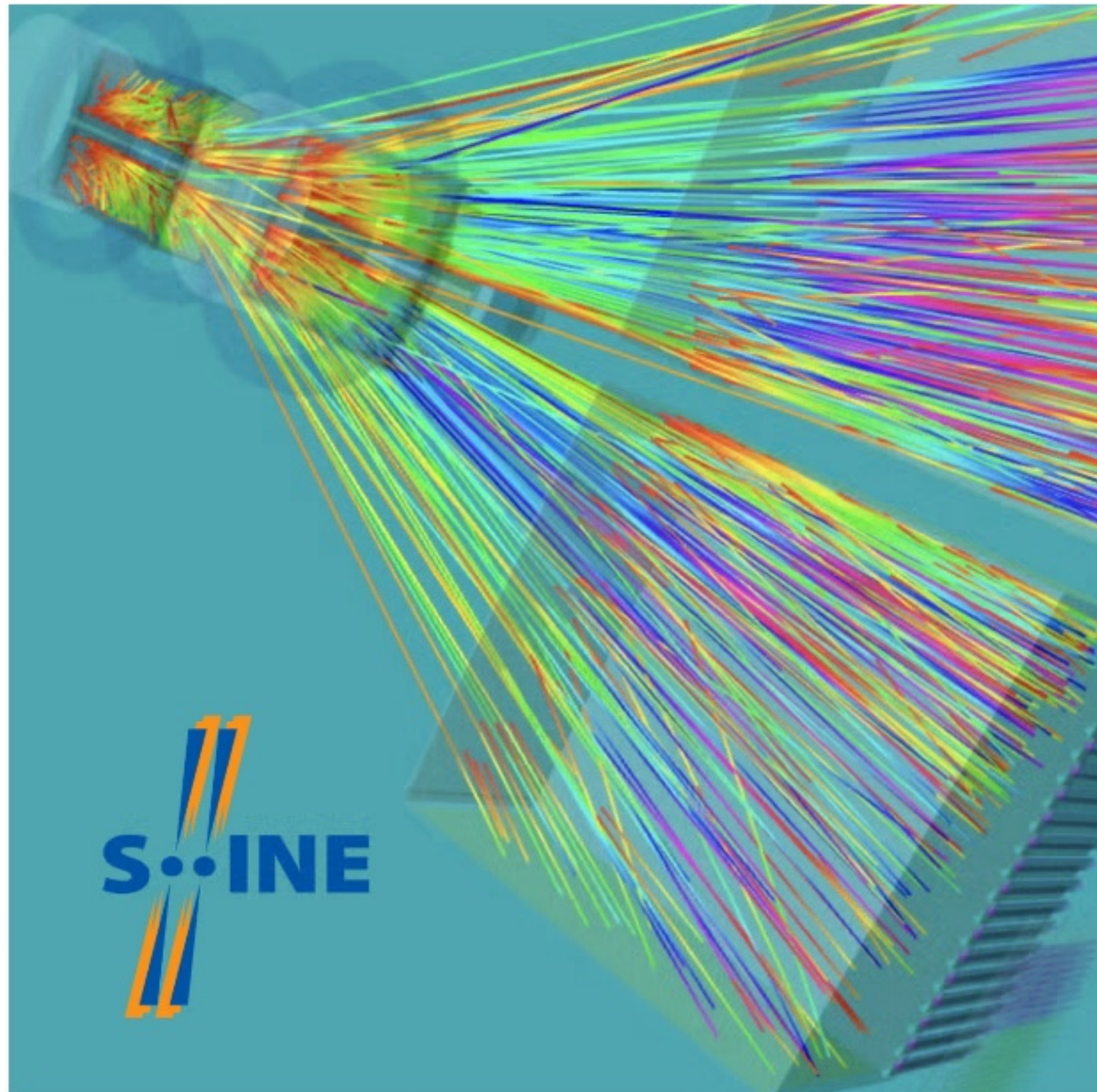


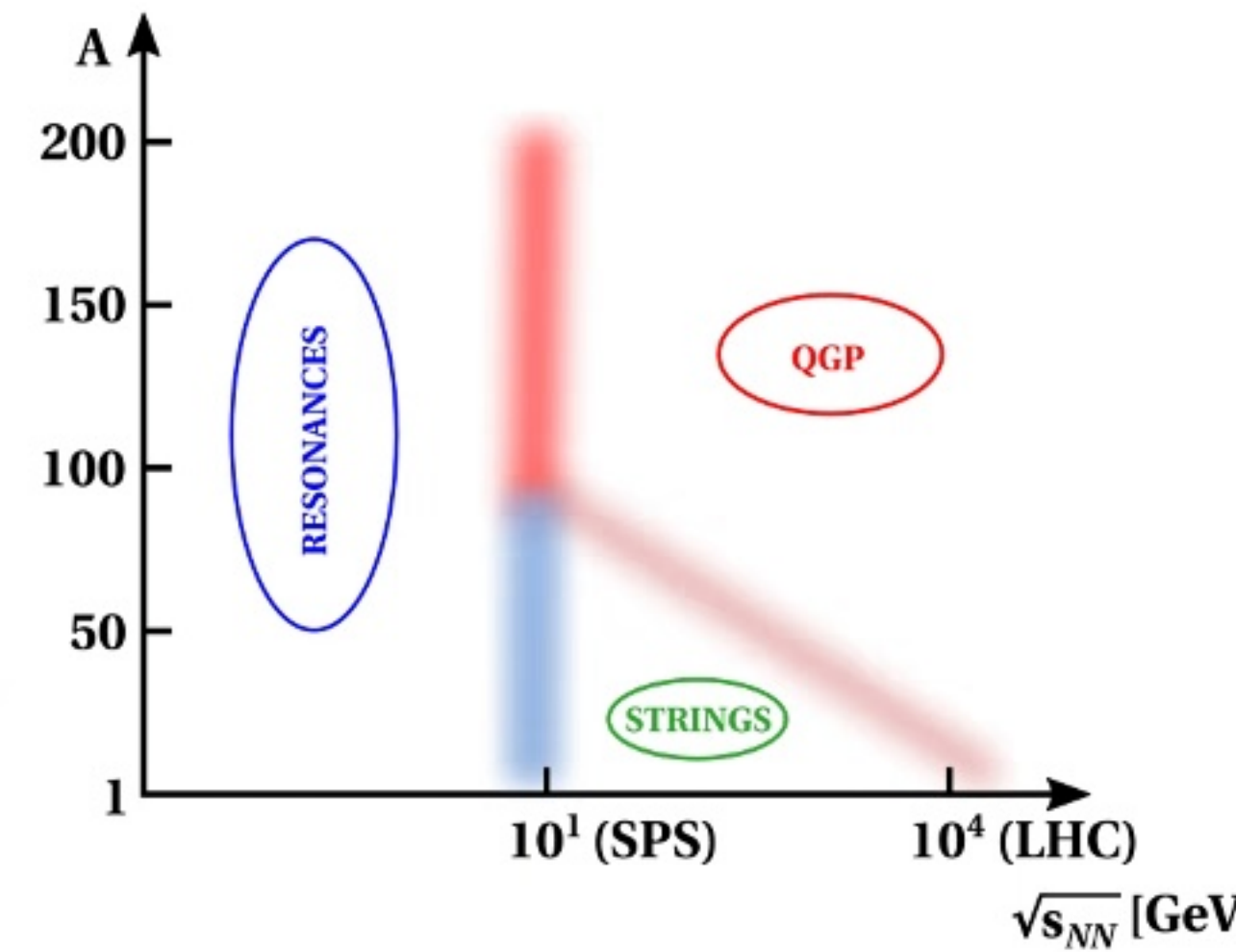
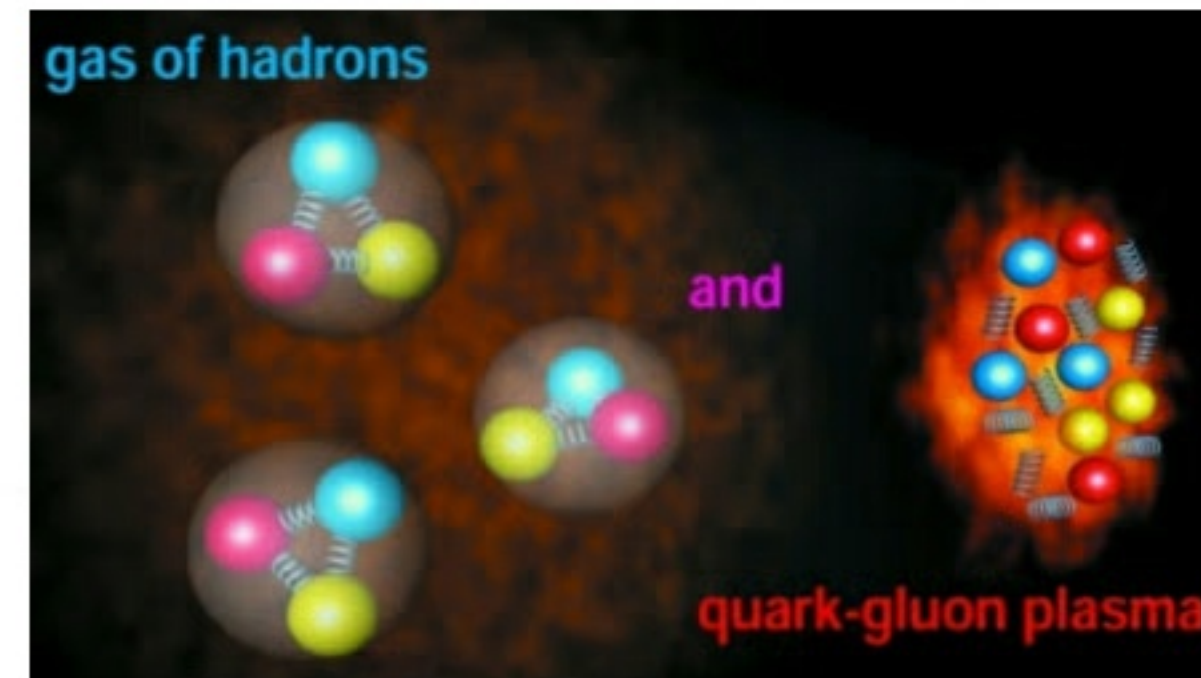
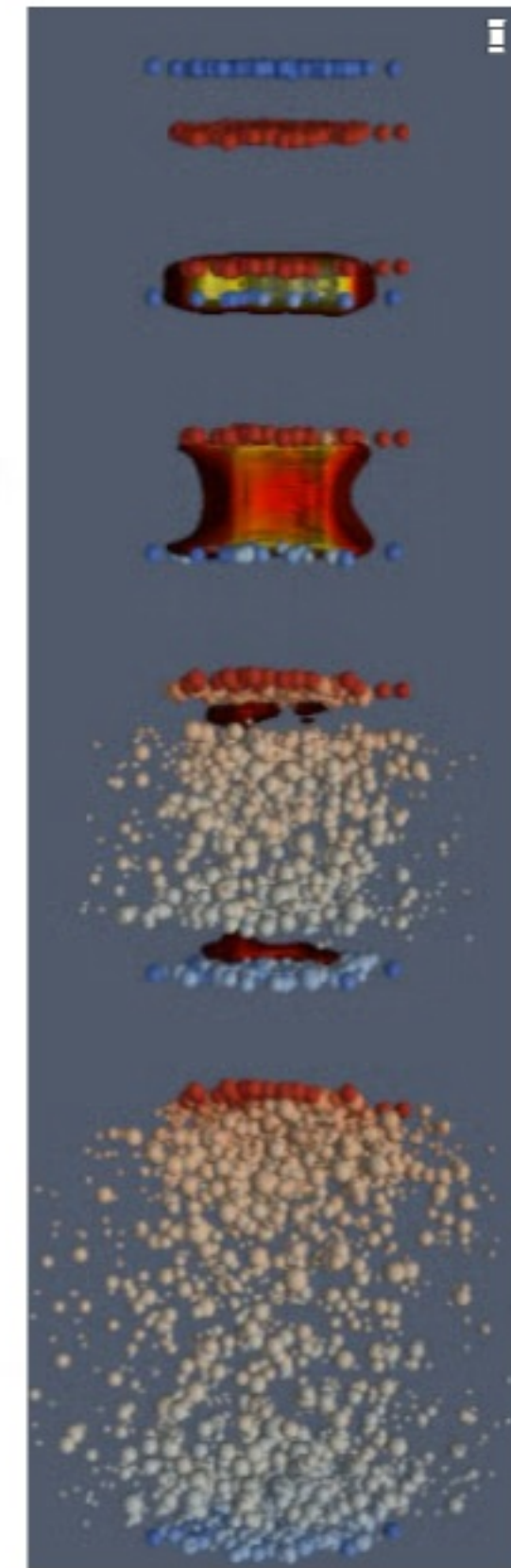
DATA ON
NUCLEUS-NUCLEUS
COLLISIONS AT HIGH ENERGY



