20 YEARS AFTER DISCOVERY OF A NEW STATE OF MATTER

STUDIES OF PHASE DIAGRAM OF STRONGLY INTERACTING MATTER AT CERN SPS

M. GAZDZICKI, KIELCE, FRANKFURT

■ QUARK-GLUON PLASMA (1986 – 2003)

■ ■ CRITICAL STRUCTURES (1997 – 2025 ?)

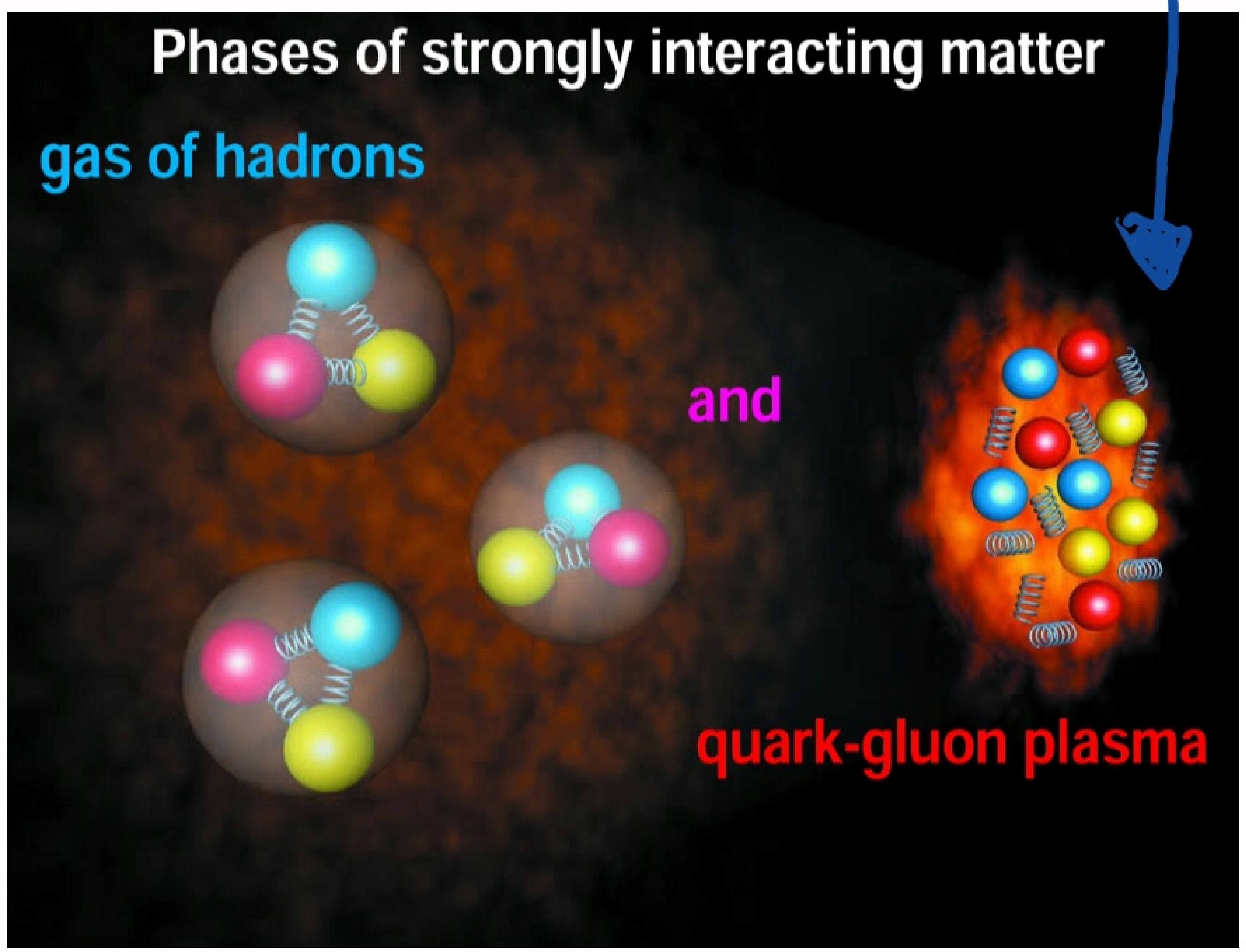
■ ■ ■ INVENTING FUTURES

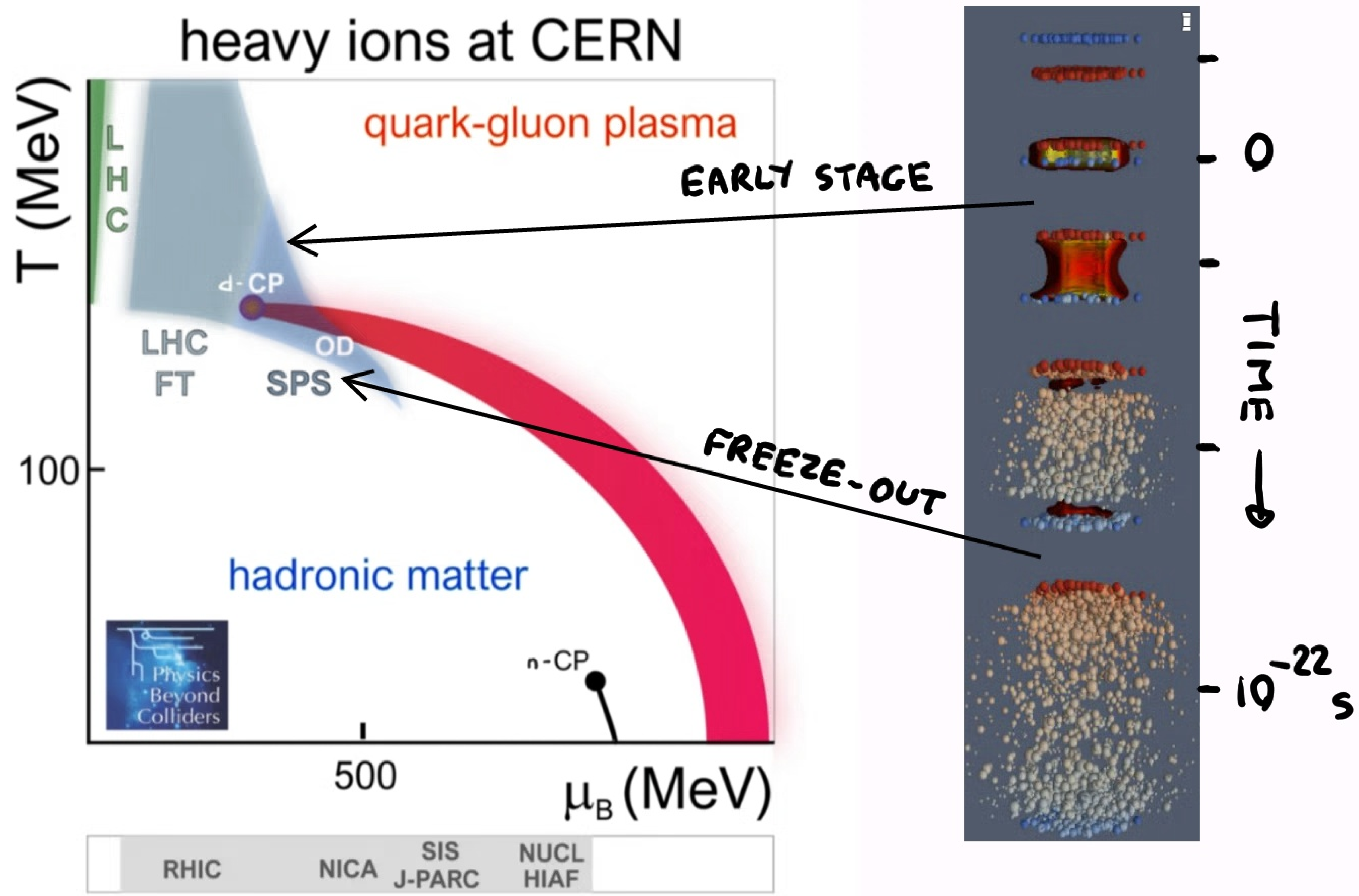
Cracow School of Theoretical Physics

DETAILS, REFERENCES: MG, GORENSTEIN, SEYBOTH, 2004.02255

QUARK-GLUON PLASMA : VOCABULARY

ASSEMBLY OF INTERACTING QUARKS AND GLUONS IN EQUILIBRIUM





THE IDEA BORN IN 1965, 5 YEARS AFTER THE SCHOOL

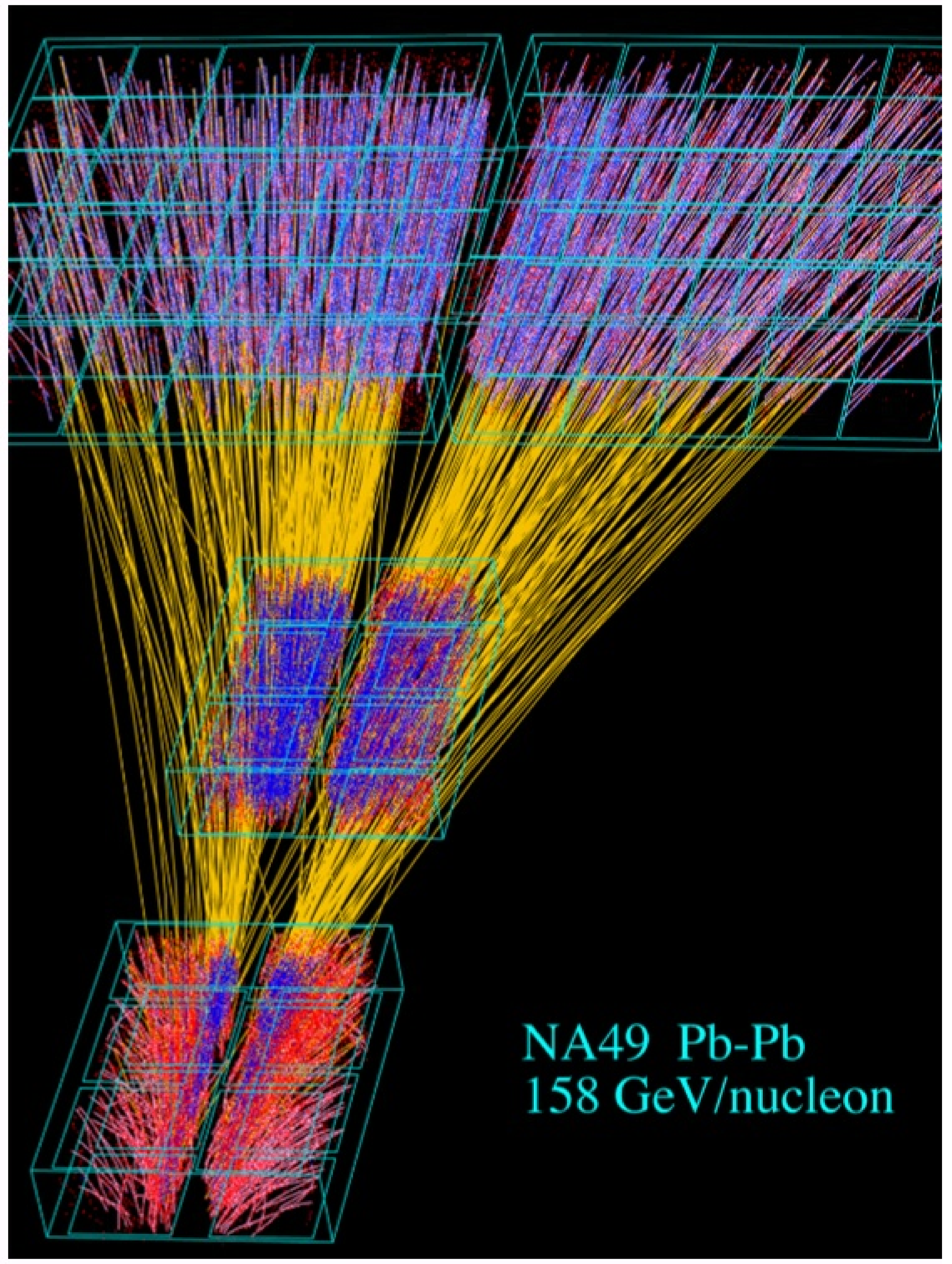
QUARK-GLUON PLASMA : 1986 - 2003

PREDICTED QGP SIGNALS:

- DILEPTON/PHOTON QGP RADIATION (SHURYAK, 1980)
- STRANGENESS AND MULTI-STRANGE HYPERON ENHANCEMENT (RAFELSKI, MULLER, 1982)
- J/ψ SUPPRESSION (MATSUI, SATZ, 1986)

MEASURMENTS:

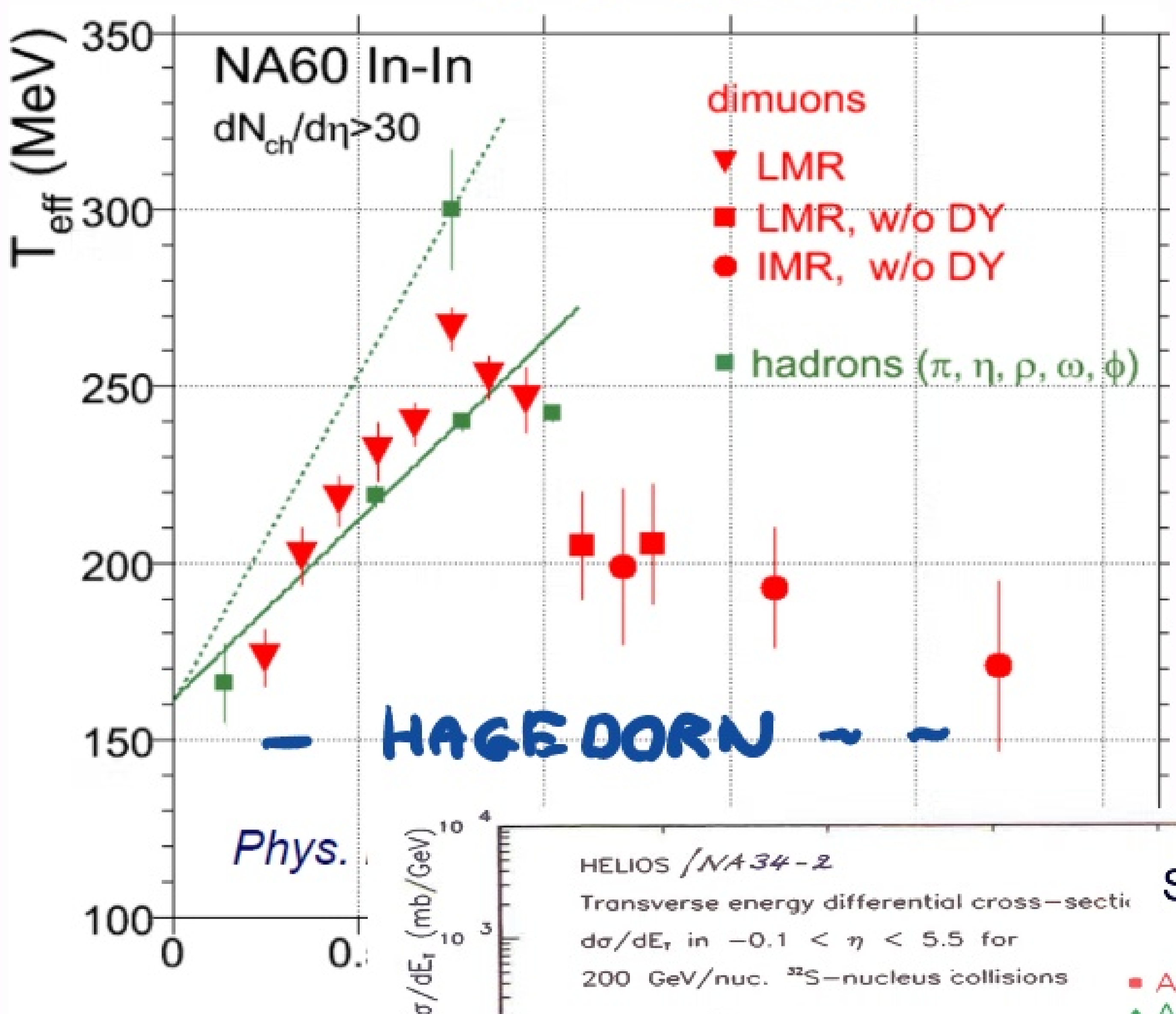
- 1986-1987: OXYGEN AND SULPHUR AT 200A GEV (NA34-2, 35, 36, 38, WA80, 85, 94)
- 1996-2003: LEAD AND INDIUM AT 158A GEV (NA44, 45, 49, 50, 52, 57, 60, WA97, 98)

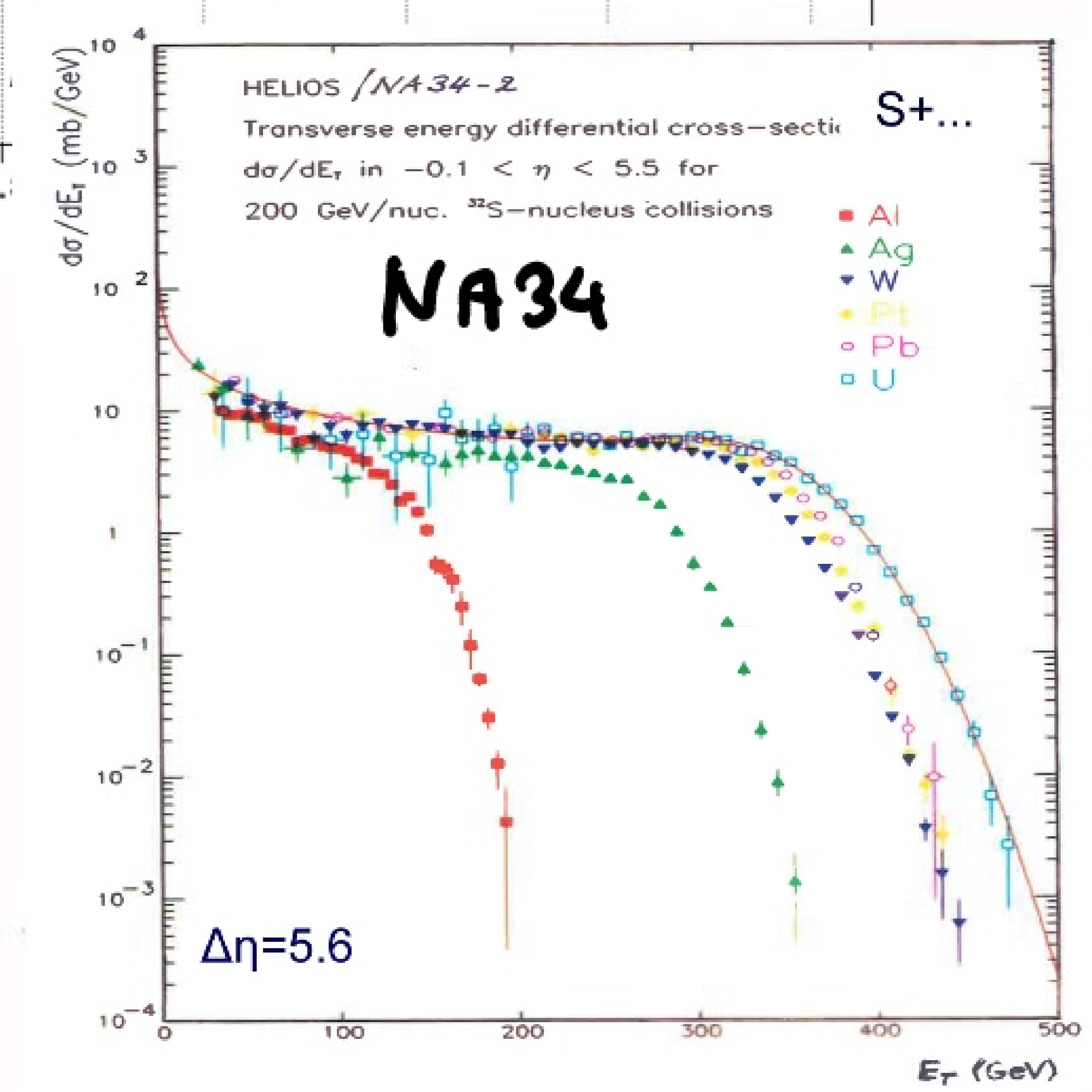


QUARK-GLUON PLASMA: EVIDENCE: 1986 – 2003

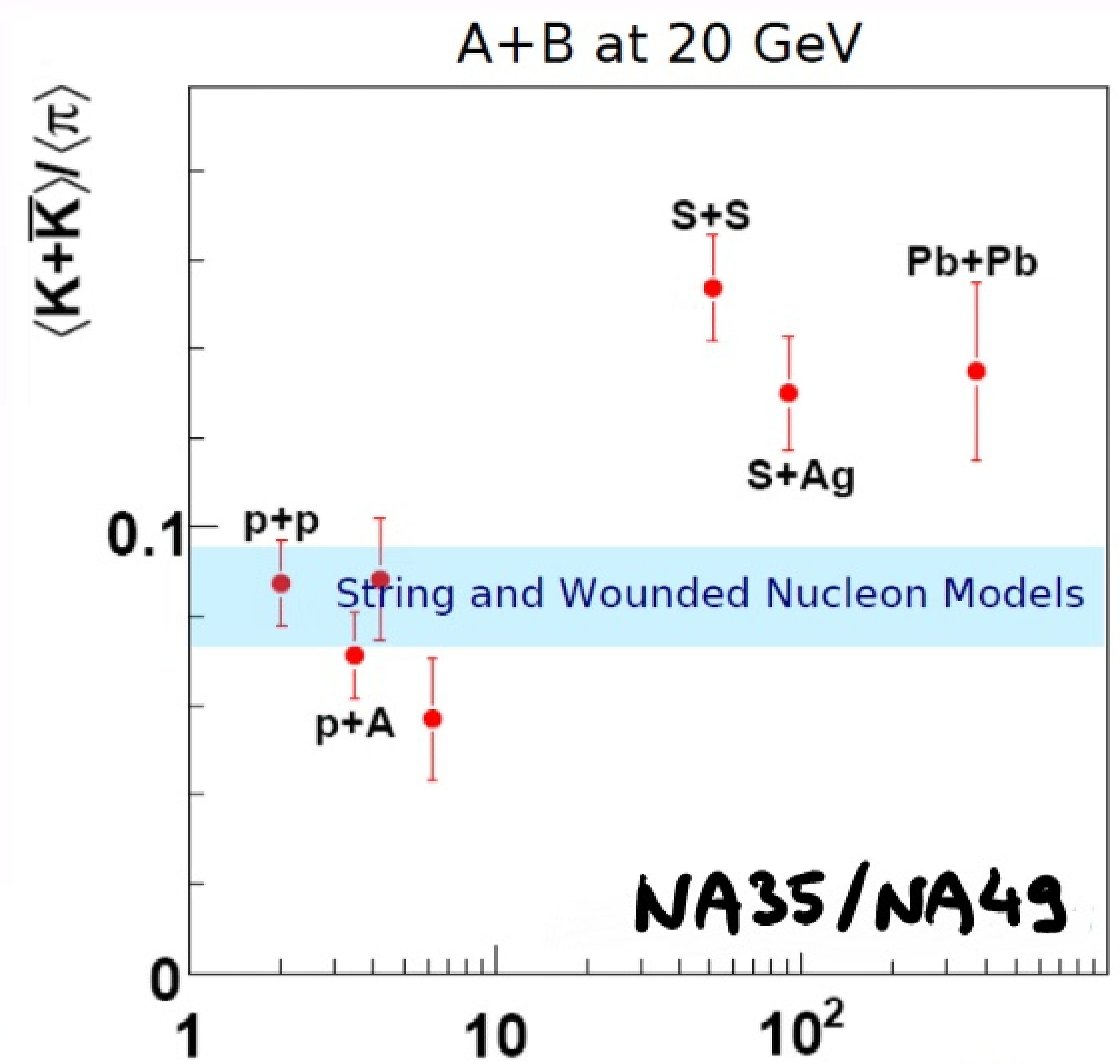
RESULTS ARE CONSISTENT WITH A QGP BEING CREATED ...

