Highlights from ALICE

P. Giubellino
INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS
Erice 2016
Nuclear Physics has changed...

Nuclear Energy Physics experiments are nowadays world-wide high-tech projects of extreme complexity, which develop over decades!

- Eiffel tower: ~ 7300 tons
- ALICE magnet: ~ 8000 tons

Big data

- Pile of CDs with ALICE data (~ 20 Km, 20 million CDs)
- Concorde (15 Km)
- Mt. Blanc (4.8 Km)
Using the World’s most powerful accelerator: the Large Hadron Collider LHC

- 27 km circumference
- ~ 100 m underground
- Design Energy 14,000 GeV (pp)

4 Main Experiments
- CMS
- ATLAS
- LHCb
- ALICE

Studying Heavy Ions
An amazing LHC
Not only an LHC, but a LpC, a Lg-Ion C... an accelerator which opens a world of scientific opportunities!

First pA Collision, september 2012
ALICE: a world-wide effort

1660 Scientists - 42 Countries – 169 Institutes
ALICE Continues to grow!

Number of participating institutes in ALICE

- Total
- Full Members
- Associate Members

No sign of saturation!
15 new institutions in 2015

A scientific and technological program with great prospects!
ALICE in 2001
The preparation required a decade of R&D for the experiments, to meet the LHC Challenges

For ALICE:

In detector Hardware and VLSI Electronics

- **Inner Tracking System (ITS)**
  - Silicon *Pixels* (RD19)
  - Silicon *Drift* (INFN/SDI)
  - Silicon *Strips* (double sided)
  - low mass, high density *interconnects*
  - low mass *support/cooling*
- **TRD**
  - bi-dimensional (time-space) read-out, on-chip
  - trigger (TRAP chip)
- **TPC**
  - *gas mixtures* (RD32)
  - advanced *digital electronics*
  - low mass *field cage*
- **EM calorimeter**
  - new scint. *crystals* (RD18)
- **PID**
  - Multigap RPC’s (LAA)
  - solid photocathode *RICH* (RD26)

In DAQ & Computing:

How to digest 2 (now 4..) Gygabytes/s of data…

- scalable architectures with consumer electronics commercial components (COTS)
- high perf. *storage media*
- GRID computing
Multigap Resistive Plate Chambers

- DOUBLE STACK OF 0.5 mm GLASS
- Resistive layer (cathode)
- Resistive layer (anode)
- cathode pick up pad
- anode pick up pad
- Edge of active area
- 5 gaps

Example: Time Of Flight
Breakthrough after > 5 years of R&D

- π, K, p PID
- for π, K for p < 2 GeV/c
- p for p < 4 GeV/c

- 0.9 < η < 0.9
- full φ

- 150 kchann. over ~150 m²

Prof. A. Zichichi’s group

Typical time spectrum

σ = 53 ps minus 30 ps jitter of timing scintillator = 44 ps

STRIP 10 H.V. +- 6 kV

0 200 400 600 800 1000
Entries/50 ps

-1000 -500 0 500 1000
Time with respect to timing scintillators [ps]
ITS Installation 15.3.07

... in construction ...

Traversing the TPC
ALICE in 2008

Installation of final muon chamber

Insertion of final TOF super module

Formal end of ALICE installation July 2008
A program of major impact

• A very large community of physicists involved
  – over one and a half thousands just in ALICE, hundreds in the other LHC experiments

• A huge scientific output
  – Over 150 ALICE papers on arXiv
  – High impact papers (average of ~80 citations per paper) : the top cited papers at the LHC after the Higgs discovery ones are HI physics papers (source: ISI).
  – Several hundred presentations at international conferences each year
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<td>5522</td>
<td>30071</td>
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</tbody>
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1. **Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC**
   - Group Authors: ATLAS Collaboration
   - PHYSICAL LETTERS B Volume: 716 Issue: 1 Pages: 1-29 Published: SEP 17 2012
   - Citations: 0 138 1042 1007 549 2736 684.00

2. **Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC**
   - By: Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; et al.
   - Group Authors: CMS Collaboration
   - PHYSICAL LETTERS B Volume: 716 Issue: 1 Pages: 30-61 Published: SEP 17 2012
   - Citations: 0 124 992 934 535 2685 646.25

3. **Combined results of searches for the standard model Higgs boson in pp collisions at root s=7 TeV**
   - By: Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; et al.
   - Group Authors: CMS Collaboration
   - PHYSICAL LETTERS B Volume: 710 Issue: 1 Pages: 25-48 Published: MAR 29 2012
   - Citations: 0 221 98 49 25 393 98.25

4. **Combined search for the Standard Model Higgs boson using up to 4.8 fb(-1) of pp collision data at root s=7 TeV with the ATLAS detector at the LHC**
   - By: Aad, G.; Abbott, B.; Abdallah, J.; et al.
   - Group Authors: ATLAS Collaboration
   - PHYSICAL LETTERS B Volume: 710 Issue: 1 Pages: 49-66 Published: MAR 29 2012
   - Citations: 0 223 79 29 21 352 88.00

5. **Elliptic Flow of Charged Particles in Pb-Pb Collisions at root s(NN)=2.76 TeV**
   - By: Aamodt, K.; Abelev, B.; Albaucues Quintana, A.; et al.
   - Group Authors: ALICE Collaboration
   - PHYSICAL REVIEW LETTERS Volume: 105 Issue: 25 Article Number: 252302 Published: DEC 13 2010
   - Citations: 48 82 78 67 27 302 50.33

6. **Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at root s(NN)=2.76 TeV with the ATLAS Detector at the LHC**
   - By: Aad, G.; Abbott, B.; Abdallah, J.; et al.
   - Group Authors: ATLAS Collaboration
   - PHYSICAL REVIEW LETTERS Volume: 105 Issue: 25 Article Number: 252303 Published: DEC 13 2010
   - Citations: 44 80 86 61 30 301 50.17

7. **Suppression of charged particle production at large transverse momentum in central Pb-Pb collisions at root s(NN)=2.76 TeV**
   - Group Authors: ALICE Collaboration
   - PHYSICAL LETTERS B Volume: 696 Issue: 1-2 Pages: 30-39 Published: JAN 24 2011
   - Citations: 66 80 71 46 27 292 58.40

8. **Higher Harmonic Anisotropic Flow Measurements of Charged Particles in Pb-Pb Collisions at root s(NN)=2.76 TeV**
   - By: Aamodt, K.; Abelev, B.; Albaucues Quintana, A.; et al.
   - Group Authors: ALICE Collaboration
   - PHYSICAL REVIEW LETTERS Volume: 107 Issue: 3 Article Number: 032301 Published: JUL 11 2011
   - Citations: 11 78 84 77 37 287 57.40

9. **Transverse-Momentum and Pseudorapidity Distributions of Charged Hadrons in pp Collisions at root s=7 TeV**
   - By: Khachatryan, V.; Sirunyan, A. M.; Tumasyan, A.; et al.
   - Group Authors: CMS Collaboration
   - PHYSICAL REVIEW LETTERS Volume: 105 Issue: 2 Article Number: 022002 Published: JUL 6 2010
   - Citations: 69 54 48 33 30 246 41.00

10. **First Evidence for the Decay B-s(0) -> mu(+)+mu(-)**
    - By: Aaij, R.; Abellán Beteta, C.; Adametz, A.; et al.
    - Group Authors: LHCb Collaboration
    - PHYSICAL REVIEW LETTERS Volume: 110 Issue: 2 Article Number: 021801 Published: JAN 7 2013
    - Citations: 0 0 119 59 10 196 65.33
A worldwide effort to study the world’s most energetic and most complicated collisions

What for?
Origin of hadron masses

• most of the mass of the hadrons is a dynamical effect of quark confinement

• Higgs boson gives mass to quarks, but interactions among confined quarks & gluons ⇒ ~99% of all mass of visible matter!

