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on High Energy Physics Problems
Relativistic Nuclear Physics & Quantum Chromodynamics

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Recent results of strong interaction program from NA61/SHINE experiment at CERN SPS

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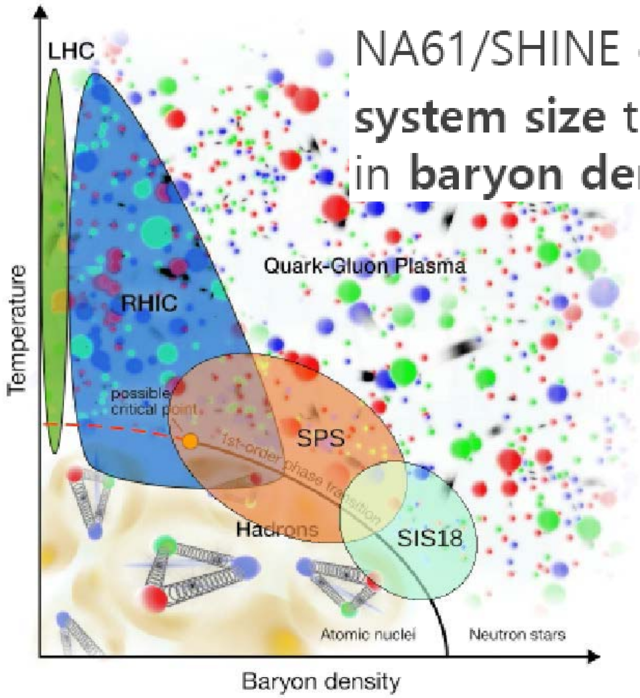
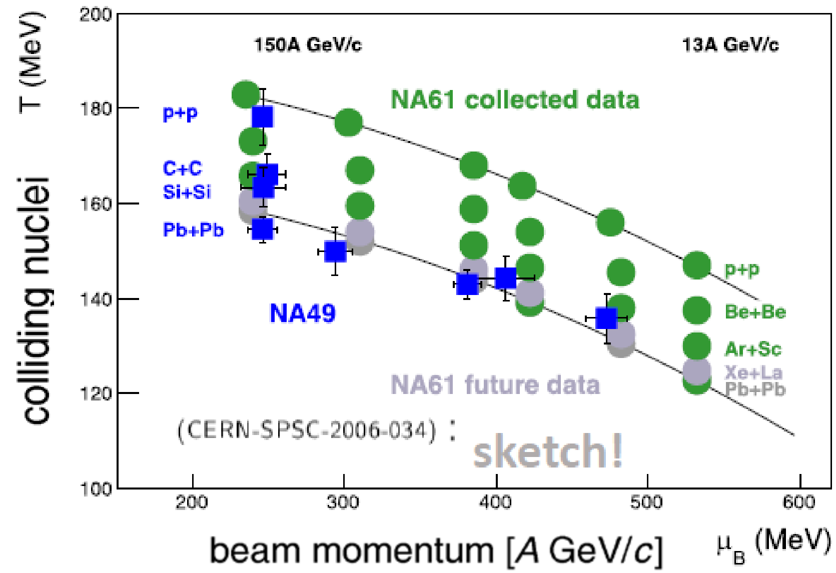
for NA61/SHINE Collaboration

Research program NA61/SHINE

NA61/SHINE experiment performs 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter in **baryon density and temperature**





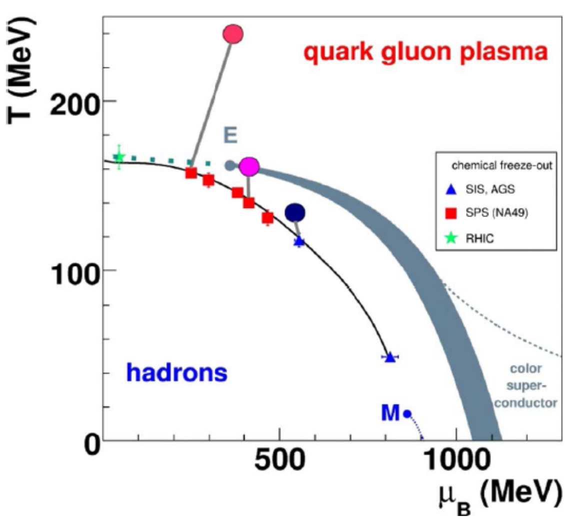
p+p

Be+Be

Ar+Sc

Xe+La

Pb+Pb

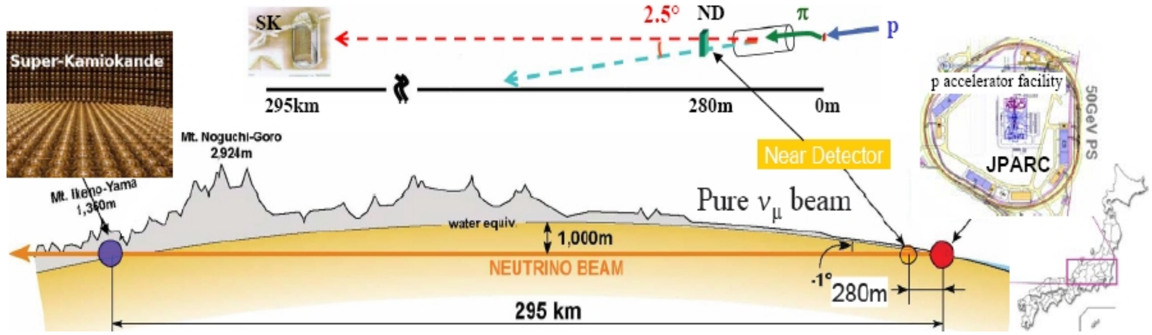


Search for the **critical point** of strongly interacting matter

Study of the properties of the **onset** of **deconfinement**

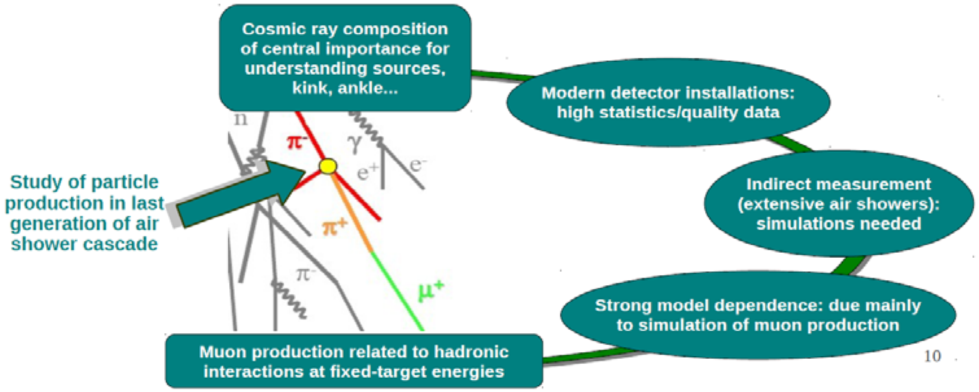
Measurement **open charm** at SPS energies beyond 2020

Program for neutrino and cosmic ray experiments



Hadron production measurements for neutrino experiments

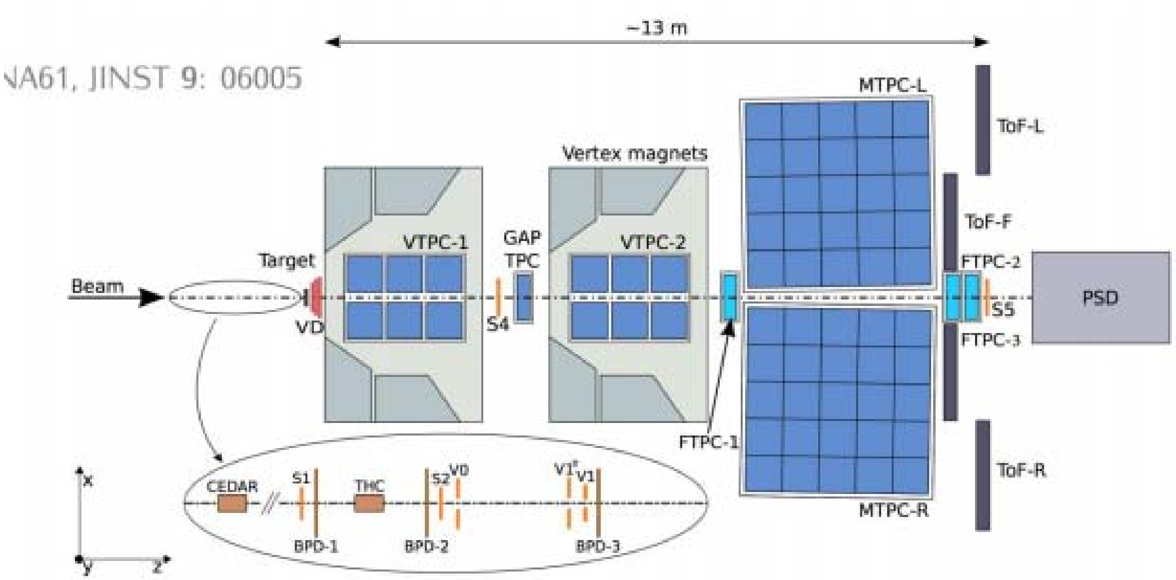
→ reference measurements for neutrino experiments for computing initial neutrino fluxes at J-PARC and FERMILAB

