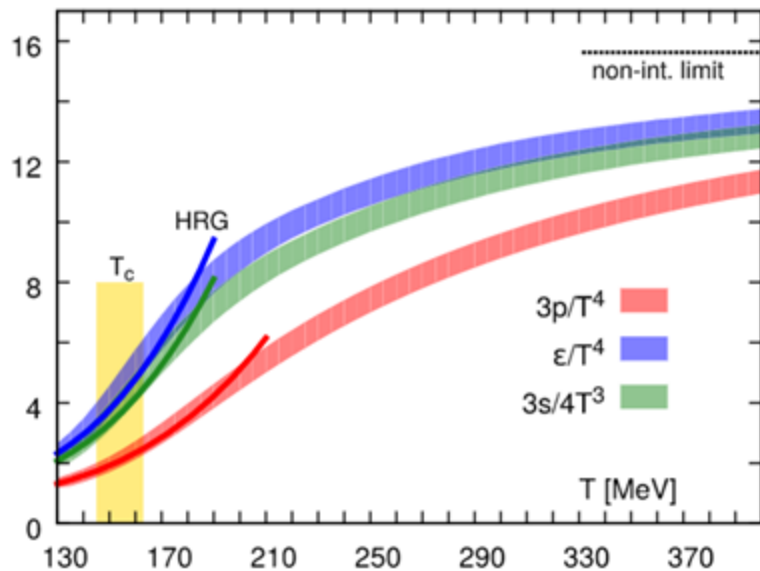
→ hadronisation very close to the phase transition

- 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^* , $p/\Lambda/\Xi$
 - 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

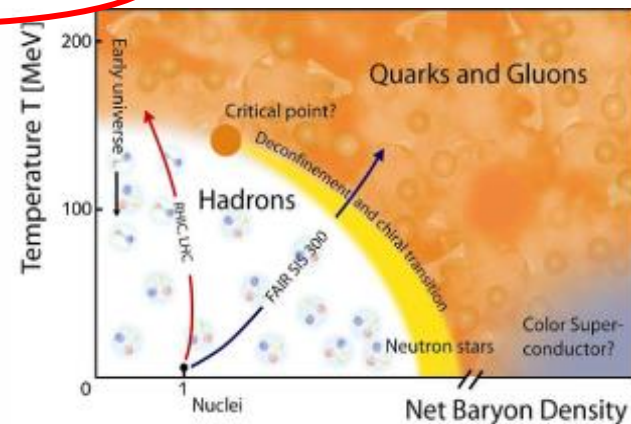
- the rigorous way of performing calculations in the non-perturbative regime of QCD
- discretisation on a space-time lattice
 - → ultraviolet (i.e. large-momentum scale) divergencies can be avoided



[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
- $T_c = (156.5 \pm 1.5) \text{ MeV}$ [A Bazavov et al. Phys.Lett.B 795 (2019) 15]

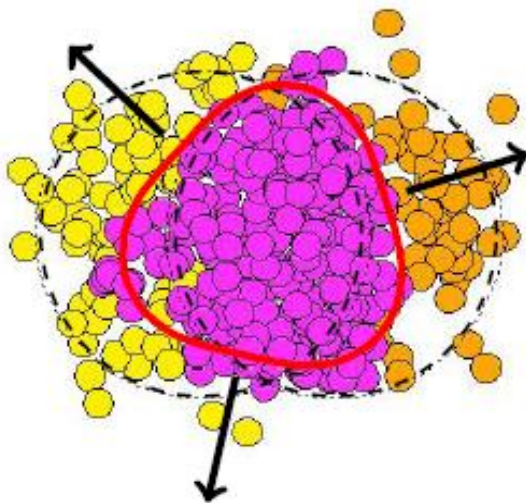
- $\epsilon \sim O(\text{GeV}/\text{fm}^3)$



Higher harmonics: a beautiful tool...

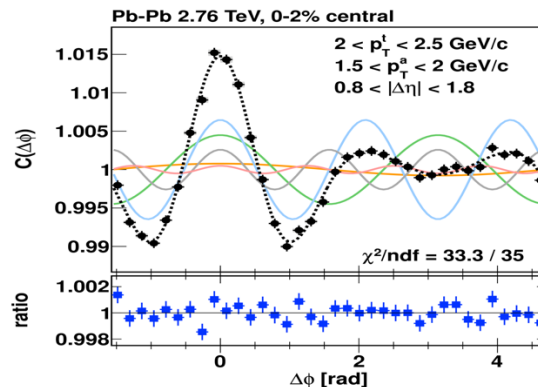
initial-state geometrical asymmetries $\longrightarrow$ final state momentum asymmetries

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

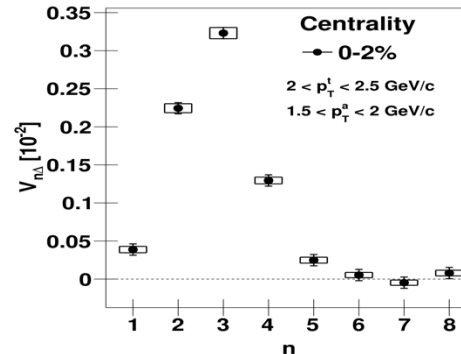


$\rightarrow$ Fourier decomposition of azimuthal distribution

- “flow harmonics”
- sensitive to transport parameters of medium



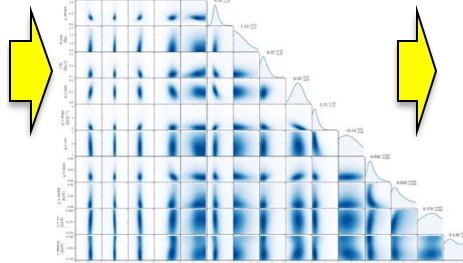
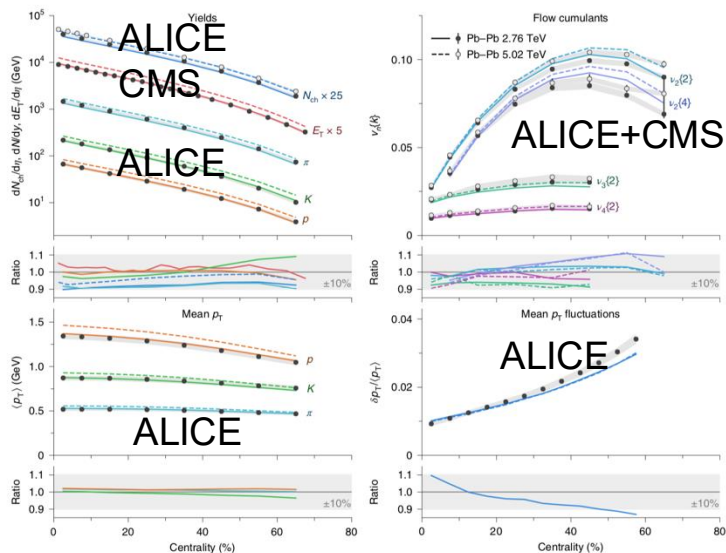
ALICE-PUB-14115



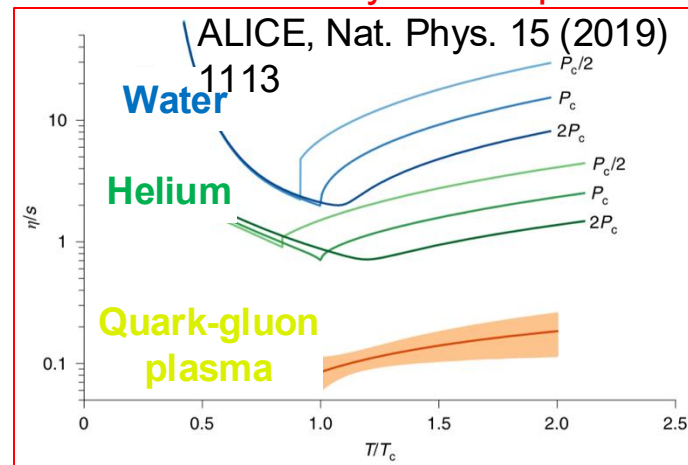
ALICE-PUB-14119

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



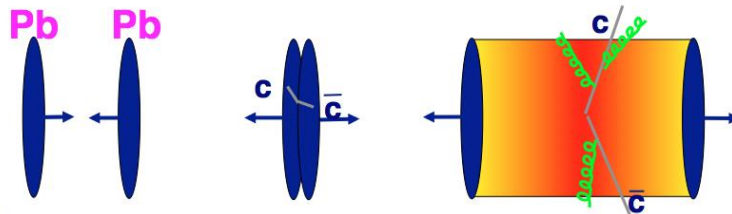
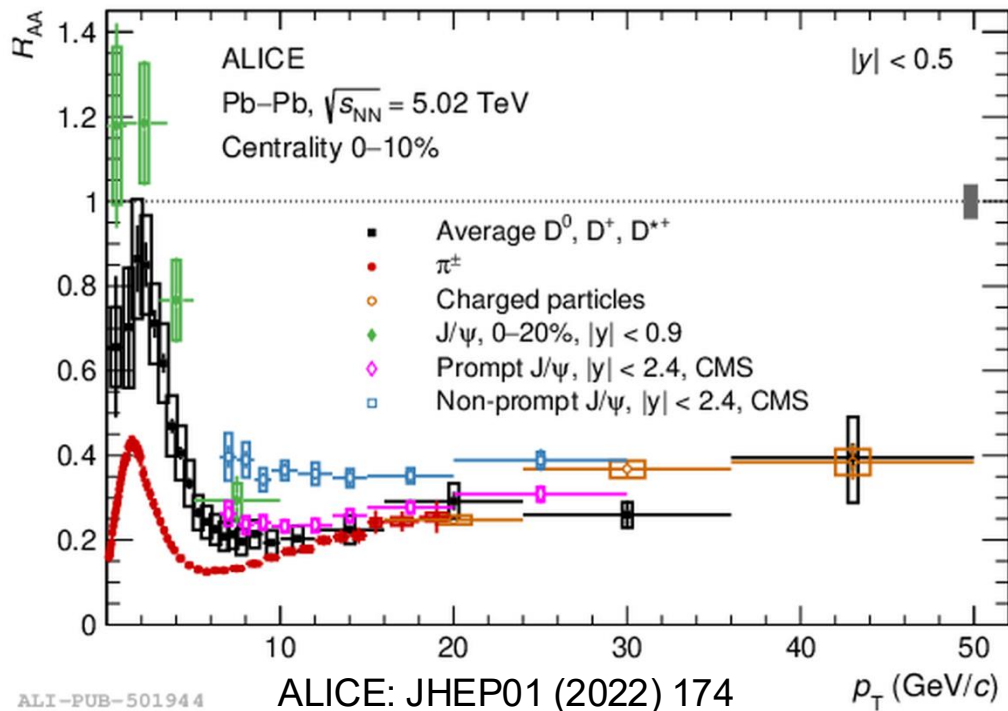
QGP shear viscosity vs. temperature



- QGP viscosity with $\sim 20\%$ precision
- QGP ~ 10 times less viscous than any other form of matter

Heavy flavour!

a gold mine!

