Results from ALICE

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Phase diagram of nuclear matter

Quark Gluon Plasma – a liquid of quarks and gluons created at temperatures above \( \sim 170 \text{ MeV} \times (2 \cdot 10^{12}\text{K}) \) – over a million times hotter than the core of the sun.

The phase transition in the laboratory

![Diagram showing the phase transition in the laboratory with labels for QGP (quark-gluon plasma), Hadron Gas, Phase Transition/Cross-Over, Chemical Freeze-Out, Thermal Freeze-Out, and time marker τ₀.](image-url)
Size: 16 x 26 meters
Weight: 10,000 tons
Δη=1.4, Δφ=107°

Installed in Fall 2014
Δη=1.4, Δφ=60°

- Lead-scintillator sampling calorimeter
- 13 k towers
- Each tower Δη x Δφ = 0.014 x 0.014
- σ(E)/E = 0.12/√E + 0.02
EMCal & DCal

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Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV

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p+p collisions

3D image of each collision
Pb+Pb collisions
ALICE Performance


- Low-$p_T$ tracking: down to 150 MeV/c
- PID: anti-$^3$He observed directly
- Vertexing capabilities: heavy flavors, $V^0$, cascades, conversions
Data collection

- Pb–Pb at 5.02 TeV: up to 0.5 nb\(^{-1}\)
- pp at 13 TeV and 4 days at 5.02 TeV (~100 nb\(^{-1}\))
- Upcoming p–Pb at 5.02 and 8 TeV: 10 times more statistics than in RUN-I
Charged particle multiplicity

- **ALICE**: Pb–Pb at 5.02 TeV — highest energy so far
  - For 0–5% most central collisions, confirms trend from lower energies
- \( \langle dN_{ch}/d\eta \rangle \) vs. \( \langle N_{part} \rangle \): similar evolution with centrality between 5.02 and 2.76 TeV
  - Provides further constraints for models
  - \( \approx 20\% \) increase going from 2.76 to 5.02 TeV
Energy dependence from $dE_T/dy$

$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$

- Higher than extrapolations of RHIC data

RHIC

QGP formation

Standard estimate $\tau_0 \approx 1$ fm/c

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Direct photons in Pb-Pb collisions

- Low-$p_T$: 2.6σ excess w. r. t. models in 0–20% central — thermal contribution
- $T_{\text{eff}} = 304 \pm 11\,(\text{stat.}) \pm 40\,(\text{syst.})$ MeV in central Pb–Pb collisions at 2.76 TeV
- 30% higher than at RHIC (Au–Au at $\sqrt{s_{\text{NN}}}=200$ GeV)

Relativistic fluids

- Initial overlap asymmetric → pressure gradients
- Momentum anisotropy → Fourier decomposition:

\[
\frac{d^2 N}{d p_T d \phi} \approx 1 + 2 v_1 \cos(d \phi) + 2 v_2 \cos(2 d \phi) + 2 v_3 \cos(3 d \phi) + 2 v_4 \cos(4 d \phi) + 2 v_5 \cos(5 d \phi) + \ldots
\]
Ratio of $v_n$ at different energies

\[ R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma^{pp}/dp_Td\eta} \]

- \( R_{AA} > 1 \): enhancement
- \( R_{AA} < 1 \): suppression
- Strong modification of the spectrum shape in most central collisions
- Strong centrality dependence
- \( R_{AA} \) at 5.02 TeV similar to 2.76 TeV
Heavy-Flavor $R_{AA}$

- Heavy flavor electron $R_{p\text{Pb}}$ consistent with unity for $p_T > 2$ GeV/c
- Large suppression at high $p_T$ heavy quark in-medium energy loss
- $R_{AA}(D)$ and $R_{AA}(\pi)$ compatible with uncertainty at high $p_T$
Jet $R_{AA}$

- Out-of-cone radiation: energy loss in jet cone
  - Jet yield suppression, di-jet energy imbalance, jet-jet/hadron-jet acoplanarity…

