Shiny charm at charming SHINE

(Open charm measurements at NA61/SHINE)

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c quark

J/ψ suppression

D^0 meson

NA61/SHINE

Pilot run results – SAVD

Current measurements – VD

Future ideas – open charm correlations

Summary

- fermion
- mass: 1.27 ± 0.02 GeV/c^2
  $m_c/m_s \approx 12$
  $m_b/m_c \approx 4.5$
- charge: $\frac{2}{3}e$
- charm: $+1$

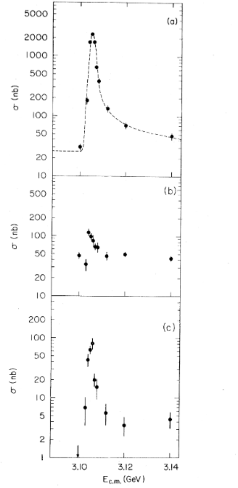


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

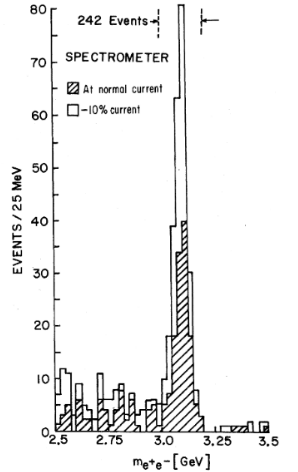
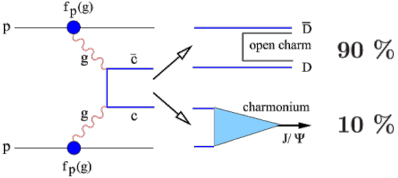
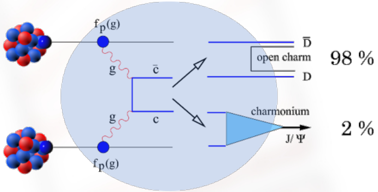


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

PRL 33 (1974) 1404
PRL 33 (1974) 1406

Matsui-Satz model suggests total suppression of J/ψ formation within QGP after some threshold $T \approx 1.5T_c \approx 300$ MeV





- $r_D(T)$ is a color screening radius, going down while increasing temperature;
- $r_{J/\psi}(T)$ is a binding radius of a $c\bar{c}$ pair (i.e. size of the J/ψ meson);
- at $T \approx 300$ MeV its expected that color screening will overcome the $c\bar{c}$ binding, ($r_D(T) < r_{J/\psi}(T)$), bound systems of $c\bar{c}$ can no longer exist (Though production of J/ψ will still take place at the transverse perimeter of the nuclei)

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

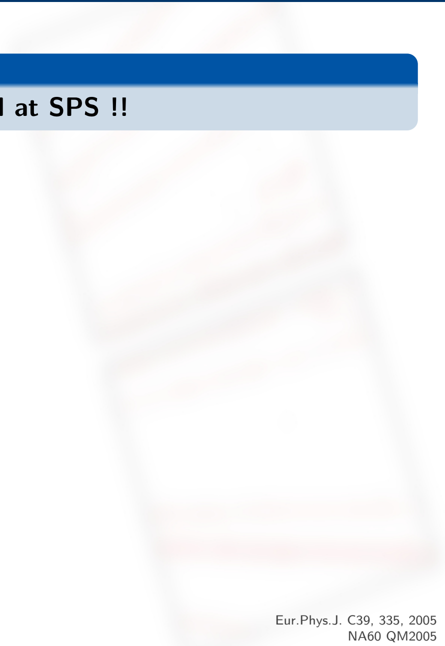
may serve as a measurable QGP signature!

Matsui, Satz, PLB 178 (1986) 416
Satz, Adv. High En. Phys. (2013) 2429

J/ψ suppression

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

not yet measured at SPS !!



