Charm physics in NA61/SHINE

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Overview

1. Motivation of open charm measurements

2. First measurements in NA61/SHINE

3. Precise open charm studies after Long Shutdown 2

Motivation of open charm measurements

Motivation of open charm measurements

Three main questions that motivate open charm measurements at the CERN SPS:

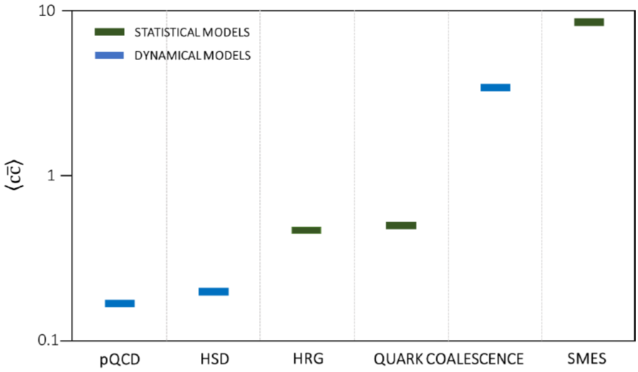
1. What is the mechanism of open charm production?
2. How does the onset of deconfinement impact open charm production?
3. How does the formation of quark-gluon plasma impact J/ψ production?

To answer these questions **mean number of charm quark pairs** $\langle c\bar{c} \rangle$ produced in the full phase space in A+A collisions has to be known.

Up to now corresponding experimental data **does not exist**.

Models of charm production

Predictions for $\langle c\bar{c} \rangle$ in central Pb+Pb collisions at beam momentum of $158A$ GeV/c differ by a factor of **50**.



pQCD
Gavai *et al.* IJMP A 10 2999.
Braun-Munzinger, J. Stachel, PL B 490, 196.
HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367
HRG, Quark Coalesc. Stat.
Gorenstein, Kostyuk, Stoecker, Greiner, PL B 509, 277.
Quark Coalesc. Dyn.
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G 27, 703
SMES
Gazdzicki, Gorenstein, APP B30, 2705.

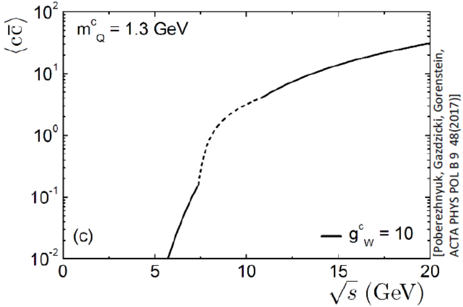
Charm yield as the signal of deconfinement

Phase Transition: $T_c \approx 150$ MeV

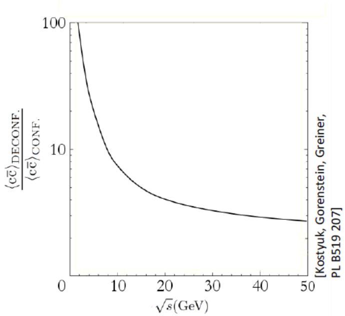
confined matter	$\longrightarrow$	quark-gluon plasma
$D\bar{D}$ mesons	$\longrightarrow$	(anti-)charm quarks
$g_D = 4$	$\longrightarrow$	$g_c = 12$
$2M \approx 3.7$ GeV	$\longrightarrow$	$2m \approx 2.6$ GeV

central Pb+Pb collisions

Statistical Model of Early Stage

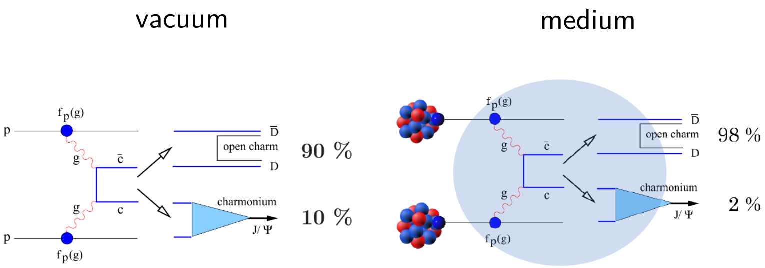


QCD-inspired calculations



J/ψ suppression as the signal of deconfinement

Open charm and J/ψ production within Matsui-Satz model [PL B178 416]



[Satz, Adv. High Energy Phys. 2013 (2013) 242918]

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

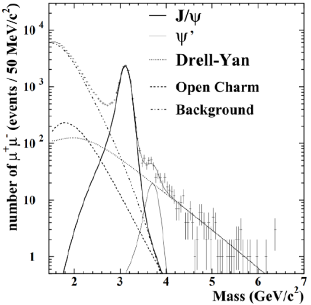
Medium reduces probability of J/ψ production.

