Hunting for criticalities
NA61/SHINE results

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for the NA61/SHINE Collaboration

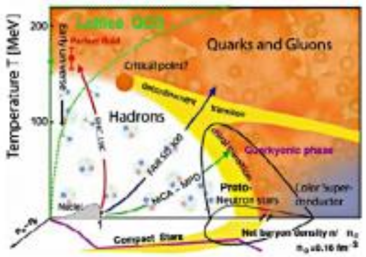
Sixth Biennial
"Workshop on Discovery Physics at the LHC"
Kruger 2022

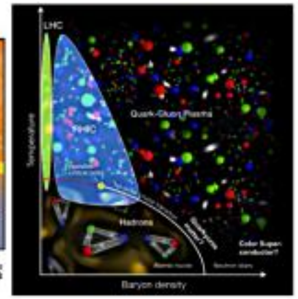
Uniwersytet Wrocławski

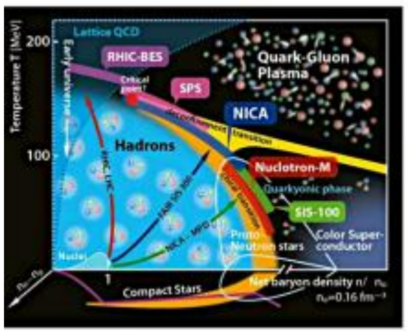
1. Introduction
   - Criticalities in Hadronic Matter
   - Signatures of Criticalities in HIC
   - NA61/SHINE experiment

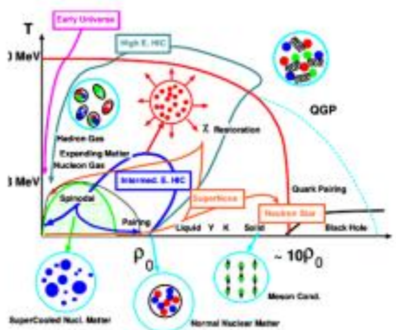
2. Predictions and Results
   - Phase Transition Effects
   - Deconfinement Effects
   - Onset of the QGP