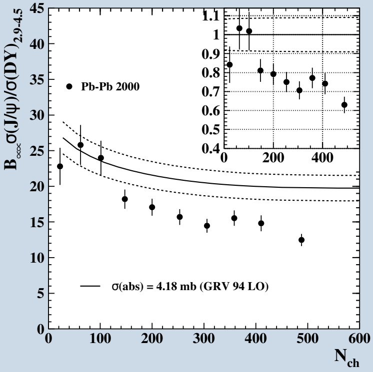
Eur.Phys.J. C39, 335, 2005
NA60 QM2005

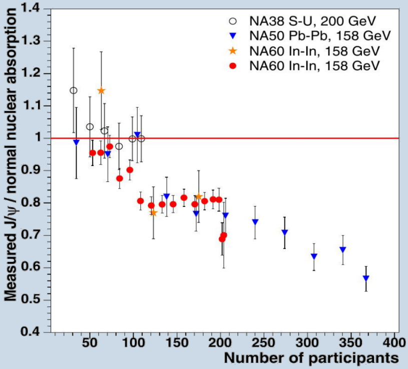
J/ψ suppression

⟨$c\bar{c}$⟩

not yet measured at SPS !!

⟨J/ψ⟩





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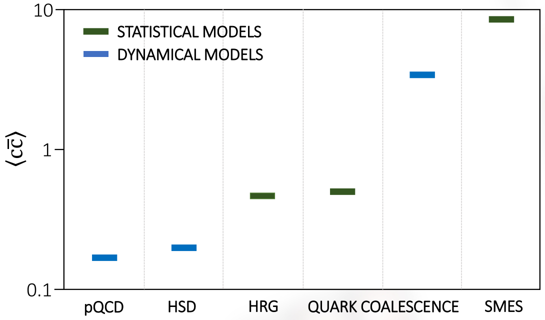

HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367

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

- models differ in predictions of $\langle c\bar{c}\rangle$ by factor ≈ 50
- clearly, measurement of open charm mesons is needed

D^0 meson

- $c\bar{u}$
- mass: 1.864 GeV/c^2
- life time: 410×10^{-15}s
- $c\tau$: 0.123 mm
- charge: 0
- charm: $+1$
- decay: $D^0 \to K^- \pi^+$ (3.89%)

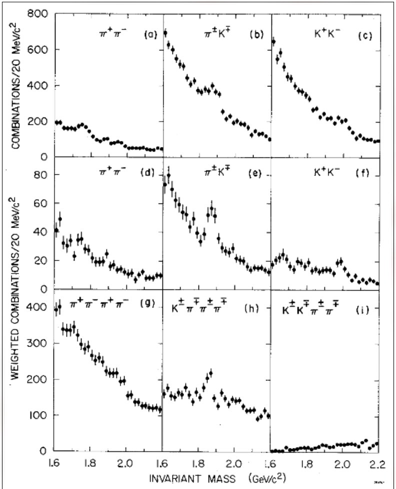

FIG. 1--Invariant mass spectra for neutral combinations of charged particles.

Phys. Rev. Lett. 37(1976) 255

c quark

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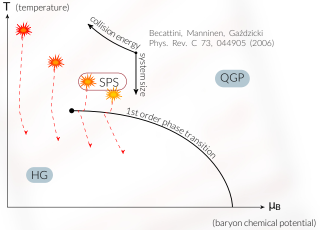
Current measurements – VD

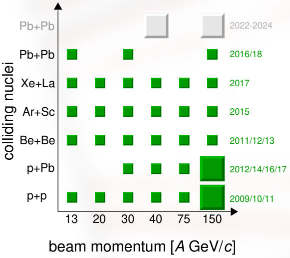
Future ideas – open charm correlations

Summary



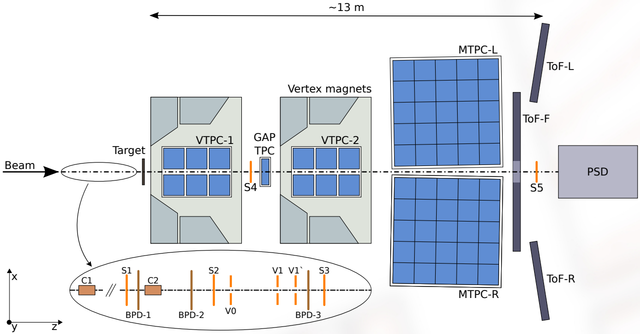
Strong interactions physics:

- study the properties of the **onset of deconfinement**
- search for the **critical point** of strongly interacting matter



And more:

- measurements for neutrino programs at J-PARC and Fermilab
- measurements for cosmic rays physics



Be, Ar, Xe, Pb beams at 13A – 150A GeV/c

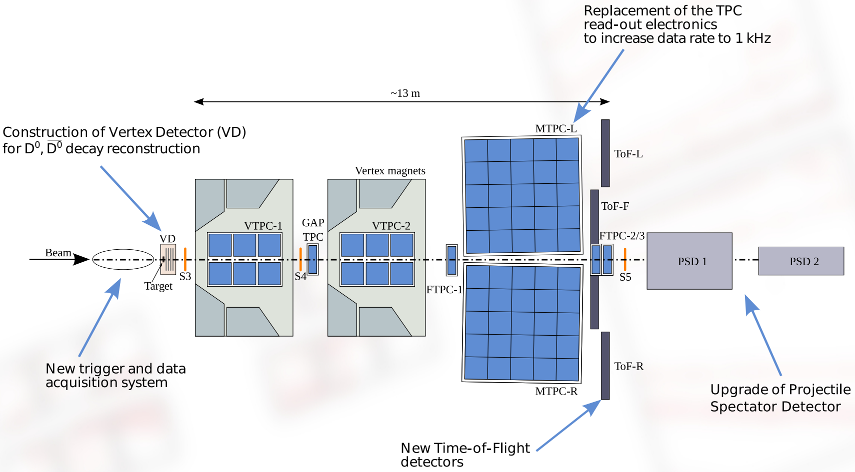
p, π, K beams at 13 – 400 GeV/c

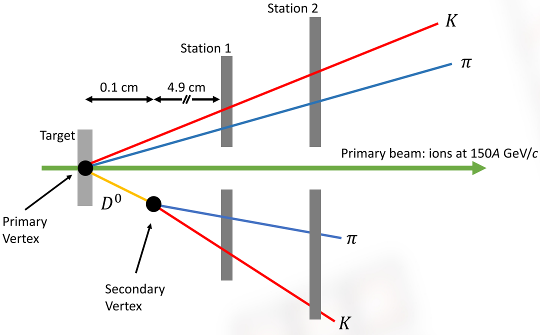
coverage up to 50% of produced charged particles starting from $p_T \approx 0$

$\sqrt{s_{NN}} \approx$ **5 – 17 GeV**

- **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** – a calorimeter which is positioned downstream of the time of flight detectors measure energy of projectile fragments.

A major upgrade for direct measurement of **open charm** in Pb+Pb at 150A GeV/c ($\sqrt{s_{NN}} \approx 17$ GeV)





- daughters of D^0 (π and K) are recognized as a pair forming a secondary vertex displaced form the primary vertex
- $c\tau(D^0) \approx 0.123$ mm, however, due to Lorentz boost ($\beta\gamma \approx 10$) the displacement is on the level of 1 mm $\rightarrow$ advantage of fixed-target experiment

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

c quark

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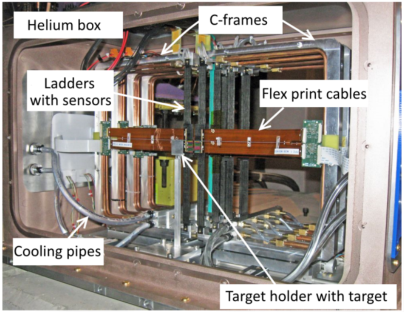
Current measurements – VD

Future ideas – open charm correlations

Summary

Pilot run results – SAVD

Small Acceptance Vertex Detector



Small Acceptance Vertex Detector (SAVD) was used during Xe+La and Pb+Pb runs in 2017 and 2018.

