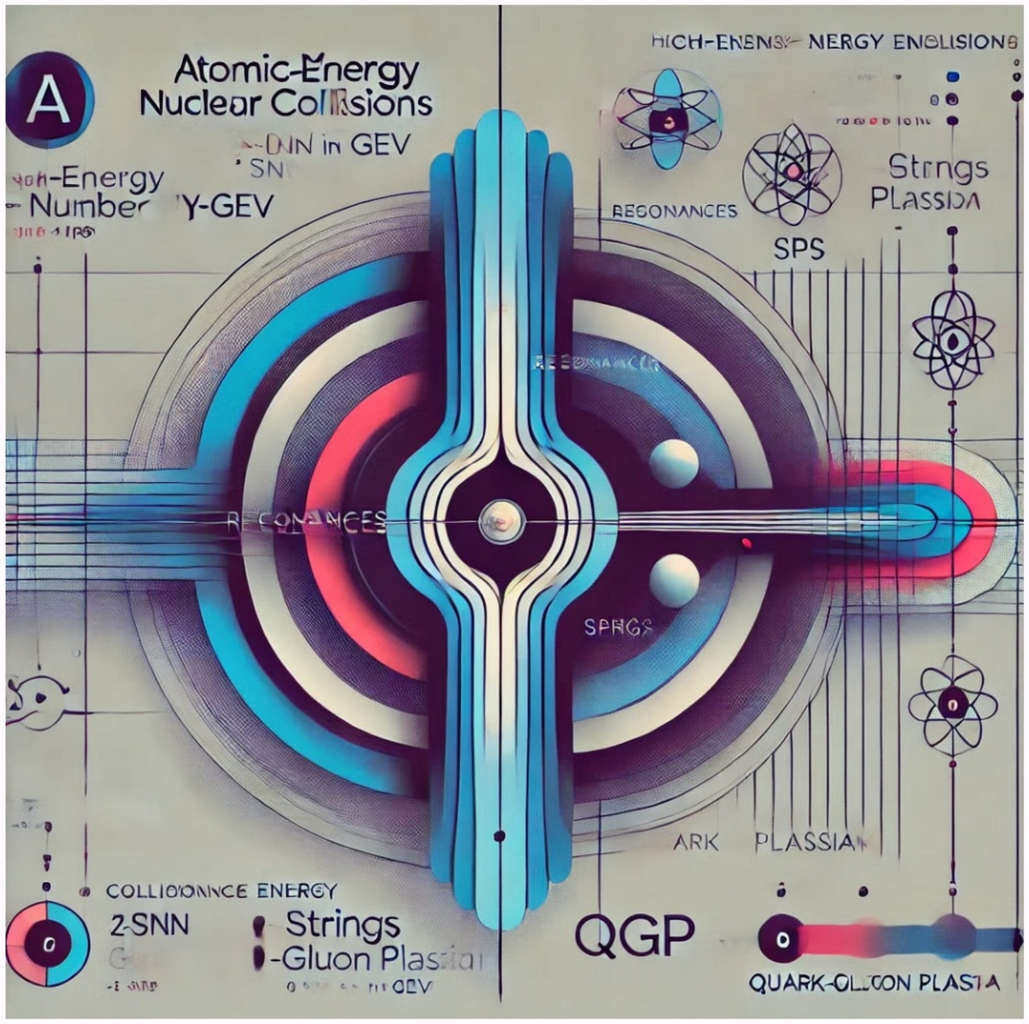
NAGI / SHINE:

DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS

S··INE MG KIELCE

TWO FAMILIES OF HORNS



WHY DO WE NEED B+B, D+D, Mq+Mq COLLISIONS?

NA61/SHINE ORIGINAL PHYSICS GOALS:

EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN-SPSC-2006-034
SPSC-P-330
November 3, 2006

Proposal (NOV 2006)

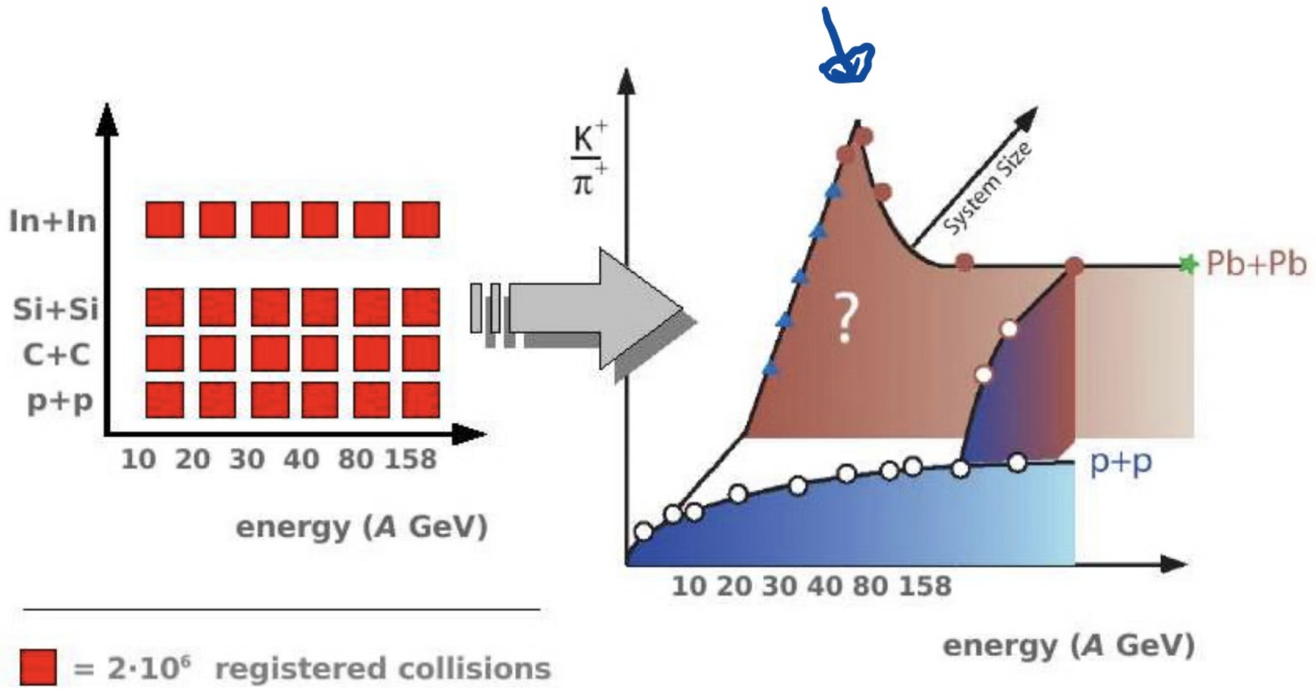
Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS

- **what is the nature of the transition from the anomalous energy dependence measured in central Pb+Pb collisions at SPS energies to the smooth dependence measured in p+p interactions?**

- **does the critical point of strongly interacting matter exist in nature and, if it does, where is it located?**

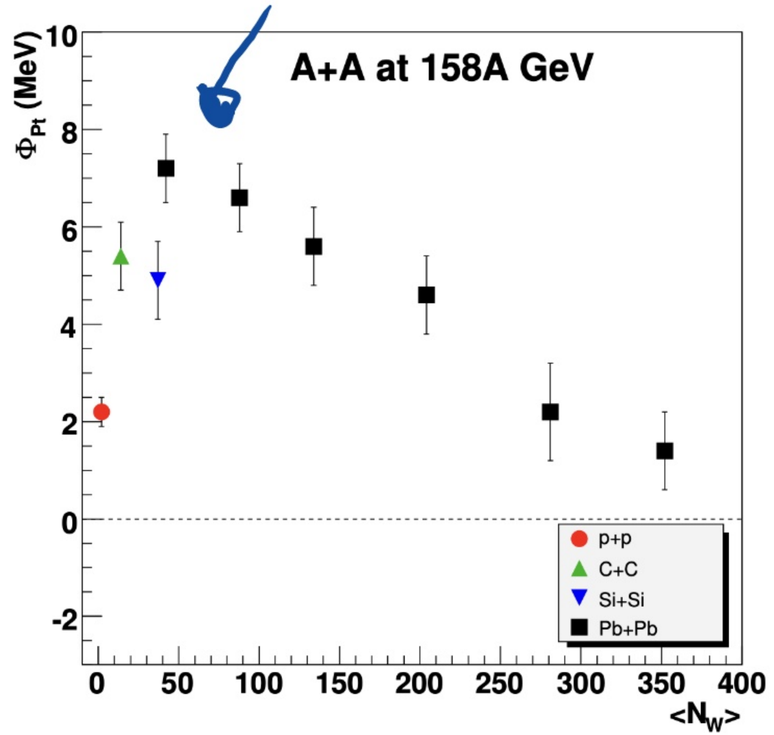
NA61/SHINE ORIGINAL PHYSICS GOALS MOTIVATED BY:

MAREK'S HORN IN K^+/π^+ RATIO



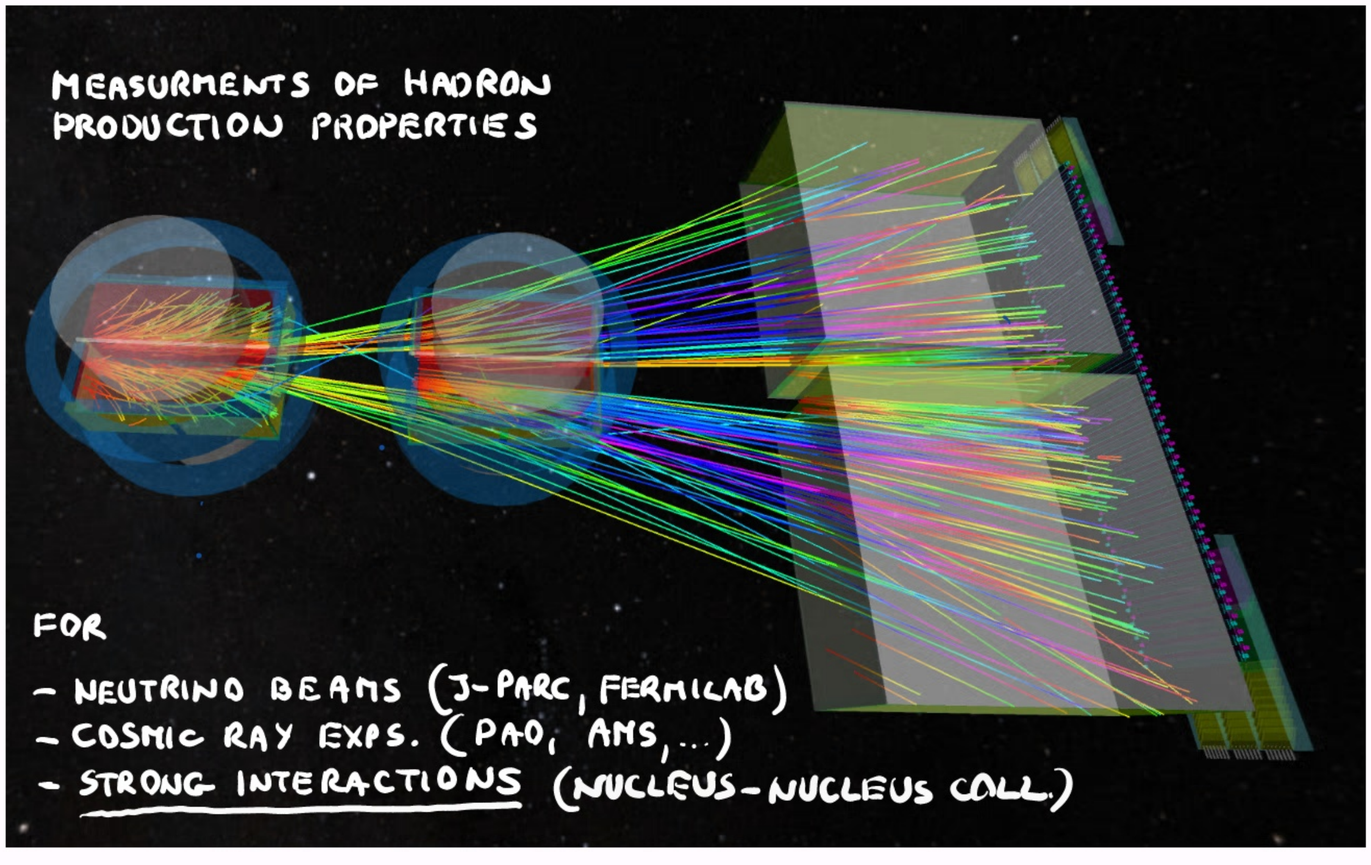
ONSET OF DECONFINEMENT ?

