# ON TRANSITIONS IN HIGH ENERGY NUCLEAR COLLISIONS

## NEWS FROM NA61/SHINE AT CERN SPS

M. GAZDZICKI, FRANKFURT, KIELCE

- VOCABULARY
- ONSET OF FIREBALL
- ONSET OF DECONFINEMENT
- SEARCH FOR CRITICAL POINT

STUDY OF PHASE TRANSITIONS IN STRONG INTERACTIONS STARTED 40 YEARS AGO:

**Phase Transitions in the Statistical Bootstrap Model with an Internal Symmetry**
K. Redlich, L. Turko (Wroclaw U.). Nov 1979. 17 pp.
Published in **Z.Phys. C5 (1980) 201**
WROCLAW-490
DOI: 10.1007/BF01421776

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

Detailed record - Cited by 133 records 100+

NOW ONE OF THE STRONGEST THEORY GROUPS IN THE FIELD. VERY INTERNATIONAL.

SINCE SEVERAL YEARS STEADILY INCREASING EXPERIMENTAL GROUP.
PARTICIPATION IN NA61/SHINE AT CERN SPS

VOCABULARY

# NA61/SHINE

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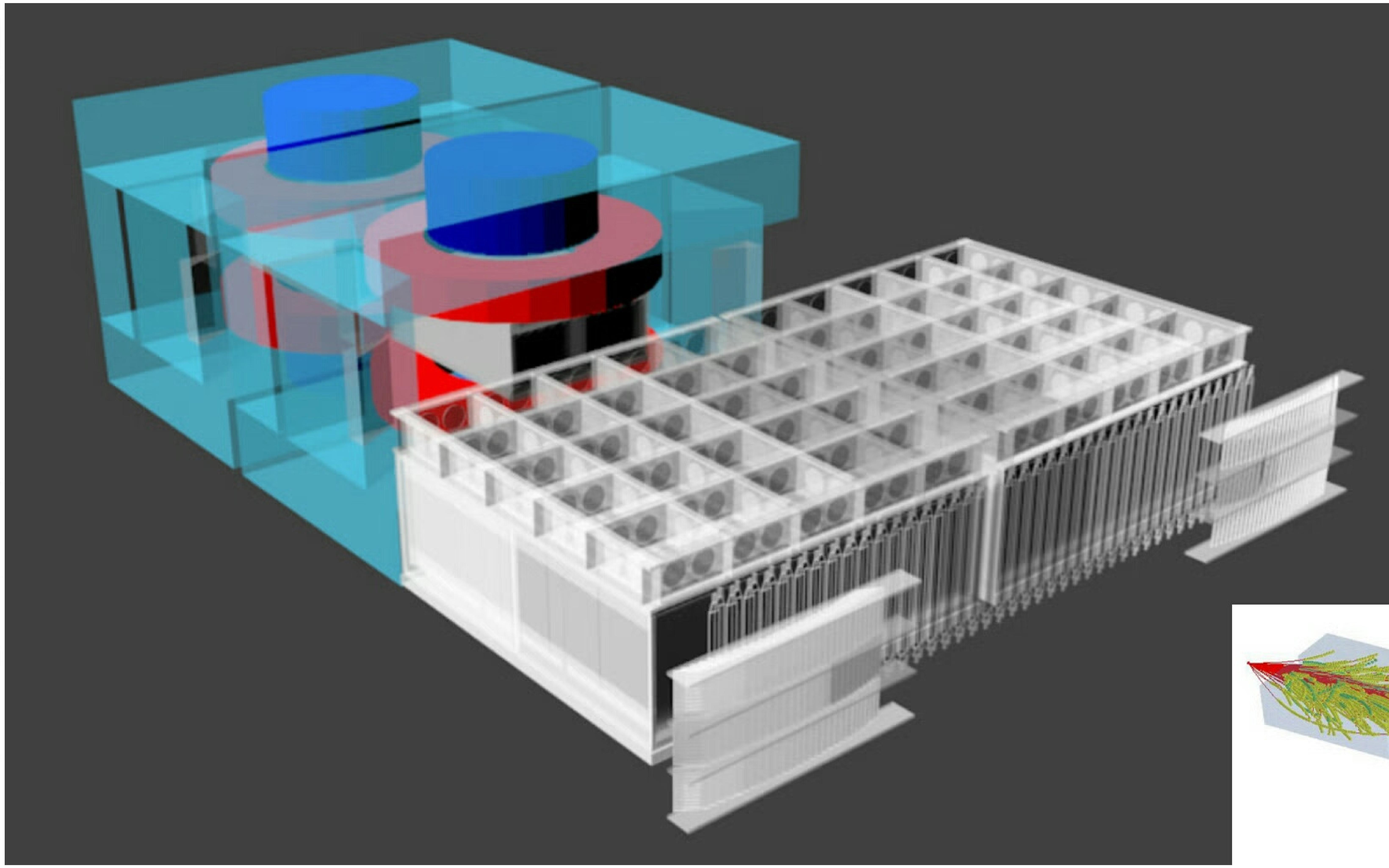
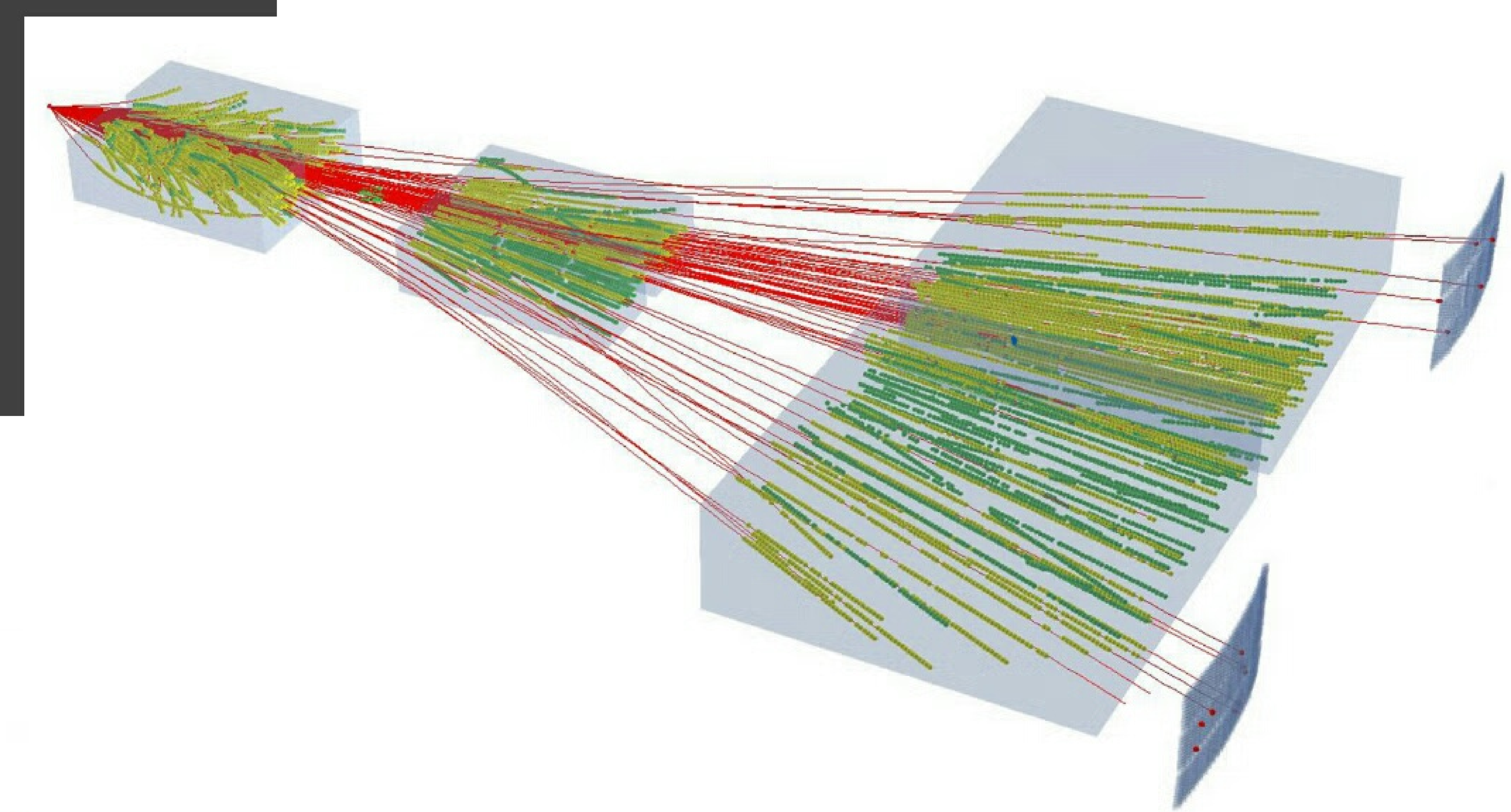
NA61/SHINE – UNIQUE MULTIPURPOSE EXPERIMENT:
HADRON PRODUCTION IN h+p, h+A, A+A
AT 13A – 150A(400) GeV/c

- ACCELERATION CHAIN
- H2 BEAM LINE
- DETECTOR

# NA61/SHINE DETECTOR



PRECISE MEASUREMENTS OF PROPERTIES OF PRODUCED PARTICLES: ELECTRIC CHARGE, MASS, MOMENTUM VECTOR



# NA61/SHINE PHYSICS

MEASURMENTS OF HADRON PRODUCTION PROPERTIES FOR

3D EVENT BROWSER BY WROCŁAW STUDENTS

- NEUTRINO BEAMS (J-PARC, FERMILAB)
- COSMIC RAY EXPS. (PAO, AMS, ...)
- STRONG INTERACTIONS (HEAVY IONS, ...) →

# STRONG INTERACTIONS



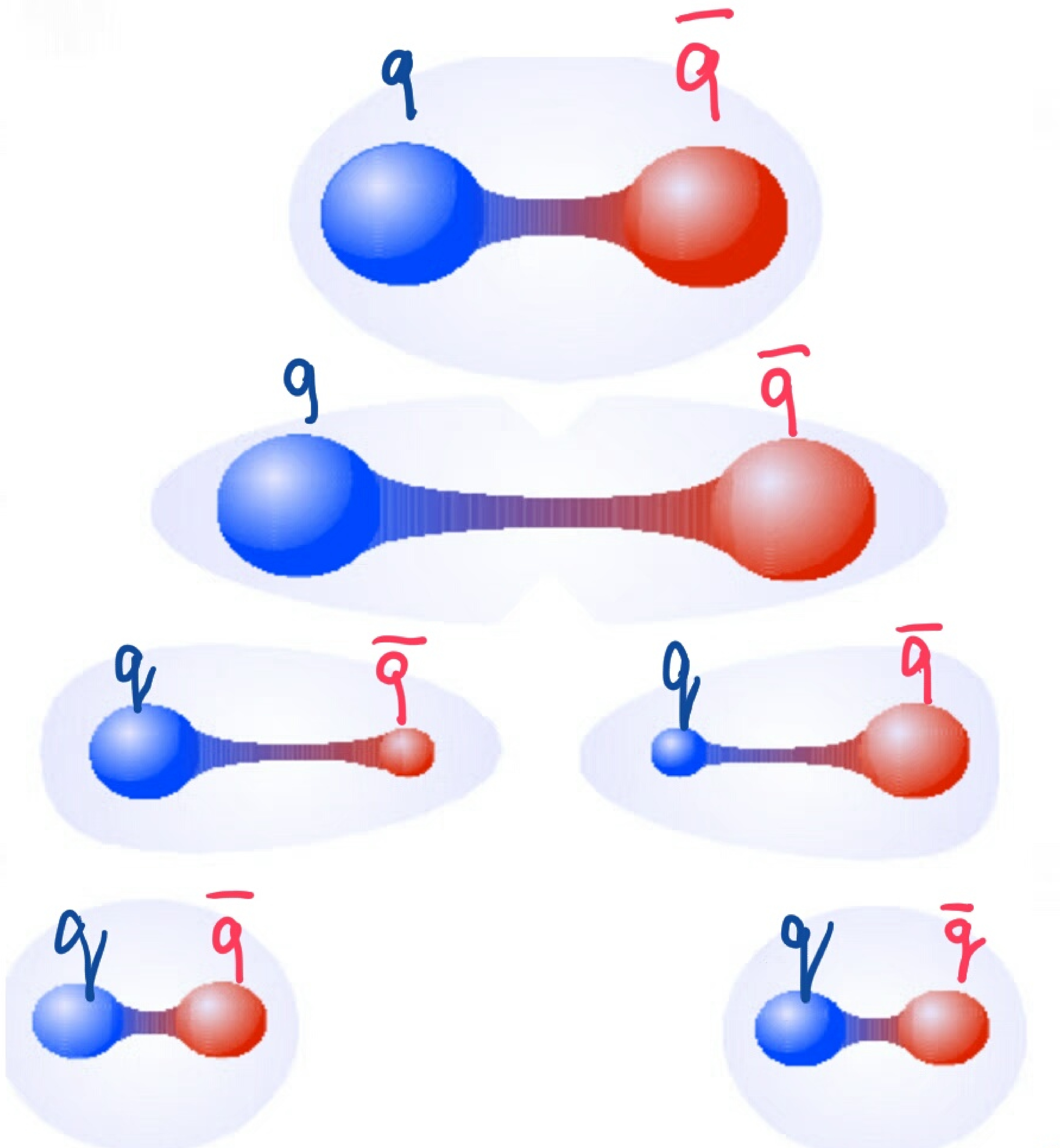
## PROPERTIES OF THE INTERACTIONS

| Property \ Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong: Fundamental | Strong: Residual |
|---|---|---|---|---|---|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | $\gamma$ | Gluons | Mesons |
| Strength relative to electromag for two u quarks at: $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | Not applicable to quarks |
| Strength relative to electromag for two u quarks at: $3\times10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | Not applicable to quarks |
| for two protons in nucleus | $10^{-36}$ | $10^{-7}$ | 1 | Not applicable to hadrons | 20 |

