The input from the Laboratory of Ultra-High Energy Physics of Saint-Petersburg State University (Russia) for the 2020 update of the European Strategy for Particle Physics

The title: **Heavy-flavour production in relativistic heavy-ion collisions and development of novel generation of extra-low-material-budget Vertex Detectors for future experiments at CERN and JINR**

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Abstract.

One of the key requirements to be met by the future experimental installations like ALICE is to increase the accuracy of secondary vertices reconstruction in order to meet the challenging task of high precision studies in relativistic heavy-ion collisions of such rare processes like heavy-flavour production. This task requires the further reduction of the existing values of material budget of the Inner Tracking System and it is one of the main goals of the ALICE upgrade during the Long Shutdown 3 (LS3) in the period 2023-2024. The Inner Tracking System (ITS2) – the main vertex detector of ALICE – already has the record level of 0.3% radiation length (X/Xo) per layer. The new task is the development of a new high granularity fast detector which will be capable to ensure X/Xo below of 0.05% per layer. This challenge of development of high precision Vertex Detector is relevant not only to ALICE but to all experimental HEP installations both in Europe and Russia.

The proposal of the ALICE/ITS Collaboration, aimed at the R&D of the Ultra Lightweight Vertex Detector for the future ITS3 to be installed after the LS3, was developed recently and the Saint-Petersburg State University team is one of the participants. This Ultra Lightweight Vertex Detector will consist of ultra-thin (~20μm) silicon sensors with MAPS technology, arranged in perfectly cylindrical layers, featuring an unprecedented low material budget of 0.05% X_0 per layer. The given task is also paving the way for the construction of a new all-silicon tracker with unprecedented low mass, that would allow reaching down to an ultra-soft region of the phase space and to measure the production of very-low transverse momentum lepton pairs, photons and hadrons at the LHC after Long Shutdown 4 (LS4). Among the real strong challenges to be met are the design and development of the extra-lightweight, state-of-the-art support structures capable to ensure the high level of thermo- and mechanical- stability of the large arrays (of many square meters) of these ultra-thin silicon sensors. Another challenge is the efficient, very low speed, gas cooling system that will provide the functionality of these MAPS sensors.

The implementation of these advanced detector and carbon fiber composite technologies to the vertex trackers will also expand considerably the heavy-flavour research physics programs at the fixed-target NA61/SHINE at the SPS, during the LS2 in 2019-2021, and to the future BM@N, MPD and SPD experiments at NICA collider at JINR.

Comprehensive overview

Scientific context

Among the main physics objectives of the ALICE physics programme in the next decade are the measurements of low momentum charmed hadrons and low-mass dielectrons produced in heavy-ion collisions at the LHC. These studies will provide a deeper insight into the properties of the QGP formed in these collisions. In particular, the heavy flavour measurements are of the primary interest due to the following still unsolved questions concerning heavy-flavour production and interactions with the QGP medium [1]:

- Thermalisation and hadronisation of heavy quarks in the medium, which can be studied by measuring the heavy-flavour baryon/meson ratio, the strange/non-strange ratio for charm, the azimuthal anisotropy v2 for charm and beauty mesons, and the possible in-medium thermal production of charm quarks.
- Heavy-quark in-medium energy loss and its mass dependence, which can be addressed by measuring the nuclear modification factors R_{AA} of the p_T distributions of D and B mesons separately in a wide momentum range, as well as heavy flavour production associated with jets.

The high statistic and high efficiency measurements of rare processes of heavy-flavour production are needed in order to understand the dynamics of the QGP. This could be achieved by the considerable improvement of charged particle tracking accuracy and by the extension of the low pT region of charged particle registration. The high efficiency for a detailed measurement of low-mass dielectrons is also needed that will give access to [1]:

- Thermal radiation from the QGP, via real and virtual photons detected as dielectrons.
- In-medium modifications of hadronic spectral functions related to chiral symmetry restoration, in particular for the ρ meson in its e^+e^- decay mode.

The production measurement of hypernuclear states, like ${}^3{}_\Lambda H \rightarrow {}^3 He + \pi^-$, should also largely benefit from the improved tracking resolution and the high envisaged integrated luminosity.

The design goals of highly efficient tracking over an extended momentum range, with special emphasis on very low momenta and very precise reconstruction of secondary vertices from decaying charm and beauty hadrons, are being met already at present by the ALICE Collaboration basing on the 0.18 μm CMOS technology by TowerJazz that has been selected for the implementation of the Pixel Chip for all layers of the new ALICE Inner Tracking System [1]. The Summary of the Physics reach [1] planned to be reached by ALICE ITS2 after the year 2020 in compare with the current ITS1 performance is presented in the Table 1 below.

