PHYSICS PERSPECTIVES FOR ALICE IN RUN 4

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ON BEHALF OF THE ALICE COLLABORATION
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HEAVY-ION PHYSICS AND QUARK–GLUON PLASMA

- Primary goal of heavy-ion program at the LHC: study of the properties of colour-deconfined strongly interacting matter, *quark–gluon plasma (QGP)*

- The QGP is created in *ultra-relativistic heavy-ion collisions at the LHC*
  - initial energy density ~ 15 GeV/fm³
  - after a pre-equilibrium phase expands hydrodynamically like a nearly perfect fluid
  - hadronises in thermal equilibrium

- Ideal probes: *heavy-flavour (HF) quarks*
  - created at short time scales
  - experience the full system evolution
  - Brownian motion markers of the QGP
Run 3 and 4: increase collected Pb-Pb luminosity by more than one order of magnitude
  ▪ upgrades to LHC needed for Pb-Pb luminosity will be completed in LS2

Main Physics motivations:
  ▪ HF hadrons at low $p_T$ (charm and beauty interaction and hadronisation in the QGP)
  ▪ Quarkonia down to $p_T = 0$ (melting and regeneration in the QGP)
  ▪ Thermal dileptons, photons, vector mesons (thermal radiation, chiral symmetry restoration)
  ▪ Precision measurements of light (hyper)nuclei and searches for charmed hypernuclei

Main requirements:
  ▪ Increase readout rate, reduce data size for storage (online data reduction)
  ▪ Improve tracking and vertexing at low $p_T$
  ▪ preserve particle-identification (PID) capabilities
CURRENT: ALICE UPGRADES FOR LHC RUN 3

Fast Interaction Trigger
Poster by S. A. Bysiak
Poster by S. R. Torres

Time Projection Chamber

Upgrade readout electronics for TOF, TRD, MUON spectrometer, ZDC, V0, EMCAL

Muon Forward Tracker

Inner Tracking System 2

P. Gasik 25 May, 16h45
NEXT: ALICE UPGRADES FOR LHC RUN 4

Inner Tracking System 2

Replace
3 inner-most layers

Forward Calorimeter

FoCal-H

FoCal-E

Inner Tracking System 3

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FoCal: A FORWARD CALORIMETER

- **FoCal**: forward electromagnetic and hadronic calorimeters
  - **FoCal-E**: high-granularity Si-W sampling calorimeter for the measurement of direct $\gamma$ and $\pi^0$
  - **FoCal-H**: Pb-Sc sampling calorimeter for photon isolation and jets

**Main goal:**
- constrain nuclear PDFs at small $x$, in particular gluon PDFs
- Even for proton limited information about gluons for $x < 10^{-4}$
  - from DIS, HERA: gluon density increases rapidly at low $x$
  - further growth predicted by DGLAP, BFKL

Infinite growth or mechanism that “tame” the gluons at low $x$
- gluon fusion / gluon saturation?
FOCAL: A FORWARD CALORIMETER

**EM and DIS measurements**

- **DIS experiments**
  - Classical method to measure PDFs
  - Not sensitive to the gluon PDFs at the leading order (LO)

- **Measure isolated $\gamma$ forward**
  - At LO more than 70% from Compton
  - Direct sensitivity to gluon density

- **Lower $x$ reached compared to LHCb thanks to pseudorapidity coverage**

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![Graph showing EM and DIS measurements with regions for LHCb, FOCAL, EIC1, EIC2, NMC/EMC, and $Q_s(P_b)$ and $Q_s(P)$ axes.]

**LOI: ALICE-PUBLIC-2019-005**

[26 May 2020] Fabrizio Grosa - LHCP 2020
EXPECTED PERFORMANCE: ISOLATED PHOTON MEASUREMENT

\[ R_{ppb} = \frac{1}{\langle N_{\text{coll}} \rangle} \cdot \frac{dN_{ppb}/dp_T}{dN_{pp}/dp_T} \]

- Expected 20% of relative uncertainties above 6 GeV/c
- Significant improvement up to factor 2 on EPPS16 gluon nuclear PDF
Recent nNNPDF from DIS measurements unconstrained for $x < 10^{-2}$

Current constraints provided by HF measurements at forward rapidity by ALICE and LHCb

arXiv:1912.09128

FOCAL is expected to provide significant constraints at $\sim 10^{-5} < x < 10^{-2}$

