Recent ALICE Results

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The year 2017

25 Articles submitted for publication, 4 from Run 2, 21 from Run1 and many many interesting preliminaries shown at QM, SQM, IS, EPS etc

1. Search for collectivity with azimuthal J/ ψ -hadron correlations in high multiplicity p-Pb collisions at sNN = 5.02 and 8.16 TeV (PLB https://arxiv.org/abs/1709.06807)

2. J/ψ elliptic flow in Pb-Pb collisions at sNN = 5.02 TeV (PRL https://arxiv.org/abs/1709.05260)

3. D-meson azimuthal anisotropy in mid-central Pb-Pb collisions at sNN=5.02 TeV (PRL https://arxiv.org/abs/1707.01005)

4. Energy dependence of forward-rapidity J/ψ and ψ(2S) production in pp collisions at the LHC https://arxiv.org/abs/1702.00557 Eur. Phys. J. C 77 (2017) 392

5.Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions. https://arxiv.org/abs/1606.07424 Nature Physics 13, 535–539 (2017)

Many results from Run1 and Run 2, I will give some highlights. I have selected only a few of the Run 1 and Run 2 results and preliminaries.

Outline

1. Hadronization, particle spectra and abundances

2. Collective Expansion

3. Hard Processes

1. Hadronization, particle spectra and abundances

Historically an enhanced production of strangeness was proposed as a signature of QGP in A-A collisions (PRL 48 (1982) 1066–1069)



ALI-DER-80680

Enhancement of strange particles with respect to non-strange yield is also observed for high multiplicity pp and p-Pb collisions



- Smooth evolution of particle ratios with multiplicity
- Challenges universality and factorization of fragmentation (Fischer, Sjostrand, JHEP01(2017)140)
- Study of hadronization mechanisms
- Possible explanation: Multiple Parton Interactions? (MPI)

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Strangeness Pb-Pb at $\sqrt{S_{NN}}$ =5.02 TeV



-Pb-Pb ratios follow the trend from pp and p-Pb

-In Pb-Pb hadrons produced in apparent near thermal and chemical equilibrium

-The ratios of integrated yields seem to be saturating for higher values of $dN_{_{Ch}}/d\eta.$

-Will pp and pPb also saturate?

EPS 2017 presentation

Heavy flavor vs multiplicity: quarkonia



ALI-PREL-118226

Initial stages 2017 Presentation

Heavy flavor vs multiplicity: quarkonia



Increase is not linear: highlights importance of other physical processes: MPI, percolation effects, color re-connection

Initial stages 2017 Presentation

Heavy flavor vs multiplicity

Run 2 pp collisions dN_{J/ψ}/dy ⟨dN_{J/ψ}/dy⟩ 22 ALICE, pp 20 $J/\psi \rightarrow e^+e^-$, |y|<0.918 √s=13 TeV, Preliminary $16 \longrightarrow J/\psi \rightarrow e^+e^-, |y| < 0.9$ \s=7 TeV, PLB 712 (2012) 165 14 D, |y|<0.5, 2<p_<4 GeV/c \s=7 TeV, JHEP 1509 (2015) 148 12 ſ Į 10 8 6 **Massimiliano Marchisone** 4 ЩŌ Wednesday's Morning Session 2F 0 2 3 5 6 9 4 8 $dN_{ch}/d\eta$ $\langle dN_{ch}/d\eta \rangle$

-Similar effects observed for D's

ALI-PREL-126584

-Hadronization doesn't seem to play a role

Astrid Morreale Etretat 2017 13

Heavy flavor vs multiplicity

pp collisions



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Heavy flavor vs multiplicity



pp collisions



-Similar effects observed for D's

-Hadronization doesn't seem to play a role

Mid-rapidity and Pb-going direction:

-Qualitatively similar behaviour as in pp collisions

p-going direction: Saturation at high multiplicities (Bjorken-x range in the domain of shadowing / saturation)

Nuclei and hyper nuclei measurements



NB: Hyper nuclei, nuclei in which one or several p/n is replaced by a strange baryon EPS Presentation

Hyper nuclei measurements



Run 2



ALI-PREL-130195

New ALICE result from Pb-Pb at 5.02 TeV is consistent to the free Λ prediction

This is one of the most precise measurements of hypertriton lifetime

EPS Presentation

2. Collective Expansion

Identified particle spectra



Radial flow boosts hadrons:

- low $p_{_{T}}$: mass dependent slope, high $p_{_{T}}$ common hardening of $p_{_{T}}$ spectra
- -The spectra become harder for more central collisions
- -The change is most pronounced for heavier particles: effect of radial flow Initial Stages 2017 Presentation