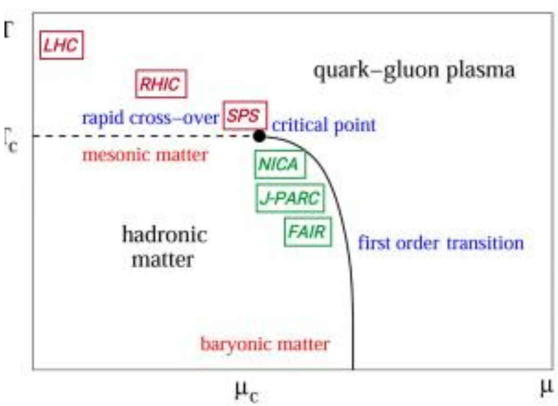
Hadronic Matter - Phase Diagrams

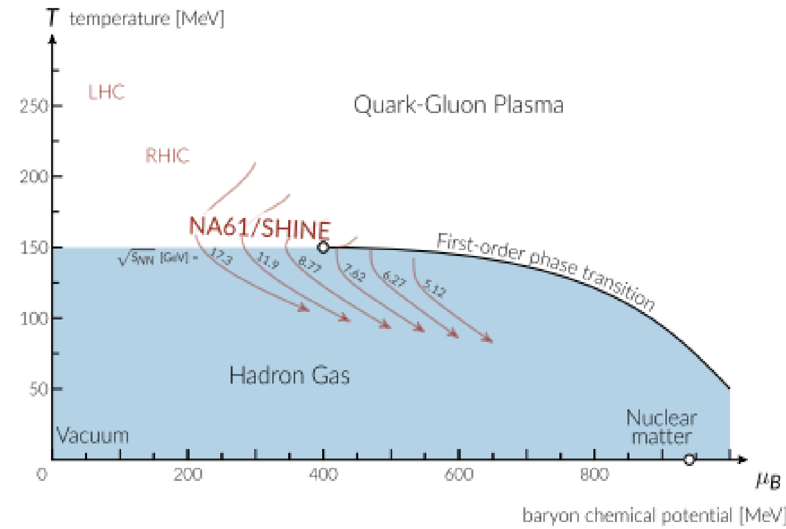






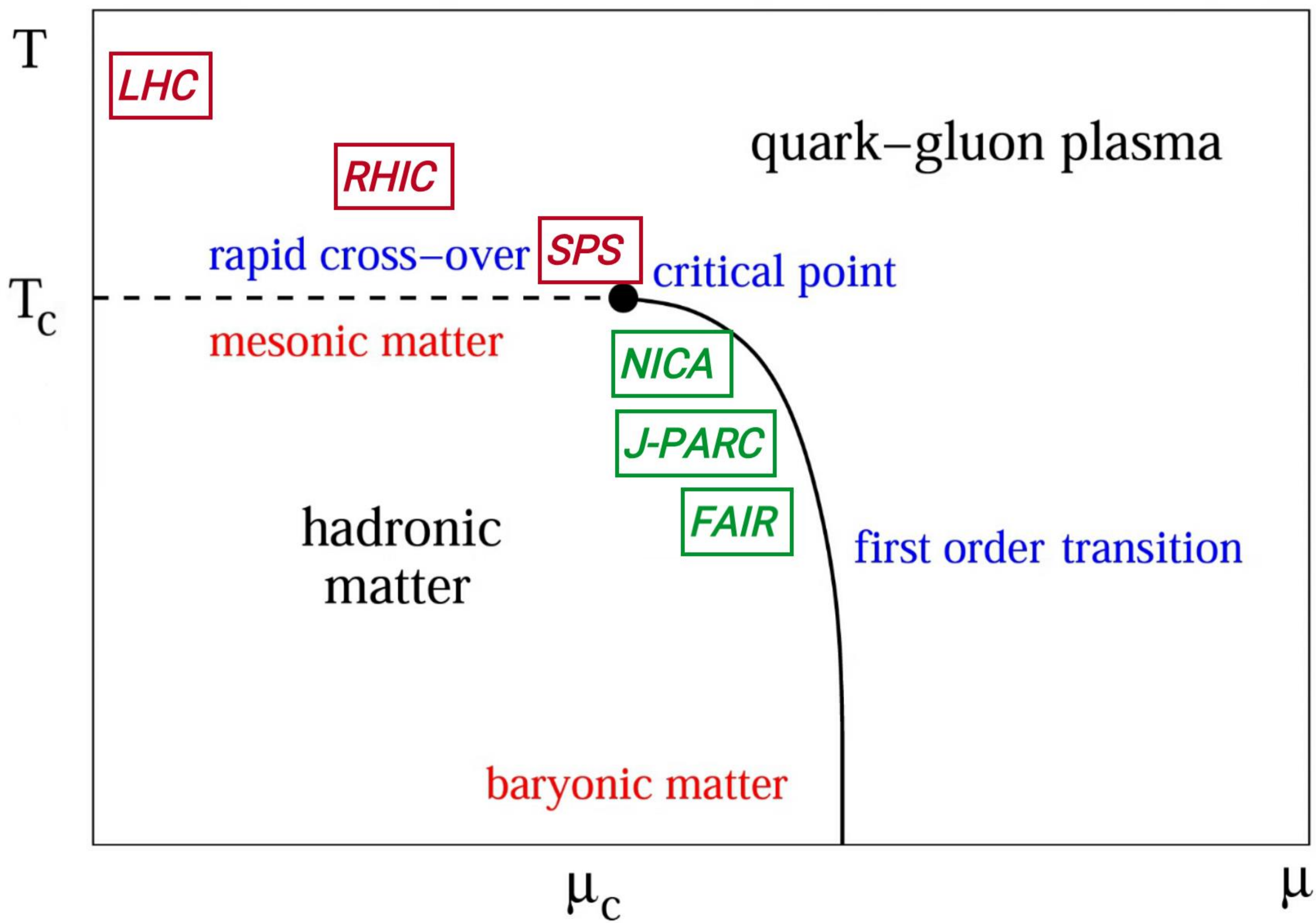




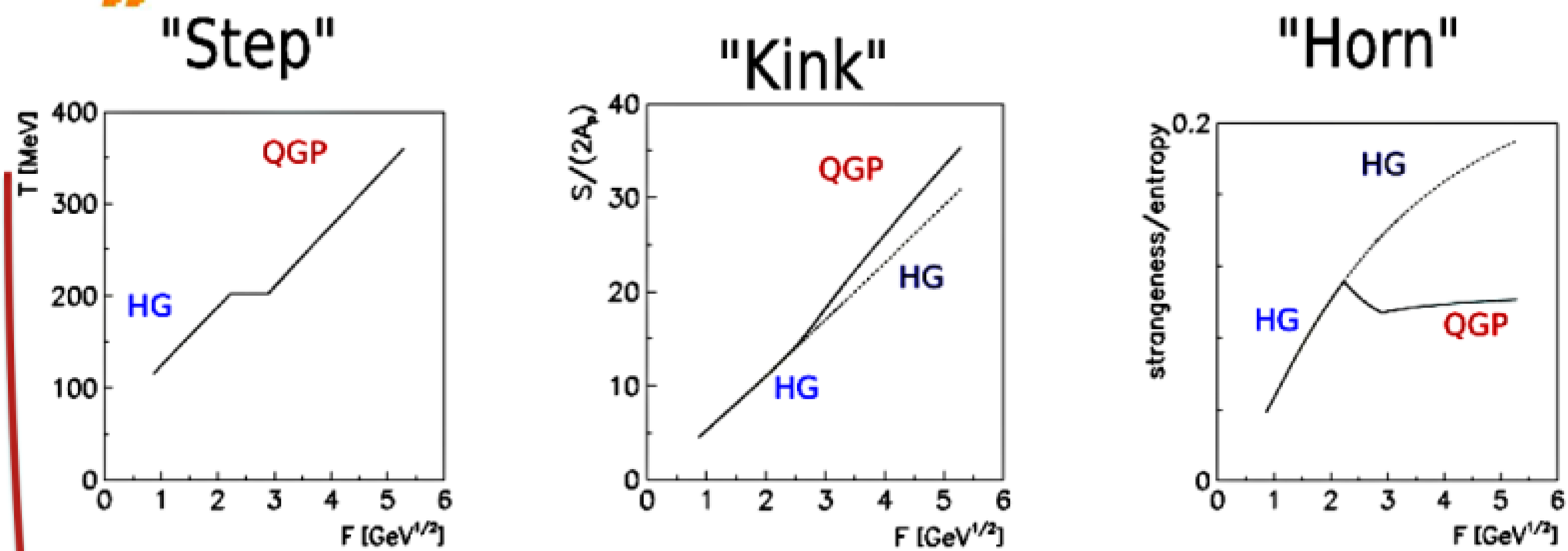


T-temperature and μ_B-baryon chemical potential

are fitted to the chosen thermal model


T
LHC
quark–gluon plasma
RHIC
rapid cross–over
SPS
critical point
T_c
mesonic matter
NICA
J-PARC
FAIR
first order transition
hadronic
matter
baryonic matter
μ_c
μ

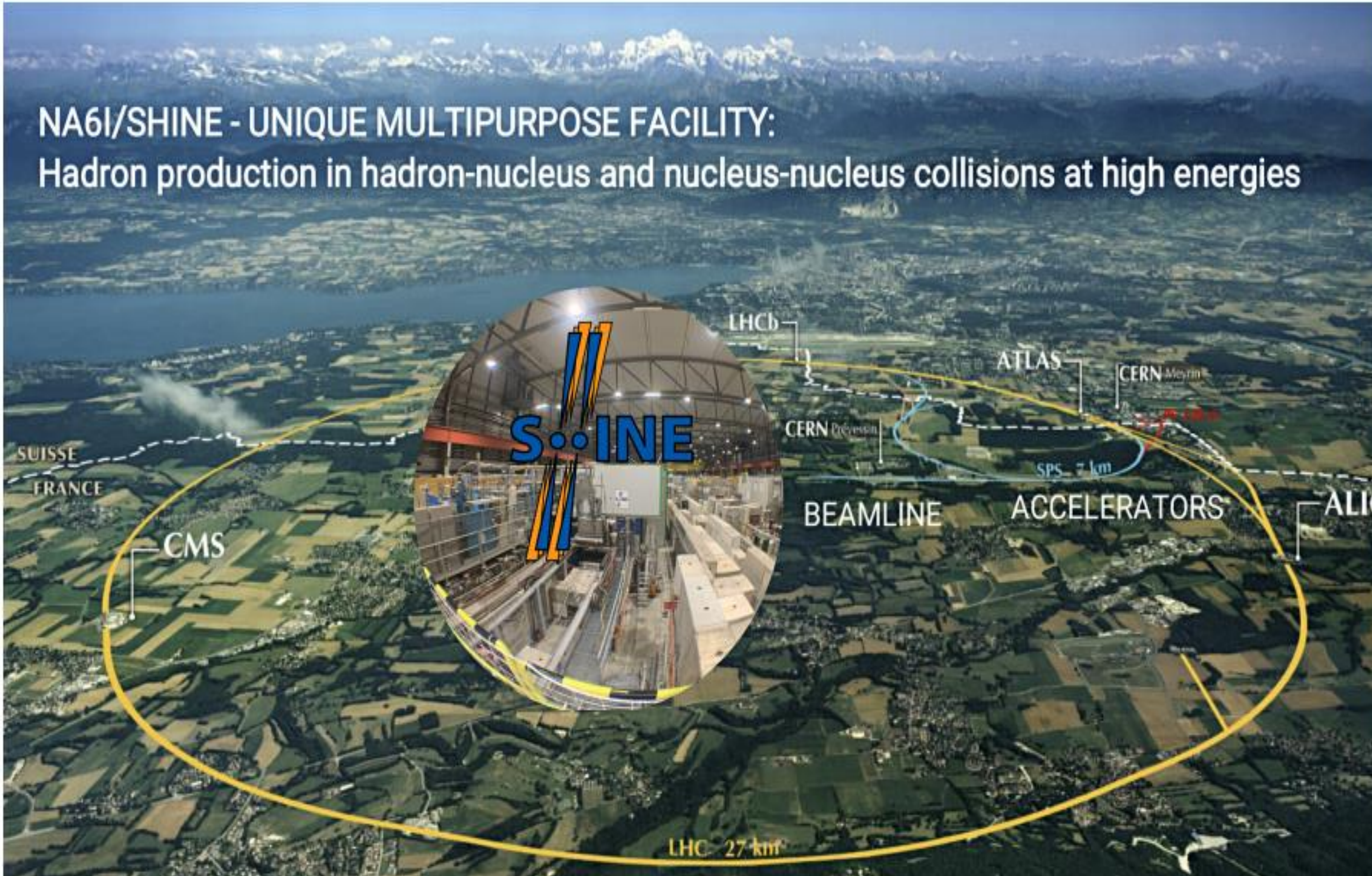
Theoretical predictions of signatures for phase transition at SPS and its volume dependence



$F \approx \sqrt[4]{s_{NN}}$ Gazdzicki, Gorenstein, Acta Phys. Polon. B30, 2705 (1999)

T means here not the temperature, but the inverse slope parameter T in rapidity spectra of produced $K^{\pm}$

$$\frac{d^2 n}{dy\, dm_T} = A\, m_T \exp - \frac{m_T}{T};\ m_T = \sqrt{p_T{}^2 + m_T^2}$$


NA6I/SHINE - UNIQUE MULTIPURPOSE FACILITY:
Hadron production in hadron-nucleus and nucleus-nucleus collisions at high energies
LHCb
ATLAS
CERN
CERN
SUISSE
FRANCE
SPS 7 km
BEAMLINE
ACCELERATORS
CMS
LHC 27 km

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NA61/SHINE – about

❖Located at the CERN SPS

❖Successor of NA49

❖Large acceptance spectrometer for fixed target experiment on primary (ions) and secondary (ions, hadrons) beams

❖Data taking since 2009

❖NA61/SHINE is the second largest non-LHC experiment at CERN

Physics program

Strong interactions program

•search for the critical point of strongly interacting matter
•study of the properties of the onset of deconfinement
•study high p T particles production (energy dependence of nuclear modification factor)

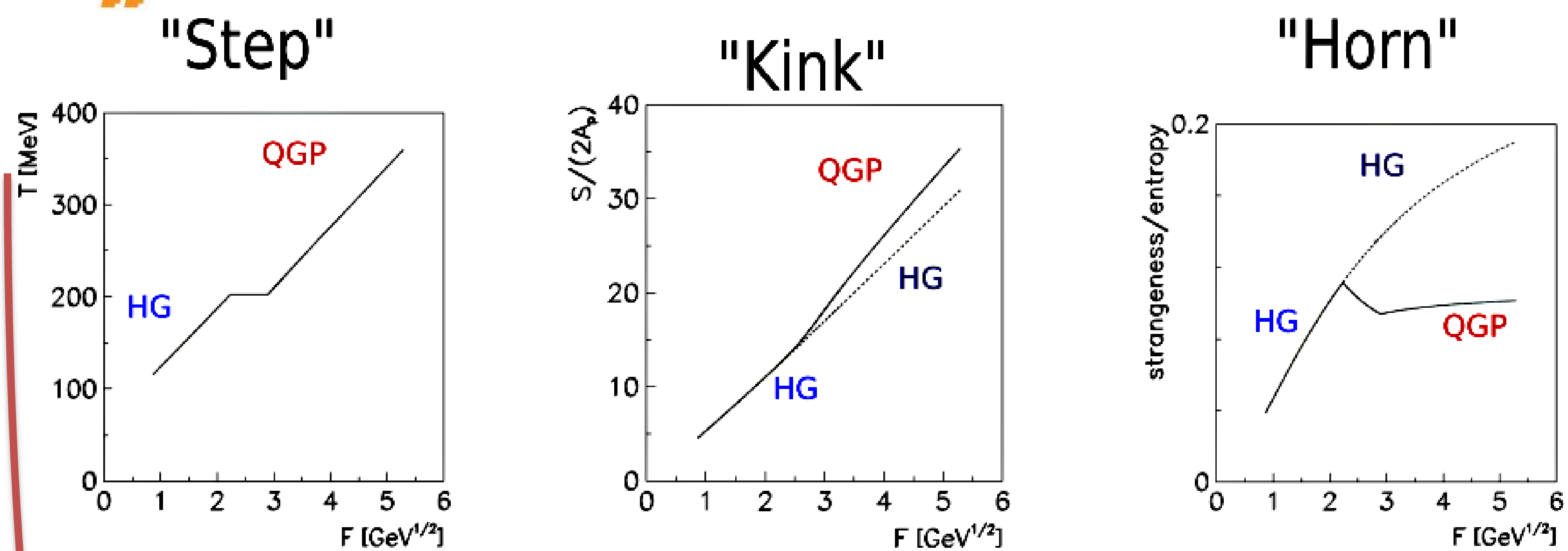
Hadron-production measurements for neutrino experiments