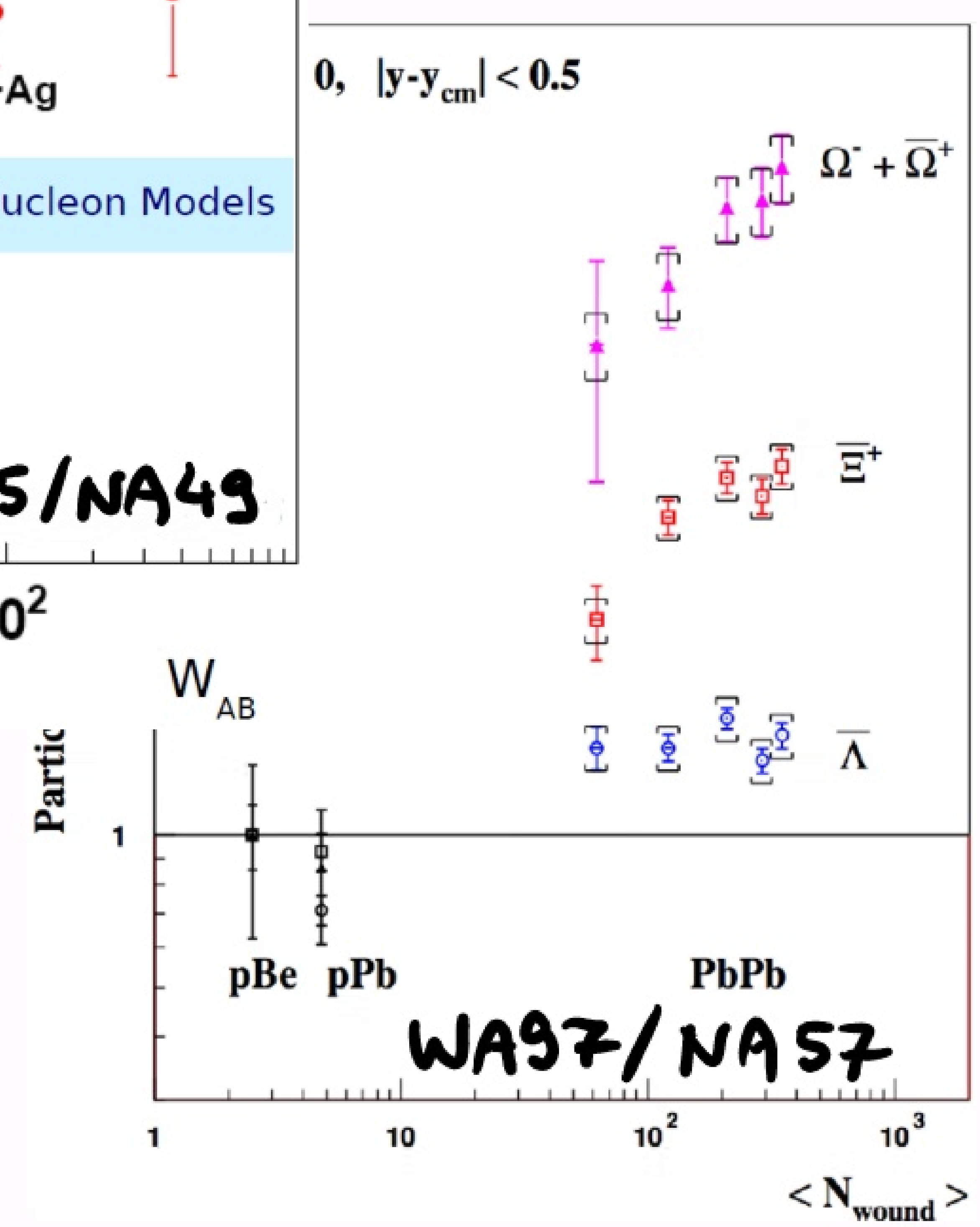
QGP TEMPERATURE
$T \approx 200$ MEV





STRANGENESS AND MULTI-STRANGE HYPERON ENHANCEMENT IN QGP

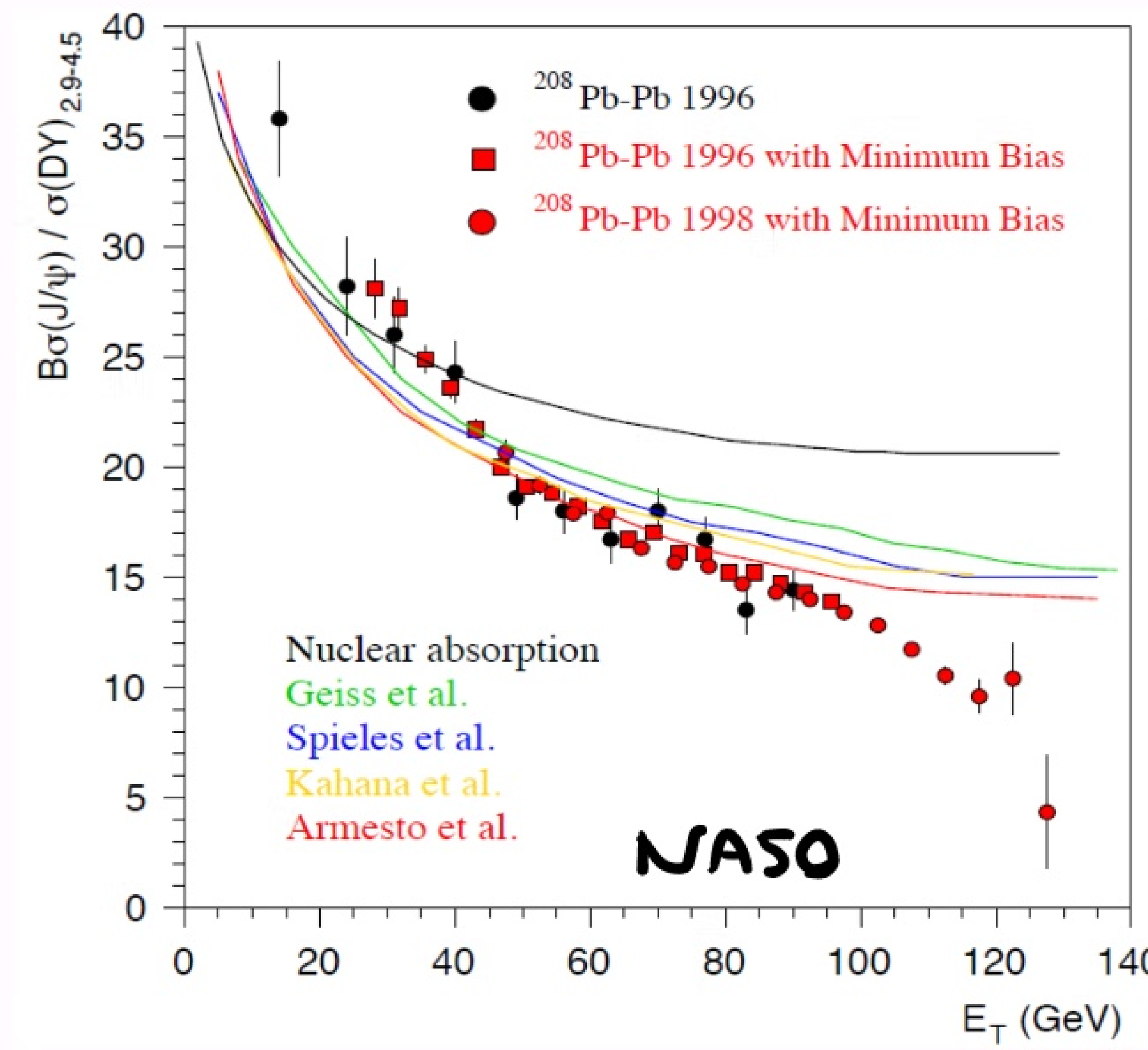




AND ENERGY DENSITY

$\varepsilon \gtrsim 1\ GeV/fm^3$

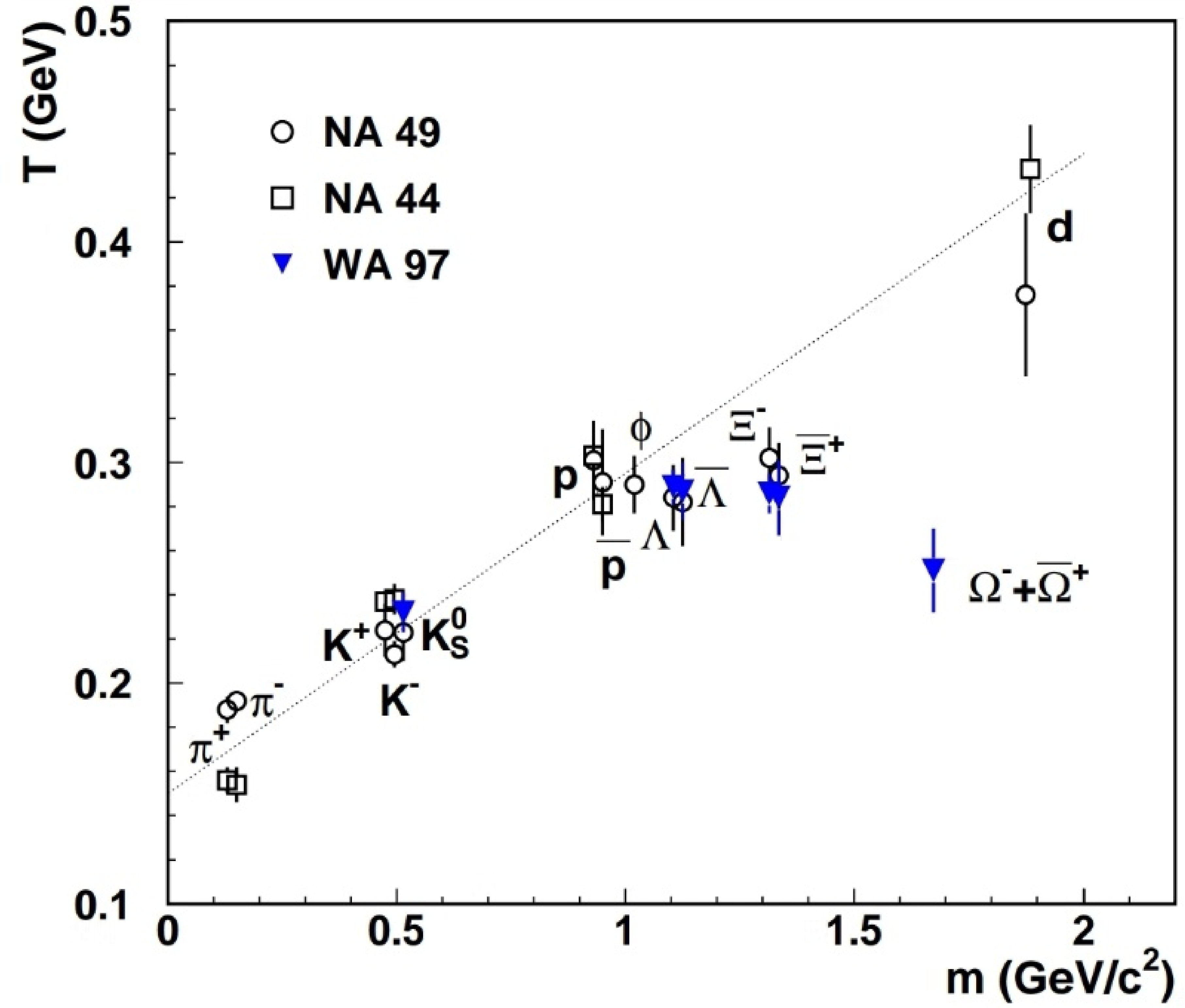
J/ψ MELTING IN QGP



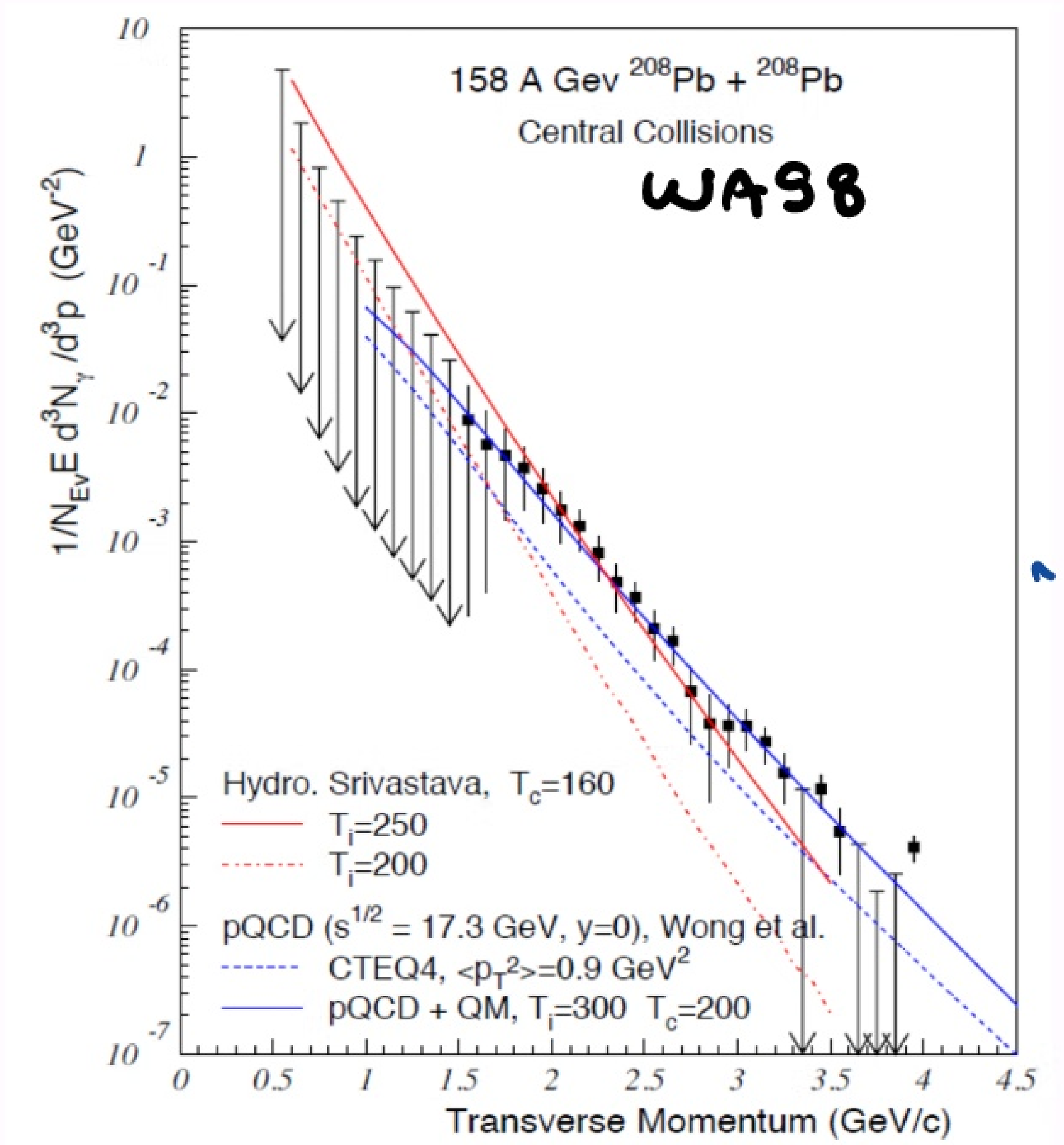
QUARK-GLUON PLASMA: STANDARD MODEL OF HIC: 1986 – 2003

... MATTER EXPANDS, RADIATES PHOTONS AND DILEPTONS ...

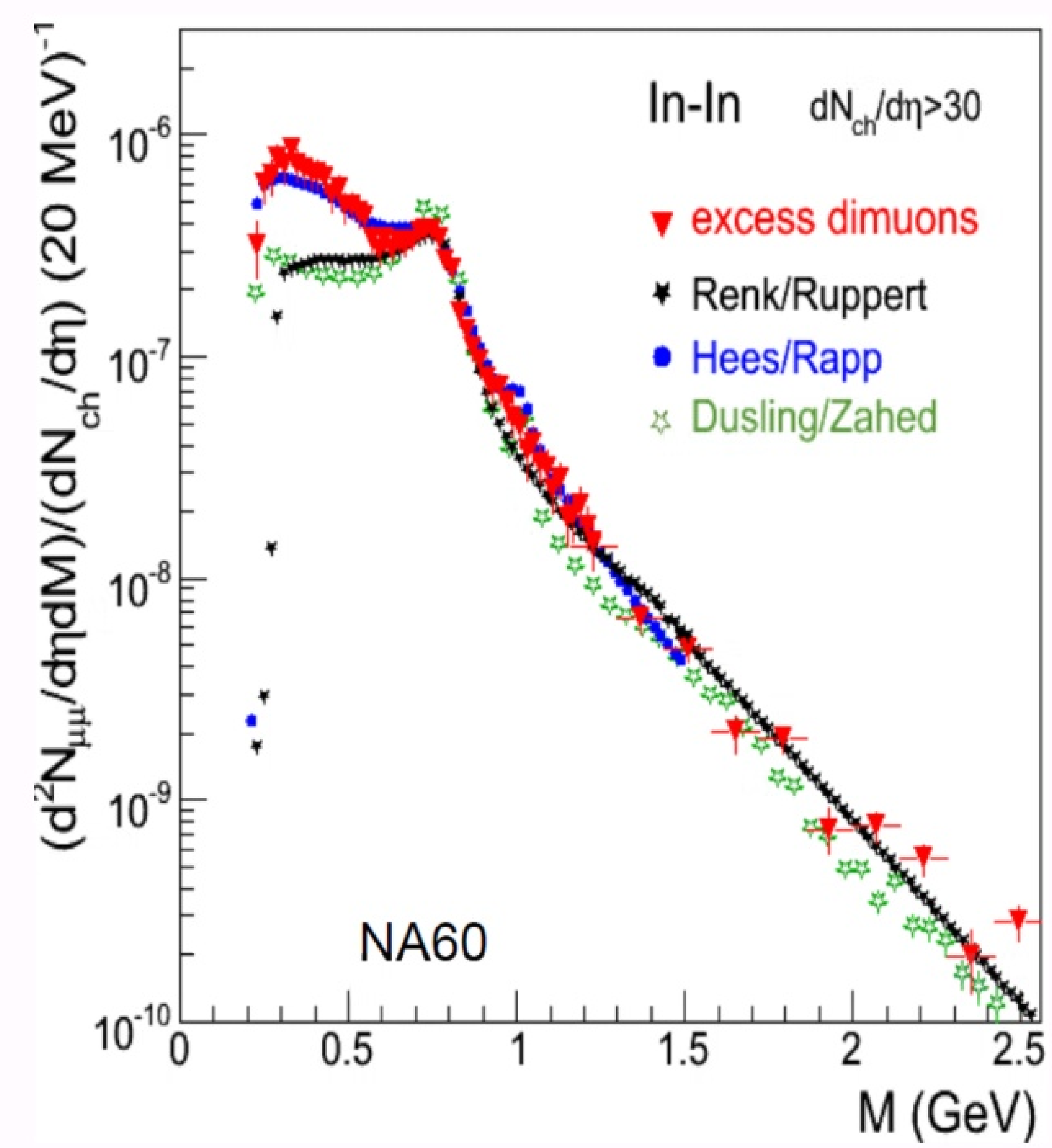
TRANSVERSE EXPANSION



PHOTON RADIATION



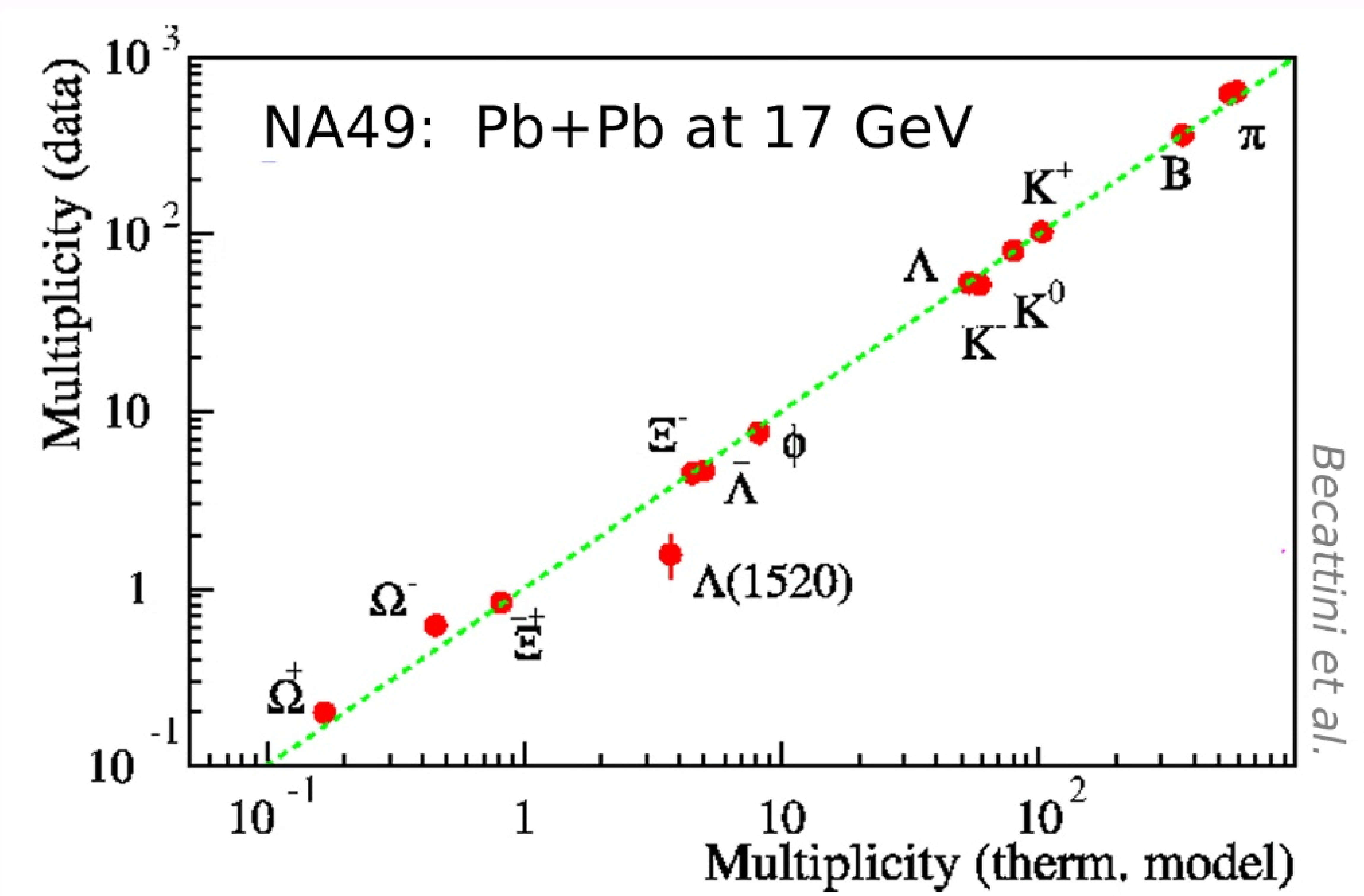
DIMUON RADIATION



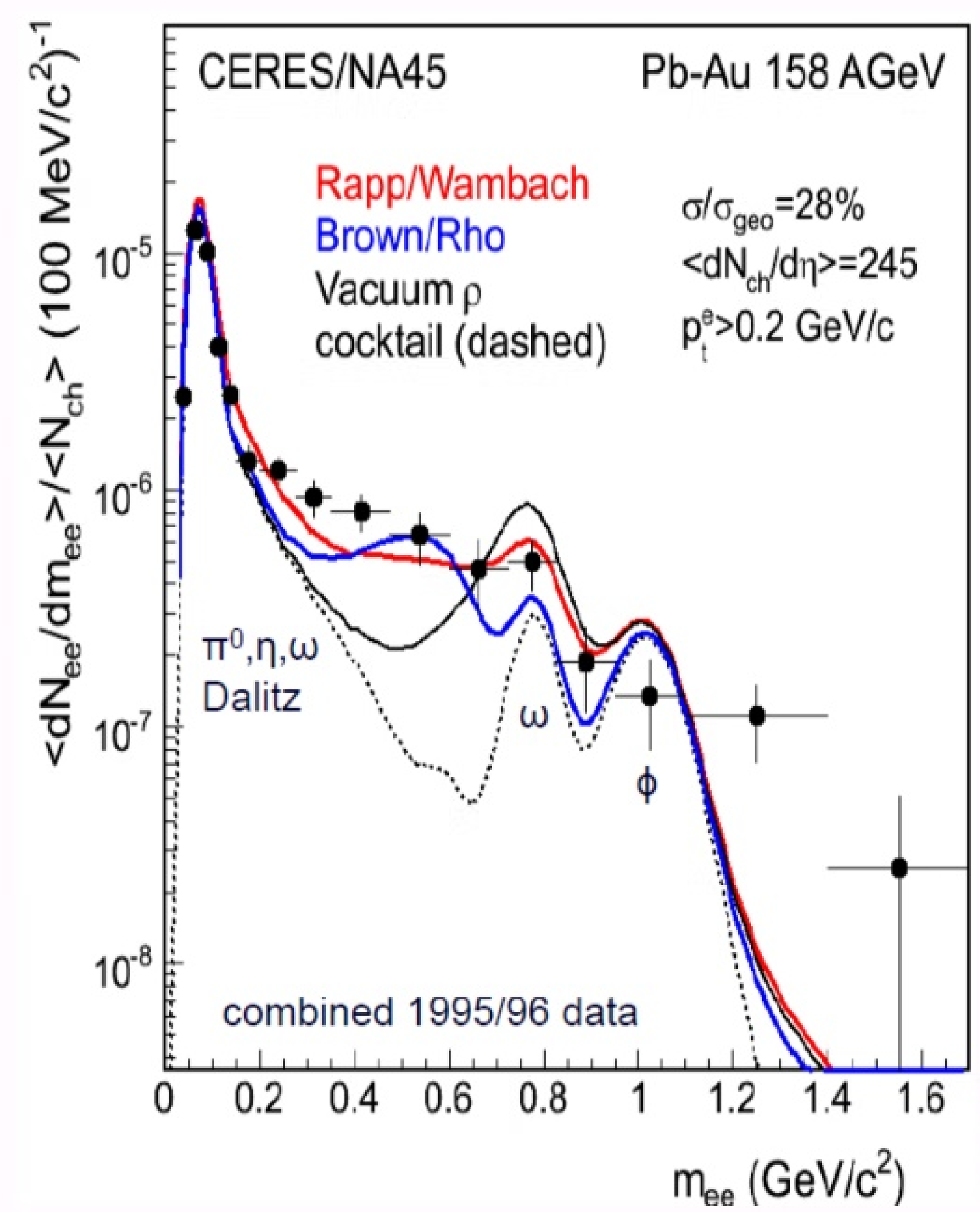
QUARK-GLUON PLASMA: STANDARD MODEL OF HIC: 1986 – 2003

