Review of physics with LHC Run 3 & 4

Part 1: dileptons, nuclei, heavy-flavor production & flow

Alexander Kalweit, CERN
ALICE 3 workshop, 19th October 2021
## Boundary conditions: LHC long term schedule

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- **Run 3**
- **Long Shutdown 3 (LS3)**
- **Run 4**
- **LS4**

**Legend:**
- Blue: Shutdown/Technical stop
- Light blue: Protons physics
- Green: Ions
- Purple: Commissioning with beam
- Turquoise: Hardware commissioning/magnet training
### Indicative Run 3 luminosity targets [from link]

<table>
<thead>
<tr>
<th></th>
<th>ATLAS &amp; CMS</th>
<th>LHCb</th>
<th>ALICE</th>
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<tbody>
<tr>
<td>p-p</td>
<td>160 fb⁻¹</td>
<td>25-30 fb⁻¹ (~50 fb⁻¹ by LS4)</td>
<td>200 pb⁻¹</td>
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<tr>
<td>Pb-Pb</td>
<td>7.5 nb⁻¹ (13 nb⁻¹ by LS4)</td>
<td>1 nb⁻¹ (2 nb⁻¹ by LS4)</td>
<td>7.5 nb⁻¹ (13 nb⁻¹ by LS4)</td>
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<tr>
<td>p-Pb</td>
<td>0.5 pb⁻¹ (~1.2 pb⁻¹ by LS4)</td>
<td>0.1 pb⁻¹ (~0.6 pb⁻¹ by LS4)</td>
<td>0.25 pb⁻¹ (~0.6 pb⁻¹ by LS4)</td>
</tr>
<tr>
<td>O-O</td>
<td>0.5 nb⁻¹</td>
<td>0.5 nb⁻¹</td>
<td>0.5/nb⁻¹</td>
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N.B.: pp reference data at 5.x TeV will also be collected

**ALICE will increase its integrated luminosity:**
- in min. bias Pb-Pb by x100 wrt Run 2
- in min. bias p-Pb by x1000 wrt Run 2
- in pp 13.6 TeV by x20-3000 wrt Run 2, depending on the channel
First TED shots and pilot beamtest

TED shots → 9th of Oct 2021

Pilot beam → 21st of Oct – 1st Nov 2021

- 900 GeV pp collisions (injection energy)
- 20 hours at few kHz interaction rate
- Main goal: detector alignment, reconstruction, calibration commissioning
- Test analysis chain to the level of physics results

Cosmics data ITS
**Boundary conditions: experiment upgrades (1)**

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**Installed and commissioned large upgrades for ALICE & LHCb:**

- Run 3
- Long Shutdown 3 (LS3)
- Run 4
- LS4
Boundary conditions: experiment upgrades (2)

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<td>Run 4</td>
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Installed and commissioned large upgrades for ALICE & LHCb:

Approved Phase-II upgrades for ATLAS & CMS:

Smaller upgrades for ALICE (TDR in preparation):

ALICE ITS3: Ultra-light, fully cylindrical inner barrel tracking layers

CMS & ATLAS inner tracking systems:
- Increase coverage to $|\eta| < 4.0$
- Timing layers: PID with TOF
- Plus much more: calorimeters, muon system upgrades etc.

ALICE Forward Calorimeter:
$\rightarrow$ high-granularity Si-W EM calorimeter for photons and $\pi^0$

FoCal-H

FoCal-E
Addressing the initial state: FoCal

→ At leading order, more than 70% of forward photons originate from Compton-scattering that gives direct access to the gluon density.
1. Dedicated pp 13.6 TeV program

2. Dileptons

3. Heavy-flavor production & flow

4. Linking charm and nuclei production
Dedicated pp 13.6 TeV program of ALICE

Very high multiplicity pp collisions:
→ Probe collective effects, e.g. if multi-strange particle production will exceed Pb-Pb (thermal) production rates

Hadron-hadron correlations:
→ Test ab-initio Lattice QCD calculations for interactions

Hypertriton production:
→ Distinguish production mechanisms: thermal or coalescence?

[Public note on ALICE pp program]
Direct measurement of three body forces

Neutron Stars with hyperons and nucleons: repulsive three body forces ΛNN could stiffen the equation of state. Are those forces repulsive?

Cumulants method allows to extract the genuine three-body correlation -> Access to three-body forces!!

