Overview of recent results from heavy-ion collisions at ultra-relativistic energies

Zinhle Buthelezi
Senior Scientist
Department of Subatomic Physics,
iThemba LABS, Somerset West, South Africa
Disclaimer

- Field of ultra-relativistic heavy-ions physics is very rich: 6 large active experiments, with more than 20 years of experimental history, very active and broad theory community
- The presentation will focus on a selection of recent results from an experimental point of view
- The slides were inspired by a few lectures given by various people, and in some by presentations from QM2018. I would like to acknowledge everyone I drew inspiration from
What is the point of ultra-relativistic heavy-ion collisions?

- Study the QCD phase transition from nuclear matter to the deconfined state of (“free”) quarks and gluons – the Quark Gluon Plasma (QGP) → State of strongly interacting matter where quarks and gluons are not confined to hadrons

- Studying Physics of the QGP
  → role of chiral symmetry in the generation of mass in hadrons → accounts for 99% of mass of nuclear matter
  → nature of quark confinement

- Phase transitions of hadrons to QGP well established from lattice QCD
  Temperature, $T \approx 170$ MeV ($\sim 2.10^{12}$K)
  Energy density $\varepsilon_c \approx 1$ GeV/fm$^3$

- Ultra-relativistic heavy-ion experiments → ideal environment for QGP factory!!
The Quark Gluon Plasma (QGP)

- Key observable to understand the early Universe
- Correspond to the state of the universe \( \sim 1 \, \mu s \) after the Big Bang
- QCD phase transition: QGP to normal matter (hadrons) happens at \( t_{\text{Universe}} \sim 10 \, \mu s \)

Creating the QGP: “little Big Bang”
- Collide heavy ions at the highest centre-of-mass energy per colliding nucleon, \( \sqrt{s_{NN}} \), → large energy density (> 1 GeV/fm\(^3\)) over large volume (>> 100 fm\(^3\))
- For a short time span (about \( 10^{-23} \, s \), or few fm/c) the conditions for deconfinement are recreated

- The QGP fireball first expands, cools and then freezes out into a collection of final-state hadrons
- Evolution: Pre-equilibration → QGP → hadronization → freeze out
- Use particles in the final state to study the evolution of a heavy–ion collision → study the properties of the QGP
Measuring the QGP in heavy-ion collisions

- Perform various measurements which, when combined, can provide reliable proof of the formation of the QGP → signatures of the QGP
The paradigm

**CORE business: Heavy-ion collisions → create and characterize the QGP**
- Global properties ↔ the QGP fireball
- Strangeness enhancement ↔ historic signature of the QGP
- Anisotropy, correlations ↔ collective expansion of the QGP
- Bulk particle production ↔ hadronisation of the QGP
- High-$p_T$ and jets ↔ opacity of the QGP
- Heavy-flavour production ↔ transport properties of the QGP
- Quarkonium production ↔ de-confinement in the QGP

**Role of the small systems:**

- **Proton-nucleus (p-A) collisions:** Control experiment
  - disentangle initial and final state effects
  - Investigate cold nuclear effects

- **Proton-proton (pp) collisions:**
  - Baseline (reference)
  - Test pQCD theories
Definition of concepts
Centrality

- Geometry of the heavy-ion collision $\rightarrow$ system size strongly dependent on collision centrality
- Given by the impact parameter, $b$

$N_{\text{coll}}$: number of inelastic nucleon-nucleon collisions
$N_{\text{part}}$: number of nucleons which underwent at least one inelastic nucleon-nucleon collisions

- Classify events in “centrality classes”
- Given as percentiles of total hadronic AA cross section
- Determine $\langle N_{\text{part}} \rangle$ and $\langle N_{\text{coll}} \rangle$ with a model of the collision geometry (Glauber model)

Central collisions: small $b \rightarrow$ large $N_{\text{part}}$
Peripheral collisions: high $b \rightarrow$ small $N_{\text{part}}$
Basic Observables

- **Transverse momentum**

\[ p_T = p \sin \theta \]

Transverse mass:

\[ m_T = \sqrt{p_T^2 + m^2} \]

\[ p = \sqrt{p_L^2 + p_T^2} \]