4 x 8 coordinate-sensitive pixel detectors (sensors)

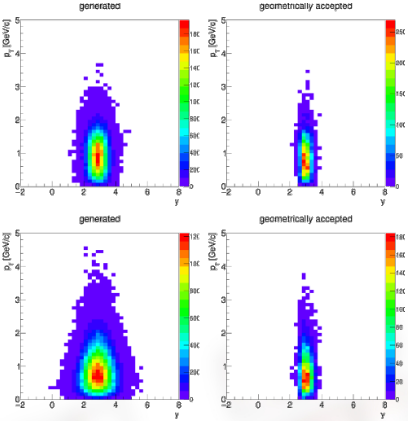
each sensor consist of 663.5k pixels MIMOSA-26AHR (MAPS) on the CMOS technology

spatial resolution for clusters: $\sigma_x = \sigma_y \approx 5\mu m$

primary vertex resolution: $\sigma_{z,vtx} \propto$ tens of micrometers

Pilot run results – SAVD

Acceptance



rapidity vs p_T for $D^0 + \bar{D}^0$ mesons from Xe+La at 150*A* GeV/*c* for all (*left*) and accepted (*right*) particles obtained with AMPT (*top*) and PHSD (*bottom*) models

Estimated geometrical acceptance of SAVD for D^0:

Xe+La simulations:

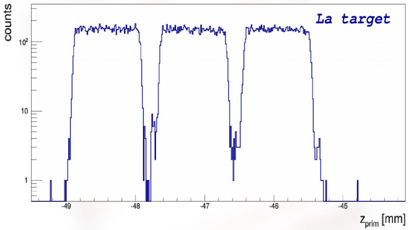
- AMPT $\rightarrow \epsilon \approx 7.8\%$
- PHSD $\rightarrow \epsilon \approx 5.9\%$

Pb+Pb simulations:

- AMPT $\rightarrow \epsilon \approx 8.4\%$
- PHSD $\rightarrow \epsilon \approx 6.8\%$

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, respectively



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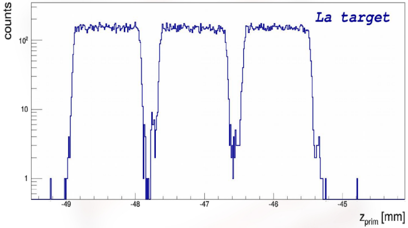

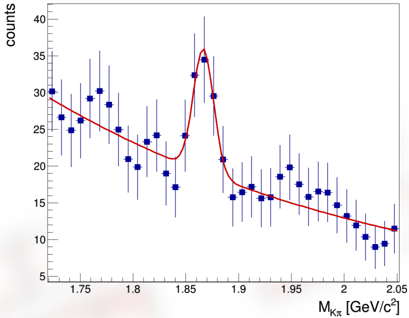

Invariant mass distribution of unlike charge sign π and K decay track candidates

1.8M Pb+Pb collisions at 150A GeV/c

obtained mass: 1.87 GeV/c^2

width: 10 MeV/c^2

The total yield: $\sim$60 with $\pm 3\sigma$

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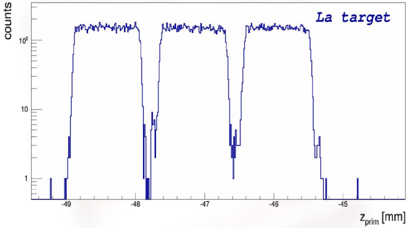

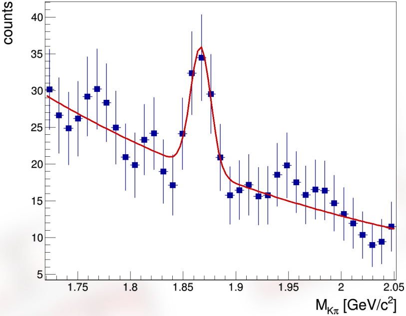

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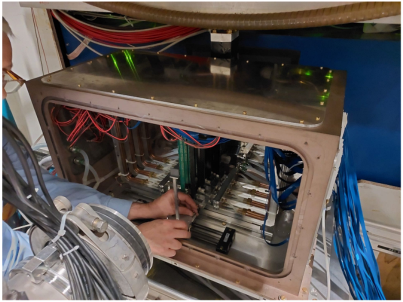
The total yield: $\sim$60 with $\pm 3\sigma$

$$\langle D^0 + \bar{D}^0 \rangle_{Pb+Pb} = 0.39 \pm 0.21 \longrightarrow \langle c\bar{c} \rangle \approx 0.68$$