J/ψ suppression as the signal of deconfinement

Calculation of $P(c\bar{c} \rightarrow J/\psi)$ requires data on:

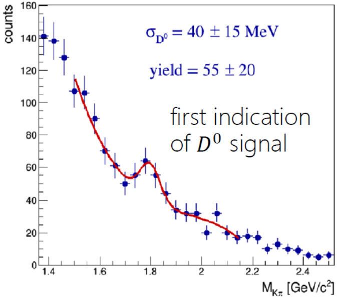
- $\langle J/\psi \rangle$ - precise data at SPS by NA38, NA50, NA60
- $\langle c\bar{c} \rangle$ - can be estimated from open charm measurements started by NA61/SHINE

NA50



[NA50, arXiv:hep-ex/0412036v1]

NA61

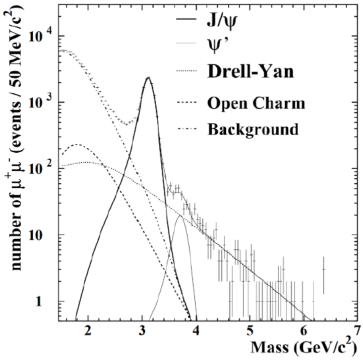


[CERN-SPSC-2017-038]

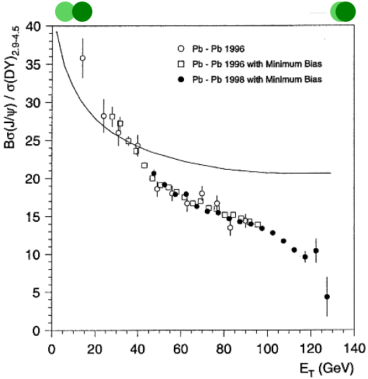
central Pb+Pb at 150-158A GeV/c

J/ψ production at CERN SPS

Data on J/ψ production has been normalized by the Drell-Yan yield



[NA50, arXiv:hep-ex/0412036v1]



[NA50, PL B 477 28–36]

Interpretation of these results is based on assumption:

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

First measurements in NA61/SHINE

Open charm distribution

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

charm conservation

c = $\bar{c}$

violation of izospin symetry

D^0 ($c\,\bar{u}$) 0.360 ≈ 2.6 D^+ ($c\,\bar{d}$) 0.137

$\bar{D}^0$ ($\bar{c}\,u$) 0.369 ≈ 2.6 D^- ($\bar{c}\,d$) 0.141

$\Downarrow$ $\Downarrow$

higher mass states

D_s^+ ($c\,\bar{s}$) 0.056, Λ_c (udc) 0.035 $>$ D_s^- ($\bar{c}\,s$) 0.053, $\bar{\Lambda}_c$ ($\bar{u}\bar{d}\bar{c}$) 0.025

Mean number of charm hadrons per event

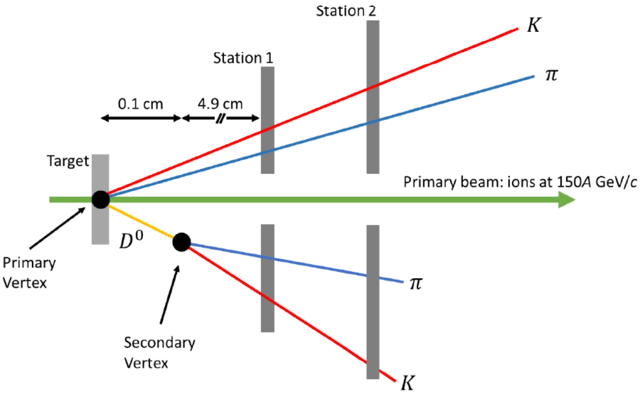
PHSD, Elena Bratkovskaya & Taesoo Song, private communication

What can NA61/SHINE measure?

