Open charm measurements in NA61/SHINE experiment at the CERN SPS

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for the NA61/SHINE Collaboration

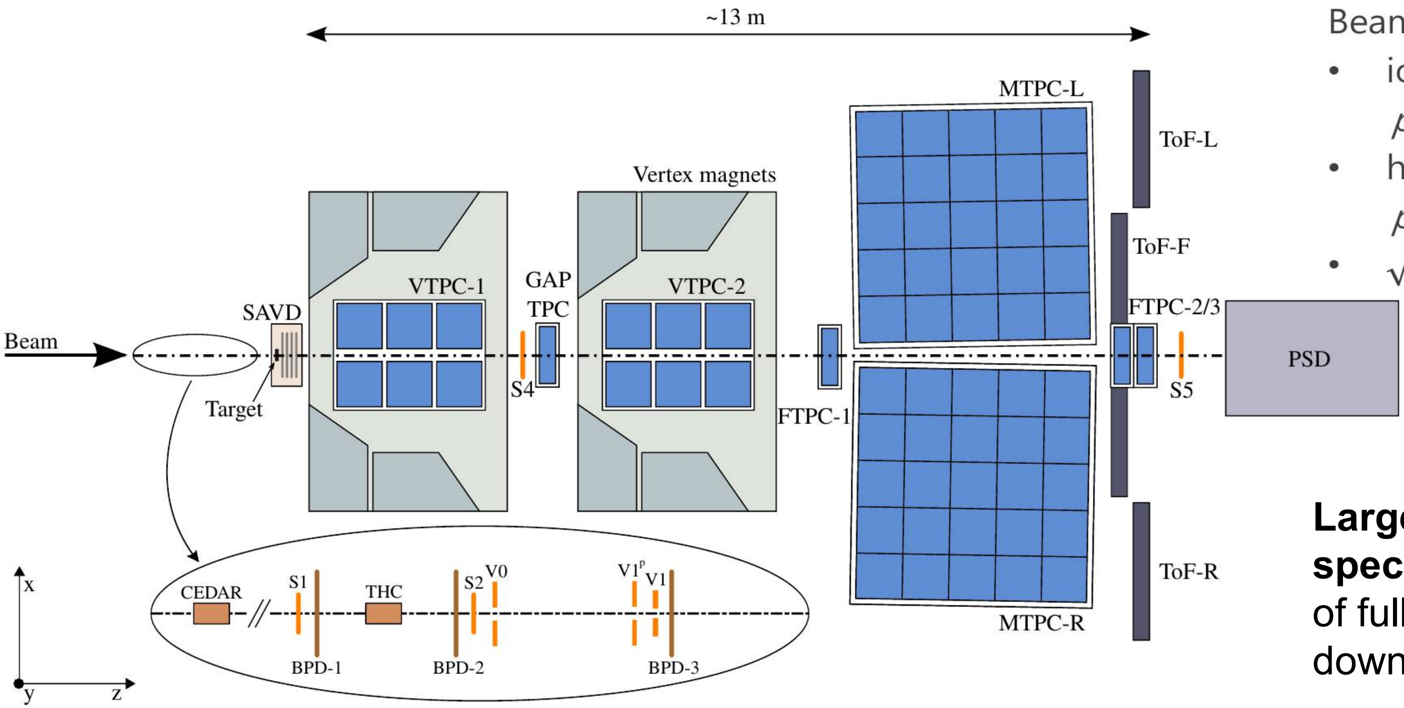
Exploring High-μ_B Matter with Rare Probes, 13 October 2021, Trento

Outline

1. Introduction
2. Physics motivation for open charm measurements
3. Performance of Small Acceptance Vertex Detector
4. Upgrades and proposed measurements after LS2

Introduction

NA61/SHINE Experiment



Beams:

- ions (Be, Ar, Xe, Pb) p_{beam}=13A–150A GeV/c
- hadrons (π, K, p) p_{beam}=13–400 GeV/c
- $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

Large acceptance hadron spectrometer – coverage of full forward hemisphere, down to p_T = 0

Beam detectors and triggering → a set of upstream scintillator and Cherenkov counters and beam Position detectors provides timing reference, charge and position measurements

Time Projection chambers → four large four small volume TPC's serve as tracking detectors, provide PID

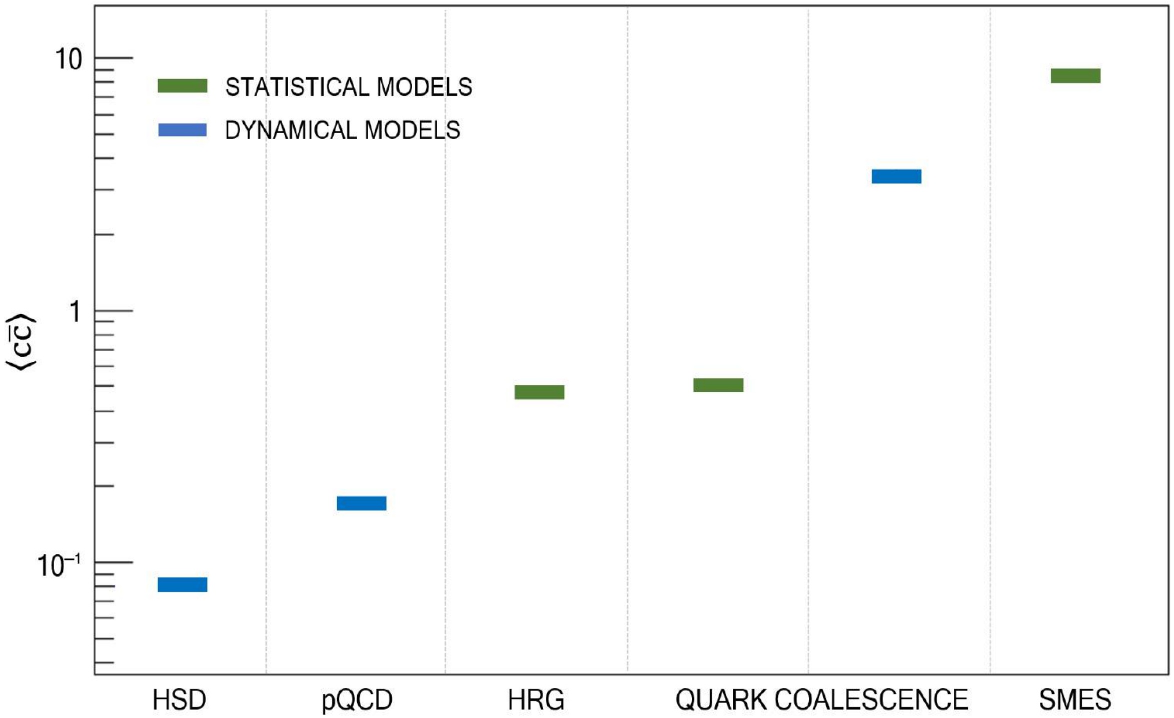
Time of Flight walls → used for hadron identification

Projectile Spectator Detector (PSD) → a calorimeter which is positioned downstream of the time of flight detectors measure energy of projectile fragments.

Small Acceptance Vertex Detector → precise tracking close to the target

Physics motivation for open charm measurements

Model predictions for $\langle c\bar{c} \rangle$ in central Pb+Pb at 150A GeV/c



HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367

pQCD
Gavai et al. IJMP A 10 2999
Braun-Munzinger, J. Stachel, PLB 490, 196

HRG, Quark Coalesc. Stat.
Gavai et al. IJMP A10 2999
Braun-Munzinger, J. Stachel, PLB 490, 196

Quark Coalesc. Dyn.
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G27, 703

SMES
Gazdzicki, Gorenstein, APP B30, 2705

- Different models differ in predictions of $\langle c\bar{c} \rangle$ by factor ≈ 50
- To discriminate models the $\langle c\bar{c} \rangle$ produced in full phase space is needed
  → measurement of open charm mesons

Measurements of $\langle c\bar{c}\rangle$

0-20% Pb+Pb at 150*A* GeV/*c*

charm conservation

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

violation of isospin symmetry

$\boxed{D^0 \approx 2.6\ D^+}$ $\boxed{\bar{D}^0 \approx 2.6\ D^-}$

31% 12% 31% 12%

$\gg$ *higher mass states* $\gg$

$\boxed{D_s^+ \quad \Lambda_c}$ $\boxed{D_s^- \quad \bar{\Lambda}_c}$

5% 3% 5% 2%

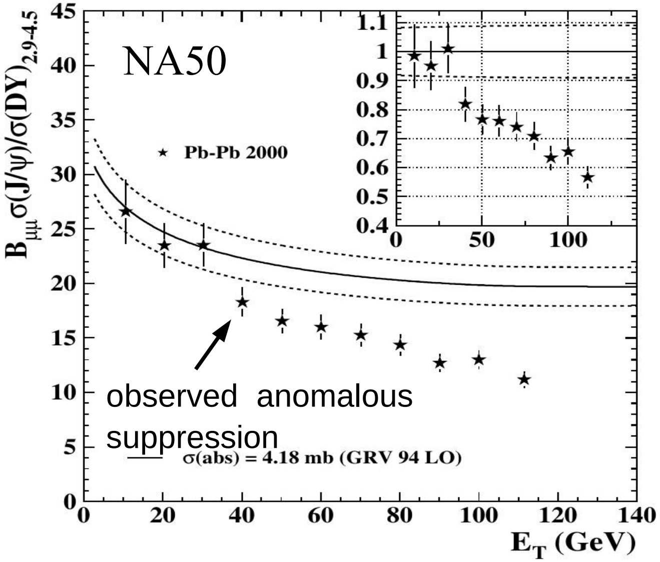
Hadrons containing charm considered for measurements in NA61/SHINE

Hadron	Decay channel	$c\bar{\tau}$ [μm]	BR
D^0	$\pi^+ + K^-$	123	3.89%
D^+	$\pi^+ + \pi^+ + K^-$	312	9.22%
D_S^+	$\pi^+ + K^- + K^+$	150	5.50%
Λ_c	$p + \pi^+ + K^-$	60	5.00%

Measuring **D^0, $\bar{D}^0$, D^+, D^-** provides good $\langle c\bar{c}\rangle$ estimate

PHSD, Elena Bratkovskaya & Taesoo Song, private communication

J/ψ suppression as signal of deconfinement



J/ψ normalized to DY measured by NA50 (Eur. Phys. J. C39, 335, 2005)

Data was interpreted in terms of suppression in the deconfined medium created in nucleus-nucleus collisions.

