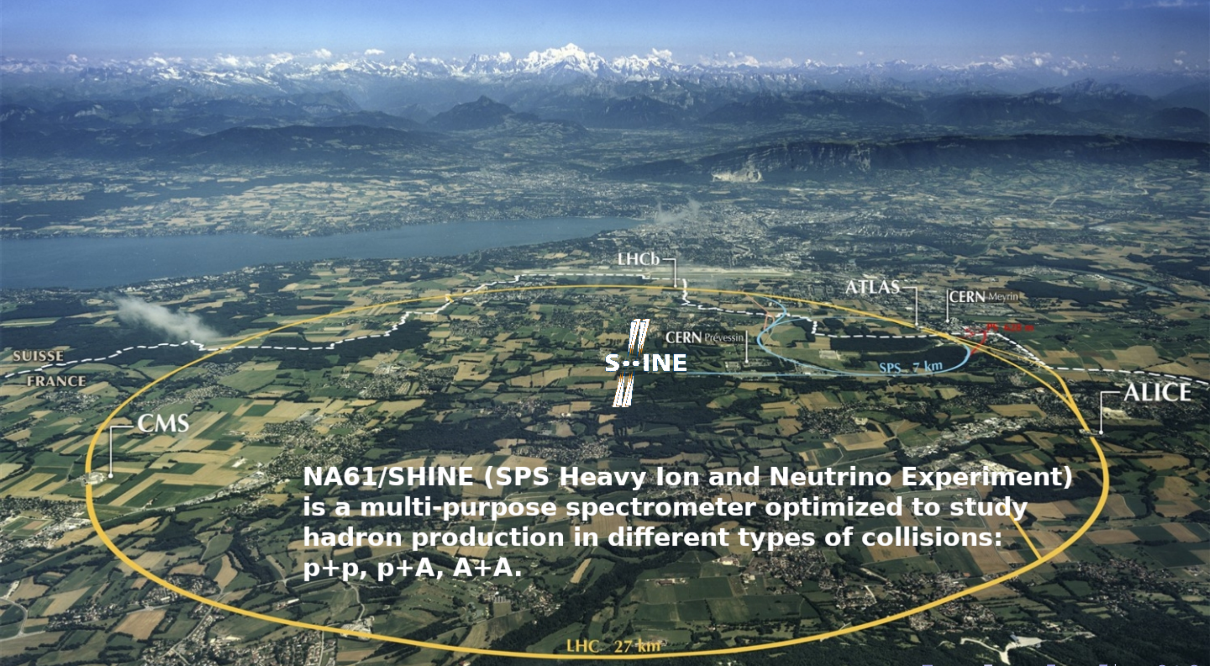
News from the strong interactions program of NA61/SHINE

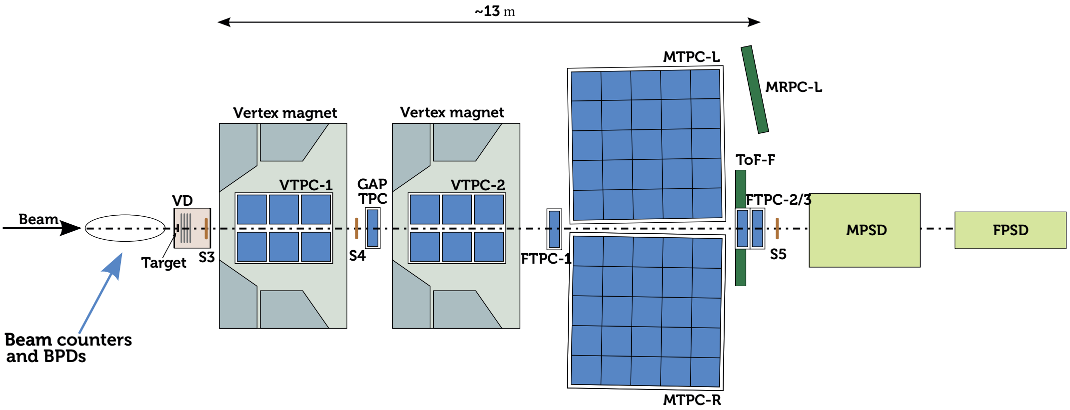
Wojciech Bryliński

for the NA61/SHINE Collaboration
Warsaw University of Technology



NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a multi-purpose spectrometer optimized to study hadron production in different types of collisions: p+p, p+A, A+A.