•reference measurements of p+C interactions for the T2K experiment for computing initial neutrino fluxes at J-PARC

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 and KASCADE experiments) for improving air shower simulations

Theoretical predictions of signatures for phase transition at SPS and its volume dependence



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HIC programs @ SPS energy range

- RHIC Beam Energy Scan (BNL, Brookhaven),
- NICA (JINR, Dubna),
- SIS-100/300 (FAIR GSI, Darmstadt)
- NA61/SHINE (CERN)

HIC programs to perform a two-dimensional scan in beam momentum and mass number of colliding nuclei

- NA61/SHINE (CERN)

NA61/SHINE is a fixed target experiment
the acceptance of NA61 starts from P_T = 0 MeV/c

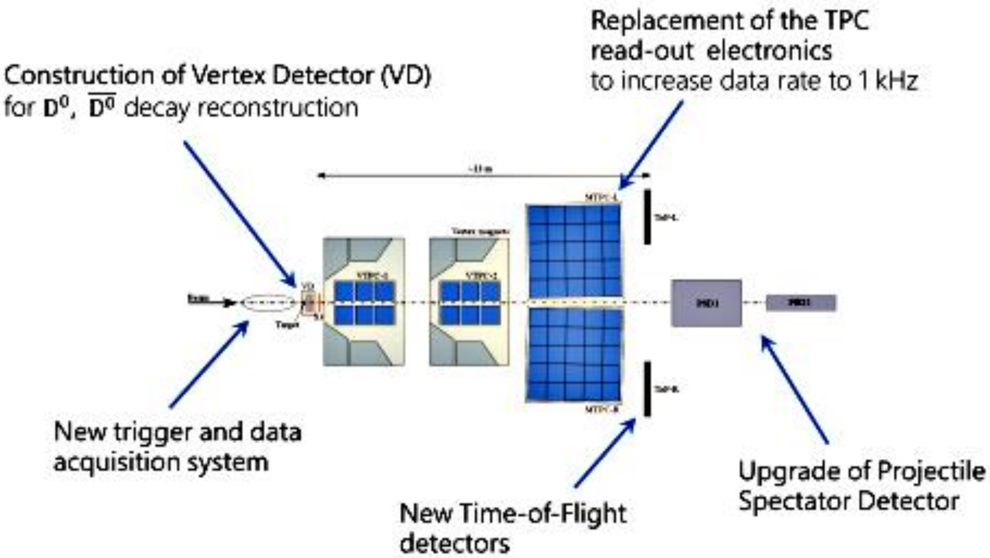
This gives

- *better analysis of spectra*
- *better analysis of fluctuations due to the CP (critical point), which show up mainly in low p_T particles*

Detector upgrades

Requied:

I. Construction of a new Large Acceptance Vertex Detector.
II. Replacement of the TPC read-out electronics.
III. Construction of a new trigger and data acquisition system.
IV. Upgrade of the Projectile Spectator Detector.



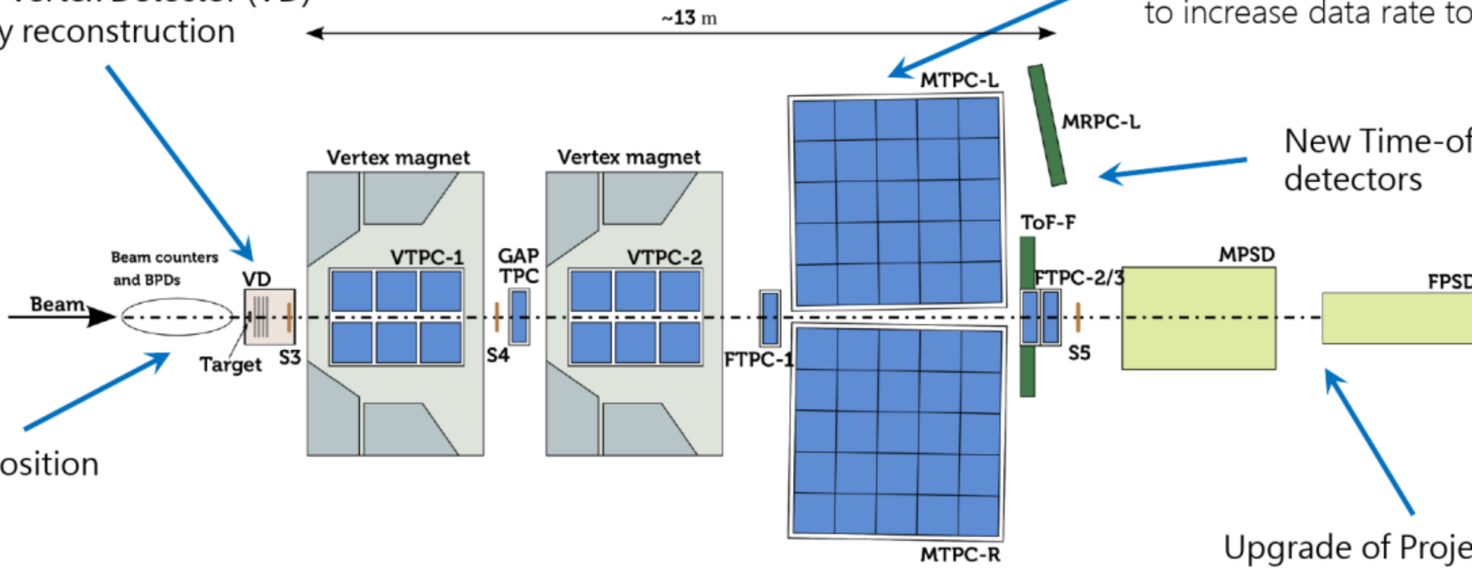
Desirable:

The construction of new Time-of-Flight detectors

NA61/SHINE Facility Upgraded

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 Time-of-Flight detectors

New Beam Position Detector

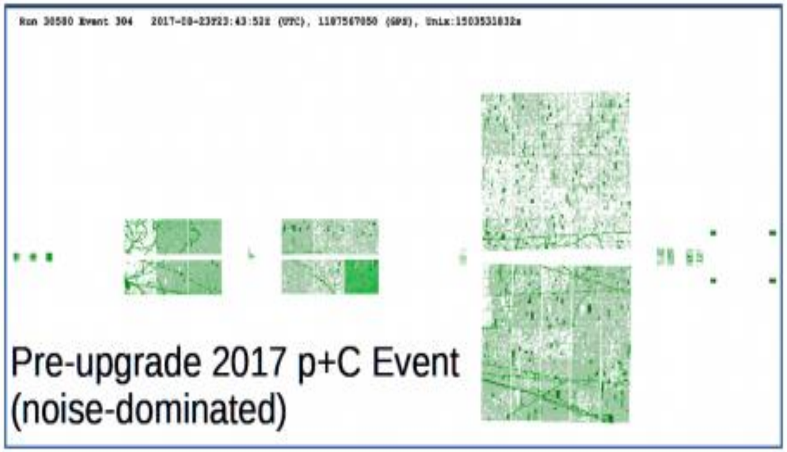
Upgrade of Projectile Spectator Detector