Medium reduces probability of J/ψ production (Matsui, Satz, PLB 178 (1986) 416)

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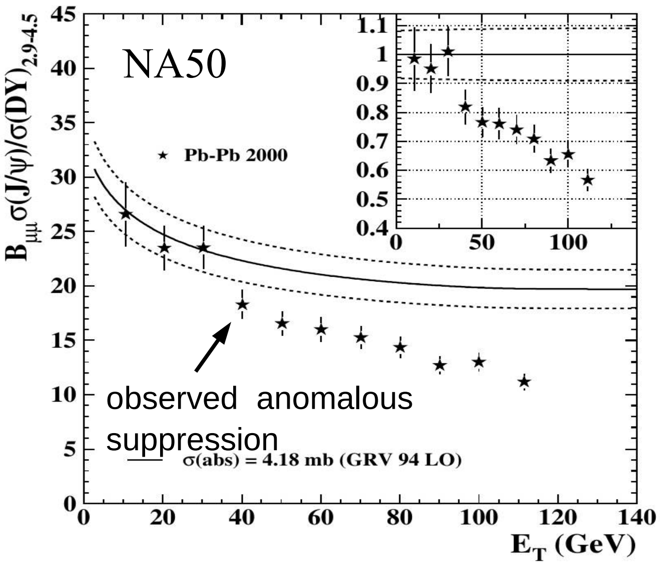

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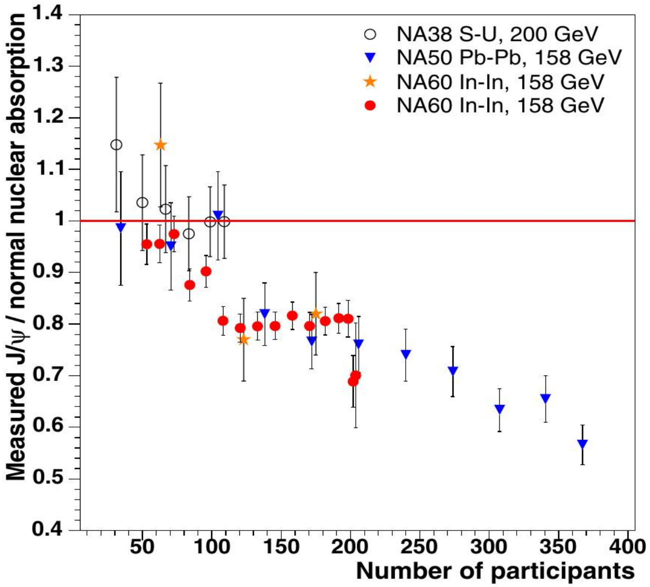
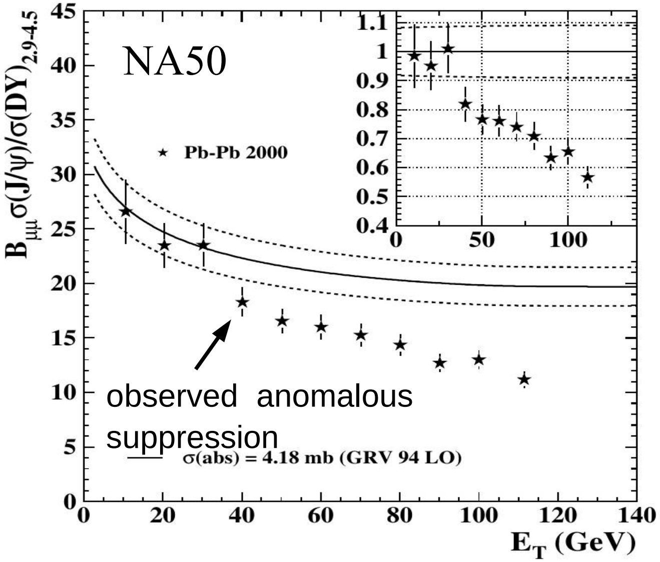


NA60 in 2005 (QM05)

J/ψ suppression as signal of deconfinement



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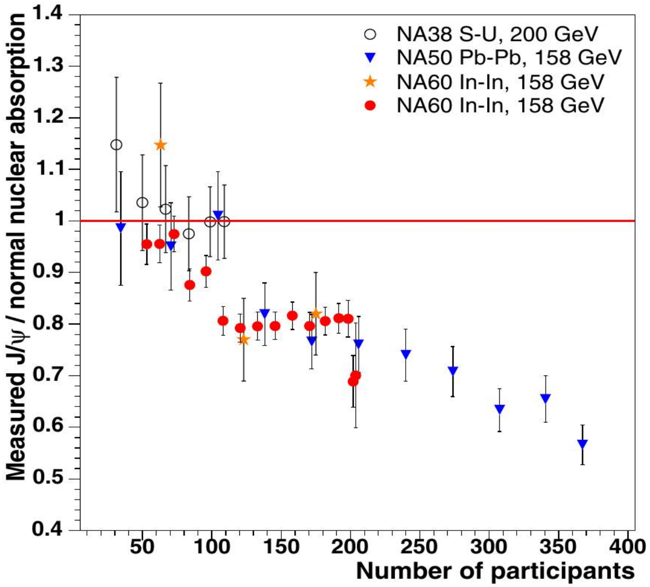
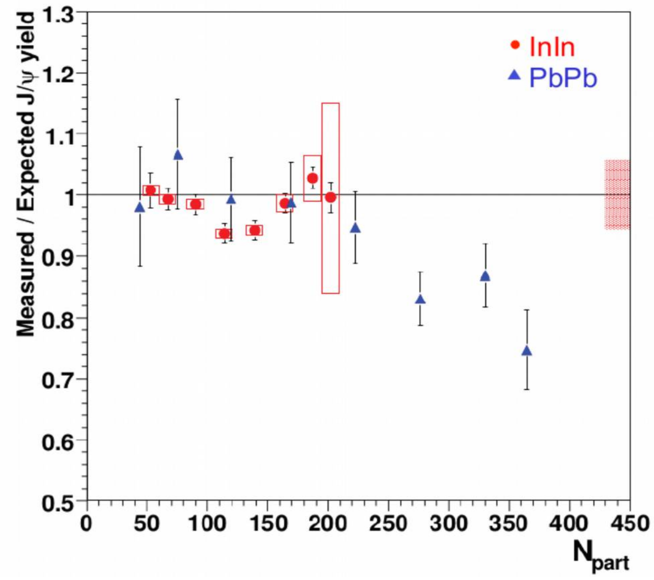


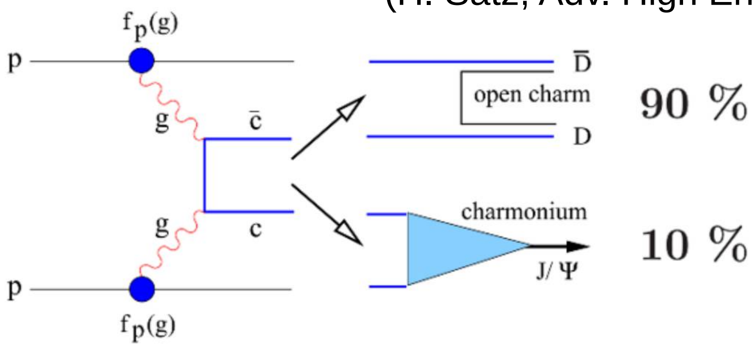
NA60 in 2005 (QM05)

NA60 in 2009



J/ψ suppression as signal of deconfinement

(H. Satz, Adv. High En. Phys. (2013) 2429)



Below LHC energies in p+p 90% $c\bar{c}$ pairs convert to open charm, remaining 10% form charmonia states.

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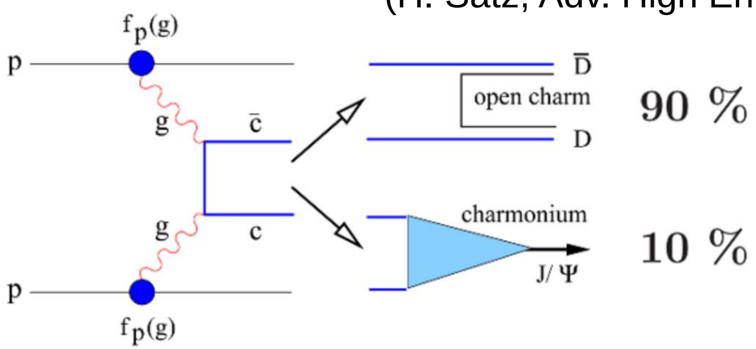

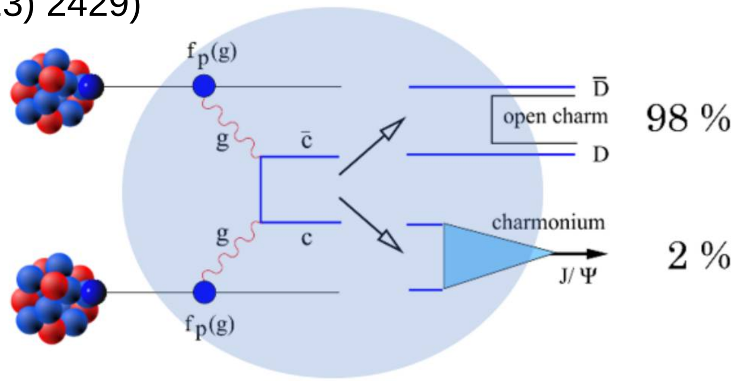

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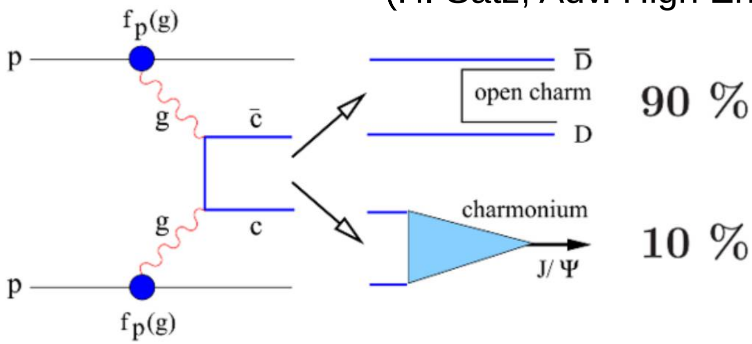

