



首届ALICE实验与重离子物理讲习班

The 1st ALICE Experiment and Heavy-Ion Physics School

**夸克-胶子等离子体五十年：
过去、现在和未来
(第三讲)**



Federico Antinori
(INFN, Padova, Italy)



上海，复旦大学，2025年11月

第二讲回顾...

Rapidity

- four momentum ($c = 1$, z coordinate along beam axis)

$$p^\mu = (p^0, p^1, p^2, p^3) = (E, \vec{p}) = (E, p_T, p_z = p_{||})$$

- addition of velocities along z :

$$v = v_1 + v_2 \quad (\text{Galileo})$$

$$\beta = \frac{\beta_1 + \beta_2}{1 + \beta_1 \beta_2} \quad (\text{relativistic})$$

$$\tanh(y_1 + y_2) = \frac{\tanh y_1 + \tanh y_2}{1 + \tanh y_1 \tanh y_2}$$

$$y = \tanh^{-1} \beta = \frac{1}{2} \log \left(\frac{1 + \beta}{1 - \beta} \right) \quad \text{“rapidity”}$$

Pseudorapidity

$$y = \frac{1}{2} \log \left(\frac{E + p_z}{E - p_z} \right)$$

$$\eta = \frac{1}{2} \log \left(\frac{p + p_z}{p - p_z} \right)$$

- in the ultrarelativistic limit: $p \sim E \rightarrow \eta \sim y$

$$\eta = -\log \tan(\theta / 2)$$



exercise: prove this



$$p_z = m_T \sinh(y)$$

$$E = m_T \cosh(y)$$

$$p_z = p_T \sinh(\eta)$$

$$p = p_T \cosh(\eta)$$

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)

Two historic predictions...

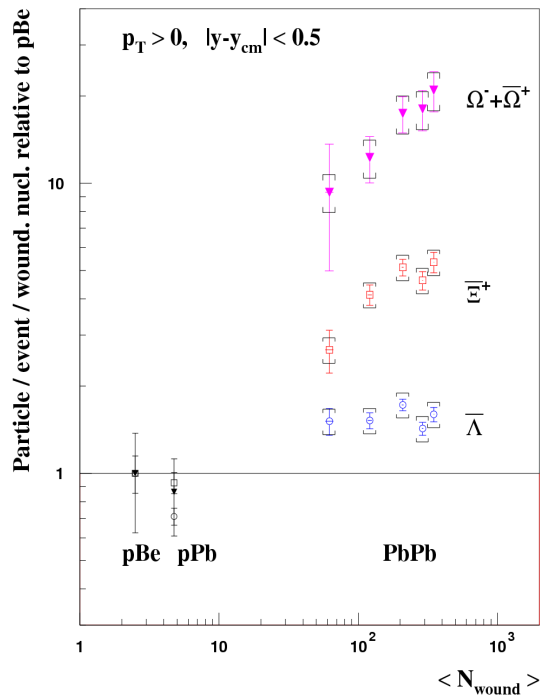
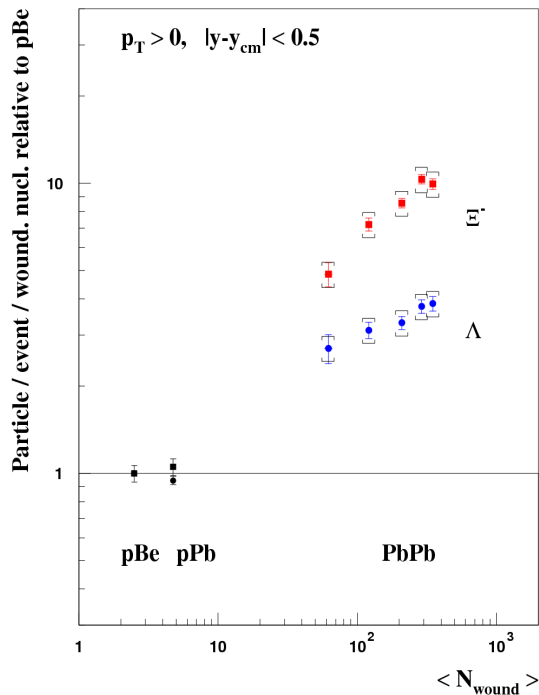
- QGP phase, if existed, would obviously be very short-lived, how to observe it?
 - is there a memory of the passage through the QGP phase?
 - are there “signatures” of the QGP that we can look for in the final state?

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 at the SPS

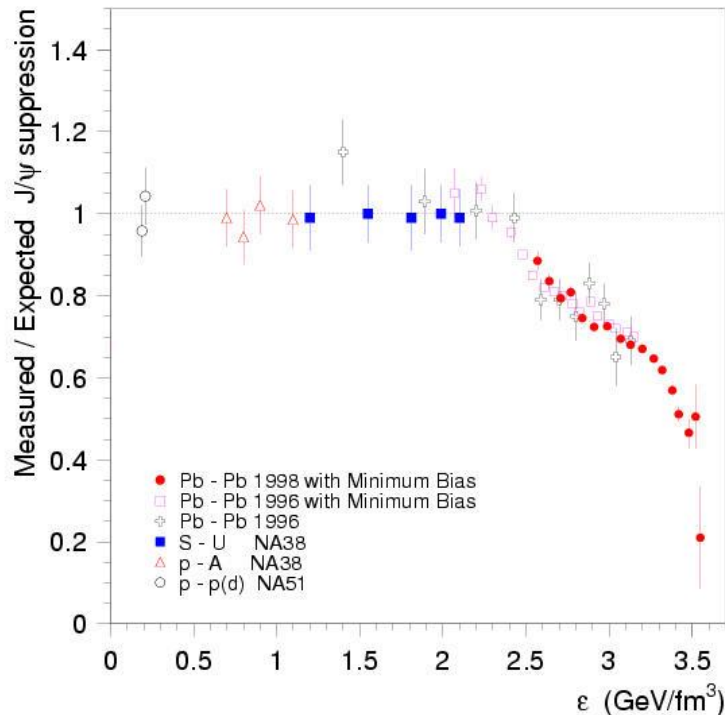
● WA97/NA57



- enhancement relative to p-Be, p-Pb
- increasing with $|S|$
- up to $\sim \times 20$ for the Ω

J/ ψ suppression at the SPS

- **NA50**: “anomalous” suppression



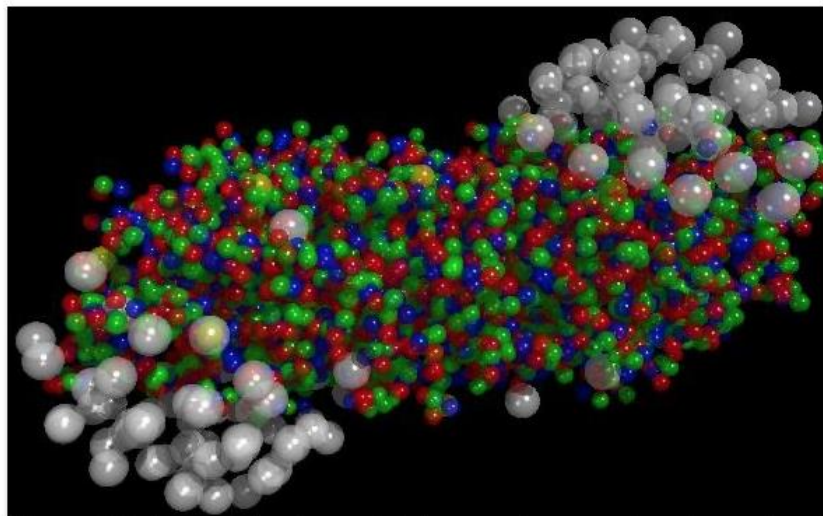
- measured/expected
- sets in at $\epsilon \sim 2.3$ GeV/fm³ ($b \sim 8$ fm)
- (on top of nuclear suppression)
 - due to nuclear absorption effects
 - measured in pA, light ion collisions
 - scaled to Pb-Pb (= 1 in the plot)

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: significant problems in production of ISABELLE magnets
- *1983: discovery of $W^{\pm}$ (January) and Z^0 (May) bosons at SPS collider*
- Jul 1983: construction of ISABELLE stopped, project cancelled
- Jul 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...)
- *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



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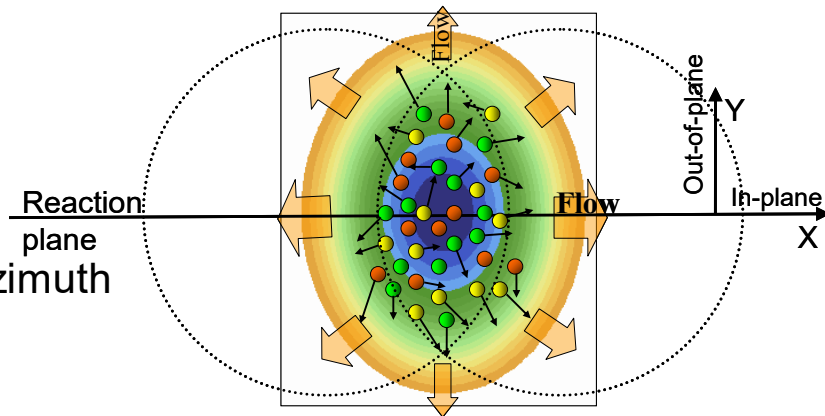


