Overview of recent ALICE results

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(for the ALICE collaboration)

This work has been supported by the Hungarian NKFIH/OTKA K 120660 grant and the János Bolyai scholarship of the Hungarian Academy of Sciences
It all started with a big bang...
“Little bangs” in the laboratory

Relativistic Heavy-Ion Collisions

Initial energy density → Hadronization → QGP phase

Kinetic freeze-out → final detected particles distributions

Collision overlap zone

Pre-equilibrium dynamics → Viscous hydrodynamics → Free streaming

\( \tau \sim 0 \text{ fm/c} \) → \( \tau \sim 1 \text{ fm/c} \) → \( \tau \sim 10 \text{ fm/c} \) → \( \tau \sim 10^{15} \text{ fm/c} \)

Courtesy of Paul Sorensen and Chun Shen
"Soft" processes

- Bulk physics: many, low-momentum particles
- From the later stages
- Thermal behavior
- Collective dynamics ("flow")
Probing the nuclear matter

- "Soft" processes
  - Bulk physics: many, low-momentum particles
  - From the later stages
  - Thermal behavior
  - Collective dynamics ("flow")

- "Hard" processes
  - Few, high-momentum particles
  - Early production in analytically calculable pQCD processes
  - Heavy flavor probes
  - Tomography of the QGP, modification in the medium
ALICE (Run-2)

A dedicated heavy-ion experiment at the LHC, excellent PID
ALICE (Run-2)

**EMCal:** energy, electron ID

**TRD:** hadron rejection by transition radiation

**TOF:** identification by precise time of flight

**central barrel:** $|\eta|<0.9$

**V0A** (-2.8<\(\eta\)<5.1) & **V0C** (-3.7 \(<\eta<-1.7\)):
centrality

**ITS:** charged-particle tracking, secondary vertex

**TPC:** charged-particle tracking, identification

**Muon spectrometer:**
forward: -4<\(\eta<-2.5\)
muon trigger and tracking

A dedicated heavy-ion experiment at the LHC, excellent PID
Reconstructed heavy-ion collision

- Up to 600 million events per second
- Signals of up to thousands of particles to be identified, processed
- 2-4 GB data every second
### ALICE data collected: Run-1 & Run-2

<table>
<thead>
<tr>
<th>System</th>
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<th>$\sqrt{s_{NN}}$ (TeV)</th>
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<tr>
<td><strong>pp</strong></td>
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<td>0.9</td>
<td>$\sim$200 $\mu$b$^{-1}$</td>
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<td></td>
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<td>7</td>
<td>$\sim$1.5 pb$^{-1}$</td>
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<td><strong>p-Pb</strong></td>
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<td>$\sim$15 nb$^{-1}$</td>
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<td><strong>Pb-Pb</strong></td>
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- Several different collision energies
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=> Towards a comprehensive understanding of the strongly interacting nuclear matter
Spectra of identified particles ($\pi$, K, p)

- High-precision measurements of identified particles
Spectra of identified particles ($\pi$, K, p)

- High-precision measurements of identified particles
- Mass-dependent hardening of spectra with increasing multiplicity

$$T_{\text{eff}} \sim T_{\text{kin}} + \frac{1}{2} m<u_T>^2 \quad \text{(at low } p_T)$$

$$\implies \text{Collective radial expansion}$$
Kinetic freezeout via blast-wave fits

- **Blast-Wave model**
  - particle production from expanding hypersurface
  - $\beta_T$: radial expansion velocity
  - $T_{\text{kin}}$: kinetic freeze-out temperature

Schnedermann et al., PRC (1993) 48, 2462

- Simultaneous fits to $\pi$, $K$, $p$ spectra in bins of multiplicity/centrality
- Similar trend observed in pp, p-Pb, Pb-Pb collisions
- Larger $\beta_T$ in small systems at similar multiplicity
Particle production across systems

- Strangeness enhancement once considered as a sign of QGP
  Rafelski, Müller, PRL 48, 1066 (1986)

- Enhancement increases with strangeness content

- No significant energy and system dependence at given multiplicity

- Smooth evolution with system size
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Production of light and strange particles are driven by the characteristics of the final state
Collectivity

- Azimuthal momentum anisotropy
  - parametrized by Fourier coefficients
  \[ E \frac{d^3 N}{d^3 p} = \frac{1}{\pi} \frac{d^2 N}{dp_T^2 dy} \left[ 1 + 2v_1 \cos (\varphi - \Psi_R) + 2v_2 (2[\varphi - \Psi_R]) + \ldots \right] \]
  - \( v_1 \): Radial expansion
  - \( v_2 \): Azimuthal anisotropy ("elliptic flow")
  \[ v_2 = \langle \cos (2[\varphi - \Psi_R]) \rangle \]
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- Flow caused many surprises...
  1. RHIC: Substantial \( v_2 \), perfect hydro, NCQ scaling
     \( \rightarrow \) strongly coupled QGP
  2. Higher harmonics are important (\( v_2 \sim v_3 \))
     \( \rightarrow \) initial state fluctuations
  3. LHC: Small systems "flow"
     \( \rightarrow \) hydro description \(!=\) QGP
Elliptic flow: light and strange particles

