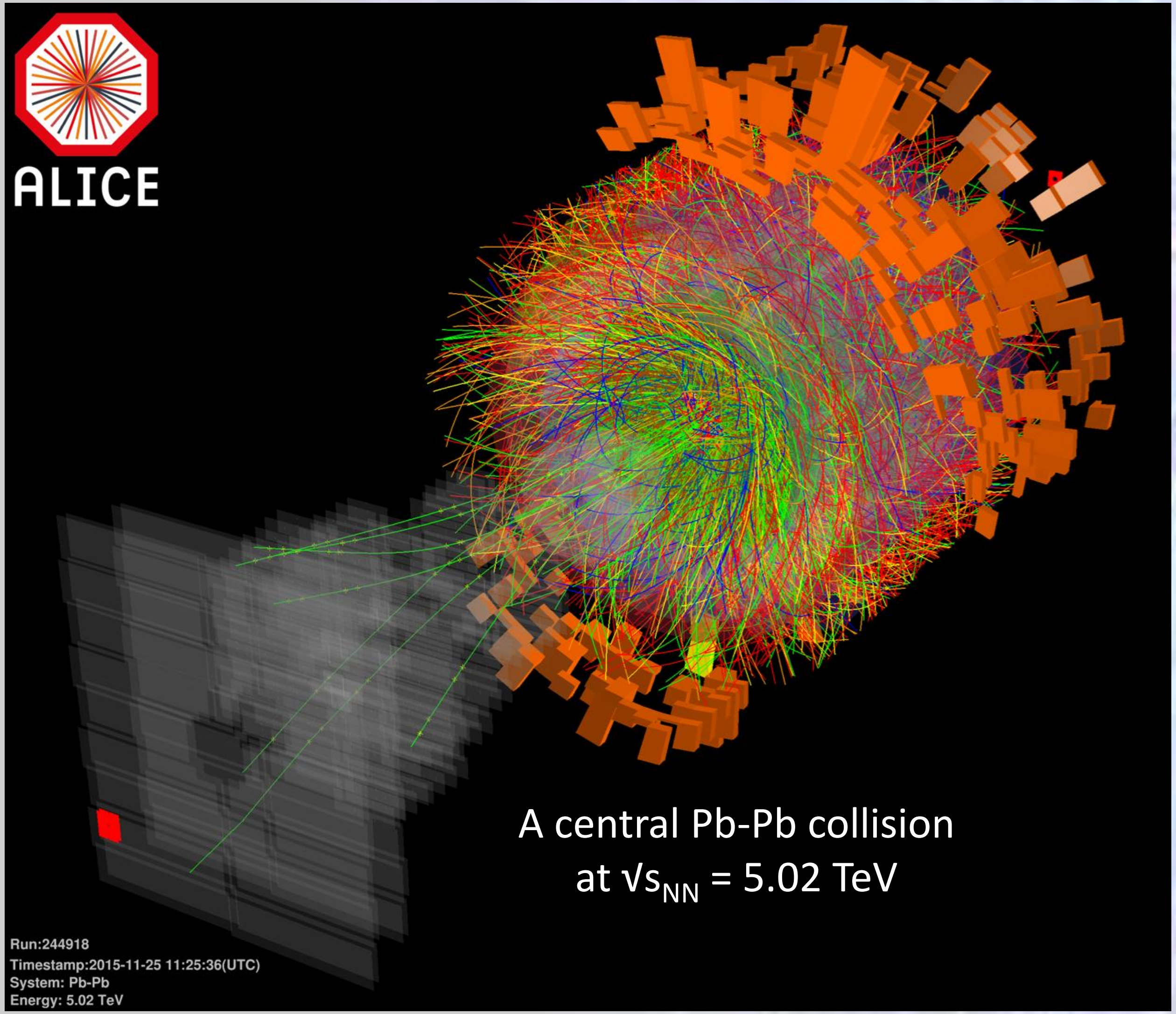
Quark-Gluon Plasma (QGP) Physics with ALICE at the CERN LHC

David Evans

The University of Birmingham

IoP Joint APP, HEPP and NP Conference
15th April 2021

Outline Of Talk

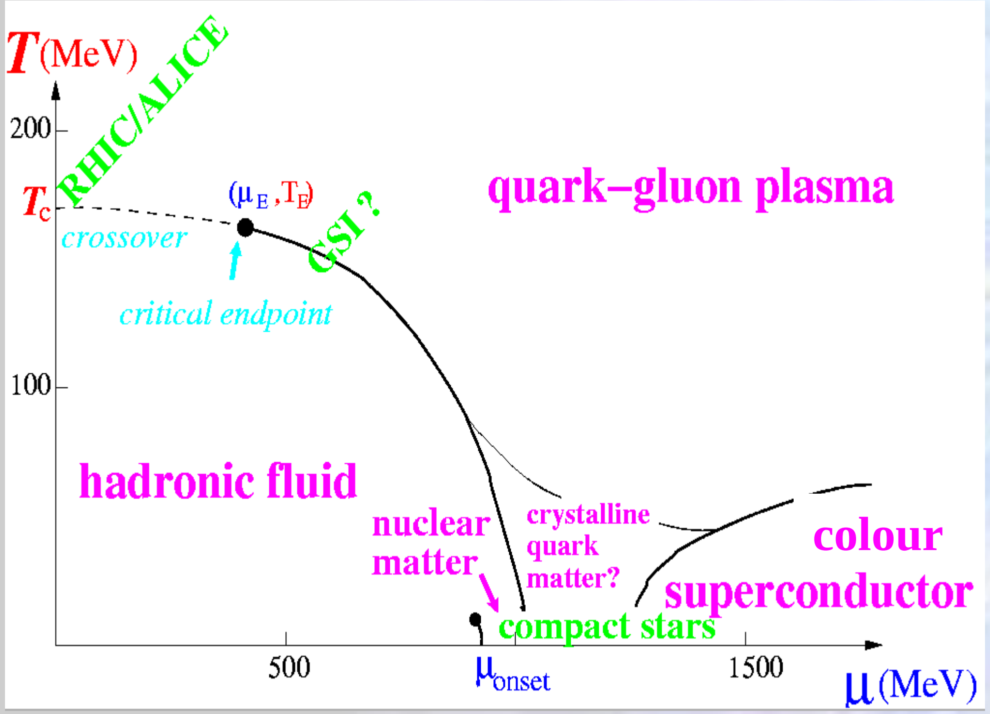


- Motivation
- ALICE detector
- Global features e.g Temperature
- Is QGP a gas or liquid?
- Strange particles
- Ultra-peripheral collisions
- Non-QGP physics example
- ALICE Upgrade (1 slide)
- Summary

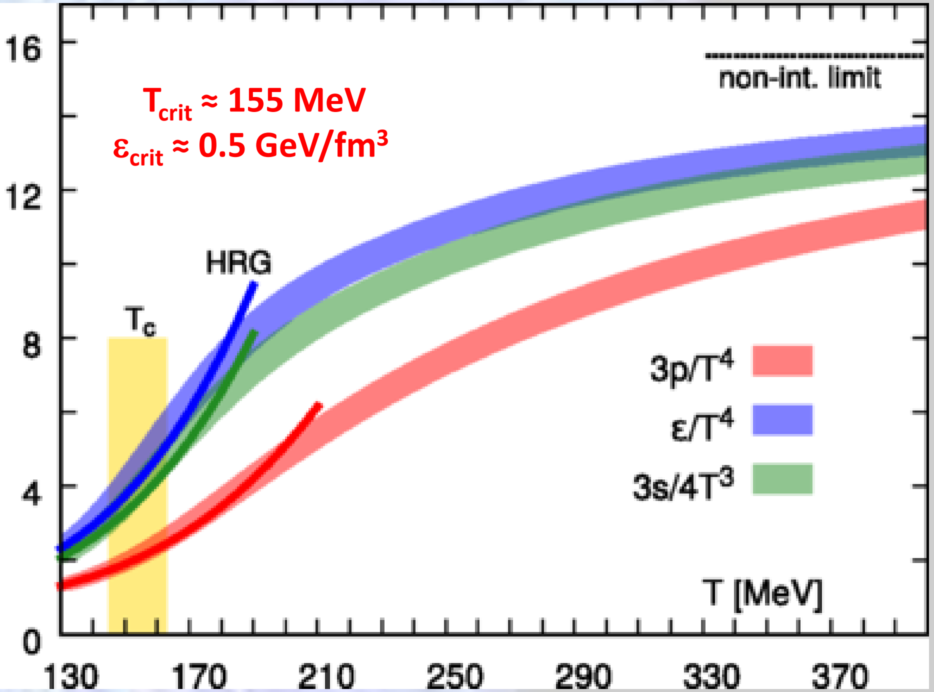
Aims of ALICE

- Study strongly interacting matter at extreme energy densities over large volumes and long time-scales.
- Study the role of chiral symmetry in the generation of mass in hadrons (accounts for vast majority of the mass of nuclear matter).
- Study the nature of quark confinement.
- Study the QCD phase transition from hadronic matter to a deconfined state of quarks and gluons - The Quark-Gluon Plasma (QGP).
- Study the physics of the Quark-Gluon Plasma (QCD under extreme conditions).
    - Early Universe would have been a QGP until ~ 10μs after the Big Bang

Phases of Strongly Interacting Matter



Both statistical and lattice QCD predict that nuclear matter will undergo a phase transition at high energy densities ($\varepsilon \sim 0.5$ - 1 GeV/fm^3)