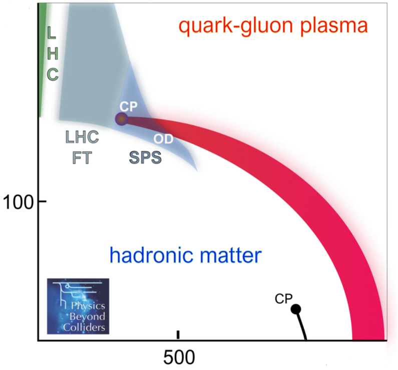
NA61/SHINE detector

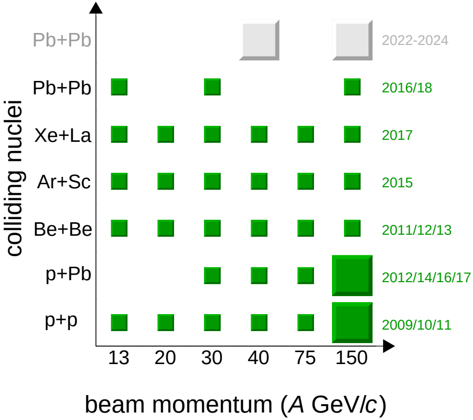


- coverage of the full forward hemisphere, down to $p_T = 0$
- ion (Be, Ar, Xe, Pb) and hadron (π, K, p) beams

NA61/SHINE heavy-ion program

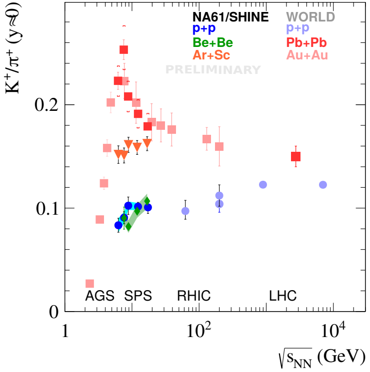
NA61/SHINE explores the phase diagram of strongly interacting matter by performing a 2D scan in collision energy and system size

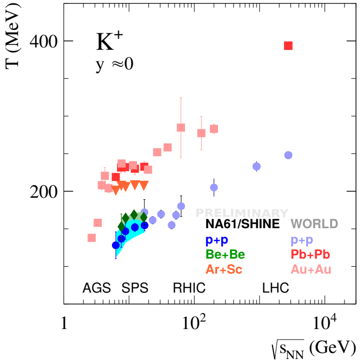




Onset of deconfinement and onset of fireball

K^+/π^+ ratio and inverse slope parameter



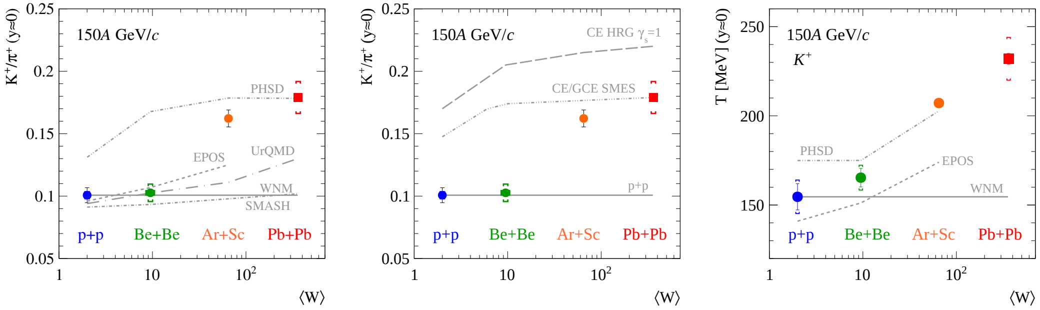


- No horn-like structure in Ar+Sc
- Be+Be close to p+p in K^+/π^+
- Plateau visible in p+p, Be+Be and Ar+Sc
- Ar+Sc significantly above Be+Be