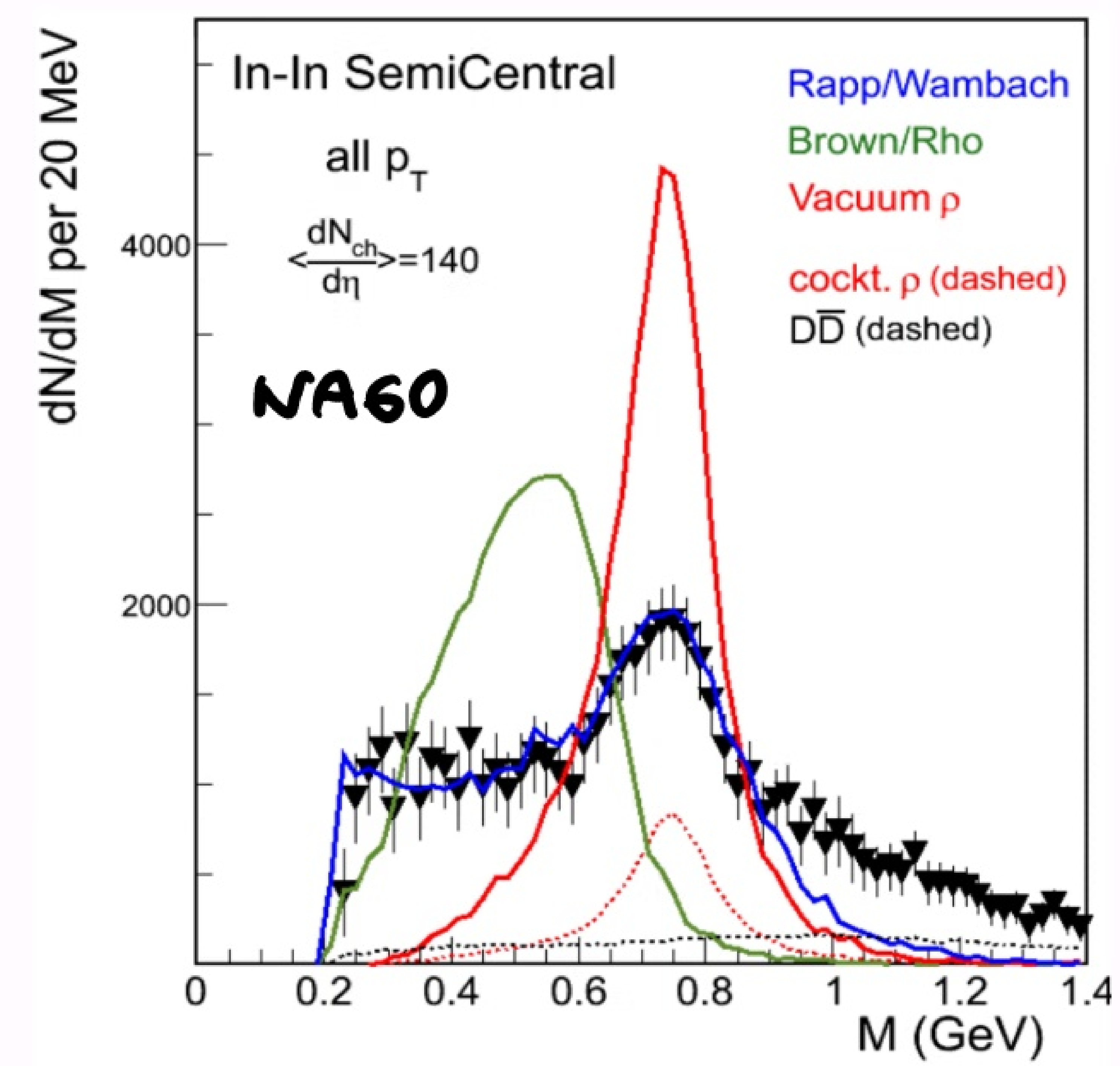
... AND AFTER STATISTICAL HADRONIZATION, THE MATTER IS STILL DENSE ENOUGH TO MODIFY HADRON PROPERTIES

STATISTICAL HADRONIZATION



MODIFICATION OF VECTOR MESON PROPERTIES





QUARK-GLUON PLASMA: CONCLUSIONS 2000

CERN PRESS RELEASE (FEB 2000)

CERN

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

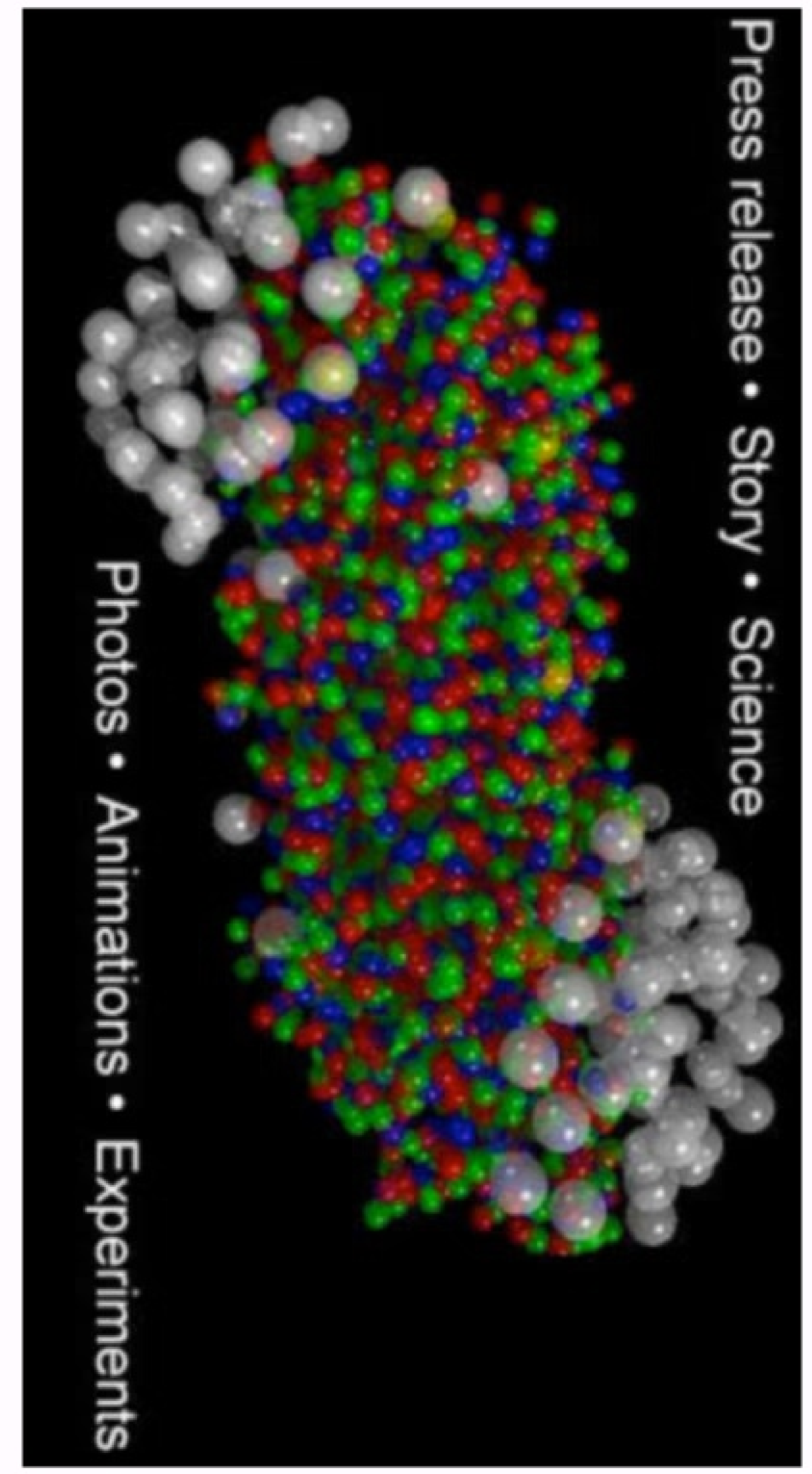
PR01.00
10.02.00

New State of Matter created at CERN

At a special seminar on 10 February, spokespersons from the experiments on CERN's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

Professor Luciano Maiani, CERN[1] Director General, said *"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider."*

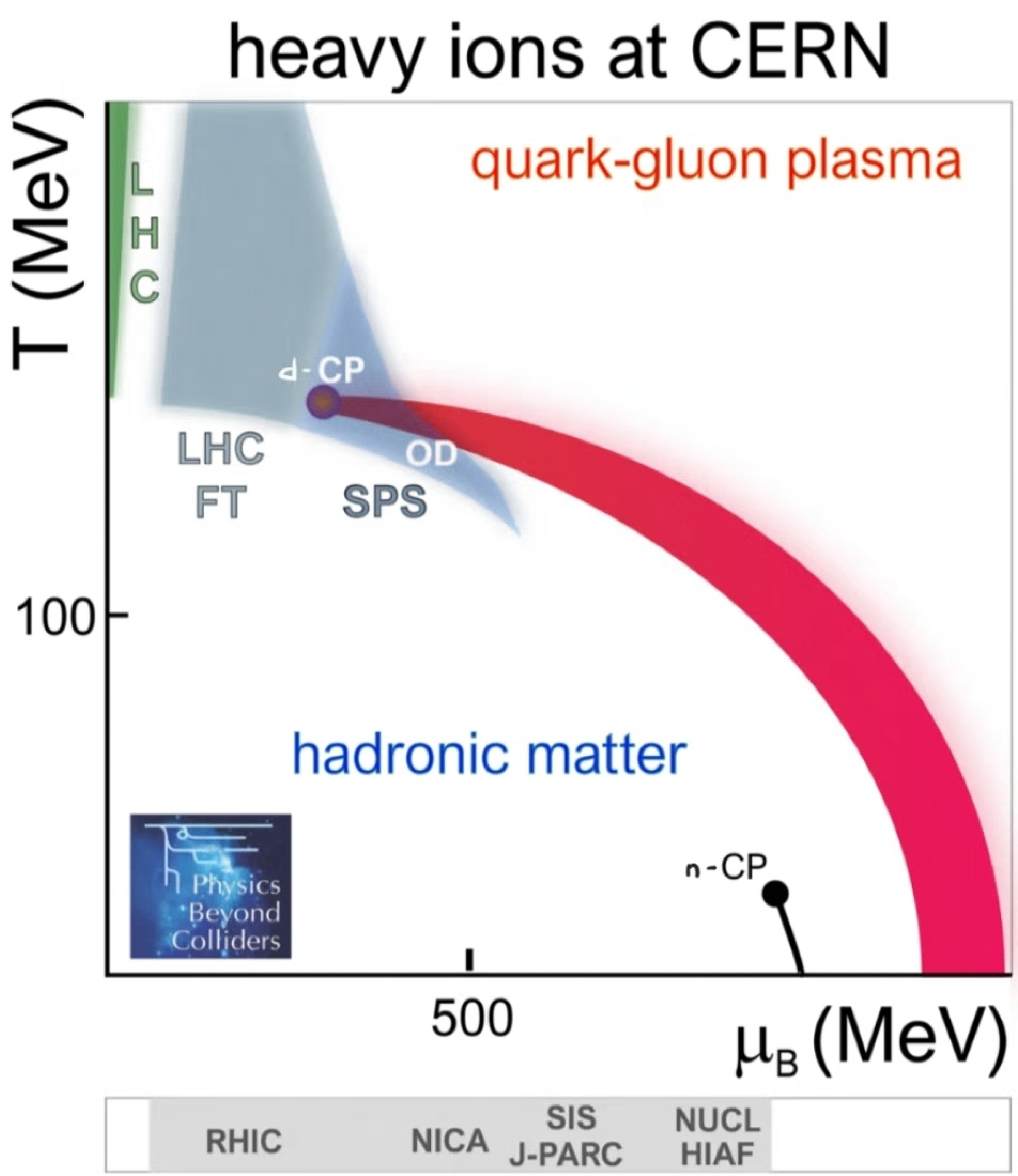


HEAVY ION COMMUNITY SPLITS:

→ PROPERTIES OF HIGH TEMPERATURE QGP → VERY HIGH ENERGIES AT RHIC, LHC

→ SEARCH FOR THE ONSET OF QGP CREATION → COLLISION ENERGY SCAN AT SPS

CRITICAL STRUCTURES: VOCABULARY



- ONSET OF DECONFINEMENT (OD) — BEGINING OF QGP CREATION WITH INCREASING COLLISION ENERGY
- CRITICAL POINT (CP) — END POINT OF FIRST ORDER TRANSITION LINE THAT HAS PROPERTIES OF SECOND ORDER PHASE TRANSITION
- ONSET OF FIREBALL — BEGINING OF CREATION OF STRONGLY INTERACTING MATTER WITH INCREASING NUCLEAR MASS NUMBER.

  TRANSITION FROM NON-EQULIBRIUM STRINGS AND RESONACES TO EQULIBRIUM HADRONGAS OR QGP

CRITICAL STRUCTURES: 1997 – 2025

PHASE I: SEARCHING FOR ONSET OF QGP CREATION

PREDICTED SIGNALS:

- PION YIELD ENHANCEMENT AND STRANGENESS TO PION YIELD SUPPRESSION (MG, GORENSTEIN 1998)
- SOFTENING OF COLLECTIVE FLOW (GORENSTEIN, MG, BUGAEV 2003, STOECKER 2004, BLEICHER 2005)

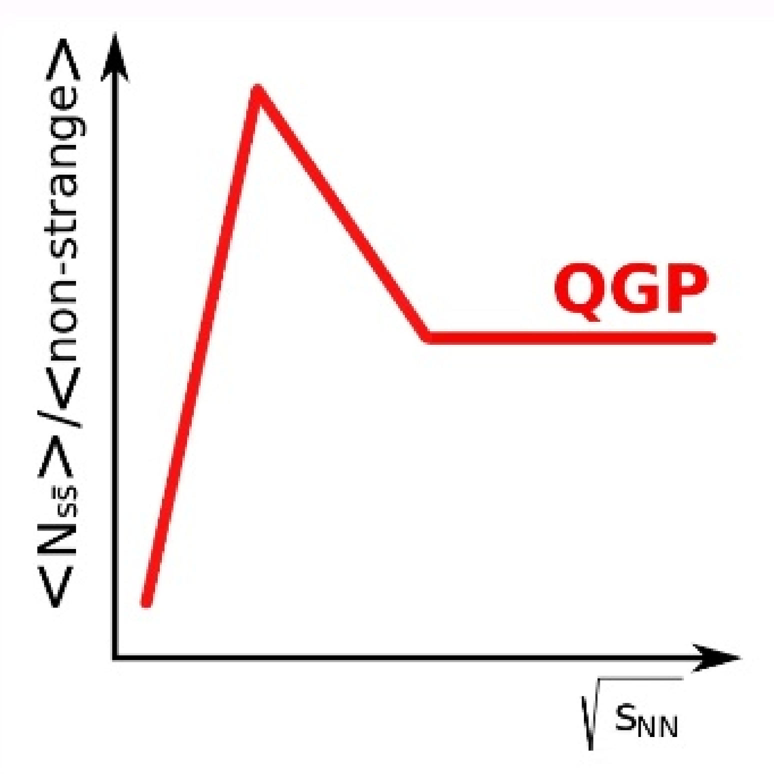
MEASUREMENTS:

- 1999 – 2002: Pb BEAMS AT 20A, 30A, 40A, 80A, 158A GEV ← CERN SPS (NA49, NA45, NA57, NA60) ⟶
  - ⟶ 2010 – 2014: Au BEAMS AT EQUIV. 30A – 200A GEV ← BNL RHIC (STAR, PHENIX : BES I)

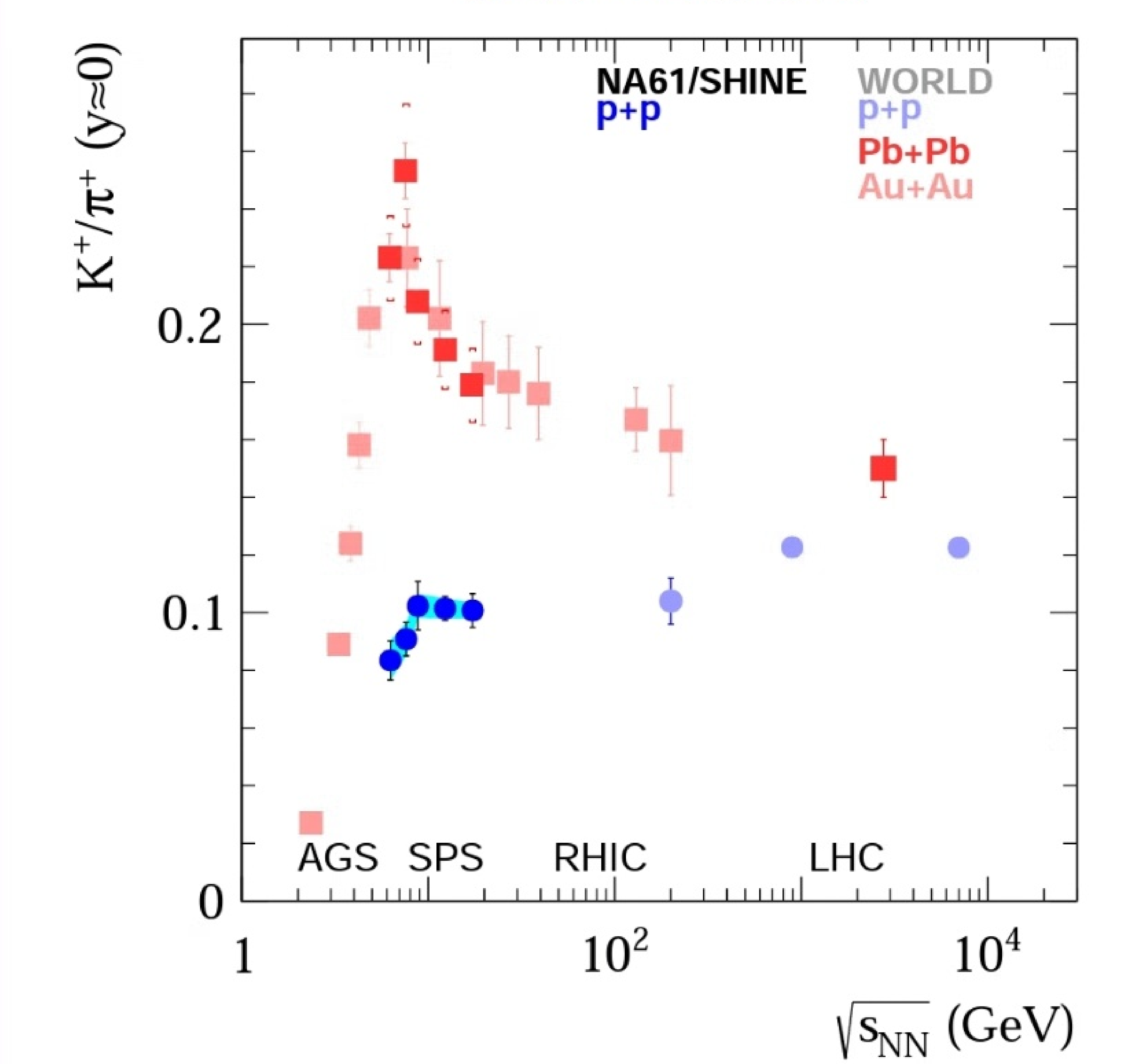
CRITICAL STRUCTURES: 1997 – 2006

PHASE I: SEARCHING FOR ONSET OF QGP CREATION

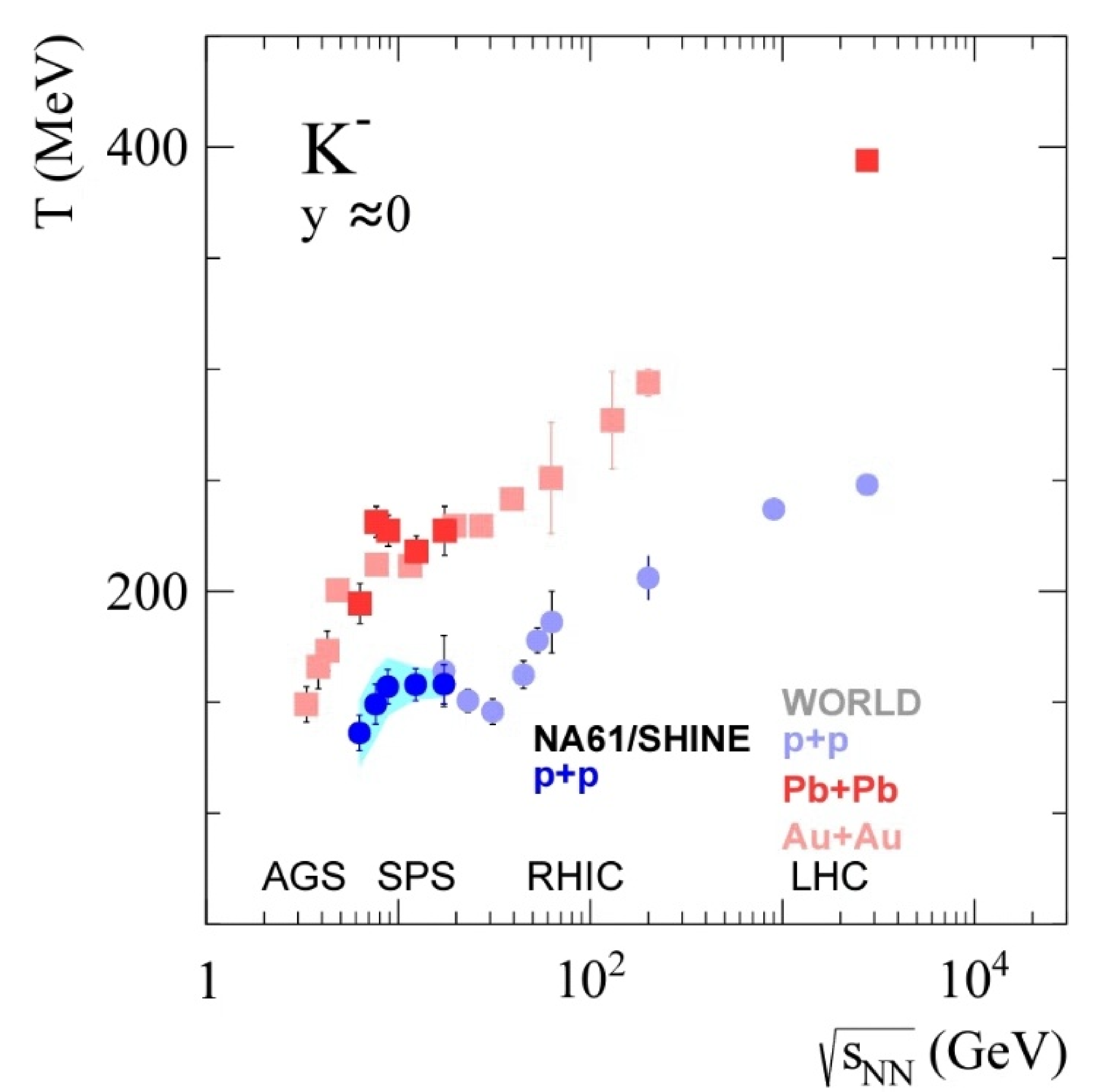
OBSERVED ANOMALIES IN COLLISION ENERGY DEPENDENCE ARE CONSISTENT WITH THE QGP ONSET AT LOW SPS ENERGIES



