NA61/SHINE: detector upgrades and physics plans beyond 2020

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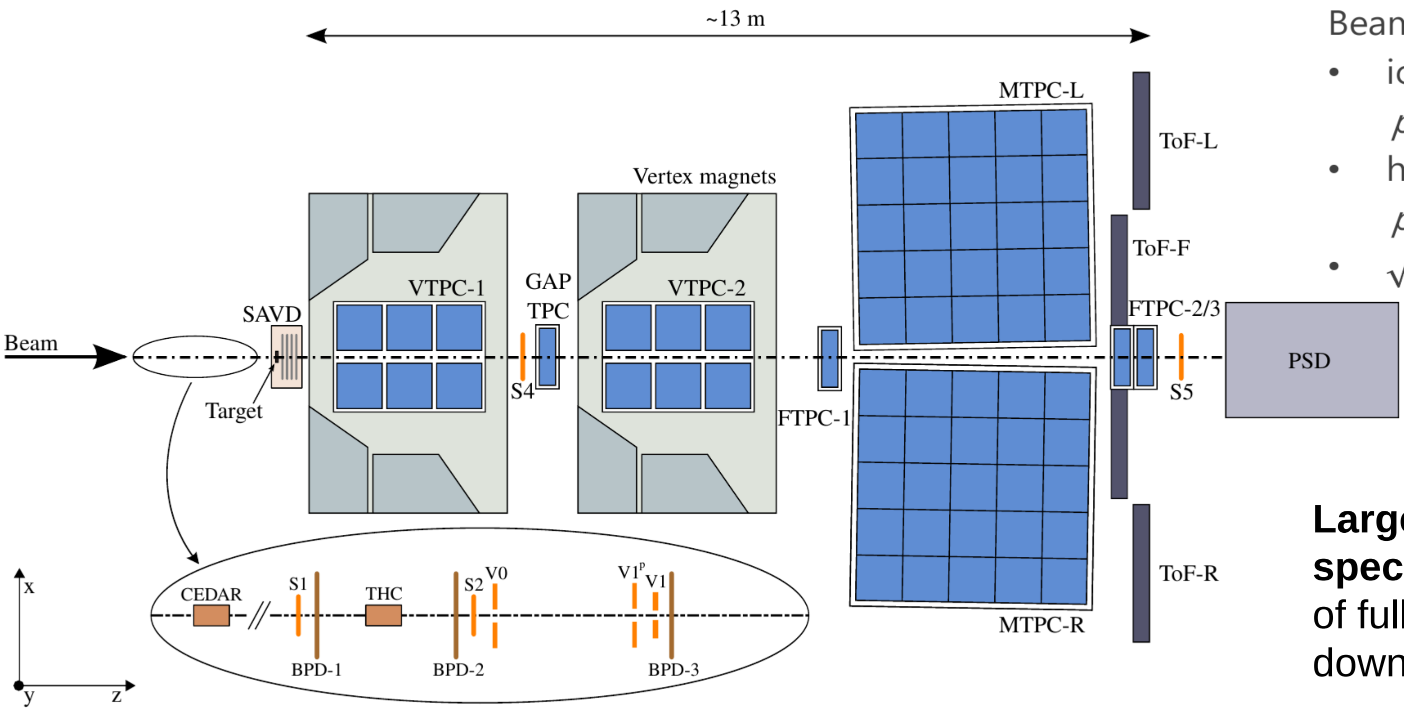
Outline

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

Research program

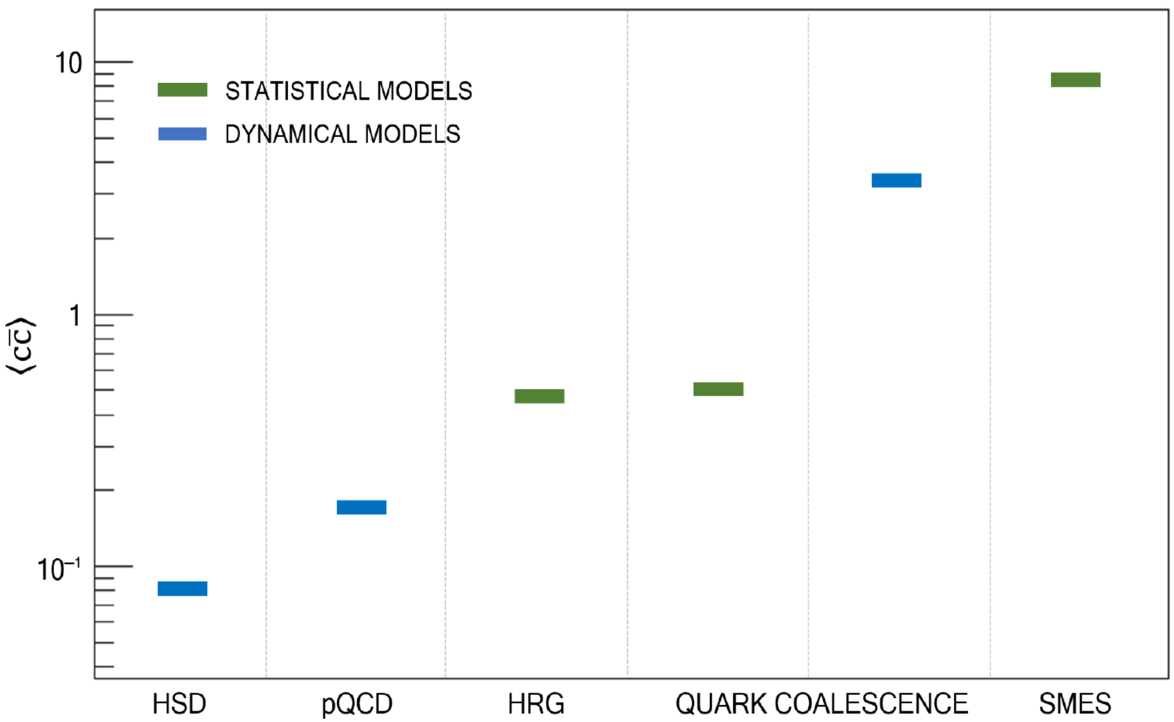
- **Strong interaction: 2D scan of energy and system size to study phase diagram of strongly interacting matter**
  → search for critical point of strongly interaction matter
  → study of the properties of the onset of deconfinement
  → electromagnetic effects
  → particle flow measurements
  (refer to talks by A. Rybicki, M. Kiełbowicz….)

- **Hadron production measurements for neutrino experiments**
  → reference measurements for neutrino experiments for computing initial neutrino fluxes at J-PARC and FERMILAB

- **Hadron production measurements for cosmic ray experiments**
  → reference measurements of p+C, p+p, π+C and K+C interactions for cosmic-ray physics (Pierre-Auger, KASCADE) for improving air shower simulations

Physics motivation (strong interactions)

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%

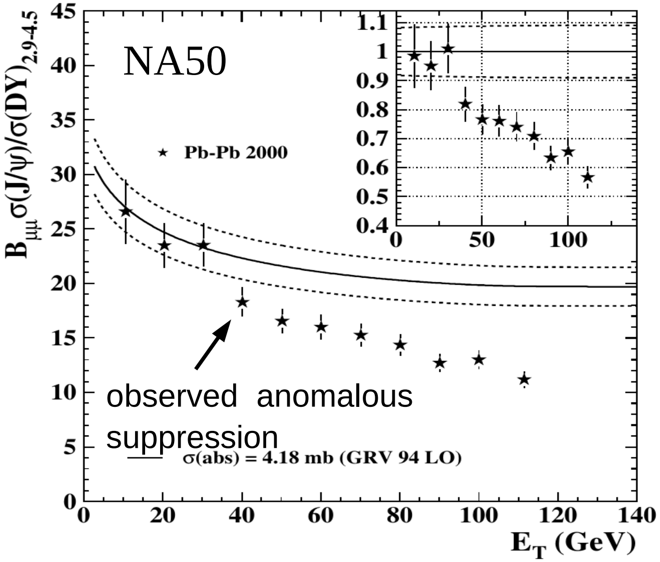
Hadrons containing charm considered for measurements in NA61/SHINE

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 final state interaction 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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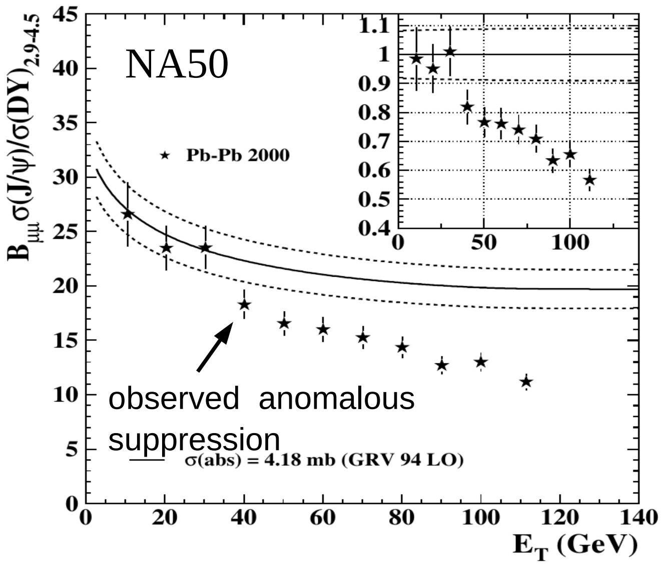

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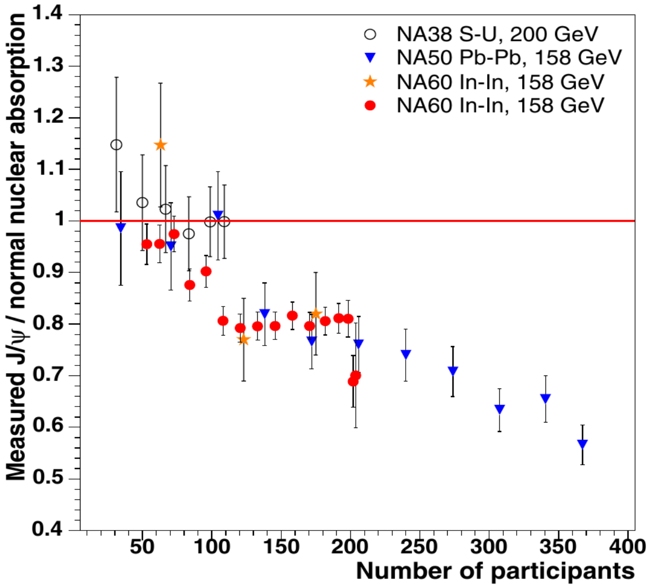

NA60 in 2005 (QM05)

