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Open charm measurements at CERN SPS energies in the NA61/SHINE experiment - status and plans

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Outline

- Open charm measurements motivation;
- The NA61/SHINE experiment for open charm measurements;
- Vertex Detector project;
- Data taking results with Vertex Detector;
- Future plans of the NA61/SHINE experiment for open charm measurements.

Models of charm production

- The measurement of mesons containing heavy flavour is of high importance for better understanding of nucleus–nucleus collisions at relativistic energies;

- Predictions of charm yield
  - Dynamical approach;
  - Statistical approach;
  - Results for produced $< c\bar{c} >$ pairs differ by up to two orders of magnitude for central Pb+Pb collisions at top SPS energy (150*A* GeV/c ($\sqrt{s_{NN}}$= 16.8 GeV));
- Good estimate of $< c\bar{c} >$can be obtained measuring yields of D^0, D^+ and their antiparticles (~ 85% of the total produced charm);
- Up to now, only indirect measurements of open charm production in AA collisions at the SPS energies exist and they are not precise enough to distinguish the dynamical and statistical approaches
  → One needs direct measurements of open charm yields.

Charm particles as a signal of deconfinement

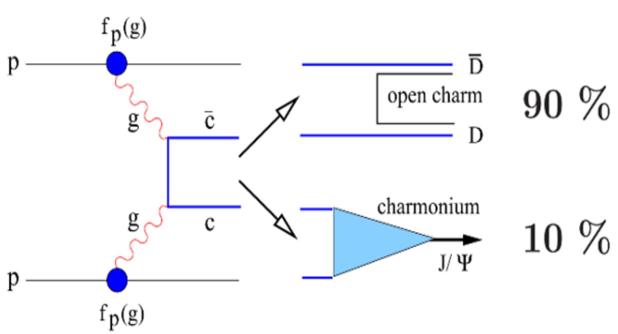
- The production of charm is expected to be different in confined and deconfined matter.

- Confined matter:
  lightest charm carrier – D meson;
  production of $<D\bar{D}>$pair ~3.7 GeV;
- Deconfined matter:
  charm carrier – (anti-)charm quark;
  production of $<c\bar{c}>$pair ~2.6 GeV.

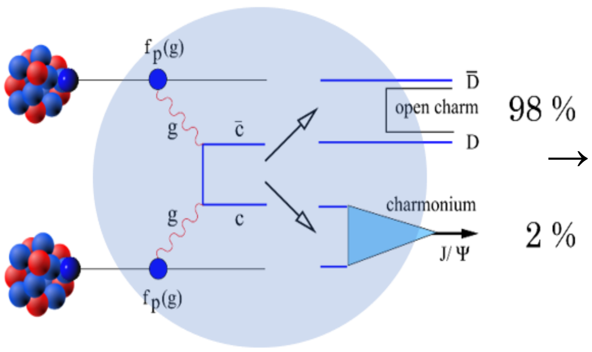
More abundant charm production is expected in deconfined than in confined matter;

→ change of collision energy dependence may be a signal of onset of deconfinement

vacuum



medium

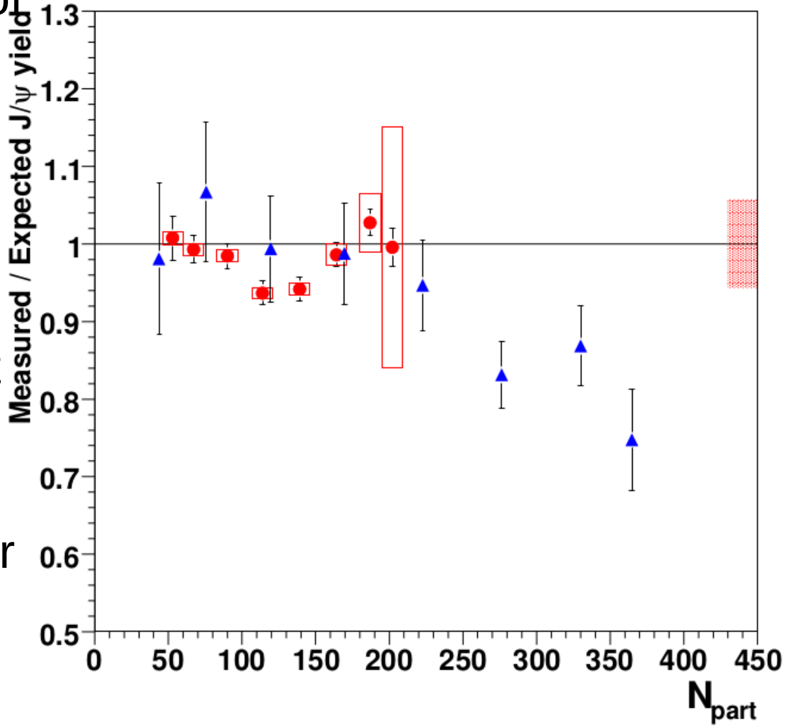


→ Medium reduces probability of J/ψ production

Abnormal J/ψ suppression

- NA60 experiment measured the production of J/ψ in In+In and Pb+Pb collisions;
- For lower number of participants the yields are consistent with the theoretical estimations;
- However, at $N_{part} \sim 200$ the result shows significant drop, which is known as the effect of anomalous J/ψ suppression;
- It was initially attributed to onset of QGP formation in nuclear collisions, however other explanations have also been proposed.

Nucl. Phys A 830 239c (2006)



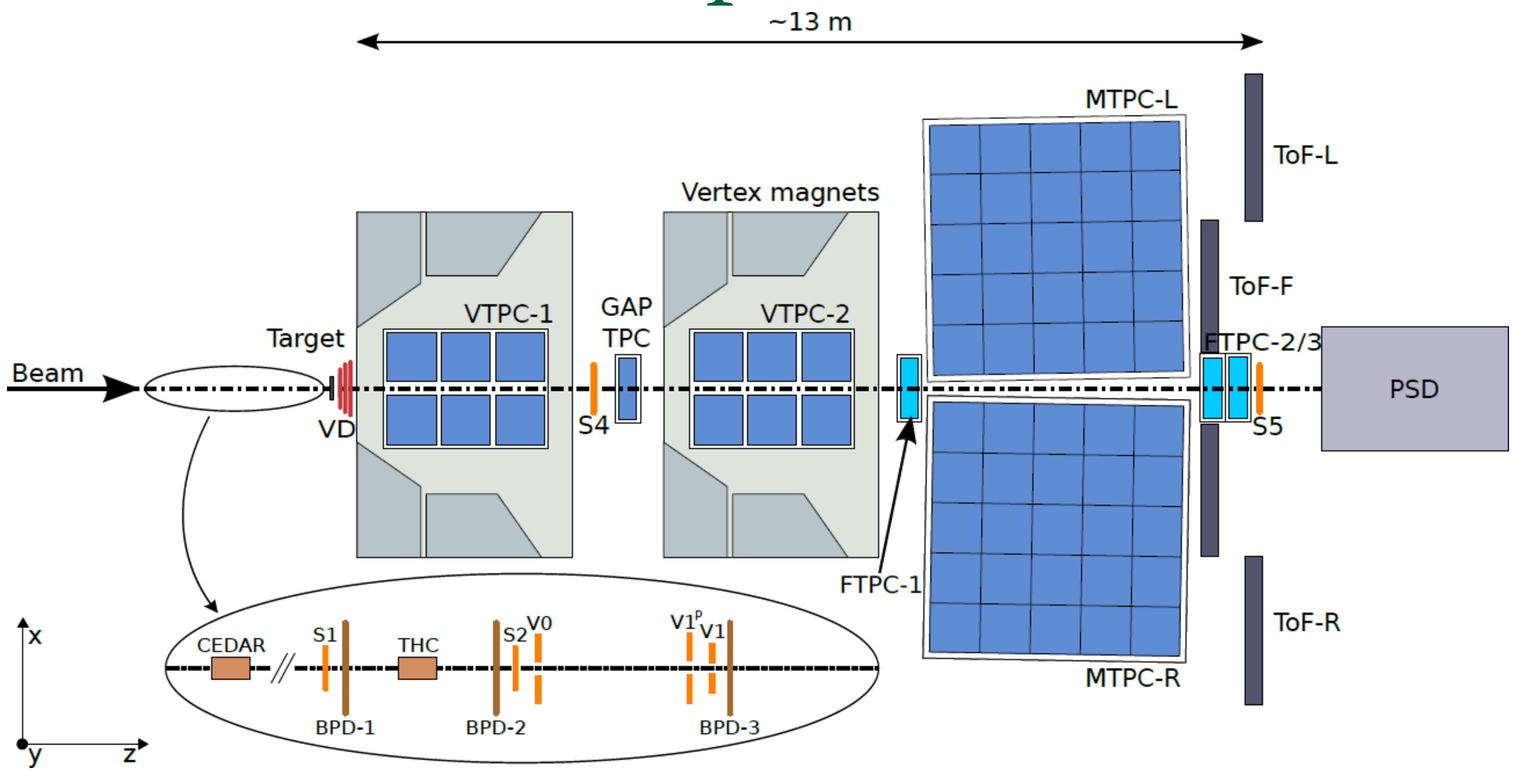
- To verify observed signature of QGP formation one needs to obtain information on total balance of charm.
- This can be achieved by measurement of open charm production in all channels.

Open charm measurements motivation

- Questions addressed by the charm measurements:
  - What is the mechanism of open charm production?
  - How does the onset of deconfinement impact open charm production?
  - How does the formation of quark-gluon plasma impact *J/ψ* production?

- To answer these questions mean number of charm quark pairs $< c\bar{c} >$ produced in the full phase space in A+A collisions has to be known.
- Up to now corresponding experimental data does not exist;
- → One needs direct measurements of open charm yields.

