The ALICE experiment: probing QCD matter at the Large Hadron Collider

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Kruger Park, 5 December 2022

Contents

- Introduction
  - QCD, deconfinement, the QCD phase diagram, ultrarelativistic nuclear collisions
- The ALICE experiment
- A selection of results
  - with a zoom on heavy flavours
- Where do we go from here?
- Upgrade plans
- Summary and conclusions

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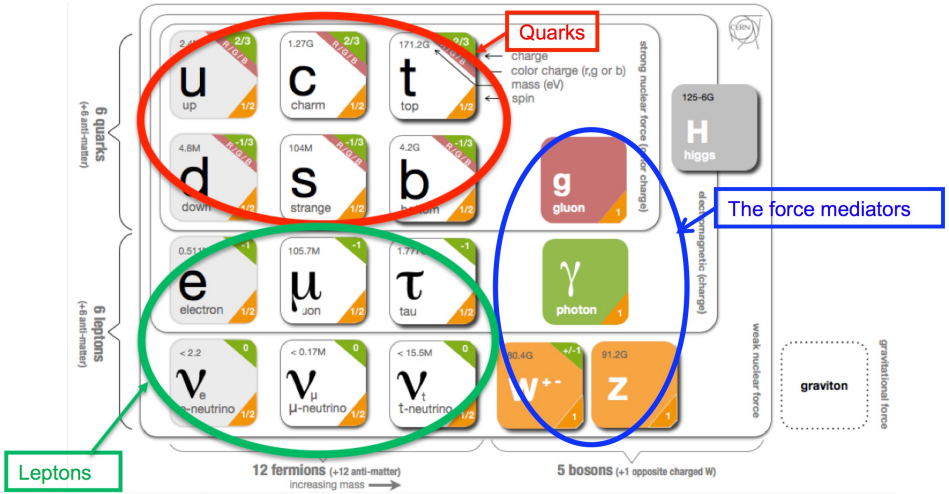
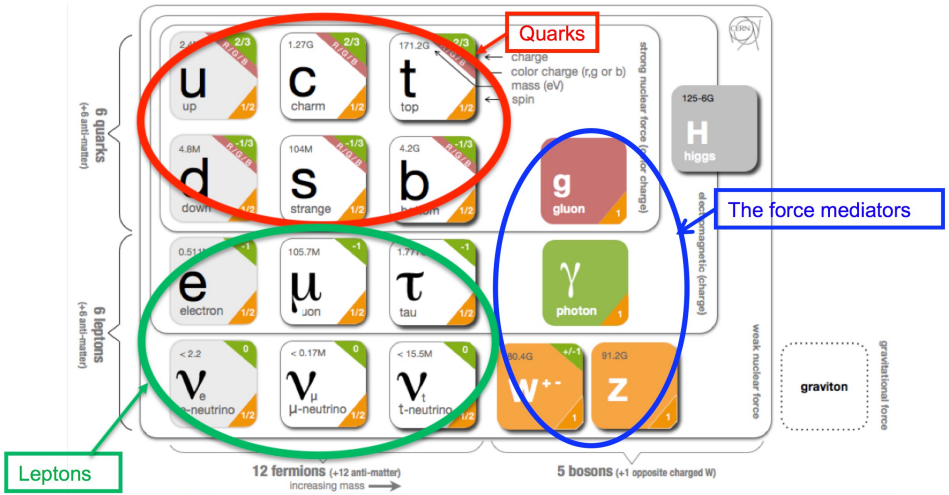
The Standard Model and QCD



- strong interaction
  - binds quarks into hadrons
  - binds nucleons into nuclei
- described by QCD
  - quantum chromodynamics
  - interaction between colour charges (quarks, gluons)
  - mediated by strong force carriers (gluons)
- very successful theory!
  - jet production, heavy flavour production, …
- ... but with outstanding puzzles...

Two puzzles in QCD



- hadron masses
  - e.g.: a proton contains 2 u, 1 d quarks
  - $m_u + m_u + m_d \approx 12$ MeV
  - but m(p) = 938 MeV!
  - → how is the extra mass generated?

- confinement
  - nobody ever detected an isolated quark
  - quarks appear to be permanently confined
  - → it seems that one half of the fundamental fermions are not directly observable!
  - compelling arguments this is due to non-abelian nature of QCD (no rigorous proof, though…)

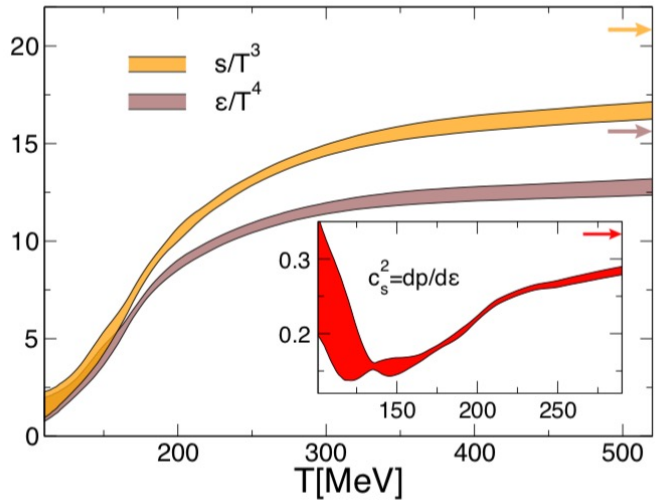
Lattice QCD and deconfinement

- the most rigorous way of doing calculations in the non-perturbative regime
- discretisation on a space-time lattice
  - ultraviolet (large-momentum scale) divergencies can be avoided

→ at high energy density: phase transition to QCD plasma (quark-gluon plasma")

  - e.g.: energy density vs temperature

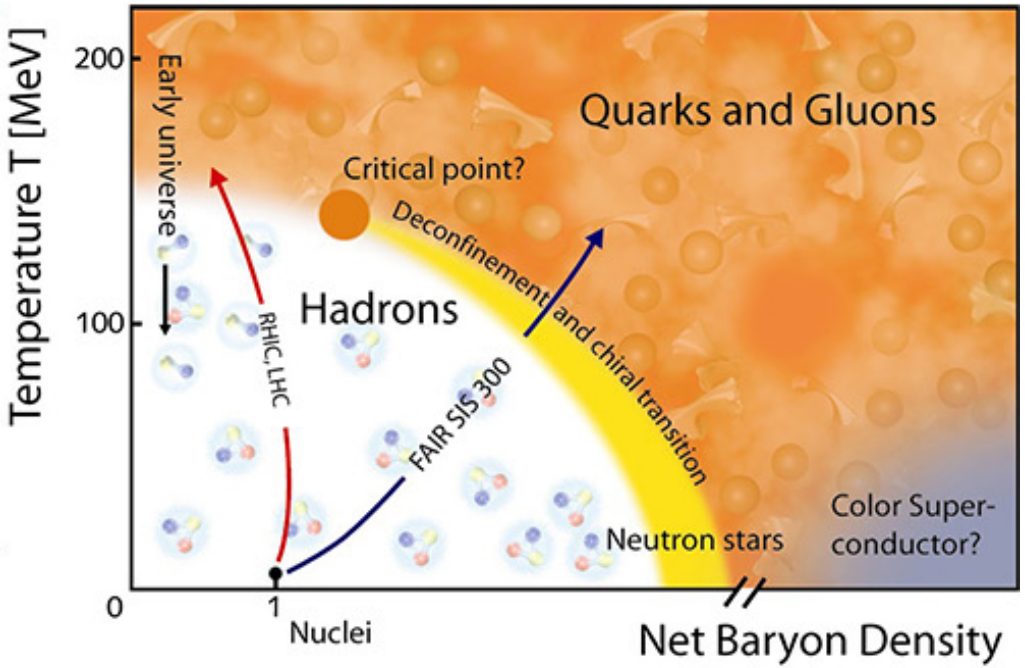
S Borsányi et al: Phys. Lett. B 370 (2014) 99



- ε, s change rapidly around T_c
  → activation of partonic degrees of freedom

- $T_c \approx 160$ MeV (→ $\varepsilon_c \approx$ GeV/fm^3)

The QCD phase transition

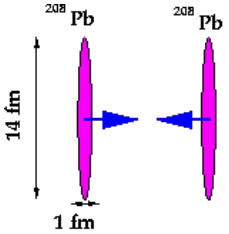


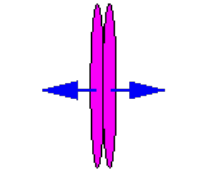
- Big Bang evolution
  - QGP to hadrons at t ~ 10 μs
- origin of nucleon masses
- phase transition in quantum field theory
  - the only experimentally accessible one!
- fundamental constituents ←→ matter
  - in a single step!

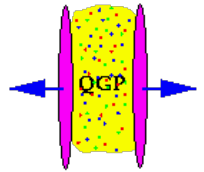
Ultrarelativistic nuclear collisions

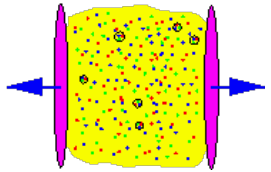
- how can we compress/heat matter to such cosmic energy densities?
- by colliding two nuclei accelerated to ultrarelativistic energy!
  the conditions for deconfinement are recreated, for ~ 10^{-23} s
  the system then expands and cools down → back to hadrons

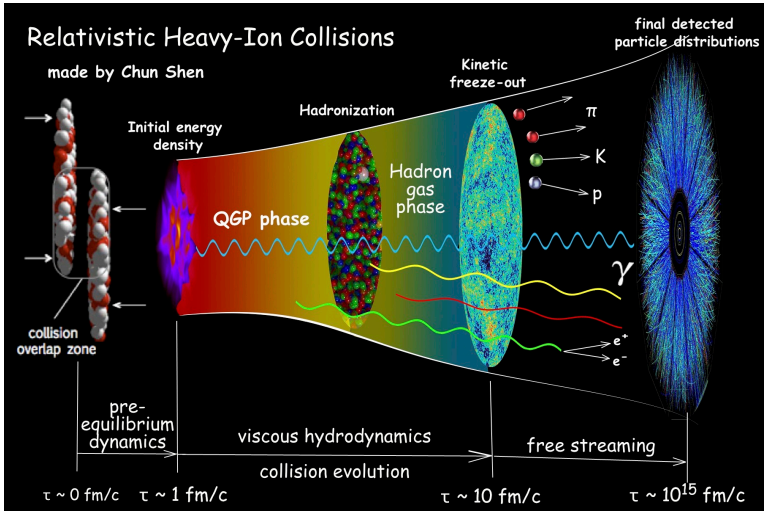
→ condensed-matter physics of QCD!

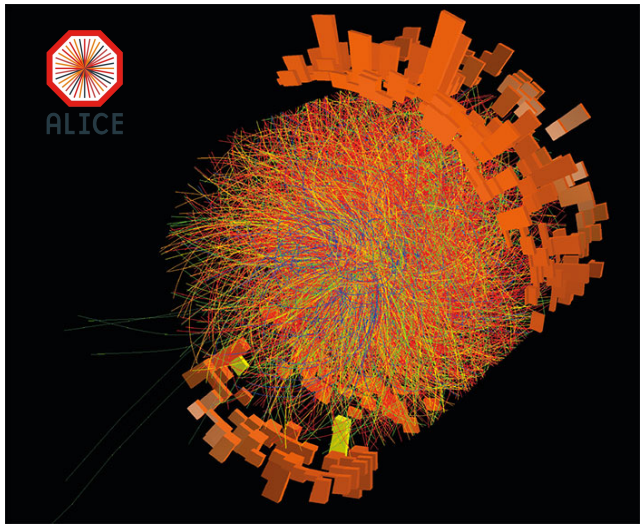












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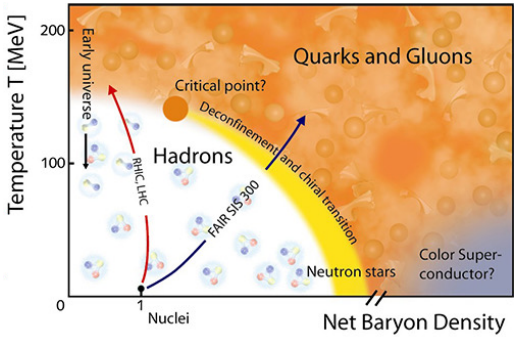
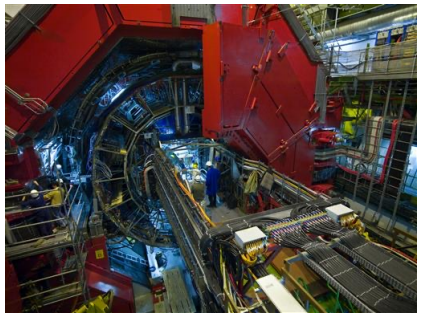
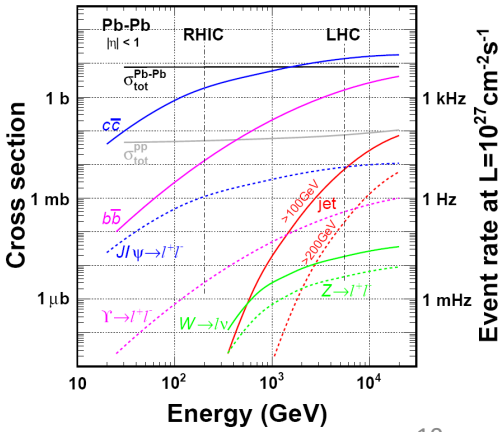
Nuclear collisions at the Large Hadron Collider

- 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
  - 1036 authors, 170 institutions, 40 countries
- ATLAS, CMS, LHCb also participating in programme

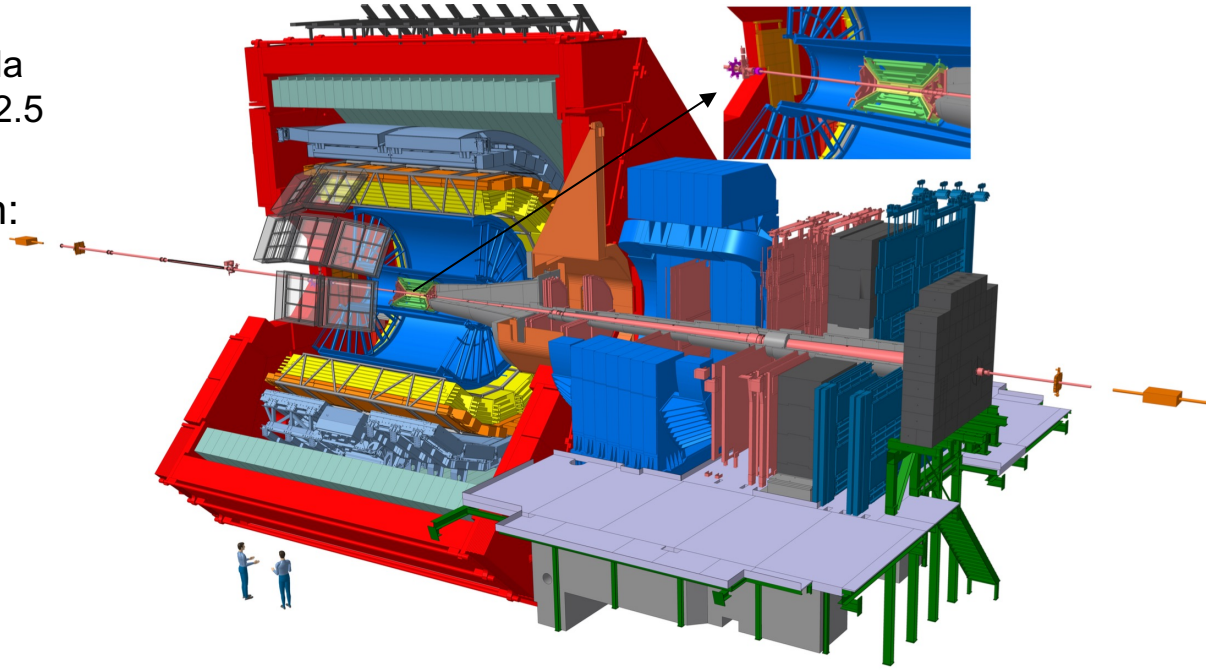






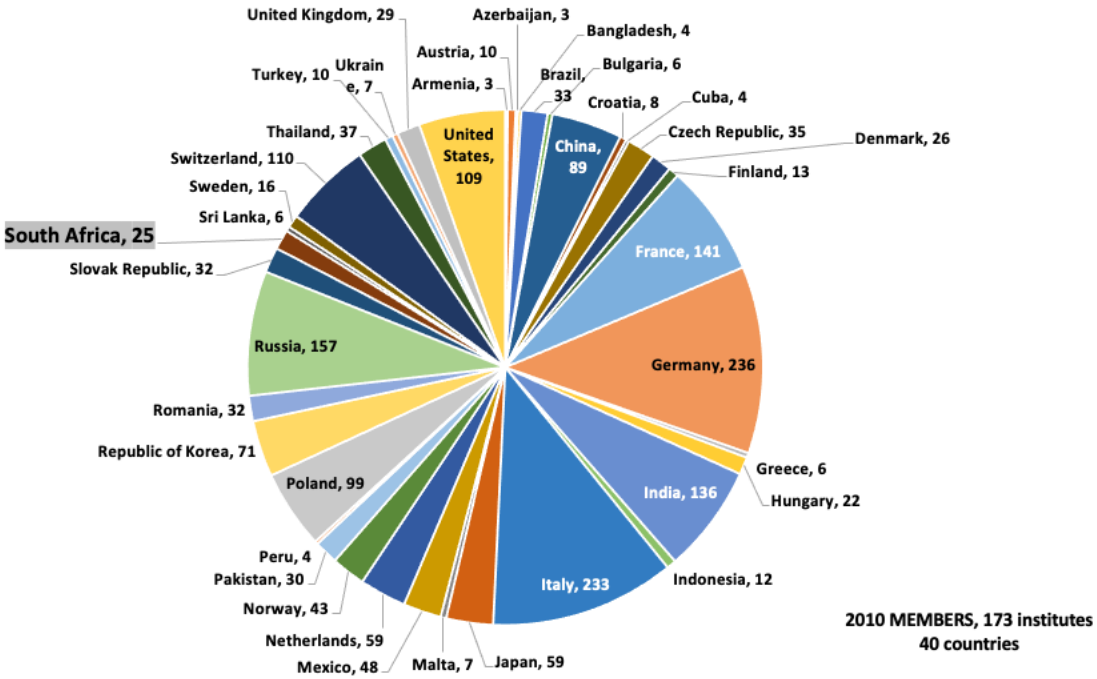
The ALICE experiment

- Two main parts:
  - barrel ($|\eta|<0.9$), B = 0.5 Tesla
  - muon spectrometer, $-4<\eta<-2.5$
- High precision reconstruction:
  - low material tracking
  - high resol. 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

Important contribution from SA!



iThemba LABS
University of Cape Town
University of Witwatersrand

- 5 scientists
- 4 PhD students

- Muon Arm
- Transition Radiation Detector
- Computing
- Physics Analysis

Important contribution from SA!