p+p $\approx$ Be+Be $\neq$ Ar+Sc $\ll$ Pb+Pb

K^+/π^+ and T vs the system size at 150A GeV/c

dynamical models | **statistical models** | **dynamical models**

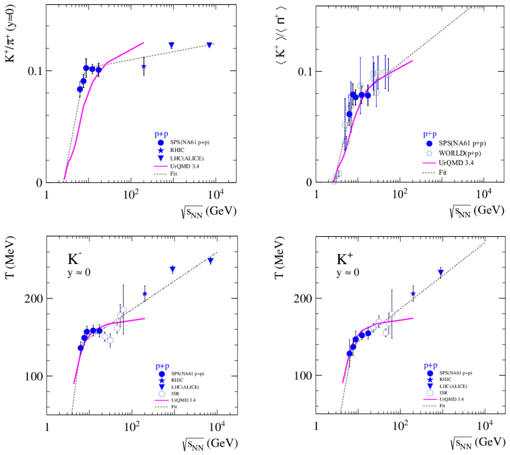


- None of the models reproduce K^+/π^+ ratio nor T for whole $\langle W \rangle$ range

PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private communication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private communication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909
SMES: Acta Phys. Polon. B46 (2015) 10, 1991 - recalculated

p+p: Eur. Phys. J. C77 (2017) 10, 671
Be+Be: Eur. Phys. J. C81 (2021) 1, 73
Ar+Sc: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C66, 054902 (2002)

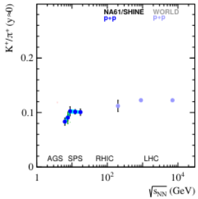
K^+/π^+ ratio and inverse slope parameter in p+p



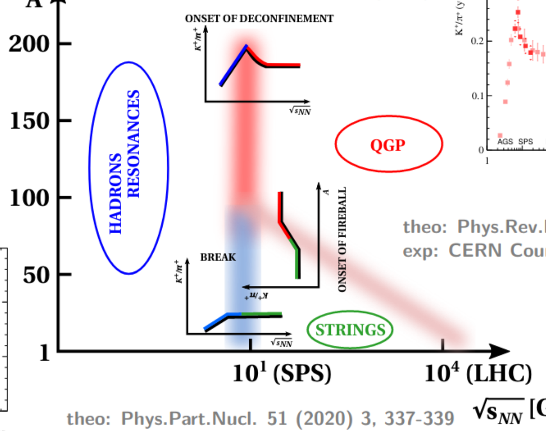
Phys.Rev.C 102 (2020) 1, 011901

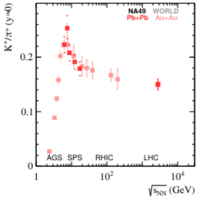
- Rates of increase of K^+/π^+ and T change sharply in p+p collisions at SPS energies
- Models assuming change from resonances to string production mechanism follow similar trend

Uniqueness of heavy ion results from NA61/SHINE

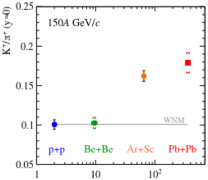


theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)



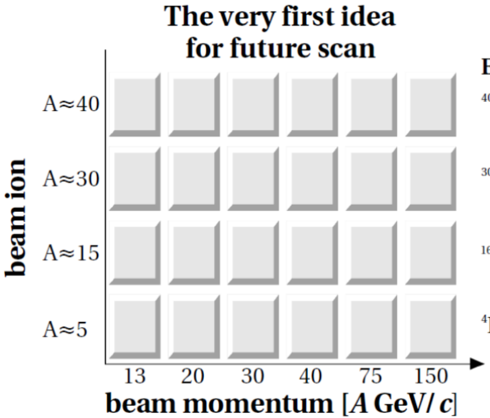


theo: Phys.Rev.D 90 025031 (2014)
exp: CERN Courier, Sep 23rd, 2019



theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Onset of fireball – measurements after LS3



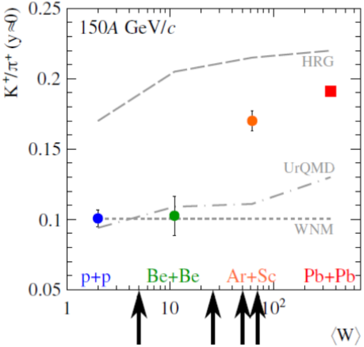
Example ion:

^{40}Ca Synergy with Gamma Factory

^{30}P

^{16}O Synergy with Cosmic-Ray LHC

^{4}He



S··INE

Search for Critical Point

Fluctuations – net-charge

$\kappa_1 = \langle N \rangle$

$\kappa_2 = \langle (\delta N)^2 \rangle = \sigma^2$

$\kappa_3 = \langle (\delta N)^3 \rangle = S\sigma^3$

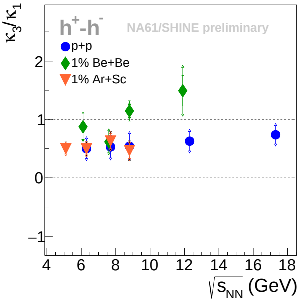
$\kappa_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 = K\sigma^4$

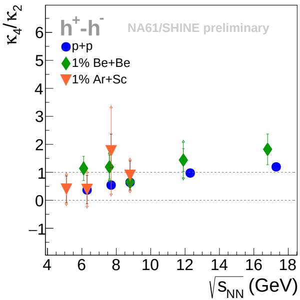
where:

N – multiplicity; $\delta N = \langle N - \langle N \rangle \rangle$

σ – standard deviation

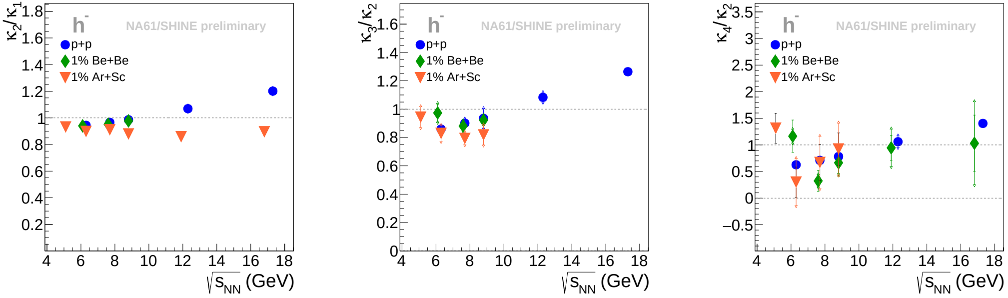
S – skewness; K – kurtosis





- κ_3/κ_1 : increasing difference between Be+Be and other systems (p+p and Ar+Sc) with collision energy
- No structure indicating critical point

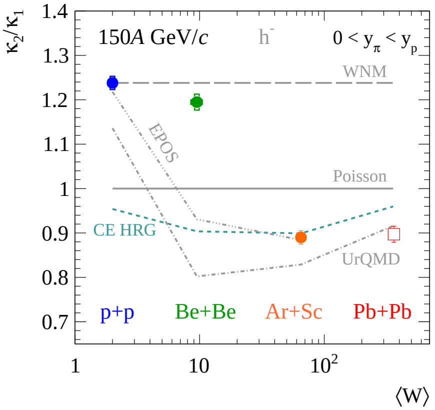
Fluctuations – multiplicity



- κ_2/κ_1 : increasing difference between small systems (p+p and Be+Be) and a heavier system (Ar+Sc) with collision energy
- κ_3/κ_2 and κ_4/κ_2 : consistent values for all measured systems at given collision energy

Scaled variance of negatively charged hadrons and the onset of fireball

- NA61/SHINE results on scaled variance of negatively charged hadrons also reveals jump between **p+p** ≈ **Be+Be** and **Ar+Sc** and **Pb+Pb**
- Dynamical models show steep decrease of κ_2/κ_1 value with the colliding system size, but do not describe Be+Be data
- Statistical model does not describe p+p and Be+Be



Phys. Rev. C99 (2019) 3, 034909

Second factorial moment - proton intermittency

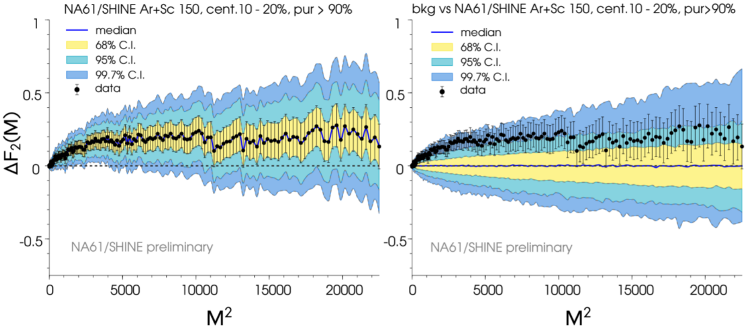
$$F_2(\delta) = \frac{\langle \frac{1}{M} \sum_{i=1}^{M} n_i(n_i - 1) \rangle}{\langle \frac{1}{M} \sum_{i=1}^{M} n_i \rangle^2}$$