- $D^0 \rightarrow \pi^+ + K^-$
  $\bar{c\tau} \approx 123\ \mu m$
  BR $= 3.89\%$
- $D^+ \rightarrow \pi^+ + \pi^+ + K^-$
  $\bar{c\tau} \approx 312\ \mu m$
  BR $= 9.22\%$
- $D_s^+ \rightarrow \pi^+ + K^+ + K^-$
  $\bar{c\tau} \approx 150\ \mu m$
  BR $= 5.5\%$
- $\Lambda_c^+ \rightarrow p + \pi^+ + K^-$
  $\bar{c\tau} \approx 60\ \mu m$
  BR $= 5.0\%$

Up to now only $\langle D^0 \rangle$ measurements were simulated and tested, but it is probable that after LS2 NA61/SHINE will be able to measure all of the most popular carriers of c and $\bar{c}$ quarks.

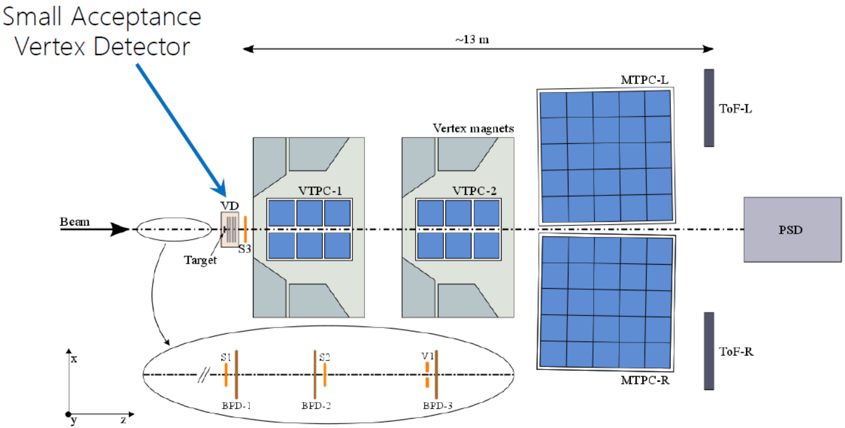
Open charm measurement concept



$D^0 \rightarrow \pi^+ + K^-$
$c\bar{\tau} \approx 123\ \mu m$
$\mathrm{BR} = 3.89\%$

Vertex Detector is needed to reconstruct primary vertex and secondary vertices with high precision.

NA61/SHINE detector



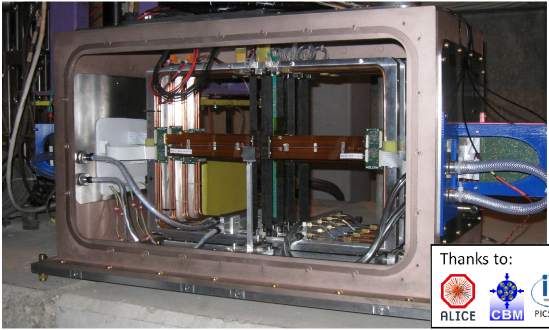
Small Acceptance Vertex Detector (SAVD)

Small Acceptance Vertex Detector introduced in 2016:

- 16 CMOS MIMOSA-26 sensors located on two horizontally movable arms
- target holder integrated

Achieved goals:

- tracking in large track multiplicity environment
- precise primary vertex reconstruction
- TPC-SAVD track matching
- first search of D^0 and $\bar{D}^0$ signal

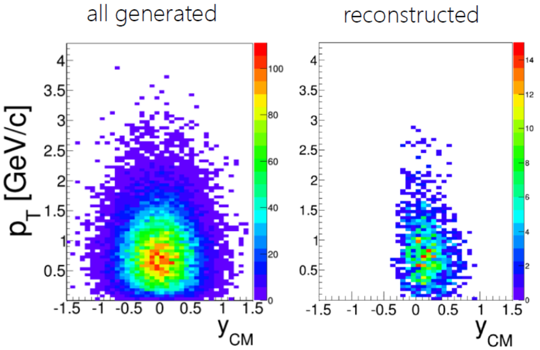


Thanks to:

ALICE CBM IPHC PICSEL Group TRB - collaboration

Acceptance of SAVD

AMPT simulations for central Pb+Pb collisions at 150A GeV/c
SAVD reconstructs 4% out of all $D^0 \rightarrow \pi^+ + K^-$ decays



Data taking

Data taking with Small Acceptance Vertex Detector before Long Shutdown 2:

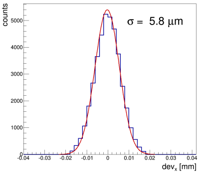
- December 2016 – test run for SAVD – Pb+Pb at 150A GeV/c
- November 2017 – Xe+La at 150A GeV/c and 75A GeV/c
- 2018 – pilot data taking – Pb+Pb at 150A GeV/c