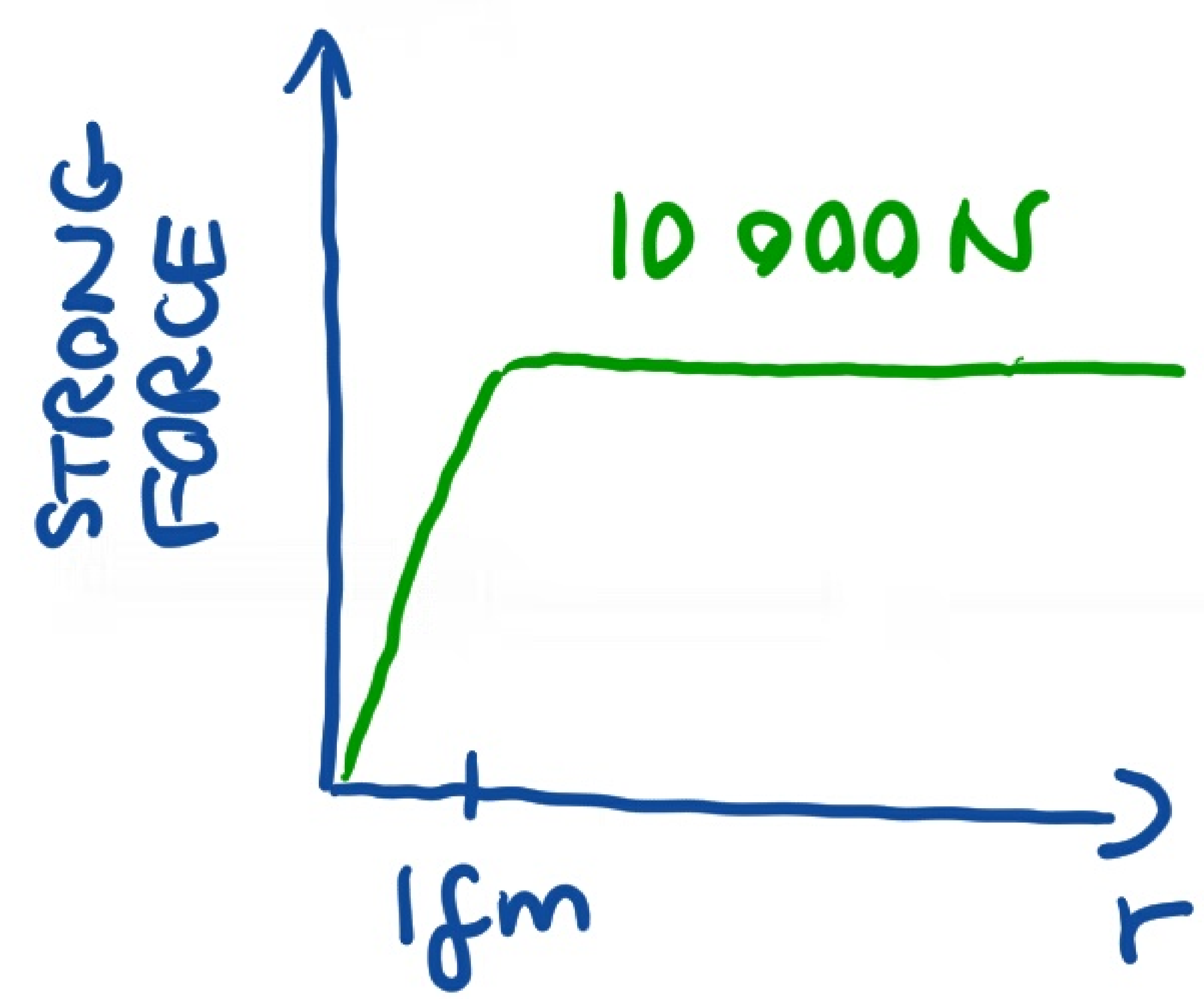
TWO TYPES OF STRONGLY INTERACTING PARTICLES: QUARKS, GLUONS ↑ ; HADRONS ↑

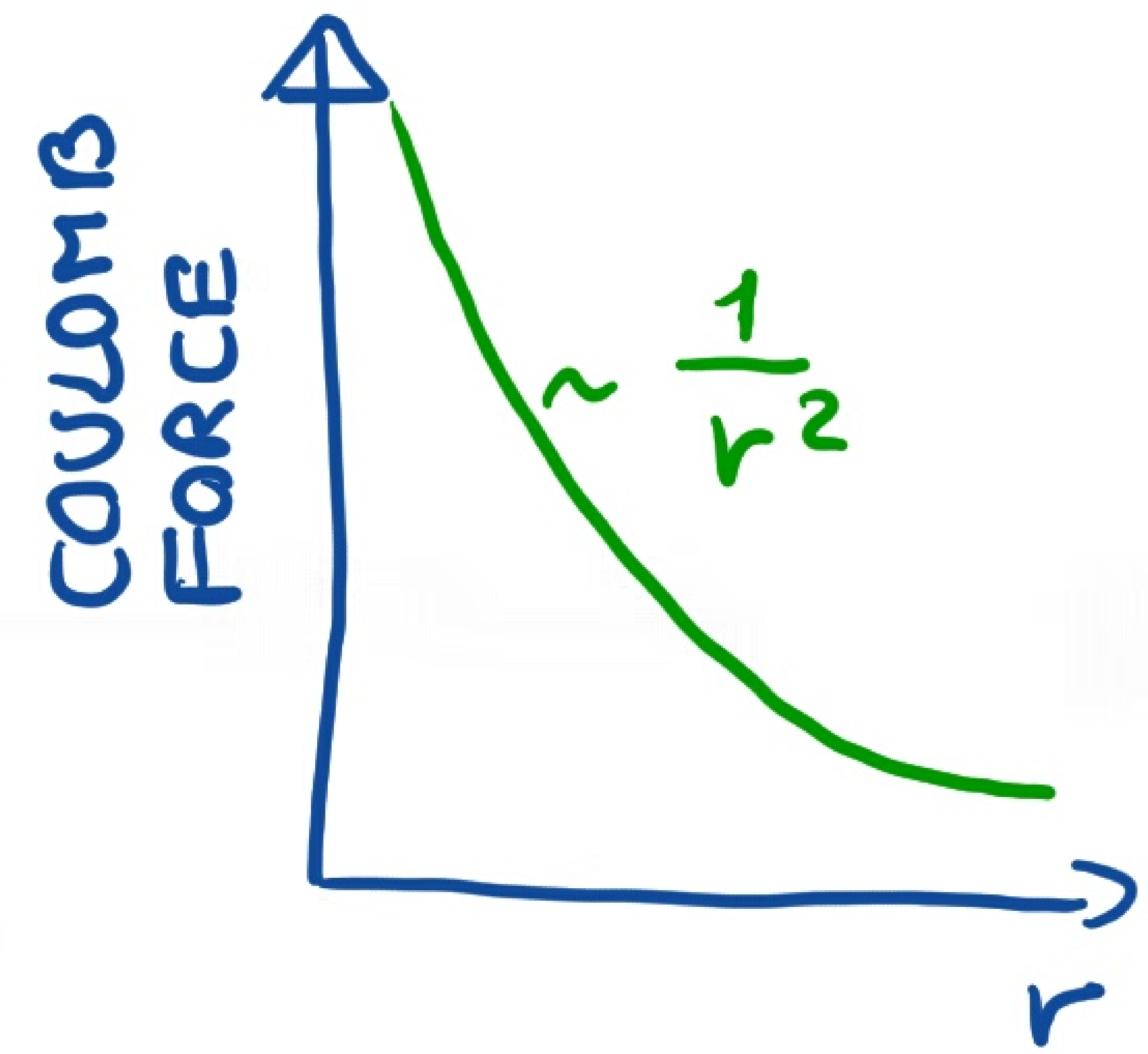
HADRONS ≡ BAGS FILLED WITH QUARKS, GLUONS

# QUARK (AND GLUON) CONFINEMENT INSIDE HADRONS



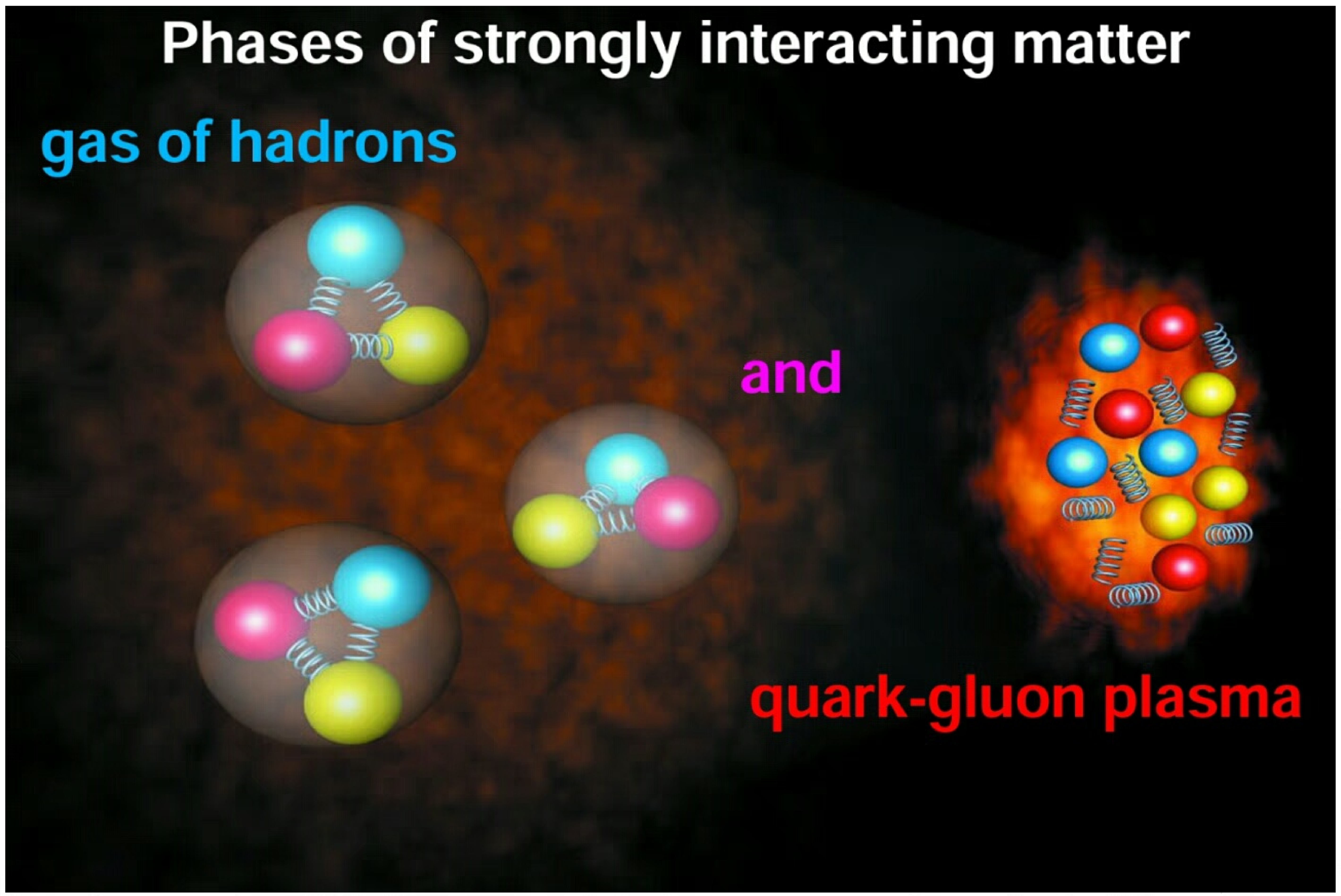

HADRONS "CONSISTS" OF QUARKS
BUT
QUARKS CANNOT BE FOUND INDIVIDUALLY



# STRONGLY INTERACTING MATTER

≡ MAXIMUM ENTROPY STATE OF ISOLATED SYSTEM OF STRONGLY INTERACTING PARTICLES
(ALL MICROSTATES HAVE EQUAL PROBABILITY TO APPEAR)