δ – size of each of the $M = \frac{\Delta}{\delta}$ subdivision intervals of the p_T

n_i – number of particles in i-th p_T bin

At the second order phase transition $F_2(M)$ exhibits a power-law dependence on M:
$F_2(M) \sim (M^2)^{\varphi_2}$

APPB 19 (1988) 863
PLB 253 (1991) 436
NPB 273 (1986) 703
PRL 97 (2006) 032002

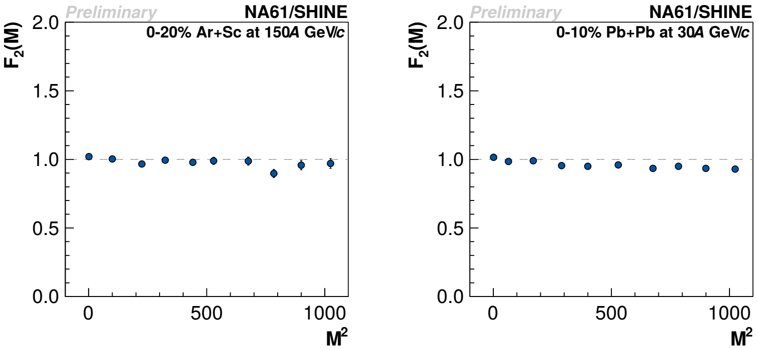


- Analysis of peripheral Ar+Sc collisions at 150A GeV$/c$ reveals a non-trivial scaling effect; however, large uncertainties in $F_2(M)$ and M-bin error correlations prevent an unbiased estimation of φ_2 confidence intervals

Second factorial moment - proton intermittency

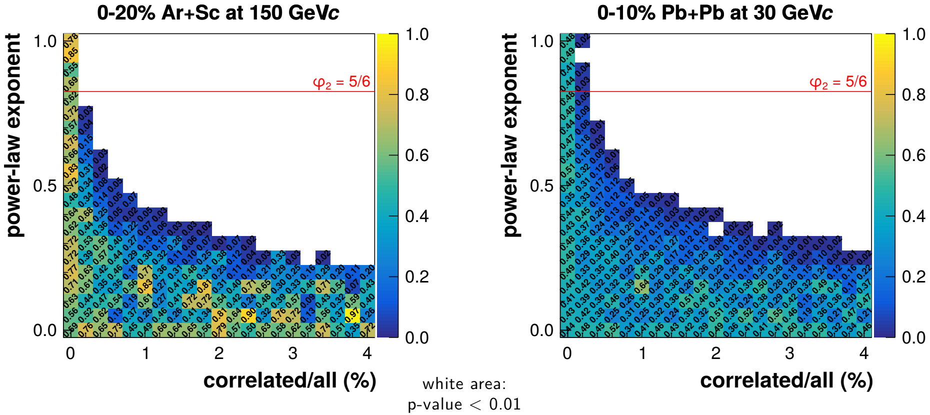
using cumulative variables and independent points

- Independent bin analysis using cumulative variables shows no intermittency effect in Ar+Sc at 150*A* GeV/*c*, as well as in Pb+Pb at 30*A* GeV/*c*



statistical uncertainties only

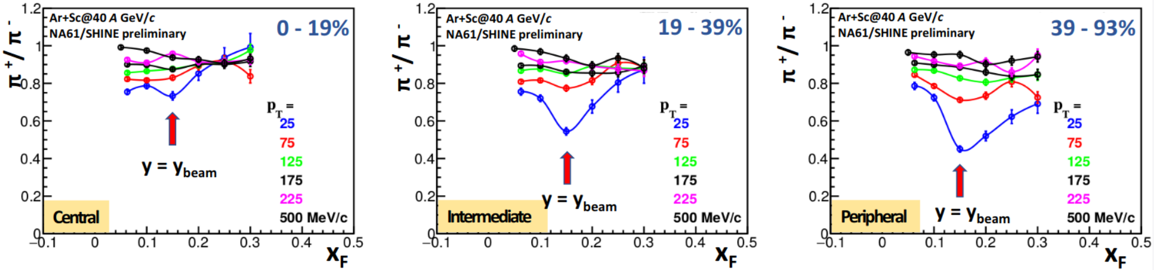
Exclusion plots for parameters of simple power-law model