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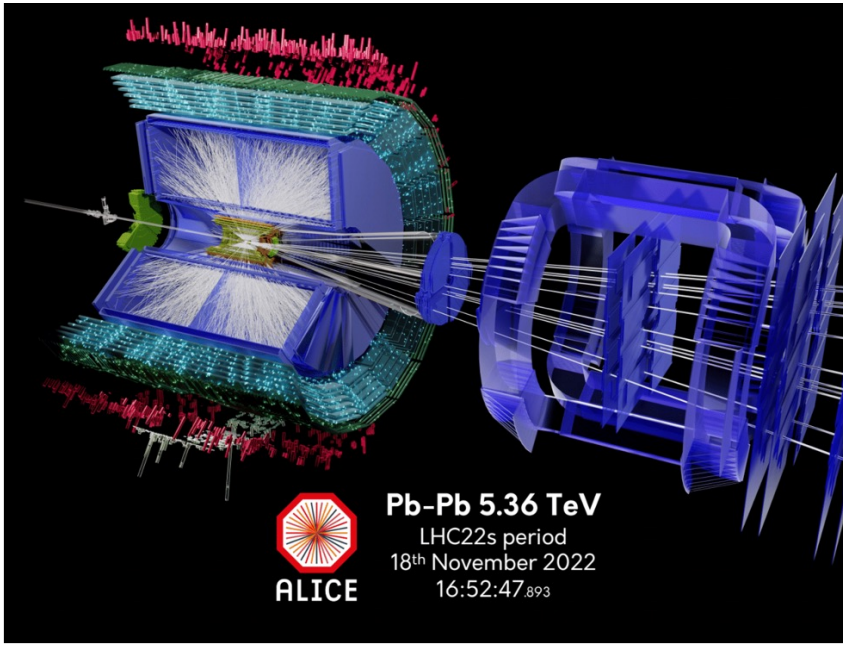
Status of data taking

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011	2.76	75 μb^{-1}
	2015, 2018	5.02	800 μb^{-1}
	2022	5.36	0.15 μb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
p-Pb	2013	5.02	15 nb^{-1}
	2016	5.02, 8.16	3 nb^{-1}, 25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	200 μb^{-1}, 100 nb^{-1}, 1.5 pb^{-1}, 2.5 pb^{-1}
	2015, 2017	5.02	1.3 pb^{-1}
	2015-2018	13	36 pb^{-1}
	2022	13.6	18 pb^{-1}



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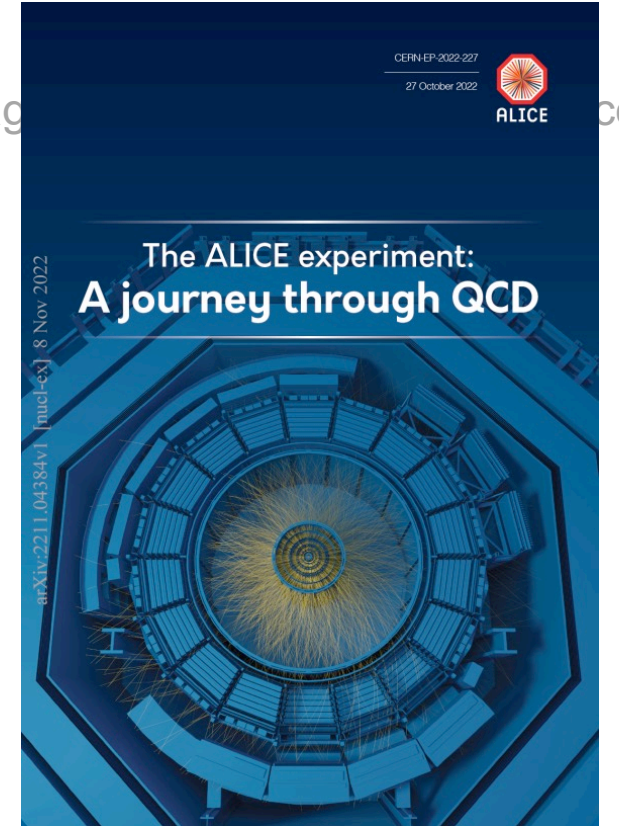
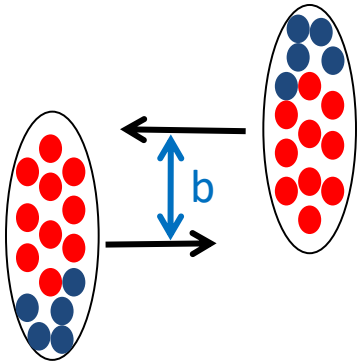
much more here!



arXiv:2211.04384 (just out!)

Geometry of a nucleus-nucleus collision



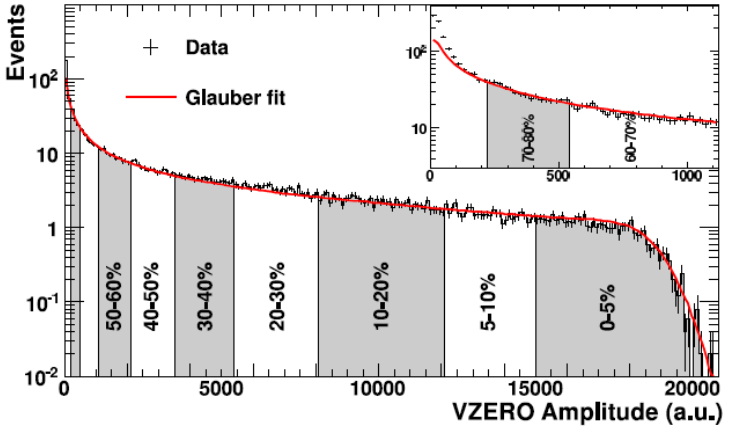
- central collisions
  - small impact parameter b
  - high number of participants → high multiplicity
- peripheral collisions
  - large impact parameter b
  - low number of participants → low multiplicity

for example: sum of the amplitudes in the ALICE V0 scintillators →

reproduced by Glauber model fit (red):

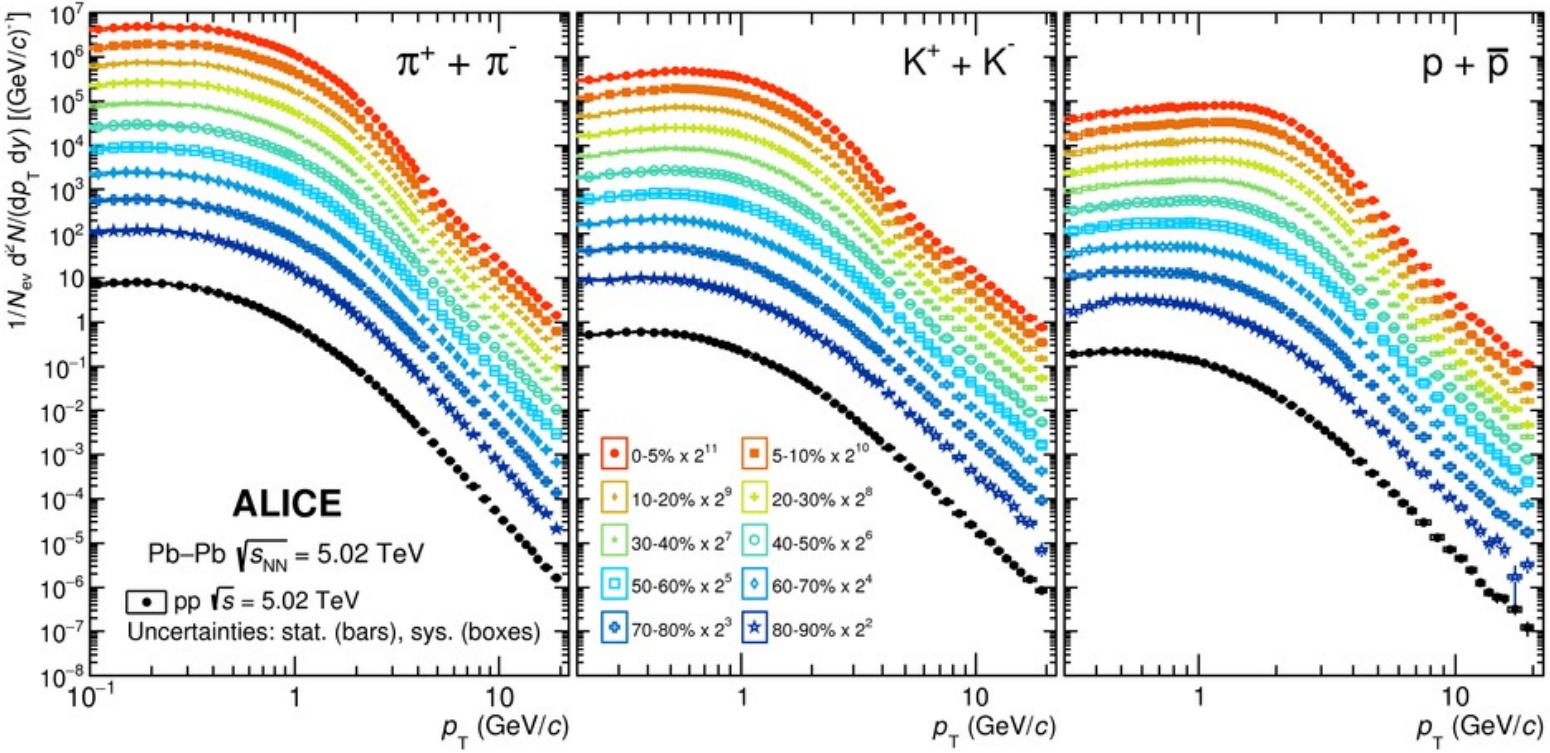
- Woods-Saxon distribution inside nucleus
- random relative position of nuclei in transverse plane
- simple particle production model

(deviation at very low amplitude expected due to non-nuclear (EM) processes)



Identified particles

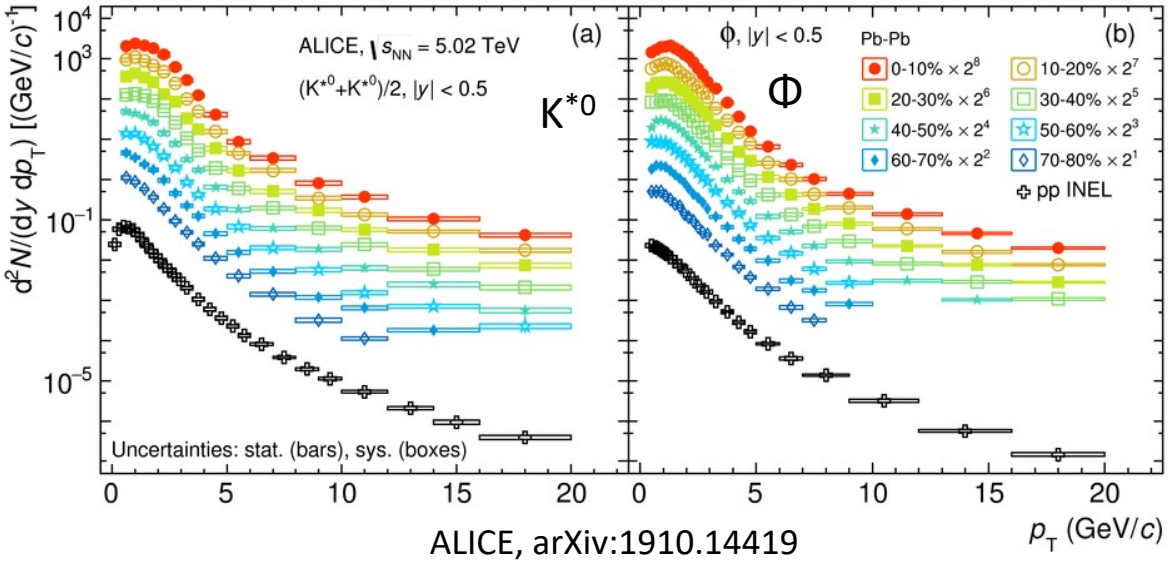
Textbook-quality Run 2 data!



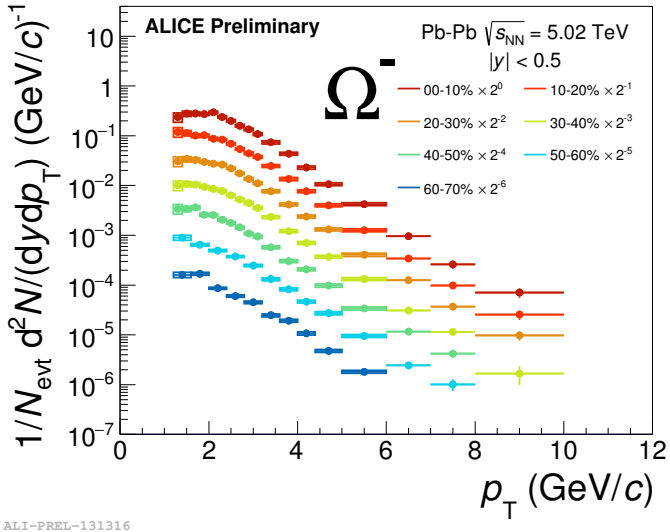
ALICE, arXiv:1910.07678

More and more species

Resonances, hyperons,…



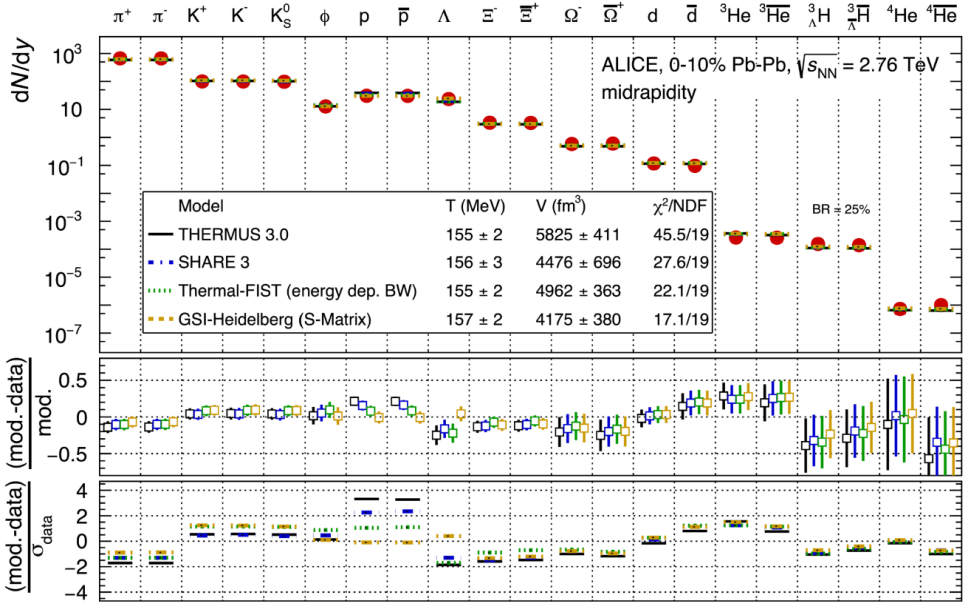
ALICE, arXiv:1910.14419



ALI-PREL-131316

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

Integrated yields



arXiv:2211.04384

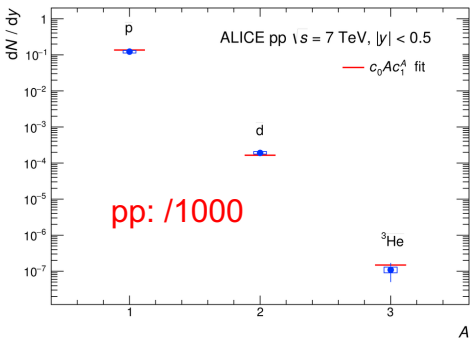
$T_{chem} \approx T_C \approx 156$ MeV

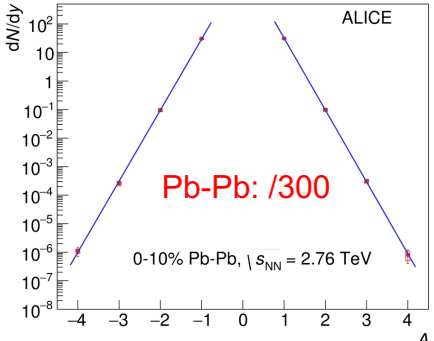
→ hadronisation very close to the phase transition

- 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

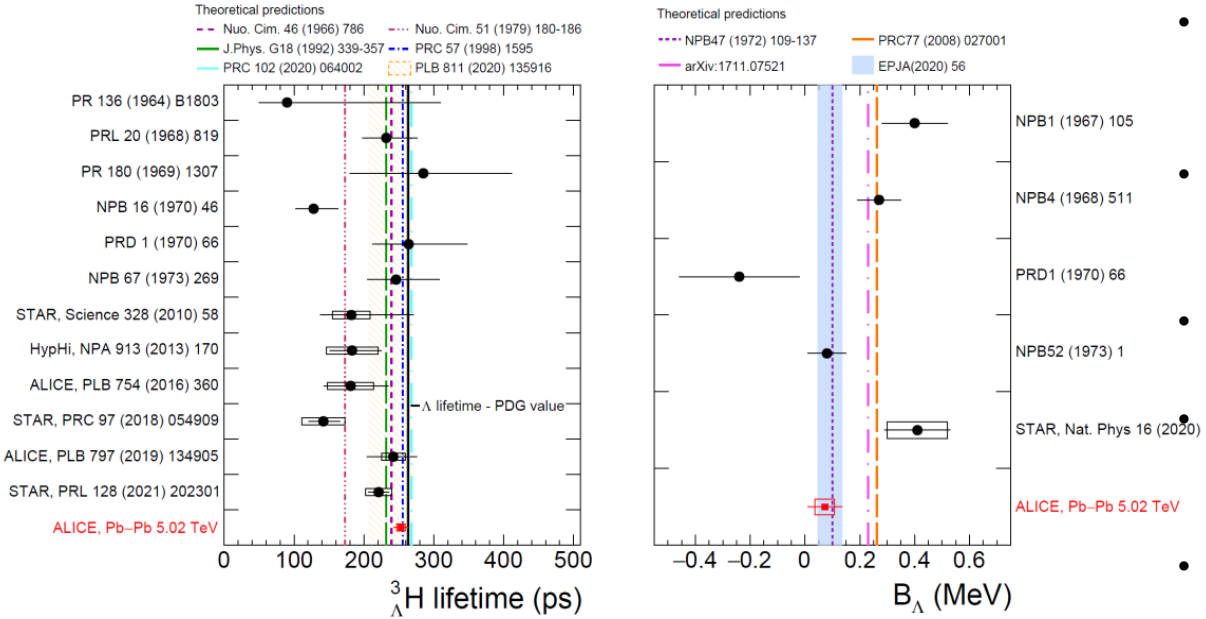
… even for nuclei, hypernuclei

- in spite of very low binding energy!
- substantial enhancement wrt pp
- → AA is a (hyper-)nuclei factory
- for each additional nucleon:





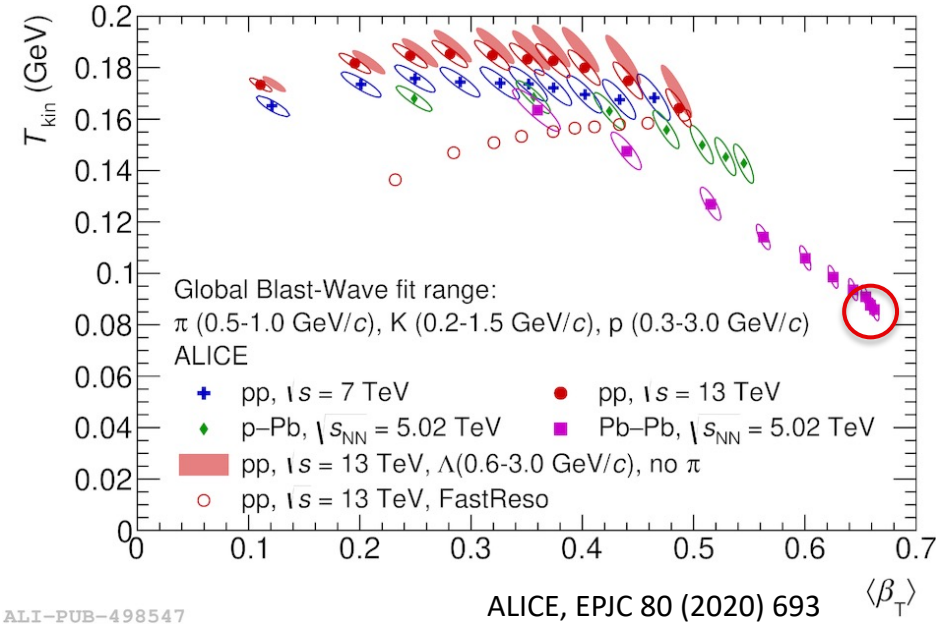
Hypertriton lifetime



- binding energy: 130±30 keV
  - one of the smallest E_{bind} observed
- abundantly produced in QGP
  - even if size comparable to medium!
- unprecedented precision!
- ~ free Λ lifetime
  - no evidence of deviation
- loosely bound d-Λ molecule!