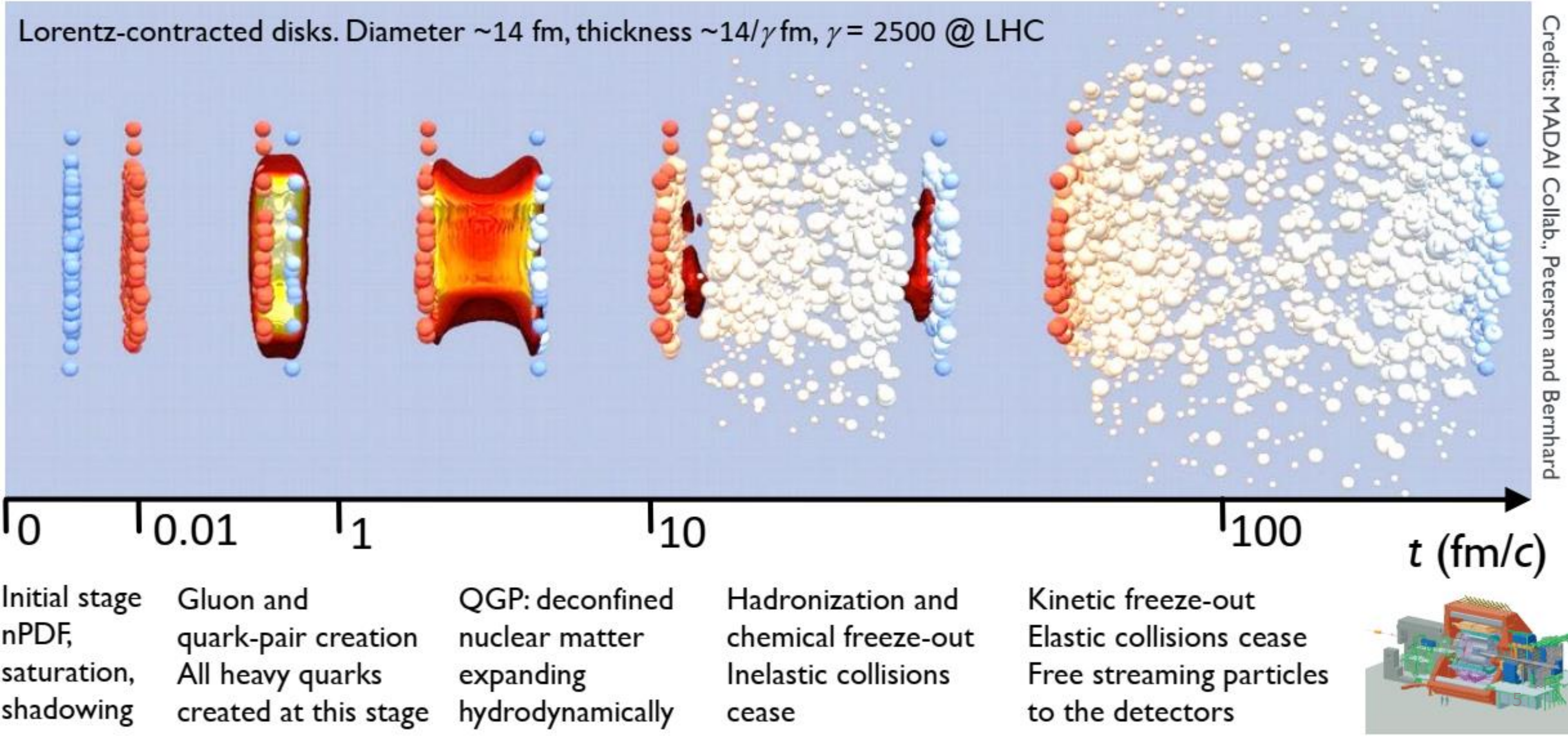


HotQCD Collaboration: Phys. Rev. D90 (2014) 094503

At high temperature or high baryon density, nuclear matter undergoes a **phase transition** into an unbound state of quarks, anti-quarks, and gluons - a **quark-gluon plasma** (**QGP**)

Heavy Ion Collisions

Create QGP by colliding ultra-relativistic heavy ions (at the LHC)



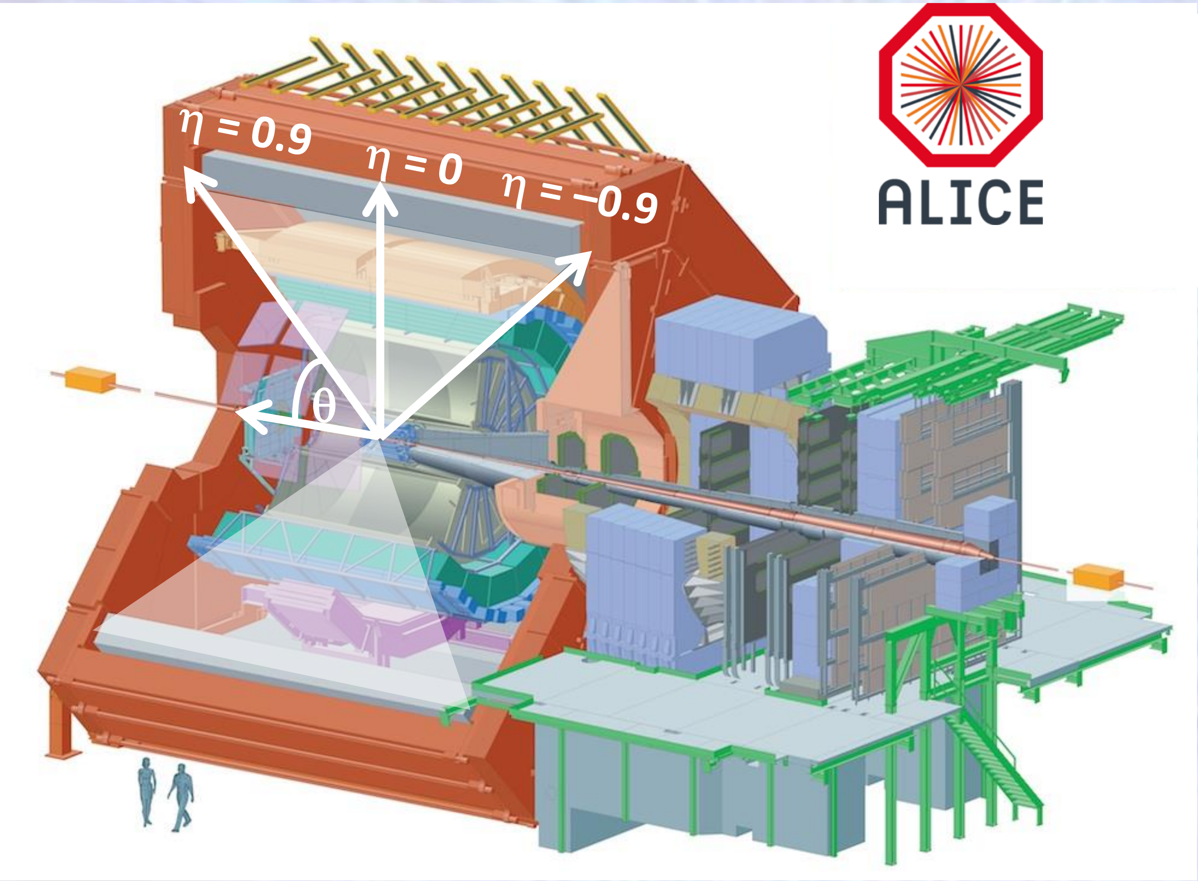
ALICE (A Large Ion Collider Experiment)

Central barrel
Tracking detectors
Particle identification
Calorimetry
B = 0.5 T

Acceptance
$\phi = \{0, 2\pi\}$
$|\eta| < 0.9$

Definition:
Pseudorapidity

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

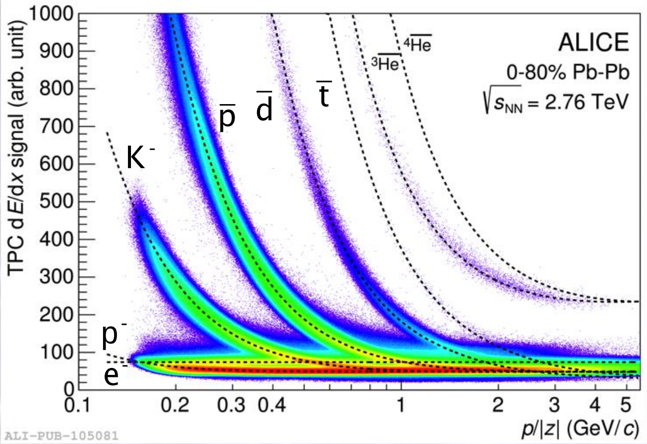


Forward region
Muon spectrometer

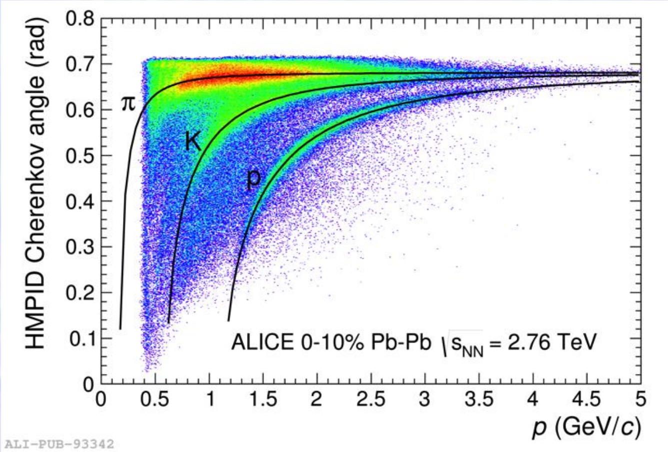
ALICE-UK
Central Trigger Processor
Inner Tracking System

UNIVERSITY OF BIRMINGHAM
UNIVERSITY OF LIVERPOOL
UNIVERSITY of DERBY
Science & Technology Facilities Council

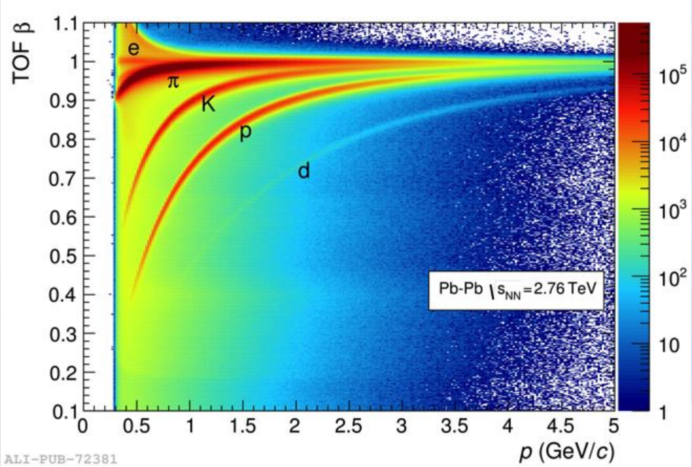
Particle Identification



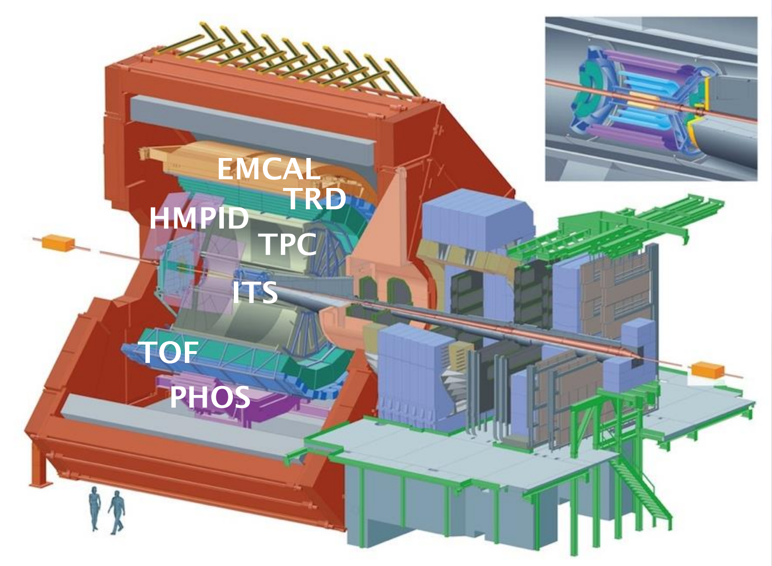
TPC (+ ITS) dE/dx



HMPID – Cherenkov radiation



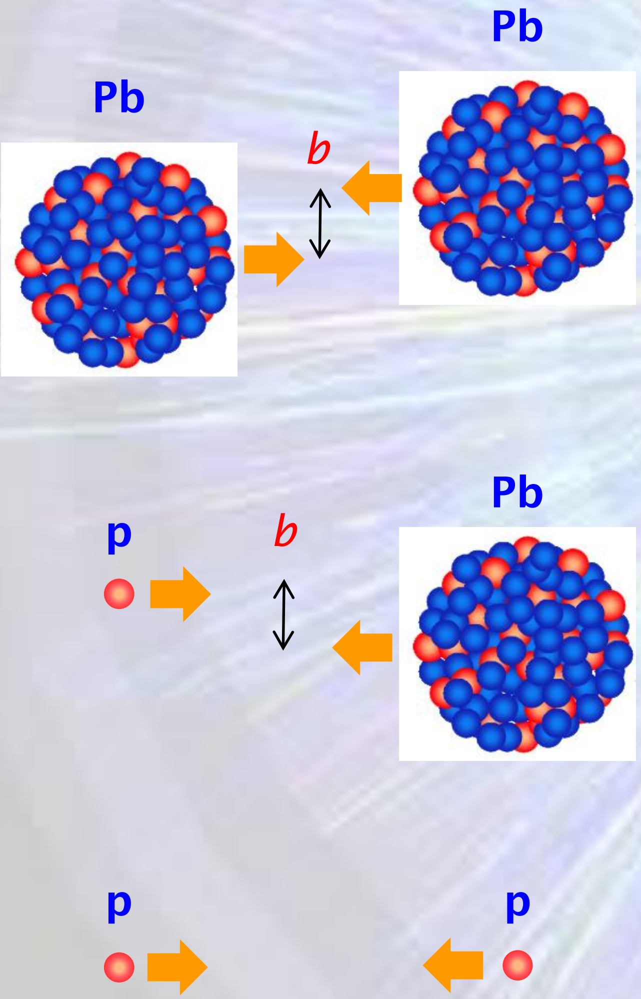
Barrel Time of Flight (TOF)



plus Transition radiation detector (TRD)
Photon spectrometer (PHOS), EM calorimeter (EMCAL)