MODELS



STATISTICAL AND
HYDRODYNAMICAL
MODELS



PHASE DIAGRAM OF
STRONGLY INTERACTING MATTER

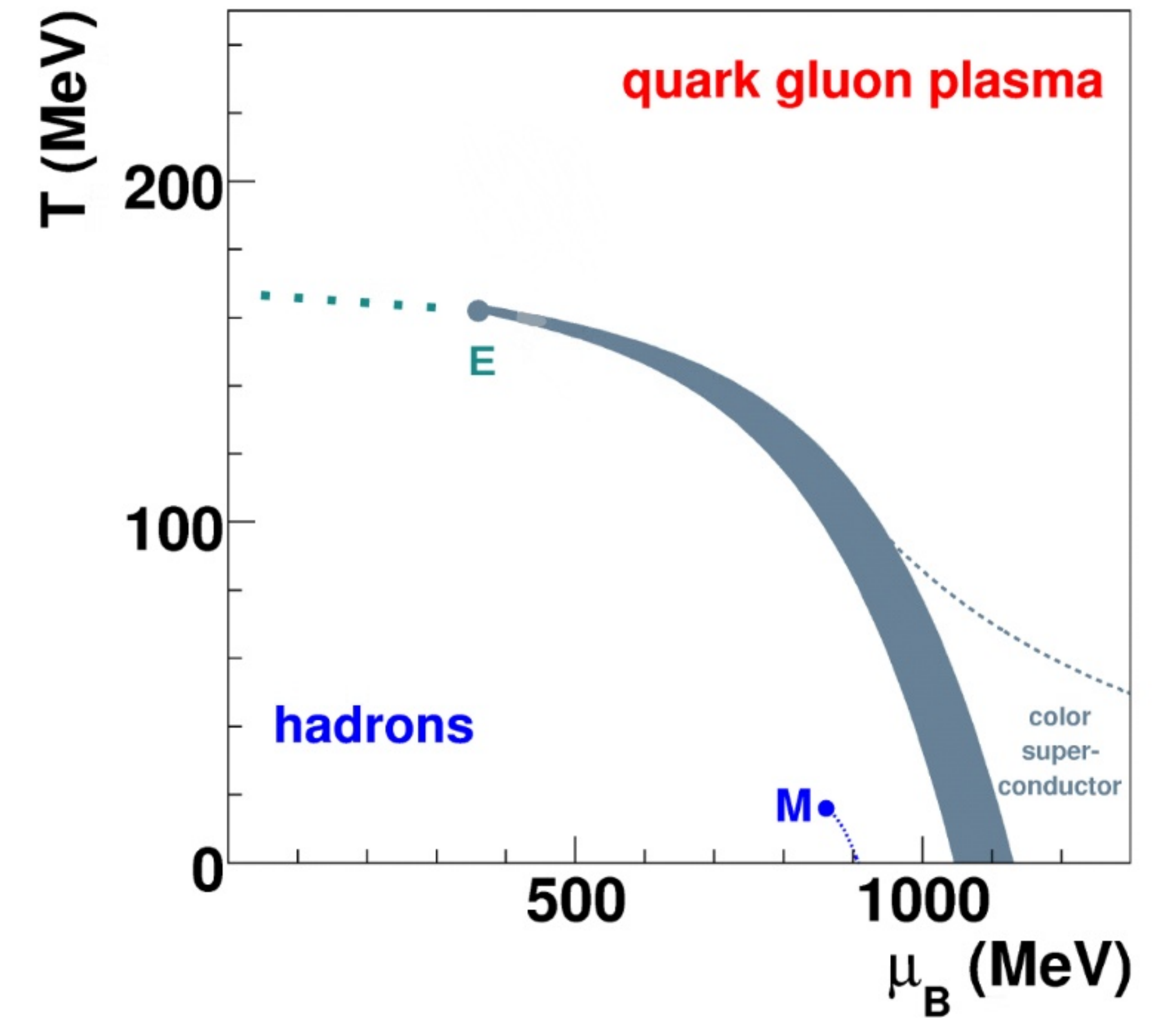


DIAGRAM OF HIGH-ENERGY
NUCLEAR COLLISIONS

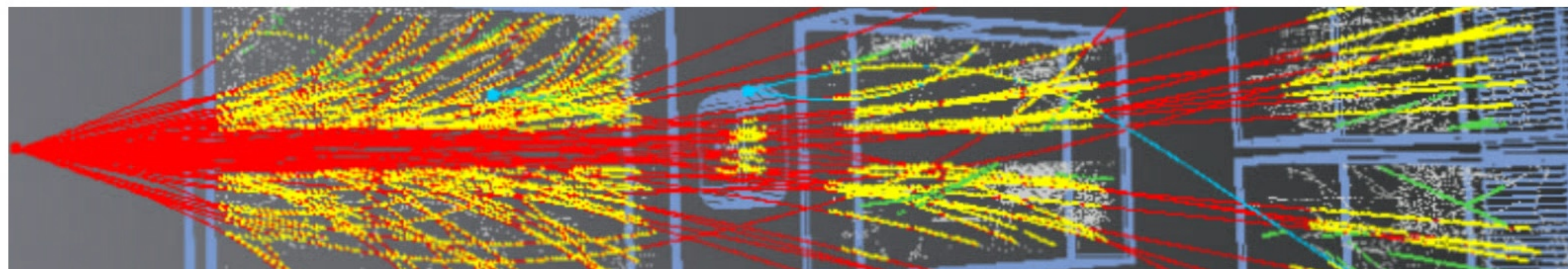
DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS FROM NA61/SHINE

M. GAZDZICKI, JAN KOCHANOWSKI UNIVERSITY, KIELCE
FOR NA61/SHINE

■ DEFINITIONS

■ ■ IDEAS AND DATA

■ ■ ■ DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS





DEFINITIONS: DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS

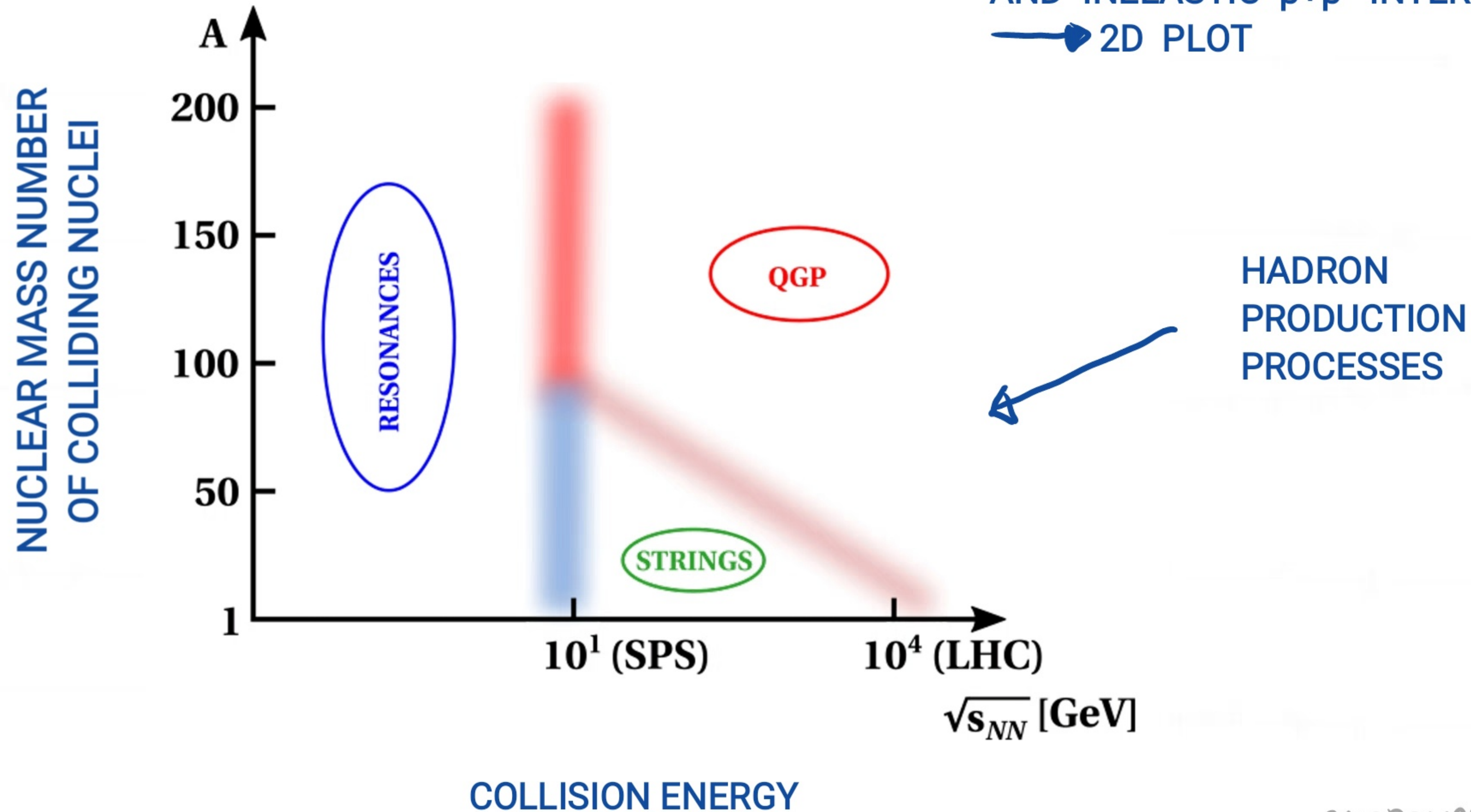


CHART SHOWING EXPERIMENTAL CONDITIONS
(COLLISION ENERGY, NUCLEAR MASS NUMBER, ...)
AT WHICH DISTINCT HADRON PRODUCTION PROCESSES DOMINATE