Radial flow

“Blast-Wave” fits to hadron spectra



ALICE, EPJC 80 (2020) 693

ALI-PUB-498547

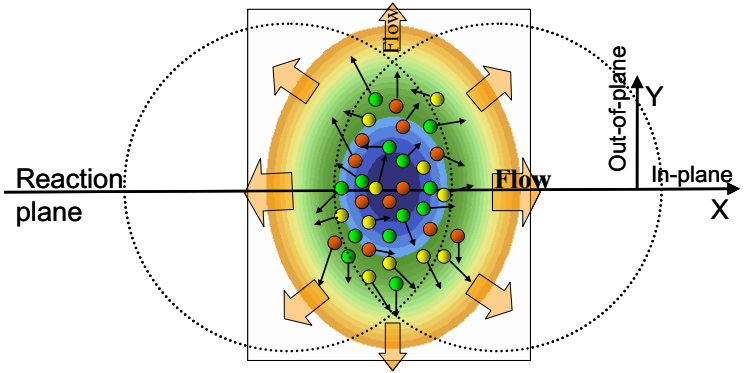
- model of radial expansion
  mass dependence → kinetic parameters
  - T_{kin}: kinetic freeze-out temperature
  - β_T: radial flow velocity
- Run 2 (5.02 TeV)
  - ~ 2/3 c (largest β_T ever observed)

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

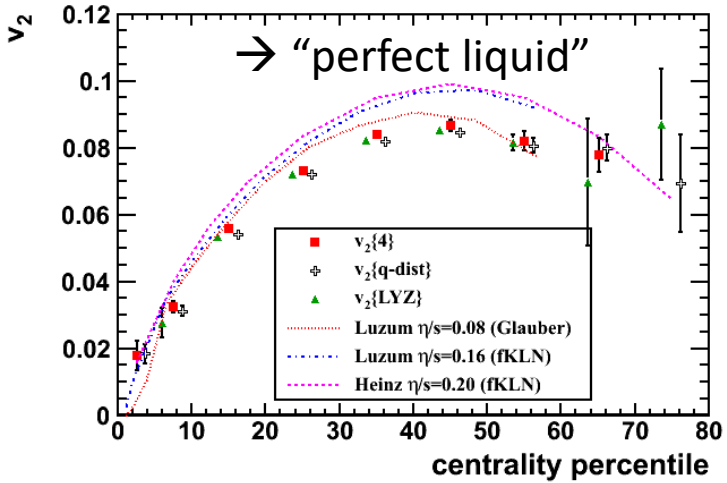
- to quantify the asymmetry:

  → Fourier expansion of the angular distribution:

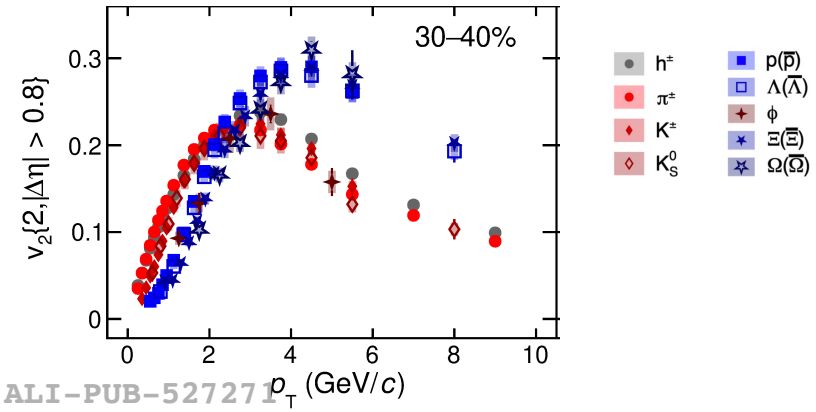
  $$\propto 1 + 2v_1\cos(\varphi - \psi_1) + 2v_2\cos(2[\varphi - \psi_2]) + \ldots$$

  – in the central detector region ($\vartheta \sim 90°$) → $v_1 \sim 0$ → asymmetry quantified with v_2

- experimentally: v_2 ~ as large as expected by hydrodynamics



radial expansion → signature in ID particle v_2

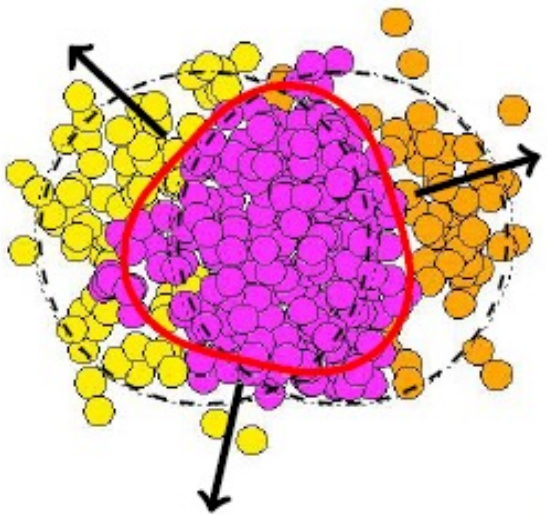


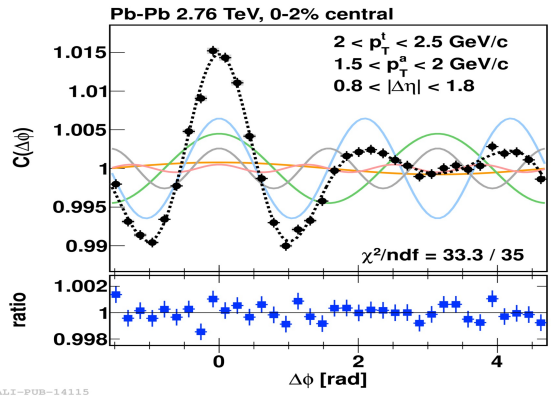
JHEP 09 (2018) 006

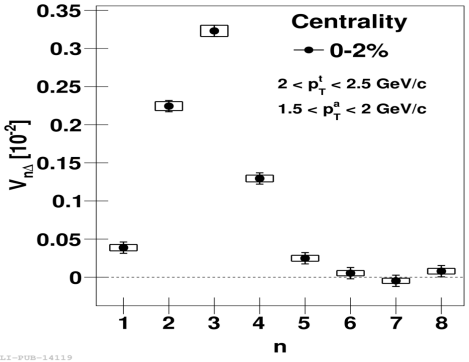
Higher harmonics: a beautiful tool…

initial-state geometrical asymmetries → final state momentum asymmetries

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





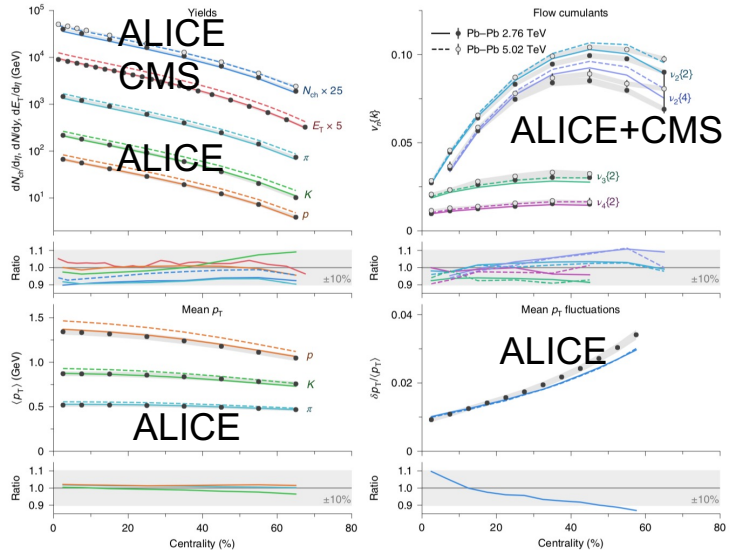


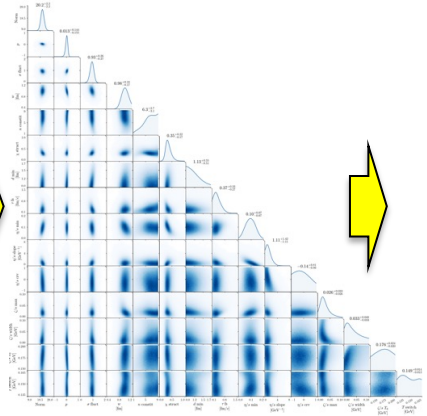
→ Fourier decomposition of azimuthal distribution

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

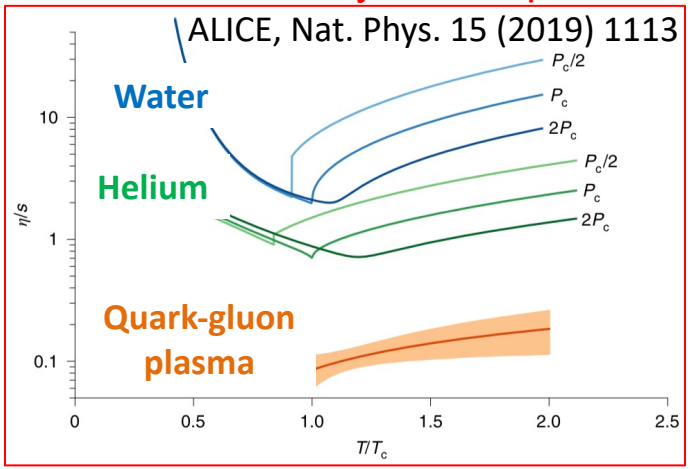
Entering precision era!

- 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

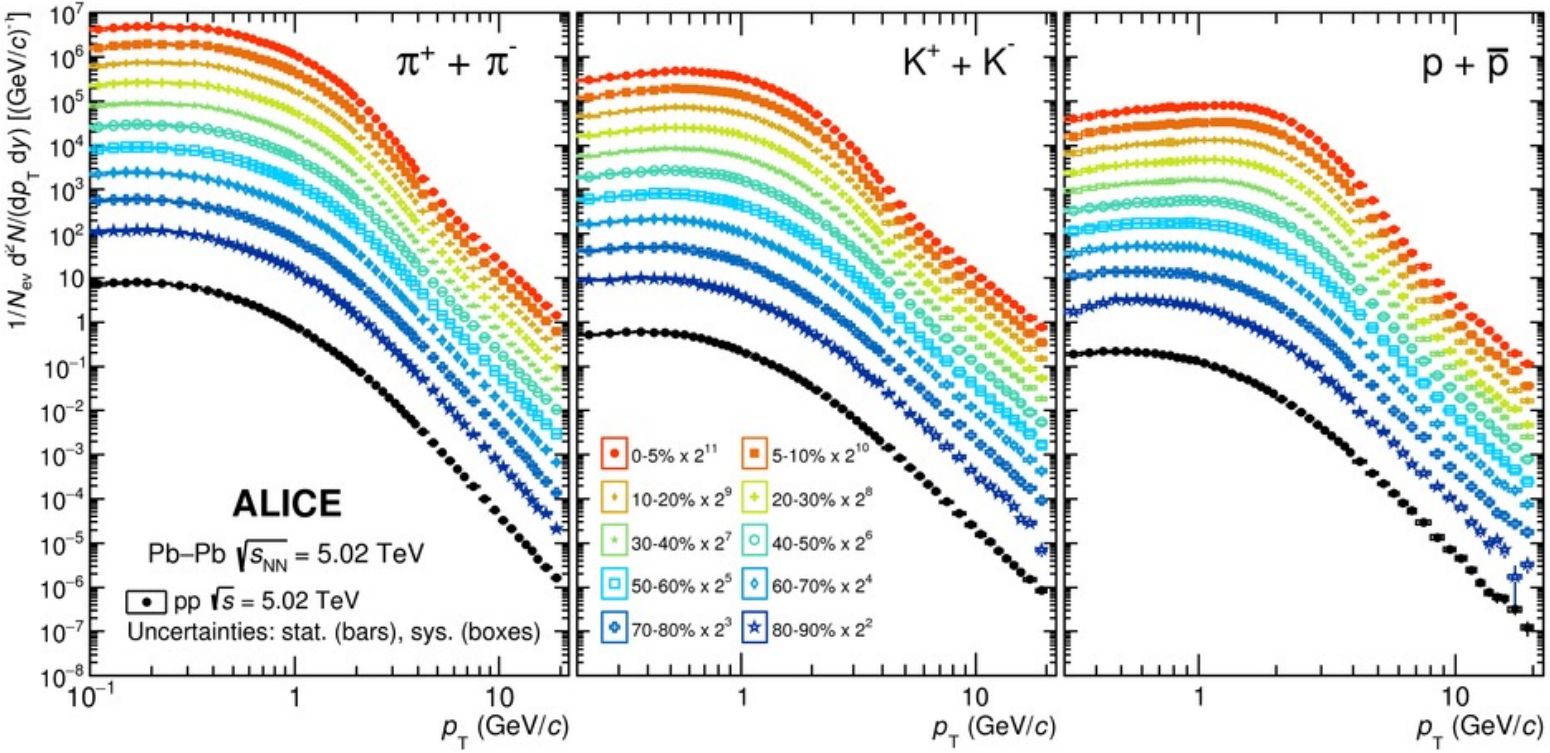


→ QGP viscosity with ~20% precision

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

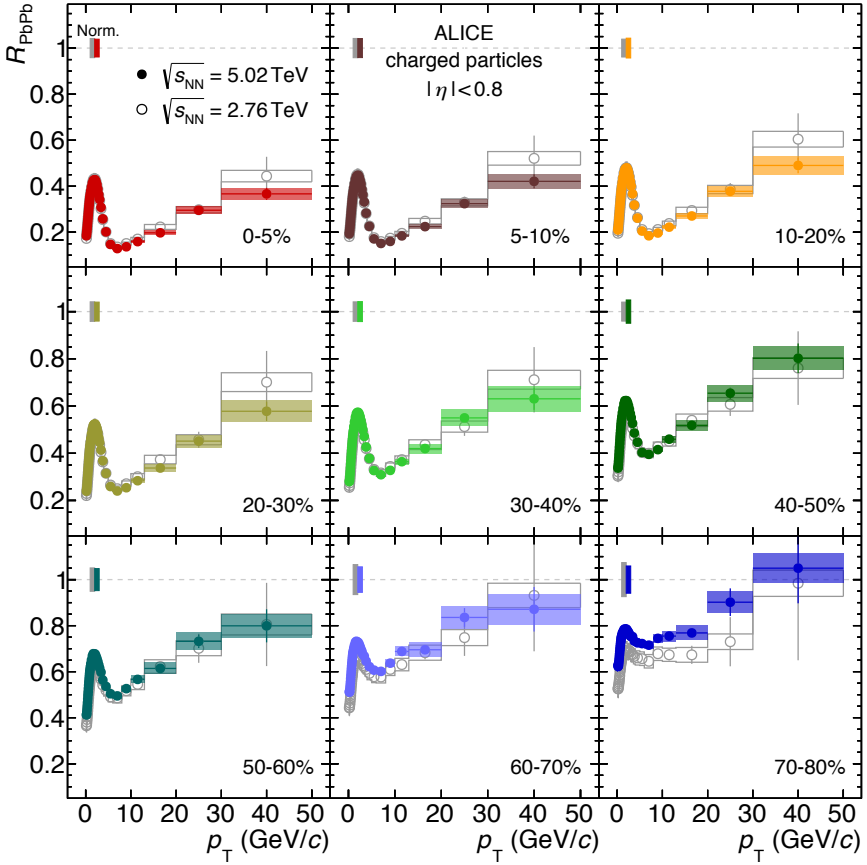
Identified particles

Textbook-quality Run 2 data!



ALICE, arXiv:1910.07678

Nuclear modification factor



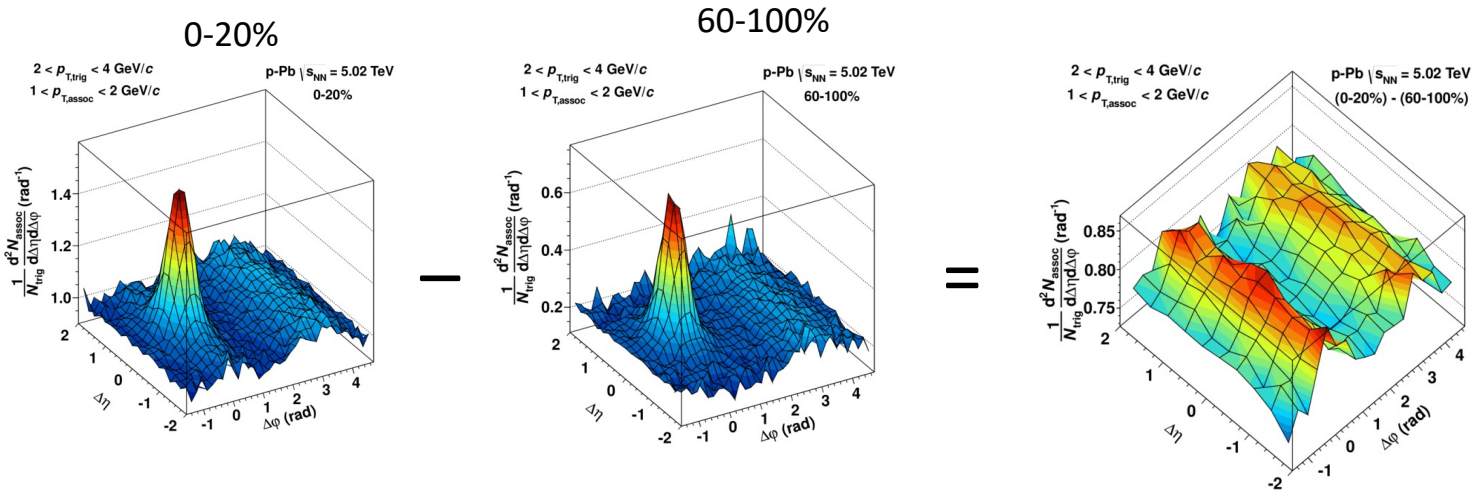
$$R_{AA} = \frac{(dN/dp_T)_{AA}}{\langle N_{coll} \rangle (dN/dp_T)_{pp}}$$

- sensitive to energy loss of partons
  - before hadronisation
- very strong quenching!
- very similar at 2.75 and 5.02 TeV
  - although spectra harden with √s

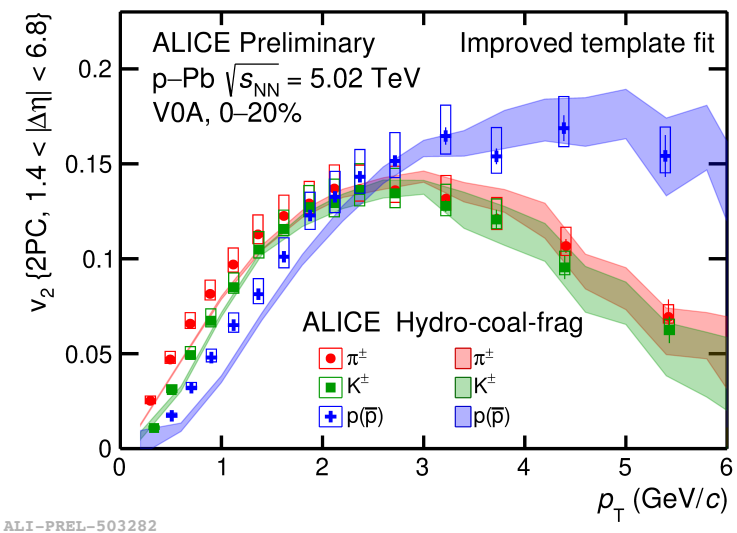
[ALICE, arXiv:1802.09145]

Small systems: a new frontier

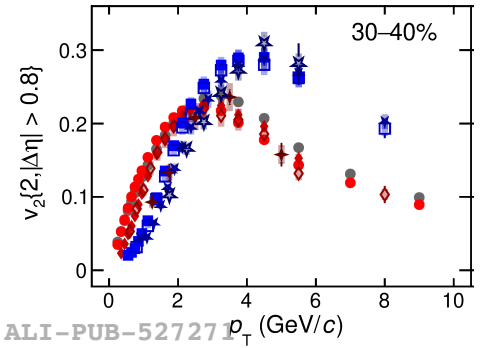
- evidence for collective behaviour in high-multiplicity p-Pb, pp
  - e.g. symmetric double-ridge when subtracting low from high mult'y p-Pb



v_2 for identified particles in p-Pb



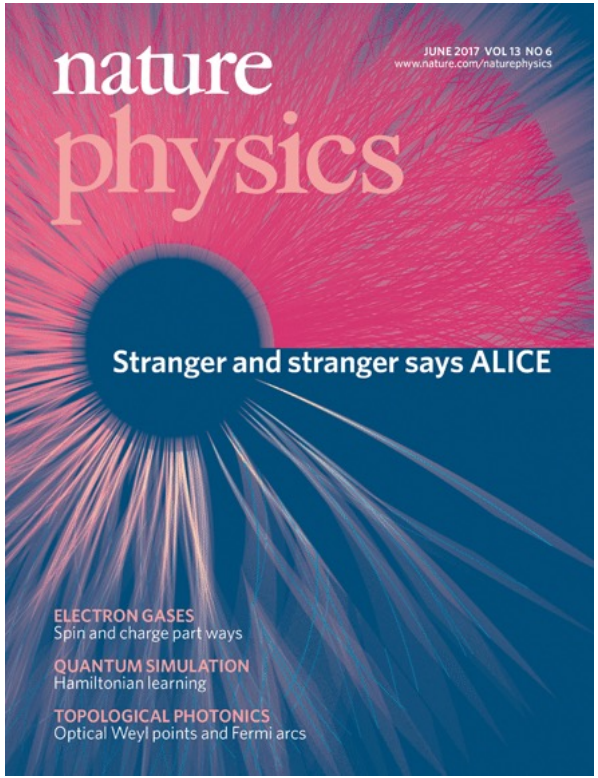
- clear mass ordering at high multiplicity
  - same as in Pb-Pb



- consistent with common velocity field

→ consistent with hydrodynamic expansion!

Strangeness enhancement in pp!