Collision Systems

Run 1: 2010-2013
Run 2: 2015-2018



Pb-Pb collisions
Hot QCD matter studies

$\sqrt{s_{NN}}$ = 2.76, 5.02 TeV

p-Pb collisions
Cold nuclear matter effects

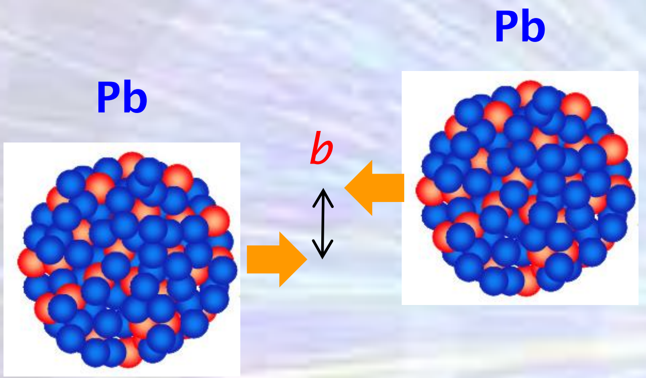
$\sqrt{s_{NN}}$ = 5.02, 8.16 TeV

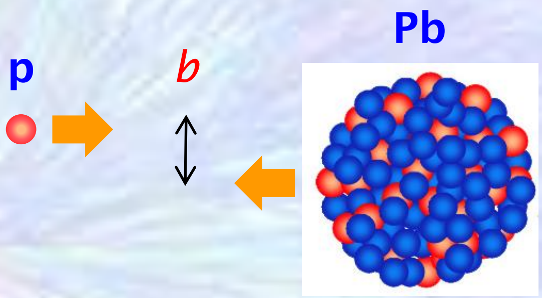
pp collisions
Standard QCD reference

$\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 13 TeV

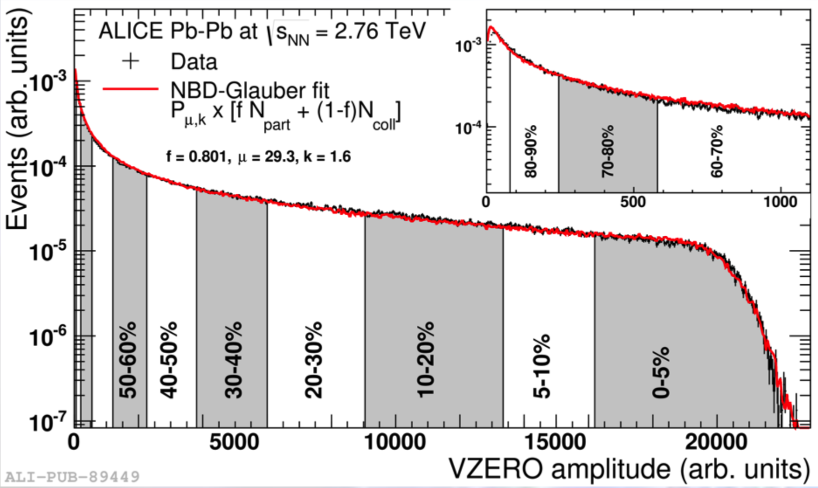
Are QGP effects really absent here?

Measuring Centrality

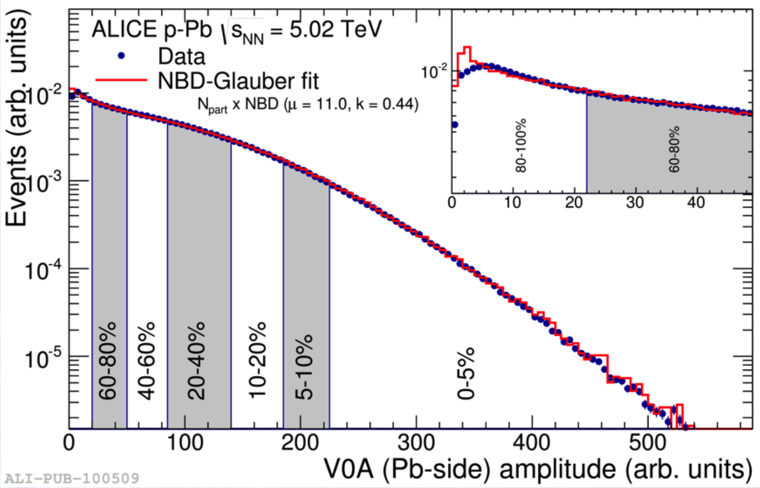




Phys. Rev. C 88 (2013) 044909



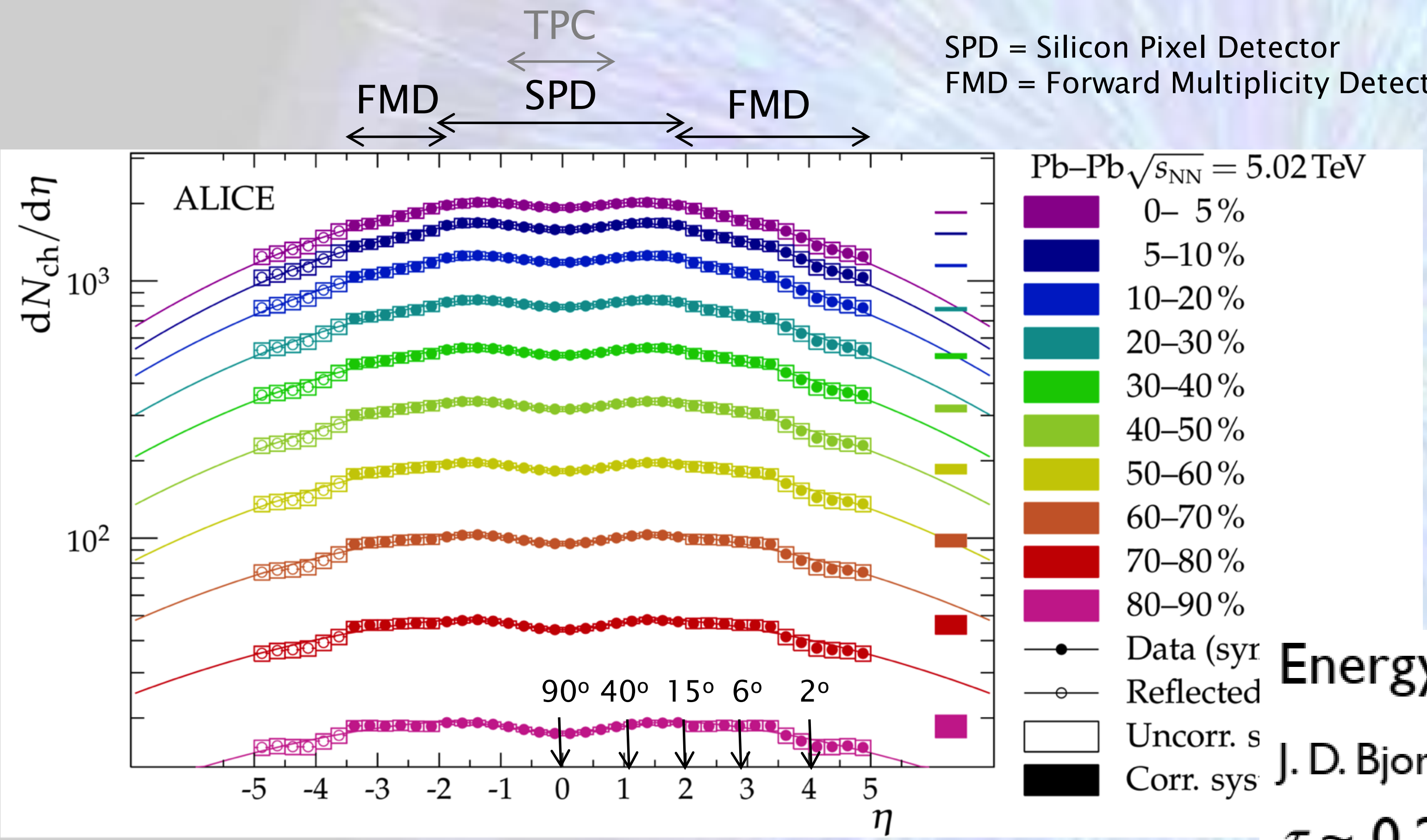
Phys. Rev. C 91 (2015) 064905



Events are classified by dividing the **multiplicity** distribution into **percentiles**. **Central** collisions typically **top 5% or 10%** highest multiplicity.