Expected to be more precise than electron-ion collider (EIC) experiments for $x < 10^{-3}$

LOI: ALICE-PUBLIC-2019-005
arXiv:1904.00018
**ITS3: A TRULY CYLINDRICAL INNER TRACKING SYSTEM**

- **New detector technology:**
  - three truly cylindrical Si pixel layers based on ultra-thin wafer-sized curved sensors
  - no external connections nor cooling
  - new beam pipe
  - new concept for future detectors

<table>
<thead>
<tr>
<th>inner layers</th>
<th>ITS1</th>
<th>ITS2</th>
<th>ITS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X/X_0$</td>
<td>1.14%</td>
<td>0.38%</td>
<td>0.05%</td>
</tr>
<tr>
<td>innermost radius</td>
<td>39 mm</td>
<td>22 mm</td>
<td>18 mm</td>
</tr>
<tr>
<td>pixel size</td>
<td>50x425 $\mu$m$^2$</td>
<td>30x30 $\mu$m$^2$</td>
<td>O(15x15 $\mu$m$^2$)</td>
</tr>
</tbody>
</table>

- **Pointing resolution improves by a factor 2** compared to ITS2 in the full $p_T$ range
- **Tracking efficiency increases by a factor 1.2-2** compared to ITS2 in $p_T < 100$ MeV/c

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MEASUREMENTS THAT WILL BENEFIT FROM THE ITS3 UPGRADE

- Low-mass dileptons
- Beauty-strange mesons
  - exclusive reconstruction of $B_s^0$
  - non-prompt $D_s^+$ (~50% from $B^{0,+}$ and ~50% from $B_s^0$)
- Beauty baryons
  - non-prompt $\Lambda_c^+$
  - exclusive reconstruction of $\Lambda_b^0$
- Charm strange and multi-strange baryons
  - $\Xi_c^0(cds)$, $\Xi_c^+(cus)$, $\Omega_c^0(css)$
- Searches for light charm hypernuclei
  - bound state of a $\Lambda_c^+$ and a neutron (c-deuteron)
  - bound state of a $\Lambda_c^+$ and a deuteron (c-triton)

Extremely challenging measurements in a high multiplicity environment (up to ~ $10^4$ charged tracks per event)
The thermal radiation contributes to the low-mass dilepton $M_{ee}$ distribution

- $M_{ee}$ slope $\rightarrow$ QGP temperature

**EXPECTED PERFORMANCE: LOW-MASS DILEPTONS AND THERMAL RADIATION**

**ALICE Upgrade Simulation**

- **Pb-Pb $\sqrt{s_{NN}} = 5.5$ TeV, 0-10%**
- $L_{int} = 3 \text{ nb}^{-1}$
- ITS3, $B = 0.2$ T
- $|\eta_{c}| < 0.8$
- $p_{T,c} > 0.2 \text{ GeV}/c$
- $\rho_{c}^{\text{meas.'}} - c\bar{c} + \text{cocktail}
- Syst. uncert. sig. + bkg.
- Sum

**EXPECTED PERFORMANCE:low-mass dilepton**

- $1/N_{cut} \frac{d^{2}N_{\text{dilepton}}}{dM_{ee}d\eta}$ (GeV/c^2)^{-1}
- $0 \rightarrow 2.5$
- $M_{ee}$ (GeV/c^2)

- Reduction of statistical uncertainties by a factor 1.3

**ITS3:**

- Better charm rejection (vertexing)
- Reduced contribution from conversion (low material budget)
- Reduction of systematic uncertainties by a factor 2
• Study beauty-quark hadronisation mechanism
  ‣ $B_s^0$ production expected to be enhanced
    ‣ hadronisation of beauty quarks via recombination
      + enhanced strange-quark production in the QGP

$B_s^0 \rightarrow D_s^- \pi^+ \rightarrow \phi \pi^- \pi^+ \rightarrow K^+ K^- \pi^- \pi^+$

ALICE Upgrade Projection
$B_s^0 \rightarrow D_s^- \pi^+$
$0-10\% Pb-Pb, \sqrt{s_{NN}} = 5.5$ TeV
$L_{\text{int}} = 10$ nb$^{-1}$

- ITS2
- ITS3
- Unc. signal estimation
- Unc. background estimation

• Improvement by a factor 2 in significance with ITS3
  ‣ provide access to $B_s^0$ measurement at very low $p_T$
**EXPECTED PERFORMANCE: NON-PROMPT D_{S}^{+} NUCLEAR MODIFICATION FACTOR**