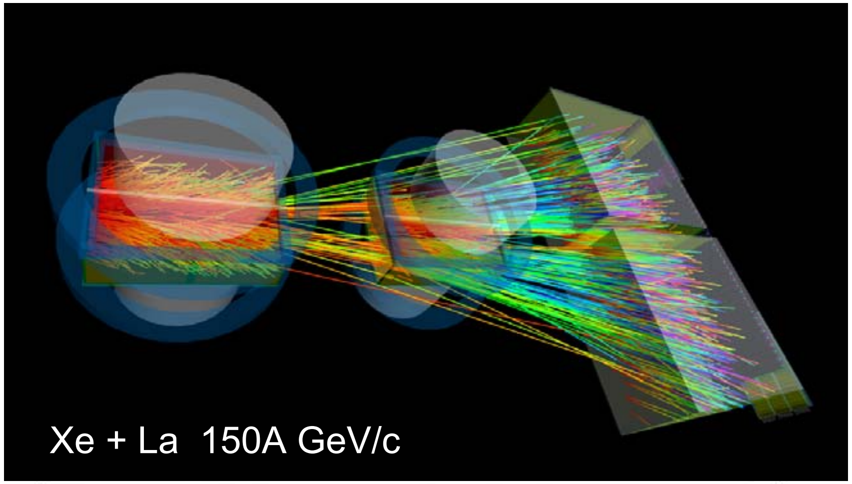


Hadron production measurements for cosmic ray experiments

→ 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

NA61/SHINE at CERN SPS

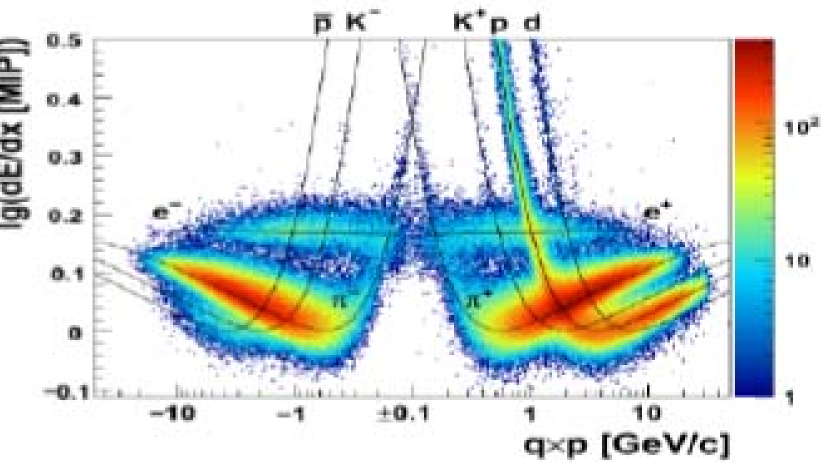


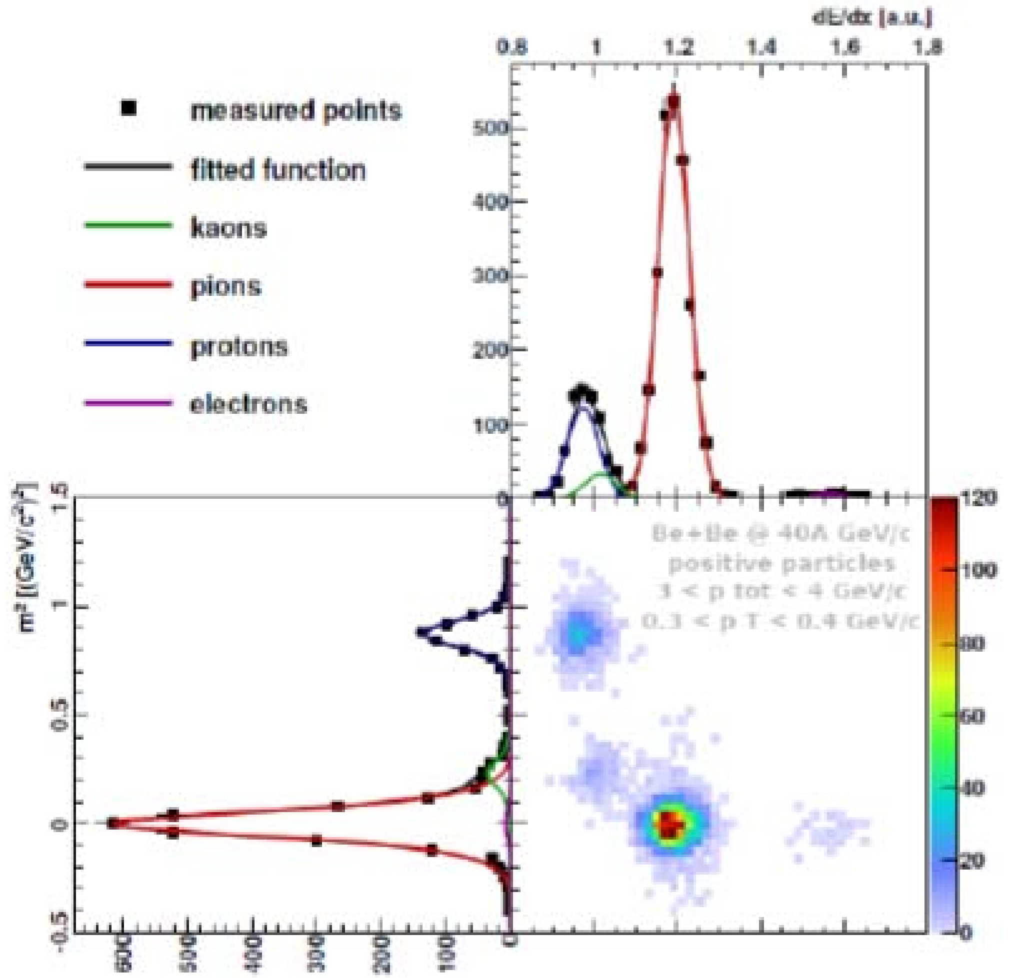


NA61/SHINE 3D event visualization

- Large acceptance hadron spectrometer - coverage of the full forward hemisphere, down to $p_T = 0$ GeV/c
- Performs measurements on hadron production in h+p, h+A, A+A at 13A – 150(8)A GeV/c
- Event selection in A+A collisions by measurements of forward energy with PSD
- Recent upgrades:
  - Vertex detector (open charm measurements)
  - FTPC-1/2/3

Methods charged particle analysis

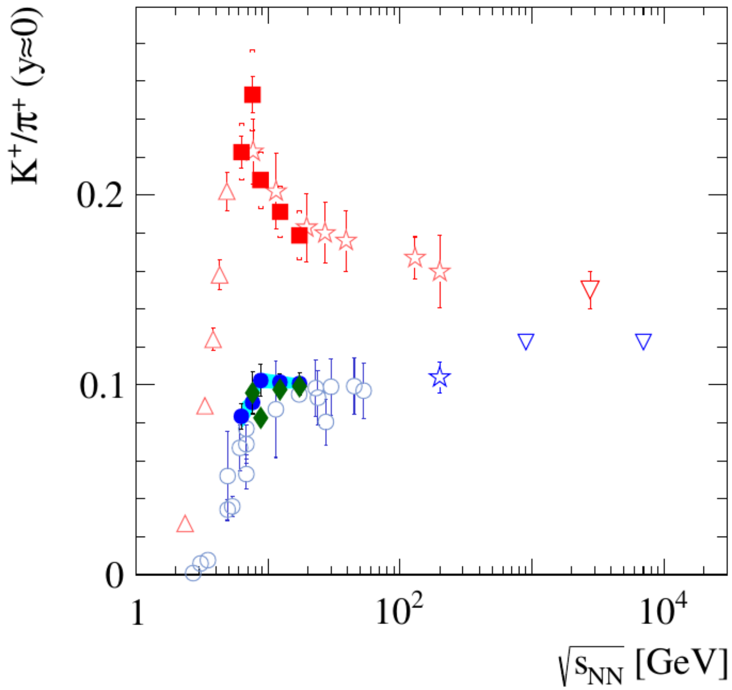


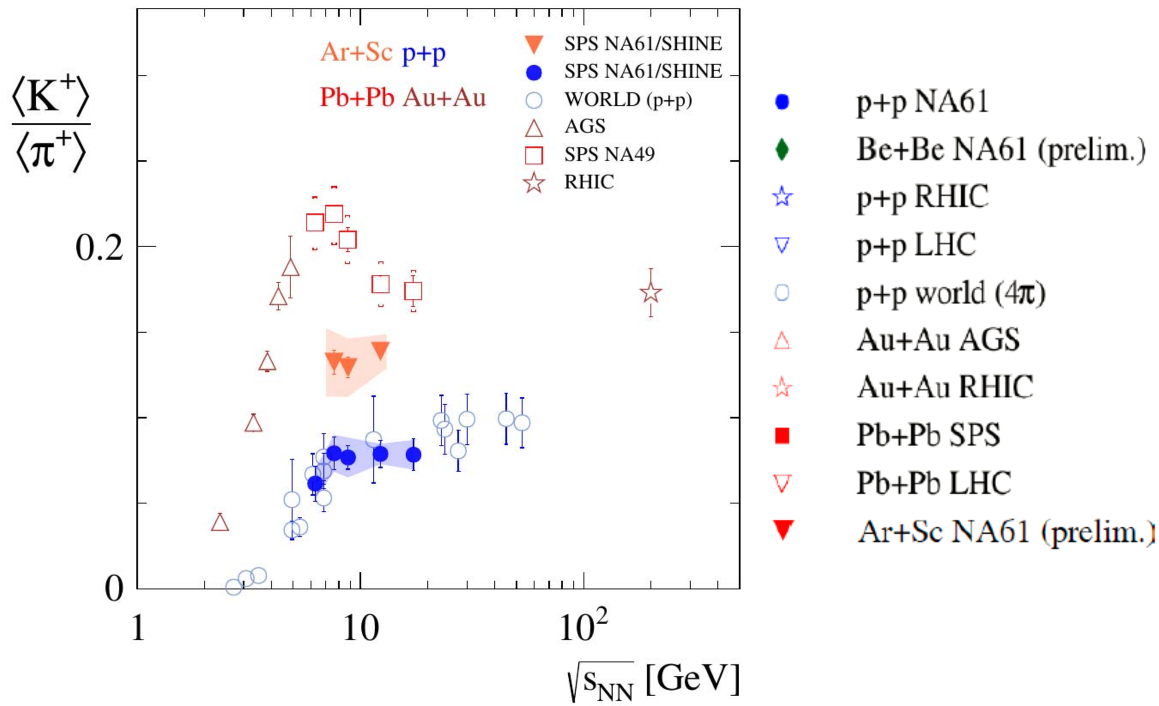


- **h⁻ analysis** based on the fact that the majority of negatively charged particles are π ⁻ mesons. Contribution of the other particles is subtracted using EPOS Monte-Carlo
- **dE/dx** analysis uses TPC energy loss information to identify particles
- **tof-dE/dx** method estimates number of π, K, p using an energy loss and a particle time of flight measurements