QUARK GLUON PLASMA:
A LARGE ($V_{QGP} \gg V_h$) BAG
FILLED WITH $q$ AND $g$

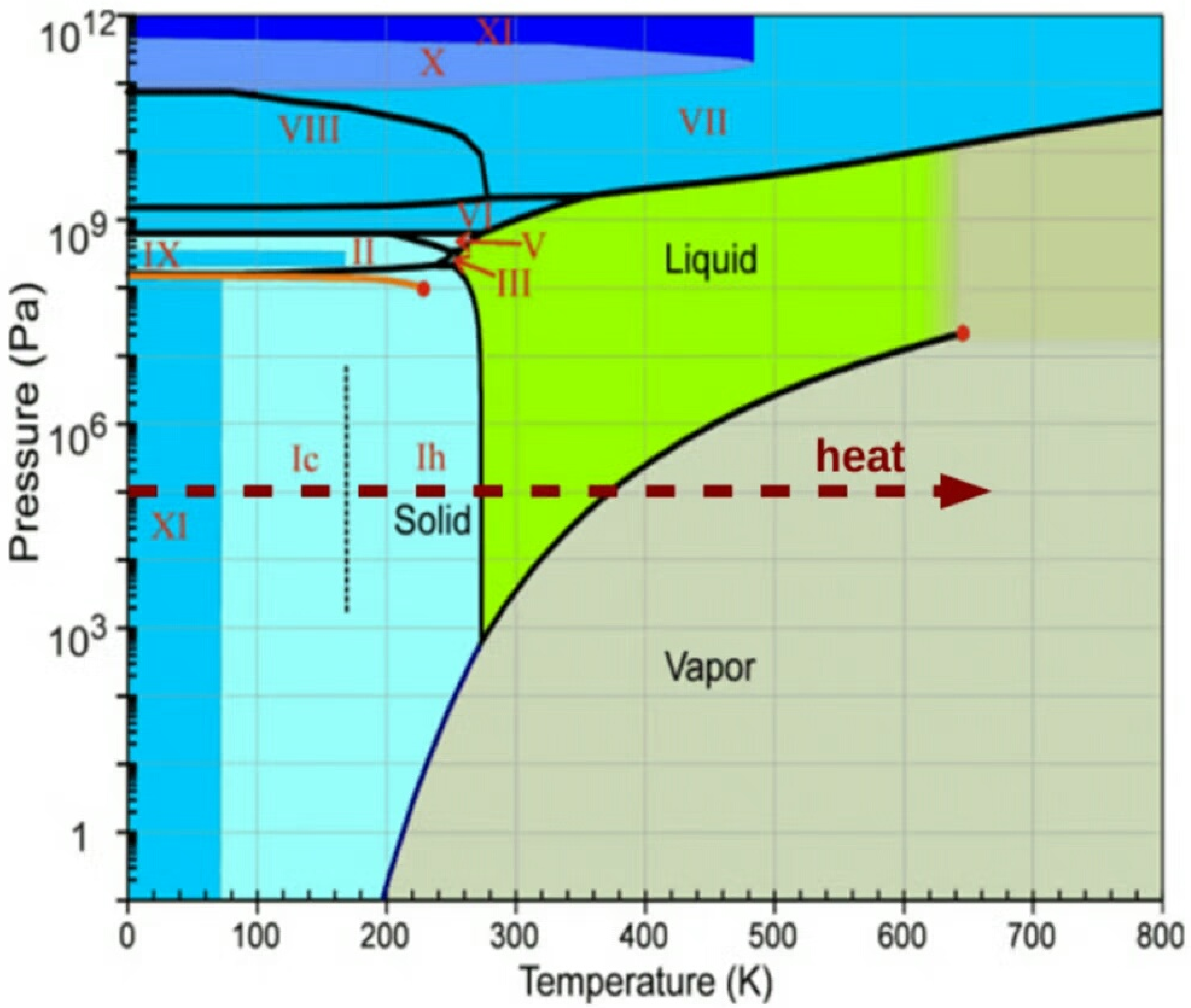
STRONGLY INTERACTING MATTER IN QGP PHASE IF

ENTROPY(QGP) > ENTROPY(HG)

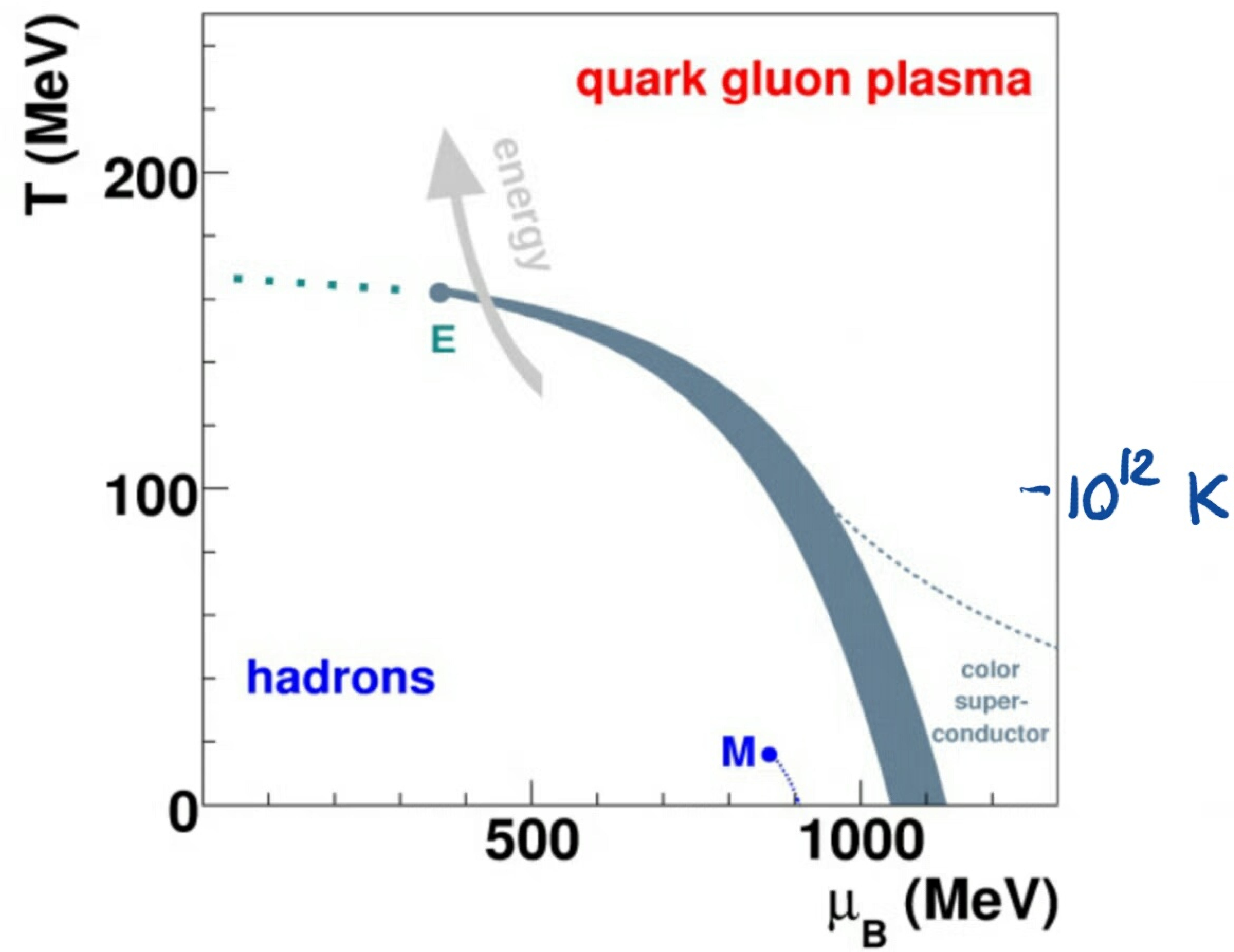
AT FIXED $V, E, B, \ldots$

# PHASE DIAGRAM

OF WATER




OF STRONGLY INTERACTING MATTER




NAGI / SHINE:

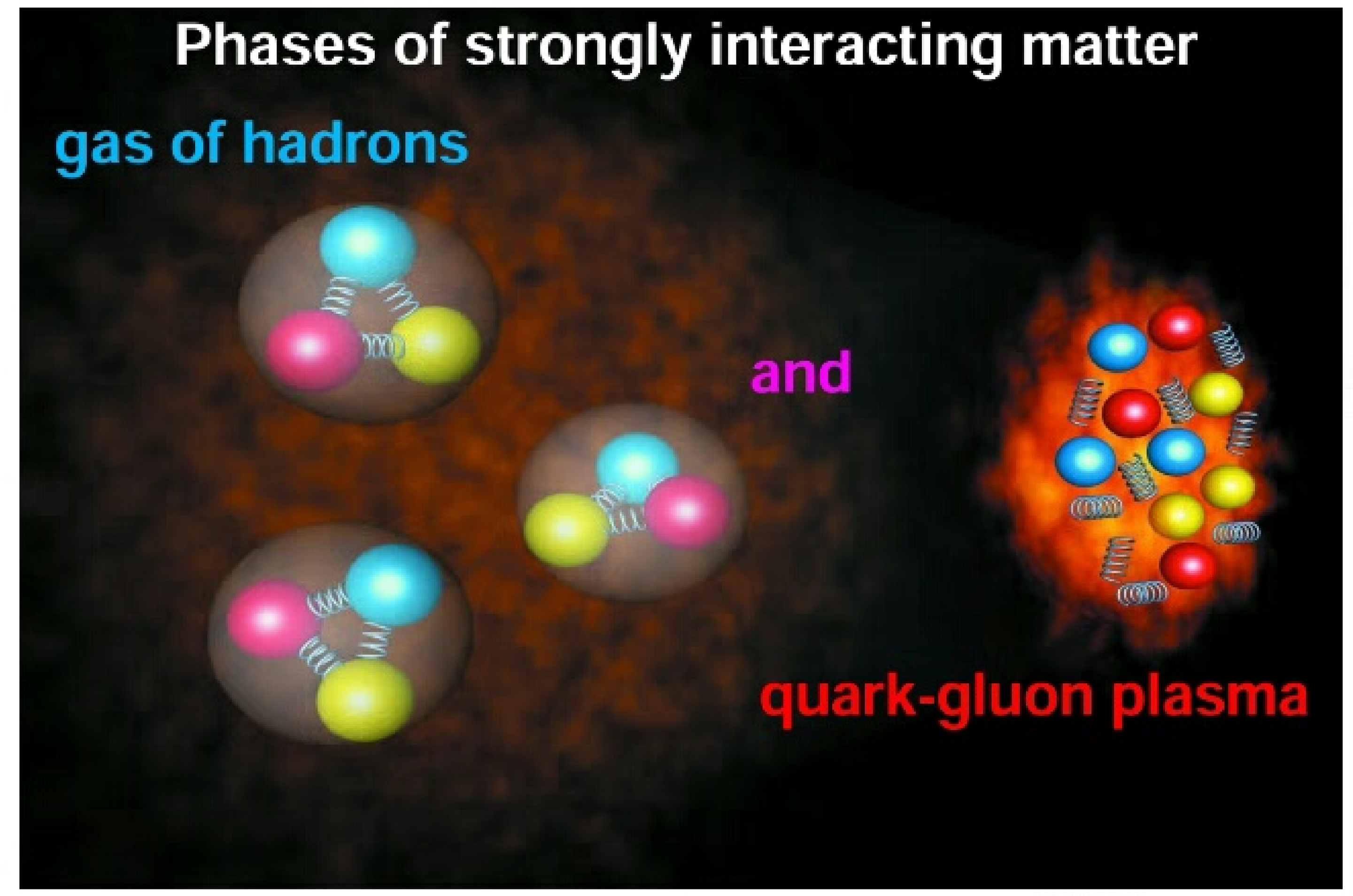
→ PHASE TRANSITION VS VOLUME

→ SEARCH FOR CRITICAL POINT

# TOY MODEL OF PHASE TRANSITION

IDEAL GAS OF MASSLESS PIONS:

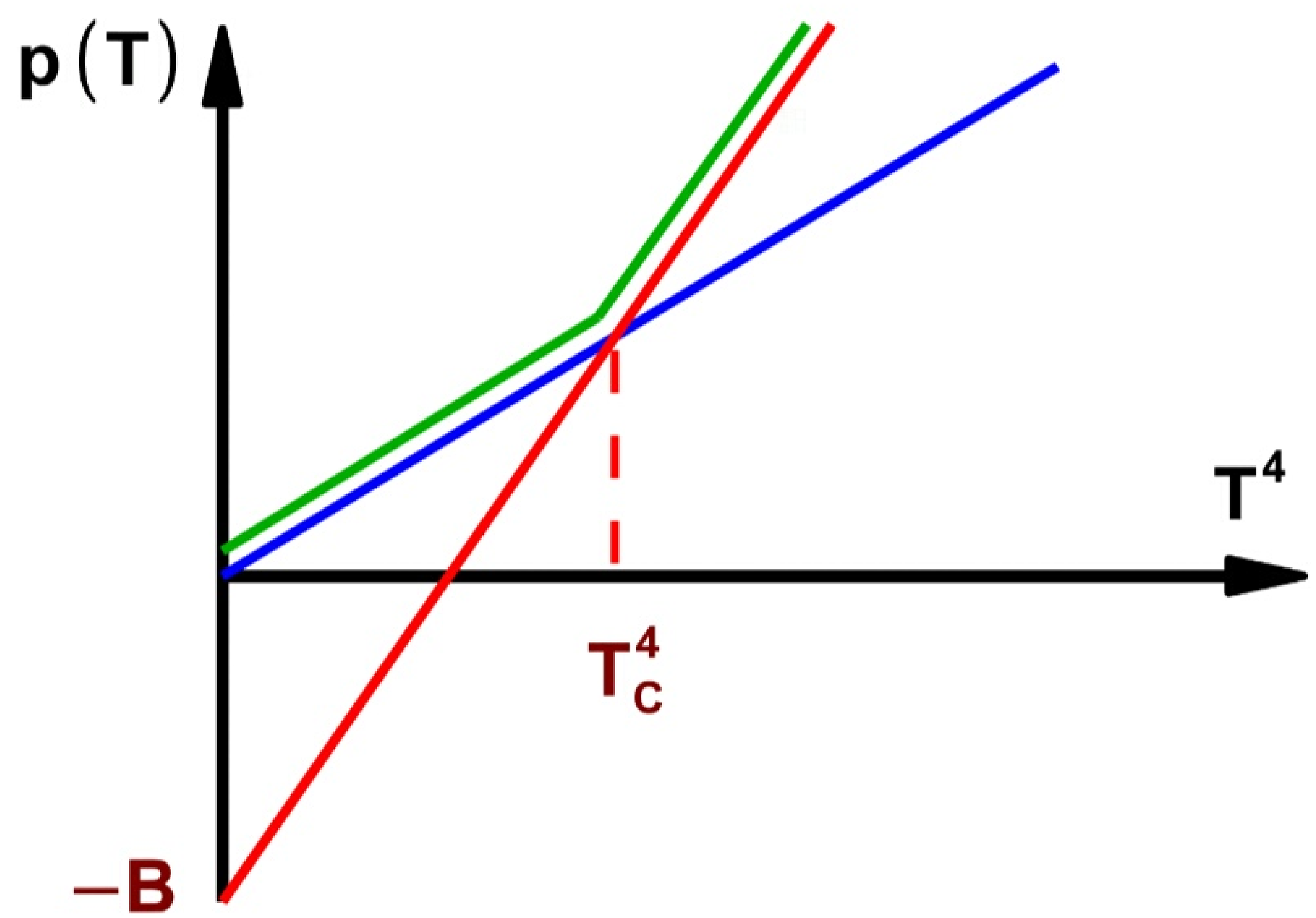
$$P_{HG} = \frac{\pi^2 g_{HG}}{90} \cdot T^4$$