Current measurements – VD



Vertex Detector (VD) used for Pb+Pb data takings in November 2022

based on the ALICE PIxel DEtector (ALPIDE)

increase of efficiency up to $\approx 100\%$ keeping low noise level ($\leq 10^{-6}$ vs $\leq 10^{-4}$ hits per pixel per readout frame)

larger acceptance: 13.8 x 30 (75%) vs 10.6 x 21.2 cm2 (50%)
spatial resolution for clusters:
$\sigma_{\mathrm{x}} = \sigma_{\mathrm{y}} \approx 6\mu\mathrm{m}$

Estimated improvement in VD acceptance for D^0 mesons: from about 8% to about 30%.

35M (**!!**) Pb+Pb at 150A GeV/c collisions recorded in November 23-28 2022.

4 weeks requested in October 2023 and 4 in 2024 (500M events in total).

Stay tuned as the analysis is ongoing...

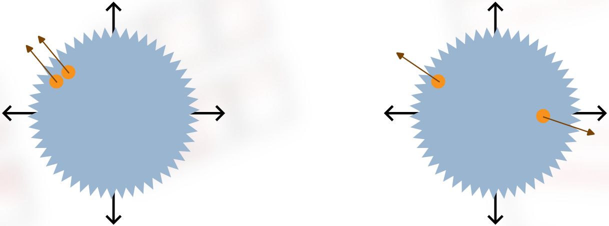
Future ideas – open charm correlations

Testing charm production locality and spatial diffusion of heavy flavor

at high energy densities

Depending on the creation points and spatial diffusion properties of the charm in the medium, the charm hadron and the anti-hadron emission points can be either close or distant.

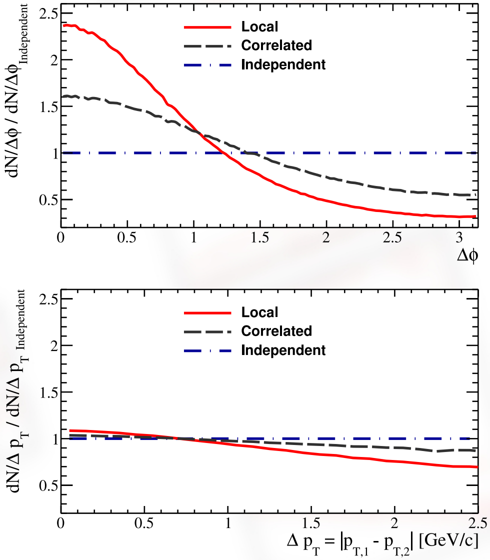
- In a locally thermalised and expanding system, the charm hadrons have an average momentum dependent on the fluid cell's drift speed (flow).
- If the emission points of the hadrons are close, they will have a similar drift, and thus their momenta will be correlated.



Future ideas – open charm correlations

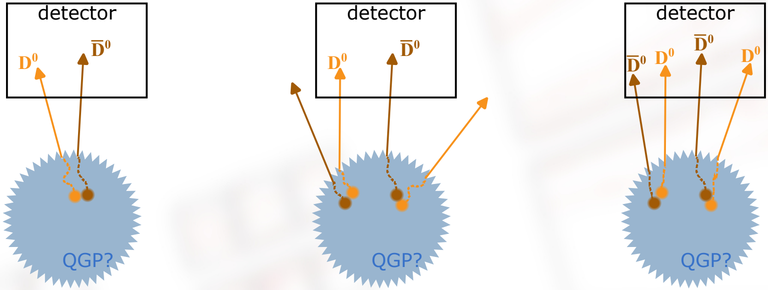
Final-state momenta of charm hadrons are given by the superposition of the flow and a random (thermal) contribution due to statistical hadronisation