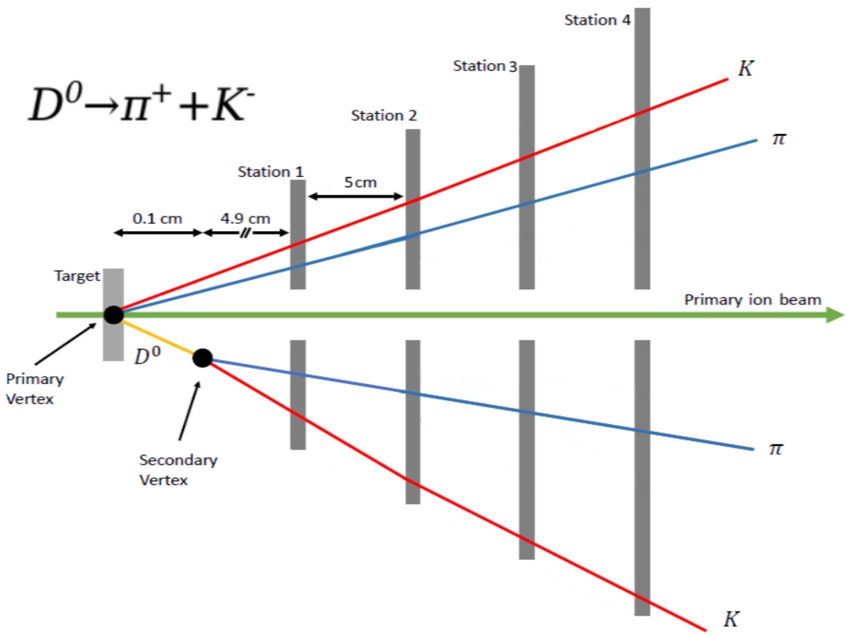
NA61/SHINE experiment



- The strong interactions programme of the NA61/SHINE experiment at the CERN SPS is expanding to allow precise measurements of particles with short lifetime, such as D-mesons and multistrange hadrons;
- → The NA61/SHINE experiment was upgraded in 2016 with the new Small Acceptance Vertex Detector (SAVD).

Programme for open charm measurements

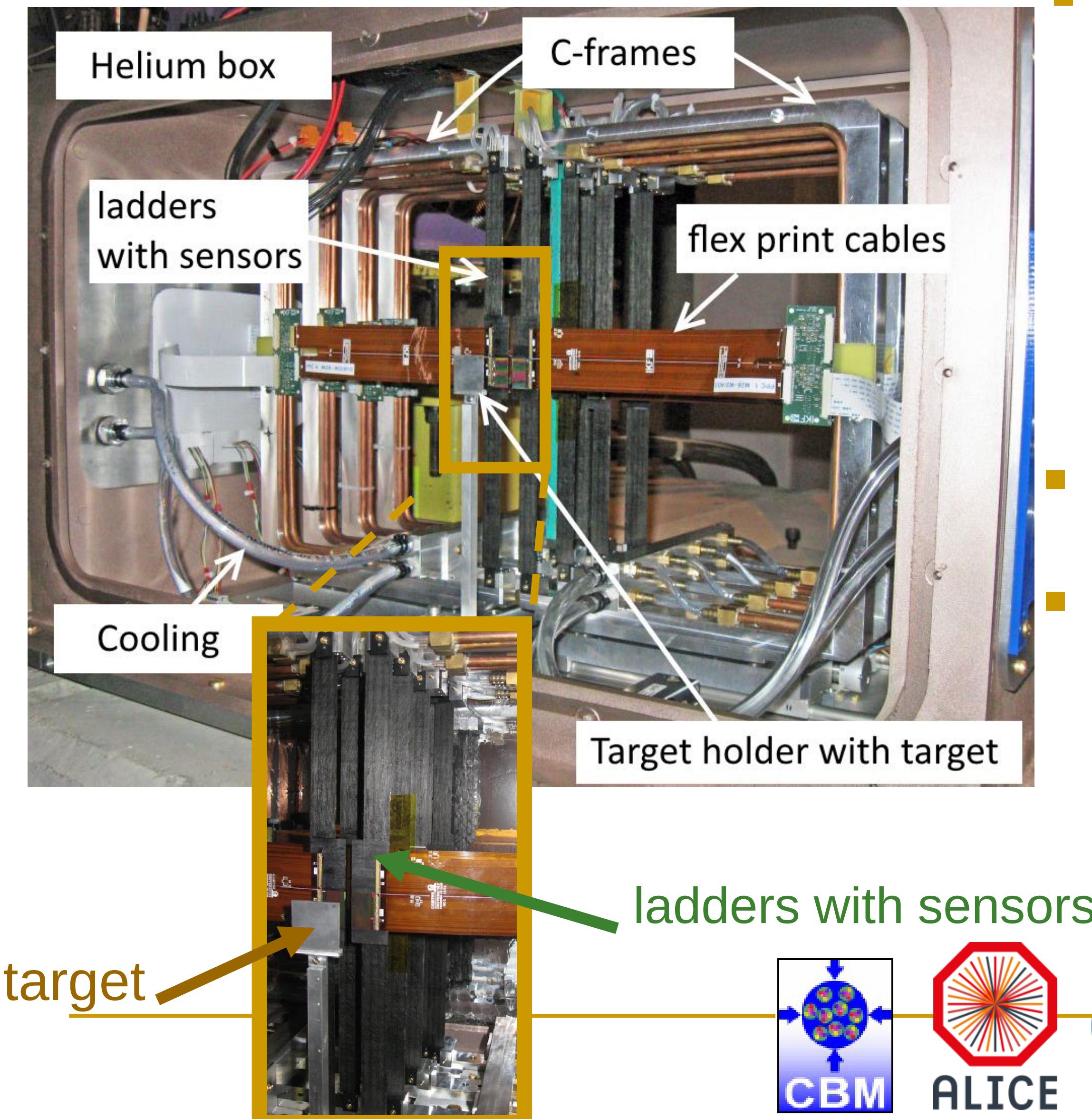
- The low yields of charmed particles → require precise tracking and low material budget close to the primary vertex;
- The short mean life-time of D mesons → rather small distance between the decay vertices of D mesons and the primary vertex.



→ Vertex Detector project based on CMOS pixel detectors.

Meson	Decay channel	$c\tau$	Branching ratio
D^0	$D^0 \to K^- + \pi^+$	122.9 μm	(3.91±0.05)%
D^0	$D^0 \to K^- + \pi^+ + \pi^+ + \pi^-$	122.9 μm	(8.14±0.20)%
D^+	$D^+ \to K^- + \pi^+ + \pi^+$	311.8 μm	(9.2±0.25)%
D_s^+	$D_s^+ \to K^+ + K^- \pi^+$	149.9 μm	(5.50±0.28)%
D^{*+}	$D^{*+} \to D^0 + \pi^+$	...	(61.9±2.9)%

Vertex Detector



- Main purpose of the Vertex Detector is the improvement of track resolution near the interaction point to allow reconstruction of secondary vertices;

- SAVD is positioned between the target and the VTPC-1;
- Four planes of coordinate-sensitive detectors are located at 5, 10, 15 and 20 cm distance from the target.

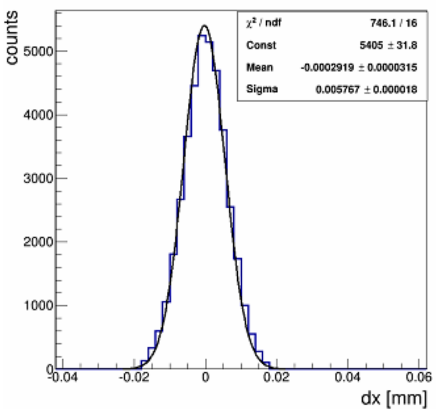
CBM ALICE iPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

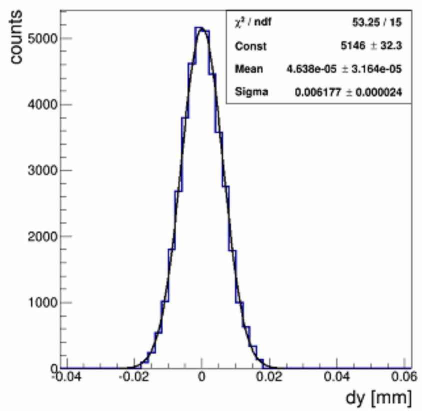
Reconstruction algorithm in SAVD

- The SAVD consists of two arms: Jura and Saleve, in which track reconstruction can be done independently;
- The magnetic field in SAVD volume is inhomogeneous (B_y = 0.13÷0.25T);
- Track reconstruction is done iteratively:
  1. Finding 4-hit tracks by a combinatorial method with straight line track model;
  2. Reconstruction of the primary vertex;
  3. Using information about the primary vertex position one can find 3-hit tracks using the Hough Transform method;
  4. Fitting tracks with a parabola in (XZ) plane and a straight line in (YZ) plane.
- Track matching between VD and TPC is done using the following algorithm: tracks are fitted to the VD primary vertex and then interpolated to other VD stations and the matching clusters are collected;
- Finally, the whole track is refitted using the Kalman Filter.

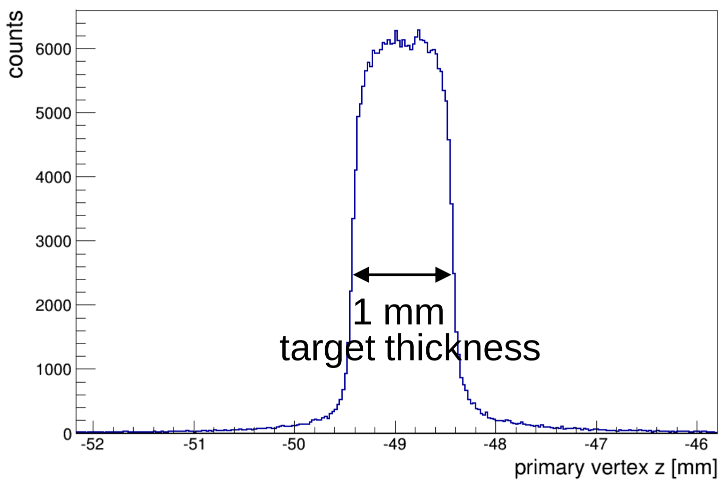
Performance of SAVD for Pb+Pb 150A GeV/c

- December 2016
  SAVD was installed for Pb+Pb data taking
  at 150A GeV/c ($\sqrt{s_{NN}}$= 16.8 GeV) and a pilot data set was collected.





- Spatial sensor resolution obtained by looking at residuals between hits and reconstructed tracks for non-field runs is σ_x = 4.7μm and σ_y = 5.0μm.