The Laboratory of Ultra-High Energy Physics of Saint-Petersburg State University was involved since 1992 into the development of the ALICE ITS1 that was successfully in 10 years of operation in the RUN-1 data taking till the end of the year 2018. Strongly improved physics scope might be reached with the recent innovations in silicon imaging technology that provides a significant advancement in the measurement of low momentum charmed hadrons and low-mass dielectrons in HI collisions at the LHC, and the Laboratory is actively participating since 2011 in the R&D for the ALICE ITS2.

Table 1. The Summary of the Physics reach by ALICE after 2020 (see Table 8.6 in [1]):

Observable	Current, $0.1\,\mathrm{nb}^{-1}$		Upgrade, $10\,\mathrm{nb}^{-1}$	
	$p_{\mathrm{T}}^{\mathrm{min}}$ (GeV/c)	statistical uncertainty	$p_{\mathrm{T}}^{\mathrm{min}}$ (GeV/c)	statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 %	0	0.3 %
$\mathrm{D_s}$ meson R_{AA}	4	15 %	< 2	3 %
D meson from B R_{AA}	3	30 %	2	1 %
J/ψ from B R_{AA}	1.5	15 % (p_{T}-int.)	1	5 %
B^+ yield	not accessible		2	10 %
Λ_{c} R_{AA}	not accessible		2	15 %
$\Lambda_{\mathrm{c}}/\mathrm{D}^0$ ratio	not accessible		2	15 %
Λ_{b} yield	not accessible		7	20 %
D meson v_2 ($v_2 = 0.2$)	1	10 %	0	0.2 %
$\mathrm{D_s}$ meson v_2 ($v_2 = 0.2$)	not accessible		< 2	8 %
D from B v_2 ($v_2 = 0.05$)	not accessible		2	8 %
J/ψ from B v_2 ($v_2 = 0.05$)	not accessible		1	60 %
Λ_{c} v_2 ($v_2 = 0.15$)	not accessible		3	20 %
Dielectrons				
Temperature (intermediate mass)	not accessible			10 %
Elliptic flow ($v_2 = 0.1$) [4]	not accessible			10 %
Low-mass spectral function [4]	not accessible		0.3	20 %
Hypernuclei				
${}^{3}_{\Lambda}\mathrm{H}$ yield	2	18 %	2	1.7 %

Recently a proposal by the ALICE Collaboration at the LHC was prepared [2] for the construction of a novel vertex detector consisting of curved wafer-scale ultra-thin (~20 μm) silicon sensors arranged in perfectly cylindrical layers, featuring an unprecedented low material budget of 0.05 % X0 per layer, with the innermost layer positioned at only 18 mm radial distance from the interaction point. This new vertex detector ITS3 is planned to be installed during the LS3 to replace the innermost three layers of the ITS2 (the ALICE ITS2 is to be running after the LS1). After the LS2, the novel ITS3 will provide a larger reduction of the material budget in the region close to the interaction point and a larger improvement of the tracking precision and efficiency at low transverse momentum (see Fig.1). Thus it will be also possible to consider this technology for future construction of a new, all-silicon tracker with unprecedented low mass, that would allow reaching down to an ultra-soft region of phase space and to measure the production of very-low transverse momentum lepton pairs, photons and hadrons at the LHC after the Long Shutdown 4 (LS4).