STRNGENESS/PION SUPPRESSION



SOFTENING OF COLLECTIVE FLOW



9

CRITICAL STRUCTURES: 1997 - 2006

PHASE II: SEARCHING FOR CRITICAL POINT

APRIL 2004: WORKSHOP IN ECT TRENTO:

→ RESULTS ARE CONSISTENT WITH QGP ONSET IN Pb+Pb AT LOW SPS ENERGIES →

→ SEARCH FOR CRITICAL POINT

→ SCAN IN ENERGY AND NUCLEAR MASS NUMBER

CERN COURIER SEPT. 2004

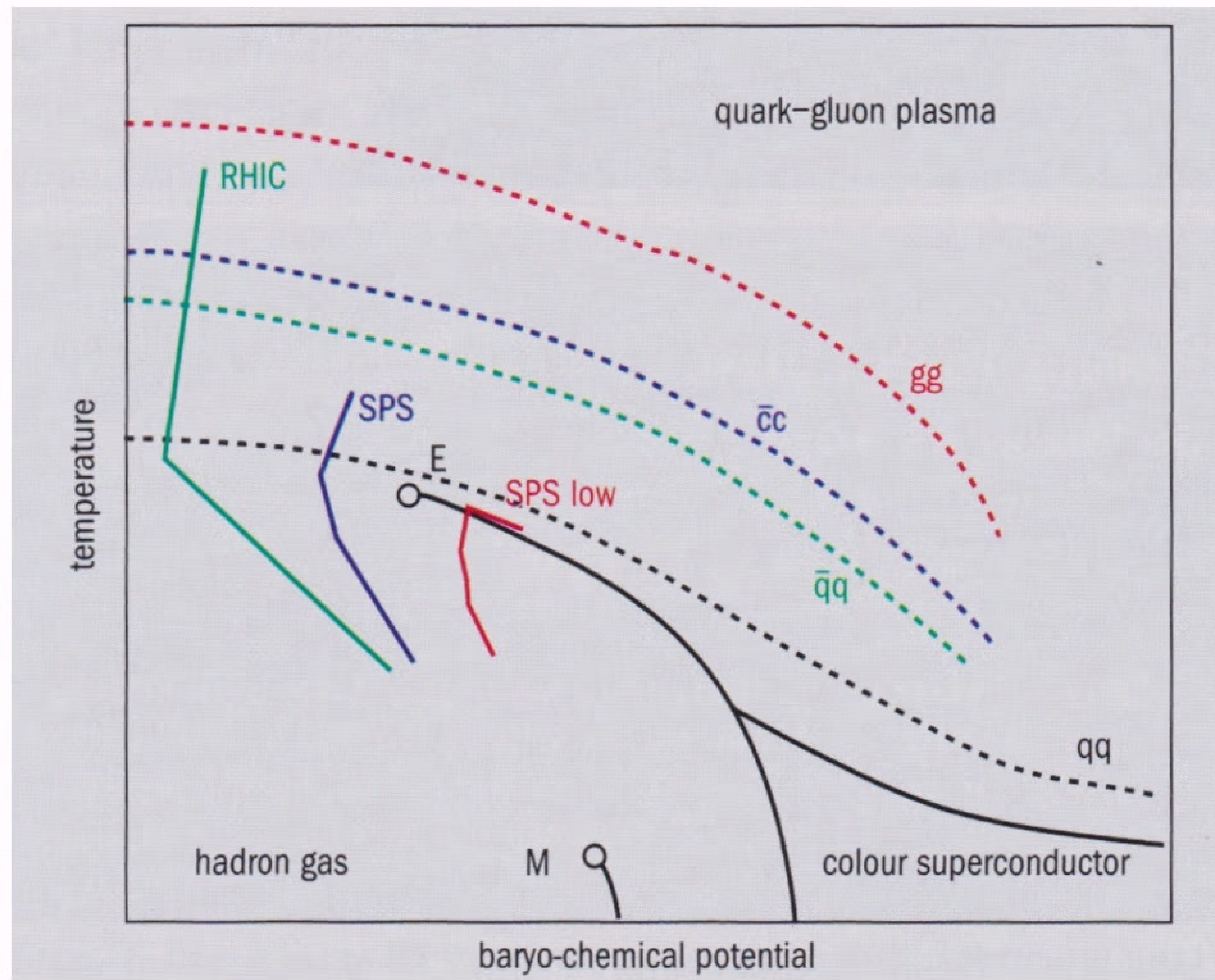
HEAVY IONS

When quarks and gluons become free

Recent results and future experiments were the topics in a workshop to look into exactly what happens as strongly interacting matter becomes deconfined.

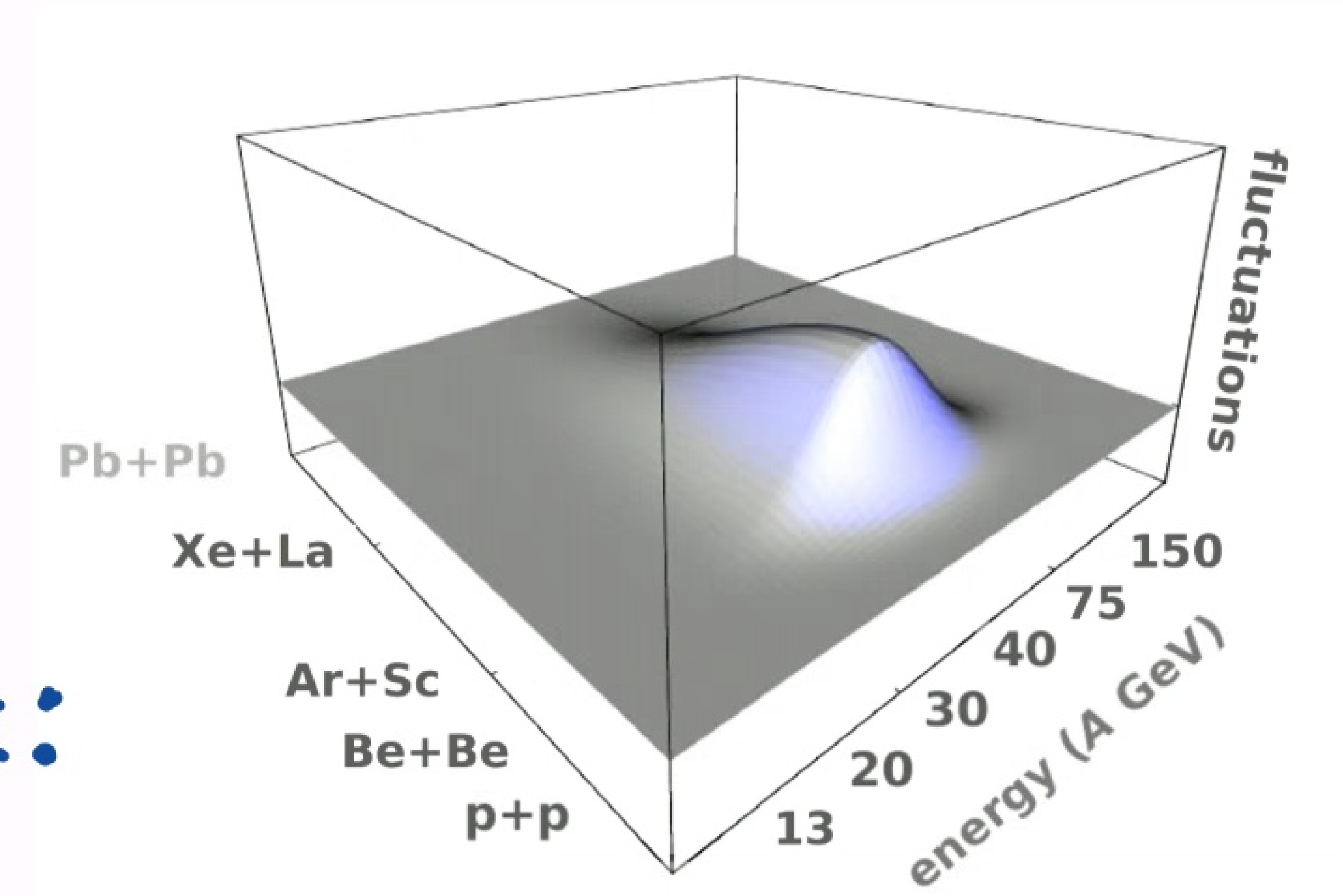
MG
SEYBOTH
SHURYAK

BEGINING OF CRITICAL POINT AND ONSET OF DECONFINEMENT WORKSHOPS



CRITICAL STRUCTURES: 2004 – 2025

PHASE II: SEARCHING FOR CRITICAL POINT



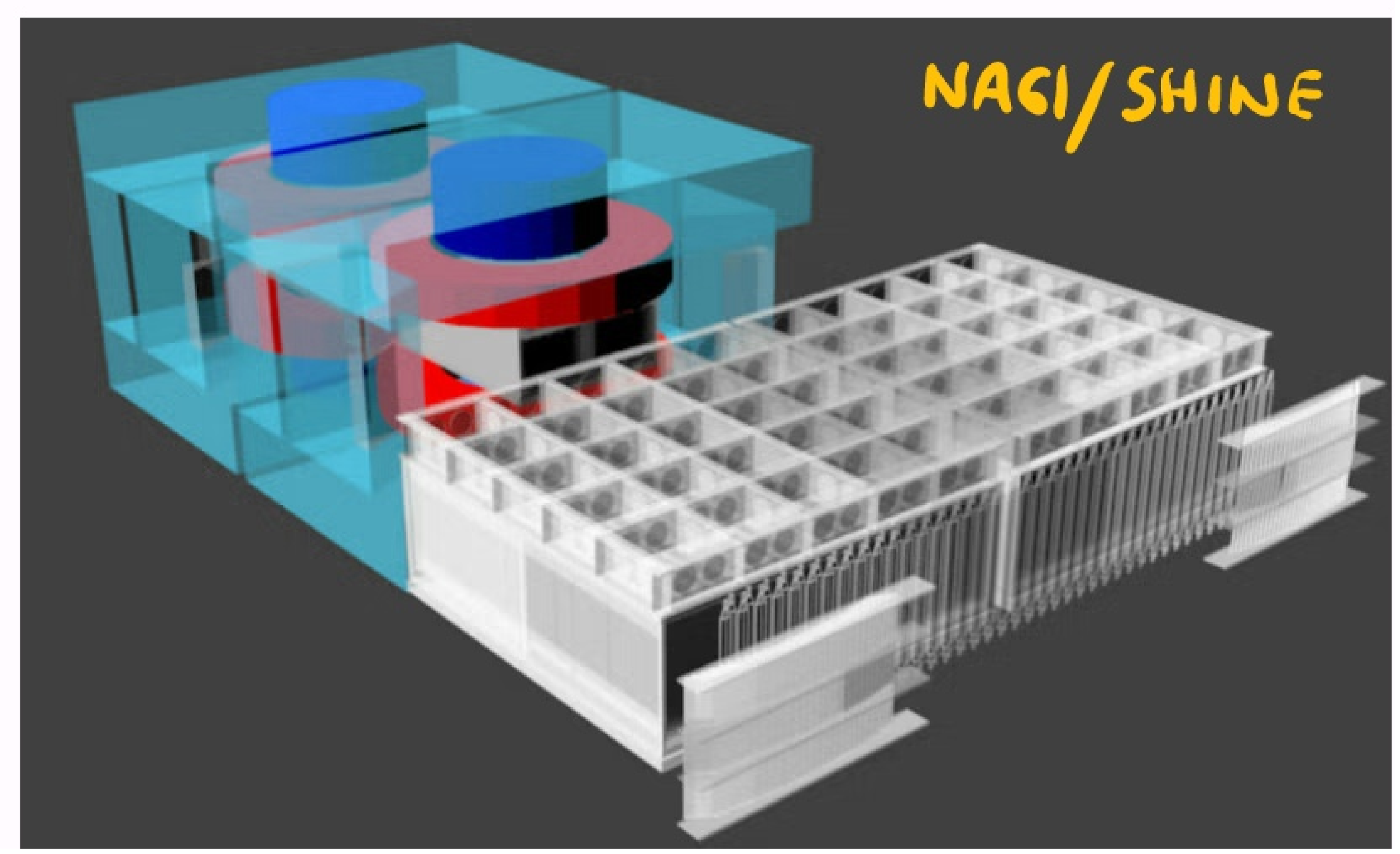
PREDICTED SIGNALS:

- MAXIMUM OF FLUCTUATIONS IN (COLLISION ENERGY) – (NUCLEAR MASS NUMBER) PLANE:
  - INTERMITTENCY AND PROTON FLUCTUATIONS (BIALAS, HWA 1991, ANTONIOU, DIAKONOS, KAPOYANIS 2006, STEPHANOV 2011)
  - PION p_T–N FLUCTUATIONS (STEPHANOV, RAJAGOPAL, SHURYAK 1998)

MEASUREMENTS:

- 2009 – 2018: SCAN IN $\sqrt{s_{NN}}$ – A (NA61/SHINE AT CERN SPS)

- 2010 – 2020: SCAN IN $\sqrt{s_{NN}}$ WITH Au (STAR, PHENIX AT BNL RHIC; BES I/II)

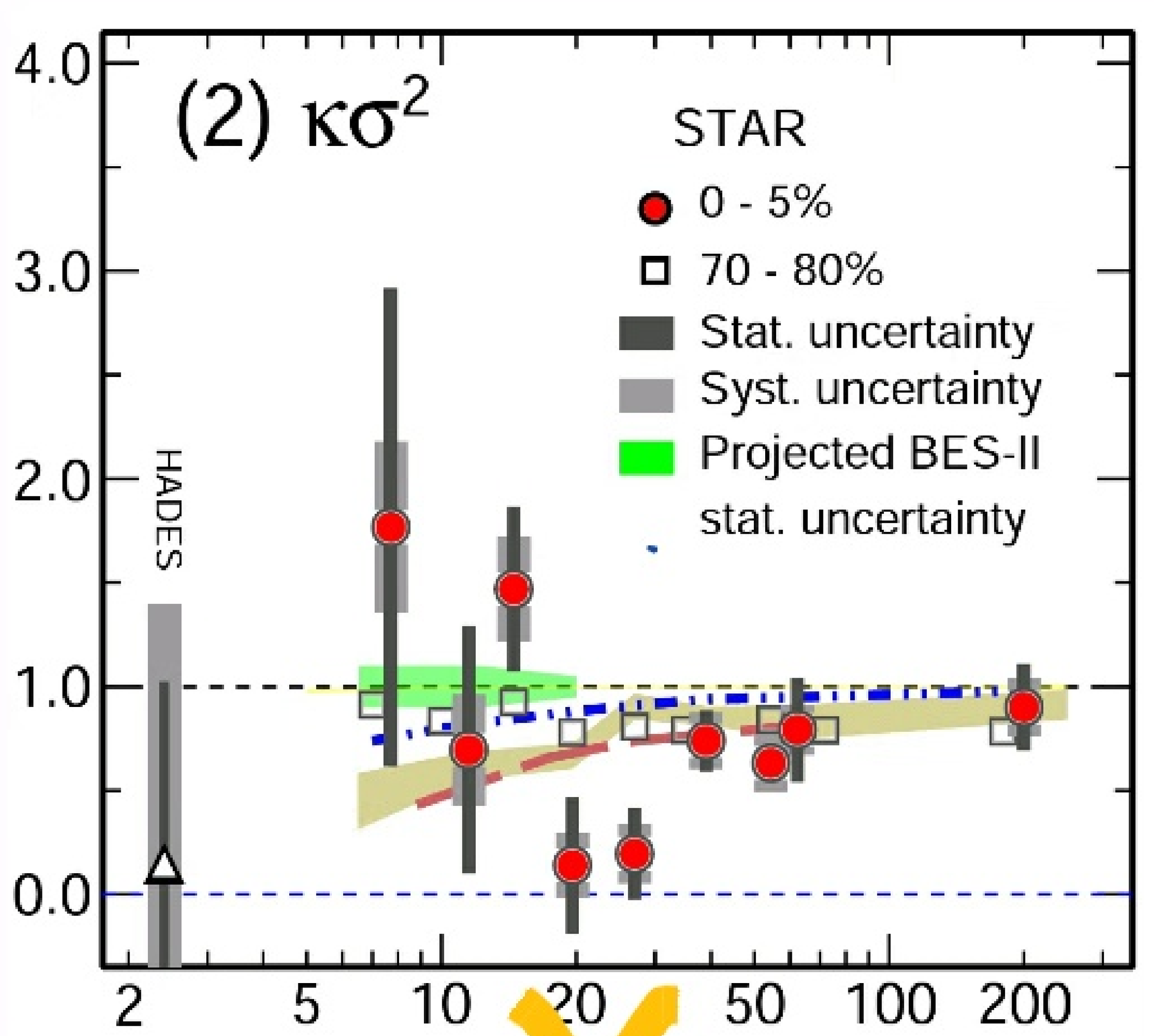


CRITICAL STRUCTURES : 2004 – 2025

PHASE II: SEARCHING FOR CRITICAL POINT

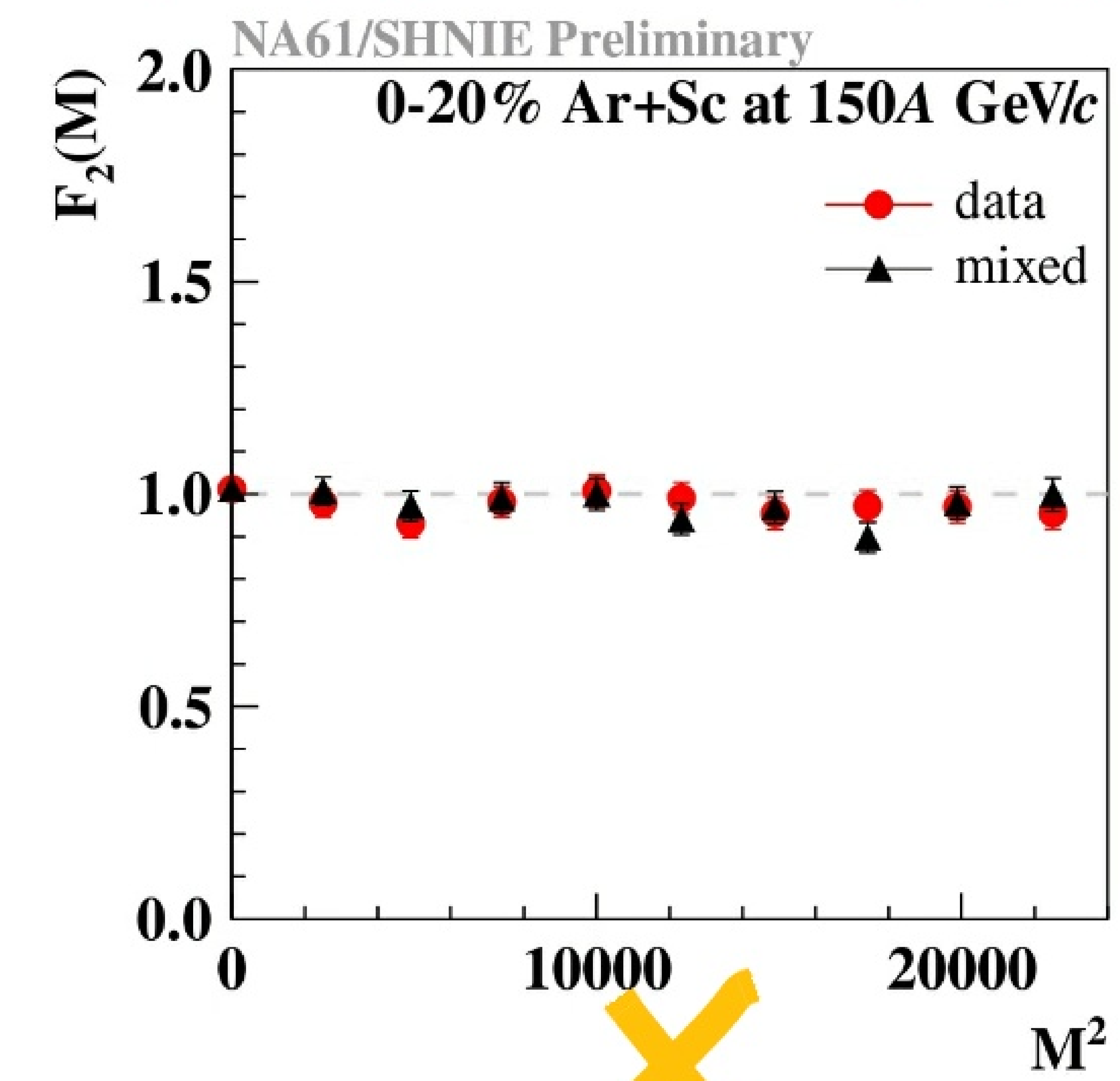
CP INDICATIONS → DIFFERENT ENERGIES/REACTIONS