BAG MODEL OF QUARK GLUON PLASMA:

$$P_{QGP} \approx \frac{\pi^2 g_{QGP}}{90} T^4 - B$$

FIRST ORDER PHASE TRANSITION GIVEN BY GIBBS CONDITION:
$P_{HG} = P_{QGP}$ (EQUIVALENT TO MAXIMUM ENTROPY CONDITION)

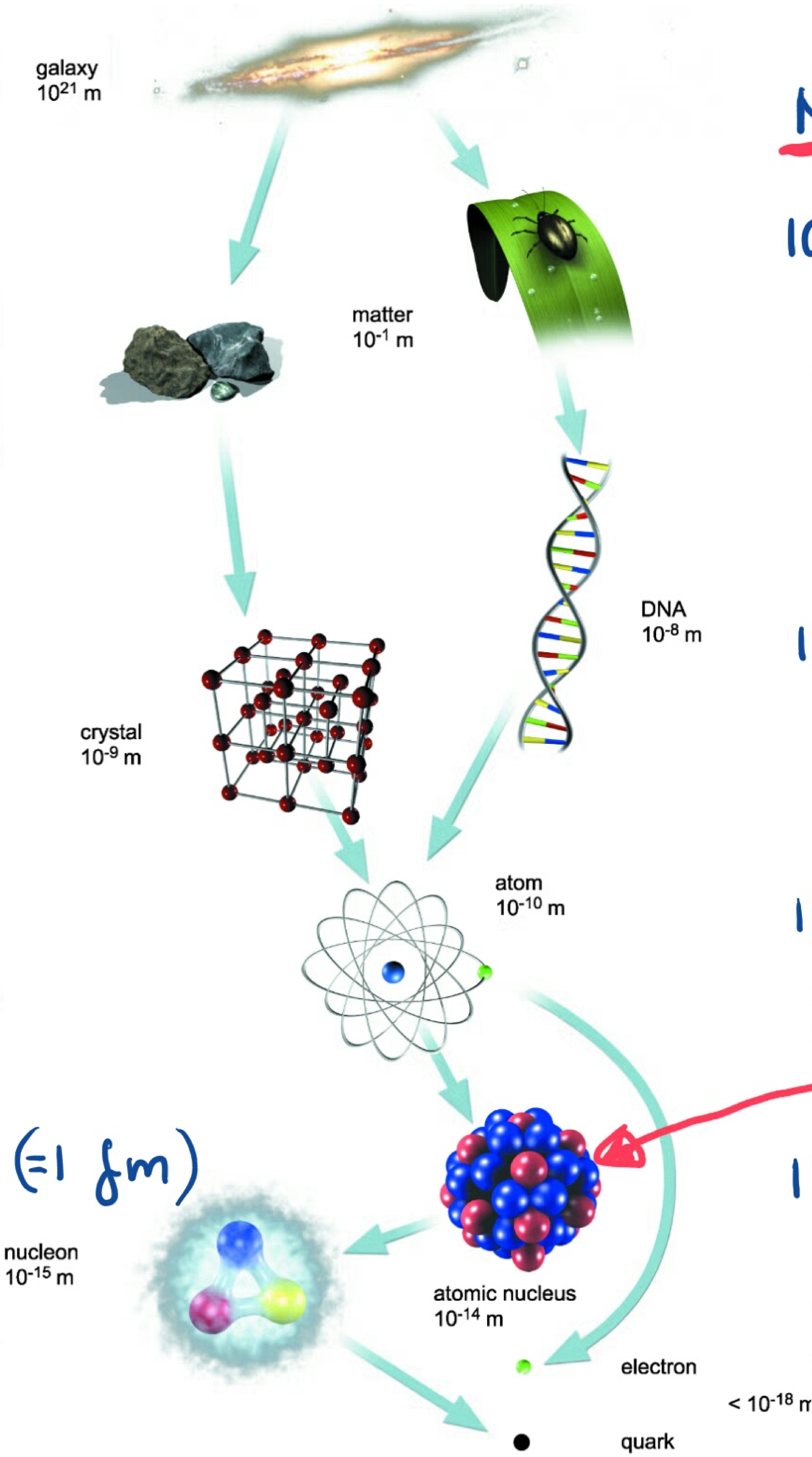



$$T_c = \left[\frac{90 \cdot B}{\pi^2 (g_{QGP} - g_{HG})}\right]^{1/4}$$

FOR $B > 0$, $g_{QGP} > g_{HG}$

# NUCLEUS-NUCLEUS COLLISIONS






$10^{-1}$ m ← US

$10^{-8}$ m

NUCLEI – THE LARGEST SYSTEMS OF STRONGLY INTERACTING PARTICLES IN LAB

$10^{-10}$ m

$10^{-14}$ m

$10^{-15}$ m (=1 fm)

FUNDAMENTAL PARTICLES

NUCLEI ACCELERATED TO ≈ LIGHT VELOCITY COLLIDE (AT SPS $v/c \approx 0.9997$)

# NUCLEUS-NUCLEUS COLLISIONS


STRONGLY INTERACTING MATTER (HG, QGP, MIXED) IS CREATED ACCORDING TO MAXIMUM ENTROPY PRINCIPLE

↕

STATISTICAL MODEL OF THE EARLY STAGE OF A+A COLLISIONS ≡ SMES

FERMI, LANDAU

MG, GORENSTEIN

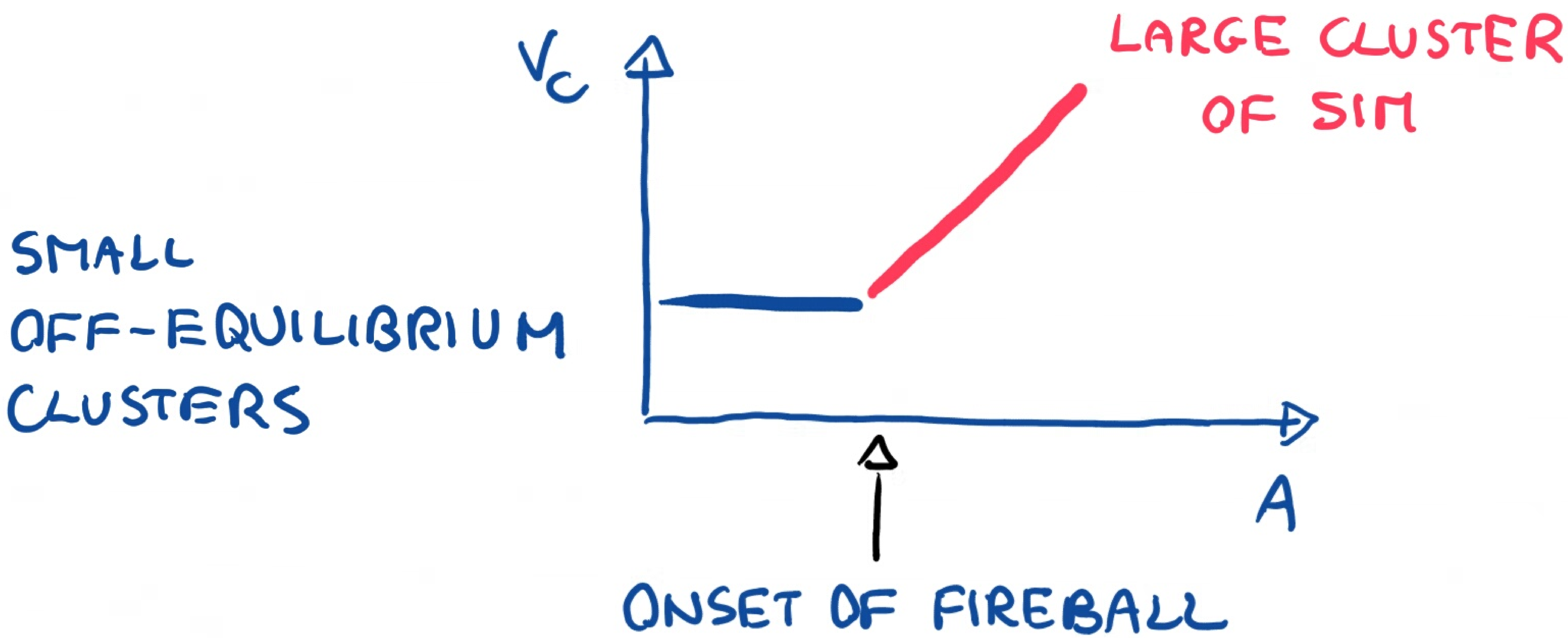
THE SYSTEM EXPANDS AND DECAYS INTO HADRONS MEASURED IN DETECTORS

↕

STANDART MODEL OF A+A COLLISIONS

# ONSET OF FIREBALL

≡ BEGINNIG OF CREATION OF LARGE CLUSTERS OF STRONGLY INTERACTING MATTER (SIM) IN NUCLEUS-NUCLEUS (A+A) COLLISIONS WITH INCREASING NUCLEAR MASS NUMBER (A)