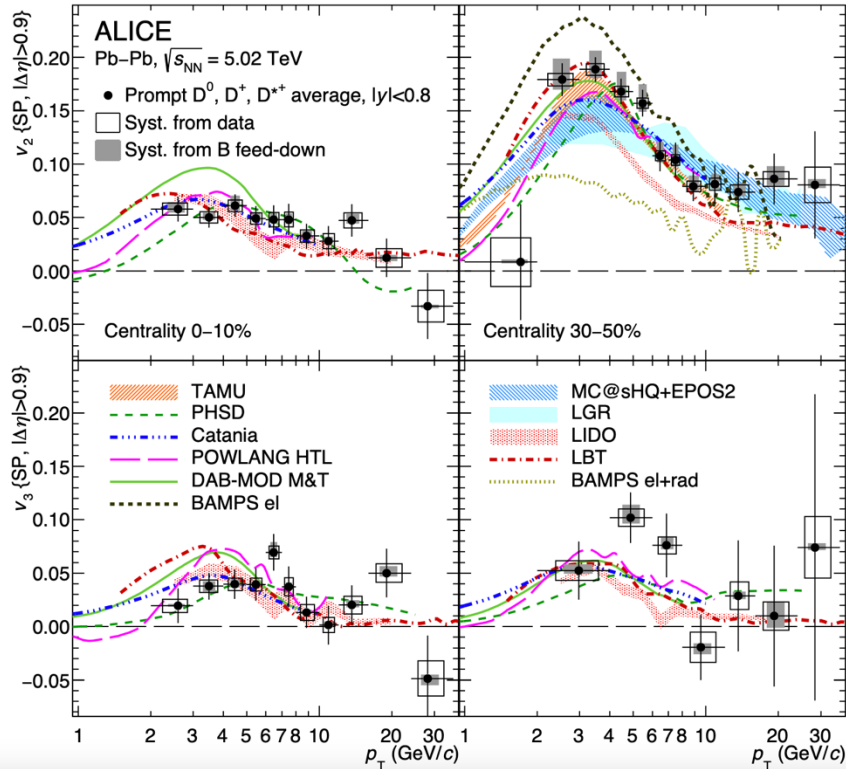


- controlled probe
 - mass
 - colour charge
 - pQCD
- generated in initial parton scattering
- conserved throughout evolution
- large mass $\rightarrow$ “Brownian” probe
- powerful probe of hadronisation

experimentally:

- strongly coupled to medium
- clear hierarchy at low p_T

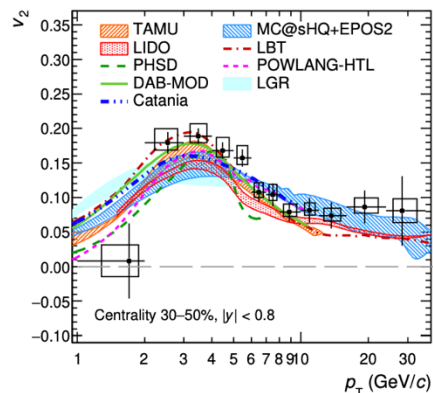
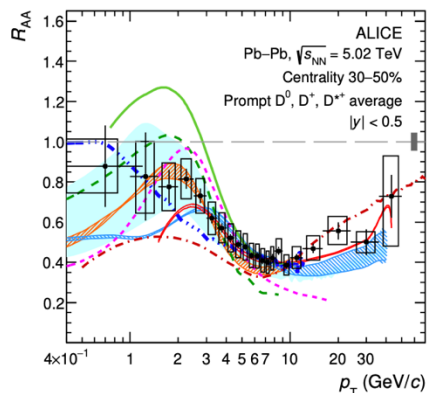
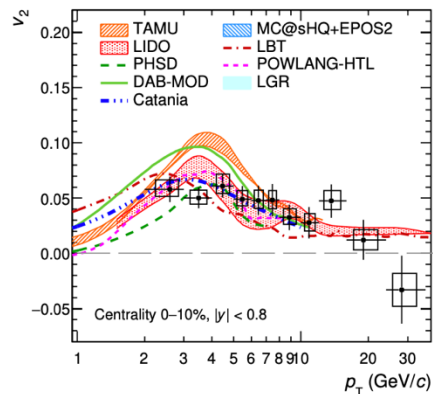
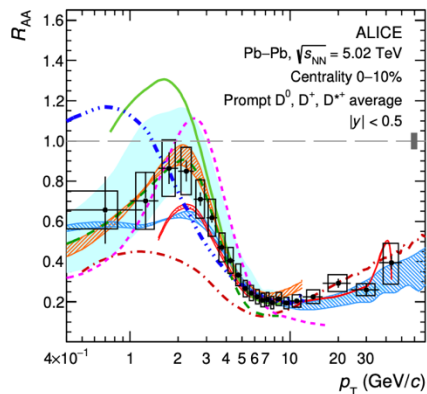
Strongly involved in the flow



v_2

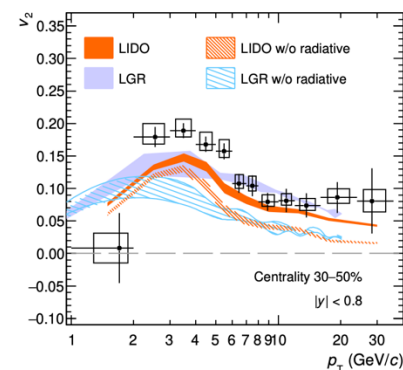
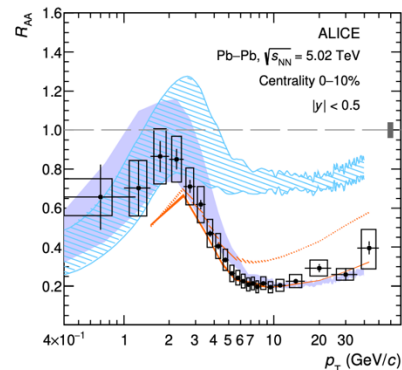
and v_3 !

State-of-the-art...

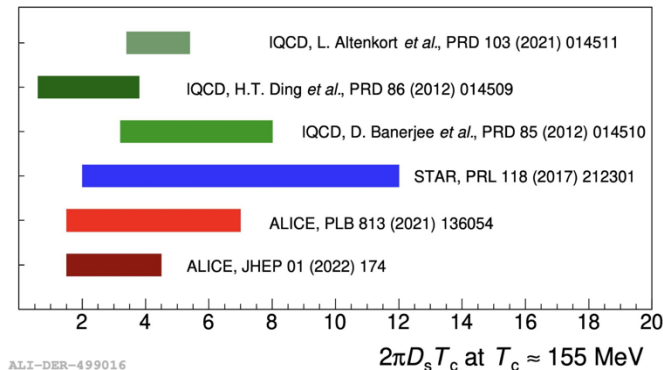


ALICE: JHEP01 (2022) 174

- substantial model constraints...

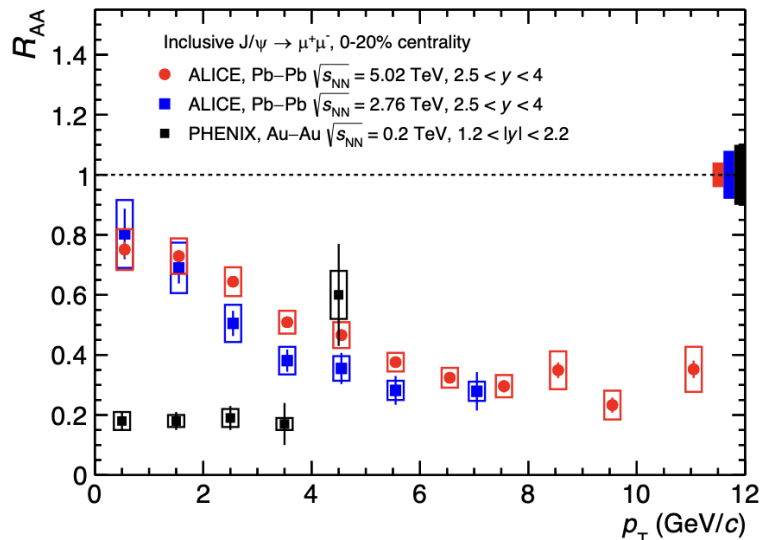
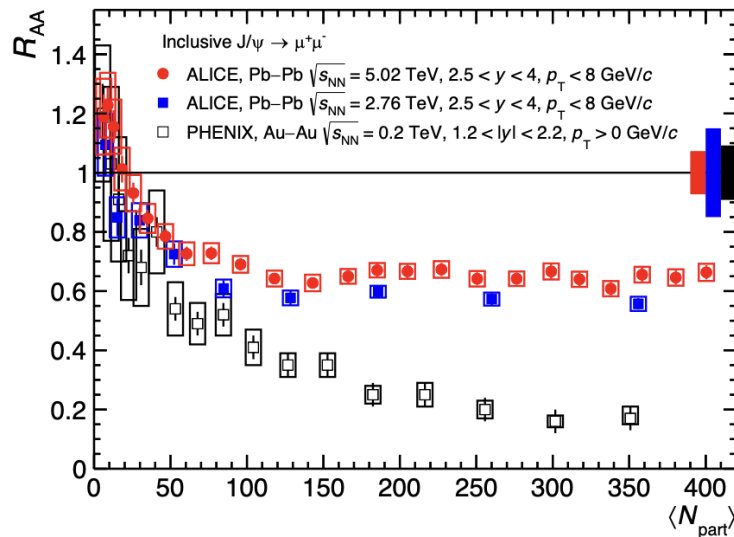


- 50% uncertainty on diffusion coefficient
 - it starts to be a measurement!



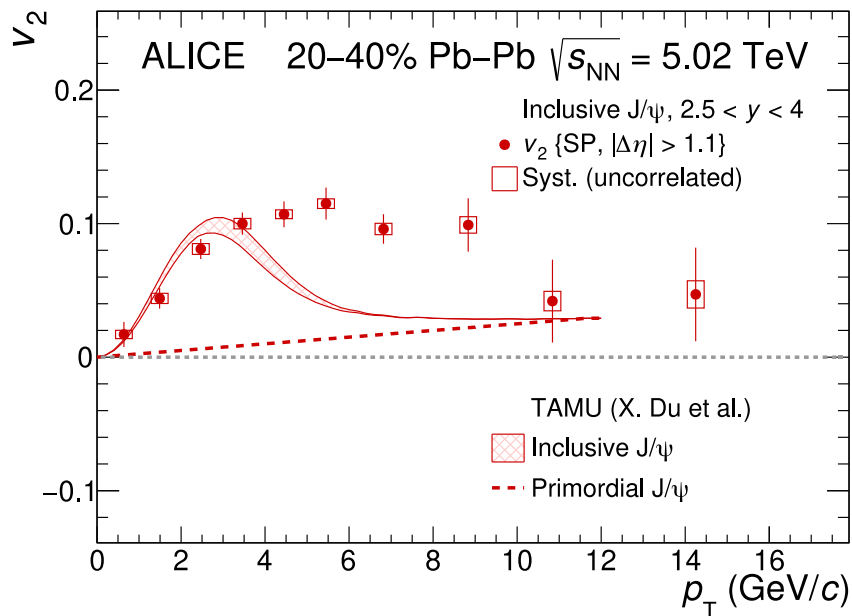
A new regime for J/ψ production!

- a remarkable change of behaviour from SPS/RHIC!

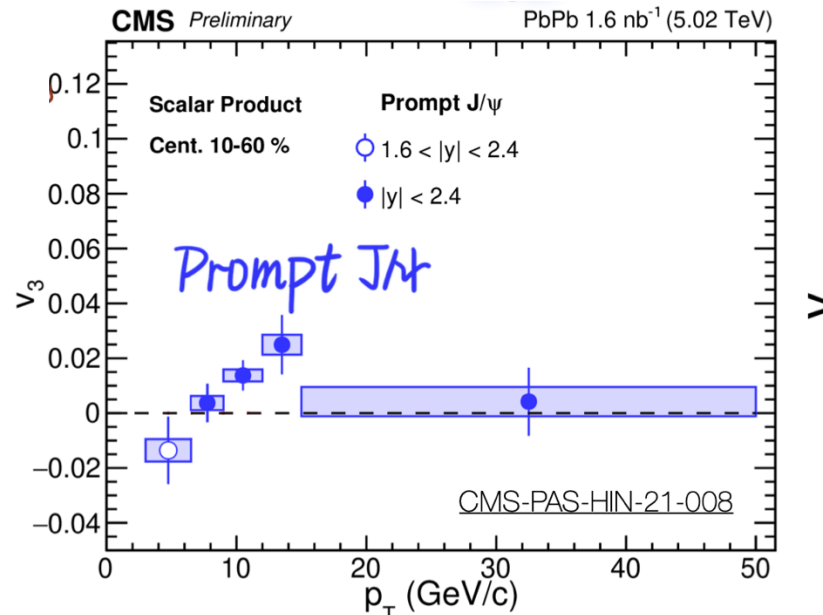


- in both the centrality and the p_T dependence
- evidence for production by recombination of exogamous $c\bar{c}$ pairs!