Charged particle multiplicity

SPD = Silicon Pixel Detector
FMD = Forward Multiplicity Detector



ALI-PUB-115086

Total number of charged particles ≈ **21,500** in **0-5%** **central collisions**

$dN_{ch}/d\eta\,|_{\eta=0}$ = 1943 ± 54 equivalent to **ε ~ 18 GeV/fm^3**

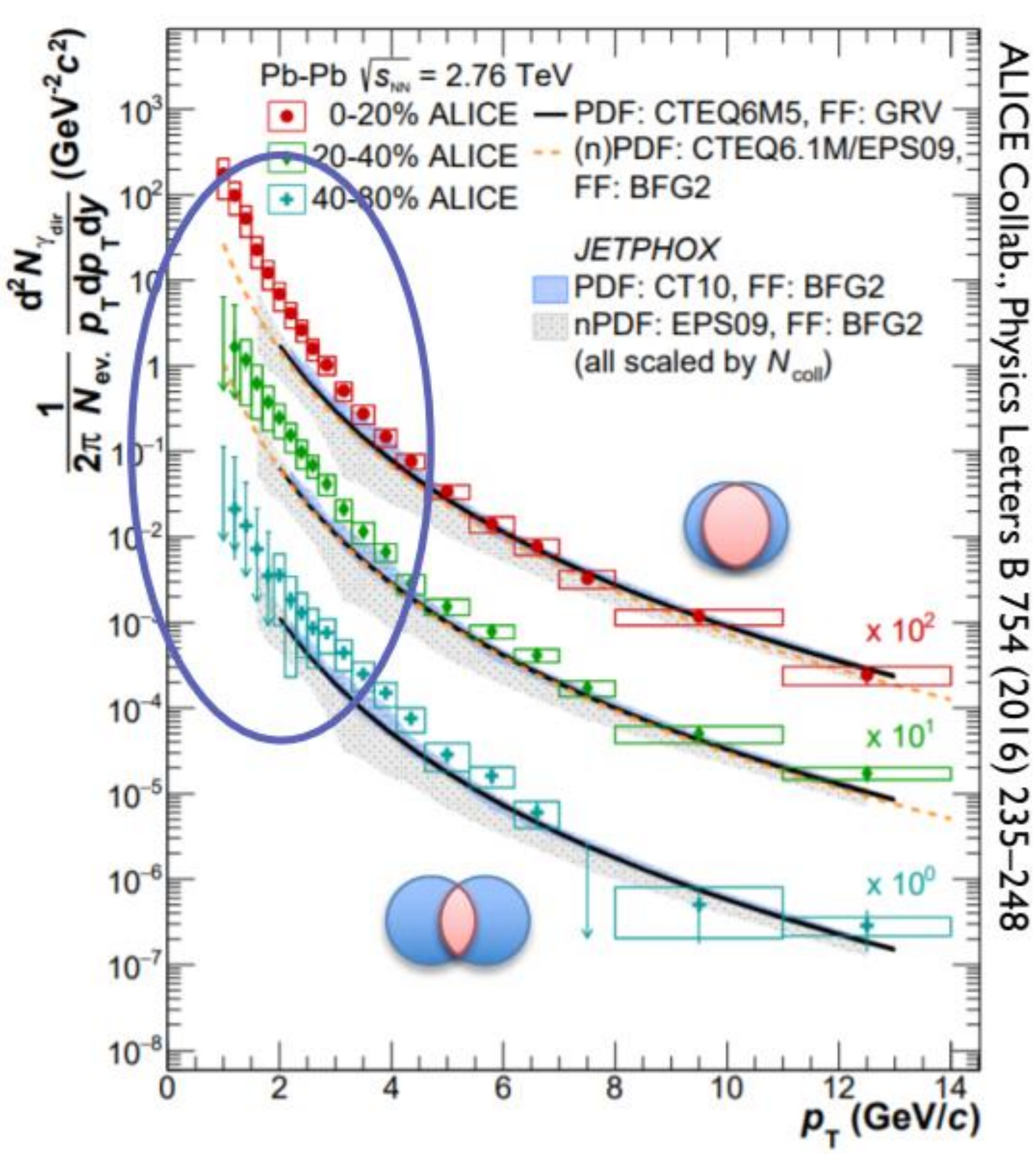
Energy density from Bjorken's formula

J. D. Bjorken, Phys. Rev. D27, 140 (1983)

τ ~ 0.2 – 0.6 fm/c

$$\boxed{\epsilon(\tau) = \frac{< m_T >}{\tau \pi R^2} \frac{dN_{ch}}{d\eta}}$$

QGP Temperature from Direct Photons



- Excess at low p_T (< 4 GeV/c) wrt pQCD
  - Predictions related to thermal photons
- Excess yield fitted with exponential

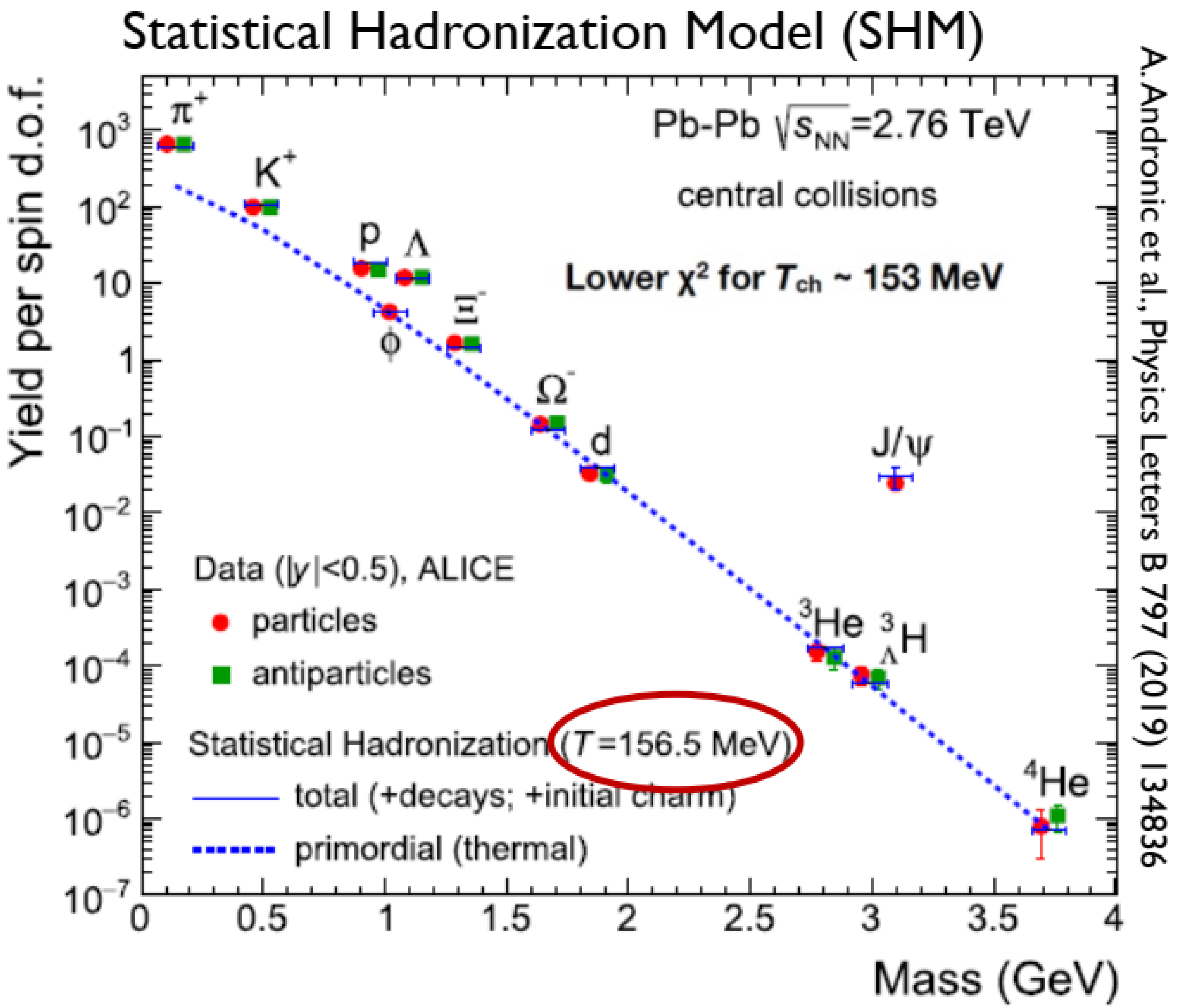
$$\propto \exp(-p_T/T_{eff}).$$

- T_{eff} reflects an effective average temperature of the system during its evolution.

- T_{eff} (0-20%) = $297 \pm 12\, stat \pm 41\, sys$ MeV

“Temperature” ≈ 300 MeV (→ highest man-made temperature)

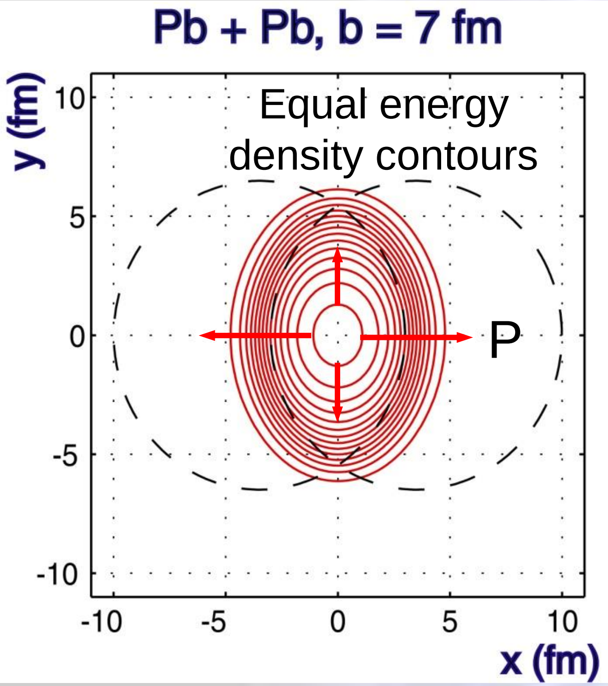
Temperature at Hadronization

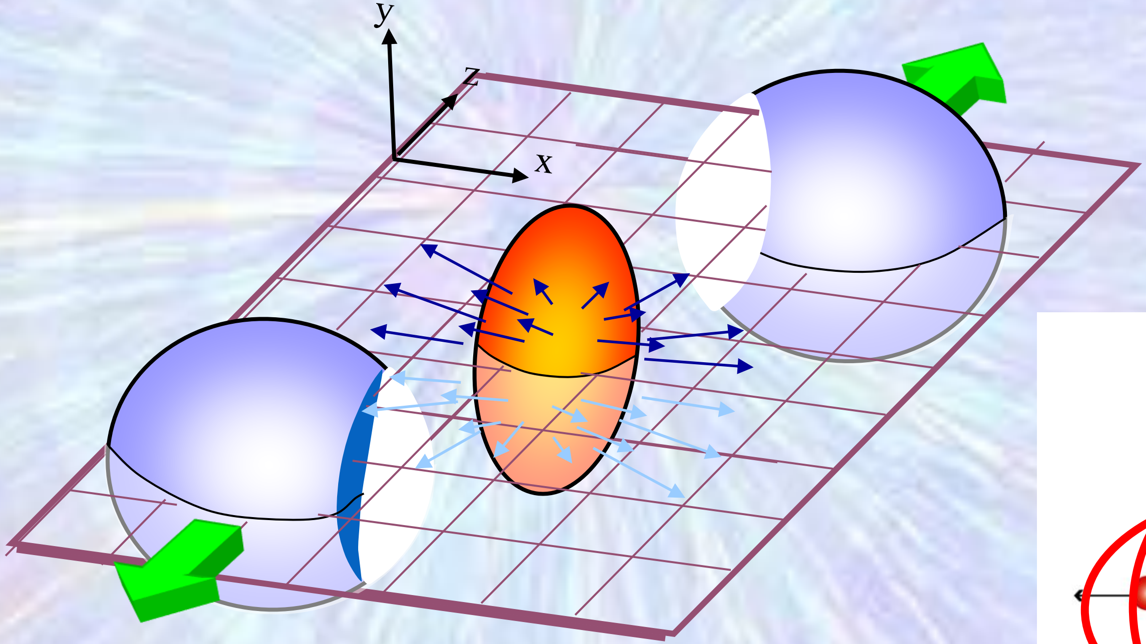


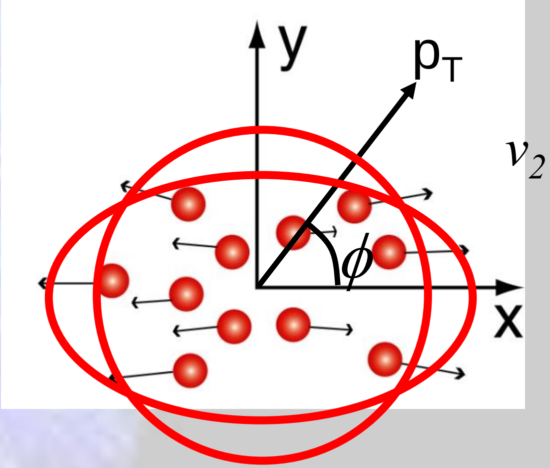
- At hadronization, system is close to thermal equilibrium.
- A rapid freeze-out takes place at the phase boundary
- Hadron yields described well by thermal model over 9 orders of magnitude.
- Even loosely bound objects (light nuclei etc) are well described.