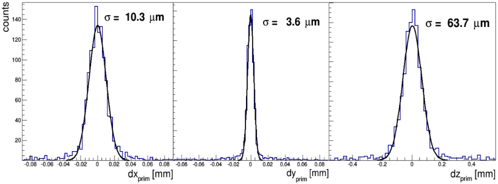
December 2016 – Pb+Pb at 150A GeV/c

From the analysis of collected Pb+Pb data:

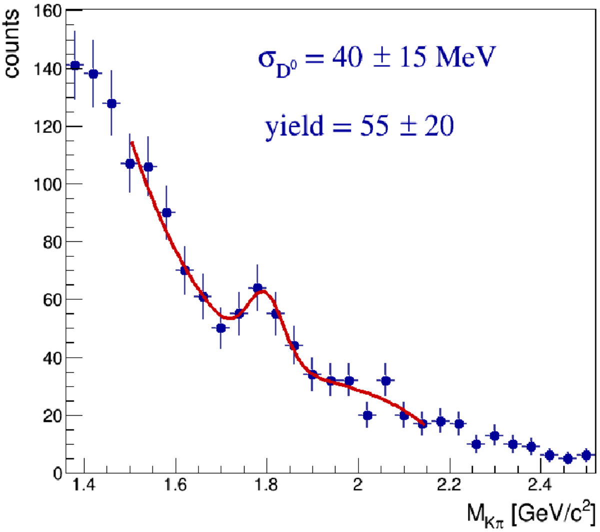
- Clusters spacial resolution: $\sigma_{x,y}(Cl) \approx 5\ \mu m$
- Primary Vertex resolution:
  $\sigma_x(PV) \approx 5\ \mu m$
  $\sigma_y(PV) \approx 1.8\ \mu m$
  $\sigma_z(PV) \approx 30\ \mu m$

$\sigma_x(PV) > \sigma_y(PV)$ due to magnetic field difference: $B_y > B_x \approx 0$





First indication of D^0 and $\bar{D}^0$ peak

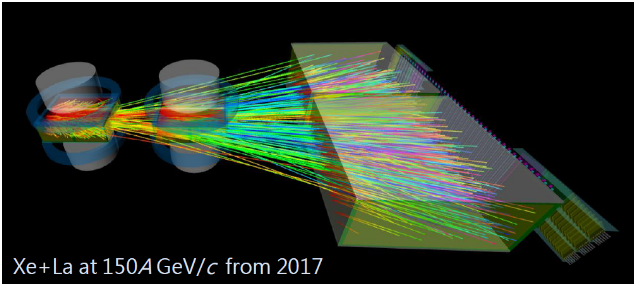


November 2017 – Xe+La at 150A GeV/c

About 5M central events were collected at the beginning November 2017.

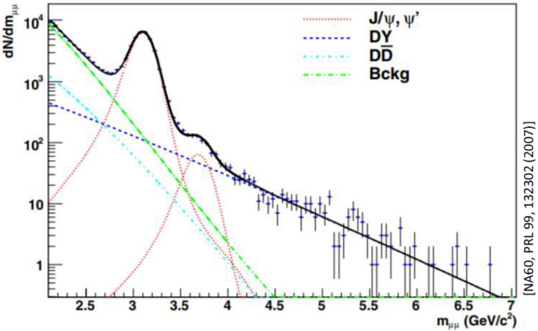
Based on simulations from Pb+Pb and p-QCD inspired system size dependence, one expects several hundred of $D^0 + \bar{D}^0$ meson decays to be reconstructed.

This should allow to obtain the **first physics results** on open charm production in heavy ion collisions at the CERN SPS.



Impact of Xe+La data

J/ψ production in In+In (A = 115) collisions at 158A GeV/c was precisely measured by NA60.



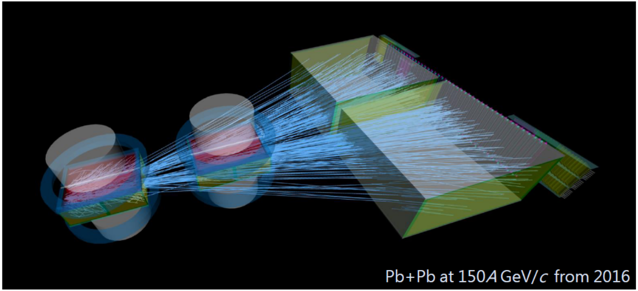
This data together with NA61 results on open charm production in Xe+La (A = 129, A = 139) collisions at 150A GeV/c will strongly challenge theoretical models.