- **non-prompt D_{S}^{+}** from B decays:
  - even if not direct measurement, sensitive to B_{s}^{0}
  - larger statistical precision than exclusive B_{s}^{0} reconstruction
- Comparison between non-prompt D_{S}^{+} and non-strange D mesons sensitive to beauty-quark hadronisation and strangeness enhancement

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\[
D_{S}^{+} \rightarrow \phi \pi^{+} \rightarrow K^{+}K^{-}\pi^{+}
\]

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

**ALICE Upgrade Projection**

- 0-10\% Pb-Pb, \( \sqrt{s}_{NN} = 5.5 \text{ TeV} \)
- \( L_{\text{int}} = 10 \text{ nb}^{-1} \)

Non-prompt D\(^{+}\)

- ITS2
- ITS3
- TAMU

**ALI-SIMUL-344147**

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EXPECTED PERFORMANCE: NON-PROMPT D_{s}^{+} AZIMUTHAL ANISOTROPY

- Non-prompt D_{s}^{+} azimuthal anisotropy
  - Participation of beauty quarks in the collective motion and possible thermalisation in the QGP
  - Information about beauty-quark diffusion coefficient in the QGP

- ITS3:
  - sensitivity to discriminate azimuthal anisotropy for prompt and non-prompt D_{s}^{+} (charm vs. beauty)
charm baryon-over-meson ratios in Run 2

- Enhanced production of HF baryons in pp even more in Pb-Pb collisions
  - probes of heavy-quark hadronisation and baryon formation
- Measurement of $\Lambda_b^0$ in Pb-Pb collisions already accessible with ITS2
- Expected improvement of statistical significance up to a factor 2.5 with ITS3
**EXPECTED PERFORMANCE: C-DEUTERON**

- Predicted already **in the 70s** \(\text{PRL 39, 1506 (1977)}\)
- Never observed
- Lighter possible state: c-deuteron (bound state of \(\Lambda_c^+\) and neutron)
- Considered decay \((\Lambda_c^+ n) \to d K^- \pi^+\)

\[\begin{align*}
\text{ALICE simulation} & \quad \text{Pb-Pb} \quad s_{NN} = 5.5 \text{ TeV} \\
1 < p_T < 2 \text{ GeV/c} & \\
\text{ITS2} & \\
\text{primary } d & \\
d \text{ from } d_{\Lambda_c} \to d K^- \pi^+ & \\
\text{ITS3} & \\
\text{primary } d & \\
d \text{ from } d_{\Lambda_c} \to d K^- \pi^+ & \\
\end{align*}\]

- \(c\tau (\Lambda_c^+) \approx 59.9 \mu\text{m}\) \(\text{PRD 98, 030001 (2018)}\)
- Impact-parameter distribution of decay deuteron crucial to discriminate signal from background

ALI-SIMUL-350149

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The ALICE experiment is undergoing a major upgrade in LS2 in view of LHC Run 3.

New upgrades for LHC Run 4:

- **FoCal**
  - high granularity Forward Calorimeter to instrument the forward region
  - measure photons, $\pi^0$, and jets and constrain the nuclear PDFs in the low $x$ region
- **ITS3**
  - truly cylindrical silicon detector
  - novel detector technology based on ultra-thin wafer-sized curved sensors
  - improve measurements of low-mass dileptons and HF particles
  - searches for exotic nuclei
Expression of interest for a “all silicon” detector to be installed during LS4
- increase rate capabilities
- high spatial resolution (~3-5 μm)
- wide momentum and pseudorapidity acceptance
- particle identification via time-of-flight layers

Submitted as input to the European Strategy Update

Access to new measurements in heavy-ion collisions
- multi-charm baryons
- precision measurements of di-lepton spectra
- soft and ultra-soft photons

R. Preghenella 25 May, 15h00
The design of the detector:

- 20 layers: $W \ (3.5 \text{ mm} \sim 1X_0)$
- Si sensors of 2 types:
  - low granularity (LG) Si pads
  - high granularity (HG), pixels (e.g. CMOS MAPS)

- Moliere radius $\sim 1$-2 cm
Small direct $\gamma$ over $\pi^0$ ratio requires rejection of decay photons

Direct rejection: pair mass selection + shower shape selection enabled by high granularity

Isolation cut: reject decay (+fragmentation) photons based on energy in cone

Combined background rejection factor around 10
GLUON SATURATION

• BFKL as well as DGLAP are linear equations and only include parton splitting.