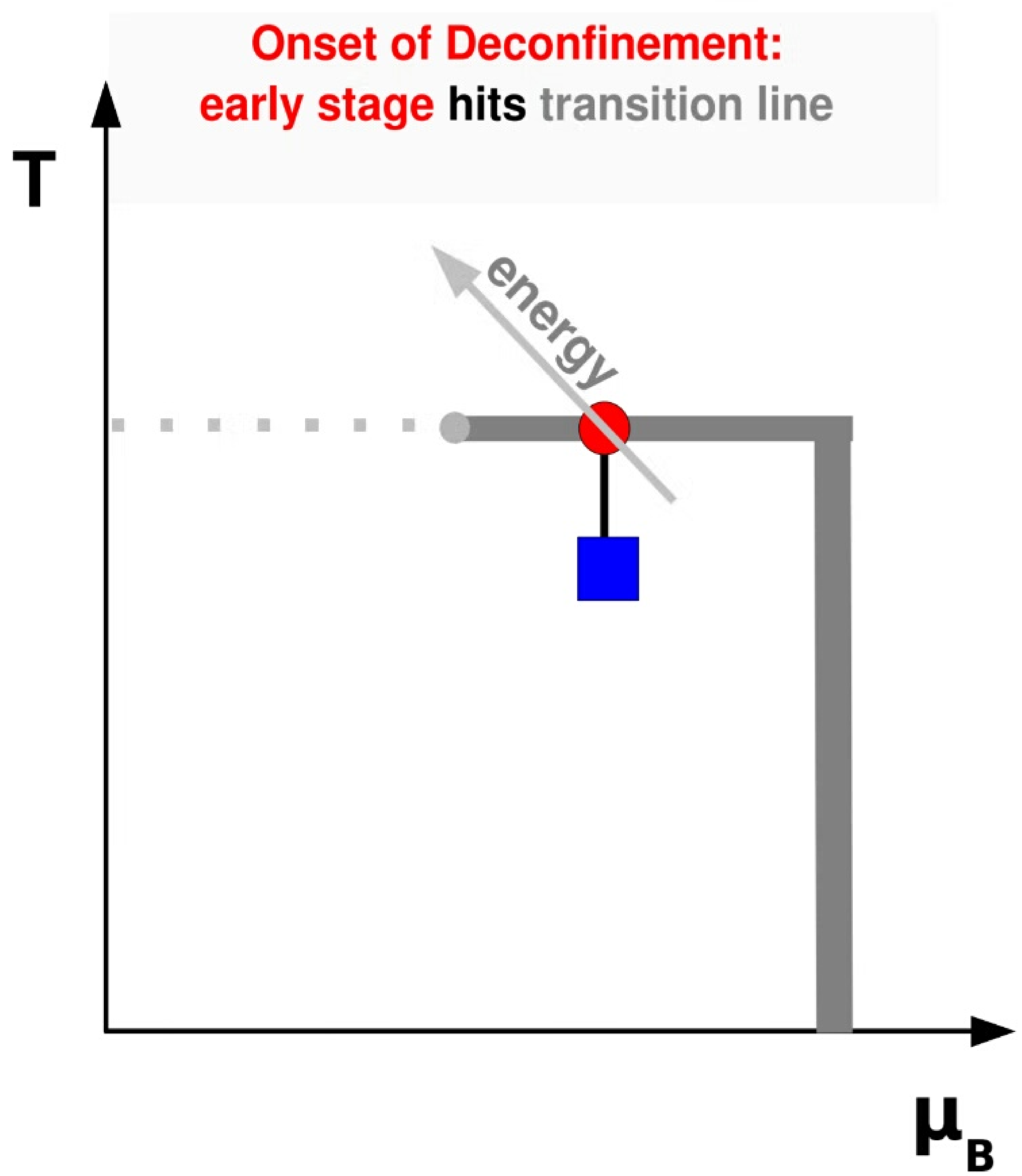


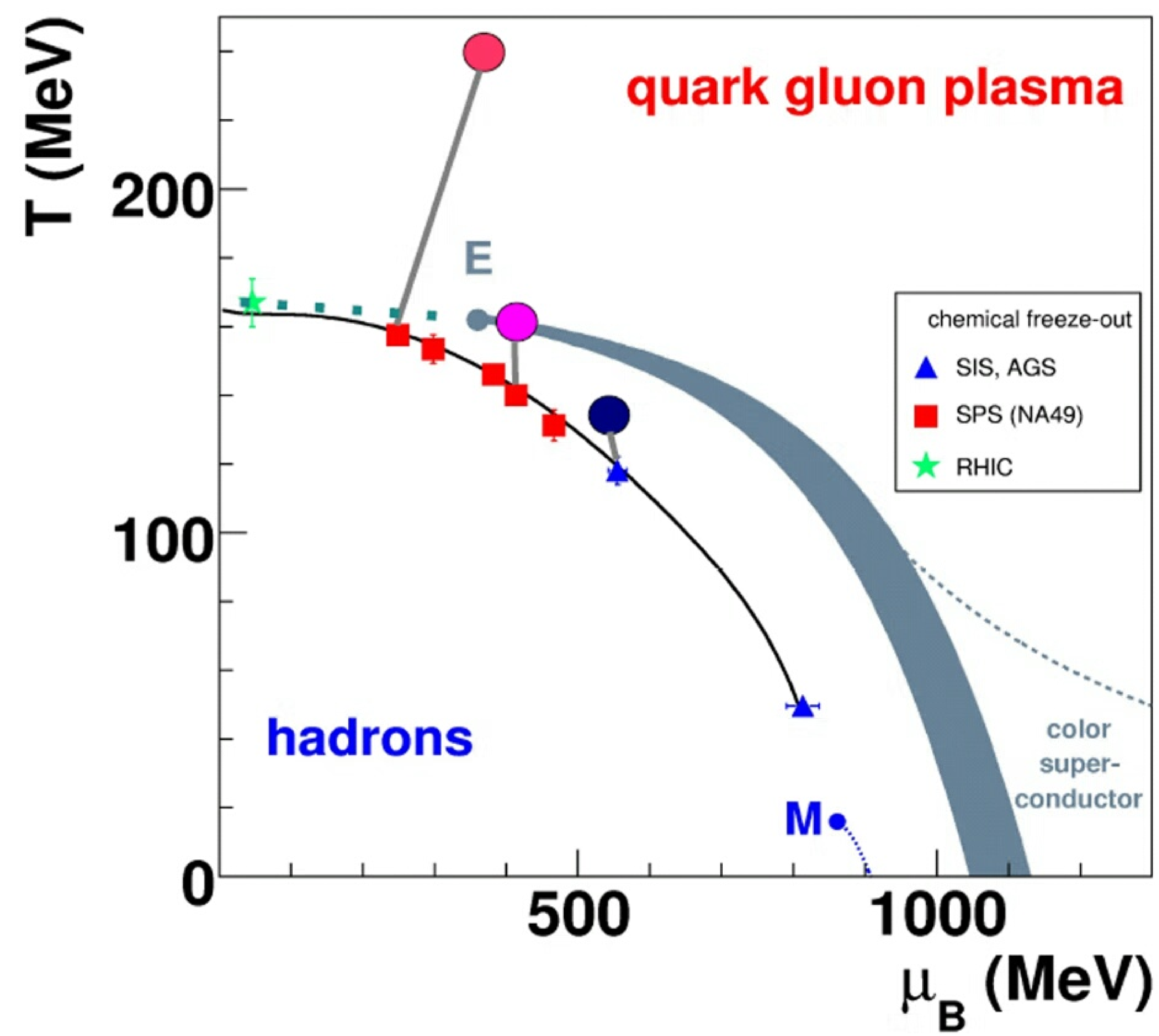

≡ FIREBALL

→ POSSIBLE VALIDITY OF SMES

# ONSET OF DECONFINEMENT

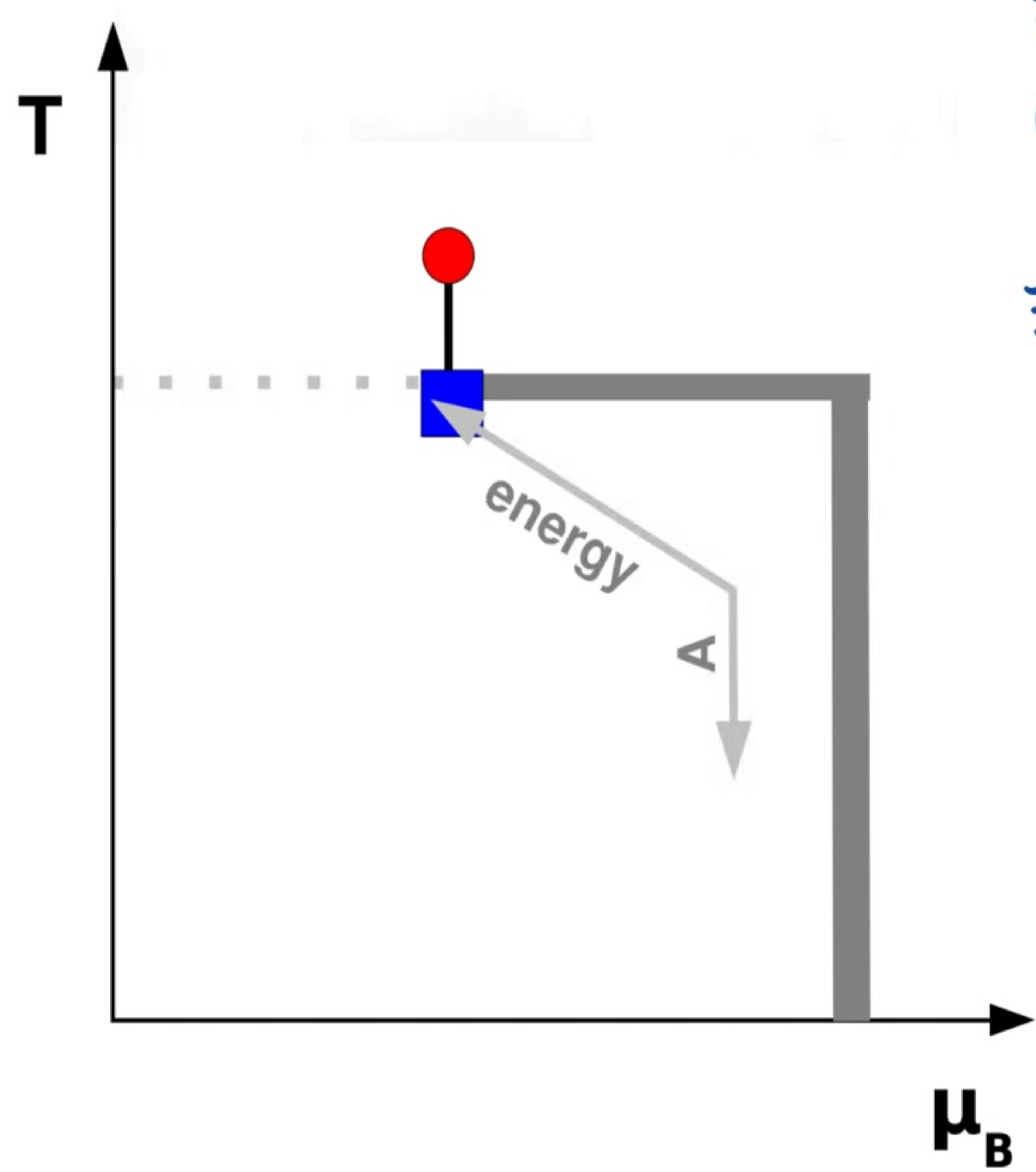
≅ BEGINING OF CREATION OF QUARK-GLUON PLASMA IN NUCLEUS-NUCLEUS COLLISIONS WITH INCREASING COLLISION ENERGY ($\sqrt{s_{NN}}$)