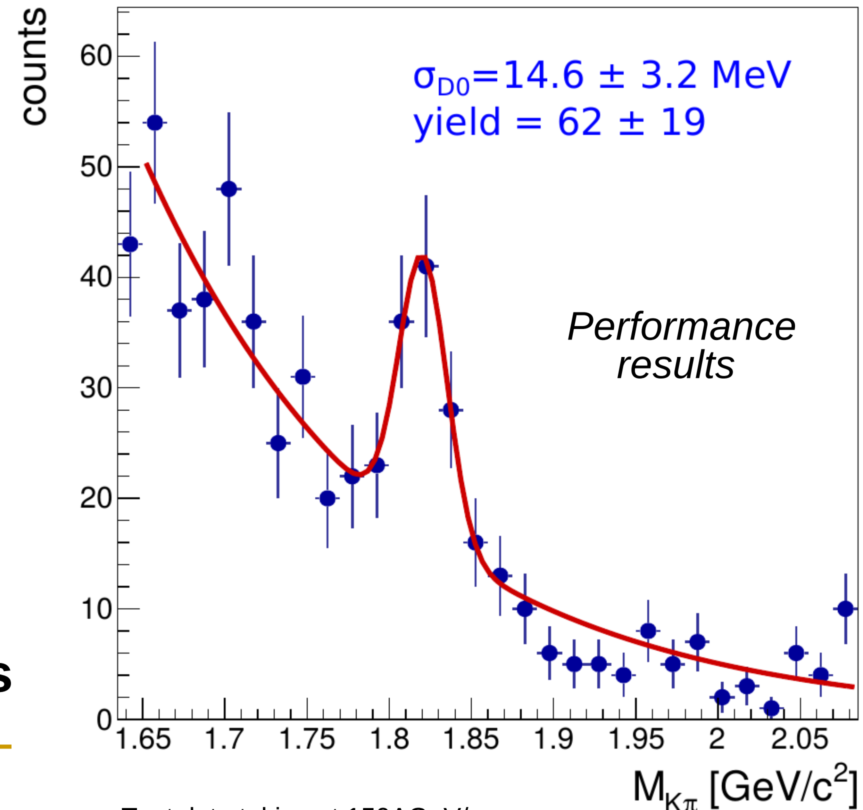


- Spatial resolution of the primary vertex:
  σ_x = 5 μm, σ_y = 1.5 μm, σ_z = 30 μm.
- The difference between σ_x and σ_y is attributed to the presence of the vertical component of the magnetic field.

Reconstruction of D^0 signal

- SAVD tracks matched to TPC tracks are used in the search for the D^0 signal;
- Each SAVD track is paired with another SAVD track and is assumed to be either a kaon or pion;
- To suppress the background one needs to introduce cuts:
  - Cut on transverse momentum $p_T > 0.34$ GeV/c;
  - Cut on the track impact parameter at decay vertex $d > 34$ μm;
  - Cut on the longitudinal position $V_z > 475$ μm of the track pair vertex relative to primary vertex;
  - Cut on the parent particle impact parameter $D < 21$ μm.

First observation of D^0 peak in Pb+Pb collisions at SPS energies

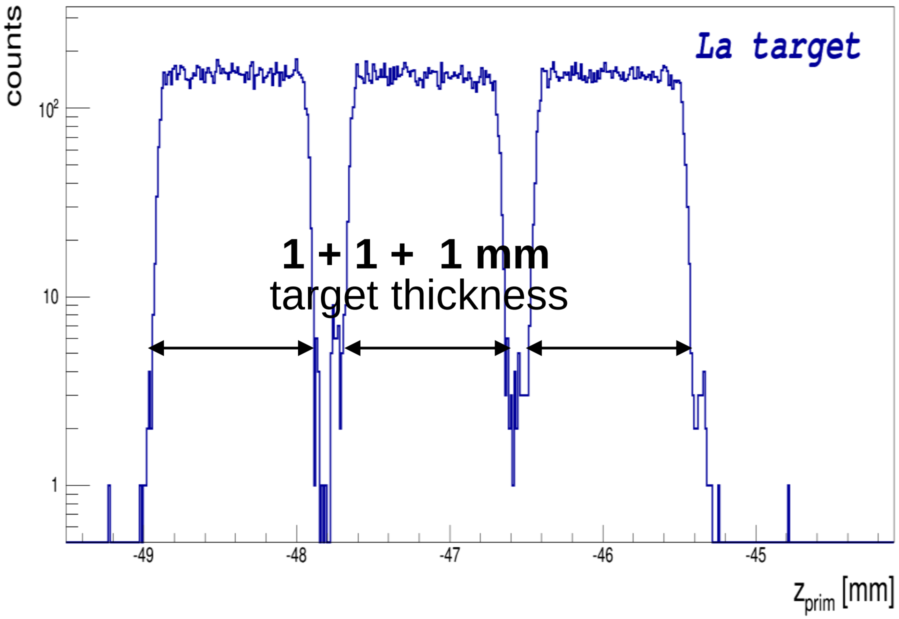


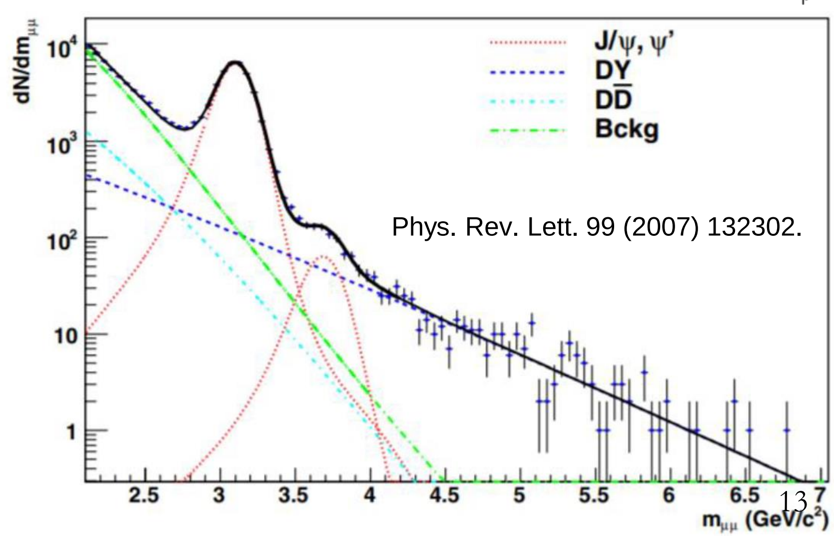
Test data taking at 150AGeV/c

Performance for Xe+La data taking

- November-December 2017:
  Large statistic Xe+La data taken at 150*A*, 75*A and 40 A*GeV/*c*.
  - La target consisted of 3 layers of 1mm thickness each.
    The structure of the target can be well seen in Z_{prim} distribution plot;
  - Spatial resolution of the primary vertex: σ_x = 1.3 μm, σ_y = 1 μm and σ_z = 15 μm.

- The combination of NA60 results on hidden charm in In+In (A = 115) and NA61 results on open charm in Xe+La (A = 129, A = 139) will provide a total balance on charm production.
- These data should allow for reinterpretation of J/*ψ* yields measured by the NA60 collaboration.





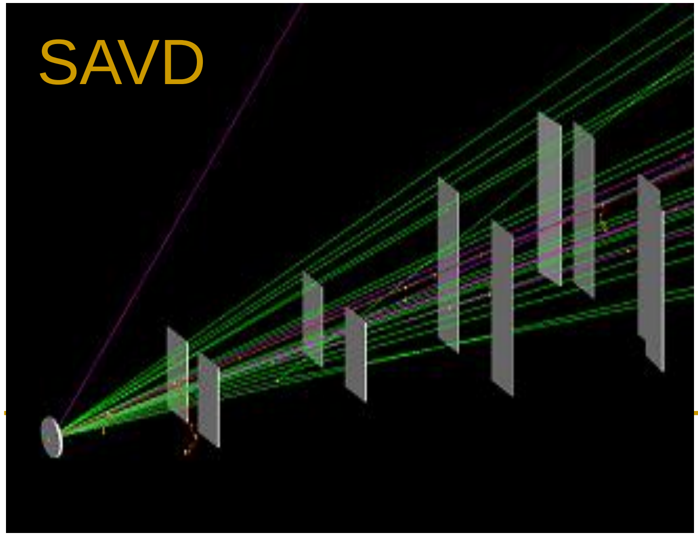
Future plans for open charm measurements
in the NA61/SHINE experiment

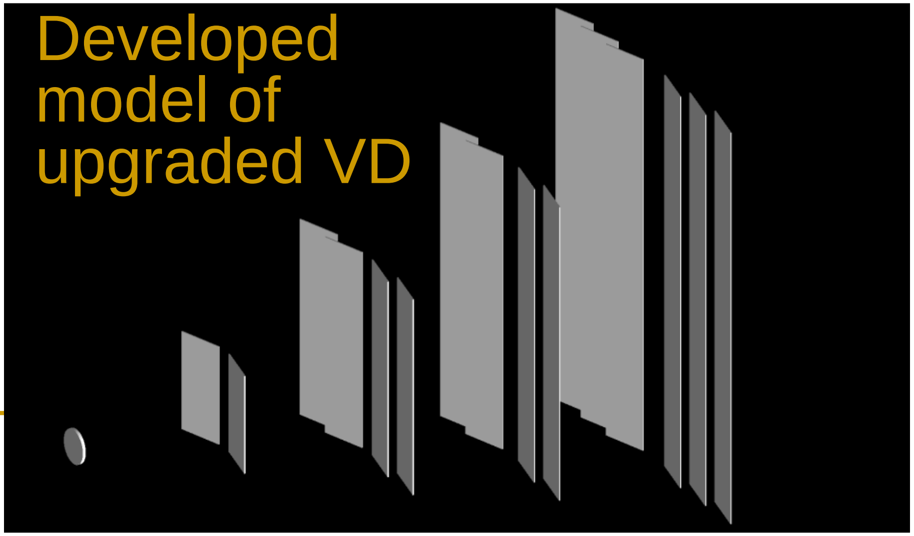
Upgrades of NA61/SHINE setup after LS2

- The NA61/SHINE experiment will be upgraded to increase the data taking rate from 80Hz to 1kHz.

- The upgraded VD will be based on the same layout and mechanical support as SAVD, but will instead be possibly based on 46 ALPIDE sensors developed for ALICE ITS, and will have larger acceptance for each station.