Onset deconfinement- 'HORN'-structure

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:

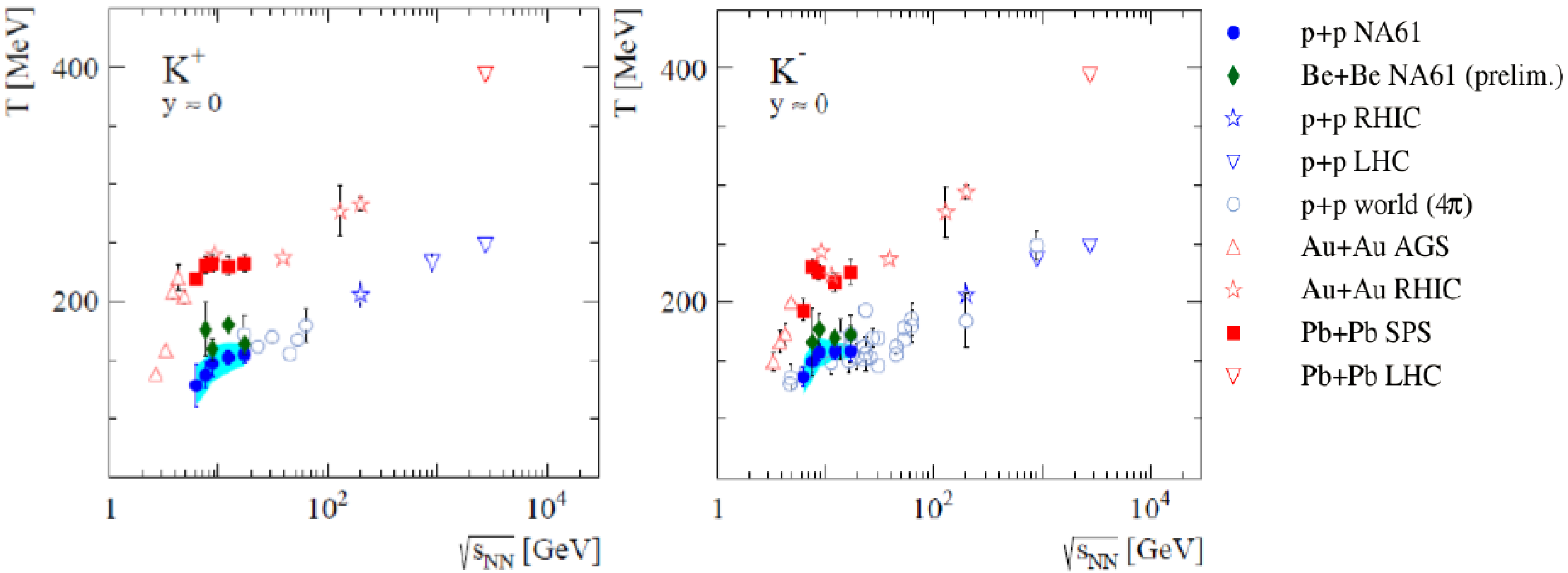
- plateau like structure visible in p+p
- Be+Be consistent with p+p

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

Horn – a strong maximum of the ratio K^+/π^+ multiplicities.
A reduced shadow of the horn-like structure is visible in p+p and Be+Be reactions

Onset deconfinement- ‘STEP’-structure

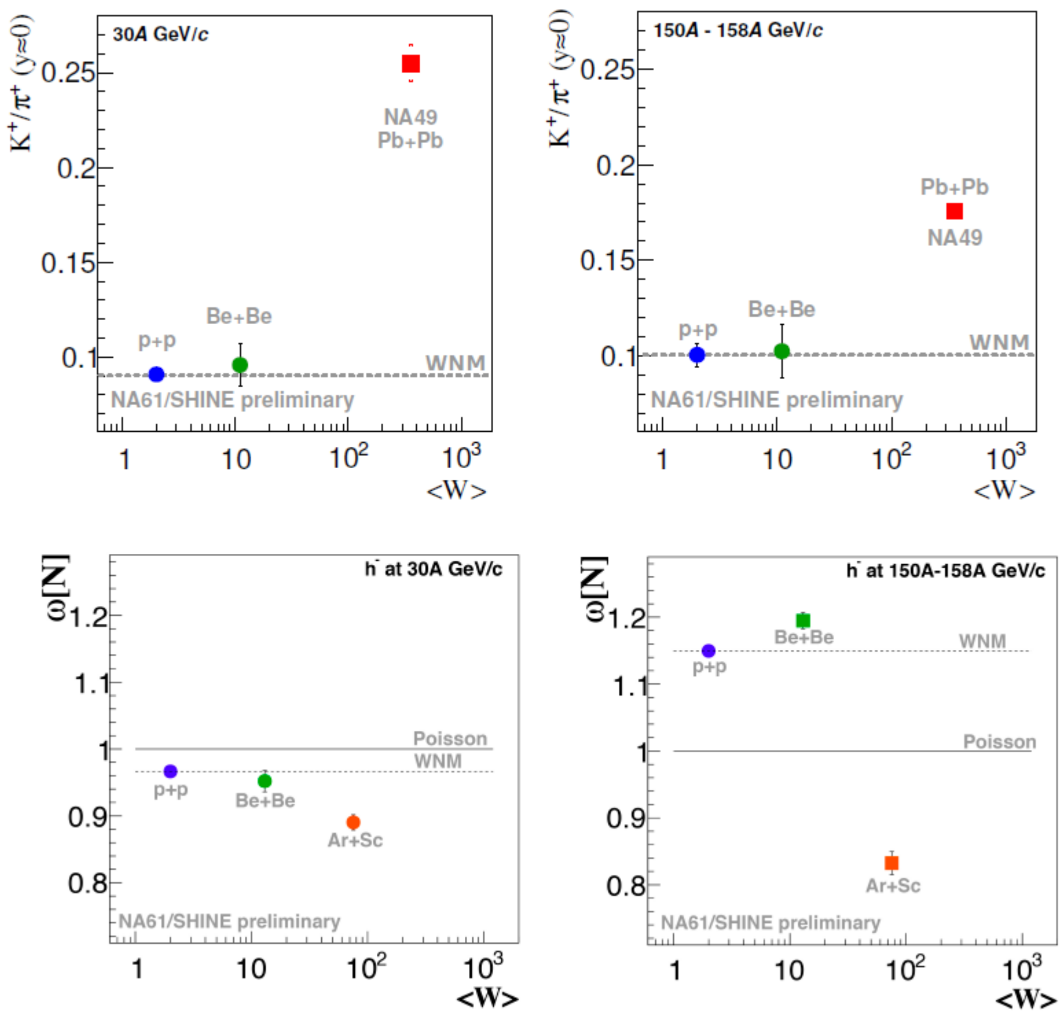
Plateau – **STEP** – in the inverse slope parameter of m_T spectra in Pb+Pb collisions observed. It is expected for the onset of deconfinement due to mixed phase of HRG and QGP (SMES).



Qualitatively similar structure is visible in p+p and Be+Be collisions

Be+Be data is slightly above p+p

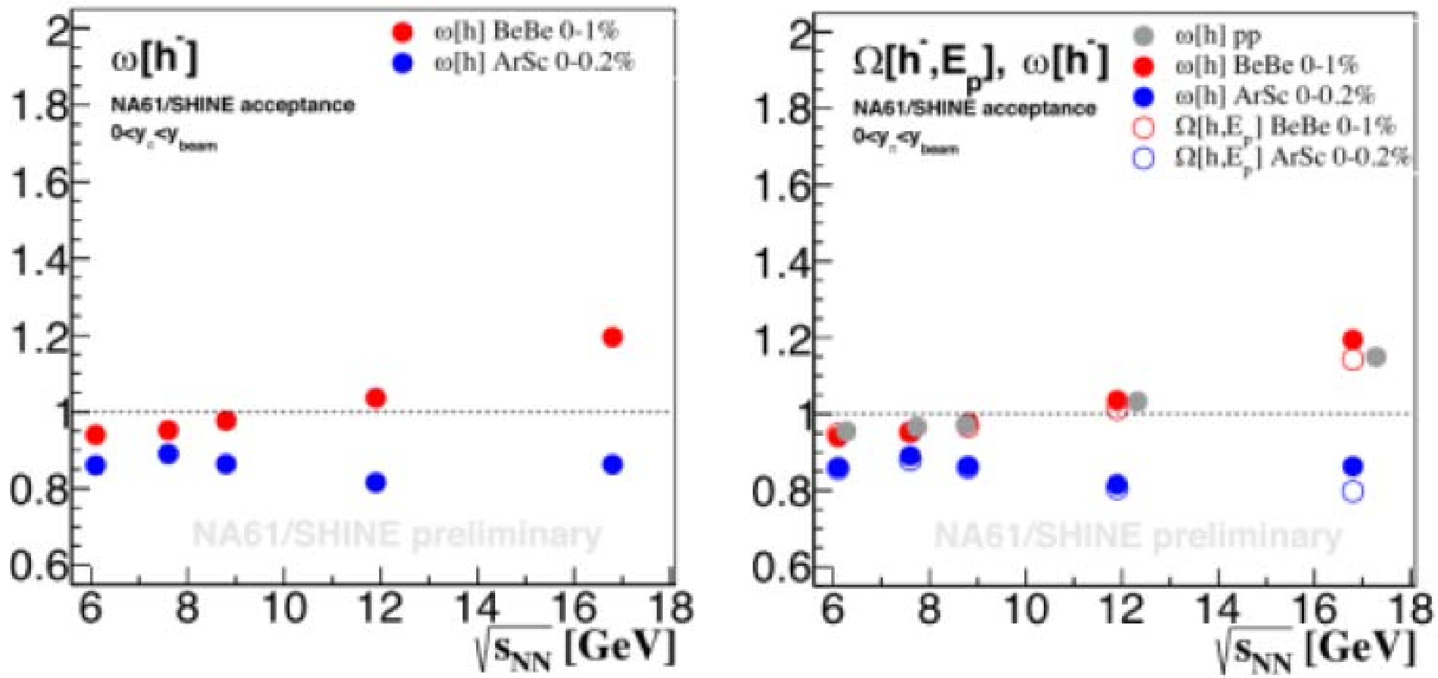
Particle ratio and fluctuation 30AGeV, 150AGeV