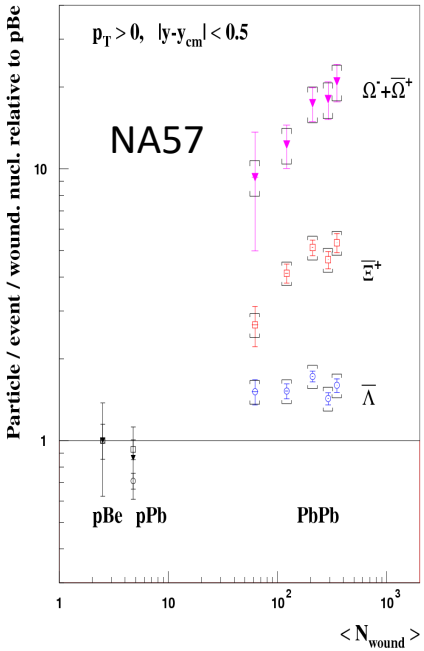
Nature Physics (2017) doi:10.1038/nphys4111

- one of the hallmarks of QGP
- predicted in 1982
  J Rafelski & B Müller, PRL 48 (1982) 1066

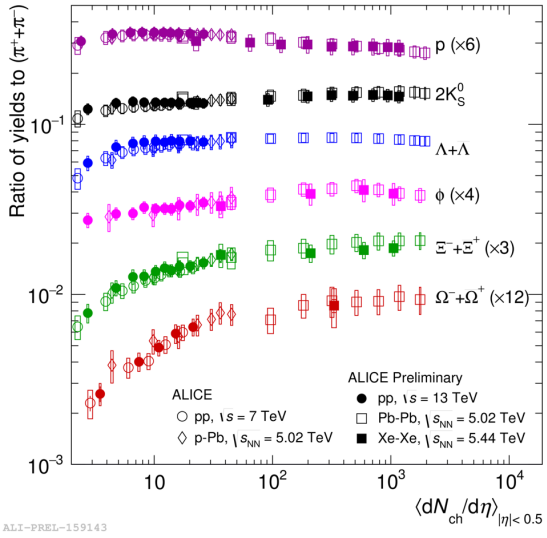
→ observed at SPS in the 90's
  WA97, NA57, NA49

- 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!



Hadron chemistry vs system size



- strangeness enhancement vs size
  - smooth evolution vs event multiplicity
- challenge for pp event generators
  - e.g.: T Sjostrand at Quark Matter 2018

→ new avenue to microscopic understanding of buildup of collectivity!

→ could help resolve muon puzzle in cosmic rays?

T Pierog et al, UHECR 2018, EPJ Web Conf
S Baur et al, arXiv:1902.09265
T Pierog, ESPP Symposium, Granada
T Pierog, ICRC 2019, Madison

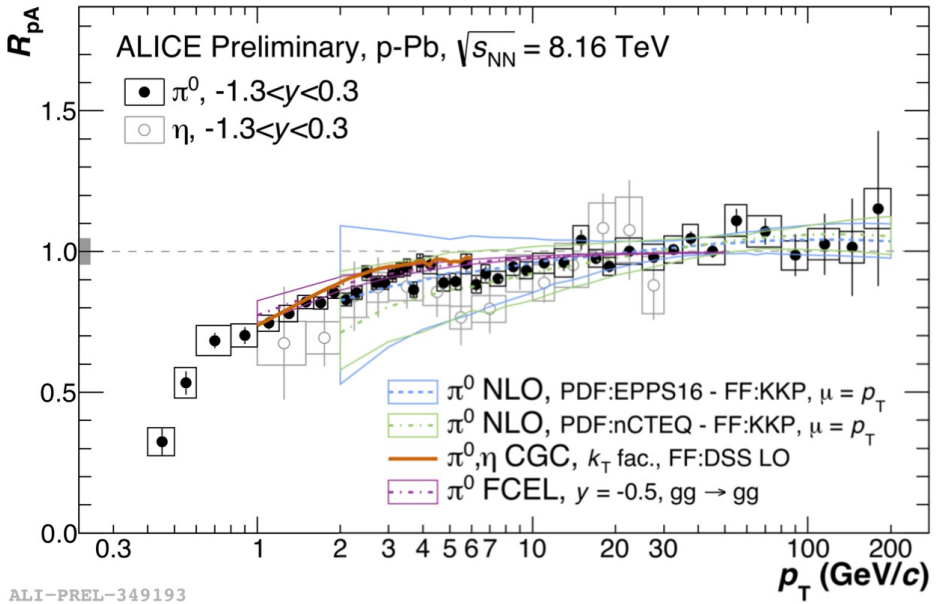
Summary and outlook

- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.
- String close-packing likely to influence hadronization, before (shoving), during (ropes) and after (rescattering).
- Currently no known unique solution, so free to explore.
- Several recent & ongoing studies look promising, but much work and few active with pp generator outlook.
- Further experimental input crucial!

Whole new field of study opening up!

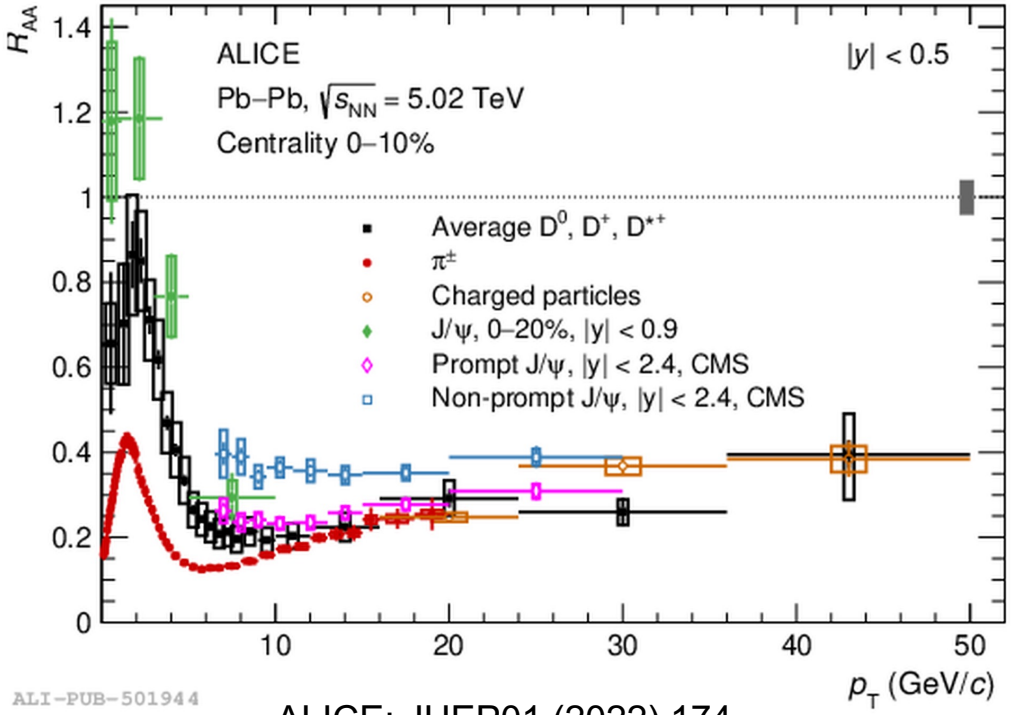
But no sign of quenching yet!

- e.g.: RpPb for π^0



[ALICE: PLB 827 (2022) 136943]

Heavy flavour: a gold mine!



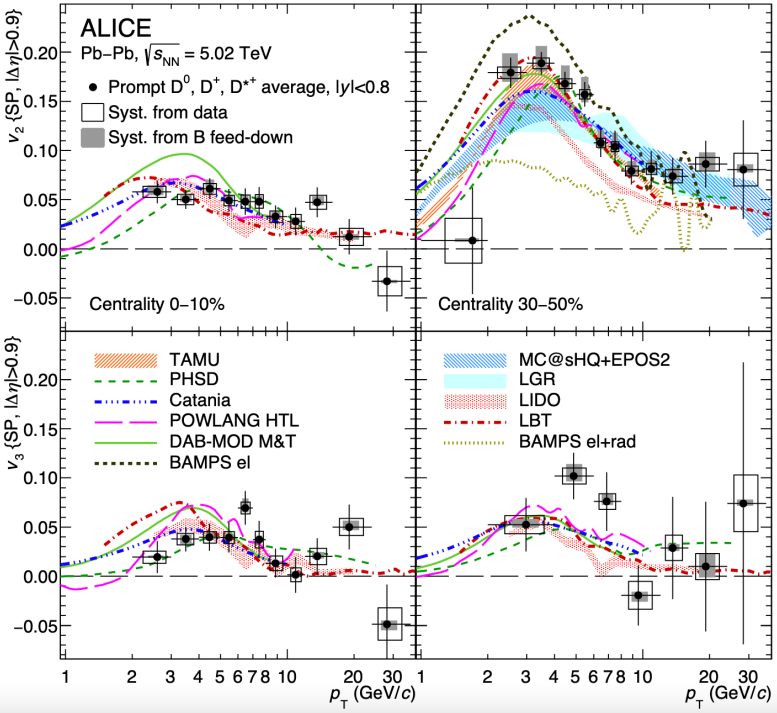
ALICE: JHEP01 (2022) 174

- 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

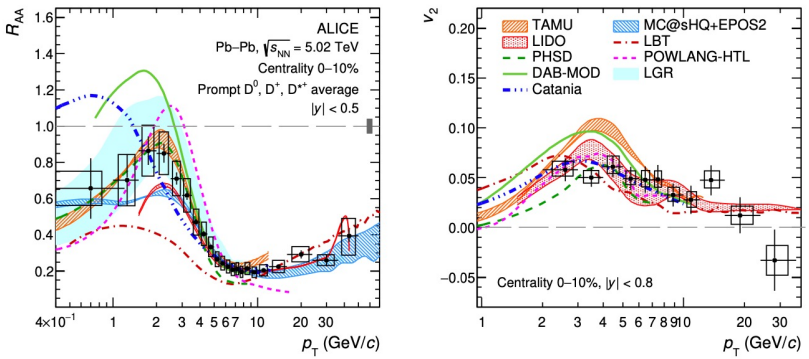
Strongly involved in the flow

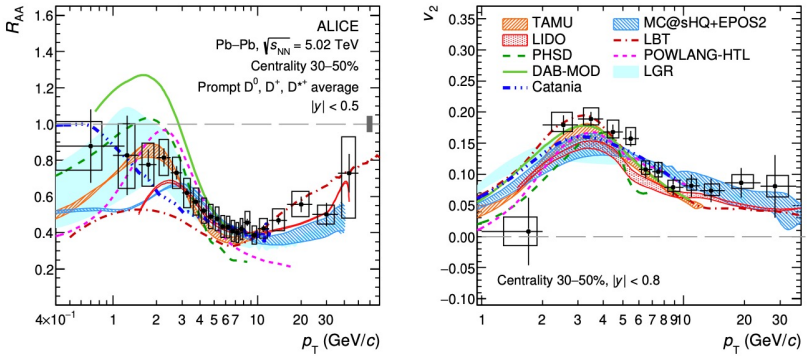


ALICE, PLB 813 (2021) 136054

- v_2 (geometry-driven)
- v_3 (fluctuations-driven)

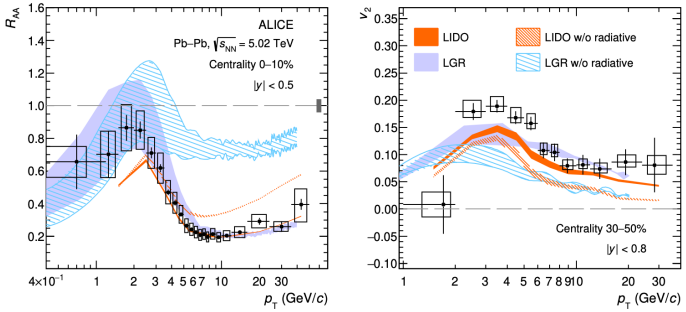
State of the art



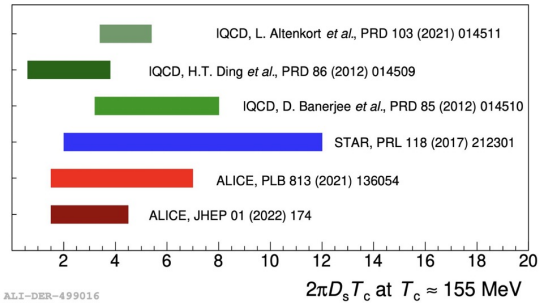


ALICE: JHEP01 (2022) 174

- substantial model constraints...

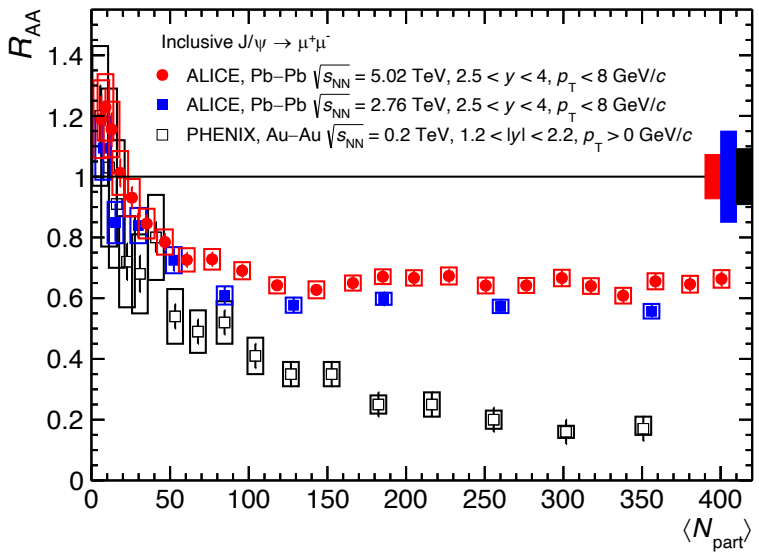


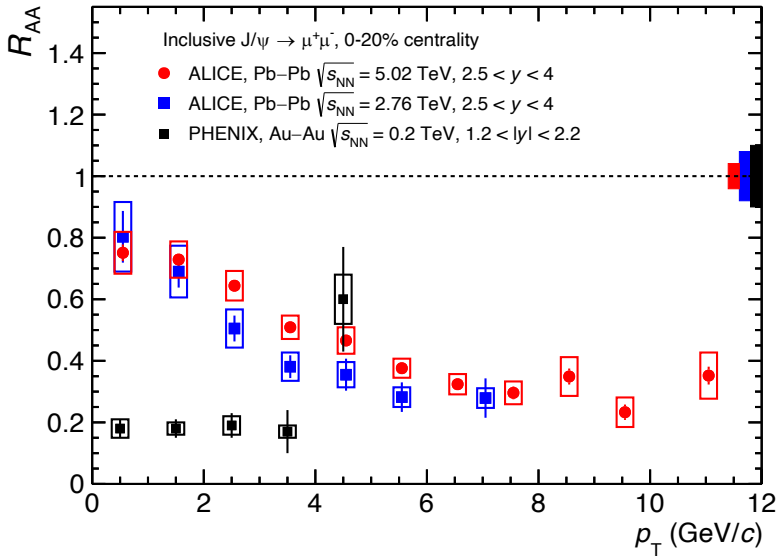
- 50% uncertainty on diffusion coefficient
  - it starts to be a measurement!



A new regime for J/ψ production!

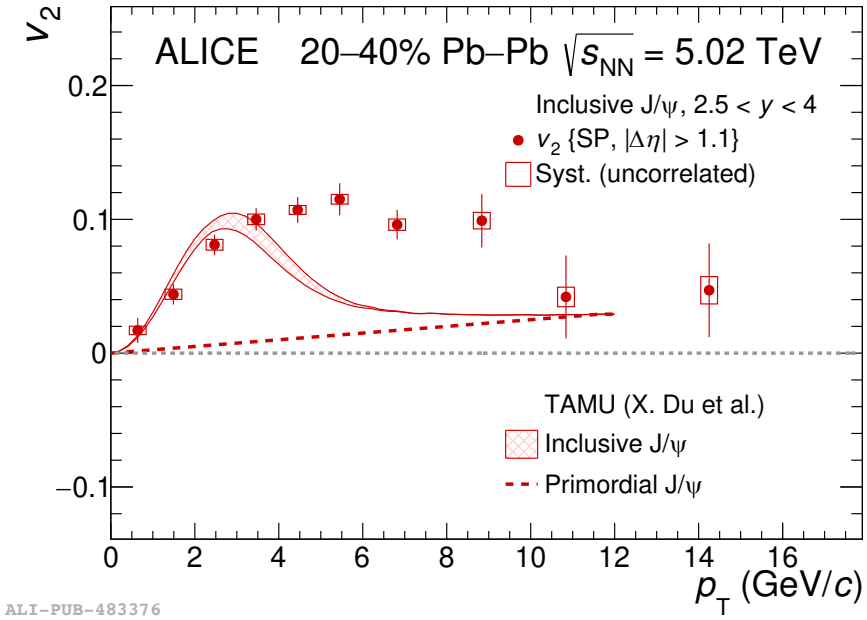
- a remarkable change of behaviour from SPS/RHIC!





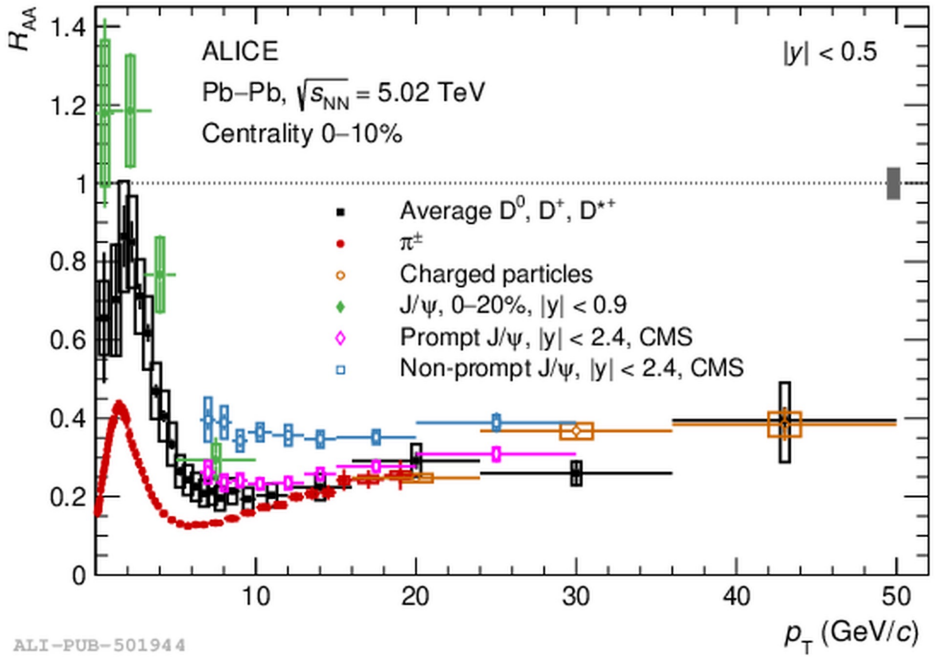
- in both the centrality and the p_T dependence
- evidence for production by recombination of exogamous $c\bar{c}$ pairs!