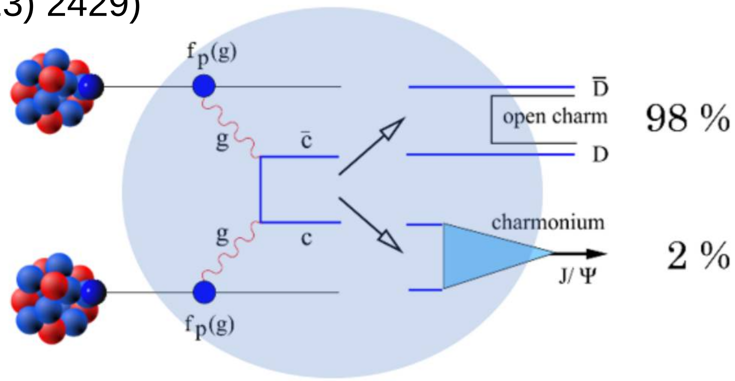

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Due to shadowing, parton energy loss etc., the number of $c\bar{c}$ pairs produced in A+A may well be less than the scaled number from p+p → initial state effects can reduce charmonium production rate in A+A ralative to p+p collisions.

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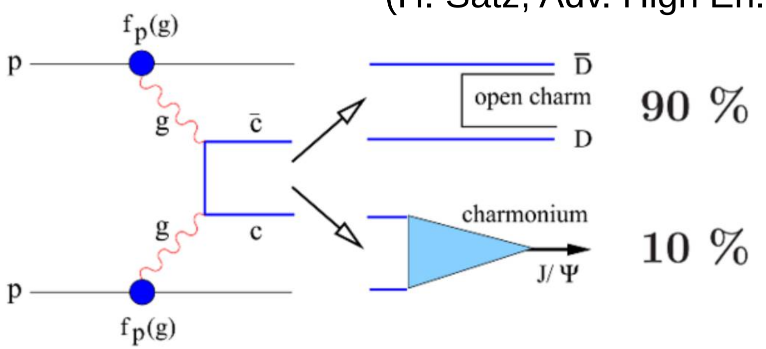

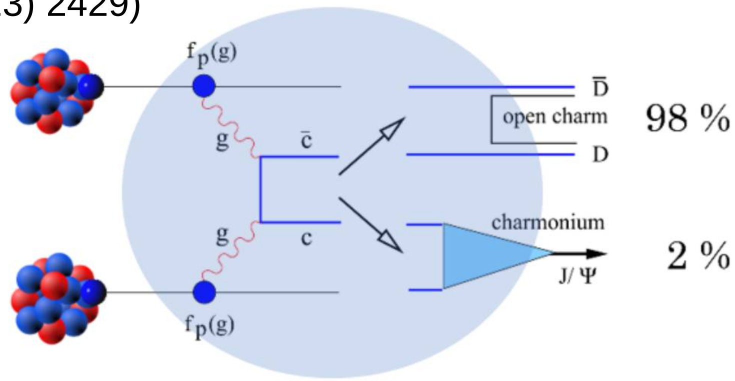

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→ the effect of the medium on $c\bar{c}$ binding can only be determined by comparing the ratio of $\langle J/\psi \rangle / \langle c\bar{c} \rangle$ in A+A to that in proton-proton collisions.

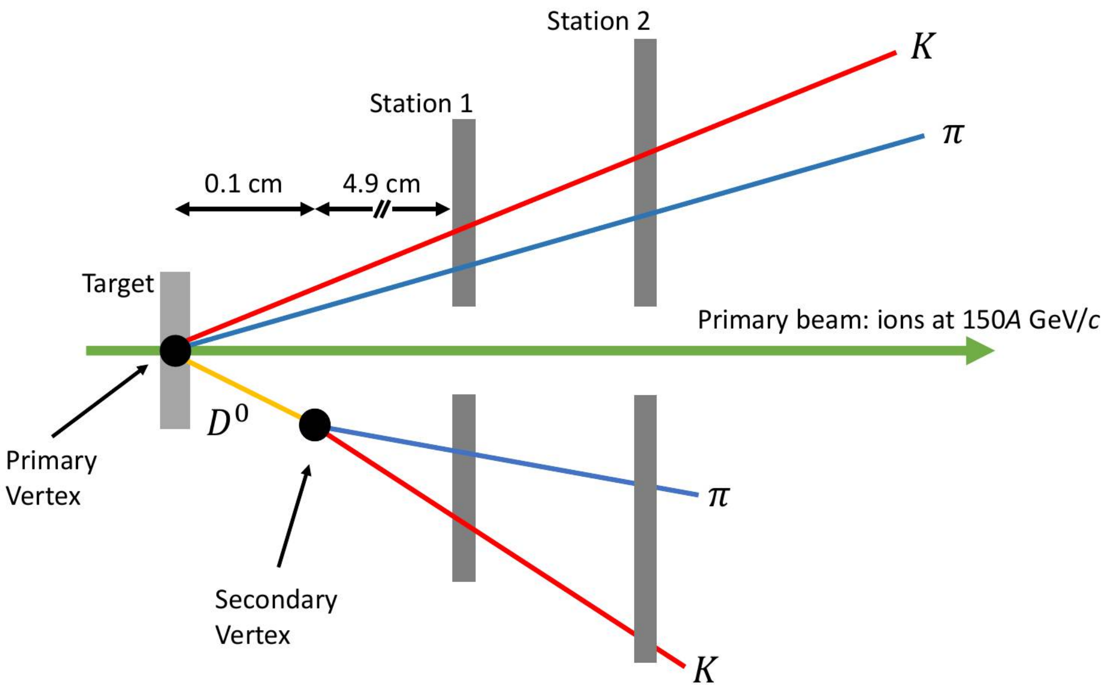
→ measurements of open charm in A+A needed!!!

$$P\left(c\bar{c} \to J/\psi\right) \equiv \frac{\langle J/\psi \rangle}{\langle c\bar{c} \rangle} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$$

Performance of **S**mall **A**cceptance **V**ertex **D**etector (SAVD)

Why Vertex Detector is needed to measure open charm?

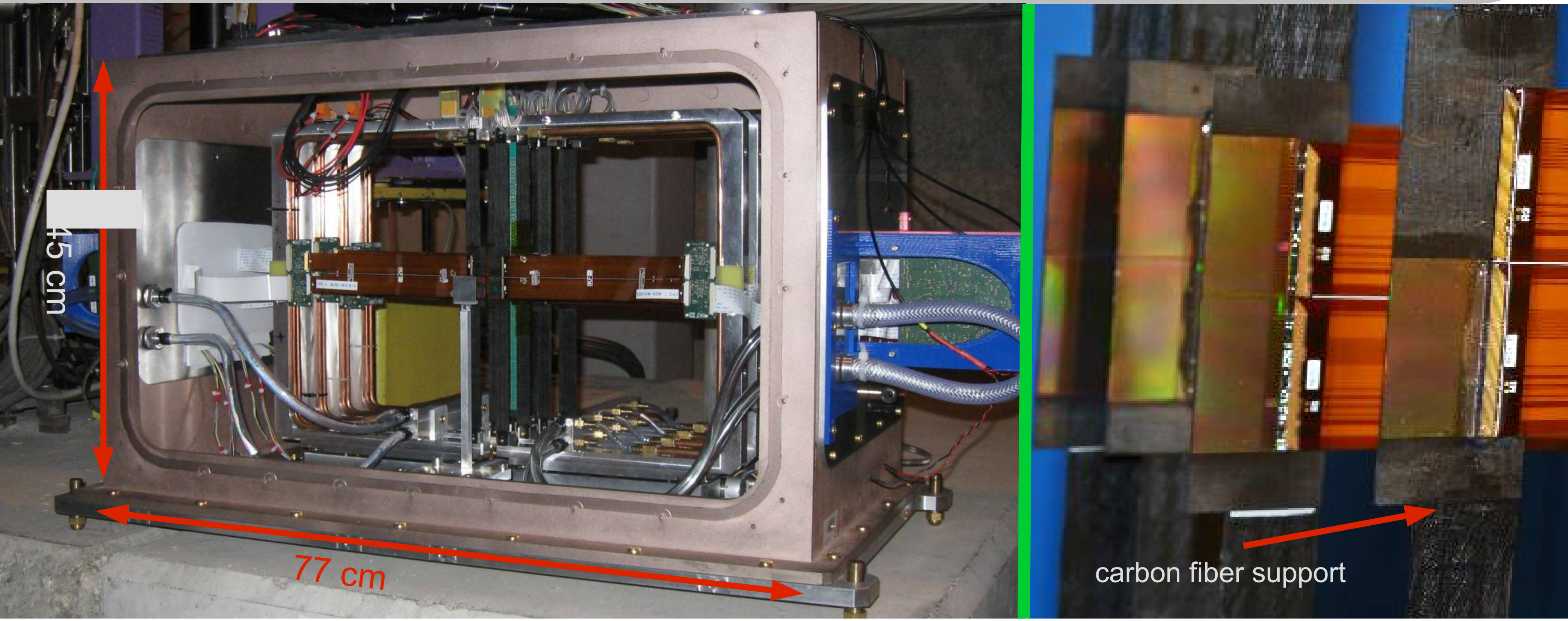
$$D^0 \rightarrow \pi^+ + K^-$$



- Daughters of D^0 (π and K) are recognized as a pair forming a secondary vertex displaced form the primary vertex
- $c\tau(D^0) \simeq 122$ μm, however, due to Lorentz boost ($\beta\gamma \approx 10$) the displacement is on the level of 1 mm.
- This holds also for other charm mesons like D^+, D^-, D^+_s
- The Lorentz Boost makes the measurements significantly easier in fix target experiments than in the collider experiments

Vertex detector is needed to reconstruct **primary vertex** and **secondary vertexes** with high precision.