Surprisingly Be+Be results are very close to p+p independent of collision energy

Data suggest jump between light (BeBe) and heavier (ArSc) systems

Multiplicity fluctuation dependence on energy



Be+Be

p+p

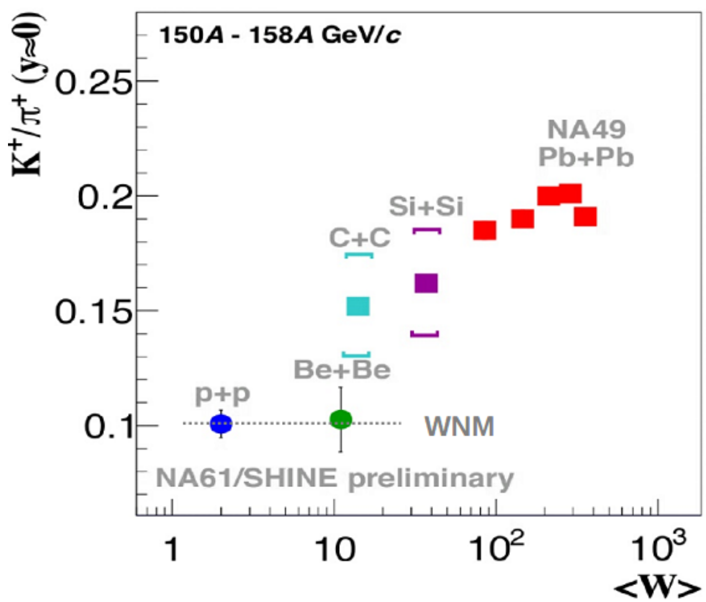
Ar+Sc

Scaled multiplicity and energy fluctuations of negatively charged hadrons undergo rapid changes between BeBe and ArSc sizes

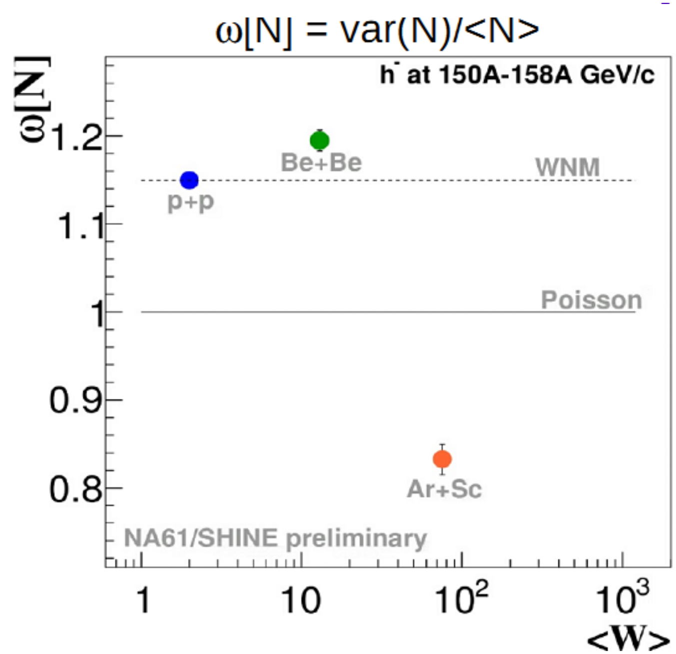
Effect does not depends on energy, but on the size of system only

At increasing size of colliding systems light clusters produced more copiously, as at some density they start to overlap and to reach percolation threshold

Particle ratio and fluctuation 150AGEV



Mean multiplicities ratio



Scaled multiplicity fluctuations

versus mean number of wounded nucleons <W>

K^+/π^+ and **multiplicity fluctuations** change rapidly when moving from light (p+p, Be+Be) to intermediate and heavy systems.

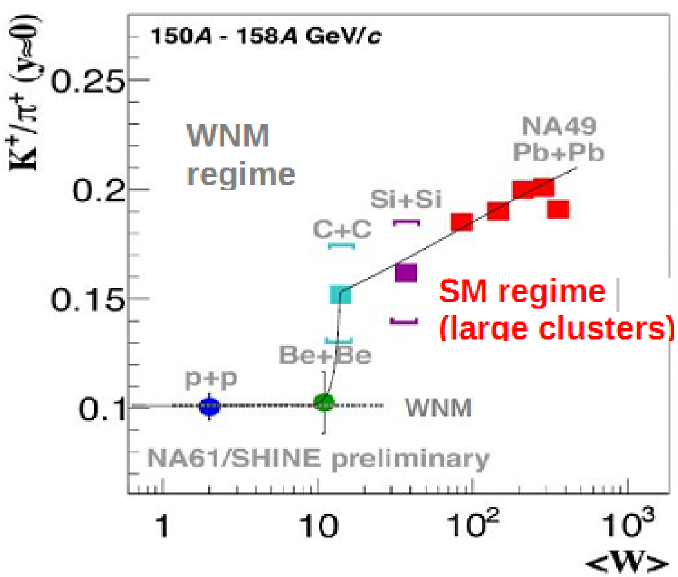
For heavy systems they are closer to predictions of statistical models for **large volumes**.

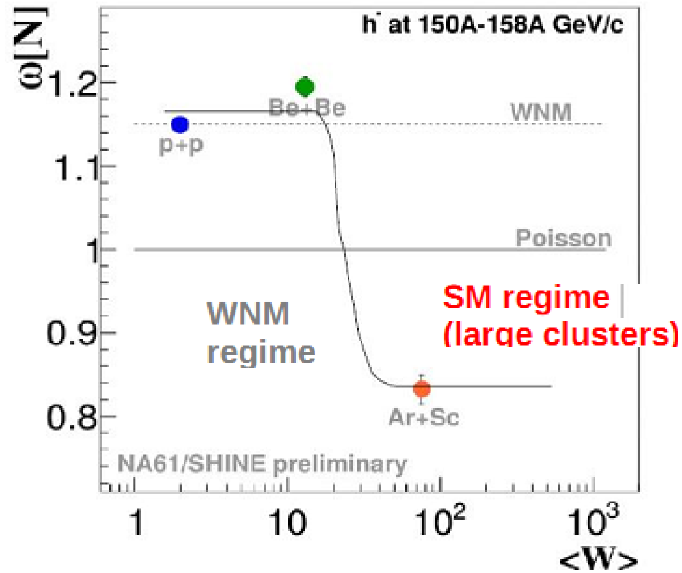
→ beginning of creation of large clusters of strongly interacting matter - Onset of fireball

Surprisingly Be+Be results are very close to p+p independent of collision energy

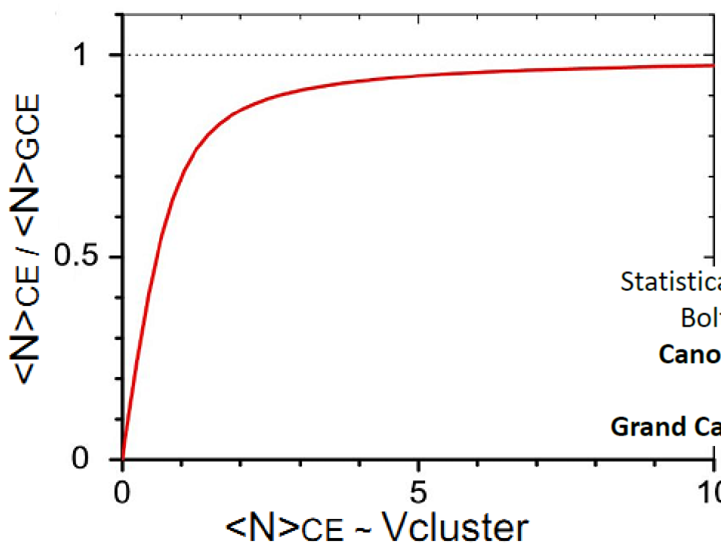
It is like cluster- fireball size rapidly increases – jump above Be+Be collision