Baryon to meson ratio

Run 2

- -Pb-Pb no significant energy dependence
- Radial flow pushes protons to intermediate $p_{_{\rm T}}$ and depletes low $p_{_{\rm T}}$
- Stronger radial flow in central Pb–Pb collisions

-Low to mid-p₇ described by **hydrodynamic models**

- Similar effects observed in high-multiplicity pp and p–Pb collisions



Initial Stages 2017 Presentation



Identified particles in pp





Would be interesting to perform studies as a function of multiplicity of these same particles (possible hardening of particle spectra with increasing event multiplicity)

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Anisotropic flow



Light meson flow



-Low p_{τ} : Mass ordering expected in a collective expansion scenario.

-Low- p_{τ} : v_{2} sensitive to hydrodynamic expansion and initial conditions (geometry).

Run 2

Light meson flow



-Low p_{τ} : Mass ordering expected in a collective expansion scenario.

-Low- p_{τ} : v_{2} sensitive to hydrodynamic expansion and initial conditions (geometry).

-Similar results observed in a high multiplicity p-Pb environment.

-Effect in these systems may be due to initial state (saturation?) or final state effects (expansion and/or thermal equilibrium ?)

SQM 2017 presentation

Light meson flow



 $V_{\scriptscriptstyle A}$ more sensitive to interactions and less to initial state

- hydrodynamic models work at low p T (pT<1 GeV/c)
- only describes trend at intermediate pT (1<pT <2 GeV/c)

Charm flows

arXiv:1707.01005



Run 2



Non zero v2 for D-meson

Audrey Francisco Tuesday Morning

Non zero v2 for J/Psi's

Strong coupling of c-quark with the medium

Julien Charles Hamon Wednesday Morning

Participation of low p_{τ} charm to collective motion in the QGP

Additionally for the J/Psi this is interpreted as proof of recombination.

SQM 2017 presentation

3. Hard Processes

Energy loss in the medium

Run 2

-High momentum partons lose energy while propagating through the QGP -Energy loss depends on parton type and properties of the medium.

$$R_{\rm AA} = \frac{\rm AA}{\rm scaled \ pp} = \frac{\rm d^2 N_{AA}/\rm dp_T \rm dy}{\langle N_{\rm coll} \rangle \rm d^2 N_{pp}/\rm dp_T \rm dy}$$



Expectation:

Jet fragmentation is modified by the medium

- suppression of jet yield
- broadening of jet shape
- di-jet imbalance

Findings:

Strong suppression of jet yields in most central Pb-Pb collisions

Francois Arleo, Quenching Shu-yi We, Angular correlations Tuesday

Energy loss in the medium

Run 2

-High momentum partons lose energy while propagating through the QGP -Energy loss depends on parton type properties of the medium.

-It can modify color flow





Time →

-QGP screens the $c\overline{c}$ interaction and quarkonia can be suppressed

-If many $c\overline{c}$ are created in the collision quarkonia on the other hand can form via quark recombination.



Stronger suppression at RHIC despite larger LHC densities: regeneration? Larger suppression for higher p_{τ}

Mohamad Tarhini Tuesday Morning



Stronger suppression at RHIC despite larger LHC densities: regeneration? Larger suppression for higher p_{τ} , similar to that of pions Mohamad Tarhin

Smaller suppression at mid-rapidity

Mohamad Tarhini Tuesday Morning



 $\psi(2S)$ indicates larger suppression than J/ψ

Mohamad Tarhini (Victor Feuillard)

Tuesday Morning

EPS 2017 Presentation

Run 2

Summary

- Interesting new emerging phenomena for high multiplicity events in pp and pPb Lack of a consistent picture yet.

- Collective flow is observed also for massive particles (charm), this requires strong interaction with the QGP. High $p_{\tau} v_{2}$ is a challenge to models

- Charm meson R_{AA} (high p_T) similar to that of light mesons. Precise measurements of J/ ψ R_{AA} now available. ψ (2S) will need more statistics and detector upgrades.