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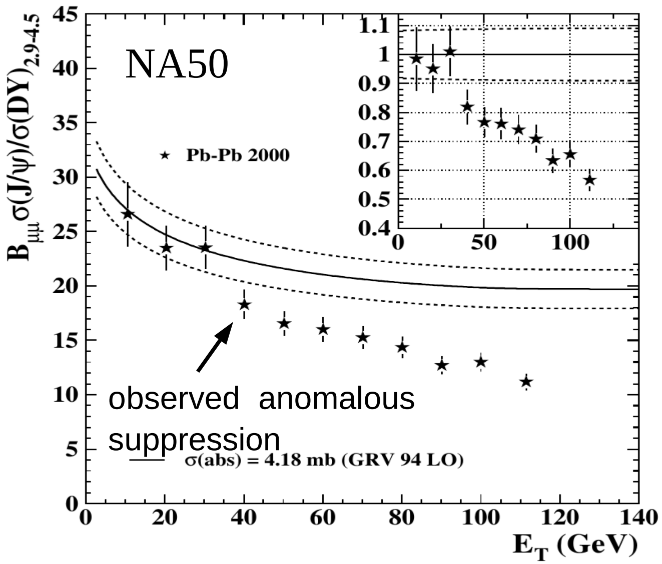

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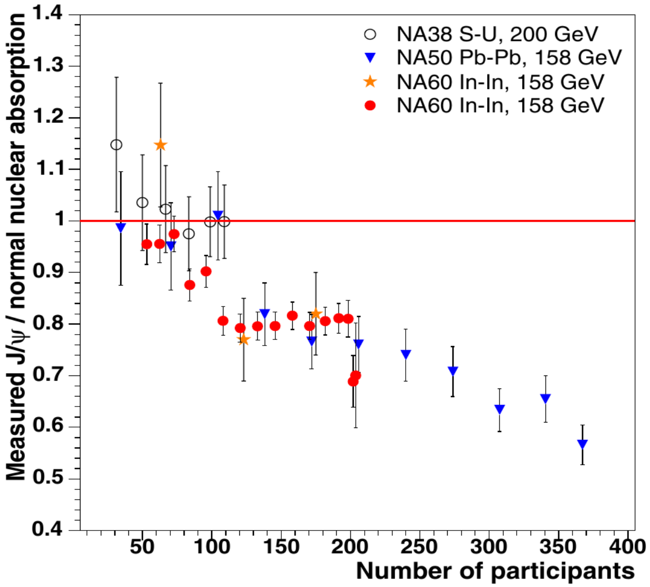
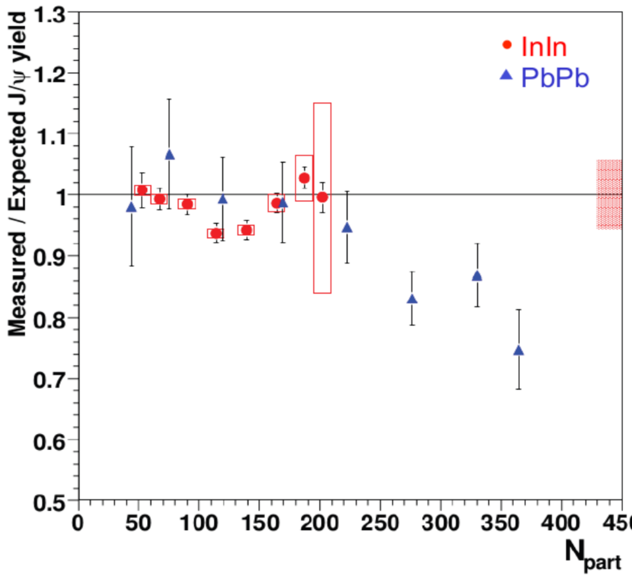


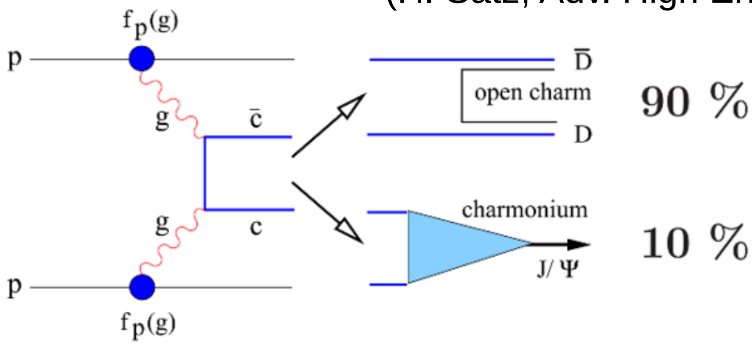
NA60 in 2005
(QM05)

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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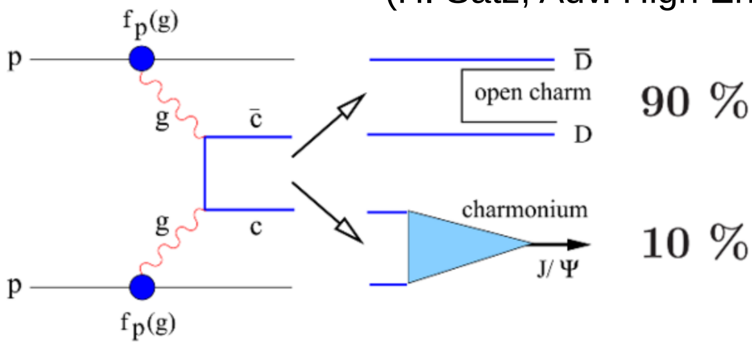

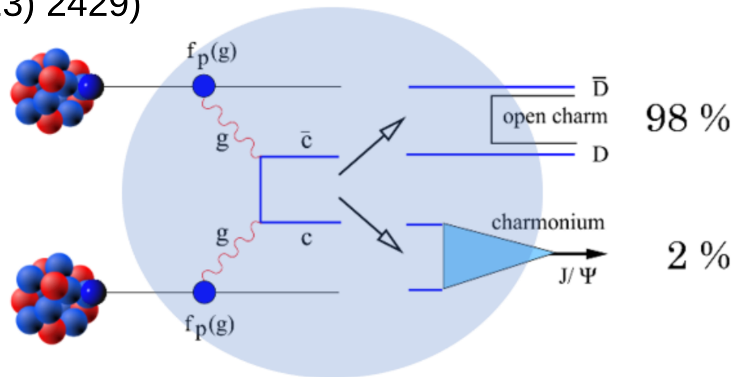

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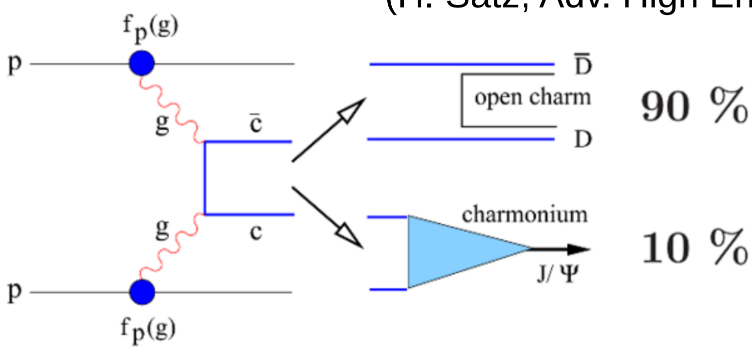

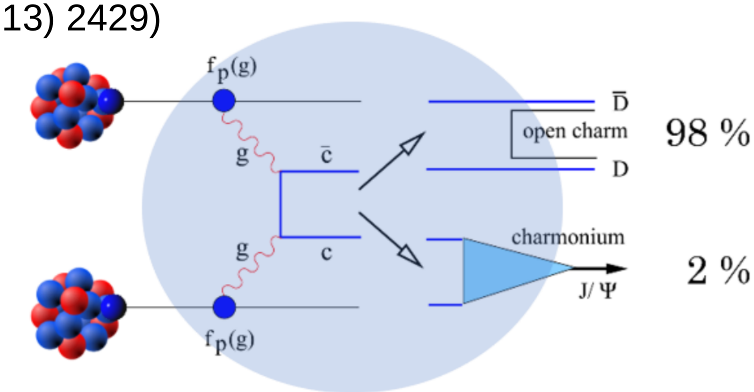

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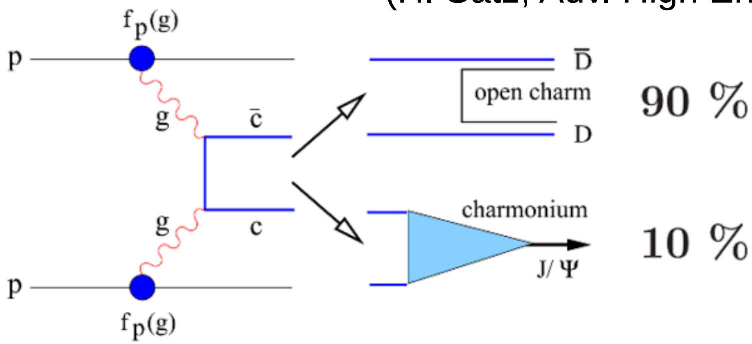

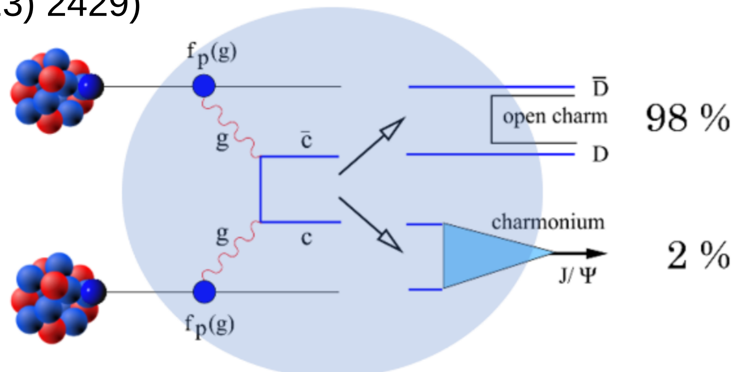

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→ the effect of the medium on $c\bar{c}$ binding can only be determined by comparing the ratio of $\langle J/\psi\rangle/\langle c\bar{c}\rangle$ in A+A to that in proton-proton collisions.

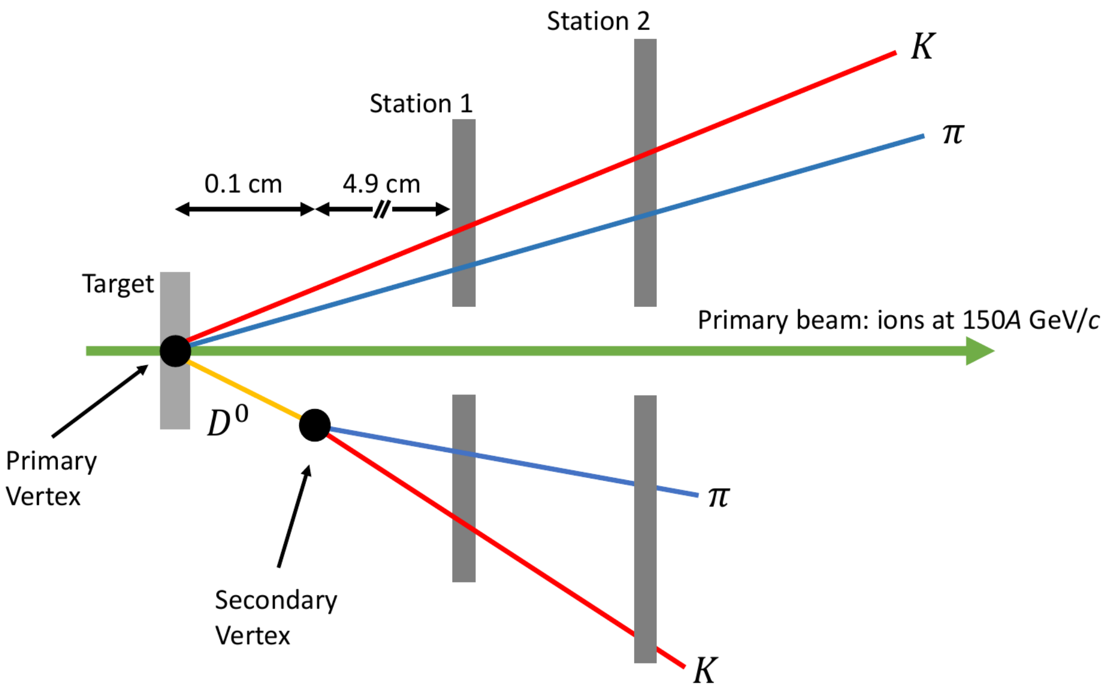
→ measurements of open charm in A+A needed!!!