- **Rapidity \( y \) (additive under Lorentz transformation)**

\[ y = \text{arctanh} \ \beta_L = \frac{1}{2} \ln \frac{1 + \beta_L}{1 - \beta_L} = \frac{1}{2} \ln \frac{E + p_L}{E - p_L} \]

- **Pseudorapidity \( \eta \)**

\[ \eta \approx m \frac{1}{2} \ln \frac{1 + \cos \vartheta}{1 - \cos \vartheta} = - \ln \left[ \tan \frac{\vartheta}{2} \right] =: \eta \]
In-medium energy loss of particles is quantified by the **nuclear modification factor**: comparison of particle yield in A-A collisions to that in binary-scaled pp collisions.

\[
R_{AA}(p_t, \eta) = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_t d\eta}{d^2 N_{pp} / dp_t d\eta}
\]

= 1 if no medium effects \(\rightarrow\) no modification

< 1 \(\rightarrow\) it means a **suppression of particle production**
Elliptic flow

- The nature of flow provides information about the transport properties of the medium (QGP)
  - Flow at high $p_T$ → path length dependence of energy loss
  - Flow at low $p_T$ → thermalization / collective motion

- Given by $\nu_n$ coefficients: second harmonic coefficient ($\nu_2$) is generated from the system’s approximately almond (elliptic) shape → elliptic flow

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left(1 + \sum_{n=1}^{\infty} 2\nu_n \cos [n(\phi - \Psi_R)] \right)$$

$\nu_1$: Direct flow: $\langle \cos \phi \rangle$  
$\nu_2$: Elliptic flow = $\langle \cos 2\phi \rangle$

- Elliptic flow, $\nu_2$ is related to the geometry of the overlap zone
Core business:
high-energy heavy-ion experiments
## Heavy-ion experiments

<table>
<thead>
<tr>
<th>Year</th>
<th>Facility</th>
<th>Particle Beams</th>
<th>Energy, $\sqrt{s_{NN}}$</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>Bevalac @ Berkeley</td>
<td>Gold (Au - fixed target)</td>
<td>0.2-1 GeV</td>
<td>Collective phenomena: direct ($v_1$) and elliptic flow ($v_2$)</td>
</tr>
<tr>
<td>1992</td>
<td>AGS @ Brookhaven</td>
<td>Au-Au (fixed target)</td>
<td>5 GeV</td>
<td>Below critical energy density, $\varepsilon_c$</td>
</tr>
<tr>
<td>1994</td>
<td>SPS @ CERN</td>
<td>Lead (Pb) on Pb (fixed target)</td>
<td>17 GeV</td>
<td>Estimated energy density $\sim 1 \times$ critical value, $\varepsilon_c$. First signature of the QGP observed</td>
</tr>
<tr>
<td>2000</td>
<td>RHIC @ Brookhaven</td>
<td>Au-Au</td>
<td>8-200 GeV</td>
<td>Discovery of several properties of the QGP</td>
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<td>2010-2011</td>
<td>LHC @ CERN</td>
<td>Pb-Pb</td>
<td>2.76 TeV</td>
<td>Qualitative similar results in A-A</td>
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<td>2010-2014</td>
<td>RHIC-BES Phase I @ Brookhaven</td>
<td>Au-Au</td>
<td>62, 130 and 200 GeV</td>
<td>Direct flow ($v_1$) of charged hadrons similar to hydro-model predictions?</td>
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<tr>
<td>2013</td>
<td>LHC @ CERN</td>
<td>p-Pb</td>
<td>5.02 TeV</td>
<td>Control experiment:-- disentangle initial &amp; final state effects</td>
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<td>2015 – 2017</td>
<td>LHC RUN 2 @ CERN</td>
<td>Pb-Pb, p-Pb, Xe-Xe Pb-Pb</td>
<td>5.02 TeV</td>
<td>Ongoing… Precise characterization of the QGP, new probes available</td>
</tr>
<tr>
<td>2018</td>
<td>From 2017</td>
<td>RHIC-BES Phase II @ Brookhaven</td>
<td>Au-Au (fixed target)</td>
<td>Access $\sim \mu_B$ from 400 MeV (current) to $\sim 800$ MeV, (corresponds to $\sqrt{s_{NN}} \sim 2.5$ GeV in QCD phase diagram)</td>
</tr>
</tbody>
</table>
Discovery of strangeness enhancement at the CERN SPS