- The intermittency index φ_2 for a system freezing out at the QCD critical endpoint is expected to be $\varphi_2 = 5/6$ assuming that the latter belongs to the 3-D Ising universality class.

Electromagnetic effects

Spectator-induced electromagnetic effects



- Charged pion trajectories can be modified by electromagnetic interactions (repulsion for π^+ and attraction for π^-) with the spectators $\rightarrow$ the effect is sensitive to the space-time evolution the system

  Phys.Rev.C75 (2007) 054903, Phys.Rev.C102 (2020) 1, 014901

- Spectator-induced EM effects are stronger with rapidity closer to the spectator rapidity and with low p_T
- First time ever observation of the spectator-induced electromagnetic effects in peripheral small systems: Ar+Sc at 40A GeV/c
- Similar effects observed in intermediate centrality Ar+Sc collisions at 150A GeV/c (NA61/SHINE) and peripheral Pb+Pb (NA49) at 158A GeV/c Acta Phys.Polon.B 49 (2018) 711

Open charm measurements in NA61/SHINE experiment

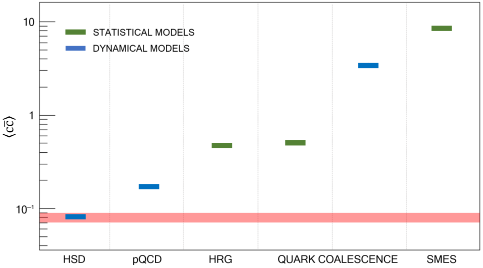
Motivation of the open charm measurements

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

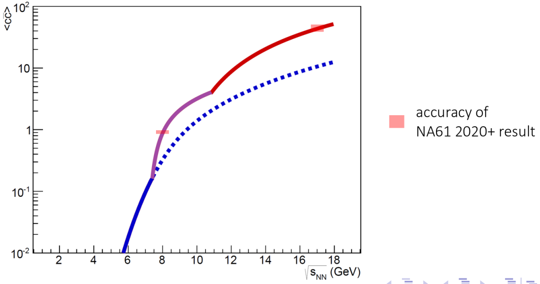
1. What is the mechanism of open charm production?
2. How does the onset of deconfinement impact open charm production?
3. How does the formation of quark-gluon plasma impact J/ψ production?

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**.



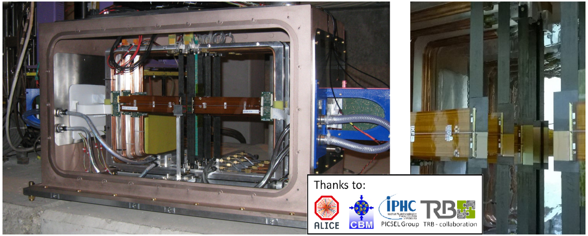
Statistical Model of Early Stage (SMES)



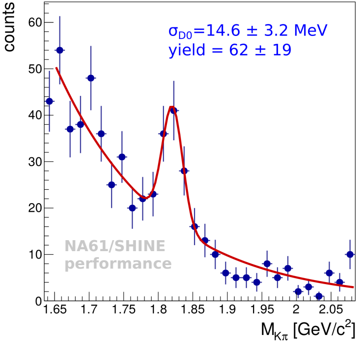
Small Acceptance Vertex Detector (SAVD)

Small Acceptance Vertex Detector introduced in 2016:

- 16 CMOS MIMOSA-26 sensors located on two horizontally movable arms
- first indication of D^0 and $\bar{D}^0$ signal