Vertex Detector tests with Pb+Pb at 150*A* GeV/*c*



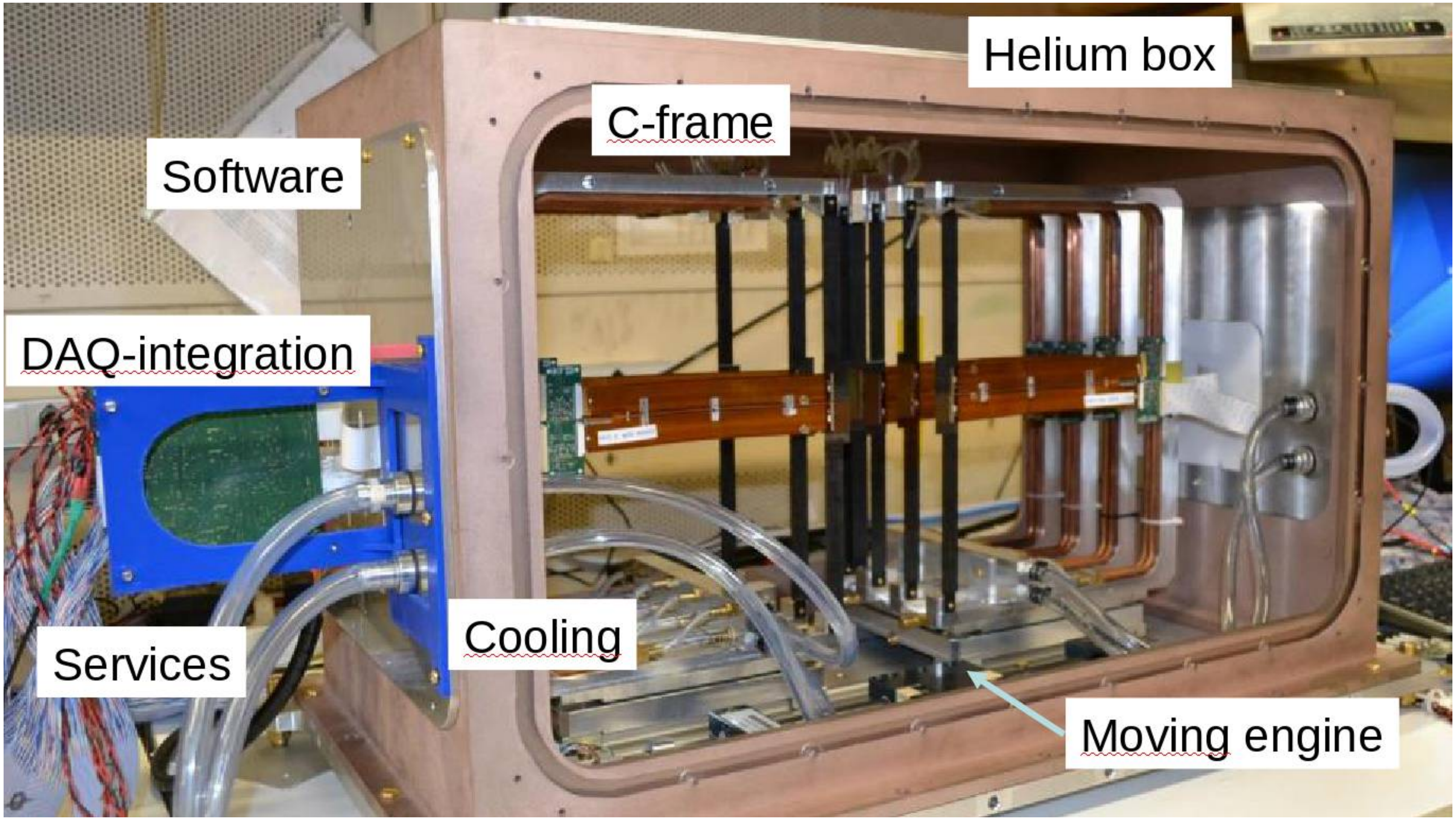
SAVD:

- 16 MIMOSA-26 sensors located on 2 horizontally movable arms.
- Target holder integrated with SAVD base plate

Achieved goals:

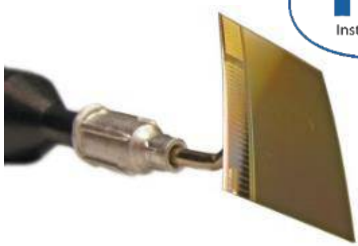
- tracking in the large track multiplicity environment
- precise Primary Vertex reconstruction
- TPC and SAVD track matching
- first search for D^0 signal

Main project components



System integration and project leadership:
Jagiellonian University Krakow,
supported by AGH Krakow, WUT Warsaw

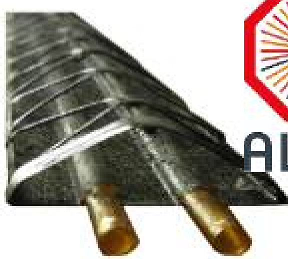
Main project components (cont.)



MIMOSA-26AHR

- 1152x576 pixels of $18.4 \times 18.4 \mu m^2$
- 3.5 μm resolution, 0.05% X_0
- Readout time: 115.2 μs, 50μm thin

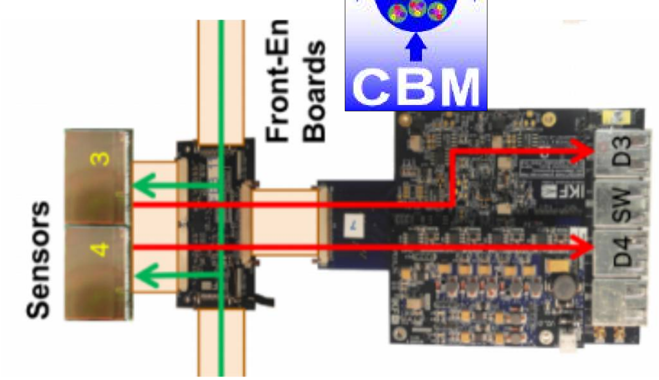
PICSEL Group, IPHC Strasbourg



ALICE ITS ladder

- Ultra light carbon fibre
- < 0.3% X_0 including water cooling

St. Petersburg, CERN



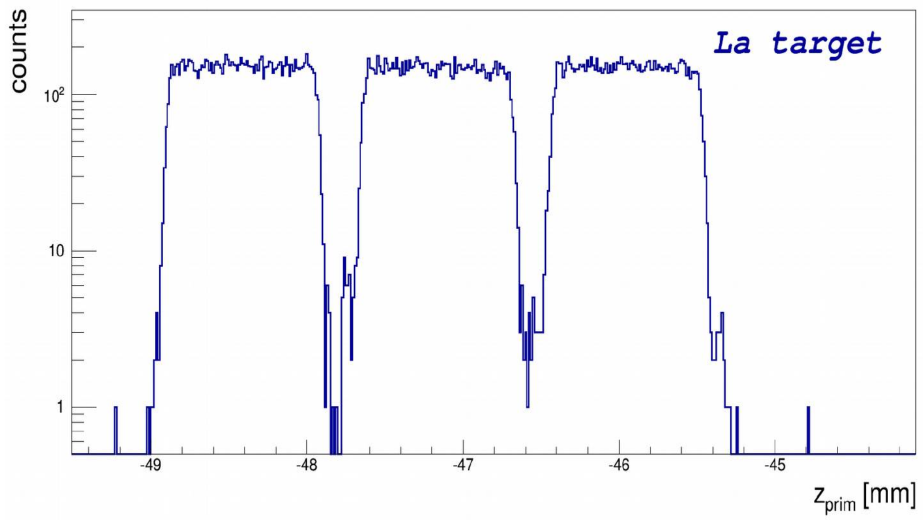
CBM Micro Vertex Detector Prototype

- Sensor integration
- Flex print cables, Front-end boards
- Read-out based on TRB3 FPGA Board

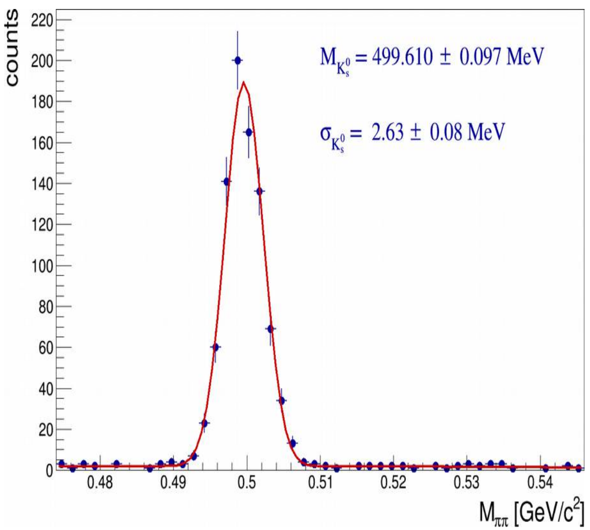
Goethe Universitet Frankfurt am Main

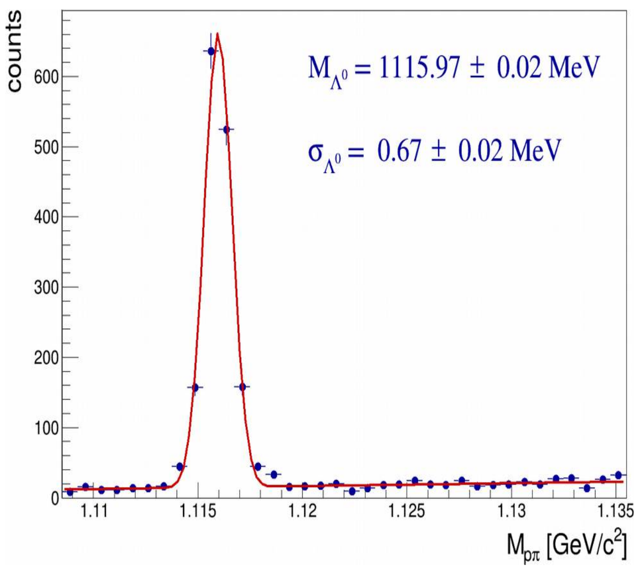
SAVD performance: K^0_s and Λ

Results for 1.1M events of Xe+La at 150A GeV/c



- Large statistic Xe+La data taken in 2017 at 150*A* GeV/*c*.
- Segmented target was used (tree 1mm thick La blocks squeezed together). The structure of the target seen in the data.
- Primary vertex spacial resolution: 1.3, 1.0 and 15 μm in *x*, *y* and *z* coordinate, respectively.