Charm quarks themselves flow

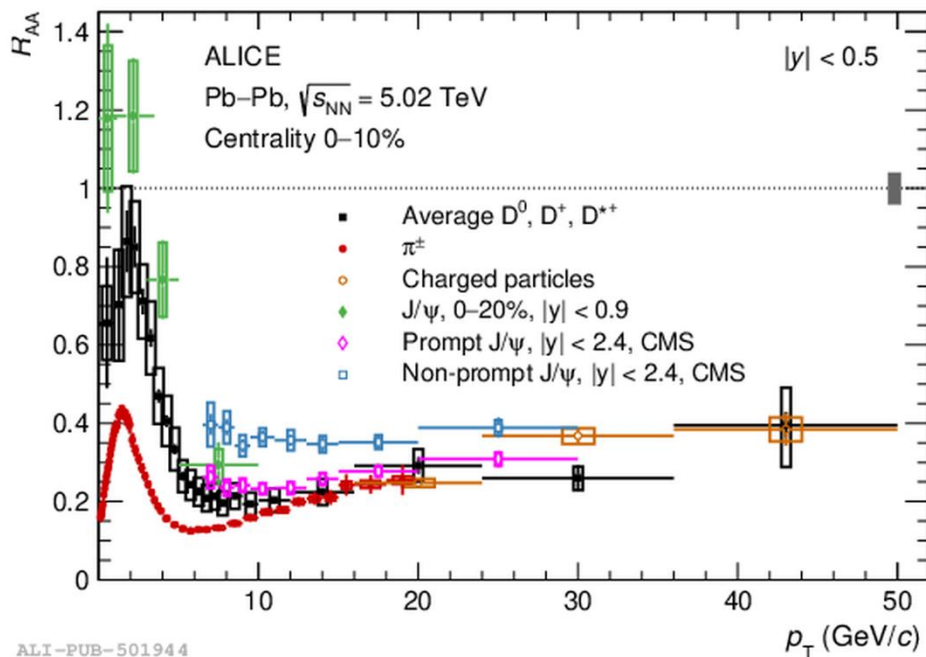


ALICE: JHEP 10 (2020) 141

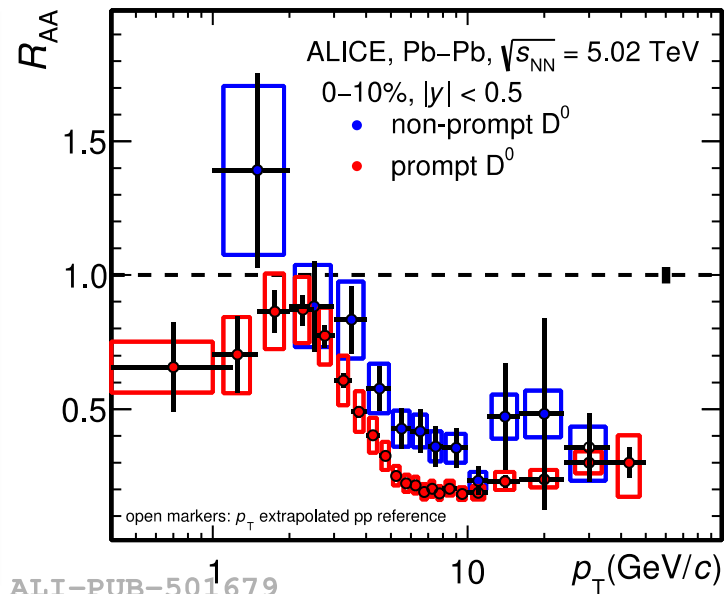


CMS: PAS-HIN-21-008

Beauty is quenched, too...



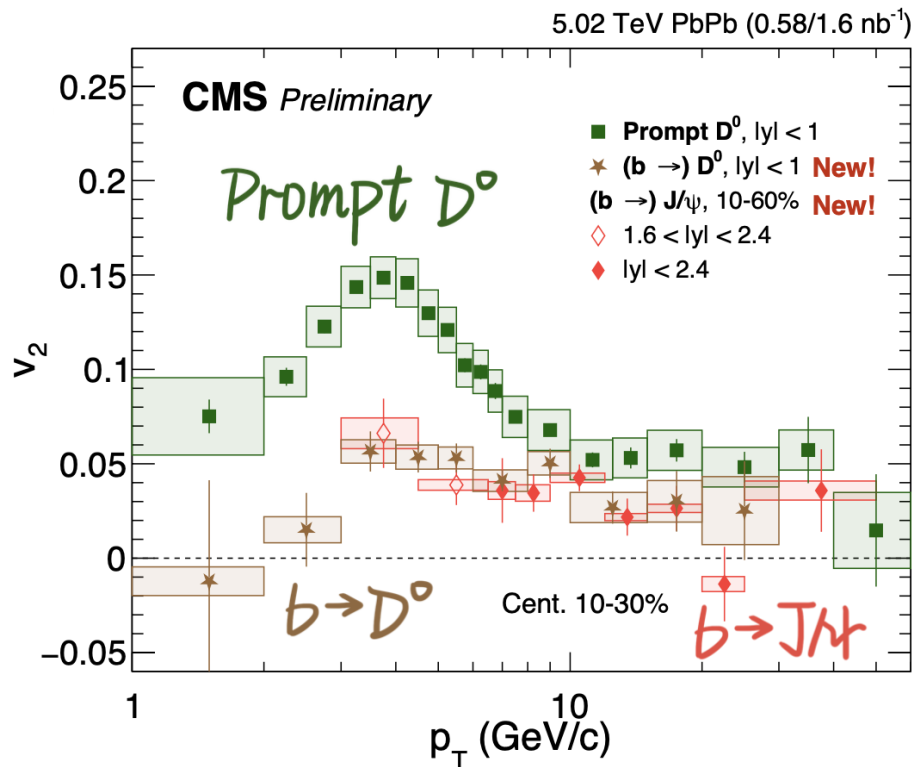
ALI-PUB-501944



ALI-PUB-501679

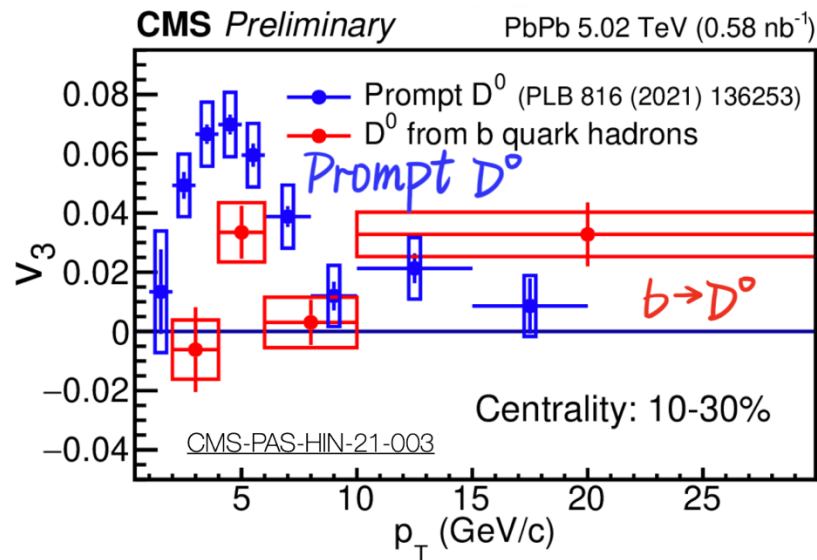
- less so than charm...

... and it flows, too...

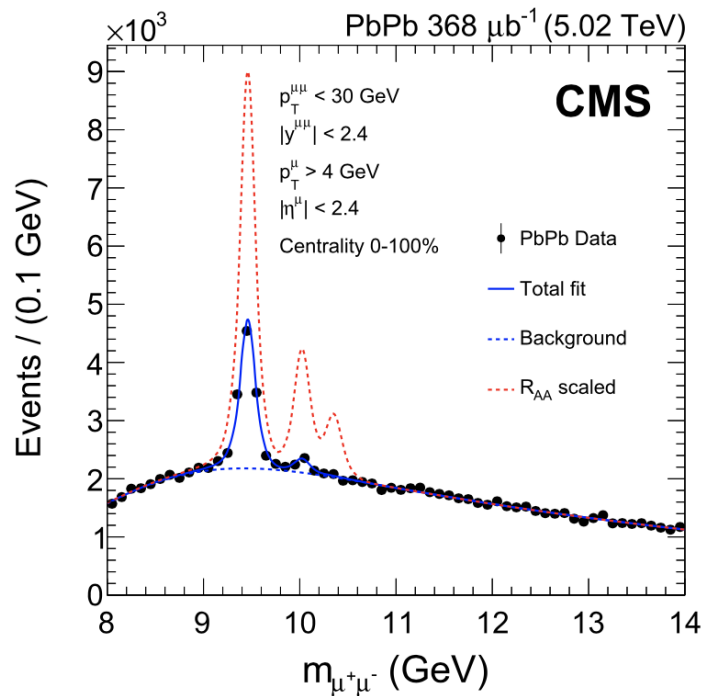


- less so than charm...

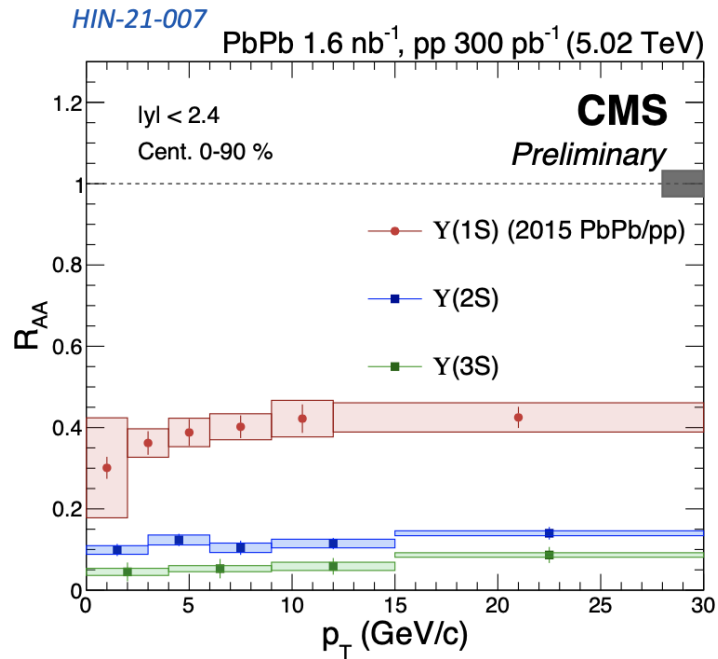
- similar trend for v_3 :



Υ states seem to follow a sequential suppression pattern

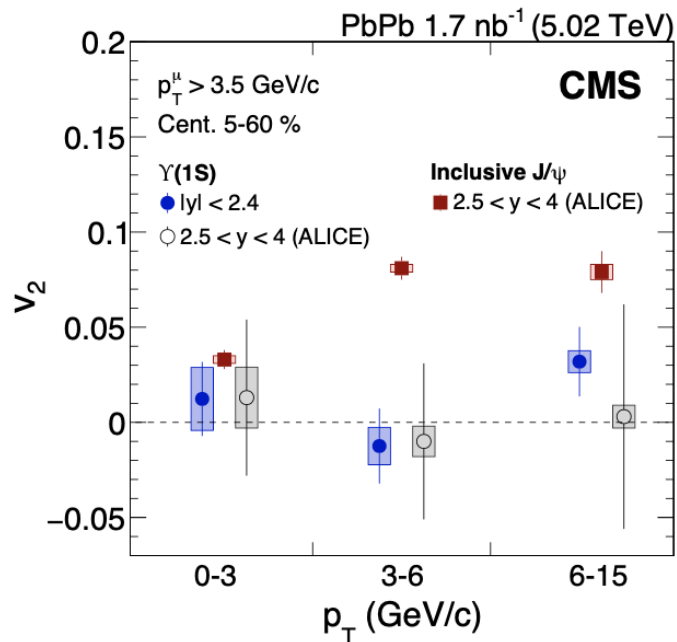


CMS: PLB 790 (2019) 270



CMS: PAS-HIN-21-007

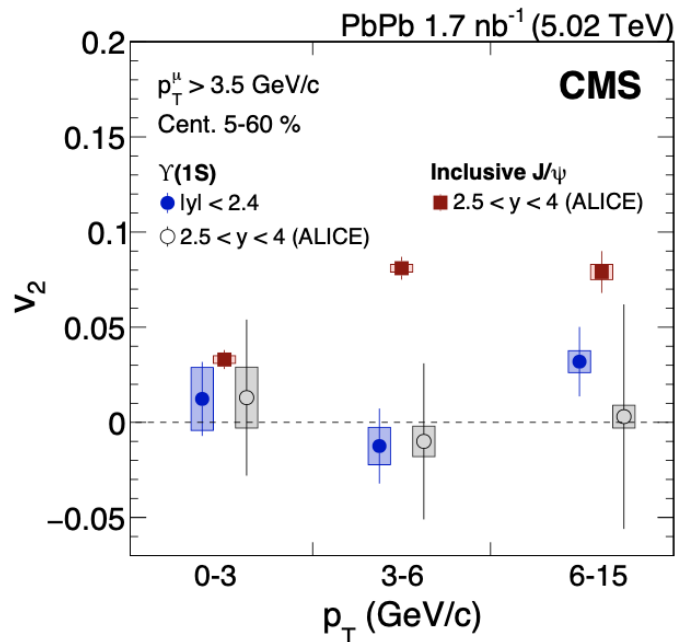
... but the Υ doesn't seem to flow much...