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

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

Why Vertex Detector is needed to measure open charm?

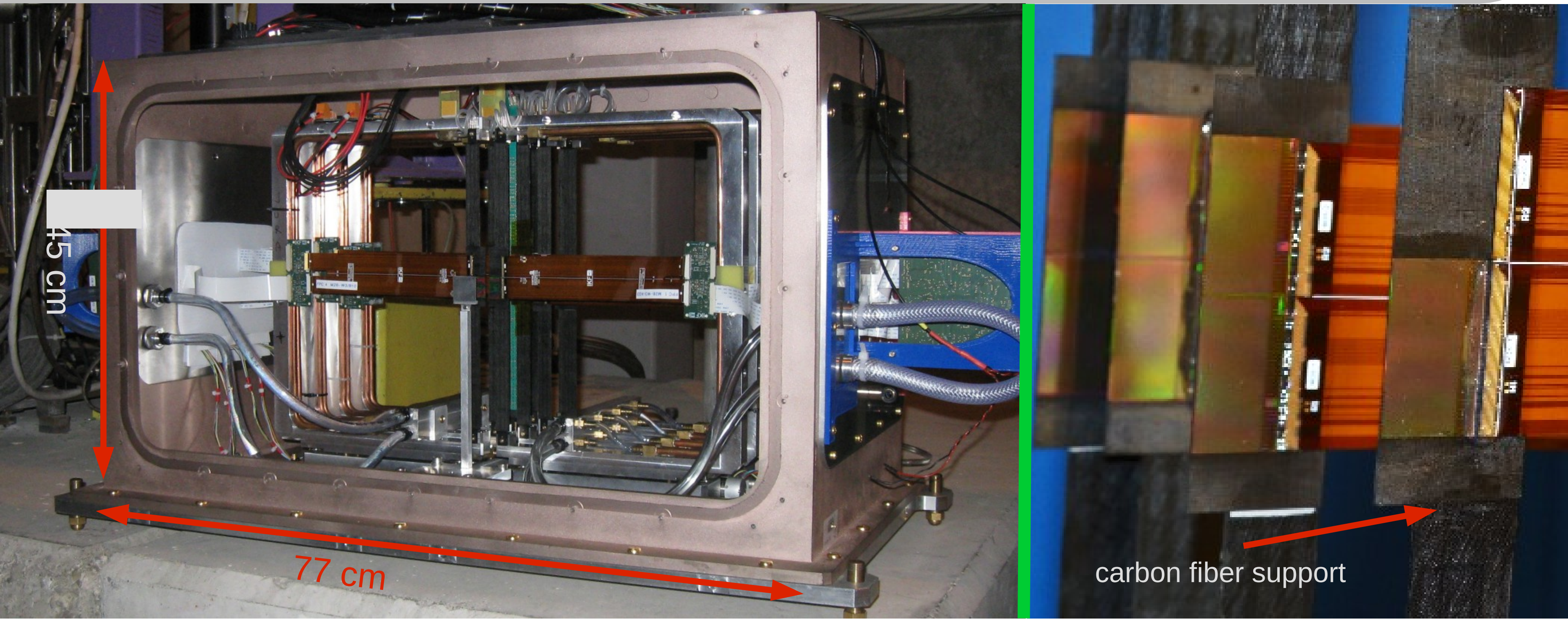
$$D^0 \rightarrow \pi^+ + K^-$$



- 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 than in case of 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*



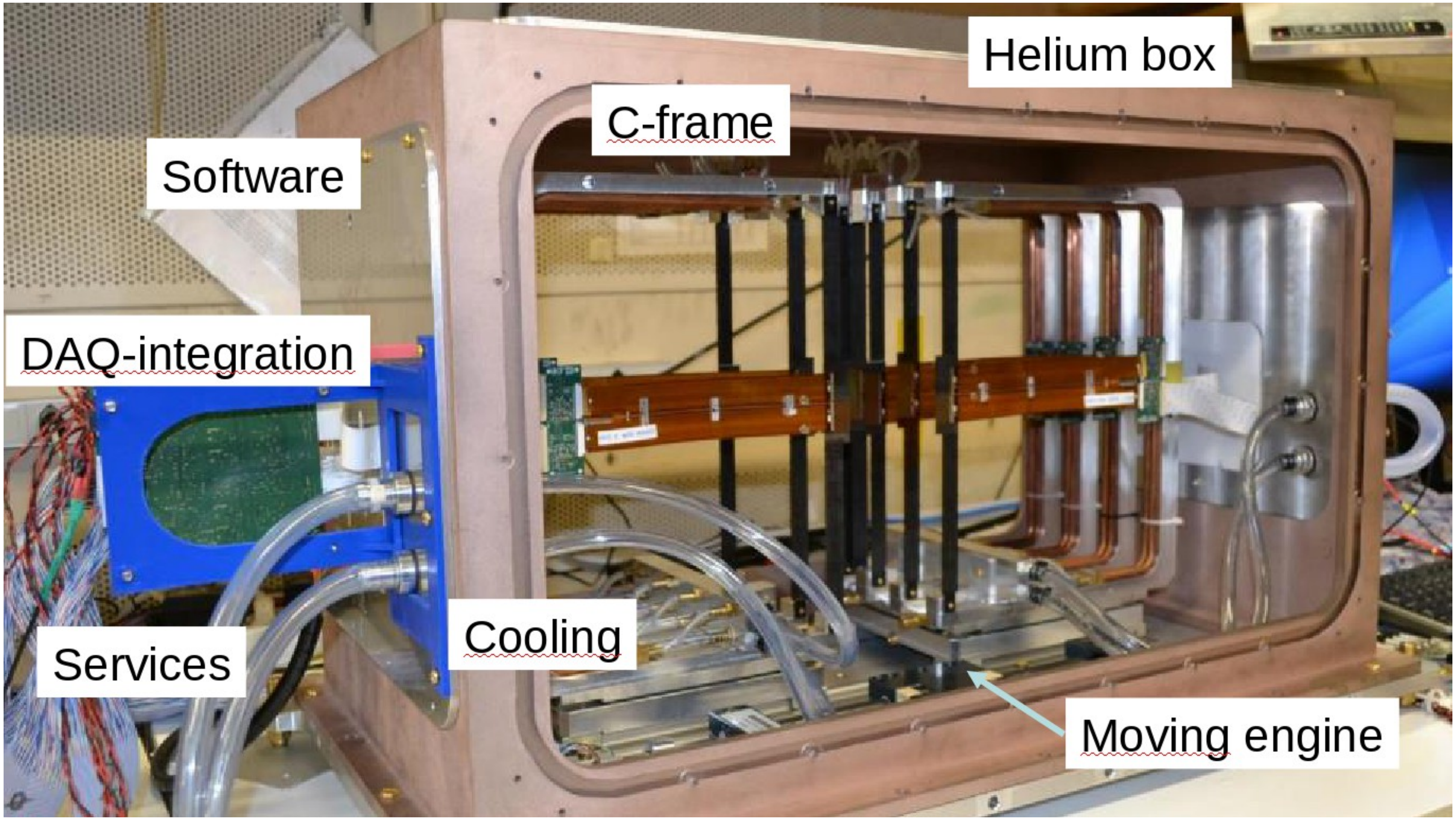
SAVD:

- 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



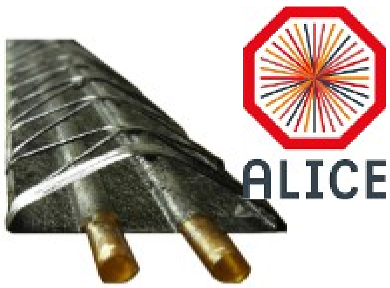
System integration and project leadership:
Jagiellonian University Krakow,
supported by AGH Krakow, WUT Warsaw

Main project components (cont.)

MIMOSA-26AHR

- 1152x576 pixels of 18.4x18.4µm²
- 3.5 µm resolution, 0.05% X_0
- Readout time: 115.2 µs, 50µm thin