Is QGP a Liquid or Gas?

Study angular dependence of emitted particles







v_2

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_n)]\right)$$

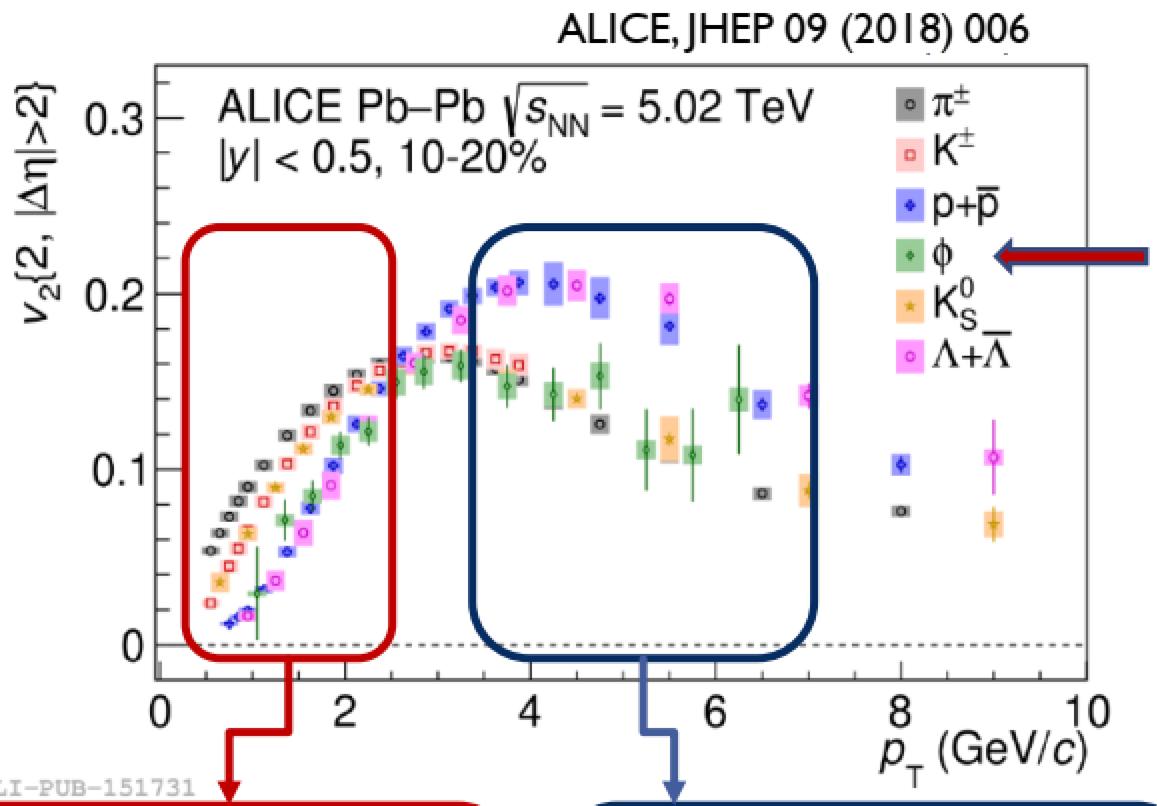
Fourier coefficient

Angle of reaction plane

$$v_2 = \langle \cos 2\phi \rangle$$

V_1 = directed flow. V_2 = elliptic flow.

Elliptic Flow of System



Mass ordering (higher mass → lower v_2): interplay between radial and elliptic flow

Higher n_q higher v_2 → quark coalescence as dominant particle production mechanism

- Viscosity/Entropy density (**η/S** dimensionless number in natural units)
- Theory prediction **η/S > 1/4π ≈ 0.08**

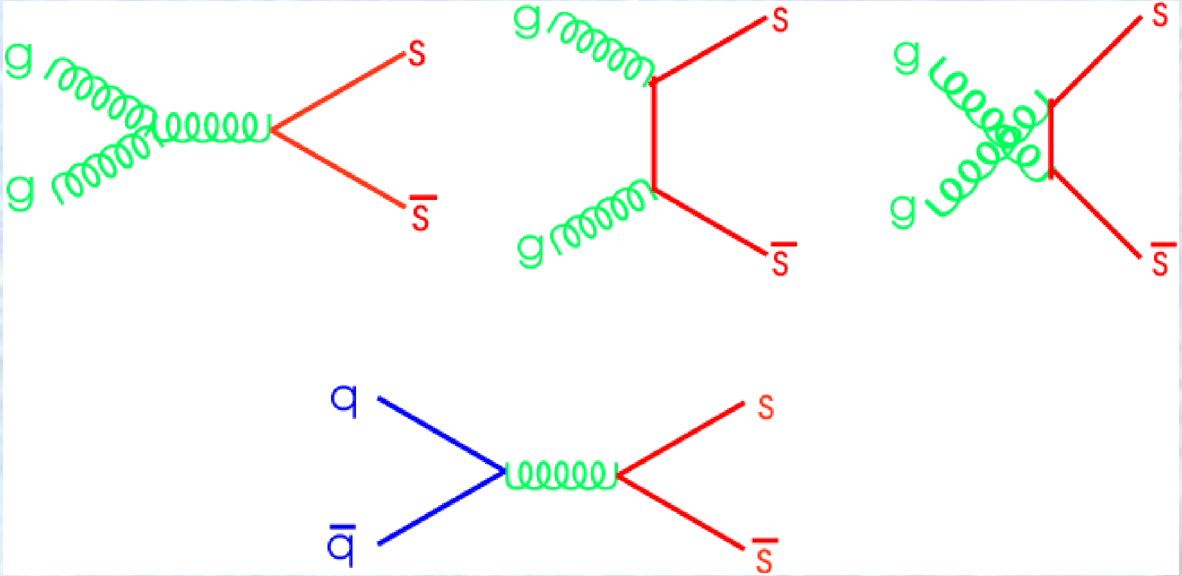
- **Result:** The QGP is a (almost) perfect liquid

QGP almost **ideal fluid**, **η/S** $\leq$ 0.2

Strangeness Enhancement in QGP

Gluon-rich QGP:

Energy needed to produce ss pair = $2m_s$ ~ 200 MeV due to partial chiral symmetry restoration.
QGP temperature ~ 200 MeV
∴ easy to produce ss pairs.



Much more difficult to produce strange particles in hadronic interactions (esp. multi-strange).

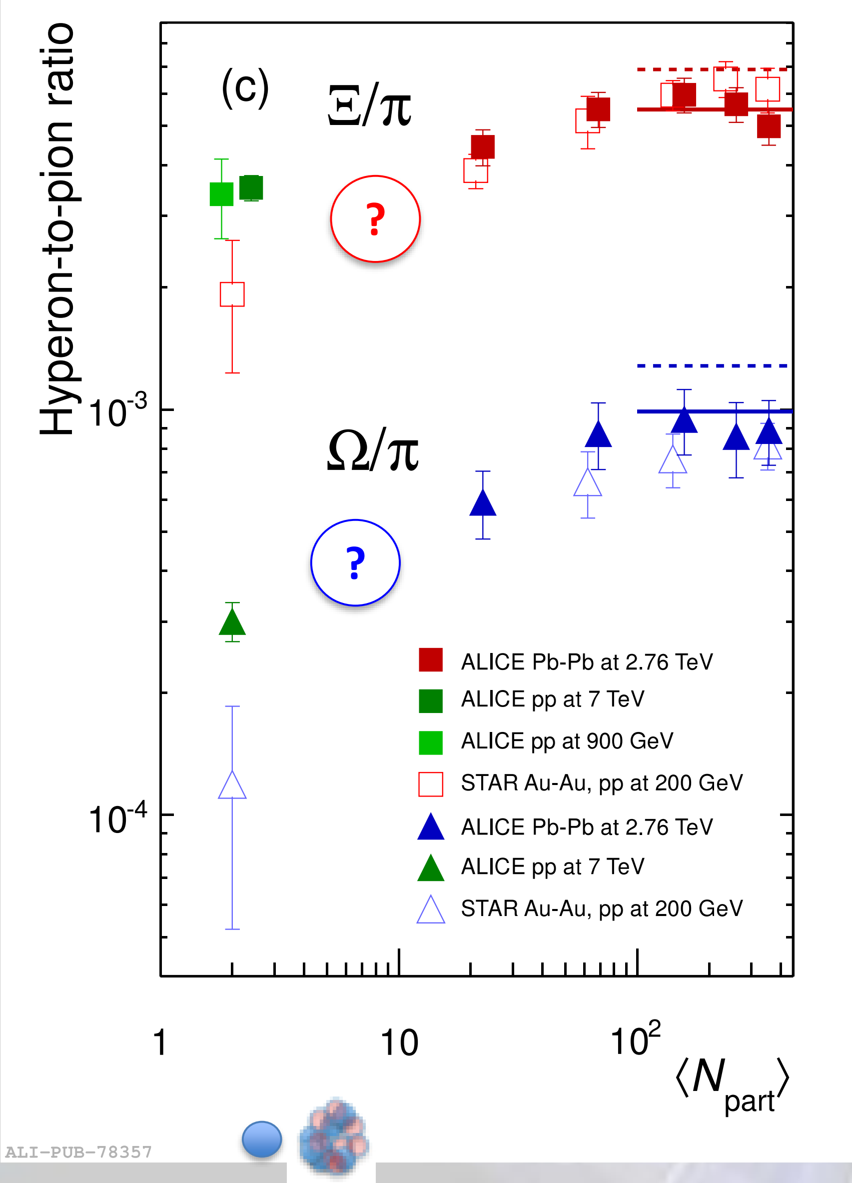
Originally proposed as a **signature of QGP formation** in heavy-ion collisions

Rafelski and Muller, PRL 48, (1982) 1066

Enhancement of strange particles expected, increasing with strangeness content for QGP