	SAVD	Future VD
Sensor	MIMOSA-26	ALPIDE
№ sensors	16	46
Active surface	$32cm^2$	$190cm^2$
Spatial resolution	$3.5\mu m$	$5\mu m$
Time resolution	$115.2\mu s$	$10\mu s$

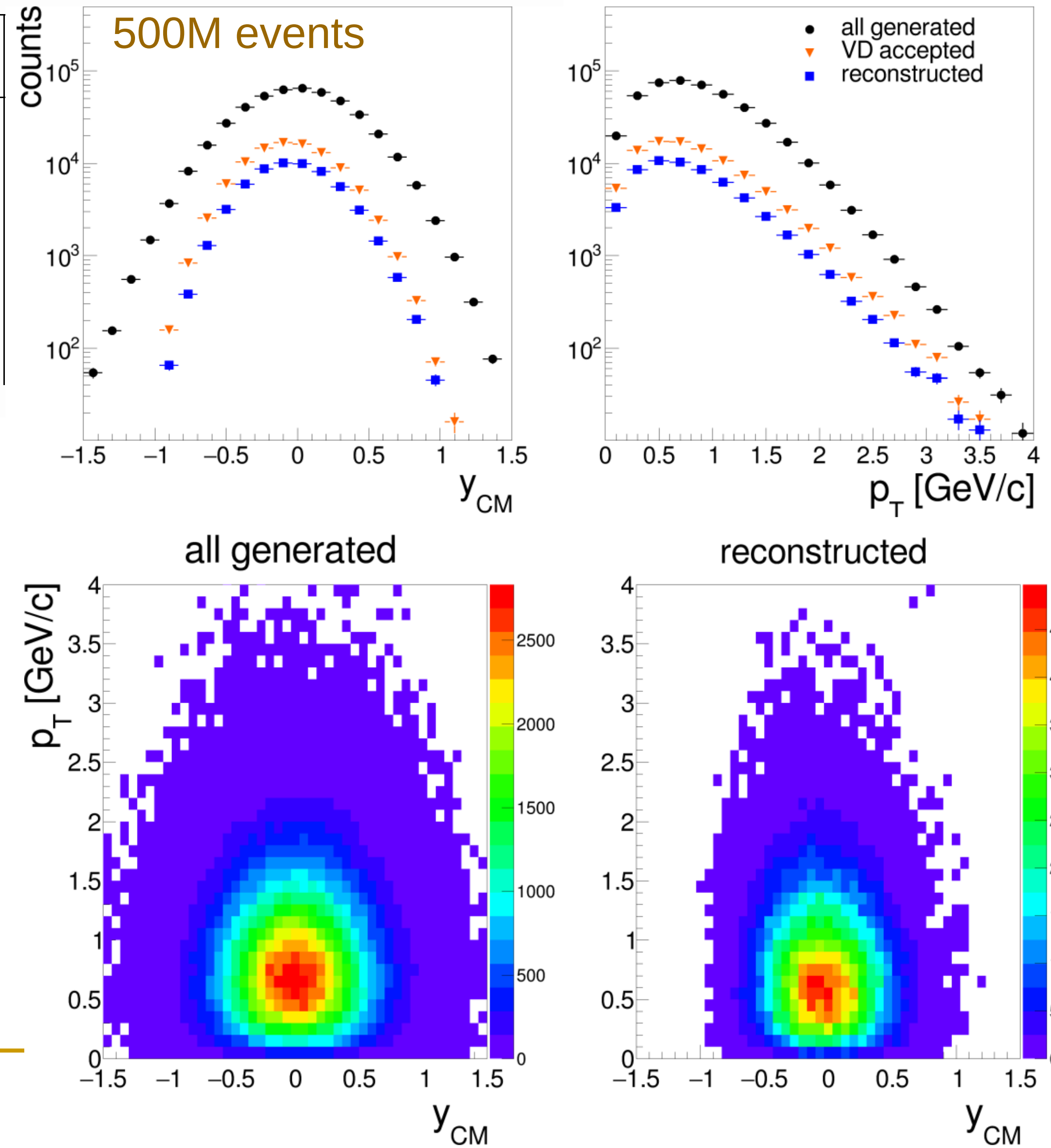




Upgraded Vertex Detector: D^0 & antiD^0

Meson	Decay channel
$\boxed{D^0}$	$\boxed{D^0 \rightarrow K^- + \pi^+}$
D^0	$D^0 \rightarrow K^- + \pi^+ + \pi^+ + \pi^-$
D^+	$D^+ \rightarrow K^- + \pi^+ + \pi^+$
D_s^+	$D_s^+ \rightarrow K^+ + K^- \ \pi^+$
D^{*+}	$D^{*+} \rightarrow D^0 + \pi^+$

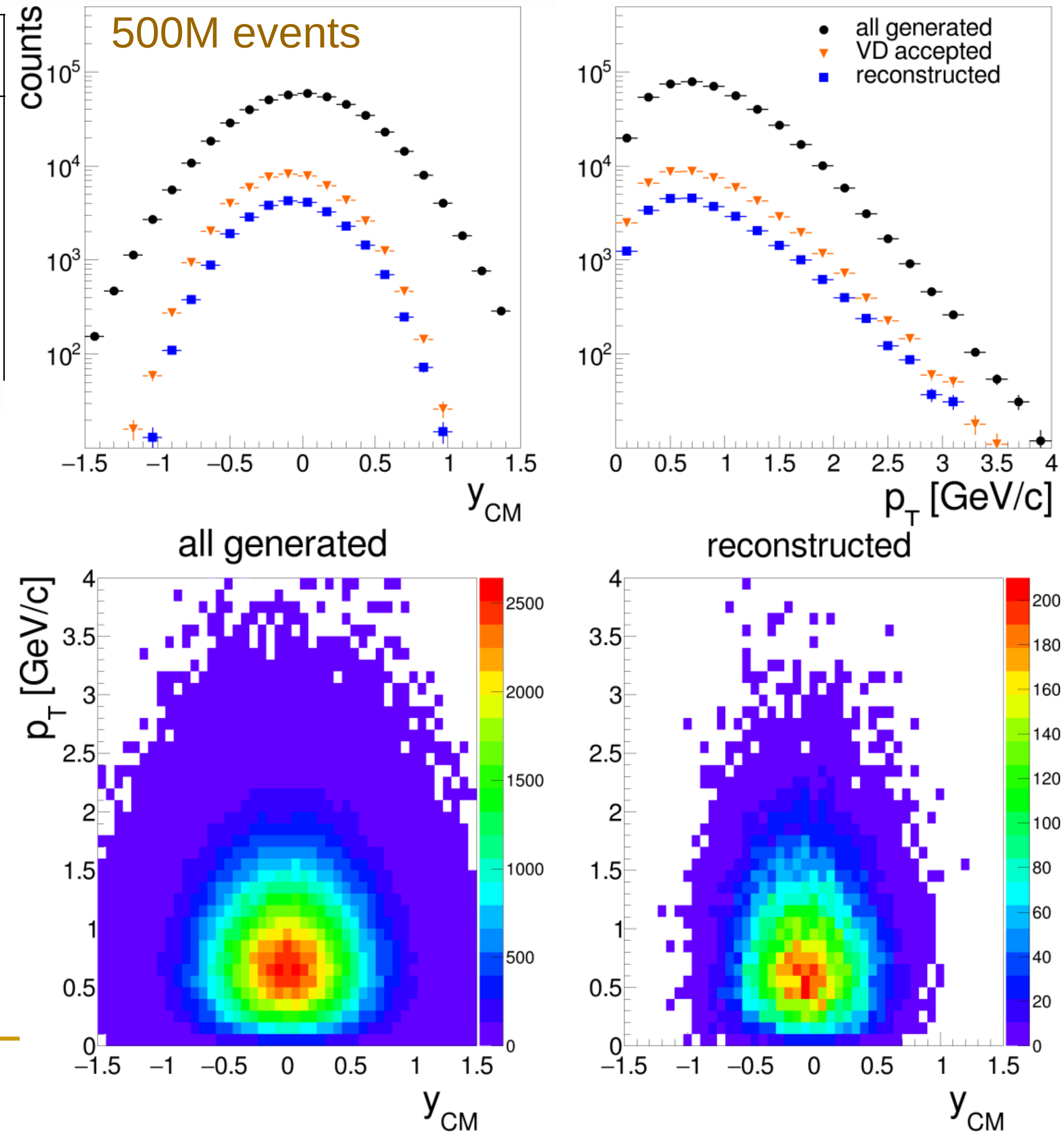
- Simulations were done using phase space of D mesons from AMPT event generator



Upgraded Vertex Detector: D^+ & D^-

Meson	Decay channel
D^0	$D^0 \rightarrow K^- + \pi^+$
D^0	$D^0 \rightarrow K^- + \pi^+ + \pi^+ + \pi^-$
D^+	$D^+ \rightarrow K^- + \pi^+ + \pi^+$
D_s^+	$D_s^+ \rightarrow K^+ + K^- \pi^+$
D^{*+}	$D^{*+} \rightarrow D^0 + \pi^+$

- Simulations were done using phase space of D mesons from AMPT event generator



Summary & plans

- Data taking with SAVD:
  - 2016 Dec: Pb+Pb at 150*A* GeV/*c*
    →**first direct observation of D^0 signal in nucleus-nucleus collisions in fixed target experiment**;
  - 2017 Nov–Dec : Xe + La run at 150*A*, 75*A* and 40*A* GeV/*c*
    →reconstruction is ongoing;
  - 2018 Nov-Dec: Pb+Pb at 150*A* GeV/*c*
    Open Charm production beam time;
    Expected to collect 10M central events.

- After LS2 high statistic Pb+Pb data taking with upgraded Vertex Detector is proposed:

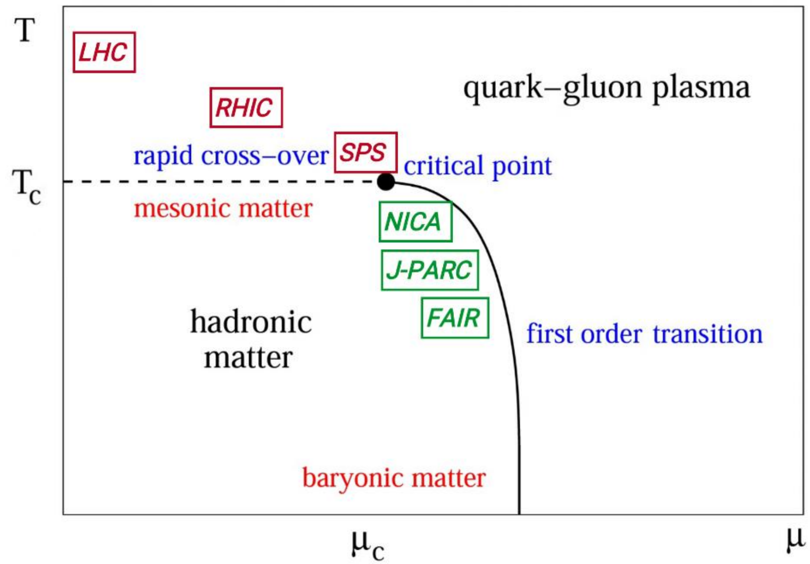
Year	Reaction	Number of events	D^0 & antiD^0	D^+ & D^-
2021	Pb+Pb 150*A* GeV/c	250M	38k	23k
2022	Pb+Pb 150*A* GeV/c	250M	38k	23k
2023	Pb+Pb 40*A* GeV/c	250M	3.6k	2.1k

- The measurements will provide the long-awaited data crucial for the following topics:
  - J/ψ production as the signal of deconfinement;
  - Open charm yield as signal of deconfinement;
  - Open charm production mechanism: pQCD vs Statistical models.