Cluster-volume dependence <N> , Var<N>/<N>

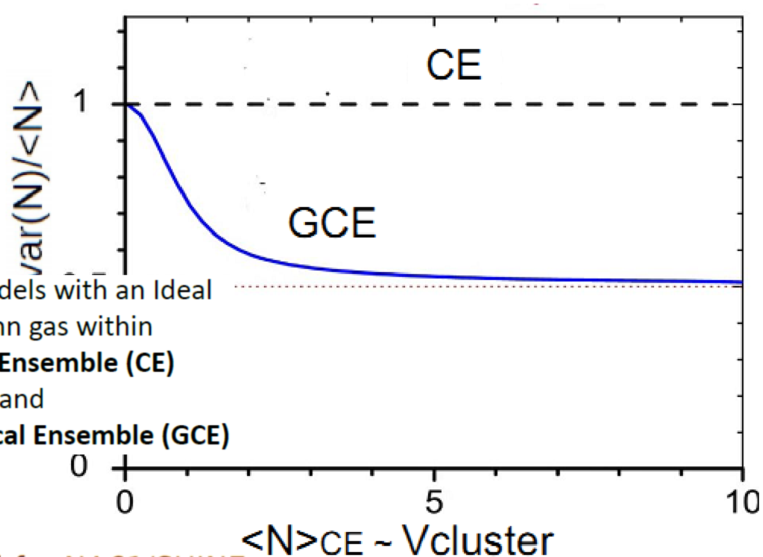




“canonical suppresion” of <N>



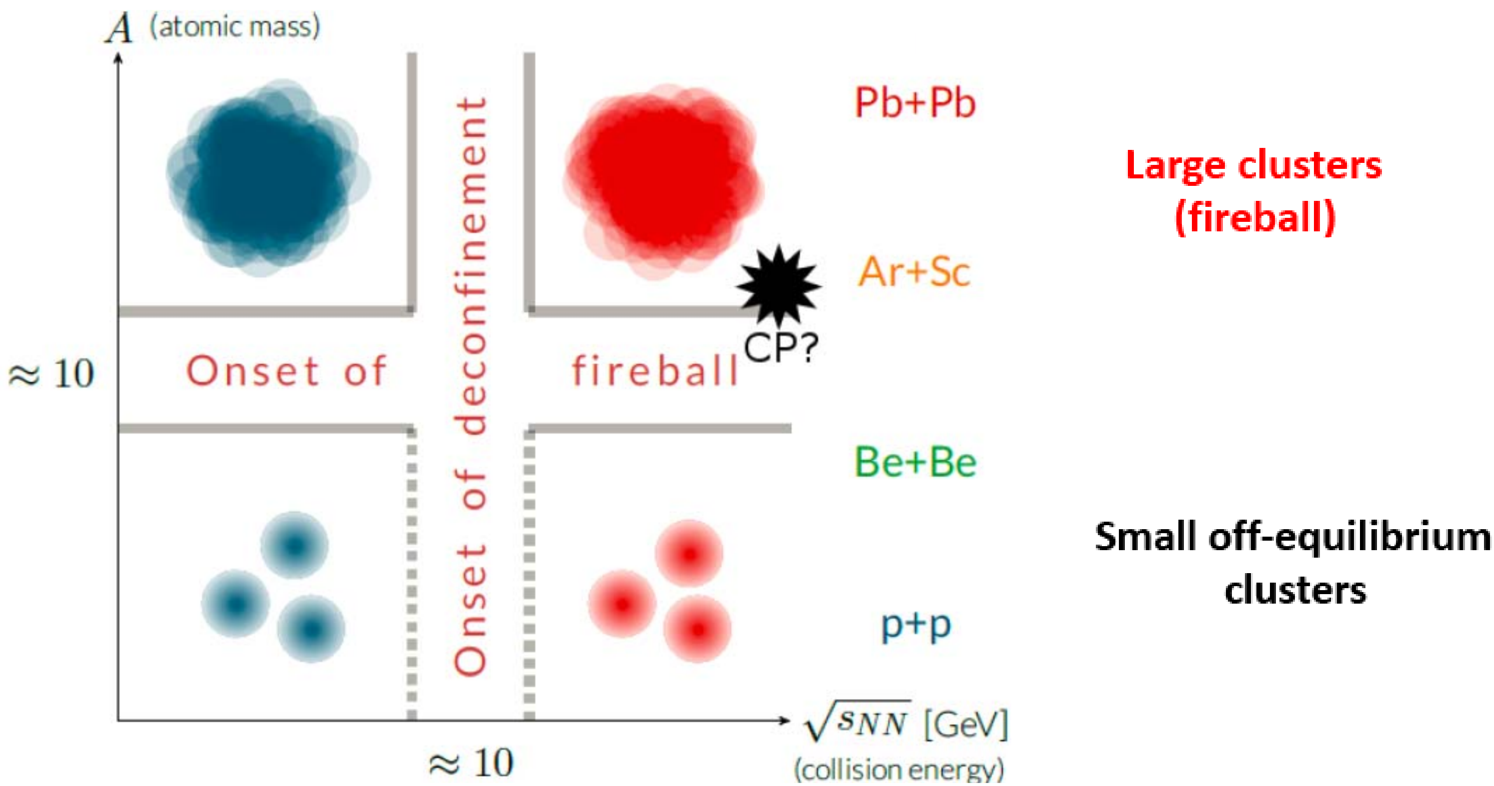
“canonical enhancement” of ω[N]



Statistical Models with an Ideal Boltzmann gas within **Canonical Ensemble (CE)** and **Grand Canonical Ensemble (GCE)**

M. Gazdzicki for NA61/SHINE, CPOD2017, 1801.00178

Onset deconfinement vs. Onset fireball



- 2D scan conducted by varing collision energy and system size indicated two thresholds:
  - Onset of deconfinement
  - Onset of fireball

→ four domains of hadron production

Completion of analysis a new data for Xe+La awaited to verify this picture

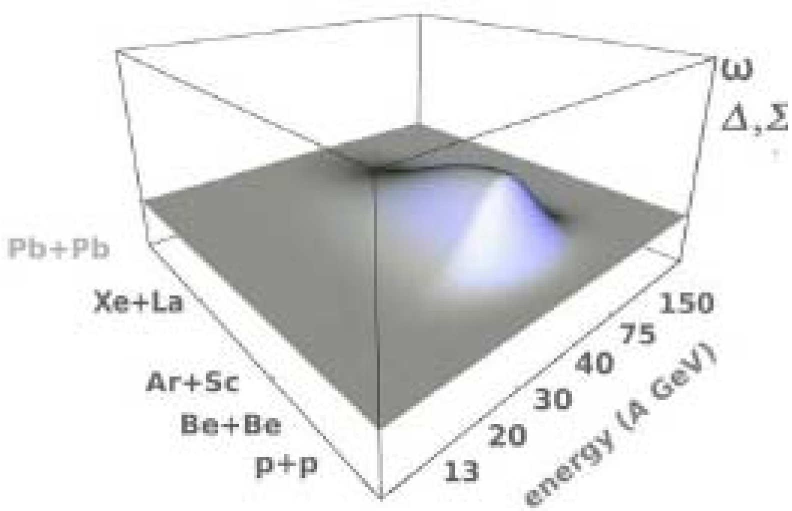
Critical point and fluctuations

$\Sigma[P_T,N]$: **strongly intensive** (*independent on system volume and its fluctuations, insensitive to material conservation laws*

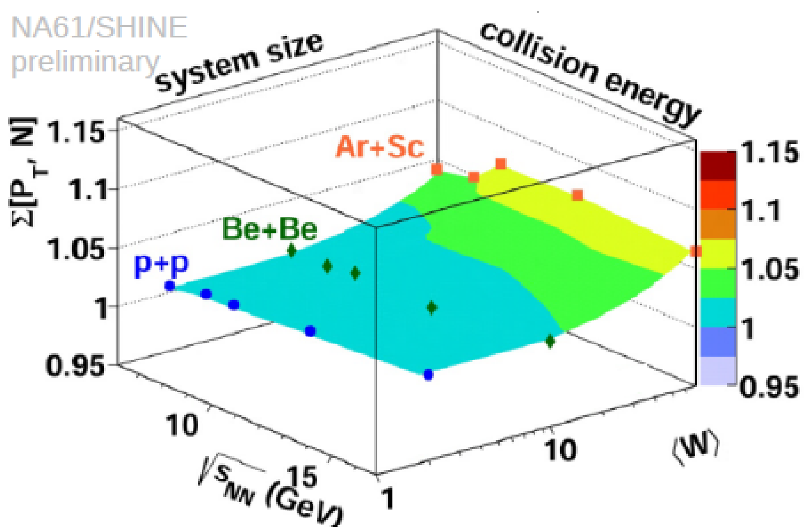
$$\Sigma[P_T,N] = \frac{1}{\langle N\rangle\omega[p_T]}\left[\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2(\langle P_T N\rangle - \langle P_T\rangle\langle N\rangle)\right]$$

where $P_T = \sum_{i=1}^{N} p_{T_i}$ and $\omega[p_T]$ is the scaled variance of the inclusive p_T spectrum.

CP --> "Fluctuation Hill"



NA61/SHINE data



No sign of any anomaly that can be attributed to the critical point (so far)

Intermittency signal critical point

N.Antoniou et al., NPA693,799(2001); PRL97,032002(2006)

- at the critical point local density fluctuations with power-law singularity expected both in configuration and momentum space
  - σ field: density of σ particles, related to low-mass $\pi^+\pi^-$ pairs
  - baryonic density: related to net baryon number (≈ protons)

- experimental observation via factorial moments in p_T space:
  (subdivided into M bins in $p_{T,x}$ and $p_{T,y}$)

$$F_2(M) = \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \cdot (n_i - 1) \right\rangle / \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \right\rangle^2 \quad \propto \quad M^{2\Phi_2}$$

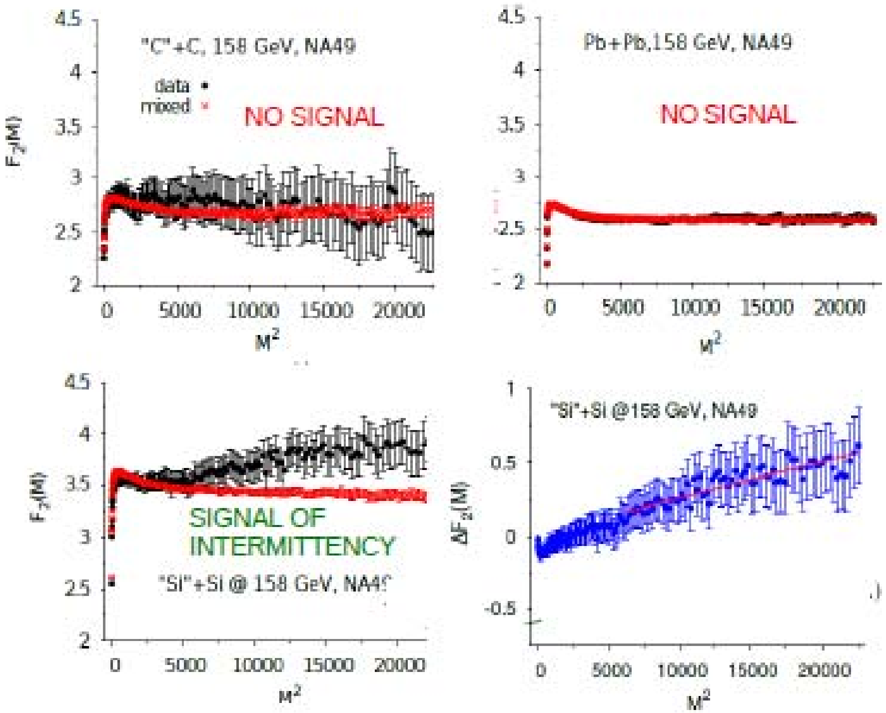
predicted intermittency index at critical point: Φ_2 = 2/3, 5/6