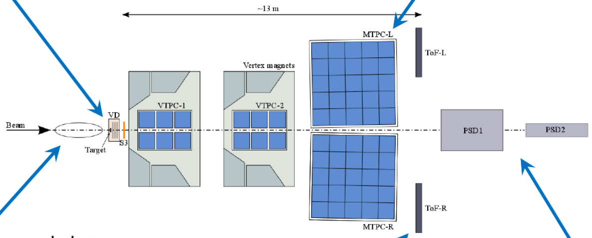
Pb+Pb at 150*A* GeV/*c*



NA61/SHINE upgrades

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

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



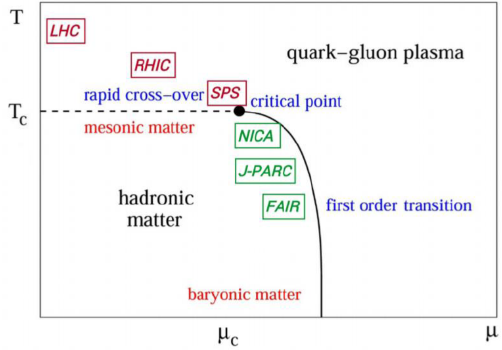
New trigger and data acquisition system

New Time-of-Flight detectors

Upgrade of Projectile Spectator Detector

Uniqueness of NA61/SHINE 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

Summary

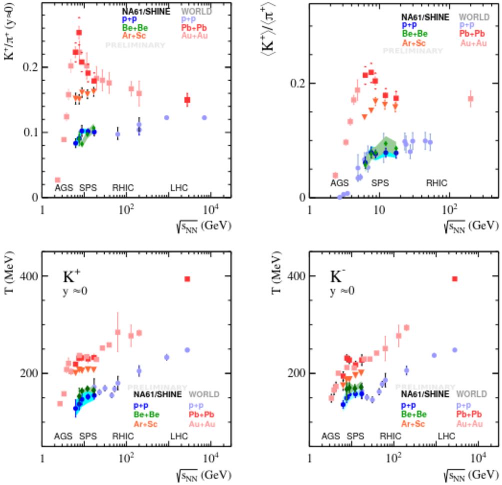
- NA61/SHINE 2D scan in system size and energy is completed
- Unique NA61/SHINE data delivered rich information related to the onset of deconfinement
- Unexpected system size dependence was revealed – onset of fireball
- So far, no convincing indication of the critical point
- Electromagnetic effects in Ar+Sc at 40A GeV/c were observed for the first time
- NA61/SHINE will measure the open charm production at the SPS energies in 2022-2024

Thank you!

Have a SHINY day!

Backup

Onset of deconfinement observables



Acta Phys.Polon.B 46 (2015) 10, 1991

K^+/π^+ **and** $\langle K^+\rangle/\langle\pi^+\rangle$**:**

- No horn-like structure in Ar+Sc
- Be+Be close to p+p
- Jump-like change in the system size dependence of K^+/π^+

Inverse slope parameter:

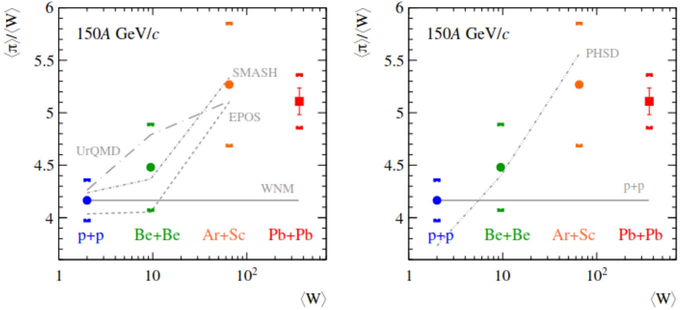
- Be+Be slightly above $p + p$
- Ar+Sc significantly above Be+Be

$p{+}p \approx$ **Be+Be** $\neq$ **Ar+Sc** $\leqslant$ **Pb+Pb**

$\langle\pi\rangle/\langle W\rangle$ ratio vs the system size at 150A GeV/c

Dynamical models

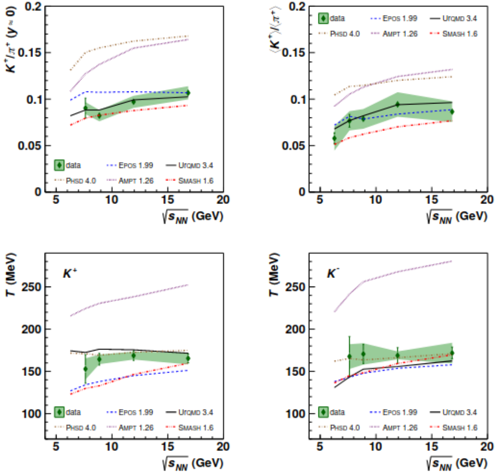
without transition to QGP | with transition to QGP