上海，复旦大学，2025年11月

Azimuthal asymmetry

... in the transverse momentum distribution
of produced particles

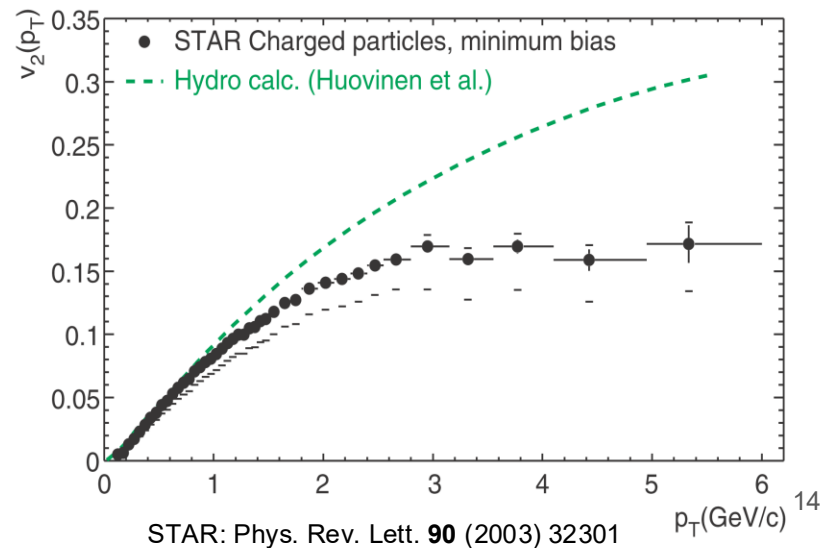
- why is it important?
- non-central collisions are asymmetric in azimuth
azimuth = angle in the plane of the screen



- 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

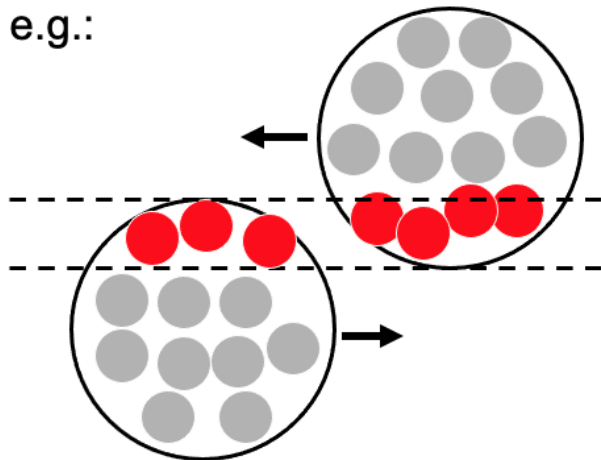
- to quantify the asymmetry:
 - Fourier expansion of the angular distribution:
 $\propto 1 + 2v_1 \cos(\varphi - \psi_1) + 2v_2 \cos(2[\varphi - \psi_2]) + \dots$
 - in the central detector region ($\vartheta \sim 90^\circ$) $\rightarrow v_1 \sim 0 \rightarrow$ asymmetry quantified with v_2
 - v_2 : “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”

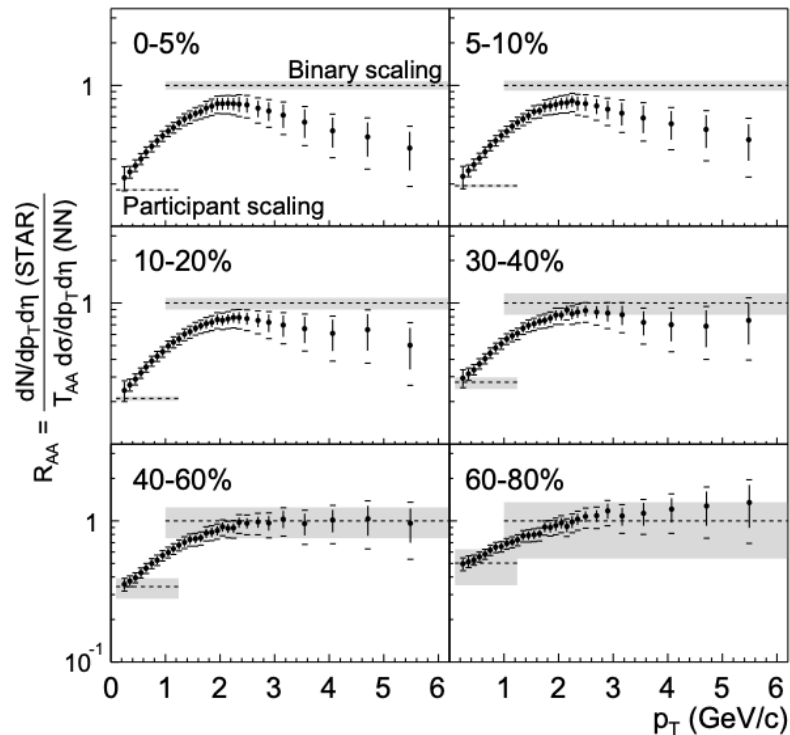
$N_{\text{coll}} = 12$ “binary collisions”

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

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

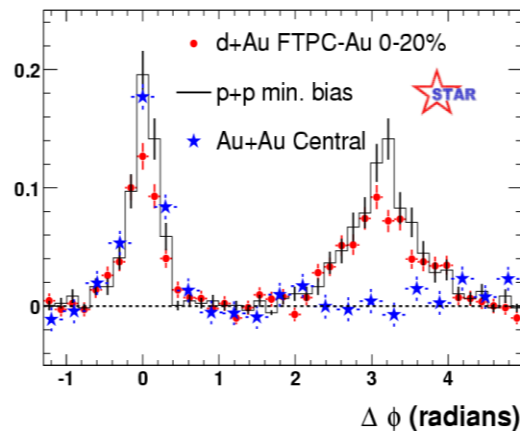
- “soft”, large cross-section processes expected to scale like N_{part}
- “hard”, low cross-section processes expected to scale like N_{coll}

Nuclear modification factor at RHIC

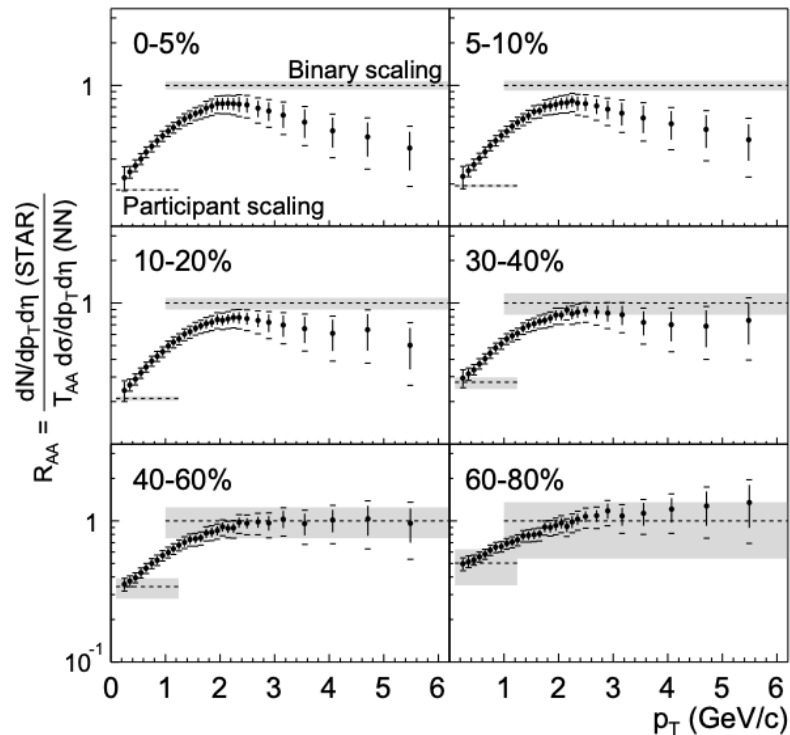


STAR: Phys.Rev.Lett. 89 (2002) 202301

- 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

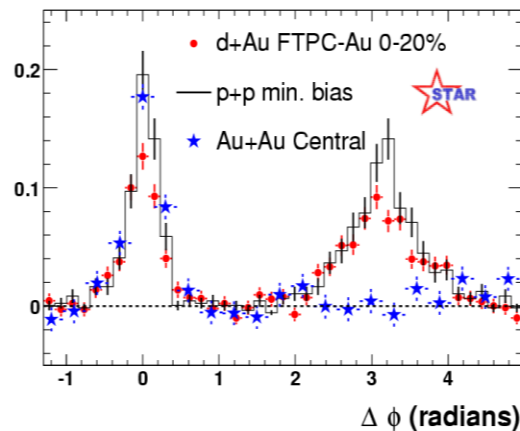


Nuclear modification factor at RHIC

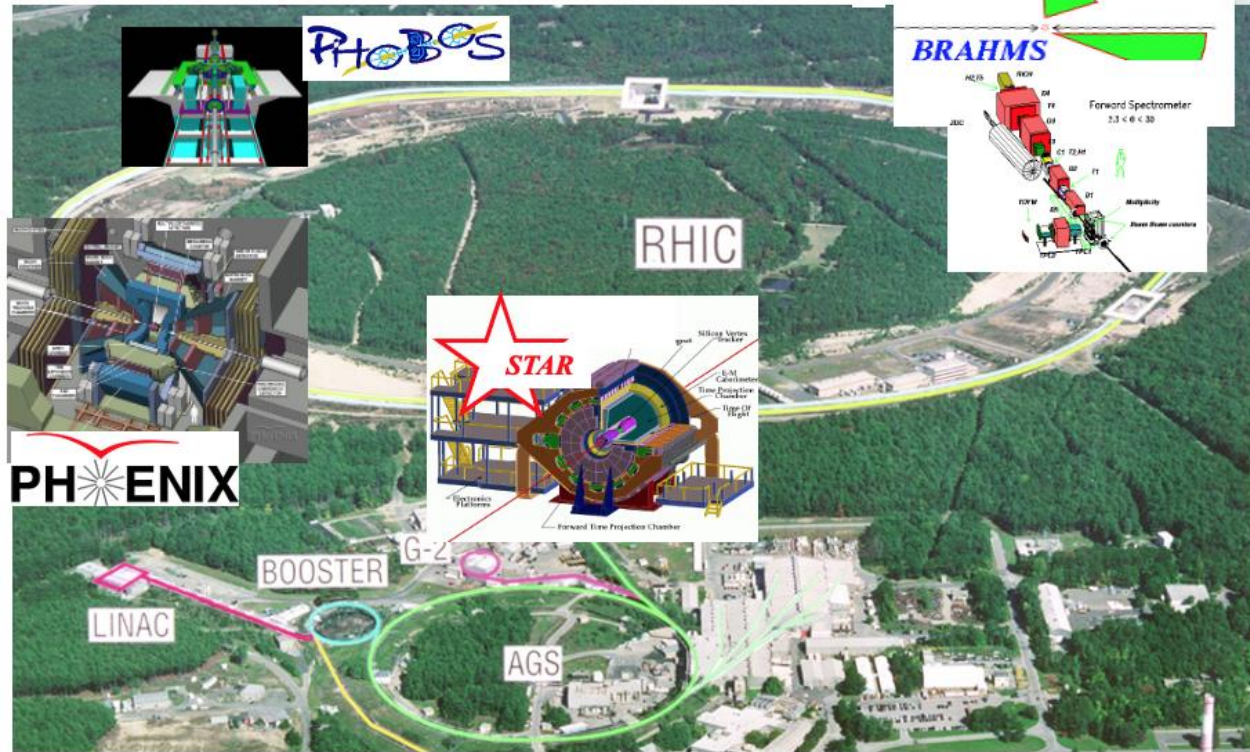


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The RHIC experiments



→ 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!