- estimate combinatorial and misidentification background by mixed events and subtract

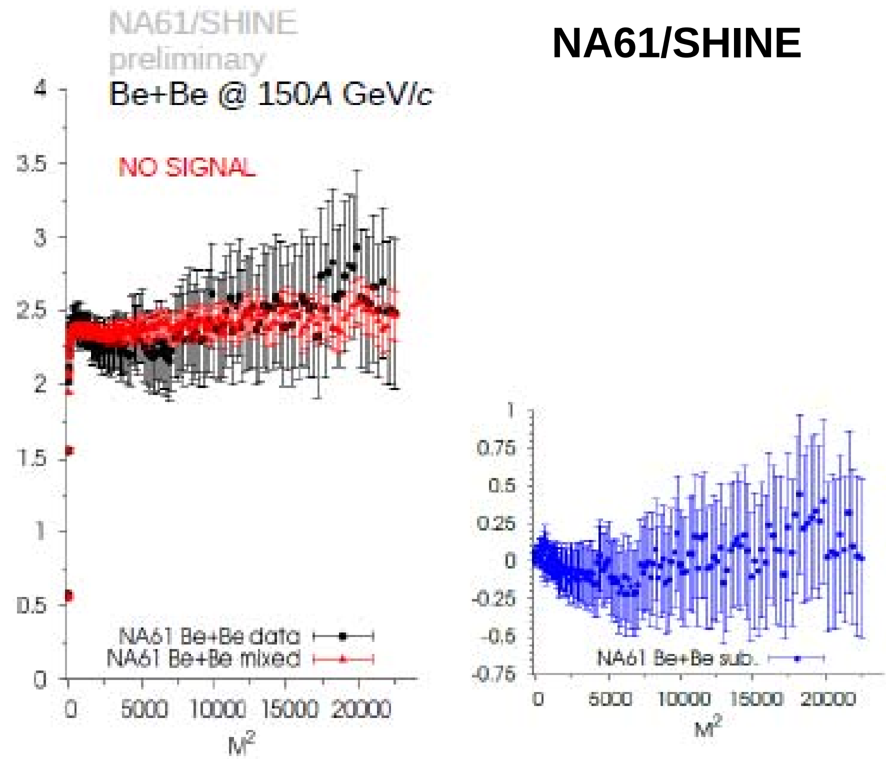
$$\Delta F_2(M) = F_2^{data} - F_2^{mix} \propto M^{2\Phi_2}$$

Intermittency signal critical point

NA49



NA61/SHINE



NA49 T.Anticic et al., Eur.Phys.J.C.75(2015) 587

Previous **NA49**: significantly power-low fluctuations of proton and pion-pion densities in Si+Si at 158A GeV/c with a power-low exponent consistent with theoretical expected critical values. No intermittency behavior visible in C+C and Pb+Pb systems at the same energy.

No intermittency effect is observed in Be+Be **NA61/SHINE** preliminary data at 150A GeV/c. Ongoing **NA61/SHINE**: in medium-size systems intermittency signature expected to be feasible for at least Ar+Sc system 150A GeV/c as suggested in above **NA49** data.

Motivation open charm measurements

What is the mechanism of open charm production ?

How does the onset of deconfinement impact open charm production ?

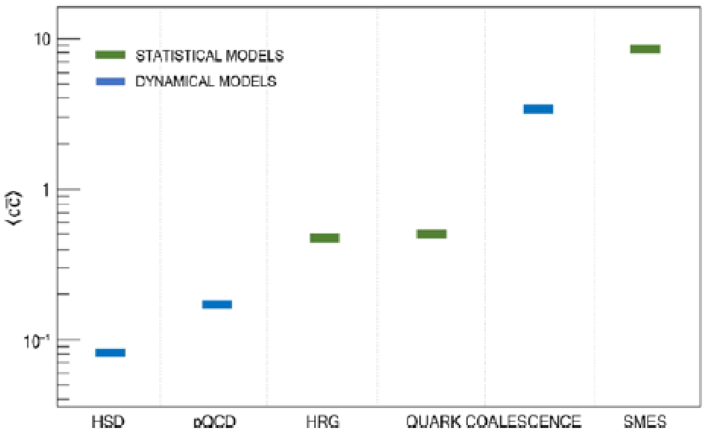
How does the formation of quark-gluon plasma impact J/ψ production ?

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**.

The physics program NA61/SHINE recently extended by open charm measurements in Pb+Pb collisions
Small Acceptance Vertex Detector commissioned in 2015 and tested by D0 meson data collected in 2016 and 2017
Precise measurements of open charm in Pb+Pb collisions planned for 2021-2024

Motivation open charm measurements

- **What is the mechanism of open charm production ?**



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

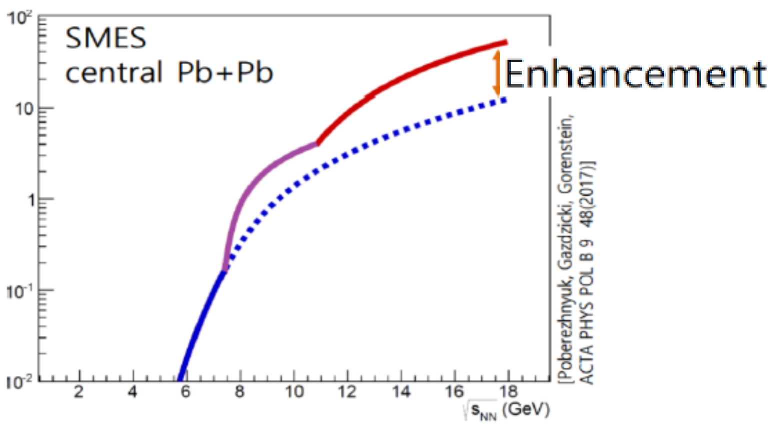
- Model predictions by a factor up to 50 for Pb+Pb collisions at top SPS energy
- Production in full phase space required to discriminate models

Hadrons containing charm considered for measurements in NA61/SHINE

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

To discriminate models the ⟨*cc*⟩ in full phase space needed measurement of open charm mesons

- **How does the onset of deconfinement impact open charm production ?**



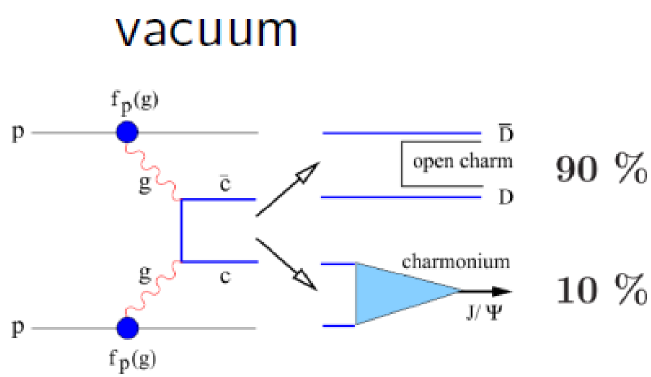
- Enhancement in $\langle c\bar{c}\rangle$ production predicted by SMES
- Different charm carriers in deconfined (c quark) and confined (D mesons) matter
- Mesurement of both J/ψ and $\langle c\bar{c}\rangle$ required to calculate probability of $\langle c\bar{c}\rangle$ to J/ψ hadronization

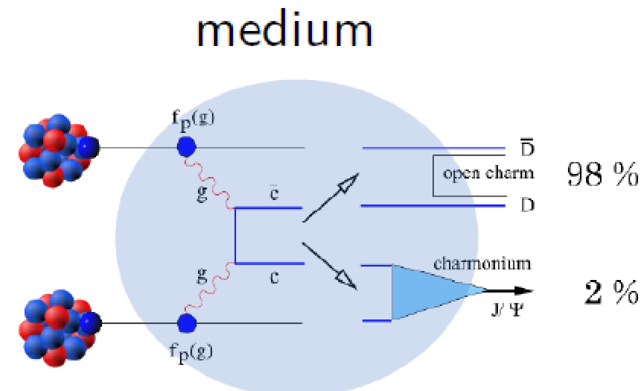
Observing an enhancement might indicate a phase transition

- **How does the formation of quark-gluon plasma impact J/ψ production ?**

J/Ψ suppression – signal deconfinement

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





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

In A+A color screening reduces fraction of $c\bar{c}$ pairs going into charmonia in respect to p+p at the same energy

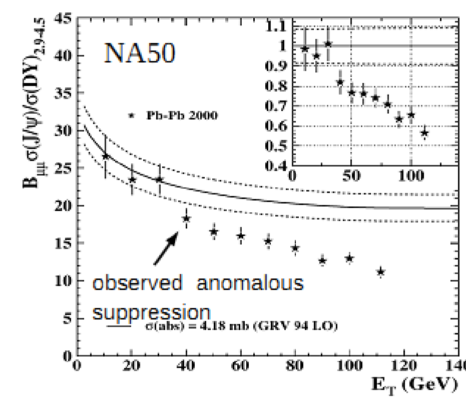
Due to shadowing, parton energy loss etc., the number of $c\bar{c}$ pairs in A+A may well be less than scaled from p+p→ initial state effects can reduce charmonium production rate in A+A relative to p+p collisions.