Extras

Run 2 Publications

1. Search for collectivity with azimuthal J/\$\psi\$-hadron correlations in high-multiplicity p-Pb collisions at \$\sqrt{s}\$ = 5.02 and 8.16 TeV PLB https://arxiv.org/abs/1709.06807

2. J/\$\psi\$ elliptic flow in Pb-Pb Collisions at 5.02 TeV PRL https://arxiv.org/abs/1709.05260

3. \$\Dzero\$, \$\Dplus\$, \$\Dstar\$ and \$\Ds\$ azimuthal anisotropy in mid-central Pb-Pb collisions at \$\mathbf{\sqrtsNN=5.02}\$ TeV PRL https://arxiv.org/abs/1707.01005

4. Energy dependence of forward-rapidity j/psi and psi (2S) production in pp collisions at the LHC EPJC https://arxiv.org/abs/1702.00557

5. Centrality dependence of the pseudorapidity density distribution for charged particles in Pb-Pb collisions at $\operatorname{s_{\rm NN}}=5.0$ PLB http://arxiv.org/abs/1612.08966

 $6.J/\psi$ suppression at forward rapidity in Pb-Pb collisions at sqrt(sNN) = 5.02 TeV PLB https://arxiv.org/abs/1606.08197

7. Anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{sNN} = 5.02$ TeV PRL http://arxiv.org/abs/1602.01119

8. Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\operatorname{s_{\rm NN}} = 5.02 \ PRL \ http://arxiv.org/abs/1512.06104$

9. Pseudorapidity and transverse-momentum distribution of charged particles in proton-proton collisions at \sqrt{s} = 13 TeV PLB http://arxiv.org/abs/1512.06104

Centrality determination in ALICE

 Correlate the multiplicity of produced particles with the geometry of the system i.e. impact parameter (not directly accessible), volume and (roughly) the shape...



In the details, the situation is "slightly" more complicated: \rightarrow after centrality, fluctuations play an important role

Z

Slide from B Hyppolyte



Courtesy of B. Hyppolyte



In vacuum production of meson via string break-up

Probability to produce $(q_i \overline{q}_i)$

Probability to form $(q_{i-1}\overline{q}_i)$

Factorization: production of $(\mathbf{q}_i \overline{\mathbf{q}}_i)$ independent of

q_{i-1} but the pair mass quark (flavour) is relevant.

 \Rightarrow Fragmentation in $(q_{i-1}\overline{q}_i) \equiv meson$

Production of $(\mathbf{q}_i \overline{\mathbf{q}}_i)$ via quantum mechanical tunneling:

Classically, the pair is pulled apart by the field (no annihilation);

 Quantum mechanically, the pair is created at one point then tunnels out with a non zero probability (mass and flavor dependence).

In vacuum production of baryon with the diquark model

Relative probability to produce a <u>di</u>quark <u>pair</u> wrt quark pair Extra suppression associated to s content Spin suppression (spin 1 diquarks wrt spin 0 diquarks) Weighted probability relative to 3-q state symmetry \Rightarrow Fragmentation in $(q_{i-1}q_iq_i) \equiv$ baryon





- 2) compute V0M = sum (V0A+V0C signals)
- 3) for each V0M percentile interval, extract the $\langle dN_{ch}/d\eta \rangle$ corresponding to a corrected distribution of charged tracks in the central region $|\eta| < 0.5$

Courtesy of B. Hyppolyte

- Global event class... several possibilities to select events
 - relevant for consistency checks between experiment and model comparisons non single diffractive ? inelastic ? (with one charged track in a selected n interval ?)





- Smooth transition from pp to Pb-Pb is observed, peripheral Pb-Pb at 5 TeV is consistent with p-Pb

- The increase of the d/p ratio with charged particle multiplicity from pp to Pb-Pb is consistent with the coalescence picture at low multiplicity
- low multiplicity: corona effects can lead to a depletion of the d/p ratio going to the pp values
- high multiplicity: possible different rescattering of protons and deuterons after chemical freeze-out leads to a depletion

NB:Trend at high multiplicities currently under investigation (determination of the uncorrelated systematics)

EPS Presentation

Run 2

Production mechanism of compound objects

PRC21,1301 (1980)



Thermal Model:

-Hadrons emitted from the interaction region in statistical equilibrium once the chemical freeze-out temperature is reached.

-Abundance of a species proportional to e^{-m/Tchem}

-The large mass of Hyper nuclei gives a strong dependence on $\rm T_{\rm chem}$

Coalescence Model:

-Anti-baryons close in phase space at the kinetic freeze-out stage can form anti-hyper nuclei

- These newly formed nuclei can **break** or **regenerate** in the time interval between chemical and kinetic freeze-out

NB: Hyper nuclei, nuclei in which one or several p/n is replaced by a strange baryon

EPS Presentation

What can we learn from measuring hard processes

"Simplest way" to establish the properties of a system calibrated probe and calibrated interaction suppression pattern tells about density profile

Hard processes serve as calibrated probe (pQCD)