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- initial conditions
- QGP phase
- hadronic phase
Elliptic flow: light and strange particles

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- High $p_T$: parton energy loss dominant
Flow harmonics across systems

- Long-range multiparticle correlations in all systems
- Two-particle, multi-particle and subevent methods are qualitatively the same
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- Model description of pp and p-Pb data is not satisfactory (PYTHIA8, IP-Glasma+MUSIC+UrQMD)
Direct photons are all photons except from hadron decays: Hard scattering, jet radiation, sQGP, hadron gas
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Excess in direct photon production over models and pp at low $p_T$

Thermal radiation
Thermal photons: QGP temperature

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- Excess in direct photon production over models and pp at low $p_T$
  - Thermal radiation

- Effective ('average') temperature: $T_{\text{eff}} \approx 297 \pm 12(\text{stat}) \pm 41(\text{syst})$ MeV
  - much higher than $T_C \sim 170$ MeV
  - $\Rightarrow$ deconfined matter!

- $T_{\text{ini}} \sim 300 - 600$ MeV (via models)
Direct photons in p-Pb collisions

- **Excess in direct photon production over models and pp at low $p_T$**
  - Thermal radiation

- **No such excess seen in pPb collisions above model calculations**
Flow of direct photons

- Direct photon flow is as large as decay photon flow (ie. final state)
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No role of earlier states at all?

These results question the current understanding of thermal photons!
Penetrating probes of the medium

- **pp**: pQCD benchmark and reference for larger systems
- **p-A**: cold nuclear matter effects
- **A-A**: hot nuclear matter effects
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- **Nuclear modification**

\[
R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}
\]

- Clearly an effect of the QGP in AA collisions
Light and strange hadron energy loss

- **Universal, strong suppression at high-\(p_T\)**
  - Regardless of hadron types (light or strange)
- **Sensitivity to radial flow, hadronization at low-\(p_T\)**

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![Graph 1](image1.png)

**PRC 98 (2018), 044901**

![Graph 2](image2.png)

**PRC 95 (2017), 064606**
Jet-medium interactions

- **Low $p_T$:** Azimuthal h-h correlations, per-trigger normalized
  - **Broadening** of central angular correlation peaks in the $\Delta \eta$ direction
  - Understanding: rescattering with radial flow (AMPT)
Jet-medium interactions

- **Low** $p_T$: Azimuthal h-h correlations, per-trigger normalized
  - Broadening of central angular correlation peaks in the $\Delta \eta$ direction
  - Understanding: rescattering with radial flow (AMPT)
- **Higher** $p_T$: Azimuthal h-h correlations, $I_{AA} = Y_{AA}/Y_{pp}$
  - Narrowing of the peak in central events in the $\Delta \eta$ direction
  - Jet structure modifications? No proper understanding by models.
Jet Substructure

- First intra-jet splitting $z_g$

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$
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Jet Substructure

- First intra-jet splitting $z_g$
  - At small angles ($\Delta R < 0.1$): consistent $z_g$ distributions in Pb-Pb and vacuum
  - At large angles ($\Delta R > 0.2$): $z_g$ distributions are steeper in medium than in vacuum

- Early jet development influenced by medium
Probes with heavy flavor

- Heavy quarks are...
  - (Mostly) produced in early hard processes
    \[ \tau_{c,b} \sim \frac{1}{2} m_{c,b} \sim 0.1 \text{ fm} \ll \tau_{\text{QGP}} \sim 5-10 \text{ fm} \]
  - Their numbers are (almost) conserved:
    No flavour changing, negligible thermal production
    → Very little production or destruction in the sQGP
    \[ m >> \Lambda \ (m_c \sim 1.5 \text{ GeV}, \ m_b \sim 5 \text{ GeV}) \]
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- Open heavy flavor: Transport through the whole system
  - Access to transport properties of the system
  - Flavor-dependent hadronization
    fragmentation: color charge effects, dead cone; coalescence
  - Penetrating probes down to low momenta

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- Quarkonia: dissociation and regeneration in the QGP
  - Debye screening of the color charge
  - Sequential melting of different states
  \( \rightarrow \) QGP thermometer
  - However: strong regeneration of charmonia at LHC!
Heavy flavor jets in p-Pb

- Heavy-flavor jets measured down to $p_T = 10$ GeV/c
- No mid-rapidity nuclear modification of HFE jets visible
  - Regardless of chosen jet resolution parameter
- Cross section of beauty jets tagged with displaced vertices also described by POWHEG HVQ x A (pp) within uncertainty
**Pb-Pb - Heavy-flavor energy loss**