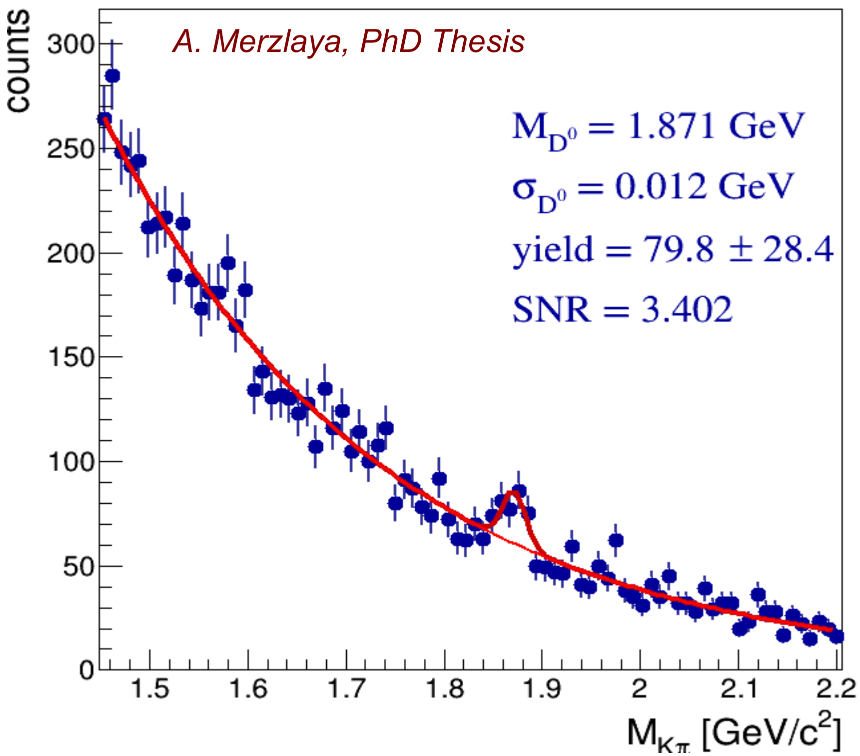


Background suppression → cuts on:

1. track p_T
2. track impact parameter
3. longitudinal distance of pair vertex to primary vertex
4. parent impact parameter
5. DCA

SAVD performance: D^0

First result for 1.9 M 0-20% central events of Xe+La at 150A GeV/*c*



Analysis details (*CERN-SPSC-2017-038*):

1. Global fit (VD+TPCs) using Kalman Filter.
2. Overall reconstruction efficiency > 90%
3. Overall detection efficiency ~ 80%.
4. PID information not used yet (dE/dx was not calibrated yet) → noticeable improvement expected

Background suppression → cuts on:

1. track p_T **> 0.32** GeV/*c*
2. track impact parameter **d > 37** μm
3. longitudinal distance of pair vertex to primary vertex V_z **> 1050 μm**
4. parent impact parameter **D < 18** μm
5. **DCA < 36 μm**

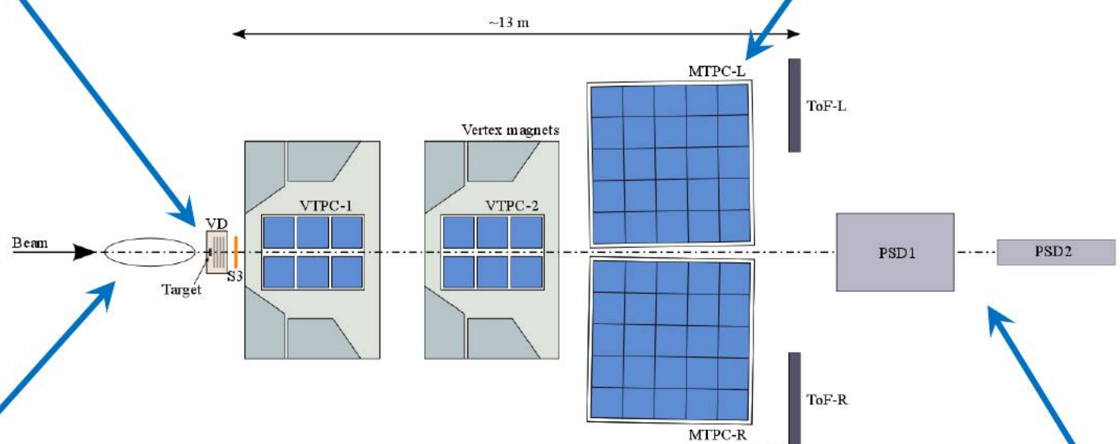
Analysis of Pb+Pb at 150A GeV/*c* in progress

Upgrades and proposed measurements beyond LS2

LS2 upgrades of NA61/SHINE setup

Replacement of the TPC read-out electronics to increase data rate to 1 kHz

Construction of Vertex Detector (VD) for $\mathbf{D^0}$, $\overline{\mathbf{D^0}}$ decay reconstruction



New trigger and data acquisition system

New Time-of-Flight detectors

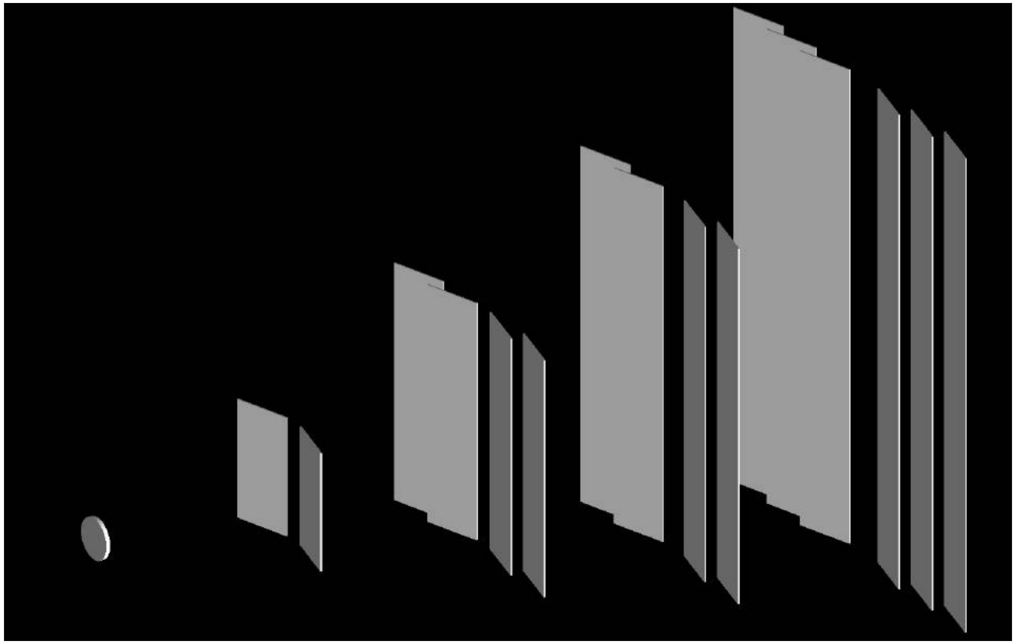
Upgrade of Projectile Spectator Detector

Upgrades are needed to increase rate capability of NA61/SHINE by one order of magnitude to 1 kHz

Upgrade of Vertex Detector

	MIMOSA-26AHR	ALPIDE
Sensor thickness (μm)	50	50
Spatial resolution (μm)	3.5	5
Dimensions (mm^2)	10.6×21.2	13.8×30
Power density (mW/cm^2)	250	40
Time resolution (μs)	115.2	10
Detection efficiency (%)	>99	>99
Dark hit occupancy	$\lesssim 10^{-4}$	$\lesssim 10^{-6}$

- Mimosa 26AHR will be replaced by ALPIDE developed for ALICE-ITS
- 16 → 46 sensors
- Increase surface 32 cm^2 (SAVD) → 190 cm^2