• Can be studied by bringing the system of strongly interacting matter to very high temperature or baryon density ⇒ “Partial Restoration of Chiral Symmetry”
The Strong force and confinement

- The force between quarks increases with distance (unlike the electrical force)
- More and more energy is stored in the color field as quarks are pulled apart
- At some point it becomes energetically convenient to Convert part of the energy into a quark-antiquark pair
- We get two hadrons instead of one, and we are never able to obtain a free quark
A long way...

- Hagedorn 1965: mass spectrum of hadronic states
  \[ \Rightarrow \text{Critical temperature } T_c = B \]
- QCD 1973: asymptotic freedom
  - D.J. Gross and F. Wilczek, H.D. Politzer
- 1975: asymptotic QCD and deconfined quarks and gluons
  - N. Cabibbo and G. Parisi, J. Collins and M. Perry

Interpretation of the Hagedorn temperature as a phase transition rather than a limiting temperature:

"We suggest … a different phase of the vacuum in which quarks are not confined"

First schematic phase diagram (Cabibbo and Parisi, 1975)

Nobel Prize in Physics 2004

Prize motivation: "for the discovery of asymptotic freedom in the theory of the strong interaction"
The QCD phase diagram

T.D. Lee (1975) “it would be interesting to explore new phenomena by distributing a high amount of energy or high nuclear density over a relatively large volume “ How? Colliding nuclei at very high energy

Complex picture, with many features

Study how collective phenomena and macroscopic properties of strongly interacting matter emerge from fundamental interactions
The exploration of the phase diagram of strongly interacting matter: a world wide enterprise

At CERN, involves over 1500 scientists in three large experiments ALICE, CMS, ATLAS and LHCb (2010-2028…)

At BNL, involves about 1000 scientists in two large experiments (STAR and PHENIX) (2000-2020…)

At CERN, involves about 300 scientists (SHINE) (2005-2018…)

Under construction at JINR, involves about 500 scientists (MPD) (from ~ 2019)

New laboratory under construction in Darmstadt, extension of GSI. The HADES (active) and CBM (from ~ 2020) experiments involve about 1000 scientists.

In Japan, new project now under study
Why HI Collisions?

- What are the fundamental properties of strongly interacting matter as a function of temperature and density?
- What are the microscopic mechanisms responsible for them?
  - What are the microscopic degrees of freedom and excitations of matter at ultra-high temperature and density?
  - Which are its transport properties and equation of state?
- How did its properties influence the evolution of the early universe?
- How is mass modified by the medium it moves in?
- How do hadrons acquire mass?
- What is the structure of nuclei when observed at the smallest scales, i.e. with the highest resolution?

**Heavy--Ion collisions:**
Laboratory studies of the bulk properties of non--Abelian matter

...with deep connections to other fields in physics:
  - String Theory, Cosmology, Condensed Matter Physics, Ultra--Cold Quantum Gases
Many critical features of our universe were established in these very early moments. **WHEN MATTER FIRST STARTED TO HAVE STRUCTURE**
Temperature $\sim 170$ MeV ($\sim 10^{12}$ K): How hot is it? 100,000 times the temperature at the center of the Sun!
Why Heavy Ions @ LHC?

• It is a **different matter** as compared to RHIC (and even more to SpS)
  – Larger temperature, volume, energy density and lifetime
    • Study QGP properties vs T ...
  – small net-baryon density at mid-rapidity \((\mu_B \approx 0)\), corresponding to the **conditions in the early universe**
  – large cross section for **'hard probes'**: high \(p_T\), jets, heavy quarks,...
  – First principle methods (pQCD, Lattice Gauge Theory) more directly applicable
  – new generation, large acceptance state-of-the-art detectors
    • Atlas, CMS, ALICE, [LHCb, for pA]
• A comprehensive program, **complementary** to the one at RHIC (and later FAIR)
Difficult! Space-time Evolution of the Collisions

Freeze-out
(~ 10 fm/c)
(no more elastic collisions)

Hadronization
particle composition is fixed (no more inel. Collisions)

QGP (~ few fm/c)

Hard Scattering + Thermalization
(< 1 fm/c)
The Experiments

- **ALICE**
  - Experiment designed for Heavy Ion collision
    - only dedicated experiment at LHC, must be comprehensive and able to cover all relevant observables
    - **VERY robust tracking** for \( p_T \) from 0.1 GeV/c to 100 GeV/c
      - high-granularity 3D detectors with many space points per track (560 million pixels in the TPC alone, giving 180 space points/track)
      - very low material budget (< 10%\( X_0 \) in \( r < 2.5 \) m)
    - **PID** over a very large \( p_T \) range
      - use of essentially all known technologies: TOF, dE/dx, RICH, TRD, topology, EM calor.
    - Hadrons, leptons and photons + Excellent vertexing

- **ATLAS and CMS**
  - General-purpose detectors, optimized for hard processes
    - Excellent Calorimetry = Jets
    - Excellent dilepton measurements, especially at high \( p_T \)
    - Very large acceptance tracking

- **Now Joined by LHCb**
  - Excellent dilepton measurement and PID in forward direction

Each required 20 years of work by a worldwide collaboration...
ALICE detector specificities

Excellent track and vertex reconstruction capabilities (TPC, ITS) in a high multiplicity environment over a wide transverse momentum range.

**CENTRAL BARREL**
acceptance: $|\eta|<0.9$

**B=0.5 T**

**Inner Tracking System**
Vertexing, Tracking, PID

**Time Projection Chamber**
Tracking, PID
ALICE detector specificities

Particle identification over a wide momentum range

**ElectroMagnetic CALorimeter**
Calorimeter, electron ID

**Time Projection Chamber**
Tracking, PID

**High Momentum PID**
PID

**Transition Radiation Detector**
PID

**Time Of Flight**
PID

**CENTRAL BARREL**
acceptance: $|\eta|<0.9$
B=0.5 T

**Inner Tracking System**
Vertexing, Tracking, PID
ALICE performance: tracking/vertexing

TPC+ITS: charged track reconstruction in |\eta| < 0.9

High precision vertexing and high resolution on track impact parameter with the ITS

Allows to resolve the decay vertices of charm and beauty hadrons

|\eta| < 0.9

Di-muon invariant mass

-4 < \eta < -2.5
ALICE performance: PID

- ALICE uses practically all known techniques

Statistical separation in relativistic rise region
The ALICE program

Core Business: PbPb
- Study the properties of strongly interacting matter under extreme conditions of temperature and density.
  • Understand confinement, producing and studying in the lab a deconfined plasma of quark and gluons (QGP)
  • Understand evolution of matter from the hot and dense deconfined phase towards ordinary hadrons (analogous to the early Universe evolution)

pp
- collect ‘comparison data’ for heavy ion program
  • many observables measured ‘relative’ to pp
- comprehensive study of MB@LHC
  • tuning of Monte Carlo (background to BSM)
- soft & semi-hard QCD
  • very complementary to other LHC experiments
  • address specific issues of QCD
- very high multiplicity pp events
  • dN_{ch}/dh comparable to the one in HI => mini-plasma ?