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

CMS: PLB 819 (2021) 136385

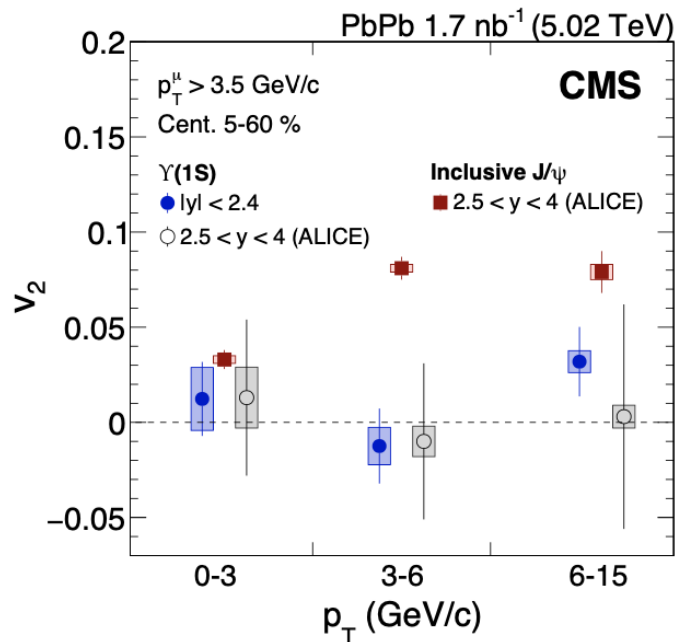
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CMS: PLB 819 (2021) 136385

- could it be that b quarks don't flow?
 - and B get their flow from light quarks?
- but should Υ flow reflect b quark flow?
 - recombination component should be small

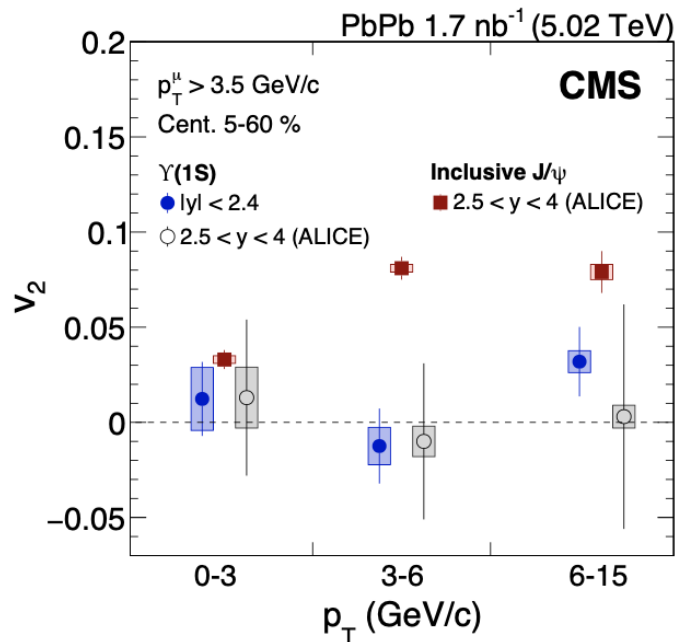
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CMS: PLB 819 (2021) 136385

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

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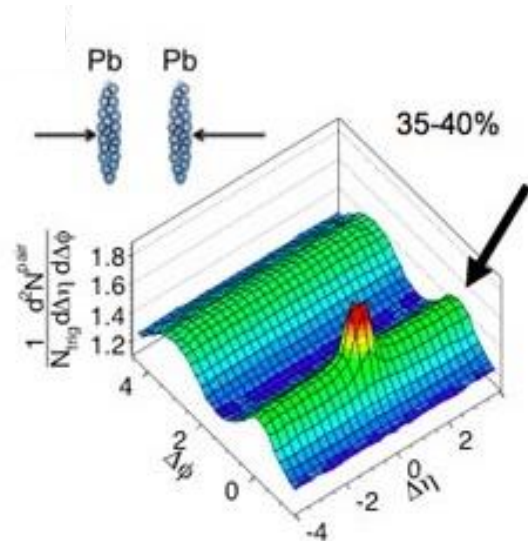
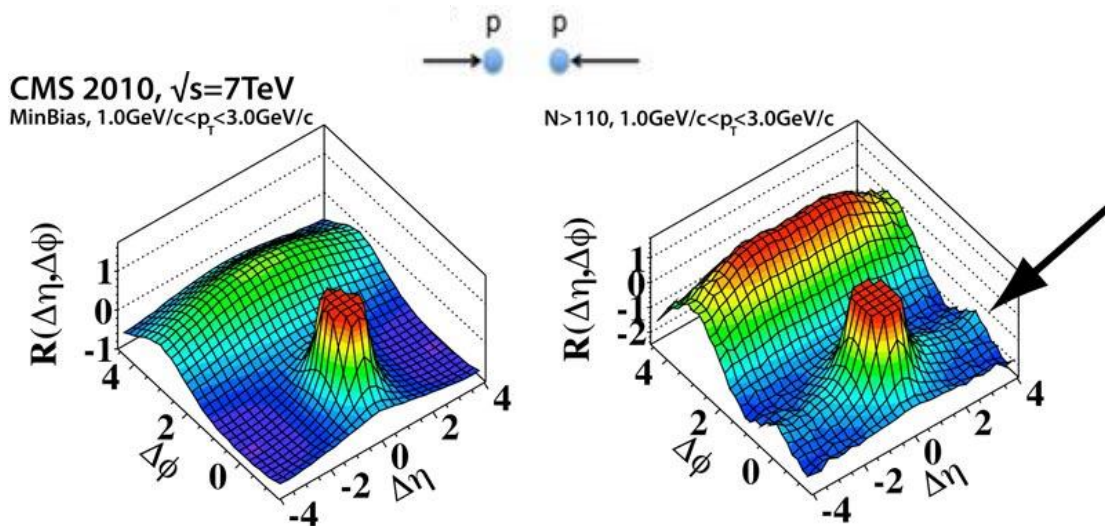


CMS: PLB 819 (2021) 136385

- could it be that b quarks don't flow?
 - 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?
- 🤔 ...

Small systems: a new frontier

- long-range ridge on near side in high-multiplicity pp collisions at the LHC!
- very similar structure as in Pb-Pb collisions
 - where it is connected with v_2

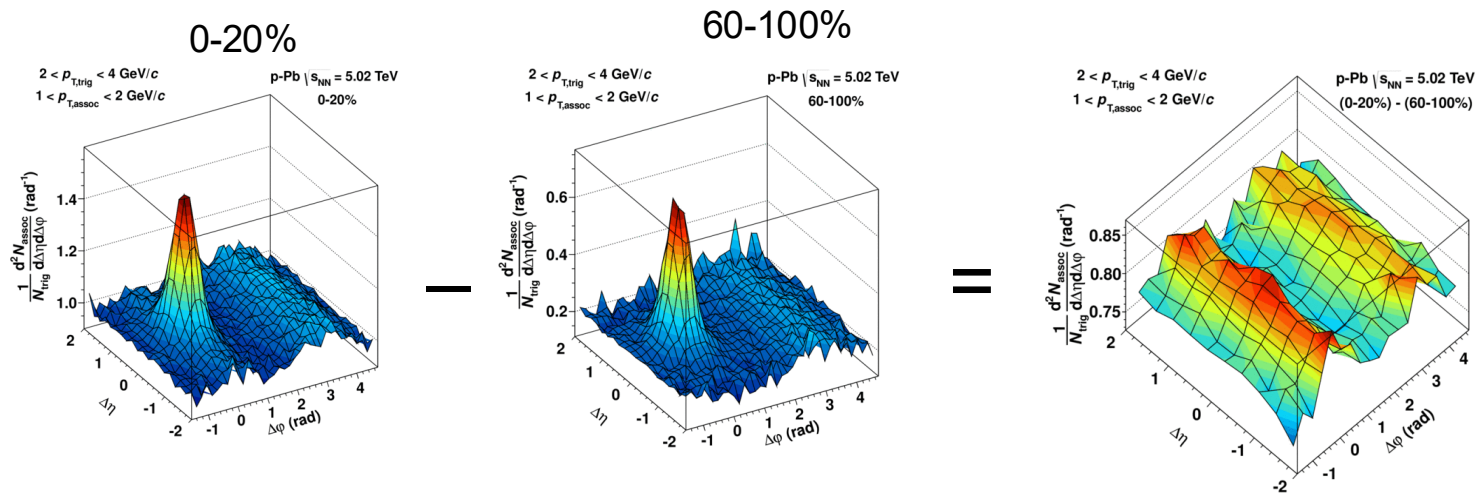


CMS: JHEP 1009:091,2010

ALICE: Phys Lett B 719 (2013) 29

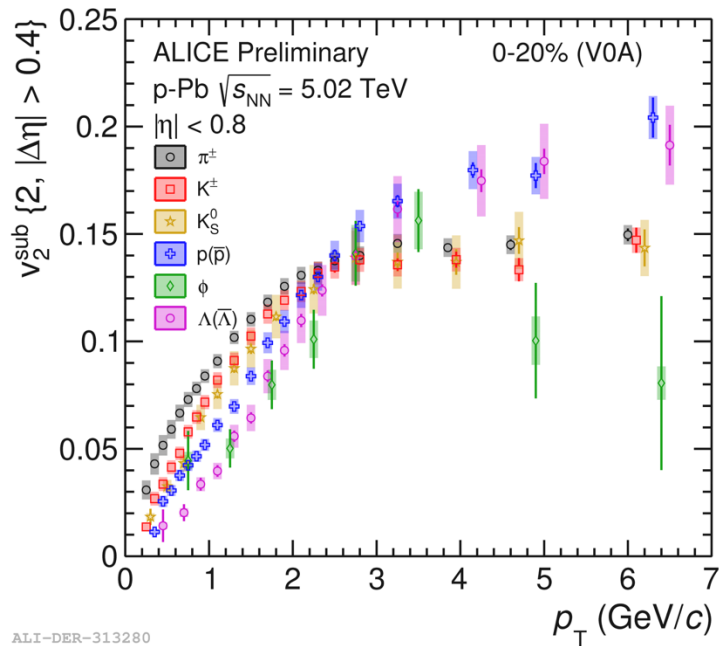
Near- and away-side ridge in p-Pb

- evidence for collective behaviour in high-multiplicity p-Pb,
 - e.g. symmetric double-ridge when subtracting low from high mult'y p-Pb

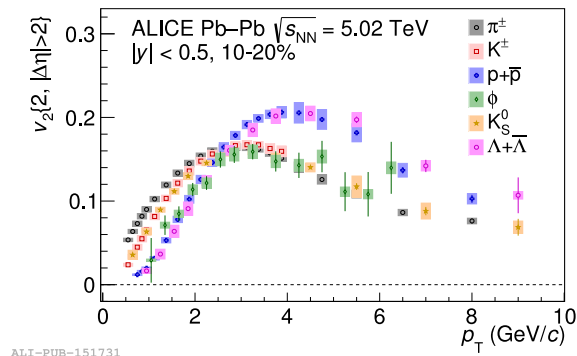


ALICE: Phys Lett B 719 (2013) 29

v_2 for identified particles in p-Pb

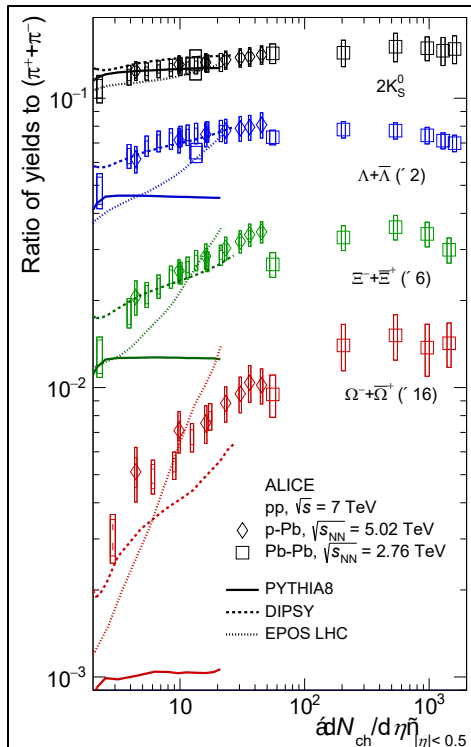


- clear mass ordering at high multiplicity
 - same as in Pb-Pb

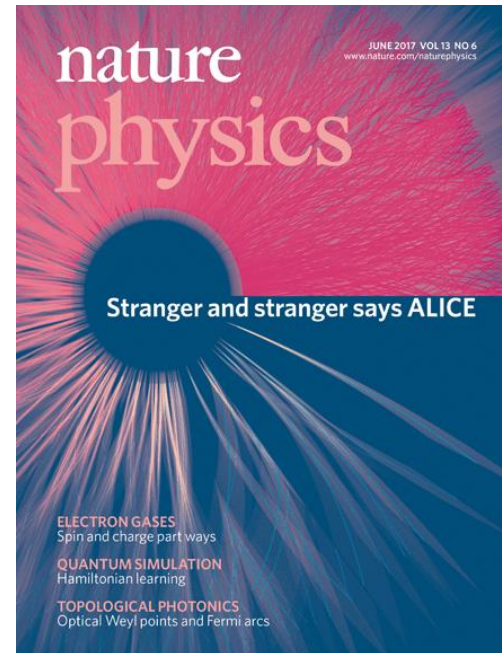


- consistent with common velocity field
- consistent with hydrodynamic expansion!