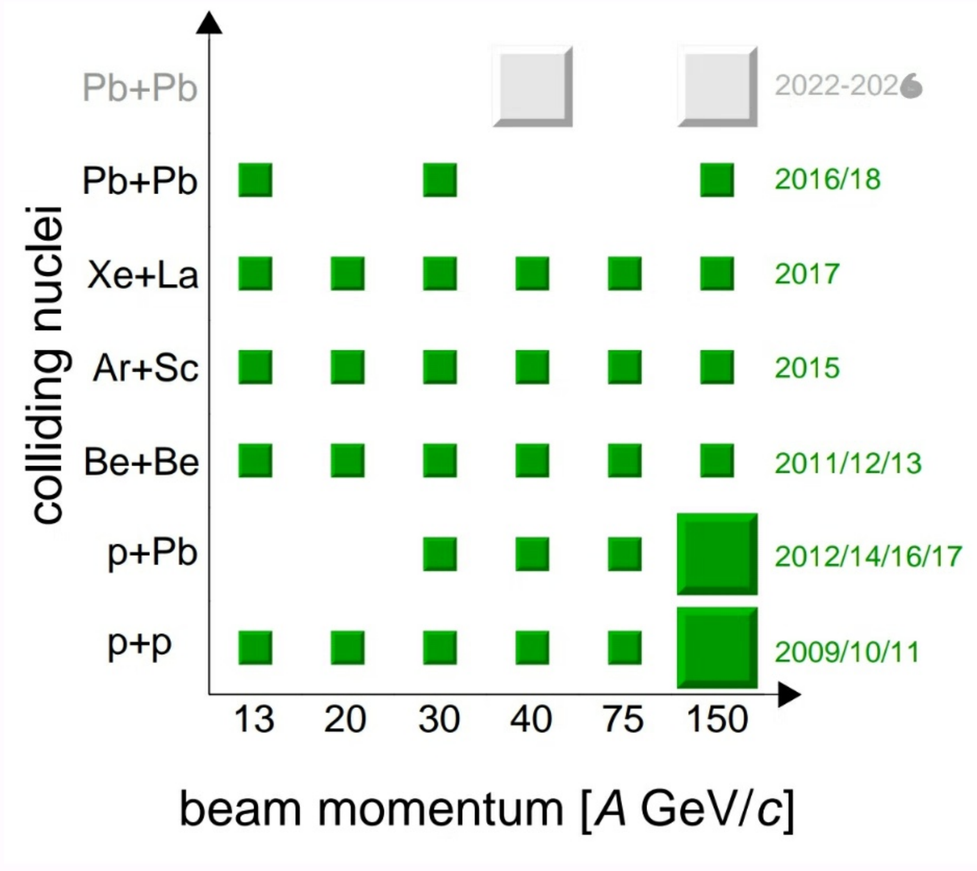
KASIA'S MAXIMUM IN FLUCTUATIONS



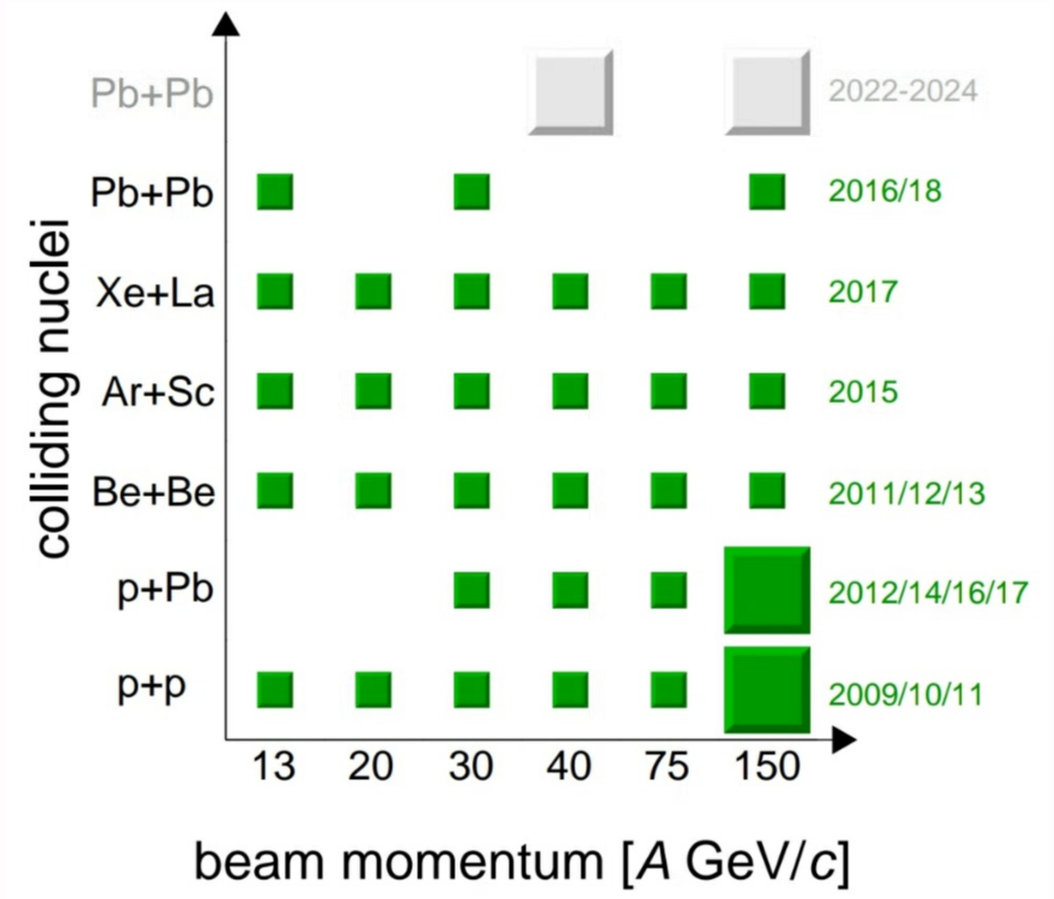
CRITICAL POINT ?

DETECTOR AND COLLECTED DATA:

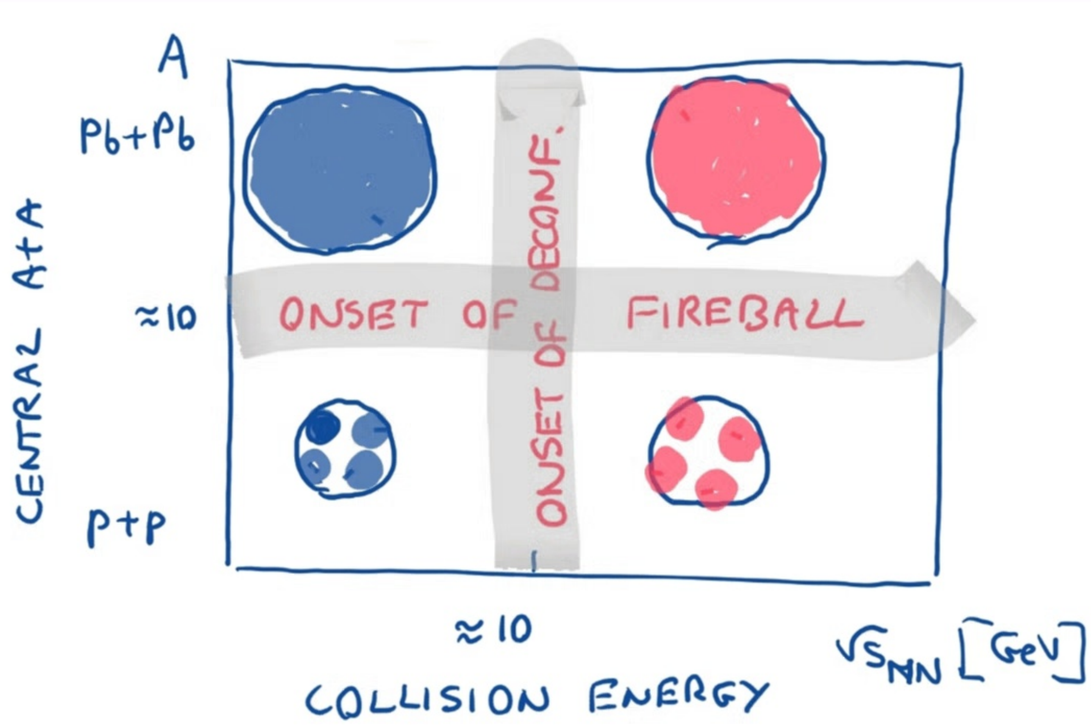




RICH DATA ON NON-EQULIBRIUM AND EQULBRIUM PROCESSES → EMERGING NEW CONCEPT OF DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS



THE CROSS PLOT

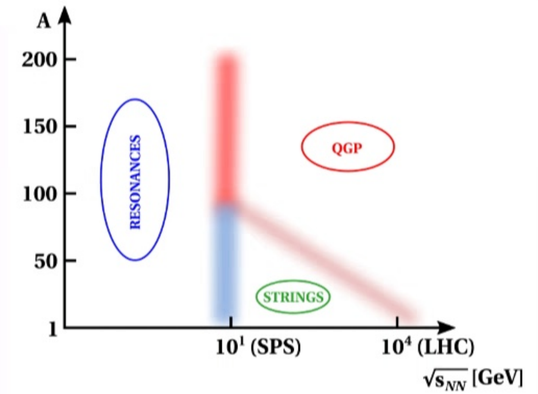


NA61/SHINE ORIGINAL PHYSICS GOALS:

- what is the nature of the transition from the anomalous energy dependence measured in central Pb+Pb collisions at SPS energies to the smooth dependence measured in p+p interactions?

- does the critical point of strongly interacting matter exist in nature and, if it does, where is it located?

HAVE BEEN GENERALIZED TO



- ESTABLISHING DIAGRAM OF HIGH-ENERY NUCLEAR COLLISIONS

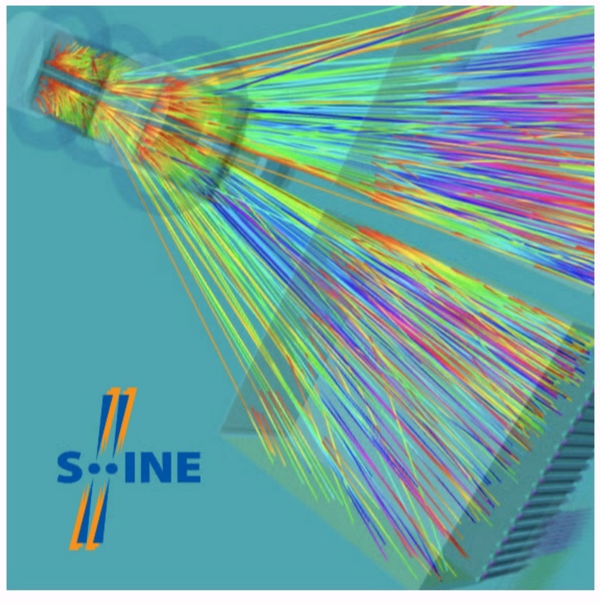
  ≡ CHART SHOWING EXPERIMENTAL CONDITIONS (COLLISION ENERGY, MASSES OF COLLIDING NUCLEI, ...)

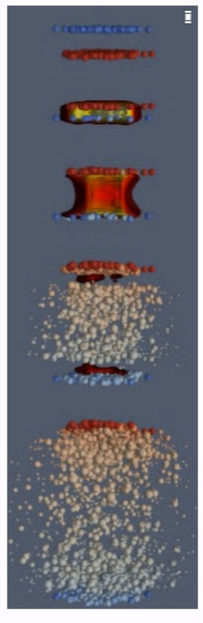
  AT WHICH DISTINCT HADRON PRODUCTION PROCESSES DOMINATE

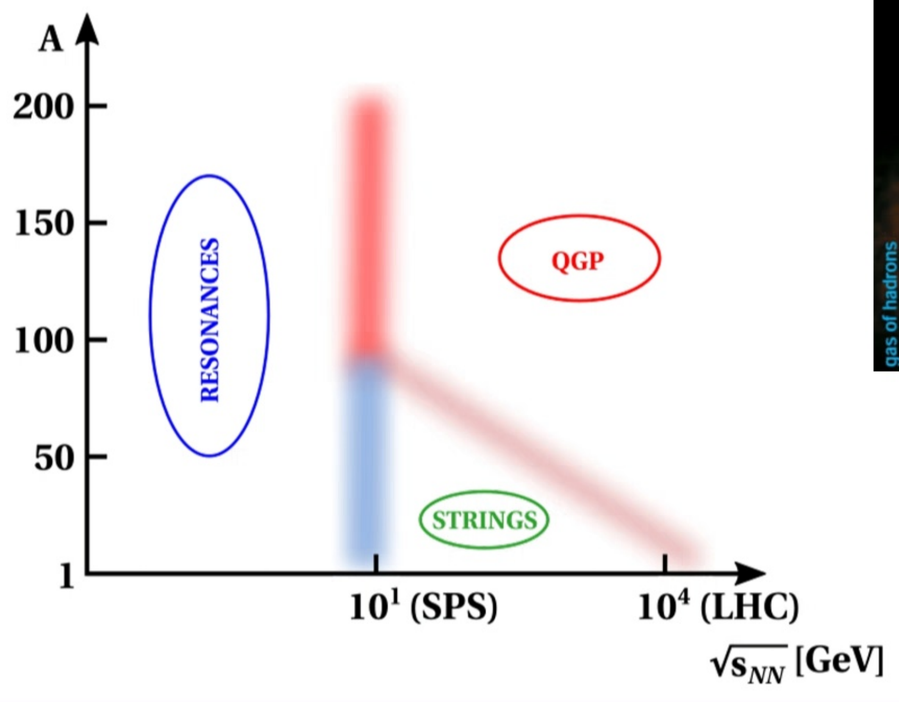
TWO DIAGRAMS!