CMS

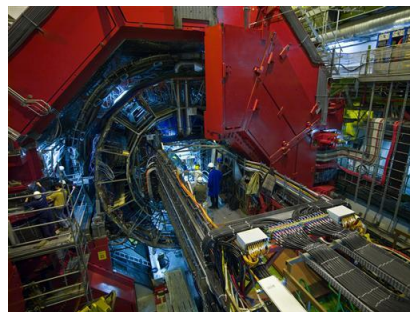
LHCb

ALICE

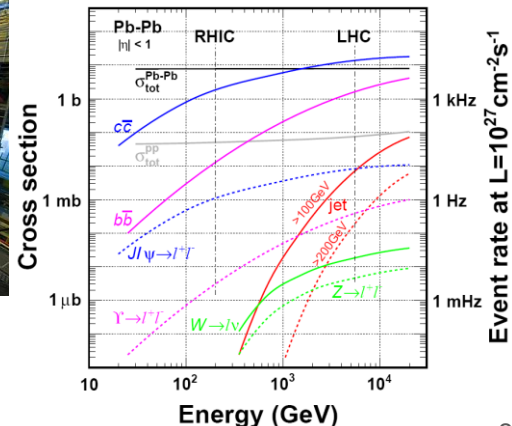
ATLAS

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

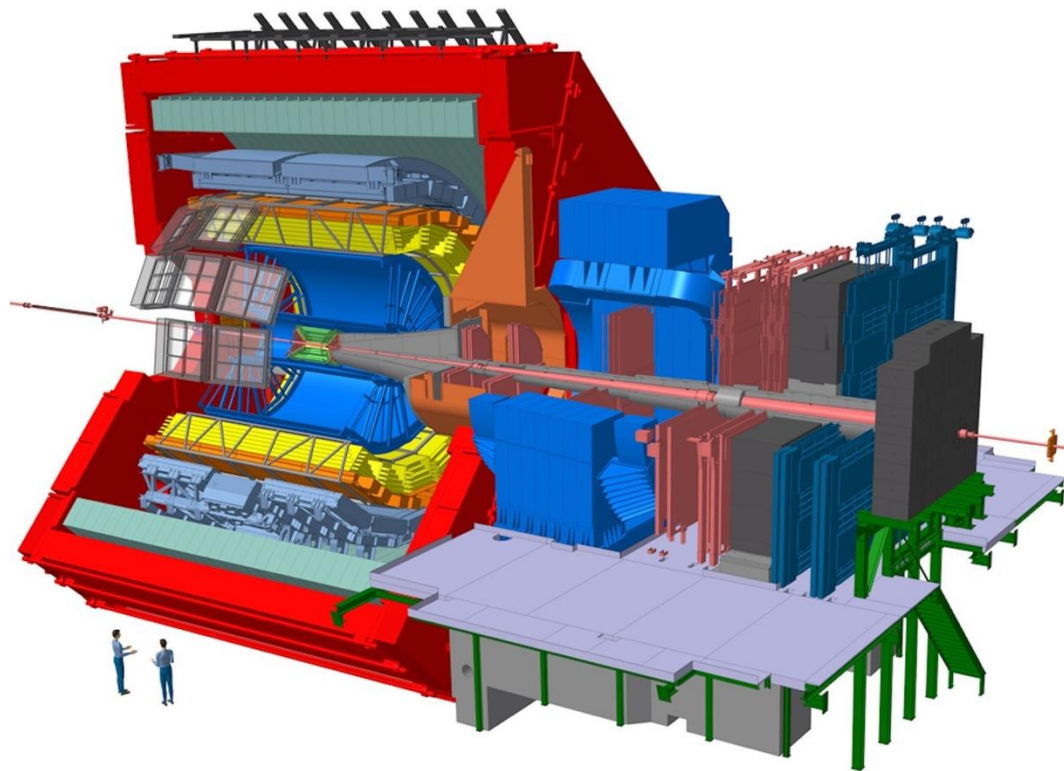


- ALICE
 - dedicated experiment
 - ~1070 authors, ~ 170 institutions, 40 countries
- ATLAS, CMS, LHCb also participating in programme