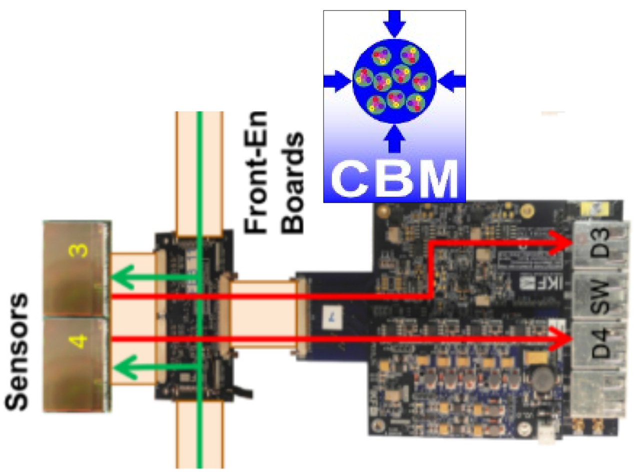
PICSEL Group, IPHC Strasbourg



ALICE ITS ladder

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

St. Petersburg, CERN



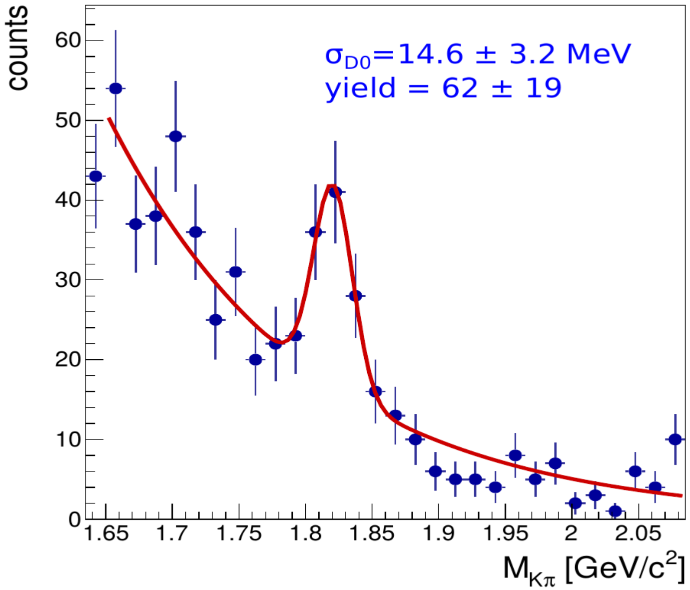
CBM Micro Vertex Detector Prototype

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

Goethe Universitet Frankfurt am Main

Highlights of SAVD performance

First results for 140k events of Pb+Pb at 150A GeV/c



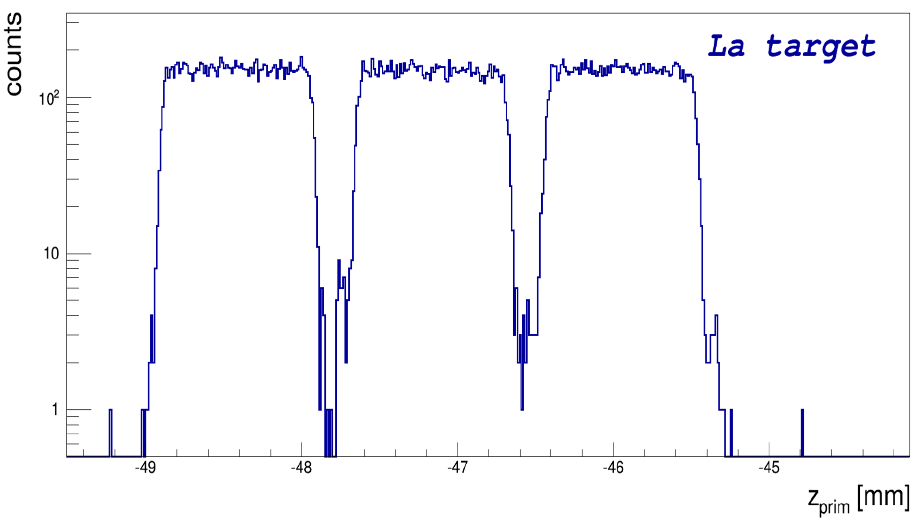
Background suppression → cuts on:

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

Analysis details:

1. Global fit (VD+TPCs) using Kalman Filter
2. PID not used yet (should reduce background by factor of 5)

Allocated beam time in 2018: 10M 0-20% central Pb+Pb → 2.5k $D^0 + \overline{D}^0$



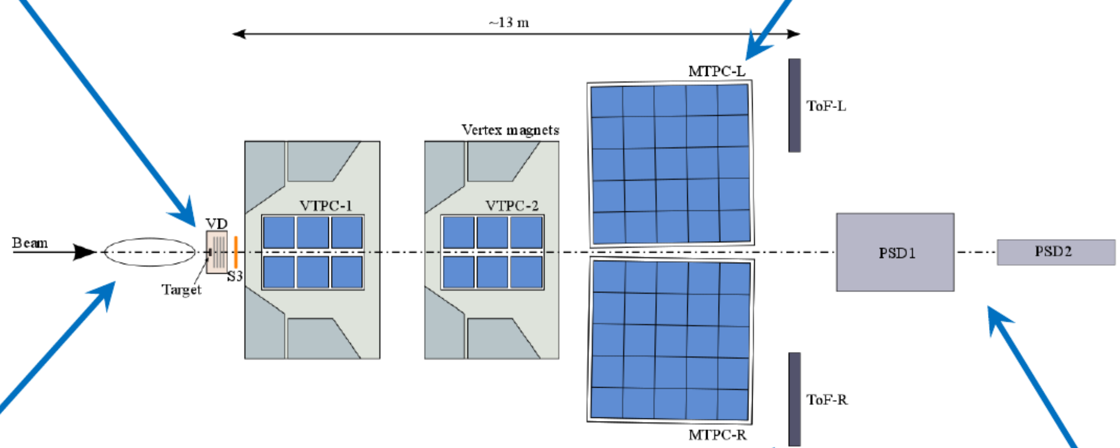
- Large statistic Xe+La data taken in 2017 at 150*A* and 75*A* GeV/*c*.
- Segmented target was used (tree 1mm thick La blocks squeezed together). The structure of the target seen in the data.
- Primary vertex spacial resolution: 1.3, 1.0 and 15 μm in *x*, *y* and *z* coordinate, respectively.

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 D^0, $\overline{D^0}$ decay reconstruction



New trigger and data acquisition system

New Time-of-Flight detectors

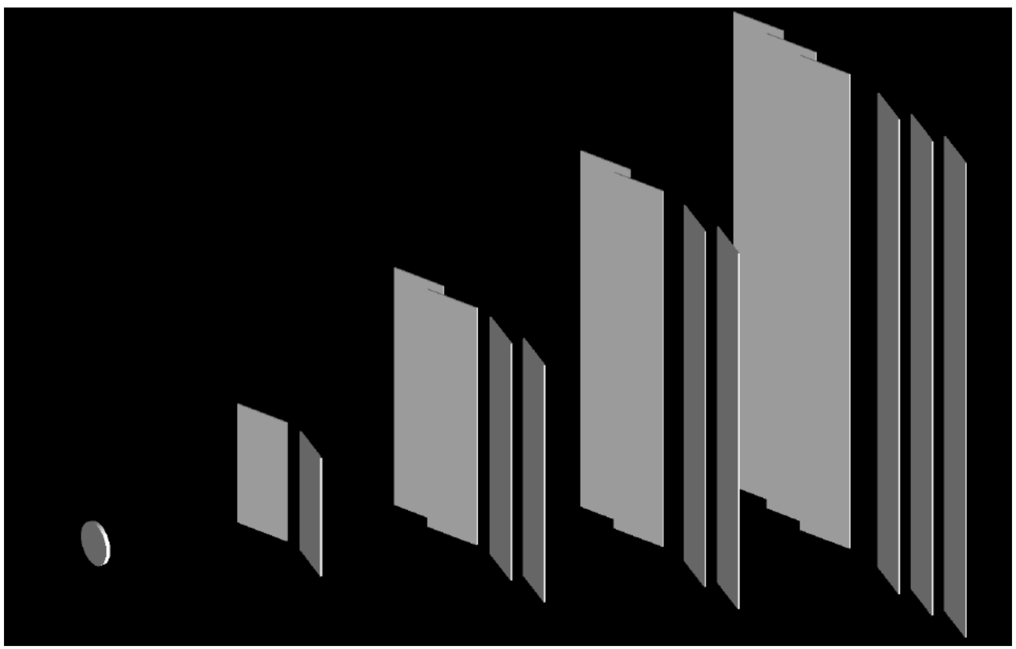
Upgrade of Projectile Spectator Detector

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

Upgrade of Vertex Detector

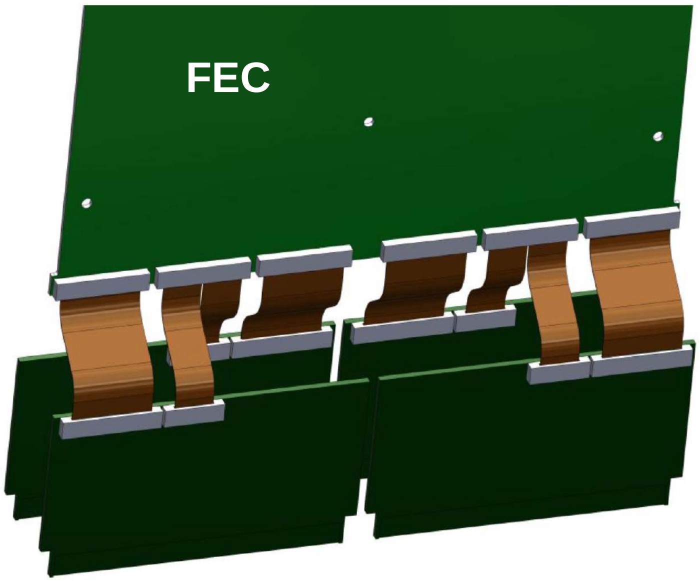
	MIMOSA-26AHR	ALPIDE
Sensor thickness (μm)	50	50
Spatial resolution (μm)	3.5	5
Dimensions (mm^2)	10.6×21.2	13.8×30
Power density (mW/cm^2)	250	40
Time resolution (μs)	115.2	10
Detection efficiency (%)	>99	>99
Dark hit occupancy	$\lesssim 10^{-4}$	$\lesssim 10^{-6}$

- 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 feedthrough
  → modification of ladders fixation bars

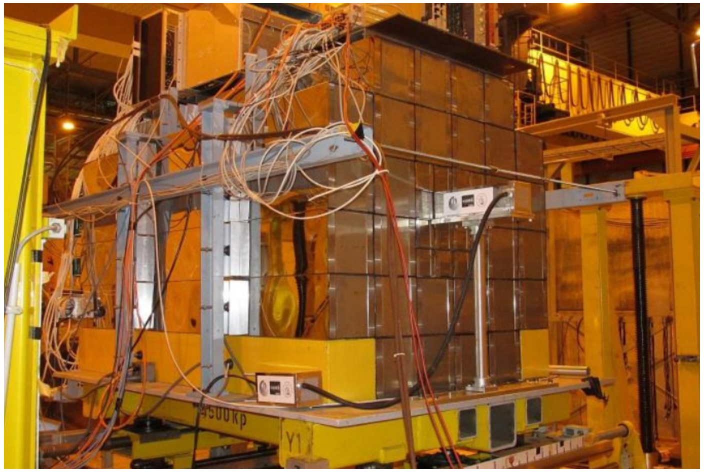
Upgrade of TPC



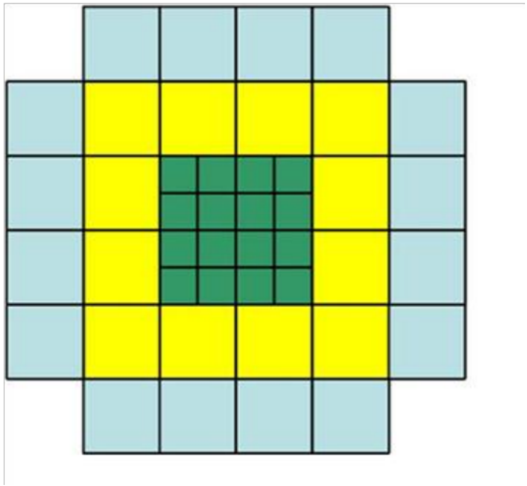
		NA61/ SHINE	ALICE
dynamic range		120:1	900:1
MIP S:N ratio		14:1	14/20/18:1
noise	e	1100	<1000
ADC number of bits		8	10
number of time slices		512	1000
power consumption	mW/ch	51	35
sampling rate	MHz	5, 10	5, 10
readout frequency	MHz	0.1	5, 10
integrated non-linearity	%	<2	0.2

- New readout used in ALICE TPC will allow for 1 kHz operation (MoU between ALICE and NA61/SHINE)
- Major challenges:
  - → Development of dedicated FPC
  - → Flexible connection between FEC and ROU.