•pp: understand production mechanisms, probe PDFs, (particularly gluon's PDF's down to low x: gluon saturation), provide a reference to p-Pb and Pb-Pb measurements

In Heavy-ion collisions:

- p-Pb: probe cold nuclear matter effects (i.e. modification of the PDFs, saturation, Cronin enhancement...)
- Pb-Pb: probe the formation and properties of the QGP
 - Traverse through the medium and interact strongly
 - Suppression pattern provides density measurement
 - General picture: parton energy loss through medium-induced gluon radiation and collisions with medium constituents

Francois Arleo Tuesday afternoon

Radiative energy loss

...depends on S. Wicks et al., Nucl. Phys. A 784 (2007) 426 1.0 - Medium properties (e.g. density, temperature, mean free path) 0.8 \rightarrow transport coefficients (\hat{q}) - Path length in the medium (L) 0.6 - Parton properties (colour charge and mass) R_Q(p_↑) traversing the medium \rightarrow Casimir coupling factor $(C_{\rm R})$: 0.4 $C_{\rm R}$ = 4/3 for quarks and 3 for gluons u.d quarks R. Baier et al., Nucl. Phys. B483 (1997) 291 (BDMPS) 0.2 $\langle \Delta E_{medium} \rangle \propto \alpha_s C_R \hat{q} L^2$ 0.0 'n 8 18 20 Dead-cone effect: gluon radiation 10 р_т (GeV) suppressed at small angles ($\theta < m_{O}/E_{O}$) Y. Dokshitzer, D. Kharzeev, PLB 519 (2001) 199, hep-ph/0106202 hot and dense QCD matter parton Expectation: $\Delta E_{q} > \Delta E_{u,d,s} > \Delta E_{c} > \Delta E_{b}$ $R_{\Delta\Delta}(\pi) < R_{\Delta\Delta}(D) < R_{\Delta\Delta}(B)$

Collider Physics and the Cosmos 2017

Inclusive results compared to NRQCD



All models properly account for higher mass resonance decays

NRQCD models differ in the set of LRME that is used, the $p_{_{\rm T}}$ at which fits are

performed and the datasets considered.

At low p_{τ} (right), NRQCD is coupled to a CGC description of the proton

Predictions are quite different at high p_{T} , but in both cases, non-prompt J/ ψ constitute a sizable contribution to the inclusive cross section

Inclusive results compared to NRQCD

Summed NRQCD and FONLL calculations assuming fully uncorrelated uncertainties.



Agreement to the data is much improved, already at intermediate p_{τ} and especially for the calculation from Ma *et al.*

Note that the calculations are completely independent, and that there was no data at this energy, this rapidity and at such high p_{τ} before

Evolution if the heavy ion collision



Coalescence

- If baryons at freeze-out are close enough in phase space (i.e. geometrically and in momentum) and match spin state a (anti-)nucleus can be formed
- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
- The yield of any nucleus can be determined as:

$$\gamma_A \frac{d^3 N_A}{dp_A^3} = \left(\frac{2s_A + 1}{2^A}\right) \left(\frac{4\pi}{3} p_0^3\right)^{A-1} \left(\gamma_p \frac{d^3 N_p}{(dp_A^3/A)}\right)^Z \left(\gamma_n \frac{d^3 N_n}{(dp_A^3/A)}\right)^N$$

- Assuming that p an n have the same mass and have the same $p_{\rm T}$ spectra

$$E_{A} \frac{d^{3}N_{A}}{dp_{A}^{3}} = B_{A} \left(E_{p} \frac{d^{3}N_{p}}{dp_{p}^{3}} \right)^{A}$$
$$d \propto p^{2}$$
$$^{3}\text{He} \propto p^{3}$$

Statistical thermal model

- Thermodynamic approach to particle production in heavy-ion collision: all the particles are produced at chemical freeze-out
- Starting point: Grand Canonical partition function (Z) for an relativistic ideal quantum gas of hadrons of particle type i (i = pion, proton,... \rightarrow full PDG)
- For each hadron i:Z depends on the temperature T, the volume V and the chemical potentials $\mu_{B'}\mu_{S'}\mu_Q: Z(T,V,\mu_B,\mu_S,\mu_Q) = \sum_i Z_i$



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Statistical thermal model

- Particle density n_i can then be calculated as:
- If ratios are considered (n_i/n_i) Volume (V) cancels -> ratio depends only on T, μ and m
- Thermal model can predict also the yields of (anti-)nuclei not taken into account: nuclei are considered as not compour
 - → Exponential dependence of the yield: $\frac{dN}{dy} \propto e^{\left(-\frac{m}{T_{chem}}\right)}$ the second sec