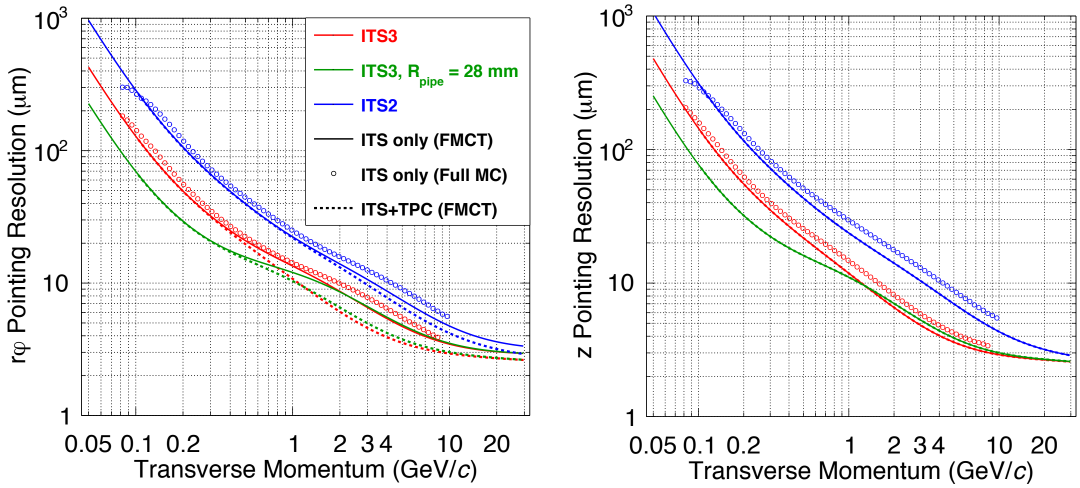

Figure 1 (see Figure 10 in [2]): Impact parameter resolution for primary charged pions as function of the transverse momentum for the ITS2 upgrade (blue) and the ITS3 upgrade (red) in the transverse plane (left panel) and in the longitudinal direction (right panel). The green curves (ITS3, Rpipe = 28 mm) refer to the detector configuration with the innermost two layers inside the vacuum chamber (see the text for further details). All solid lines show the results with Fast Monte Carlo Tool (FMCT), and ITS only, all dashed lines show the results with FMCT and ITS+TPC, all open circles show the results with Full MC and ITS only. [2]

A comparison of the performance with ITS2 (using the new centrality range and p_T binning) and ITS3 is shown in Fig. 1 ([2]) for the statistical significance $S/\sqrt{(S + B}$ (left) and signal-to-background S/B ratio (right). S and B are the signal and background yields in an invariant-mass range of $\pm 3\sigma$ around the Λ_c mass, where σ is the invariant-mass resolution (about 5 to 15 MeV/c^2 depending on p_T). The statistical significance is given for 8 billion events in the 0 –10 % centrality class, corresponding to $L_{int} = 10$ nb^{1}. An improvement is found with ITS3 of a factor about four for the significance and ten for the S/B ratio, because the better pointing resolutions allow for a larger rejection of the combinatorial background and a larger efficiency for the signal selection [2]. In particular, the significance in the lowest interval $2 < p_T < 3$ GeV/c, where the baryon-to-meson ratio is maximal for Λ/K^0_S, is marginal with ITS2 (~ 20% relative statistical uncertainty) and large with ITS3 (~ 4% uncertainty)[2].

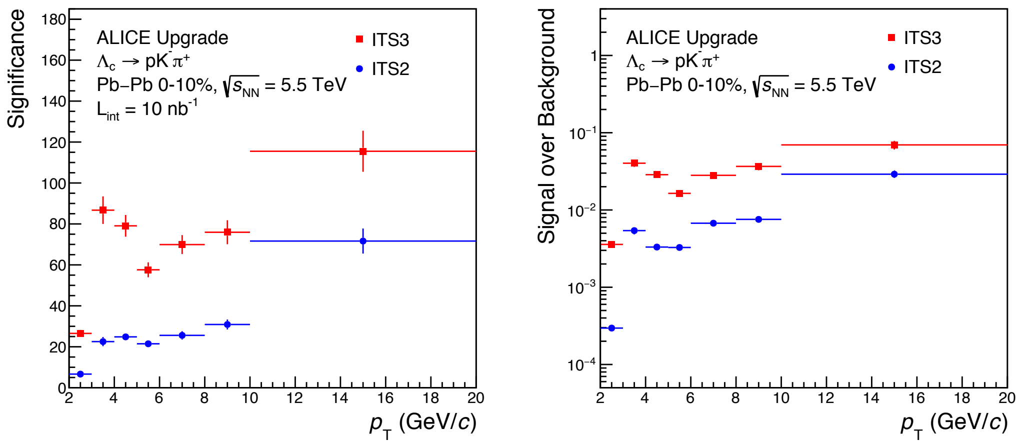

Figure 2 (see Figure 12 in [2]): $\Lambda_c{}^{+} \rightarrow pK^{-}\pi^{+}$ in central Pb–Pb collisions at $\sqrt{s_{NN}}$ =5.5TeV(L_{int} = 10nb^{-1}): statistical significance (left) and S/B ratio (right) as a function of p_T.

Objectives

The objectives of this proposal is to provide the high statistic and high efficiency measurements of rare processes of heavy-flavour production in Pb+Pb collisions by the considerable improvement of charged particle tracking accuracy and by the extension of the low p_T region of charged particle registration by the currently existing vertex detectors (in particular, of the ALICE ITS).

The participation of Saint-Petersburg State university group will be focused in two aspects:

(i) theoretical investigations of the initial state effects and heavy flavor production mechanisms and

(ii) development of the new extra-lightweight, state-of-the-art support structures capable to ensure the high level of thermo- and mechanical-stability together with the efficient, very low speed, gas cooling system that will provide the functionality of the arrays of ultra-thin (~20μ) silicon sensors with MAPS technology.