THE EXAMPLE DISCUSSED HERE:

ONLY CENTRAL A+A COLLISIONS
AND INELASTIC p+p INTERACTIONS

→ 2D PLOT





DEFINITIONS: HADRON PRODUCTION PROCESSES

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



DEFINITIONS: QUANTITATIVE MODELS

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)



DEFINITIONS: EXPERIMENTAL PROBE

THE RATIO OF POSITIVELY-CHARGED KAONS AND PIONS
MEASURED AT MID-RAPIDITY,

$$K^+ / \pi^+$$

- APPROXIMATELY PROPORTIONAL 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)

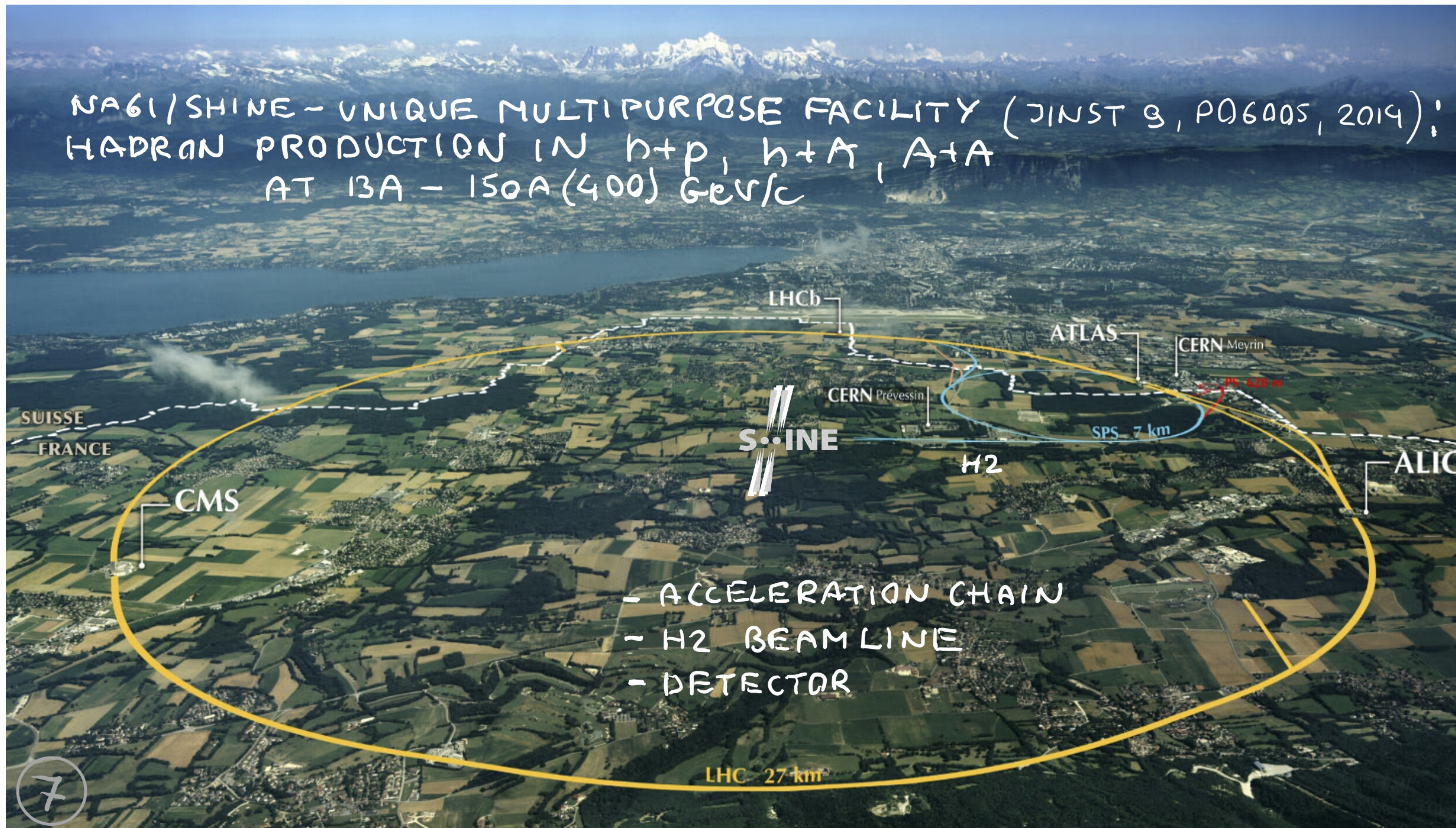
MG, GORENSTEIN
APP B 30, 2705 (1999)

- RICH EXPERIMENTAL DATA IN HIGH-ENERGY NUCLEAR COLLISIONS



DEFINITIONS: NA61/SHINE

NA61/SHINE - UNIQUE MULTIPURPOSE FACILITY (JINST 9, P06005, 2014):
HADRON PRODUCTION IN $h+p$, $h+A$, $A+A$
AT 13A - 150A (400) GeV/c