- First signature of the QGP - observed in the 1980s at CERN SPS
- Strange hadrons contain 1 or more strange quark(s). They are heavier than normal matter around
  - Harder to produced → “freshly” made from the kinetic energy of the colliding system
  - Their abundance is sensitive to conditions, structure and dynamics of the QGP
    → if number is large, it can be assumed that the QGP has been formed
- Measurements:
  - Count strange particles produces and calculate the ratio = strange particles/non-strange particles
  - Higher ratio than predicted by theories that do not predict the QGP → enhancement has been observed.
Discovery of several properties of the QGP at Relativistic Heavy Ion Collider (RHIC)

- 2 independent rings; circumference: 3.8 km
- Au-Au, $\sqrt{s_{NN}} = 200$ GeV

**RHIC Scientists Serve Up Perfect Liquid** (BNL 2005-10303), issued on 18 April 2005

"New state of hot, dense matter .. quite different and even more remarkable than had been predicted .."
"In fact, the **degree of collective interaction**, rapid thermalization, and **extremely low viscosity** of the matter being formed at RHIC make this the most **nearly perfect liquid** ever observed,"

"...other measurements at RHIC have shown "jets" of high-energy quarks and gluons being dramatically slowed down as they traverse the hot fireball produced in the collisions. This "jet quenching" demonstrates that the energy density in this new form of matter is extraordinarily high — much higher than can be explained by a medium consisting of ordinary nuclear matter."
Does the QGP have flow?

Measurement of the elliptic flow ($v_2$) of identified particles vs $p_T$ showed that as the deconfined matter (QGP) evolves it flows due to pressure gradients

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi} \left( 1 + 2v_1 \cos(\phi - \Psi_1) + 2v_2 \cos[2(\phi - \Psi_2)] + \ldots \right)$$

$v_1$: Direct flow = $\langle \cos \phi \rangle$  
$v_2$: Elliptic flow = $\langle \cos 2\phi \rangle$

- Elliptic flow almost as large as expected at hydro limit $\Rightarrow$ Flow patterns consistent with ideal hydrodynamics
- Looks like a “liquid”
  - Small viscosity over entropy density ($\eta/s$)
  - Particles interact frequently
- strongly coupled QGP is nearly a ”perfect liquid“
Jet quenching in heavy-ion collisions

- Fast partons produced from HIC propagate through the QGP fireball lose energy via gluon radiation or elastic scattering.
- They are **observable as jets of hadrons** when they hadronize and **the energy loss becomes evident** in a phenomenon known as “jet quenching”  
  → Instead of two jets going back-to-back (e.g. pp collision) and having similar energies, a **striking imbalance is observed**: one jet being almost absorbed by the medium.
Jet Quenching at RHIC

- Where does the radiated energy (gluon) go?

→ Measure the $R_{AA}$ of jets and direct photons ($\gamma$)

$$R_{AA}(p_T, \eta) = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}}{dp_T d\eta} / \frac{d^2N_{pp}}{dp_T d\eta}$$

- Hadron suppression at high $p_T$, "Jet quenching"
- Direct photons are not
- Evidence of parton energy loss (creation of a dense and opaque system)
Heavy Ions at the CERN Large Hadron Collider (LHC)

Fundamental Questions:

- Can the quarks inside the protons and neutrons be freed?
  → a state in which colour confinement is removed
- Why do protons and neutrons weigh 100 times more than the quarks they are made of?
  → and chiral symmetry is approximately restored
- What happens to matter when it is heated to 100,000 times the temperature at the centre of the Sun?
  → a high-density QCD medium of “free” quarks and gluons

Answers to these questions will help us study the properties of the QGP
Heavy-ion collisions at the LHC

- **LHC RUN 1 (2010-2013)**
  - Qualitatively similar results in AA collisions $\rightarrow$ confirm findings from RHIC
  - A surprise: striking similarities between pp/p-Pb /Pb-Pb