HIGHER ORDER MOMENTS



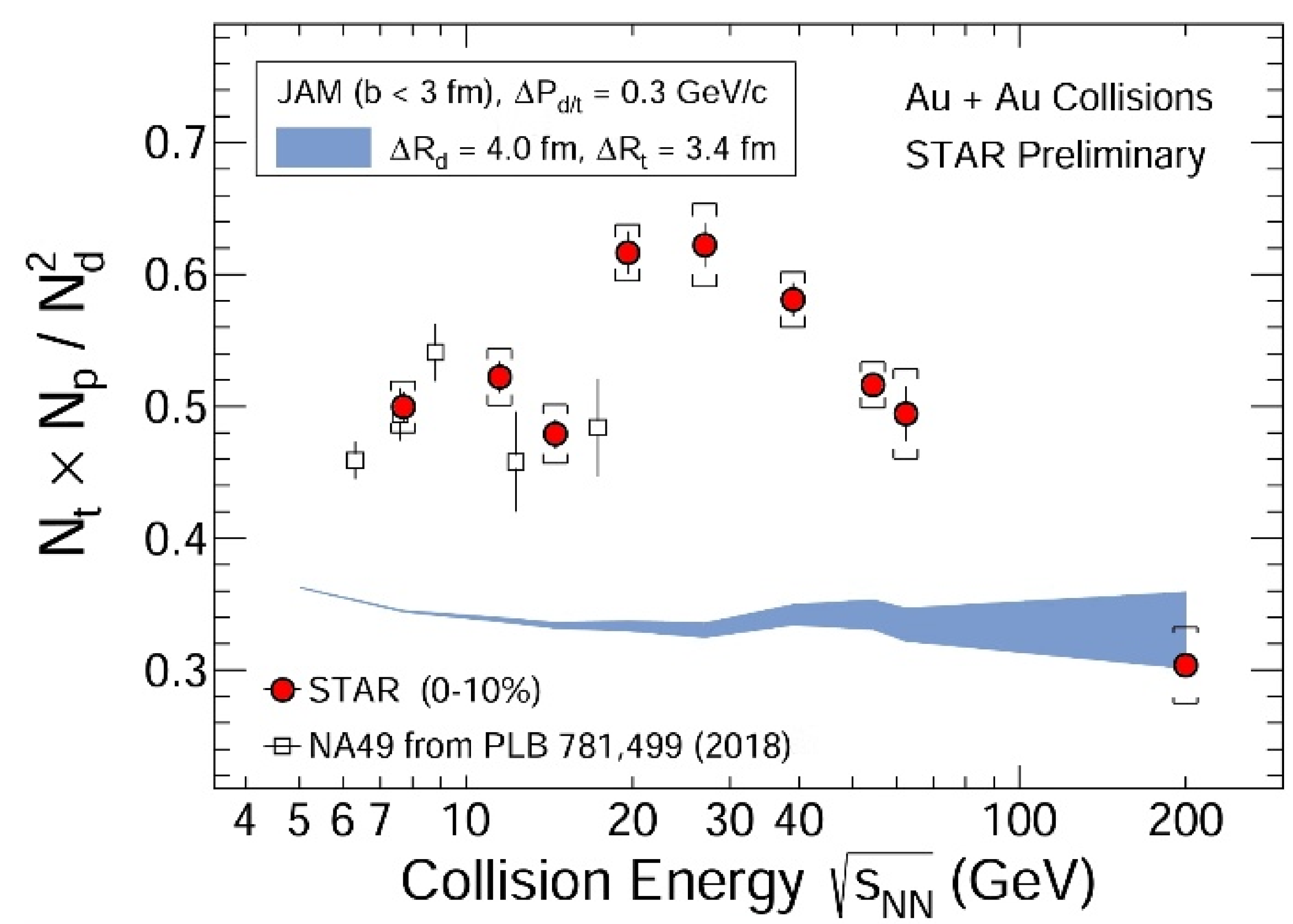
≈ 7 GeV

PROTON INTERMITTENCY



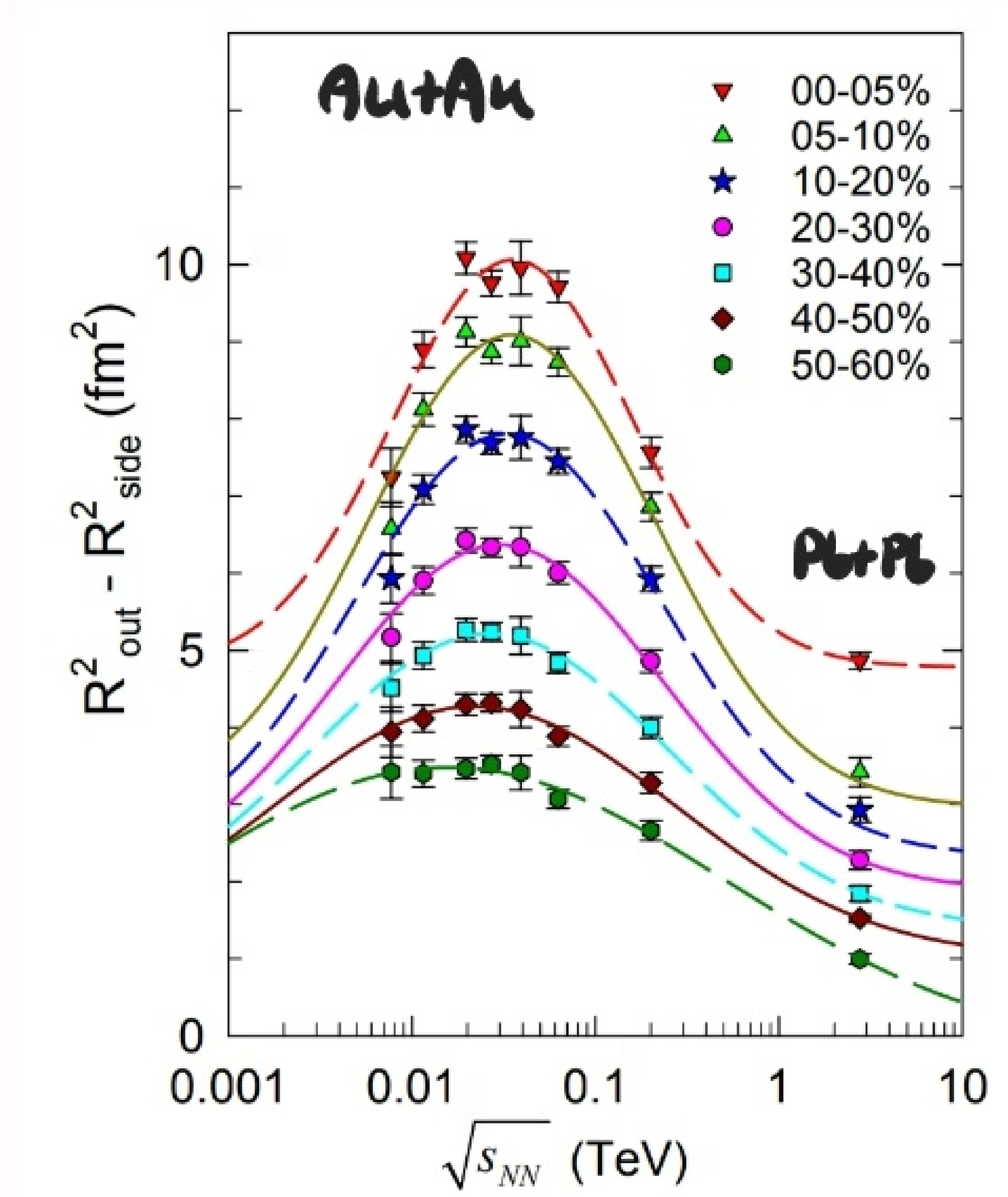
≈ 17 GeV

LIGHT IONS



≈ 20 GeV

SHORT-RANGE CORRELATIONS



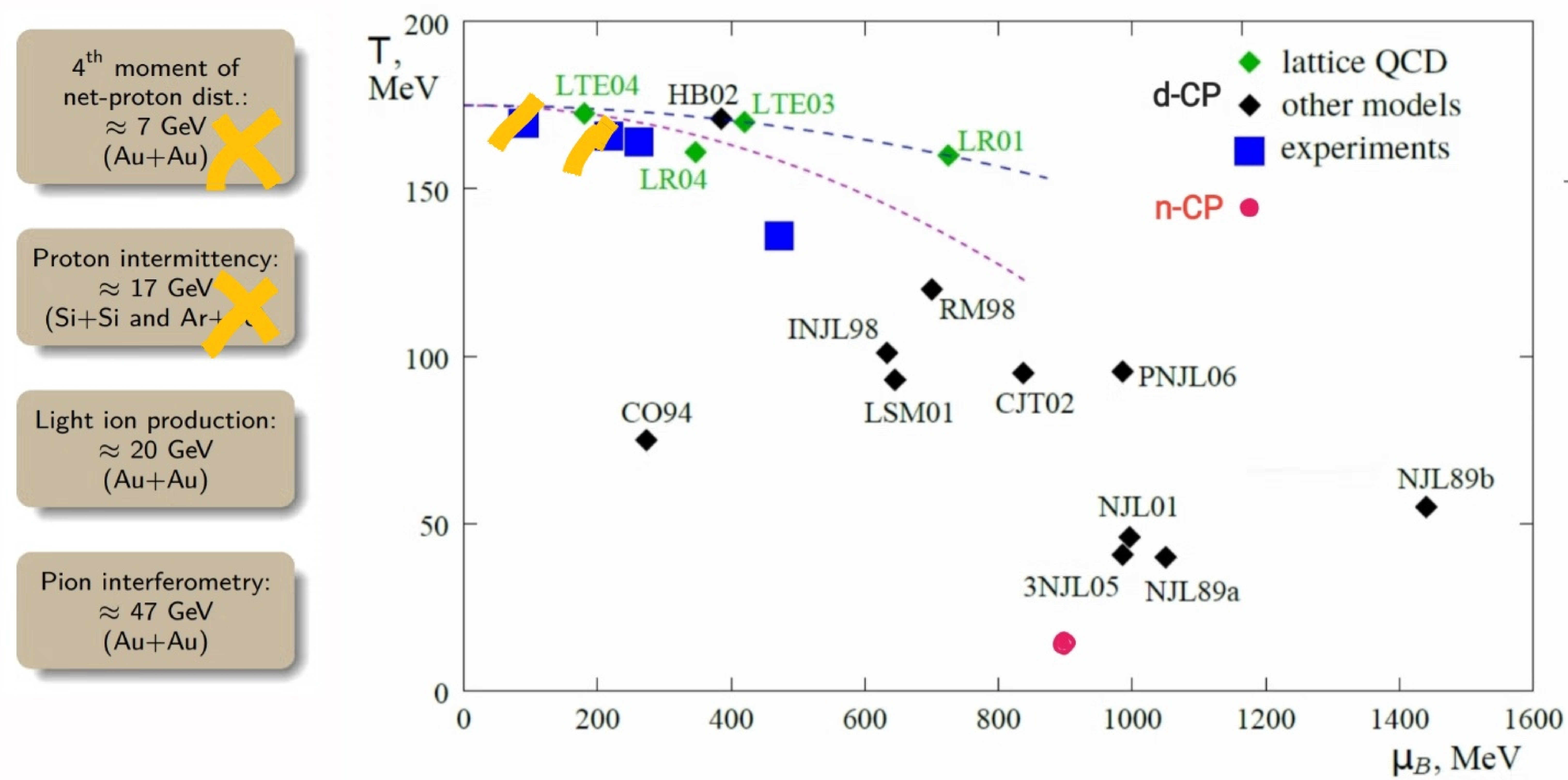
≈ 50 GeV

CRITICAL STRUCTURES: 2004–2025

PHASE II: SEARCHING FOR CRITICAL POINT

AS FOR NOW EXPERIMENTAL AND THEORETICAL RESULTS ARE INCONCLUSIVE / CONFUSING

CZAPOWICZ SQM 2019

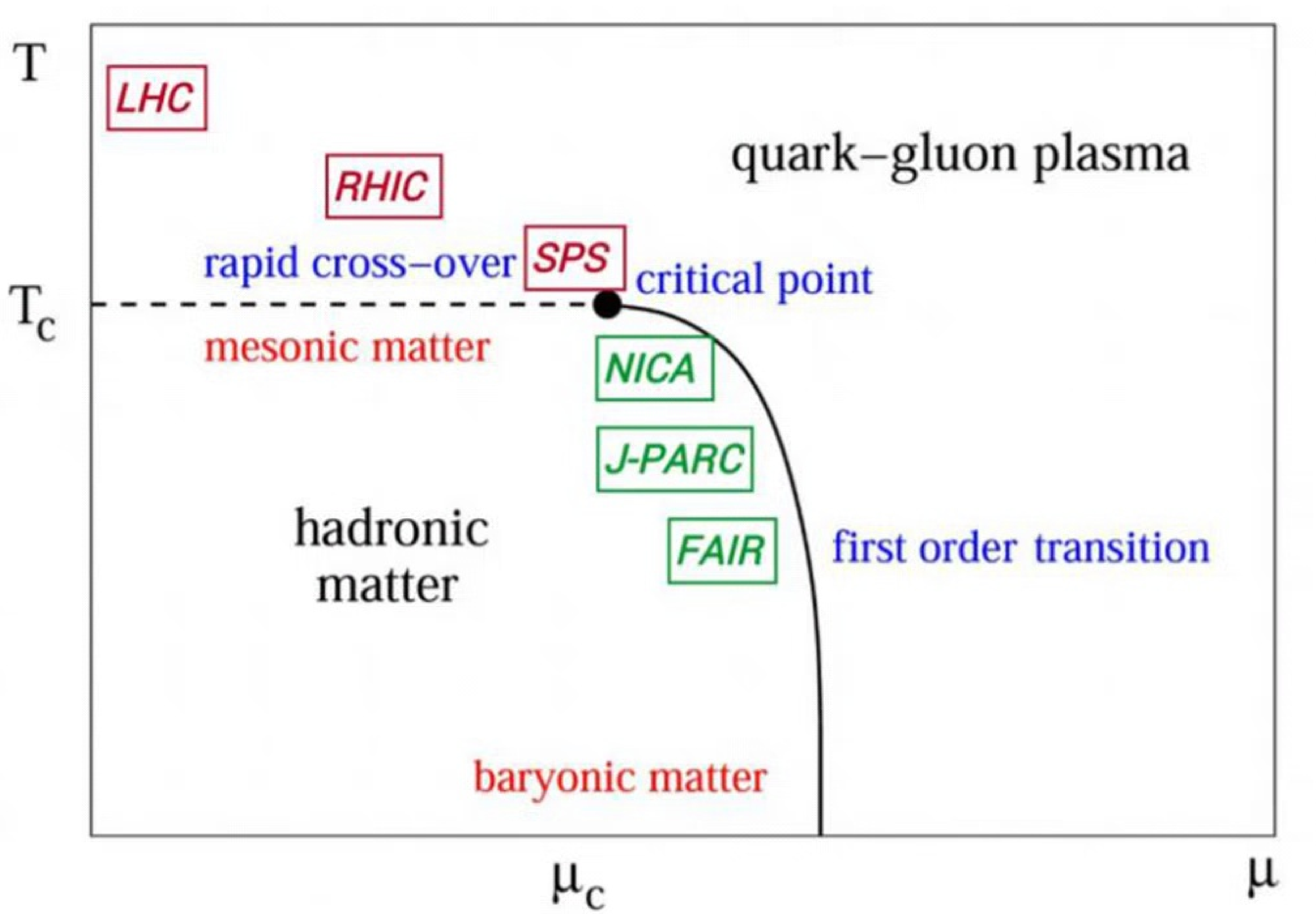


NEW RESULTS EXPECTED SOON FROM NA61/SHINE AND STAR BES II

■ ■ ■ INVENTING FUTURES:

QGP ONSET AND CHARM

LANDSCAPE OF PRESENT AND FUTURE HEAVY ION EXPERIMENTS



POTENTIAL FOR DATA ON CHARM

LHC and RHIC at high energies ($\sqrt{s_{NN}} \geq$ 200 GeV):
measurements in limited phase space due to collider geometry and kinematics

RHIC BES (3 − 39 GeV):
measurement not under consideration

NICA (< 11 GeV):
under consideration during stage 2

J-PARC (< 6 GeV) :
maybe possible after 2025

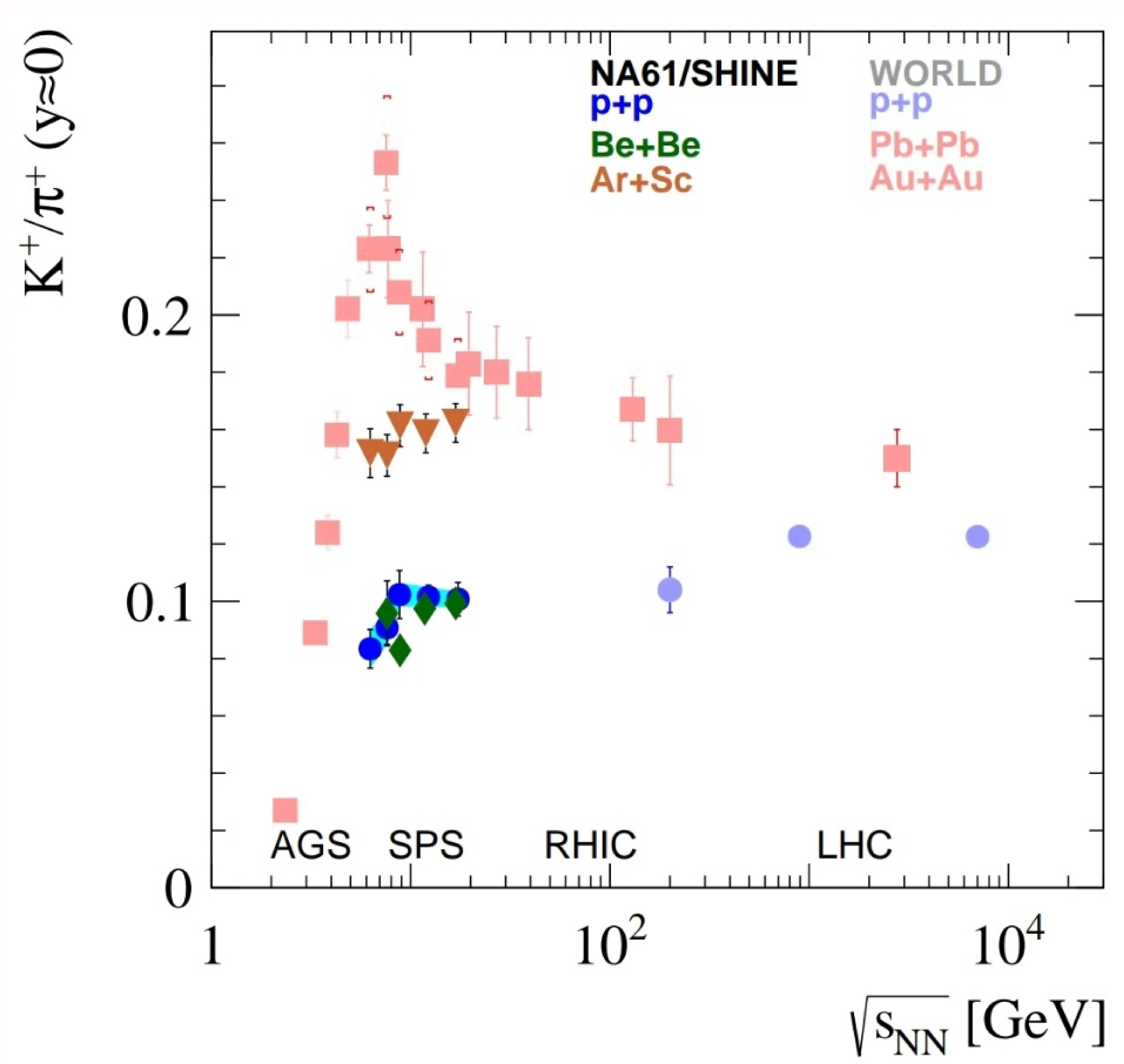
FAIR SIS-100 (< 5 GeV):
not possible at SIS-100,