Upgrade of PSD



- **M**ain **PSD** (MPSD) – 44 modules with beam hole in center (ϕ=60mm)
- **F**orward **PSD** (FPSD) – 9 modules w/o beam hole
- $\sigma_b/b \simeq$ 0.1, reaction plane resolution $\simeq$ 40 deg
- Beam rates up to 50 kHz



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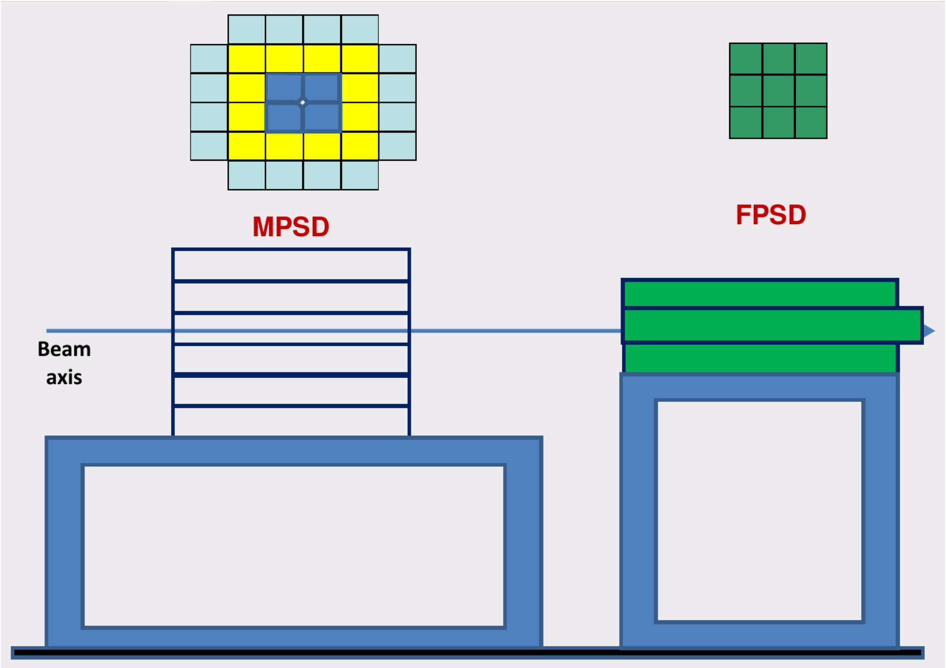
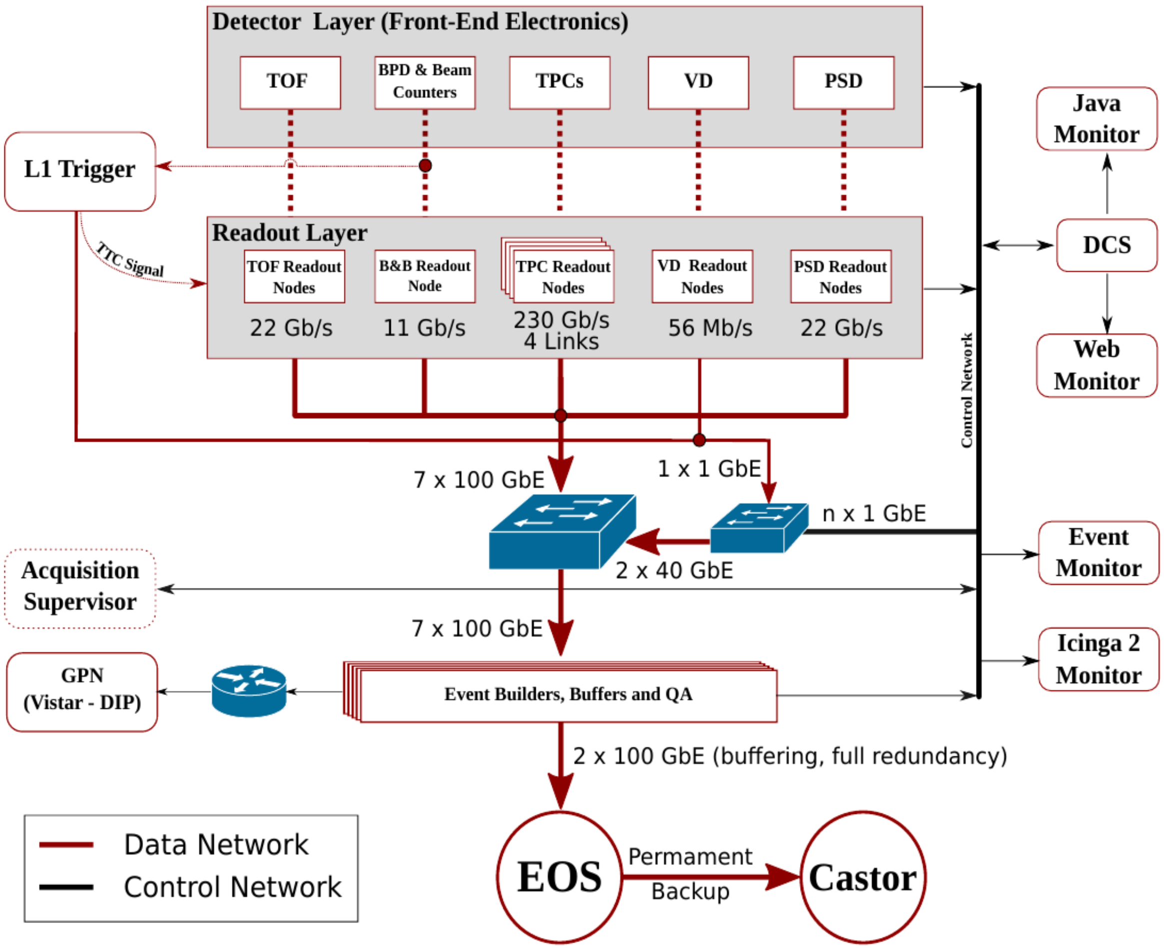


Upgrade of DAQ



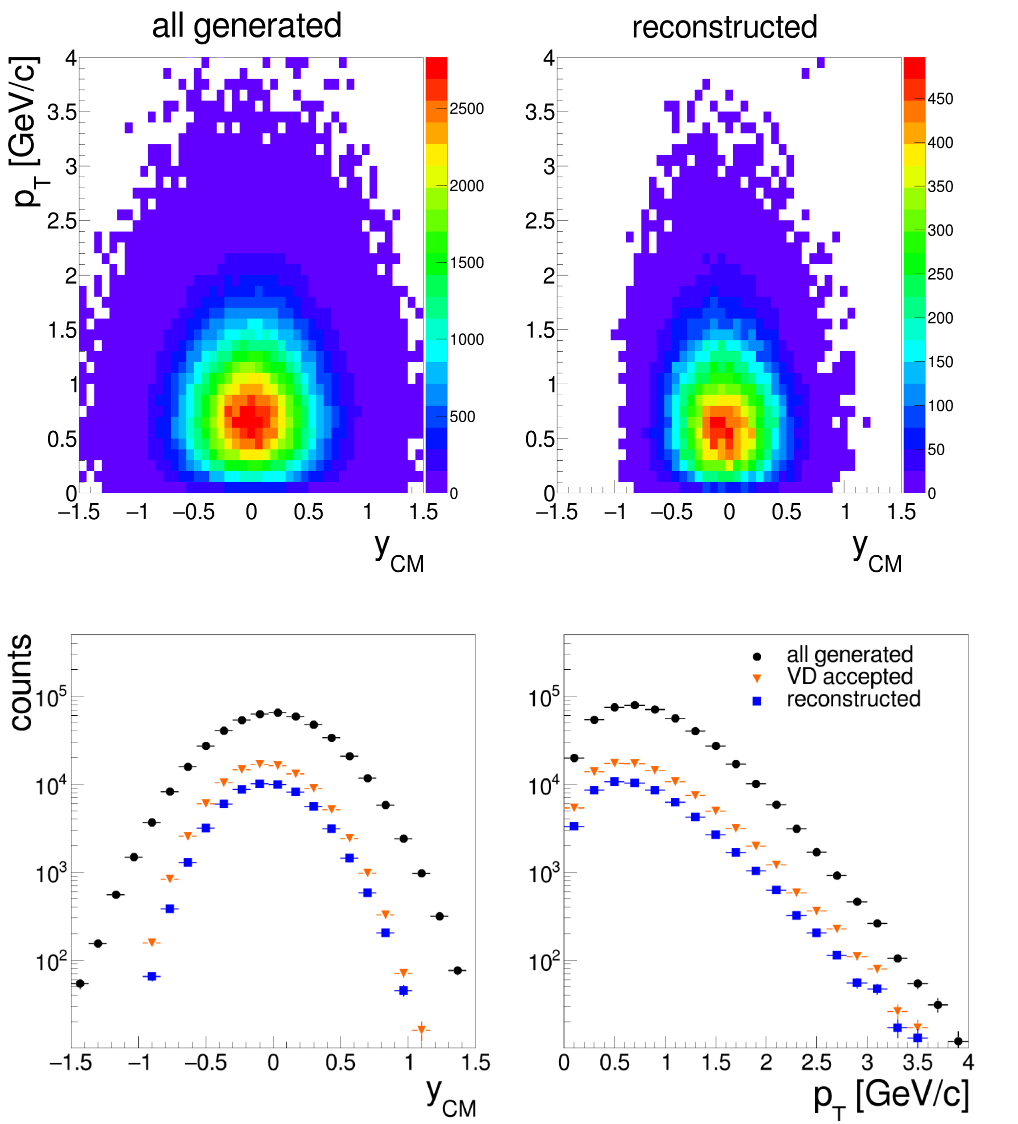
- Inhomogeneous Nodes → flexible choice of sub-detector readout system.
- Homogeneous Core → data from all subsystems treated in the same way.
- For 1 kHz expected data rate is 160 Gb/s
- Other features:
  - → Extendibility
  - → Transparency
  - → Use of commercial components
  - → Robustness