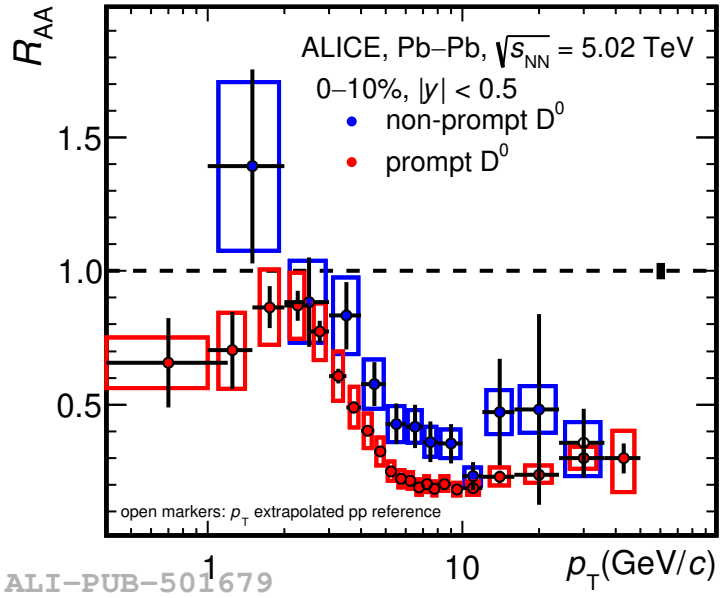
Charm quarks themselves flow



ALICE: JHEP 10 (2020) 141

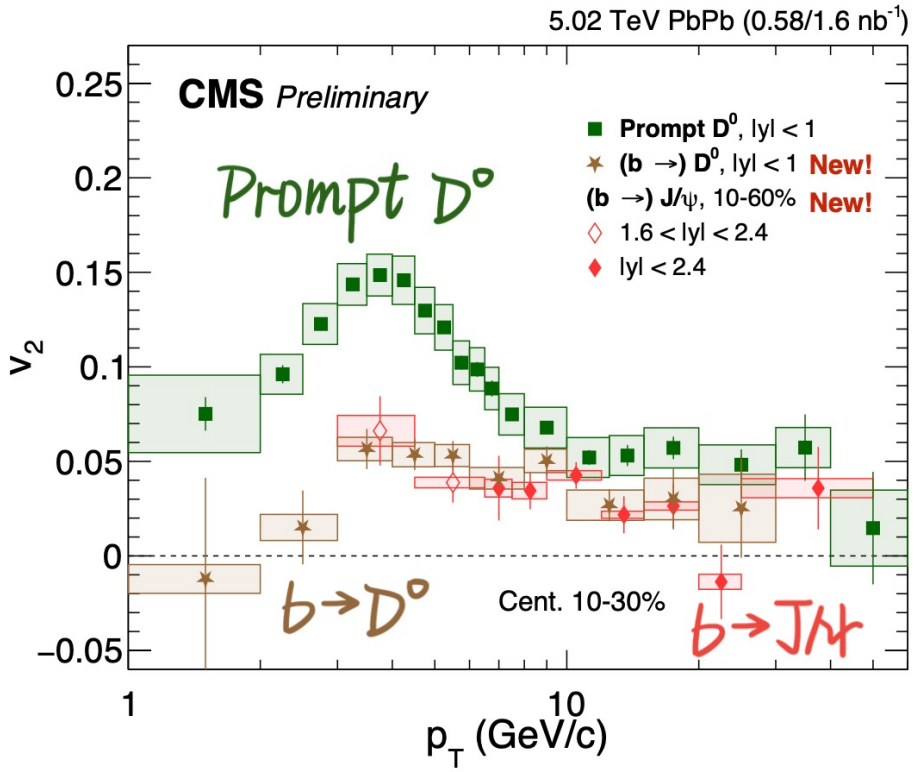
Beauty is quenched, too...



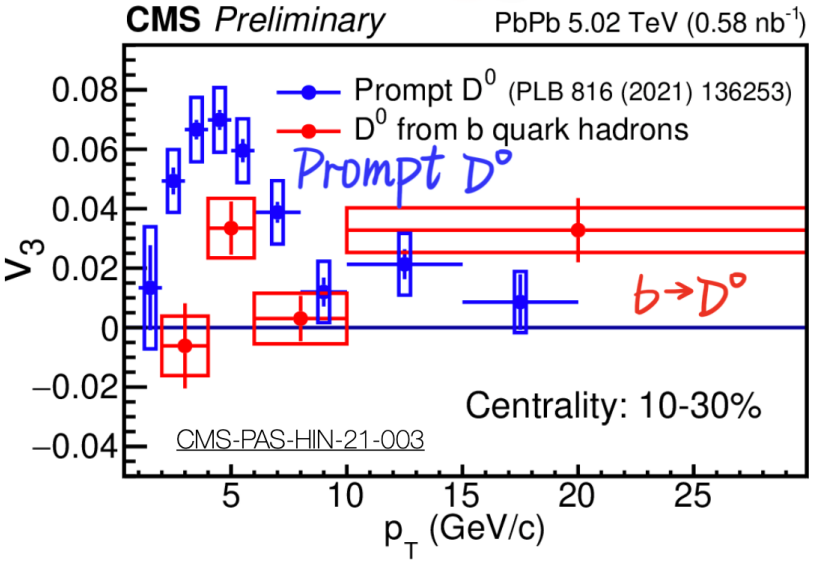


- less so than charm...

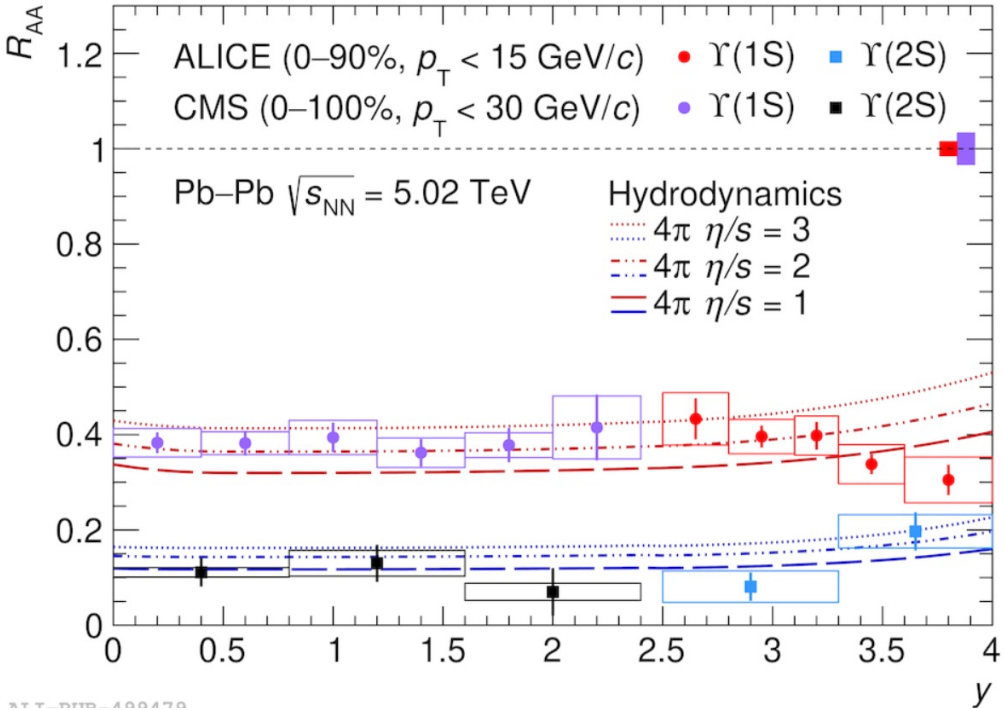
... and it flows, too...



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

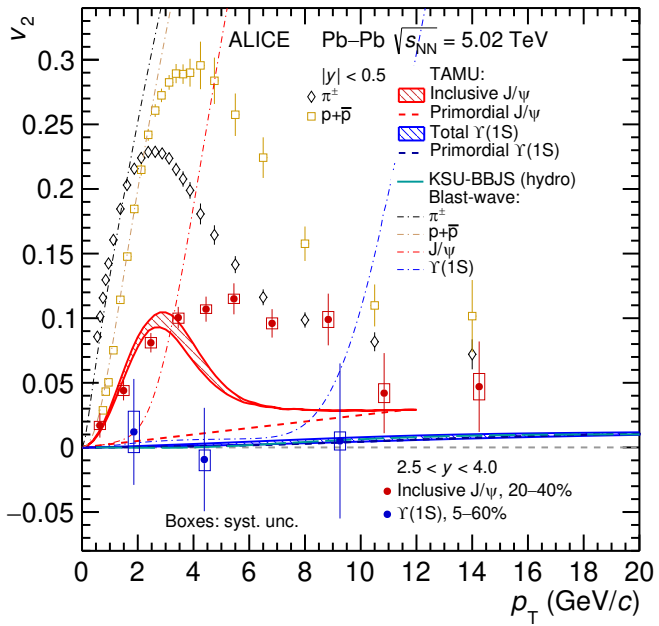


ϒ states seem to follow sequential suppression



ALICE, arXiv:2211.04384

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

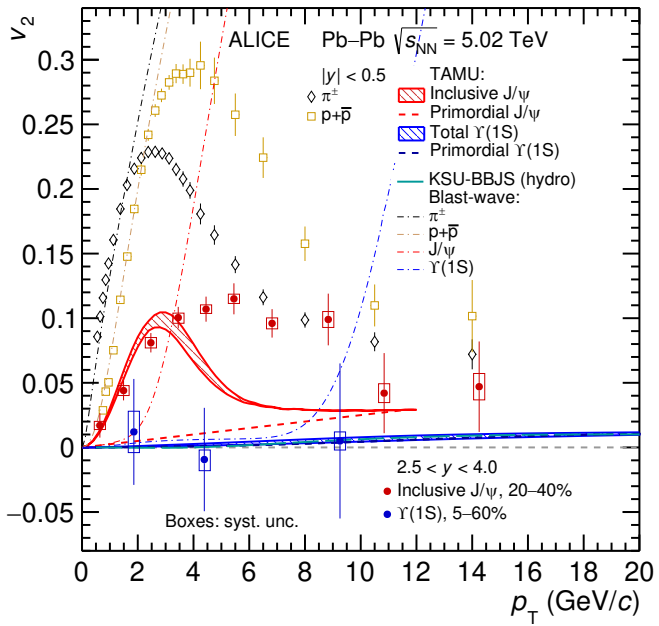


ALI-DER-498850

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

ALICE: PRL 123 (2019) 192301

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



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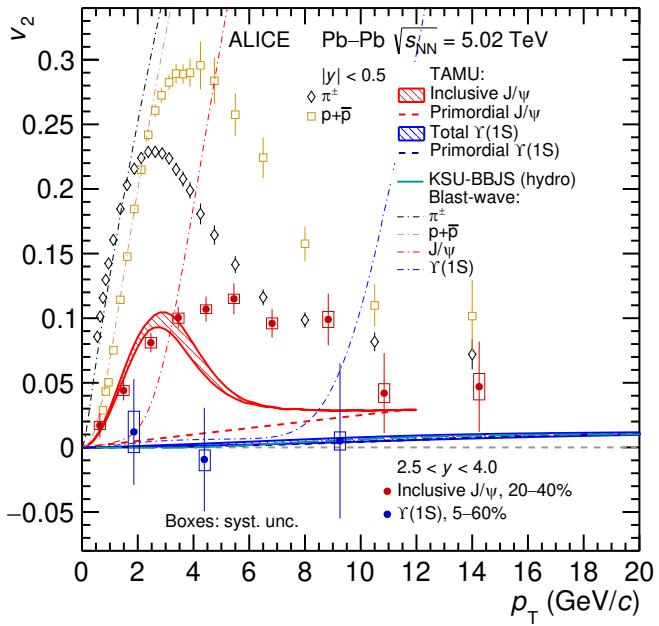

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  - shouldn't that asymmetry be there, at least?

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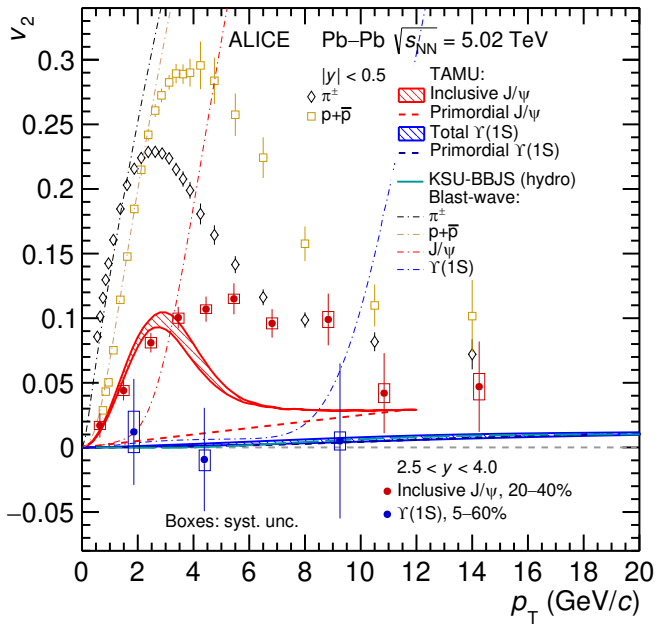

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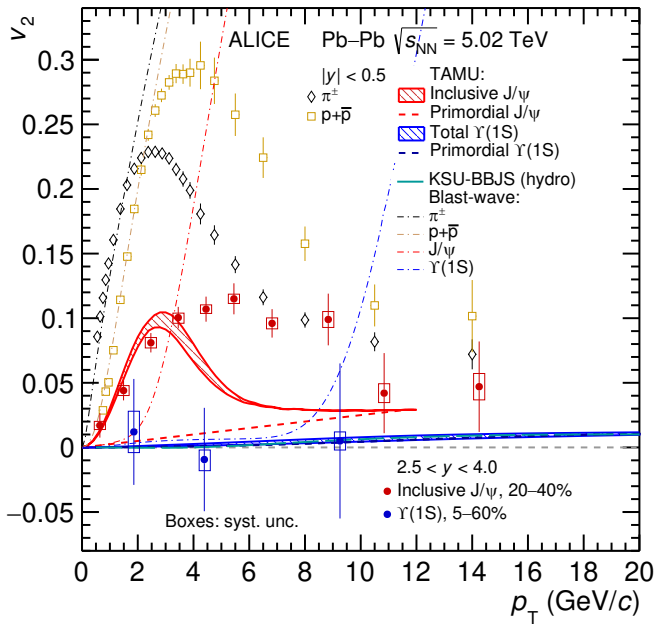
- perhaps two populations?
  - e.g.: colour octet and colour singlet?
  - colour octet disappears?
  - colour singlet goes through ~ isotropically?

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



ALI-DER-498850

ALICE: PRL 123 (2019) 192301

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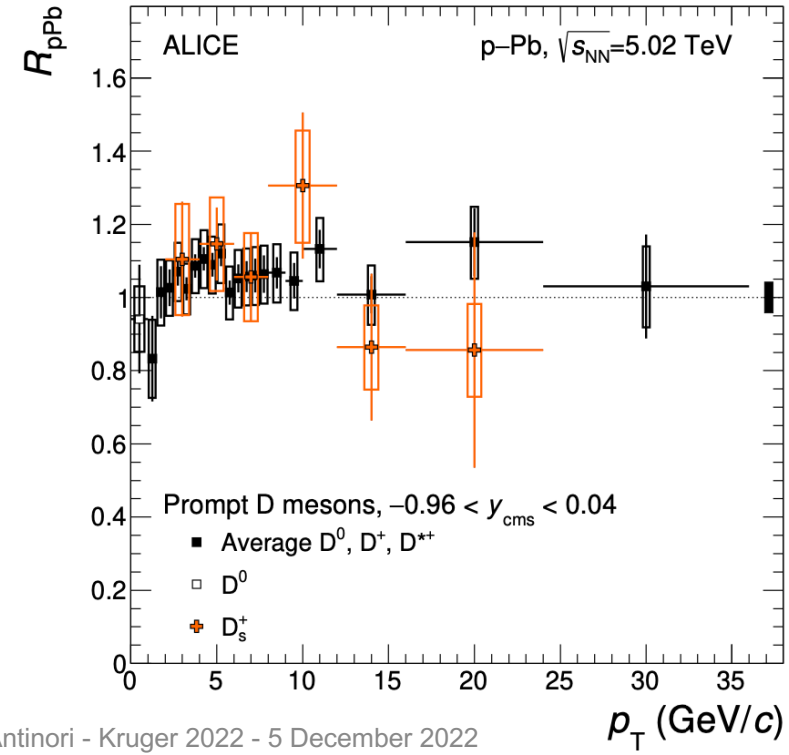
- perhaps two populations?
  - e.g.: colour octet and colour singlet?
  - colour octet disappears?
  - colour singlet goes through ~ isotropically?
- 🤔...

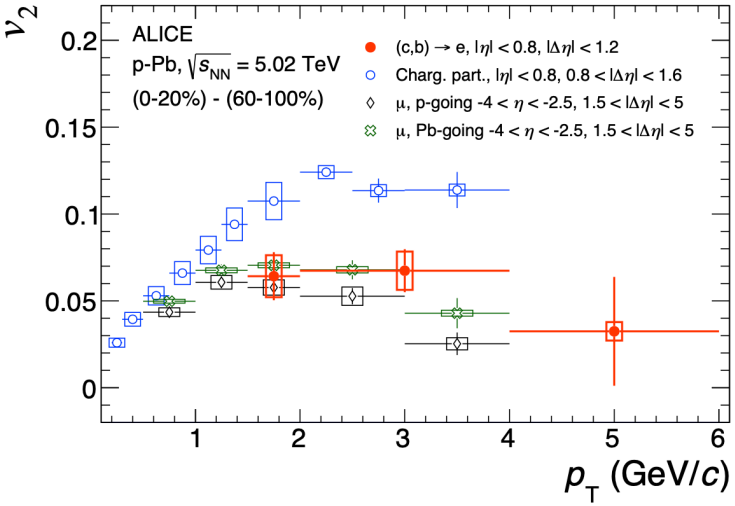
How about small systems?

- no sign of quenching for charm (like for everything else...)



ALICE: JHEP 2019 (2019) 92

...but flow seems to be there...!

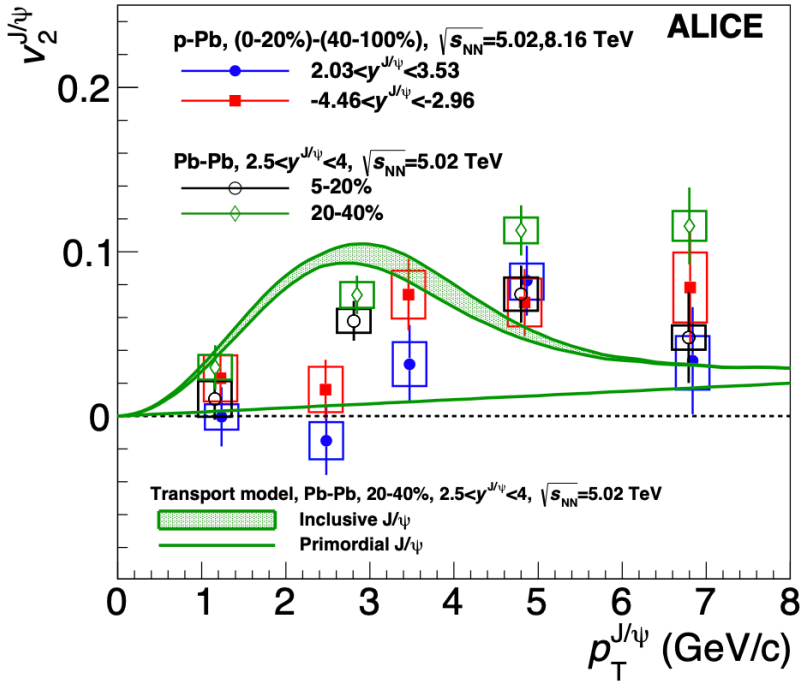


ALICE: PRL 122 (2019) 072301

- ... what's this??? (isn't charm produced isotropically in initial parton-parton scattering?)
  - a sign of azimuthally-dependent energy loss??? 🤔...

- could it just be the light quarks...?

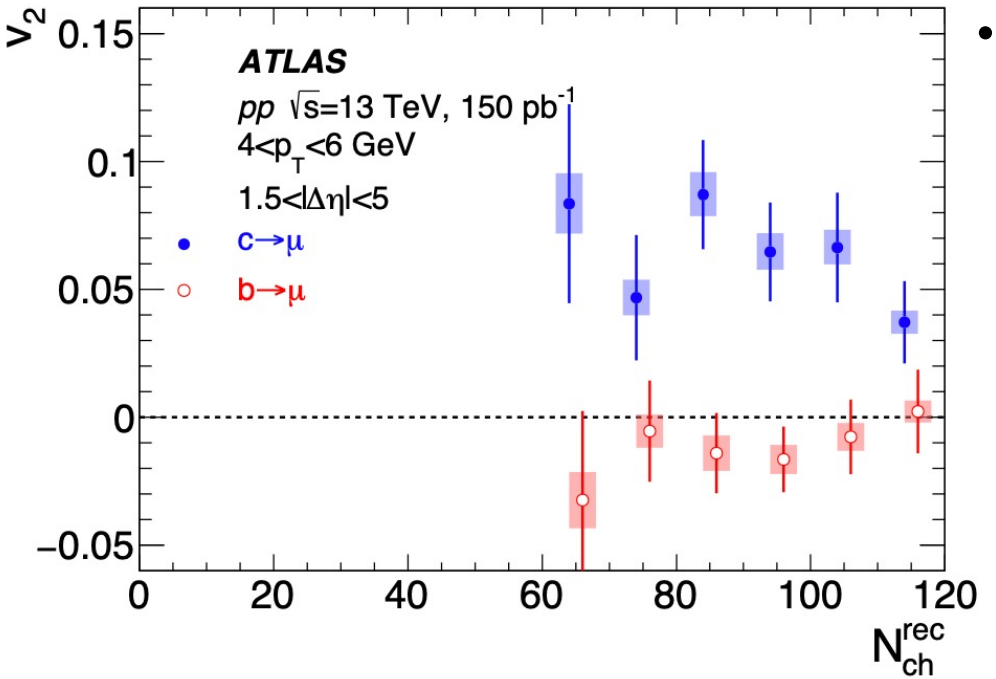
... also for J/ψ...