Thank you for your attention!

Uniqueness of NA61/SHINE program

- LHC and RHIC at high energies ($\sqrt{s_{NN}} \geq 200$ GeV): significantly limited acceptance due to collider kinematics and related detector geometry;
- RHIC BES collider and fixed-target ($\sqrt{s_{NN}} = 3-39$ GeV): measurement not considered in the current program;
- NICA ($\sqrt{s_{NN}} < 11$ GeV): measurements during stage 2 (after 2023) are under consideration;
- J-PARC-HI ($\sqrt{s_{NN}} \leq 6$ GeV): measurement under consideration, may be possible after 2025;
- FAIR SIS-100 ($\sqrt{s_{NN}} < 5$ GeV): subthreshold charm production measurements are considered. Systematic charm measurements are planned with SIS-300.



- → only NA61/SHINE is able to measure open charm in heavy ion collisions in full phase space in the near future.

Open charm distribution

0-20% Pb+Pb at 158 GeV/c

charm conservation

$\boxed{c} = \boxed{\bar{c}}$

violation of izospin symetry

$\boxed{D^0 \; c\bar{u}} \approx 2.6 \; \boxed{D^+ \; c\bar{d}}$

31% 12%

$\boxed{\bar{D}^0 \; \bar{c}u} \approx 2.6 \; \boxed{D^- \; \bar{c}d}$

31% 12%

higher mass states

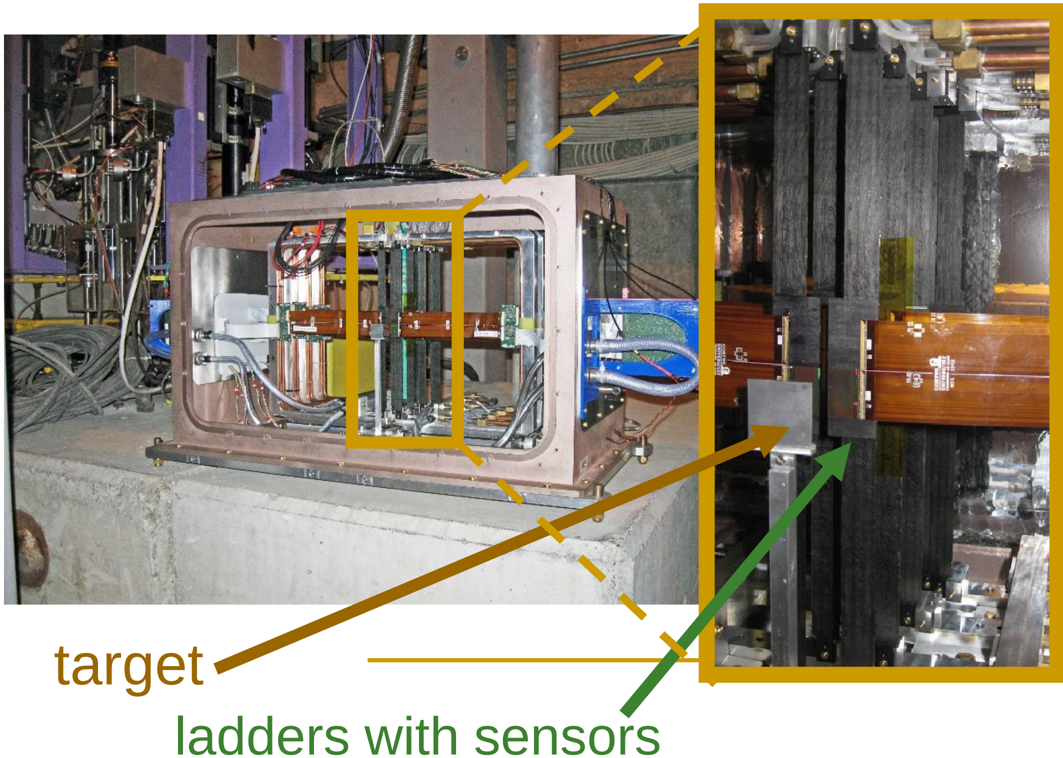
$\boxed{D_s^+ \; c\bar{s}} \quad \boxed{\Lambda_c \; udc} \quad > \quad \boxed{D_s^- \; \bar{c}s} \quad \boxed{\bar{\Lambda}_c \; \bar{u}\bar{d}\bar{c}}$

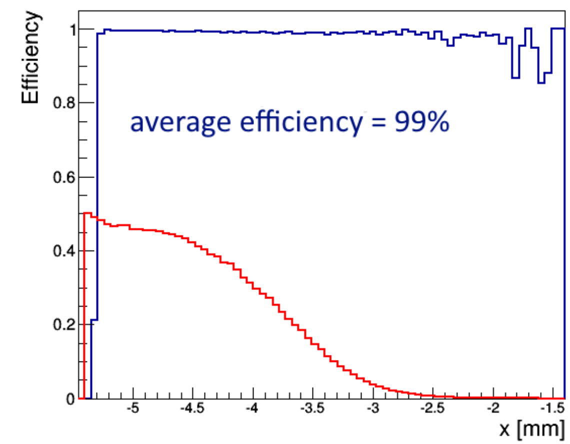
5% 3% 2% 5%

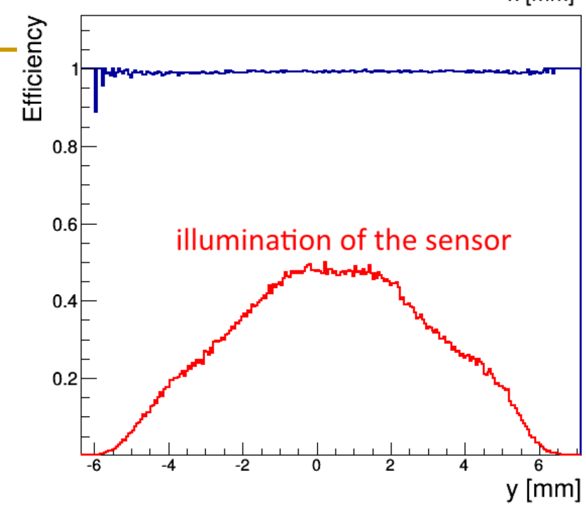
$\langle n \rangle / \langle n_{ALL} \rangle$

PHSD, Elena Bratkovskaya & Taesoo Song, private communication

Performance of SAVD







- The sensor efficiency is determined using the reference track method;
- The sensor efficiency (blue line), and illumination of the sensor by the reference tracks (red line) is shown in the plot;
- The indicated average efficiency (99%) refers to selected sensor.

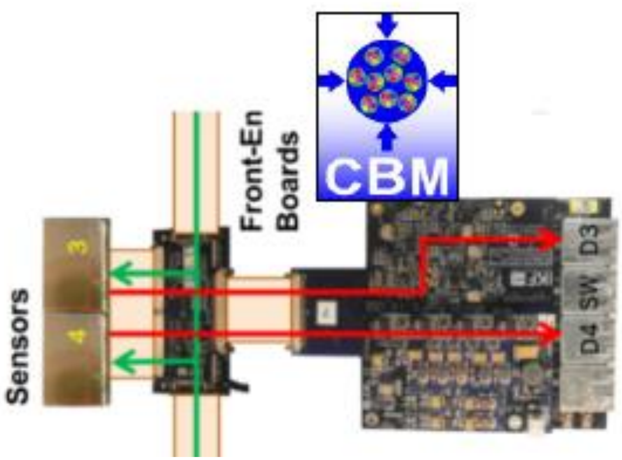
Main Vertex Detector components

- MIMOSA-26AHR
  - 1152x576 pixels of 18.4x18.4µm2
  - 3.5 µm resolution, 0.05% X0
  - Readout time: 115.2 µs, 50µm thin

  PICSEL Group, IPHC Strasbourg

- ALICE ITS ladder
  - Ultra light carbon fibre
  - < 0.3% X0 including water cooling

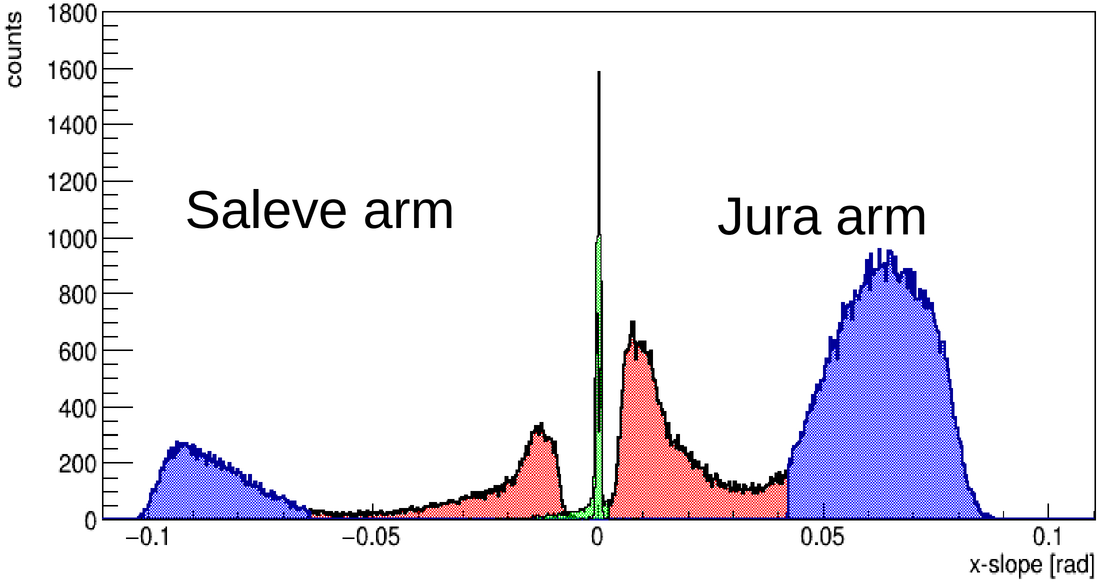
  St. Petersburg, CERN



- CBM Micro Vertex Detector Prototype
  - Sensor integration
  - Flex print cables, Front-end boards
  - Read-out based on TRB3 FPGA Board