Multi-strange particle enhancement

Phys. Lett. B 728 (2014) 216–227



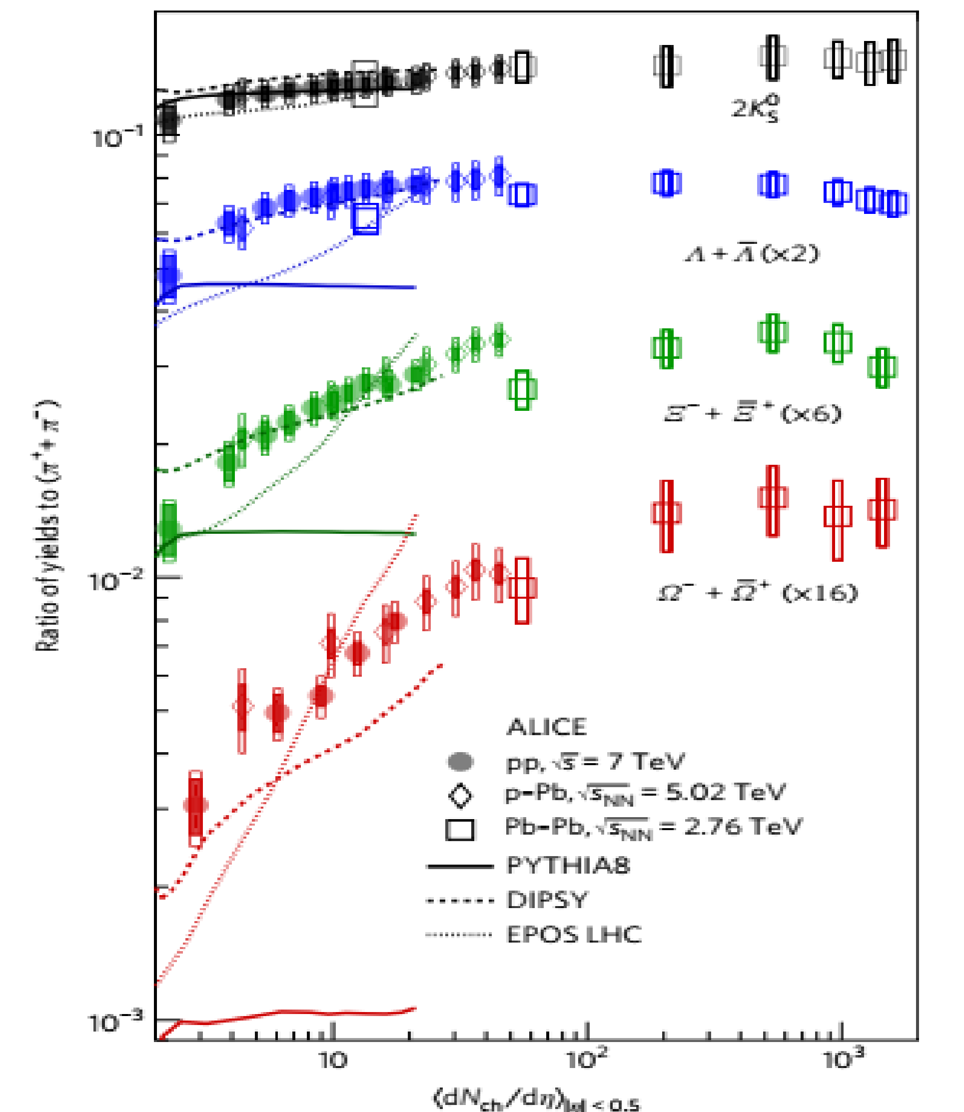
- Multi-strange particle yields in **Pb-Pb** collsions are **enhanced** with respect to those in **pp** collisions
- Enhancement increases with strangeness content
- But at LHC energies, multiplicity in p-Pb collisions almost reaches that in peripheral Pb-Pb.

Is there evidence of an onset of strangeness enhancement going from **small** to **large** systems?

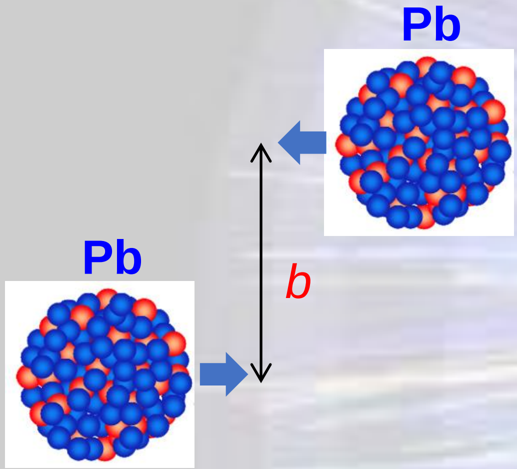
Enhancement of Strange Particles

- Smooth evolution of particle production from small to large systems (vs multiplicity)
- Strangeness enhancement increasing with multiplicity until saturation in Pb-Pb
- The higher the strangeness content, the steeper the enhancement
- Depends on multiplicity only – not system size or energy
- **Common mechanism for all systems?**
- **Will enhancement saturate in p-Pb and p-p at the same level as Pb-Pb?**

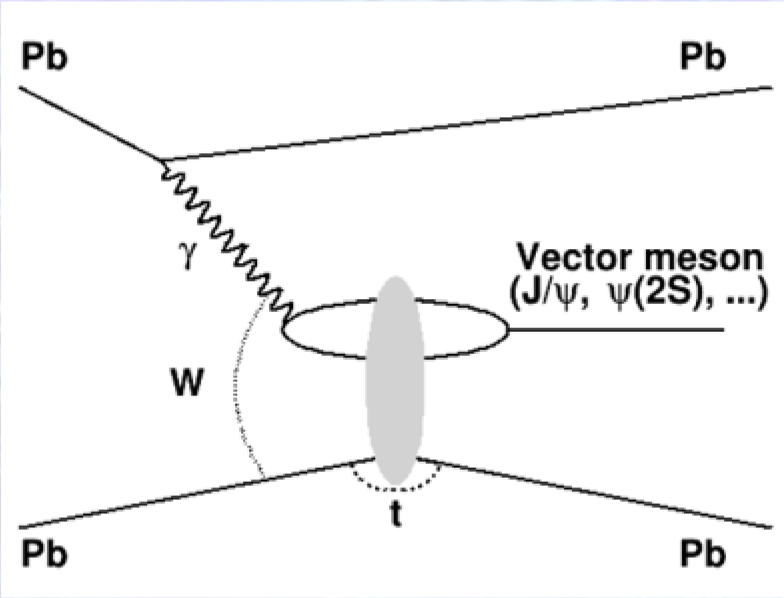
Nature Physics 13, 535-539 (2017)



Ultra-Peripheral Collisions (UPC)

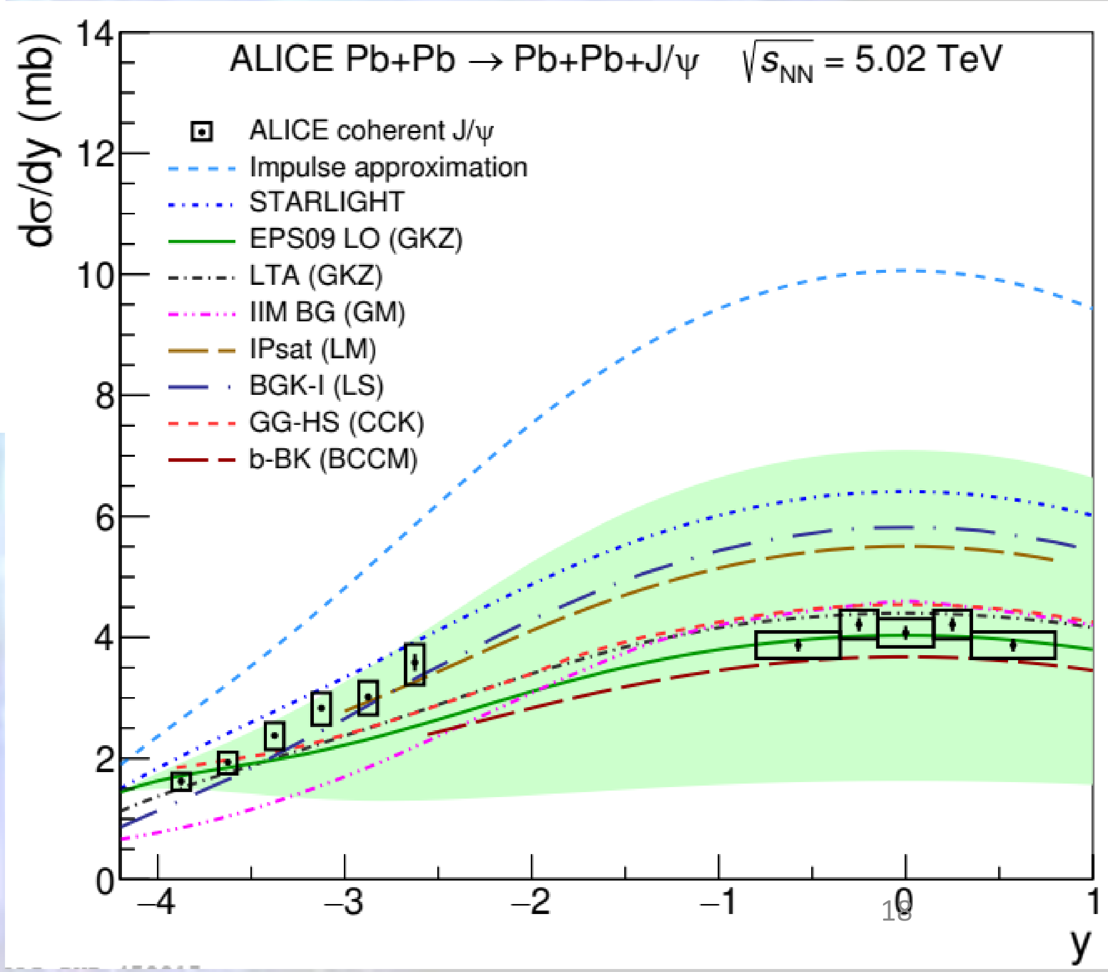


- Provides source of ~1 TeV (quasi-real) photons to probe nuclear Generalised Parton Distribution functions (UPC Pb-Pb) and proton structure functions (UPC Pb-p).