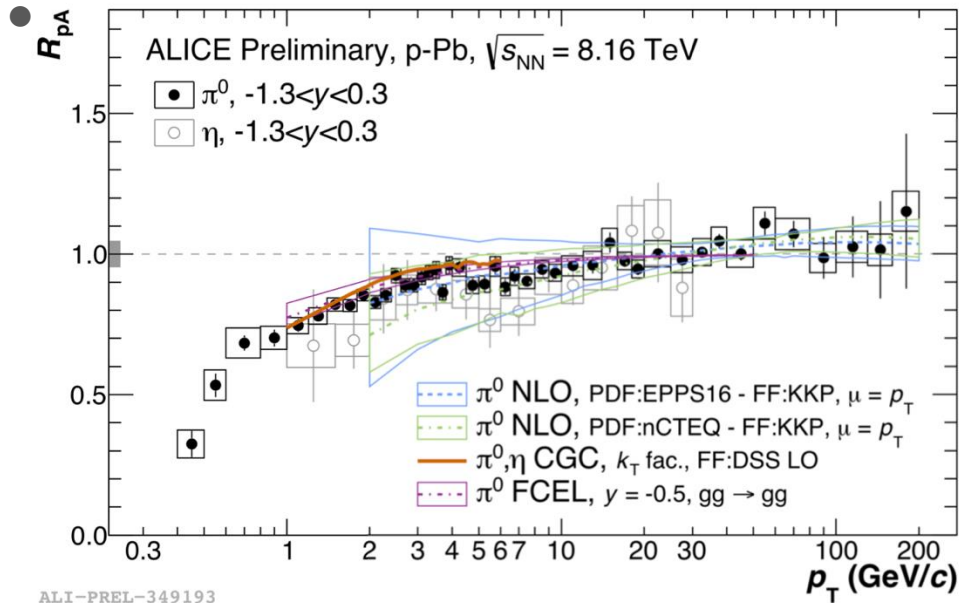
Strangeness enhancement in pp!



- one of the hallmarks of QGP
- predicted in 1982
J Rafelski & B Müller, PRL 48 (1982) 1066
- ➔ observed at SPS in the 90's
WA97, NA57, NA49
- now observed in high-mult pp!
 - not reproduced by models
- a precursor phenomenon?
- QGP in high-mult pp???
- ➔ new directions for research!
 - study effects turn-on, evolution
 - new weapon: pp generators!



But no sign of quenching yet!

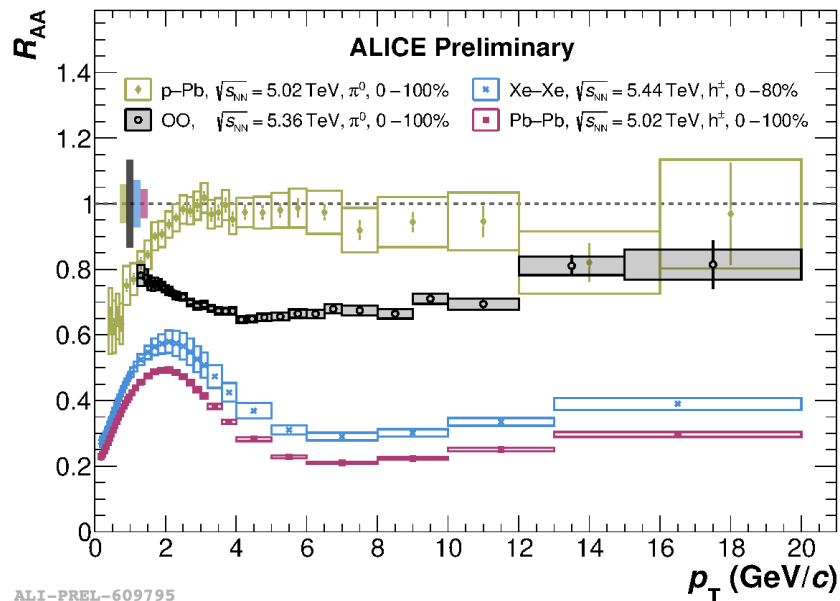


[ALICE: PLB 827 (2022) 136943]

Light ions in the LHC!

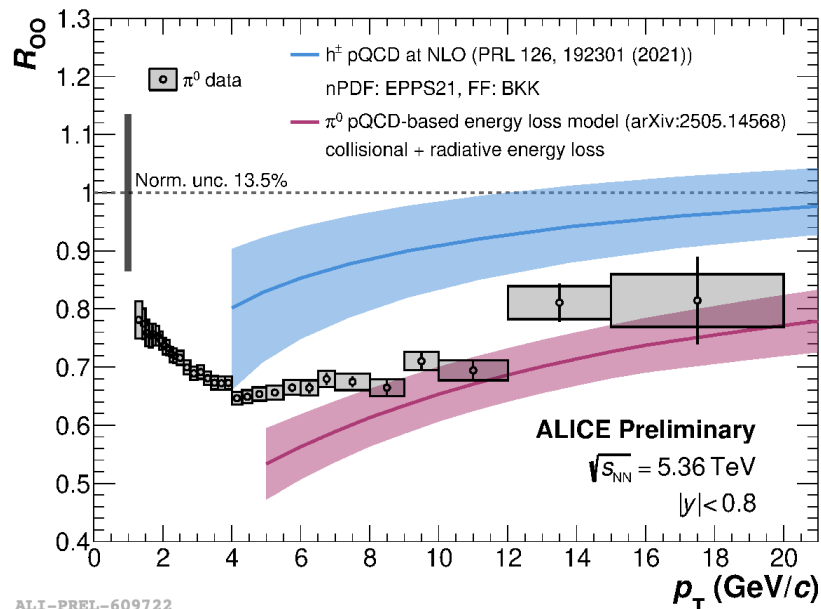
OO, pO and Ne-Ne collisions in the LHC in July

- significant quenching observed!



ALI-PREL-609795

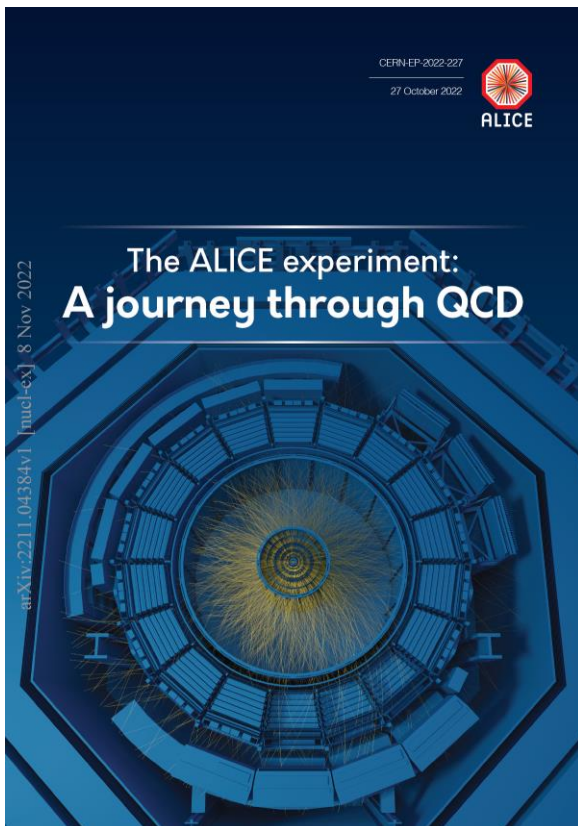
- beyond nPDF suppression



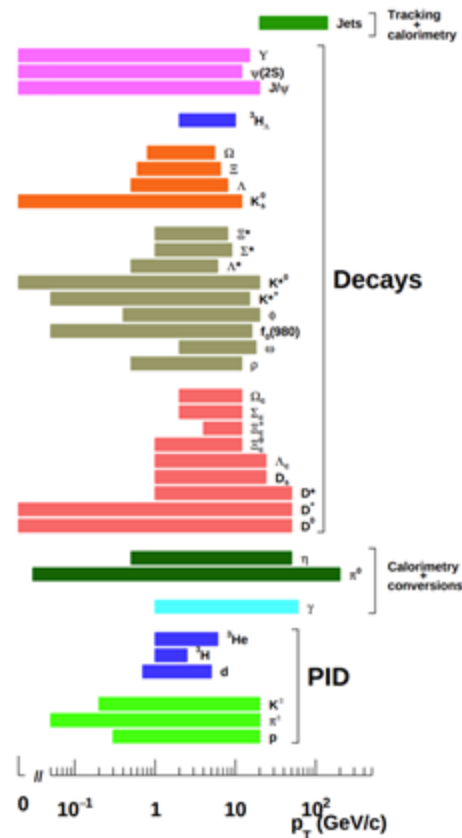
ALI-PREL-609722

→ stay tuned!