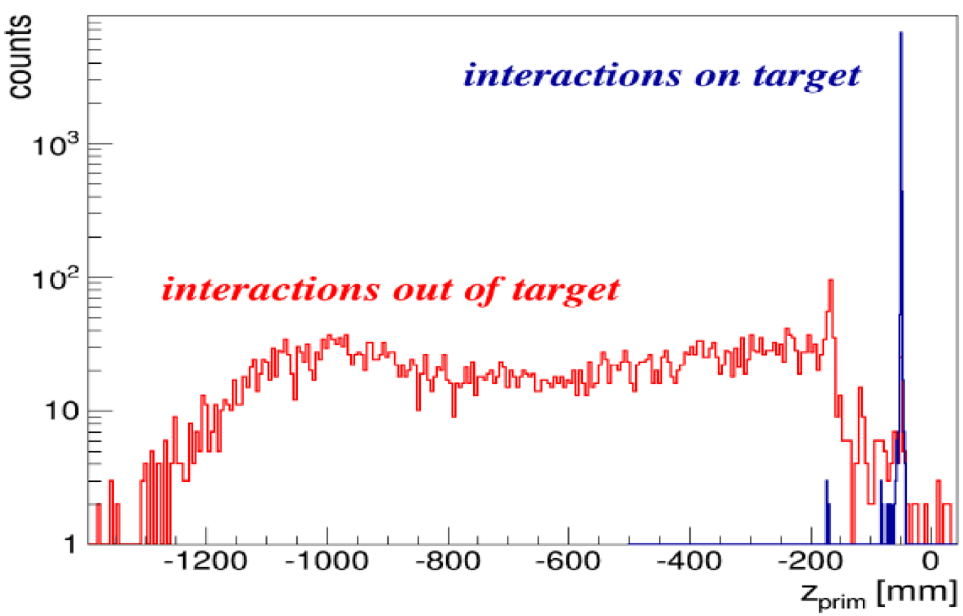
  Goethe Universitet Frankfurt am Main

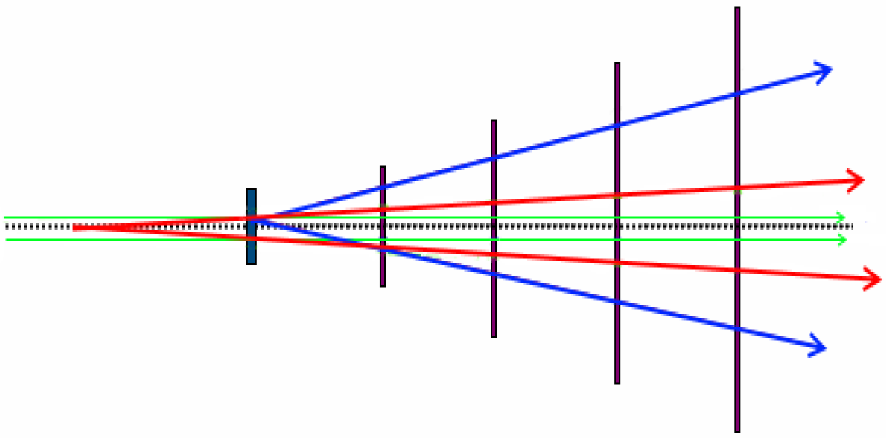
Angle distribution



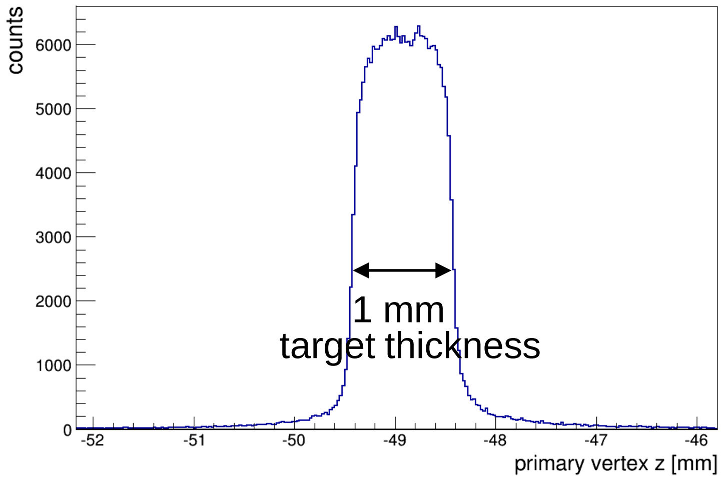
The angular distribution in x direction of the reconstructed tracks for Jura and Saleve arms has a clear three peak structure.

Reconstruction of primary vertex allows to separate in- and out-of target interactions