2018 – Pb+Pb at 150A GeV/c

Data taking in 2018 on central Pb+Pb collisions for open charm measurement recommended by CERN SPSC in October 2017.

Three weeks of data taking:

- 10M central collisions recorded
- 4000 D^0 and $\bar{D}^0$ decays is expected to be reconstructed

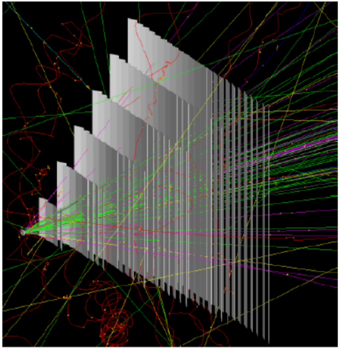


Precise open charm studies after Long Shutdown 2

Large Acceptance Vertex Detector (LAVD)

General requirements:

- precise vertex measurement
- fast detectors with high granularity
- low material budget
- large acceptance



Technology developed for
ALICE ITS – ALPIDE sensors:

- very low noise
- fast readout
- two possible working modes: continuous and triggered readout

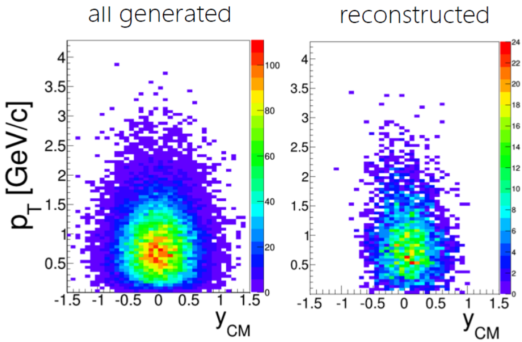
About 200 sensors located on 6 stations – final layout still under discussion

Acceptance of LAVD

AMPT simulations for central Pb+Pb collisions at 150A GeV/c

LAVD reconstructs 12% out of all $D^0 \rightarrow \pi^+ + K^-$ decays

Corrected results will cover **most of the phase space** (more than 90%)



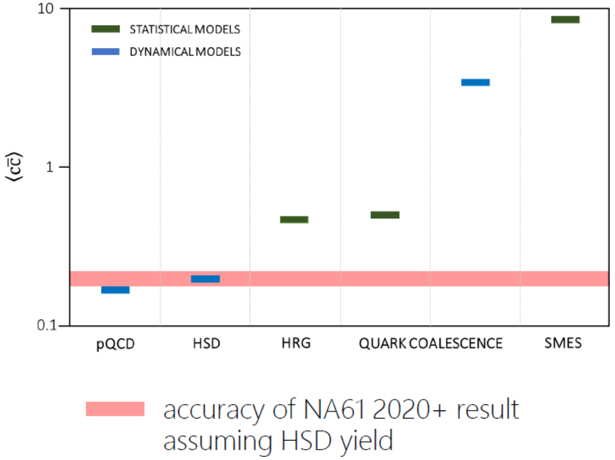
Total systematic uncertainty of $\langle D^0 \rangle$ and $\langle \bar{D}^0 \rangle$ is expected to be about 10%.

Beam request for 2021-2024

Year	Beam	Duration	Purpose	$D^0 + \bar{D}^0$ stat.
2021	p at 150A GeV/c	4 weeks	detector test	
2022	Pb at 150A GeV/c	2 weeks	charm in central collisions	40k
2022	Pb at 150A GeV/c	4 weeks	charm in peripheral collisions	8k
2023	Pb at 150A GeV/c	2 weeks	charm in mid-central collisions	20k
2024	Pb at 40A GeV/c	4 weeks	charm in central collisions	2k

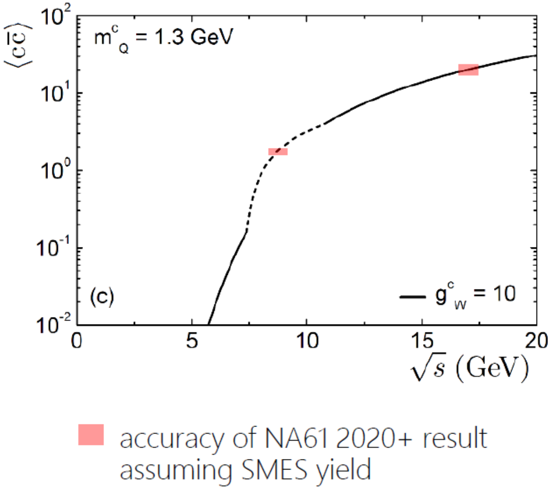
Impact of NA61/SHINE open charm measurements