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



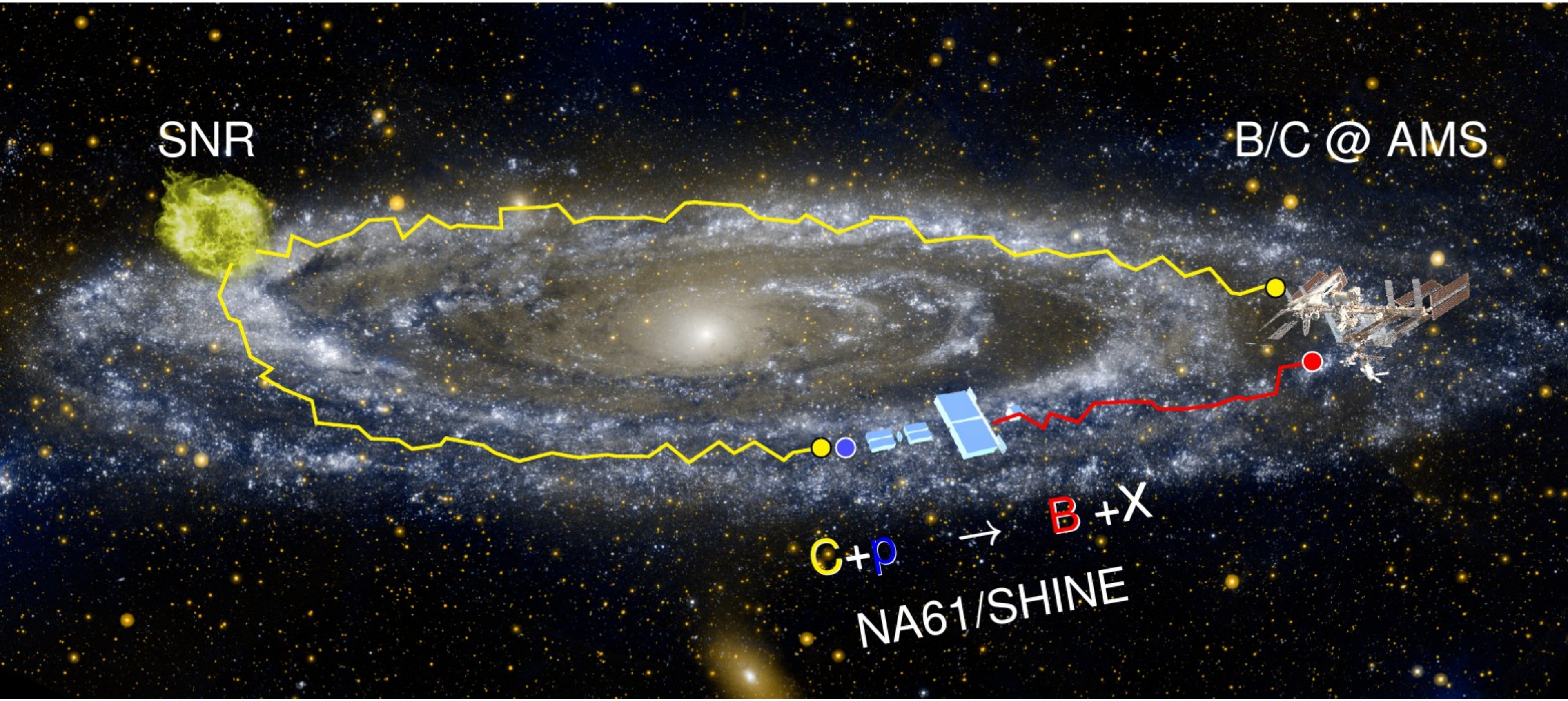
- Precise measurements of charm hadron production by NA61/SHINE are expected to be performed in 2022-2024.
- The Lorentz boost makes the measurements significantly easier than in case of collider experiments.
- Unlike in a typical collider experiment the acceptance extends down to p_T=0 → accurate measurements 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

Measurement of Nuclear Fragmentation Cross Sections (NFCS)

Motivation: NFCS of intermediate mass nuclei are needed to understand the propagation of cosmic rays in our Galaxy

→ background for dark matter searches with space-based experiments as AMS and PAMELA.



Beam requests in 2022

- **Heavy Ion Physics**
  → 42 days of primary Pb beam at 150*A* GeV/*c* for data taking on charm hadrons production in Pb+Pb collisions.
- **Cosmic Ray Physics**
  → 24 days of secondary light ion beam at 13A GeV/*c* for data taking on nuclear fragmentation cross section
- **Neutrino Physics**
  → 35 days of proton beam at 31 GeV/*c* for data taking on hadron production from the T2K replica target and the Super-Sialon thin target.
  → 28 days of K^+ beam at 60 GeV/*c* for data taking on hadron production by induced K^+ mesons.

In addition in 2021 beams for commissioning and calibrations.

Summary

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

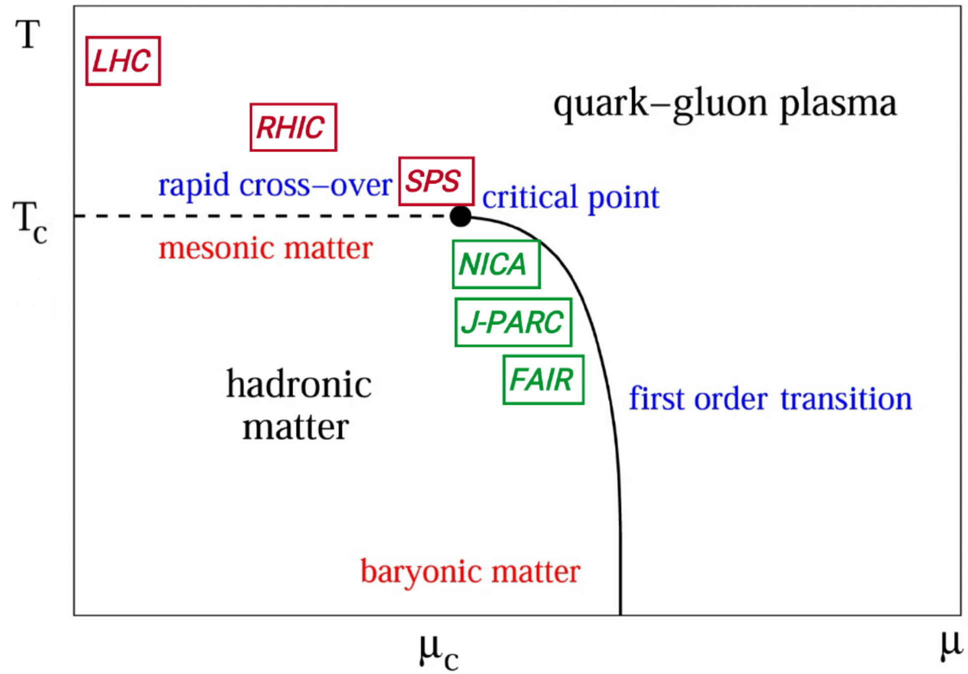
- After LS2 high statistic Pb+Pb data taking with upgraded detector is proposed
  The results from high statistic runs are expected to:
  - → distinguish between many existing models of charm production in Pb+Pb collisions
  - → initiate a measurement of collision energy dependence of open charm yield
  - → verify signal of the QGP formation by measurements of centrality dependence of charm production
- We will continue with strong interaction program which is not related to charm
- NA61/SHINE plan to continue measurements for neutrino physics
- Request of dedicated secondary beams for measurements of NFCS

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

Backup slides

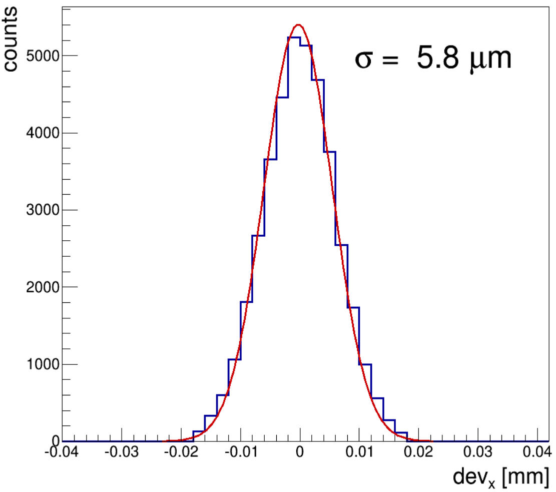
NA61/SHINE program: complementarity and uniqueness

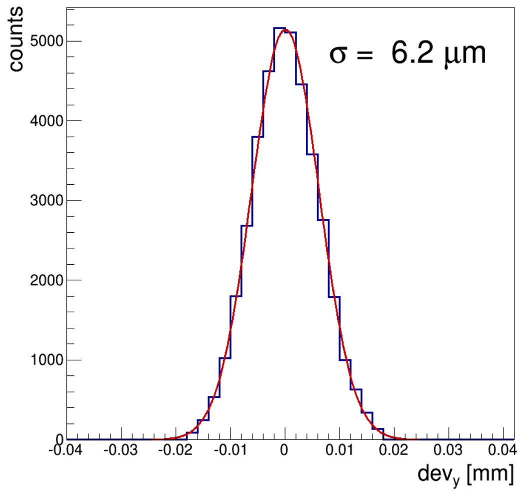
- **LHC** and **RHIC** at high energies ($\sqrt{s_{NN}} \geq$ 200 GeV): significantly limited acceptance due to collider kinematics and related detector geometry
- **RHIC BES** collider and fixed-target ($\sqrt{s_{NN}}$ = 3−39 GeV): measurement not considered in the current program
- **NICA** ($\sqrt{s_{NN}}$ < 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**

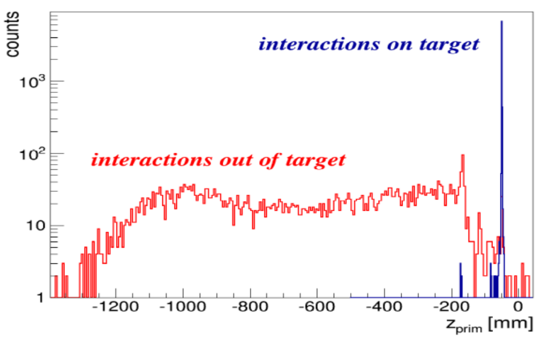
Vertex Detector performance

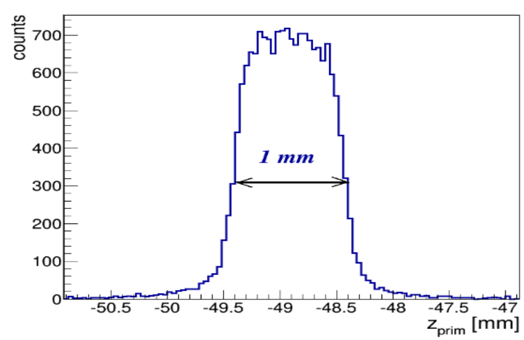




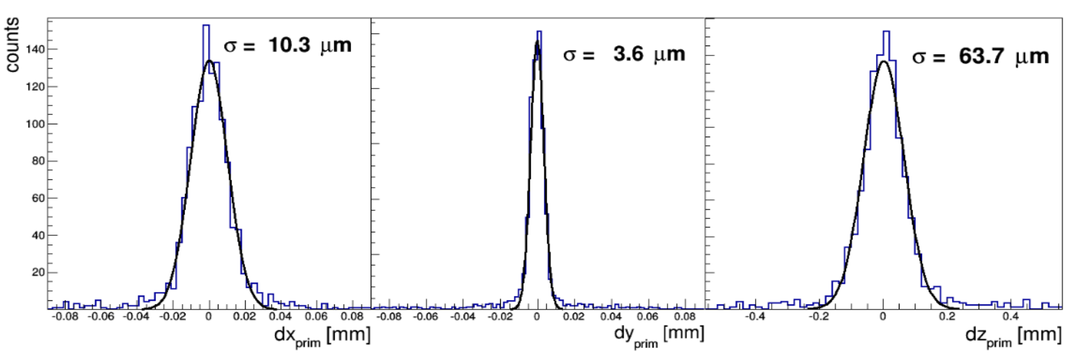
Spacial resolution of the sensor < 5μm as expected

$$\sigma_{x/y} = \sqrt{\frac{2}{3}}\,\sigma_{dev_{x/y}}$$





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



Spacial primary vertex resolution:

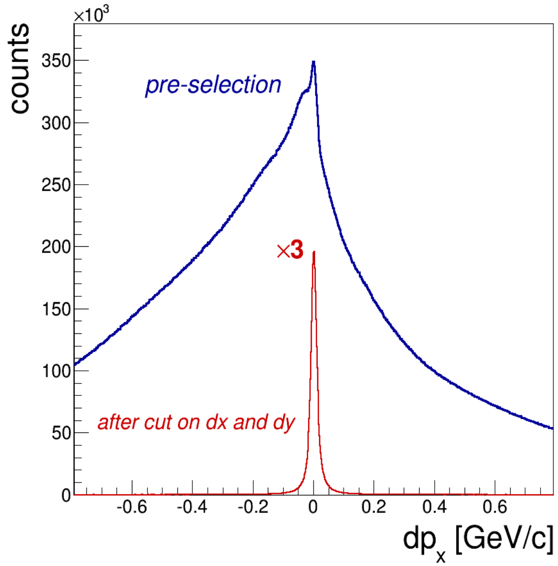
$\sigma_x = 5$ μm

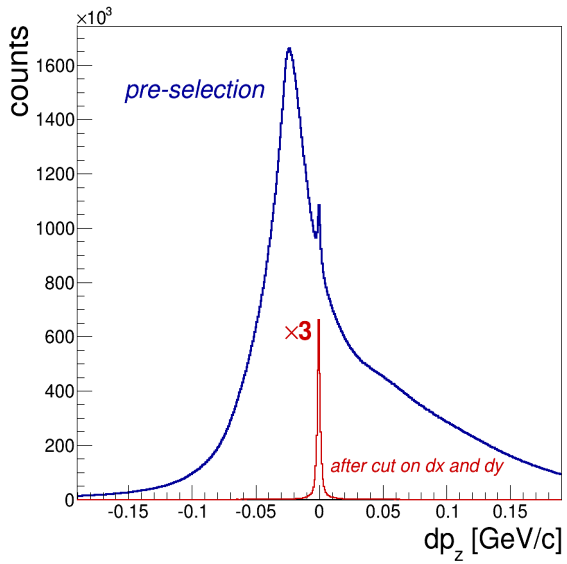
$\sigma_y = 1.8$ μm

$\sigma_z = 30$ μm

Worse resolution in x due to presence of magnetic field (B_y)

VD – TPC track matching

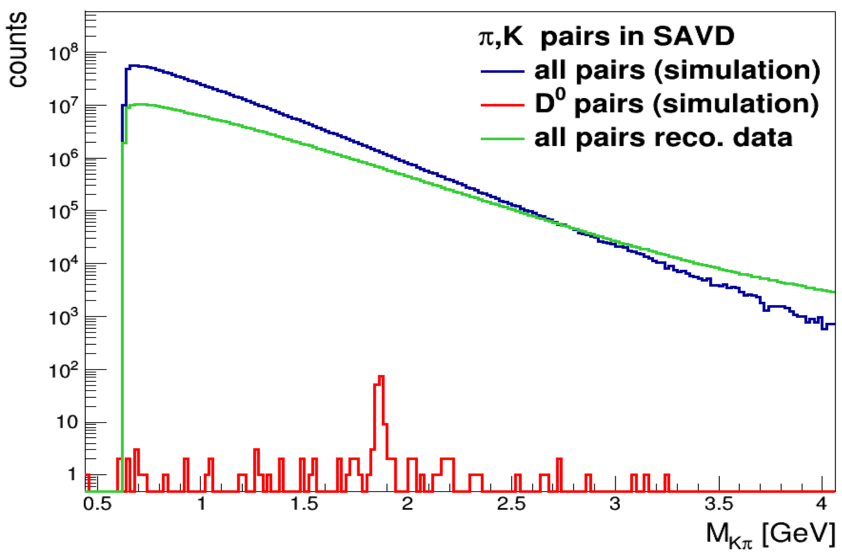




Extrapolate SAVD tracks to TPC volume.

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

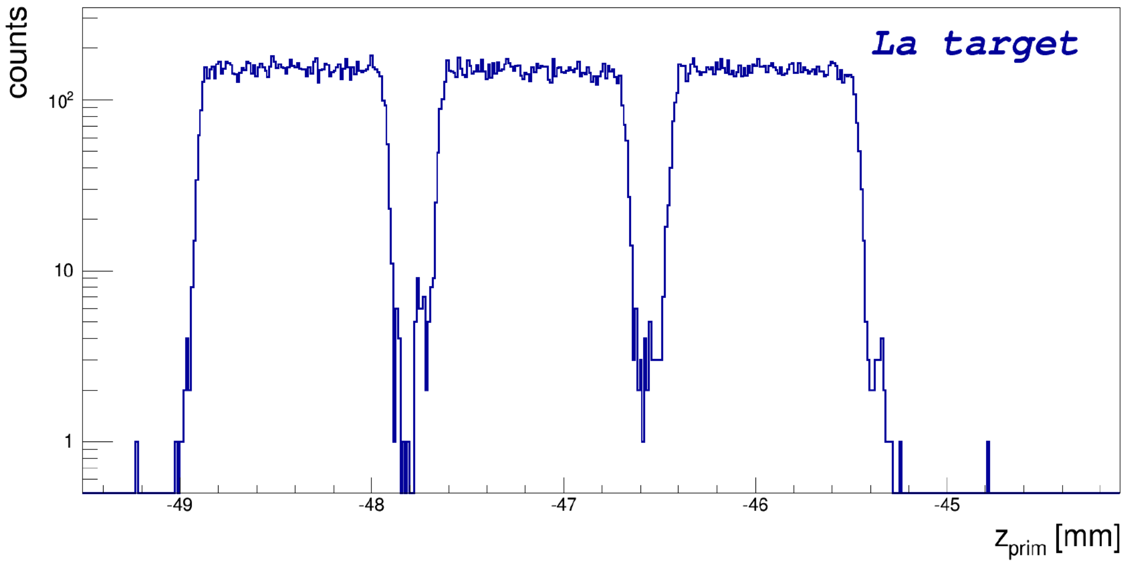
After cuts on dx and dy clear correlation peaks are seen in dp_x and dp_z

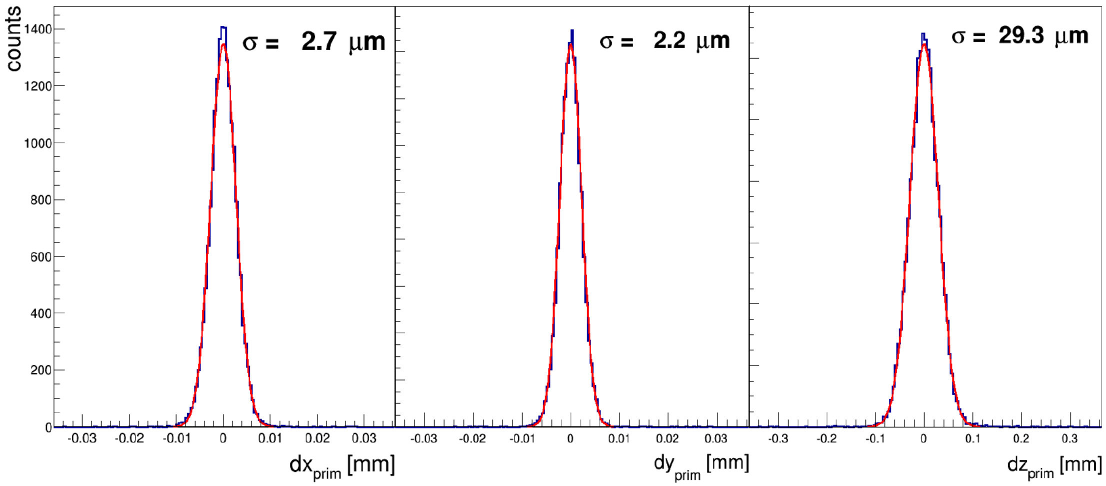


Matching with TPC provides: momenta and PID to VD tracks

→ invariant mass distribution

Performance for Xe+La at 150A GeV/c





- Large statistic Xe+La data taken in late 2017 at 150A and 75A 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*

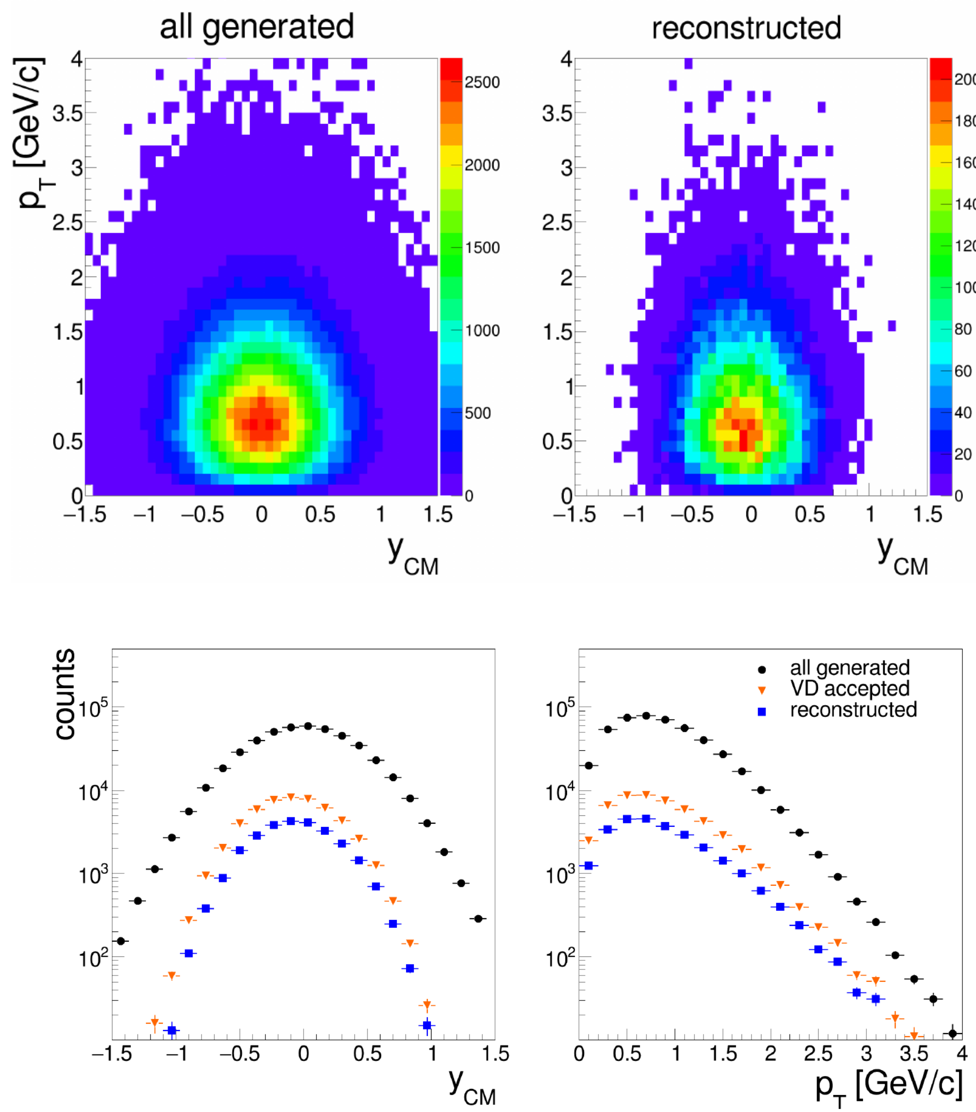
- Detector commissioning
- Good detector performance
- D^0 likely seen