→ The thermal model predicts an exponential decrease of particle yields with increasing mass at a given temperature

$$\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T}\right)$$

ne:
$$\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T}\right)$$

 $n_i = \frac{\langle N_i \rangle}{V} = \frac{Tg_i}{2\pi^2} \lambda_1 K_2 \left(\frac{m_i}{T}\right)$

Particle ratio, comparison to NRQCD

Many systematic uncertainties cancel in the particle ratio, for both data and theory



Both calculations follow the same trend but have very different uncertainties. This was already the case at $\sqrt{s} = 7$ TeV (see ALICE EPJC 74 (2014) 2974)

Calculation from Y-Q Ma et al. tends to overestimate the $\psi(2S)$ -to-J/ ψ ratio

Contributions from non-prompt J/ ψ and ψ (2S) have little impact here because they enter both the numerator and denominator, with a similar (small) magnitude

Data at all energies vs p_{τ} compared to NRQCD

Extensive data-theory comparisons done at all energies available at the LHC so far.

Good agreement between the model and the data is observed for all measured cross sections, for both J/ψ and $\psi(2S)$

For $\psi(2S)$ -to-J/ ψ cross section ratios the model tends to be slightly above the data especially at \sqrt{s} =13 TeV.

This tension appears mainly because of the error cancellation between the uncertainties on the J/ ψ and ψ (2S) cross sections.



Data at all energies vs p_{τ} compared to NRQCD

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Good agreement between the model and the data is observed for all measured cross sections, for both J/ψ and $\psi(2S)$



Data all energies vs y compared to NRQCD

Extensive data-theory comparisons done at all energies available at the LHC so far.

Good agreement between the model and the data is observed for all measured cross sections, for both J/ψ and ψ(2S)



Mean p₋energy dependence



 $<p_{-}>$ is measured using fits to the p_{-} distributions.

A steady increase of $< p_{\tau} >$ with increasing \sqrt{s} .

Consistent with the expected hardening of the of the J/ ψ and $\psi(2S)$ p₊ distributions.

Values at mid- are systematically larger than at forward-rapidity.

Could be attributed to an increase in the longitudinal momentum at forward-rapidity leaving less energy available in the transverse plane. 56

What about model comparisons?



Figure from KNIEHL B. Quarkonium 2016 VA, USA

Butenschön,

 $(O_8^{J/\psi}({}^1S_0)) = 0.0497 \text{ GeV}^3$

 $(O_{0}^{J/\psi}(^{3}S_{1})) = 0.0022 \text{ GeV}^{3}$

 $(O_8^{J/\psi}({}^{3}P_0)) = -0.0161 \text{ GeV}^5$

Gong, Wan,

J.-X. Wang,

H.-F. Zhang:

 $(Q_{1}^{f^{0}}(^{1}S_{n})) = 0.097 \text{ GeV}^{2}$ $(Q_{1}^{f^{0}}(^{1}S_{n})) = -0.0001 \text{ GeV}^{2}$

 $\begin{array}{l} (\Omega_{i}^{(0)}(^{1}S_{i}))=-0.0046~GeV^{2} \quad (\Omega_{i}^{(0)}(^{1}S_{i}))=0.0014~GeV^{2} \\ (\Omega_{i}^{(0)}(^{1}P_{i}))=-0.0214~GeV^{2} \quad (\Omega_{i}^{(0)}(^{1}P_{i}))=0.0085~GeV^{2} \end{array}$

(0)³/³S/(i = 0.0022 GeV⁴

K. Wang,

Y.-J. Zhang:

 $(O_n^{J/\psi}({}^1S_0)) = 0.089 \text{ GeV}^3$

 $(O_8^{J/\psi}({}^3S_1)) = 0.003 \text{ GeV}^3$

 $(O_8^{J/\psi}({}^3P_0)) = 0.0126 \text{ GeV}^5$

Kniehl:

$d\sigma/dy$ as a function of \sqrt{s}



Steady increase of d σ /dy as a function of increasing \sqrt{s} .

For the J/ ψ (left), the cross sections are compared to a calculation done by in the CEM framework (PRC 87 014908) Data lies on the upper side of the calculation and the difference to the central value becomes larger with increasing \sqrt{s} .

J/ψ at 7 TeV compared to the Color Singlet Model



LO misses the pT dependence

- NLO improves somewhat the description but still lies below the data
- NNLO gets closer to the data at the expense of large theoretical uncertanties.
- Note that FONLL is not included in these descriptions, rather a flat scale factor is applied to the model to account for non-prompt quarkonia.