# CRITICAL POINT OF SIM

≡ HYPOTHETICAL END POINT OF FIRST ORDER TRANSITION LINE THAT HAS PROPERTIES OF SECOND ORDER TRANSITION

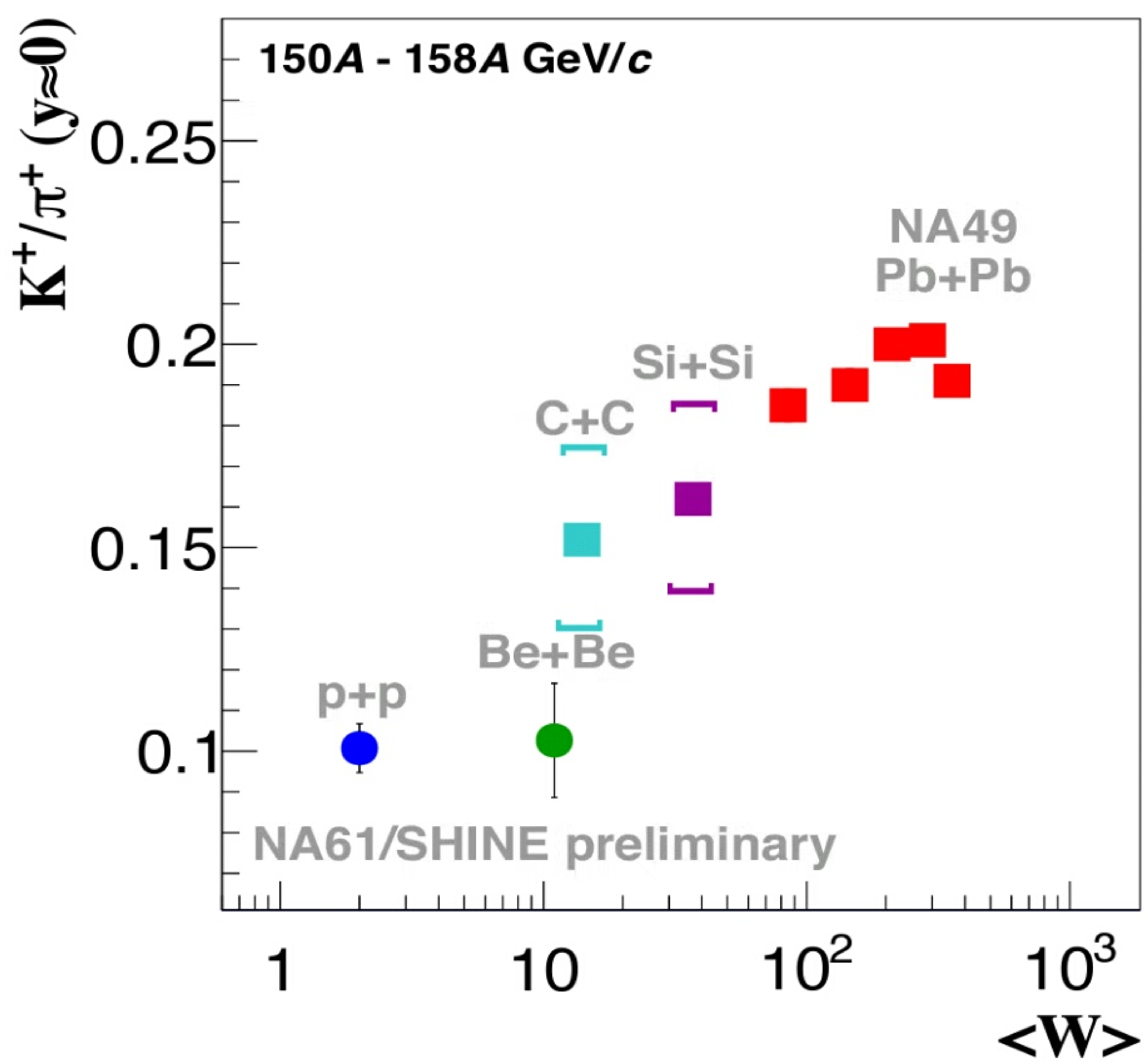



SEARCH FOR CRITICAL POINT (CP) OF SIM IN A+A COLLISIONS

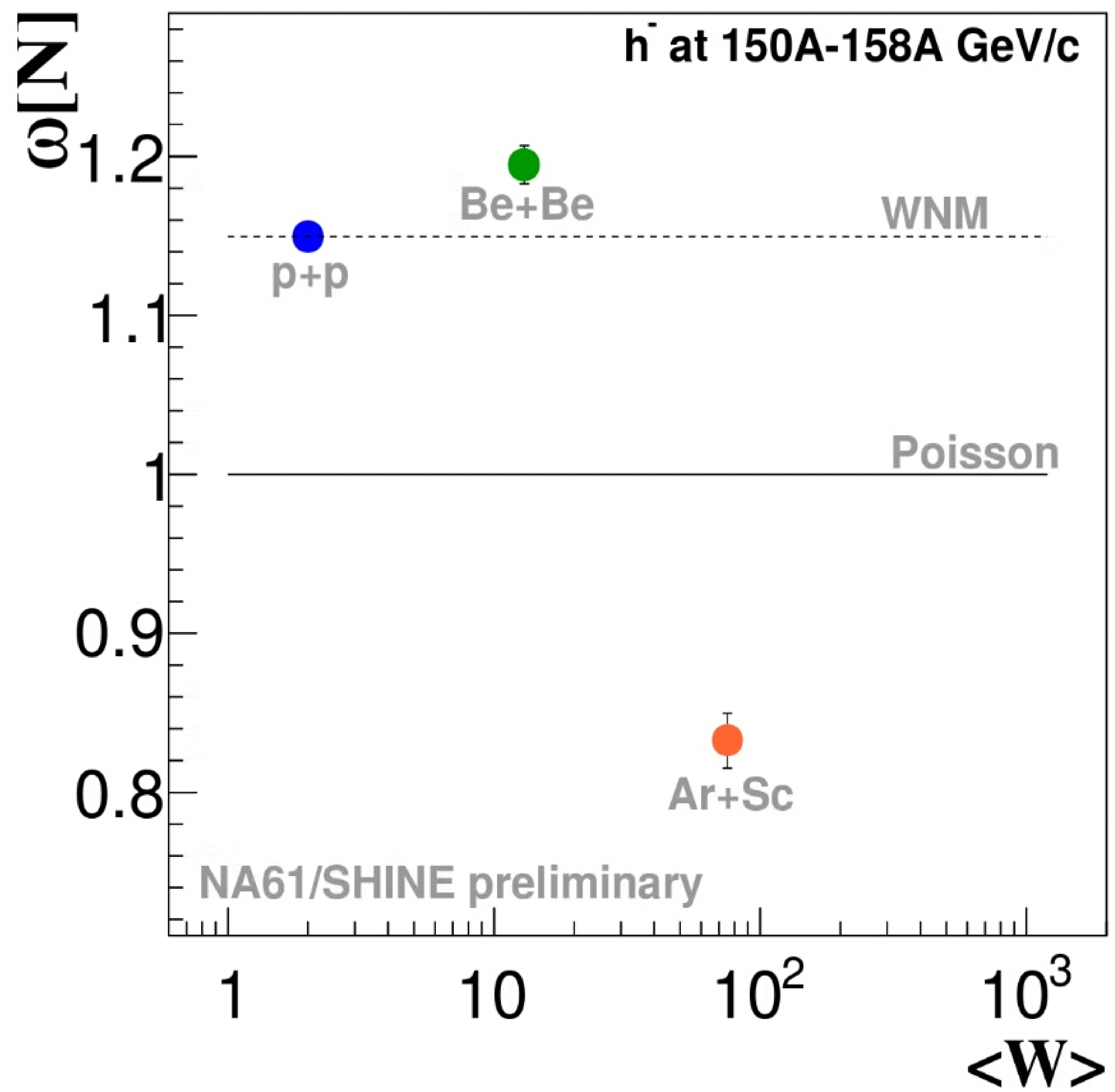
≡ SCAN IN $\sqrt{s_{NN}}$ AND A TO POSITION FREEZE-OUT POINT CLOSE TO CP

# ONSET OF FIREBALL

MEAN MULTIPLICITY RATIO




MULTIPLICITY FLUCTUATIONS

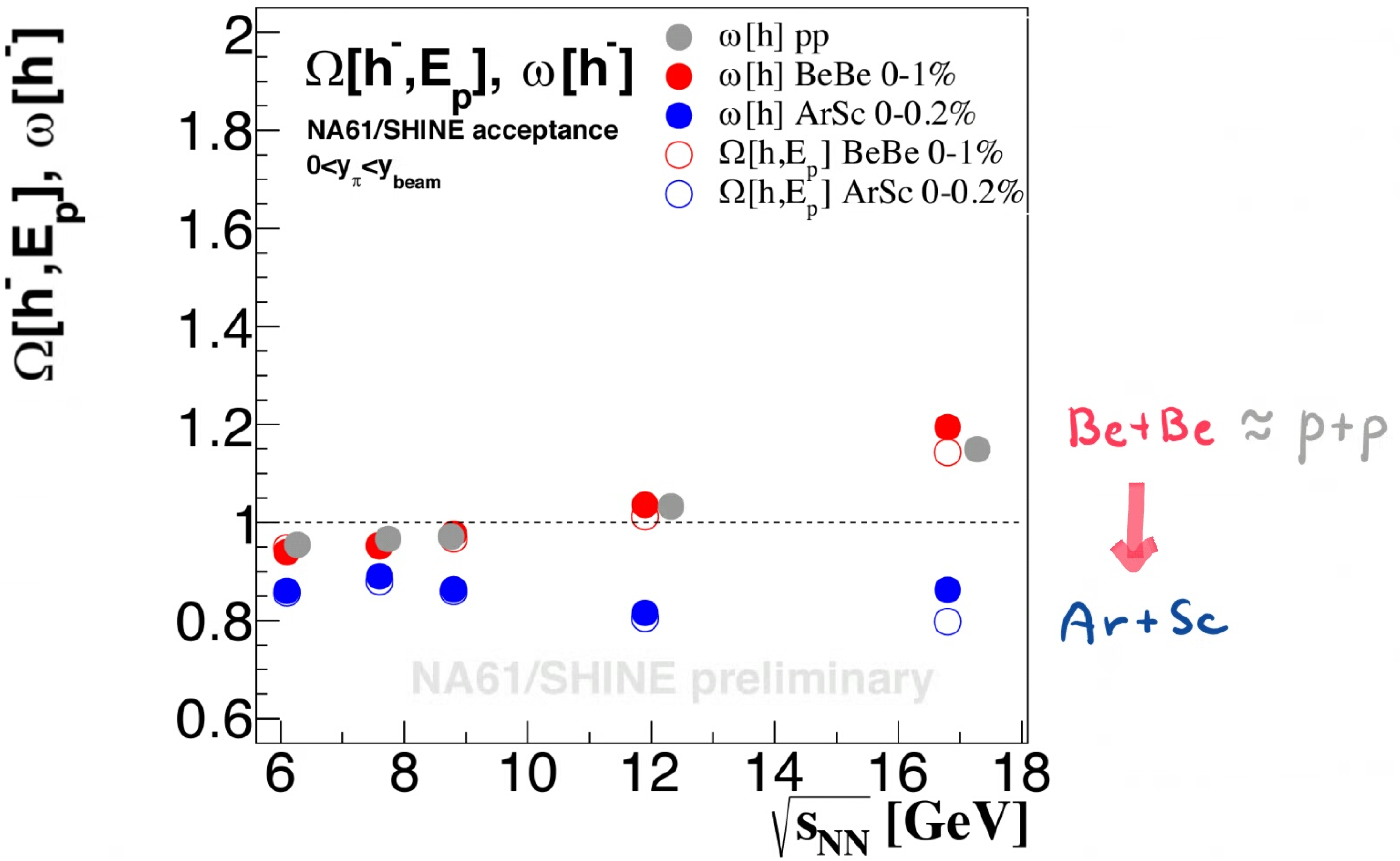



$\omega[N] \equiv$
$\equiv Var[N]/\langle N\rangle$

(NUMBER OF WOUNDED NUCLEONS)

↑ ONSET OF FIREBALL? ↑

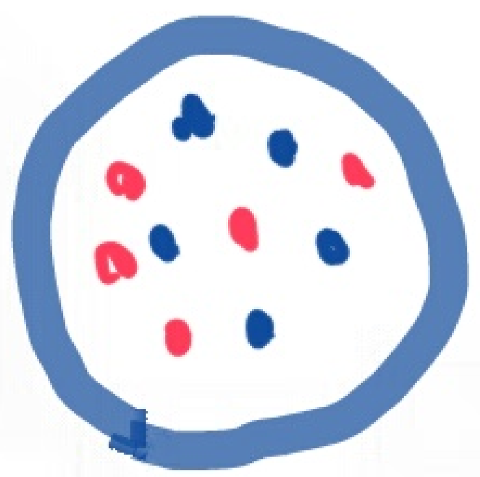
# MULTIPLICITY FLUCTUATIONS




RAPID CHANGE OF A-DEPENDENCE AT A ≈ 10
OBSERVED AT ALL SPS COLLISION ENERGIES

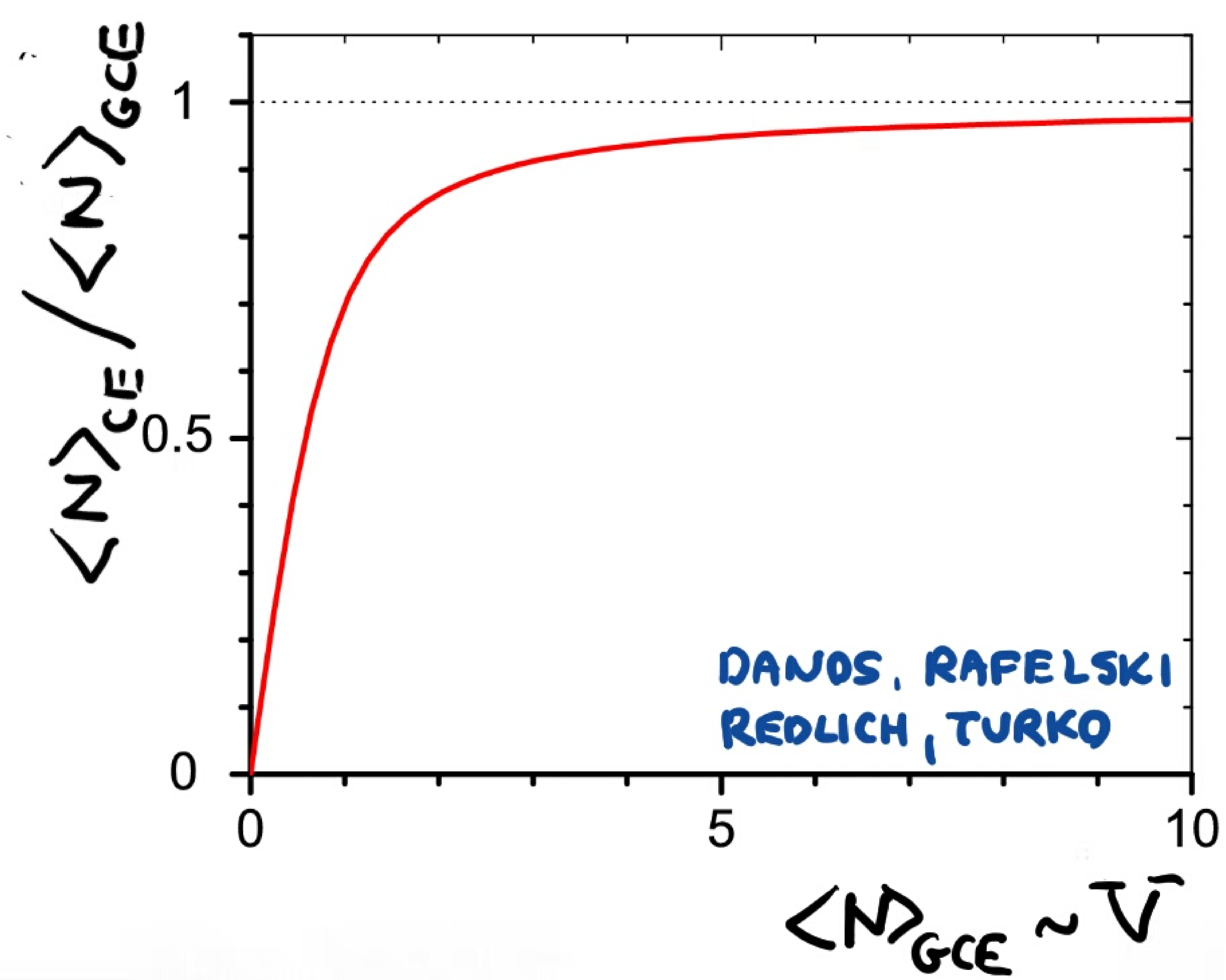
# VOLUME DEPENDENCE OF ⟨N⟩ AND ω[N]