Models:
Eur.Phys.J.A 56 (2020) 9, 223,
arXiv:1908.00451,
J.Phys.G47 (2020) 6, 065101
and private communication;
data:
Eur.Phys.J.C74 (2014) 3, 2794,
Eur.Phys.J.C81 (2021) 2, 144,
Phys.Rev.C66, 054902 (2002),
2101.08494;

- Model predictions for $\langle\pi\rangle/\langle W\rangle$ approximately agree with the data
- However, they should be complemented with calculations for Pb+Pb

K/π in Be+Be and models



- NA61/SHINE – the only world data for Be+Be collisions
- K^+/π^+ ratio and inverse slope parameter T - smooth energy dependence

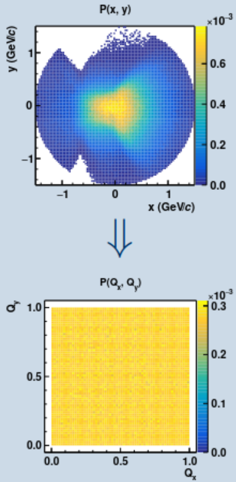
  Note the limited energy range of data
- None of actual models describe all measured quantities

Eur.Phys.J.C 81 (2021) 1, 73

Instead of using p_x and p_y, one can use cumulative quantities:

$$Q_x = \int_{min}^{x} \rho(x)dx / \int_{min}^{max} \rho(x)dx \qquad Q_y(x) = \int_{y_{min}}^{y} P(x,y)dy/P(x)$$

- transform any distribution into uniform one (0,1)
- remove the dependence of F_2 on the shape of the single-particle distribution
- intermittency index of an ideal power-law correlation function system described in two dimensions in momentum space was proven to remain approximately invariant after the transformation



(example for 0-5% Ar+Sc at 150*A* GeV/c)

Bialas, Gazdzicki, PLB 252 (1990) 483
Antoniou, Diakonos, https://indico.cern.ch/event/818624/

Simple power-law model

Comparison with simple power-law model

A simple model that generates momentum of particles for a given number of events with a given multiplicity distribution.

It has two main parameters:

- ratio of correlated to uncorrelated particles,
- power-law exponent.

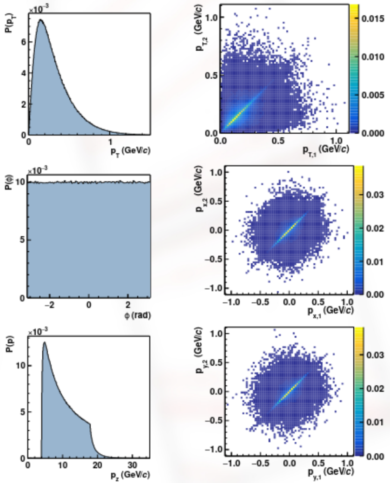
Uncorrelated particles (background)

$\rho_B(p_T) = p_T \cdot e^{-6p_T}$

Correlated pairs (signal)

$$\rho_S(p_{T,1}, p_{T,2}) = \rho_B(p_{T,1}) \cdot \rho_B(p_{T,2}) \cdot \left[|\Delta p_x|^{\phi} + \epsilon \right]^{-1} \cdot \left[|\Delta p_y|^{\phi} + \epsilon \right]^{-1}$$

Examples for: $\phi = 0.80$
$\epsilon = 1e^{-5}$
N_B=Poisson(30)
N_S=2



Lots of model data sets generated:

- correlated-to-all ratio: vary from 0.0 to 4.0% (with 0.2 step)
- power-law exponent: vary from 0.00 to 1.00 (with 0.05 step)

and compared with the experimental data

For the construction of exclusion plots, statistical uncertainties were calculated using model with statistics corresponding to the data.