- In-cone radiation: medium modified fragmentation
  - Jet shape broadening, modification of transverse energy profile…

- Consistent with $R_{AA}$ of charged particles and charged-jet $R_{AA}$ at 2.76 TeV

$$R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{pp}/dp_Td\eta}$$
Hadronic Phase

- Reconstructible resonance yields may be changed by hadronic scattering processes after chemical freeze-out:
  - **Regeneration:** pseudo-elastic scattering of decay products
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a different resonance (e.g. r)
    - Resonance not reconstructed through invariant mass
Other Resonances

$K^*(892)^0$

- $d\bar{s}\rightarrow \pi^-$
- $m = 896 \text{ MeV}/c^2$
- $\Gamma = 47.4 \text{ MeV}/c^2$
- B.R. = 66.6%

$\phi$

- $s\bar{s}\rightarrow K^-$
- $m = 1019 \text{ MeV}/c^2$
- $\Gamma = 4.266 \text{ MeV}/c^2$
- B.R. = 48.9%

$\Xi^*(0)$

- $uus\rightarrow \pi^+$
- $m = 1532 \text{ MeV}/c^2$
- $\Gamma = 9.1 \text{ MeV}/c^2$
- B.R. = 66.7%

$\Sigma^*-$

- $d\bar{d}s\rightarrow \pi^-$
- $m = 1383 \text{ MeV}/c^2$
- $\Gamma = 36.0 \text{ MeV}/c^2$
- B.R. = 87%

$\Sigma^{*+}$

- $u\bar{u}s\rightarrow \pi^+$
- $m = 1387 \text{ MeV}/c^2$
- $\Gamma = 39.4 \text{ MeV}/c^2$
- B.R. = 87%
Ratios to Stable Hadrons

- Suppression of $\rho^0/p$ and $K^{*0}/K$ in central Pb–Pb w.r.t. peripheral, pp, p–Pb, thermal model
  - Suggests that re-scattering is dominant over regeneration
  - Well described by EPOS+UrQMD
- $K^{*0}/K$ in small systems:
  - Decreasing trend observed in p–Pb (slope not consistent with 0)
  - Multiplicity-dependent suppression in pp
- No suppression of $\phi/K$, no strong centrality dependence
  - Central Pb–Pb consistent w/ thermal model
  - Lifetime of $\phi \sim 10 \times$ longer than $K^{*0}$, $\sim 35 \times$ longer than $\rho^0$, re-scattering effects not significant
  - Ratio in p–Pb consistent with trend from pp to peripheral Pb–Pb

\[ \text{NEW} \]
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Jet mass and virtuality

\[ M = \sqrt{p^2 - p_T^2 - p_z^2} \]
\[ p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i \]
\[ p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i \]

- Jet mass increases with the radial distance of the constituents from the jet axis
  - Soft constituents, away from the jet axis within the cone → larger mass
  - Few hard constituents → smaller mass
- E.g. gluon vs quark jets jet mass difference
Comparison to models

- Quenching models (JEWEL, Q-PYTHIA) show a larger mass than pp-like PYTHIA jets
  - JEWEL: 2→2 pQCD matrix elements with parton shower taking into account radiation. For charged jets the background subtraction is implemented by shifting the distribution considering the background estimated for full jets and the difference between full and charged jets in pp
  - Q-PYTHIA: PYTHIA with medium effects in the final state branching through an additive term in the splitting functions computed in the multiple-soft scattering approximation
- JEWEL with “recoil off” (removing recoil centres before hadronization) shows a depletion of the jet mass wrt pp due to less low-\(p_T\) fragments wrt recoil on
- Pb-Pb measurement can discriminate among these predictions
Conclusions

• Precision tracking and PID enable precision measurements of
  – Global observables ($N_{ch}$, $E_T$)
  – Direct photons
  – Hydrodynamical flow
  – Jets
  – Resonances

• More to come!
  – Results from DCal
  – Upgrades for run 3