- **LHC Run 2 (2015 -2018)**
  - Equivalent energy runs:
    - $\sqrt{s_{NN}} = 5.02$ TeV ($\sqrt{s} = 1.045$ PeV),
    - $E_b = \begin{cases} 
      6.37$ Z TeV & in Pb – Pb \\
      4$ Z TeV & in p – Pb \\
      2.51$ TeV & in p – p 
    \end{cases}$
  - Data analysis ongoing $\rightarrow$ available results

Plot taken from slides of...
Heavy-ion experiments at the LHC
**ALICE**

**Size:** 16 x 26 meters  
**Weight:** 10,000 tons  
**Detectors:** 18

**HI collisions:** measure all known observables to characterise the QGP  
**pp collisions:** baseline for HI and to test pQCD models  
Complementary kinematic coverage at the LHC
Example of an event from a Pb-Pb collision at the LHC
A few results from measurements of global properties
Energy density reached in HI collisions at the LHC

Bjorken’s formula

$$\varepsilon = \frac{E}{V} = \frac{1}{S c \tau_0} \frac{dE_T}{dy} \bigg|_{y=0}$$

- $S$ – transverse dimension of nucleus
- $\tau_0$ – “formation time” $\sim$1 fm/c

1 femtometer (fm) $\rightarrow$ 1x10$^{-15}$ meter (m)

- Transverse dimension:
  - $S \approx 160 \text{ fm}^2$ ($R_A \approx 1.2 \text{ A}^{1/3} \text{ fm}$)

At the ALHC the transverse energy is $\sim$3 x RHIC. Estimated $\varepsilon > 15 \text{ GeV/fm}^3$
Size of the QGP fireball

- Determine the freeze-out volume ($V_{fo}$) and emission time ($\tau_f$)
- Method: Hanbury Brown and Twiss (HBT) interferometry radius $\rightarrow$ two-pion Bose-Einstein correlations

**Freeze-out volume:** $V_{fo} \sim (2\pi)$

**Emission time:** $\tau_f R_{long} \sqrt{m_T/T_f}$

At LHC: $V_{PbPb,central} \approx 5000 \text{ fm}^3$, $V_{Pb} \approx 800 \text{ fm}^3$ $\Rightarrow V_{PbPb,central} \approx 6.25 \times V_{Pb}$
What is the QGP temperature?

- Use direct photons ($\gamma$). They are produced from initial hard-scattering (prompt $\gamma$ and fragmentation of jets)
  - Not coming from decays of hadrons
  - They leave the reaction zone unscathed due to larger mean-free path than nuclear scales
  - Provide a direct means to examine the early hot phase of the collision
- Thermal $\gamma$ are produced throughout the evolution of a HI collision and after the transition of the QGP to a hot gas of hadrons
- Experimental challenge: detection from huge background from hadronic decays
QGP temperature from photon spectra

- Prompt $\gamma = \text{Inclusive } \gamma - \gamma$ from $\pi^0$ decays
- Direct $\gamma$ from QCD processes:
  - Power law spectrum - dominant at high $p_T$
- Thermal Photons - emitted by the hot system (analogy with black body radiation):
  - Exponential spectrum - dominant at low $p_T$

$T = 304 \pm 51 \text{ MeV} \Rightarrow 2T_c \Rightarrow 1.4T_{\text{RHIC}}$
Elliptic Flow of identified particles at the LHC

- $v_2$ large at the LHC

- System still behaves very close to ideal liquid

- Similar hydrodynamic behaviour

ALICE, PRL 105(2010) 252302
Strangeness enhancement at the LHC

ALICE, PR 142 (1986) 167

- Increase production of strange hadrons
- Copious production of $s\bar{s}$ pairs by gg fusion PR 88(1982) 331, PRL 48(1982) 1066
- Restoration of chiral symmetry

- Deconfinement: stronger effect for multi-strange baryons
- Strangeness enhancement increases with strangeness content
Jet Quenching at the LHC

- Pb-Pb @ 2.76 TeV events with large di-jet imbalance observed
- $R_{AA} \approx 0.5$ in central collisions
- Not much $p_T$ dependence of the jet suppression