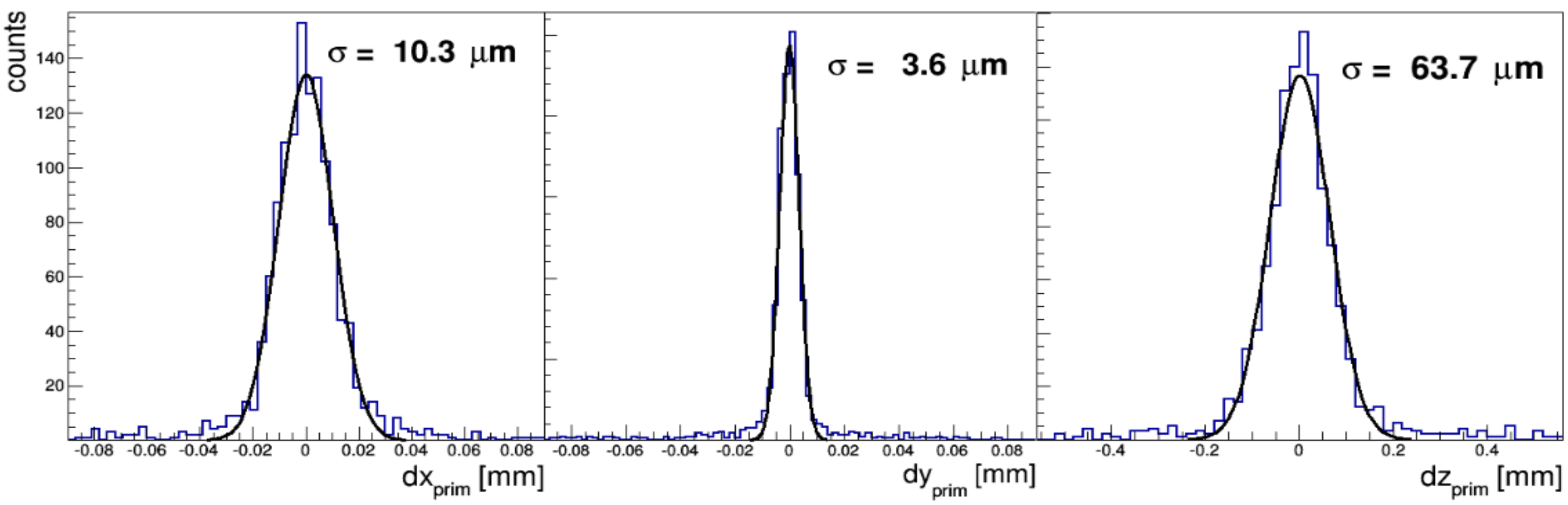




Primary vertex reconstruction

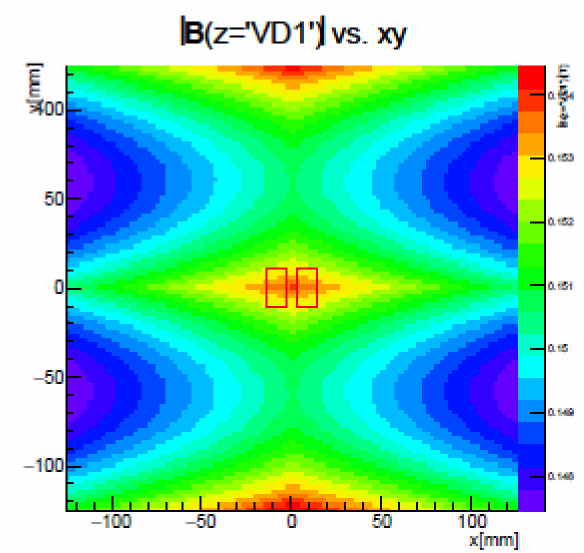


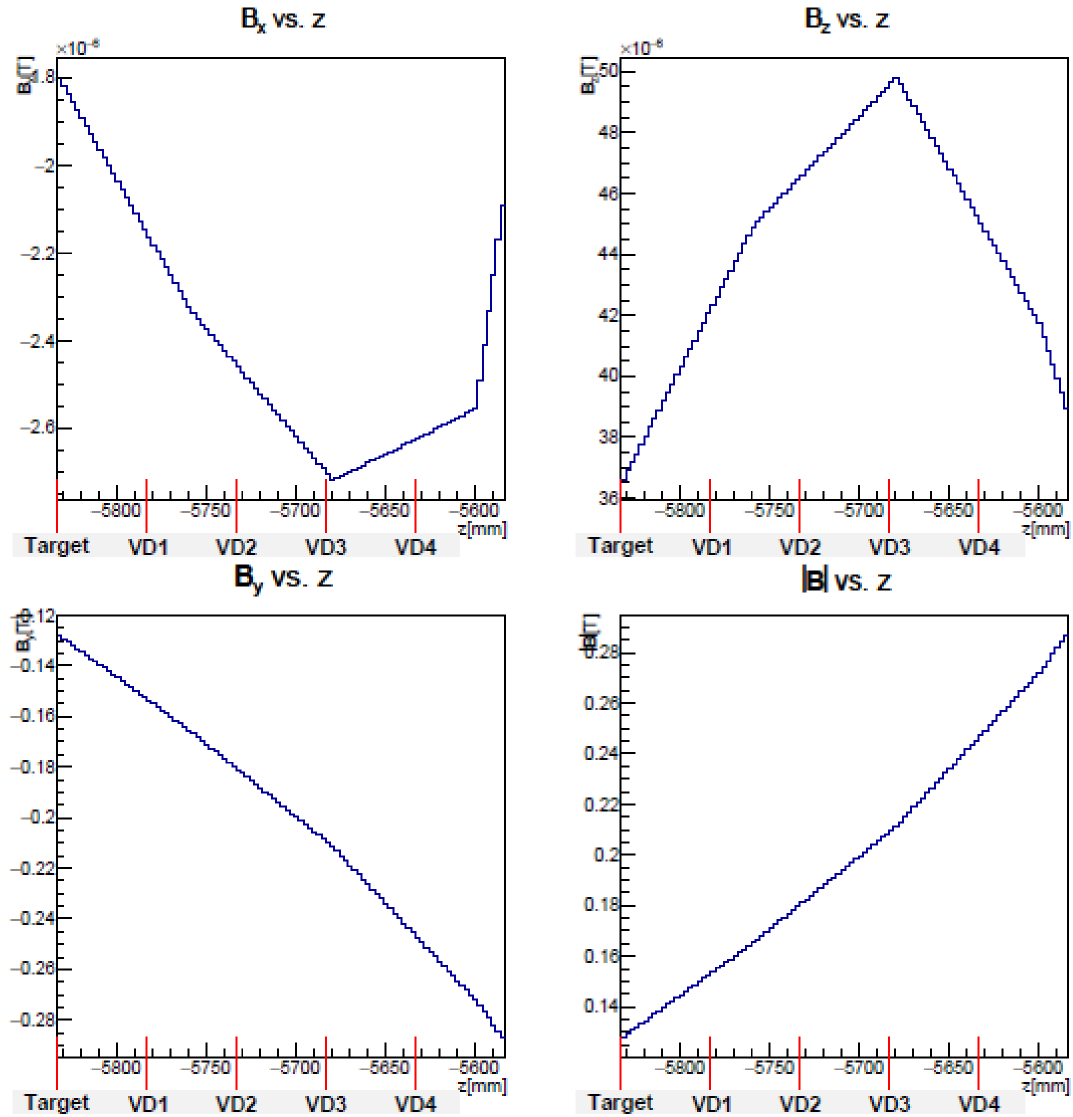
- ~~Spatial resolution of the primary vertex~~: σ_x = 5 μm, σ_y = 1.5 μm and σ_z = 30 μm.
- The difference between σ_x and σ_y can be attributed to the presence of the vertical component of the magnetic field which deteriorates description of tracks trajectories in the x direction.



Magnetic field in VD

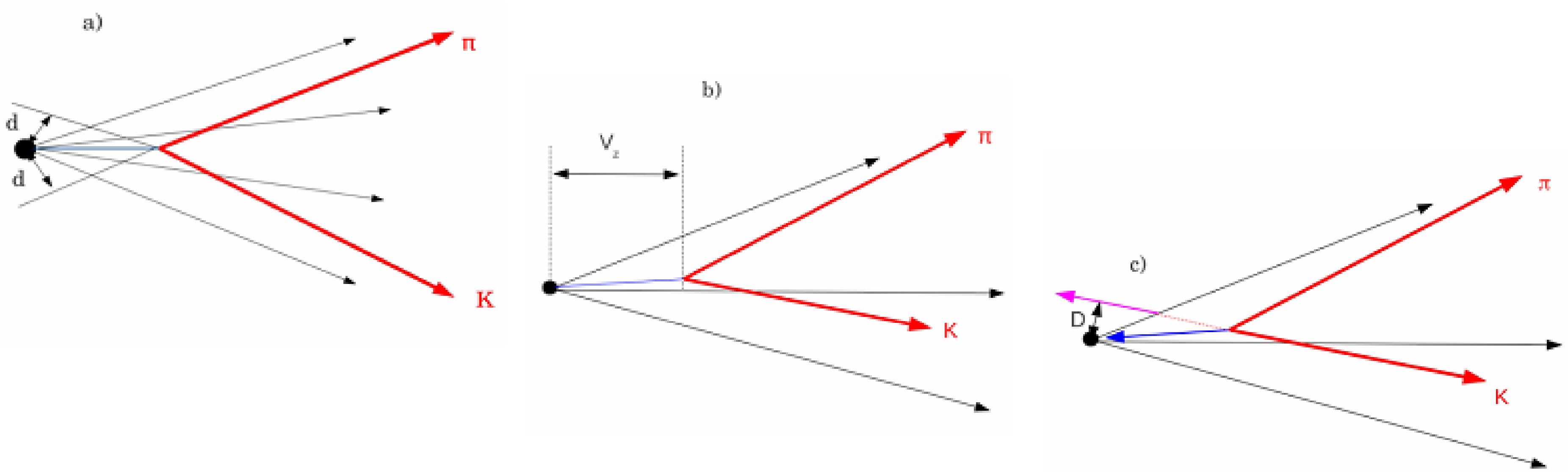
- Inhomogeneous magnetic field (0.13÷0.25T) in Vertex Detector volume.





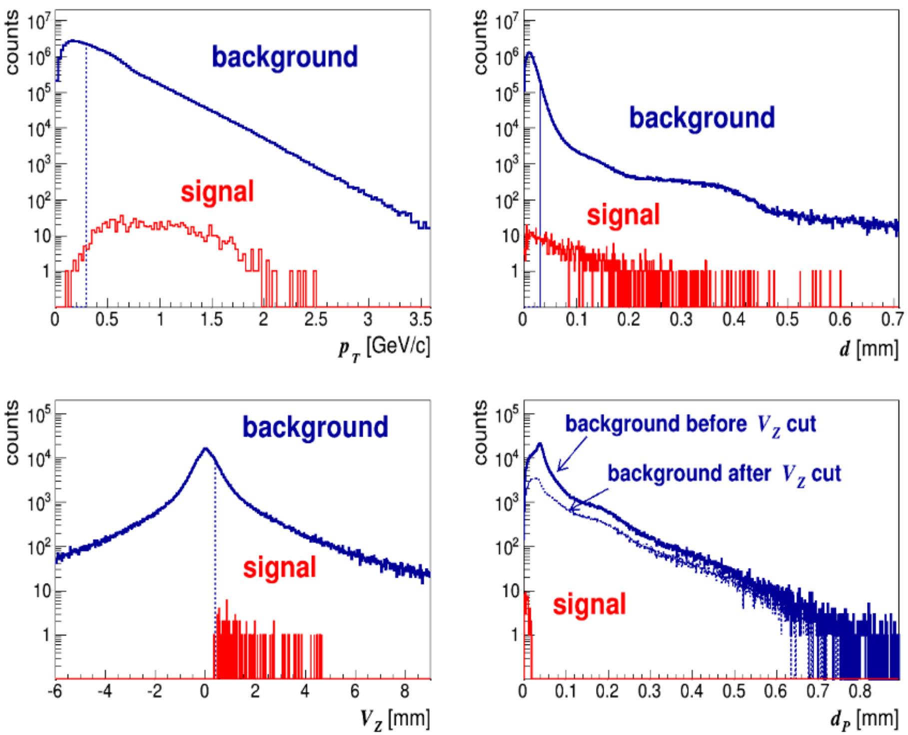
Open charm cuts

- Cut on transverse momentum $p_T > 0.34$ GeV/c;
- (a) Cut on the track impact parameter $d > 34$ μm;
- (b) Cut on the longitudinal position $V_z > 375$ μm of the track pair vertex relative to primary vertex;
- (c) Cut on the parent particle impact parameter $D < 21$ μm.