ALICE results from LHC Run 1, 2: full review

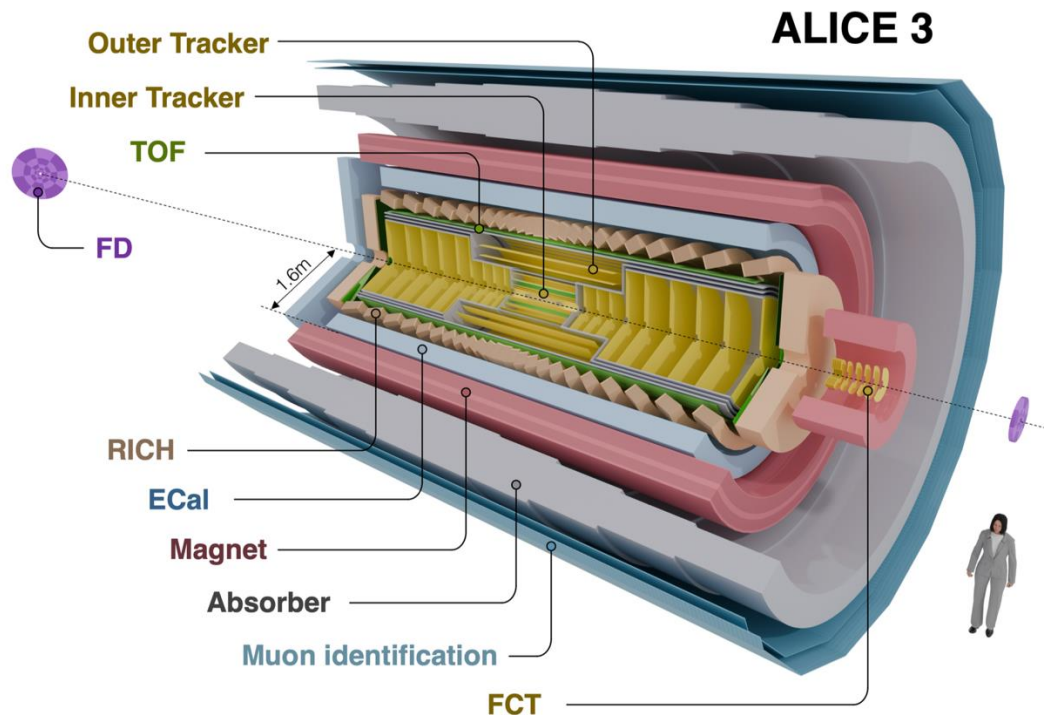


arXiv:2211.04384



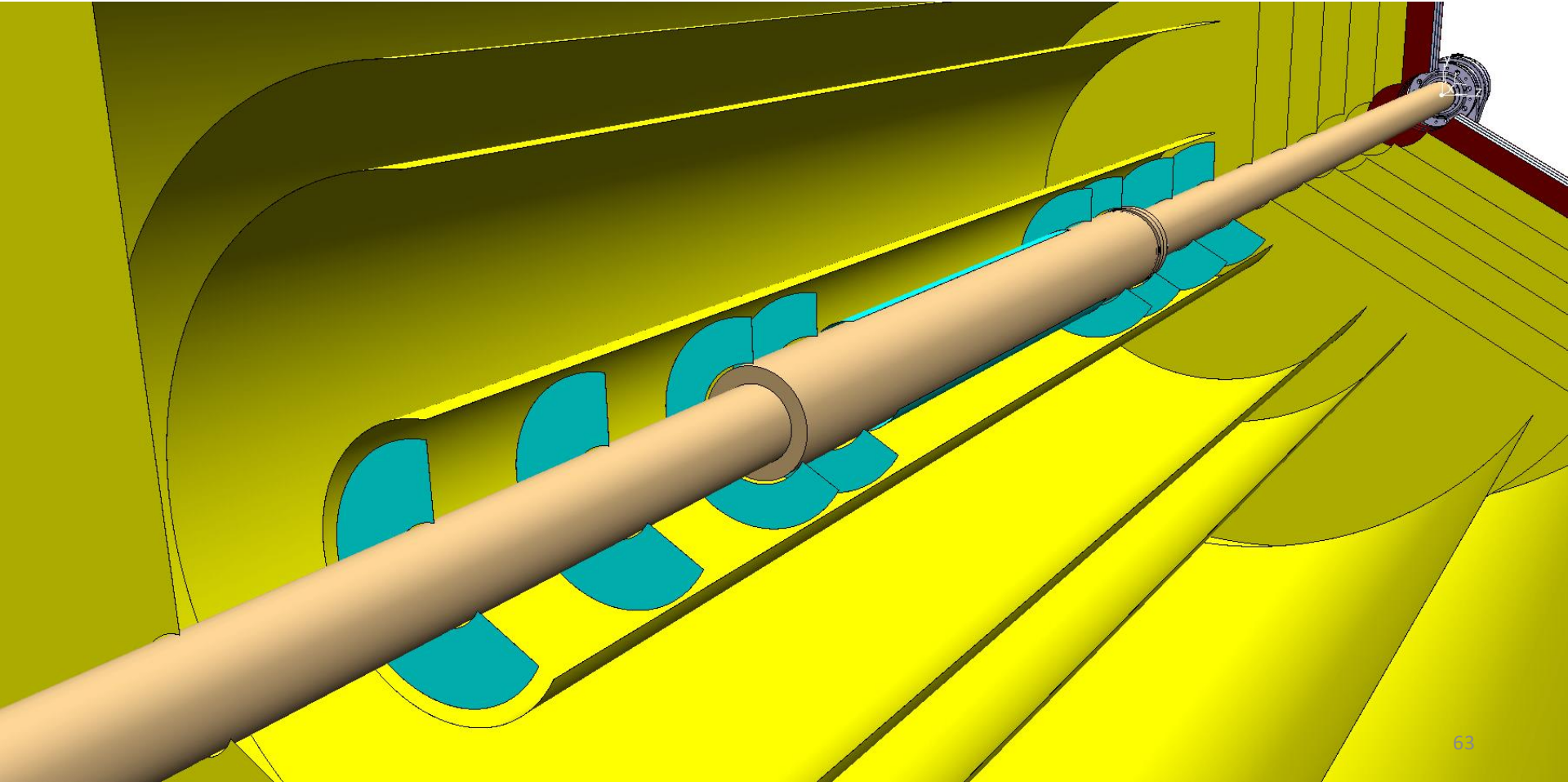
The new frontier: ALICE 3!

a next-generation heavy-ion experiment at the LHC

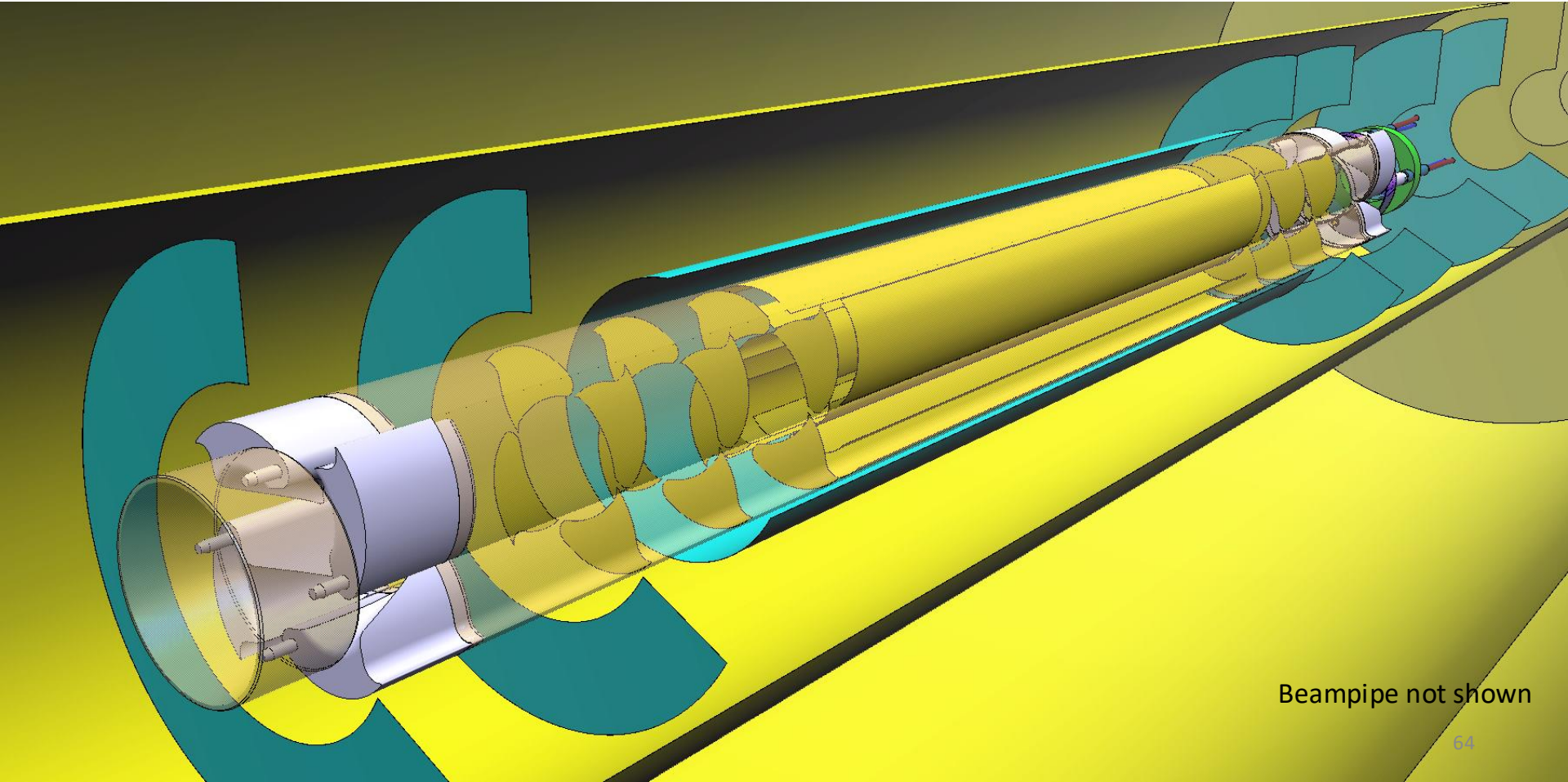


- compact, “all-silicon” tracker
- wide rapidity acceptance (8 units)
- high-resolution vertex detector
 - as close as possible to beams!
- superconducting magnet system
- hadron, muon, electron identification
- forward conversion tracker