→ 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.

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

→ measurements of open charm in A+A needed

The Mean number of charm quark pairs, $\langle c\bar{c}\rangle$, produced in the full phase space in A+A collisions



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

SVD test performance

→ Vertex Detector project of the NA61/SHINE experiment

Small Acceptance Vertex Detector introduced to NA61/SHINE in 2016 for Open Charm measurements

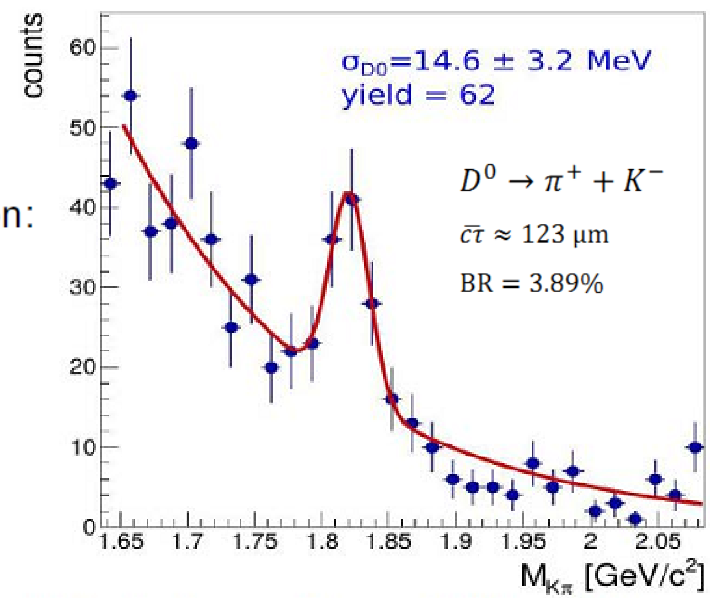
Pb+Pb 158 GeV/c (pilot) (2016), Xe+La (2017), Pb+Pb (2018)

Upgraded Large Acceptance Vertex Detector expected to be introduced in 2021

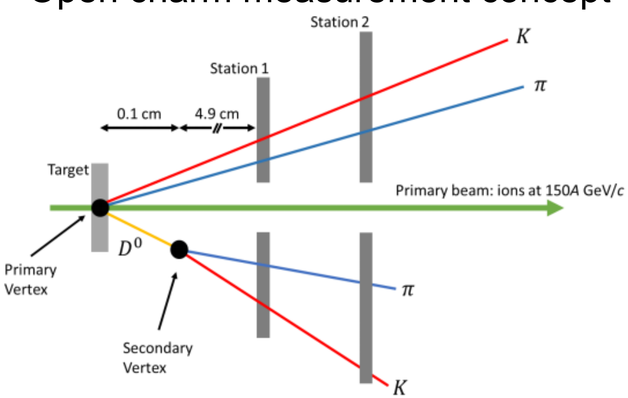
Large statistics Xe+La data taken in 2017 at 150*A* and 75*A* GeV/*c*.

Primary vertex spacial resolution: 1.3, 1.0 and 15 μm in *x, y* and *z* coordinate, respectively.

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



Open charm measurement concept



Primary Vertex resolution:

$\sigma_x(PV) \approx 5\mu m$

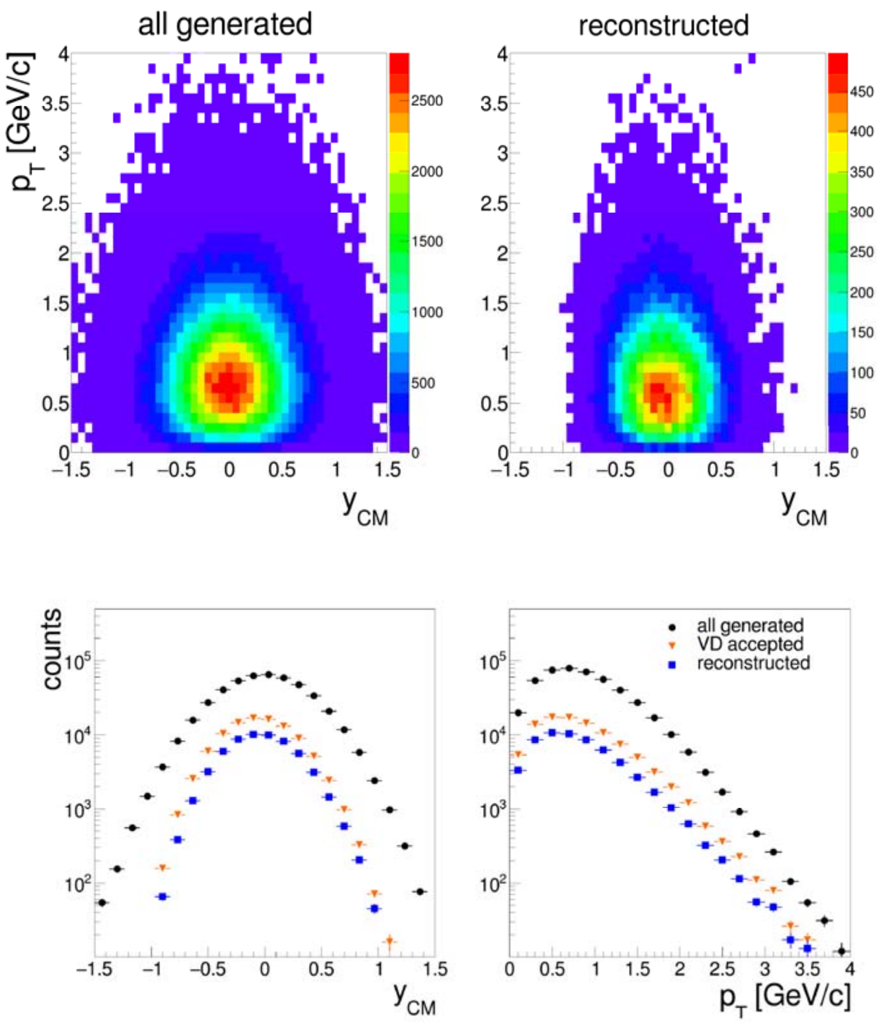
$\sigma_y(PV) \approx 1.8\mu m$

$\sigma_z(PV) \approx 30\mu m$

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

- The analysis of pilot data on Pb+Pb collisions at 150*A* Gev/c (low statistics - 140k events) proved the measurement of D^0 production by Small Acceptance Vertex Detector is possible

Anticipated results charm measurements



Main Topics:

- Charm yields versus centrality
- Charm yields as a signature of deconfinement
- Charm production mechanism (dynamical vs. statistical models)

- Precise measurements of charm hadron production by NA61/SHINE are expected to be performed in 2022-2024.
- Lorentz boost makes measurements significantly easier than in collider experiments.
- 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, D^0, D^+, D^-, (D^+_s) production versus collision energy and centrality

Expected open charm statistics

Expected number of charm mesons to be recorded
in Pb+Pb collisions at 150A GeV/c and 40A GeV/c

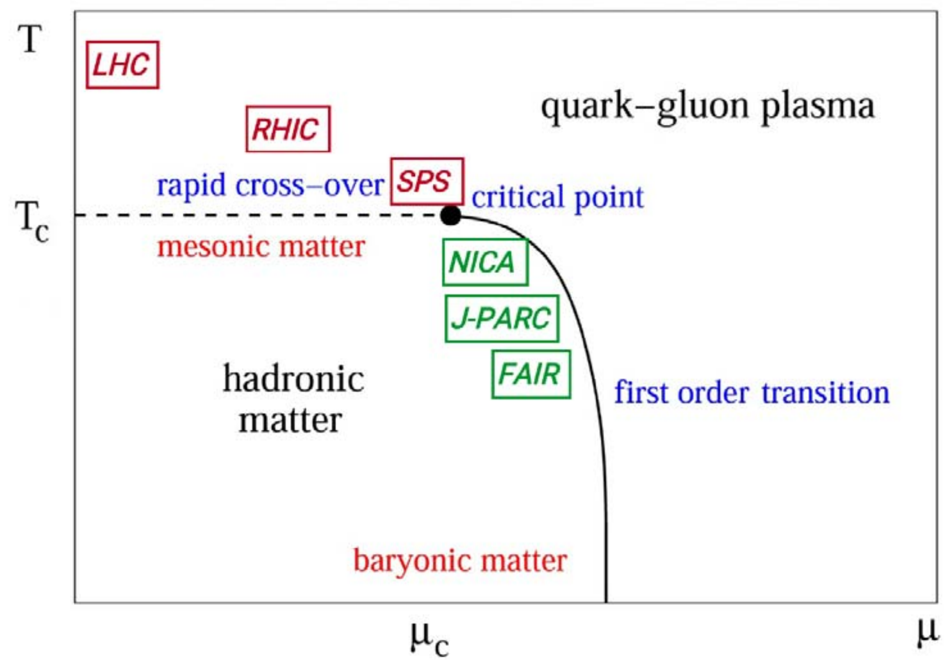
Year	Beam	#days	#events	$\#(D^0 + \overline{D^0})$	$\#(D^+ + D^-)$
2022	Pb at 150A GeV/c	42	250M	38k	23k
2023	Pb at 150A GeV/c	42	250M	38k	23k
2024	Pb at 40A GeV/c	42	250M	3.6k	2.1k

Expected number of charm mesons to be recorded in centrality
selected Pb+Pb collisions at 150AGeV/c