New trigger and data acquisition system

Upgrading - effects

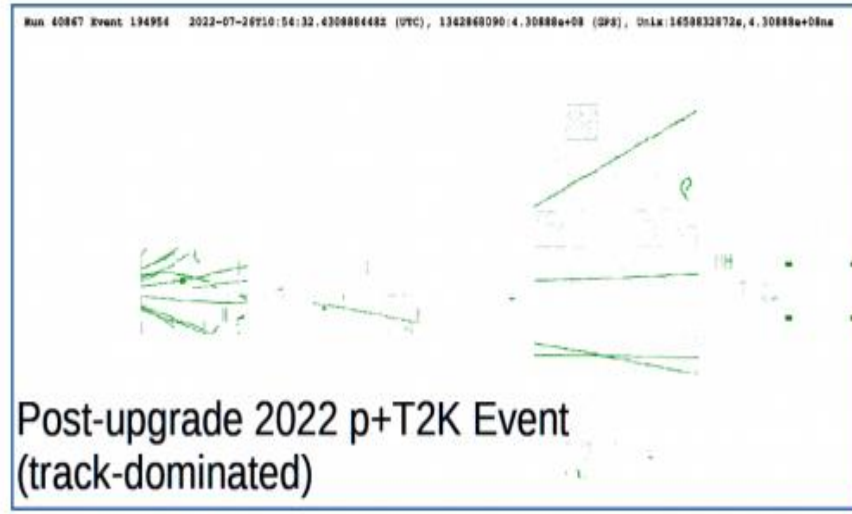
- Very substantial noise visible

Upgrading - effects



Pre-upgrade 2017 p+C Event
(noise-dominated)

- Very substantial noise visible



Post-upgrade 2022 p+T2K Event
(track-dominated)

Significant increase in the TPC raw data quality - new electronics

- First physics running after detector upgrade with a replica of target used to generate neutrinos in the beamline at J-PARC for T2K

Beams and targets

Possible beams

Hadrons

I. Primary protons at 400 GeV/c
II. Secondary (π,K,p) at 13-350 GeV/c

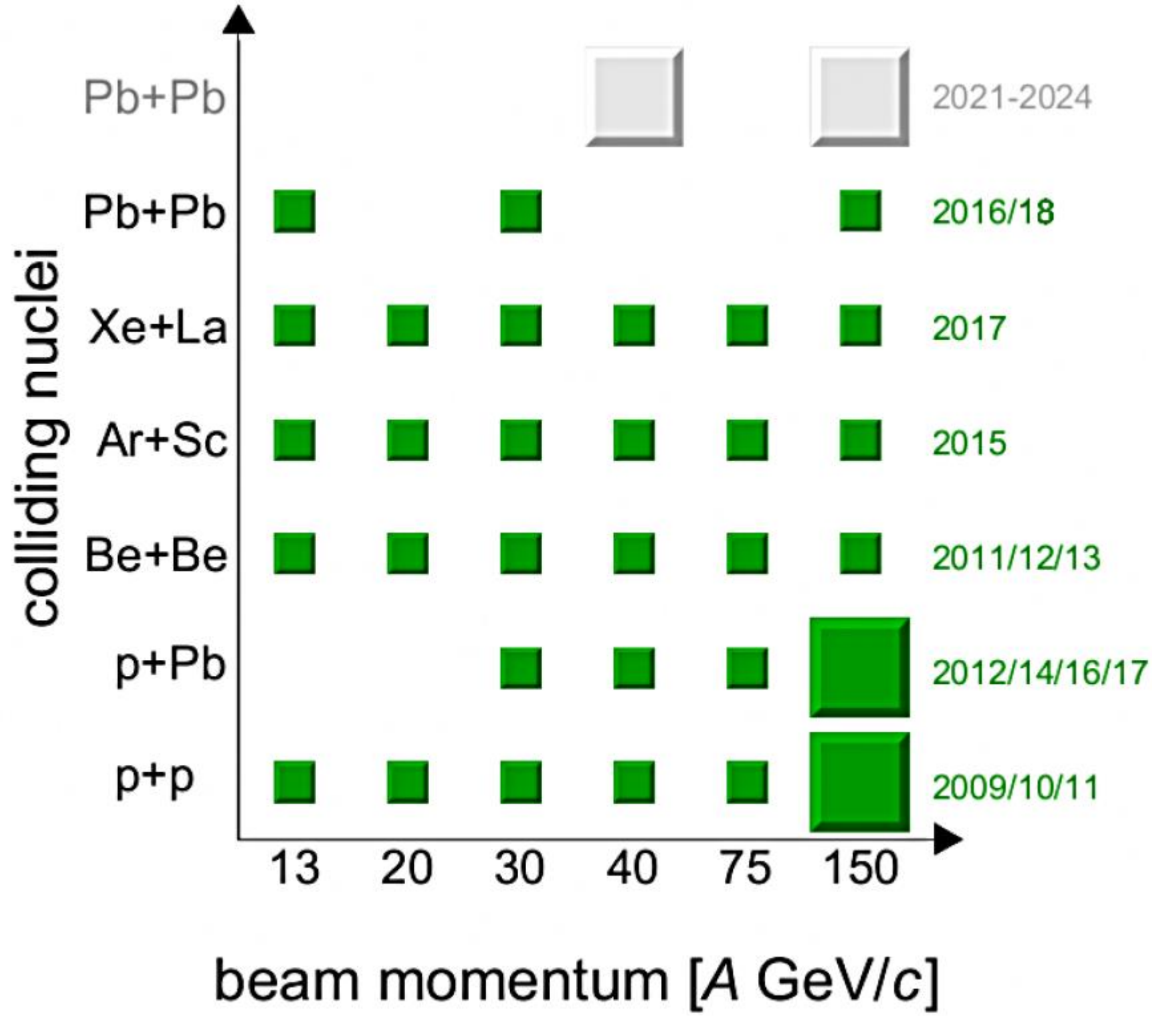
Ions

I. Primary: Ar, Xe, Pb at 13A-150A GeV/c
II. Secondary from Pb fragmentation (e.g. Be) a 13A-150A GeV/c

Targets

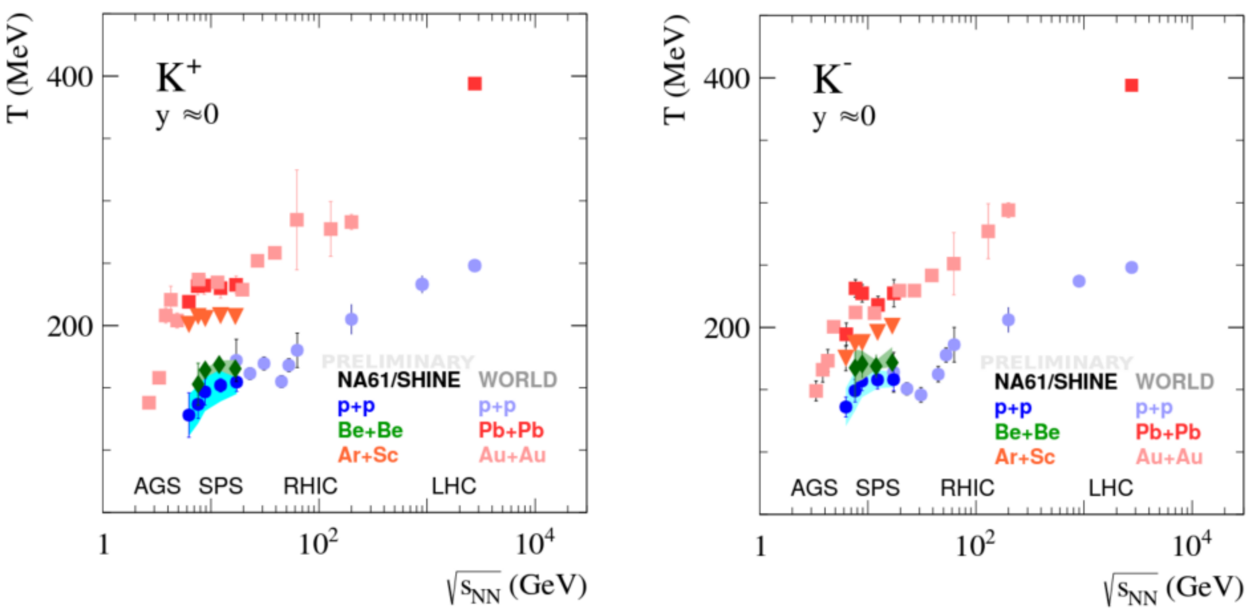
I. Almost any solid state (from 500 μm to 1 m)
II. Liquid hydrigen (20cm)

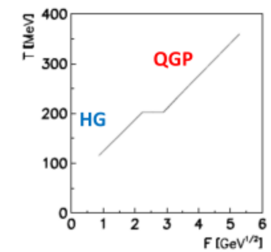
Data taking – strong interaction program



Evidence for phase transition at SPS and its volume dependence - *the Step*

Onset of deconfinement: step



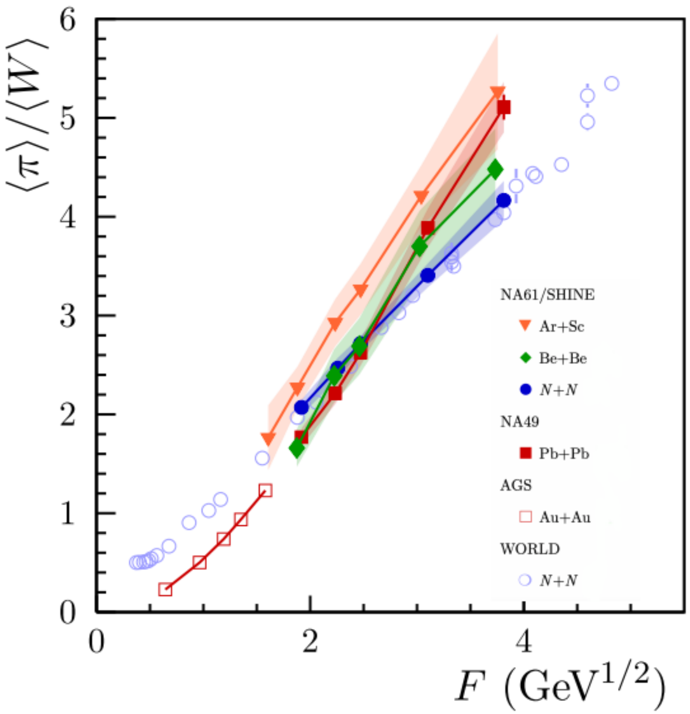


- Qualitatively similar energy dependence is seen in p+p, Be+Be, Ar+Sc and Pb+Pb.
- Magnitude of T increases with the system size.

