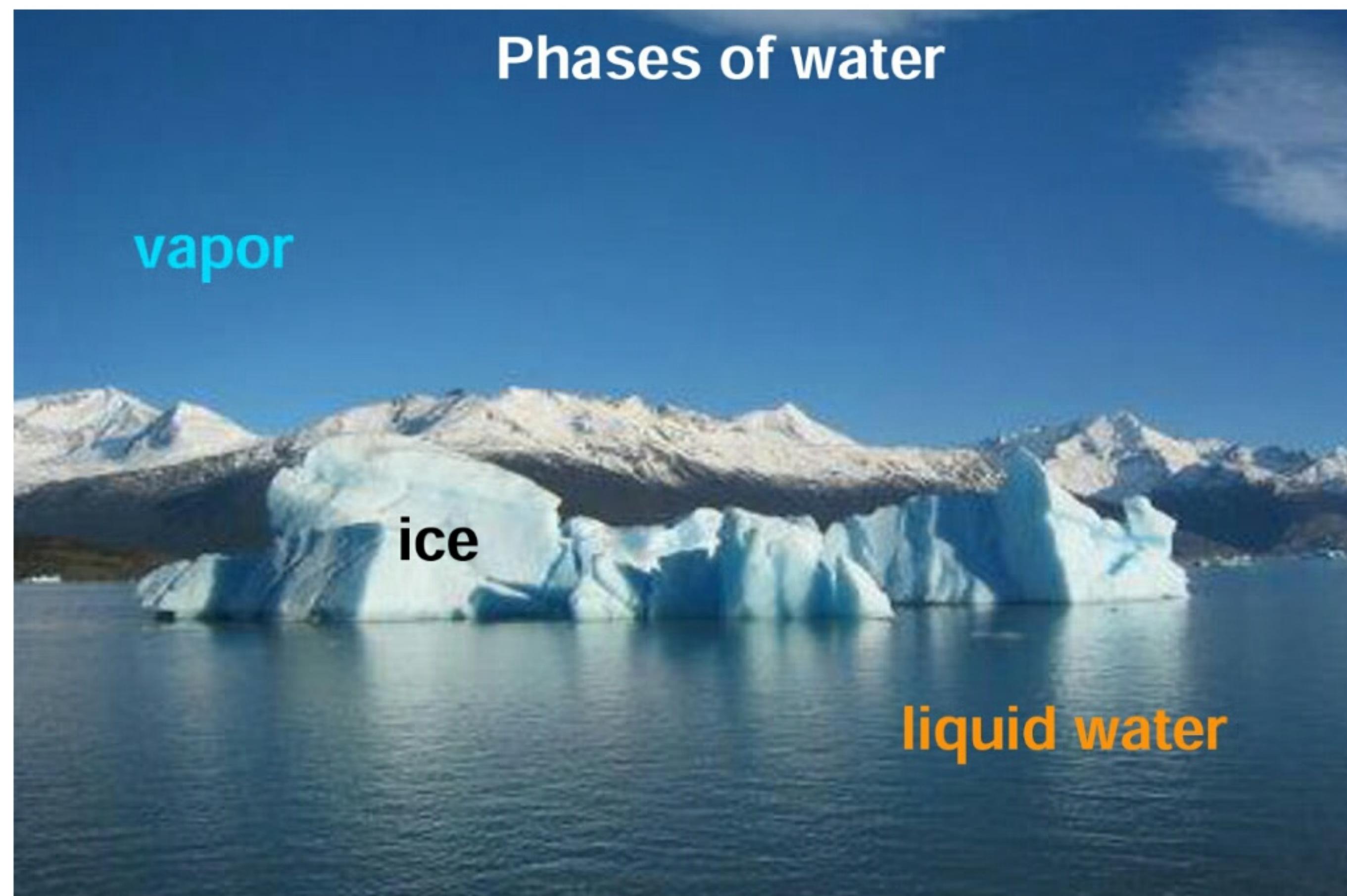
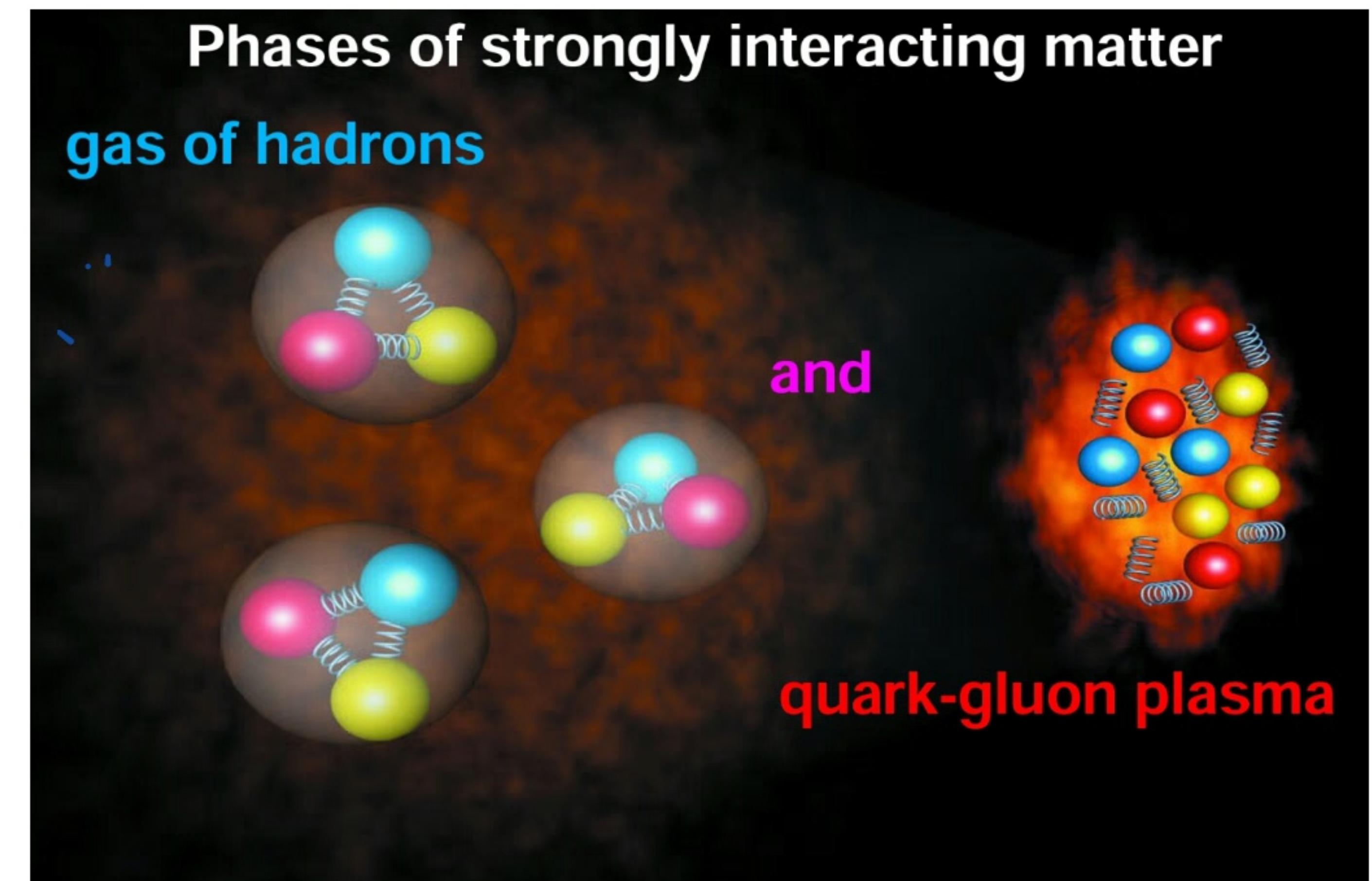


SHORT HISTORY OF A LONG-LASTING EFFORT
TO ANSWER THE SIMPLE QUESTION:

WHAT ARE PHASES AND TRANSITIONS (\rightarrow CRITICAL STRUCTURES)
IN STRONGLY INTERACTING MATTER?



$T \approx 300 \text{ K}$



$T \approx 10^{12} \text{ K}$

20 YEARS AFTER DISCOVERY OF A NEW STATE OF MATTER

STUDIES OF PHASE DIAGRAM OF
STRONGLY INTERACTING MATTER AT THE CERN SPS

M. GAZDZICKI, KIELCE, FRANKFURT



VOCABULARY



QUARK-GLUON PLASMA
(1986 - 2003)



CRITICAL STRUCTURES
(1997 - 2025 ?)



INVENTING FUTURES

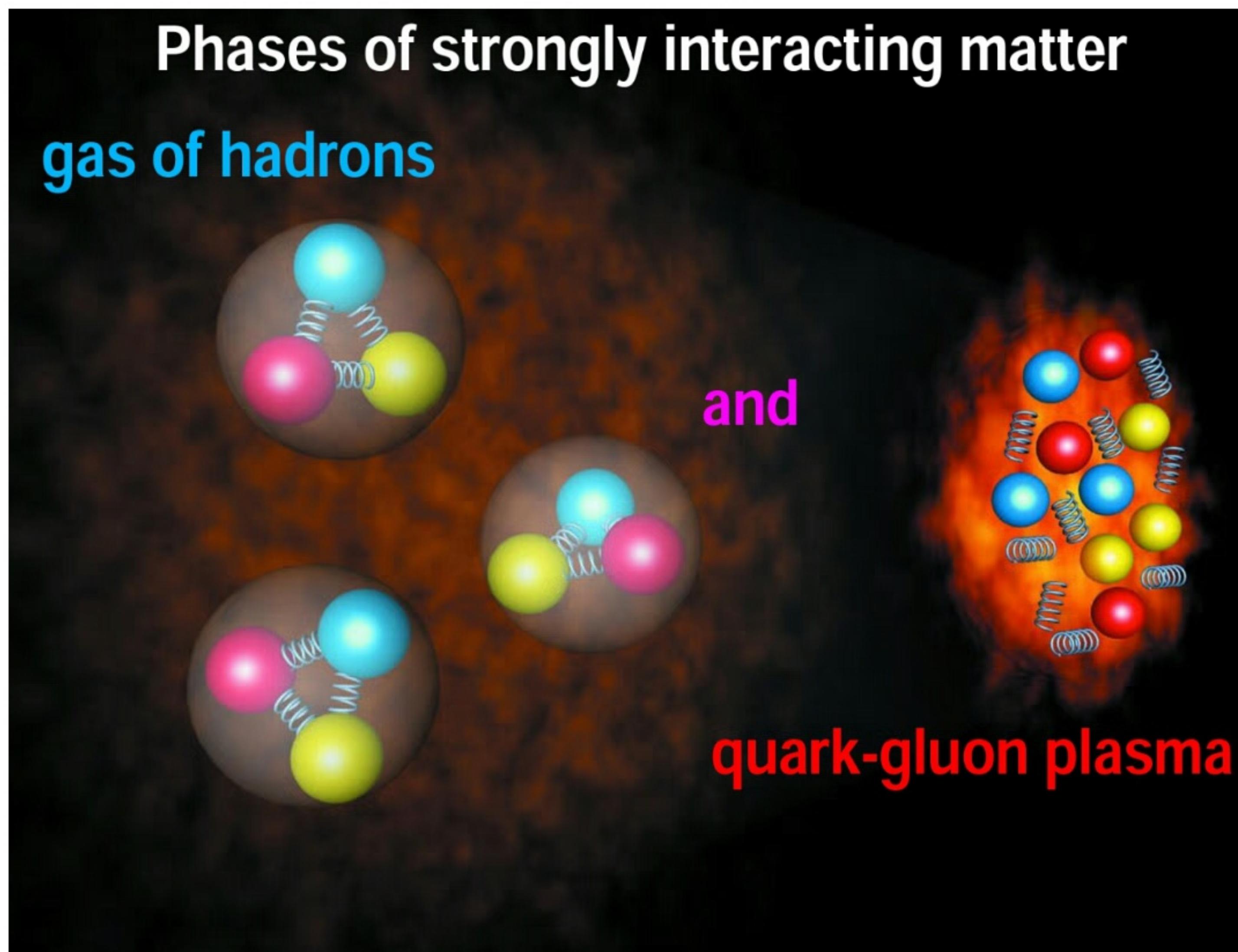
DETAILS, REFERENCES: MG, GORENSTEIN, SEYBOTH , 2004.02255



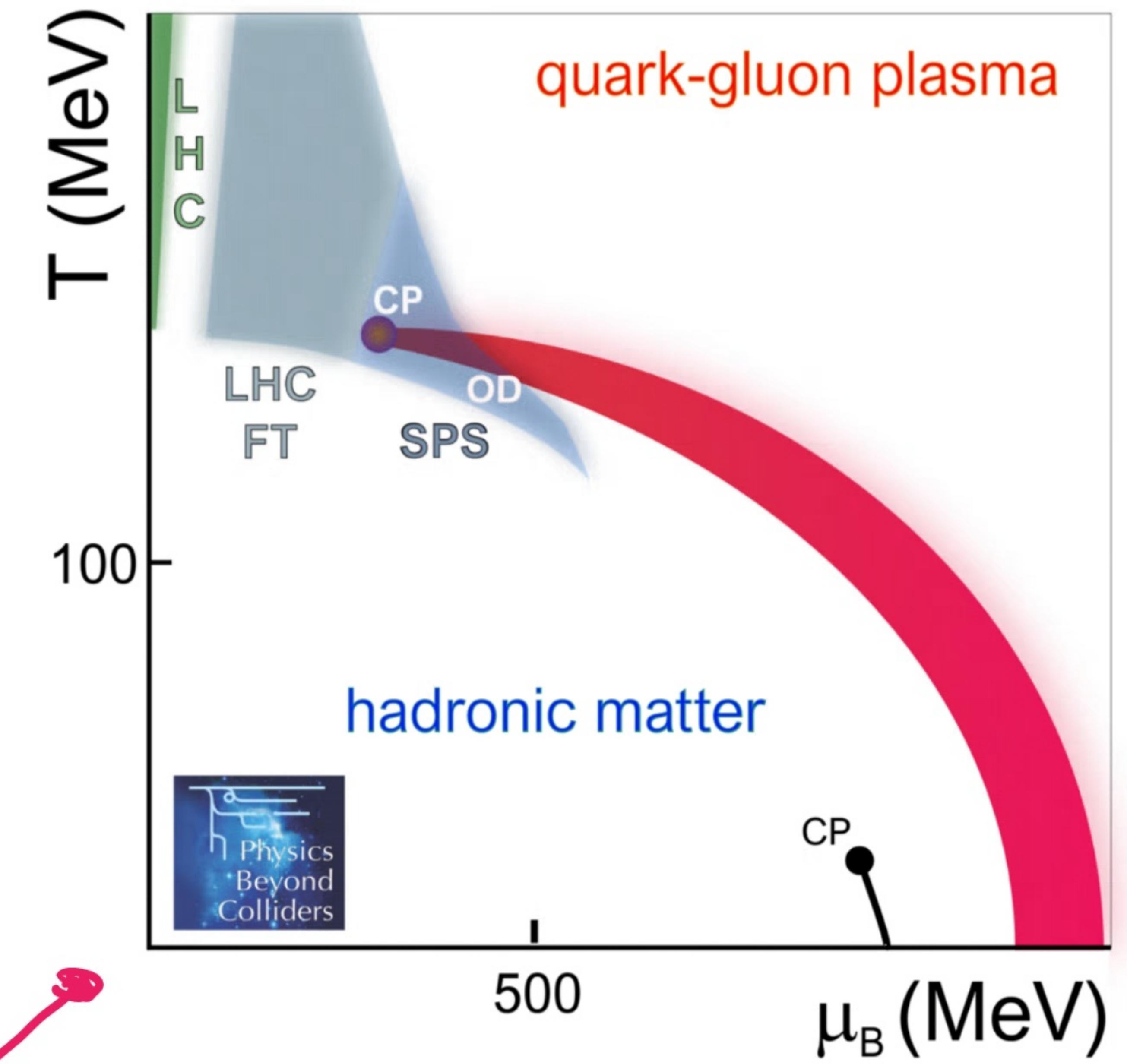
VOCABULARY

2

THE QUARK-GLUON PLASMA HYPOTHESIS (1965 - 1975)



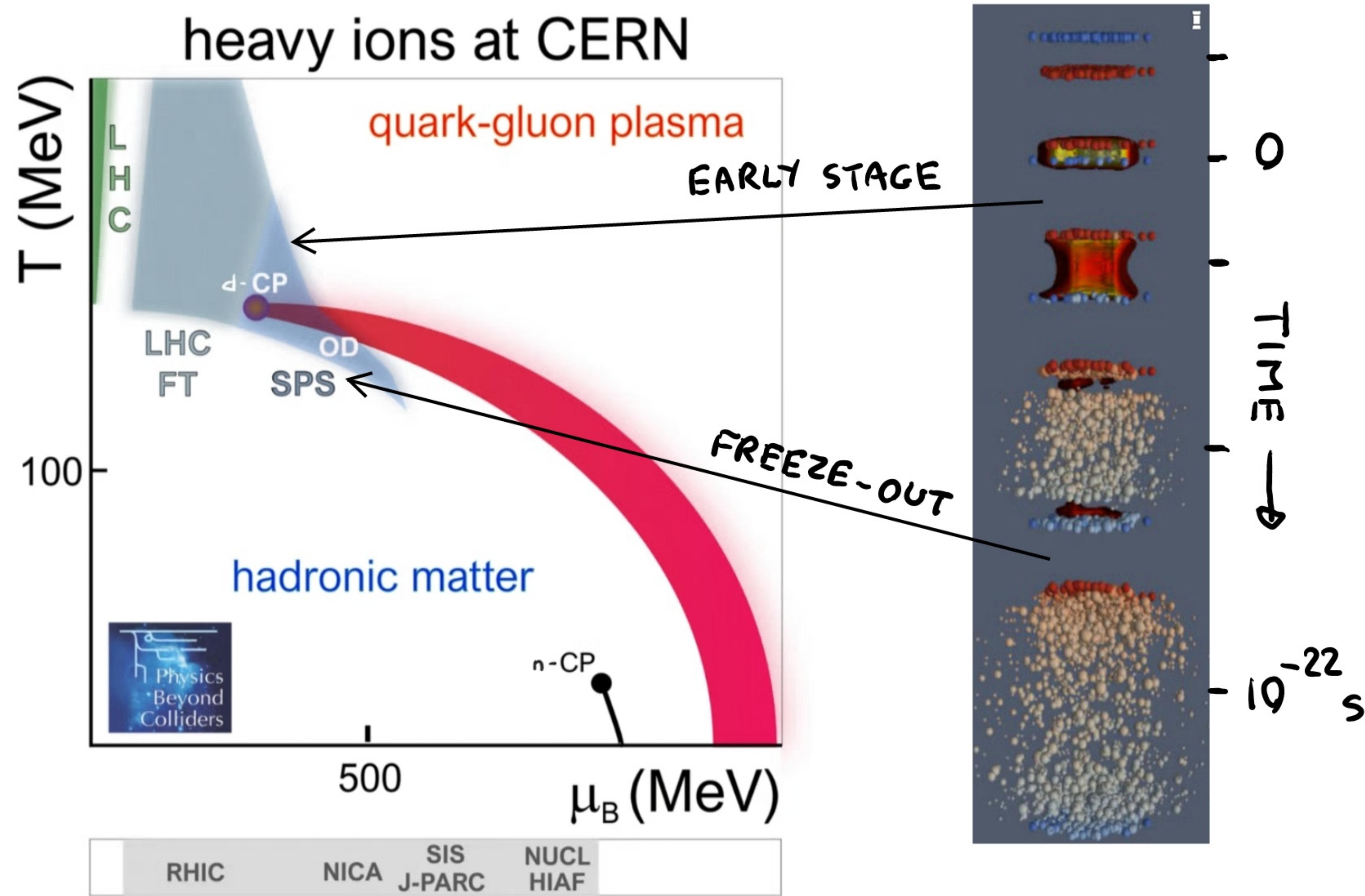
EARLY UNIVERSE
NEUTRON STARS
HEAVY ION COLLISIONS





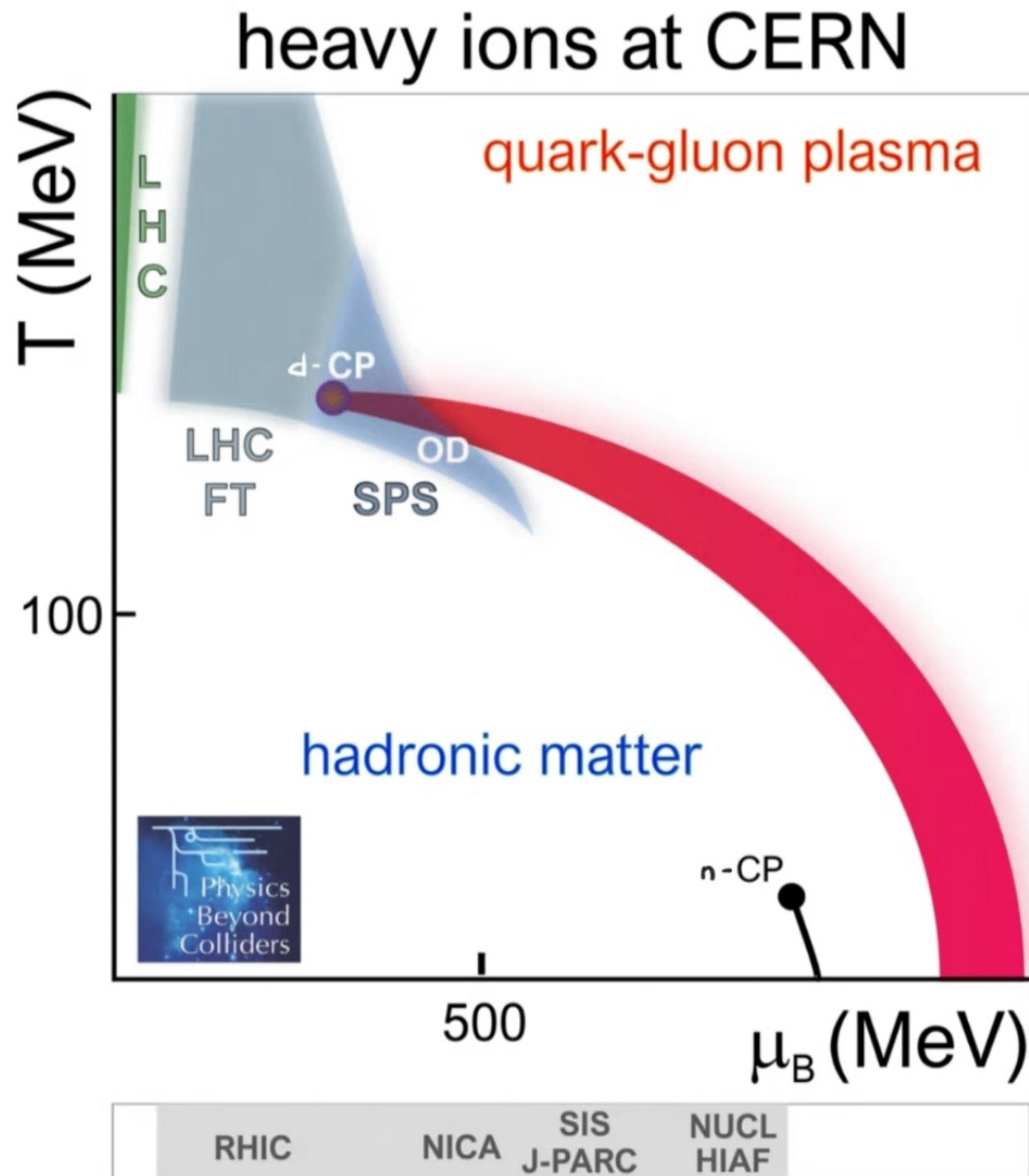
VOCABULARY

(3)





VOCABULARY



CRITICAL STRUCTURES:

- ONSET OF DECONFINEMENT (OD) – BEGINNING 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 – BEGINNING OF CREATION OF STRONGLY INTERACTING MATTER WITH INCREASING NUCLEAR MASS NUMBER.
TRANSITION FROM NON-EQUILIBRIUM STRINGS AND RESONANCES TO EQUILIBRIUM HADRON GAS OR QGP



QUARK-GLUON PLASMA

(5)

CERN PRESS RELEASE (FEB 2000)



Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

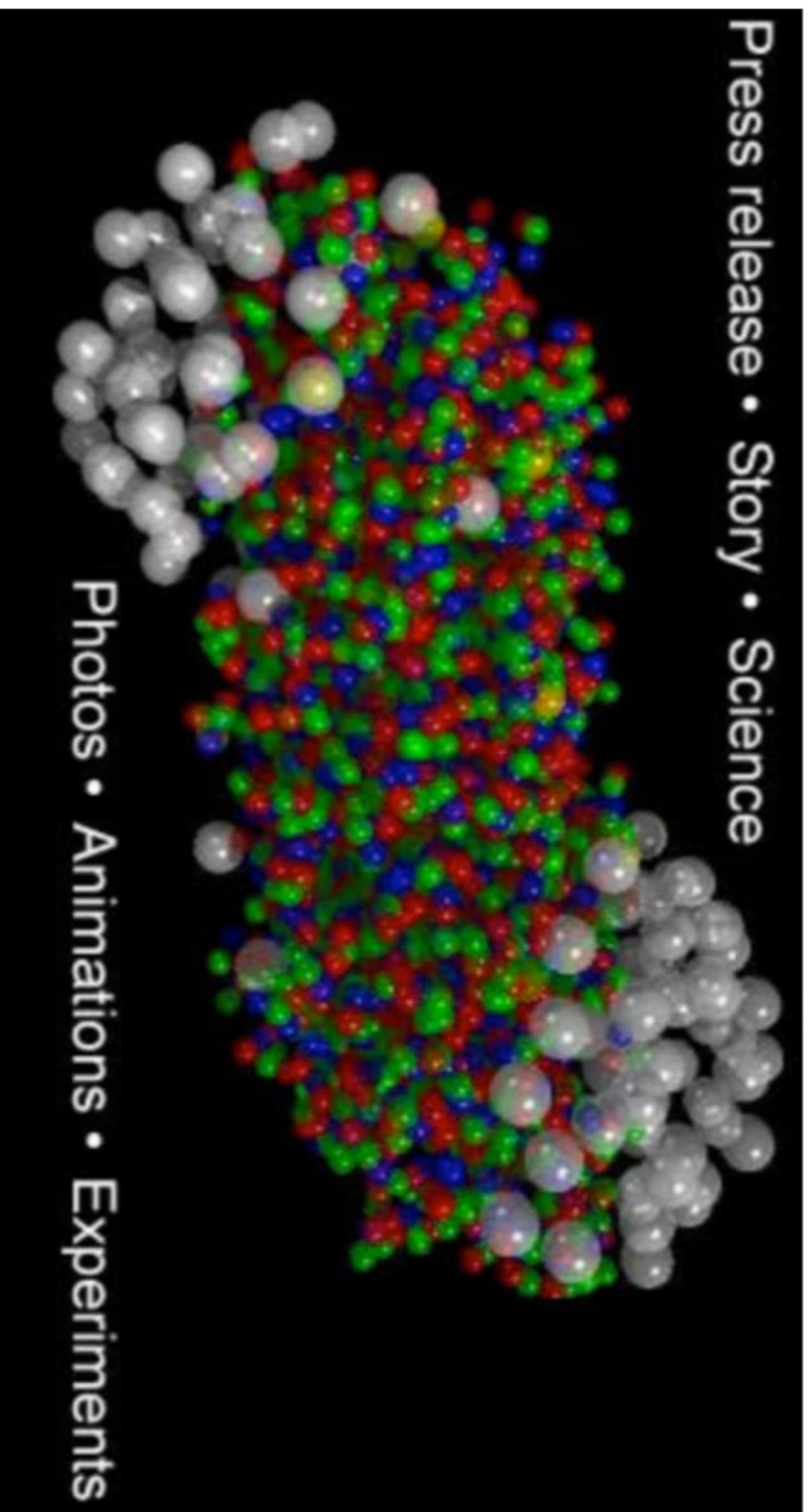
PR01.00
10.02.00

New State of Matter created at CERN

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QUARK-GLUON PLASMA

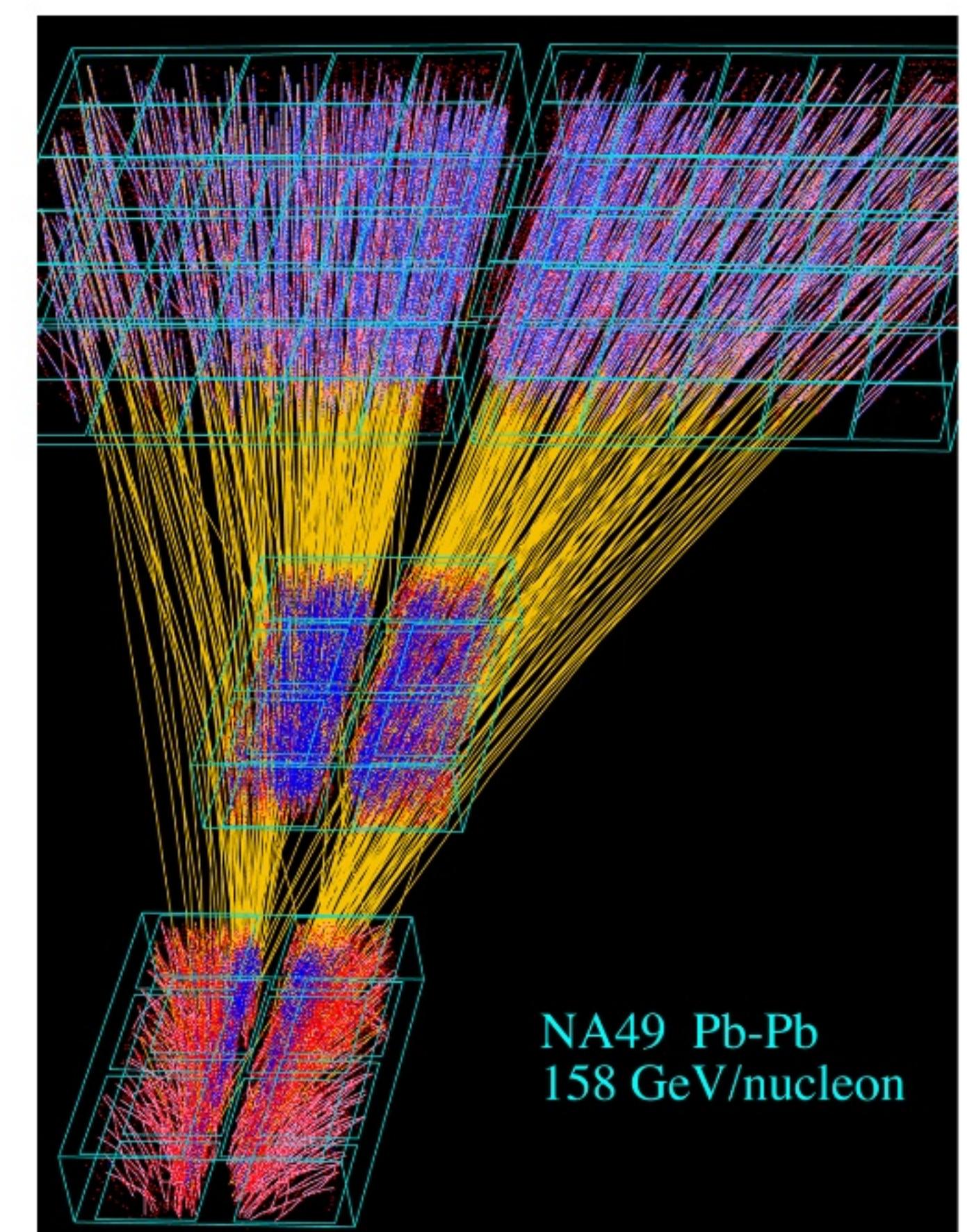
⑥

PREDICTED QGP SIGNALS:

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

MEASUREMENTS:

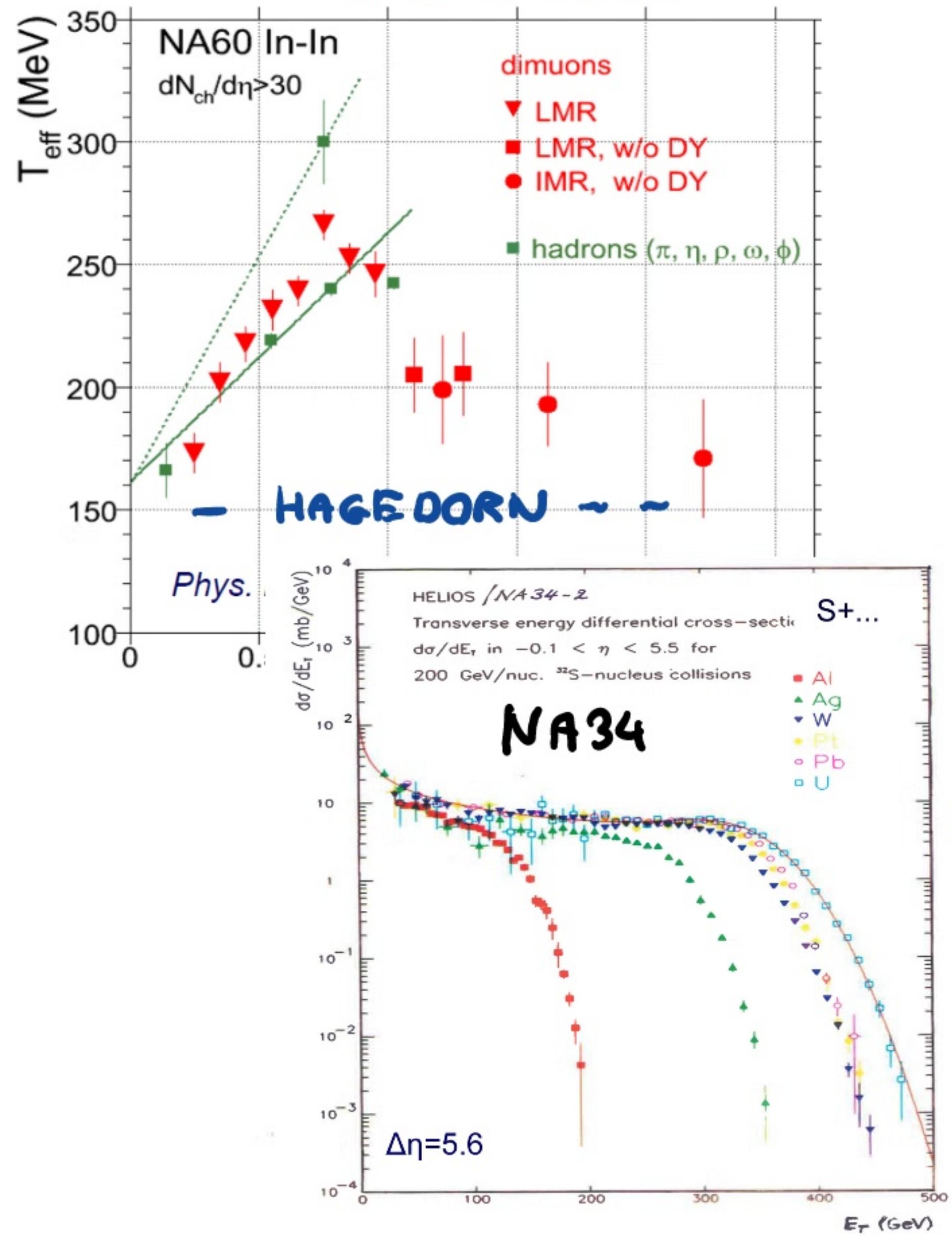
- 1986-1987: OXYGEN AND SULPHUR AT 200A GEV (NA34-2, 35, 36, 38, WA80, 85, 94)
- 1996-2003: LEAD AND INDIUM AT 158A GEV (NA44, 45, 49, 50, 52, 57, 60, WA97, 98)



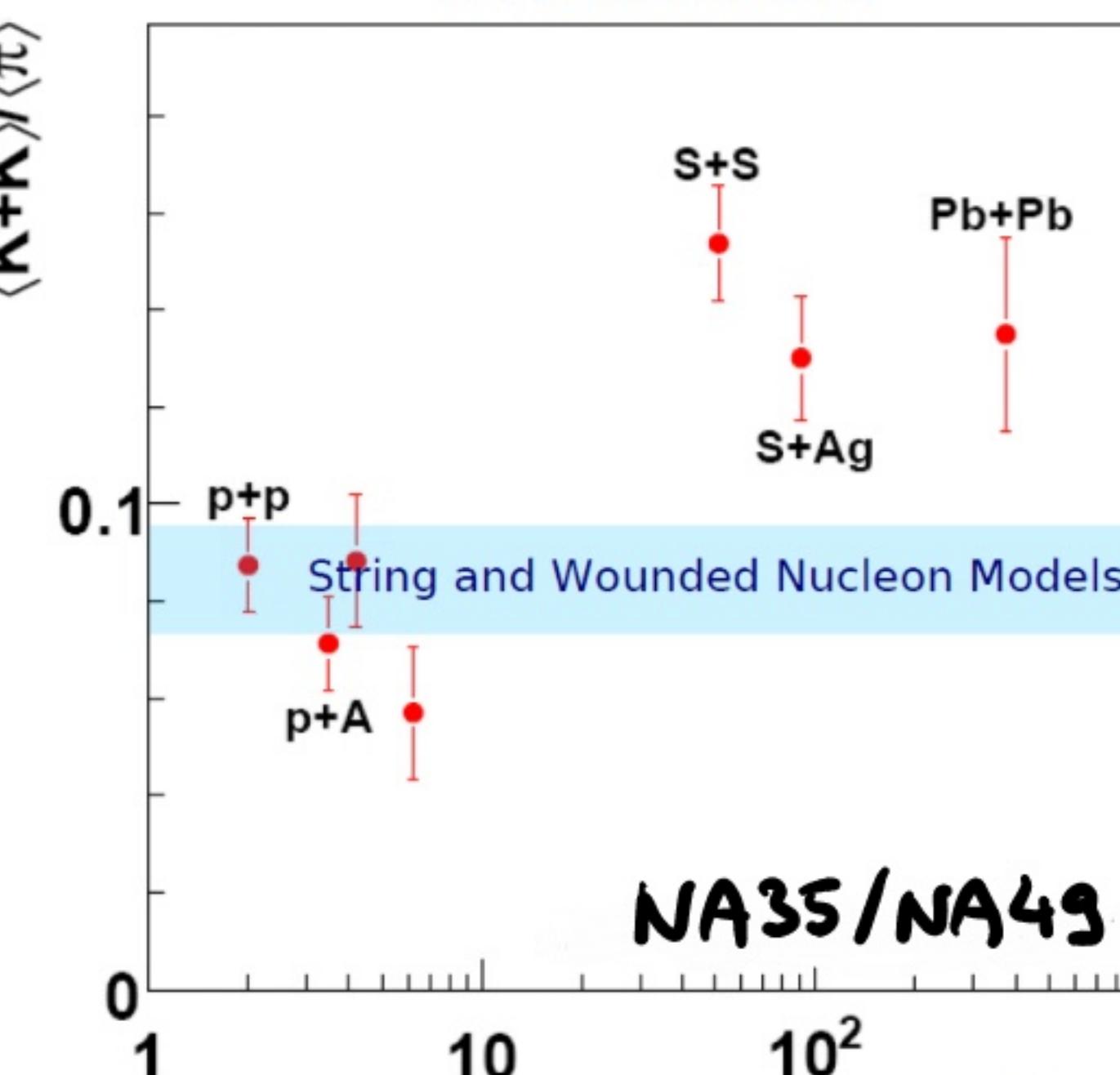
QUARK-GLUON PLASMA

RESULTS ARE CONSISTENT WITH A QGP BEING CREATED ...

QGP TEMPERATURE
 $T \approx 200$ MeV

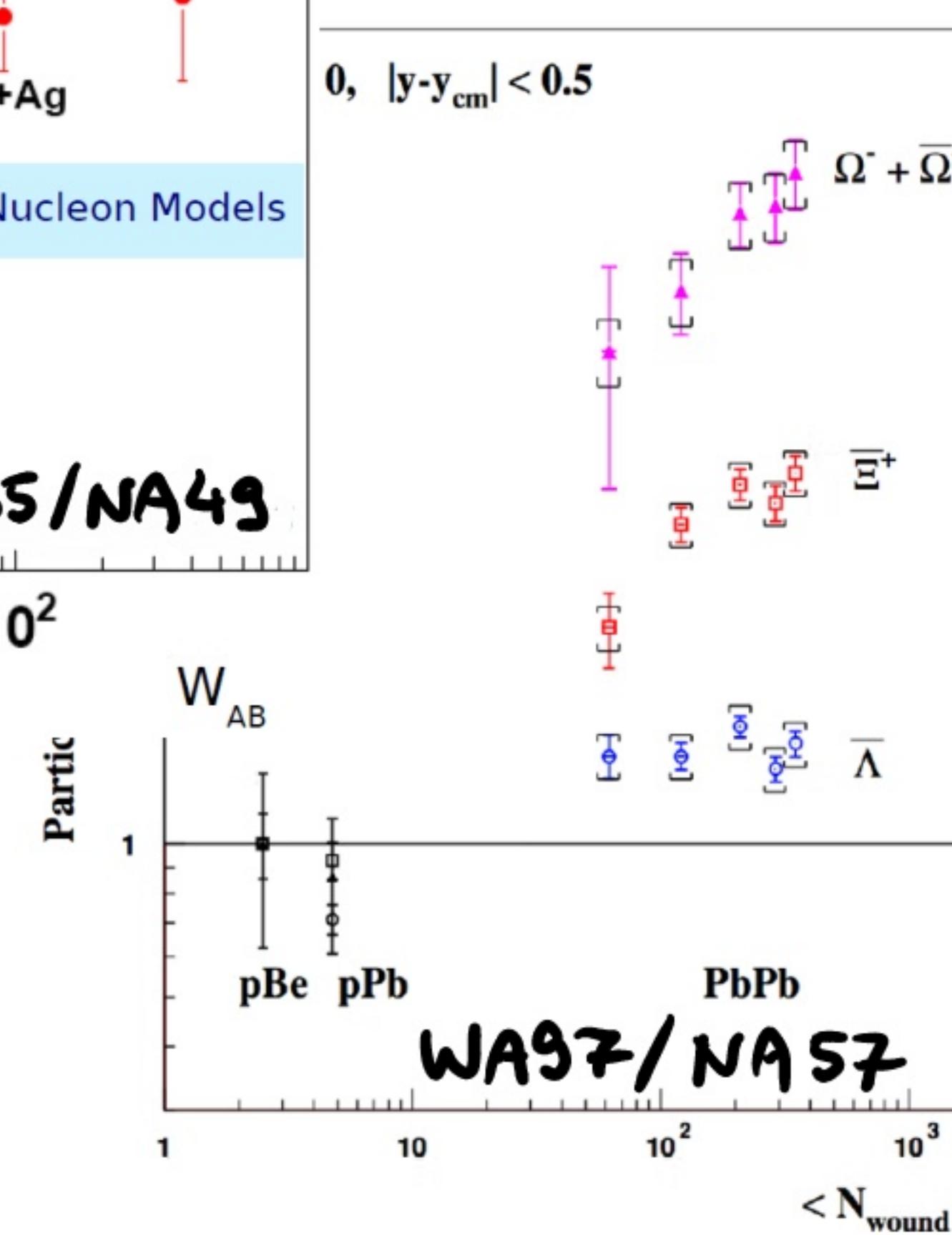


STRANGENESS AND MULTI-STRANGE HYPERON ENHANCEMENT IN QGP

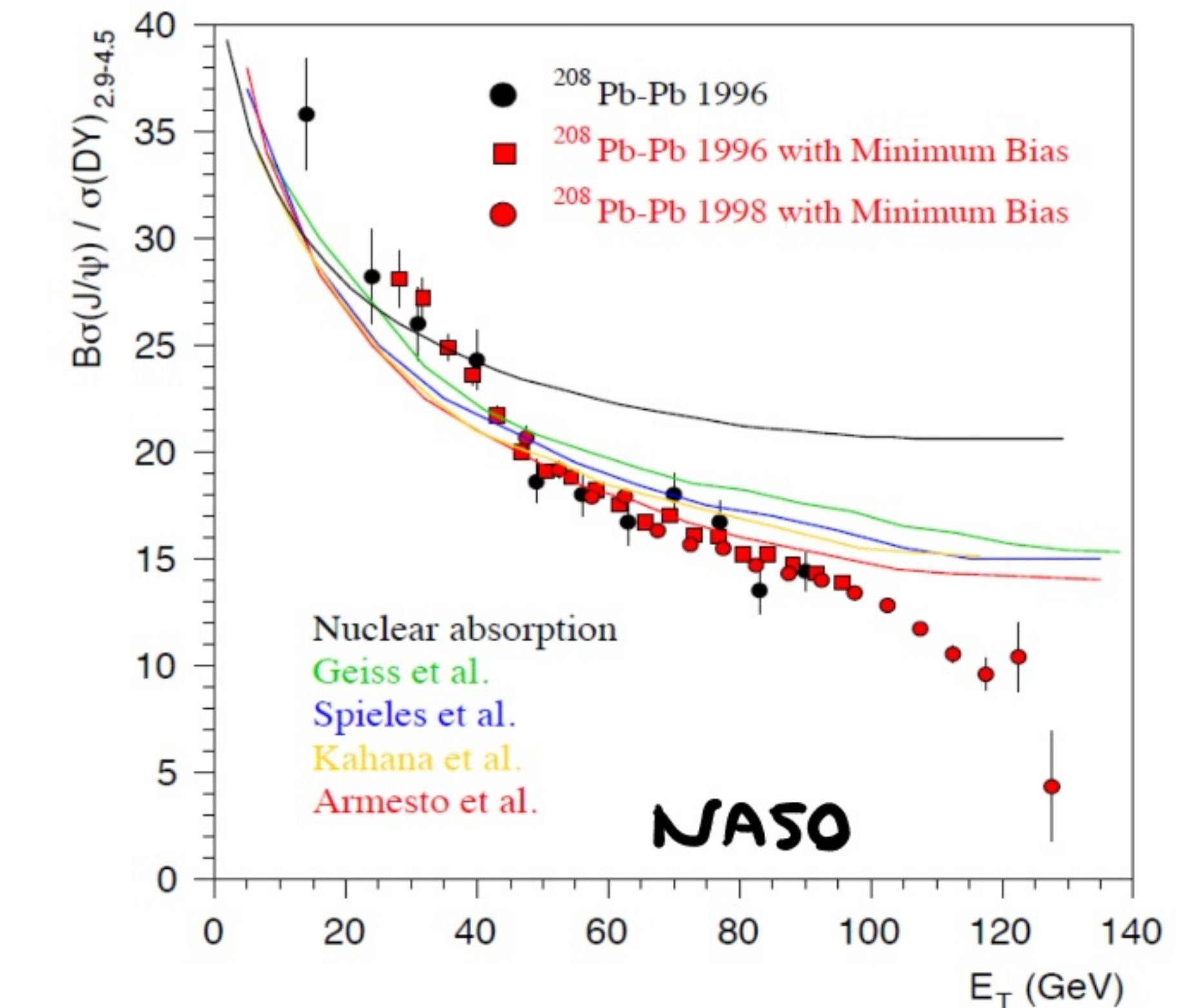


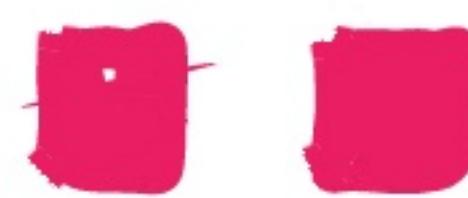
AND ENERGY DENSITY
 $\varepsilon \gtrsim 1$ GeV/fm³