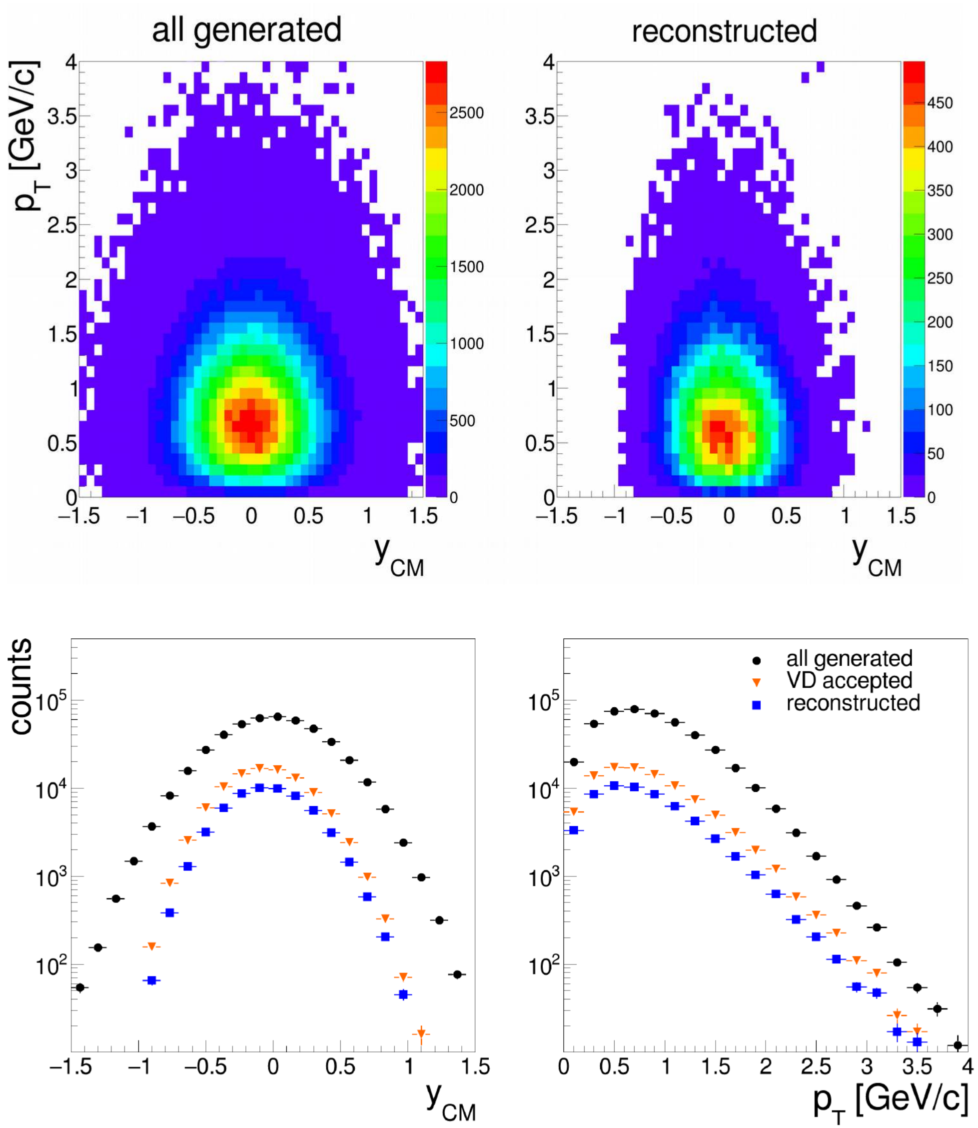
- Reuse mechanics and infrastructure of SAVD
- Minor modifications are required:
  → modifications of feed through
  → modification of ladders fixation bars

Request for Open Charm measurements

Year	Beam	#days	#events	$\#(D^0 + \overline{D^0})$	$\#(D^+ + D^-)$
2022	Pb at 150A GeV/c	42	250M	38k	23k
2023	Pb at 150A GeV/c	42	250M	38k	23k
2024	Pb at 40A GeV/c	42	250M	3.6k	2.1k

	0–10%	10–20%	20–30%	30–60%	60–90%	0–90%
$\#(D^0 + \overline{D^0})$	31k	20k	11k	13k	1.3k	76k
$\#(D^+ + D^-)$	19k	12k	7k	8k	0.8k	46k
$\langle W \rangle$	327	226	156	70	11	105

Anticipated results (D^0)



- Precise measurements of charm hadron production by NA61/SHINE are expected to be performed in 2022-2024.

- The Lorentz boost makes the measurements significantly easier than in case of collider experiments.

- Unlike in a typical collider experiment the acceptance extends down to p_T=0 → accurate measurements of total charm meson yields.

The proposed program will allow to perform systematic study of D^0, $\overline{D}^0$, D^+, D^-, (D^+_s) production versus collision energy and centrality

Summary

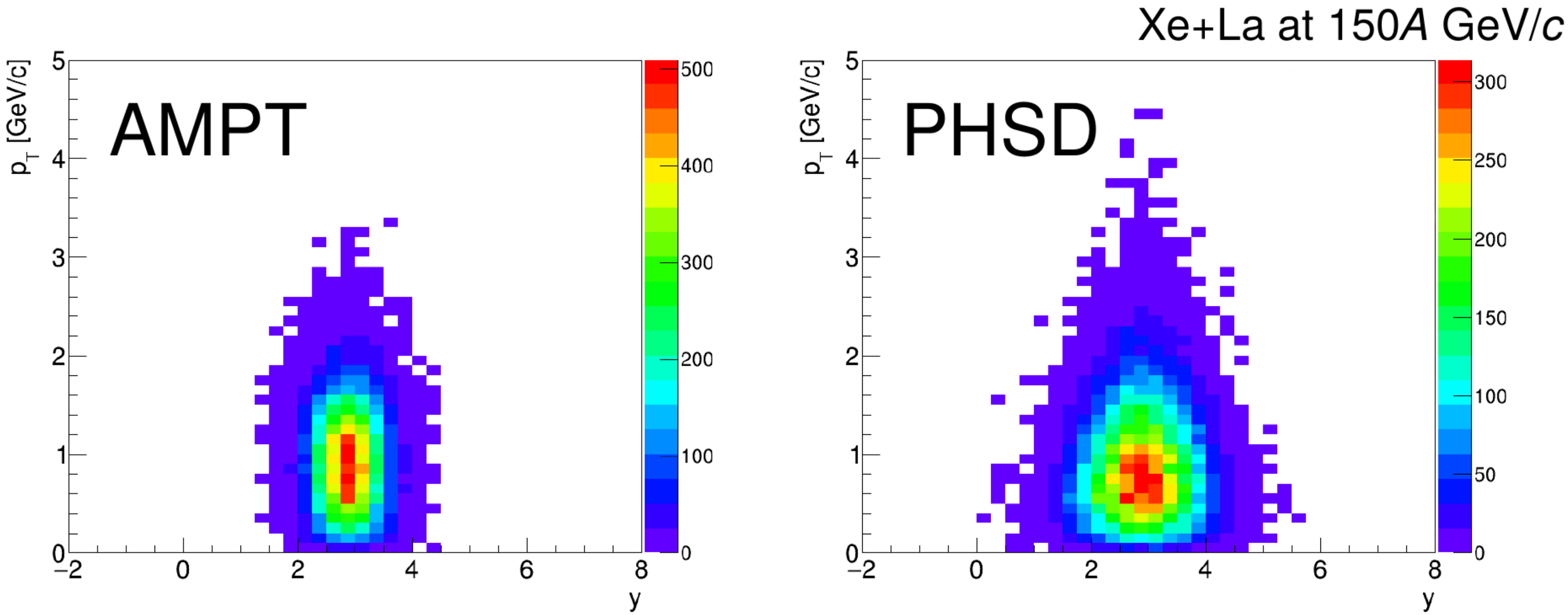
NA61/SHINE open charm production measurements started in 2017 with SAVD → first physics results await validation

- After LS2 high statistic Pb+Pb data taking with upgraded detector is proposed
  The results from high statistic runs are expected to:
  - → distinguish between many existing models of charm production in Pb+Pb collisions
  - → initiate a measurement of collision energy dependence of open charm yield
  - → verify signal of the QGP formation by measurements of centrality dependence of charm production

Details in CERN document: SPSC-P-330-ADD-10

Backup slides

Simulation using GEANT4

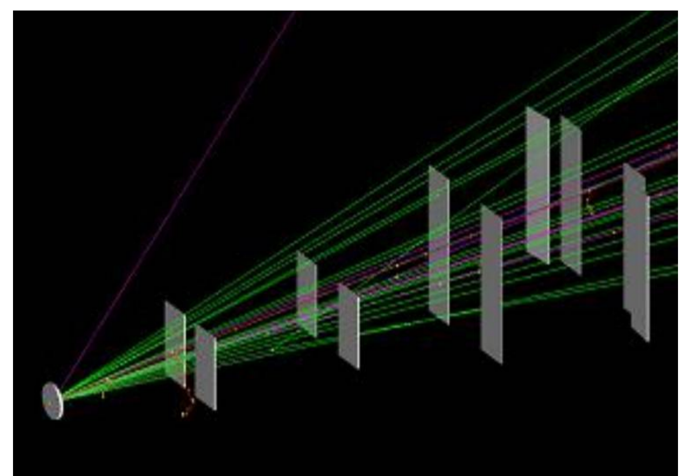


D^0 input:

1. PHSD as compare to AMPT shows noticeable broader distributions both in y and p_T

2. Background described using AMPT (mostly primary pions and kaons)

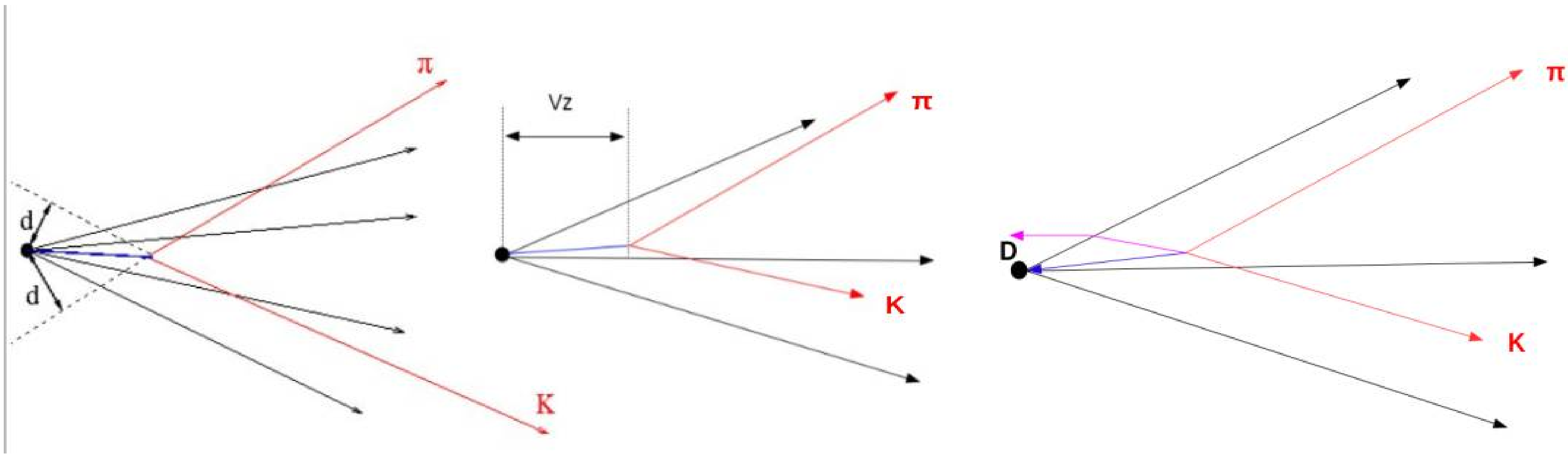
reconstruction of simulated data → corrections and comparison with model predictions