NA61/SHINE (8, 17 GeV):
$\langle c\bar{c} \rangle$ IN 2021-2024

NA60+ (6-17 GeV):
J/ψ, $\langle c\bar{c} \rangle$ AFTER 2026

INVENTING FUTURES

ONSET OF FIREBALL – RECENT NA61/SHINE DISCOVERY



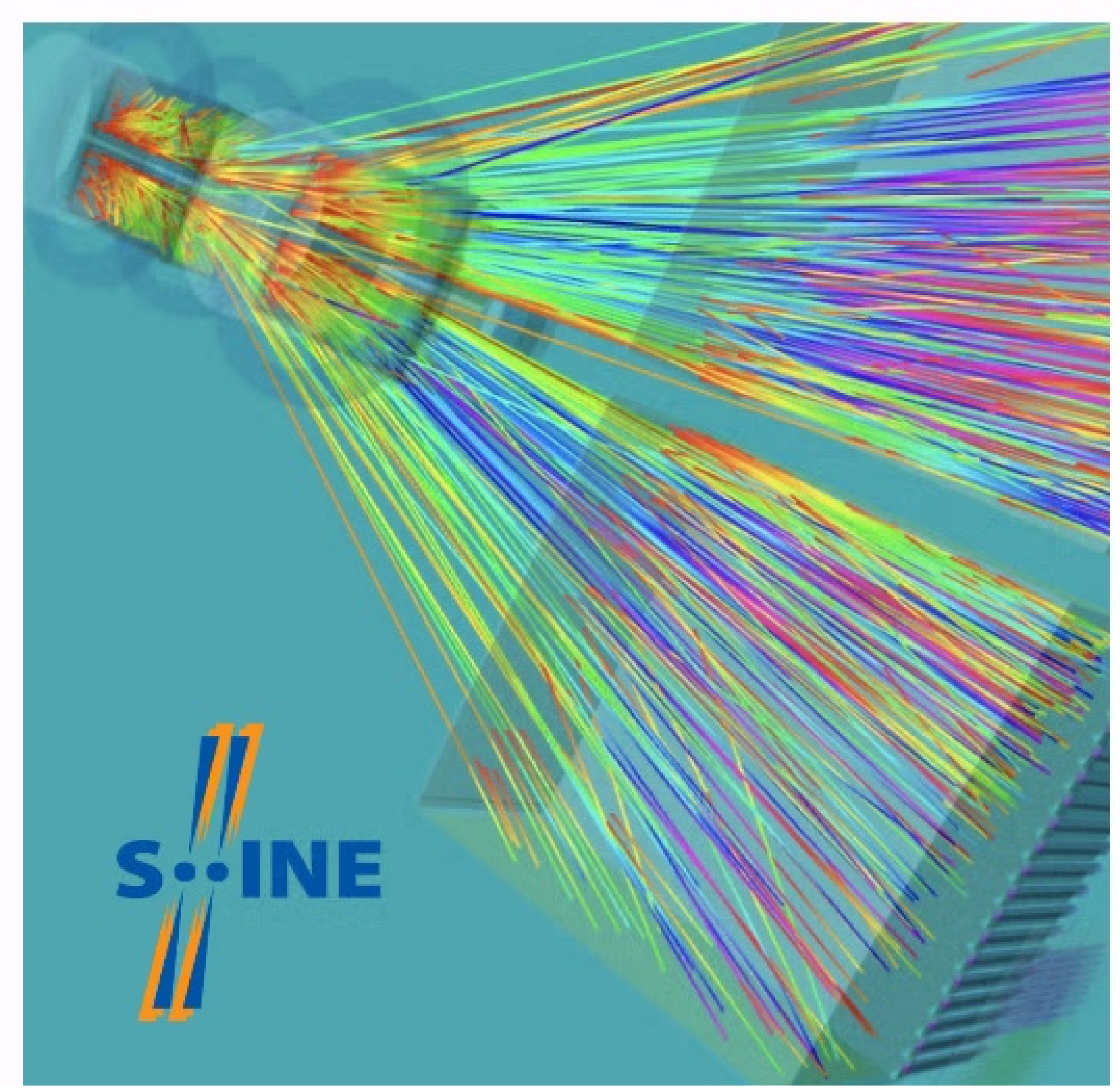
Ar+Sc ≳
≲ Pb+Pb

Be+Be ≈
≈ p+p

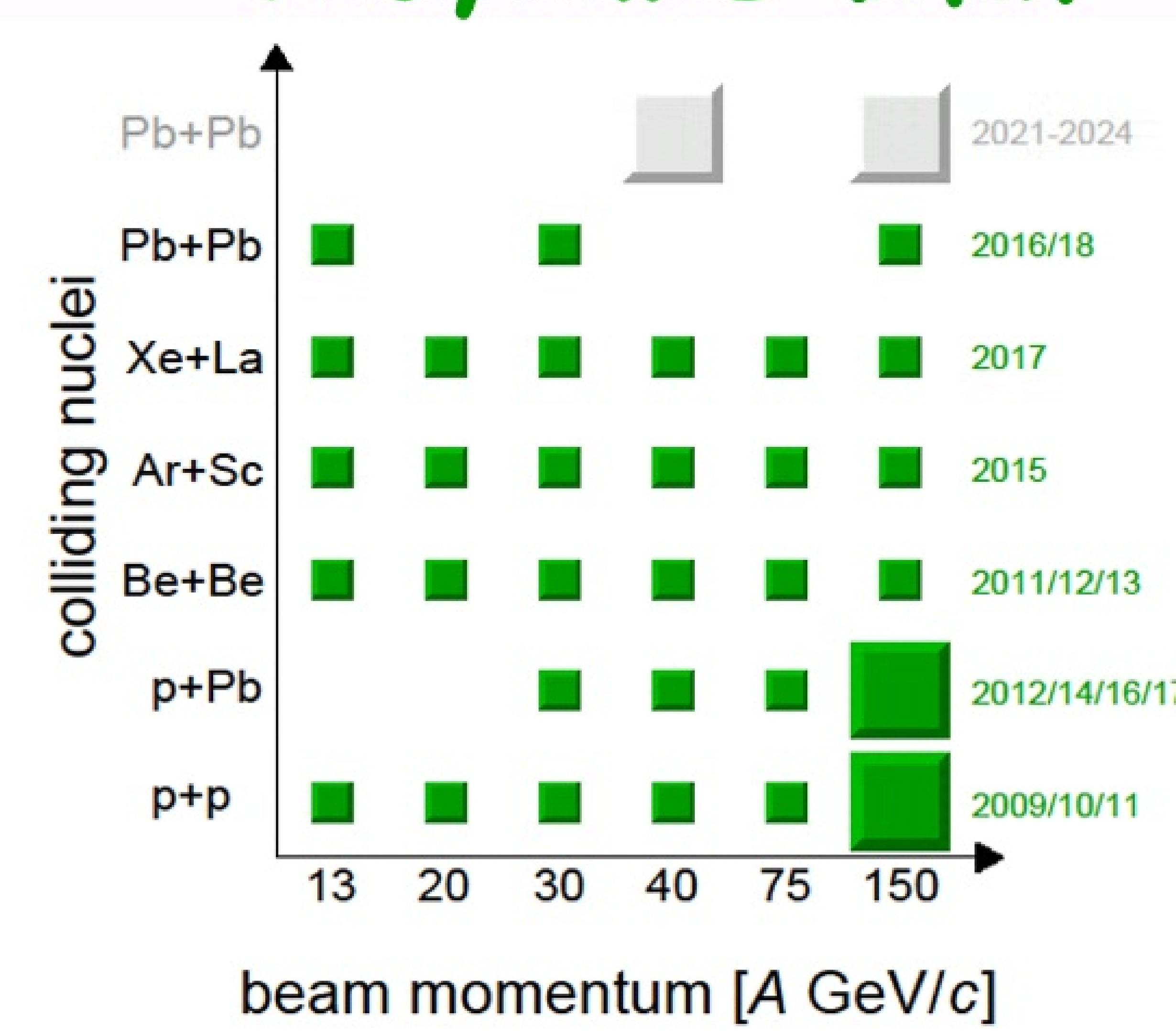
STATISTICAL MODELS

A ↑ ONSET OF FIREBALL

STRING–RESONANCE MODELS

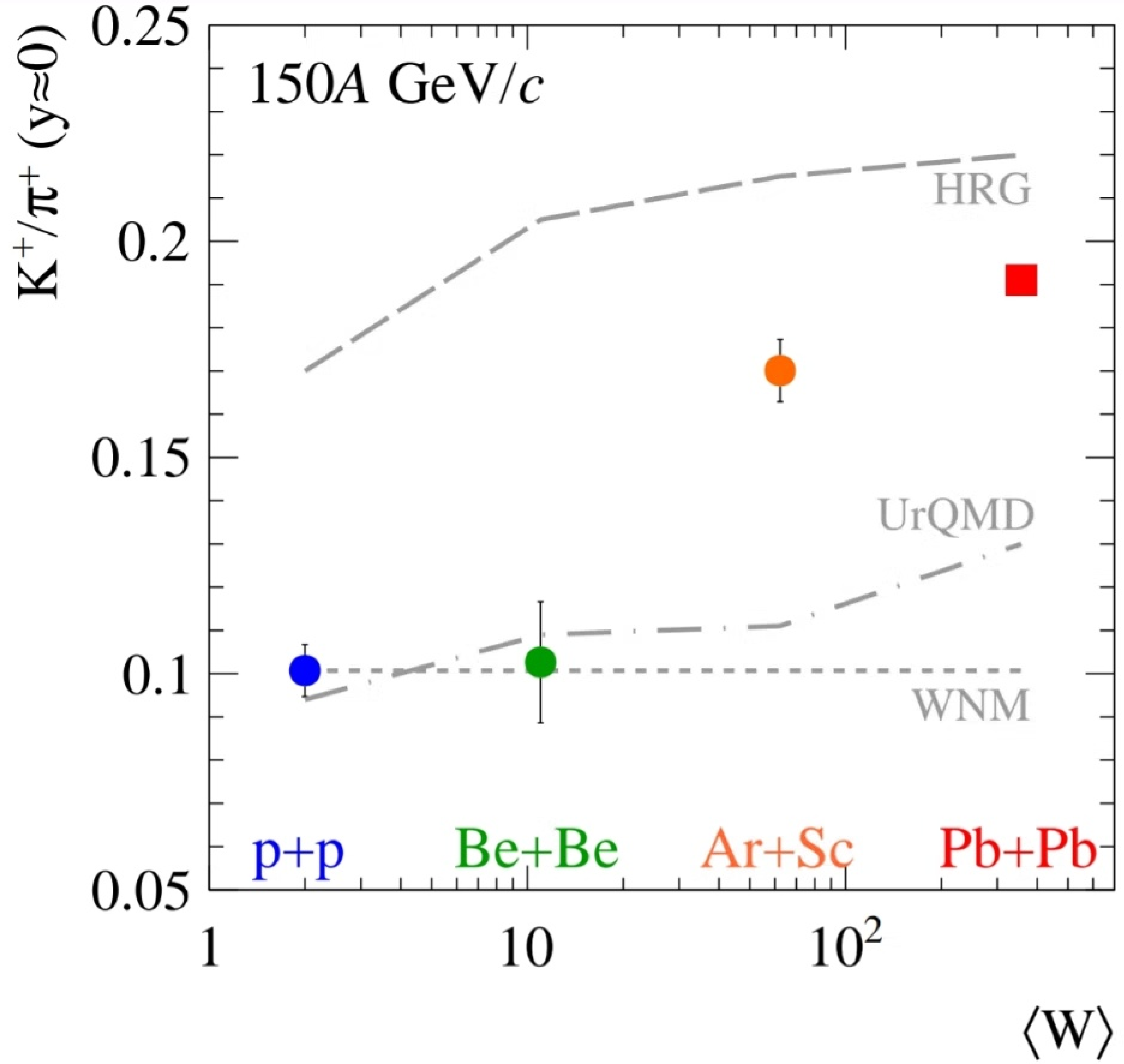


NA61/SHINE DATA



INVENTING FUTURES

ONSET OF FIREBALL – RECENT NA61/SHINE DISCOVERY



Ar+Sc ⪡
⪡ Pb+Pb

Be+Be ≈
≈ p+p

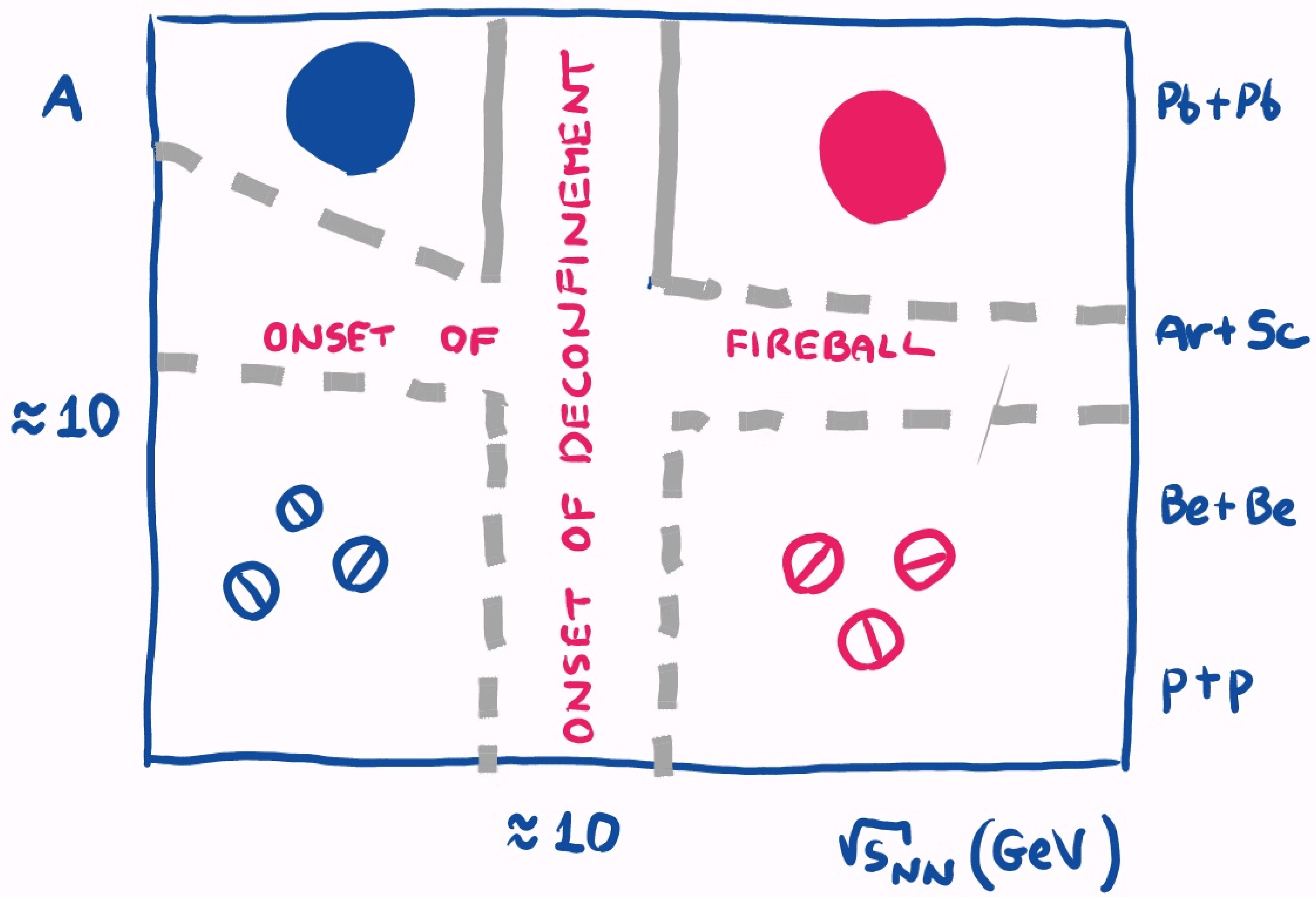
STATISTICAL MODELS

A ↑ ONSET OF FIREBAL

STRING – RESONANCE MODELS

INVENTING FUTURES

ONSET OF FIREBALL → DETAILED SCAN IN (NUCLEAR MASS NUMBER) – (COLLISION ENERGY) SHOULD BE POSSIBLE AT:



NICA (< 11 GeV); 2022+

FAIR (< 5 GeV); 2025+

SPS (5 – 17 GeV); 2025+

J-PARC (< 6 GeV); ?

SUMMARY

ONSET OF QGP (DECONFINEMENT):

- OBSERVED IN Pb+Pb/Au+Au AT ≈ 8 GEV (SPS, RHIC BES)
- RESULTS TO BE COMPLETED BY CHARM ($\langle c\bar{c} \rangle$, J/ψ) MEASUREMENTS (SPS, NICA, J-PARC ?)

CRITICAL POINT:

- INCONCLUSIVE INDICATIONS FROM SPS AND RHIC
- COMING RESULTS FROM NA61/SHINE AND STAR BES II SHOULD (AT LEAST PARTLY) REMOVE THE TENSION AND ALLOW TO DEFINE NEXT STEPS

ONSET OF FIREBALL:

- INDICATIONS FROM 2D SCAN AT SPS (NA61/SHINE)
- DETAILED SCAN ($\sqrt{s_{NN}} \lesssim 20$ GEV, $A \lesssim 100$) IS NEEDED (NICA, SPS, SIS100, J-PARC ?)

60. Jubilee Cracow School of Theoretical Physics

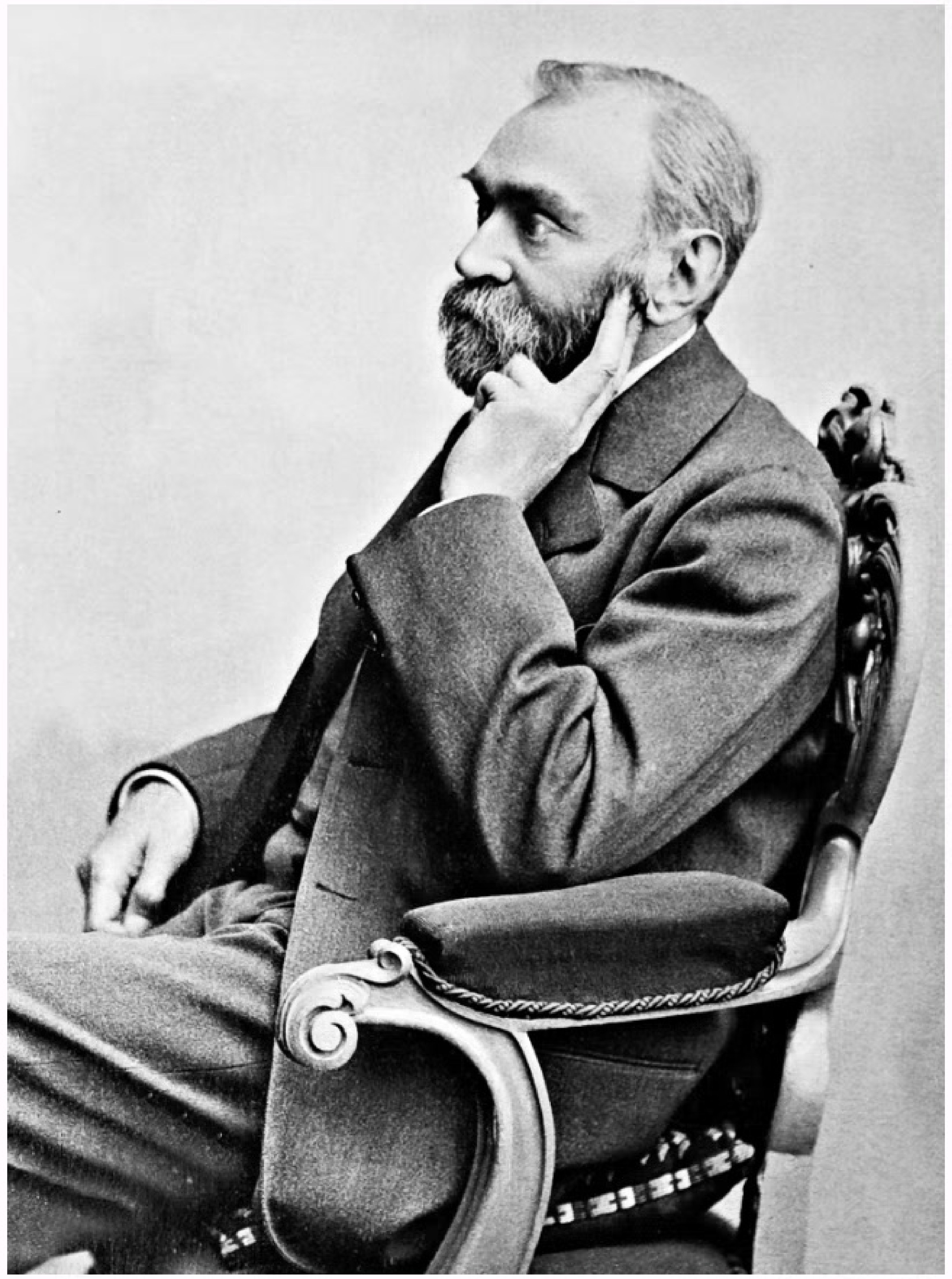
ADDITIONAL SLIDES

COMMENT ON NOBEL PRIZE

DIFFICULTIES IN OBTAINING UNIQUE AND QUANTITATIVE PREDICTIONS OF QGP SIGNALS FROM QCD

$\Downarrow$

THE NOBEL PRIZE FOR THE QGP DISCOVERY WAS NOT YET AWARDED



INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

DYNAMICAL MODEL

HADRON GAS:

$$N + N \to N + Y + K$$

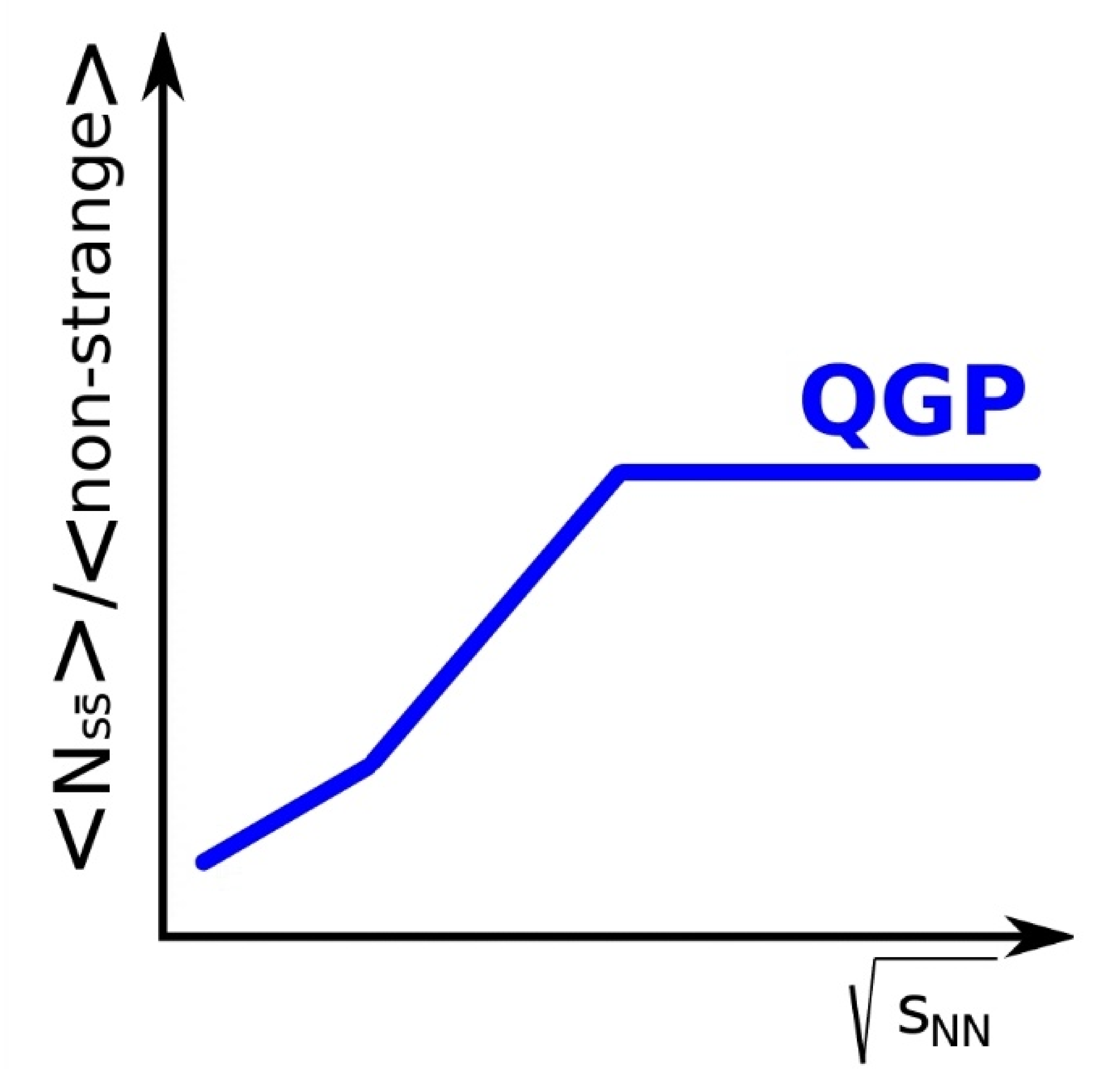
$\pi + N \to K + Y$ $\qquad$ $\pi + \overline{N} \to \overline{K} + \overline{Y}$

$\pi + Y \to \Xi + K$ $\qquad$ $\pi + \overline{Y} \to \overline{\Xi} + \overline{K}$

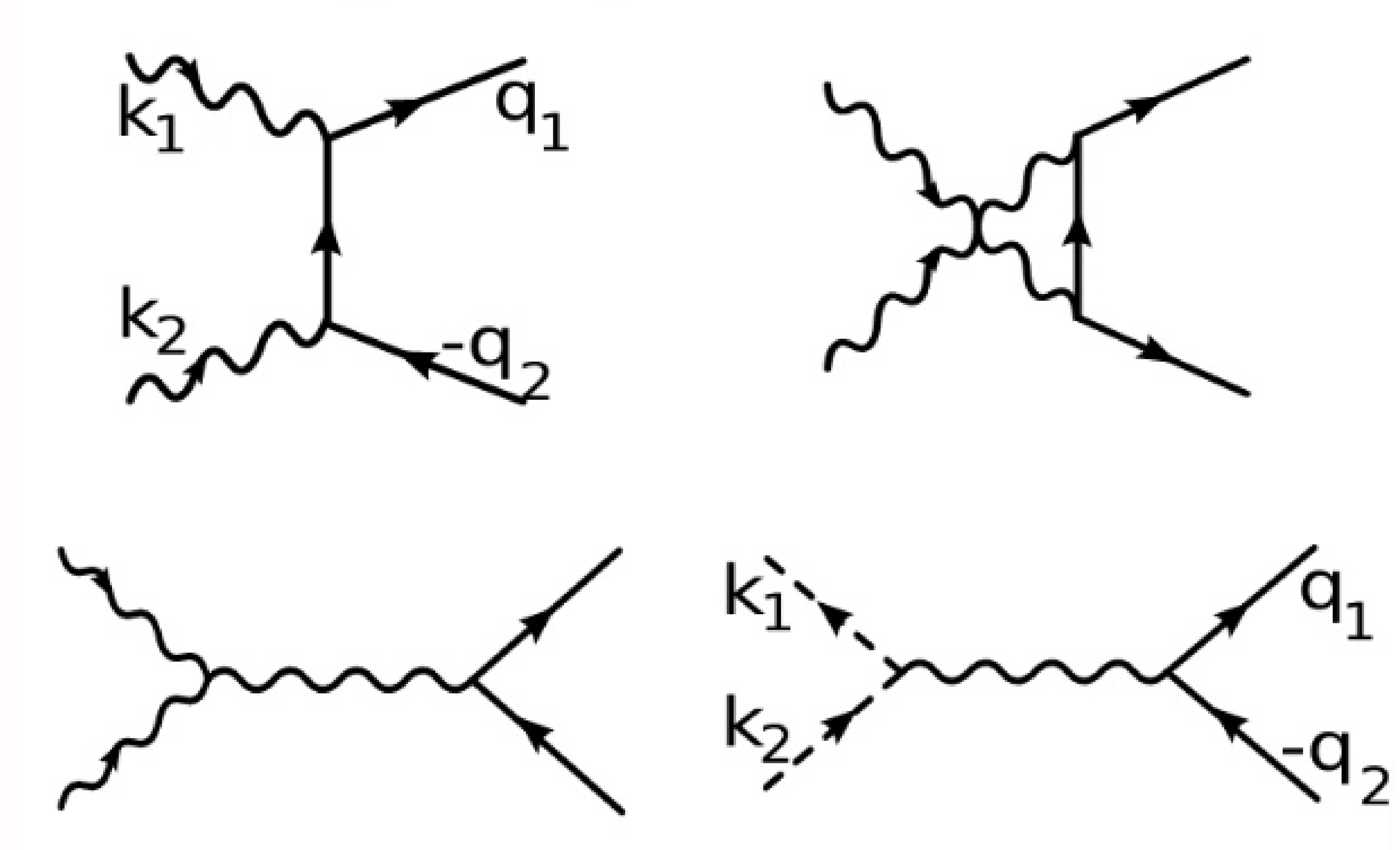
$\pi + \Xi \to \Omega + K$ $\qquad$ $\pi + \overline{\Xi} \to \overline{\Omega} + \overline{K}$