0, $|y - y_{\text{cm}}| < 0.5$



J/ψ MELTING IN QGP





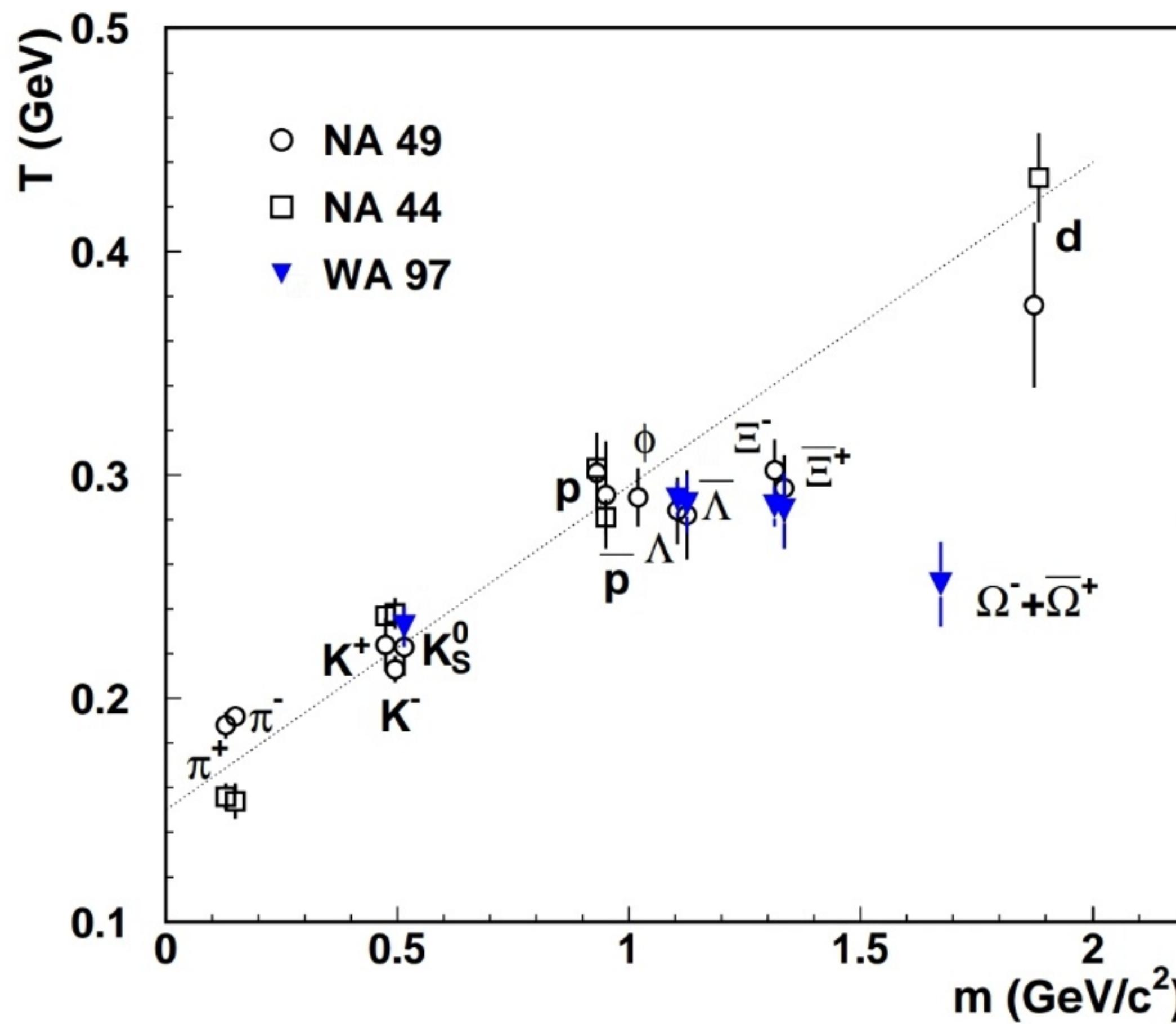
QUARK-GLUON PLASMA

8

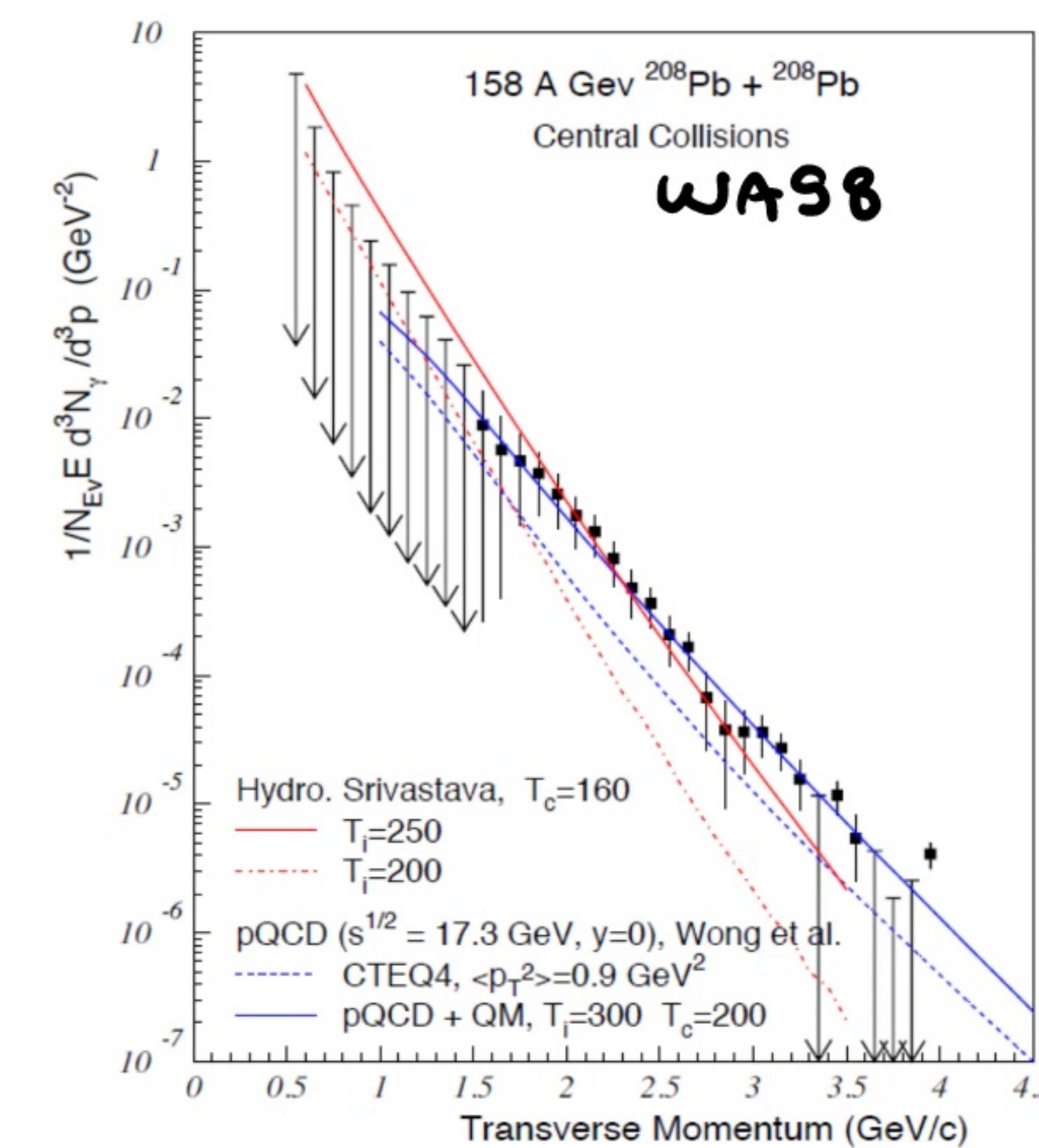
STANDARD MODEL OF HEAVY ION COLLISIONS :

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

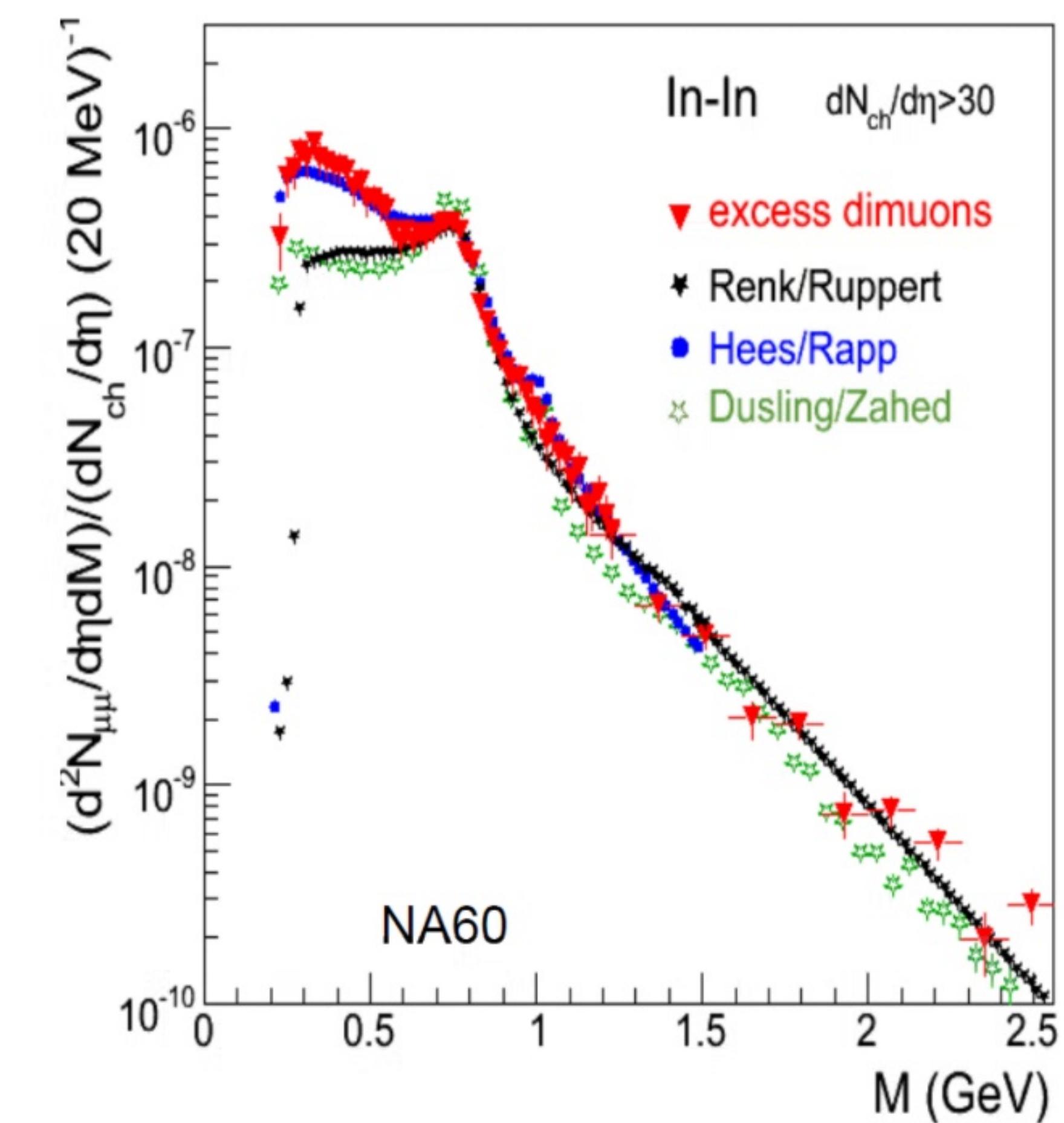
TRANSVERSE EXPANSION



PHOTON RADIATION



DIMUON RADIATION



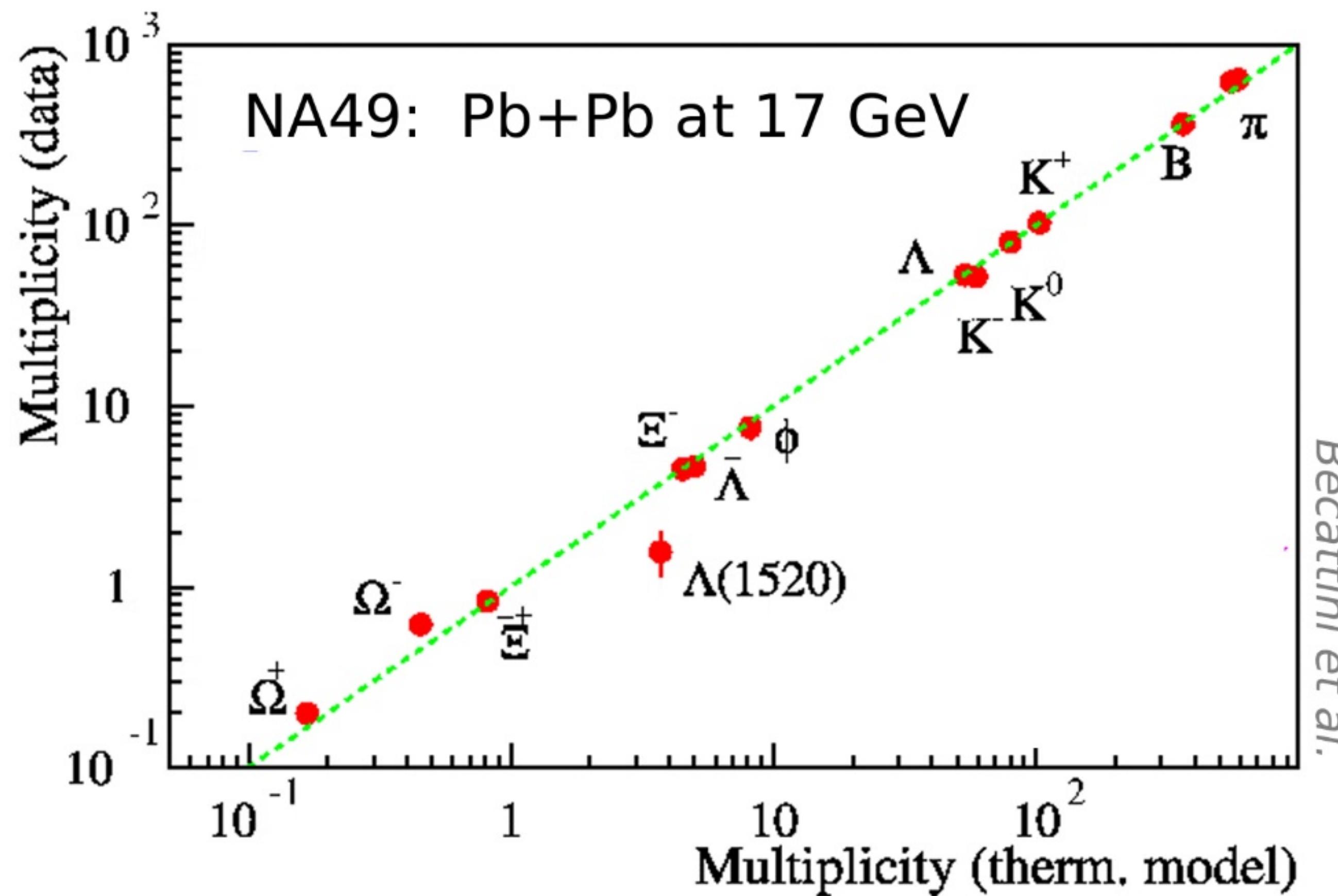


QUARK-GLUON PLASMA

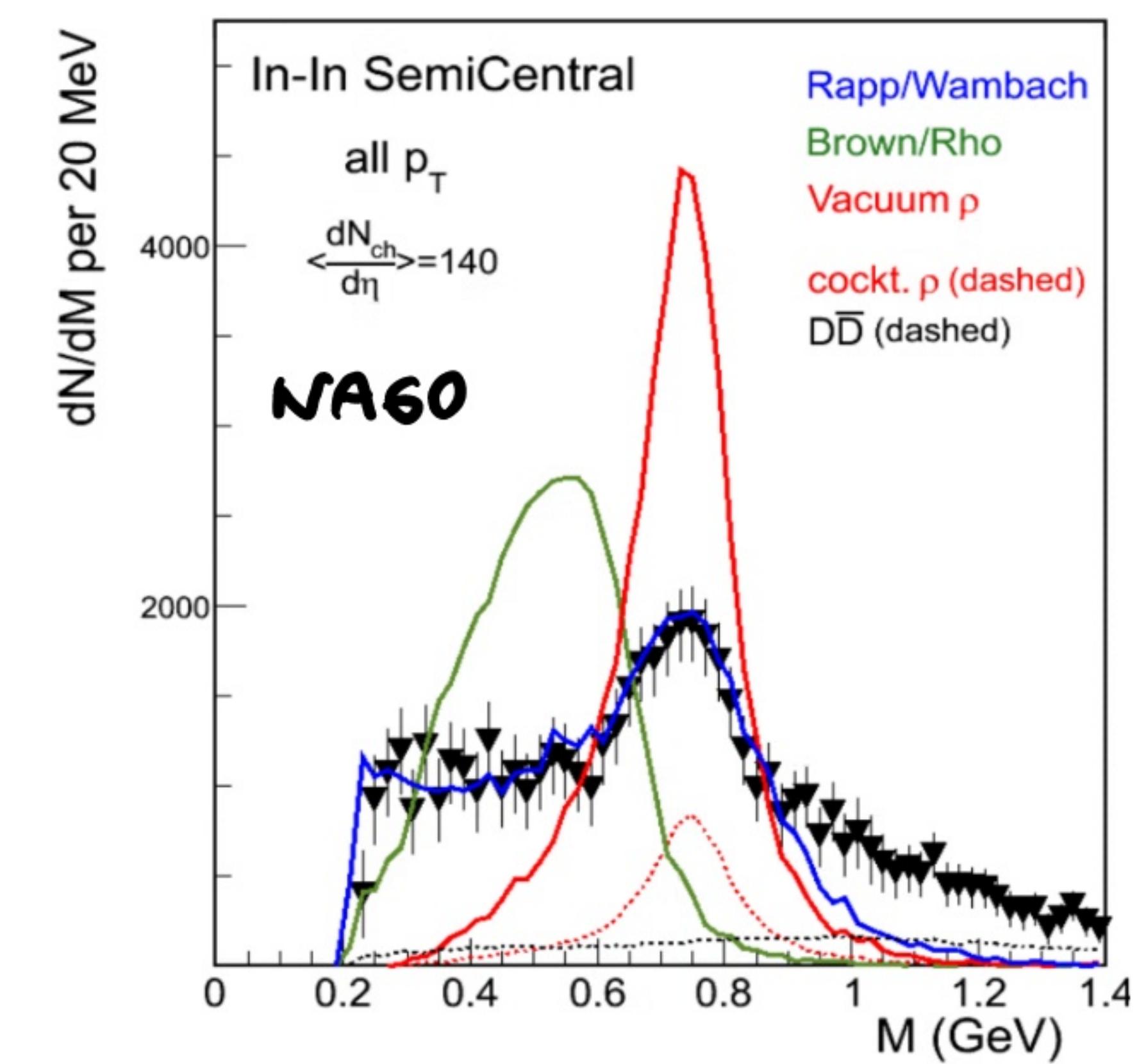
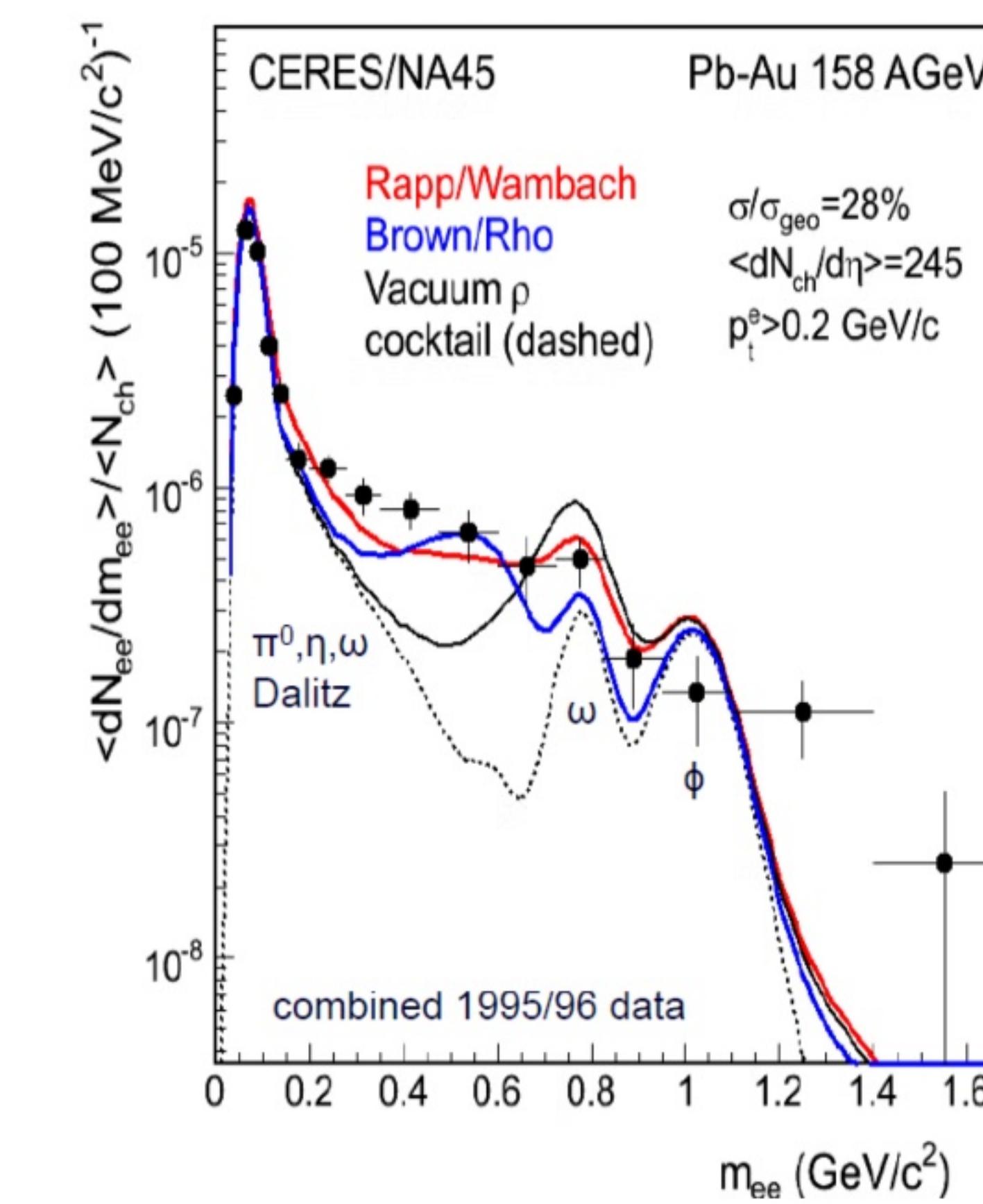
(3)

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

STATISTICAL HADRONIZATION



MODIFICATION OF VECTOR MESON PROPERTIES





QUARK-GLUON PLASMA

10

CERN PRESS RELEASE (FEB 2000)



Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

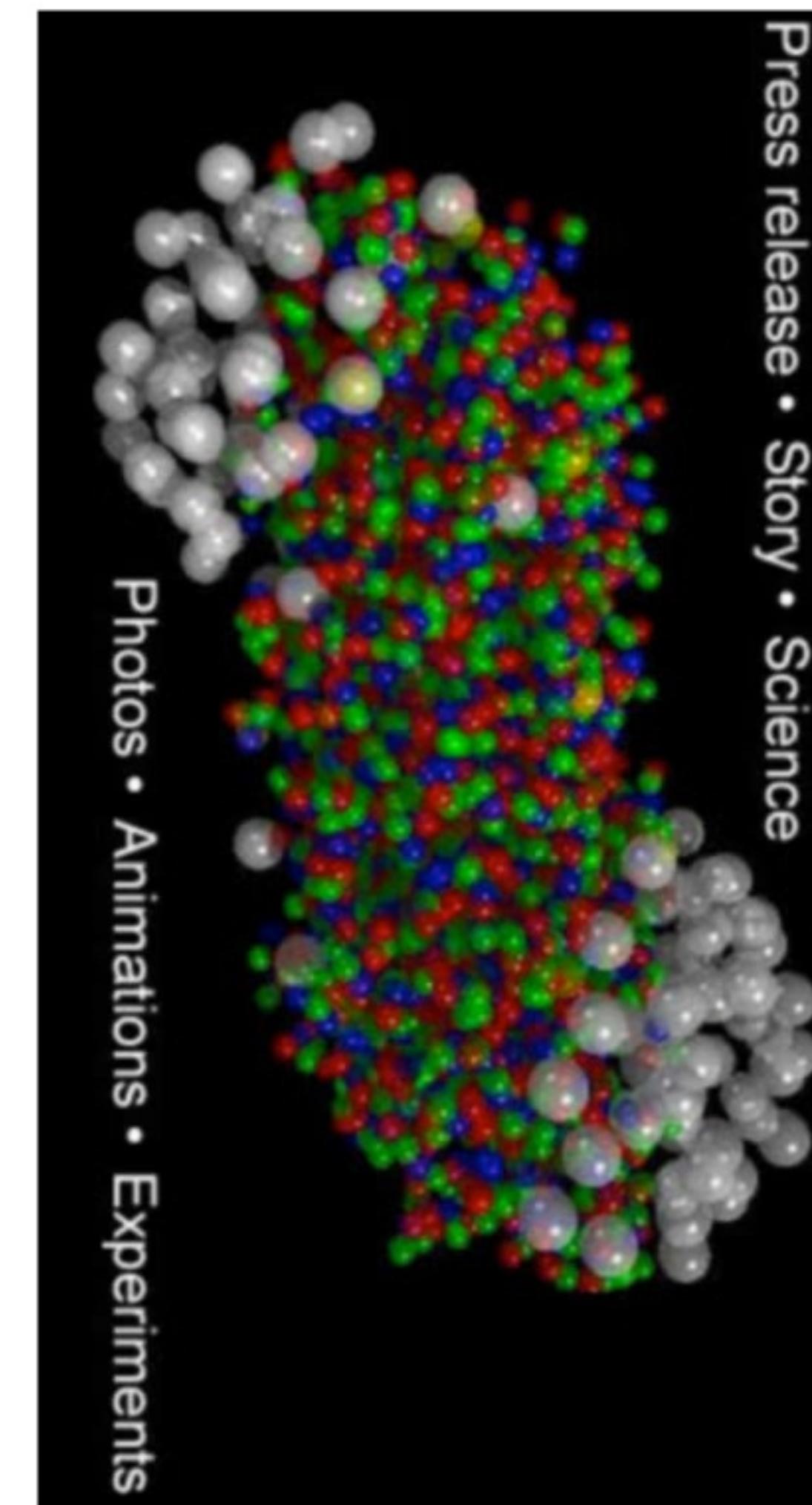
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HEAVY ION COMMUNITY SPLITS:

- PROPERTIES OF HIGH TEMPERATURE QGP → VERY HIGH ENERGIES AT RHIC, LHC
- SEARCH FOR THE ONSET OF QGP CREATION → COLLISION ENERGY SCAN AT SPS

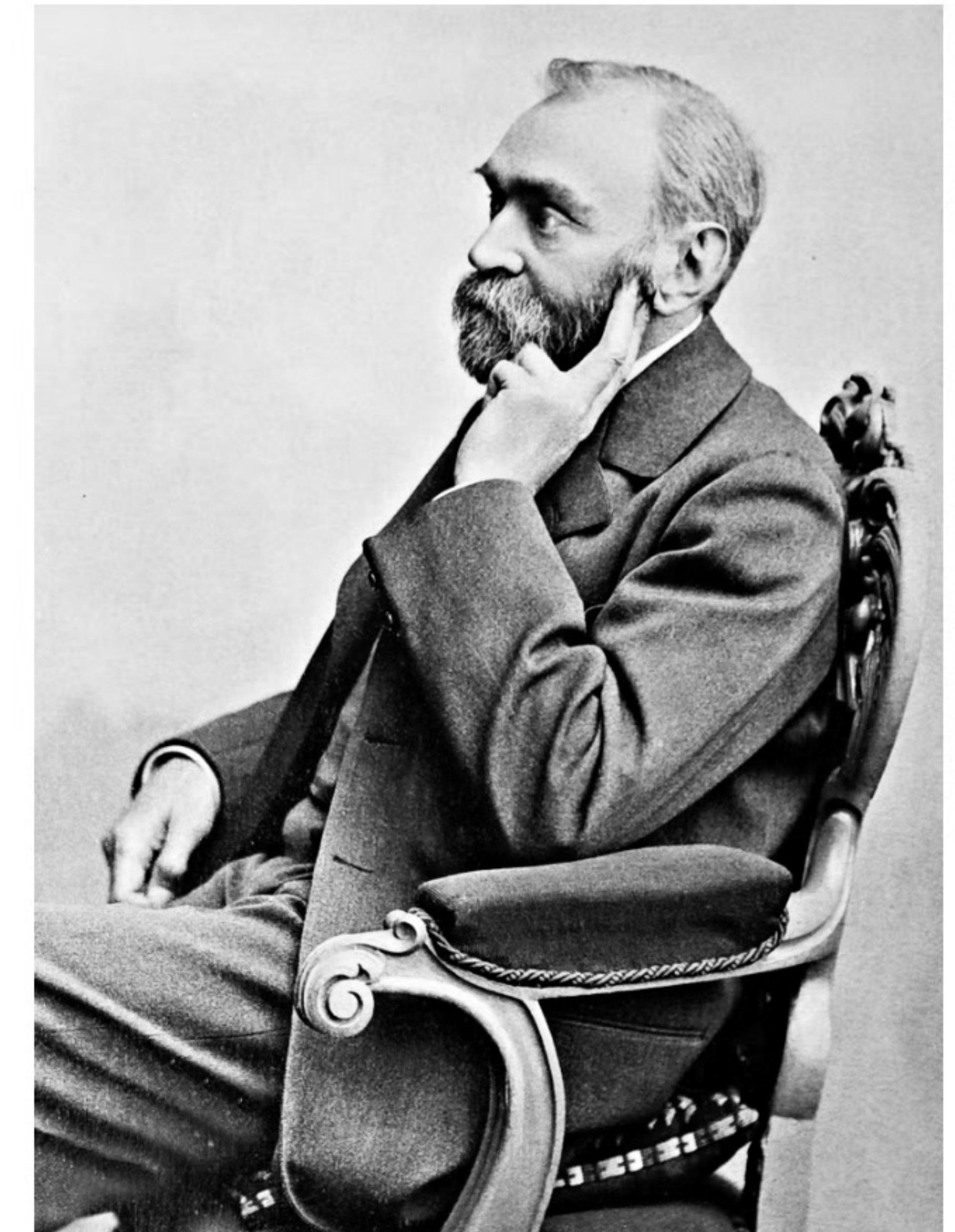
11

COMMENT ON NOBEL PRIZE

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



THE NOBEL PRIZE FOR THE QGP DISCOVERY WAS NOT YET AWARDED

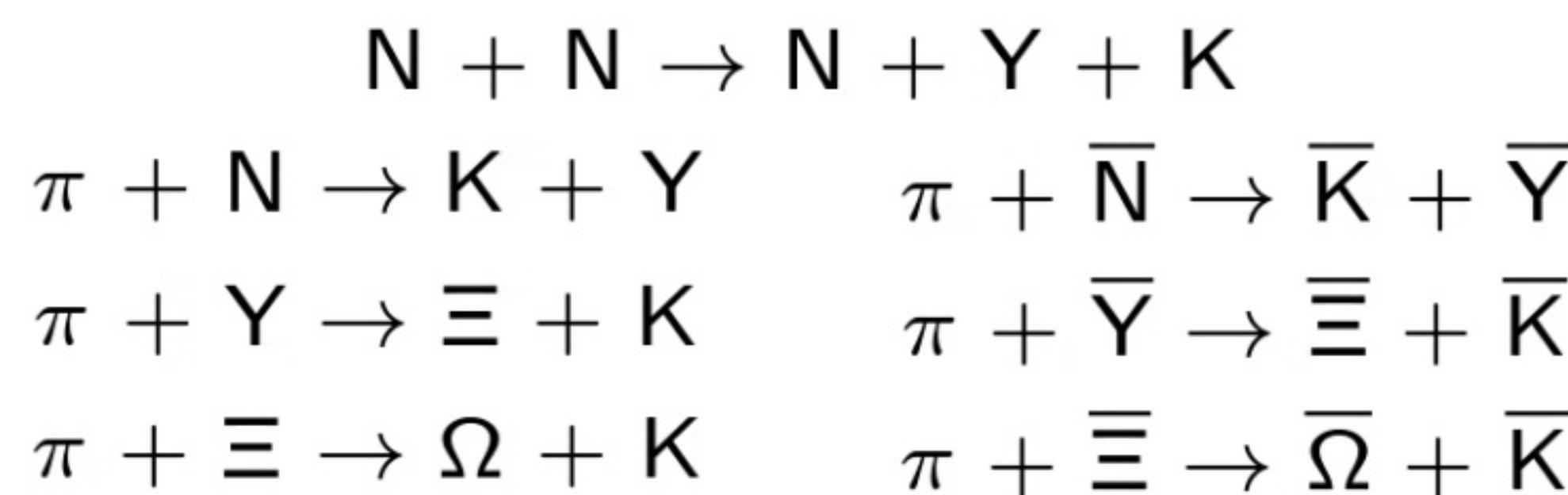


INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

(12)

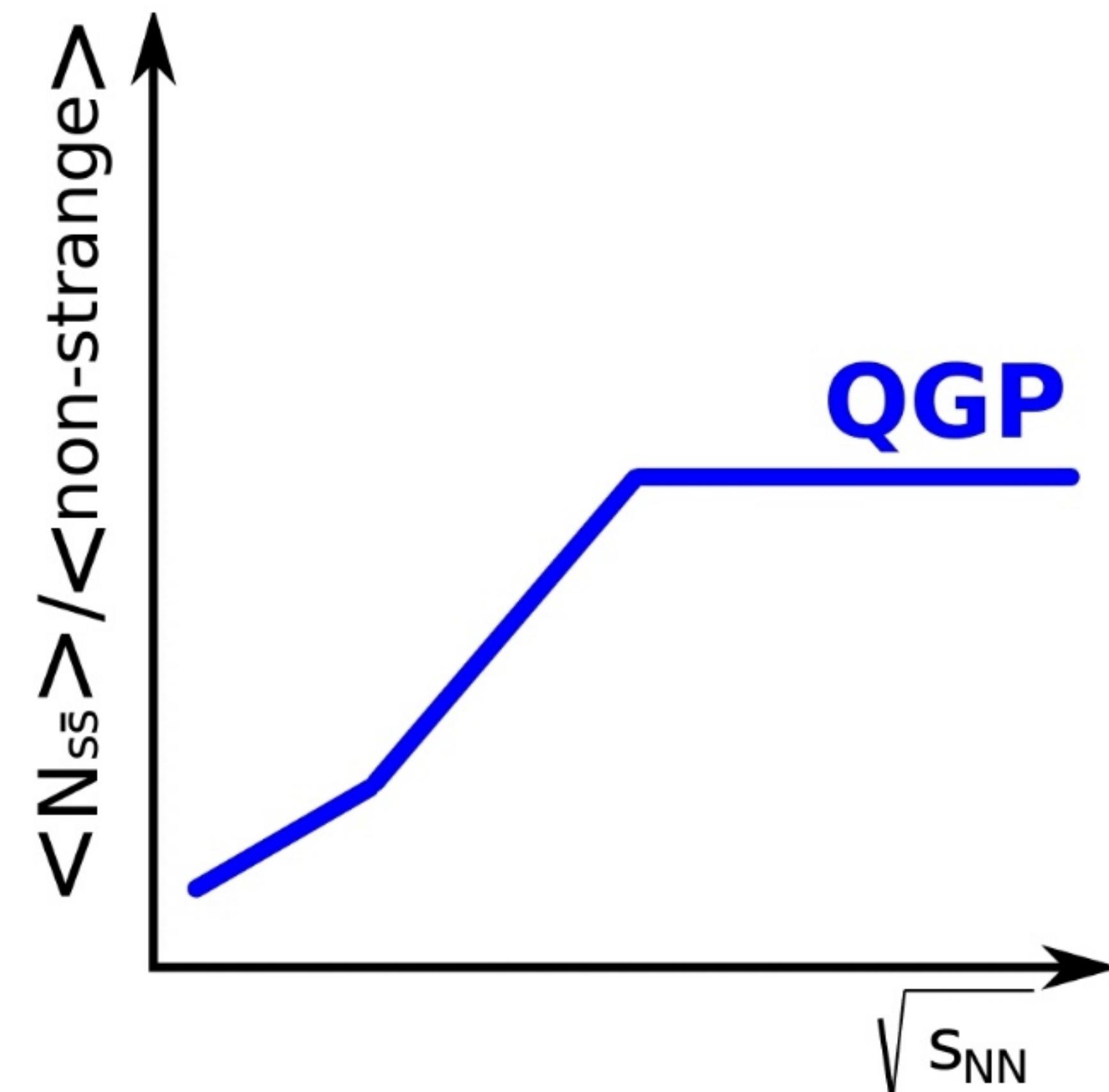
DYNAMICAL MODEL

HADRON GAS :

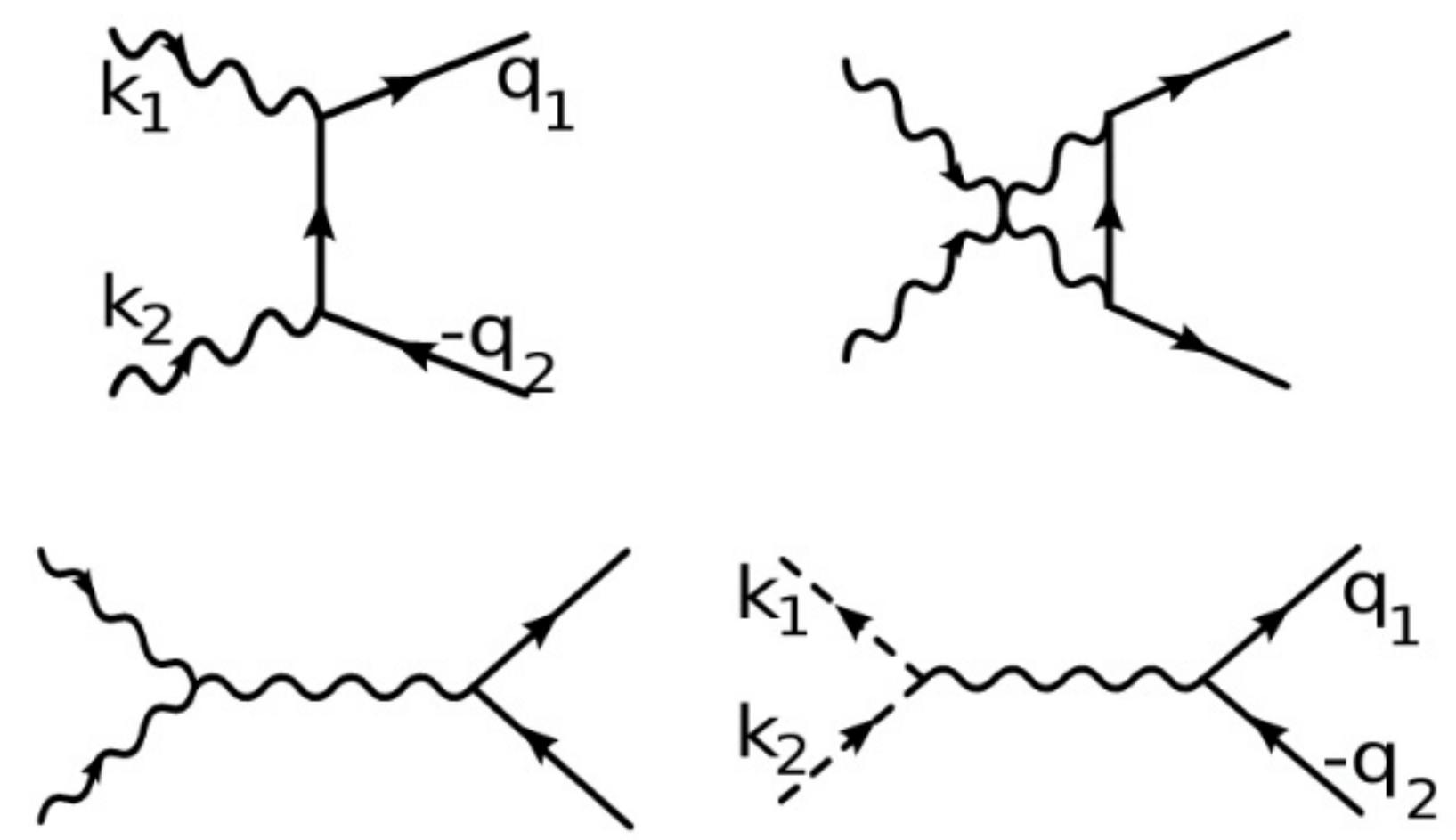


$$m_K \gg T_c \approx 150 \text{ MeV}$$

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



QUARK-GLUON PLASMA



$$m_s < T_c \approx 150 \text{ MeV}$$

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

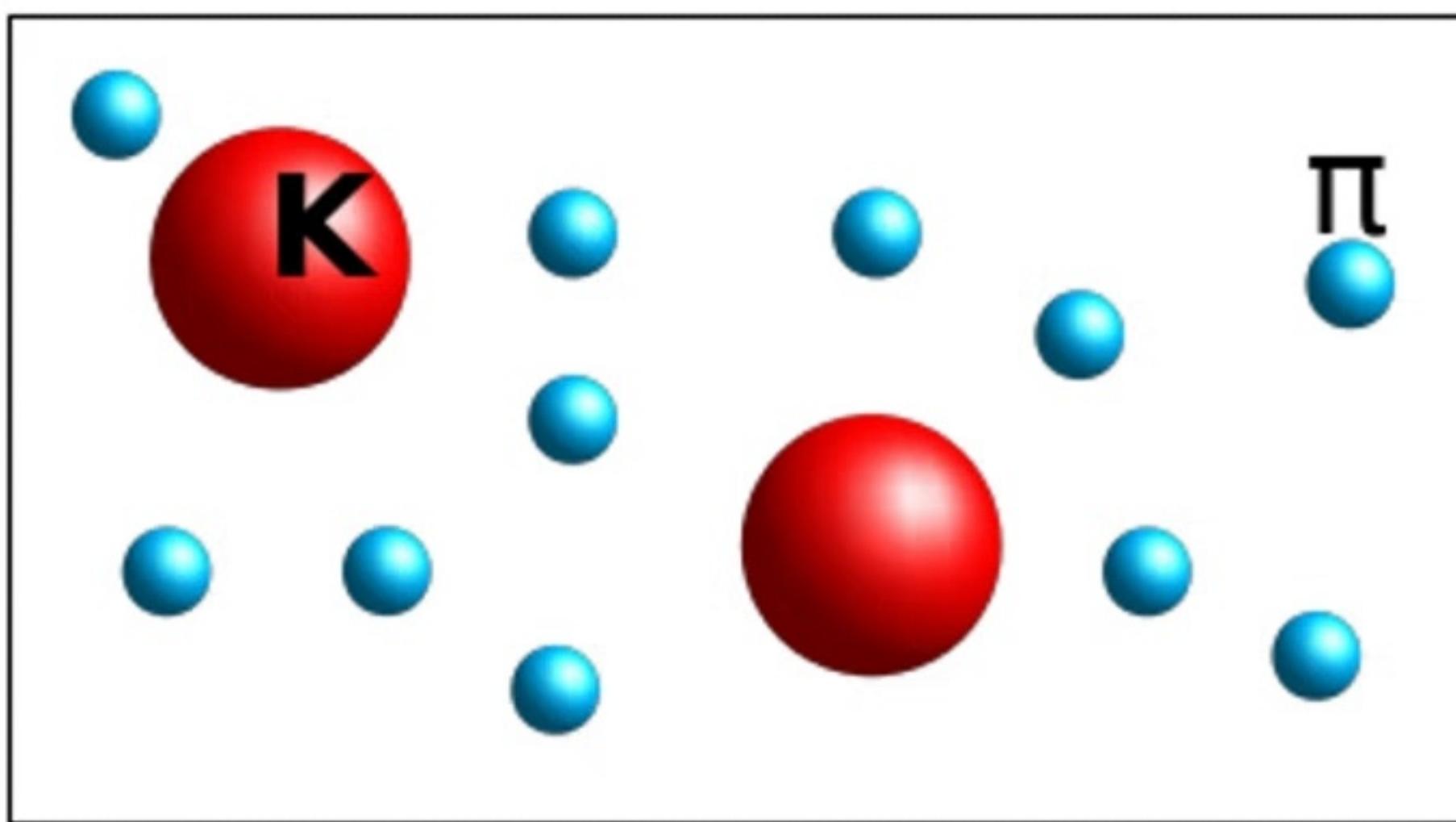
CROSSING THRESHOLD FOR QGP CREATION →
→ STRANGENESS ENHACEMENT

INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

(13)

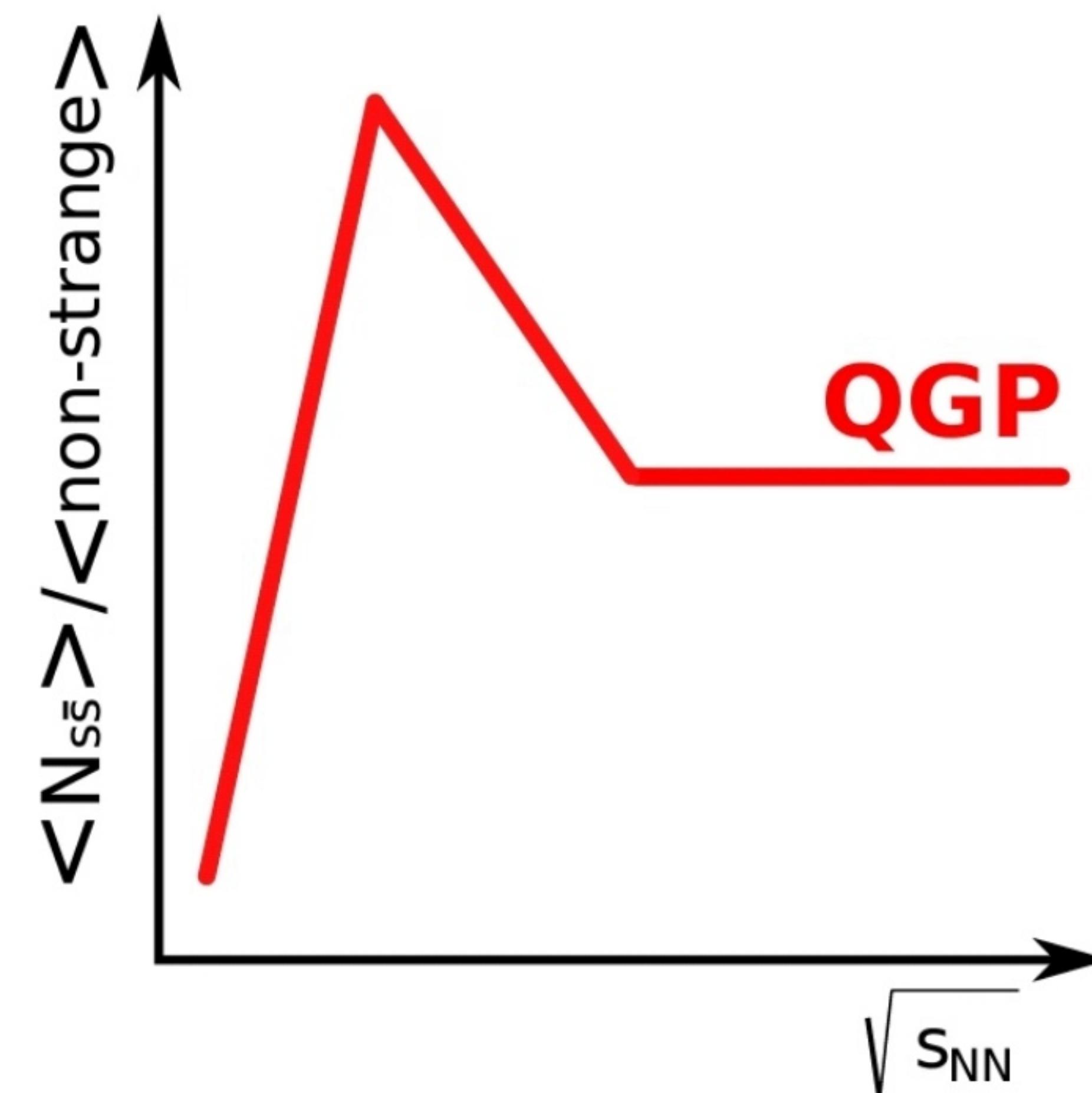
STATISTICAL MODEL OF THE EARLY STAGE

HADRON GAS.