Run 3 : Three-body online trigger for Λpp

<table>
<thead>
<tr>
<th>Data Set</th>
<th># triplets $Q_3 &lt; 600$ MeV/c</th>
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<tbody>
<tr>
<td>Run 2, pp 13 TeV HM</td>
<td>3600</td>
</tr>
<tr>
<td>Run 3, pp 13 TeV MB</td>
<td>$#_{\text{Run 2}} \times 7$</td>
</tr>
<tr>
<td>Run 3, pp 14 TeV Three-Body Trigger</td>
<td>$#_{\text{Run 2}} \times 600$</td>
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Run 3 will allow us to pin down the repulsive or attractive nature of many three-baryon interactions for the first time!
First direct experimental access to many-body interactions within SU(3)
Antinuclei production in b-quark decays (1)

\[ \chi \chi \rightarrow b\bar{b} \rightarrow \Lambda_b^0 + X \rightarrow ^3\overline{\text{He}} + X \]

\[ \chi \chi \rightarrow b\bar{b} \quad m_{\chi} = 67 \text{ GeV} \]

\[ 1 \text{ event} / (10 \text{ GeV}/n) \]

\[ \text{Events} / (4 \mu \text{m}) \]

\[ T \text{ [GeV}/n] \]

\[ \text{AMS-02 (10 yr)} \]

\[ \text{Pythia} \]

\[ \text{Pythia prompt} \]

\[ \text{Pythia } \Lambda_b \text{-tune} \]

\[ \text{Herwig} \]

\[ \text{Herwig+EvtGen} \]

\[ \text{ALICE3} \]

\[ \text{ALICE ITS3 simulation} \]

\[ pp, \sqrt{s} = 14 \text{ TeV}, \, l_{\text{int}} < 1.44, \, L_{\text{int}} = 1 \text{ fb}^{-1} \]

\[ 3 < p_T < 4 \text{ GeV}/c \]

\[ \text{Events} / (4 \mu \text{m}) \]

\[ d_0^\mu (\mu \text{m}) \]

\[ \text{simulated data} \]

\[ \text{total fit function} \]

\[ \text{primary } ^3\text{He} \]

\[ ^3\text{He} \leftrightarrow \overline{\Lambda} \]

\[ ^3\text{He} \leftrightarrow \Lambda_b^0 \]

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\[ \text{ALICE3} \]

\[ \text{ALICE ITS3 simulation} \]

\[ pp, \sqrt{s} = 14 \text{ TeV}, \, l_{\text{int}} < 0.8, \, L_{\text{int}} = 200 \text{ pb}^{-1} \]

\[ 3 < p_T < 4 \text{ GeV}/c \]

\[ \text{Events} / (4 \mu \text{m}) \]

\[ d_0^\mu (\mu \text{m}) \]

\[ \text{simulated data} \]

\[ \text{total fit function} \]

\[ \text{primary } ^3\text{He} \]

\[ ^3\text{He} \leftrightarrow \overline{\Lambda} \]

\[ ^3\text{He} \leftrightarrow \Lambda_b^0 \]

[M. Winkler, T. Linden, PRL 126 (2021)]

\[ \rightarrow \text{Anti}^{-3}\text{He originating from } \Lambda_b \text{ decays from dark matter annihilation might lead to an enhanced flux of anti}^{-3}\text{He near earth.} \]

\[ \rightarrow \text{Accelerator based experiments like ALICE are in the best position to determine the branching ratios of these rare decays.} \]
(Anti-)nuclei production in b-quark decays (2)

\[ \chi \chi \rightarrow b \bar{b} \rightarrow \Lambda_b^0 + X \rightarrow ^3\text{He} + X \]

After LHC Run 3 & 4, we will have understood the formation mechanisms of \( A < 5 \) anti- and hyper-nuclei from collisions, but will only start to probe their production in b-quark decays. Run 5 & 6 will provide the definitive answer.
1. Dedicated pp 13.6 TeV program

2. Dileptons

3. Heavy-flavor production & flow

4. Linking charm and nuclei production
Low mass dileptons (1)

- Thermal radiation contributes to the intermediate mass region ($\approx 1-2.5 \text{ GeV/c}^2$) of the di-lepton inv. mass distribution.