$m_K \gg T_c \approx 150$ MeV

$\tau_{EQUIL} \approx 100$ fm/c



QUARK-GLUON PLASMA



$m_s < T_c \approx 150$ MeV

$\tau_{EQUIL} \approx 1\text{-}10$ fm/c

CROSSING THRESHOLD FOR QGP CREATION →

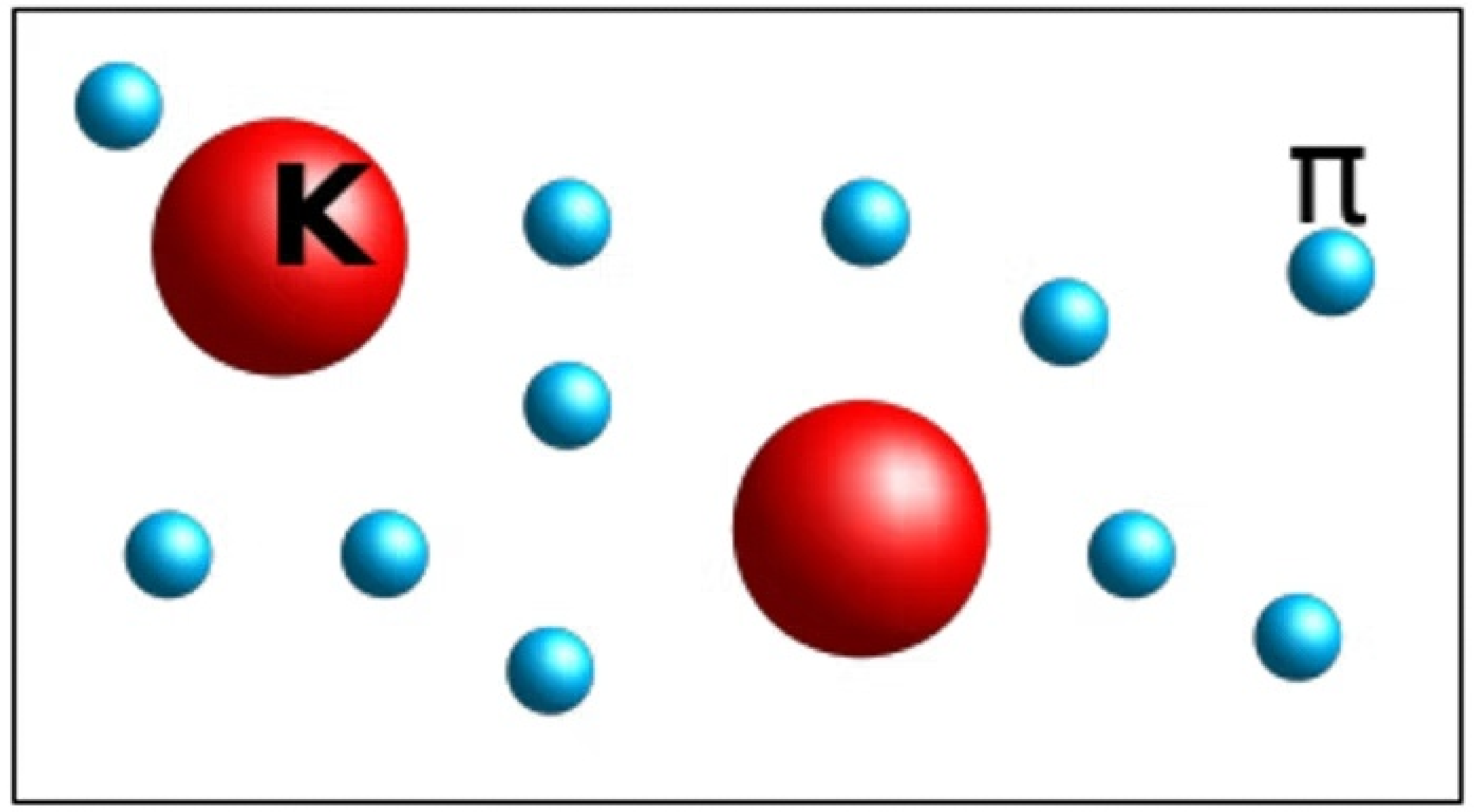
→ STRANGENESS ENHACEMENT

RAFELSKI, MULLER, GLENDENNING 1982+ ...

INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

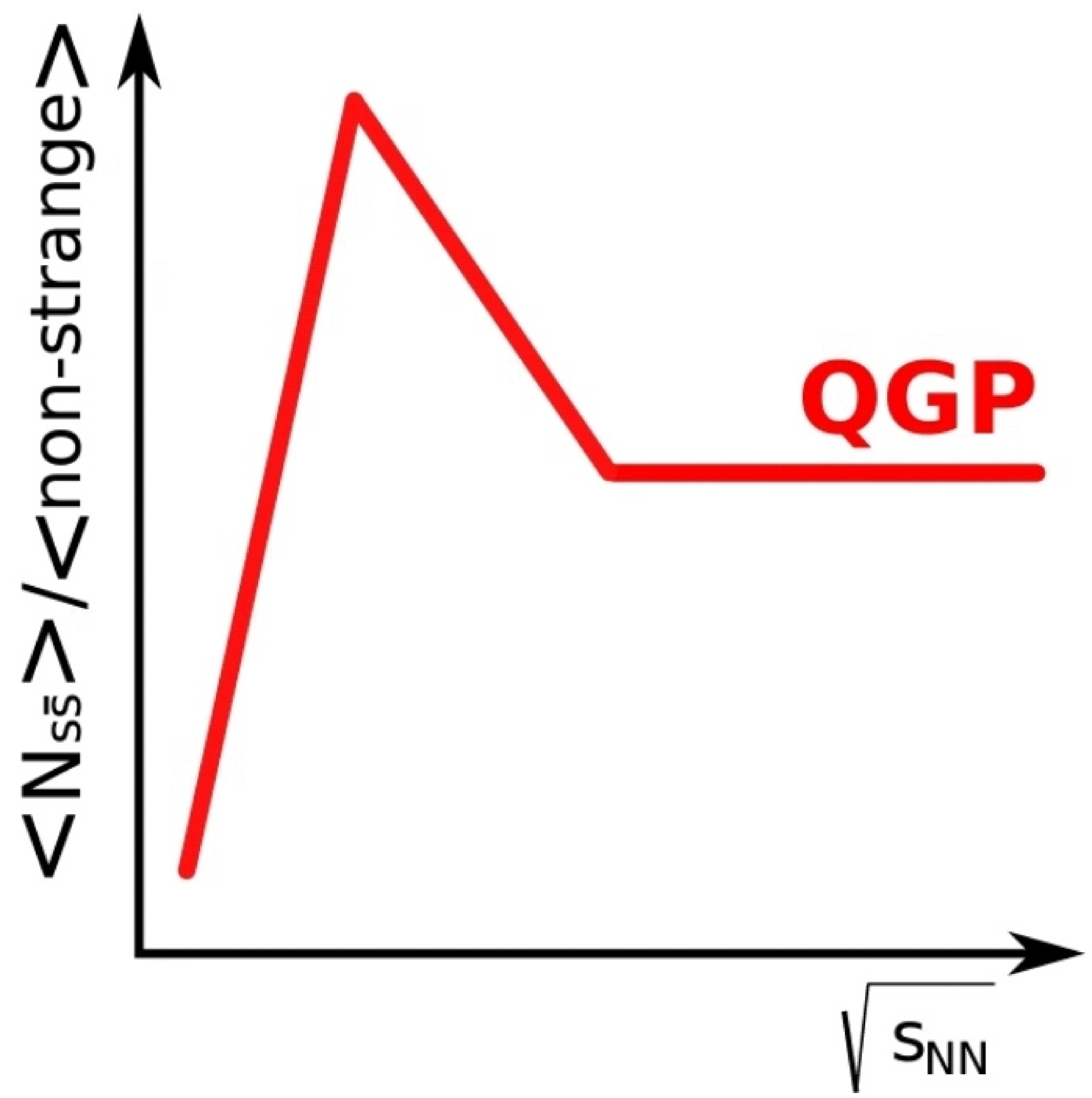
STATISTICAL MODEL OF THE EARLY STAGE

HADRON GAS

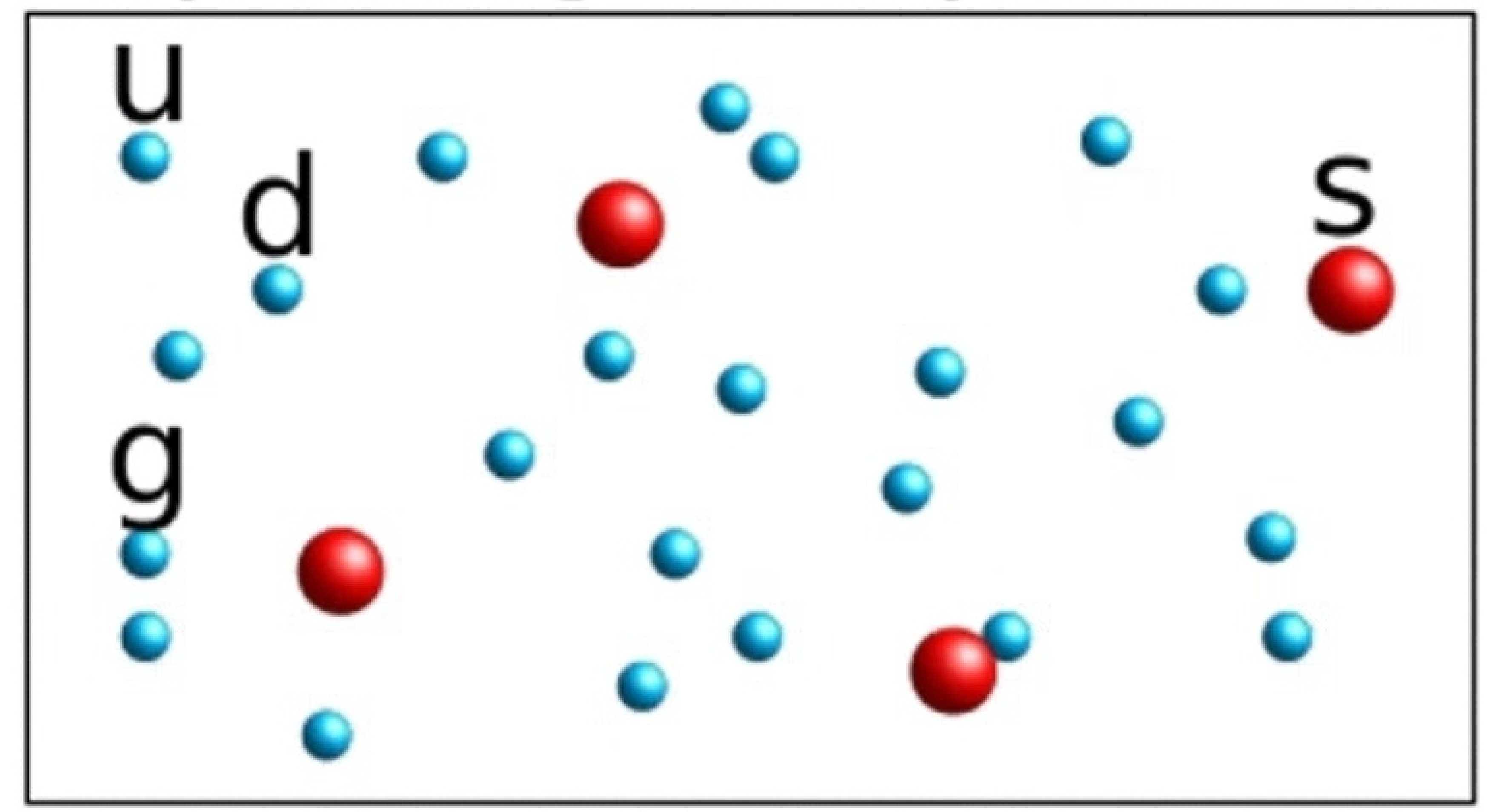


$m_K \gg T_c \approx 150$ MeV

$\langle \bar{K} \rangle \sim e^{-m_K/T}$



QUARK-GLUON PLASMA



$m_s < T_c \approx 150$ MeV

$\langle \bar{s} \rangle \sim T^3$

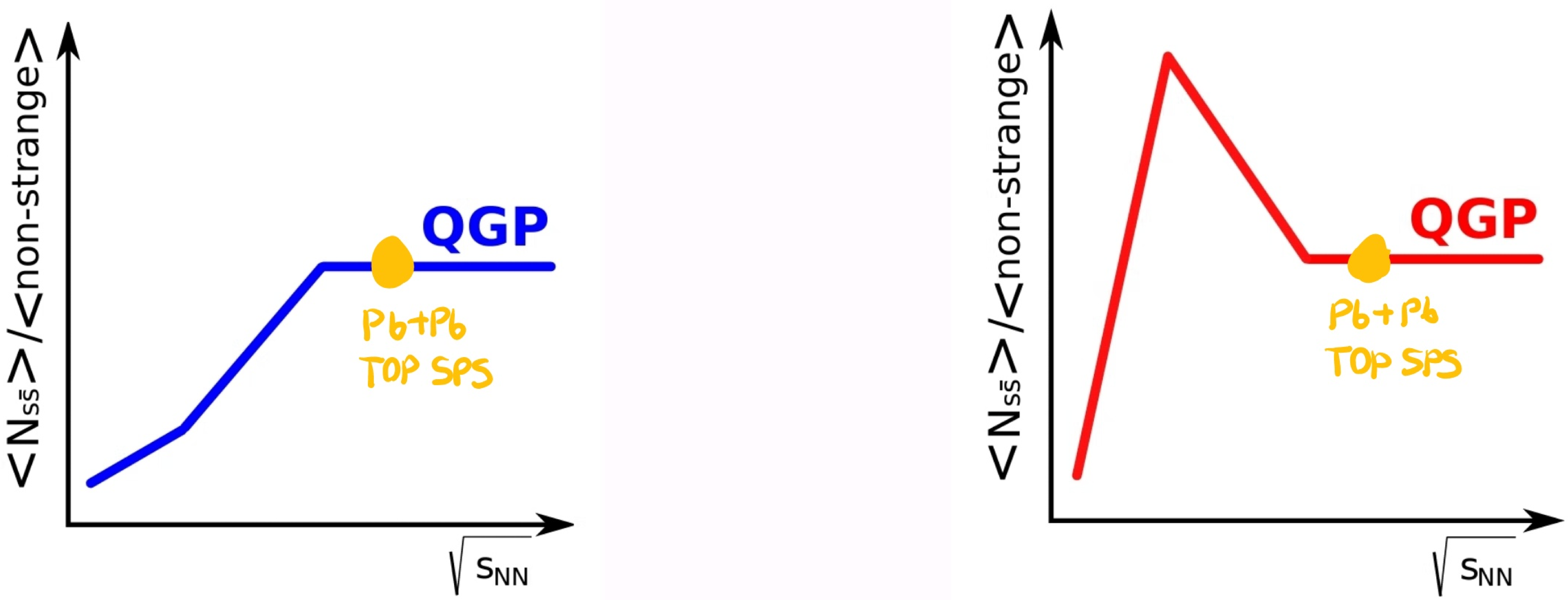
CROSSING THRESHOLD FOR QGP CREATION ⟶

⟶ HORN-LIKE STRUCTURE

MG, GORENSTEIN, 1996+

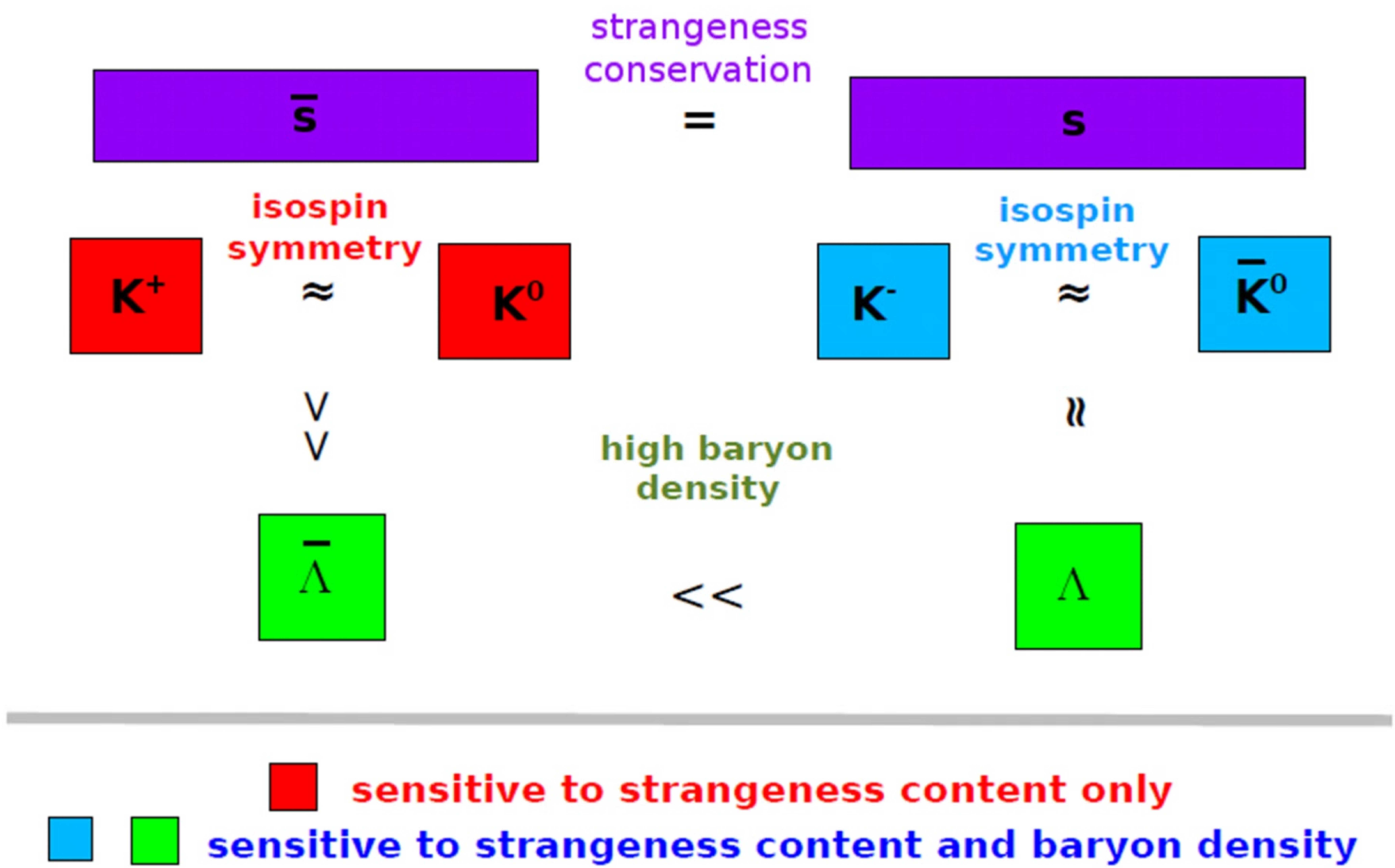
INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

DYNAMICAL VERSUS STATISTICAL MODELS



≈ 2000: COLLISION ENERGY SCAN IS NEEDED

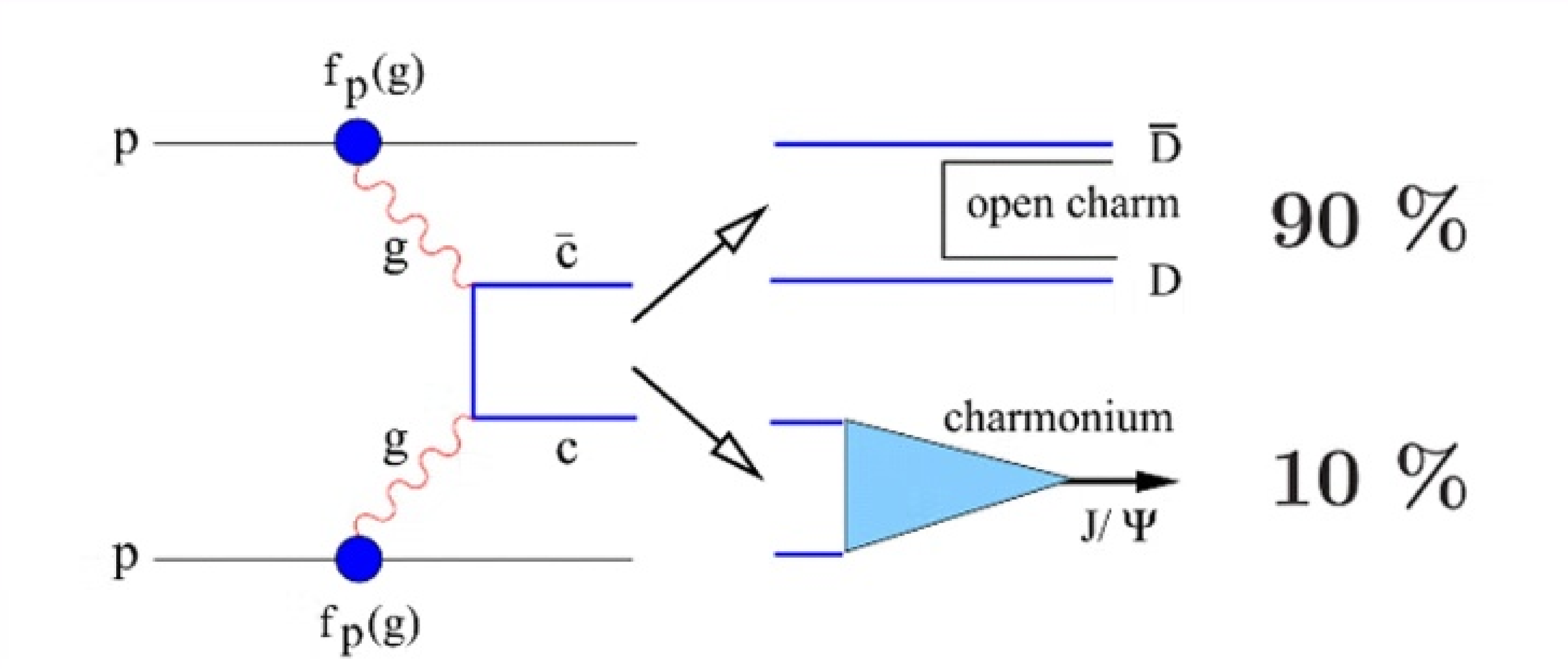
- SEARCH FOR THE ONSET OF QGP CREATION
- DISTINGUISH BETWEEN DYNAMICAL AND STATISTICAL MODELS