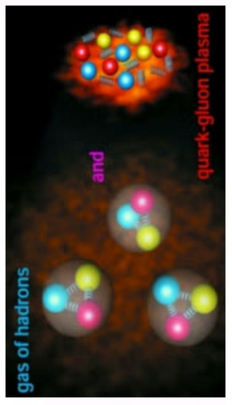
DATA + MODELS → DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS

STATISTICAL PHYSICS + $V \to \infty$ → PHASE DIAGRAM









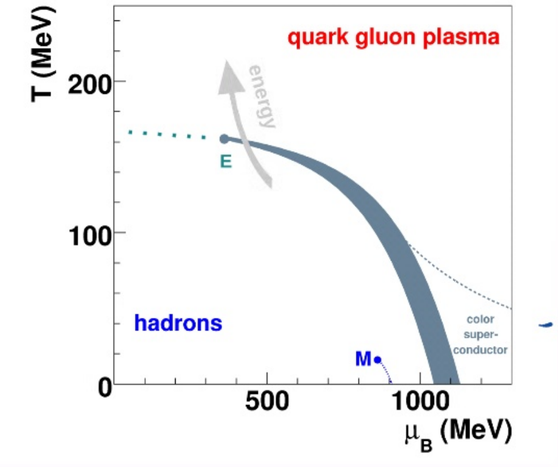


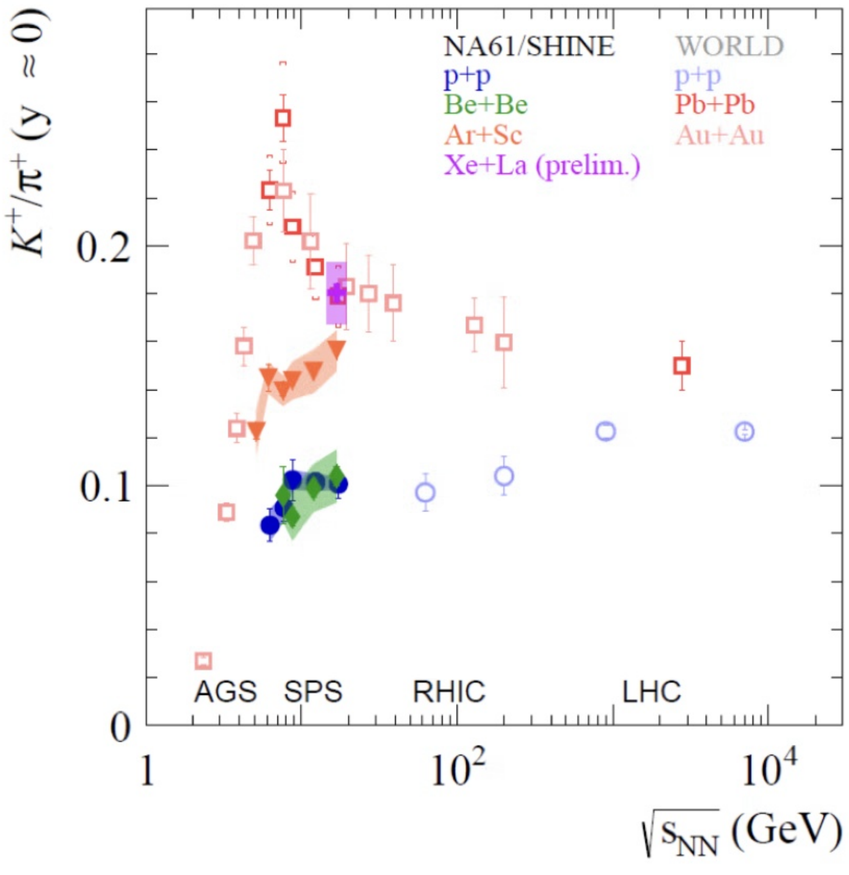
Diagram of High-Energy Nuclear Collisions †

Evgeny Andronov (St. Petersburg State U.), Magdalena Kuich (Warsaw U.), Marek Gaździcki (Frankfurt U. and Jan Kochanowski U.) (May 13, 2022)

Published in: *Universe* 9 (2023) 2, 106 • e-Print: 2205.06726 [hep-ph]

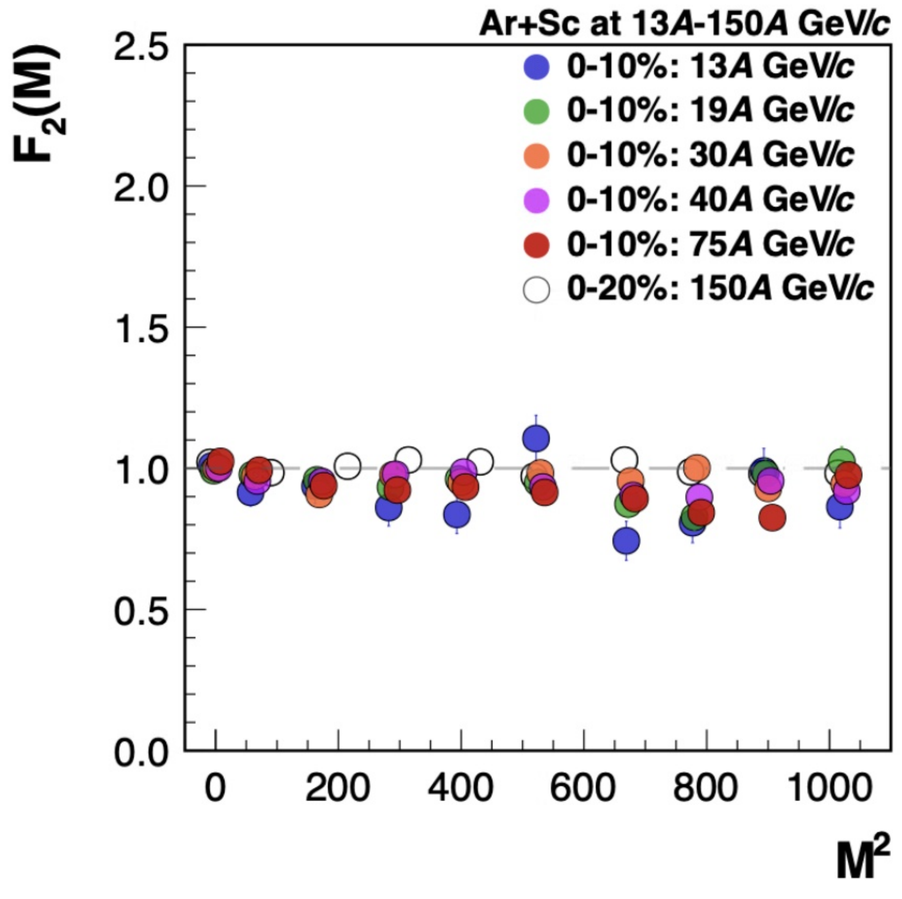
SELECTED EXPERIMENTAL RESULTS:

MEAN MULTICLICTIES



RICH PATTERN
→ THE FUN PLOT

FLUCTUATIONS



NO STRUCTURE → NO CP EVIDENCE

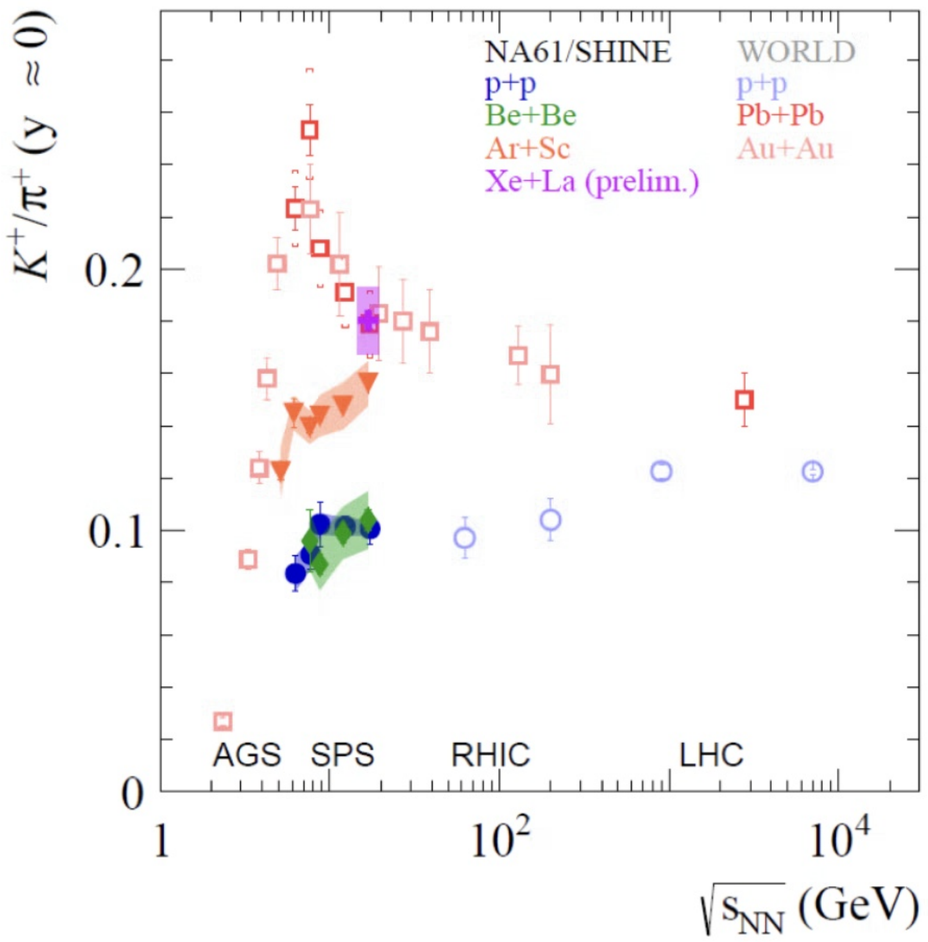
CERN-SPSC-2024-030 ; SPSC-SR-353

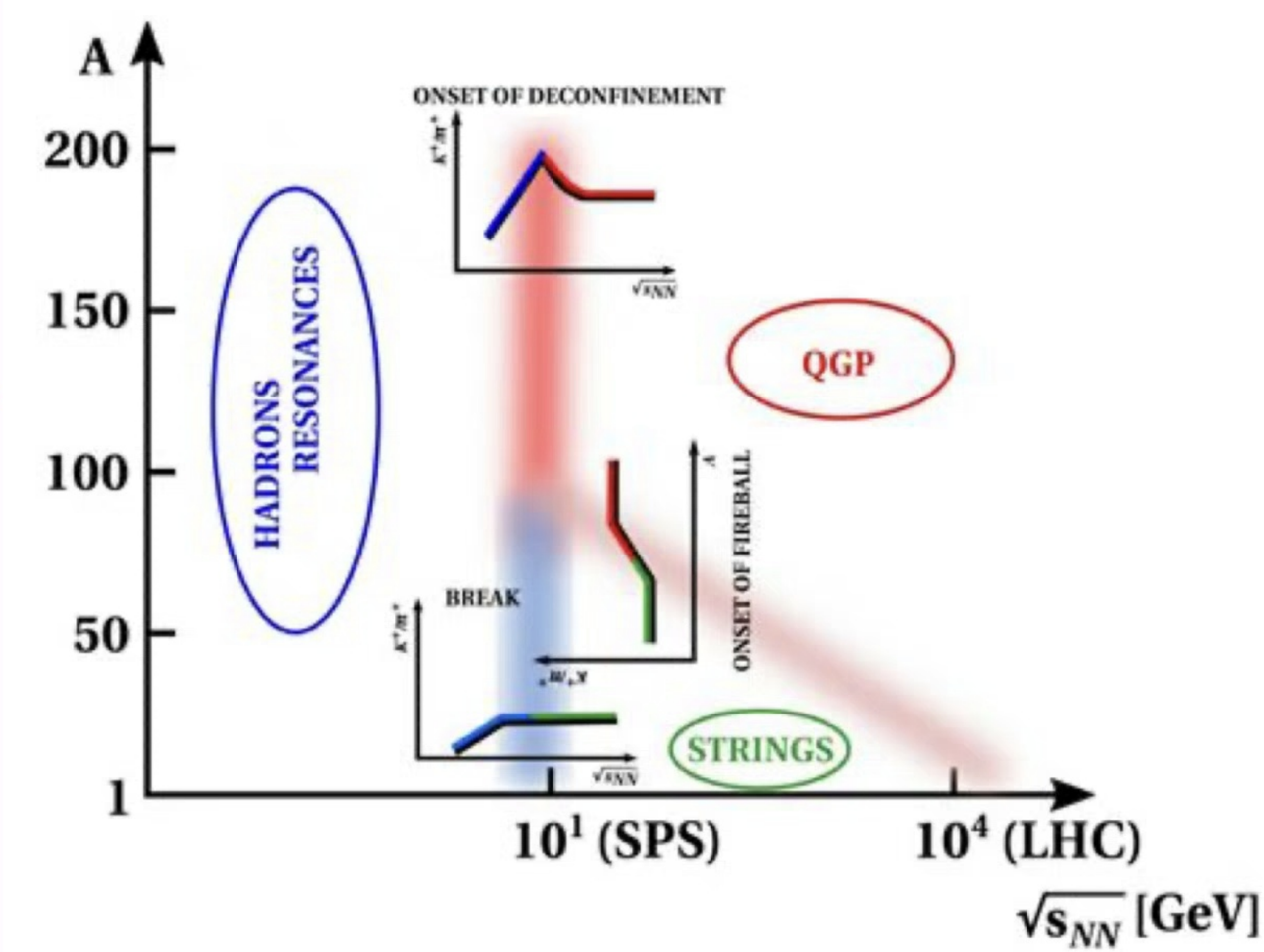
Report from the NA61/SHINE experiment at the CERN SPS