IRIS: inside the beam pipe

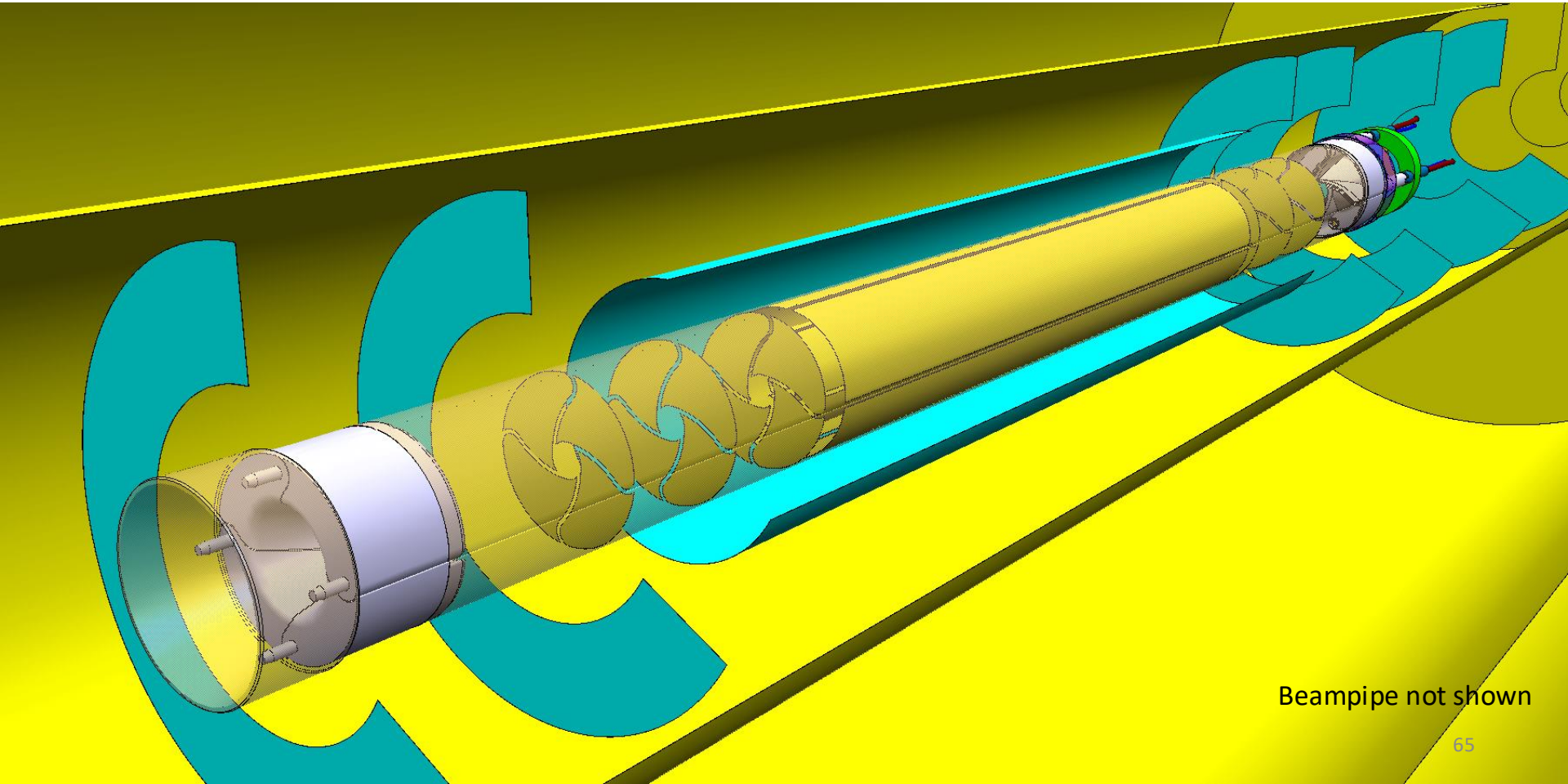


IRIS: inside the beam pipe



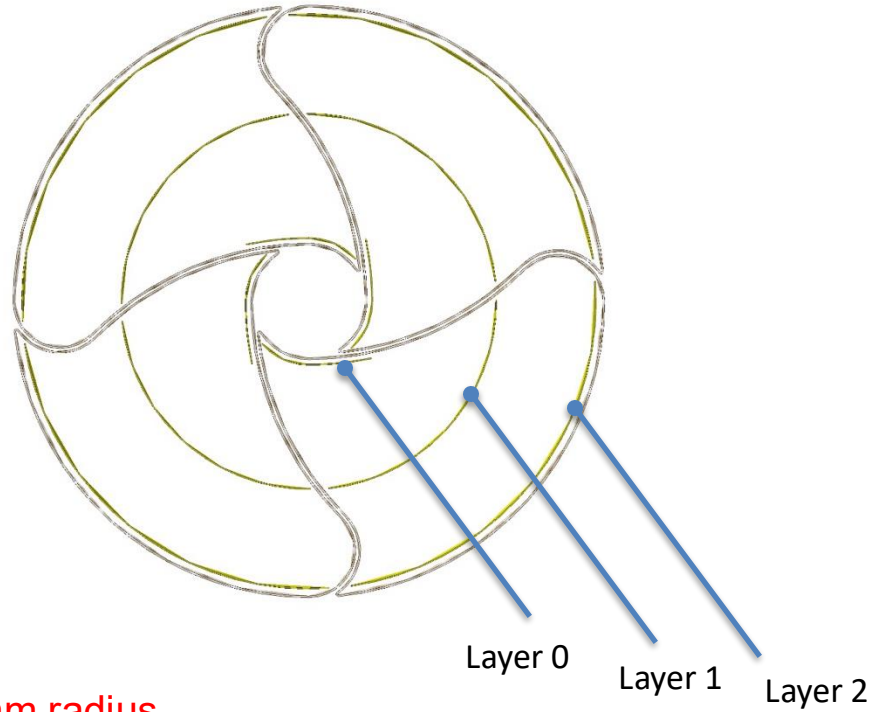
Beampipe not shown

IRIS: inside the beam pipe



Beampipe not shown

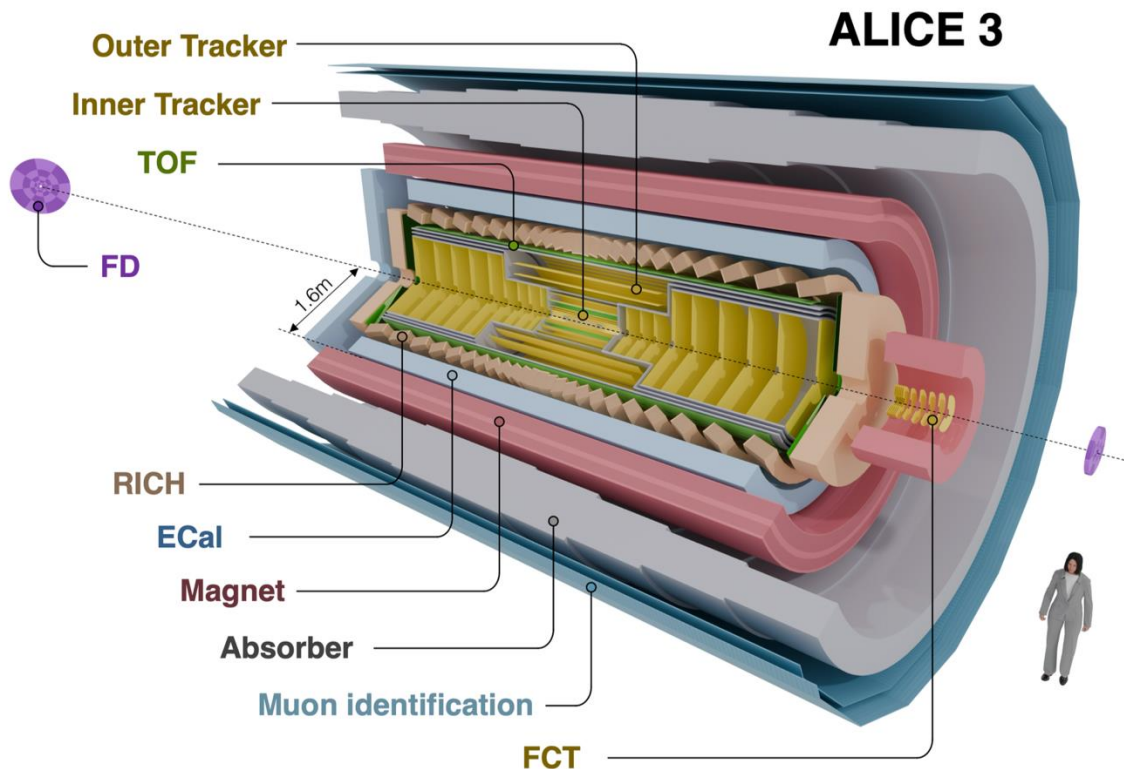
IRIS: aperture



Minimum aperture at injection: 16mm radius
Closes to 5mm radius during operation

Physics potential

- some personal favourites...

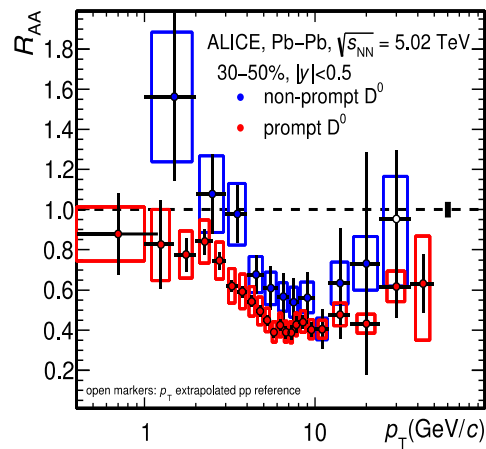
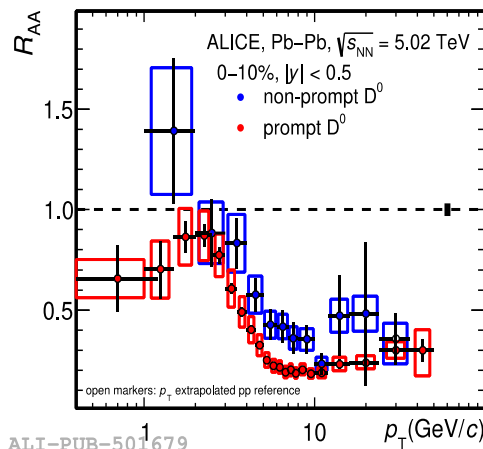


Low- p_T beauty!

- beauty not fully equilibrated?
 - less suppression than for charm
 - less flow than for charm
 - SHM seems to fail
- relaxation ~ 3 times slower than charm
 - $\tau_Q = \left(\frac{m_Q}{T}\right) D_s$ (with $m_b \sim 3m_c$)
 - of course this does not imply that b cannot fully equilibrate...
 - given enough volume/time...
 -but experimentally it looks like it doesn't...

→ b mass just at the right spot?

- to see equilibration “in action” ...?

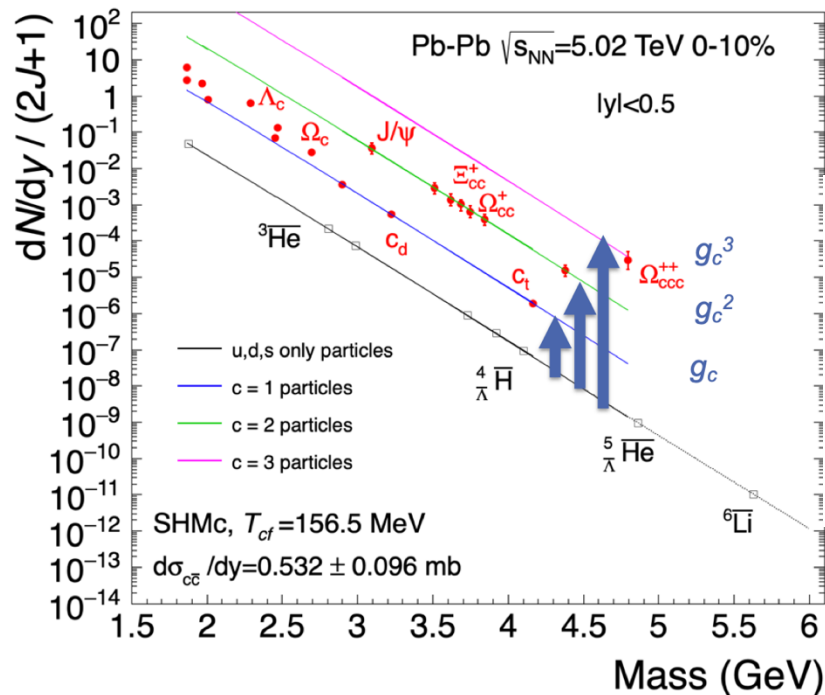


→ need high-precision b down to $p_T=0$

→ (and watch the hadrochemistry!)

Multi-charm: the final frontier?

Statistical Hadronisation Model



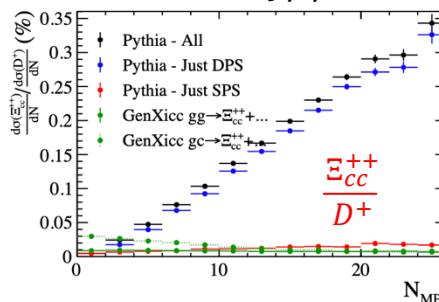
A Andronic et al.: JHEP 07 (2021) 035

- huge enhancements predicted
 - up to 10^3 wrt pQCD for the Ω_{ccc} !

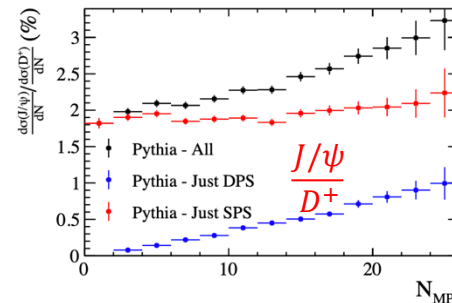
F Becattini: Phys.Rev.Lett. 95 (2005) 022301

V Minissale et al.: EPJ C (2024) 84:228

- negligible production in Single-Parton Scattering
 - unlike J/ψ



P Skands & C: arXiv:2205.15681

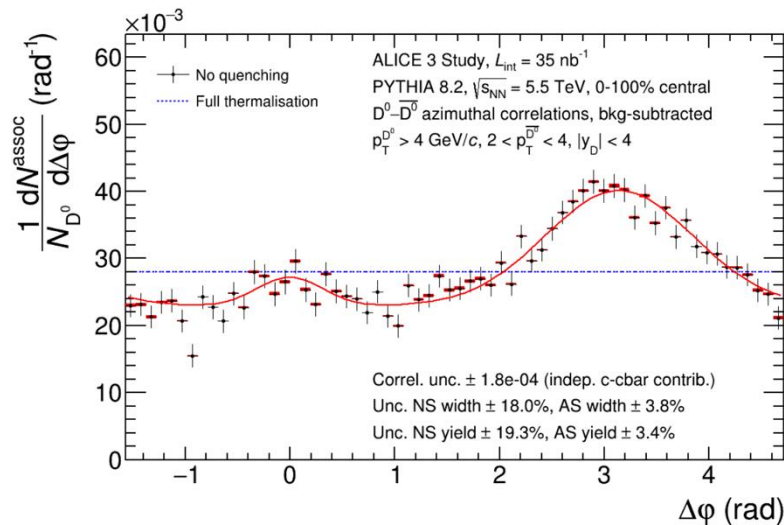


- only “exogamous” production
 - unlike J/ψ

- ultimate sensitivity to degree of c thermalisation!