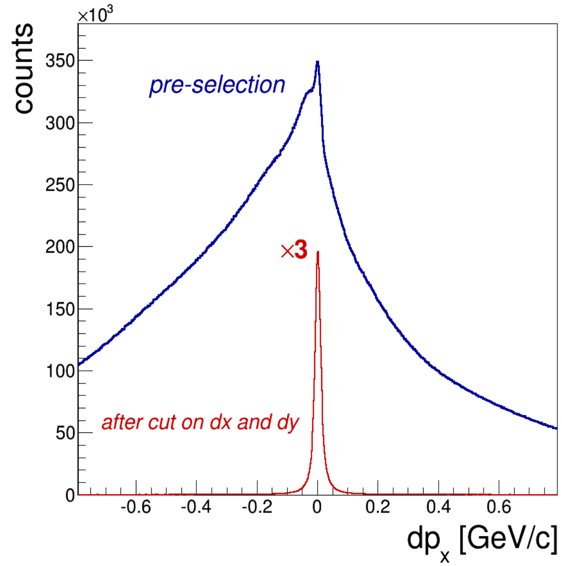
$$K_s^0 \rightarrow \pi^+ + \pi^- \qquad c\tau \approx 2.69\,cm$$

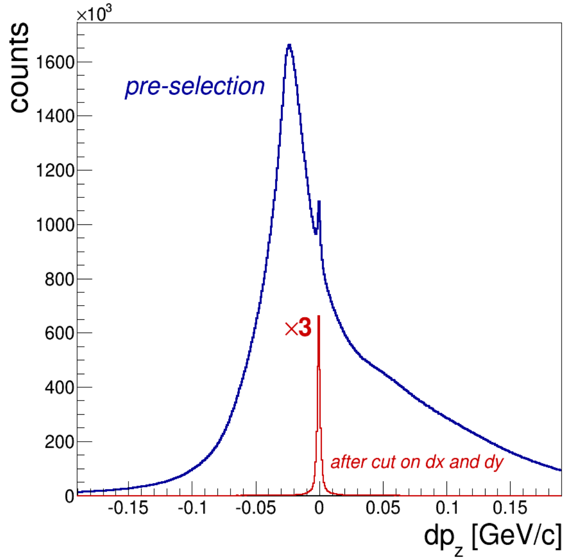
$$\Lambda^0 \rightarrow p^+ + \pi^- \qquad c\tau \approx 7.89\,cm$$

$$D^0 \rightarrow \pi^+ + K^- \qquad c\tau \approx 123\,\mu m$$



VD - TPC track matching

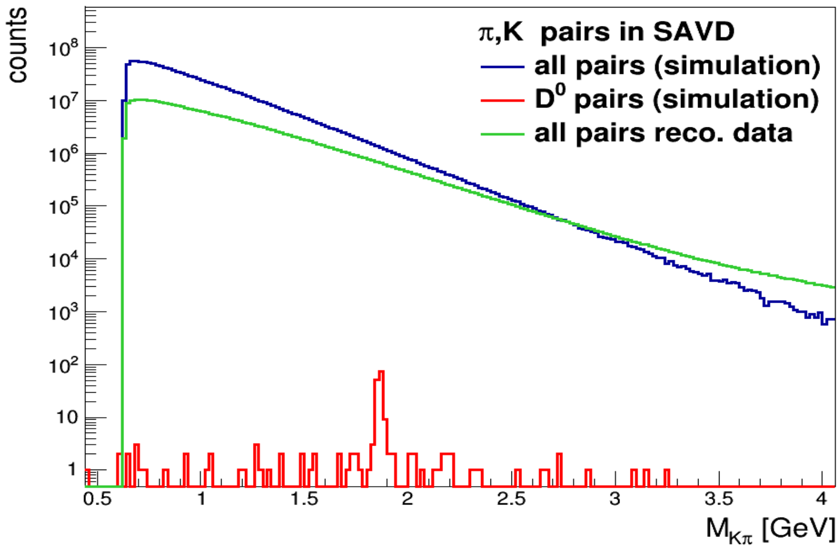




Extrapolate SAVD tracks to TPC volume.

Pre-selection: cut on y-slopes of tracks.

After cuts on dx and dy clear correlation peaks are seen in dp_x and dp_z

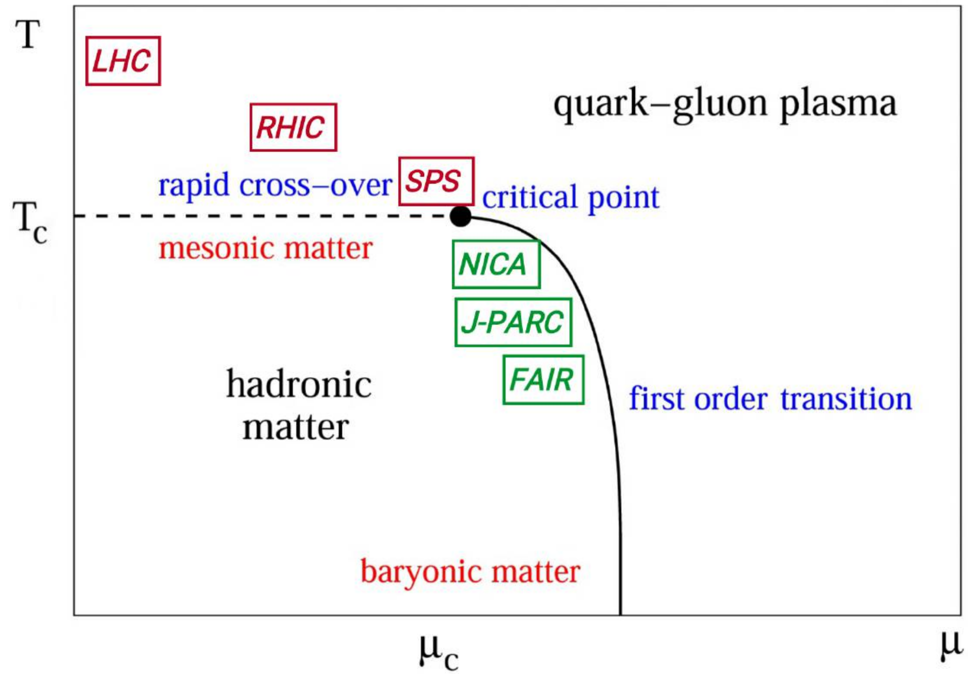


Matching with TPC provides: momenta and PID to VD tracks

→ invariant mass distribution

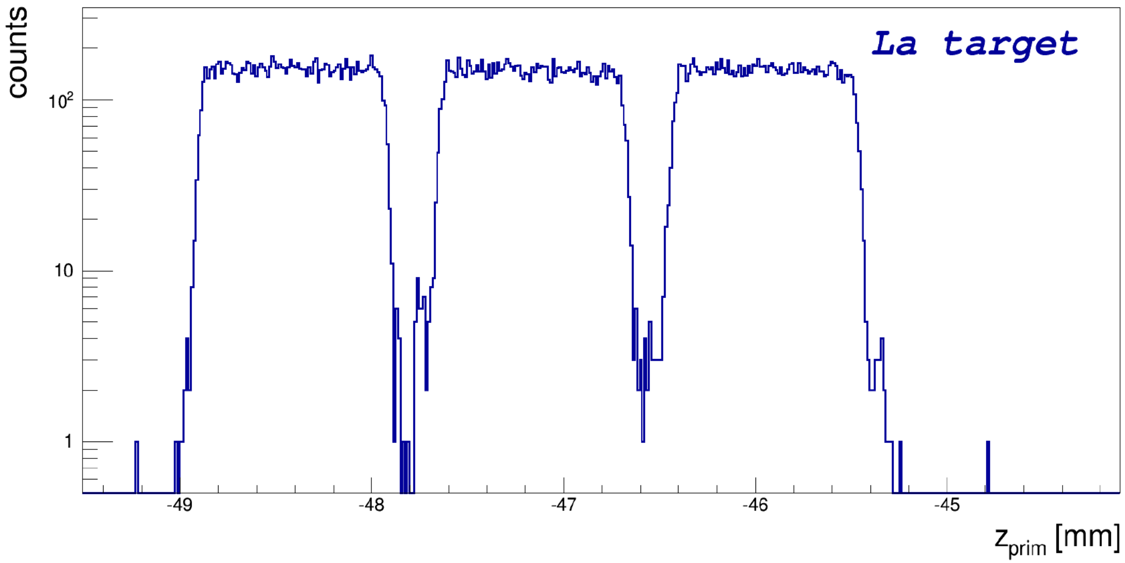
NA61/SHINE program: complementarity and uniqueness