pA
- Control experiment for PbPb
  • pp and pPb measurement are used as reference for the Pb-Pb ones.
- Important measurements in their own right
  • Probe nucleus structure in a QCD regime of very small-x (gluon saturation, shadowing,...)
  • Study behavior of small-size high-density and high-temperature system
A taste of pp results

Electrons from Heavy Flavors
=> Complementarity with ATLAS

First measurement of $J/\psi$ polarization at LHC

High-multiplicity pp collisions

Multiplicity dependence of open-charm and J/psi yield
- Increase of D-meson yield with multiplicity beyond naïve assumptions
- Factor of 15 increase for the highest multiplicities!
- Multi Parton Interactions?
- Do we understand pp? Core program for 2015 pp data taking
event 246
# mult. 7327
# muon raw digits 10468
# muon tracks 3
pass2
Initial Conditions

Centrality Determination

- Essential in all HI analysis, in ALICE based on correlation between:
  - clusters measured in central rapidity region
  - amplitudes of the signals in the forward region detectors:
    - VZERO scintillators $2.8 < \eta < 5.1$
    - $-3.7 < \eta < -1.7$
  - ZERO Degree Calorimeters

- With the full VZERO detector the resolution ranges from 0.5% in central collisions to 2% for peripheral collisions.
Global properties

Matter under extreme conditions:
~ 50 times the density of neutron star core (40 billion tons/cm³)
50 protons packed into the volume of one p
Highest temperature ever measured
More than enough for deconfinement

Exponential fit for \( p_T < 2.2 \text{ GeV/c} \)
inv. slope \( T = 304 \pm 51 \text{ MeV} \)
for 0–40% Pb–Pb at \( \sqrt{s} 2.76 \text{ TeV} \)
PHENIX: \( T = 221 \pm 19 \pm 19 \text{ MeV} \)
for 0–20% Au–Au at \( \sqrt{s} 200 \text{ GeV} \)
Measuring Volume & Lifetime

- Identical particle interferometry (Bose Einstein Correlations, HBT)
  - Quantum mechanical interference => Bose-Einstein / Fermi-Dirac statistics enhanced (bosons)/suppressed (fermions) occupation of quantum states
    - Bose Einstein Condensate at zero temperature (all particles in same state)
    - used to measure star diameter ($\gamma\gamma$) Hanbury-Brown & Twiss (ca 1953)
    - used in high energy physics ($\pi\pi$) Goldhaber (ca 1959)
- measure extend of dynamical (evolving) source

Source distribution space & time
\[ \downarrow \]
Fourier Transform
\[ \downarrow \]
Particle correlations in momentum & energy

\[ \Delta r, t \quad \gamma (\pi) \]
\[ \Delta p, E \quad \gamma (\pi) \]

Data Ratio
Distribution of momentum difference $D_p = |p_1 - p_2|$

radius ~ 1/width

- $\pi^+\pi^+$ and $\pi^-\pi^-$ combined
- pp at $\sqrt{s}=900$ GeV, 2009 run, ALICE preliminary
- Pb+Au at $\sqrt{s_{NN}}=17.2$ GeV, CERES

pp versus PbPb
Radial Flow

- pressure $P$ in center drives expansion
- flow velocity $\beta = v_0/c$ depends on $f(P, \tau, \text{EoS})$
- momentum $p = \gamma m v_0$ => particles of different mass have characteristic & different momentum

Particle Flow: **hydro properties of the plasma**

**IDENTIFIED PARTICLE SPECTRA @LHC:** significant changes in slope compared to RHIC

Most dramatically for protons

**Very strong radial flow, $\beta \approx 0.66$**

($2/3$ of c!) even larger than predicted by most recent hydro
Particle Production: Hadrochemistry

- Many particle types produced: $\pi(u\bar{d}), p(uud), K(u\bar{s}), \Lambda(uds), \Xi(uss), \Omega(sss), ...$
  - production ratios can not be calculated with QCD (non-pertubative)
    - phenomenological models ('event generators') use many adjustable parameters
- Statistical ('thermal') models:
  - particle with mass $m$ produced in 'heat bath $T$' according to phase space
  - $P(m) \sim e^{-\frac{m}{T}}$; fit depends on $T$ Temperature, $\mu_b$ Baryo-chemical potential (baryon conservation), $\gamma_s$ Strangeness suppression

<table>
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<th>$T_{ch}$: 160-170 MeV</th>
<th>$\gamma_s$: 0.9-1 (AA), 0.5-0.6 (pp)</th>
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<td>strangeness enhancement = QGP signal?</td>
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Anti-$^4\text{He}$ is the heaviest anti-nucleus ever observed.
Nuclei/Antinuclei abundance ratio

- The ratio nuclei / antinuclei is compatible with one, as for all other particle species.

- A large fraction of the systematic uncertainties on the determination of the ratios is due to the limited knowledge of the cross sections of antinuclei interacting with the material of the detector.
Spectra

- **pp**
  Invariant production spectrum well fitted by the Levy-Tsallis function

- **Pb-Pb**
  The Blast-Wave (BW) function fits well the data. Characteristic hardening of the spectrum with increasing centrality.

- These fits are used for the extrapolation of the yield to the unmeasured region at low and high $p_T$.

Same for He
Spectra

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Same for He

The simultaneous fit to the deuteron and 3He spectra allows the extraction of their common kinetic freeze-out velocity:

$$\beta_{\text{kin}} = 0.62 \pm 0.01$$
(Anti-)Hyper-triton

- Very loosely bound, binding Energy < 150 keV
- Identified as

\[ ^3_\Lambda \text{H} \rightarrow ^3 \text{He} + \pi^- \]

- Yield well described by thermal fits

From the fit to the differential yield in different \(c\tau\) bins extract the lifetime

\[ \tau = (5.4 \pm 1.6 \pm 1.0) \text{ cm} \]

\[ \tau (181^{+54}_{-39} \text{ (stat.)} \pm 33 \text{ (syst.)}) \text{ ps} \]

arXiv:1506.08453
Mass Ordering and search for exotic states

- Thermal model predicts:
  \[ \frac{dN}{dy} \propto \exp \left( -\frac{m}{T_{\text{chem}}} \right) \]
- Verified with nuclei!
- Each nucleon added gives a penalty of a factor ~300 in the integrated yield
- In RUN2 measurable for pp up to anti-alpha

- Thermal model provides a baseline for exotica searches upper limits for
  - H-dibaryon $\Lambda\Lambda \rightarrow \Lambda\rho\pi^-$
  - $\Lambda n \rightarrow \bar{d}\pi^+$
    - Limits well below the thermal model expectations

arXiv:1506.07499
Thermal fits

- The thermal model describes well the production of nuclei and hypernuclei, $T \sim 156$ MeV
- Limits on exotic nuclear states far below
Measuring mass difference

Fits to squared mass distributions performed in rigidity \((p/z)\) intervals.