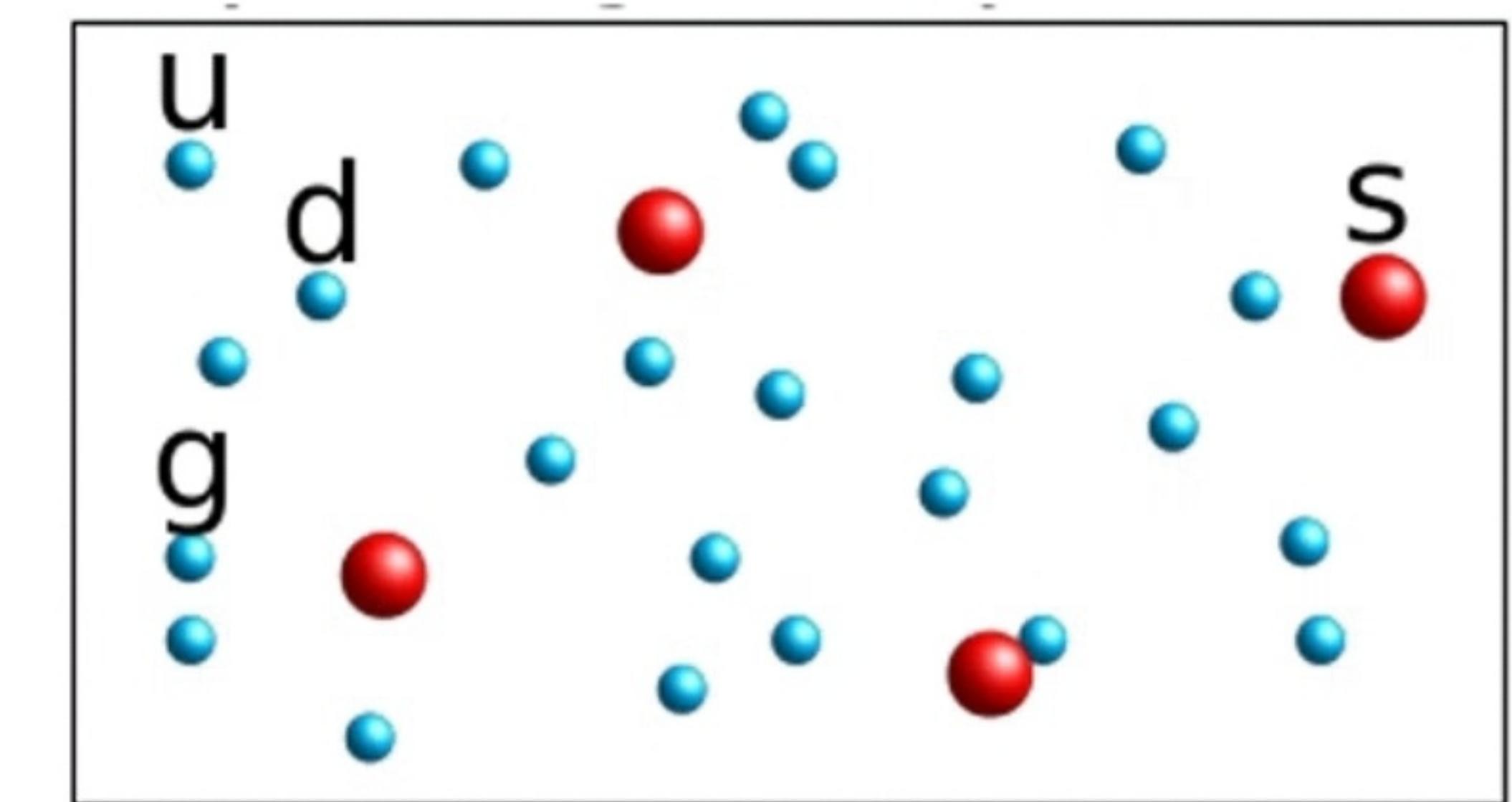


$$m_K \gg T_c \approx 150 \text{ MeV}$$

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



QUARK-GLUON PLASMA



$$m_s < T_c \approx 150 \text{ MeV}$$

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

CROSSING THRESHOLD FOR QGP CREATION →
→ HORN - LIKE STRUCTURE

MG, GORENSTEIN, 1996 +

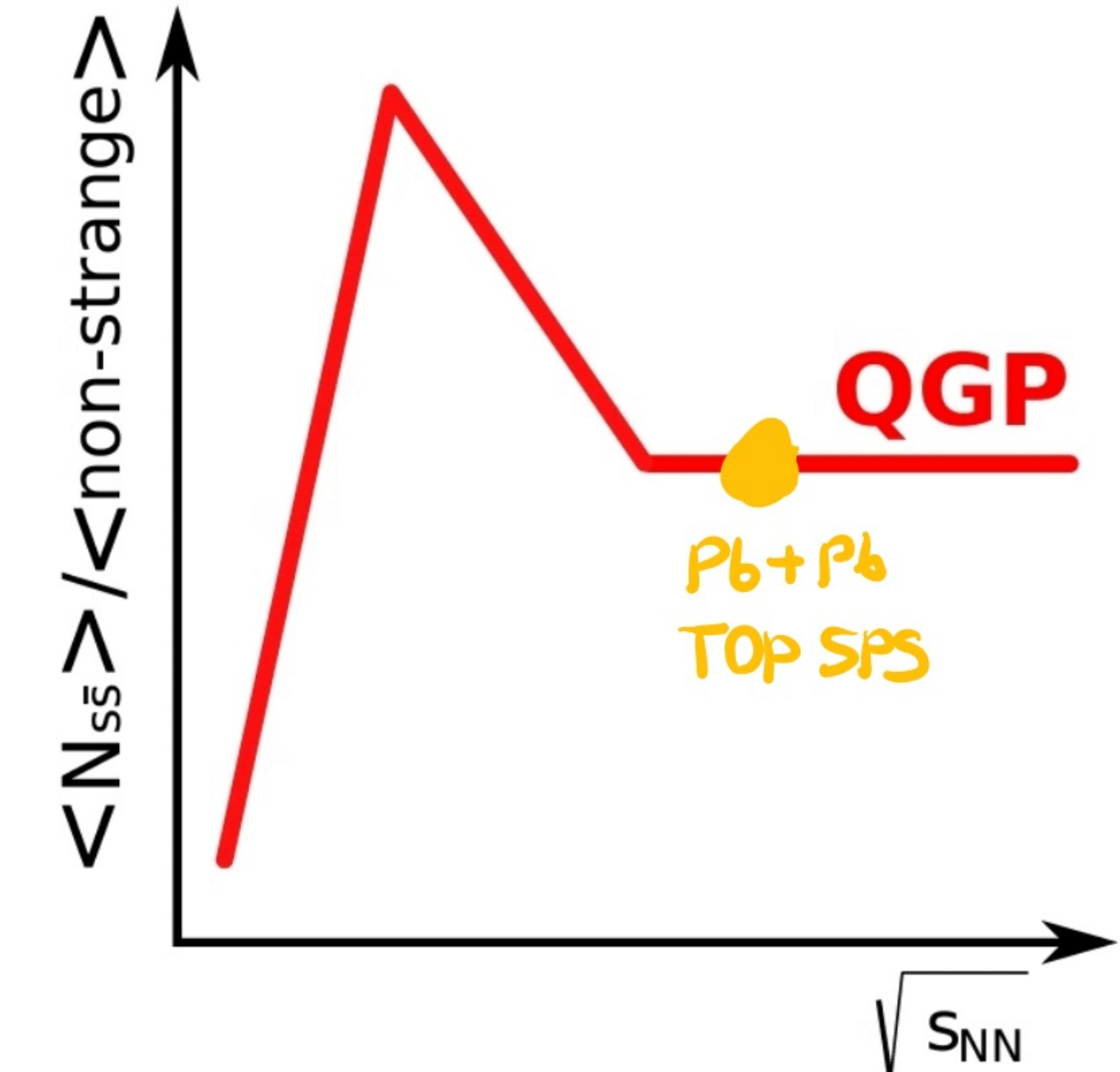
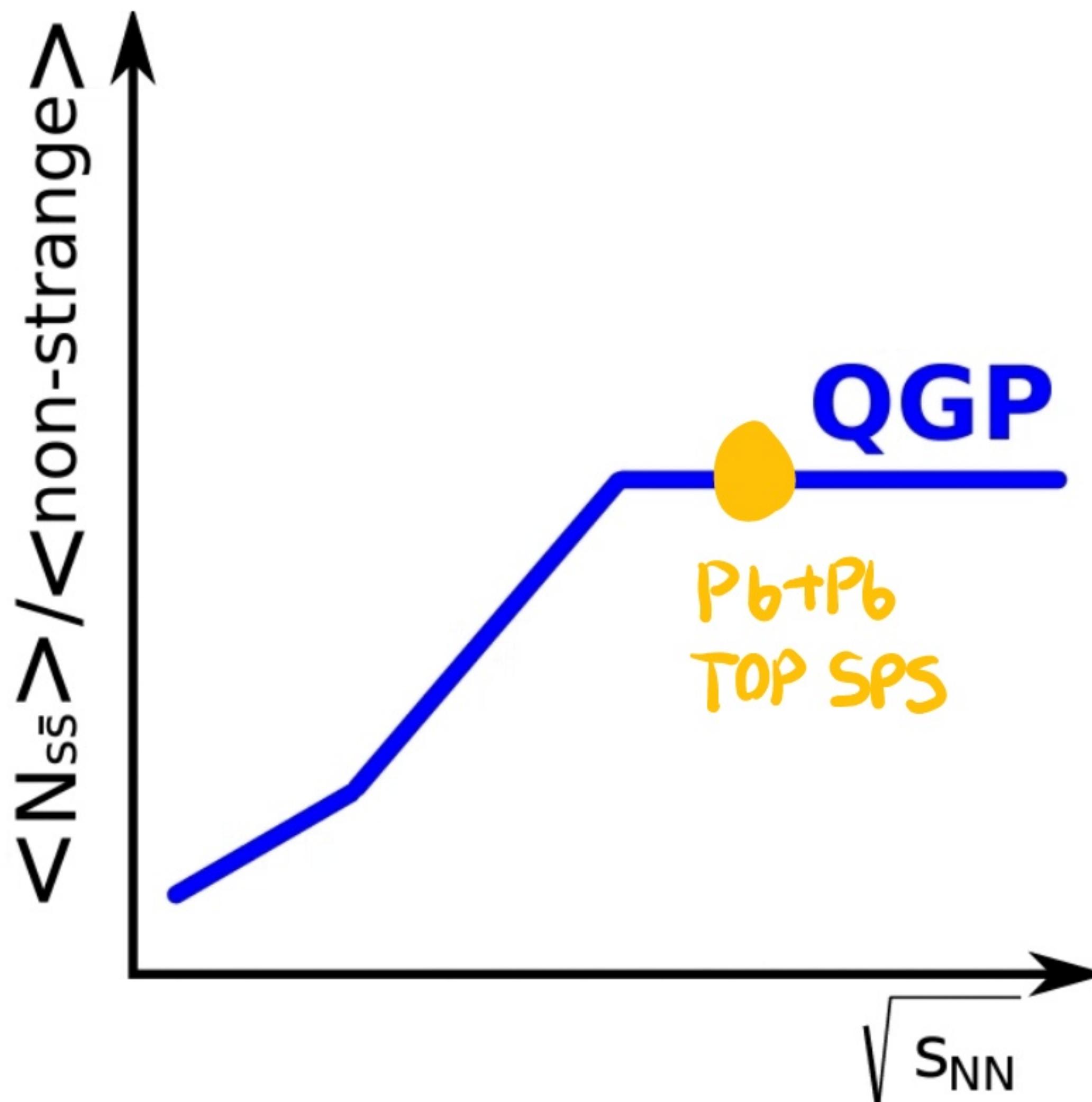
INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

(14)

DYNAMICAL

VERSUS

STATISTICAL MODELS



≈ 2000 : COLLISION ENERGY SCAN IS NEEDED

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



CRITICAL STRUCTURES

(15)

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 : BESI)

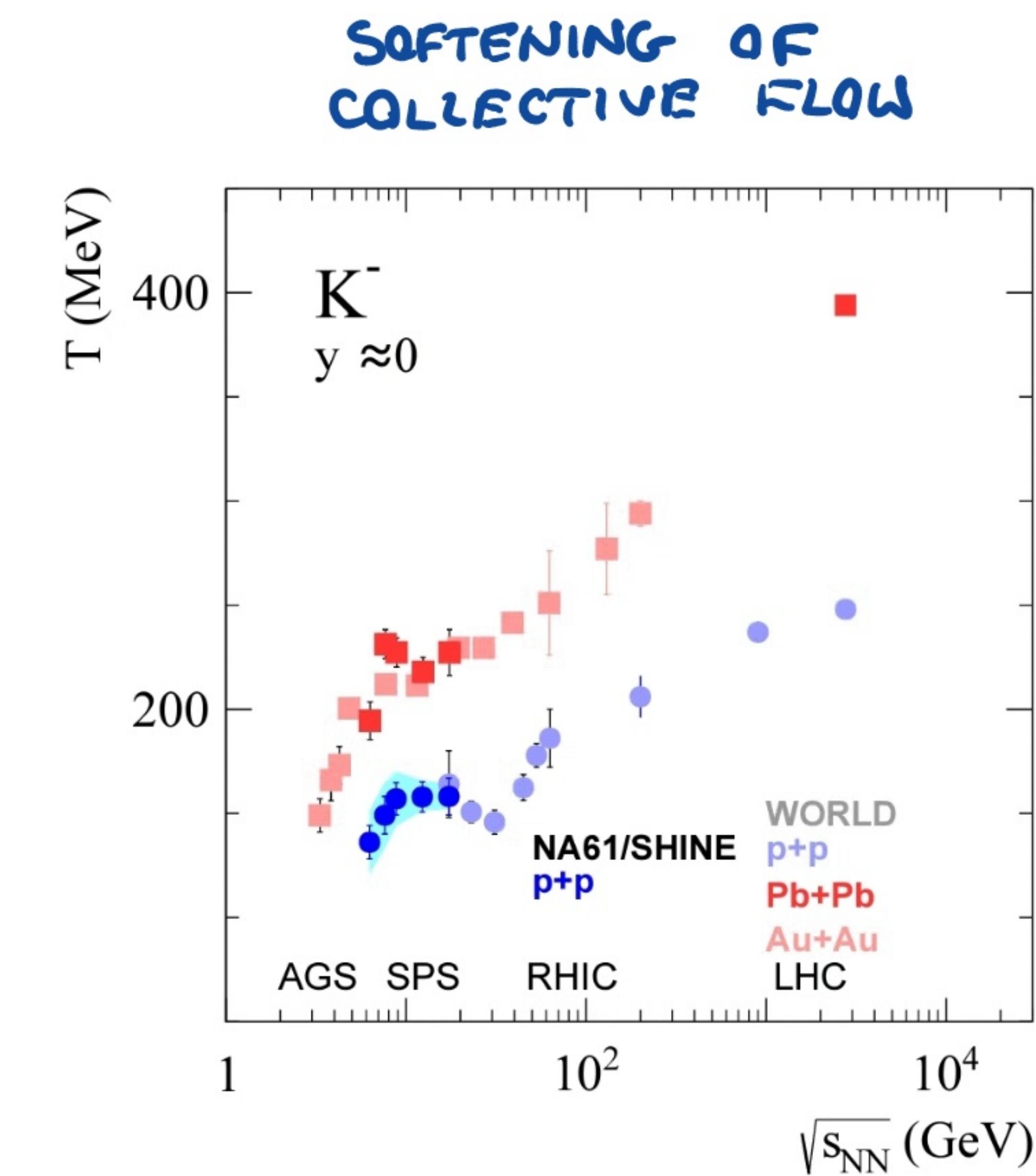
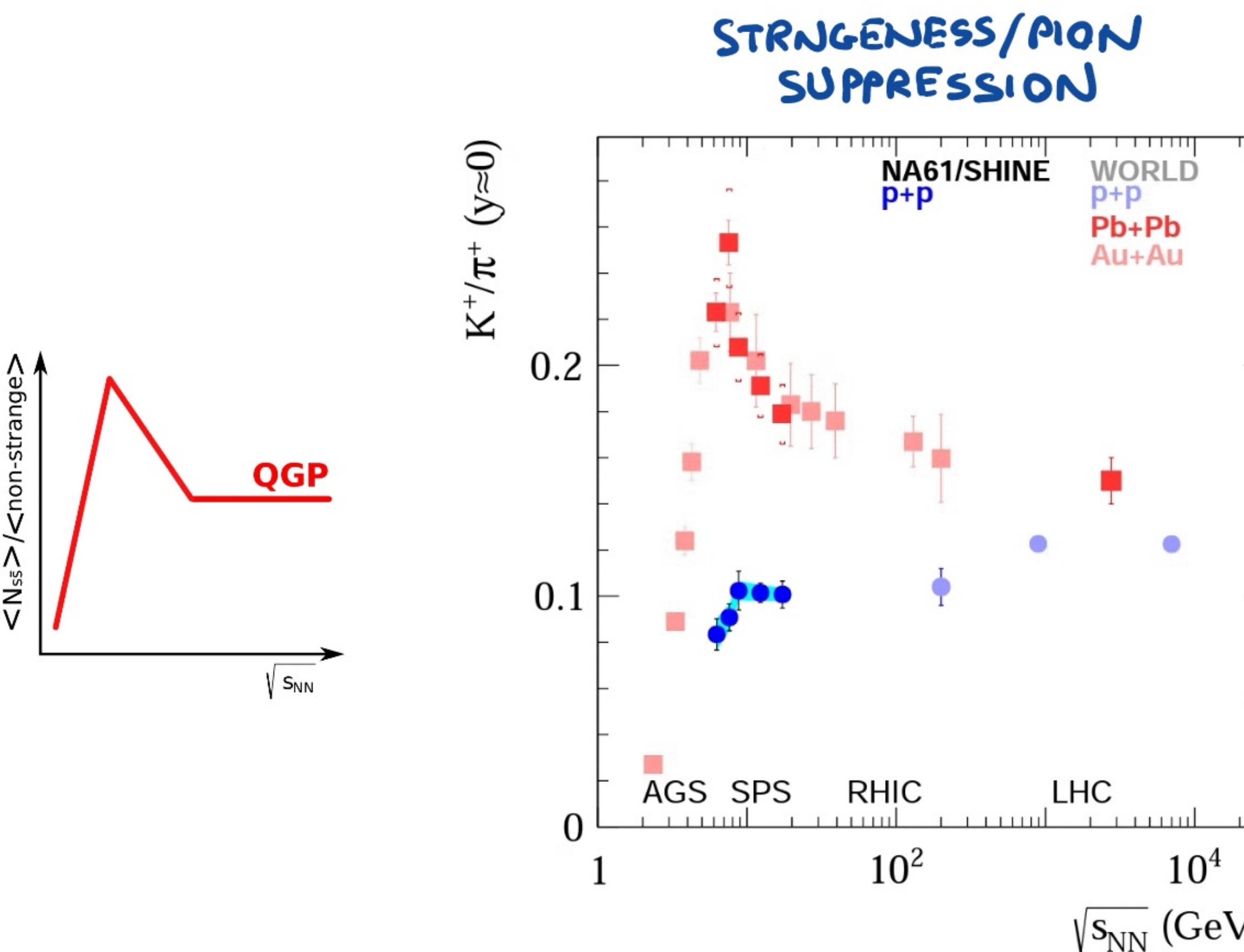


CRITICAL STRUCTURES

16

PHASE I: SEARCHING FOR ONSET OF QGP CREATION

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





CRITICAL STRUCTURES

(17)