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

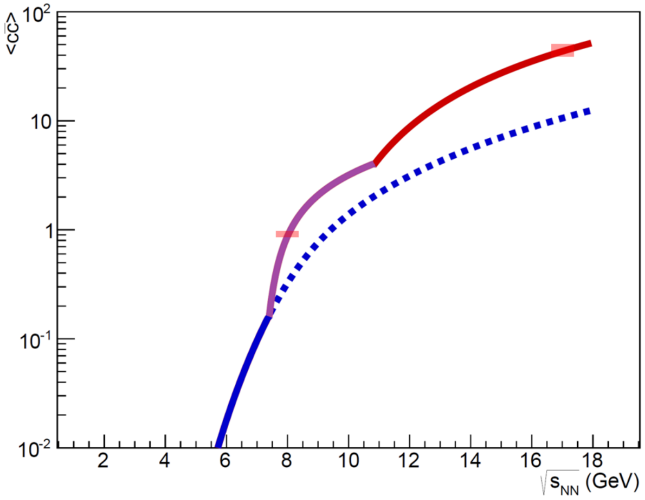
- Improved sensor efficiency
- Improved primary vertex resolution (dx=1.3μm, dy=1.0μm, dz=15μm)
- Large statistics collected:
  5.1 MEvents@150*A*GeV/*c*
  4.0 MEvents @75*A* GeV/*c*
- Analysis ongoing, expected good data quality
- Expected open charm data suited for comparison with NA61/SHINE

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

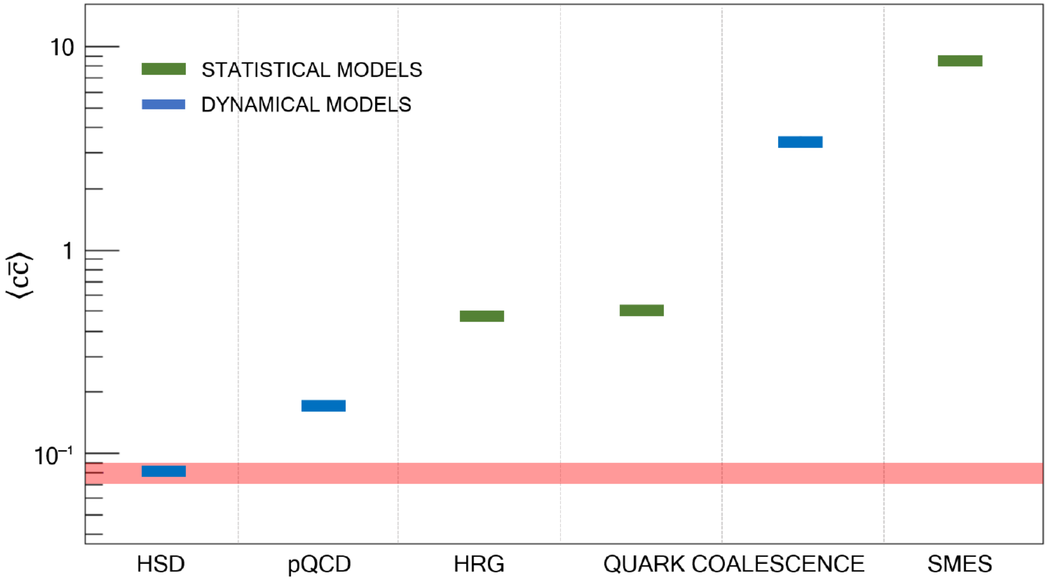
Simulated results on $D^+ + D^-$



Anticipated results

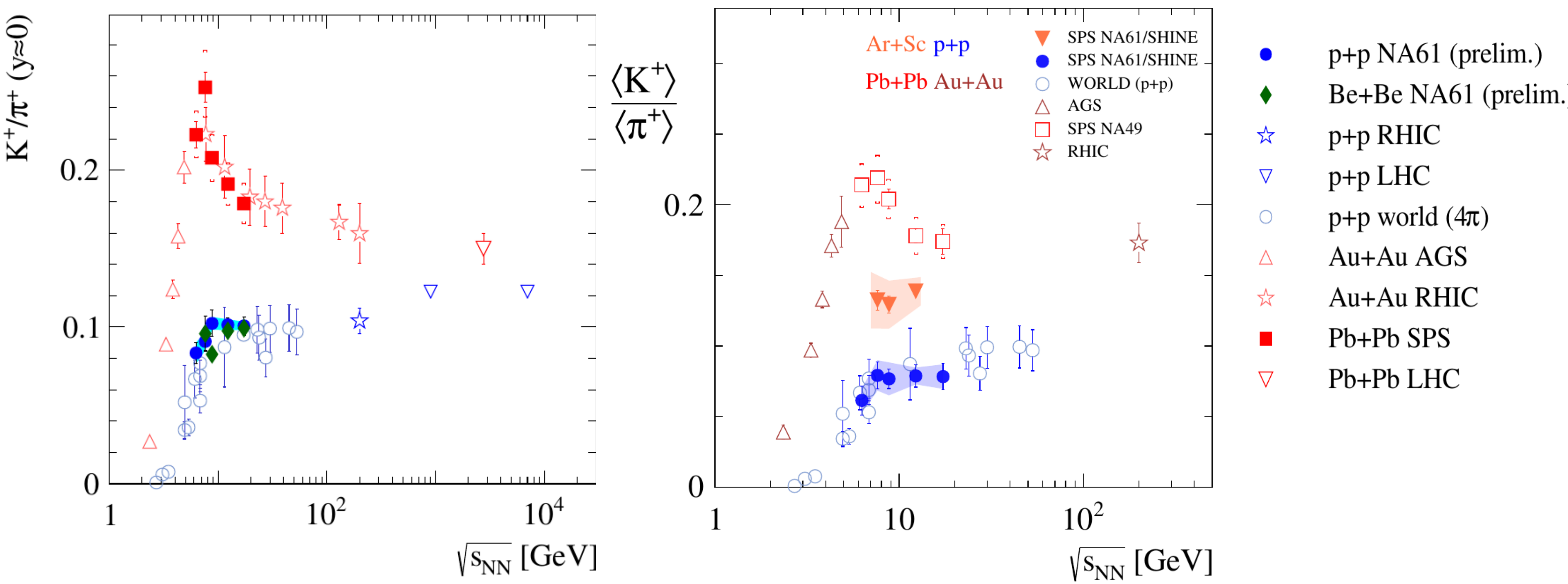


SMES predictions



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

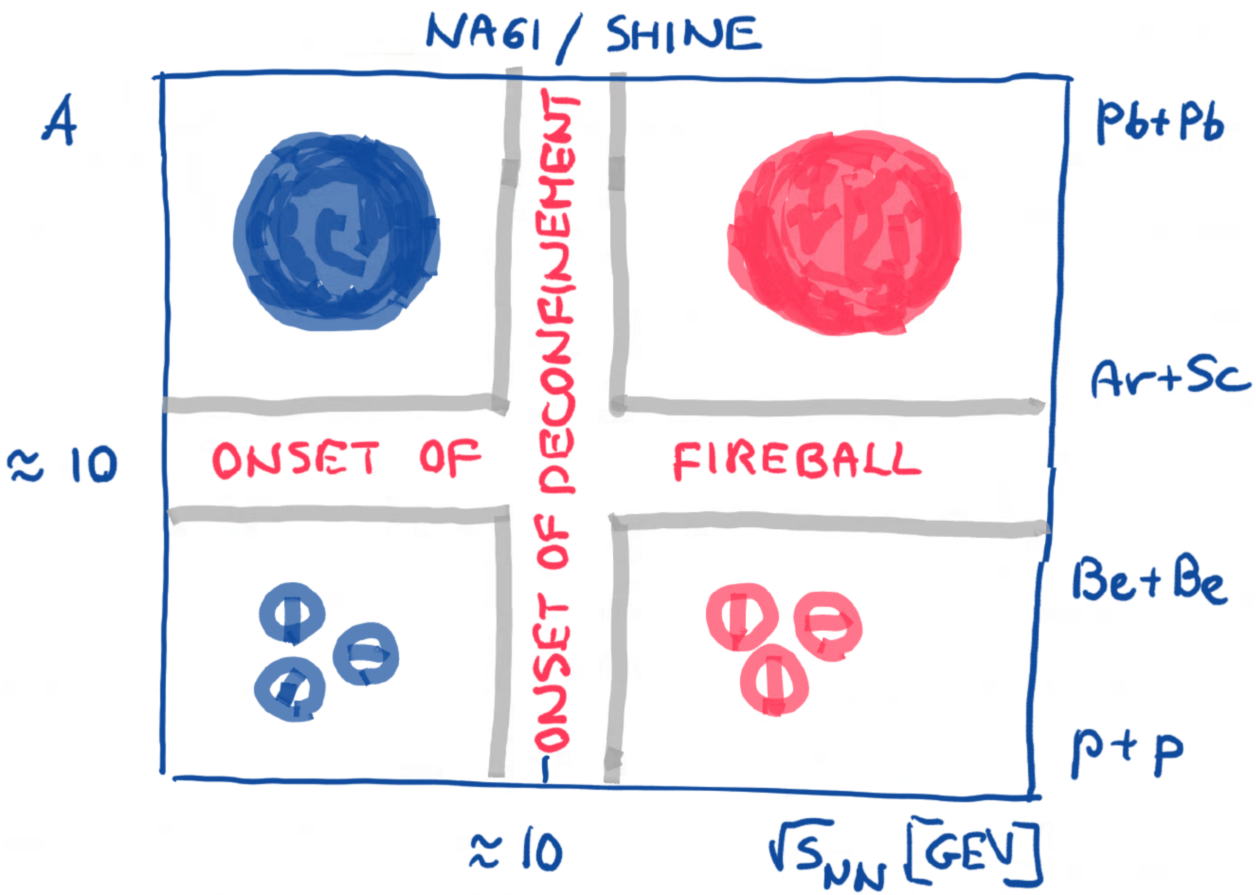


NEW RESULTS:

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

- <K⁺>/<π⁺> in Ar+Sc in between p+p, Be+Be and Pb+Pb

Tentative conclusions from 2D scan



Data on particle ratios and fluctuations indicate four domains of hadron production separated by two thresholds:

onset of deconfinement

and

onset of fireball

Completion of Ar+Sc analysis and new data for Xe+La awaited to verify this picture

NA61/SHINE

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The NA61/SHINE Collaboration

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