Predictions for $\langle c\bar{c} \rangle$ in central Pb+Pb collisions at beam momentum of $158A$ GeV/c



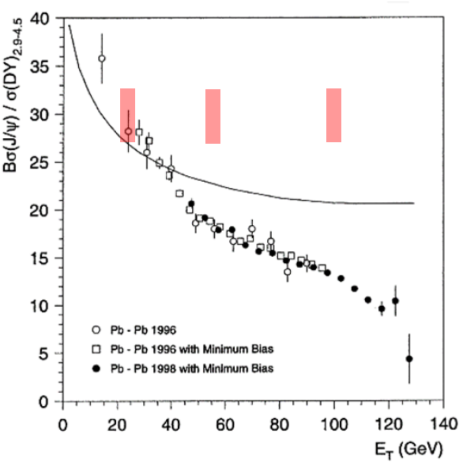
Impact of NA61/SHINE open charm measurements

Central Pb+Pb collisions at beam momentum of 158A GeV/c



Impact of NA61/SHINE open charm measurements

Pb+Pb collisions at beam momentum of 158A GeV/c



$\langle J/\psi \rangle / \langle c\bar{c} \rangle$ accuracy of NA61 2020+ result assuming

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

and scaling to

$$\langle J/\psi \rangle / \langle \mathrm{DY} \rangle$$

for peripheral collisions

Summary

NA61/SHINE charm program addresses the following questions:

1. What is the mechanism of open charm production?
2. How does the onset of deconfinement impact open charm production?
3. How does the formation of quark-gluon plasma impact J/ψ production?

To answer these questions NA61/SHINE is planning to perform precise measurements of mean multiplicity of charm quark pairs after Long Shutdown 2.

Only NA61/SHINE can perform this measurement in the near future.

VD - team

- Kraków (Jagiellonian University):
  P. Staszel (Project coordinator), Y. Ali, D. Larsen, A. Merzlaya
- Kraków (AGH): M. Baszczyk, P. Dorosz, W. Kucewicz, Ł. Mik
- GU Frankfurt: M. Deveaux, M. Gaździcki, M. Koziel, A. Snoch
  Thanks to: P. Klaus, J. Michel, M. Wiebusch
- Warsaw: A. Aduszkiewicz, W. Bryliński, D. Tefelski
- St. Petersburg State University: G. Feofilov
- ETH Zürich: S. Di Luise

and many others...

PICSEL Group

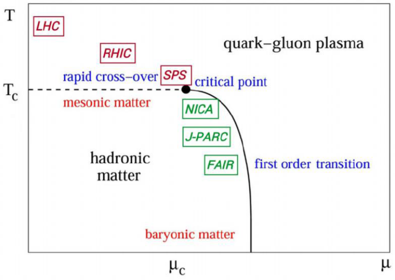
TRB - collaboration

Thank you!!!

Backup

Uniqueness of NA61 open charm program

Landscape of present and future heavy ion experiments

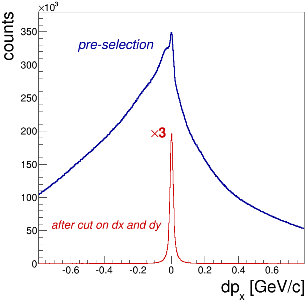


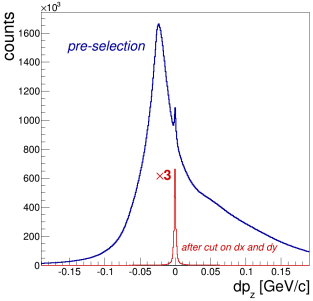
NA61/SHINE is the only experiment which is able to measure open charm production in heavy ion collisions in full phase space in the near future.