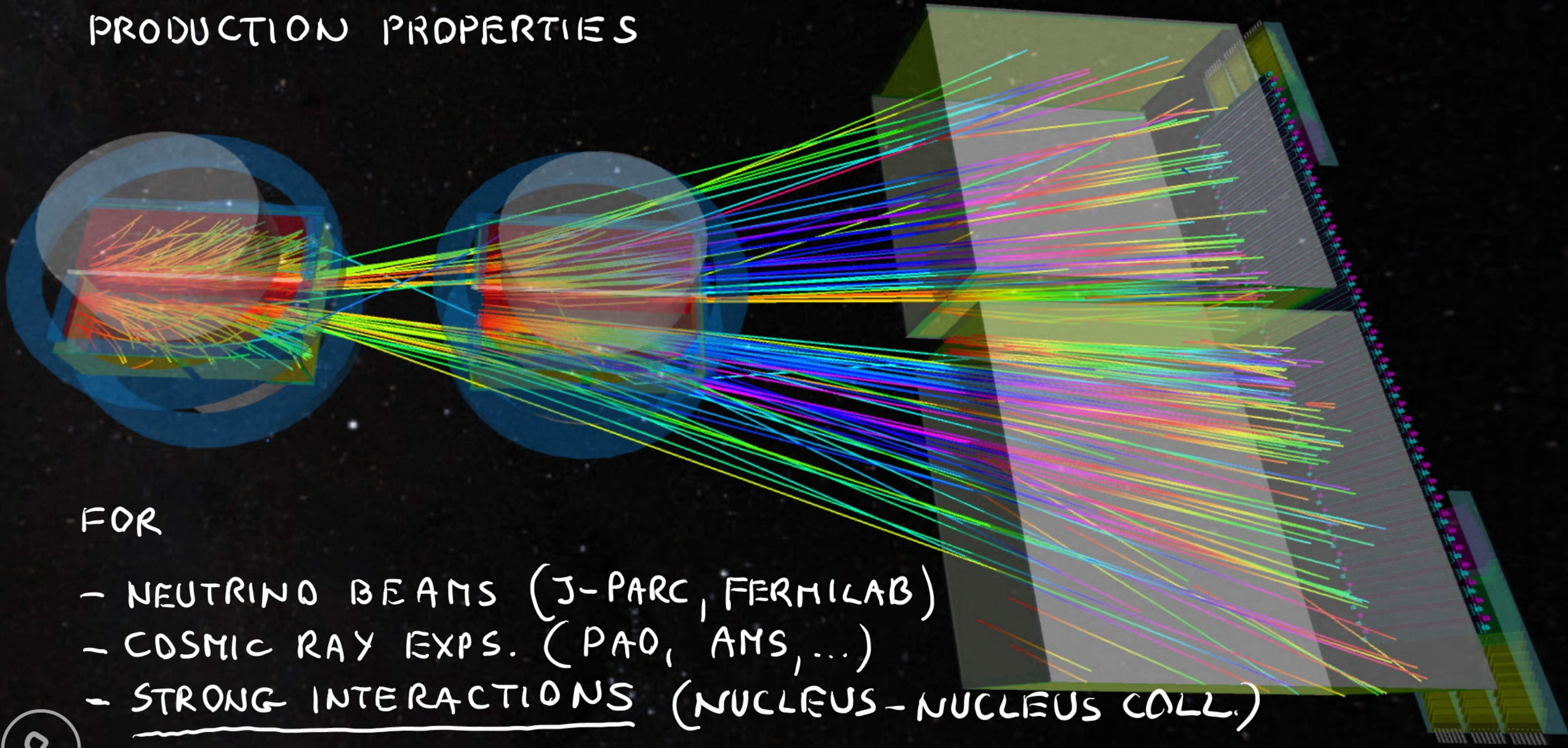


- ACCELERATION CHAIN
- H2 BEAMLINE
- DETECTOR

LHC 27 km

DEFINITIONS: NA61/SHINE PHYSICS PROGRAMMES

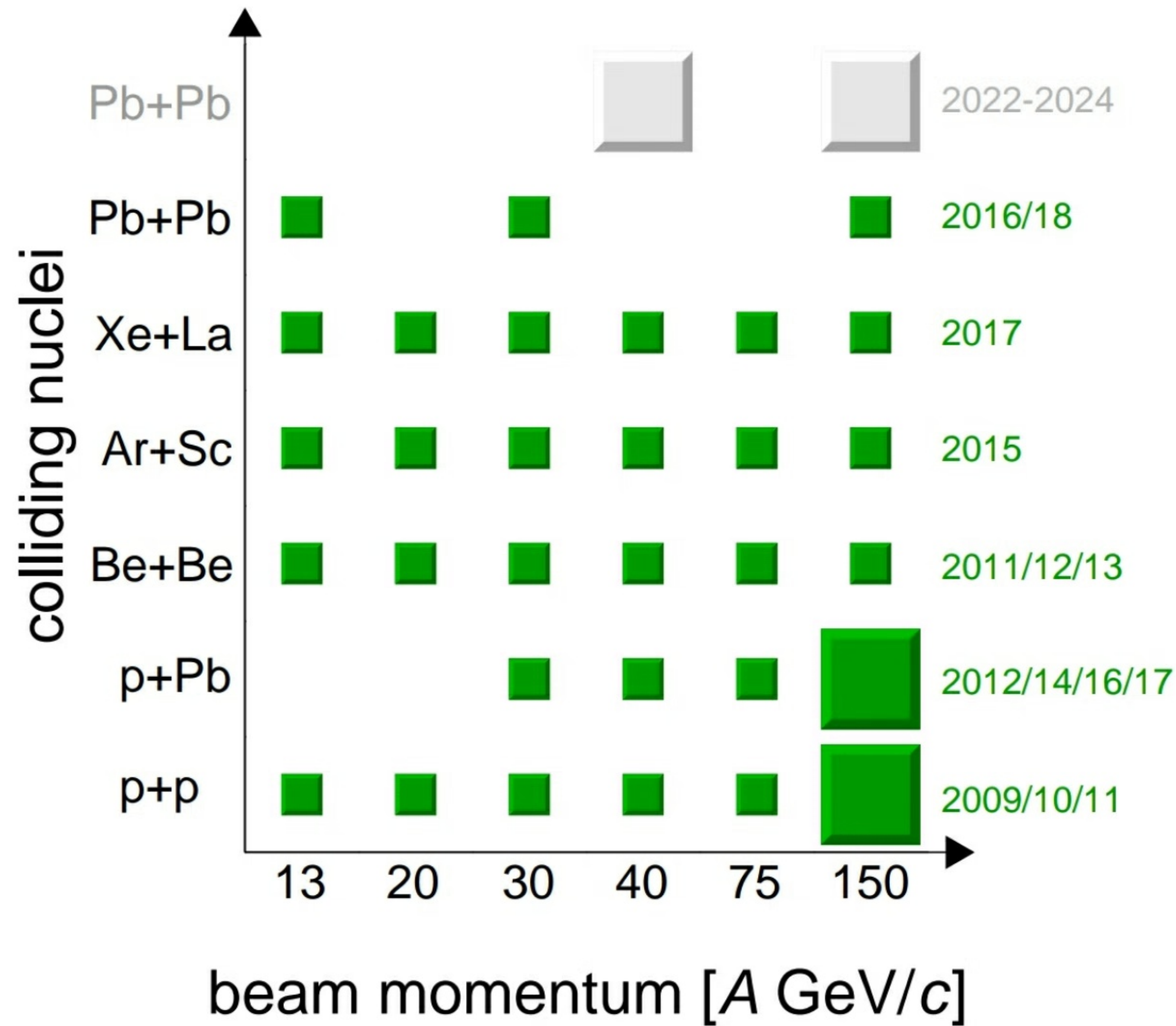
MEASUREMENTS OF HADRON
PRODUCTION PROPERTIES



FOR

- NEUTRINO BEAMS (J-PARC, FERMILAB)
- COSMIC RAY EXPS. (PADO, AMS, ...)
- STRONG INTERACTIONS (NUCLEUS-NUCLEUS COLL.)

DEFINITIONS: NA61/SHINE DATA ON HIGH-ENERGY NUCLEAR COLLISIONS

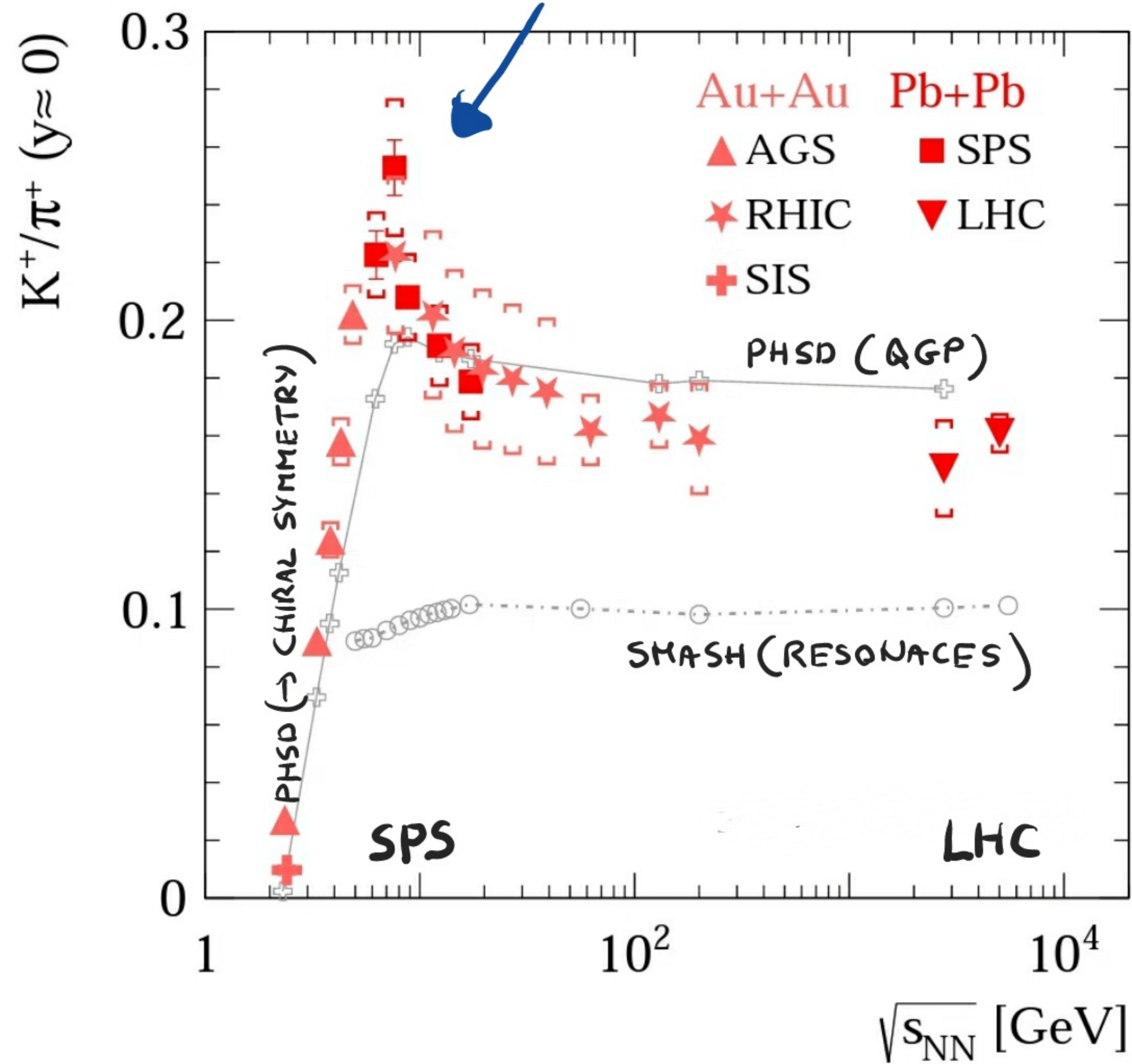


UNIQUE INPUT TO ESTABLISH
DIAGRAM OF HIGH-ENERGY
NUCLEAR COLLISIONS

$\sqrt{s_{NN}} \approx 5$ ← → 17 GeV

IDEAS AND DATA: HEAVY-ION COLLISIONS

THE HORN STRUCTURE



RESONANCES - QGP CHANGEOVER
(ONSET OF DECONFINEMENT)

MG, GORENSTEIN
APP B 30, 2705 (1959)