\[
\mu_{TOF}^2 = \left( \frac{m}{z} \right)_{TOF}^2 = \left( \frac{p}{z} \right)^2 \left[ \left( \frac{t_{TOF}}{L} \right)^2 - \frac{1}{c^2} \right]
\]
Highest precision measurement of mass difference in the nuclei sector
Improvement by 1-2 orders of magnitude compared to earlier measurements
Constraint on CPT symmetry violation improved by a factor 2 for deuteron. First measurement for (anti-)${}^{3}$He

\[
\frac{\Delta \mu_{\text{dd}}}{\mu_{d}} = [0.9 \pm 0.5 \text{(stat.)} \pm 1.4 \text{(syst.)}] \times 10^{-4}
\]

\[
\frac{\Delta \mu_{3\text{He}^3\text{He}}}{\mu_{3\text{He}}} = [-1.2 \pm 0.9 \text{(stat.)} \pm 1.0 \text{(syst.)}] \times 10^{-3}
\]

\[
\Delta \epsilon_{3\text{He}^3\text{He}} = 0.24 \pm 0.16 \text{ (stat.)} \pm 0.18 \text{ (syst.)}
\]
Azimuthal Asymmetry

Fourier expansion of azimuthal distribution:

\[
\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi} \frac{dN}{p_T dp_T dy} \left(1 + 2\nu_1 \cos(\phi) + 2\nu_2 \cos(2\phi) + \ldots\right)
\]

\[\nu_1 = \langle \cos \phi \rangle \text{ "directed flow"} \]

\[\nu_2 = \langle \cos 2\phi \rangle \text{ "elliptic flow"} \]

Flow: Correlation between coordinate and momentum space \(\Rightarrow\) azimuthal asymmetry of interaction region transported to the final state \(\rightarrow\) measure 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)
**$v_2$ Measurements at the LHC**

- Collective behavior observed in Pb-Pb collisions at LHC (+30% vs. $v_2^{RHIC}$) => ideal fluid behavior (extremely low ratio of shear viscosity to entropy density $\eta/s \approx 0$), very similar $p_T$ dependence and values to RHIC
- Testing hydrodynamical evolution

PRL 105, 252302 (2010), already over 300 citations!
Flow as a tool

• Understand initial conditions and fluctuations; measure the transport properties (e.g. $\eta/s$) of the medium

• Observables (for different event classes):
  – Higher harmonics
  – Event by Event fluctuations
  – Studies as a function of EbyE flow
  – Event plane correlations

After 6 fm/c

initial  energy density in the transverse plane  viscous
Flow patterns

Fourier series: \( \frac{dN}{d\phi} = 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + 2v_3 \cos(3\phi) + \ldots \)

all characteristics as expected from hydro:
- strength, mass/centrality/momentum dependence

Elliptic, \( v_2 \)

Triangular, \( v_3 \)

Two Particle Correlation projection on \( \phi \)

\( v_3 \) for \( \pi/K/p \) mass dependence typical for hydro!
The deuteron

- simple coalescence model does not describe deuteron $v_2$
- blast-wave prediction from $\pi/K/p$ fit does a decent job
- how do we understand this?
  - how does the fragile $d$ flow like a $\pi$?
Hard Processes to Probe the Medium (Rutherford experiment...)

- initial parton-parton scattering with large momentum transfer
  - calculable in pQCD
- particle jets follow direction of partons

- nucleus-nucleus collisions
  - hard initial scattering
  - scattered partons probe traversed hot and dense medium
  - ‘jet tomography’

Medium modification quantified via nuclear modification factor $R_{AA}$

\[
R_{AA}(p_T) = \frac{\langle N_{coll} \rangle (1/N_{evt}) \frac{d^2 N_{AA}}{d\eta dp_T}}{\langle N_{coll} \rangle (1/N_{evt}) \frac{d^2 N_{pp}}{d\eta dp_T}}
\]
Suppression of High-$p_T$ Hadrons

- Strong Suppression even larger than @ RHIC

- Nuclear modification factor $R_{AA}(p_T)$ for charged particles produced in 0-5% centrality range
  - minimum (~0.14) for $p_T \approx 6$-7 GeV/c
  - then slow increase at high $p_T$

- essential quantitative constraint for parton energy loss models!

$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N\text{bin}\rangle_{AA} \text{Yield}_{pp}(p_T)}$$

$R_{AA} = 1$ for hard QCD processes in absence of nuclear modifications

- Including CDF data

0.9 TeV * NLO (2.76 TeV)/NLO(0.9 TeV)

PLB 696 (2011) 30-39
Sensitive to path length

- Significant effect even at high $p_T$
Mass dependence of parton energy loss

• Expectation from radiative energy loss: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

• Could be reflected in an hierarchy of $R_{AA}$: $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$

• Charmed mesons (ALICE) vs. Pions

  hints for the expected hierarchy in charm/pion $R_{AA}$ ratio

  $\Rightarrow$ First indication of a dependence on heavy quark mass: $R_{AA}^B > R_{AA}^D$
D Meson Elliptic Flow

\( v_2 \) is sensitive to the Eq. of state and shear viscosity of the medium.

D meson strongly interacting with the medium.
Does that mean \textit{it flows too}?

Prompt \( D^0, D^+, D^{*+} \) average. D meson \( v_2 \) suggests collective expansion.
**J/ψ “suppression” at the LHC**

Predicted as a signature of deconfinement, due to the temperature (color charge density density) dependent screening of the color charge in a Quark-Gluon Plasma

Observed at lower energy experiments (SPS, RHIC)

ALICE measures a suppression of the J/ψ yield ($R_{AA}<1$), at both central and forward y, BUT SMALLER than at RHIC

![Color Screening Diagram](image)
J/ψ production in Pb-Pb now with full RUN1 statistics:
studied vs centrality, rapidity and transverse momentum

As expected in a scenario with cc recombination, especially at low \( p_T \)
The role of proton-nucleus collisions

- In high-energy nucleus-nucleus collisions, large energy density \( (\varepsilon >> 1 \text{ GeV/fm}^3) \) over large volume \( (>> 1000 \text{ fm}^3) \)

- In high-energy proton-nucleus collisions, large energy densities \( (?) \) in a small volume

Photon spectrum \( \rightarrow T \sim 300 \text{ MeV} \)
Transverse energy \( \rightarrow \varepsilon \sim 15 \text{ GeV/fm}^3 \)
Volume \( \sim 3 \times \text{ Pb nucleus} \)

Control experiment: calibrate the initial-modification of hard probes (jets, heavy quarks, quarkonia)
\( \rightarrow \) single-out final-state effects (hot medium) in Pb-Pb

Explore new territory in QCD: high gluon density in the initial state; potentially, high energy density in the final state, but in a small volume
Pseudorapidity density in pPb at 5.02 TeV

- Measurement based on tracklets (SPD)
- Non-single-diffractive event selection

Data favors models that incorporate shadowing
Saturation models predicted steeper \( \eta \)-dependence which is not observed in the data.