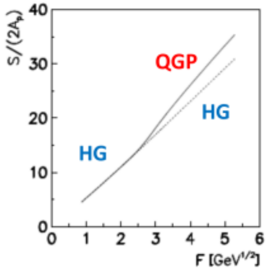
- NA61/SHINE, EPJC 81, 1, 73, 2021 and Ar+Sc preliminary results
- Sensitive to both the temperature and the radial flow.
- Kaons are only weakly affected by re-scattering and resonance decays during the post-hydro phase (at SPS and RHIC energies).
- Connected with the temperature of the freeze-out surface and not the early-stage fireball.

Evidence for phase transition at SPS and its volume dependence – the *Kink*

Onset of deconfinement: kink



W – wounded nucleons, $F = \left[\frac{(\sqrt{s_{NN}} - 2m_N)^3}{\sqrt{s_{NN}}}\right]^{1/4}$.

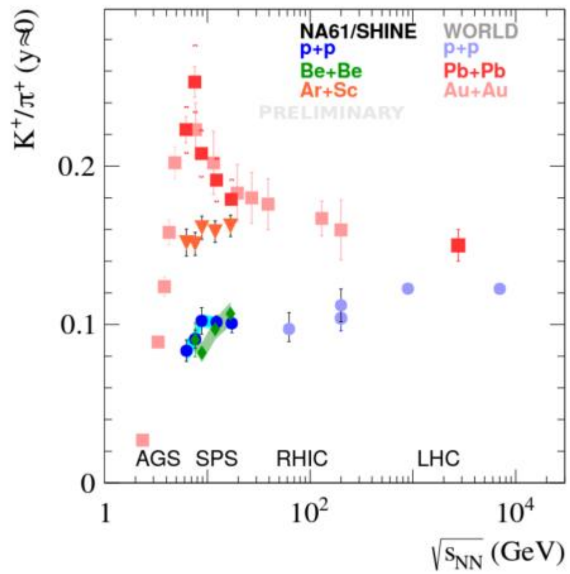


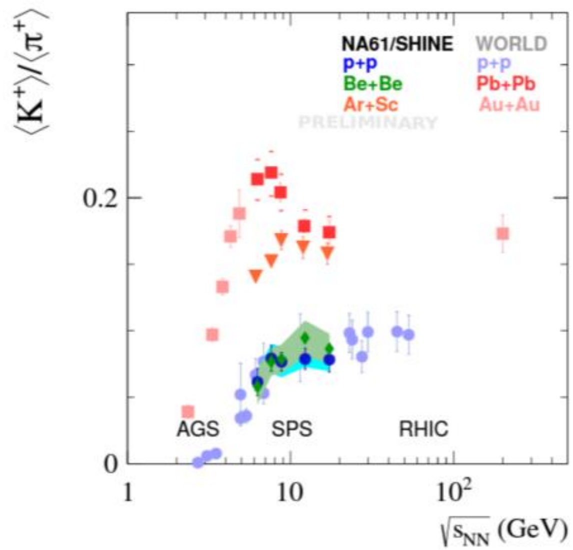
- N+N interactions agree well with the world data.
- Be+Be collisions are mostly between measurements from N+N and Pb+Pb collisions.
- Ar+Sc collisions seem to be systematically higher than the results for N+N, Be+Be and Pb+Pb collisions at the lower energies.
- Ar+Sc close to the Pb+Pb results at the highest energies.

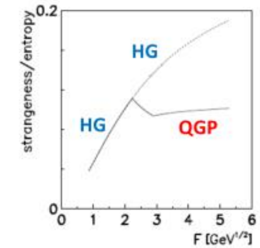
NA61/SHINE, EPJC 81, 5, 397, 2021

Evidence for phase transition at SPS and its volume dependence – the *Horn*

Onset of deconfinement: horn



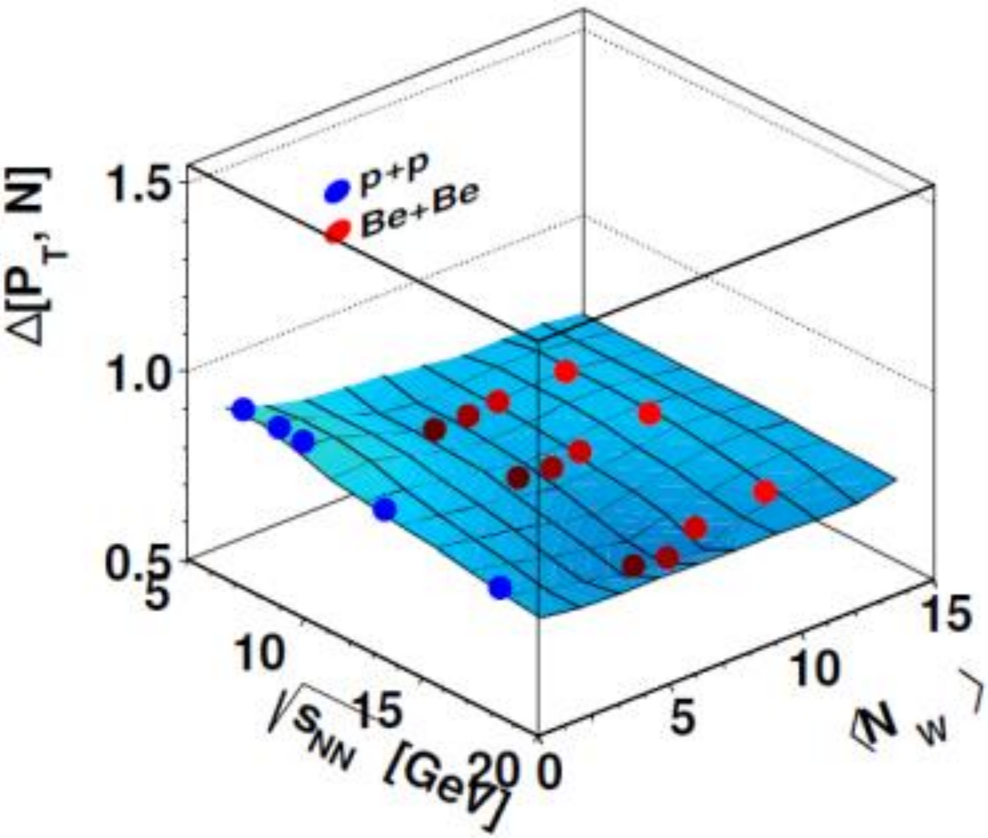




- Be+Be close to p+p in K^+/π^+.
- No horn-like structure in Ar+Sc.