- Strong reduction of material budget (from 0.35% X/X$_0$ to about 0.05% X/X$_0$) and better pointing resolution with ITS3 will allow to control the background from conversions and charm decays.
After background subtraction, the slope of the spectrum at intermediate masses corresponds to a Lorentz invariant average temperature of the QGP and fireball evolution.
While a saturation in the chemical freeze-out (after/at hadronisation) temperature has been experimentally established in LHC Run 1 & 2, the field of heavy-ion physics has to prove that $T_{\text{slope}}$ keeps increasing with $\sqrt{s}$.

After LHC Run 3 & 4, we will have measured the average temperature of the QGP and fireball evolution with di-leptons, but we will not have probed $\rho$-$a_1$ mixing and not have access to a fine-grained picture of the temperature evolution via the $p_T$-dependence.

(for ALICE performance, see talk of R. Bailhache later today)
1. Dedicated pp 13.6 TeV program
2. Dileptons
3. Heavy-flavor production & flow
4. Linking charm and nuclei production
Heavy flavor production & flow (1a)

LHC Run 3 & 4 will open a new era of comprehensive heavy flavor measurements:

- Measure baryon-to-meson ratios and strange vs non-strange production to understand hadronization/coalescence and eliminate the corresponding model uncertainties.
- Measure the total charm & beauty cross-sections and shadowing (p-Pb) to close the loop on the heavy-flavor balance.
- Measure simultaneously $R_{AA}$ and $v_2$ for several particles to constrain models and determine QGP transport coefficients at the same time (in particular the heavy-quark diffusion coefficient $D_s$).
Heavy flavor production & flow (1b)

LHC Run 3 & 4 will open a new era of comprehensive heavy flavor measurements:

- Measure baryon-to-meson ratios and strange vs non-strange production to understand hadronization/coalescence and eliminate the corresponding model uncertainties.
- Measure the total charm & beauty cross-sections and shadowing (p-Pb) to close the loop on the heavy-flavor balance.
- Measure simultaneously $R_{AA}$ and $v_2$ for several particles to constrain models and determine QGP transport coefficients at the same time (in particular the heavy-quark diffusion coefficient $D_s$).
Heavy flavor production & flow (1c)

LHC Run 3 & 4 will open a new era of comprehensive heavy flavor measurements:

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Heavy flavor production & flow (2)

LHC Run 3 & 4 will open a new era of comprehensive heavy flavor measurements:

- Measure baryon-to-meson ratios and strange vs non-strange production to understand hadronization/coalescence and eliminate the corresponding model uncertainties.
- Measure the total charm & beauty cross-sections and shadowing (p-Pb) to close the loop on the heavy-flavor balance.
- Measure simultaneously \( R_{AA} \) and \( v_2 \) for several particles to constrain models and determine QGP transport coefficients at the same time (in particular the heavy-quark diffusion coefficient \( D_s \)).
LHC Run 3 & 4 will open a new era of *comprehensive* heavy flavor measurements:

- Measure baryon-to-meson ratios and *strange vs non-strange production* to understand hadronization/coalescence and eliminate the corresponding model uncertainties.
- Measure the *total charm & beauty cross-sections* and shadowing (p-Pb) to close the loop on the heavy-flavor balance.
- Measure *simultaneously* $R_{AA}$ and $v_2$ for several particles to constrain models and determine QGP transport coefficients at the same time (in particular the heavy-quark diffusion coefficient $D_s$).
Heavy flavor production & flow (3b)

LHC Run 3 & 4 will open a new era of comprehensive heavy flavor measurements:

- Measure baryon-to-meson ratios and strange vs non-strange production to understand hadronization/coalescence and eliminate the corresponding model uncertainties.
- Measure the total charm & beauty cross-sections and shadowing (p-Pb) to close the loop on the heavy-flavor balance.
- Measure simultaneously $R_{AA}$ and $v_2$ for several particles to constrain models and determine QGP transport coefficients at the same time (in particular the heavy-quark diffusion coefficient $D_s$).
Heavy flavor production & flow (4)

LHC Run 3 & 4 will open a new era of comprehensive heavy flavor measurements:

- Measure baryon-to-meson ratios and strange vs non-strange production to understand hadronization/coalescence and eliminate the corresponding model uncertainties.
- Measure the total charm & beauty cross-sections and shadowing (p-Pb) to close the loop on the heavy-flavor balance.
- Measure simultaneously $R_{AA}$ and $v_2$ for several particles to constrain models and determine QGP transport coefficients at the same time (in particular the heavy-quark diffusion coefficient $D_s$).