ALICE, PLB 780 (2018) 7

- ... no, it's not just the light quarks...
  - it seems to be the c themselves...
- consistent with R_{pPb} measurements?
- these are supposed to be mostly pair-produced $c\bar{c}$, propagating together... right? 🤔...
- if v_2 is due to energy loss, does its amount carry information about octet v singlet?

... but not for beauty...

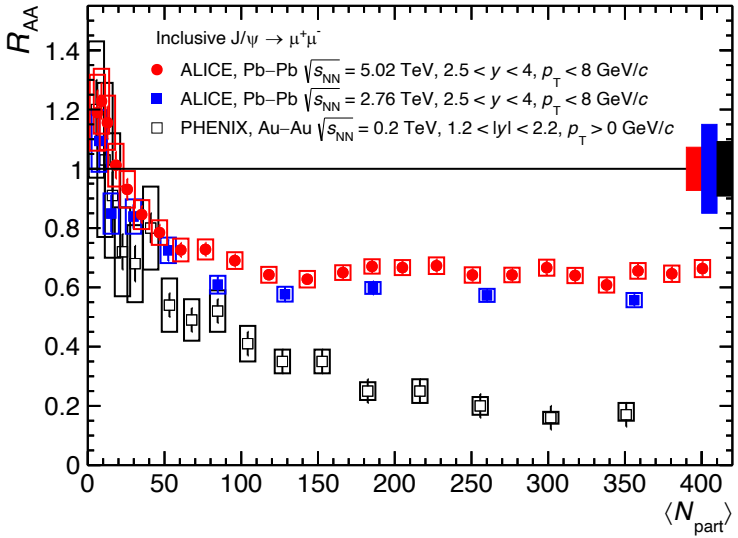


ATLAS: PRL 124 (2020) 082301

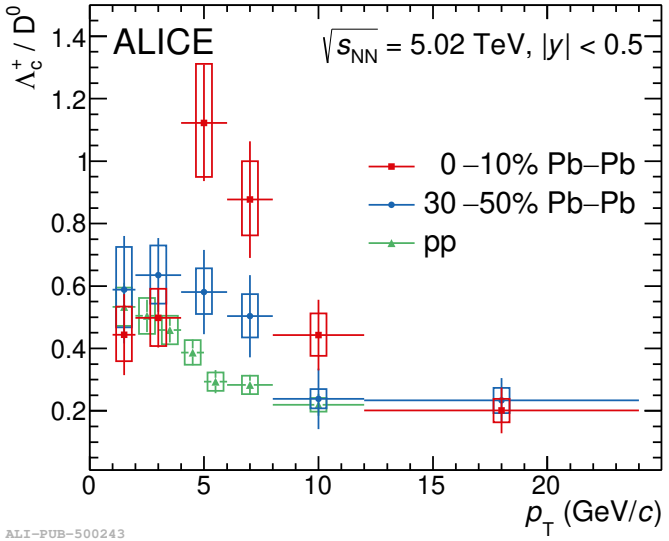
- another one of those beauty things...

In-medium hadronisation, a rich sector!

charmonium



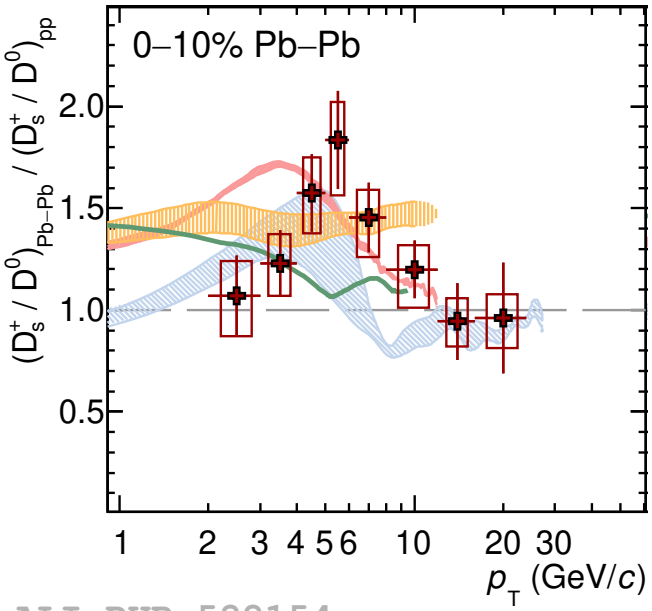
HF baryons



ALICE, arXiv:2112.08156

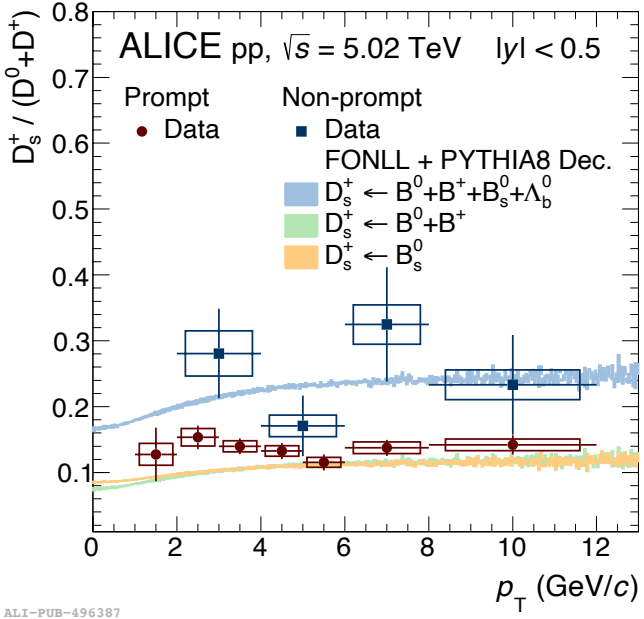
Strangeness enhancement!

D_s



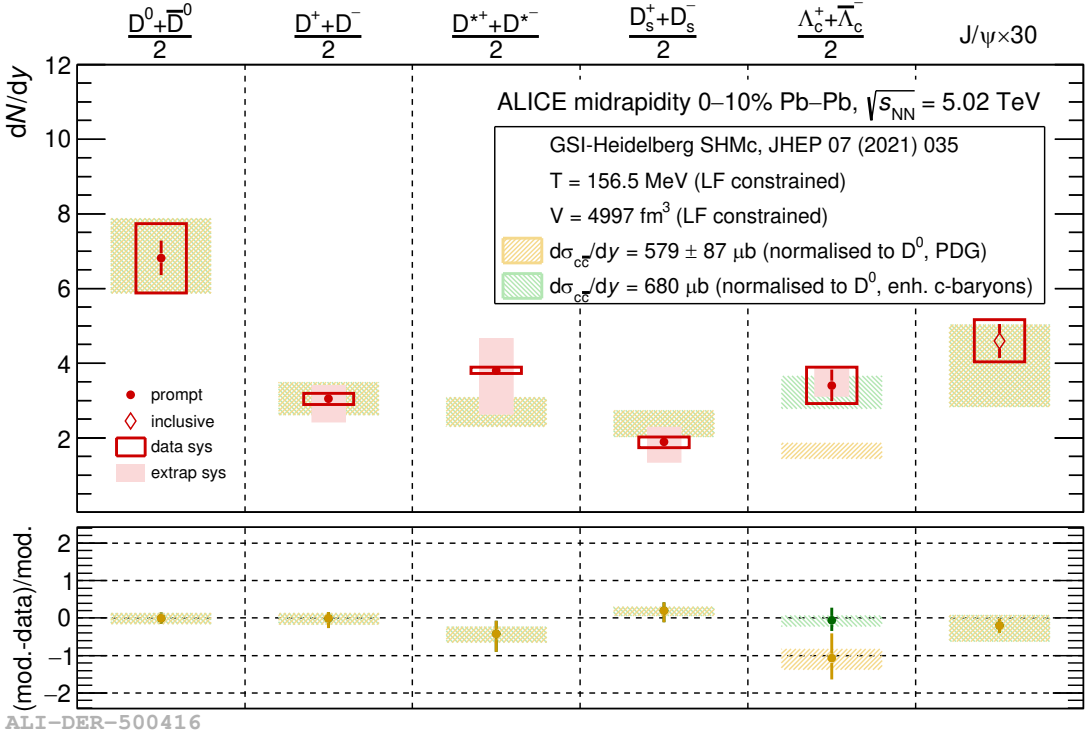
ALICE: PLB 827 (2022) 136986

B_s?

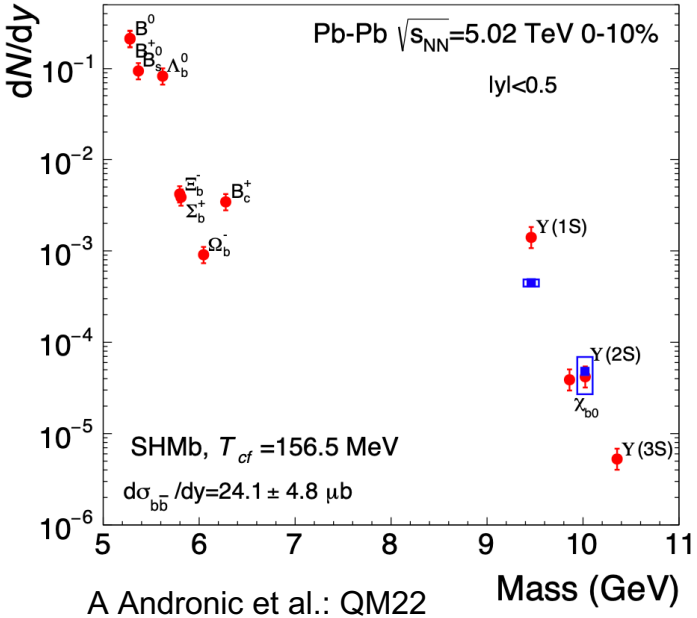


ALICE: JHEP 05 (2021) 220

Chemical equilibrium for HF hadrons?



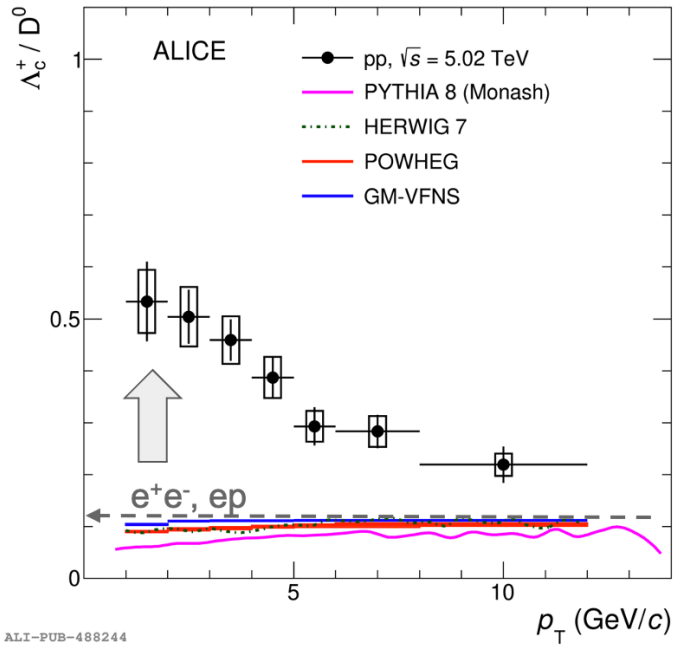
- for charm, looks like...
  - not for absolute σ, of course...
  - γ_c ~ 30 for 0-10%
- and, once again, b is different...
  - SHMb ~ 3 x data for Υ(1S)

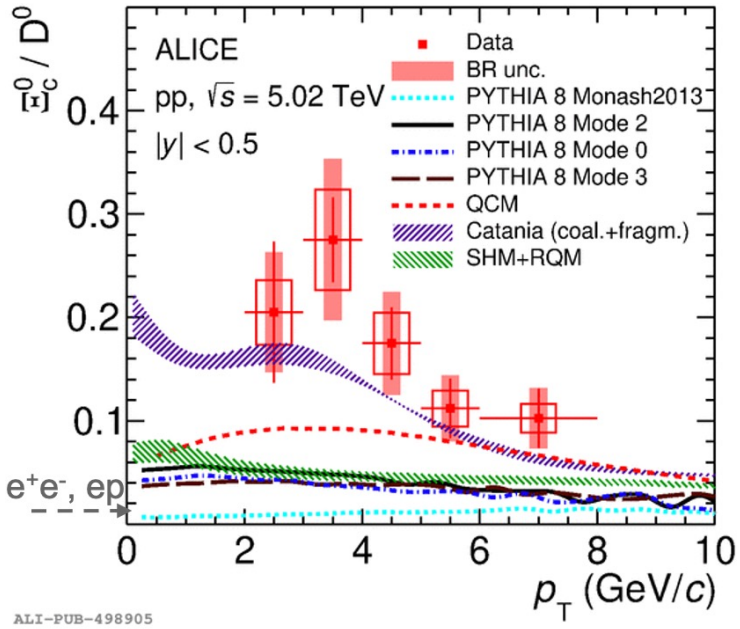


A Andronic et al.: QM22

Already in pp, p-Pb...

- HF baryon/meson enhanced wrt e^+e^- (especially at low p_T)

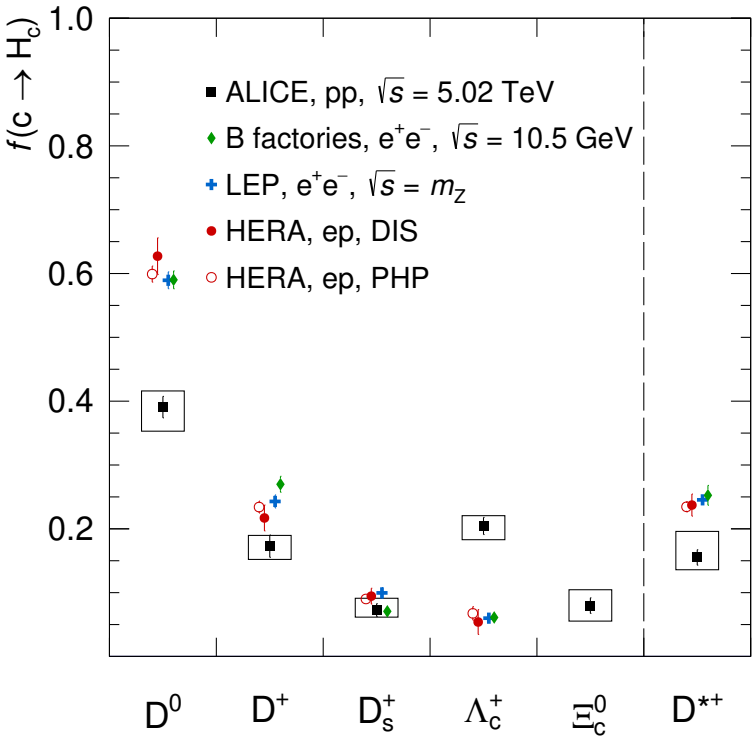




ALICE: PRL 127 (2021) 202301

ALICE: JHEP 10 (2021) 159

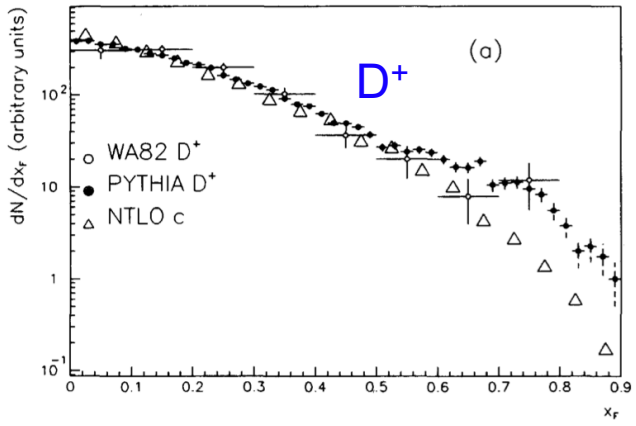
Fragmentation Fractions: pp ≠ e⁺e⁻

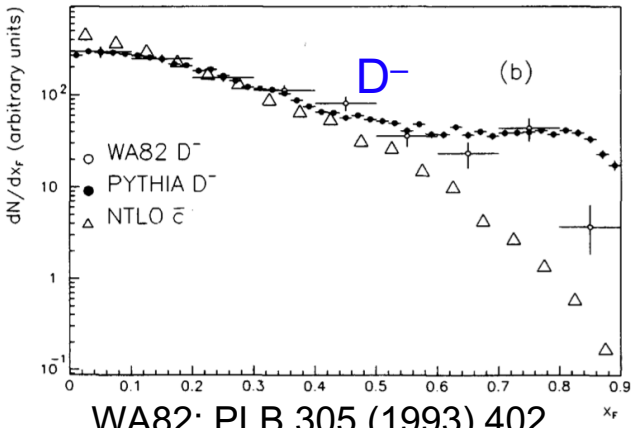


- fragmentation factorisation is violated
  - already in pp
- hadronisation in hadronic environments is a different game than in e⁺e⁻

ALICE: PRD 105 (2022) L011103

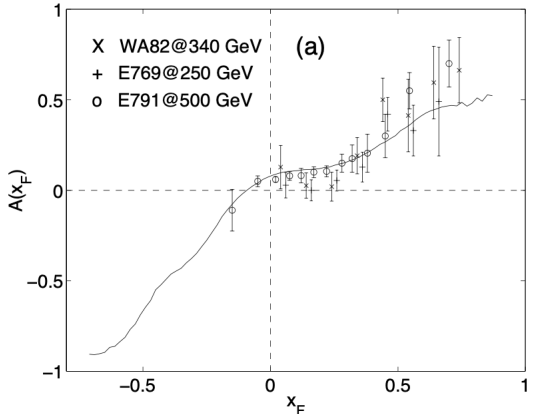
But already at the SPS...





WA82: PLB 305 (1993) 402

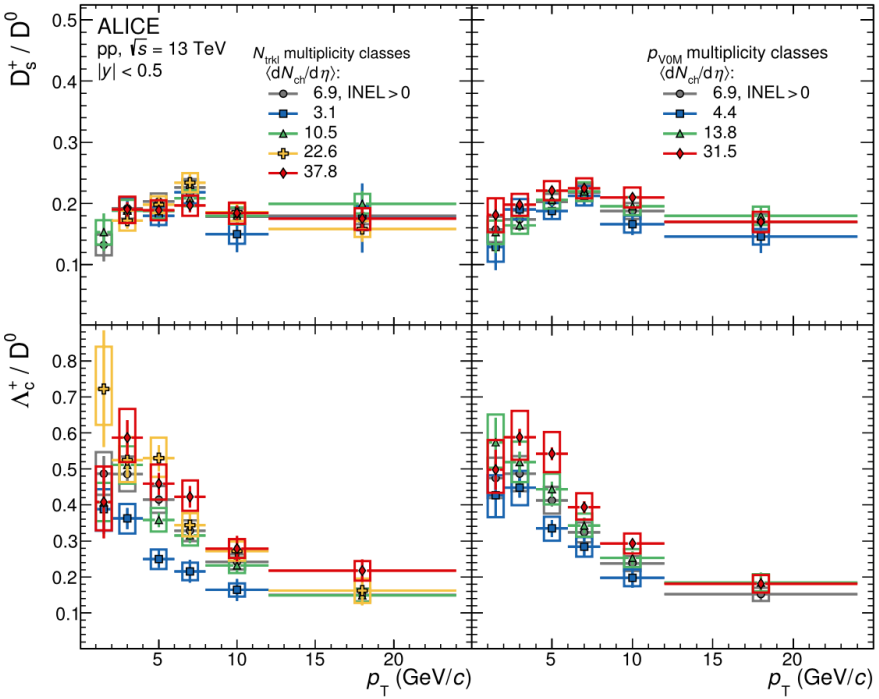
- WA82 (OMEGA): π^-A collisions
  - charm production in forward hemisphere
- beam valence: $d\bar{u}$ (π^-)
- excess of D⁻ ($\bar{c}d$) over D⁺ ($c\bar{d}$)
  - $D^-/D^+ = 1.34 \pm 0.13$
- particularly pronounced close to beam x_F
- (try and do this with Peterson's fragmentation...)
- modified PYTHIA tune:



E Norrbin and T Sjöstrand:
PLB 442 (1998) 407

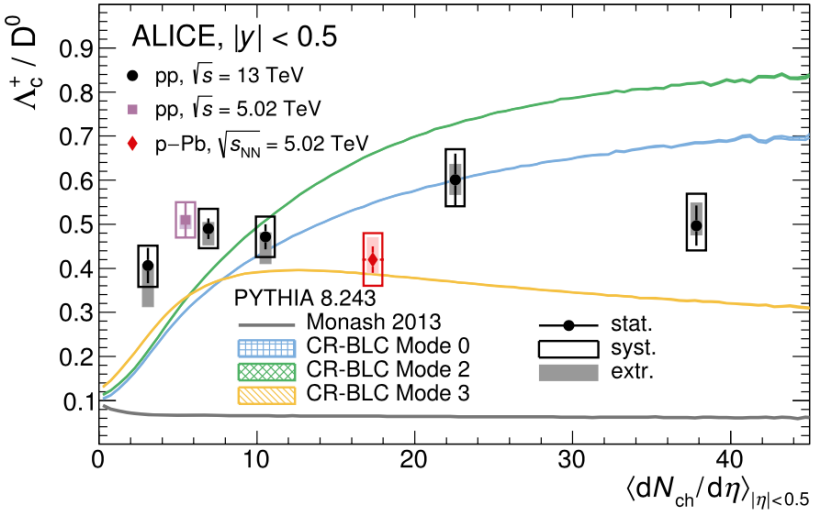
(asymmetry vs x_F)

Multiplicity evolution?