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 →

CERN COURIER SEPT. 2004

HEAVY IONS

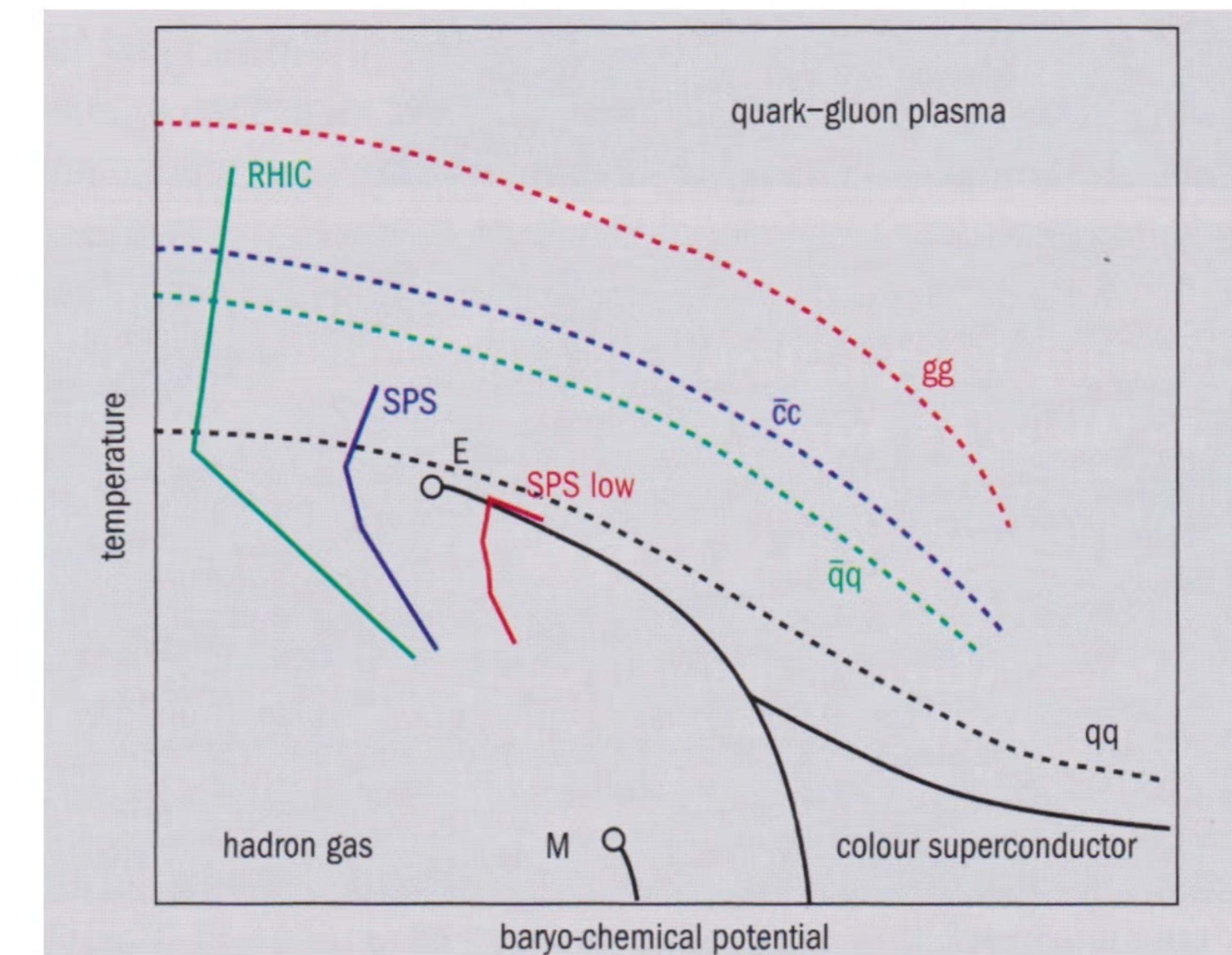
When quarks and gluons become free

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

BEGINNING OF CRITICAL POINT
AND ONSET OF DECONFINEMENT
WORKSHOPS

→ SEARCH FOR CRITICAL POINT
→ SCAN IN ENERGY AND
NUCLEAR MASS NUMBER





CRITICAL STRUCTURES

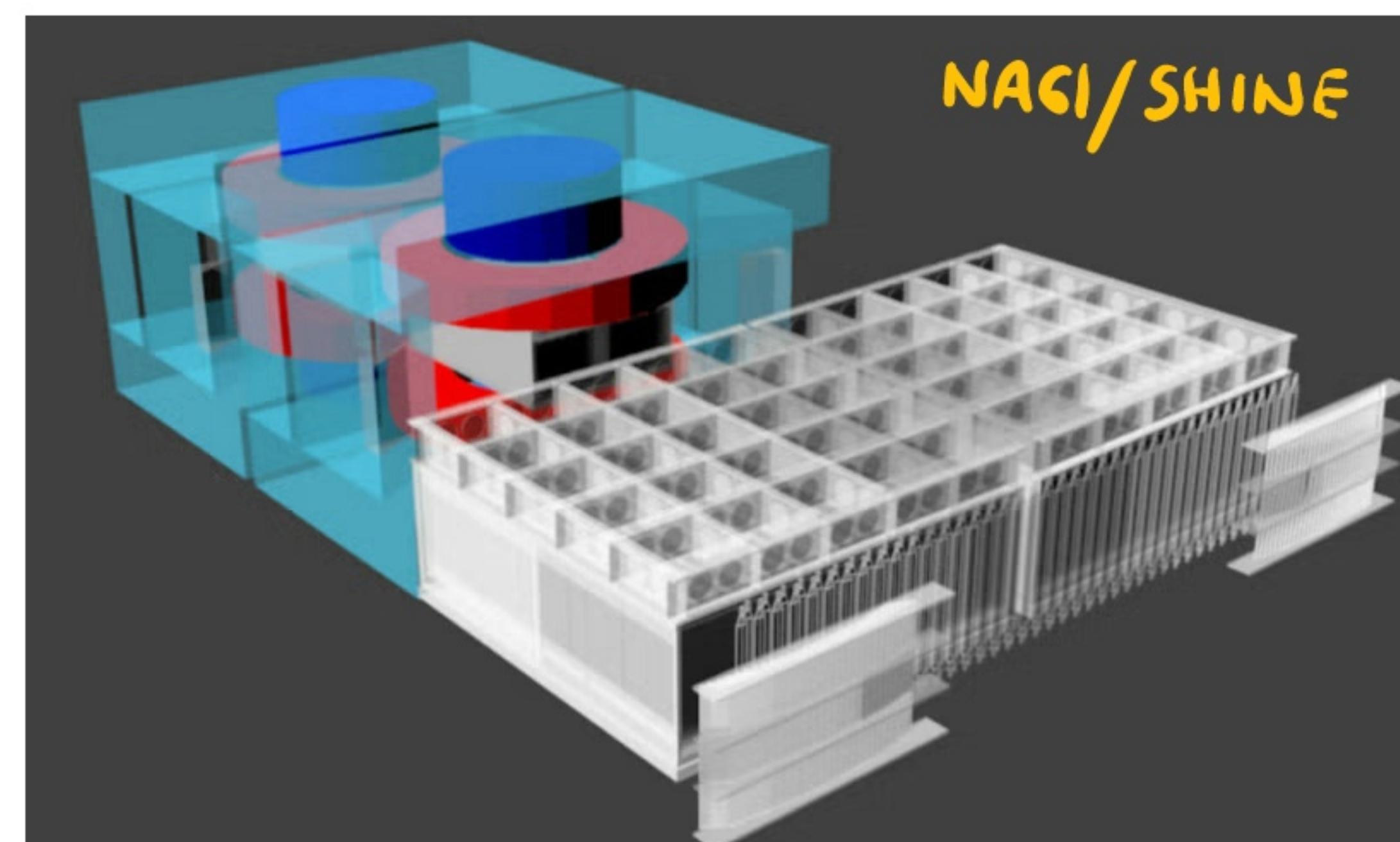
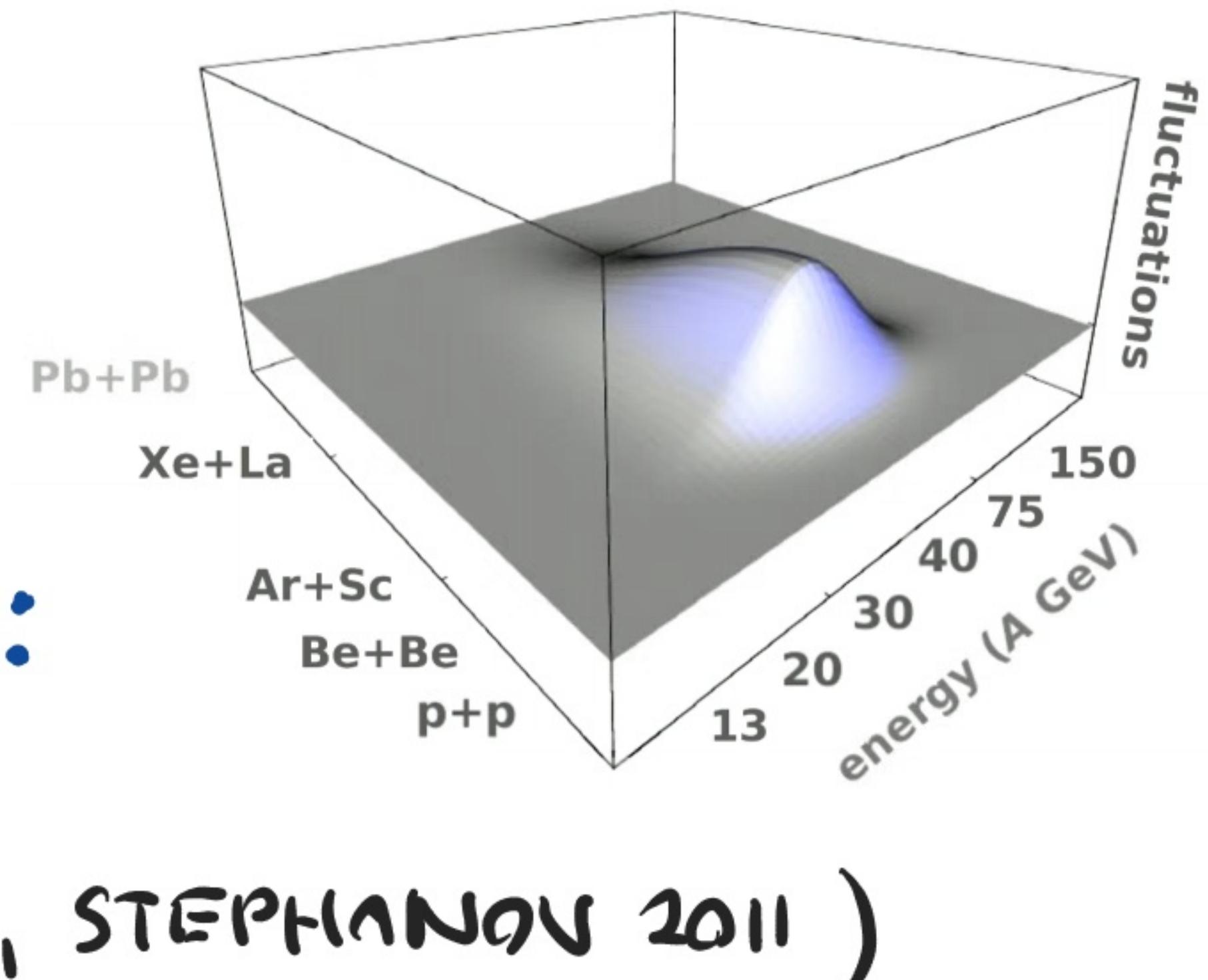
PHASE II: SEARCHING FOR CRITICAL POINT

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)
- PIAN 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)





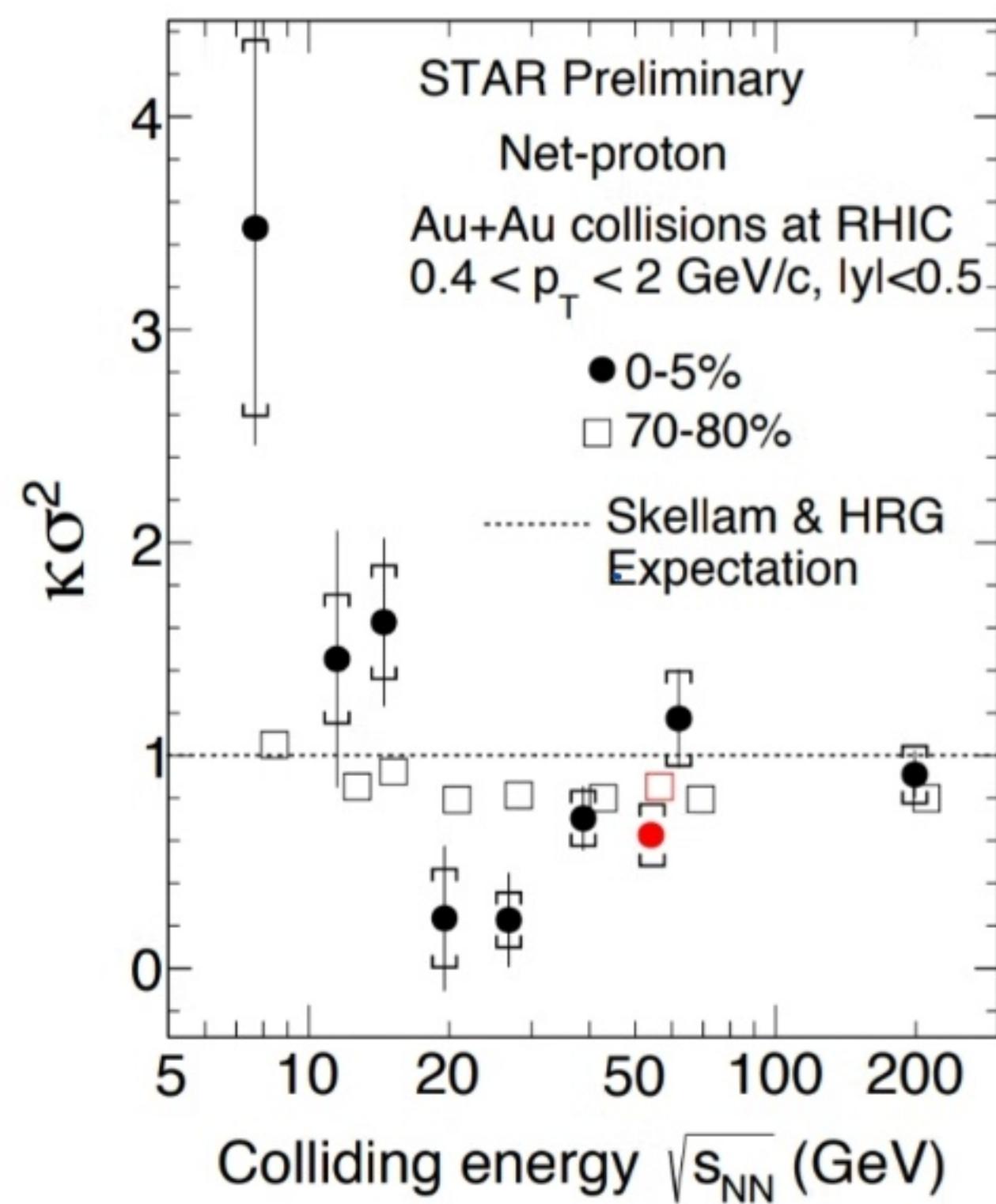
CRITICAL STRUCTURES

(19)

PHASE II: SEARCHING FOR CRITICAL POINT

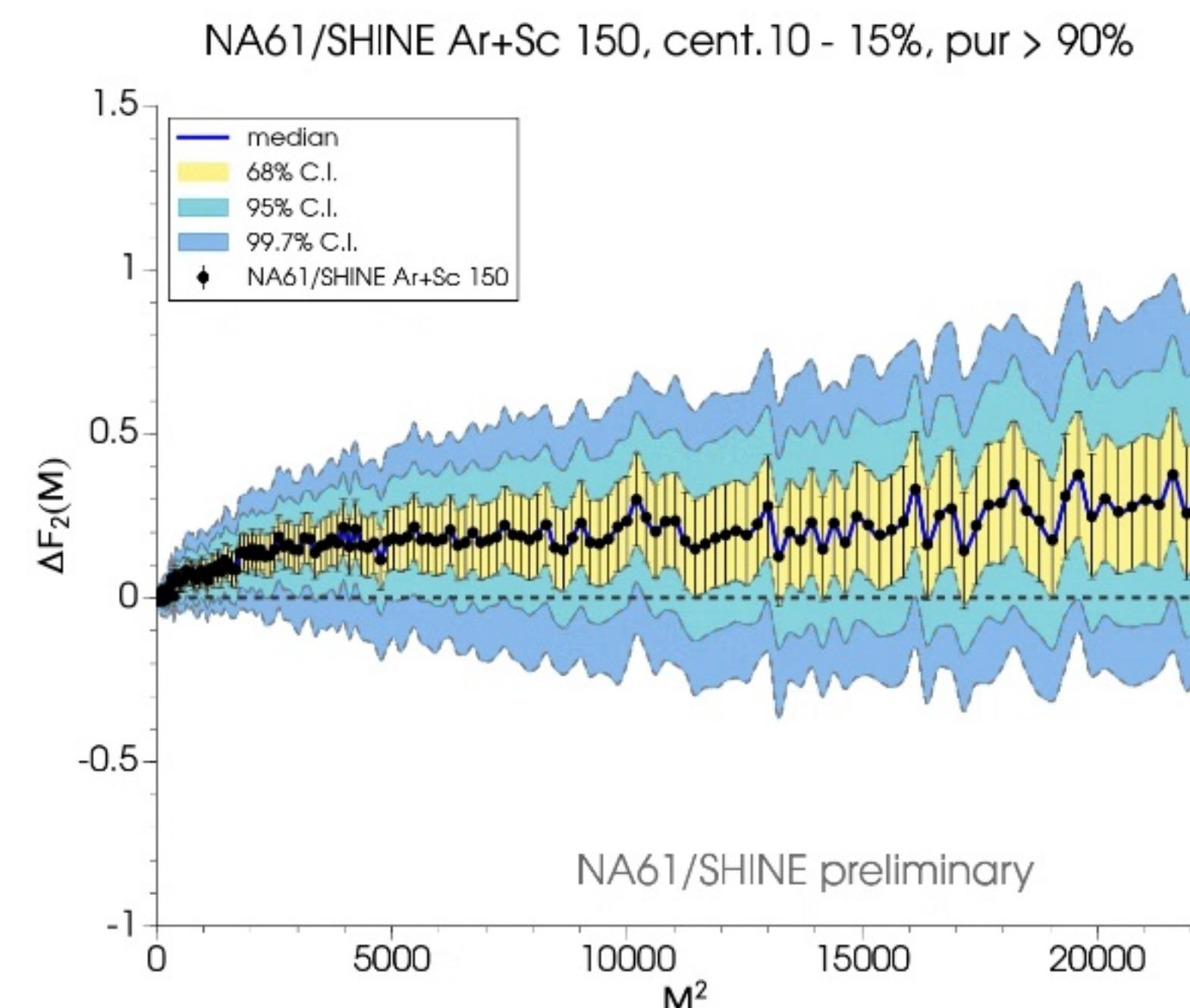
CP INITIATIONS → DIFFERENT ENERGIES/REACTIONS

HIGHER ORDER MOMENTS



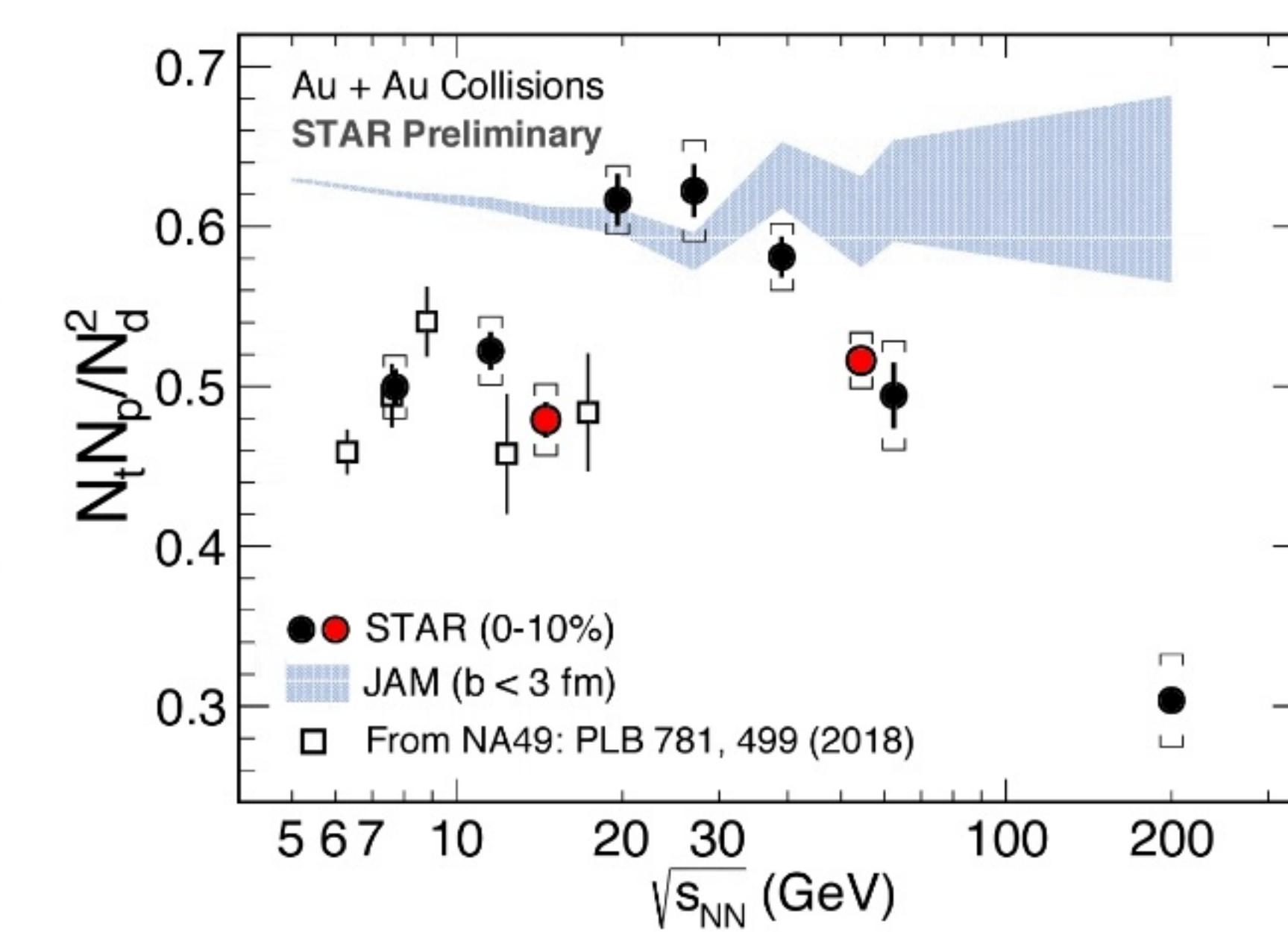
$\approx 7 \text{ GeV}$

PROTON INTERMITTENCY



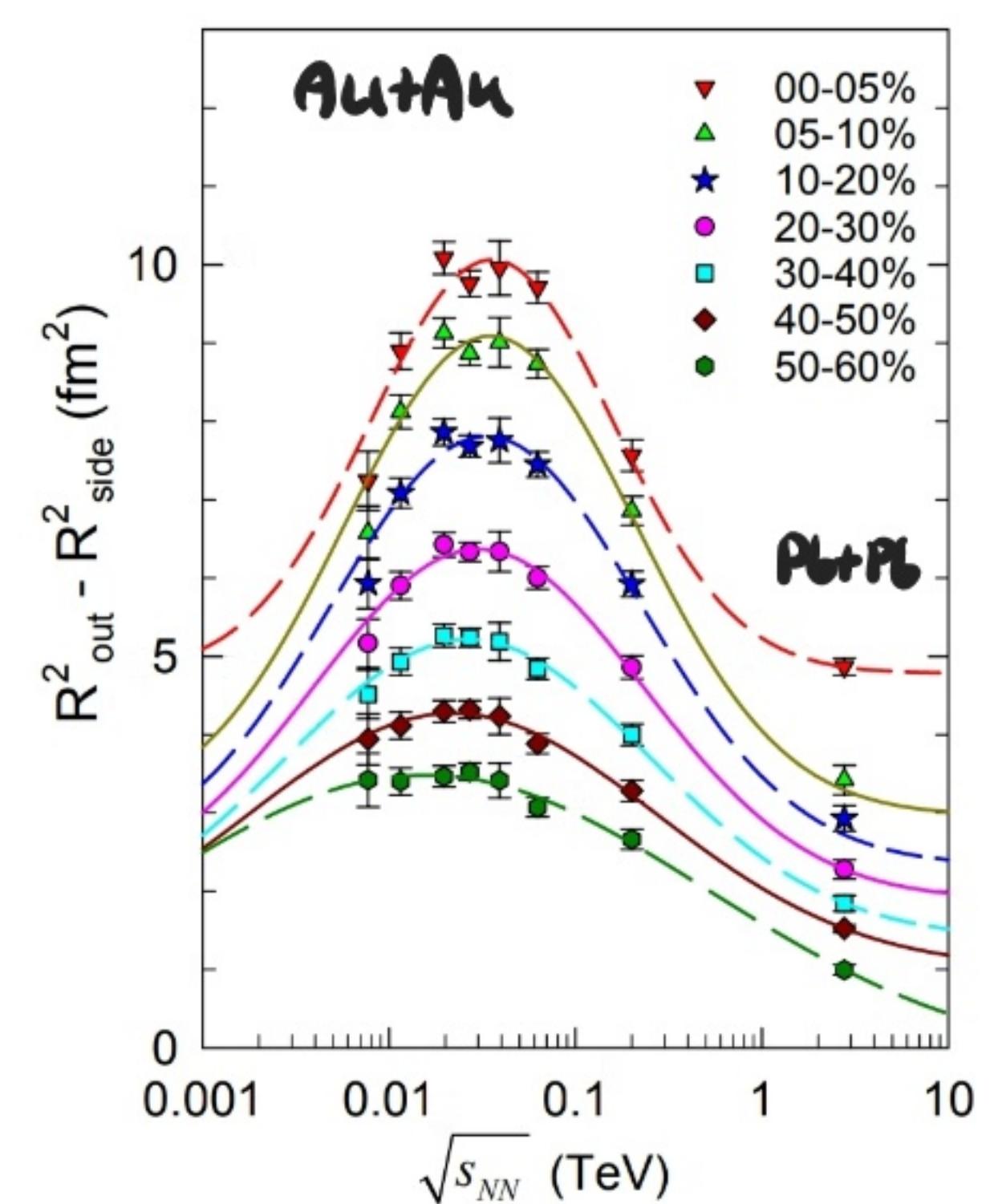
$\approx 17 \text{ GeV}$

LIGHT IONS



$\approx 20 \text{ GeV}$

SHORT-RANGE CORRELATIONS



$\approx 50 \text{ GeV}$



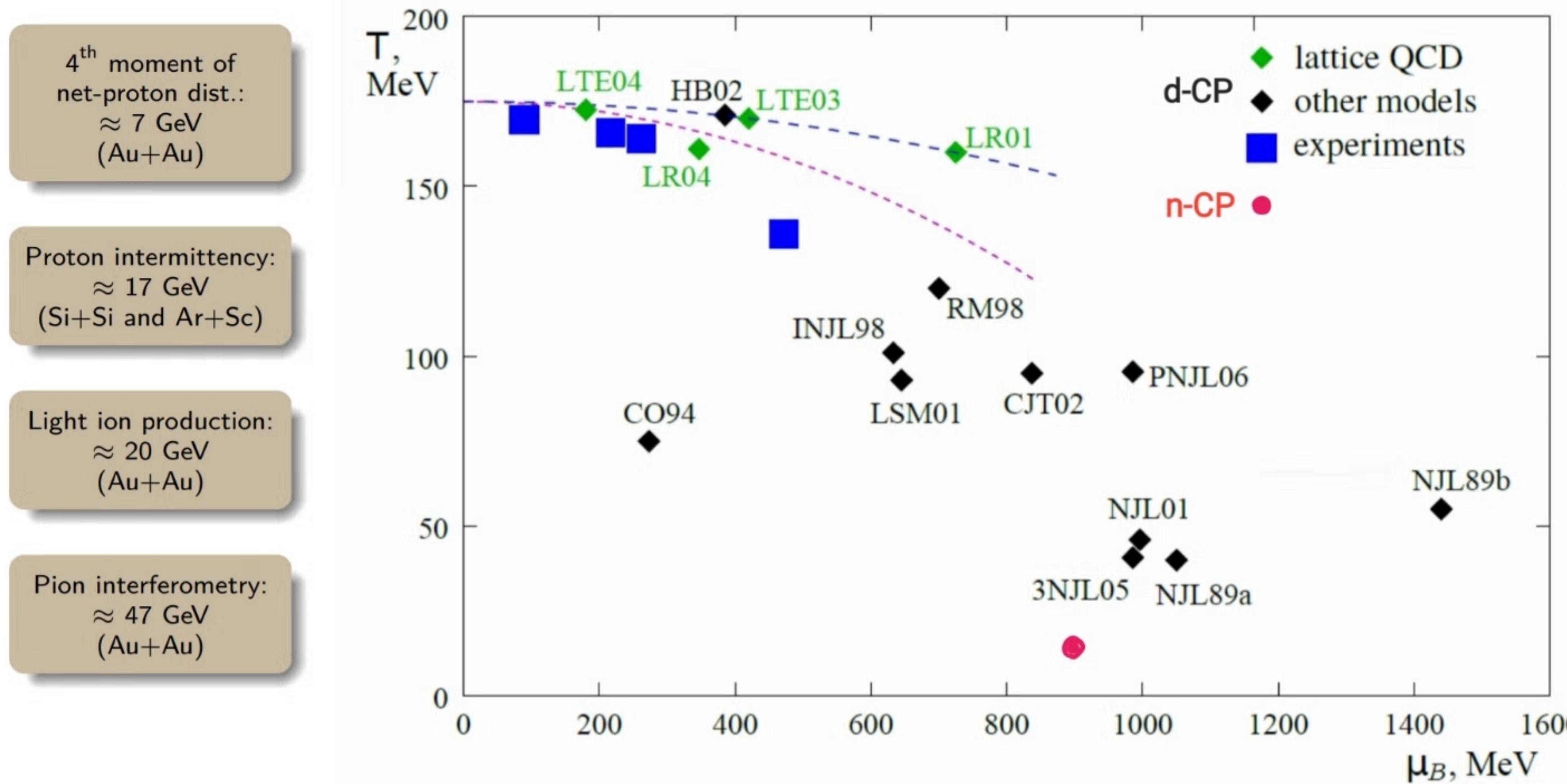
CRITICAL STRUCTURES

(20)