NA61/SHINE Collaboration • H. Adhikary (Jan Kochanowski U.) et al. (Jan 7, 2024)

Published in: *Eur.Phys.J.C* 84 (2024) 7, 741 • e-Print: 2401.03445 [nucl-ex]

THE DATA-DRIVEN DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS





9

CERN-SPSC-2024-030 ; SPSC-SR-353

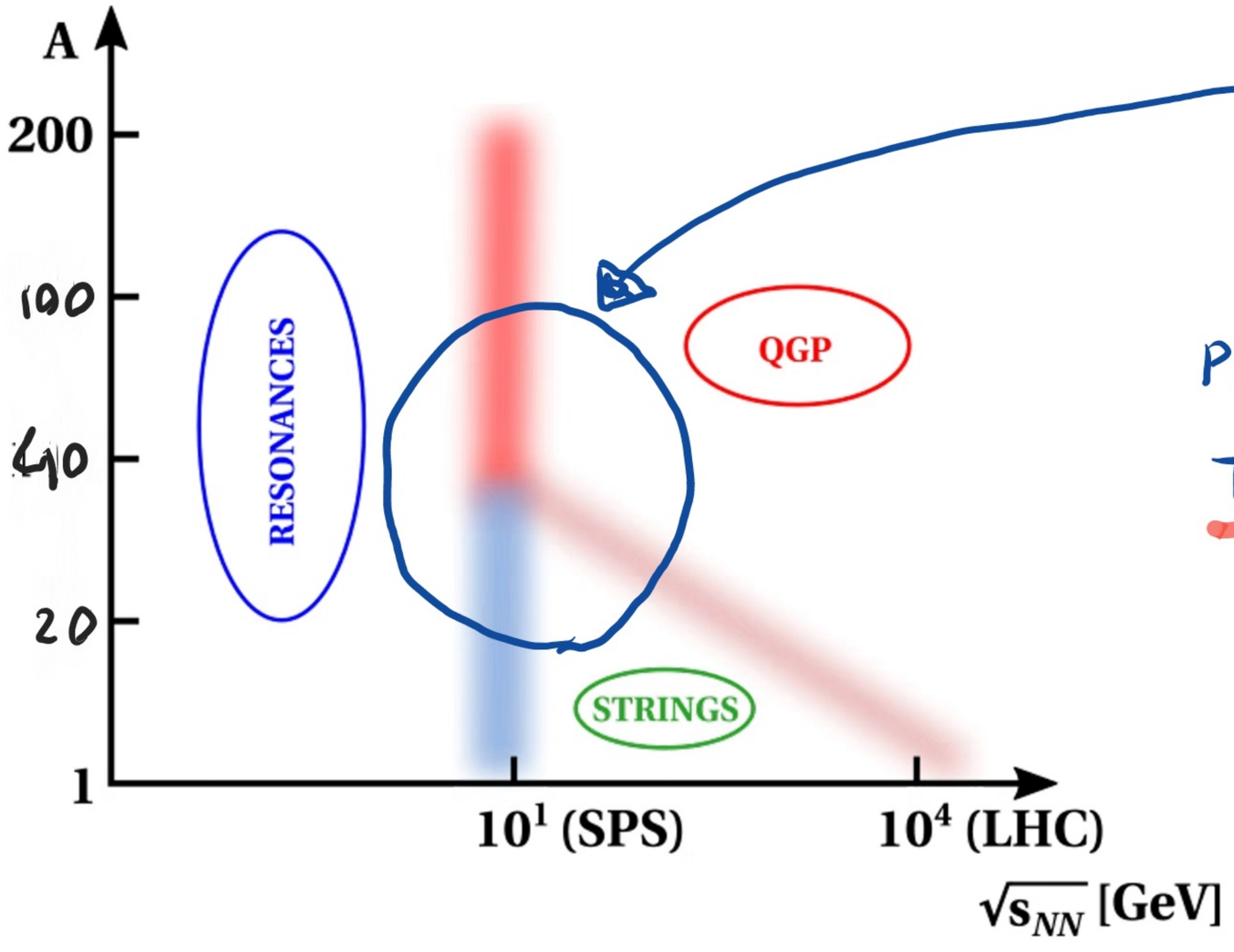
Report from the NA61/SHINE experiment at the CERN SPS

Diagram of High-Energy Nuclear Collisions †

Evgeny Andronov (St. Petersburg State U.), Magdalena Kuich (Warsaw U.), Marek Gaździcki (Frankfurt U. and Jan Kochanowski U.) (May 13, 2022)

Published in: *Universe* 9 (2023) 2, 106 • e-Print: 2205.06726 [hep-ph]

FUTURE: STUDY OF THE TRIPLE REGION

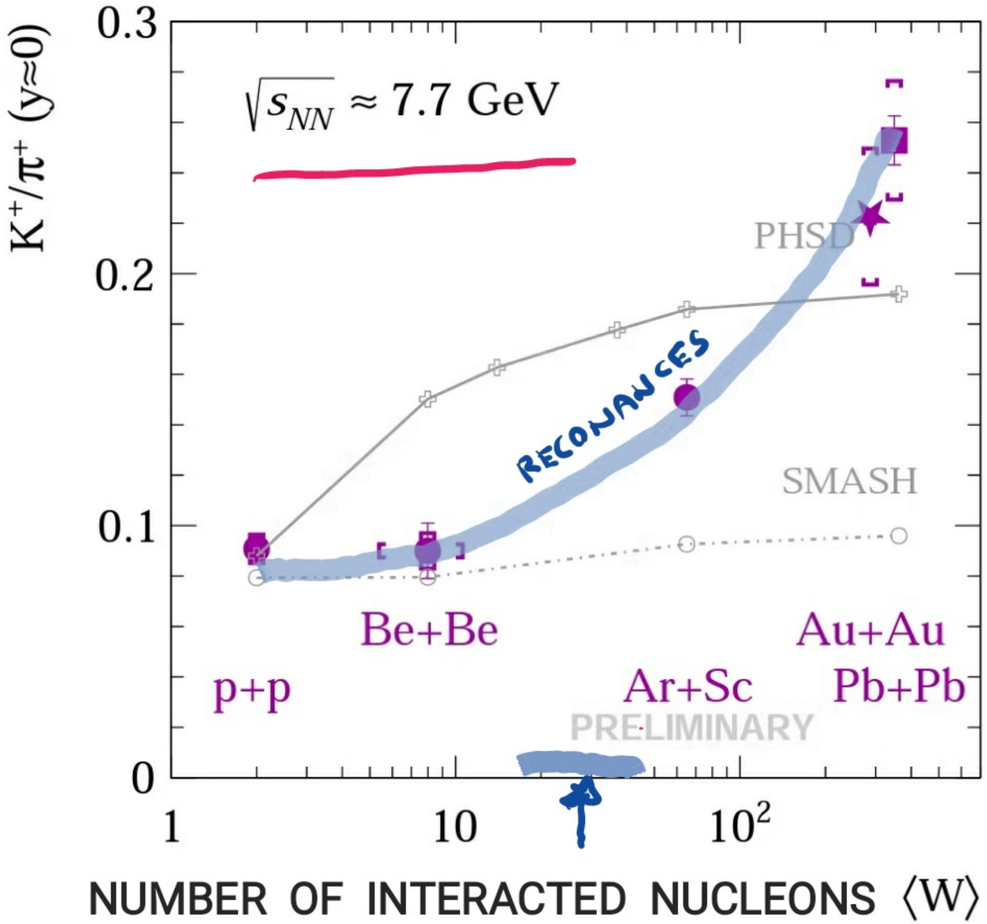


POSSIBLE SIGNAL:

TWO FAMILIES OF HORNS

TWO FAMILIES OF HORNS

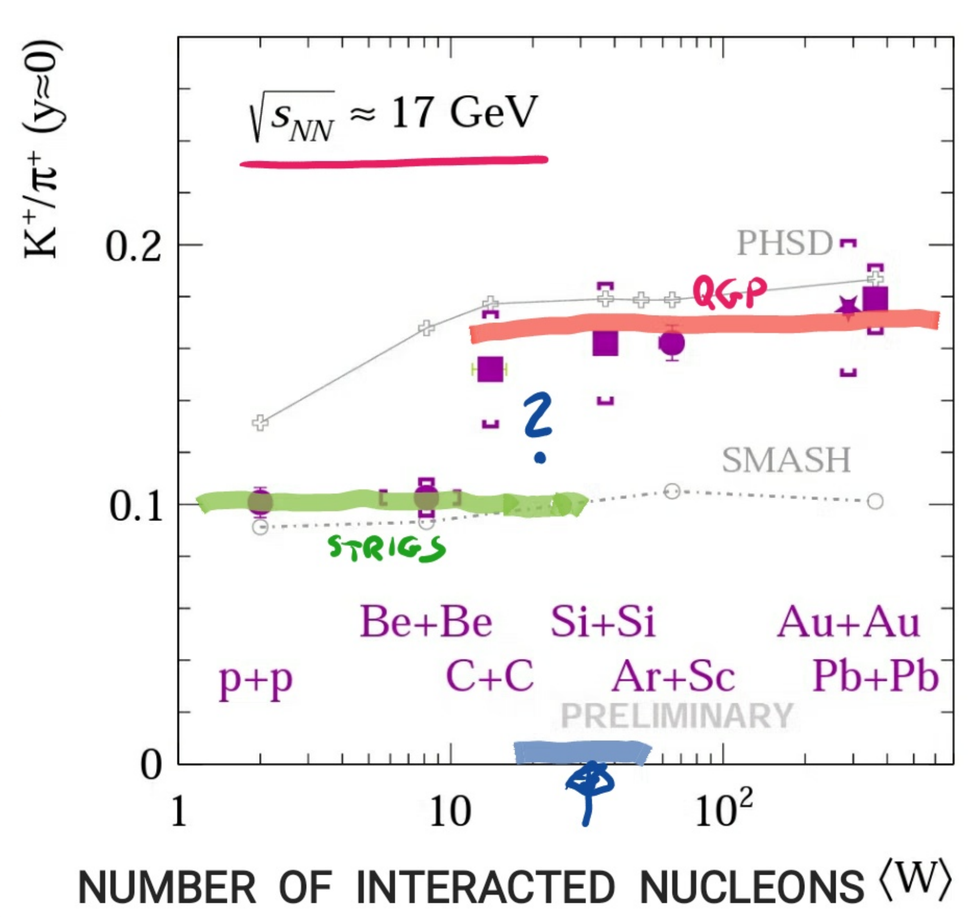
30A GeV/c



B+B, O+O, Mg+Mg

+

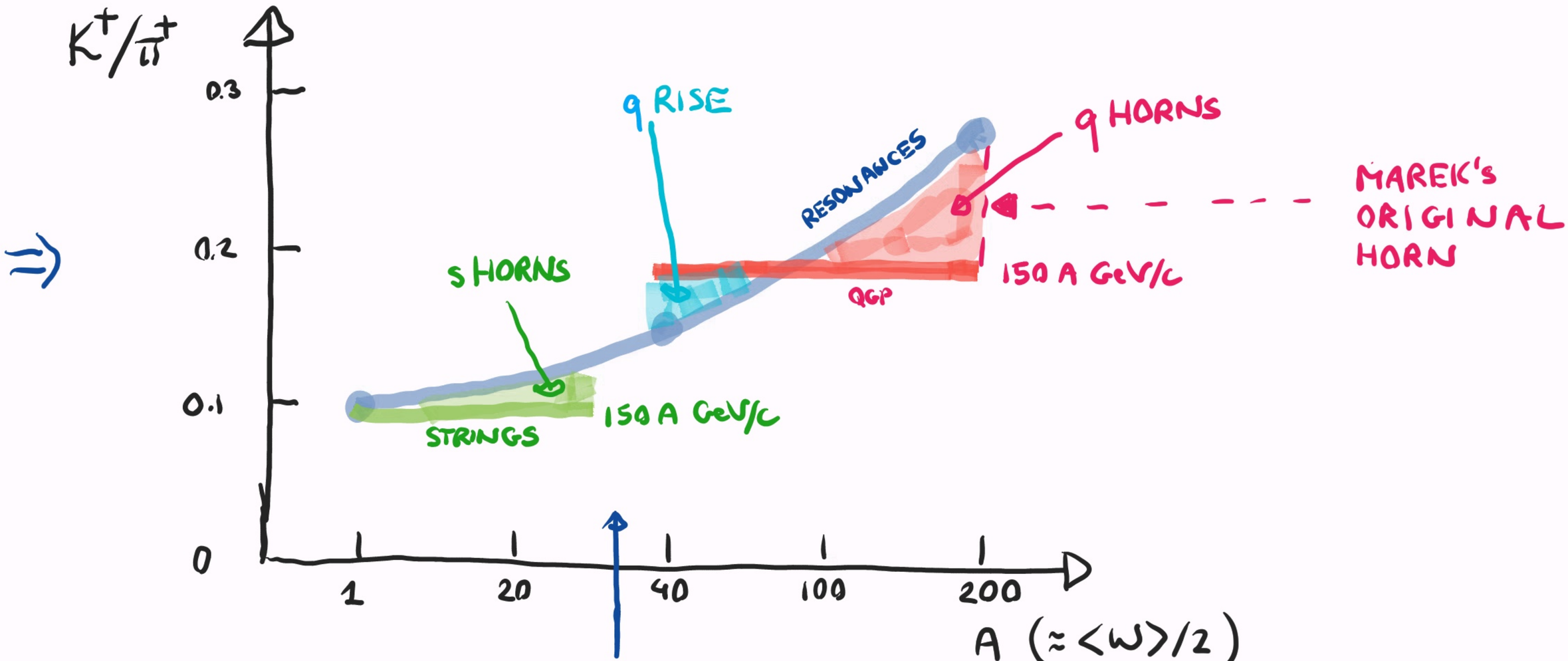
150A GeV/c



B+B, O+O, Mg+Mg

=

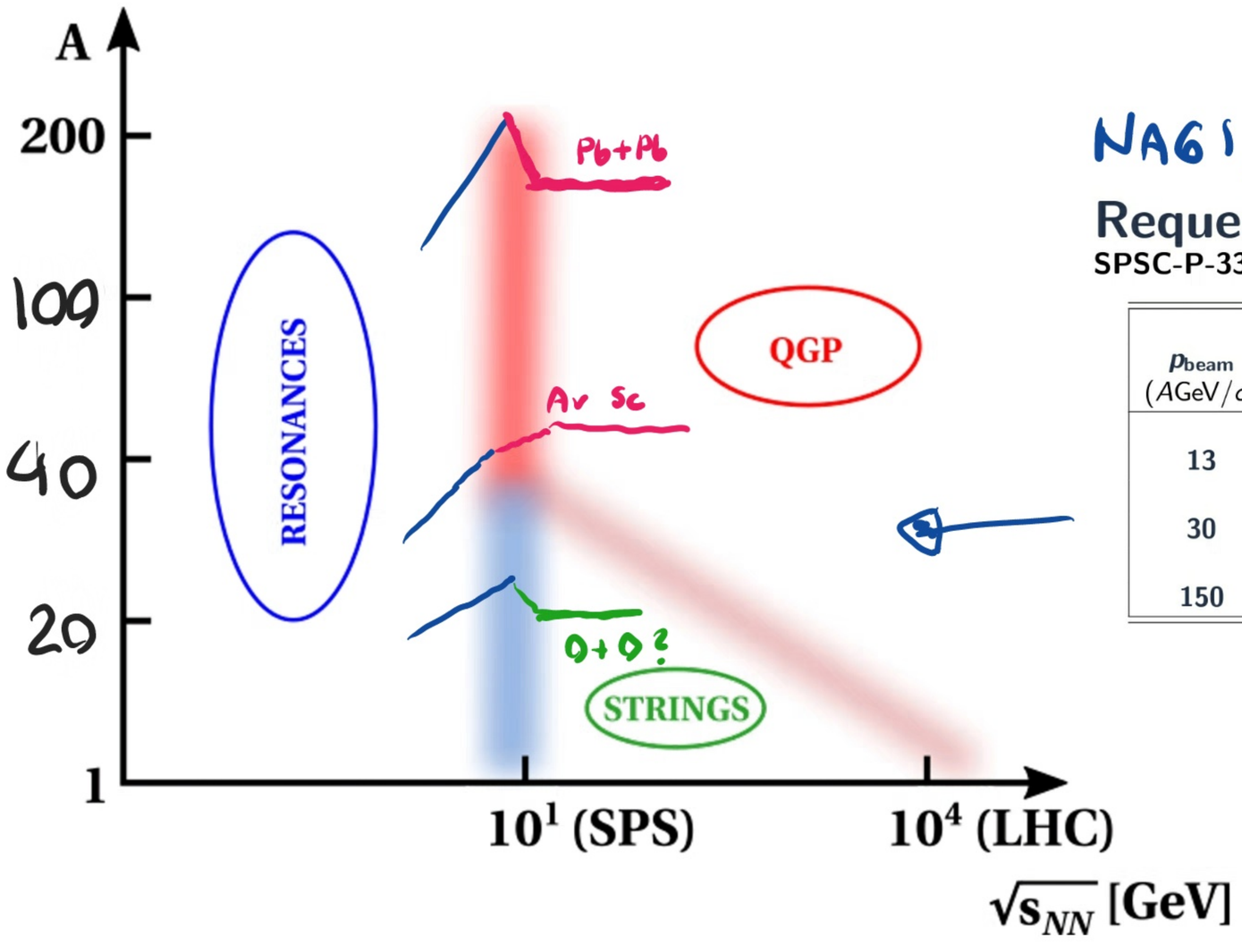
TWO FAMILIES OF HORNS : qHORNS, sHORNS



THE TRANSITION FROM sHORNS TO qRISE LOCATES THE TRIPLE REGION

MG IN PREPARATION

TWO FAMILIES OF HORNS



NA61/SHINE:

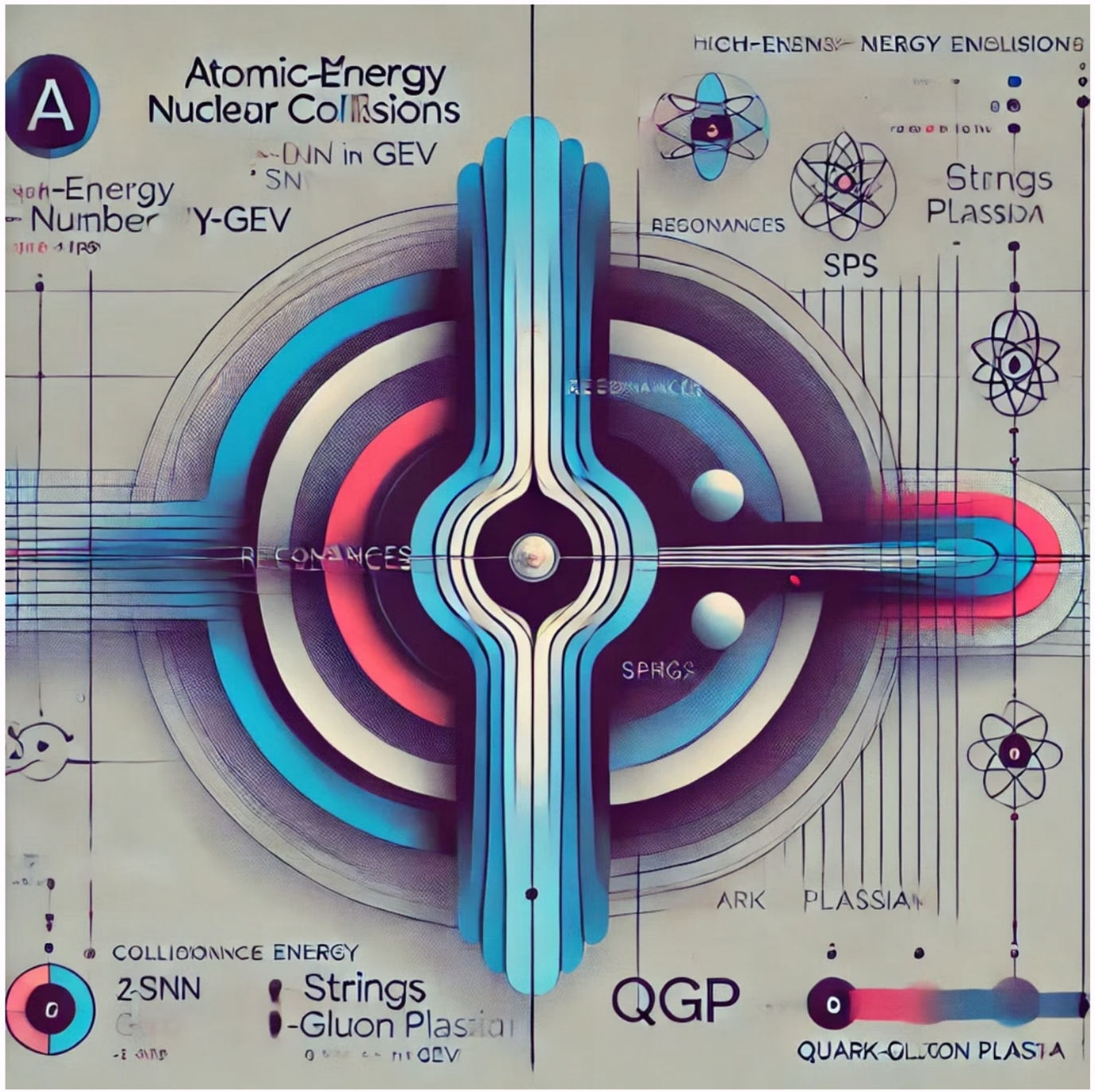
Request for light ions in Run 4

SPSC-P-330-ADD-14 request submittd to SPSC:

p_{beam} ($AGeV/c$)	$\sqrt{s_{NN}}$ (GeV)	^{10}B # days (# events)	^{16}O # days (# events)	^{24}Mg # days (# events)
13	5.1	7 (100M)	7 (100M)	7 (100M)
30	7.6	7 (100M)	7 (100M)	7 (100M)
150	16.8	7 (100M)	7 (100M)	7 (100M)

CERN SPSC RECOMMENDED FOR 2025

CHAT ON THE DIAGRAM



THE END

CONSTRUCTING DIAGRAM OF H-E NUCLEAR COLLISIONS

THE RATIO OF POSITIVELY-CHARGED KAONS AND PIONS MEASURED AT MID-RAPIDITY, K^+/π^+ ← THE FUN PLOT

- APPROXIMATELY PRPORTIONAL TO THE RATIO OF (ANTI-)STRANGE QUARKS TO ENTROPY
- SENSITIVE TO HADRON-PRODUCTION PROCESSES DUE TO MASS AND NUMBER DIFFERENCES BETWEEN STRANGE AND NON-STRANGE PARTICLES - QUARKS AND GLUONS OR HADRONS

RAFELSKI, MULLER
PRL 48, 1066 (1982)

MG, GORENSTEIN
APP B 30, 2705 (1999)

- RICH EXPERIMENTAL DATA IN HIGH-ENERGY NUCLEAR COLLISIONS

CONSTRUCTING DIAGRAM OF H-E NUCLEAR COLLISIONS

POPULAR PROCESSES FOR MODELLING HADRON PRODUCTION
IN PROTON-PROTON AND NUCLEUS-NUCLEUS COLLISIONS:

RESONANCES - CREATION, EVOLUTION AND DECAYS OF RESONANCES
- EXCITED STATES OF STABLE HADRONS

STRINGS - FORMATION, EVOLUTION AND FRAGMENTATION OF STRINGS
- GLUON-FLUX TUBES BETWEEN A PAIR OF COLOUR CHARGES

QGP - CREATION, EVOLUTION AND HADRONISATION OF QUARK-GLUON PLASMA

CONSTRUCTING DIAGRAM OF H-E NUCLEAR COLLISIONS

TWO POPULAR MODELS OF HIGH-ENERGY NUCLEAR COLLISIONS
COVERING THE DATA RANGE IN COLLISION ENERGY AND NUCLEAR-MASS NUMBER:

PHSD ~ INCLUDES RESONANCES, STRINGS AND QGP

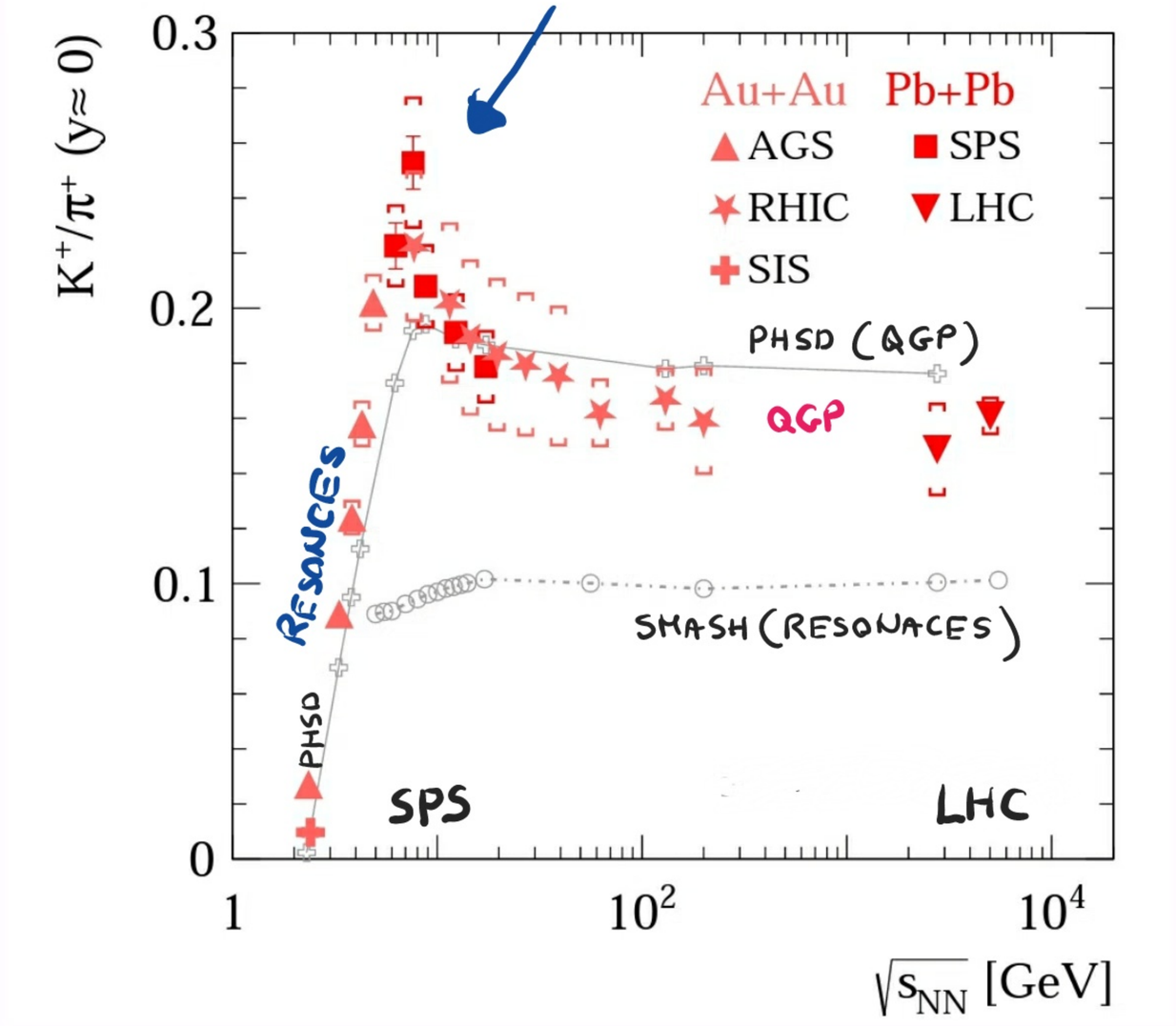
CASSING, BRATKOVSKAYA
NPA 831, 215 (2009)

SMASH ~ INCLUDES RESONANCES AND STRINGS

MOHS, RYU, ELFNER
JPG 47, 065101 (2020)

HEAVY-ION COLLISIONS

THE HORN STRUCTURE



NA49, PRC 66, 054902

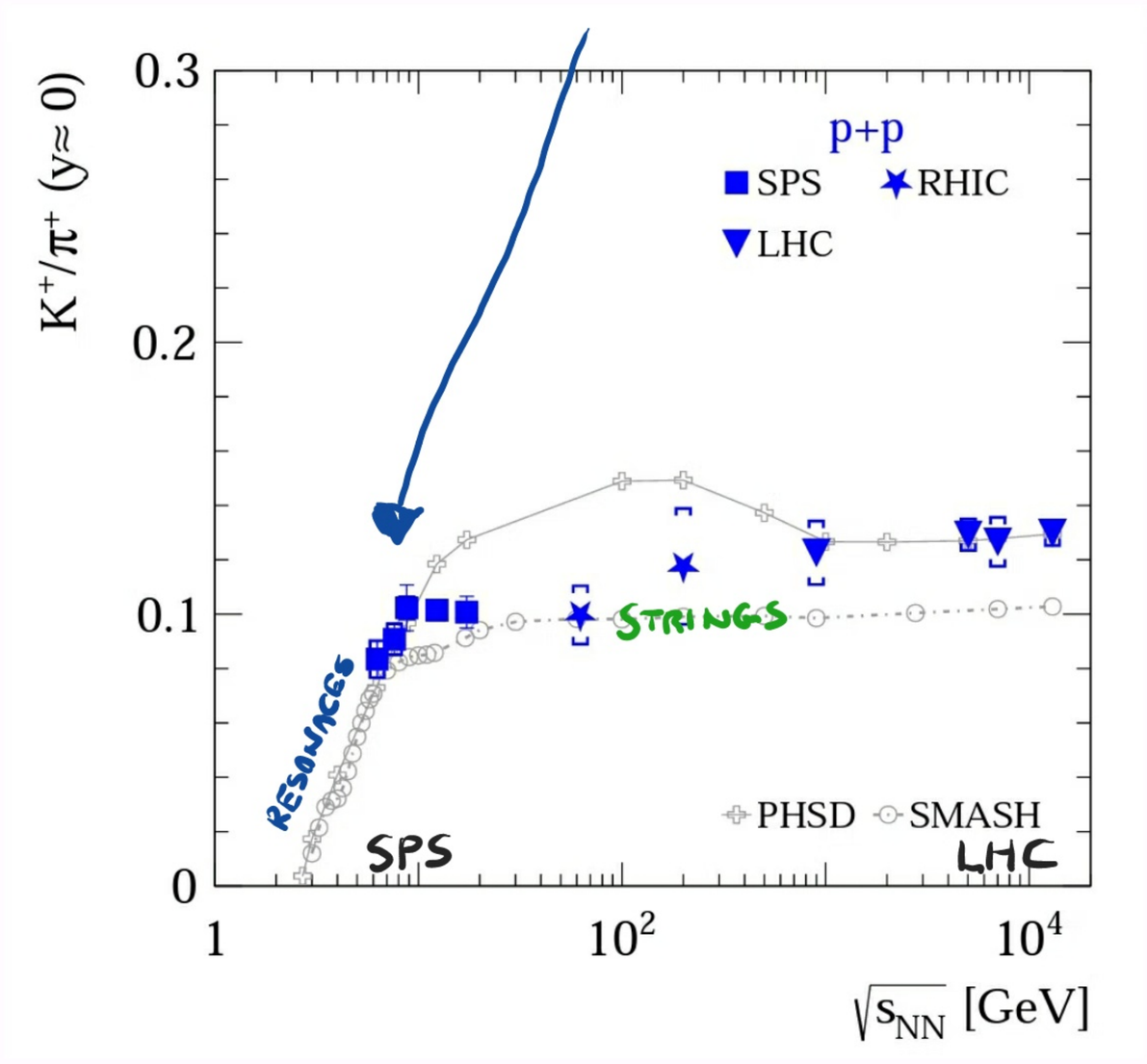
RESONANCES - QGP CHANGEOVER (ONSET OF DECONFINEMENT)

MG, GORENSTEIN APP B 30, 2705 (1999)

SUPPORTED BY AGREEMENT OF PHSD (DECONFINEMENT + CHIRAL SYMMETRY RESTORATION) AND DISAGREEMENT OF SMASH (STRINGS)

PROTON - PROTON INTERACTIONS

THE BREAK STRUCTURE →



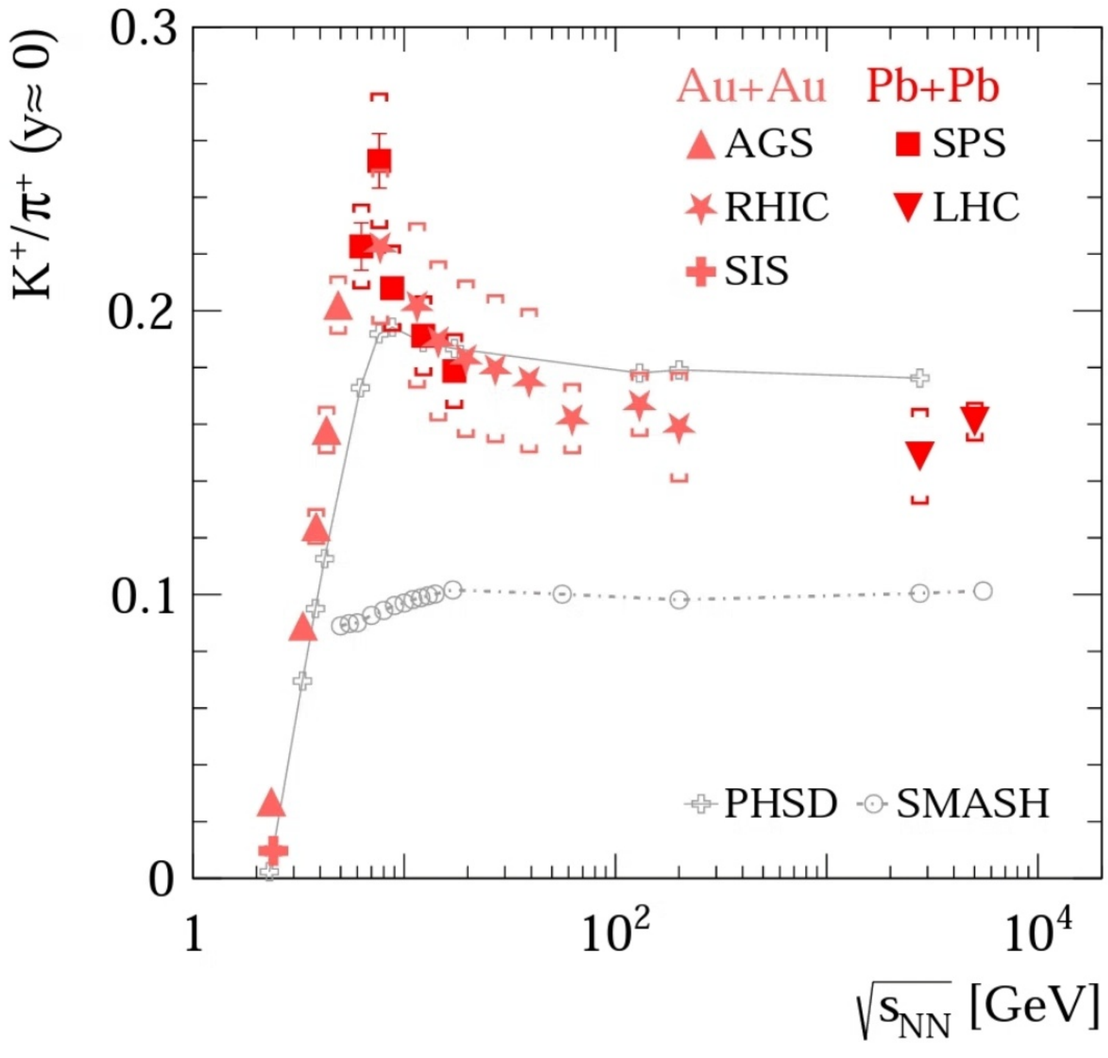
NA61/SHINE, PRC 102, 011901 (2020)