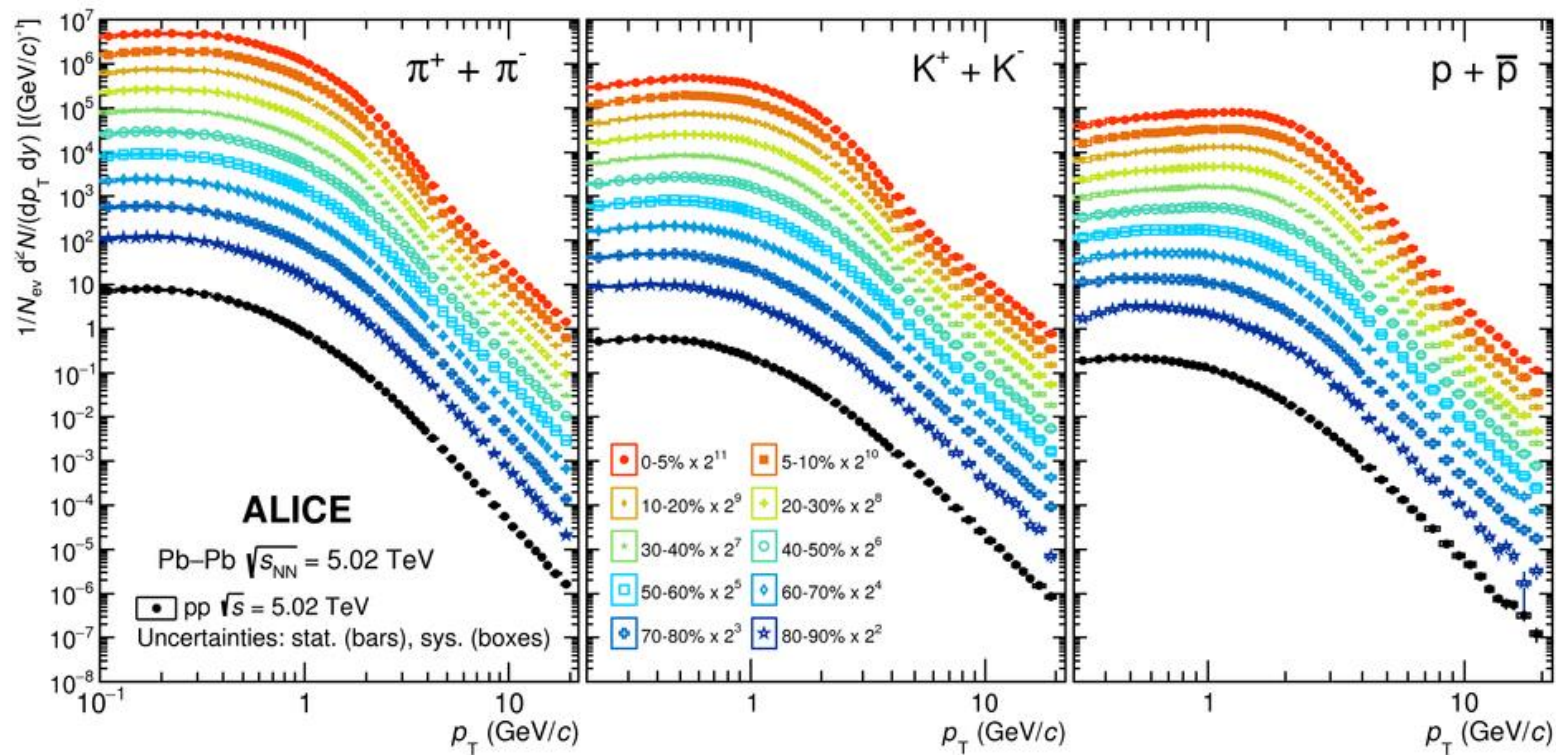
The ALICE experiment

- 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



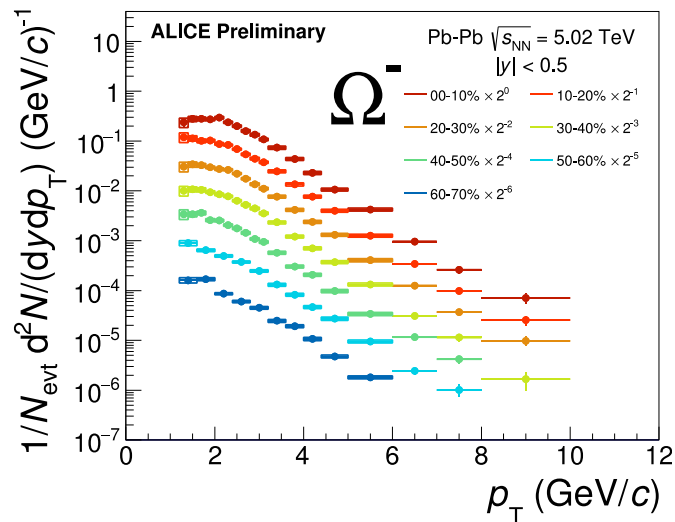
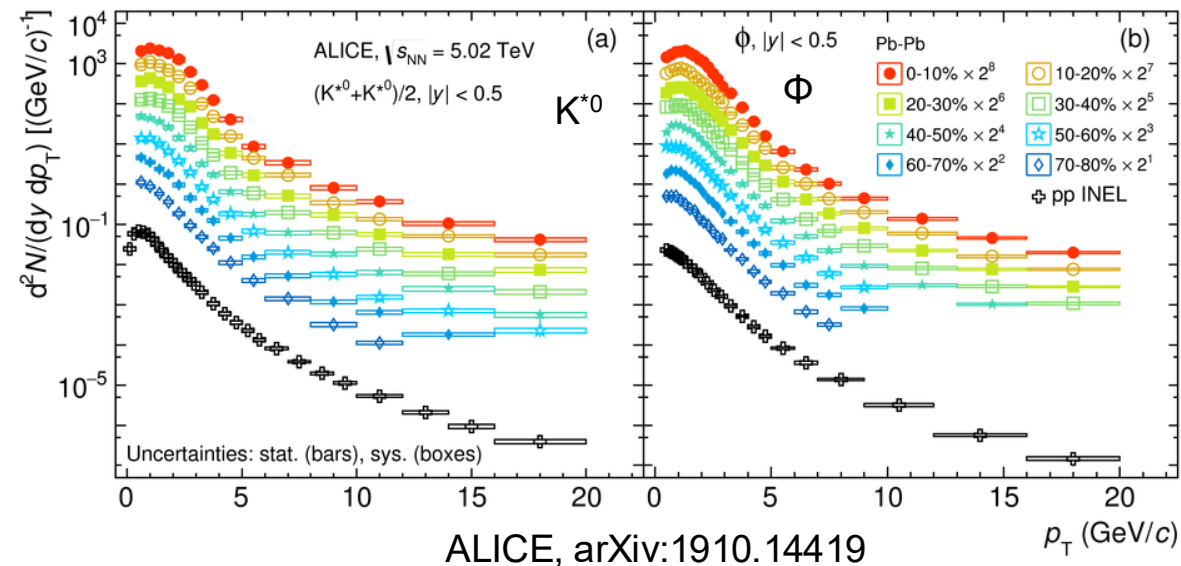
this July!

Identified particles



More and more species

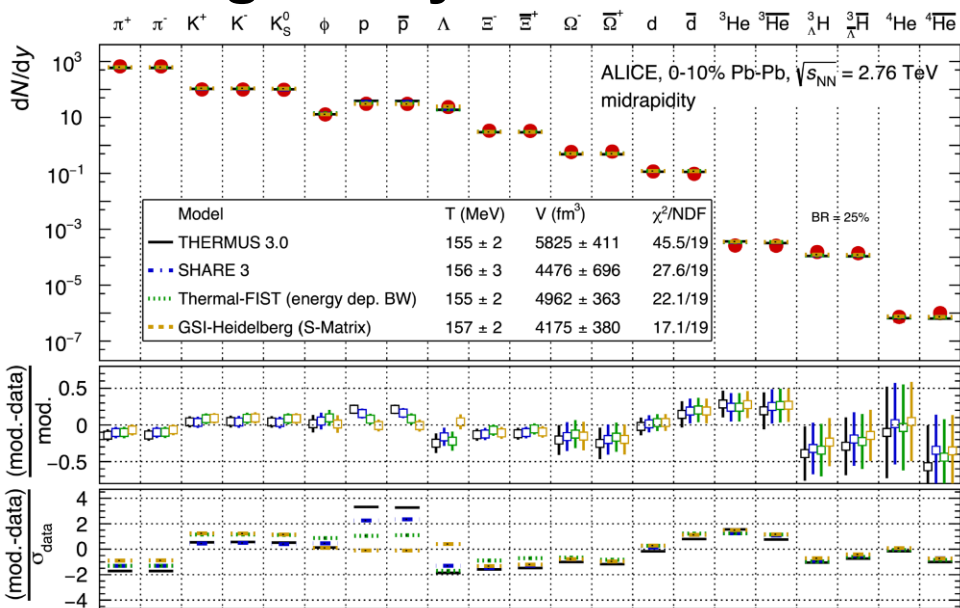
- Resonances, hyperons, ...



ALI-PREL-131316

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

Integrated yields

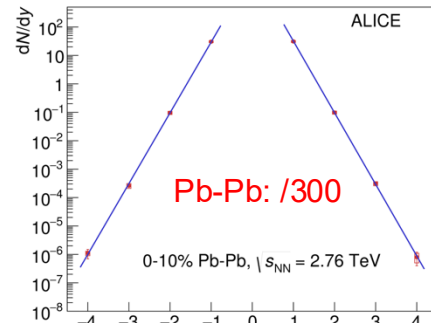
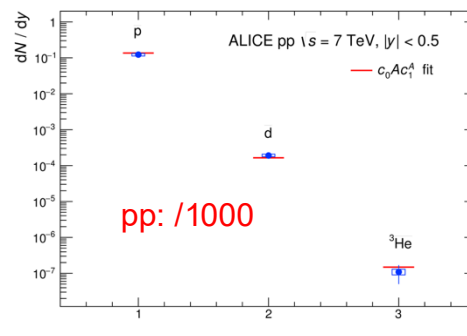


$$T_{chem} \approx T_C \approx 156 \text{ MeV}$$

arXiv:2211.04384

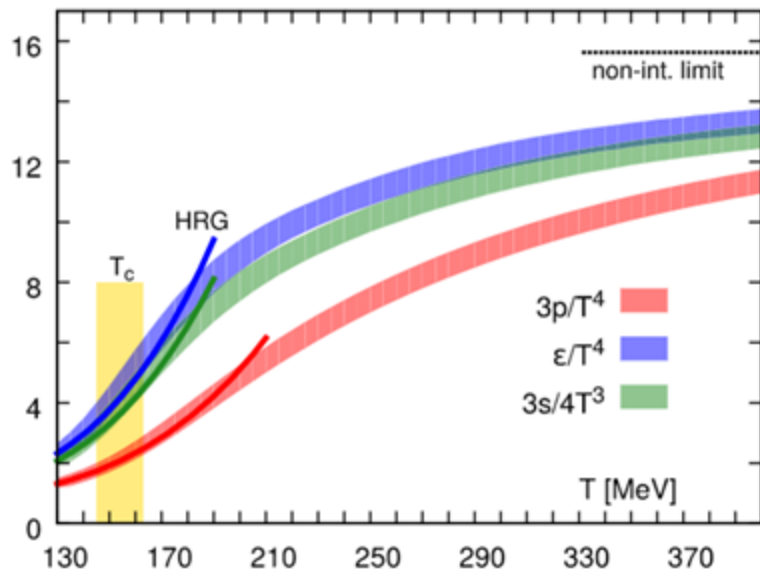
→ hadronisation very close to the phase transition

- 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

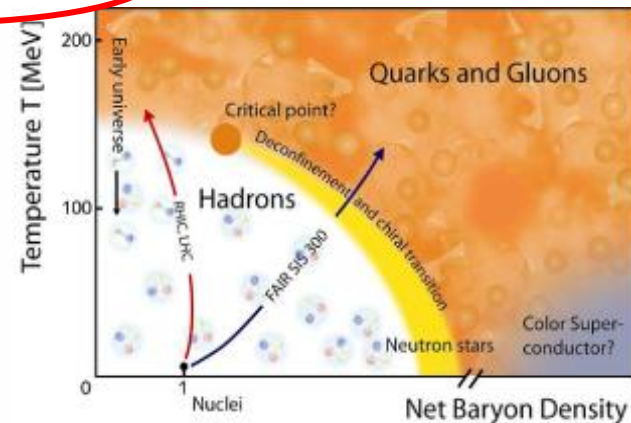
- the rigorous way of performing calculations in the non-perturbative regime of QCD
- discretisation on a space-time lattice
 - → ultraviolet (i.e. large-momentum scale) divergencies can be avoided



[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]

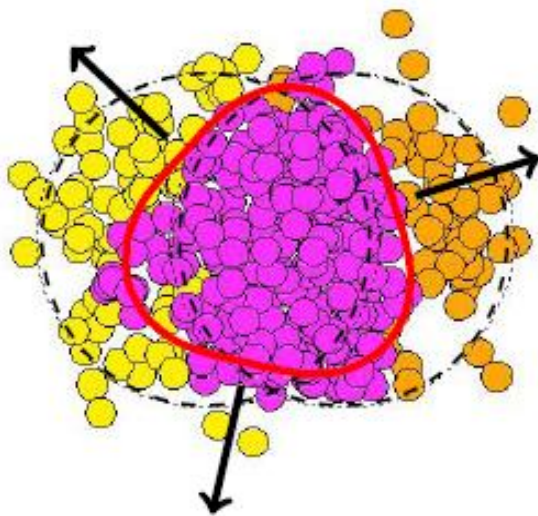
- $\epsilon \sim O(\text{GeV}/\text{fm}^3)$



Higher harmonics: a beautiful tool...