The control experiment: p-Pb collisions

High-$p_T$ charged particles exhibit binary scaling. Initial state effects are small. The high-$p_T$ suppression observed in PbPb is dominated by hot matter effects.
p-Pb at LHC as a control experiment: Jets

• Also for jets, no evident nuclear modification in p-Pb ($R_{pPb} \sim 1$)

Pb-Pb (central)  

p-Pb (minimum bias)

Large high-$p_T$ suppression in Pb-Pb ($x \sim 3-4$) is a medium effect $\rightarrow$ probes the properties of QCD interactions over extended volumes
p-Pb at LHC as a control experiment: D

- Measurements for main hard probes in minimum-bias p-Pb indicate that the effects seen in Pb-Pb are dominated by the hot medium

**Pb-Pb (central)**

**p-Pb (minimum bias)**

Open Charm: No significant nuclear modification in p-Pb ($R_{pPb} \sim 1$)
- Consistent with modest effect expected from PDF shadowing

\[
R_{pA(AA)}(p_T) = \frac{\frac{1}{N_{coll}} \frac{dN_{pA(AA)}}{dp_T}}{\frac{dN_{pp}}{dp_T}}
\]
Nuclear modification in **p-Pb** described by expected PDF shadowing
Measurements constrain nuclear modification of PDF at small and very small x
Additional suppression in Pb-Pb, more pronounced at forward rapidity, is a medium effect → colour-screening “melts” c-cbar bound states
Reduced suppression in Pb-Pb at central rapidity, wrt forward, and wrt to RHIC measurement → described by scenario of J/ψ regeneration in deconfined medium
Intriguing findings in high-multiplicity p-Pb

From p-Pb pilot run:

- 0-20%
- 60-100%

Possible interpretations:
- Hydrodynamic flow in the final state: a “medium”
- Colour reconnection: a “pure QCD effect”
  - could be interesting to understand QGP formation in Pb-Pb
- Multi-gluon processes from saturated initial-state (Colour Glass Condensate)

Structure emerging when subtracting low mult correlations from high-mult. Origin still unknown …

→ Use ALICE PID capabilities to test these possibilities
Intriguing findings in high-multiplicity p-Pb

Quantify the azimuthal modulation in terms of second order Fourier harmonics:

Pb-Pb

p-Pb, high-multiplicity

• Pb-Pb: mass ordering, interpreted in terms of collective radial and elliptic flow

Many other measurements done (e.g. baryon/meson ratios) or in progress to provide strong experimental constraints for understanding of this unexplored area of QCD

• Clear indication for mass ordering also in p-Pb

• further support for flow picture?
LHC as γPb and γp collider

Ultra-peripheral (UPC) collisions: $b > R_1 + R_2$
→ hadronic interactions strongly suppressed

High photon flux
→ well described in Weizsäcker-Williams approximation (quasi-real photons)
→ flux proportional to $Z^2$
→ high cross section for $\gamma$-induced reactions

Pb-Pb and p-Pb UPC at LHC can be used to study $\gamma$-Pb, γp and $\gamma\gamma$ interactions at higher center-of-mass energies than ever before
**J/ψ photoproduction in UPC**

- LO pQCD: coherent J/ψ photoproduction cross section is proportional to the **square of the gluon density in the target**:
  \[
  \frac{d\sigma_{\gamma A \rightarrow J/\psi A}}{dt}\Bigg|_{t=0} = \frac{M_{J/\psi}^3 \Gamma ee\pi^3 \alpha_s^2(Q^2)}{48 \alpha_{\text{em}} Q^8} \left[ xG_A(x, Q^2) \right]^2
  \]

- Mass of J/ψ serves as a hard scale: 
  \[
  Q^2 \sim \frac{M_{J/\psi}^2}{4} \sim 2.5 \text{ GeV}^2
  \]

- Bjorken \( x \sim 10^{-2} – 10^{-5} \) accessible at LHC:

- J/ψ photoproduction in p-Pb UPC (proton target) allows one to probe poorly known **gluon distribution in the proton at low \( x \)** and search for **saturation effects**

- J/ψ photoproduction in Pb-Pb UPC (lead target) provides information on **gluon shadowing in nuclei at low \( x \)** which is essentially unconstrained by existing data

\[
R_g^A(x, Q^2) = \frac{G_A(x, Q^2)}{AG_p(x, Q^2)}
\]  

– gluon shadowing factor
Coherent J/ψ production

**Dielectrons**
- \( p_T < 300 \text{ MeV/c} \)
- \( N_{J/\psi} = 265 \pm 40 \)
- \( m_{J/\psi} = 3.092 \pm 0.036 \text{ GeV/c}^2 \)
- \( \sigma_{J/\psi} = 25.0 \pm 1.9 \text{ MeV/c}^2 \)

**Dimuons**
- \( p_T < 200 \text{ MeV/c} \)
- \( N_{\mu \mu} = 291 \pm 18 \)
- \( m_{\mu \mu} = 3.096 \pm 0.002 \text{ GeV/c}^2 \)
- \( \sigma_{\mu \mu} = 25 \pm 1 \text{ MeV/c}^2 \)

Good agreement with models which include nuclear gluon shadowing.
Best agreement with EPS09 shadowing (shadowing factor \( \sim 0.6 \) at \( x \sim 10^{-3} \), \( Q^2 = 2.4 \text{ GeV}^2 \))

Incoherent J/$\psi$ at central rapidity

- Coherent: scattered on whole nucleus, Incoherent: on individual nucleon
- Almost one order of magnitude difference in the predicted cross sections
- ALICE sets strong constraints

**dimuons**
- $p_T > 200$ MeV/c

**dielectrons**
- $p_T > 300$ MeV/c

### Data
- **Pb+Pb → Pb+Pb+J/$\psi$**}

- Opposite sign muon pairs
- Like sign muon pairs
- $N_{J/\psi} = 91 \pm 15$
- $m_{J/\psi} = 3.085 \pm 0.007$ GeV/c$^2$
- $\sigma_{J/\psi} = 33 \pm 6$ MeV/c$^2$

### Data
- **Pb+Pb → Pb+Pb+J/$\psi$**}

- Opposite sign electron pairs
- Like sign electron pairs
- $N_{J/\psi} = 61 \pm 14$
- $m_{J/\psi} = 3.080 \pm 0.007$ GeV/c$^2$
- $\sigma_{J/\psi} = 25.0 \pm 1.4$ MeV/c$^2$
**J/ψ photoproduction in pPb**

Data collected in 2013:
- **p-Pb**: p towards muon spectrometer
- **Pb-p**: Pb towards muon spectrometer

Three UPC trigger options in ALICE:
- **Forward**: both muons in the muon arm
- **Central**: both leptons in the barrel
- **Semi-forward**: one muon in the muon arm, second in the barrel

→ wide gamma-proton CM energy coverage up to $W \sim 1$ TeV
→ wide $x$ coverage $10^{-2}$ to $10^{-5}$

First results from forward muons

- Access to gluon distribution in proton target at low $x$
- Advantage of p-Pb:
  - Large photon flux from Pb, The photon source is known, so $W^2 \gamma_p = 2E_pM_{J/ψ} \exp(-y)$
  - Hadronic contribution can be strongly suppressed by ensuring Pb nuclei are intact (no signal in ZDC)
  - Contamination from central exclusive $χ_c$ production negligible

More results to come from barrel/barrel and barrel/muon
## The ALICE program

- **The past:**
  - **RUN2 (2015, 2016, 2018):** will allow to approach the $1\text{ nb}^{-1}$ for Pb-Pb collisions, with improved detectors and double energy (2015 and 2018), and a p-Pb run with 10* statistics (this year)

- **The present:**
  - **2010:** Pb – Pb, $2.76\text{ TeV}$, $\sim 0.01\text{ nb}^{-1}$
  - **2011:** Pb – Pb, $2.76\text{ TeV}$, $\sim 0.1\text{ nb}^{-1}$
  - **2013:** p – Pb, $5.02\text{ TeV}$, $\sim 30\text{ nb}^{-1}$

- **The Future:**
  - **RUN3 + RUN4 (2021, 22, 23 and 27, 28, 29):** $10\text{ nb}^{-1}$ with major detector improvements (plus a dedicated low-field run and pPb)

- So: three phases, each jumping one order of magnitude in statistics and progressively improving the detectors
ALICE RUN2 restart: Cosmosics...