Current state

With expected reduced uncertainties on D-meson $R_{AA}$ after Run 3 & 4
Heavy flavor production & flow (5)

LHC Run 3 & 4 will open a new era of comprehensive heavy flavor measurements:

• Measure baryon-to-meson ratios and strange vs non-strange production to understand hadronization/coalescence and eliminate the corresponding model uncertainties.

• Measure the total charm & beauty crosssections and shadowing (p-Pb) to close the loop on the heavy-flavor balance.

• Measure simultaneously $R_{AA}$ and $v_2$ for several particles to constrain models and determine QGP transport coefficients at the same time (in particular the heavy-quark diffusion coefficient $D_s$).

[Y. Xu, J. E. Bernhard, et al., PRC97, 1, 014907]
The limits of the program: $\Xi_c^+$ with ITS3

$\Xi_c^{0,+} \rightarrow pK^{-}\pi^+$: powerful probe of hadronization and a **good showcase** to demonstrate the influence of spatial resolution improvement on secondary vertex variables

- three primary particles to be combined $\rightarrow$ huge combinatorial background
- a very rare signal ($0.45\% < \text{BR}<2\%$) but with a “perfect” $c\tau \sim 135$ micron

Measuring the $\Xi_{cc}$ would imply a further reduction of the yield by a factor of about 1/20 from the branching ratio and of about 1/50 from the production. It remains out of reach in LHC Run 3 & 4...
1. Dedicated pp 13.6 TeV program
2. Dileptons
3. Heavy-flavor production & flow
4. Linking charm and nuclei production
Charm and nuclei production: the big picture (1)

→ Probably the closest we can get experimentally to a deconfinement measure (apologies for being provocative here).

→ Charm fugacity factor quantifies the enhancement wrt the exponential yield dependence of light quarks.

→ (anti-)(hyper-)nuclei provide the baseline

Predictions of statistical-thermal hadronization model

[A. Andronic et al., JHEP 07 (2021) 035]
Predictions of statistical-thermal hadronization model

→ Probably the closest we can get experimentally to a deconfinement measure (apologies for being provocative here).

→ Charm fugacity factor quantifies the enhancement wrt the exponential yield dependence of light quarks.

→ (anti-)(hyper-)nuclei provide the baseline

[A. Andronic et al., JHEP 07 (2021) 035]
(anti-)hypernuclei

→ Light nuclei up to $A = 4$ (deuterons, tritons, $^3$He and $^4$He) are already observed today at the LHC, but with limited statistics. The same holds true for $A = 3$ hypernuclei (hypertriton).

→ $A = 4$ (anti-)hypernuclei are in well in reach of LHC Run 3 & 4.

→ Any heavier object ($A > 5$) will need to be measured in LHC Run 5 & 6…
Charm and nuclei production: the big picture (3)

→ Probably the closest we can get experimentally to a deconfinement measure (apologies for being provocative here).

→ Charm fugacity factor quantifies the enhancement wrt the exponential yield dependence of light quarks.

→ (anti-)(hyper-)nuclei provide the baseline

[A. Andronic et al., JHEP 07 (2021) 035]
c-deuteron: detector performance
The ITS3 upgrade will allow ALICE to start to become sensitive to c-deuteron production (if it exists); a definitive answer will be provided by ALICE 3.
Summary and conclusions

• Exciting times are just starting: powerful upgrades will lead to a plethora of results in LHC Run 3 & 4.

• Several longstanding questions will be definitely answered after LHC Run 3 & 4, e.g.:
  – Time-average genuine temperature of the fireball and caloric curve of QCD
  – Production mechanism of light anti- and hyper-nuclei
  – J/ψ regeneration mechanism
  – ...

• Other questions will probably not be answered after LHC Run 3 & 4, e.g.:
  – Existence of charm-nuclei
  – Hadronization and thermalization of beauty via its production and flow
  – ...

• Other questions will definitely not be answered after LHC Run 3 & 4, e.g.:
  – Production of multi-charm baryons
  – Temperature evolution of the fireball via $p_T$-differential dilepton measurements
  – $\rho$-a$_1$ mixing
  – ...
Thank you!
Additional slides
Physics performance of ITS3

→ Pointing resolution improves by a factor 2 w.r.t. to ITS2

→ ITS3 reduces significantly the uncertainties on the fireball temperature extracted with virtual photons (di-electrons) thanks to a better charm rejection and a reduced background from conversions.