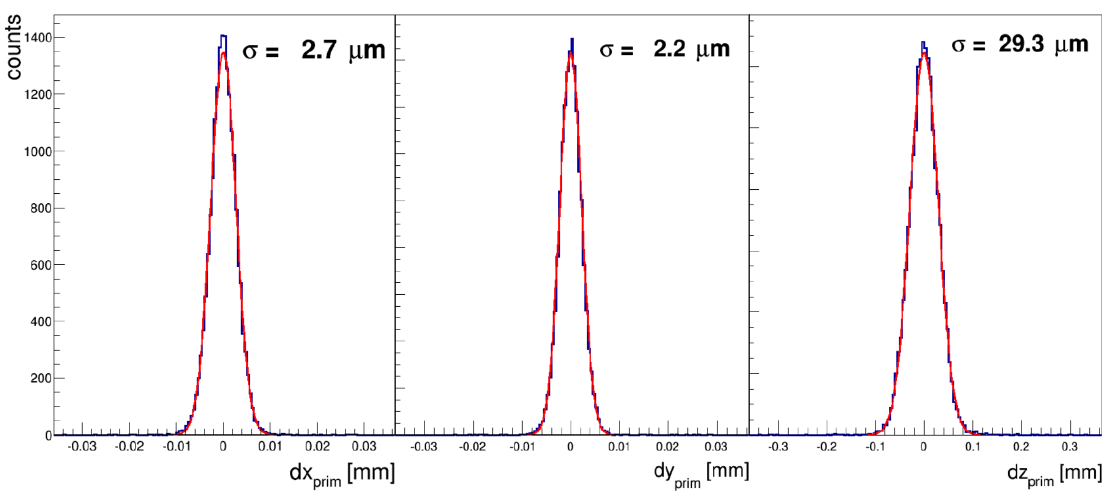
- **LHC** and **RHIC** at high energies ($\sqrt{s_{NN}} \geq$ 200 GeV): significantly limited acceptance due to collider kinematics and related detector geometry
- **RHIC BES** collider and fixed-target ($\sqrt{s_{NN}}$ = 3−39 GeV): measurement not considered in the current program
- **NICA** ($\sqrt{s_{NN}}$ < 11 GeV): measurements during stage 2 (after 2023) are under consideration (overlap in energy with NA61/SHINE)
- **J-PARC-HI** ($\sqrt{s_{NN}} \leq$ 6 GeV): under consideration, may be possible after 2025.
- **FAIR SIS-100** ($\sqrt{s_{NN}}$ < 5 GeV): sub-threshold charm production measurements are considered. Systematic charm measurements are planed with SIS-300



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

Performance for Xe+La at 150*A* GeV/*c*





- Large statistic Xe+La data taken in late 2017 at 150*A* and 75*A* GeV/*c* for minimum bias and 0-20% central events.
- Segmented target was used (tree 1mm thick La blocks squeezed together). The structure of the target can be well seen in the z_{prim} distribution plot.
- Obtained primary vertex resolution: 1.3, 1.0 and 15 μm in *x*, *y* and *z* coordinate, respectively. Significant improvement as compare to test measurement due to better setup of sensor thresholds.
- Xe+La data should allow for reinterpretation of J/ψ yields measured by NA60 for medium size systems.

Measurement program with SAVD

2016: Pb+Pb at 150*A* GeV/*c*

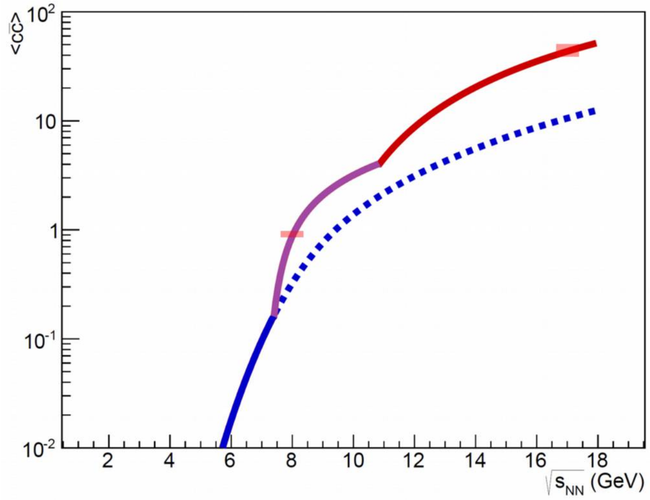
- Detector commissioning
- Good detector performance
- D^0 likely seen

2017: Xe+La at 75 and 150*A* GeV/*c*

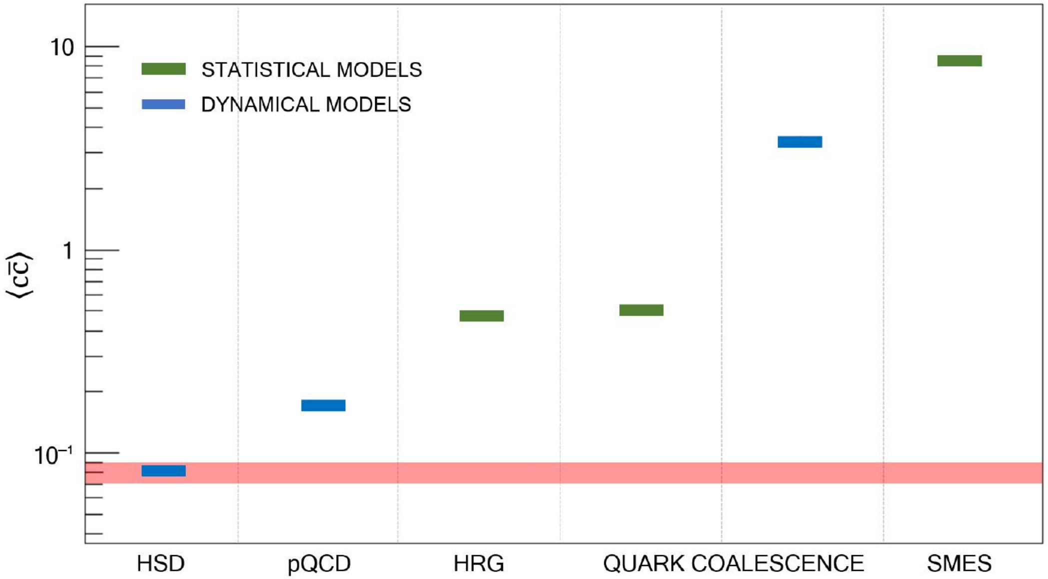
- Improved sensor efficiency
- Improved primary vertex resolution (dx=1.3µm, dy=1.0µm, dz=15µm)
- Large statistics collected:
  5.1 MEvents@150*A*GeV/*c*
  4.0 MEvents @75*A* GeV/*c*
- Analysis ongoing, expected good data quality
- Expected open charm data suited for comparison with NA61/SHINE

2018: Pb+Pb at 150*A* GeV/*c* run scheduled

Anticipated results

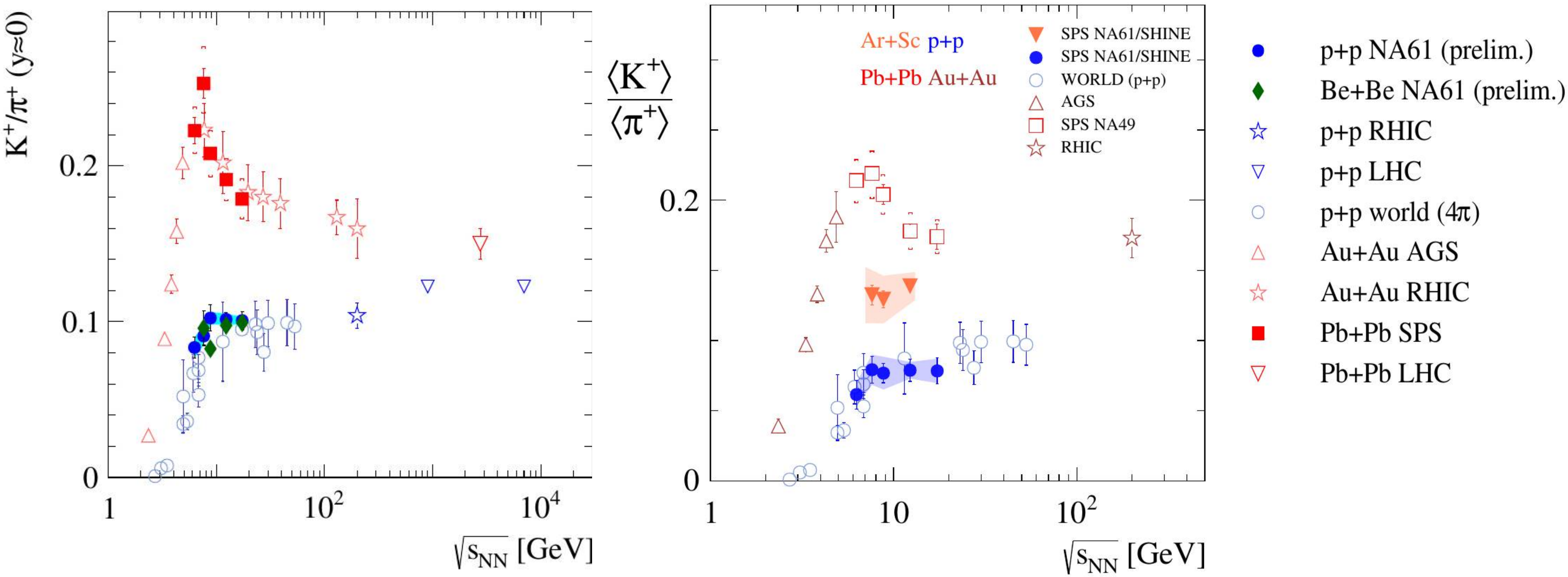


SMES predictions



Particle ratios and fluctuations (2)

Rapid changes in **K^+/π^+** (HORN) were observed in Pb+Pb collisions. It was predicted within SMES as a signature of onset of deconfinement



NEW RESULTS:

- plateau like structure visible in p+p
- Be+Be consistent with p+p

- $\langle K^+\rangle/\langle\pi^+\rangle$ in Ar+Sc in between p+p, Be+Be and Pb+Pb

NA61/SHINE

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