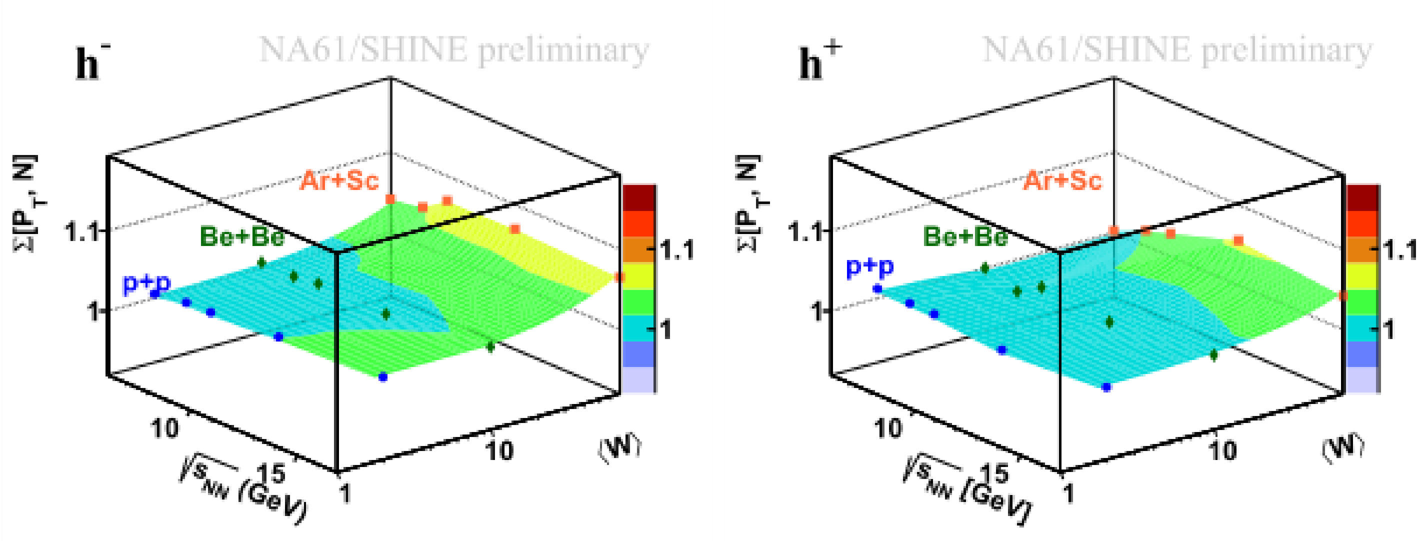
- NA61/SHINE, EPJC 81, 1, 73, 2021 and Ar+Sc preliminary results
- p+p $\approx$ Be+Be $\neq$ Ar+Sc $\ll$ Pb+Pb
- Good measure of the strangeness to entropy ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons) $\rightarrow$ probe of the onset of deconfinement

Transverse momentum fluctuations



- Search for the critical point of strongly interacting matter
- No sign of any anomaly that can be attributed to the critical point (neither in p+p nor Be+Be)

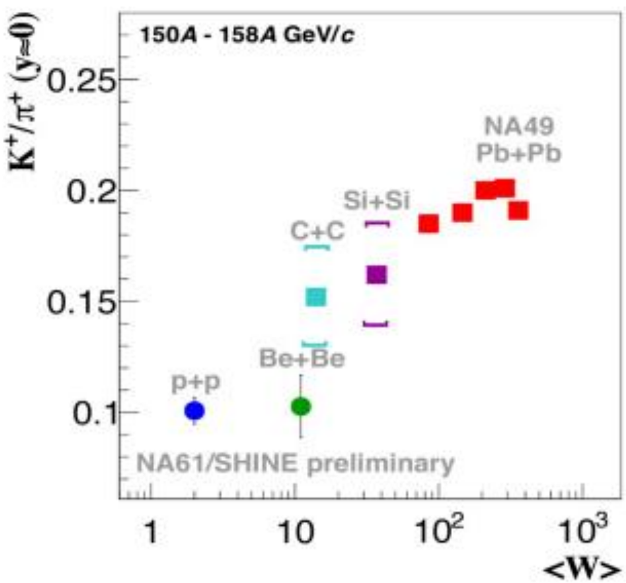
Evidence for phase transition at SPS and its volume dependence - *Transverse momentum fluctuations*



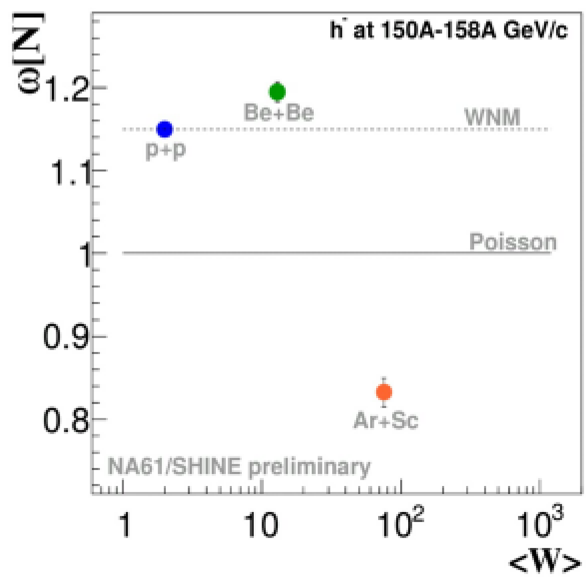
No signs of critical behaviour

Rapid changes in system size dependence

1. Be+Be results are very close to p+p at different collision energies.
2. It seems as cluster (fireball) size rapidly increases – jumps above Be+Be size collisions.



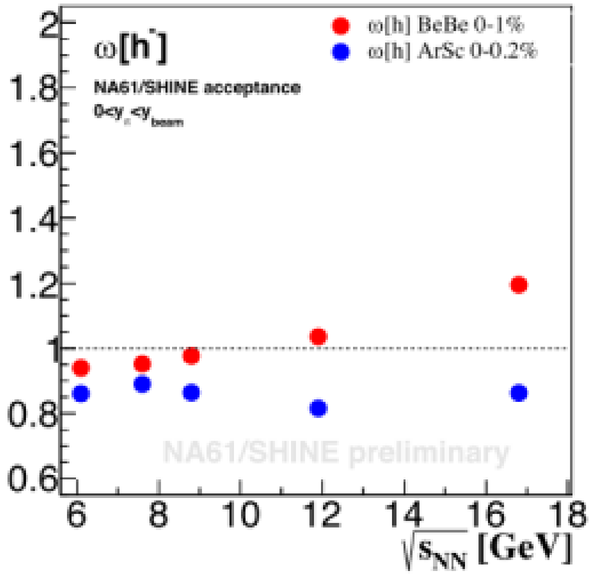
Mean multiplicities ratio

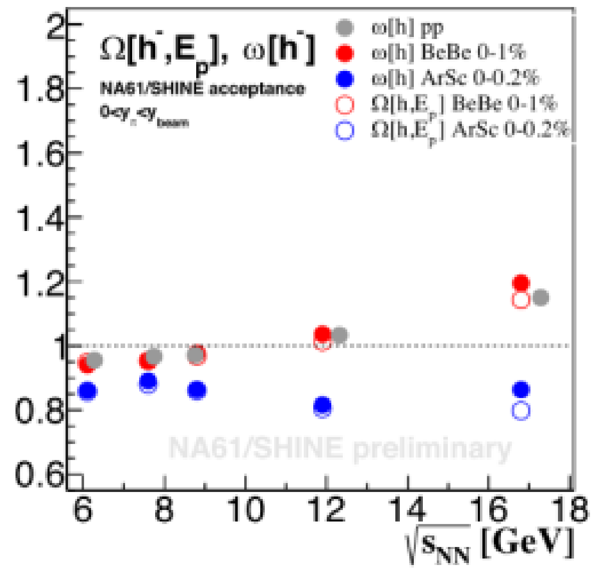


Scaled multiplicity fluctuations

versus mean number of wounded nucleons <W>

Rapid changes in system size dependence



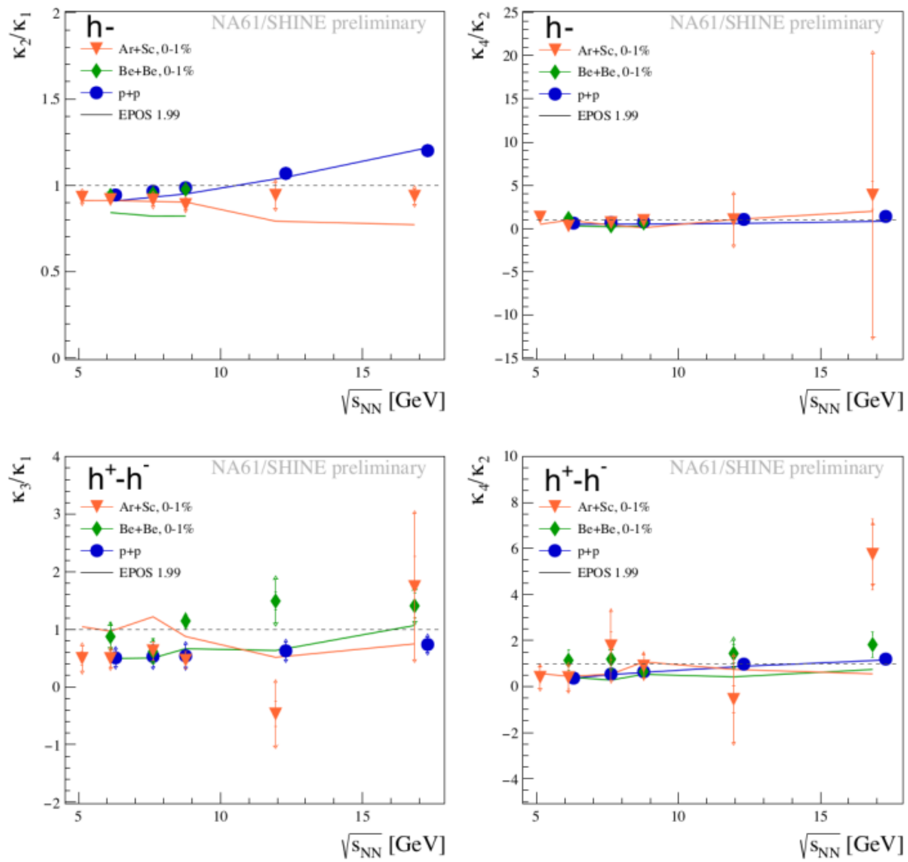


Scaled multiplicity and energy fluctuations of negatively charged hadrons undergo rapid changes between BeBe and ArSc sizes

With the increasing size of colliding systems light clusters are produced more and more copiously, as at some densitythey start to overlap – to reach ***percolation*** threshold.