V, T
Q = 0

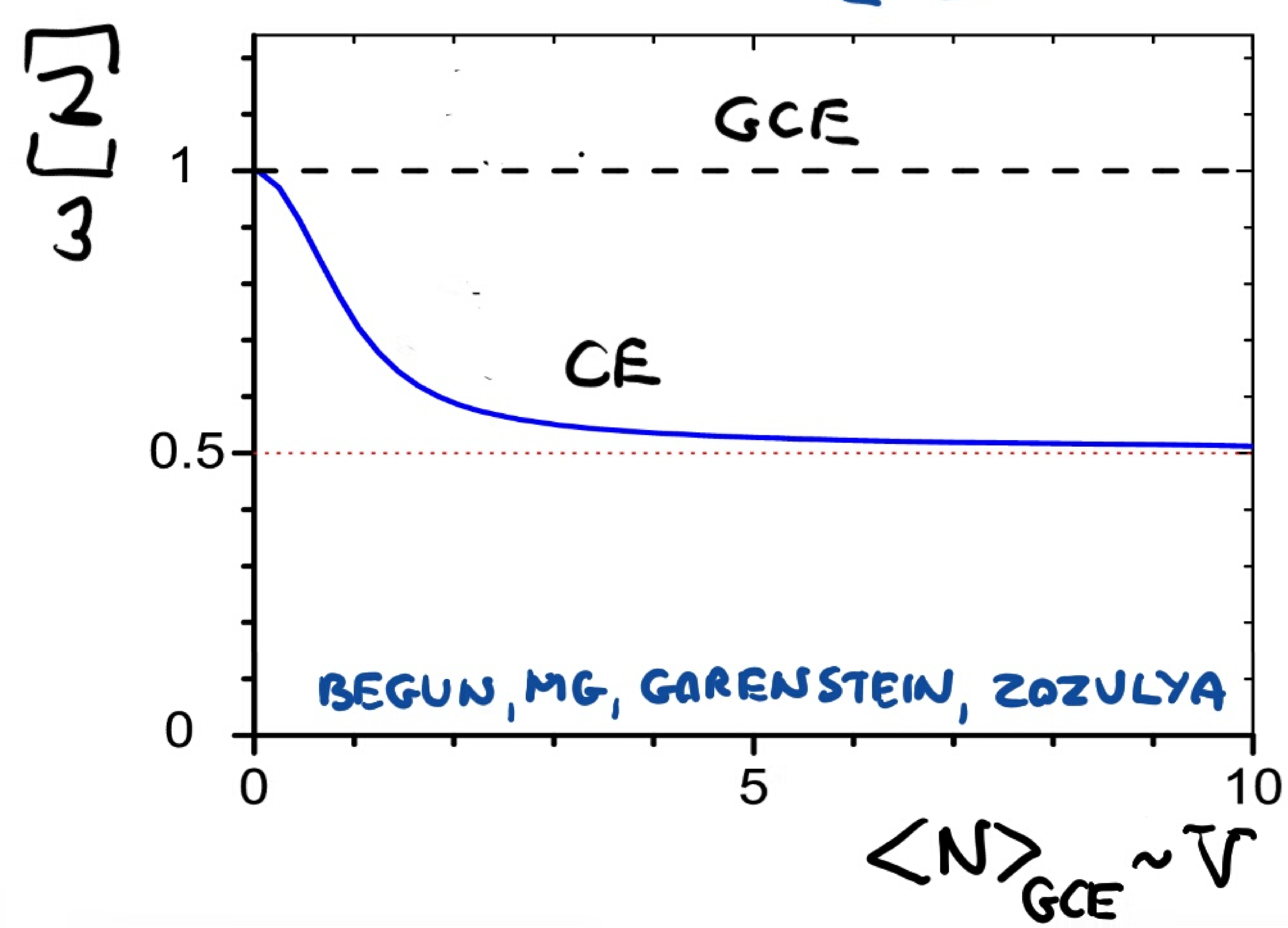


IDEAL BOLTZMANN (IB) GAS WITHIN CANONICAL ENSEMBLE (CE) → NON-TRIVIAL DEPENDENCE OF ⟨N⟩ AND ω[N] ON V

"CANONICAL SUPPRESSION" OF ⟨N⟩



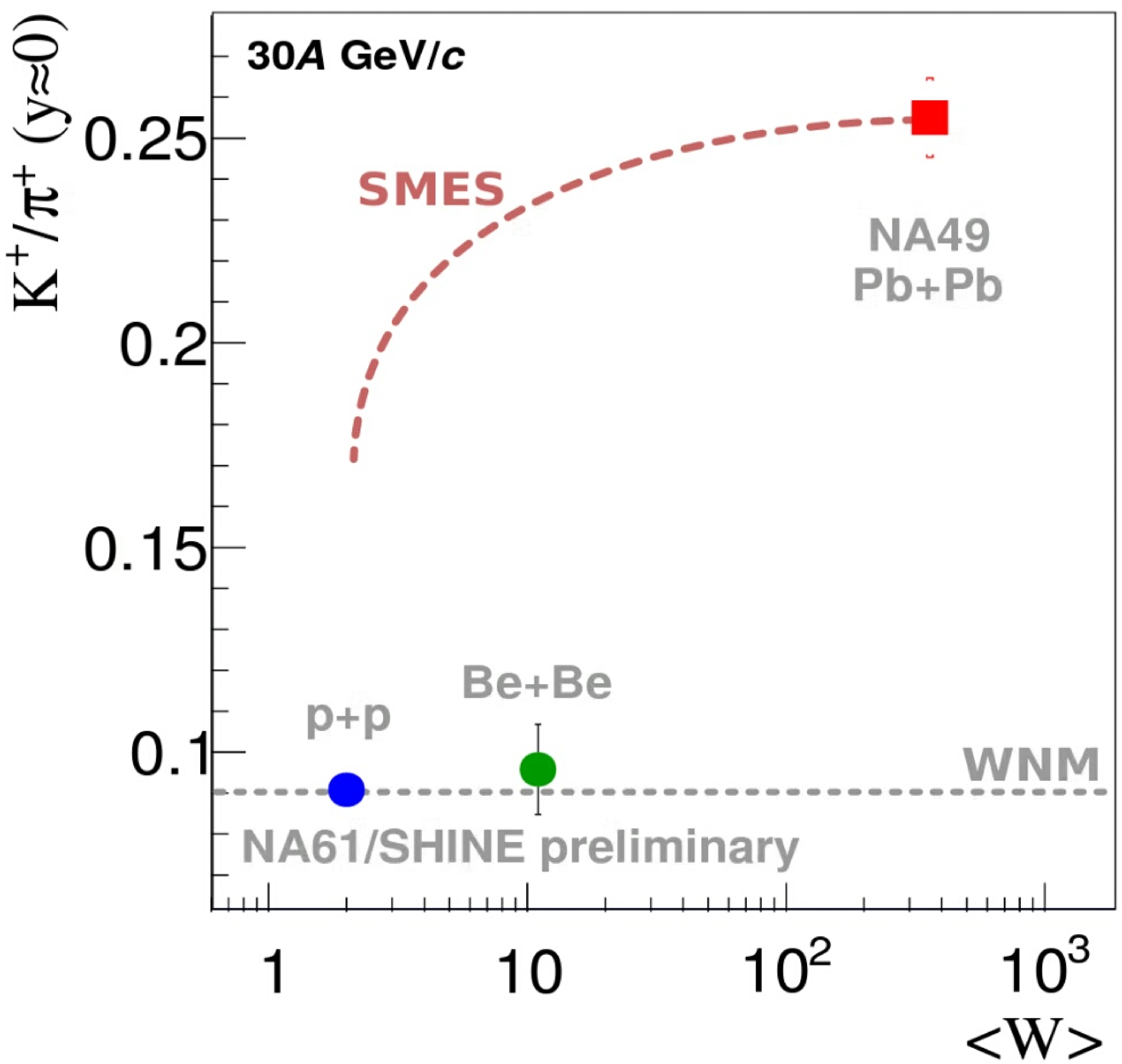

"CANONICAL ENHANCEMENT" OF ω[N]

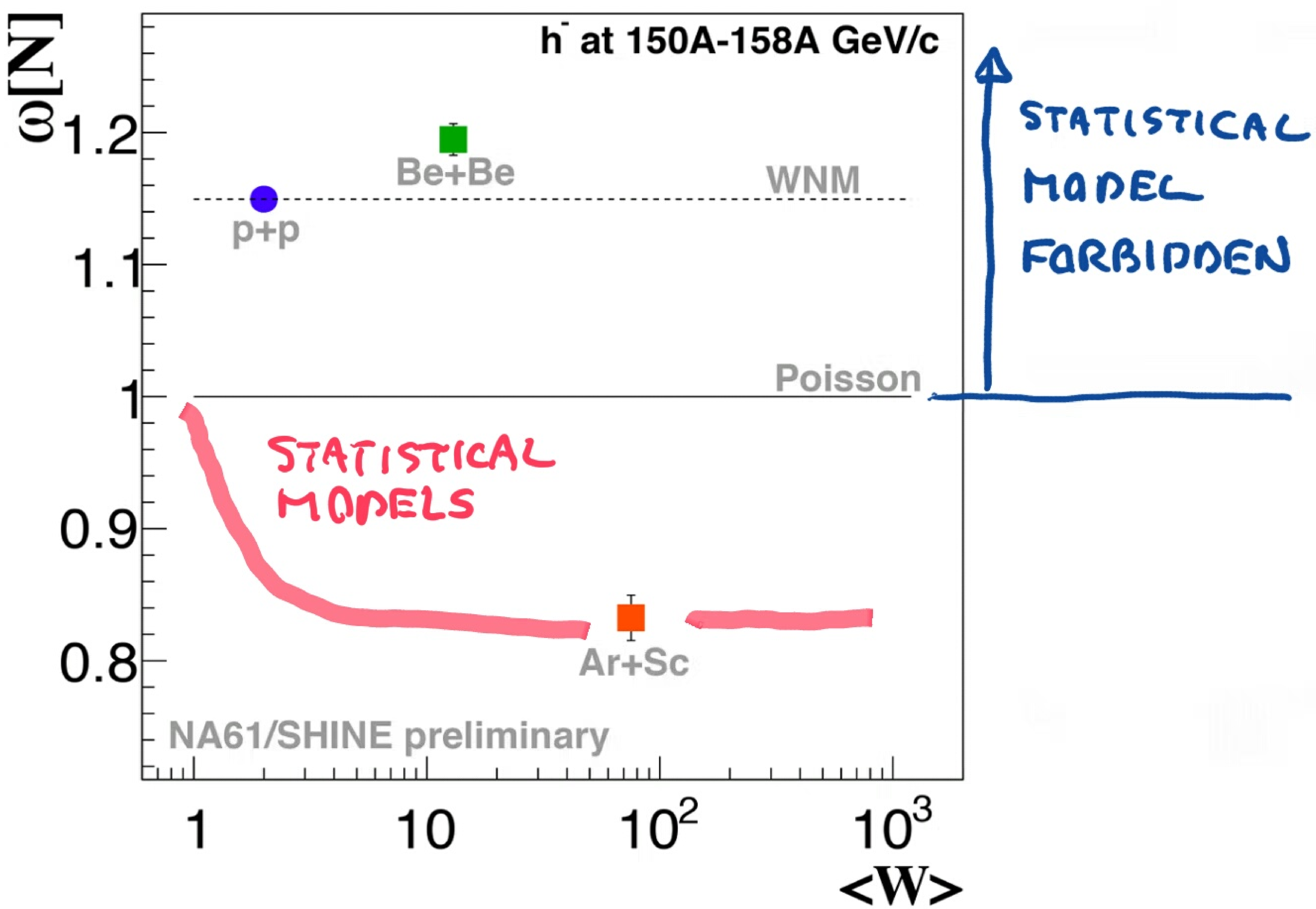



FAR INSUFFICIENT TO REPRODUCE DATA

P+P AND Be+Be SUPPERPOSITION OF "NON-STATISTICAL CLUSTERS"