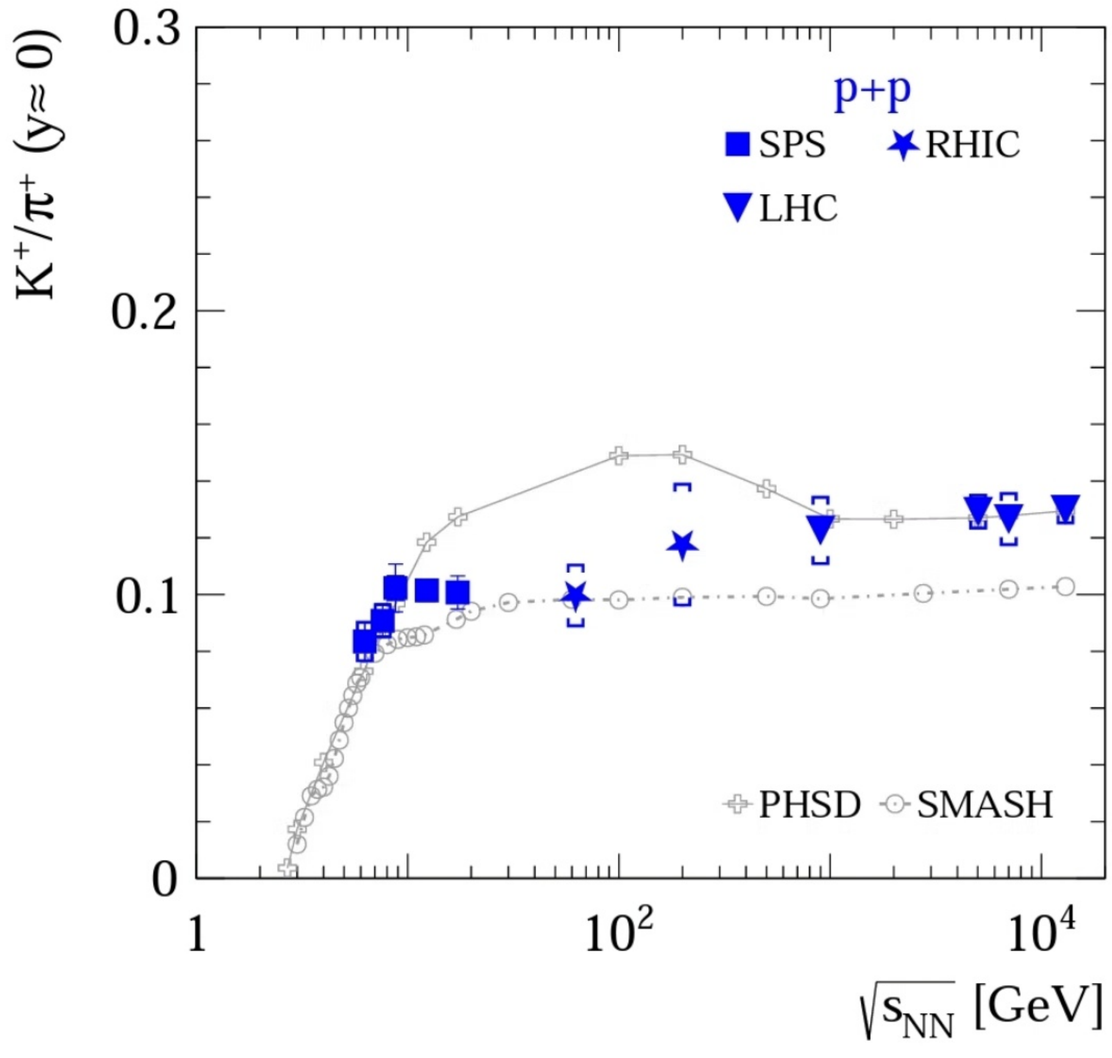
RESONANCES-STRINGS CHANGEOVER

SMASH AND PHSD INCLUDE RESONANCES-STRINGS CHANGEOVER, BUT LOCATE IT AT LOWER ENERGIES (3-4 AND 2.6 GeV)

FOR p+p THE SAME UNDERLYING PHYSICS, BUT DIFFERENT PREDICTIONS OF SMASH AND PHSD

HEAVY-IONS VS p+p

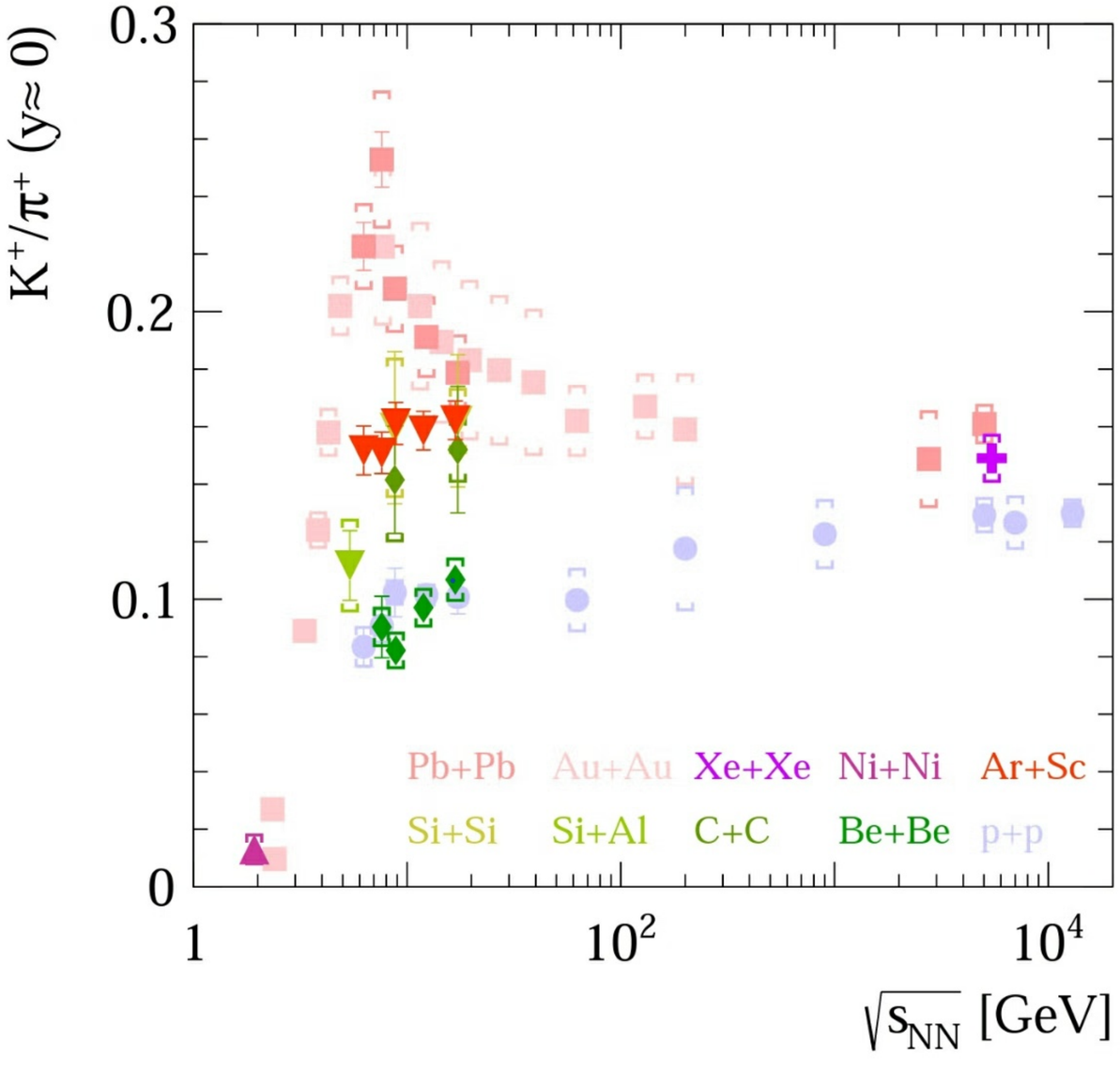




VERY DIFFERENT ENERGY DEPENDENCE

→ COLLISIONS OF INTERMEDIATE-MASS NUCLEI

INTERMIDIATE MASS NUCLEI



Be + Be ≈ p + p

NA61/SHINE:
EPJ C80, 961 (2020)
EPJ C81, 73 (2021)

Ar + Sc ≈ Pb + Pb
AT THE TOP SPS

NO HORN IN Ar + Sc

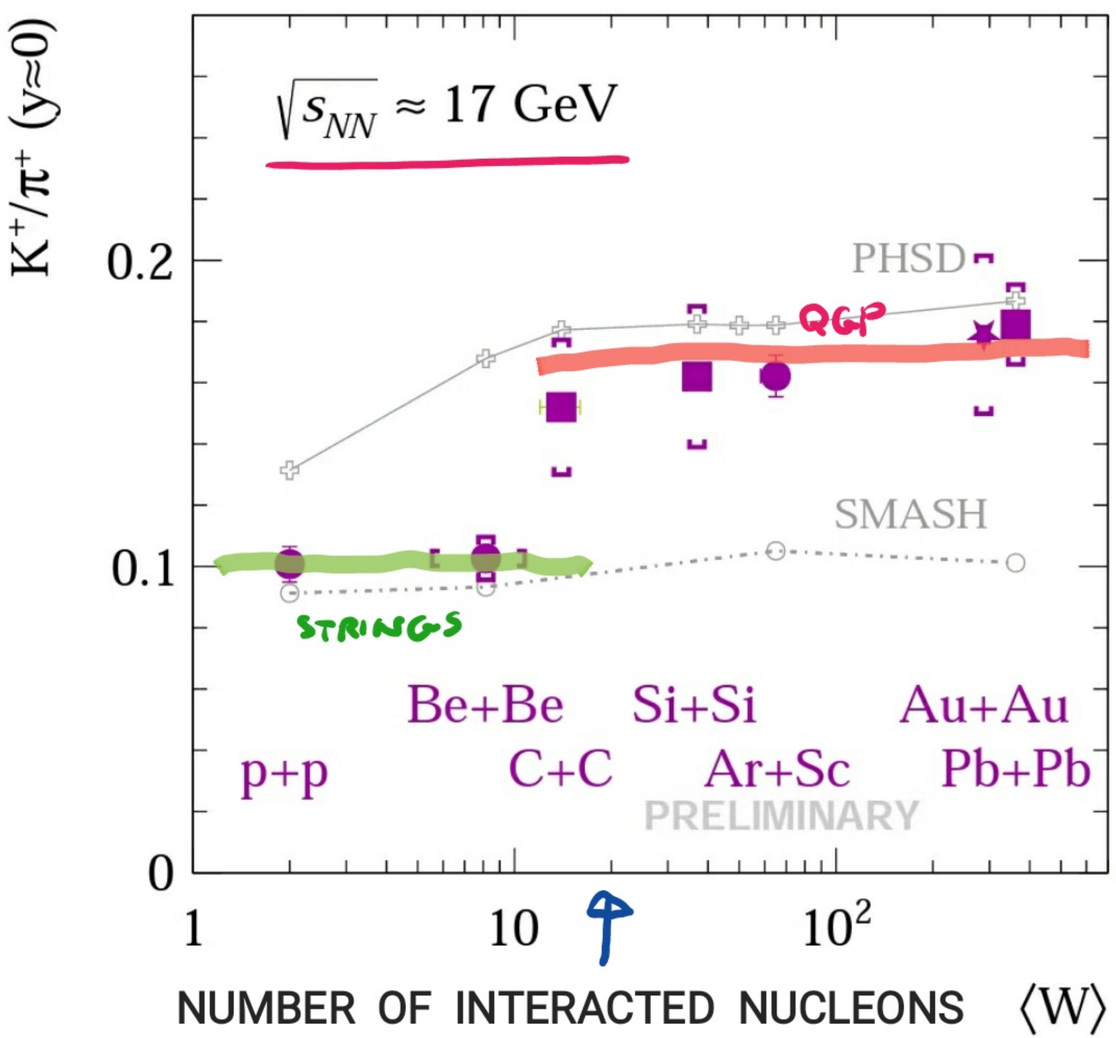
NA61/SHINE:
EPJ C 81, 397 (2021)

p + p ≈ Xe + Xe ≈ Pb + Pb AT LHC

ALICE
NATURE PHYS. 13, 535 (2017)