Effect does not depend on energy – only on the size of the system.

Multiplicity and net-charge fluctuations in p+p, Be+Be and Ar+Sc collisions

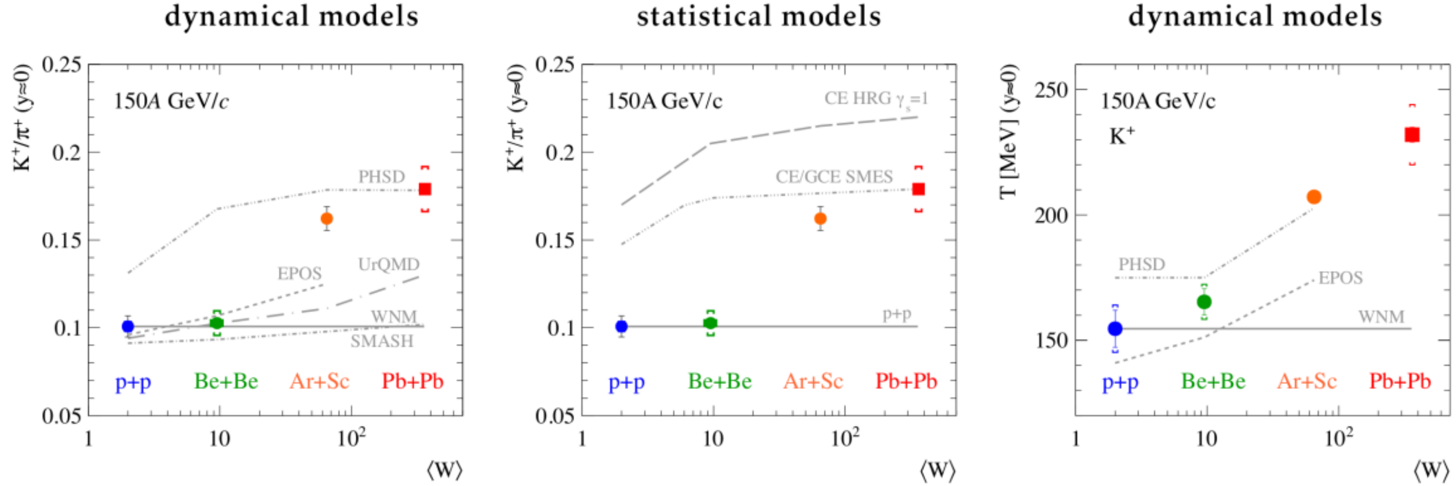


$\kappa_1 = \langle N \rangle$
$\kappa_2 = \langle (\delta N)^2 \rangle = \sigma^2$
$\kappa_3 = \langle (\delta N)^3 \rangle = S\sigma^3$
$\kappa_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 = K\sigma^4$
where:
N – multiplicity; $\delta N = N - \langle N \rangle$; σ – standard deviation; S – skewness; K – kurtosis.

- In case of h-, only the scaled variance show significant differences between heavier and lighter systems.
- In case of net-electric charge, the scaled skewness and scaled kurtosis indicate non-monotonic behaviour.
- Currently, analysis is focused on reducing the considerable systematic uncertainties.

Models versus data or data versus models

K^+/π^+ and T vs the system size at 150(8)A GeV/c

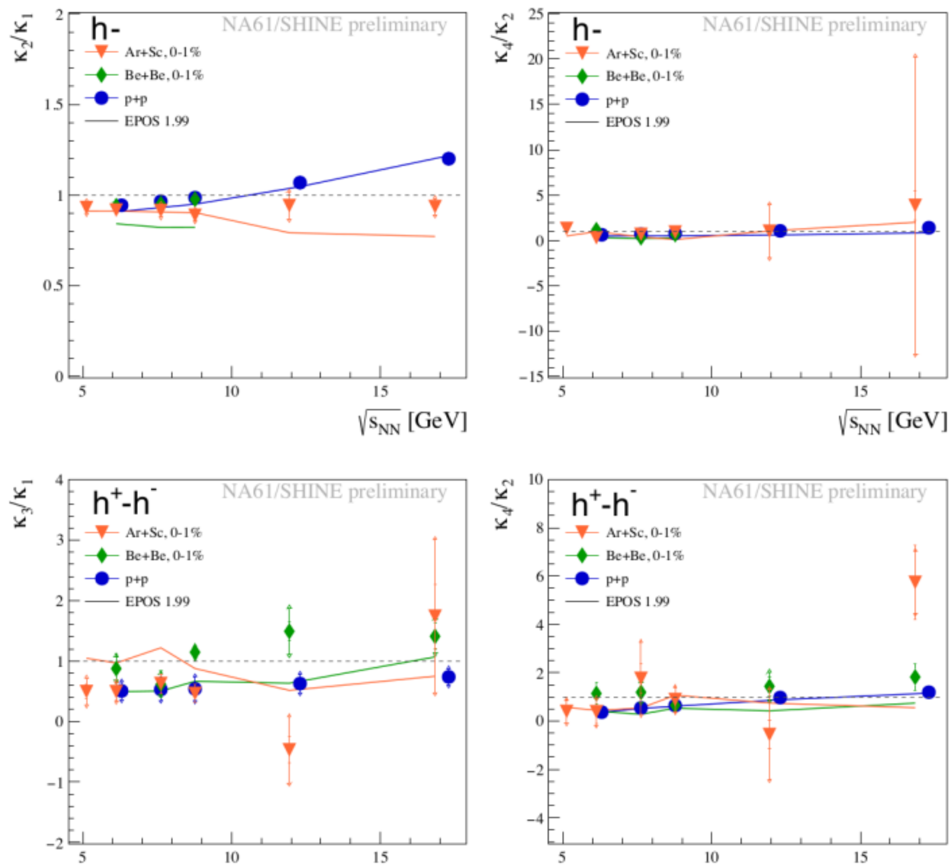


- **Onset of fireball** – rapid change of observables when going from small (p+p, Be+Be) to intermediate (Ar+Sc) and large ones (Pb+Pb) $\rightarrow$ beginning of the creation of large clusters of strongly interacting matter?
- None of the models reproduce K^+/π^+ ratio nor T for whole $\langle W \rangle$ range.

PHSD: EPJA 56, 9, 223, 2020, arXiv:1908.00451 and private communication;
SMASH: JPG 47, 6, 065101, 2020 and private communication;
UrQMD and HRG: PRC 99, 3, 034909, 2019;
SMES: APPB 46, 10, 1991, 2015

p+p: NA61/SHINE, EPJC 77, 10, 671, 2017;
Be+Be: NA61/SHINE, EPJC 81, 1, 73, 2021;
Ar+Sc: NA61/SHINE preliminary;
Pb+Pb: NA61/SHINE, PRC 66, 054902, 2002.

Multiplicity and net-charge fluctuations in p+p, Be+Be and Ar+Sc collisions



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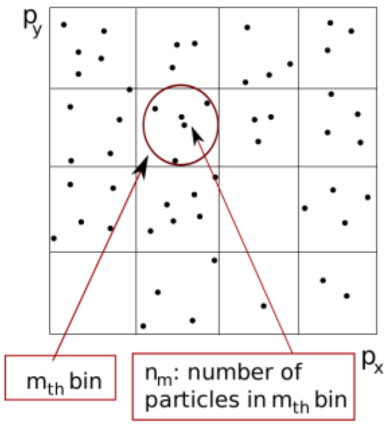
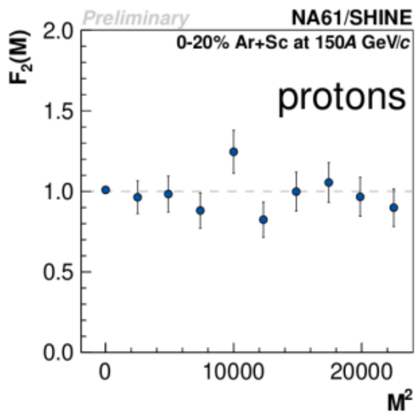
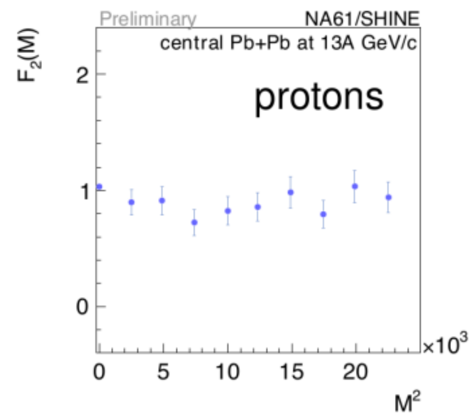
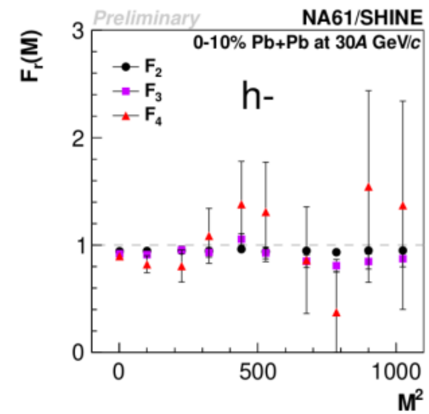
Proton and charged hadron intermittency in Ar+Sc and Pb+Pb collisions