PHASE II: SEARCHING FOR CRITICAL POINT

AS FOR NOW EXPERIMENTAL AND THEORETICAL
RESULTS ARE INCONCLUSIVE / CONFUSING

CZAPOWICZ SQM 2019



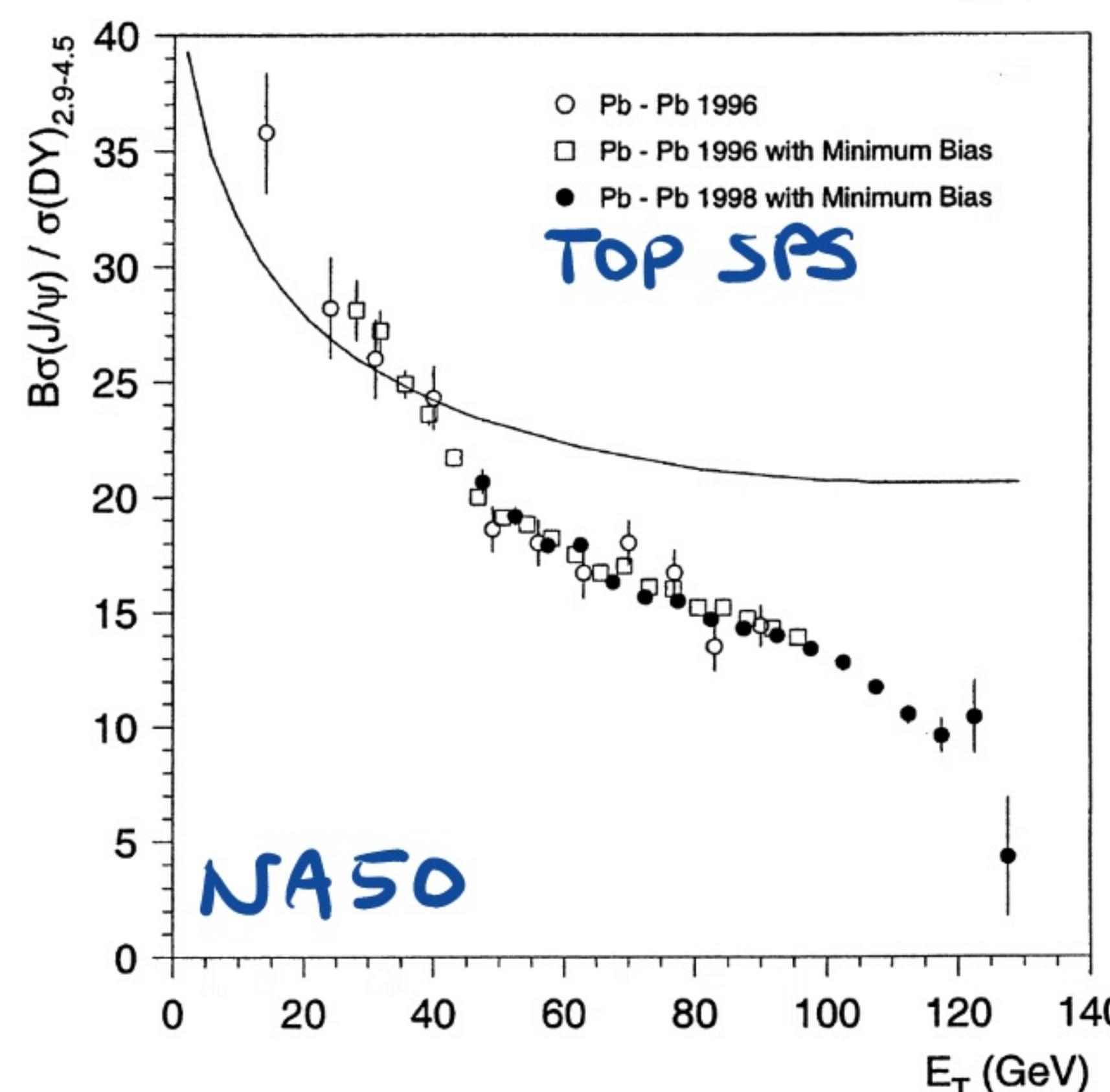
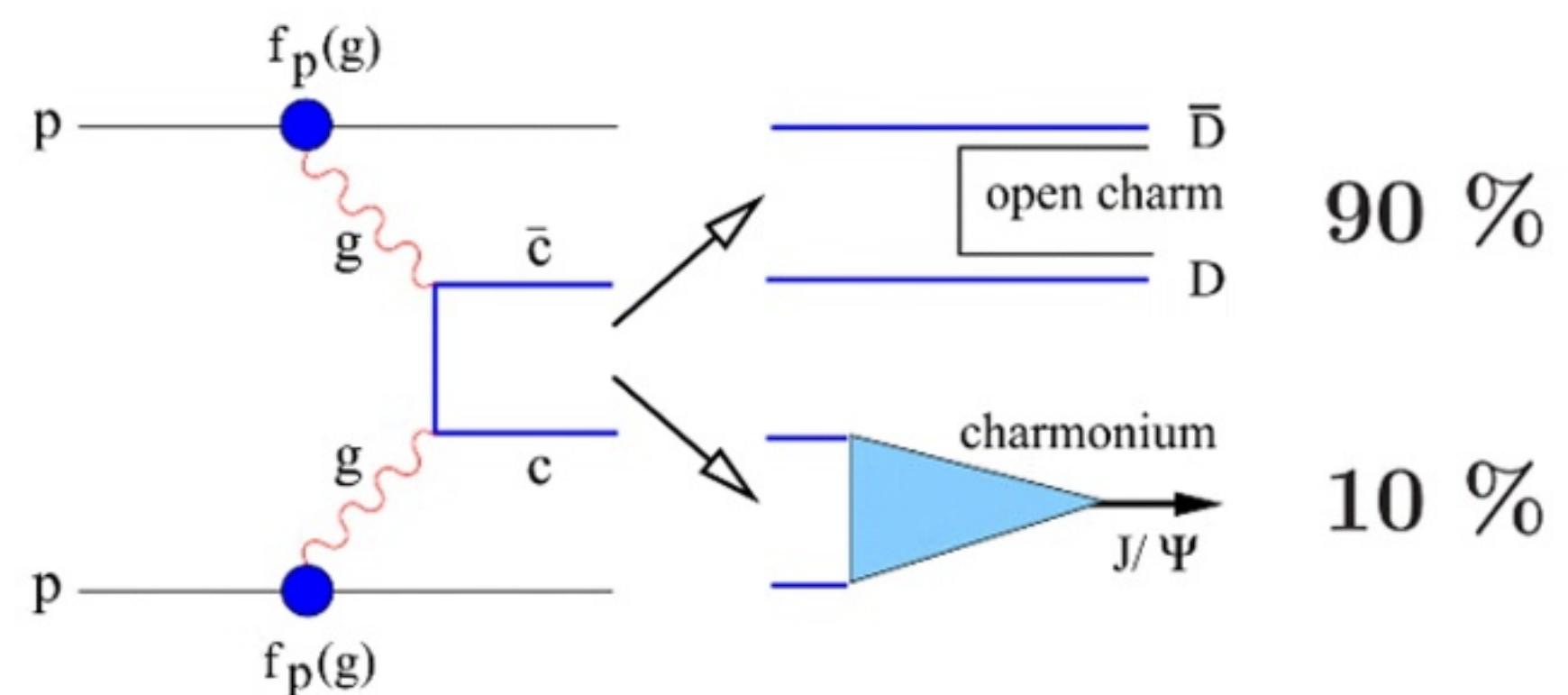
NEW RESULTS EXPECTED SOON FROM NA61/SHINE AND STAR BES II

INTERMEZZO II: CHARM PRODUCTION AND QGP

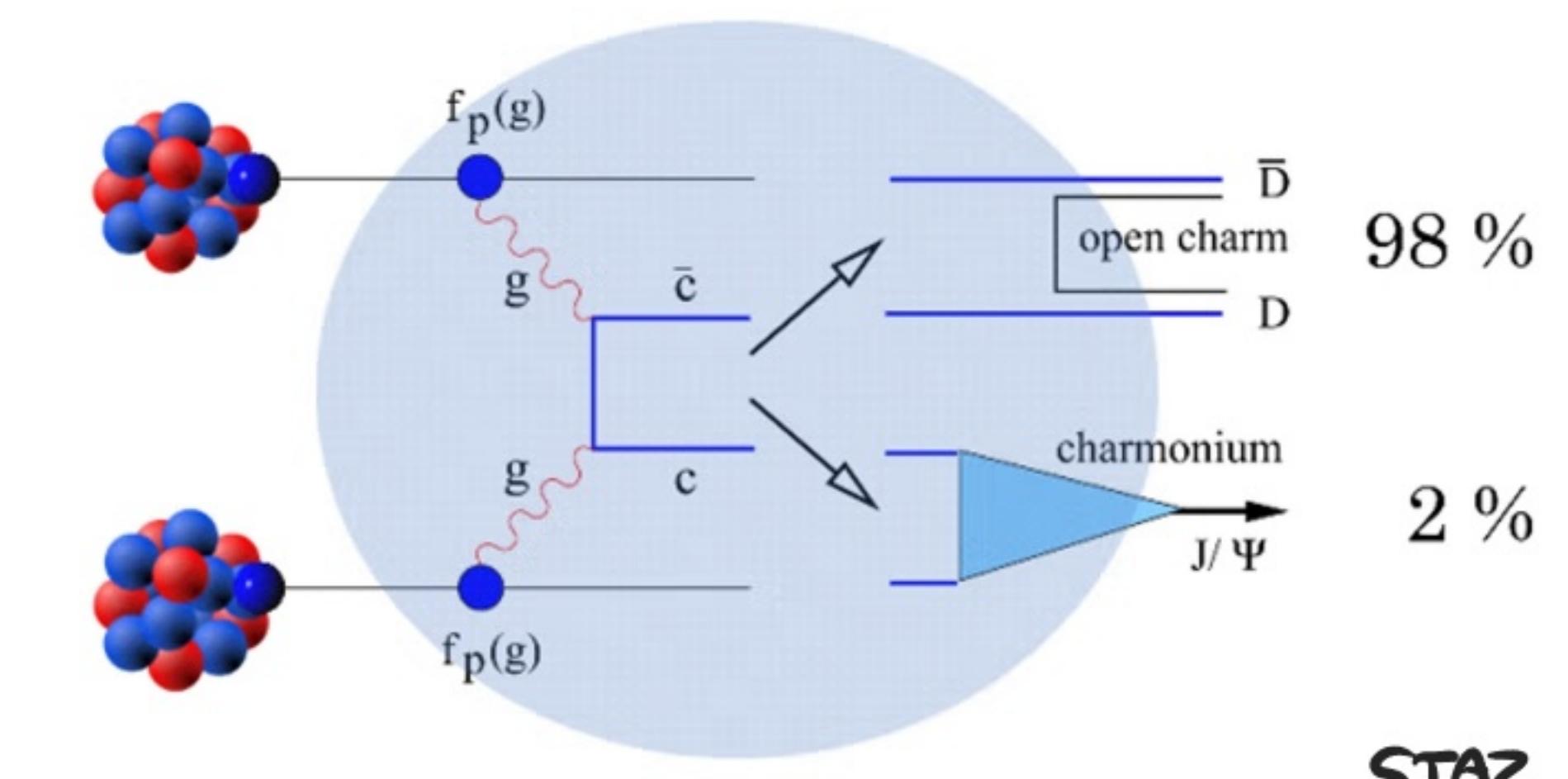
(21)

DYNAMICAL MODEL

ELEMENTARY p+p



Pb+Pb WITH QGP



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

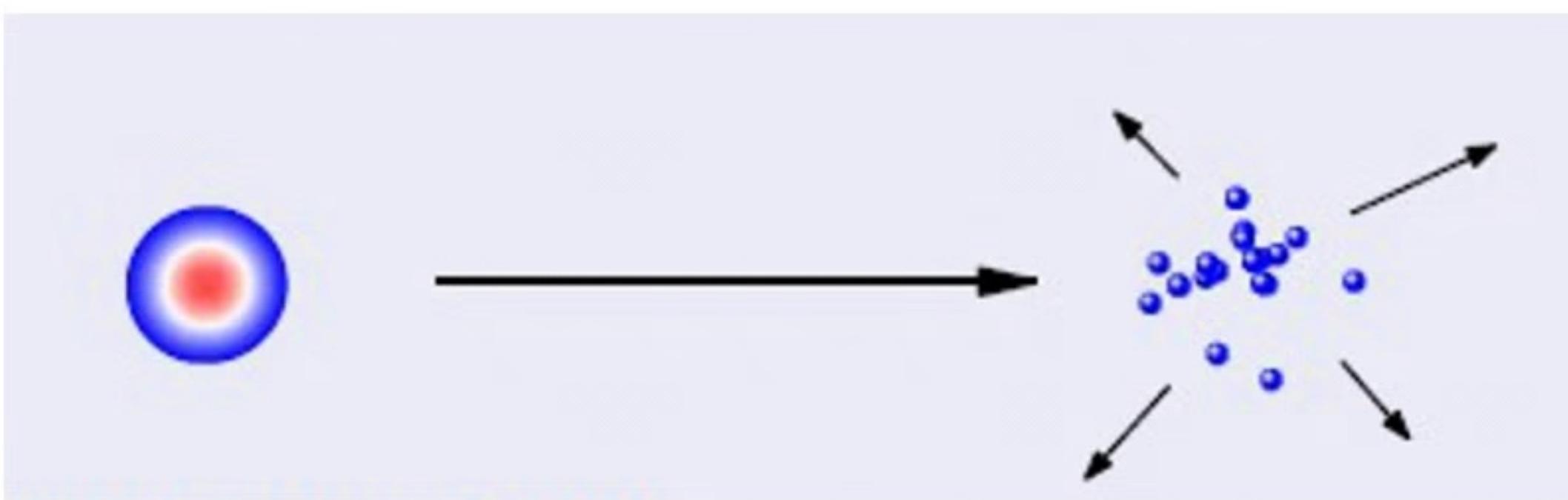
→ ASSUMPTION :
 $\langle D\bar{D} \rangle \sim \langle D\gamma \rangle$

CROSSING THRESHOLD FOR QGP CREATION →
 → ANOMALOUS SUPPRESSION OF $\langle J/\Psi \rangle / \langle c\bar{c} \rangle$ RATIO

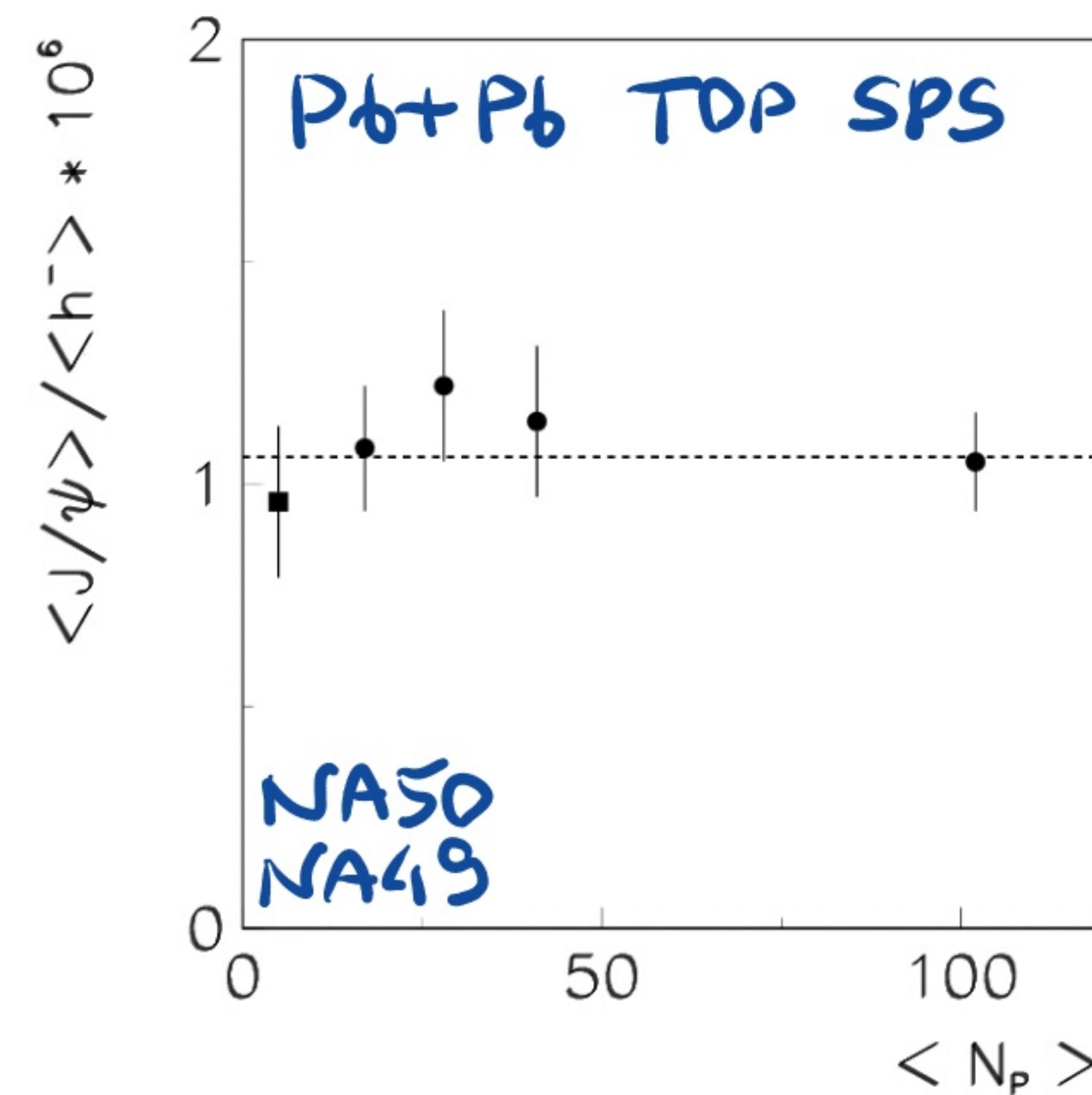
INTERMEZZO II: CHARM PRODUCTION AND QGP

STATISTICAL HADRONIZATION MODEL

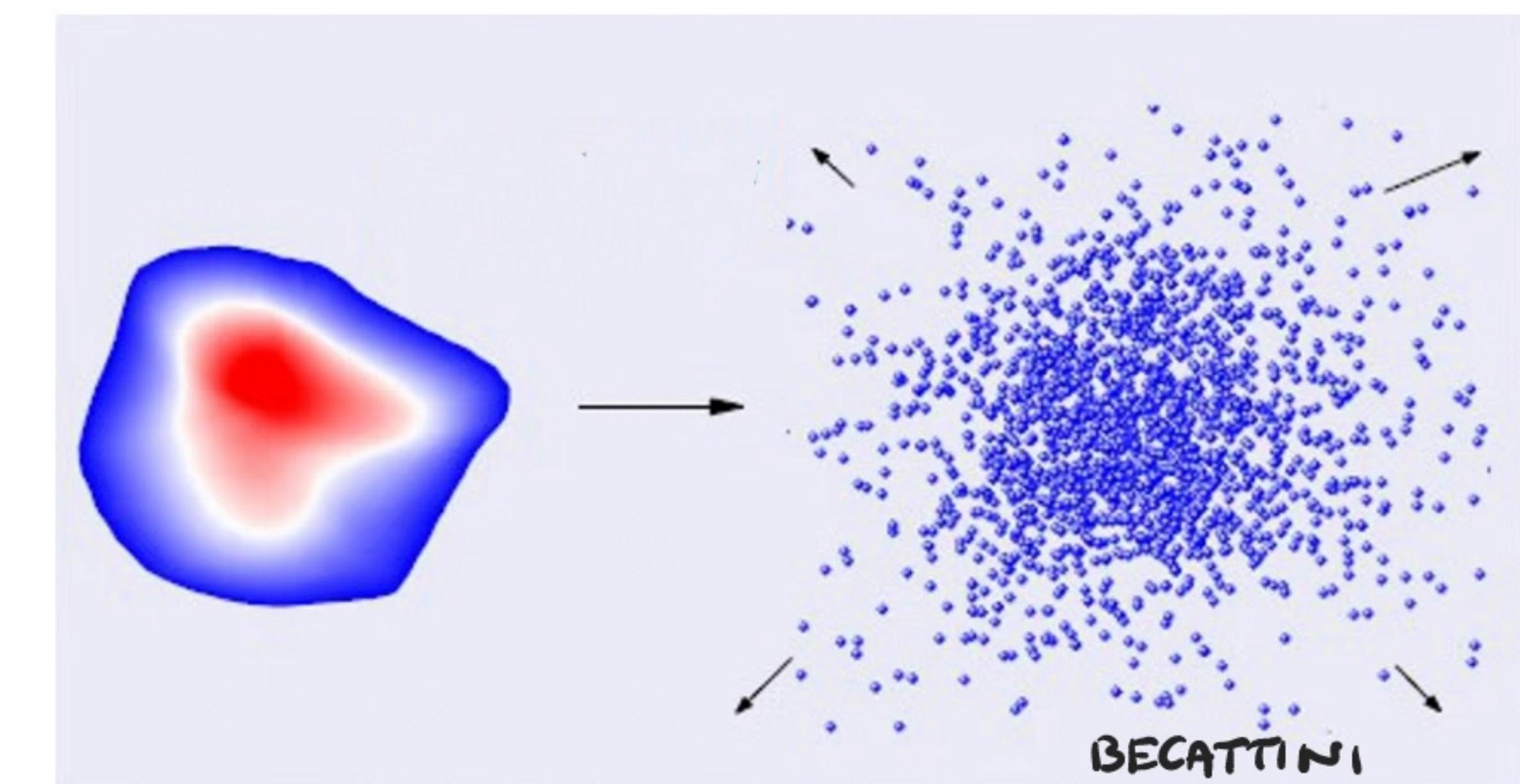
ELEMENTARY p+p



J/ψ BORN IN EQUILIBRIUM
AT $\epsilon \approx 0.5 \text{ GeV/fm}^3$



Pb+Pb WITH QGP



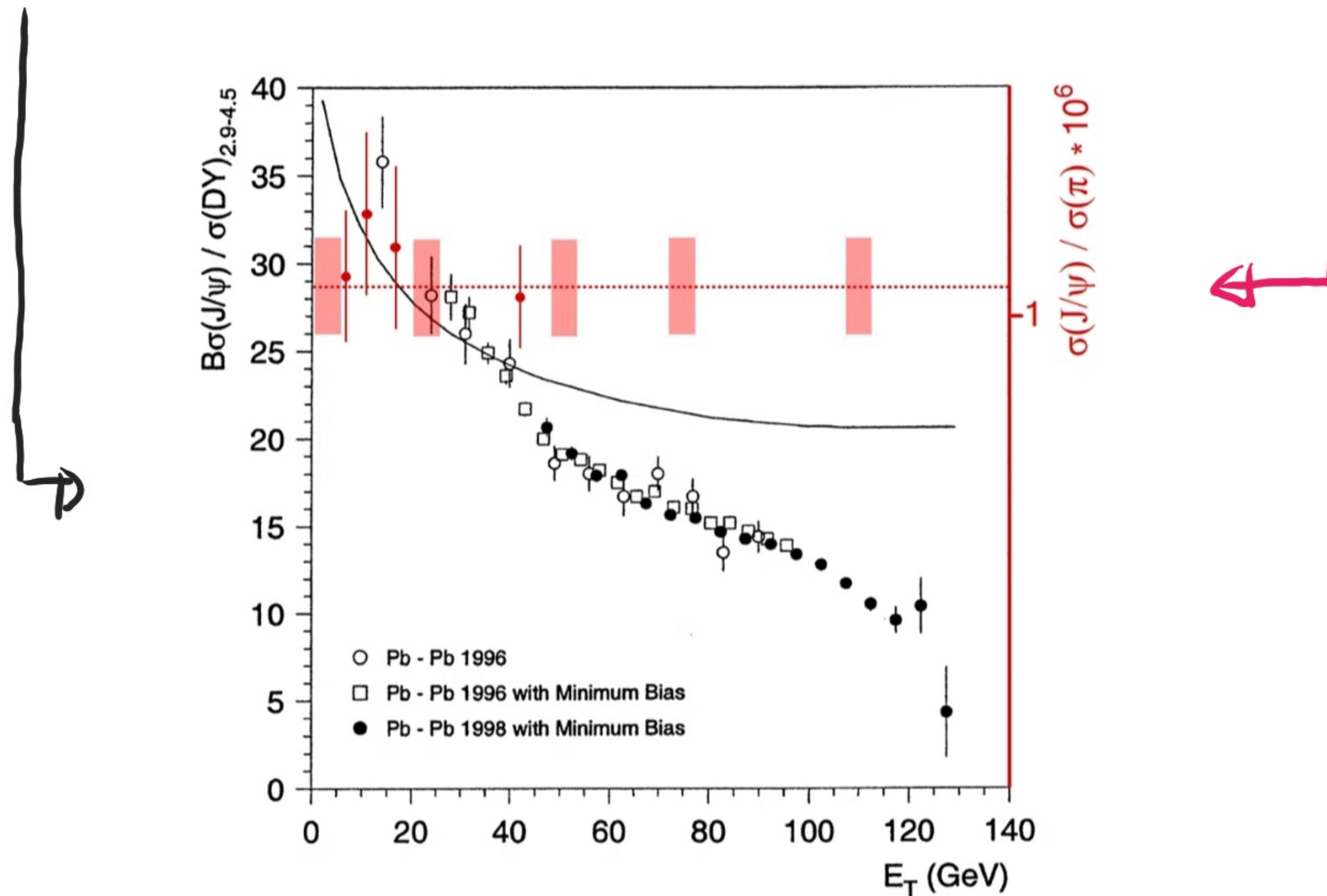
J/ψ BORN IN EQUILIBRIUM
AT $\epsilon \approx 0.5 \text{ GeV/fm}^3$