- LHC and RHIC at high energies: measurement in small phase space due to collider geometry and kinematics
- RHIC BES collider: measurement not possible due to collider geometry and kinematics
- RHIC BES fixed-target: measurement require dedicated setup – not under consideration
- NICA ($<80A$ GeV$/c$): measurement during stage 2 under consideration
- J-PARC ($<20A$ GeV$/c$): maybe possible after 2025
- FAIR ($<10A$ GeV$/c$): not possible

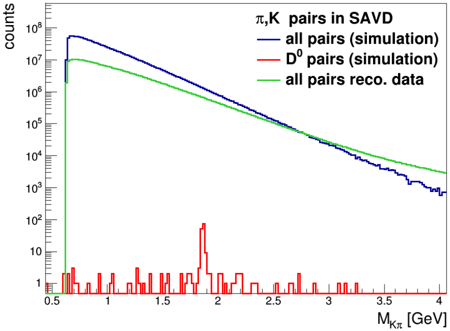
SAVD-TPC track matching

- extrapolate SAVD and TPC tracks to the common surface
- preselection: cut on y-slope of tracks
- After cut on dx and dy clear correlation peaks are visible in dpx and dpy distributions





Search for D^0 and $\bar{D}^0$

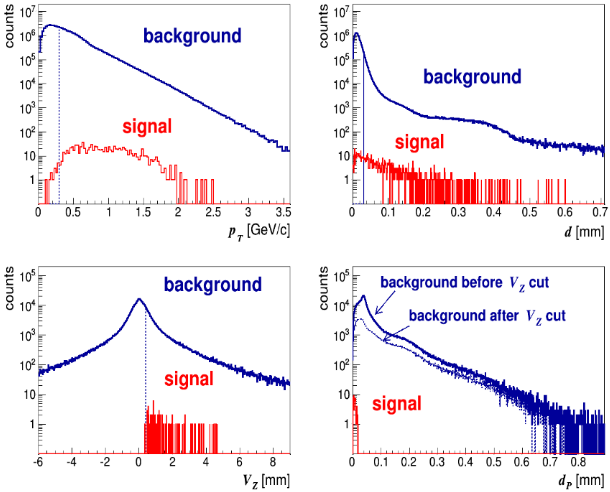


Combinatorial background is reduced by the cuts on:

- track transverse momentum
- track impact parameter
- longitudinal distance between primary and secondary vertices
- pair impact parameter