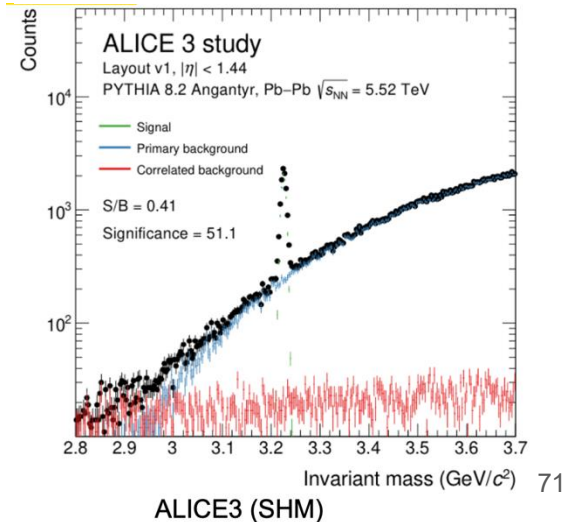
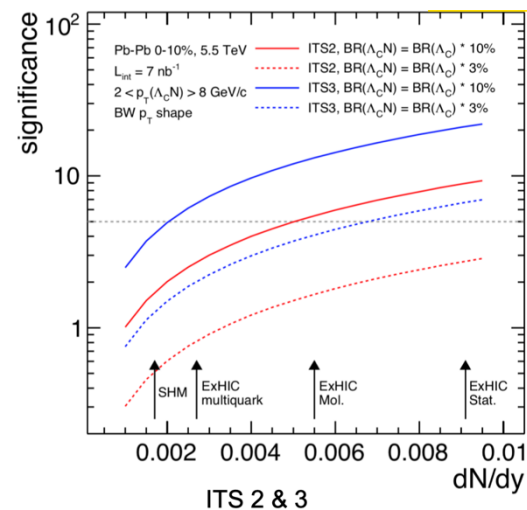
$D\bar{D}$ correlations

- ~ Rutherford experiment on QGP!
- constrain energy loss and angular decorrelation simultaneously
- collisional vs radiative eloss vs momentum scale
- full isotropisation at low p_T ?
- e.g.: ALICE 3 LoI →



Charmed hypernuclei?

- nuclei containing a charm baryon
 - sometimes called *supernuclei*
 - e.g.: c-deuteron ($\Lambda_c^+ n$), c-triton ($\Lambda_c^+ nn$)
 - first suggested in the 70's
 - C B Dover and S H Kahana, PRL 39 (1977) 1506
 - existence/stability debated ever since
-
- at SHM abundances → expected to come into view at LHC
 - if full equilibration confirmed both for c and for nuclear states...
 - discover or exclude existence!
 - + direct study of Λ_c^+ -N potential via femtoscopy?



An old dream: thermal charm?

E V Shuryak: Yadernaya Fizika 28 (1978) 403

**КВАРК-ГЛЮОННАЯ ПЛАЗМА И РОЖДЕНИЕ ЛЕПТОНОВ,
ФОТОНОВ И ПСИОНОВ В АДРОННЫХ СОУДАРЕНИЯХ**

Э. В. ШУРЯК

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

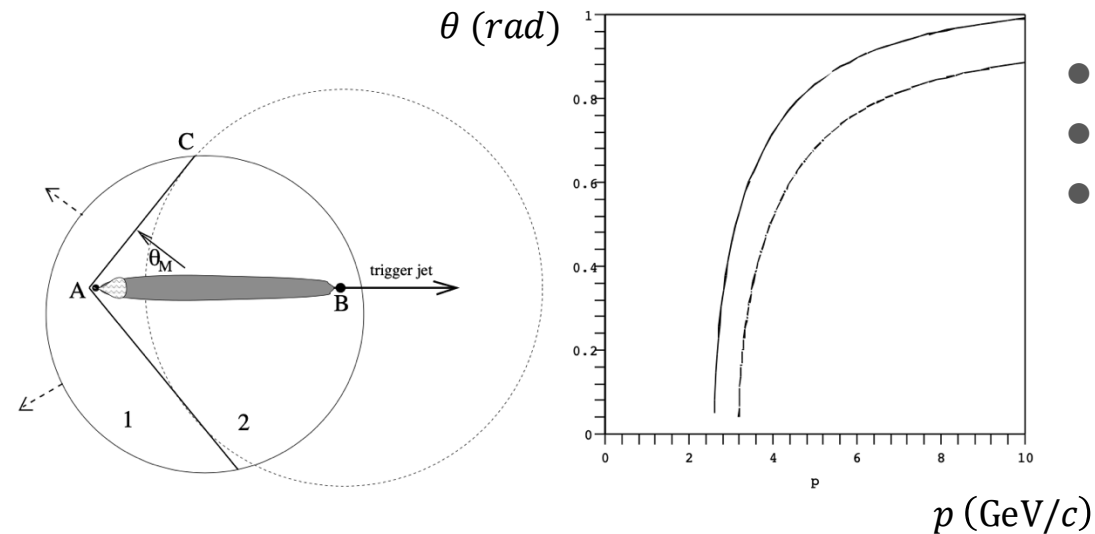
(Поступила в редакцию 14 марта 1978 г.)

Предлагается теория явлений, связанных с массами M и поперечными импульсами $p_{\perp}$, такими, что $1 \text{ ГэВ} \ll M, p_{\perp} \ll \sqrt{s}$. Для их описания применяется модель локально-равновесной кварк-глюонной плазмы, разлетающейся по определенному закону. Применение квантовой хромодинамики для вычисления скоростей ряда реакций в такой плазме позволяет вычислить спектры масс дилептонов, распределение по $p_{\perp}$ лептонов, фотонов, пионов и адронных струй, сечения рождения пар очарованных кварков и различных состояний чармония (псионов): J/ψ , χ , ψ' -мезонов. Результаты согласуются с экспериментальными данными.

- $\gamma_c \sim 30 \rightarrow$ thermal component only $\sim 3\%$
 - but that's for central Pb-Pb...
 - initial production: $Y_{in}(c\bar{c}) \propto A^{4/3}$
 - thermal production: $Y_{th}(c\bar{c}) \propto A$
 - $\gamma_c \propto \frac{Y_{in}}{Y_{th}} \propto A^{1/3}$
 - e.g. for central Ar-Ar (or $\sim 60\%$ Pb-Pb) $\gamma_c \sim 15$
- $\rightarrow$ thermal component already 6%
- + centrality / A dependence different from initial component
- $\rightarrow$ can it be separated from other centrality-dependent effects with very-large stats?
- btw: already in our minds at time of ALICE TP
 - (but theory predictions were overestimated...)

An old dream: beauty shock waves?

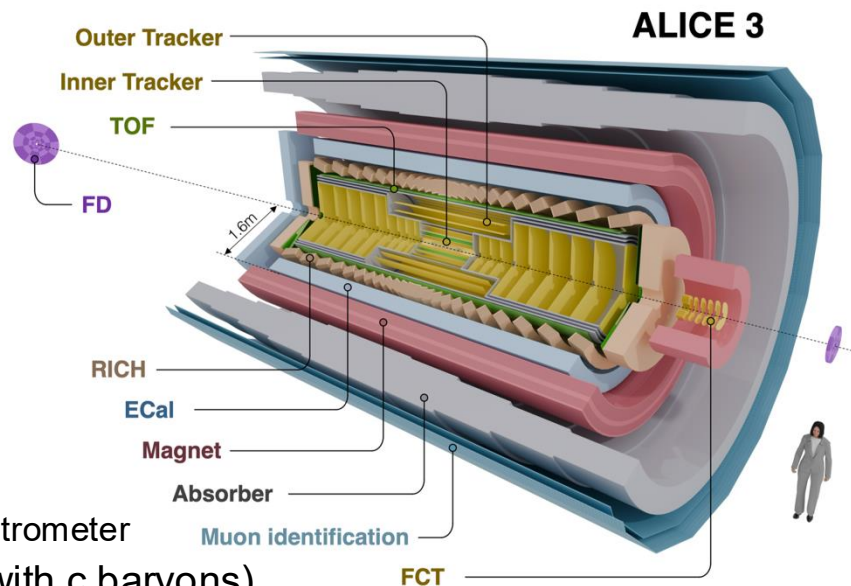
- low momentum b quarks are slow! (e.g.: at 10 GeV $\beta \sim 0.9$)
- angle of shock wave emitted by propagating b quark should depend on p



- taking $\bar{c}_s \sim 1/\sqrt{3} \dots 1/2$
- b subsonic for $p < \sim 3$ GeV/c
- p-dependent wake in multi-GeV range?
 - $\sim 40^\circ$ at 5 GeV, $\sim 55^\circ$ at 10 GeV!

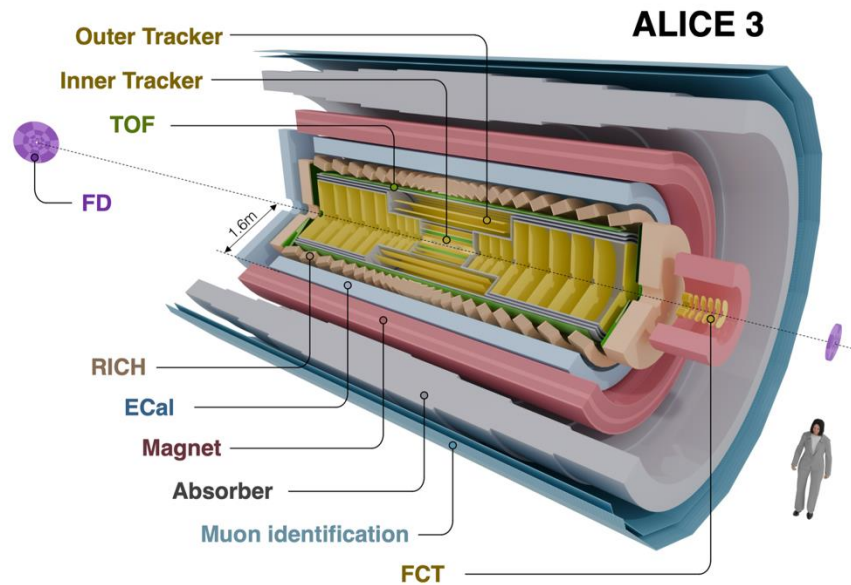
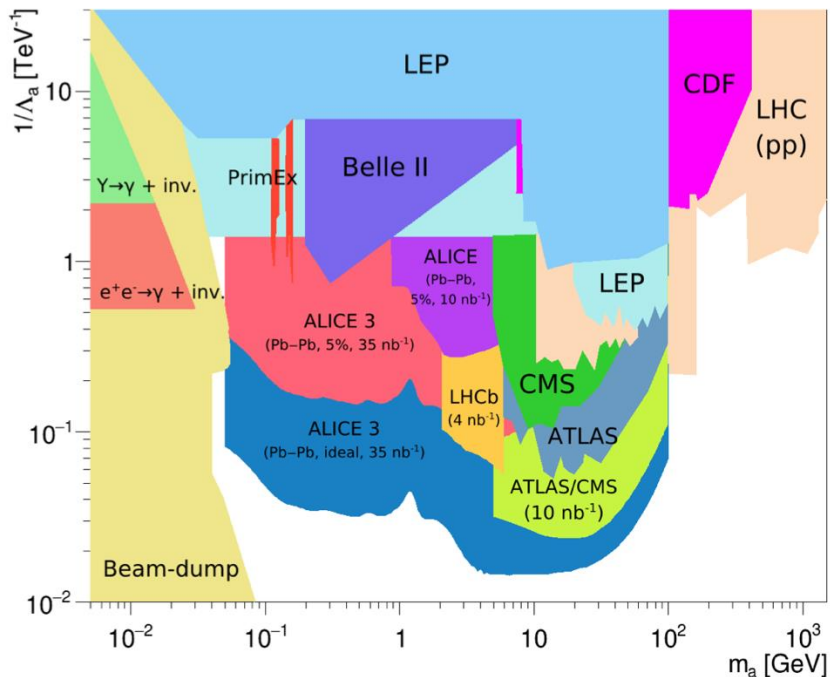
Physics potential (more examples)

- heavy flavours, quarkonia
 - multi-heavy flavoured hadrons (Ξ_{cc} , Ω_{cc} , Ω_{ccc})
 - D D correlations
 - B mesons at low p_T
 - χ_c , X, Y, Z states and exotic hadrons
- low-mass dielectrons
 - chiral symmetry restoration
 - thermal continuum (virtual photons)
- fluctuations of conserved charges
 - over wide rapidity range
- ultra-soft photons
 - down to MeV scale with dedicated forward spectrometer
- nuclei, hyper-nuclei, search for super-nuclei (with c baryons)
- BSM searches
 - dark photons
 - axion-like particles
 - ...



Letter of Intent: <https://cds.cern.ch/record/2803563>

Axion-Like Particle (ALP) searches



Conclusions

- we have come a long way!
 - from the realisation of the possible existence of deconfined matter in the 70's
 - to the first explorations of collective effects (AGS, SPS S beams)
 - through the discovery of deconfinement (SPS Pb beams)
 - through the evidence for strongly-coupled QGP (RHIC)
 - to the LHC harvest
 - parton-dependent energy loss
 - direct observation of QGP hadronisation
 - discovery of collectivity in small systems
 - quantitative access to QGP parameters
- today:
 - the plans of the community are being drawn for the next two decades
 - we are entering the next phase:
 - systematic exploration of the emergent properties of QCD condensed matter

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