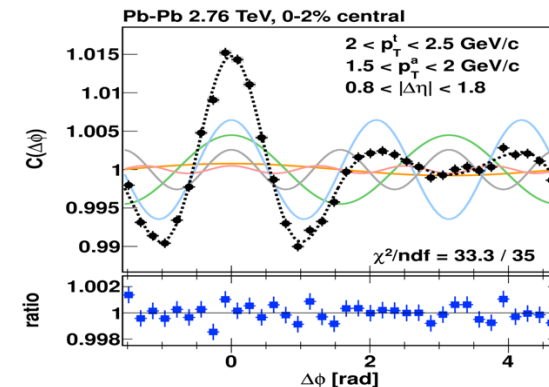
initial-state geometrical asymmetries $\rightarrow$ final state momentum asymmetries

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

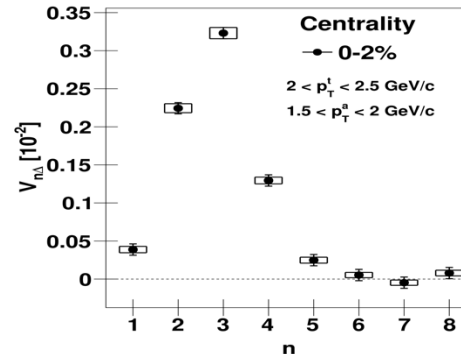


$\rightarrow$ Fourier decomposition of azimuthal distribution

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



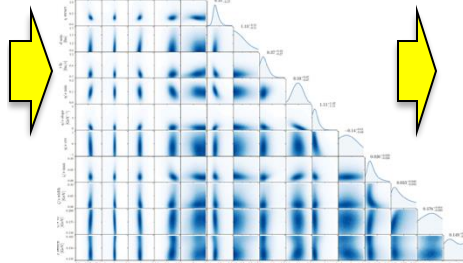
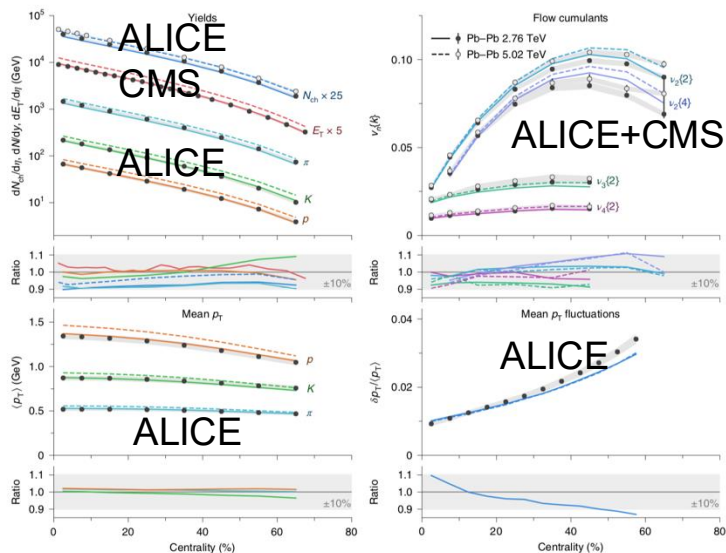
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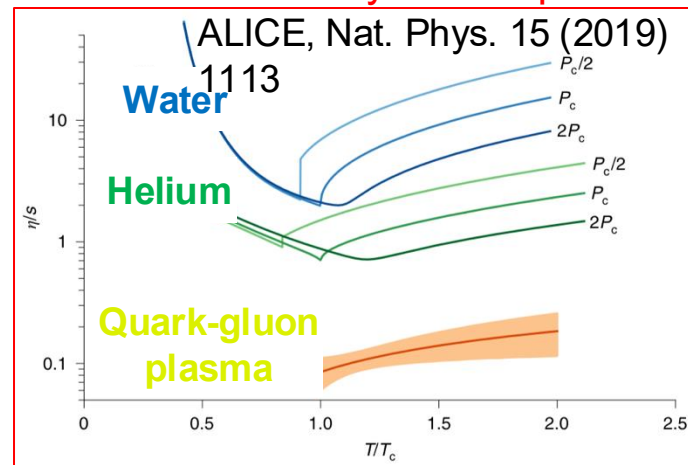
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Entering precision era!

- 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



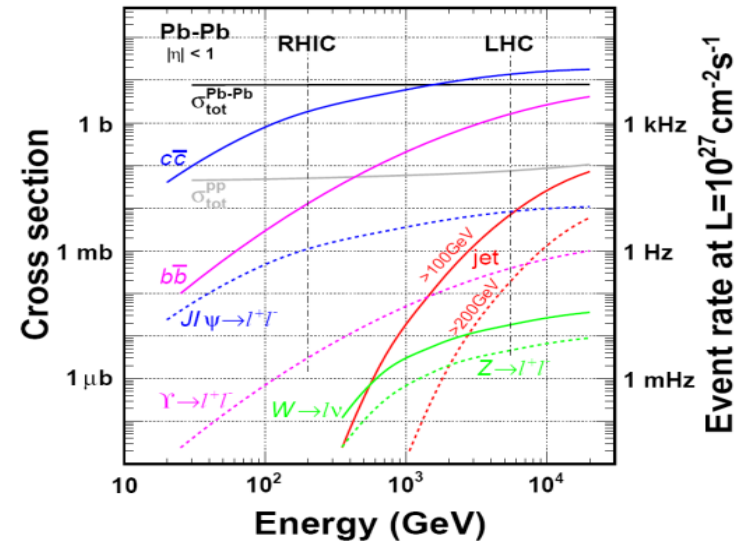
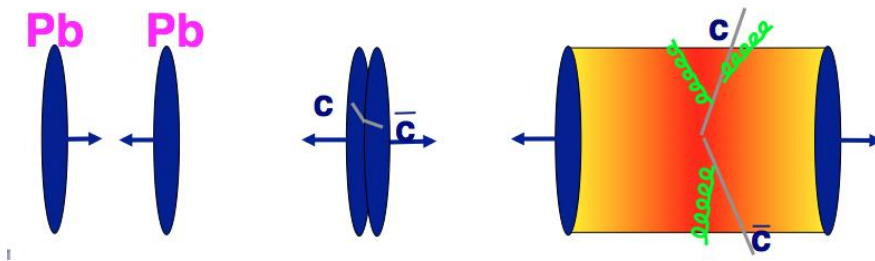
QGP shear viscosity vs. temperature



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

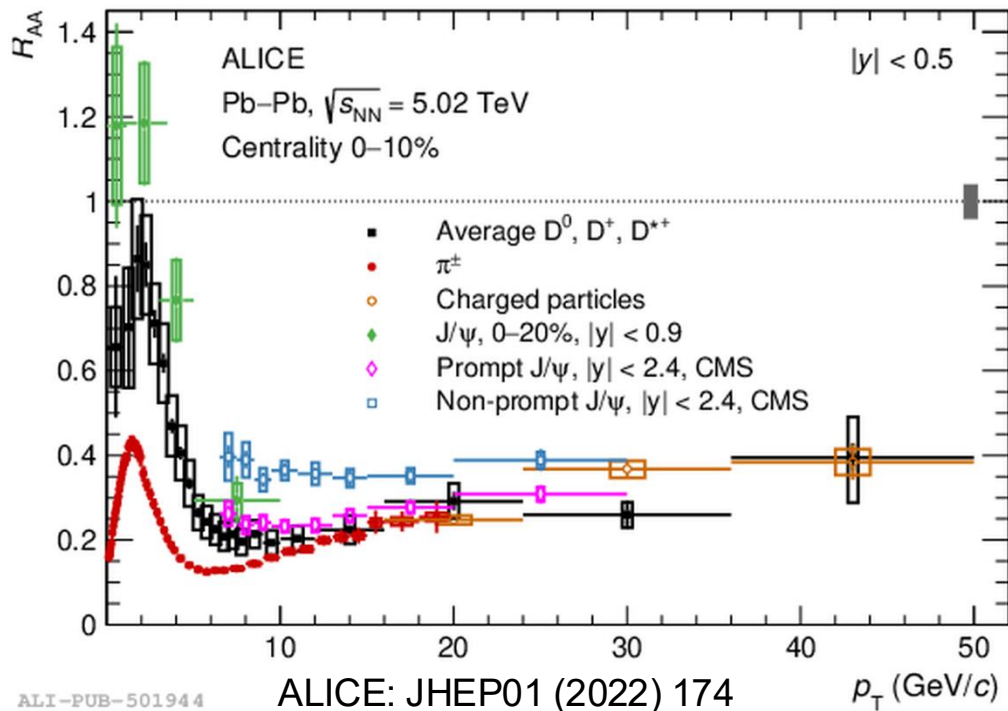
Heavy Flavour

- 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 $\rightarrow$ “brownian” probes
 - sensitive to QGP hadronisation



Beautiful data from the LHC!

a gold mine!

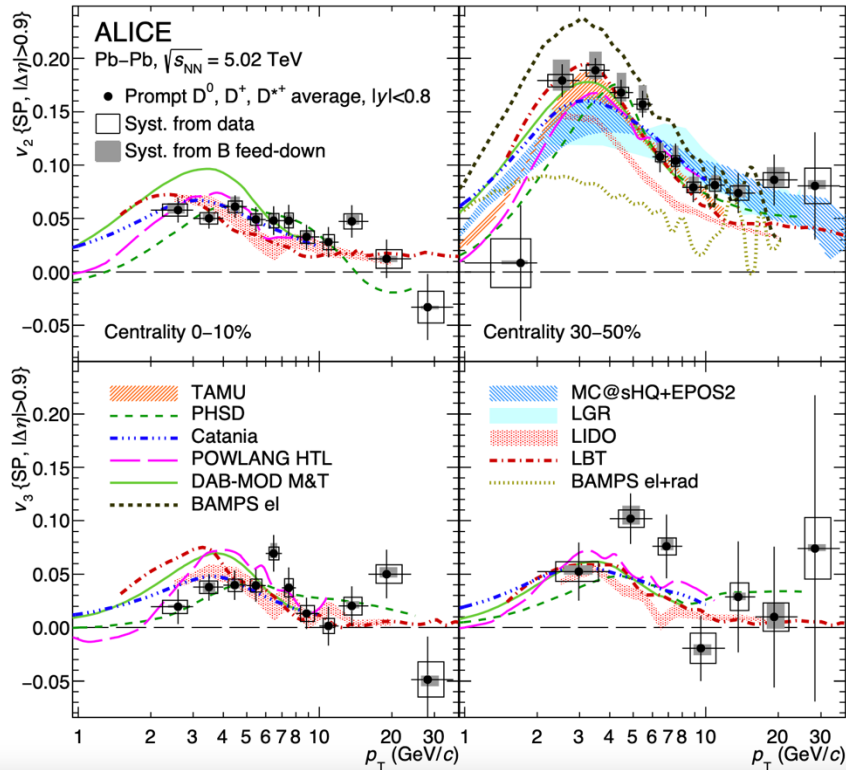


- controlled probe
 - mass
 - colour charge
 - pQCD
- generated in initial parton scattering
- conserved throughout evolution
- large mass $\rightarrow$ “Brownian” probe
- powerful probe of hadronisation

experimentally:

- strongly coupled to medium
- clear hierarchy at low p_T

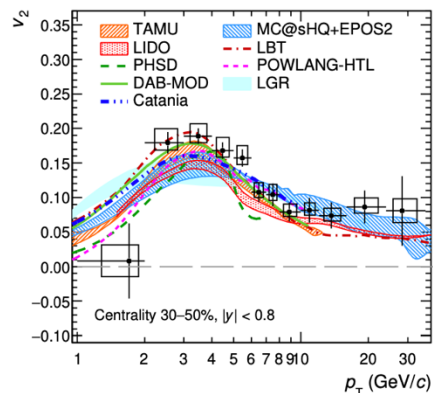
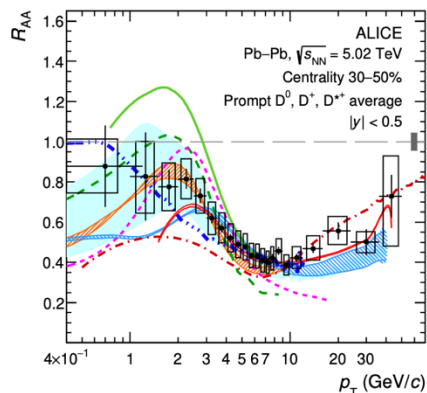
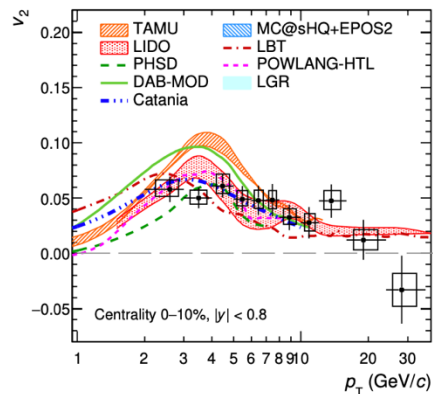
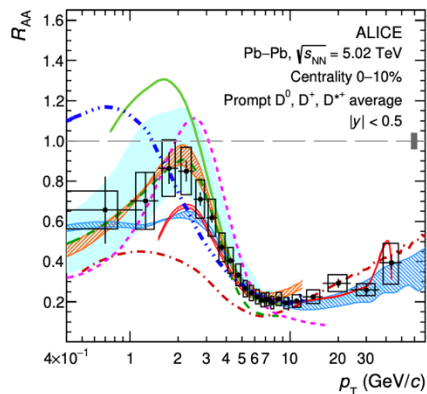
Strongly involved in the flow



v_2

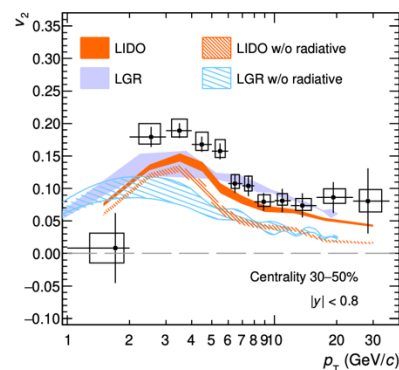
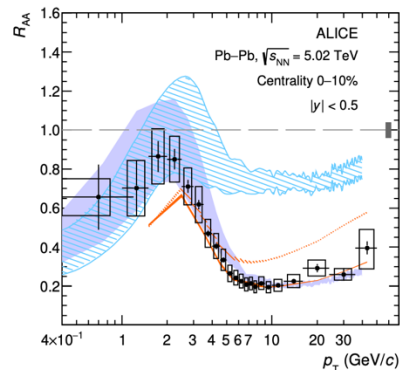
and v_3 !

State-of-the-art...

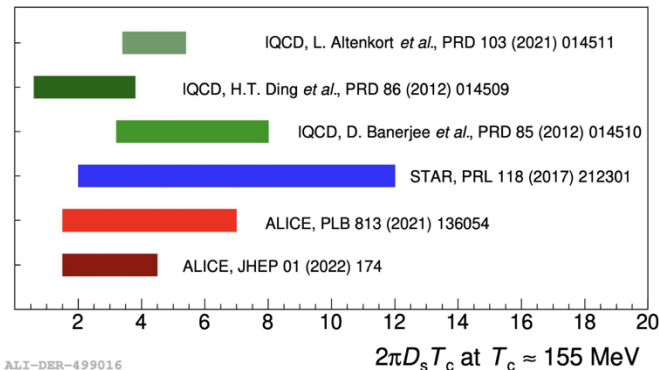


ALICE: JHEP01 (2022) 174

- substantial model constraints...

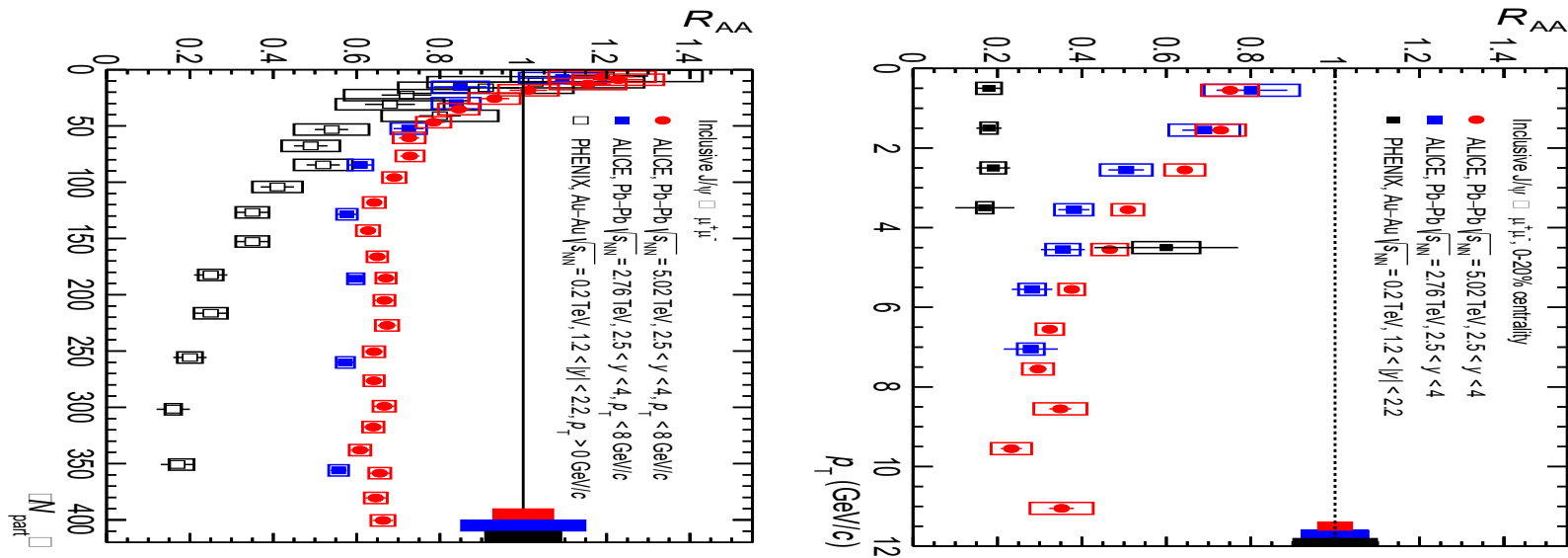


- 50% uncertainty on diffusion coefficient
 - it starts to be a measurement!



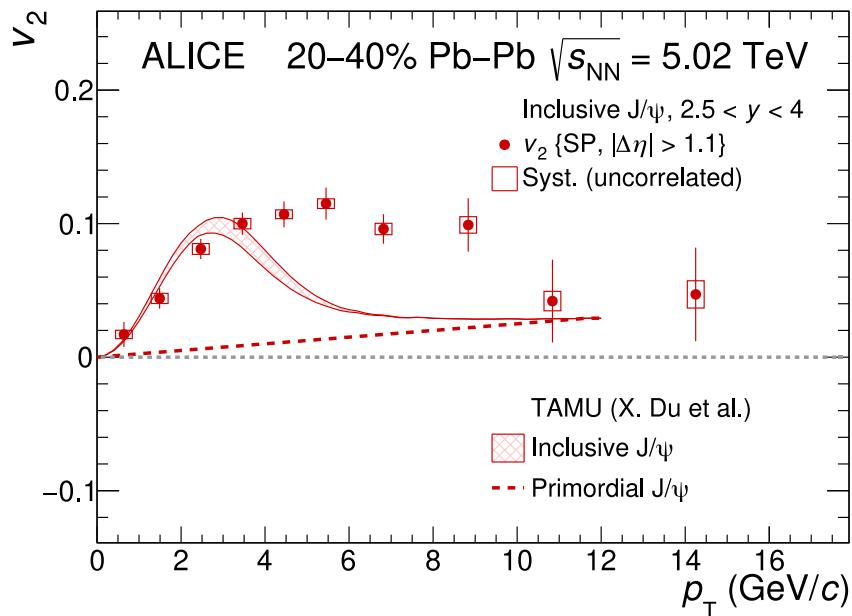
A new regime for J/ψ production!

- a remarkable change of behaviour from SPS/RHIC!

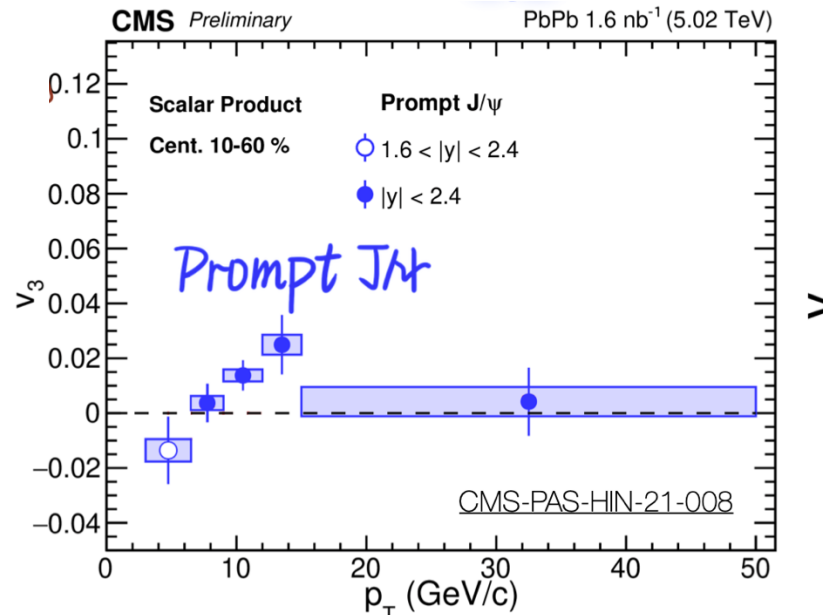


- in both the centrality and the p_T dependence
- evidence for production by recombination of exogamous $c\bar{c}$ pairs!