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

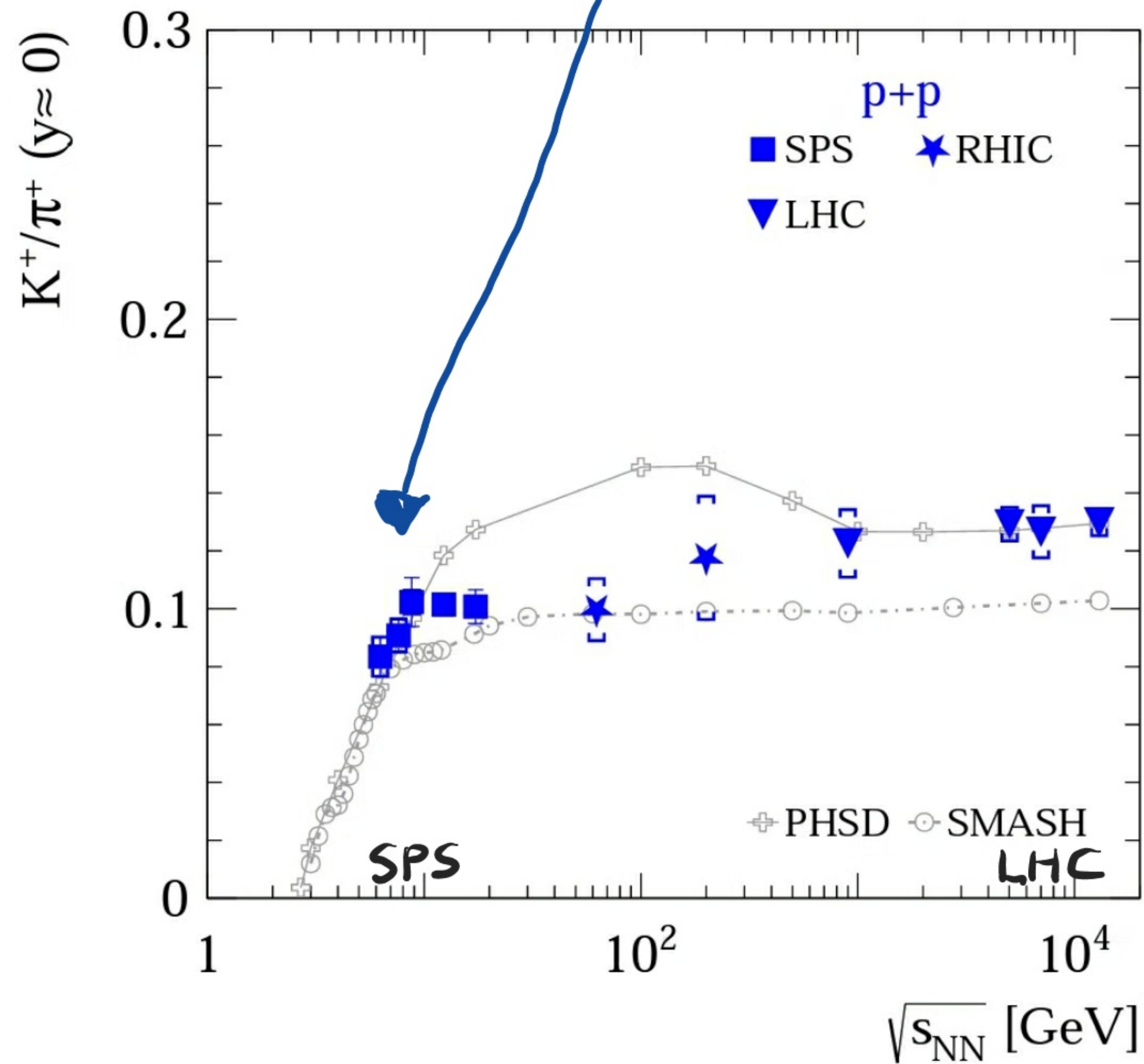
NA49, PRC 66, 054902

IDEAS AND DATA: PROTON-PROTON INTERACTIONS

THE BREAK STRUCTURE



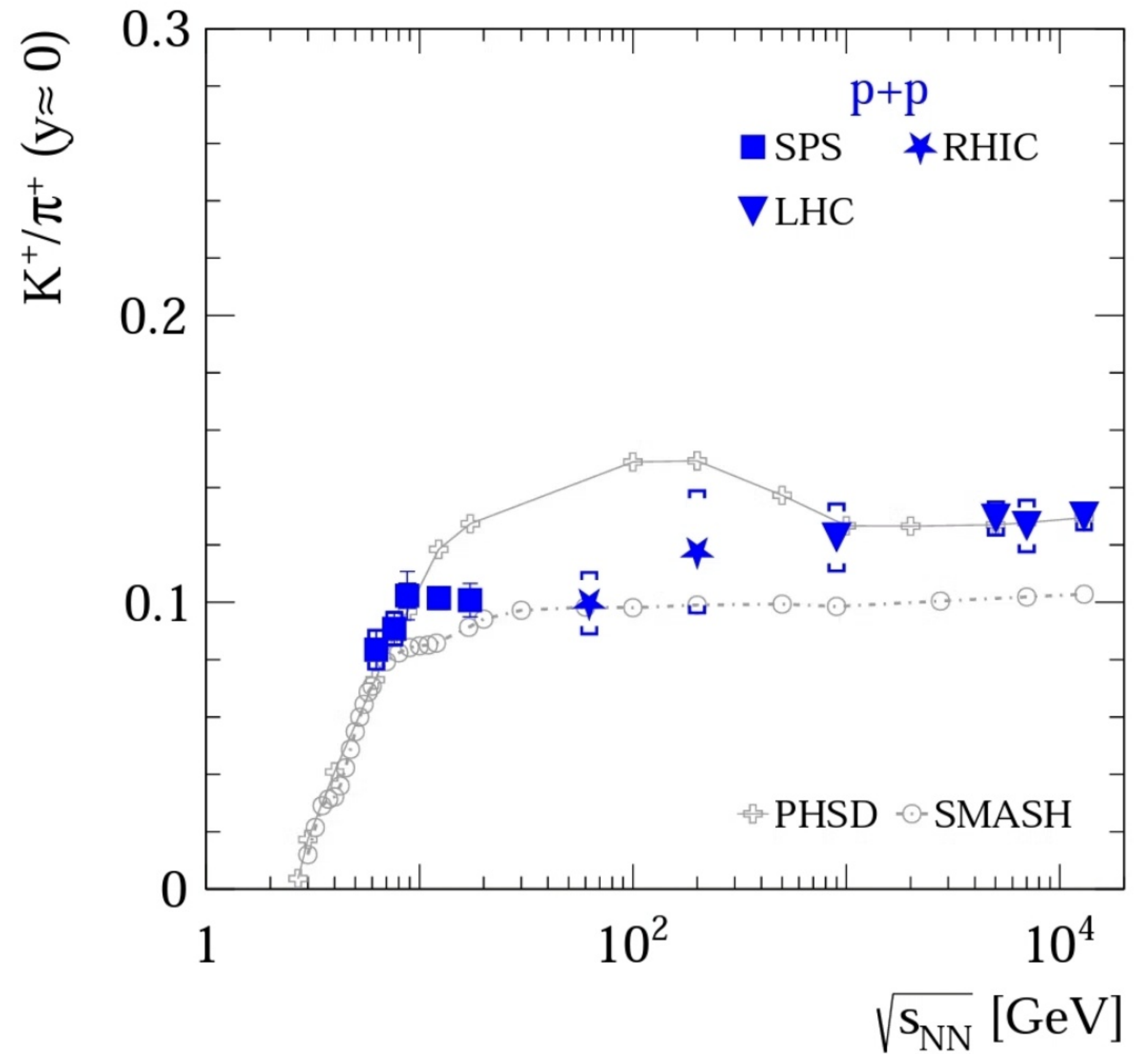
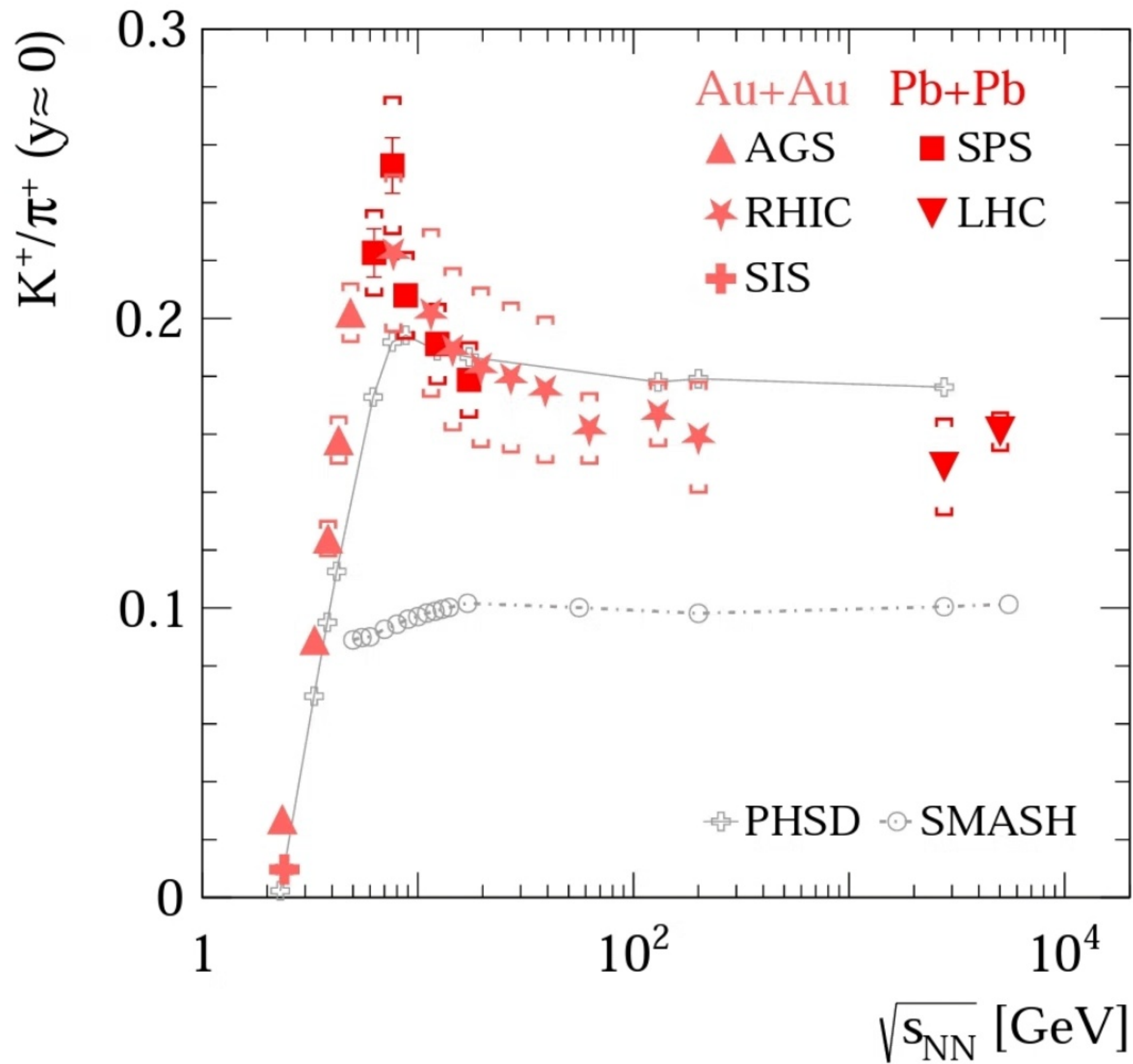
RESONANCES-STRINGS CHANGEOVER