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

INTERMEZZO II: CHARM PRODUCTION AND QGP

(23)

DYNAMICAL VERSUS HADRONIZATION MODELS



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

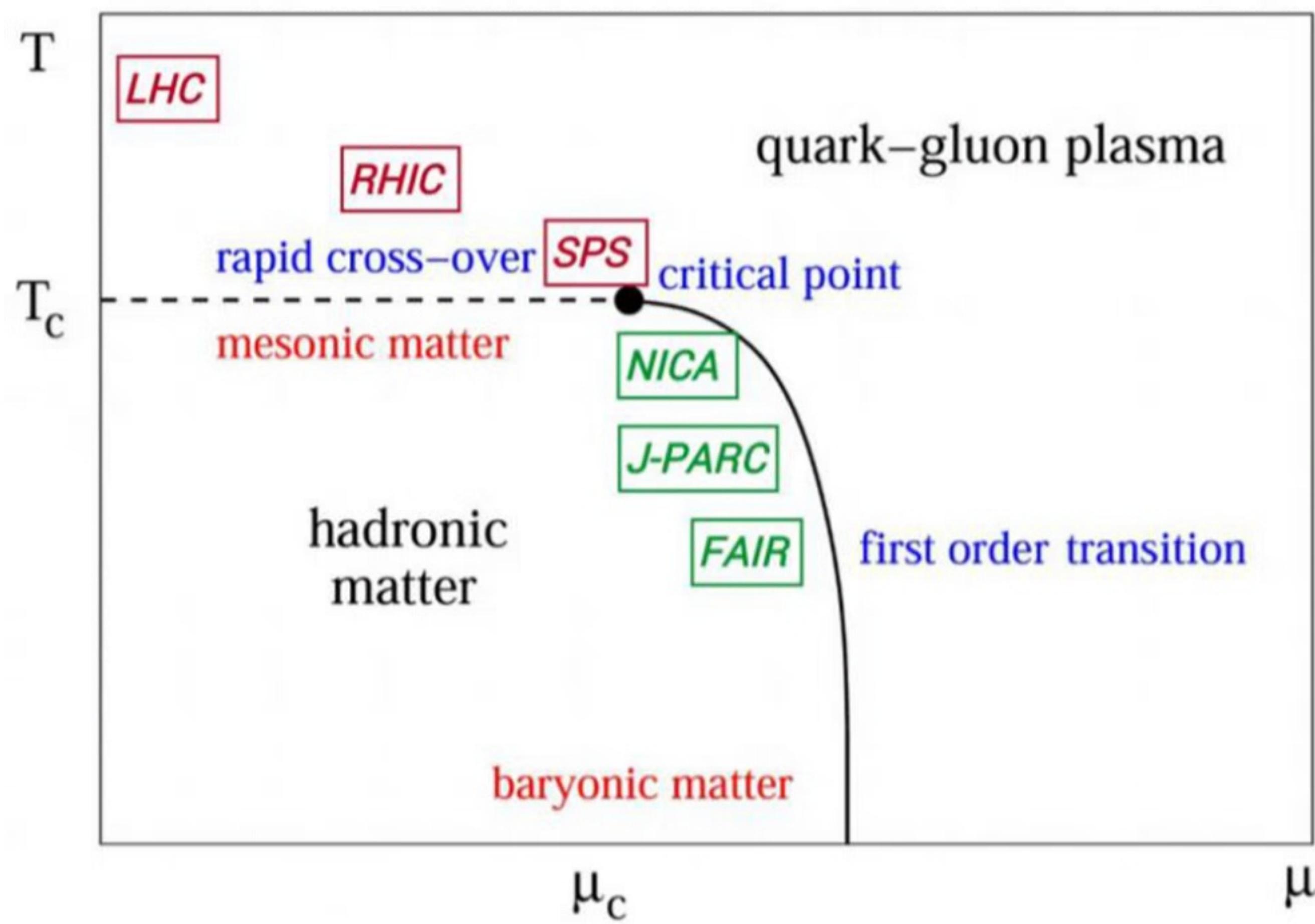


INVENTING FUTURES:

QGP ONSET AND CHARM

(24)

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,

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

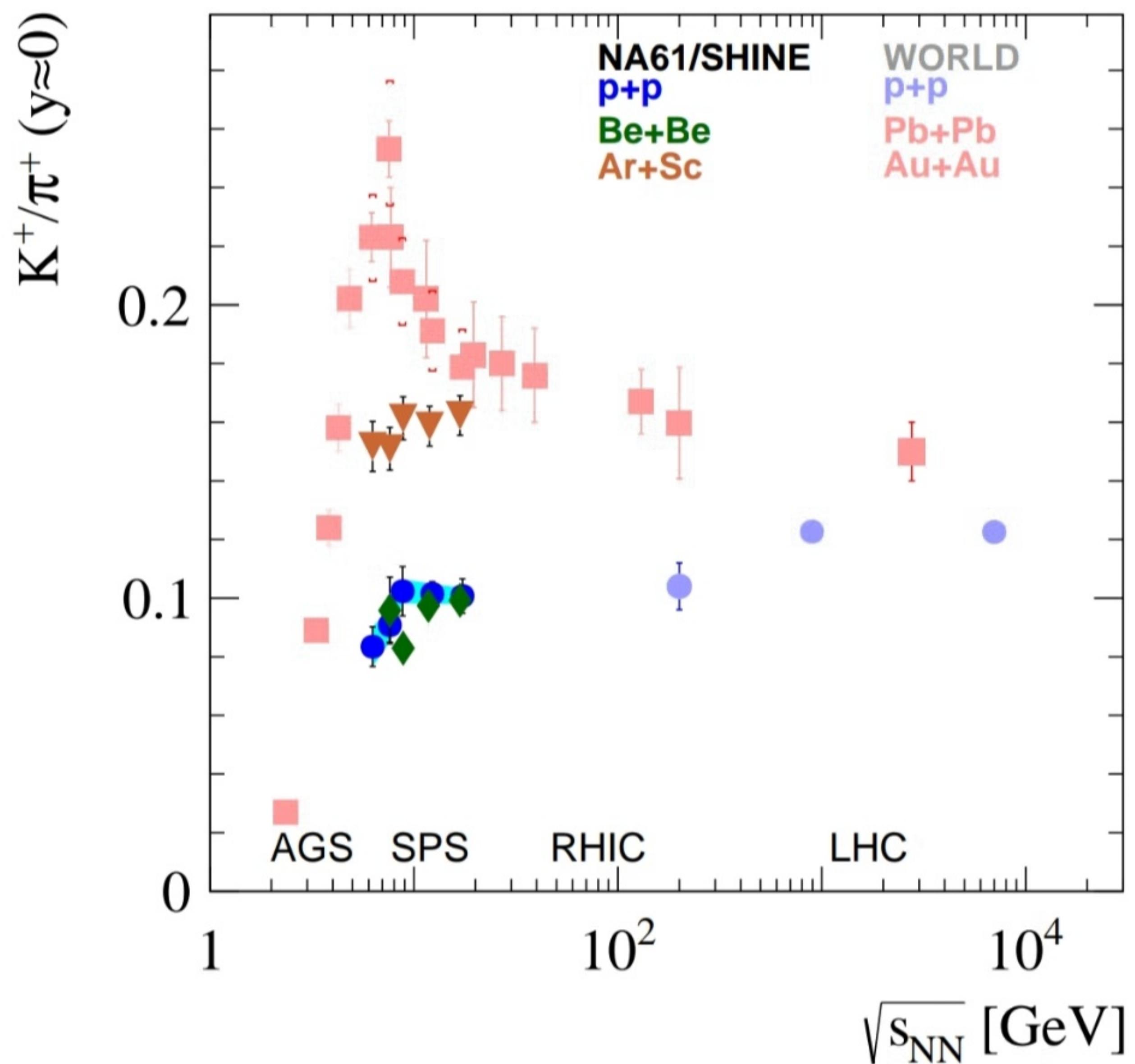
NAC0+ (6-17 GeV):
 $\Upsilon/\gamma, \langle c\bar{c} \rangle$ AFTER 2026



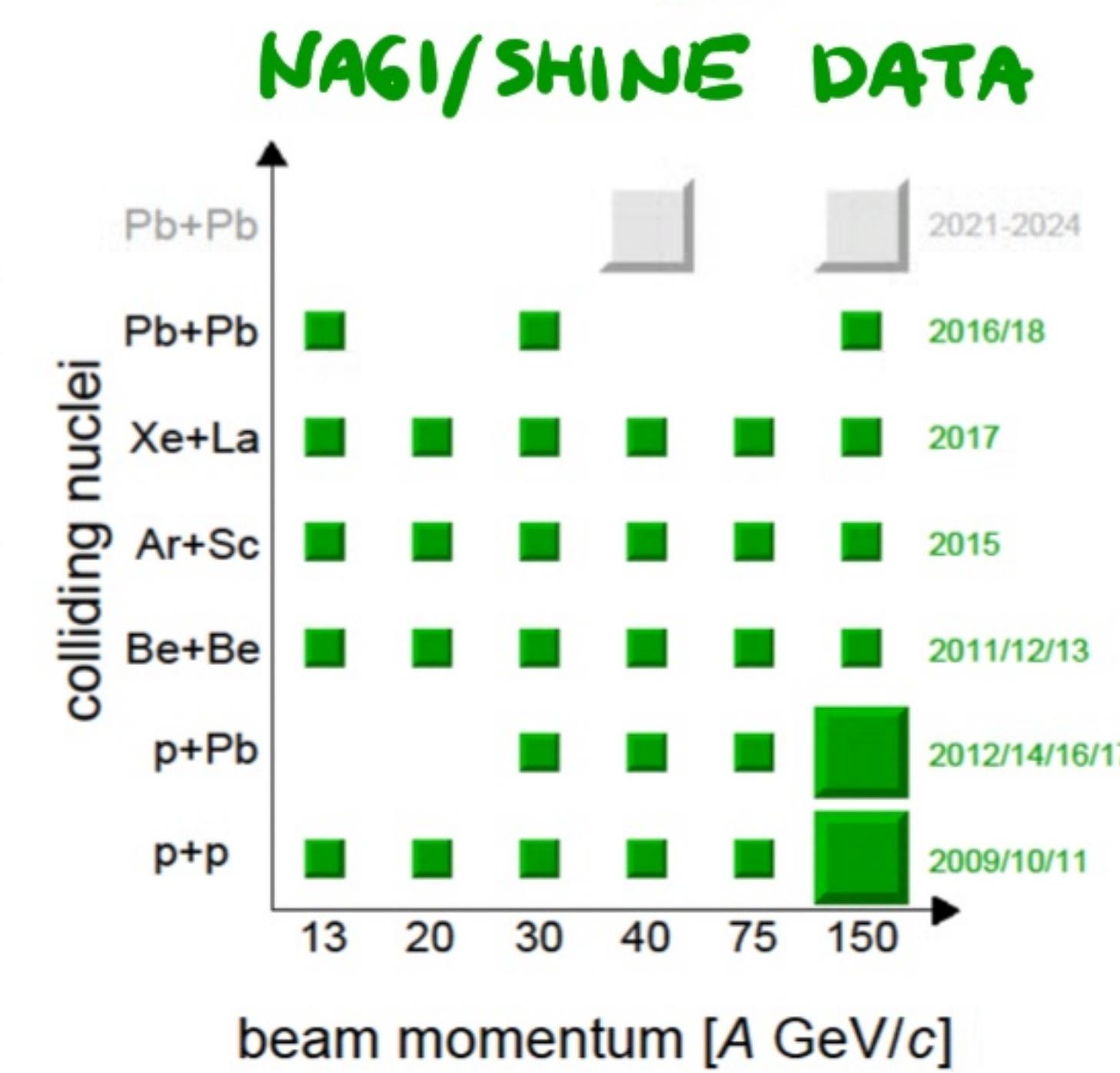
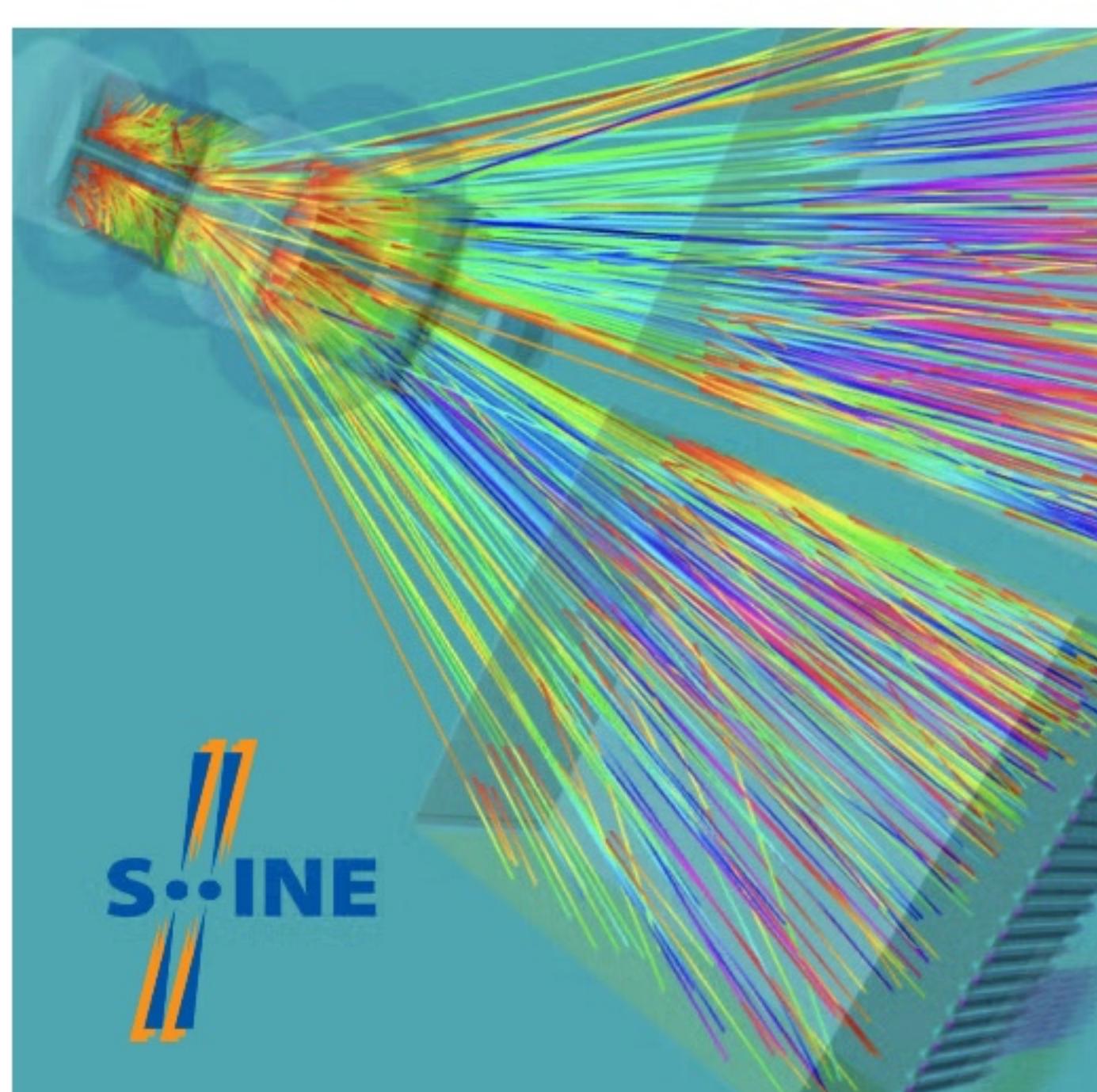
INVENTING FUTURES

(25)

ONSET OF FIREBALL - RECENT NA61/SHINE DISCOVERY



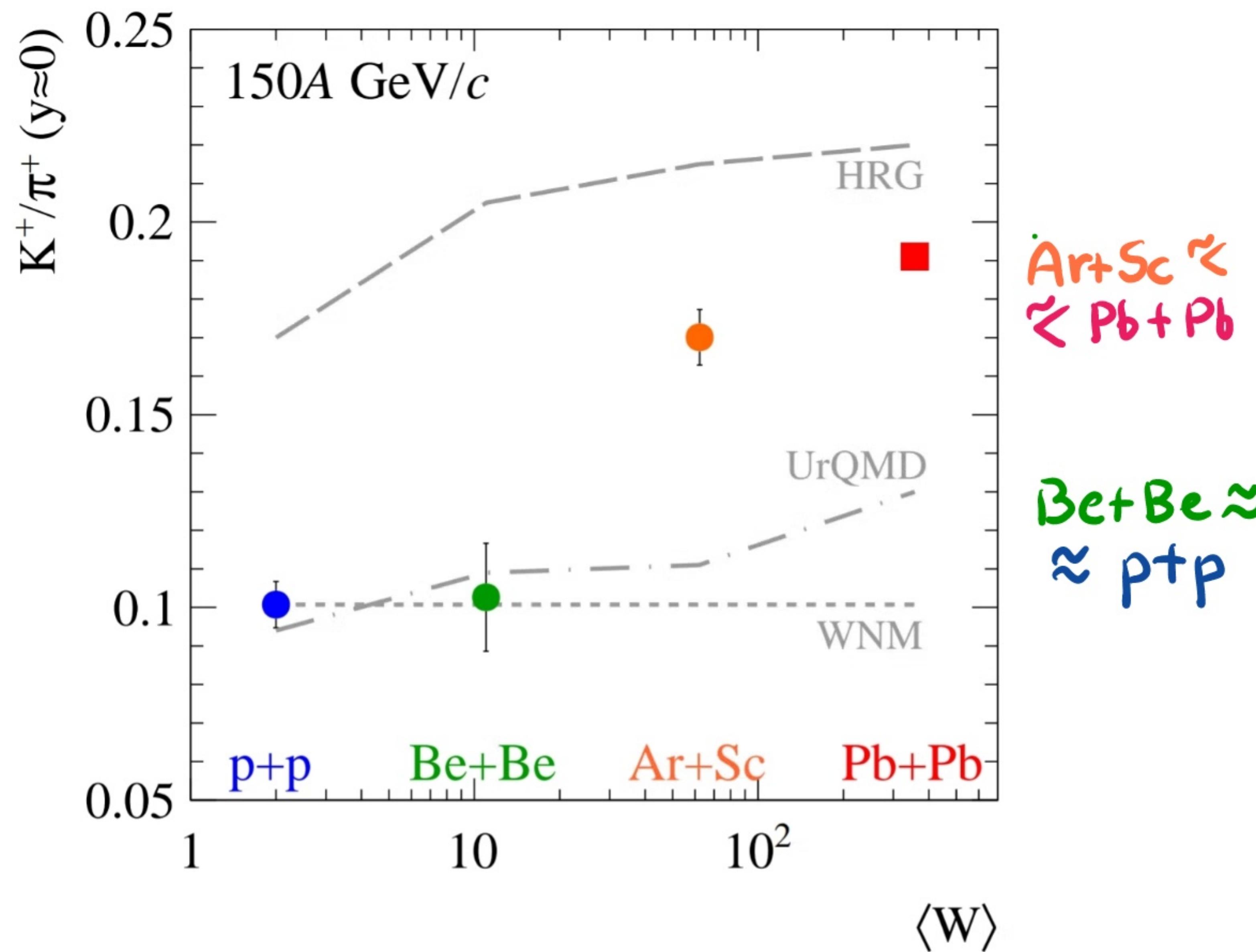
STATISTICAL MODELS
 $A \uparrow$ ONSET OF FIREBALL
STRING - RESONANCE MODELS





INVENTING FUTURES

ONSET OF FIREBALL - RECENT NA61/SHINE DISCOVERY



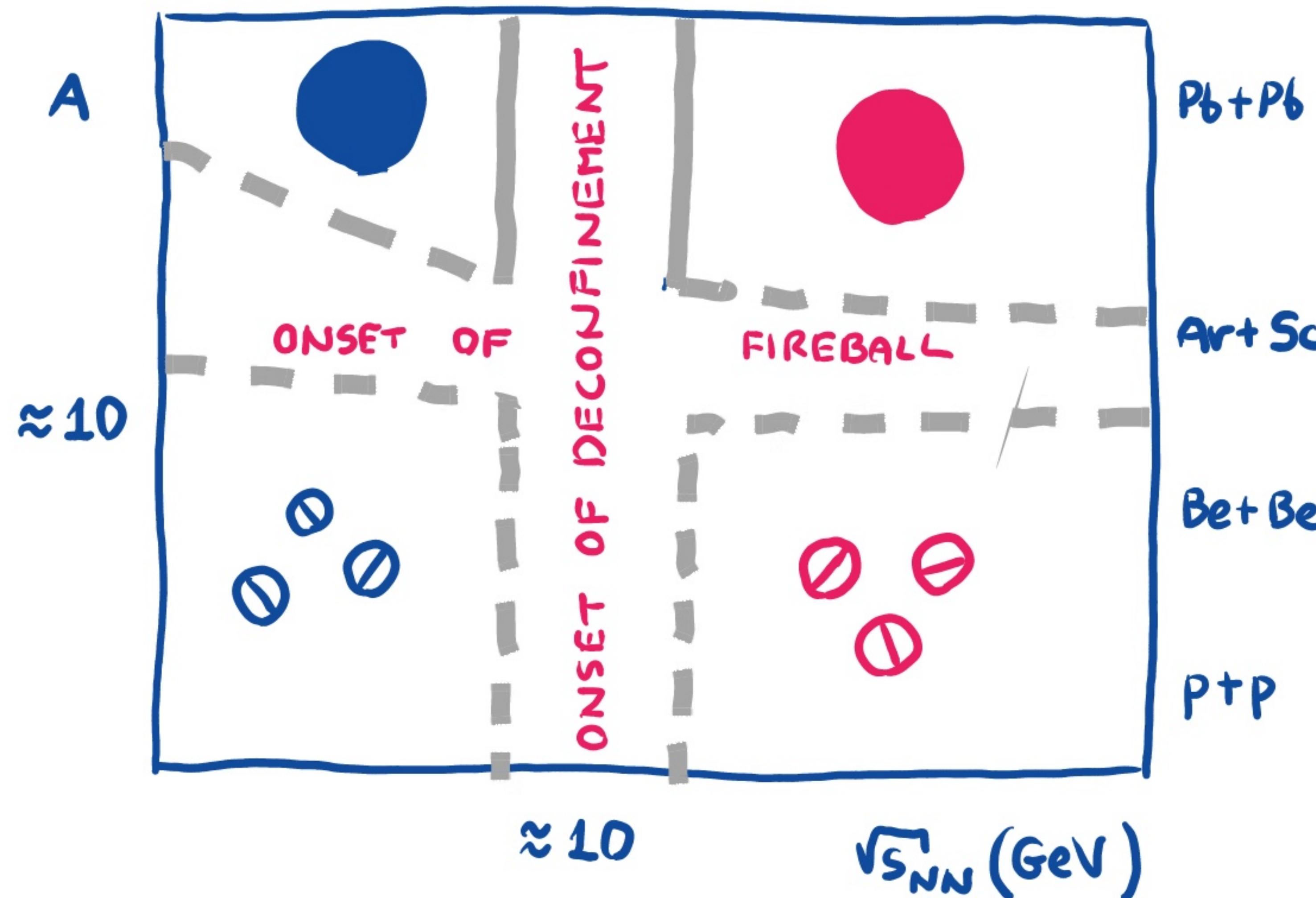
STATISTICAL MODELS
 $A \uparrow$ ONSET OF FIREBALL
 STRING-RESONANCE MODELS



INVENTING FUTURES

(27)

ONSET OF FIREBALL \rightarrow DETAILED SCAN IN (NUCLEAR MASS NUMBER) -
 \sim (COLLISION ENERGY) SHOULD BE POSSIBLE AT:



Pb+Pb NICA (< 11 GeV); 2022+

Ar+Sc FAIR (< 5 GeV); 2025+

Bet+Be SPS (5-17 GeV); 2025+

p+p J-PARC (< 6 GeV); ?

SUMMARYONSET 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/+) 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 ($\sqrt{s_{NN}} \gtrsim 20$ GEV, $A \gtrsim 100$) IS NEEDED (NICA, SPS, SIS100, J-PARC ?)

heavy ions at CERN