- Production dominated by quark jets which may lose less energy than gluon jets

ATLAS, PRL 105 (2010) 252303
arXiv:1411.2357
High $p_T$ suppression at the LHC

- Parton energy loss by
  - Medium-induced gluon radiation
  - Collisions with medium gluons

- $R_{AA}$ of charged particles produced in most central collisions at LHC
  - Minimum (~0.14) for $p_T \sim 6-7$ GeV/c
  - Slow increase at high $p_T$
  - Still Significant suppression at $p_T \sim 100$ GeV/c

- Essential quantitative constraint for parton energy loss models
A surprises from the recent results

- A surprise from the RUN 1 (2010-2013) results:
  - collective behaviour, a feature of HI, also in high-multiplicity small systems (pp, p-Pb collisions)?

- Some results from RUN 2 (2015-2017) data analysis
  - do we see collective behaviour?
Long-range two-particle correlation measurements

- Provide important **insights into the underlying mechanism of particle production** in high-energy HI collisions
- Technique: high-$p_T$ particles in the event (“trigger particle”), correlate all other particles (“associated particles”) $\rightarrow |\Delta\phi|, |\Delta\eta|$ correlation distributions
- Key feature: pronounced structure on the near side: $|\Delta\phi| \approx 0$, extending over a large $|\Delta\eta|$ up to 4 units or more: “ridge”
- **Correlations are long-range**: saturation of the $v_2$ with $|\Delta\eta|$ separation

**CMS, EPJC 72 (2012) 1005**

“away-side” becomes very broad – a **ridge in the middle appears**

“near-side ridge”

Long-range structure in $\eta$ on “away-side ridge”

Near side jet peak
Long-range correlation measurement in high-multiplicity pp and p-Pb

- **Near-side ridge** (long-range correlations in $\eta$ at $\Delta \phi=0$) observed by the CMS experiment in high-multiplicity pp and p-Pb

**Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV**

**pPb $\sqrt{s_{NN}}=5.02$ TeV, high multiplicity**

**pp at 7 TeV, high multiplicity**

Flow-like two-particle correlations become visible in high-multiplicity pp and p-Pb collisions at the LHC
Long-range two-particle correlations measurement in high-multiplicity p-Pb collisions

- **Double ridge** discovered by ALICE and ATLAS experiments → resembles structure attributed to collective phenomena (flow) occurring in the QGP created in the Pb-Pb collision.

![Graphs showing double ridge](image1)


**ATLAS, arXiv:1212.5198 [hep-ex]**

- Models producing almost identical near- and away-side ridges based on the CGC framework or hydrodynamical calculations that assume collective effects to occur also in p-Pb collisions.
Charged-particle multiplicity vs centre-of-mass-energy

\[ \frac{dN_{ch}}{d\eta} : 1167 \pm 26 \text{ Xe-Xe vs } s_{NN} = 5.44 \text{ TeV} \]
\[ 1943 \pm 54 \text{ Pb-Pb vs } s_{NN} = 5.02 \text{ TeV} \]

- Same trend established in all heavy-ion measurements
- Charged-particle multiplicity rises faster as a function of \( s_{NN} \) than pp and p-A collisions
- p-A results from LHC experiments and d-A results from RHIC fall on the curve of pp collisions

\[ \rightarrow \text{Fast rise in AA is not only related to multiple collisions undergone by the participants since the proton in p-A collisions also encounters multiple nucleons} \]
Charged-particle multiplicity vs centrality

For fixed and large number of participant ($N_{\text{part}}$) we observe that Xe-Xe is much larger than Pb-Pb → no system size scaling

NEW Run 2 data
Multiplicity vs centrality in pp, p-Pb, Xe-Xe and Pb-Pb

- **Number of particle** \((N_{\text{part}})\) **scaling violation**: → known since a long time, confirmed by new Xe-Xe data
  - well described by participant quark scaling \(N_{q-part}\) and many theoretical models

- **Central collisions of medium-size nuclei** produce more particles per \(N_{\text{part}}\) than mid-central collisions of large nuclei at the same \(N_{\text{part}}\) → not explained by participant quark scaling and not fully reproduced by models