• At sufficiently high gluon densities, gluon would also recombined as described by BK/JMWLK equations.

When these two processes are in equilibrium, the number of gluons are constant.

\[ Q_s^2 \approx \frac{x G_A(x, Q^2)}{\pi R_A^2} A^{1/3} x^{-\lambda} \]
SENSITIVITY TO LOW-X NPDS: OPEN CHARM VS. PHOTONS

Pythia8, pp, \( \sqrt{s_{\text{NN}}} = 8.8 \) TeV ALICE simulation

- line: median
- band: 90% CL

- \( \gamma : 4.0 < \eta < 4.5 \)
- \( \gamma : 3.5 < \eta < 4.0 \)
- \( D^0 : 3.5 < \eta < 4.0 \)
- \( 4 < p_T^{\text{trig}} < 5 \text{ GeV/c} \)

LO estimate
- \( \eta = 3.5 \)
- \( \eta = 4.0 \)
- \( \eta = 4.5 \)
CONSTRAIN TO NPDF$_S$ FROM FORWARD HF MEASUREMENTS

arXiv:1707.02750
PLB 774, 159 (2017)
PLB 740, 105 (2015)
PRC 94, 054908 (2016)
EPJC 78, 171 (2018)
CONSTRaining to NPDS$_s$ FROM FORWARD HF MEASUREMENTS

(c) $B \rightarrow J/\psi$

(d) $T(1S)$
GEOMETRICAL PARAMETERS OF ITS3

New Beampipe: $r \approx 16\text{mm}$, $\Delta R = 0.5\text{mm}$

L0: $r \approx 18\text{mm}$, L1: $r \approx 24\text{mm}$, L2: $r \approx 30\text{mm}$

Beam pipe thickness: 500$\mu\text{m}$ (0.14% $X_0$)

Sensor thickness: 20 – 40$\mu\text{m}$ (0.03 - 0.05% $X_0$)
 Layers supported by high-thermal conductive carbon foam (half-ring)
EXPECTED PERFORMANCE: NON-PROMPT $D^+_s$ MESONS

- Impact-parameter ($d_0$) distribution of prompt $D^+_s$ mesons only driven by resolution
- Improvement in $D^+_s$ impact-parameter resolution up to a factor 2 with ITS3
- Better separation of prompt and non-prompt $D^+_s$
CMS B_s^0 MESONS

28 pb^{-1} (pp) + 351 \mu b^{-1} (PbPb) 5.02 TeV

CMS

R_{AA}^{B_s^0} / R_{AA}^{B^+}

TAMU

CUJET3.0

|y| < 2.4

CMS

R_{AA}^{B_s^0} / R_{AA}^{B^+}

Cent. 0-100%

p_T (GeV/c)

28 pb^{-1} (pp) + 351 \mu b^{-1} (PbPb) 5.02 TeV

CMS

R_{AA}^{B_s^0} / R_{AA}^{B^+}

TAMU

B^0

B^+

CUJET3.0

|y| < 2.4

Cent. 0-100%

p_T (GeV/c)
NON-PROMPT $D_s^+$ MESONS IN RUN 2 (PP COLLISIONS)

ALICE Preliminary

Prompt $D_s^+$, $|y| < 0.5$
- Data
EPJC (2019) 79:388

Non-prompt $D_s^+$, $|y| < 0.5$
- Data
FONLL + PYTHIA8 Decayer

$\frac{d^2\sigma}{dp_T^2 dy} (\mu b GeV/c^2)$

±2.1% lumi. unc. not shown
±3.5% BR uncertainty not shown

ALICE Preliminary

Prompt: EPJC (2019) 79:388

$D^0$
$D^+$
$D_s^+$
HYPERNUCLEI IN RUN 2

ALICE Preliminary

ALICE Performance

Pb-Pb √sNN = 5.02 TeV

2 ≤ ct < 4 cm, 0-90 %

ALICE Preliminary

Pb-Pb √sNN = 5.02 TeV, 0-90%

ALI−PREL−335127

ALI−PREL−334667

3ΛH lifetime (ps)

Theoretical predictions

PRC 57 (1998) 1595
Nuo. Cim. 46 (1966) 786
PLB 791 (2019) 48-53

ALICE Preliminary Pb–Pb 5.02 TeV

ALI−PREL−333625

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