- Data for both alibration and Physics. Statistics >> RUN1
  - RUN1 results on Muon Bundles: arXiv:1507.07577
RUN2 2015: pp at 13 TeV

IL=5 Hz/ub
Charged-particle density at 13 TeV

\[ \langle dN/d\eta \rangle \text{ in } |\eta|<0.5 \]
\[ \langle dN/d\eta \rangle \text{ in } |\eta|<1.0 \]

Energy dependence fitted with power-low function as
\[ b = 0.104(2) \]
\[ b = 0.107(5) \]

Energy dependence in fair agreement with expectations from low energy extrapolations

\( dN/d\eta \) measured for two normalisation classes:
- INEL: inelastic events
- INEL>0: events having at least one charged particle in \( |\eta|<1 \)

arXiv:1509.08734
• Spectrum significantly harder than at 7 TeV
• shapes depend strongly on charged-particle multiplicity
• in fair agreement with event generators.
PbPb! PeV Collisions
Charged particles in Pb-Pb@5.02 TeV

- **charged-particle multiplicity density**
  - at mid-rapidity, $|\eta| < 0.5$ reaches a value of 1943 ± 56 in most central collisions

- **much stronger vs dependence than pp**
  - 2.4x larger charged-particle multiplicity than p-Pb at same energy scaled by the average number of participating nucleon pairs $\langle N_{\text{part}} \rangle / 2$

Anisotropic Flow in Pb-Pb@5.02 TeV


\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]
\]

- \( v_n \): harmonics of the azimuthal distribution of charged particles

- evolution from 2.76 to 5 TeV as expected from hydrodynamics

- full statistics should allow measurement of T dependence of QGP viscosity/entropy ratio
Hyperon enhancements in small systems

- one of the first proposed QGP signatures
  - J. Rafelski and B. Müller, PRL 48 (1982) 1066

- clear increase of hyperon production with multiplicity, from min bias pp to central Pb-Pb

- pp and p-Pb follow same trend vs multiplicity

- “central” p-Pb ~ Pb-Pb

- PYTHIA tunes fail to reproduce data

PLB 728 (2014) 216
ALICE – Run 2 in 2016

Running Strategy for pp at 13 TeV

Events per beam crossing: $\mu \sim 1\%$

Interaction rate up to $\sim 300\text{kHz}$ ($L = 5\text{Hz}/\mu\text{b}$)

Lifetime: $\sim 50\%$ in central barrel, $\sim 80\%$ in muon arm

Foreseen integrated luminosity: $7.5 \text{ pb}^{-1}$ in central barrel, $12 \text{ pb}^{-1}$ in muon arm

Stable Beams

22nd April

“Quiet” Beams

11th April

“TED” Shots

21st March
ALICE – Performance 2016

Data Taking

- ALICE is running with all 17 Detectors available
- Trigger selection include Minimum Bias and Rare Triggers
- ALICE is benefitting from long fills with 2000 bunches
- Overall Data Taking Efficiency is ~90%

pp data collection progressing very well;
expect to achieve goals for main pp data samples
2016 Heavy-Ion run

p-Pb run, ~ half at 8 and half at 5 TeV
ALICE Upgrade for RUN3 and RUN4 (after LS2)

- Focus on rare probes, study their coupling with QGP medium and their (medium-modified) hadronization process
- **low-transverse momentum observables** (complementary to the general-purpose detectors)
  - not triggerable => need to examine full statistics.
- Target:
  - Pb-Pb recorded luminosity $\geq 10 \text{ nb}^{-1}$ $\Rightarrow 8 \times 10^{10}$ events
  - pp (@5.5 Tev) recorded luminosity $\geq 6 \text{ pb}^{-1}$ $\Rightarrow 1.4 \times 10^{11}$ events
- Gain a factor 100 over the statistics of the approved programme

- Operate ALICE *at high rate* while preserving its *uniqueness*, superb tracking and PID, and enhance its vertexing capability and tracking at low-$p_T$
Physics goals of the ALICE upgrade

Precise measurement of heavy-flavour hadron production (spectrum, elliptic flow) in a wide momentum range, down to very low $p_T$

Jet quenching and fragmentation: PID of jet particle content, heavy flavour tagging

Measurement of low-mass and low-$p_T$ di-leptons (from $\rho, \omega, ..$ decay, in-medium $q\bar{q} \rightarrow l^+l^-$, direct photons) $\rightarrow$ electromagnetic radiation from QGP

$J/\psi, \psi'$ states down to zero $p_T$ in wide rapidity range

Heavy nuclear states
**ALICE Upgrade Physics Reach**

$p_T$ coverage ($p_T^{min}$) and statistical error for current ALICE with approved programme and upgraded ALICE with extended programme. Error in both cases at $p_T^{min}$ of “approved”.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Observable</th>
<th>Approved (1/nb delivered, 0.1/nb m.b.)</th>
<th>Upgrade (10/nb delivered, 10/nb m.b.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy flavour</td>
<td>D meson $R_{AA}$</td>
<td>$p_T&gt;1$, 10%</td>
<td>$p_T&gt;0$, 0.3%</td>
</tr>
<tr>
<td></td>
<td>D from B $R_{AA}$</td>
<td>$p_T&gt;3$, 30%</td>
<td>$p_T&gt;2$, 1%</td>
</tr>
<tr>
<td></td>
<td>D meson elliptic flow (for $v_2=0.2$)</td>
<td>$p_T&gt;1$, 50%</td>
<td>$p_T&gt;0$, 2.5%</td>
</tr>
<tr>
<td></td>
<td>D from B elliptic flow (for $v_2=0.1$)</td>
<td>not accessible</td>
<td>$p_T&gt;2$, 20%</td>
</tr>
<tr>
<td></td>
<td>Charm baryon/meson ratio ($\Lambda_c/D$)</td>
<td>not accessible</td>
<td>$p_T&gt;2$, 15%</td>
</tr>
<tr>
<td></td>
<td>$D_s R_{AA}$</td>
<td>$p_T&gt;4$, 15%</td>
<td>$p_T&gt;1$, 1%</td>
</tr>
<tr>
<td>Charmonia</td>
<td>$J/\Psi R_{AA}$ (forward $y$)</td>
<td>$p_T&gt;0$, 1%</td>
<td>$p_T&gt;0$, 0.3%</td>
</tr>
<tr>
<td></td>
<td>$J/\Psi R_{AA}$ (central $y$)</td>
<td>$p_T&gt;0$, 5%</td>
<td>$p_T&gt;0$, 0.5%</td>
</tr>
<tr>
<td></td>
<td>$J/\Psi$ elliptic flow (forward $y$, for $v_2 =0.1$)</td>
<td>$p_T&gt;0$, 15%</td>
<td>$p_T&gt;0$, 5%</td>
</tr>
<tr>
<td></td>
<td>$\psi'$</td>
<td>$p_T&gt;0$, 30%</td>
<td>$p_T&gt;0$, 10%</td>
</tr>
<tr>
<td>Dielectrons</td>
<td>Temperature IMR</td>
<td>not accessible</td>
<td>10% on $T$</td>
</tr>
<tr>
<td></td>
<td>Elliptic flow IMR (for $v_2=0.1$)</td>
<td>not accessible</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Low-mass vector spectral function</td>
<td>not accessible</td>
<td>$p_T&gt;0.3$, 20%</td>
</tr>
<tr>
<td>Heavy nuclei</td>
<td>hyper(anti)nuclei, H-dibaryon</td>
<td>35% ($^4\Lambda H$)</td>
<td>3.5% ($^4\Lambda H$)</td>
</tr>
</tbody>
</table>
Examples of performance studies