	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

Experimental landscape open charm program

- **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

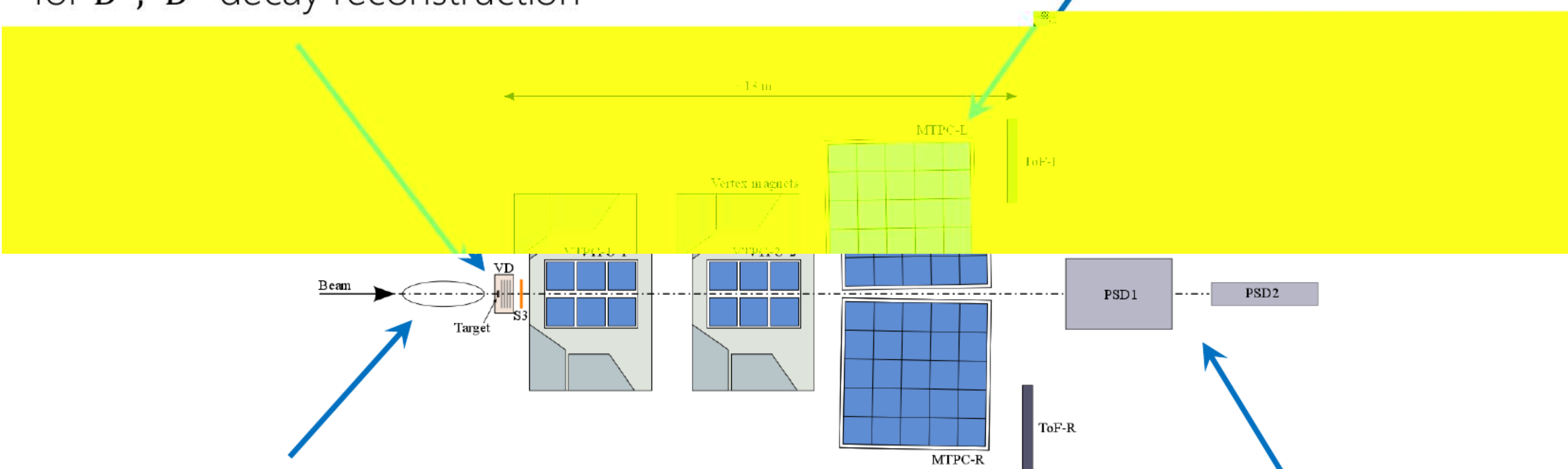


NA61/SHINE is able to measure open charm in heavy ion collisions in full phase space in the near future

Upgrade NA61/SHINE setup

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

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



New trigger and data
acquisition system

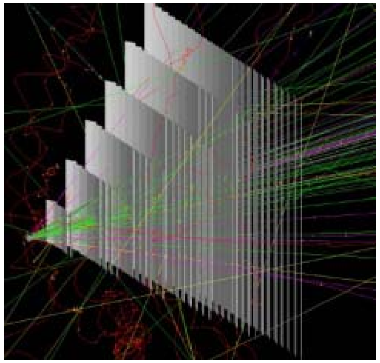
New Time-of-Flight
detectors

Upgrade of Projectile
Spectator Detector

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

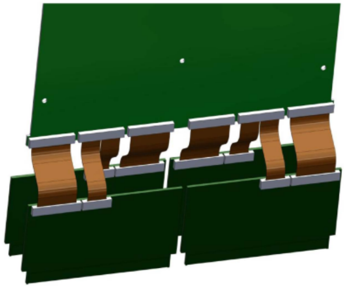
Detector upgrades

Upgrade of Vertex Detector



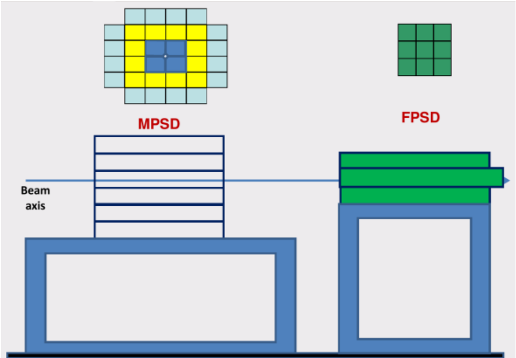
Mimosa 26AHR will be replaced
by ALPIDE developed for ALICE-ITS
16 ----> 46 sensors
Increase surface 32cm**2 (SAVD) → 180cm**2

Upgrade of TPC



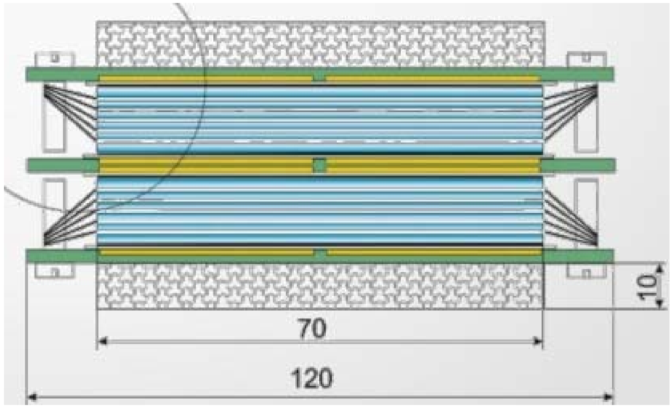
New readout used in ALICE TPC
will allow for 1kHz operation
Major challenges:
-> Development of dedicated FPC
-> Flexible connection FEC and ROU

Upgrade of PSD

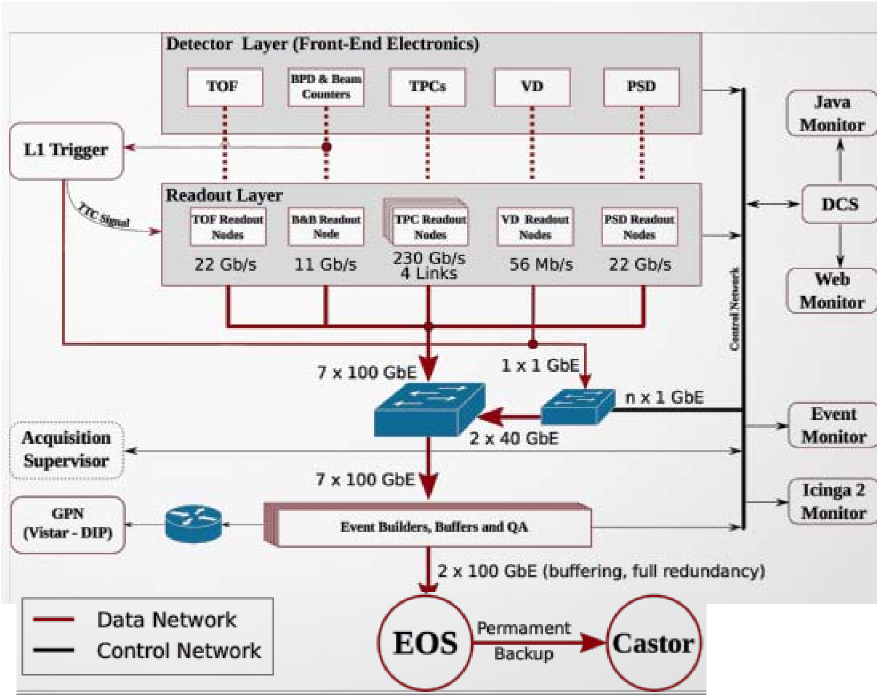


Main PSD (MPSD) - 44 modules
with beam hole in center (d=60mm)
Forward PSD (FPSD) - 9 modules
w/o hole
Reaction rates up resolution ~4 deg
Beam rates up to 5 kHz

Detector upgrades



New tof detector
Based on MRPC
gas detector
Performance expected
tof resolution ~ 60 ps



New system of 1kHz read-out-rate
Based on Ethernet both
for read-out and control

Event aggregation from
various nodes through
commercial Ethernet swiches

Future plans NA61/SHINE

- <u>Measurement plans:</u>

  - precise open charm studies in Pb+Pb collisions at 150A and 40A GeV/c with Large Acceptance Vertex Detector

  - reference measurements of nuclear fragmentation cross-section for cosmic ray experiments (DAMPE, PAMELA, CALET, GAPS) to decrease uncertainties from 20% to 0.5%

  - reference measurements of hadron production for neutrino experiments (T2K-II, Hyper-Kamionkande) to decrease systematical uncertainty for neutrino flux from 10% to 3-4%

- <u>NA61/SHINE detector upgrade:</u>

  - construction of Large Acceptance Vertex Detector for D^0, anti-D^0 decay reconstruction

  - new trigger and data acquisition system

  - replacement of the TPC readout electronics to increase data rate to 1 kHz

  - new Time-of-Flight detectors

  - upgrade of Projectile Spectator Detector

Summary and outlook (1)

- NA61/SHINE pursues unique 2D scan for systematic study of the phase diagram of strongly interacting matter to search for the critical point and study the onset of deconfinement
- Hadron production properties in heavy ion collisions found by NA49 to change rapidly in the low SPS energy domain well established as the onset of deconfinement . The NA61/SHINE results qualitatively indicate this feature could also be the case for p+p interactions and probably in Be+Be collisions
- Rapid change of particle ratios and fluctuations when moving from Be+Be and Ar+Sc can be interpreted as the creation of large clusters of strongly interacting matter- onset of fireball
- 2D scan by varying collision energy and the mass number of colliding nuclei suggests four domains of hadron production properties separated by the two thresholds – the onset of deconfinement and the onset of fireball

Summary and outlook (2)

- No clear fluctuation signal attributed to the CP so far although the ongoing intermittency analysis is expected to be feasible for at least the Ar+Sc system at 150A GeV/c as suggested by the NA49 results for the Si+Si system at 158A GeV/c
- Pilot open charm measurements and observation of D0 peak in Pb+Pb collisions at SPS energy
- Extension of NA61/SHINE program with measurements of open charm and multi-strange hyperons in 2021-2024
- Precise open charm studies in Pb+Pb collisions at 40A and 150A GeV/c with Large Acceptance Vertex Detector
- Reference measurements of nuclear fragmentation cross section for cosmic rays experiments Dampe, Pamela, Calet, Gaps
- Reference measurements of hadron production for neutrino experiments T2K II, Hyper-Kamionkande