Charm quarks themselves flow

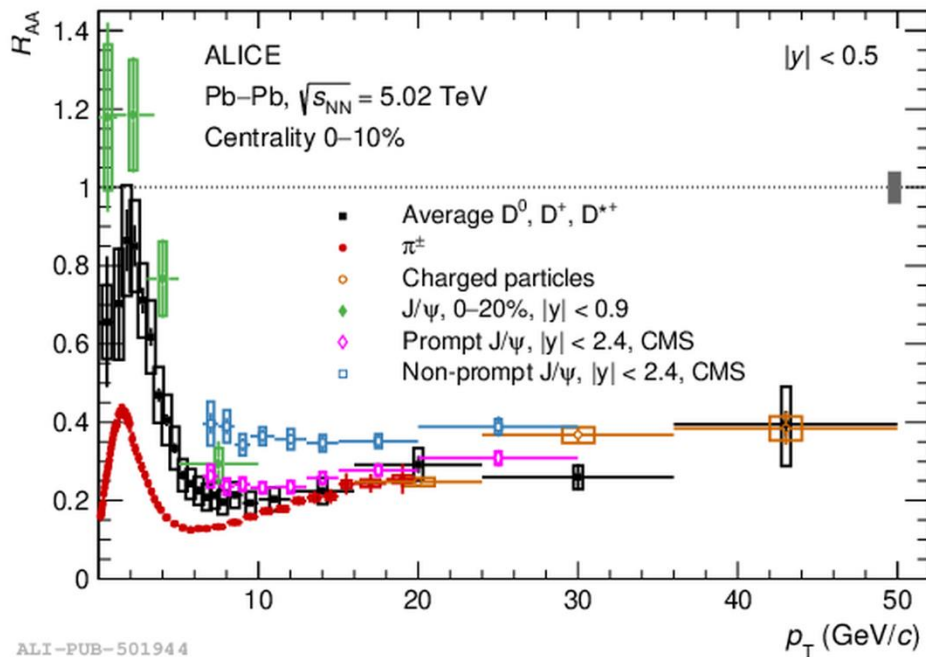


ALICE: JHEP 10 (2020) 141

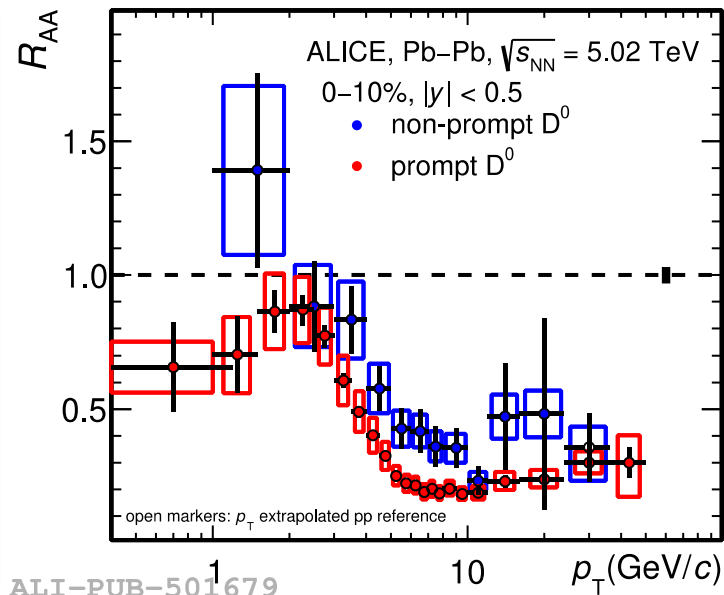


CMS: PAS-HIN-21-008

Beauty is quenched, too...



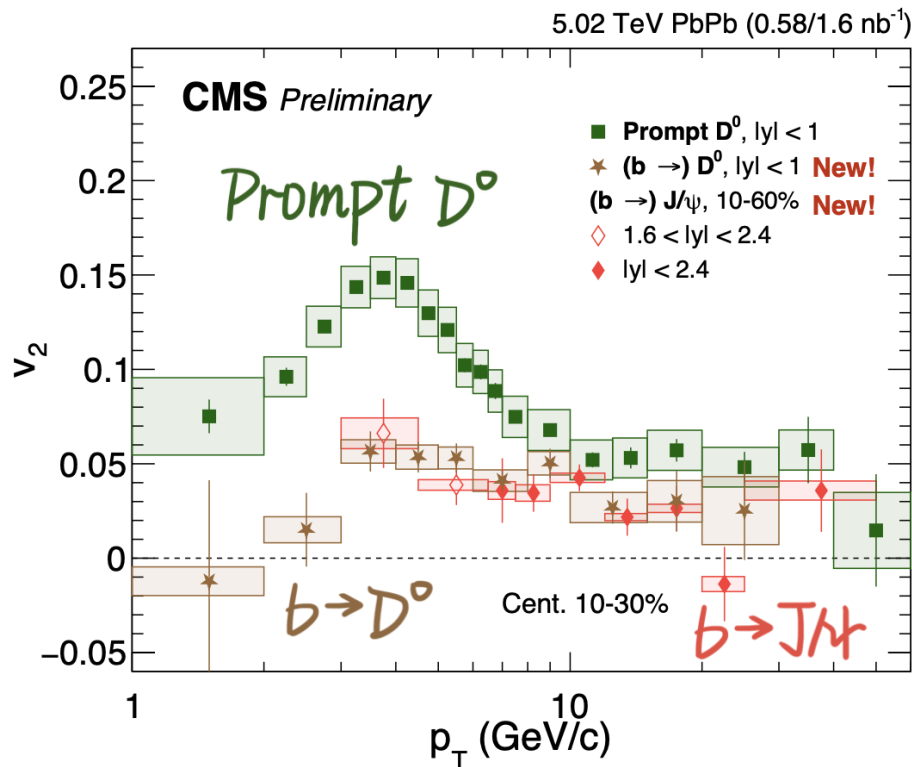
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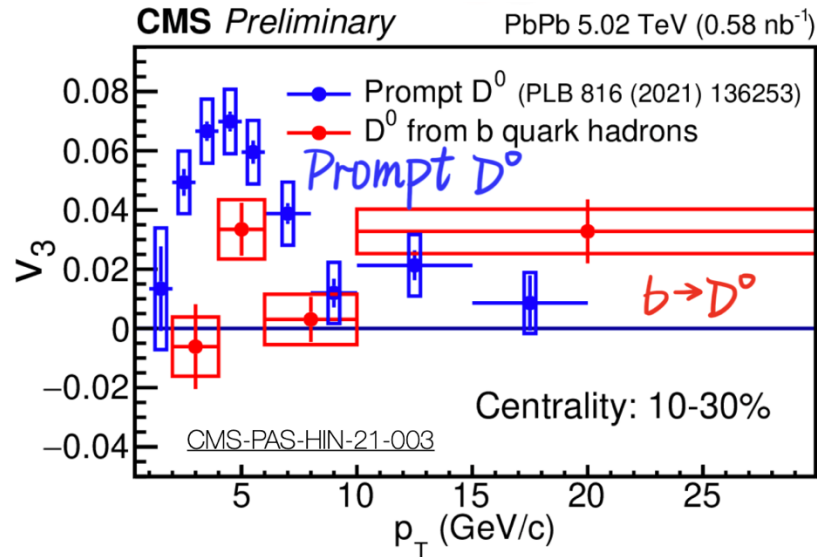
- less so than charm...

... and it flows, too...

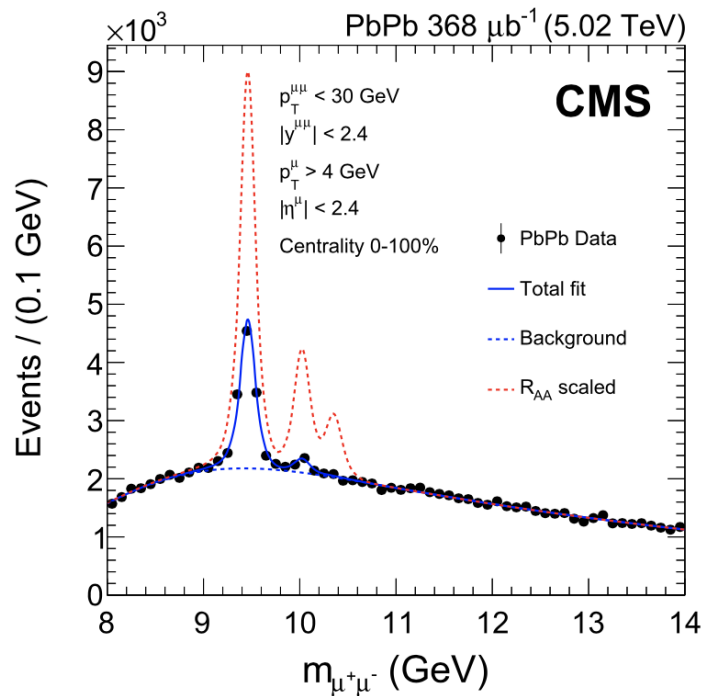


- less so than charm...