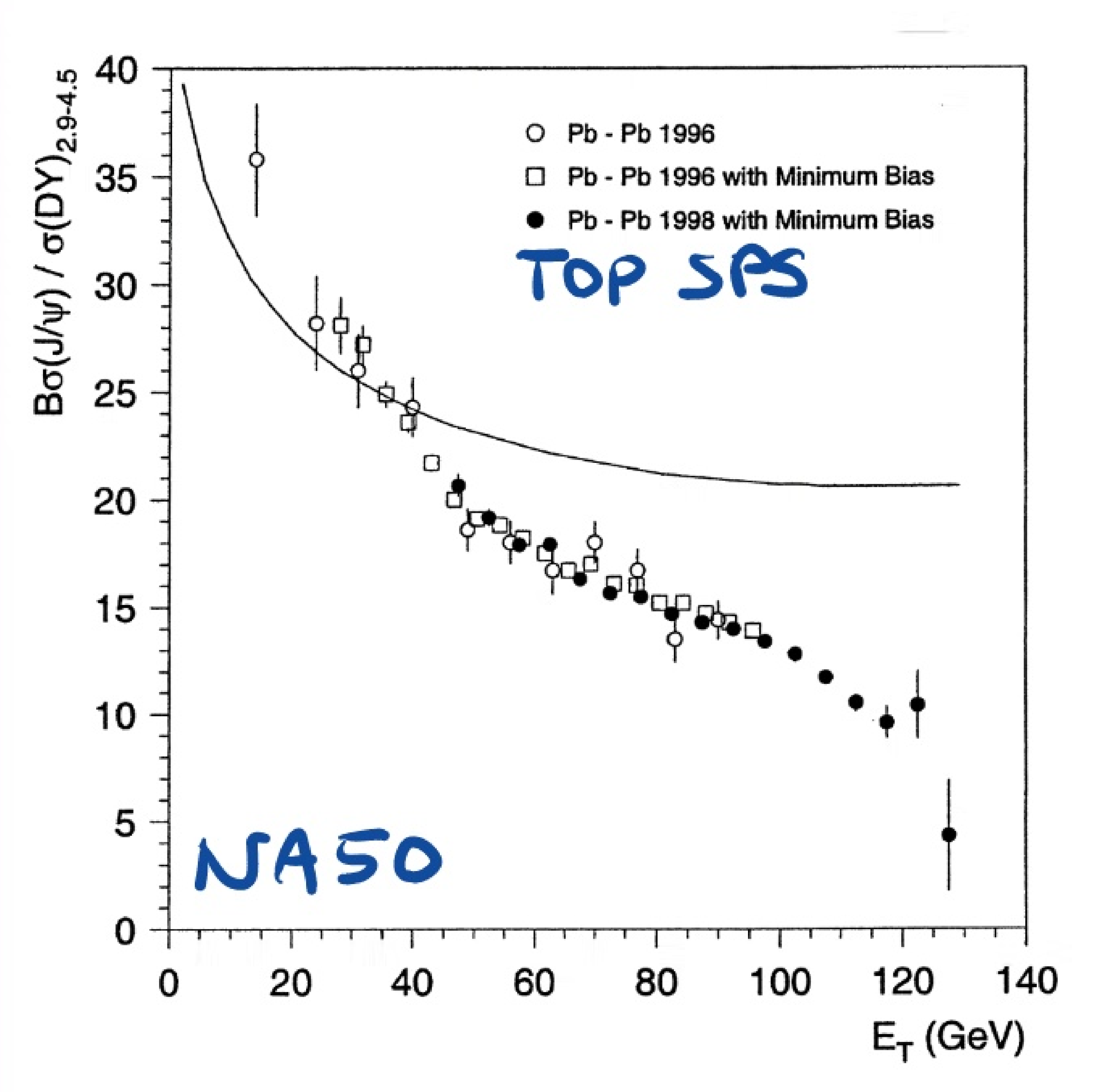

strangeness conservation
$\bar{s}$
=
s
isospin symmetry
K^+
≈
K^0
isospin symmetry
K^-
≈
$\bar{K}^0$
>>
high baryon density
≈
$\bar{\Lambda}$
<<
Λ
sensitive to strangeness content only
sensitive to strangeness content and baryon density

INTERMEZZO II: CHARM PRODUCTION AND QGP

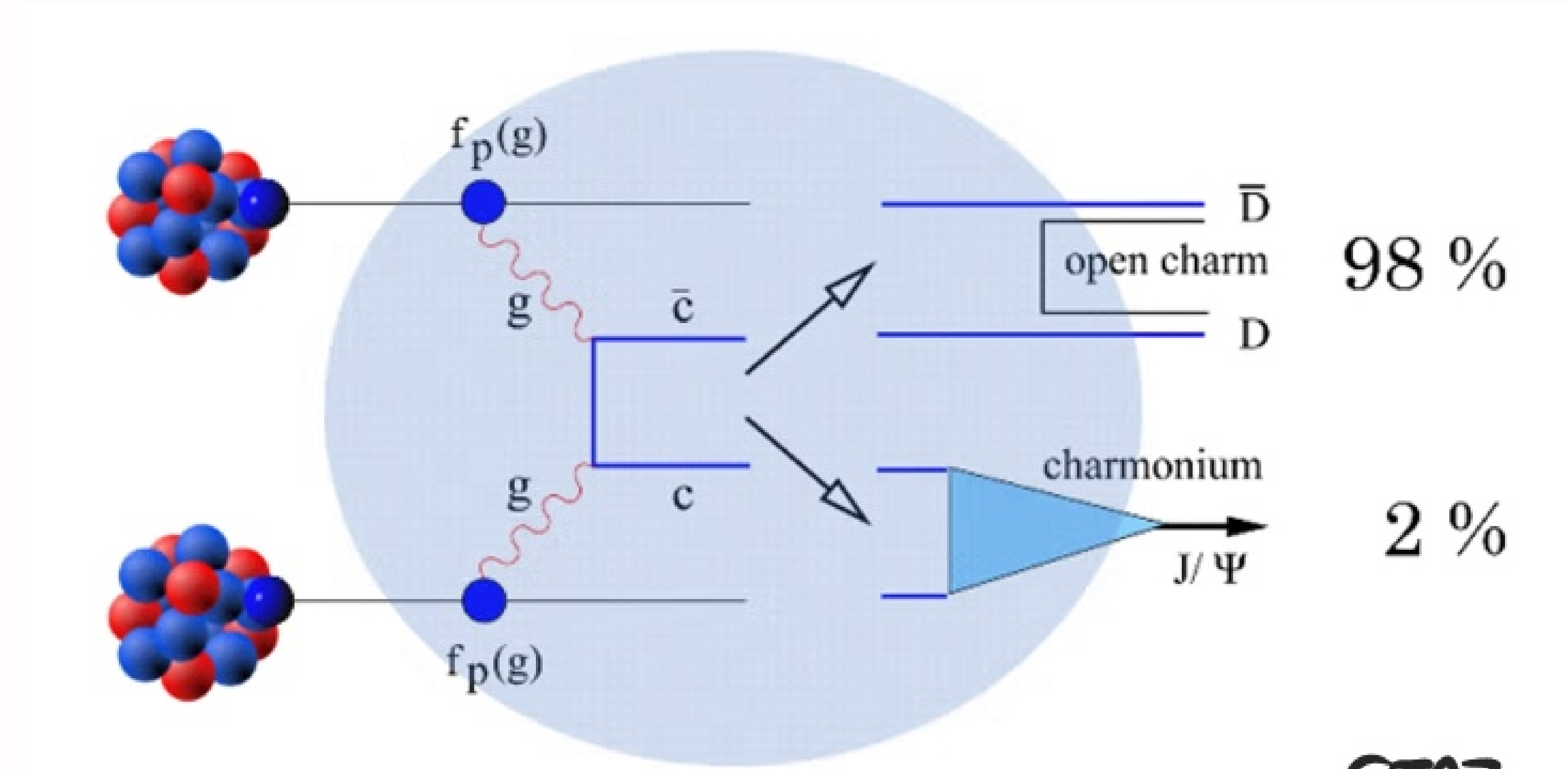
DYNAMICAL MODEL

ELEMENTARY p+p





Pb+Pb WITH QGP



STAZ

BUT THERE ARE NO DATA ON D, $\bar{D}$ PRODUCTION

→ ASSUMPTION : $\langle D\bar{D}\rangle \sim \langle DY\rangle$

CROSSING THRESHOLD FOR QGP CREATION →

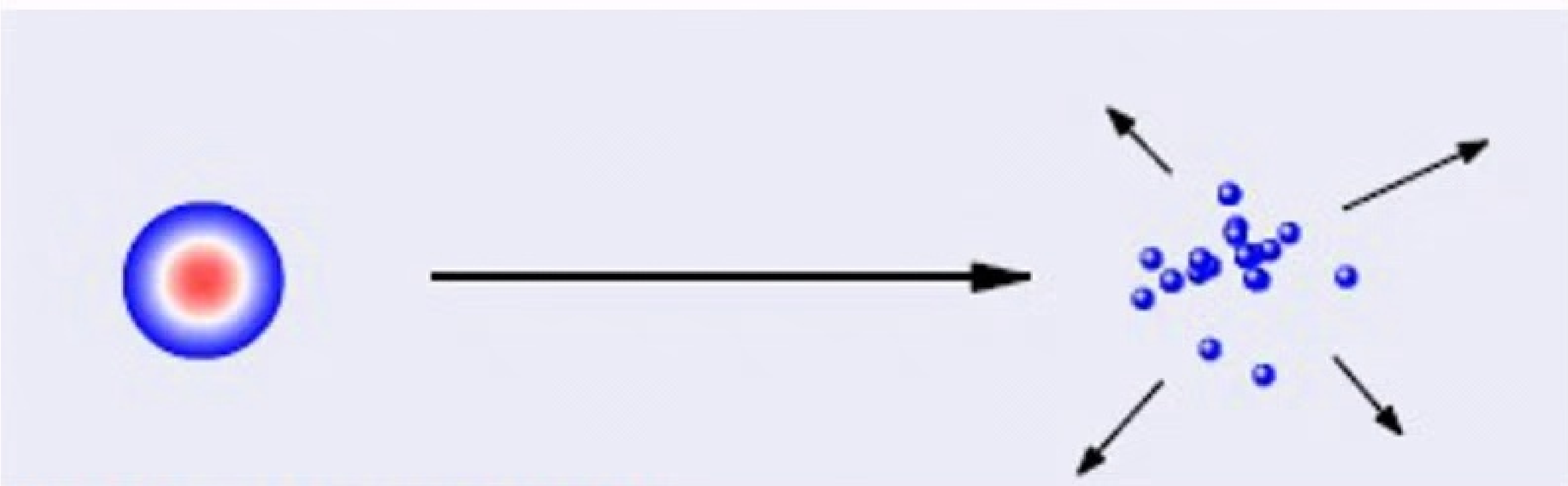
→ ANOMALOUS SUPPRESSION OF $\langle J/\psi\rangle / \langle c\bar{c}\rangle$ RATIO

MATSUI, SATZ, 1986+

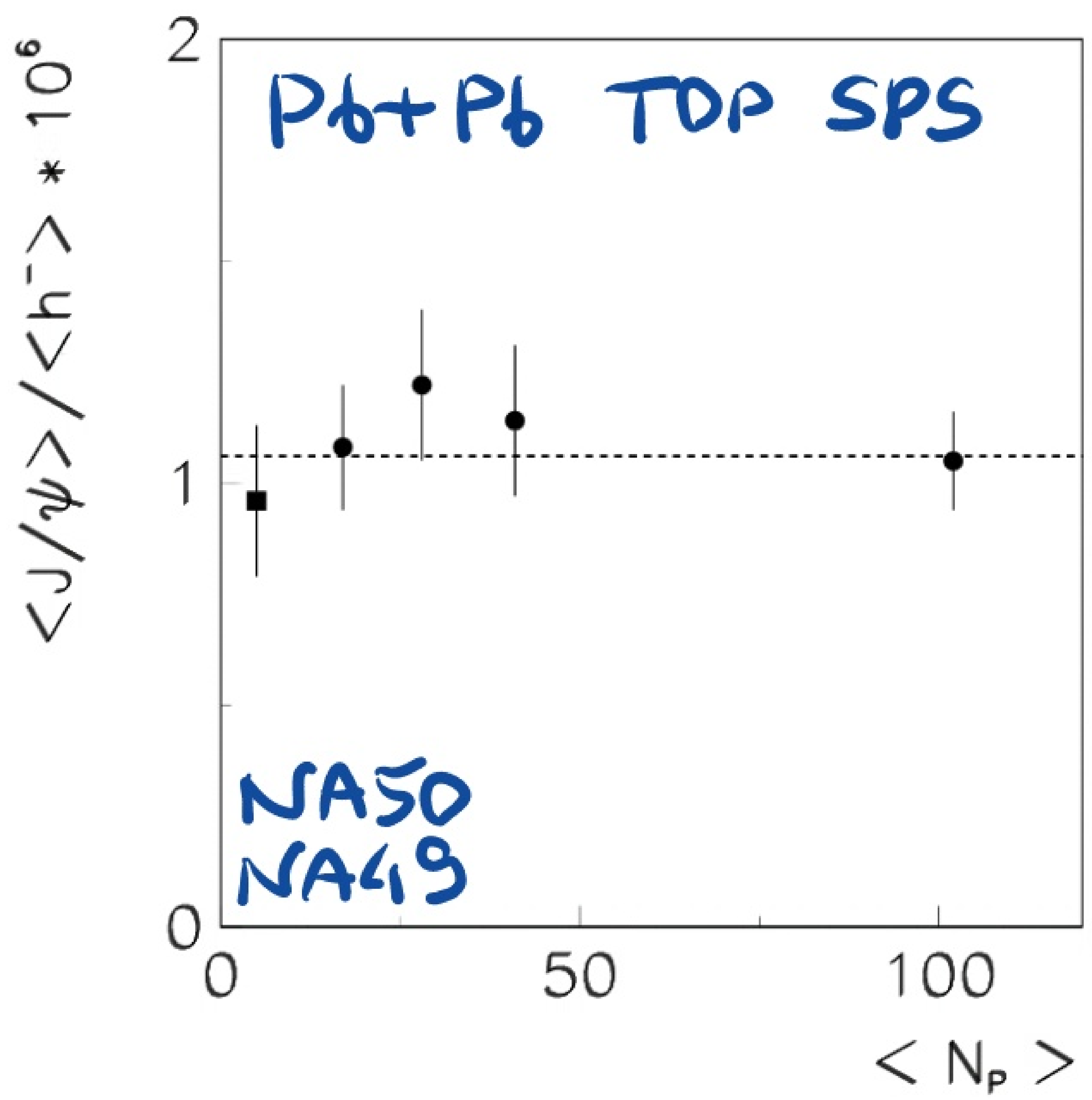
INTERMEZZO II: CHARM PRODUCTION AND QGP

STATISTICAL HADRONIZATION MODEL

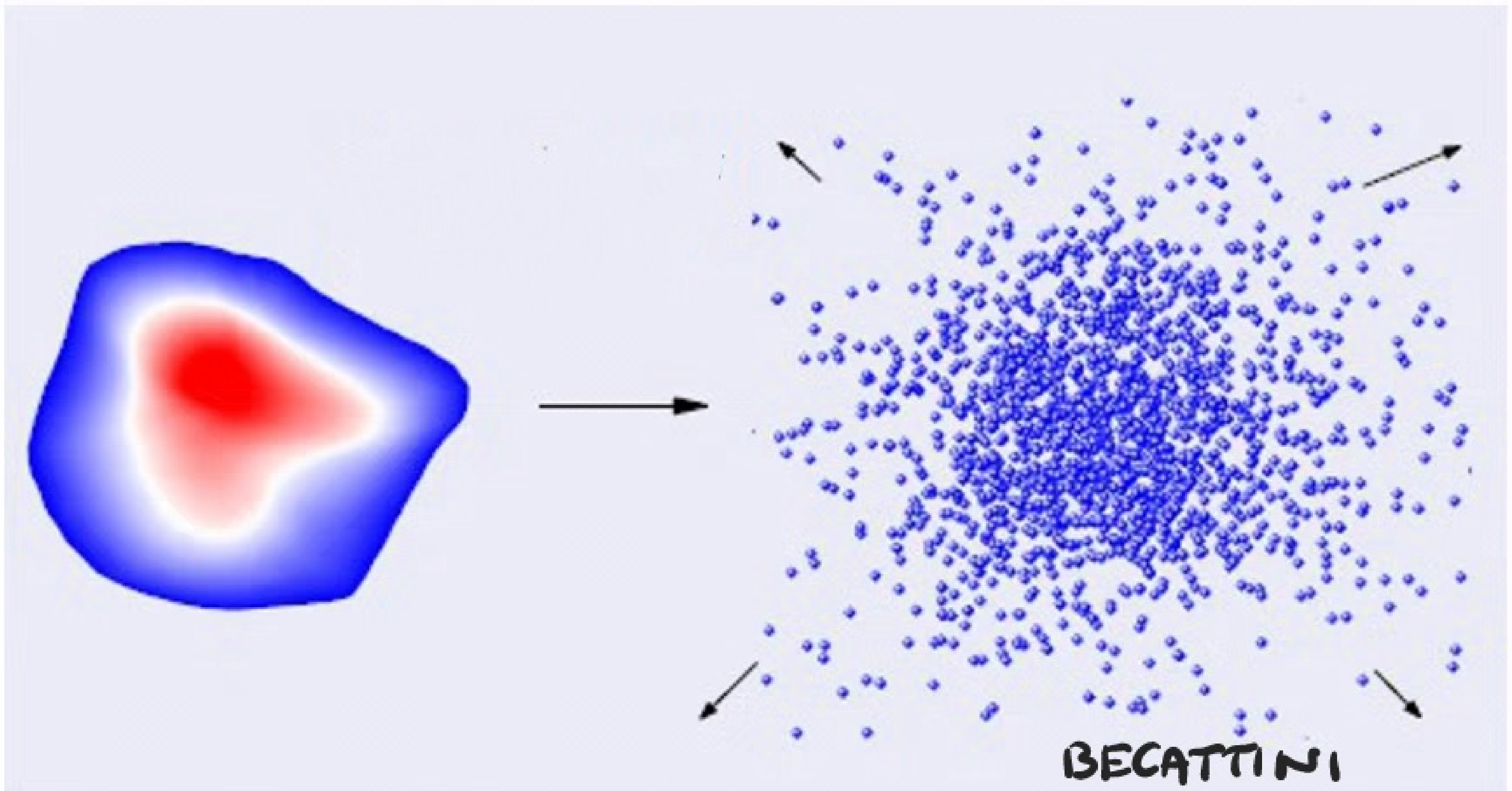
ELEMENTARY p+p



J/ψ BORN IN EQUILIBRIUM
AT $\varepsilon \approx 0.5\ GeV/fm^3$



Pb+Pb WITH QGP



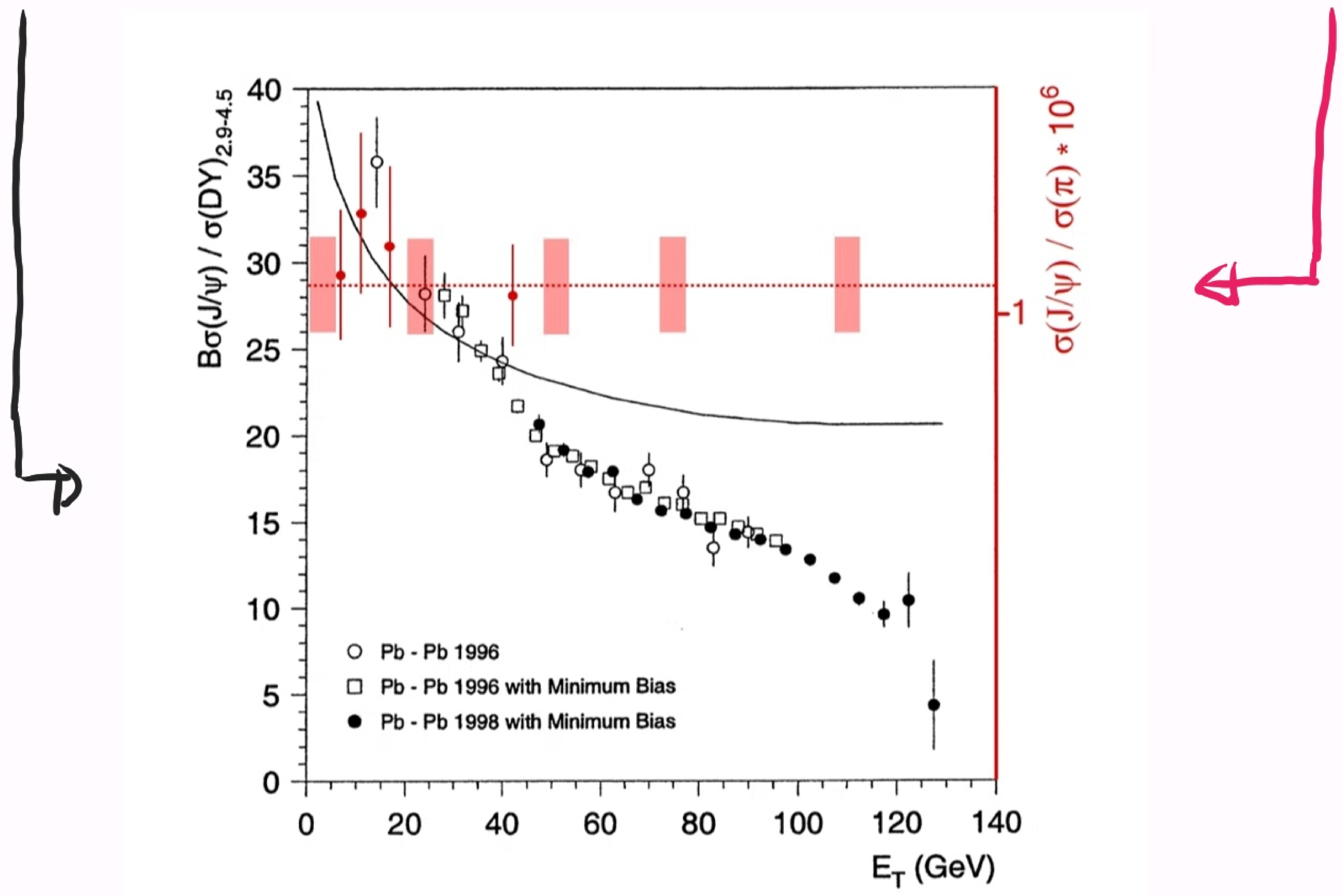
J/ψ BORN IN EQUILIBRIUM
AT $\varepsilon \approx 0.5\ GeV/fm^3$

CROSSING THRESHOLD FOR QGP CREATION →
→ NO CHANGE IN $\langle J/\psi \rangle / \langle \pi \rangle$ RATIO

M.G. GORENSTEIN, 1998 +

INTERMEZZO II: CHARM PRODUCTION AND QGP

DYNAMICAL VERSUS STATISTICAL HADRONIZATION MODELS



2020: DATA ON $\langle D\bar{D} \rangle$ AND $\langle J/\psi \rangle$ VERSUS COLLISION ENERGY AND NUCLEAR MASS NUMBER IS NEEDED