ALICE: PLB 829 (2022) 137065

- clear evolution for Λ_c/D
  - (not so much for D_s/D...)
  - (wrt neither to cent nor to fwd mult'y)
- and not much for the integrated yields?

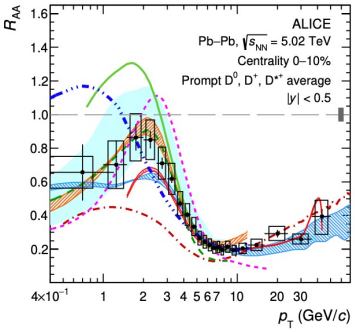


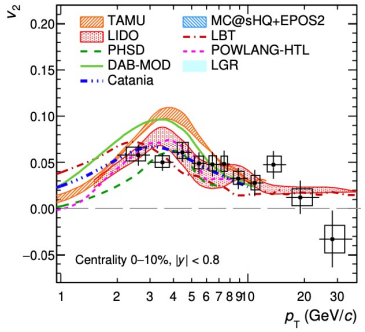
- 🤔 ...

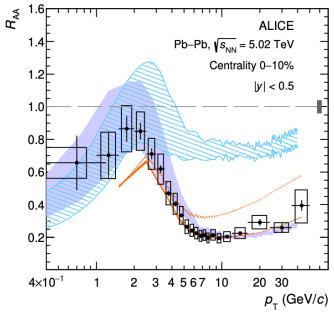
Contents

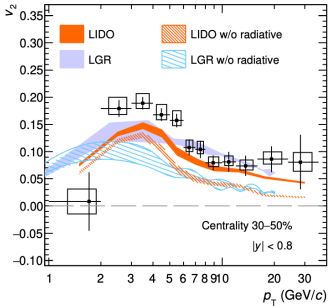
- Introduction
  - QCD, deconfinement, the QCD phase diagram, ultrarelativistic nuclear collisions
- The ALICE experiment
- A selection of results
  - with a zoom on heavy flavours
- Where do we go from here?
- Upgrade plans
- Summary and conclusions

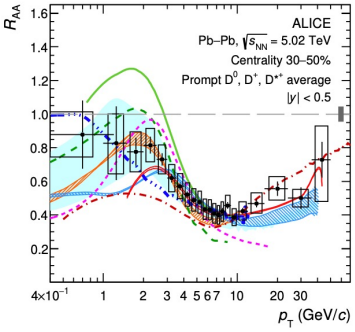
Where do we go from here...?

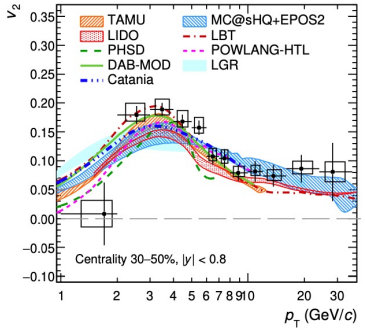


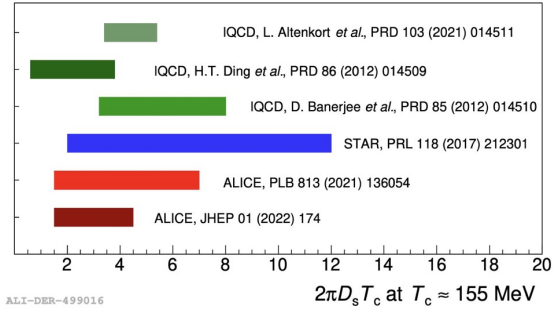








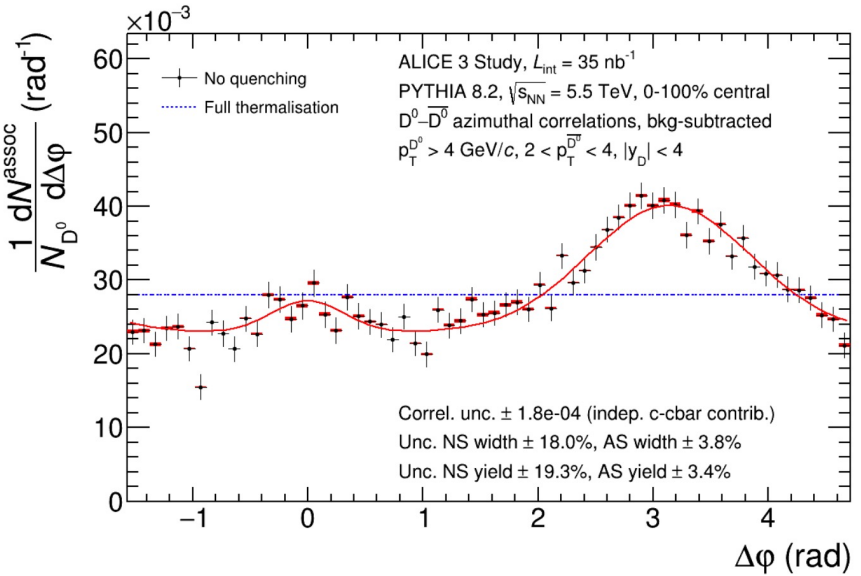




- 10-100 x expected from Run 3, 4 → entering high-precision era!

$D\overline{D}$ correlations

- constrain energy loss and angular decorrelation simultaneously
- sensitivity to collisional vs radiative eloss vs momentum scale
- full isotropisation at low p_T?
- e.g.: ALICE3 LoI



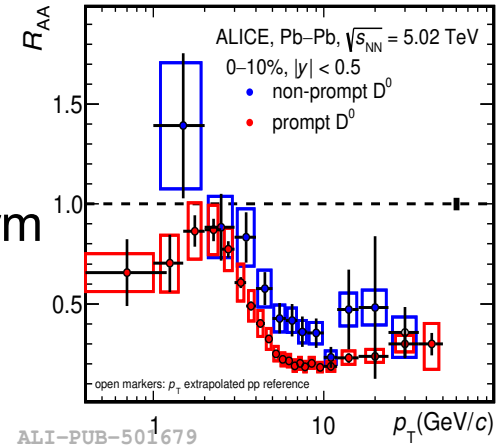
Low-p_T beauty!

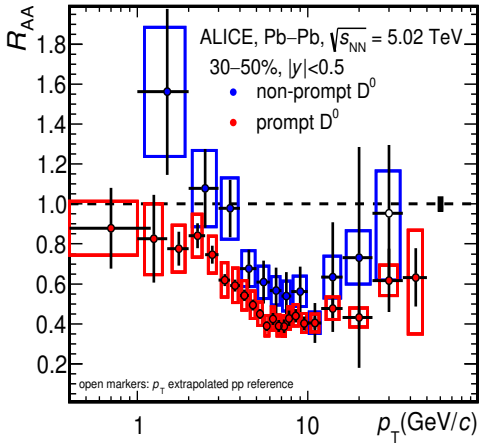
- beauty not fully equilibrated?
  - less suppression than for charm
  - less flow than for charm
  - SHM seems to fail

- relaxation ~ 3 times slower than charm
  - $\tau_Q = \left(\frac{m_Q}{T}\right) D_s$ (with $m_b \sim 3 m_c$)
  - 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 on the move...?



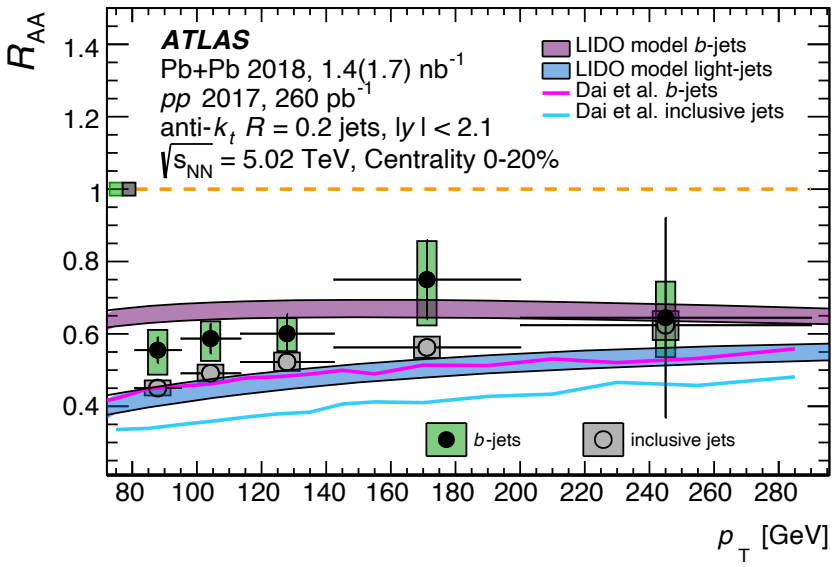


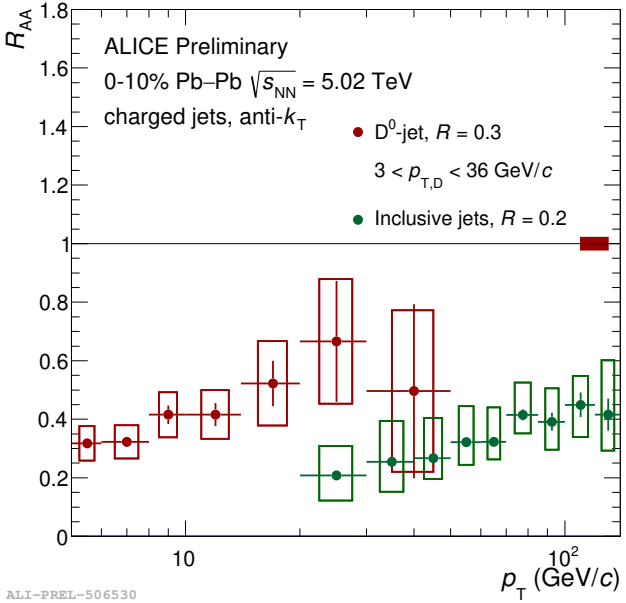
→ need high-precision b down to p_T=0

→ (and watch the hadrochemistry!)

Jets as quark proxy

- direct access to parton (ideally, at least...)

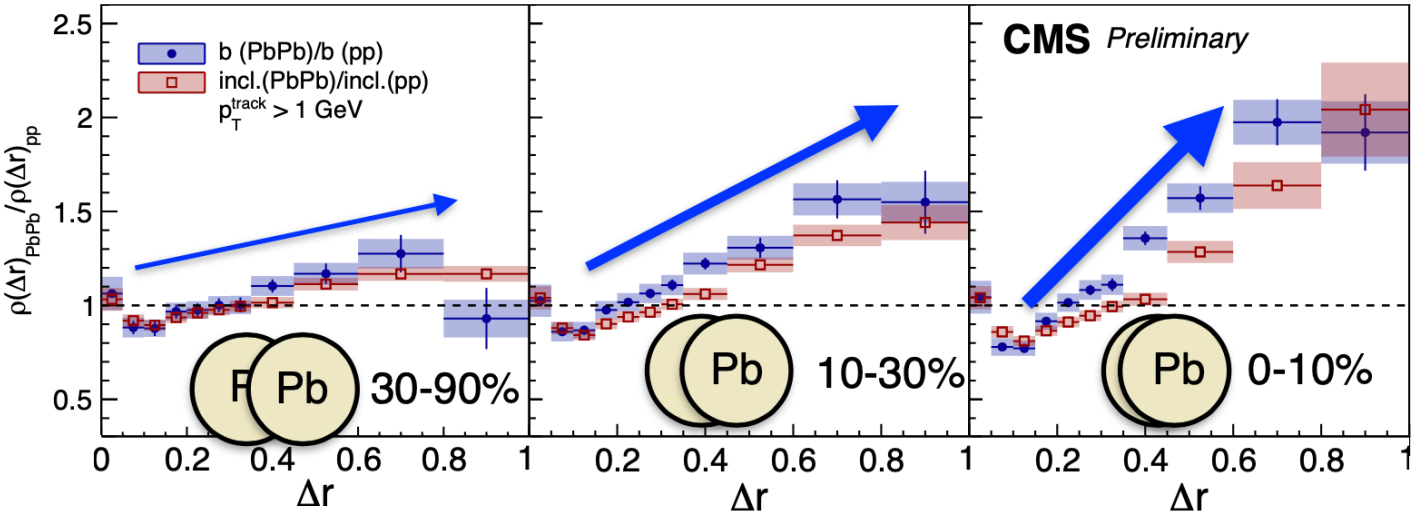




ATLAS: arXiv:2204.13530

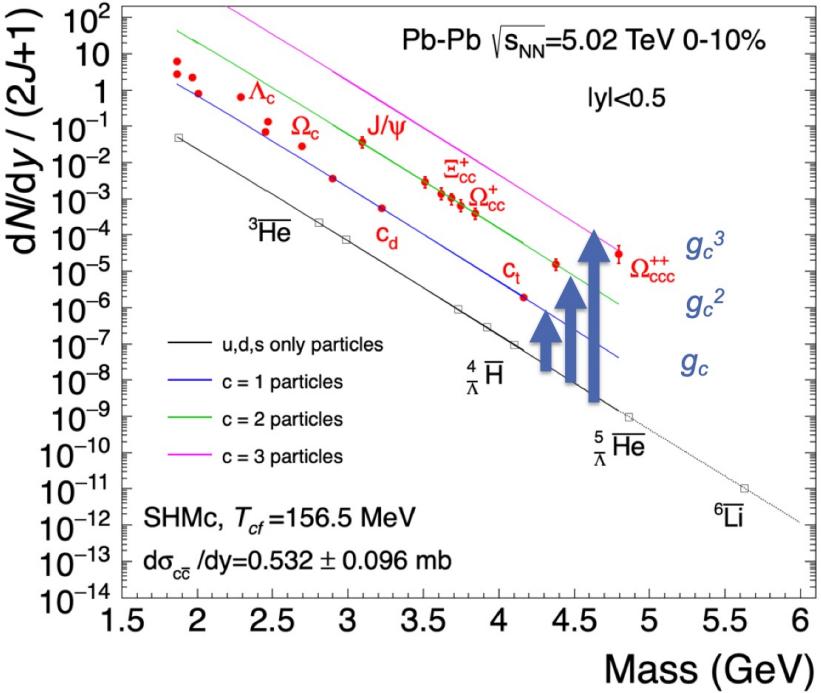
ALICE: SQM 2022

Jets as imaging of in-medium parton processes



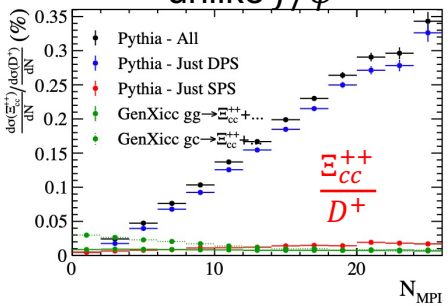
Multi-charm: the final frontier?

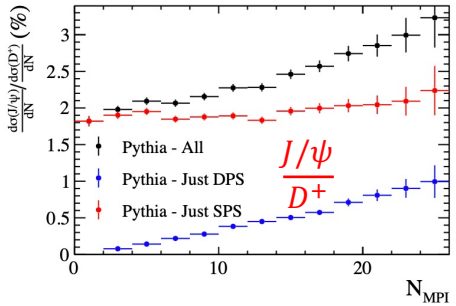
Statistical Hadronisation Model



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

- huge enhancements predicted
  - up to 10^3 wrt pQCD for the Ω_{ccc}!
- negligible production in Single-Parton Scattering
  - unlike J/ψ





P Skands & C: arXiv:2205.15681

- only “exogamous” production
  - unlike J/ψ
- <u>ultimate sensitivity to degree of c thermalisation</u>!

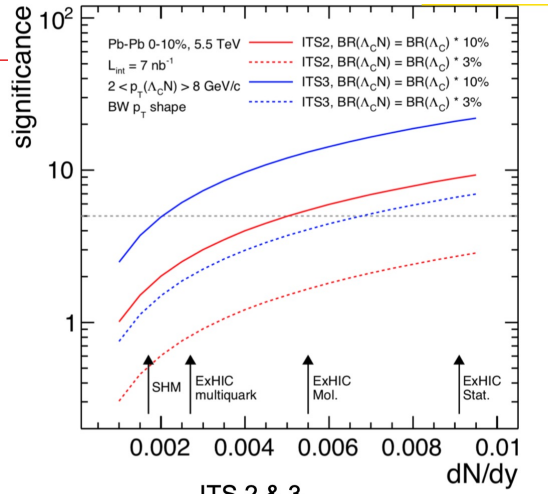
Charmed hypernuclei?

- 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

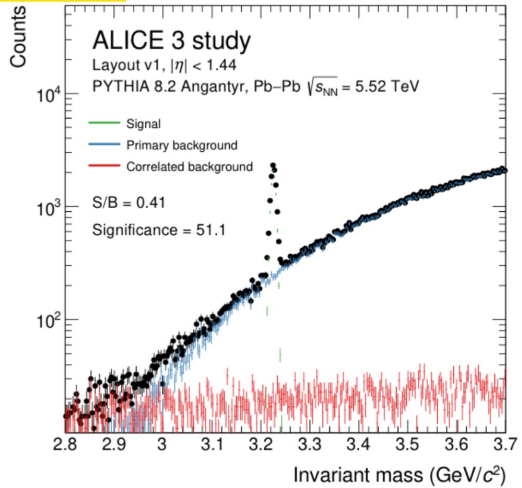
- at SHM abundances → expected to come into view at LHC
- if full equilibration confirmed both for c and for nuclear states...

→ discover or exclude existence!

- + direct study of Λ_c^+-N potential via femtoscopy?