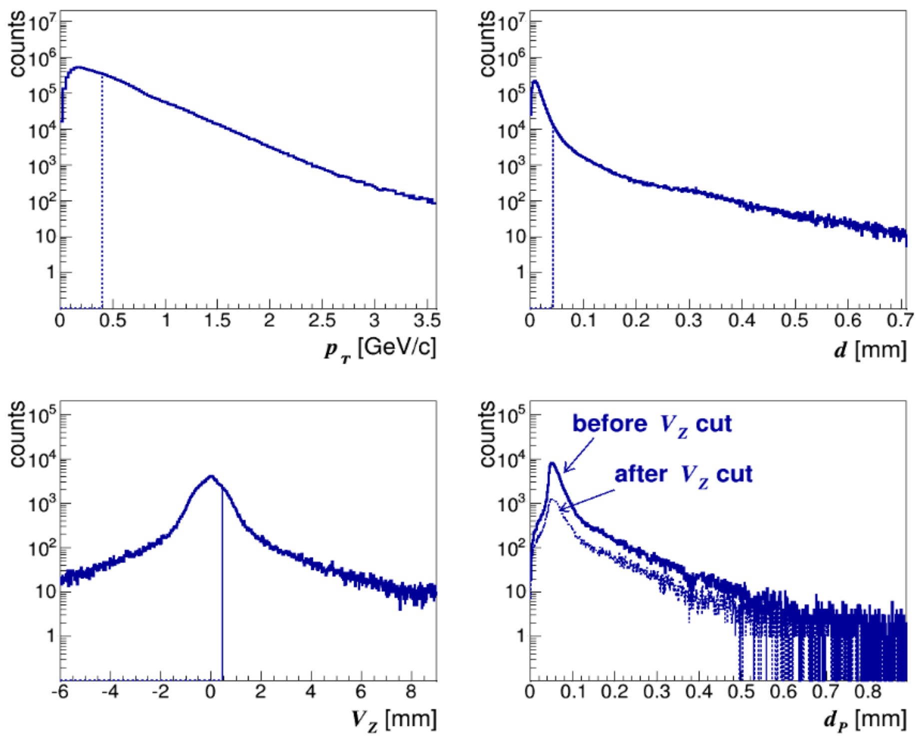


Open charm cuts

simulation

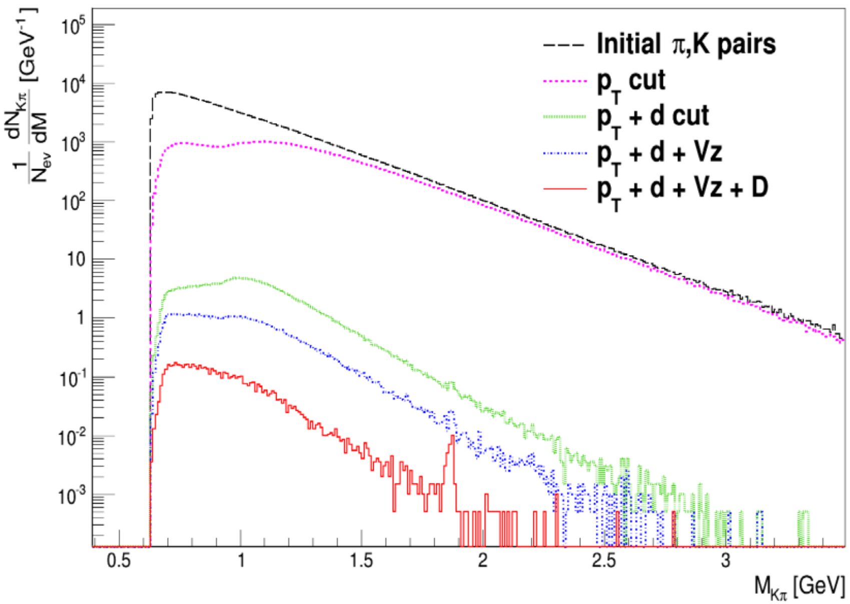


data

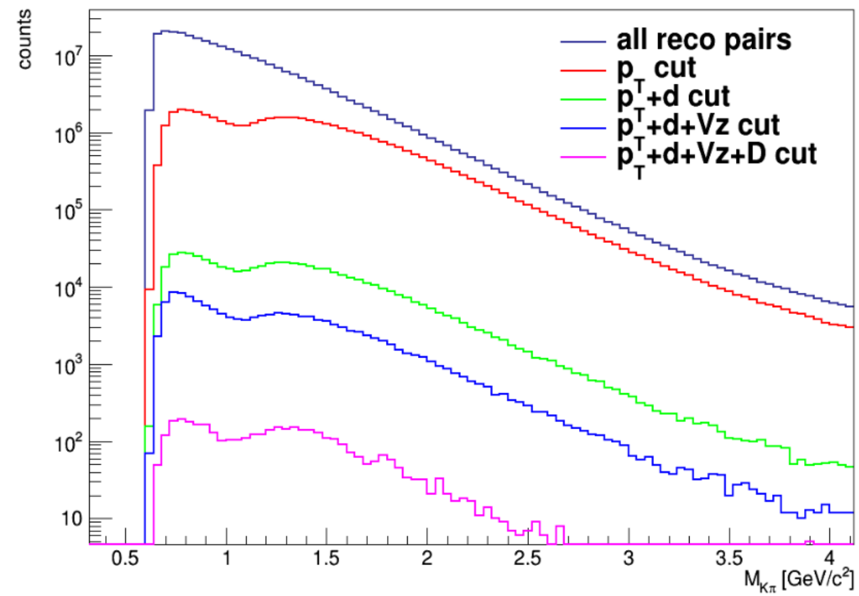


Open charm simulations

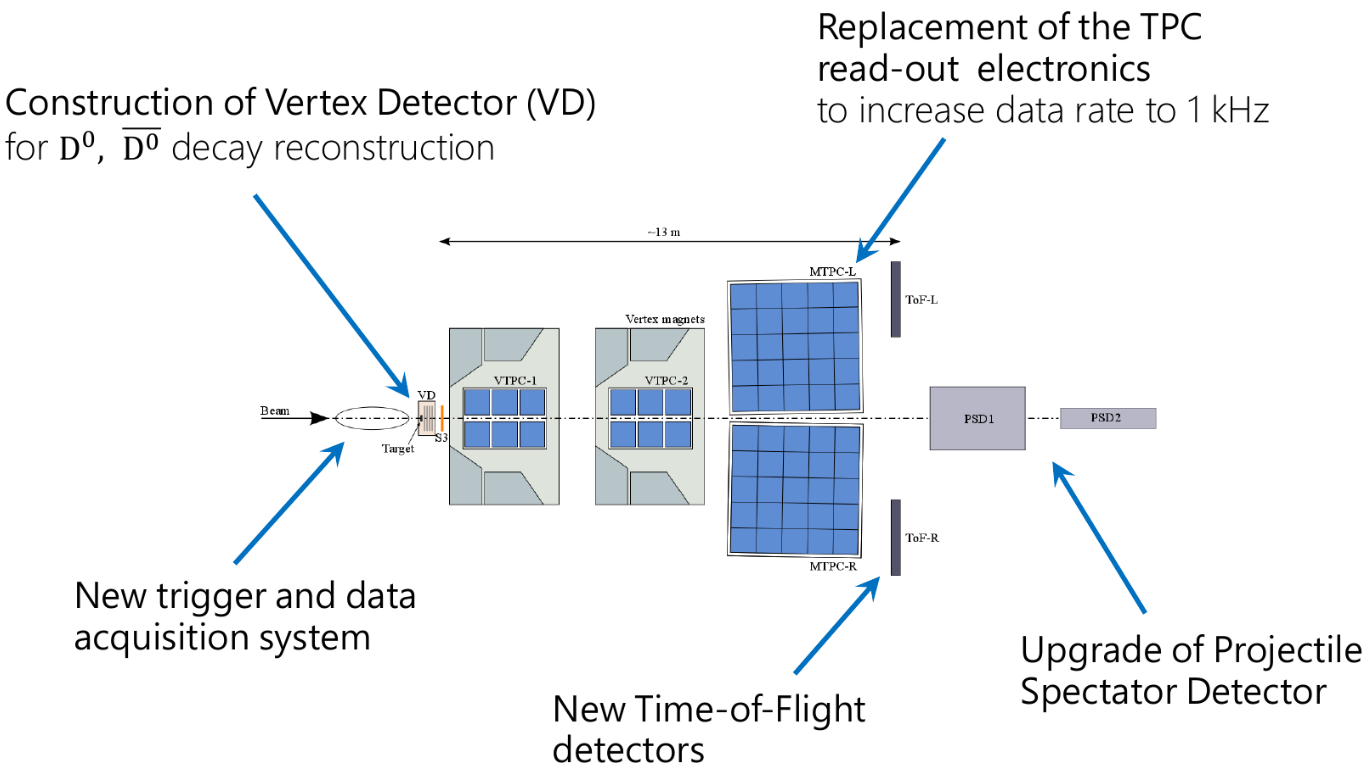
simulation



data



Upgrades of NA61/SHINE setup after LS2



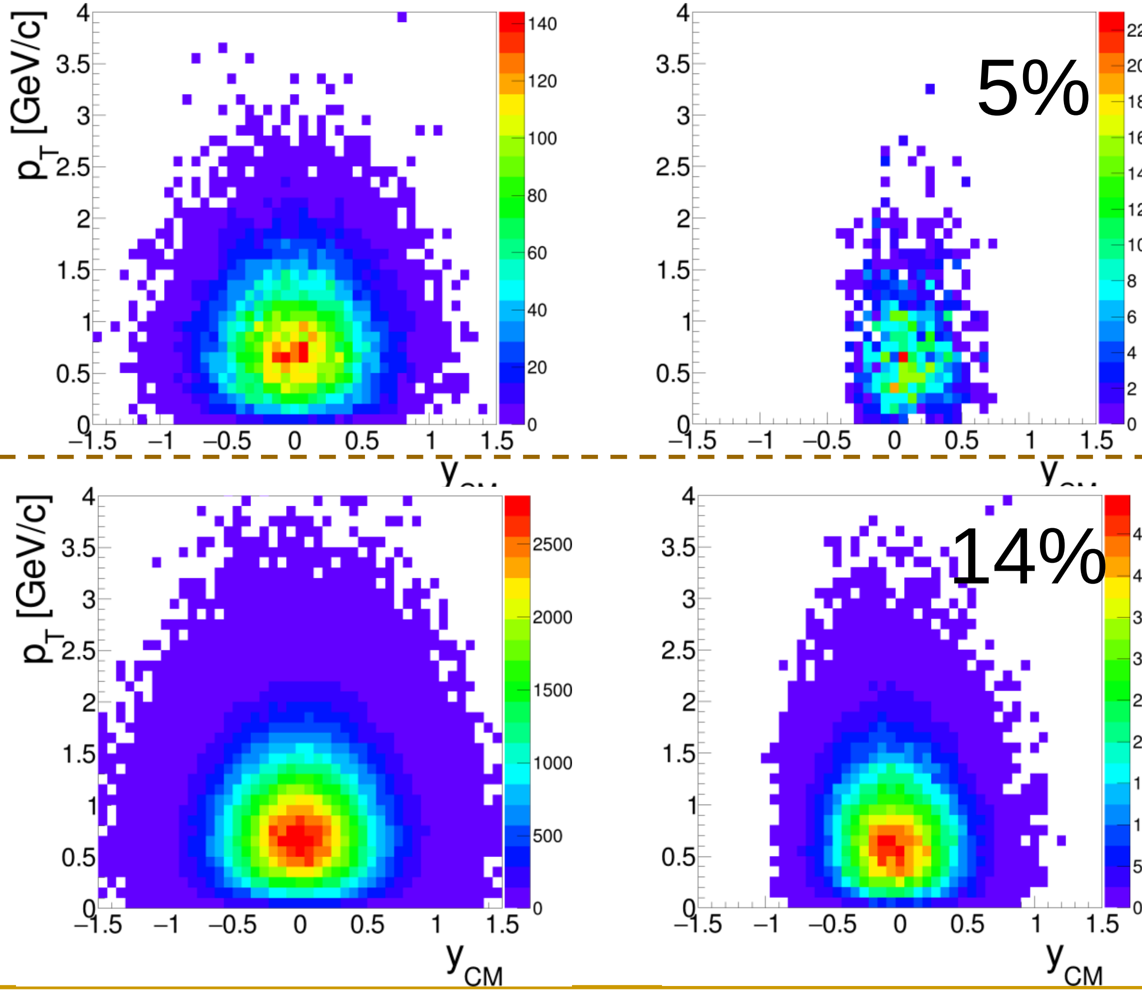
- The NA61/SHINE experiment will be upgraded to increase the data taking rate from 80Hz to 1kHz.

Upgraded VD vs SAVD

Increasing the VD acceptance:32cm^2 → 190 cm^2

SAVD

upgraded VD



Expected open charm measurements

- Precise measurements of charm hadron production by NA61/SHINE are expected to be performed in 2022–2024.
- This would be the first detailed study of open charm production in the SPS energy domain.

Year	Reaction	Events	$D^0 + \overline{D}^0$	$D^+ + D^-$
2022	Pb+Pb 150A GeV/c	250M	38k	23k
2023	Pb+Pb 150A GeV/c	250M	38k	23k
2024	Pb+Pb 40A GeV/c	250M	3.6k	2.1k