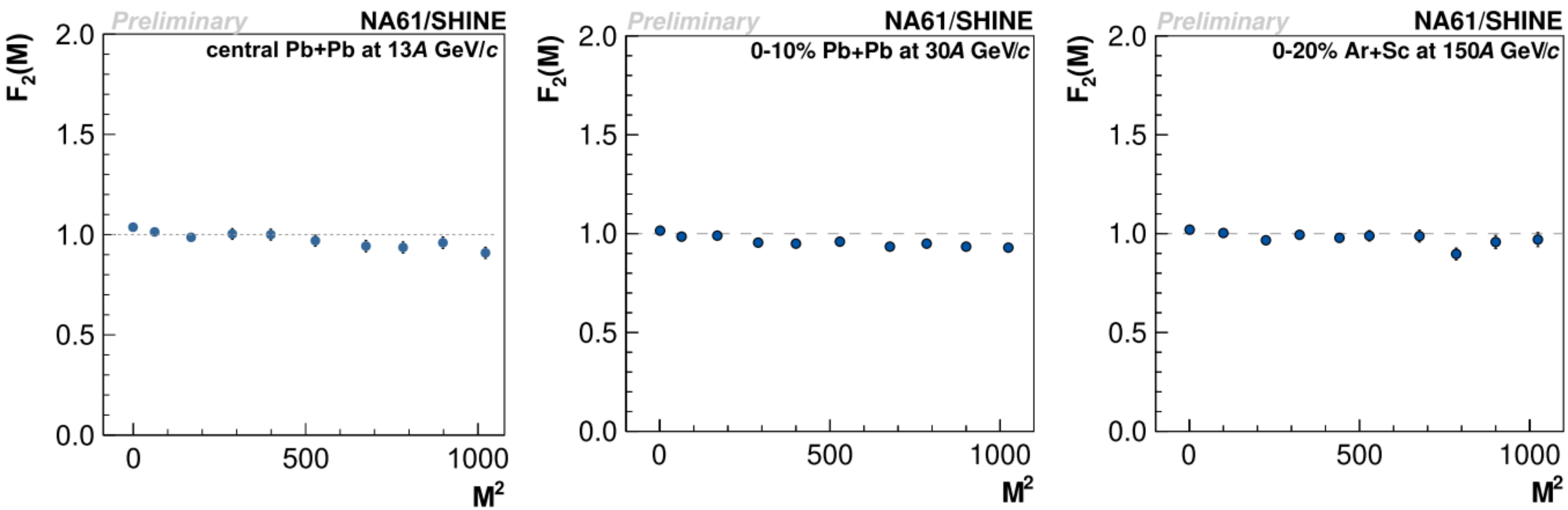
$$F_r(M) = \frac{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m(n_m-1)\dots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m \right\rangle^r},$$

where $\langle \dots \rangle$ denotes averaging over events, M is the number of cells.

- Statistically independent points, cumulative variables.
- If the system freezes-out in the vicinity of the critical point, $F_2(M)$ should reveal a power-law dependence $\rightarrow$ not observed in these analyses.
- Work on more advanced methodology ongoing.

Proton intermittency analysis result

(Experimental result on fluctuations as a function of momentum bin size)



CPOD 2021: https://indico.cern.ch/event/985460

ICNFP 2021: https://indico.cern.ch/event/1025480/

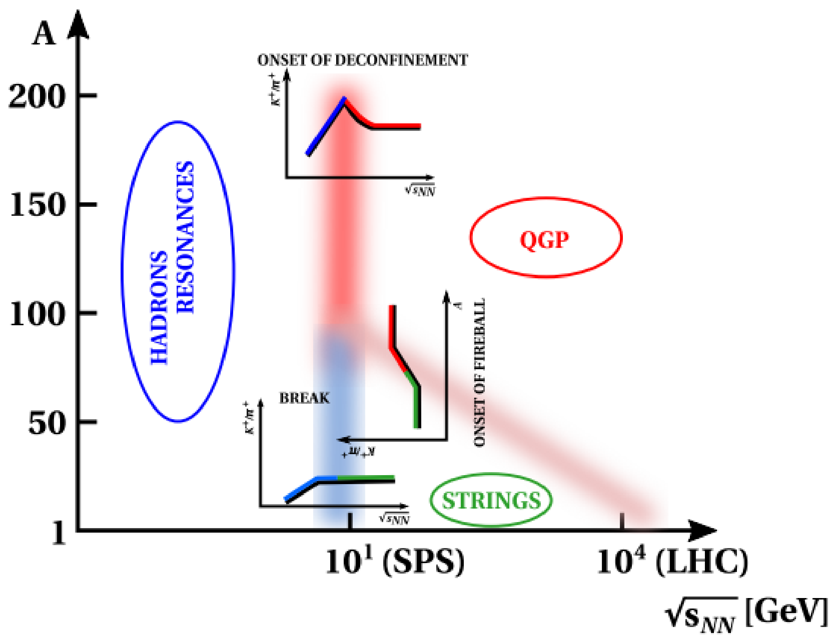
ISNP ERICE 2021: http://crunch.ikp.physik.tu-darmstadt.de/erice/2021

Quark Matter 2022 https://indico.cern.ch/event/895086/contributions/4555252/

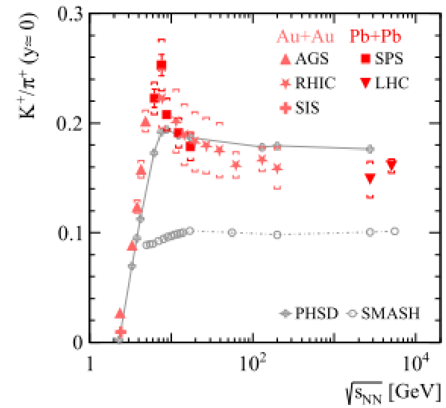
No indication for power-law increase with bin size

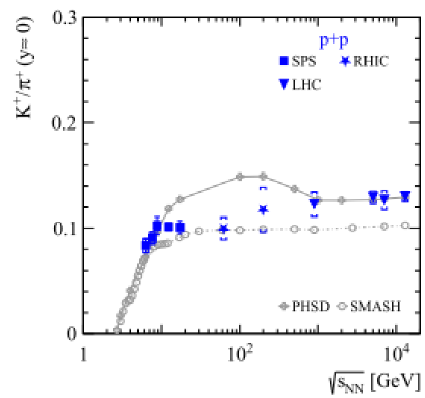
- 2D scan in system size and collision energy was completed in 2017 with Xe+La.
- NA61/SHINE delivers reach information related to the onset of deconfinement in the light and medium-size system.
- The onset of fireball - unexpected system size dependence.
- So far no convincing indication of the critical point.
- Detector upgrade almost done, open charm measurements starting this year.

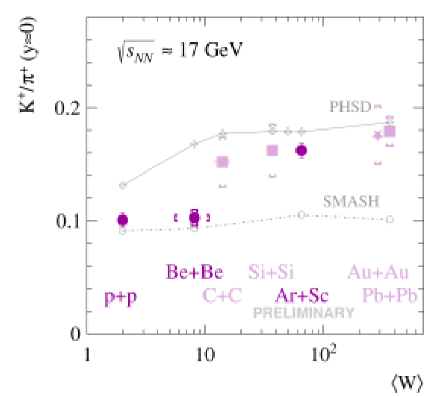
Possible interpretation of the data



arXiv:2205.06726







Ideas for 2027+

- Study of the diagram of high-energy nuclear collisions - energy scan with low and medium mass ions
- Measurements of heavy hadrons and resonances in large statistics p+p interactions
- Measurements with anti-proton beams
- Primary beams of ^{10}B, ^{16}O, ^{24}Mg and ^{40}Ar are considered
- Secondary ^{4}He beam under consideration