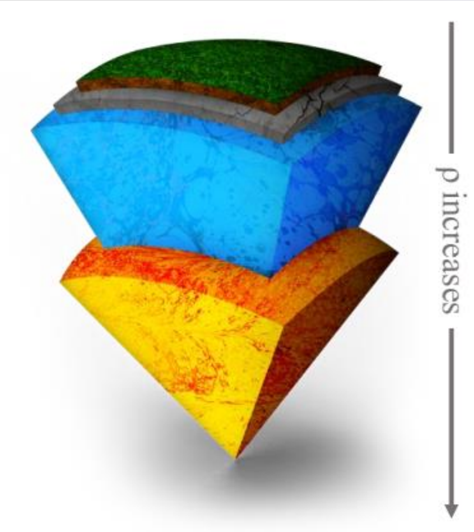


Coherent J/ψ cross-section

Favours models where colliding nuclei are partially concealed by gluon field (nuclear shadowing)

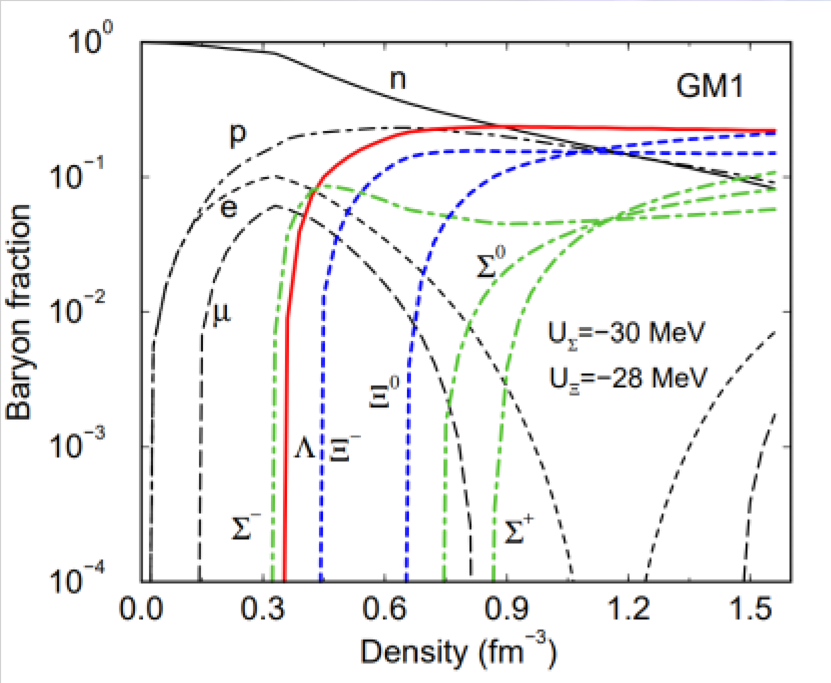


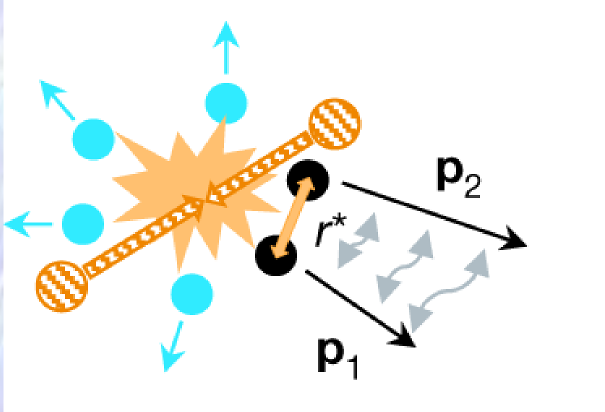
Non-QGP Physics: Hadron-Hyperon Interactions

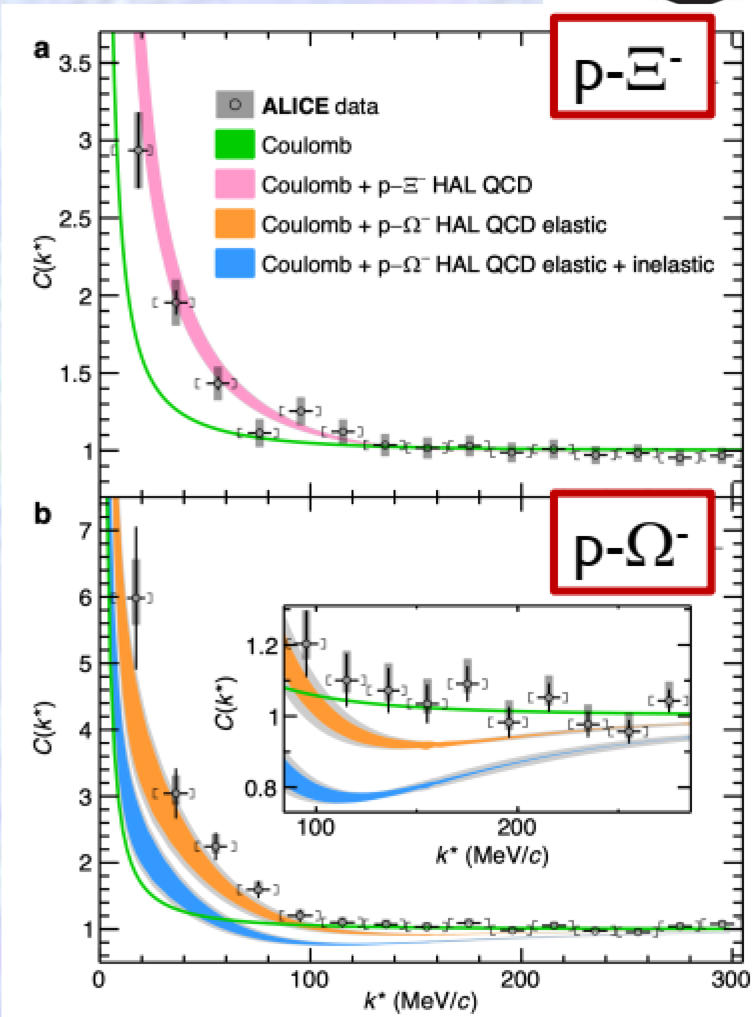


Neutron star inner core

- Composition still unknown (neutrons, protons, hyperons, quark matter?)
- Depends on constituent interactions and couplings







Nature 588, 232–238 (2020)

First precise observation of attractive strong interaction between p and Ξ^- or Ω^-

ALICE Upgrade for LHC Runs 3 & 4

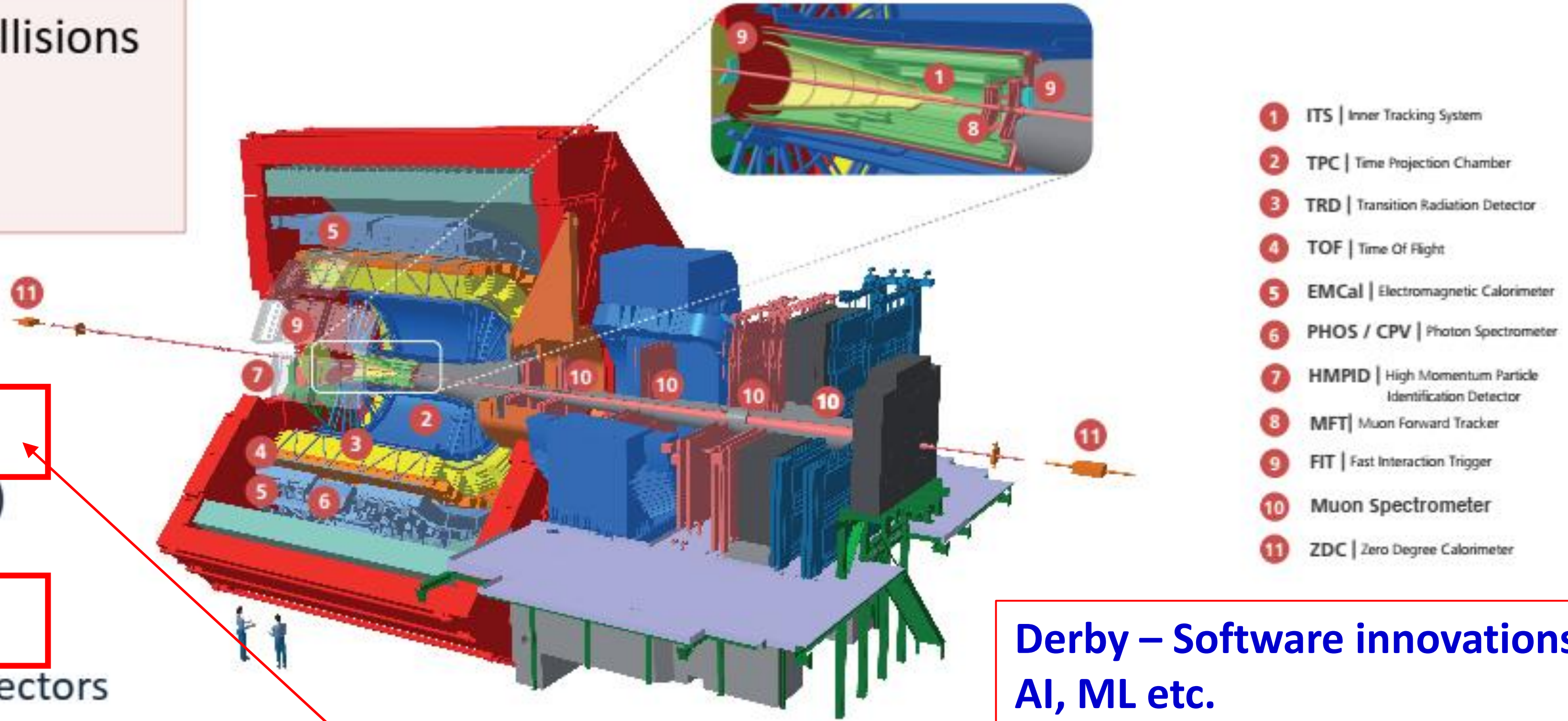
Runs 1 and 2: 1 nb^{-1} of Pb-Pb collisions

Interaction rate ~8 kHz

readout rate ≈ 1 kHz

LS2 upgrade

- New TPC R/O planes
- New silicon tracker (ITS & MFT)
- New Fast Interaction Trigger (FIT)
- New Online/Offline system (O2)
- New Central Trigger System
- Upgrade readout of all other detectors



Derby – Software innovations AI, ML etc.

> Improve tracking resolution at low p_T

x50 statistics increase for most observables

Run 3+Run 4: **13 nb^{-1} of Pb-Pb collisions**

readout rate ≈ 50 kHz (Pb-Pb), ≈ 1 MHz (pp)

online reconstruction : all events to storage!

Birmingham – sole responsibility for Trigger System

Liverpool and Daresbury Lab – built large part of outer two barrels of 12.5 G-pixel ITS

Summary

Energy density >> critical value

Flow consistent with perfect liquid

Particle yields appear to be frozen-in close to hadronisation

Strangeness enhancement observed in pp and p-Pb collisions

Ultra-peripheral collisions help to constrain initial state

Rich programme of non-QGP physics also available

…

ALICE is being upgraded ready for LHC Run 3 (2022+)

Readout rate for Pb-Pb will increase from 1 kHz to 50 kHz

New ITS will improve measurements of heavy flavour hadrons

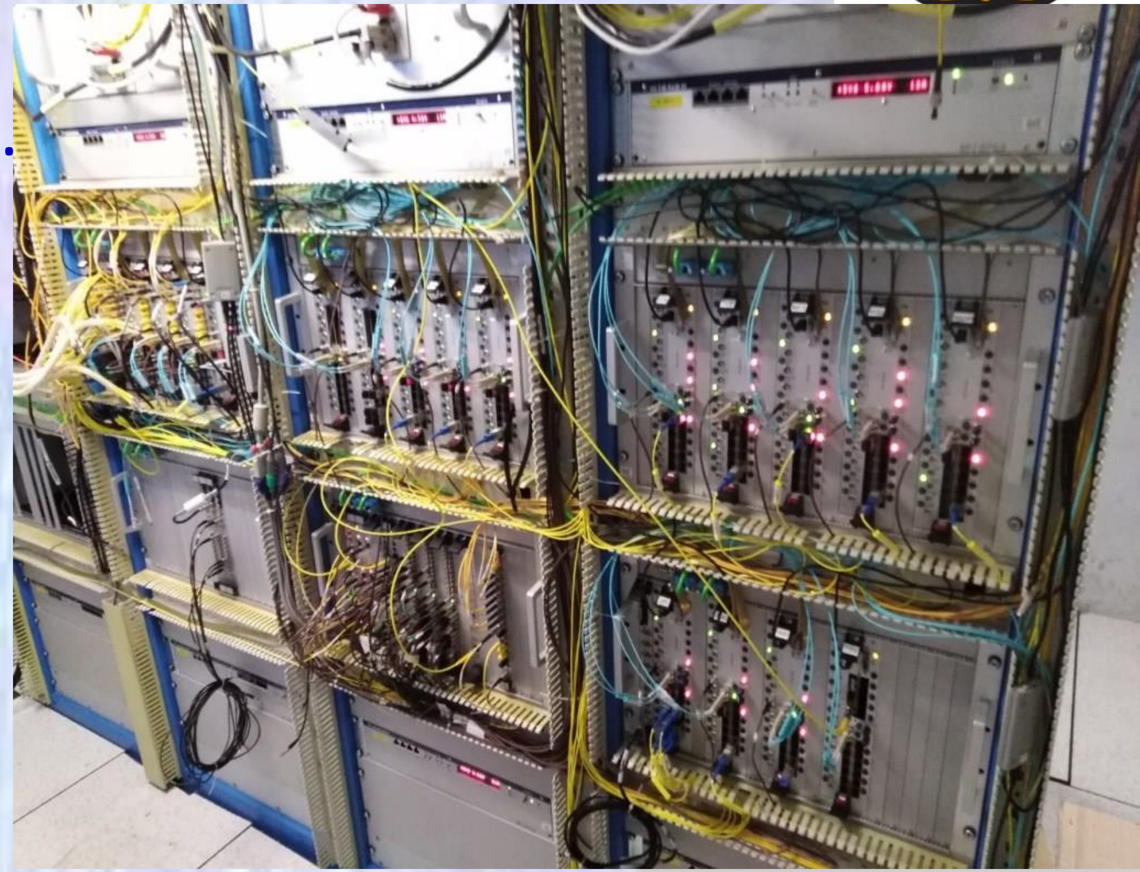
UK playing leading roles in both the upgrade and in the physics.