- **Strong suppression at high-$$p_T$$**
  - Charm is suppressed similarly to light and strange quarks
  - No mass ordering (dead cone, color charge & fragmentation effects)
- **Less suppression for D mesons at low-$$p_T$$**

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Mathematical expression:

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- **HFE: beauty appears less suppressed than charm**
  - Mass ordering
Open charm and collectivity

- Precise data constrains models at low $p_T$
  - Simultaneous description of $R_{AA}$ and $v_2$ for both $D$ and $D_s$
  - Charm - light quark coalescence on top of shadowing and collisional/radiative energy loss
Open charm flow vs. event shapes

- Unbiased D-meson flow similar in magnitude to LF flow
- Small (large) \( q_2 \) corresponds to smaller (larger) D-meson flow
- Reasonable description by transport models

\[
q_2 = \frac{\mathcal{Q}_2}{\sqrt{M}},
\]

\[
\mathcal{Q}_2 = \left( \frac{\sum_{i=1}^{M} \cos(2\phi_i)}{\sum_{i=1}^{M} \sin(2\phi_i)} \right)
\]
Quarkonia

- Quarkonium suppression due to dissociation of bound states in a colored medium (Debye-screening of qqbar potential)
- J/ψ: less suppression at LHC than at RHIC. “The J/ψ puzzle”
  - Understanding: later recombination of the c-cbar pairs
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- **J/ψ**: less suppression at **LHC** than at **RHIC**. "The J/ψ puzzle"
  - Understanding: later recombination of the c-cbar pairs
- **ϒ**: strong suppression - regeneration effect is small
  - Models: \( T_{ini} \sim 520-750 \text{ MeV} \) in \( \sqrt{s_{NN}}=5.02 \text{ TeV} \) Pb-Pb collisions (consistent with thermal photon measurements)
Anisotropy of charmonium: $J/\psi$

- **Substantial $J/\psi$ $v_2$ and $v_3$**
  - RHIC: at low-$p_T$, flow is consistent with 0
  - LHC: Sizeable, less than LF or D
  - Consistent with strong charmonium recombination
  - Quantitative description challenging
Anisotropy of bottomonium: $Y(1S)$

- First measurement
- $v_2$ consistent with 0: **Only hadron at LHC**
  - Early production, decouples from medium
  - Later recombination is not strong (#b<<#c)
Charmed baryons in \( pp: \Lambda_c^+/D^0, \Xi_c^0/D^0 \)

- \( \Xi_c^0/D^0 \) as well as \( \Lambda_c^+/D^0 \) is underestimated by models based on \( ee \) collisions: Does charm hadronization depend on collision system?
  - PYTHIA8 with string formation beyond leading colour approximation?
    Christiansen, Skands, JHEP 1508 (2015) 003
  - Feed-down from augmented set of charm-baryon states?
    He, Rapp, 1902.08889

\[ \Xi_c^0/D^0 \]
\( \Lambda_c^0 / D \) in p-Pb and Pb-Pb

- A hint of higher \( \Lambda_c^+ / D^0 \) ratio in central Pb-Pb collisions than in pp
- Trend from pp through p-Pb to Pb-Pb is not clear by current precision
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- Trend from pp through p-Pb to Pb-Pb is not clear by current precision
- Catania model including both coalescence and fragmentation describes the $\Lambda_c^+/D^0$ ratio in Pb-Pb collisions
ALICE Upgrade for Run-3 and Run-4

- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb⁻¹ (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continuous readout
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**ITS upgrade**

**Projected performance**

**Expected precision**

Summary and outlook

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- Run-3 after LS2 (2021): improved luminosity, detectors
  - Precision measurements: charmed barions, beauty etc.
  - Jet structures, event shapes: understand soft-hard boundary
Thank you!

...and stay tuned for new great results

This work has been supported by the Hungarian NKFIH/OTKA K 120660 grant and the János Bolyai scholarship of the Hungarian Academy of Sciences
Multiplicities in pp, p-Pb, Xe-Xe, Pb-Pb

- Charged-particle multiplicity density and total multiplicity vs. centrality
  - Deviation from $N_{part}$ scaling: Steeper rise in most central Xe-Xe and Pb-Pb collisions due to upward fluctuations
- Collision geometry plays an important role in particle production!
- Production of light nuclei is exponentially suppressed by $A$
- Production is consistent with thermal model
- $d/p$ ratio depends on multiplicity
  - pp, p-Pb, Pb-Pb
  - 2.76 through 13 TeV
Measurement down to $p_T = 40 \text{ GeV}/c \Rightarrow$ redistribution of energy

Only weak dependence seen in data on jet resolution $R$

Challenge to some models: stronger $R$ dependence predicted than in data
- $R_{pPb}$ of inclusive J/$\psi$ at $\sqrt{s_{NN}} = 8.16$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV are consistent within uncertainties
- Rapidity dependence for $p_T > 0$ are described by models including CNM effects