\( \Lambda_c \rightarrow pK\pi \)

- \( \Lambda_c \ c\tau = 60 \mu m \), to be compared with \( D^+ \ c\tau = 300 \mu m \)
  → practically impossible in Pb-Pb with current ITS

With new ITS and high-rate, measurement down to 2 GeV/c

- e-PID in TPC and TOF

- Dalitz rejection, conversion and charm suppression
  - New ITS improves major sources of systematic uncertainties
The LS2 ALICE upgrades

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

New Central Trigger Processor

Data Acquisition (DAQ)/High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD, ZDC
- Faster readout

New Trigger Detectors (FIT)
The ALICE Upgrade: status

- Five Pillars (each in a Technical Design Report), all approved by LHCC, UCG and RB, the latest this past September:
  - Completely new Silicon Inner Tracking System
  - New or upgraded readout for all detectors to cope with the higher rate, new CTP and Trigger Detectors
  - New readout chambers for the Time Projection Chamber
  - New Silicon Tracker in front of Muon Absorber
  - New Data Acquisition System and High Level Trigger to handle the continuous readout, new Offline
LHC Schedule

PHASE I Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS 'minor' upgrade

Heavy Ion Luminosity from $10^{27}$ to $7 \times 10^{27}$

PHASE II Upgrade
ATLAS, CMS major upgrade

HL-LHC, pp luminosity from $10^{34}$ (peak) to $5 \times 10^{34}$ (levelled)
SUMMARY

• RUN1 has started well for ALICE, the LS1 work is paying off
• Excellent data sets in pp at both 13 TeV and 5.02 TeV, and PbPb at 5.02 TeV per nucleon.
  – First results from RUN2 already coming
• In the meantime
  – The rich harvest of RUN1 Physics results continues
  – The upgrade for LS2 progresses steadily

The future is bright for ALICE
The adventure continues !!
The ALICE Upgrade

• Five Pillars (each in a Technical Design Report):

  - Completely new Silicon Inner Tracking System
  - New or upgraded readout for all detectors to cope with the higher rate
  - New readout chambers for the Time Projection Chamber
  - New Data Acquisition System and High Level Trigger to handle the continuous readout, new Offline
  - New Silicon Tracker in front of Muon Absorber

  TDR approved by LHCC, UCG and RB
  TDR discussed by LHCC UCG in June
  TDR submitted to LHCC, discussion in June
  TDR in September
  TDR in Late 2014
The integrated detector material for $R < 180$ cm and $|\eta| < 0.9$ amounts to a radiation thickness of $11.4 \pm 0.5\% X_0$ and results in a conversion probability of about 8.5%.

The precision of this measurement (currently 4.5%) directly contributes to the error in all photon analyses.
Detailed studies: Jet peak shape deformation

Long-range $\Delta \eta$ correlations subtracted Near-side “jet” peak

Conical jet shape deformed by longitudinal flow?

$\sigma_{\Delta \phi}$ constant whereas $\sigma_{\Delta \eta}$ increases with centrality.

$\sigma_{\Delta \eta} > \sigma_{\Delta \phi}$ predicted by models including longitudinal flow.

N. Armesto et al., PRL 93, 242301 (2004)
ALICE Upgrade: Objectives
(a subset!! The upgrade opens many more opportunities!)

• Detailed characterization of the Quark-Gluon-Plasma

• Measurement of heavy-flavour transport parameters
  – Diffusion coefficient (QGP eq. of state, $\eta/s$) $\rightarrow$ HF azimuthal anisotropy and $R_{AA}$
  – In-medium thermalization and hadronization $\rightarrow$ HF baryons and mesons
  – Mass dependence of energy loss $\rightarrow$ HF $R_{AA}$

• Measurement of low-mass and low-$p_t$ di-electrons
  – Chiral symmetry restoration $\rightarrow$ $\rho$ spectral function
  – $\gamma$ production from QGP (temp.) $\rightarrow$ low-mass dilepton continuum
  – Space-time evolution of the QGP $\rightarrow$ radial and elliptic flow of emitted radiation

• $J/\psi$, $\psi'$, and $\chi_c$ states down to zero $p_t$
  – statistical hadronization vs. dissociation/recombination scenario
  – transition between low and high transverse momenta
  – density dependence – central vs. forward production

• Light nuclear states
  – mass-4 and -5 (anti-)hypernuclei
  – search for H-dibaryon, $\Lambda n$ bound states, etc.

→ requires high statistics and precision measurements
Puzzles in QCD: ii) hadron masses

- A proton is thought to be made of two u and one d quarks
- The sum of their masses is around 12 MeV
- ... but the proton mass is 938 MeV!
- how is the extra mass generated?
QCD

• **strong interaction:**
  – binds quarks into hadrons
  – binds nucleons into nuclei

• **described by QCD:**
  – interaction between particles carrying colour charge (quarks, gluons)
  – mediated by strong force carriers (gluons)

• **very successful theory**
  – jet production
  – particle production at high $p_T$
  – heavy flavour production
  – ...

• ... but with some **outstanding puzzles**
Two puzzles in QCD: i) confinement

- Nobody ever succeeded in detecting an isolated quark
- Quarks seem to be permanently confined within protons, neutrons, pions and other hadrons.
- It looks like one half of the fundamental fermions are not directly observable... how does this come about?
Exploring the QCD Phase Diagram

- Being populated with experimental points...
Lattice QCD

- A rigorous way of doing calculations in non-perturbative regime of QCD discretization on a space-time lattice.

For the (2 + 1) flavor case (but zero baryon density): the phase transition to the QGP and its parameters are quantitative predictions of QCD.

\[ T_c = 173 \pm 12 \text{ MeV} \]

\[ \varepsilon_c = 700 \pm 200 \text{ MeV/fm}^3 \]

Energy density increases sharply around \( T_c \) by the latent heat of deconfinement.