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

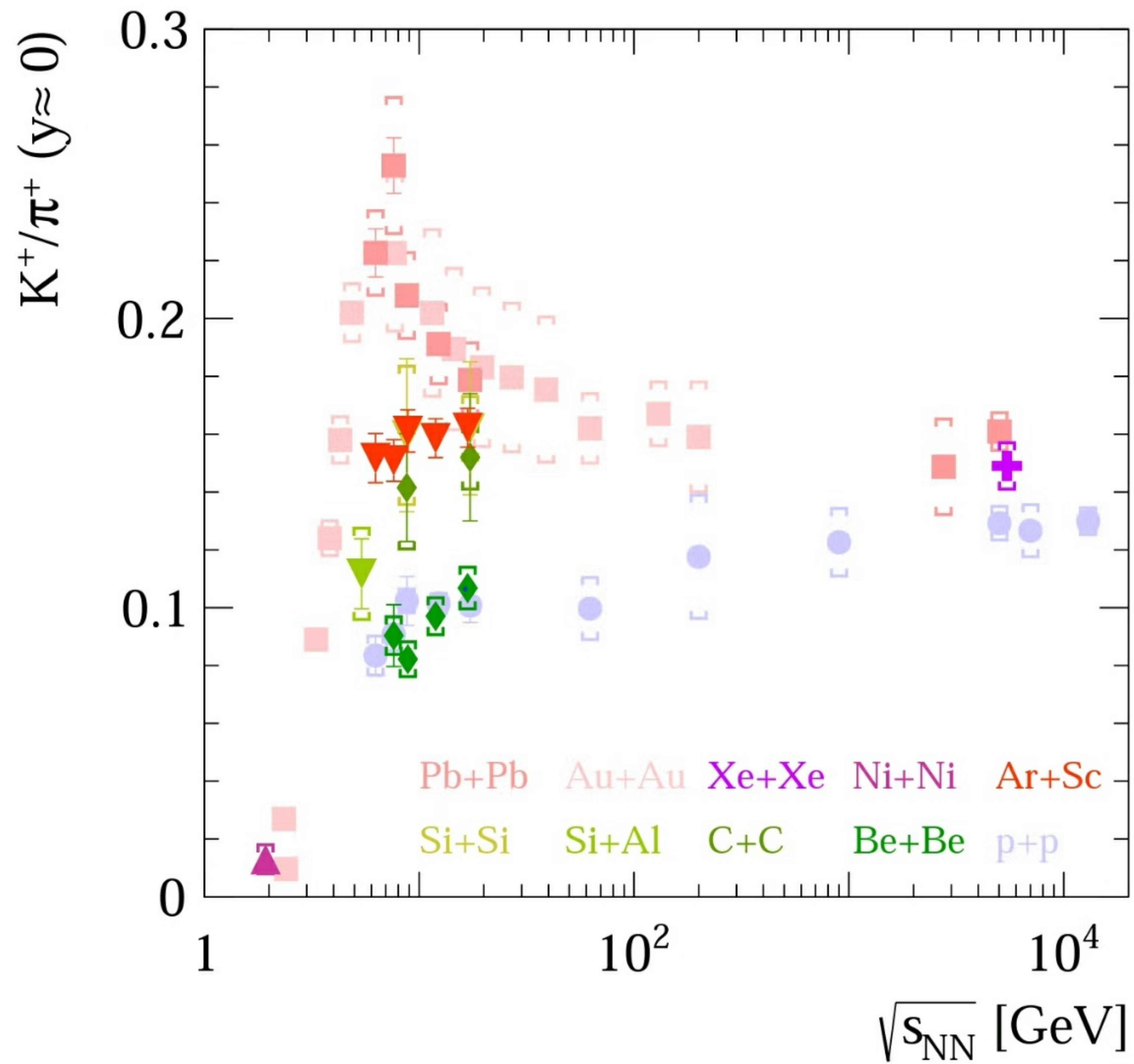
IDEAS AND DATA: Pb+Pb vs p+p



VERY DIFFERENT ENERGY DEPENDENCE

→ COLLISIONS OF INTERMEDIATE-MASS NUCLEI

IDEAS AND DATA: COLLISIONS OF INTERMEDIATE-MASS NUCLEI



◆ Be + Be \approx p + p

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

▼ Ar + Sc \approx Pb + Pb
AT THE TOP SPS

NO HORN IN Ar + Sc

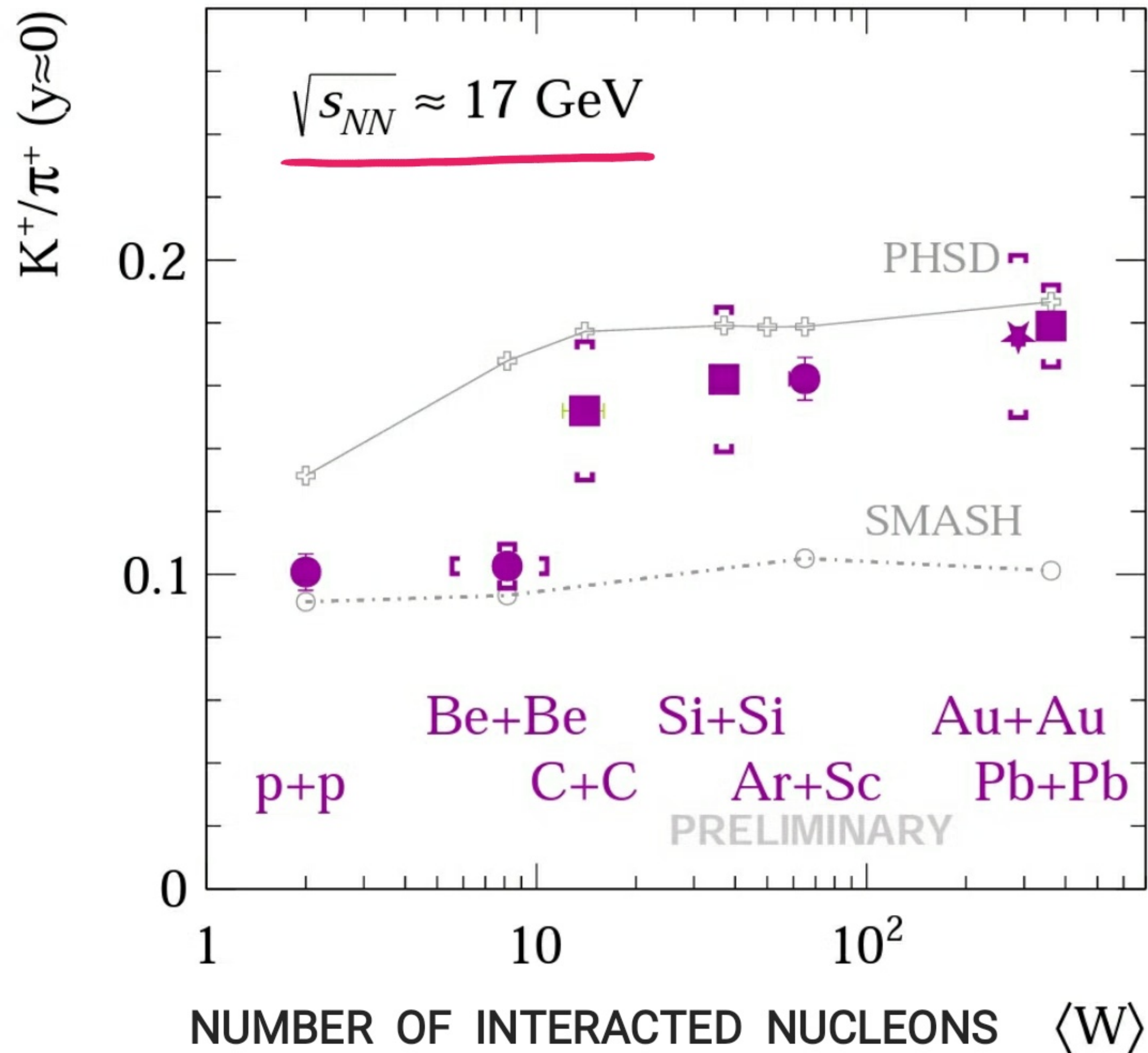
NAGI/SHINE:
EPJ C81, 337 (2021)

✦ p + p \approx Xe + Xe \approx Pb + Pb AT LHC

ALICE
NATURE PHYS. 13, 535 (2017)

⤵ QGP IN p + p AT LHC

IDEAS AND DATA: COLLISIONS OF INTERMEDIATE MASS NUCLEI



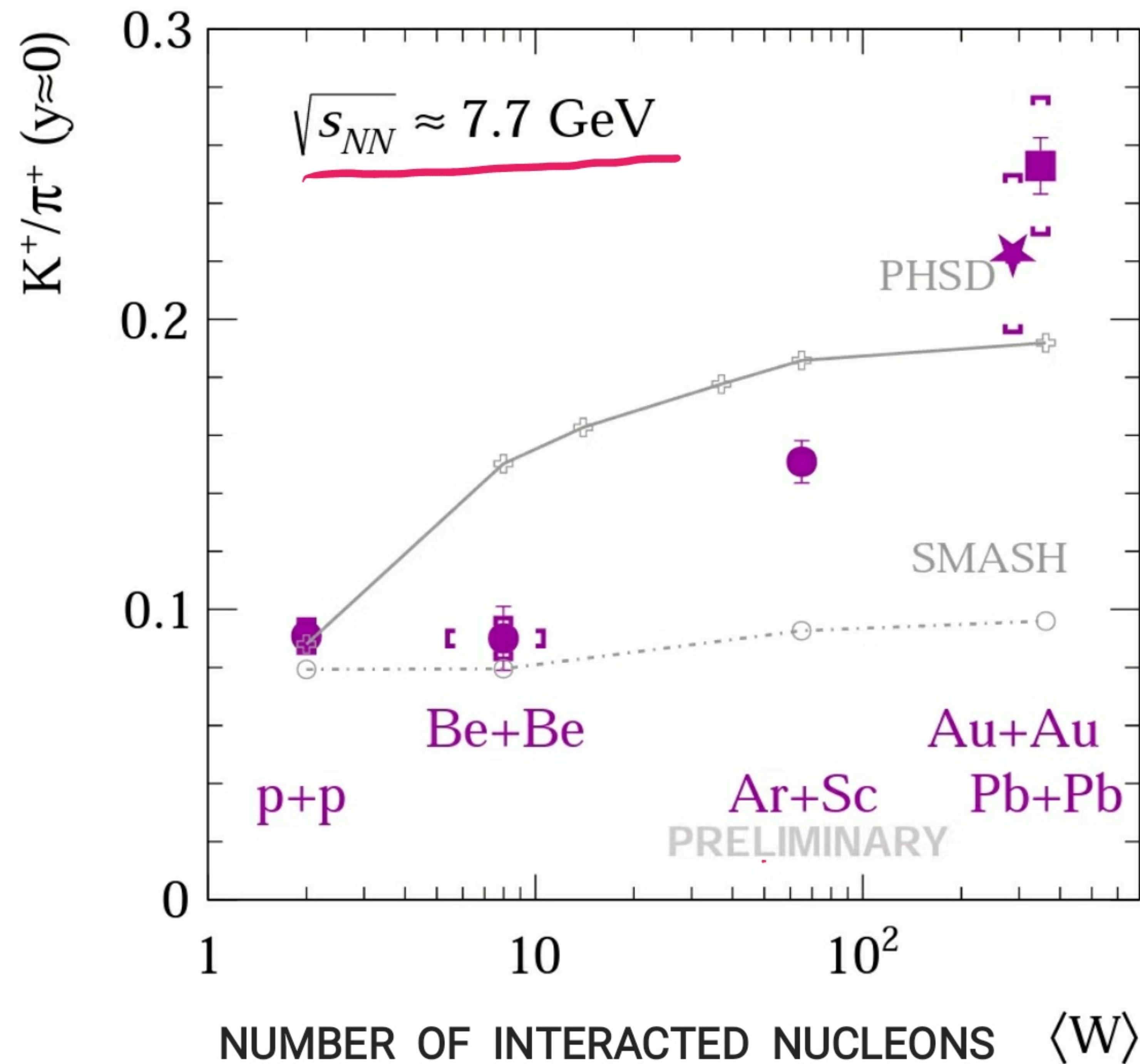
JUMP BETWEEN p + p, Be + Be AND Ar + Sc, Pb + Pb AT THE TOP SPS ENERGIES

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)

IDEAS AND DATA: COLLISIONS OF INTERMEDIATE MASS NUCLEI



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

POSSIBLY DUE TO:

- APPROACHING EQUILIBRIUM WITH INCREASING $\langle W \rangle$ AND SYSTEM LIFE-TIME
- WEAKENING OF CANONICAL STRANGENESS SUPPRESSION WITH INCREASING $\langle W \rangle$
- INCREASING ROLE OF CHIRAL-SYMMETRY RESTORATION

DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS

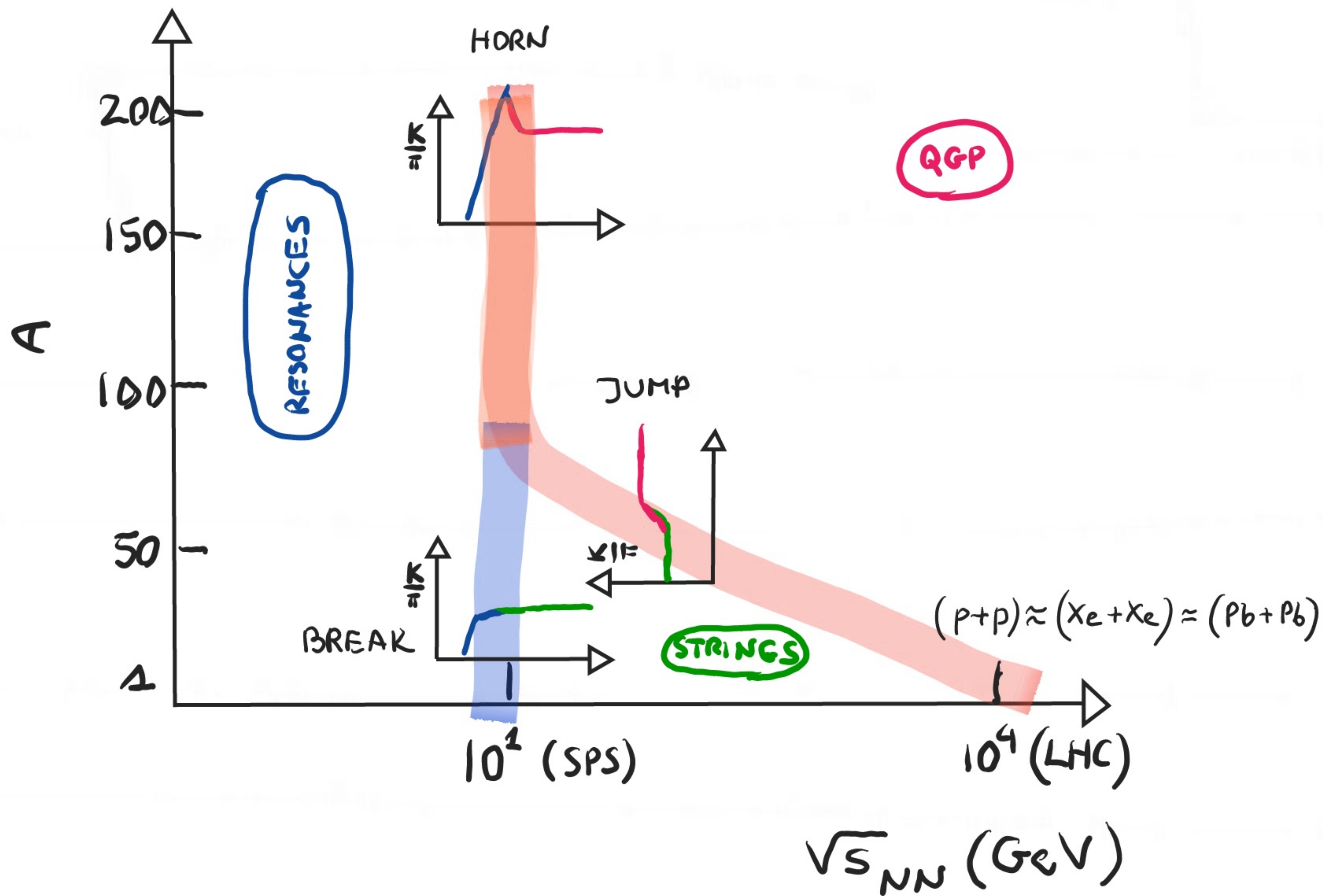




DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS

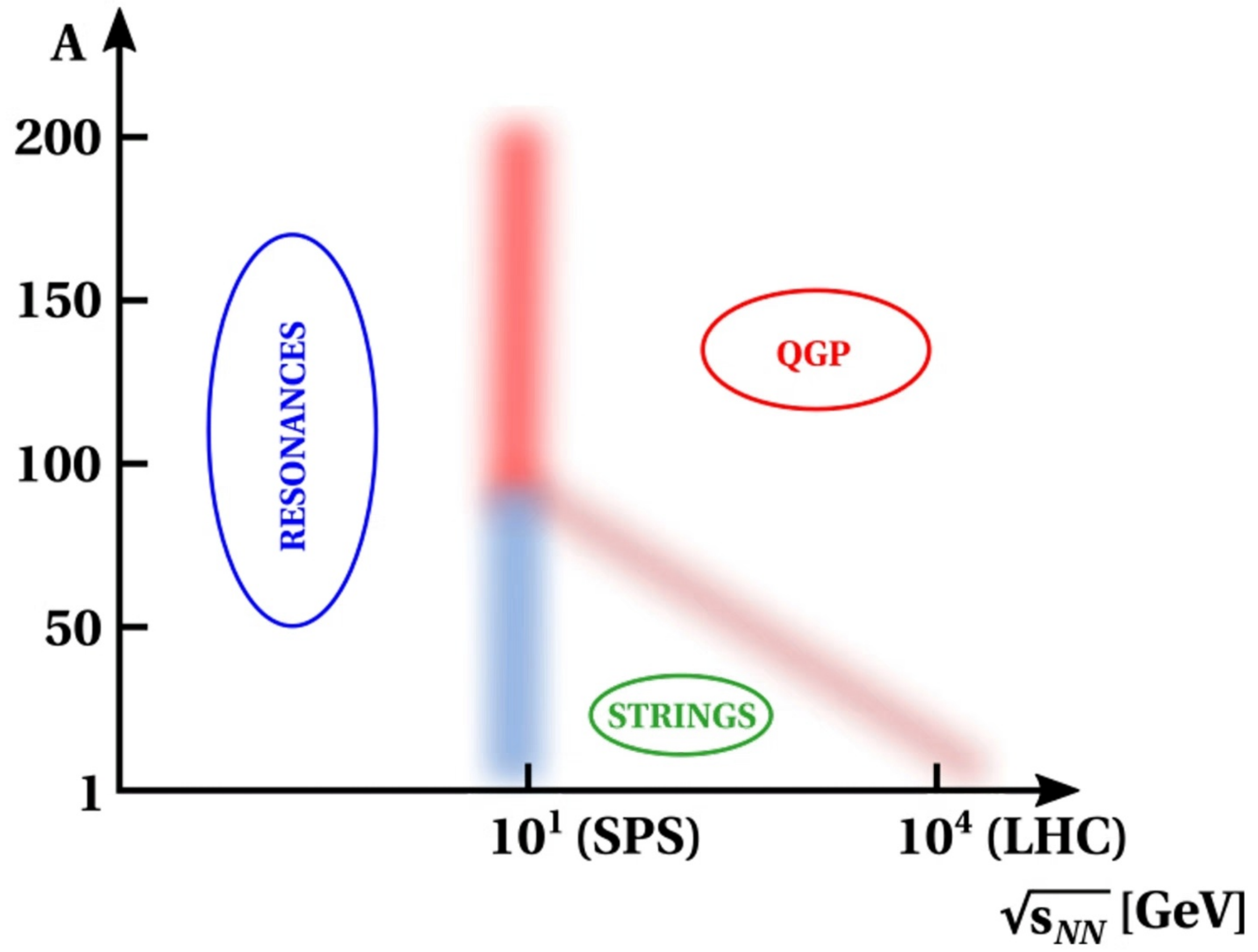




DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS ON CRITICAL POINT

PHASE DIAGRAM

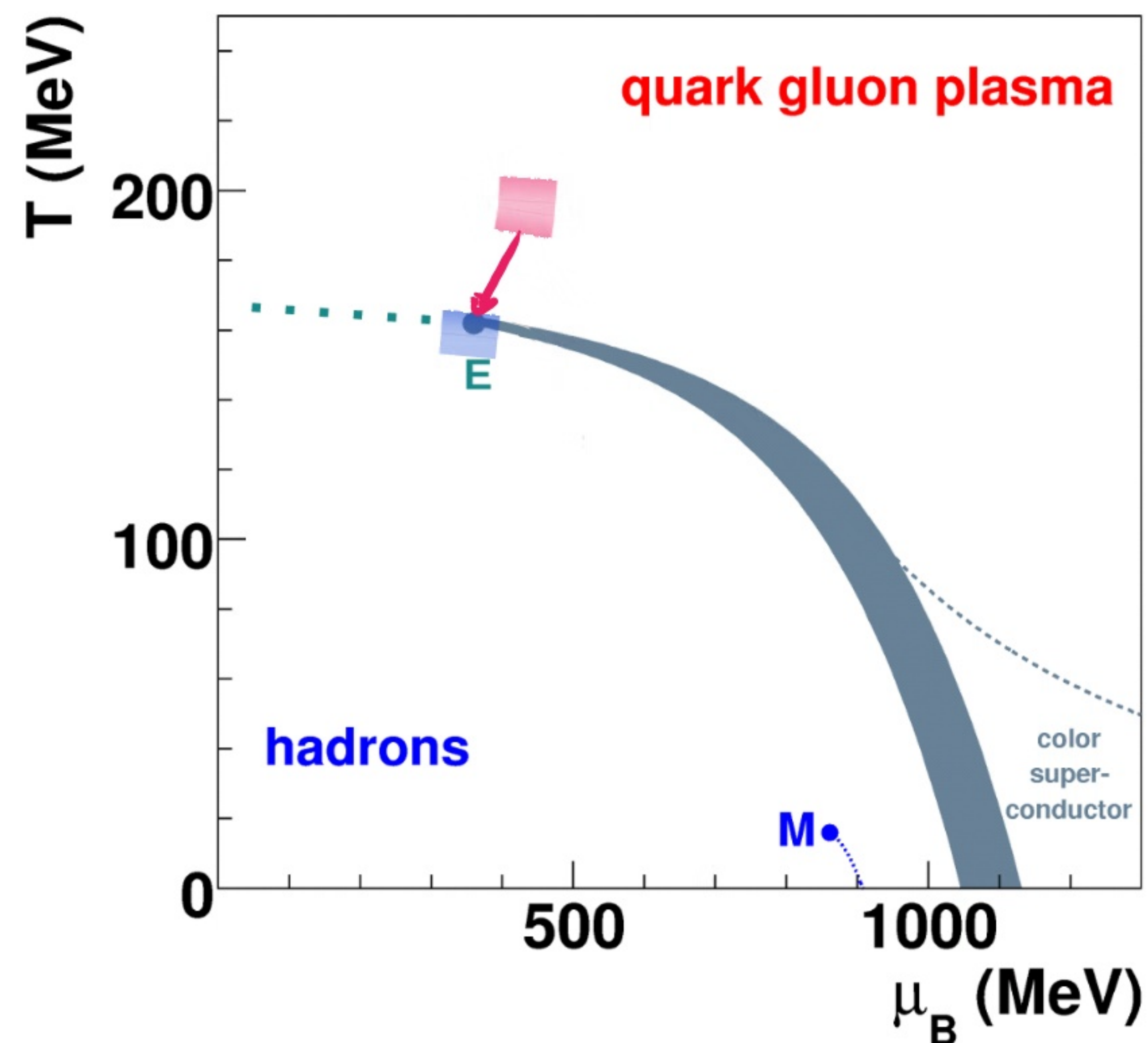
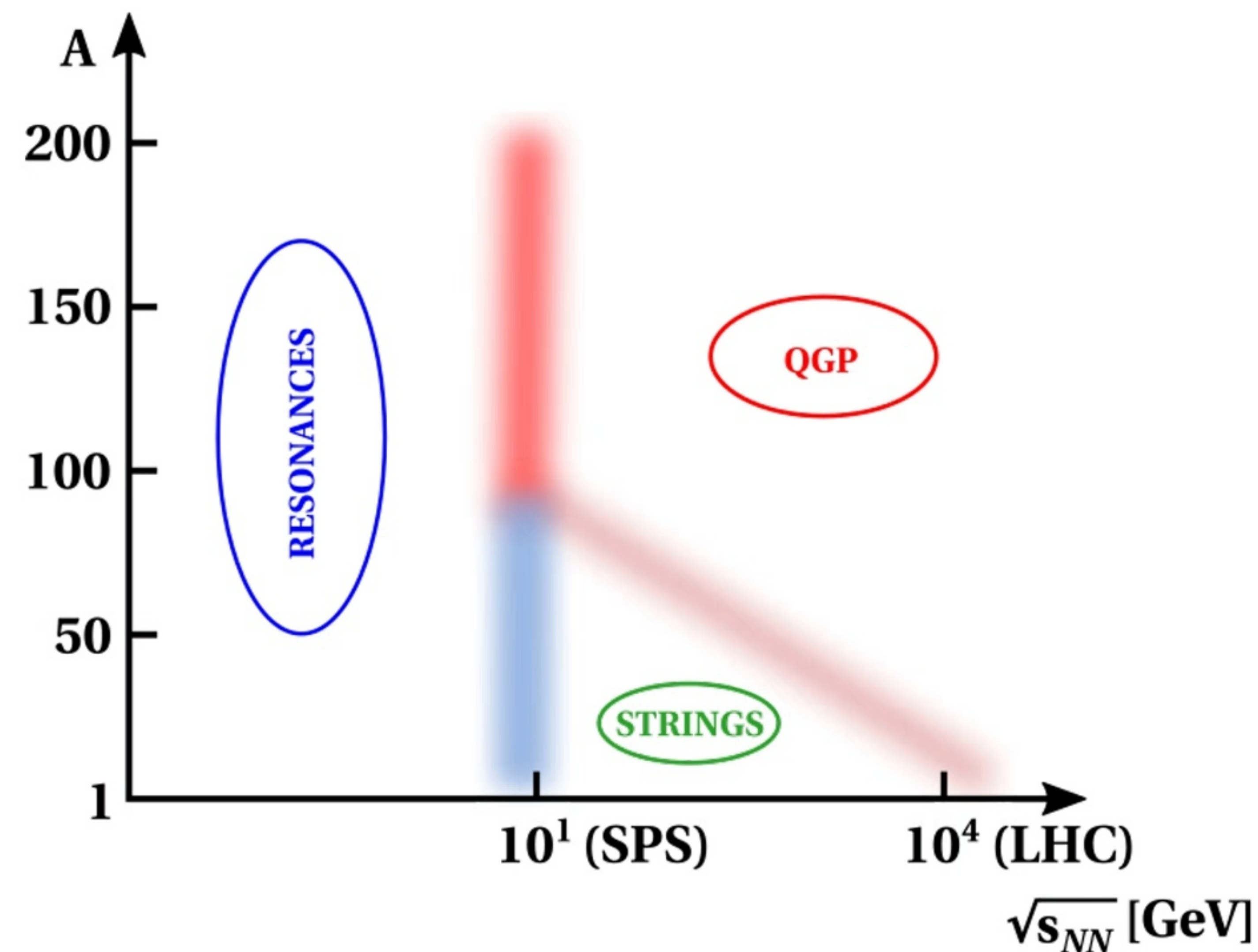


DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS



CP SEARCH IN HIC:

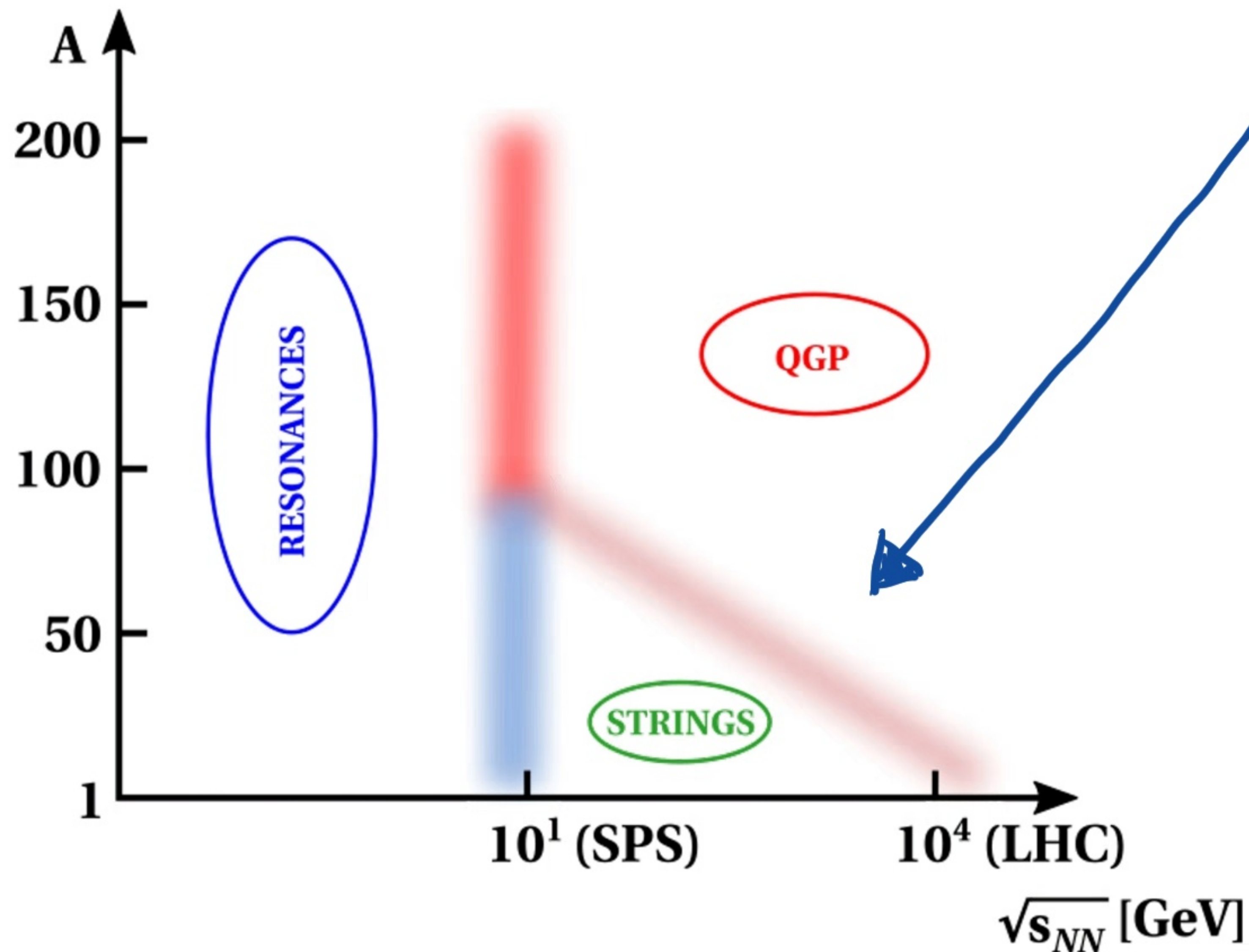
- FREEZE-OUT CLOSE TO CP ■
- QGP AT EARLY STAGE ■



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



DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS ON FUTURE MEASUREMENTS



TO ESTABLISH COLLISION-ENERGY DEPENDENCE OF THE STRINGS-QGP CHANGEOVER

PRECISION DATA ON COLLISIONS OF LIGHT AND MEDIUM-MASS NUCLEI AT CERN SPS, FIXED-TARGET LHC AND LHC ARE NEEDED

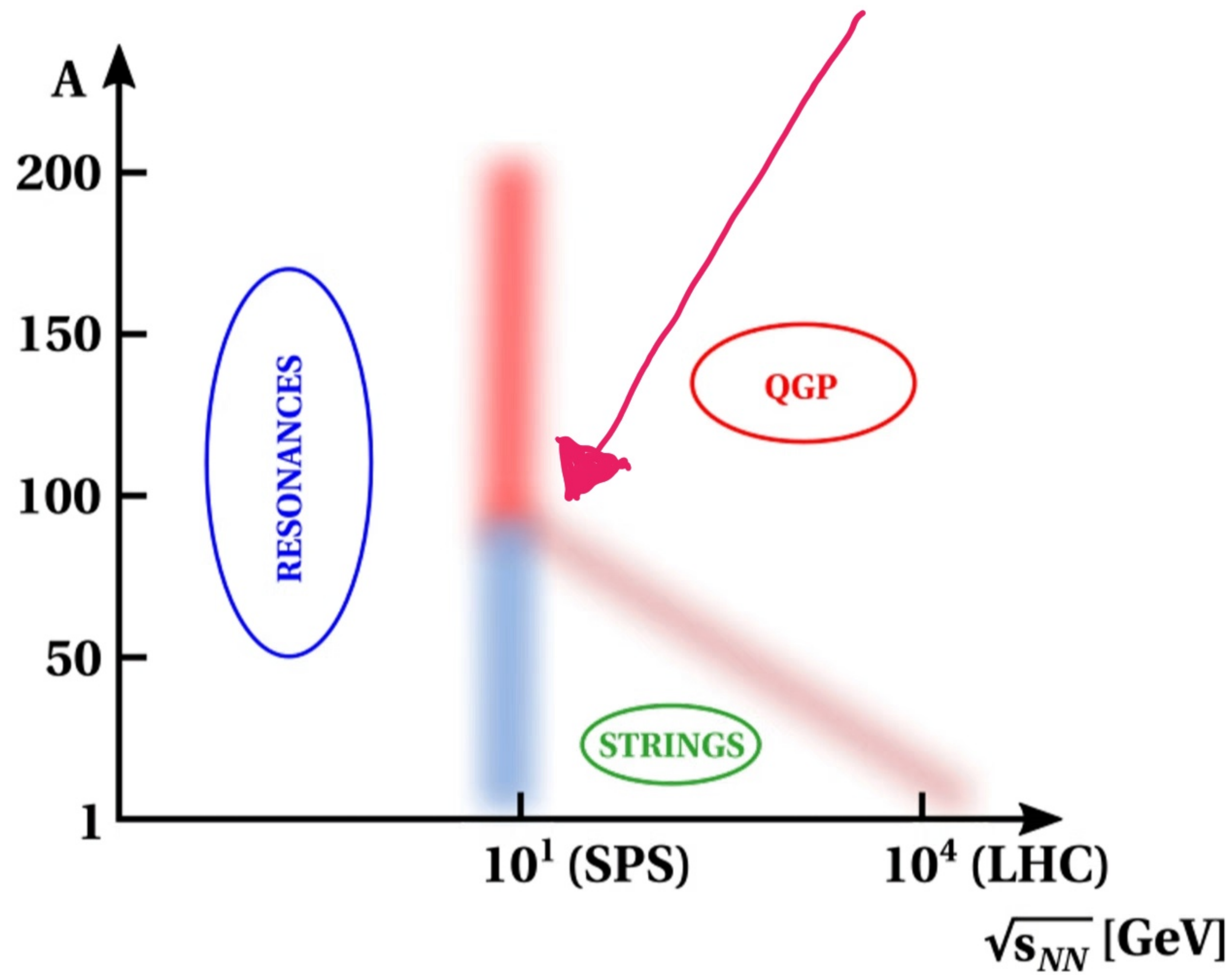
MEASUREMENTS WITH OXYGEN BEAM ARE PLANNED IN 2024 BY LHC EXPERIMENTS AND NA61/SHINE AT SPS

POST-LS3 MEASUREMENTS WITH LIGHT AND MEDIUM-MASS NUCLEI ARE DISCUSSED



DIAGRAM OF HIGH-ENERGY NUCLEAR COLLISIONS

→ TRIPLE REGION ?



NEED FOR:

- MODELLING
- SIGNALS
- EXPERIMENTAL SEARCH