Looking forward to a lot of exciting results from Run 3

Thank you for listening

New Trigger System

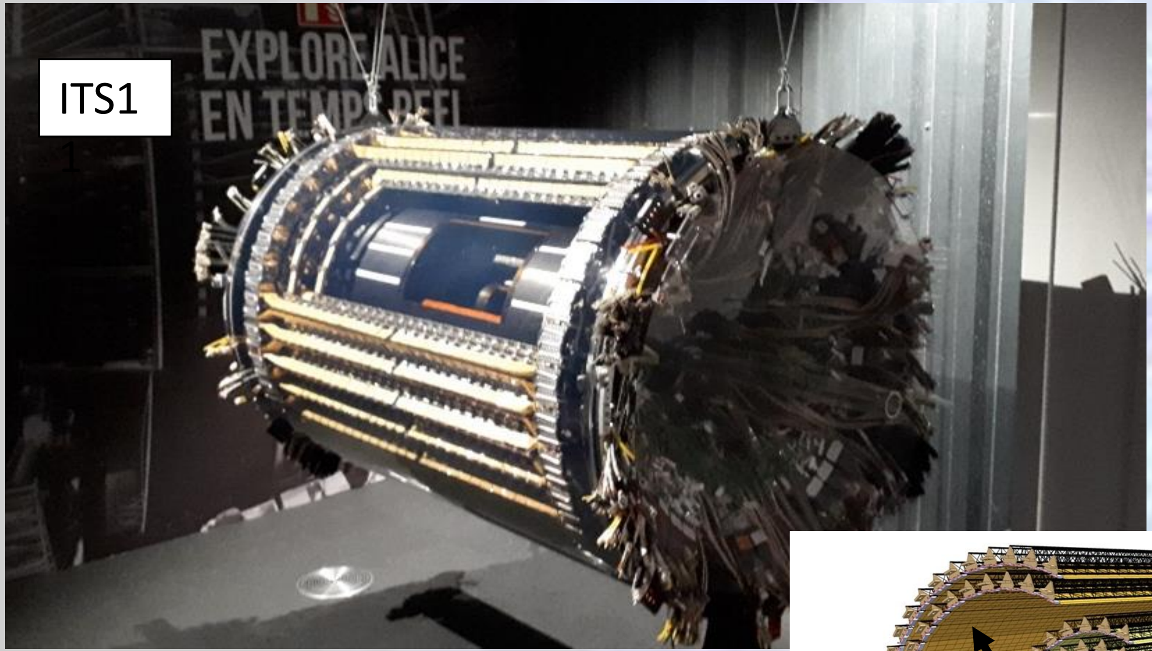
- Completely new ALICE trigger system designed and built by the UK (Birmingham).
- Consists of a Central Trigger Processor (CTP) and 14 Local Trigger Units (LTUs), one for each subdetector.
  - LTUs have built-in CTP emulator for stand-alone running.
- CTP has zero dead-time
  - i.e. can receive inputs and deliver triggers every 25ns bunch-crossing,

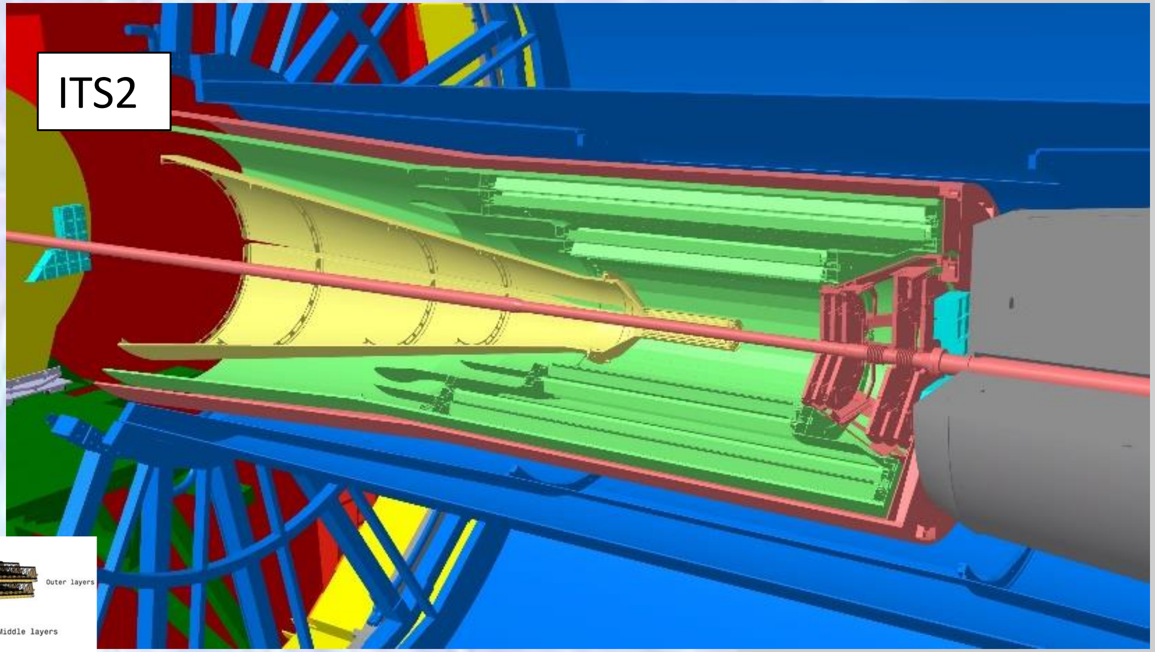


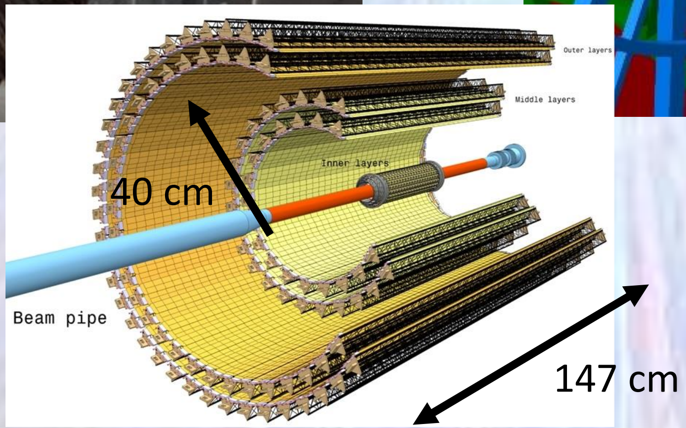
- In addition, CTP monitors and controls all (>500) Common Readout Units (CRUs) of upgraded detectors.
  - Can slow down readout rate if CRU buffers become full.

Inner Tracking System Upgrade

Liverpool and Daresbury





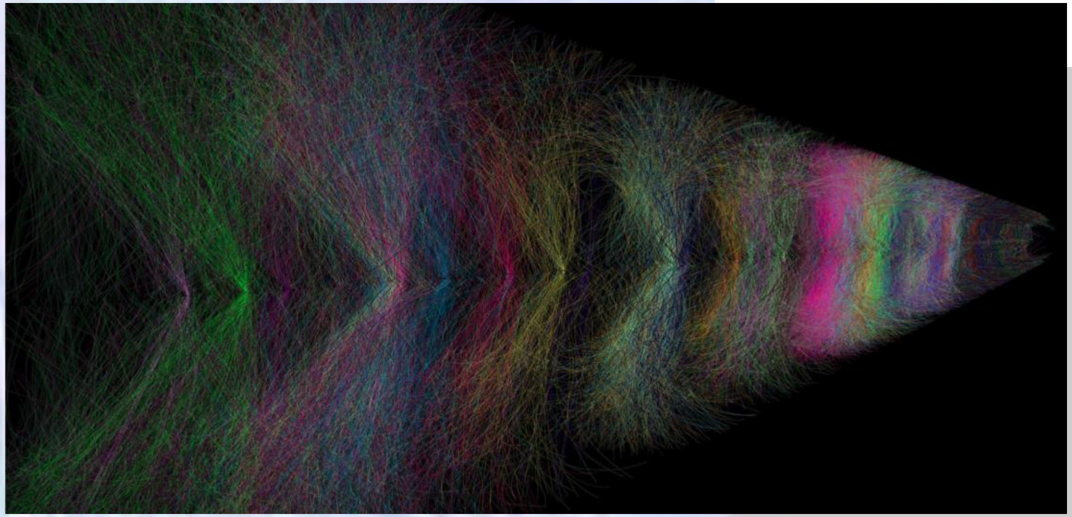


ITS2
12.5 G-pixel camera
taking 50000
pictures/s
(~10 m^2)

ITS2 has a barrel geometry:
- 7 layers; 3 (IL), 2 (ML), 2(OL)
- 192 staves; 48 (IL), 54 (ML), 90 (OL)

Contribution to Upgrade Software

- The ALICE upgrade requirements include
  - increased (~50x) data-taking rate
  - switch to continuous readout
  - prompt reconstruction of data
- Many software developments are required. The **University of Derby**'s current and recent contributions, under the O^2 umbrella, include:
  - An **AI-based approach** to detector monitoring, C. Bower "*Adversarial thresholding semi-bandits for online monitoring of ALICE detector controls*", PhD Thesis (2020)
  - Developments in **machine learning**, *Graph-based Neural Network*, for charm decay recognition (PhD ongoing)
  - **Reconstruction algorithms** for weakly decaying strange particles in the continuous readout environment (PhD ongoing)



Overlapping events in ALICE Time Projection Chamber

$$\Xi_c^0 \to \Xi^- \pi^+$$

$$\Xi_c^0 \to \Lambda K_S^0$$

Examples of charmed baryon decays with weakly decaying strange particles in decay chain