ITS 2 & 3

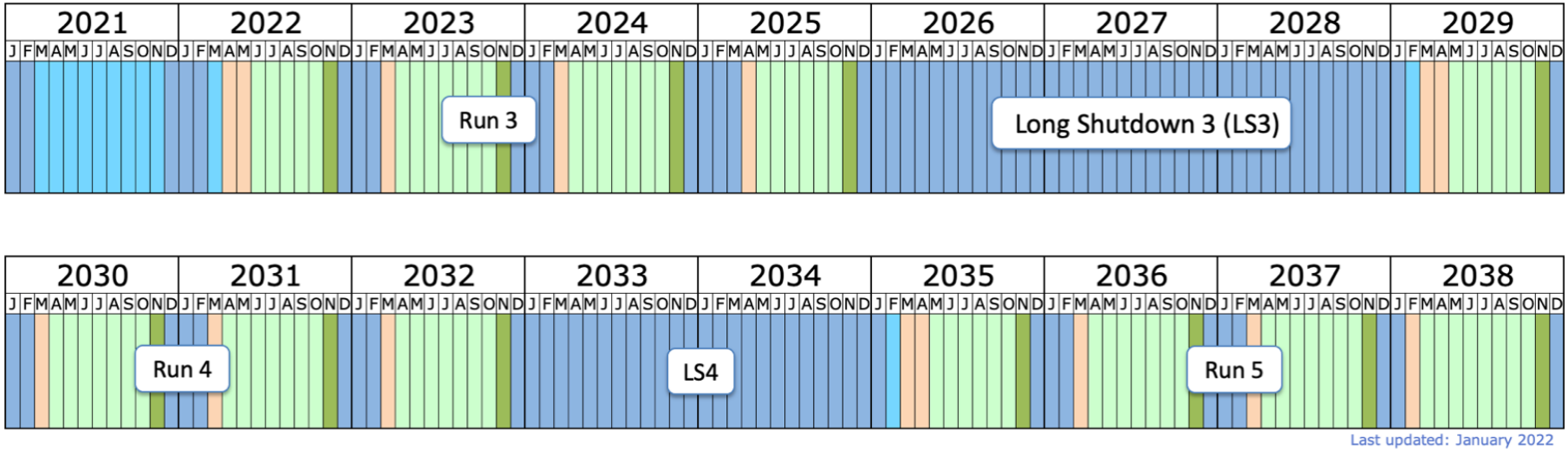


ALICE3 (SHM)

Contents

- Introduction
  - QCD, deconfinement, the QCD phase diagram, ultrarelativistic nuclear collisions
- The ALICE experiment
- A selection of results
  - with a zoom on heavy flavours
- Where do we go from here?
- Upgrade plans
- Summary and conclusions

LHC timeline

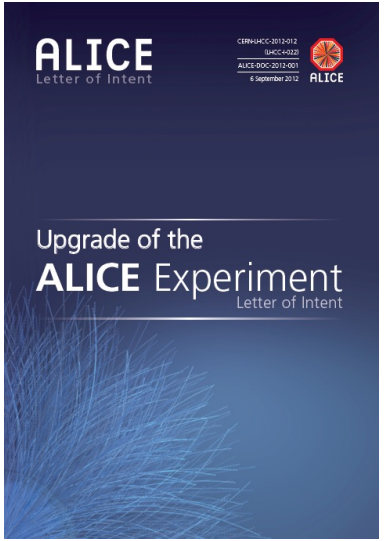


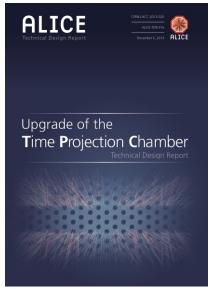
- during LS2:
  - LHC injector upgrades, Pb-Pb rate → 50 kHz (now ~10 kHz)
  - major ALICE upgrades campaign (vertexing, data collection speed)
- aim for > 13/nb Pb-Pb collisions (Run 3 + Run 4)

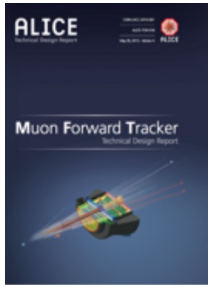
ALICE LS2 upgrades

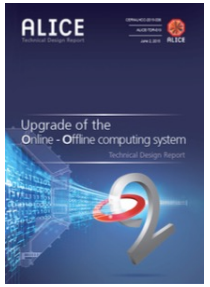
Main physics goals

- study heavy quark interaction in QCD medium
  → heavy flavour dynamics and hadronisation at low p_T
- study charmonium regeneration in QGP
  → charmonium down to zero p_T
- chiral symmetry restoration and QGP radiation
  → vector mesons and virtual thermal photons (dileptons)
- production of nuclei in QGP
  → high-precision measurement





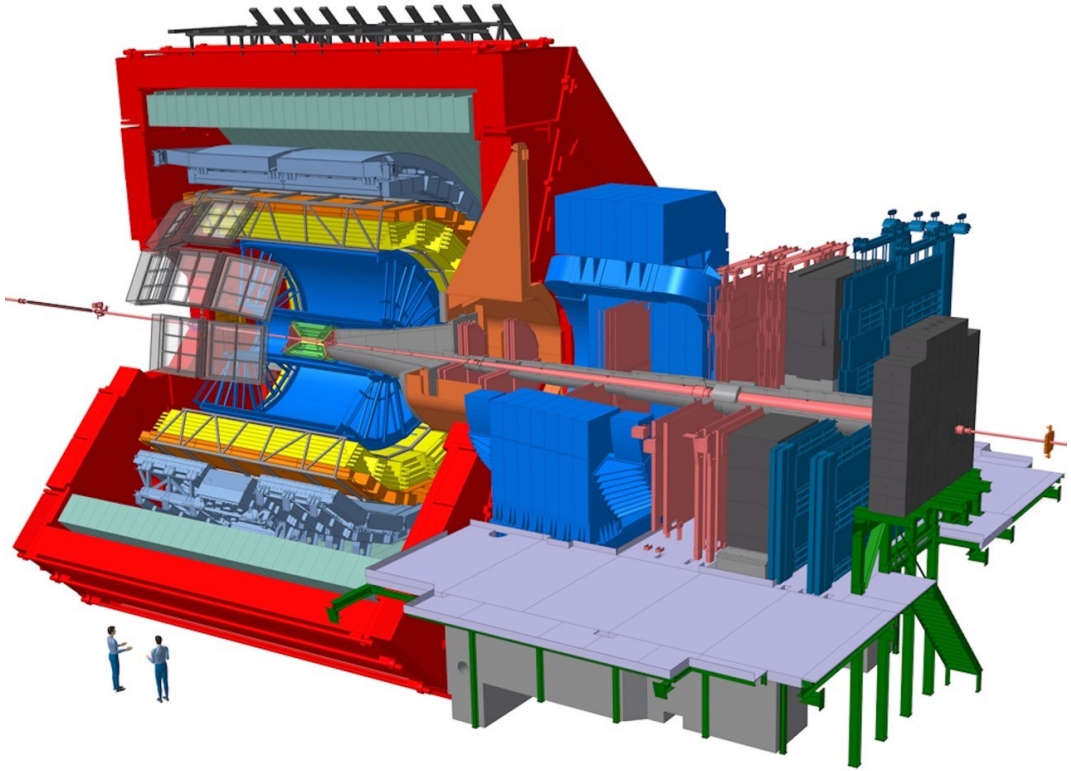




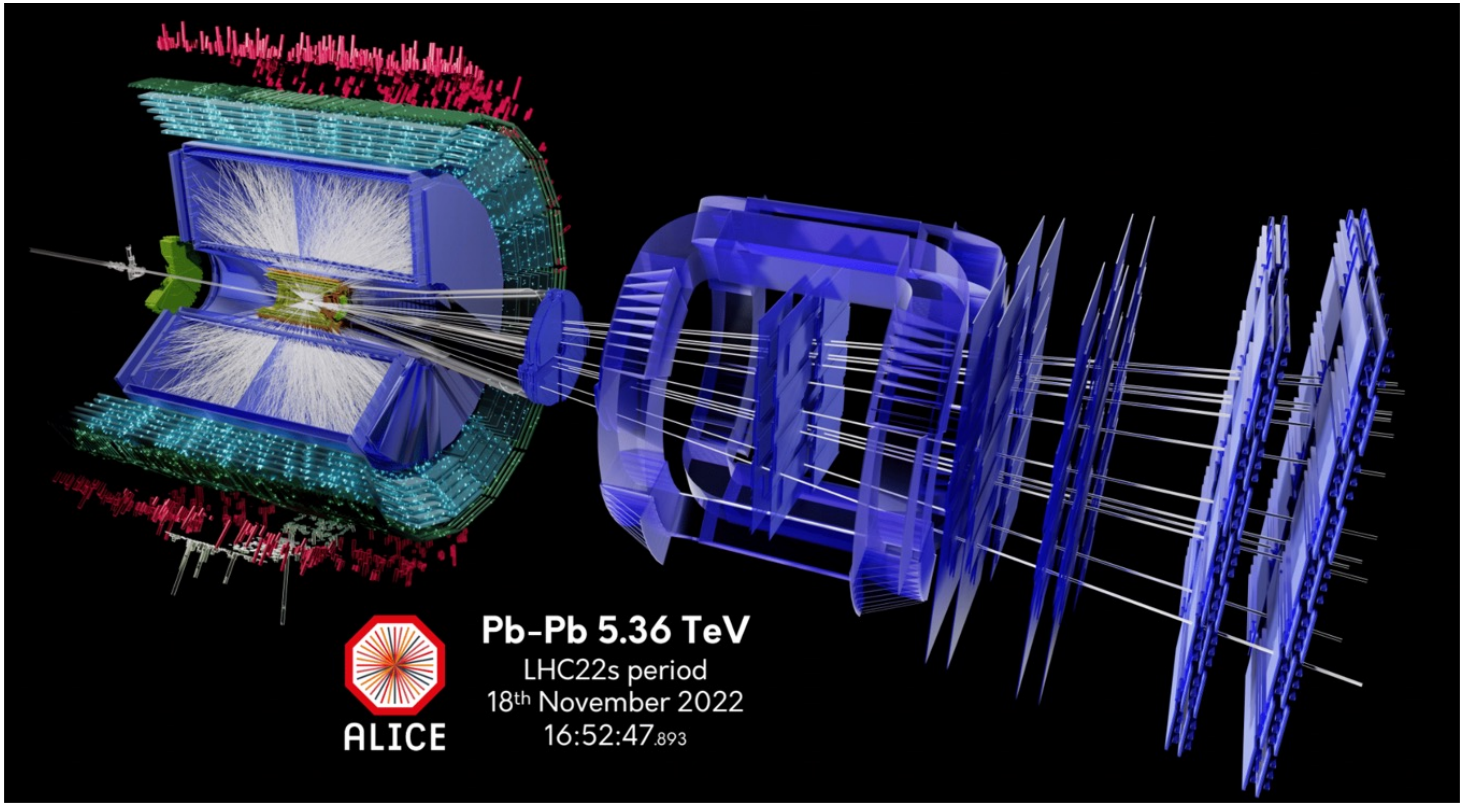
ALICE LS2 upgrades

Layout

- New Inner Tracking System (ITS)
  - MAPS: improved resolution, less material, faster readout
- New Muon Forward Tracker (MFT)
  - vertex tracker at forward rapidity
- New TPC Readout Chambers
  - 4-GEM detectors → continuous r/o
- New forward trigger detectors (FIT)
  - centrality, event plane
- Upgraded read-out for TOF, TRD, MUON, ZDC, EMCal, PHOS, new Online-Offline system (O^2)
  - record minimum-bias Pb-Pb data at 50 kHz (in Run1,2: <1 kHz)



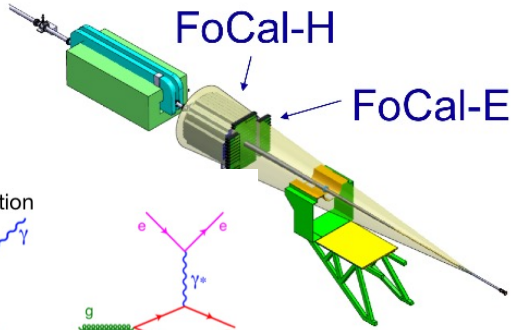
Run 3 has started!

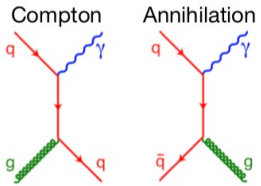


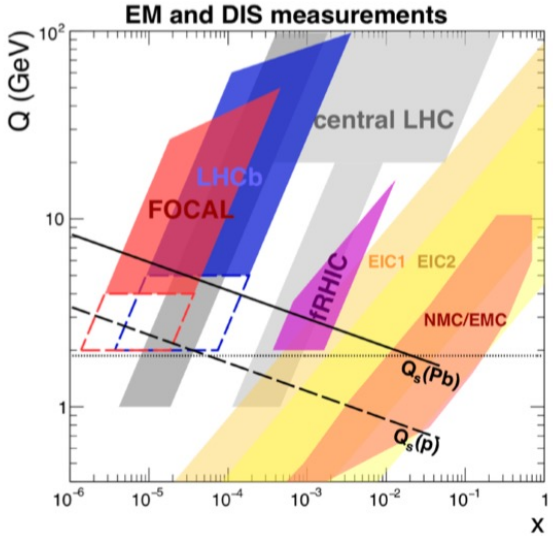
LS3 upgrades: FoCal

- proposal to instrument ALICE with a Forward Calorimeter in LS3 [ALICE-PUBLIC-2019-005]
  - FoCal-E: high-granularity Si-W sampling calorimeter
    - photons, π^0
  - FoCal-H: sampling hadronic calorimeter
    - photon isolation, jets

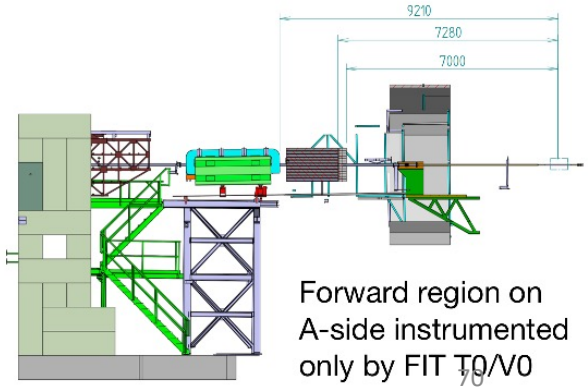
→ access to gluon parton distribution functions







+ other observables
- π^0
- jets (and di-jets)
- J/ψ, Υ in UPC
- W, Z
- event plane and centrality
- …



Forward region on A-side instrumented only by FIT T0/V0

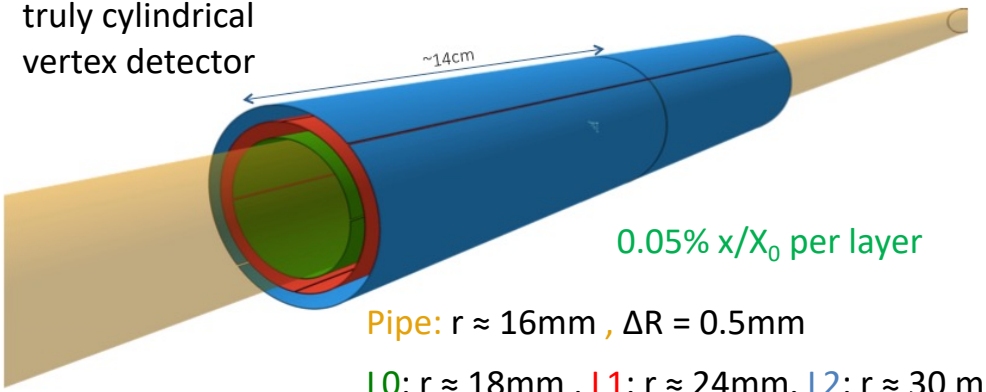
LS3 upgrades: ITS3 Vertex detector (3 inner layers)

a new, ultra-light Inner Barrel in LS3

Letter of Intent https://cds.cern.ch/record/2703140

- advances in Silicon technology: ultra-thin, wafer-scale sensors
  - eliminate active cooling (for power < 20 mW/cm^2)
  - eliminate electrical substrate (if sensor convers full stave length)
  - perfectly cylindrical geometry
    (30 μm thick can be curved to 10-20 mm radius)

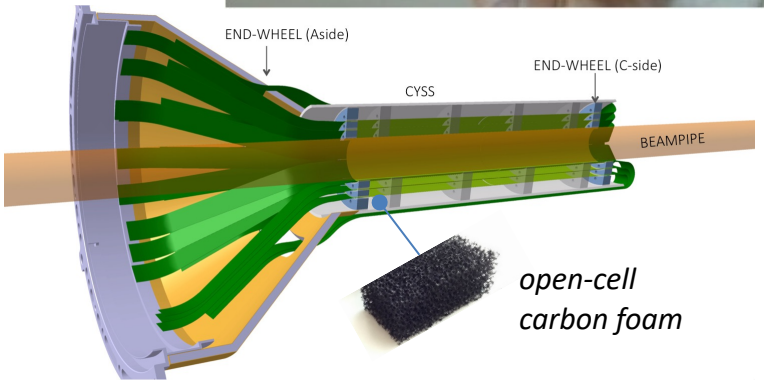
truly cylindrical
vertex detector



0.05% x/X_0 per layer

Pipe: r ≈ 16mm , ΔR = 0.5mm

L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm



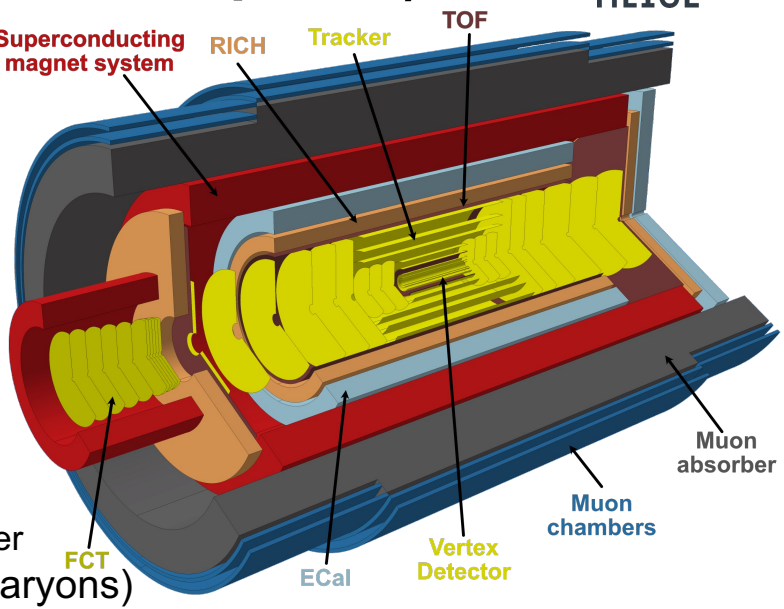
LS4: ALICE 3!

- 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
- electromagnetic calorimeter
- forward conversion tracker

arXiv:2211.02491

ALICE 3 physics potential (just a few 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
  - …



arXiv:2211.02491

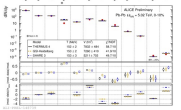
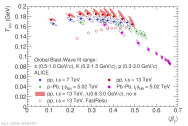
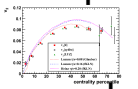
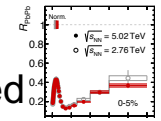
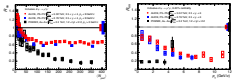
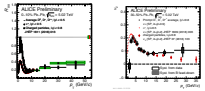
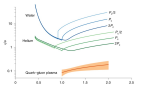
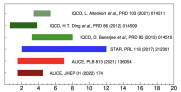
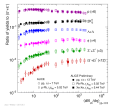
→ a new, unique instrument at the LHC for runs 5 and 6!

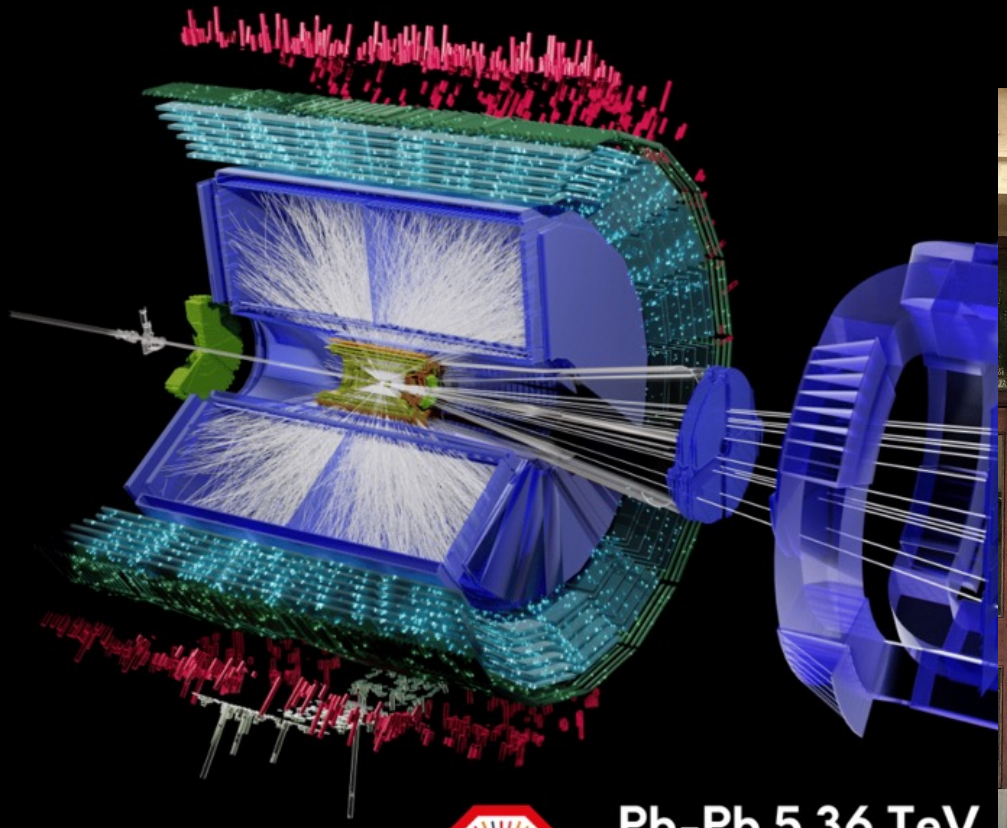
Summary and conclusions

- with high-energy accelerators, we can recreate the QCD plasma in the lab
  - direct window on collectivity with fundamental constituents, phase transition in QFT!
  - at the LHC: ideal conditions (~ baryon-free, high statistics, calibrated probes)
- particle yields appear to be thermalised (→ strangeness enhancement)
- pressure gradients result in an “explosive” radial expansion at ~ 2/3 c
- almost ideal fluid behaviour
- high-energy partons strongly quenched
- key advances in heavy-flavour sector
  - new regime for J/ψ production
  - calibrated “brownian” probe (and more...)

→ quantitative access to QGP parameters!

- collectivity in small collision systems: new dimension, new opportunities
  - explore turn-on of collectivity
- high-statistics, high-precision era about to start...



ALICE

Pb-Pb 5.36 TeV
LHC22s period
18th November 2022
16:52:47.893