Moreover, Lattice QCD predicts a rapid transition, with correlated deconfinement and chiral restoration.
Melting Matter

If the force grows with distance, at small distances it is small (asymptotic freedom)

**Idea:** obtain deconfinement using collisions of Nuclei => compression and heating

Afterwards the system expands and cools, and ordinary hadrons reconstitute after a short time (about $10^{-23}$s, or a few fm/c) … just as they did in the evolution of primordial Universe, some 11 millionth of a second after the Big Bang!
pp single- and double- diffractive and inelastic cross-sections

vdM scan (final here) + MC generators tuned to measured ratio of 1-arm to 2-arm trigger.

\[ \sigma_{\text{Inel}} \text{ at } \sqrt{s} = 7 \text{ TeV} \]

ALICE : 73.2\( \pm 2.6 \)\text{lumi} + 2.0\text{exp.} \pm 4\text{extrap.}
ATLAS : 69.4\( \pm 2.4 \)\text{syst.} \pm 6.9\text{extrap.}
CMS : 68.0\( \pm 2.0 \)\text{syst.} \pm 2.4\text{lumi} \pm 4\text{extrap.}
TOTEM: 73.5\( \pm 0.6 \)\text{stat.} +1.8\text{syst.} \pm 1.3\text{lumi}

Left-side 1-arm trigger : no signal with \( \eta > +1 \)
Right-side 1-arm trigger: no signal with \( \eta < -1 \)

Gotsman et al., arXiv:1010.5323, EPJ. C74, 1553 (2011)
Ryskin et al., EPJ. C60 249 (2009), C71 1617 (2011)

Model predictions: SD \( \Rightarrow \) \( M^2 < 0.05 \text{s} \) \ DD \( \Rightarrow \) \( \Delta \eta > 3 \)
17165 ± 722 charged particles produced in 5% most central coll

ε ≥ 16 GeV/fm³

x 100 above nuclear density

x 30 above nucleon density

x 20 above lattice-QCD prediction for quark-gluon plasma formation

**Longitudinal Scaling?**
- Is particle production in the fragmentation region invariant with beam energy? (Benecke et al., Phys Rev, v188, n5, 1969)
- Extrapolation of \( dN_{ch}/d\eta \) vs \( \eta - y_{beam} \) coincides with lower energy data
- Measurements consistent with longitudinal scaling

Matter under extreme conditions: ~ 50 times the density of neutron star core (40 billion tons/cm³)
Understanding $R_{AA}$

- Nuclear modification factor RAA studied for several identified particles
- $\Lambda R_{AA}$: interplay of suppression and baryon enhancement
Jet quenching

- partons lose energy $\Delta E$ when traversing a medium
  - $\text{Jet}(E) \rightarrow \text{Jet } (E' = E-\Delta E) + \text{soft particles}(\Delta E)$
  - QCD energy loss $\Delta E$ expected to depend on:
    - $q$: 'opacity' = property of medium ('radiation length of QGP')
    - $L$: size of medium ($\sim L$ (elastic) $\sim L^2$ (radiative), $L^3$ (AdS/CFT))
    - $c_q$: parton type (gluon > quark)
    - $f(m)$: quark mass (light $q$ > heavy $Q$)
    - $f(E)$: jet energy ($\Delta E = \text{constant or } \sim \ln(E)$)

jet quenching measures
‘stopping power' of QGP
$\Delta E \sim f(m) \times c_q \times q \times L^n \times f(E)$

- At LHC all aspects of quenching can be addressed, thanks to the large cross section and the quality of the detectors
The nuclear modification factor in p-Pb: latest news

The new ALICE preliminary results are consistent with no modifications up to $p_T = 50$ GeV/c.
HI@LHC after LS2 (~2019)

– ALICE Upgrade
  • Major upgrade of the experiment:
    – Capability to handle continuous readout of all collisions at 50 kHz of PbPb collisions => 100 times increase in statistics for low-$p_T$ observables => needs new readout for all dets, new DAQ, new HLT
    – Improved secondary vertex capability and tracking at low-$p_T$ => all new Inner Tracker
  • Endorsed by LHCC sept 6\textsuperscript{th} 2012
  • Approved by Research Board Nov 28\textsuperscript{th} 2012

– Erice final document on the European Strategy for Particle Physics
  • Heavy Ions are an integral part of the top priority of the plan:
    “Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.”
Individual events....
The $\phi$ again...

- Mass ordering $\rightarrow$ attributed to common radial expansion velocity
- $\phi$ meson behaves like a baryon
- Mass drives the $v2$ and spectra and not number of quark constituents

arXiv:1405.4632
Flow of identified particles

- Identified particle elliptic flow
  - Mass ordering at low $p_T$ described by hydrodynamics
  - Particle species dependence persists up to $p_T \approx 8$ GeV/c
Using particle identification to understand the structure

Collectivity in small systems?
\( \gamma\gamma \rightarrow e^+e^- \) in central barrel

Huge cross section: \( O(100) \) kb

**STARLIGHT**, PRC60 (1999) 014903:

(LO prediction, \( |\eta| < 0.9 \)):

- \( 2.2 \text{ GeV/c}^2 < M_{\text{inv}} < 2.6 \text{ GeV/c}^2 \): \( \sigma_{\gamma\gamma} = 128 \mu\text{b} \)
- \( 3.7 \text{ GeV/c}^2 < M_{\text{inv}} < 10 \text{ GeV/c}^2 \): \( \sigma_{\gamma\gamma} = 77 \mu\text{b} \)

**ALICE**:

- Data slightly above LO prediction
- 12% and 16% precision in two mass ranges
- ALICE data sets stringent limits on the contribution from high order terms
Lead ion injector chain

- **ECR ion source (2005)**
  - Provide highest possible intensity of Pb$^{29+}$
- **RFQ + Linac 3**
  - Adapt to LEIR injection energy
  - Strip to Pb$^{54+}$
- **LEIR (2005)**
  - Accumulate and cool Linac 3 beam
  - Prepare bunch structure for PS
- **PS (2006)**
  - Define LHC bunch structure
  - Strip to Pb$^{82+}$
- **SPS (2007)**
  - Define filling scheme
The LHC as a Heavy-Ion Collider

- 8 November 2010: the beginning of a new era for Heavy Ion Physics: a jump of more than an order of magnitude in energy since the previous record (RHIC @BNL)
- Three day to switch from protons to Pb ions

- 2011: > 10 times larger integrated luminosity + tests for pA
- 2012: first pA collisions
- 2013: pA run
Baryon/meson ratio a.k.a. baryon anomaly

- Large baryon/meson enhancement at intermediate $p_T$
- $x2$ higher in central wrt periph
- Similar peak at RHIC and LHC but shifted by $\sim1$ GeV
- Described by flow
- Vanishes at $\sim8$ GeV
  - Flow dies out
  - In-vacuum fragmentation

$\rightarrow$ low-$p_T$ $p/\pi$ and $\phi/\pi$ ratios have same shapes
$\rightarrow$ baryon anomaly due to particle mass at low $p_T$
The extremely low viscosity translates early state features into final state ones => a powerful tool!

- From the detailed study of the particles produced in the collisions, infer properties and behavior of the matter produced, and how it evolved during first $\sim 10^{-23}$ sec. of existence, including the impact of quantum fluctuations.

- Analogy to Cosmic Microwave Background Explorations: pattern recognition on present-day background allows inference of structures in universe a few hundred thousand years after Big Bang, which can be attributed to quantum fluctuations in inaccessible inflationary period just after Big Bang.

from S. Vigdor, BNL, @QM2012