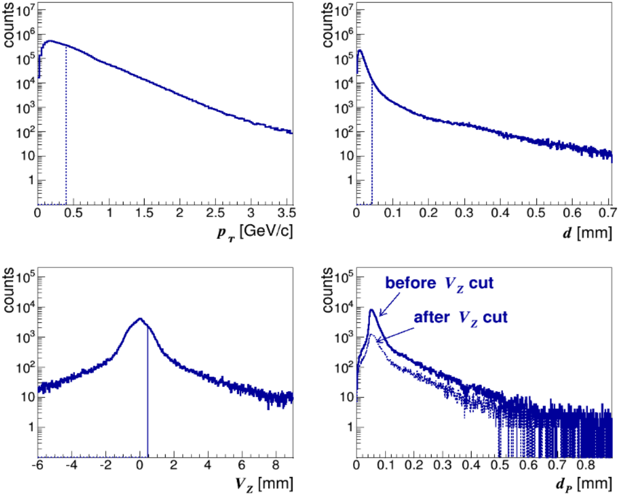
Cuts – simulations

simulation

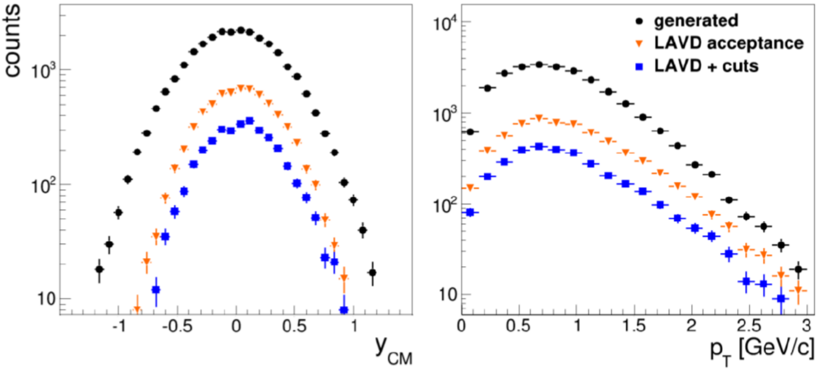


Cuts – data

data



LAVD acceptance



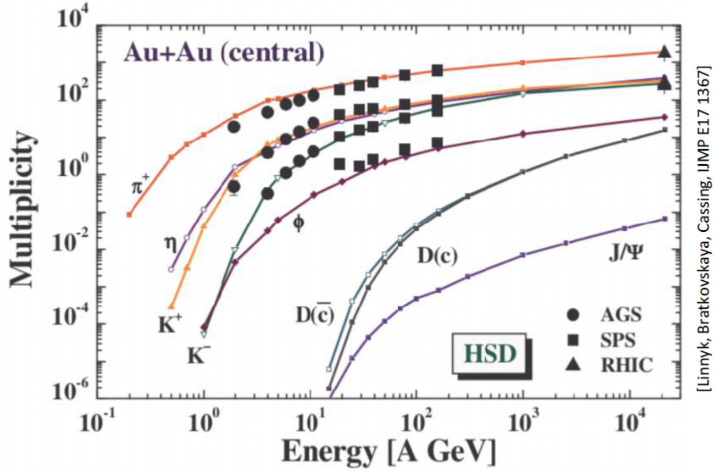
VD Efficiency

4% detection efficiency is calculated in respect to all D0s in that decayed to pi+K channel, so it includes:

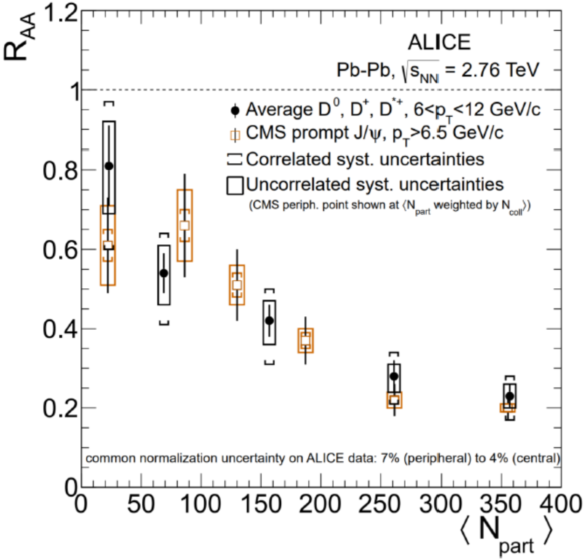
- suppression due to two particle combined acceptance of SAVD and VTPC1+VTPC2.
- suppression due to matching efficiency between SAVD and VTPCs (98% in simulation)
- suppression due to background suppression cuts. These cuts suppress background by factor of 10^6 (in the D0 invariant mass region) and D0->pi+K by factor of about 2.

Full version has efficiency of 12% mostly due to increase of the combined LAVD + VTPC1+VTPC2 acceptance for D0->pi+K by factor of 3.

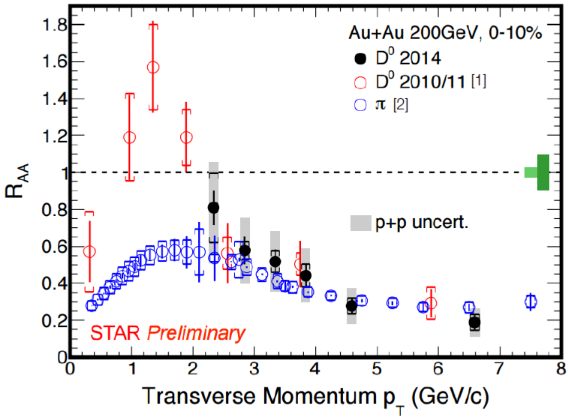
HSD predictions

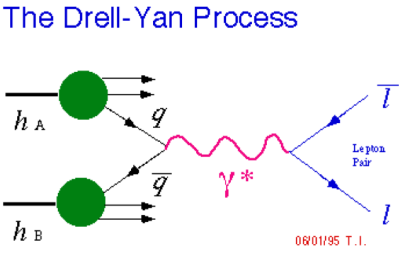


LHC charm measurements



RHIC charm measurements





- lepton pair production in hard EM interactions of two hadrons
- process not influenced by QGP production
- $\langle DY \rangle \sim \mathrm{N}_{coll}$

Example of J/ψ normal nuclear absorption:
$J/\psi + h \rightarrow D + \bar{D} + X$
$J/\psi + \pi \rightarrow D + \bar{D}$

MIMOSA-26 sensors

- 1152x576 pixels of 18.4x18.4 μm^2
- readout time: 115.2 μs
- 50 μm thin
- SAVD: 16 sensors; 32 cm^2; 10 MPixel