Measurements of low momentum charmed hadrons and low-mass dielectrons produced in heavy-ion collisions at the LHC will provide a deeper insight into the properties of the QGP formed in these collisions.

Methods of studies of long-range correlations between various observables and the application of strongly-intensive variables, that are being developed by Saint-Petersburg team, will allow to study the effects of the initial stages of collisions and the mechanisms of heavy-flavour production in the collisions of relativistic nuclei (see in [3-16]).

Methodology

The methodology for the Ultra Lightweight Vertex Detector for LS2 is based on the existing practical experience of the ALICE/ITS Collaboration, including Saint-Petersburg State University, in the development of the ITS1 and ITS2 vertex detectors.

The experience with the ultra-lightweight carbon fiber composite support structures [17] with the integrated cooling for sensors done in 0.18 μm CMOS technology by TowerJazz, that has been selected for the implementation of the Pixel Chip for all layers of the ITS2 ALICE, allows to propose the following major stages for the ITS3 development:

- Theoretical analysis of various mechanisms of heavy-flavour production in collisions of heavy-ions, long-range correlations with heavy-flavour particles, initial stages of heavy-ion collisions and requirements to the new ITS3;
- Design and model calculations of the optimal layout of the ITS3;
- The upgrade of technology for the production of the novel ultra-lightweight carbon fiber composite support structures for the new types of curved wafer-scale ultra-thin (~20μ) silicon sensors ;
- Tests of these novel ultra-lightweight carbon fiber composite support structures;
- Preparation of the test-bench for the new very-low speed, efficient gas cooling system for these novel types of curved wafer-scale ultra-thin (~20μ) silicon sensors;
- Design of the low-mass thermal screen system for cooling gas distribution to avoid any water condensation both on the ALPIDE sensors and inside the ALICE installation;
- Final design of the Vertex Detector with the account of ALICE Inner Barrel of the Inner Tracking System requirements;
- Tests of some key units

Readiness and expected challenges

- The Laboratory of Ultra-High Energy physics of Saint-Petersburg State University is currently involved in ALICE and NA61/SHINE experiments at CERN and in the MPD at NICA at JINR. It is composed of 23 participants (including students, PhD students, researches and engineers).
- The Laboratory is involved since 1992 in the development of the currently running in 2018 the ITS1 for ALICE and also since 2005 in the ALICE physics programme and data analysis. Today it is also an active participant of the ITS2 development, contributing with its know-how to the design and production of the ultra-lightweight, thermo- and mechanically- stable carbon fiber composite support structures with the integrated cooling for the ALPIDE sensors.
- The Laboratory was involved in the NA57 experiment in 1996-2003 years.
- The Laboratory is an active participant since 2006 in the NA61/SHINE at the SPS physics programme and data analysis.
- The Laboratory joined the MPD Collaboration at NICA (JINR) in 2018.

- Since 2004 the Laboratory is participating in the activity of the ENLIGHT community and is trying to provide the communication link to Saint-Petersburg in the knowledge transfer in the field of hadron therapy.
- Currently the Laboratory is coordinating all Russian ALICE GRID sites involved in the WLCG.
- The methodology for the Ultra Lightweight Vertex Detector for LS2 is based on the existing practical experience of the ALICE/ITS Collaboration including Saint-Petersburg State University in development of the ITS1 and ITS2 vertex detectors.
- The experience with the production of the ultra-lightweight carbon fiber composite support structures with the integrated cooling system [17], and tests of different modes of cooling, including gaseous cooling systems capable to provide temperatures for the detectors down to – 110^{o}C, allow to propose the given project.

The expected challenges are:

- Theoretical analysis, search of the sensitive observables and development of the physics program of studies of the initial states effects in the long-range rapidity correlations with participation of heavy flavours in heavy-ion collisions
- Development of extremely-low-mass, thermo- and mechanically stable mechanical support structures for a novel vertex detector consisting of curved wafer-scale ultra-thin (~20μ) silicon sensors arranged in perfectly cylindrical layers, featuring an unprecedented low material budget of 0.05 % X_0 per layer
- Development of the efficient, very low speed, gas cooling system, capable to ensure the functionality of these ultra-thin, high granularity, large area novel ALPIDE sensors for the future ITS-3 Ultra Lightweight Vertex Detector.
- Design of the extremely low-mass thermal screen system for cooling gas distribution where any water condensation should be avoided both on the ALPIDE sensors and around the supplying cooling ducts inside the ALICE installation.

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