2 → QGP IN p + p AT LHC

INTERMIDIATE MASS NUCLEI



B+B, O+O, Mg+Mg

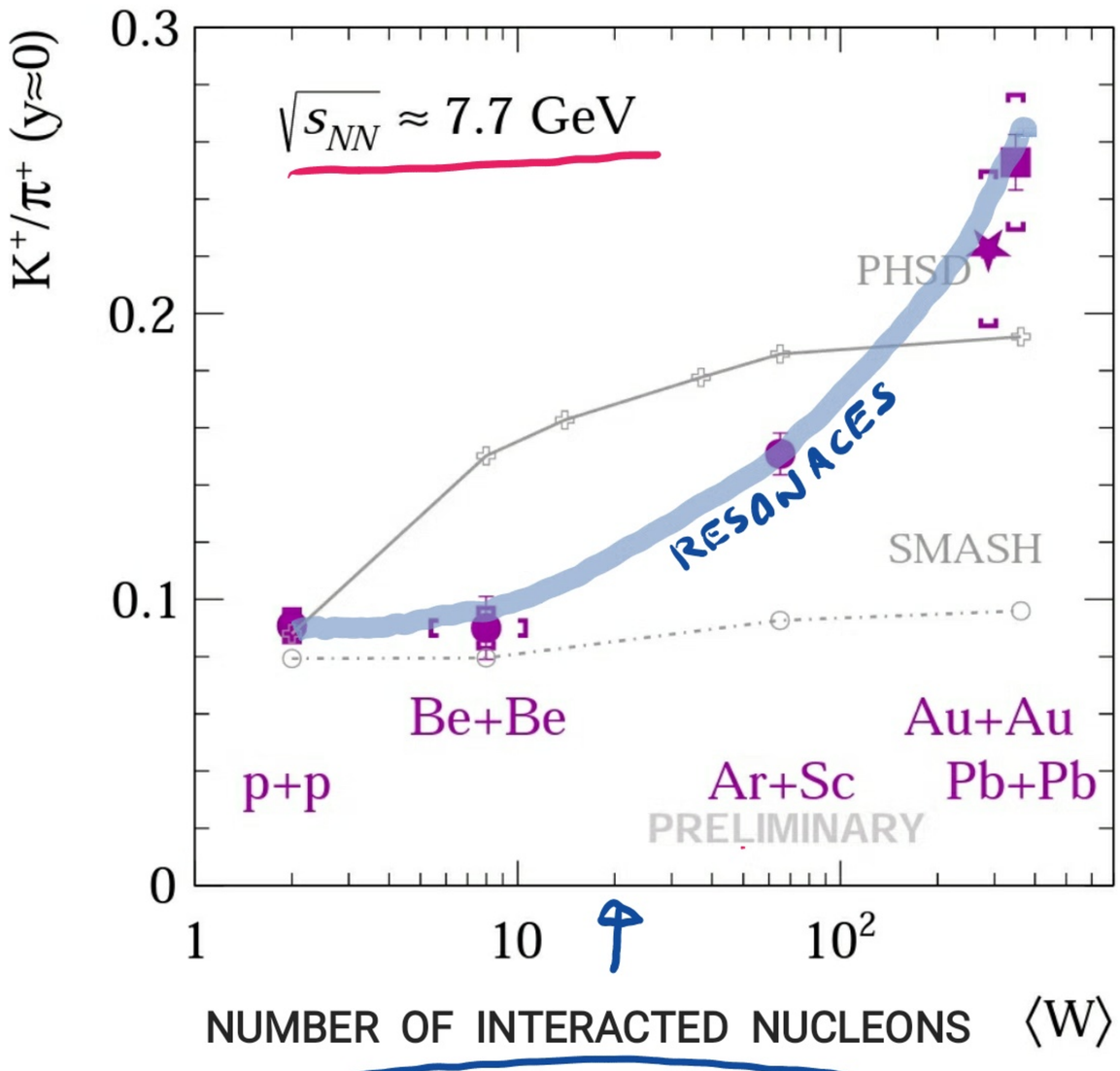
JUMP BETWEEN p + p, Be + Be AND Ar + Sc, Pb+ Pb AT THE TOP SPS ENERGIES

NOT REPRODUCED BY THE MODELS

IDEA: JUMP IS DUE TO STRINGS TO QGP COLLAPSE PICTURED AS THE BLACK-HOLE FORMATION USING AdS/CFT DUALITY

KALAYDZHYAN, SHURYAK
PRC 90, 014901 (2014)
PRD 90, 025031, (2014)

INTERMIDIATE MASS NUCLEI



B+B, O+O, Mg+Mg

SMOOTH INCREASE BETWEEN
Be + Be, Ar + Sc AND Pb + Pb
AT THE LOW SPS ENERGIES

POSSIBLY DUE TO:

- APPROACHING EQUILIBRIUM WITH INCREASING <W> AND SYSTEM LIFE-TIME
- WEAKENING OF CANONICAL STRANGENESS SUPPRESSION WITH INCREASING <W>
- INCREASING ROLE OF CHIRAL-SYMMETRY RESTORATION

SEARCH FOR CRITICAL POINT

PHASE DIAGRAM

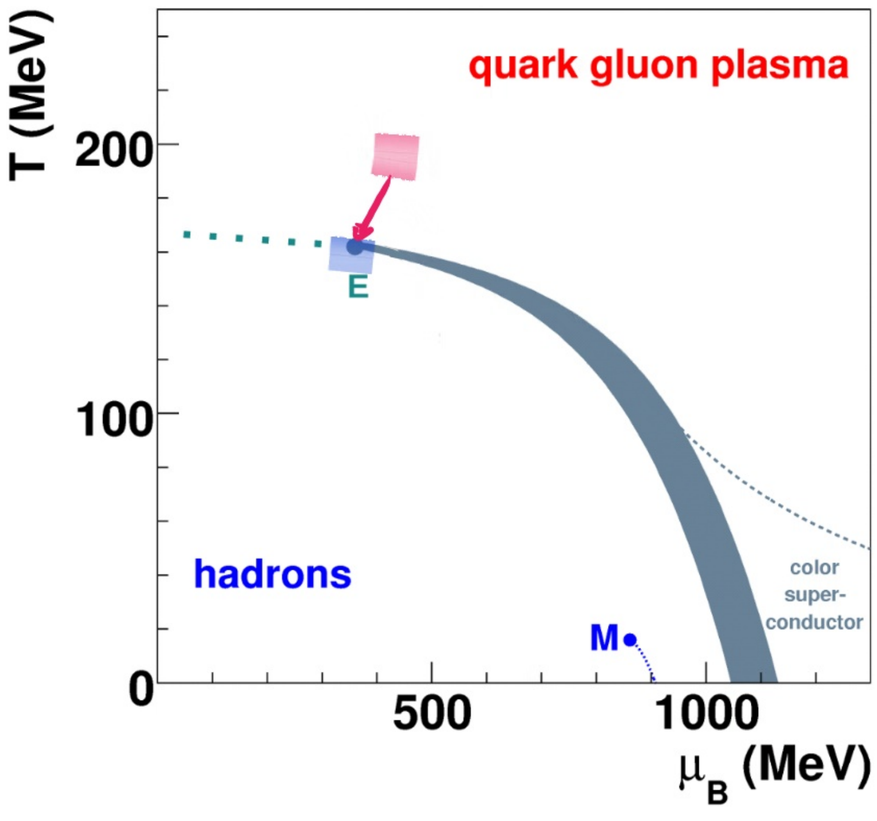
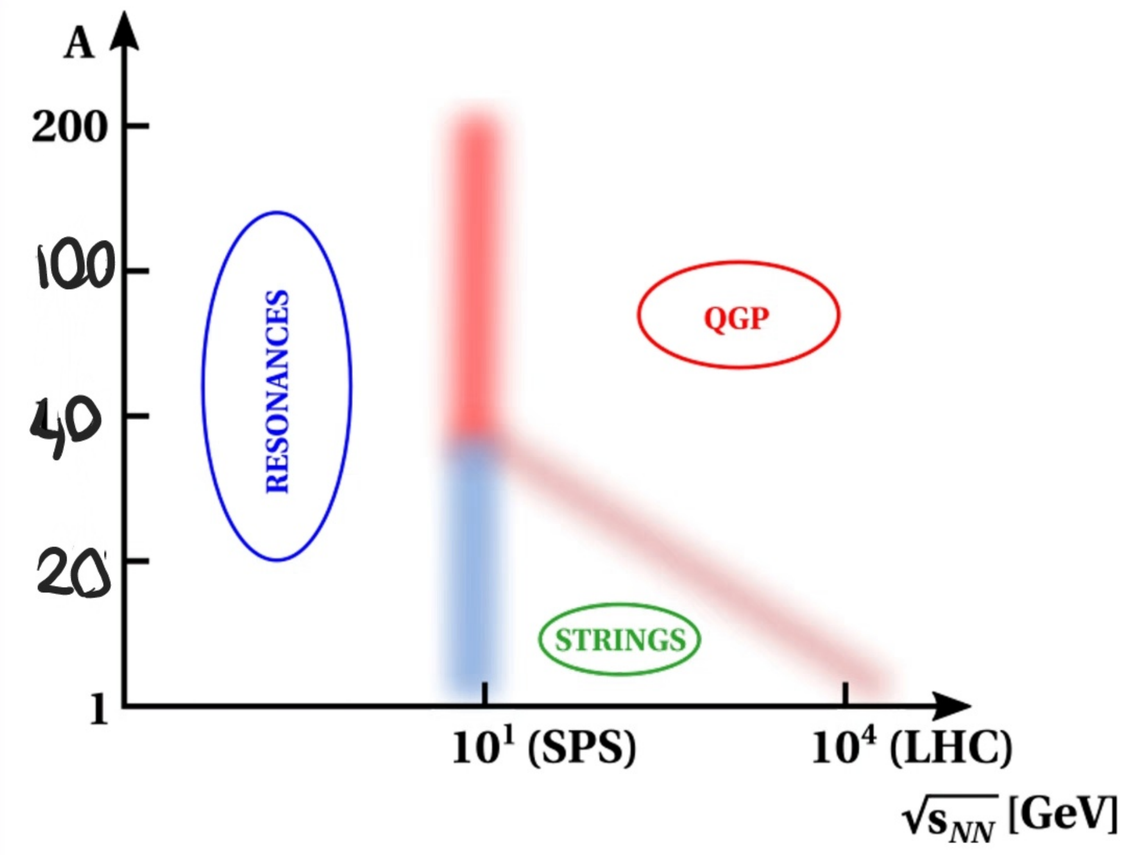


DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS

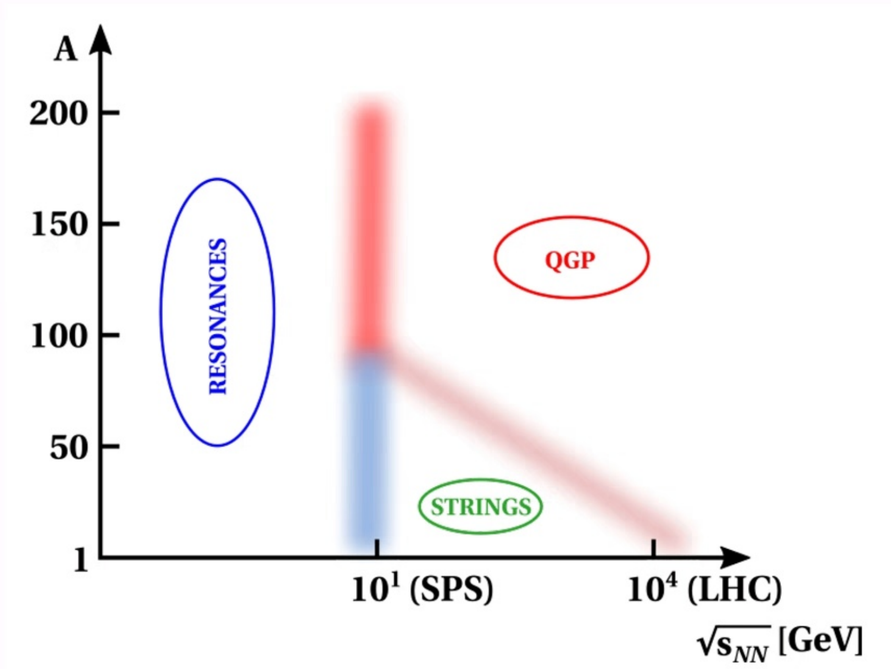


CP SEARCH IN HIC:

- FREEZE-OUT CLOSE TO CP
- QGP AT EARLY STAGE

→ SEARCH FOR CP MAKES SENSE IN THE QGP-DOMAIN OF THE DIAGRAM

(1)



The changeover resonances–strings and resonances–QGP are located at similar collision energies (≈8 GeV/c). This suggests that the resonances–QGP changeover is driven by the resonances–strings one. At high masses of colliding nuclei, strings produced above at the resonances–strings changeover would have density exceeding the strings–QGP changeover. Thus the string domain disappears, and one observes direct resonances–QGP changeover. This locates the resonances–QGP changeover at the energy of the resonances–strings one.

It is interesting to consider other diagrams of high-energy collisions. Here, we discuss a simple example of the hadron–resonance gas diagram. Hagedorn's early papers postulated that hadrons in high-energy collisions are produced according to statistical thermodynamics [71]. Thus, following Hagedorn's postulate, the diagram would include only one production process—the statistical-thermodynamical production, with Hagedorn's temperature $T_H \approx 150$ MeV. This model is clearly in contradiction with the experimental results, as it predicts the K^+/π^+ ratio to be independent of energy and nuclear mass number of colliding nuclei. Over the years, the simple Hagedorn approach evolved into many models that are much more flexible in fitting the data; for a recent review, see Ref. [72]. In particular, it has been popular to fit mean hadron multiplicities, which include multiplicities of kaons and pions, assuming that a hadron gas in equilibrium is created at high-energy collisions. The temperature, the baryon chemical potential, and the gas volume are free parameters of the model and are fitted to the data from each reaction separately. The model cannot predict the energy and nuclear mass dependence of hadron production in this formulation. Thus, it is unsuitable for the diagram construction.