ALICE arXiv:1805.04432

NEW Run 2 data
Strangeness enhancement: pp, p-Pb Xe-Xe and PbPb

- $p_T$-integrated yield ratios to pions vs multiplicity
  - Smooth evolution of particle ratios with multiplicity
  - Enhanced production of multi-strange hadrons in high-multiplicity pp collisions

- Strangeness enhancement is considered a defining feature of HI → explained as collective expansion of the system

- Now also seen in high-multiplicity pp / p-Pb!
  - Not produced by traditional soft QCD models, e.g. PYTHIA → challenges universality and factorisation of fragmentations

Summary

- Presented selection of HI results from the LHC
- Measurements in high-multiplicity pp, p-Pb collisions show:
  - Striking similarities between pp, p-Pb, PbPb
  - High-multiplicity pp and p-Pb results exhibit collective phenomena
    - Is a strongly-correlated QGP liquid also formed in small systems (pp and p-Pb collisions)?
    - Important consequence for the interpretation of all hadronic collisions!
- Exciting physics ahead
  - RUN 2 data: increased energy and luminosity, to shed light
  - Rich LHC RUN 3 (2020 onwards) upgrade programme to come
EXTRA slides
Current questions

- What are the mechanisms for the fast thermalization in HIC?
- What is the physical origin of equilibrium particle yields or how does hadronization work?
- What are the transport properties of the QGP?
  → Dependence on $T$ and $\mu_B$?
- How can one make contact with \textit{ab-initio} QCD predictions?
- Can one experimentally determine the properties of the QCD phase Diagram?
  → Nature of the transitions at $\mu_B = 0$ (crossover, 1\textsuperscript{st} order)?
  → Is there a critical endpoint? If so, where? → Being explored in the RHIC beam energy scans (BES) programme
- Can one identify the onset of de-confinement in HIC at some $\sqrt{s_{NN}}$?
- Is a strongly-correlated QGP liquid also formed in small systems (pp and p-Pb collisions)? What about e+e-...?
Heavy-flavour production

**Charm and beauty hadrons**: large masses

- Tools to characterize the properties of the interaction parton-QGP:
  - Produced at the beginning of the collision
  - No flavour change during the collision
  - No extra production at the hadronization
  - Parton Energy Loss by medium-induced gluon radiation and collisions with medium gluons depends on
    - Medium properties (energy density, size)
    - Parton colour charge (Casimir factor)
    - Parton mass

$$\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$$

$$R_{AA} \equiv \frac{1}{\langle T_{AA} \rangle} \frac{Y_{AA}}{Y_{pp}}$$

$$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$
Future Heavy-Ion Experiments

**NICA - Nuclotron-based Ion Collider fAcility @ Dubna in Russia**
- Determining the existence and location of the transition region,
- Establish the character of the associated phase transformation, namely, whether it remains a smooth cross over, or has become a first-order one, as several models predict.

**CBM - Condensed Baryonic Matter experiment @ FAIR (GSI, Germany)**
- Study the fundamental aspect of QCD: the equation-of-state of strongly interacting matter at high baryon densities, the restoration of chiral symmetry, the origin of hadron masses, the confinement of quarks in hadrons, the structure of neutron stars, the dynamics of core-collapse supernovae.
History: idea of the quark-gluon plasma (QGP)

- 1973 birth of QCD:
  - All ideas in place. Yang-Mills theory, SU(3) color symmetry, asymptotic freedom; confinement in color-neutral objects

- 1975 – idea of quark deconfinement at high temperatures and/or density:
  - Collins, Perry, PRL 34 (1975) 1353:
    - “Our basic picture then is that matter at densities higher than nuclear matter consist of a quark soap.”
    - Idea based on weak coupling (asymptotic freedom)
  - Cabbibo, Parisi, PLB, 59 (1975) 67:
    - exponential hadron spectrum not necessarily connected with a limiting temperature
    - Rather: Different phase in which quarks are confined

- It was soon realised that this new state could be created and studied in heavy-ion collisions
Probing the early UNIVERSE