- *local* emission – both charm hadrons are emitted from the same fluid cell, the average of their momenta is set by the drift velocity of the cell
- *independent* emission – emission points of charm hadrons are independent of each other, no common drift velocity
- *correlated* emission – intermediate case – flow components are different but correlated leading to the correlation in momenta



Future ideas – open charm correlations

Measuring correlations of c and $\bar{c}$ quarks from the same pair forces one to seek for events with only a single $c\bar{c}$-pair ($\langle c\bar{c}\rangle < 1$)



one **true** pair detected

one **fake** pair detected

two **true** and two **fake** pairs detected

Future ideas – open charm correlations

Required statistics estimation

$$\langle D^0\bar{D}^0\rangle_{rec} \approx \langle c\bar{c}\rangle \cdot \Big(P(c \to D^0) \cdot BR(D^0 \to K\pi) \cdot P(acc) \cdot P(sel) \cdot P(rec)\Big)^2$$

- $\langle c\bar{c}\rangle$– average number of $c\bar{c}$-pairs per event
  $\langle c\bar{c}\rangle \approx 30$ in 10% Pb+Pb 5.02 TeV
  $\langle c\bar{c}\rangle \approx 3$ in 10% Au+Au at 200 GeV
  $\langle c\bar{c}\rangle \in (0.1; 1)$ in Pb+Pb at 17 GeV
- $P(c \to D^0) = 0.31$ – probability for c-quark to hadronize into the D^0 (PHSD model)
- $BR(D^0 \to K^+\pi^-) = 3.98\%$ – branching ratio of decay channel used in the measurements
- $P(acc) = 0.5$ – probability for D^0 to be within an acceptance region of the detector (GEANT4 simulations)
- $P(sel) = 0.2$ – probability for D^0 to pass background-suppressing selection of charm meson candidates
- $P(rec) = 0.9$ – probability of reconstructing the meson (GEANT4 simulations)

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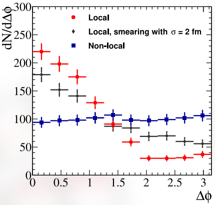

estimated statistical uncert.
for 1000 reconstructed pairs

Future ideas – open charm correlations

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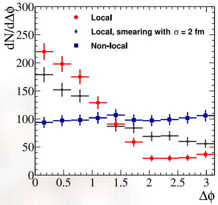
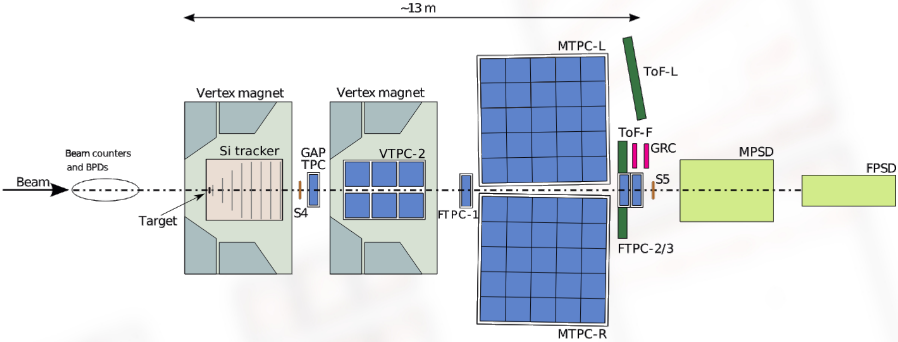


estimated statistical uncert. for 1000 reconstructed pairs

estimated data taking time

$\langle c\bar{c}\rangle$	0.1	0.2	0.5	1
1 kHz	1000 days	500 days	200 days	100 days
10 kHz	100 days	50 days	20 days	10 days
100 kHz	10 days	5 days	2 days	1 day

Future ideas – open charm correlations



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- There are **no measurements** of open charm production in heavy-ion collisions at SPS energies, and the available model predictions differ significantly

- NA61/SHINE pilot **open charm** production measurements started in 2017 with SAVD

- NA61/SHINE was proven to be capable of

- After LS2, proposed **high statistic** Pb+Pb data taking with **upgraded detector** is ongoing
  - 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

- The future possible **open charm correlations** measurements may shine some light on charm hadrons emission

Thank You!