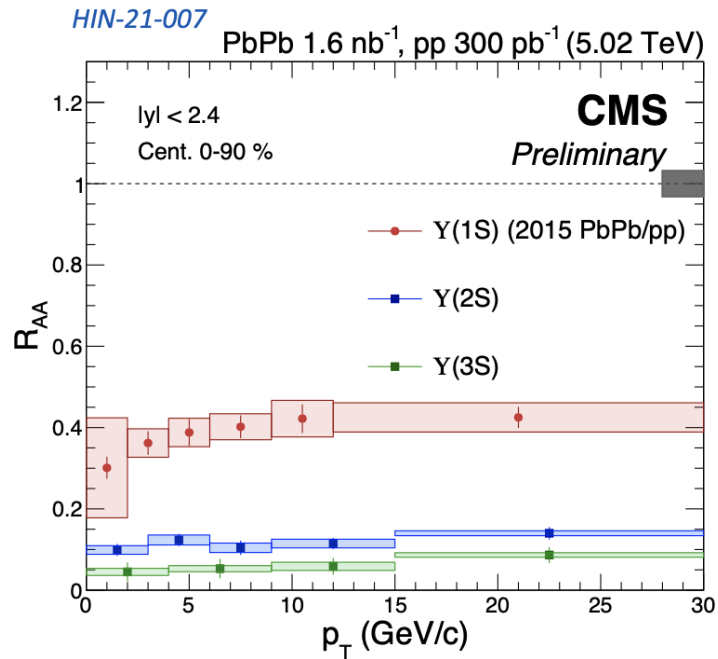
- similar trend for v_3 :



Υ states seem to follow a sequential suppression pattern

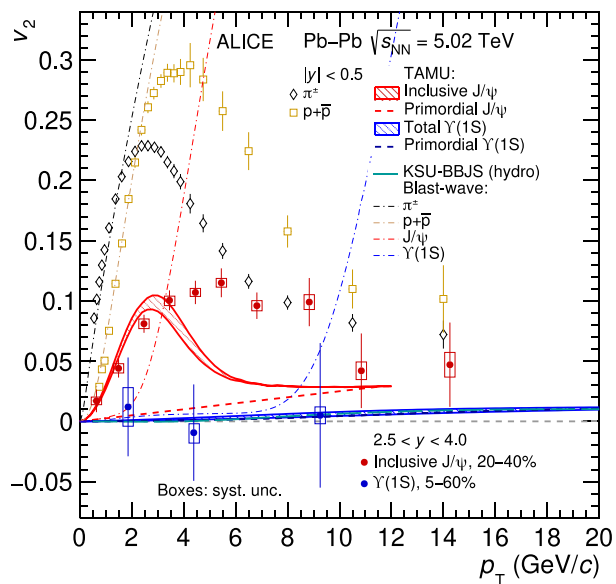


CMS: PLB 790 (2019) 270

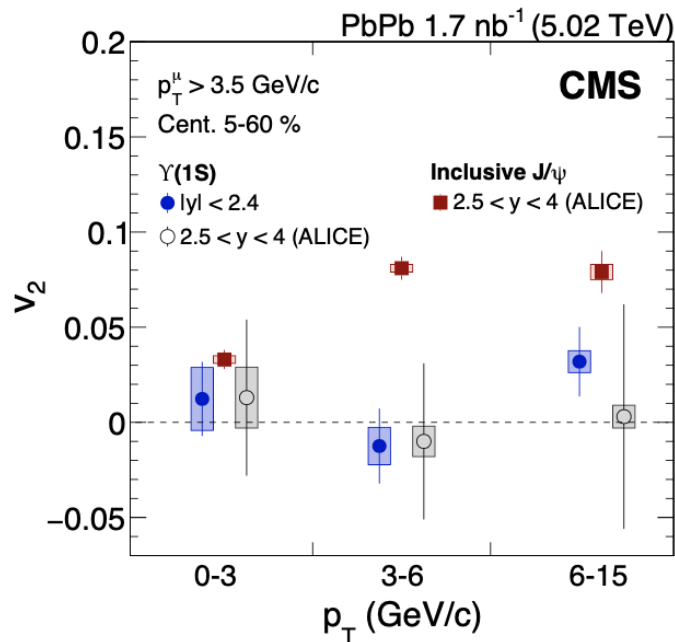


CMS: PAS-HIN-21-007

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

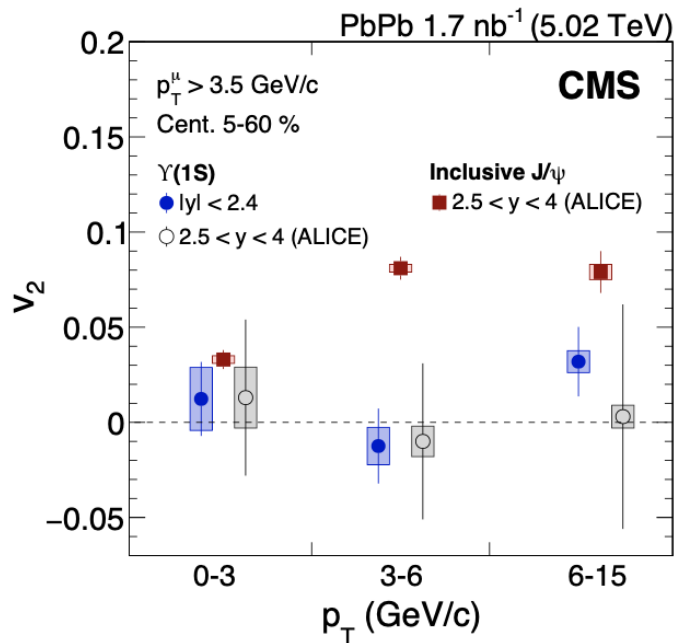


ALICE: PRL 123 (2019) 192301



CMS: PLB 819 (2021) 136385

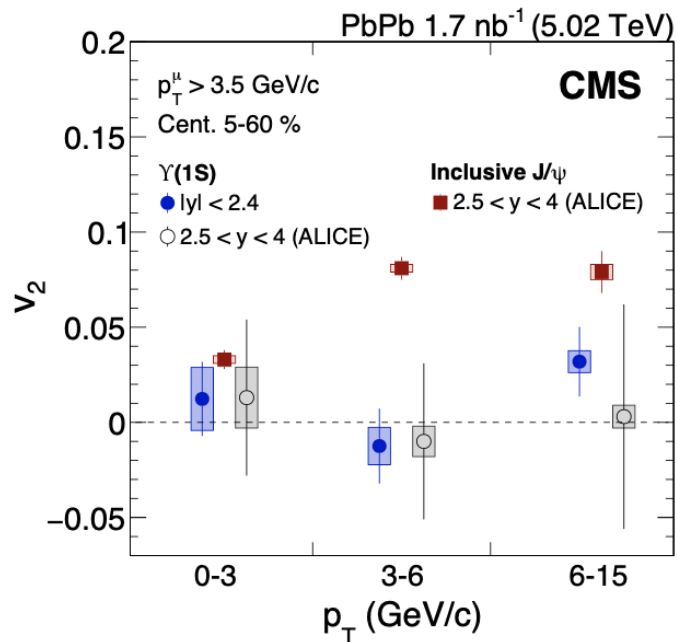
... but the Υ doesn't seem to flow much...



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

CMS: PLB 819 (2021) 136385

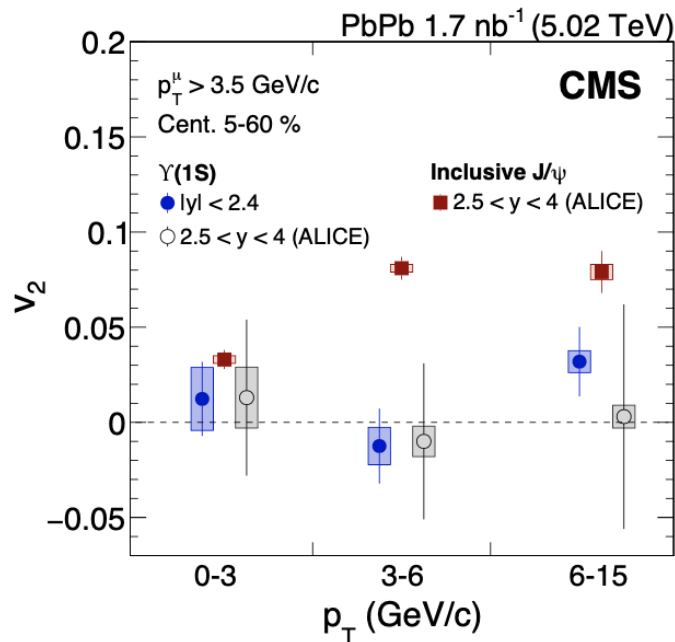
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CMS: PLB 819 (2021) 136385

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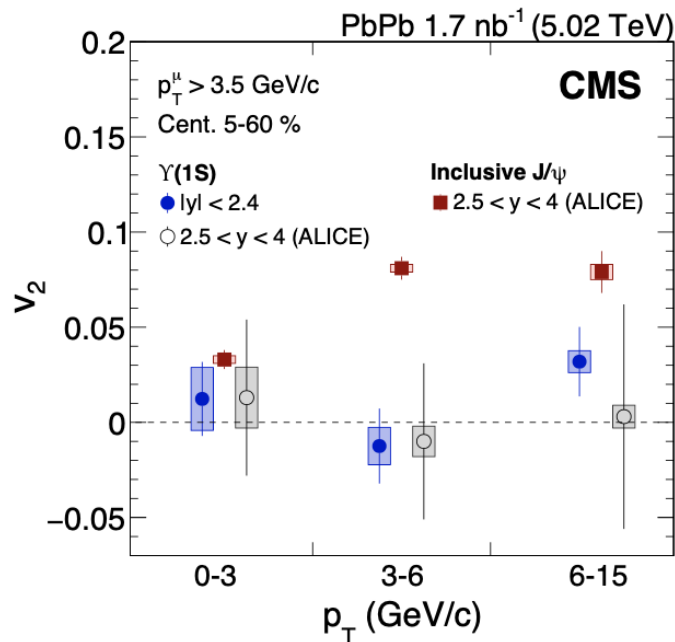
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CMS: PLB 819 (2021) 136385

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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?
- 🤔 ...