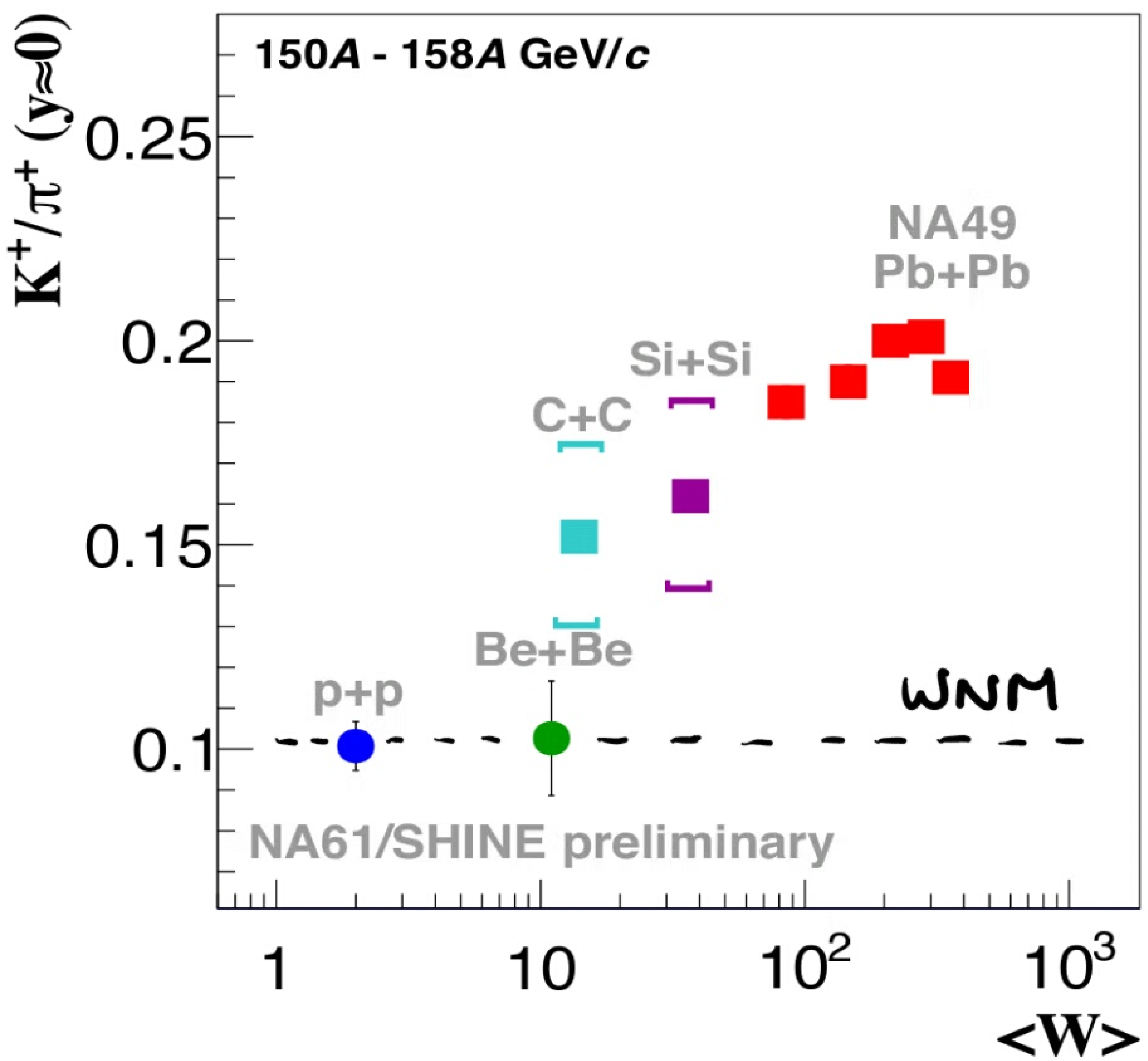




Ar+Sc AND Pb+Pb ≈ LARGE VOLUME "STATISTCAL" CLUSTER

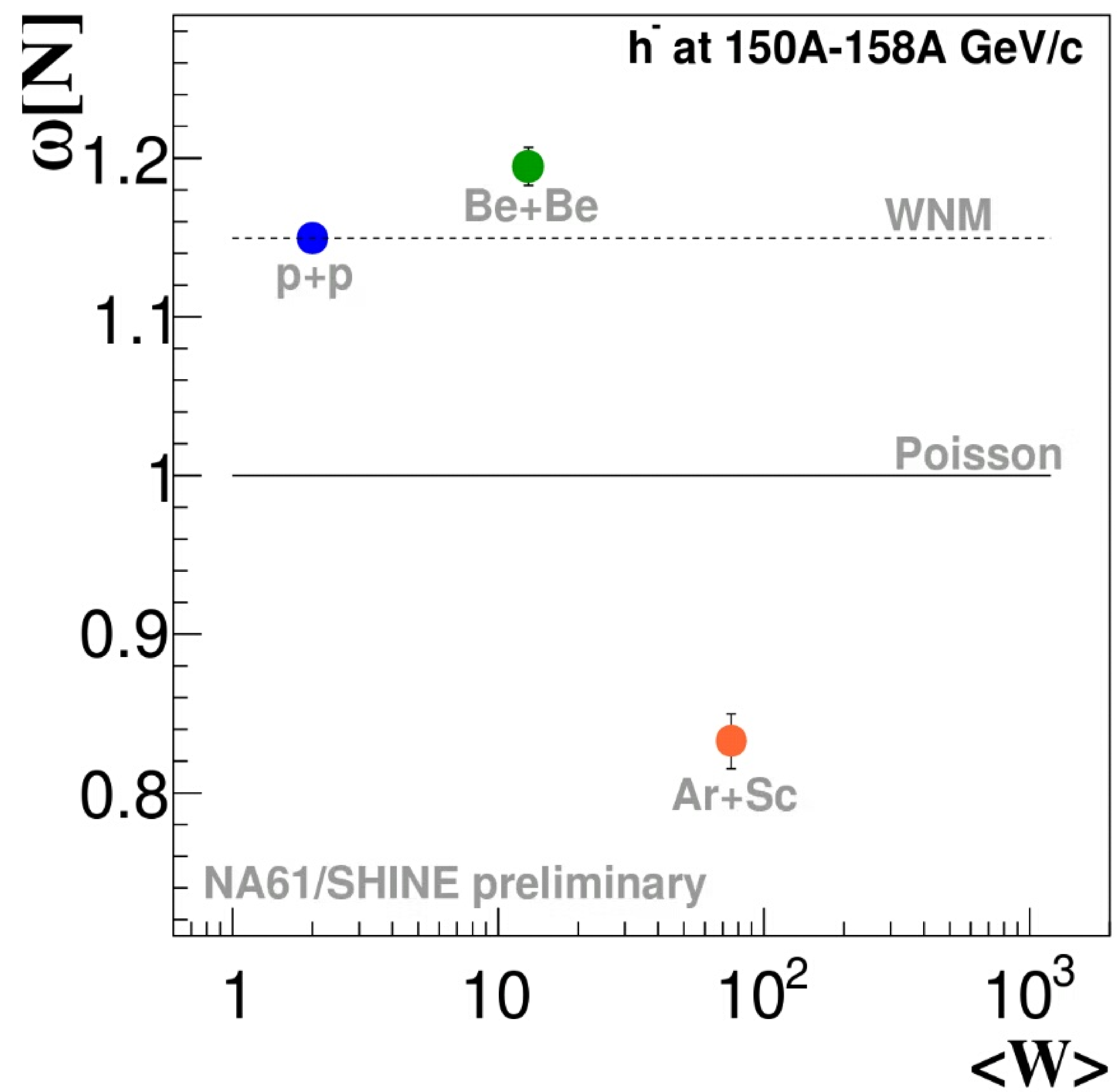
# NA61/SHINE INDICATION FOR ONSET OF FIREBALL



MEAN MULTIPLICITY RATIO




MULTIPLICITY FLUCTUATIONS




↑ ONSET OF FIREBALL ↑

# ON INTERPRETATION OF ONSET OF FIREBALL:

## PERCOLATION APPROACH

WITH INCREASING A DENSITY OF CLUSTERS (STRINGS, PARTONS, ...) INCREASES. THUS PROBABILITY TO OVERLAP MANY ELEMENTARY CLUSTERS MAY RAPIDLY INCREASE WITH A $\rightarrow$ PERCOLATION MODELS.

THIS APPROACH DOES NOT EXPLAIN EQUILIBRIUM PROPERTIES OF LARGE CLUSTERS

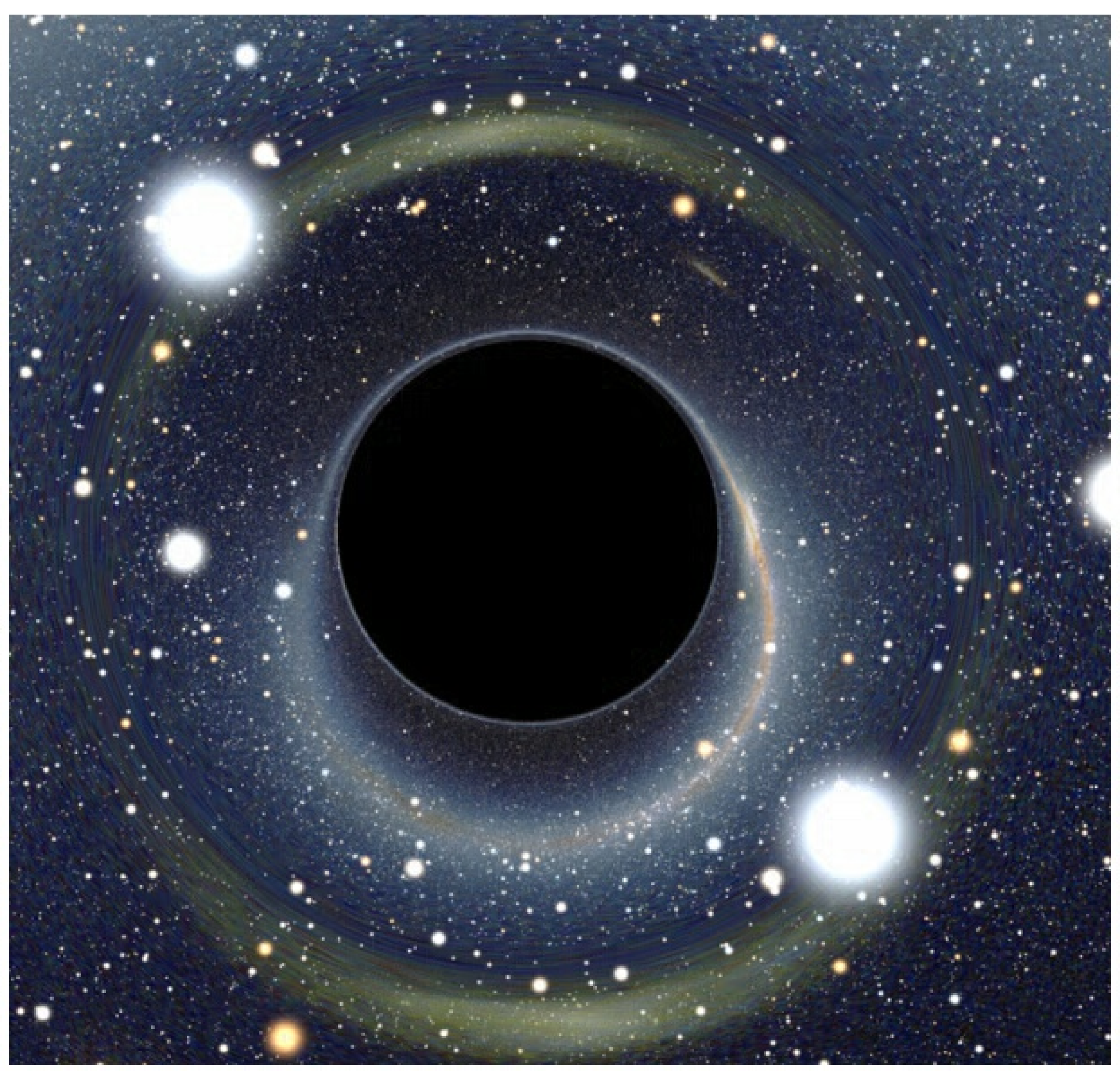

BAYM, PHYSICA A96 (79) 131
CELIK, KARSCH, SATZ PL B97 (80) 128
BRAUN, PAJARES, NP B390 (93) 542
ARMESTO, BRAUN, FERREIRO, PAJARES, PRL 77 (96) 3736
CUNQUEIRO, FERREIRO, MORAL, PAJARES PRC 75 (05) 024907

# ON INTERPRETATION OF ONSET OF FIREBALL: AdS/CFT CORRESPONDENCE

MALDACENA, INT. J. THEOR. PHYS. 38 (1999) 1113

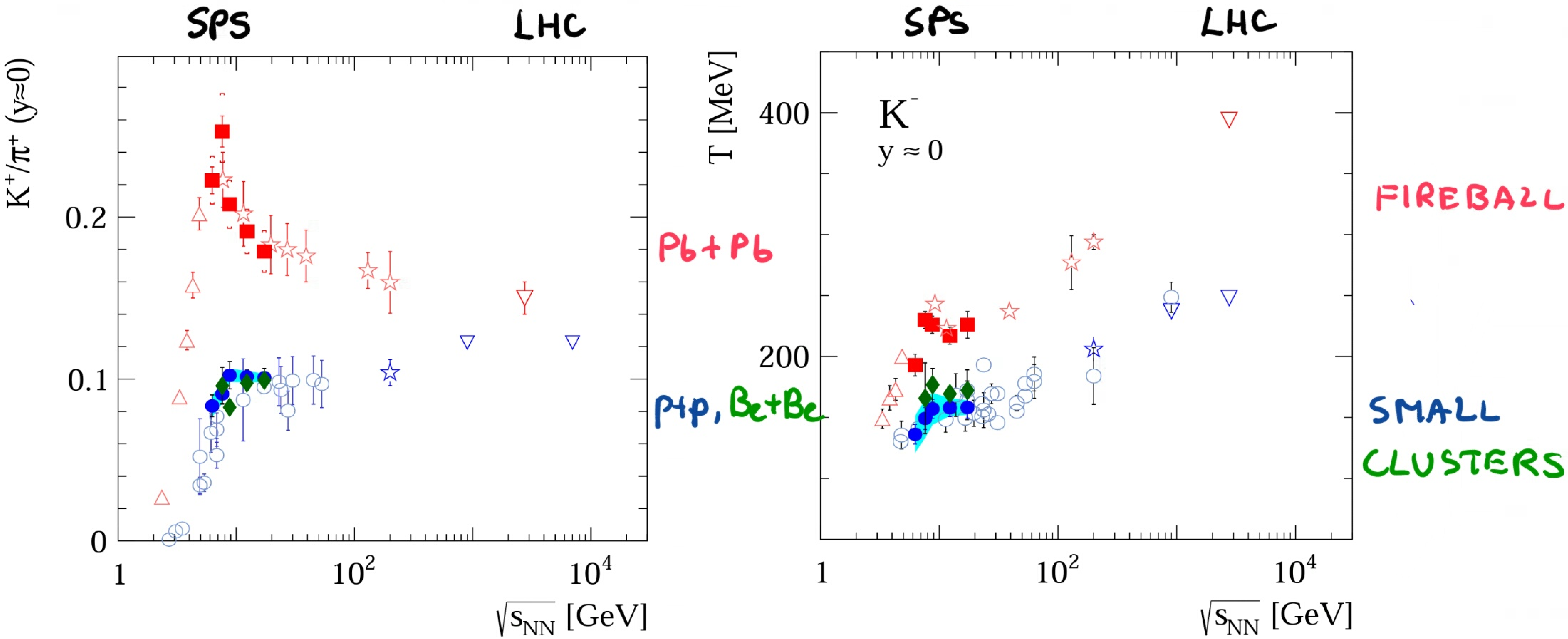
AdS (GRAVITY): FORMATION OF A BLACK HOLE HORIZON (INFORMATION TRAPPING SURFECE) TAKES PLACE WHEN CRITICAL VALUES OF MODEL PARAMETERS ARE REACHED.

CFT (QCD): ONLY STARTING FROM A SUFFICIENTLY LARGE NUCLEAR MASS NUMBER THE FORMATION OF THE TRAPPING SURFACE IN A+A COLLISIONS IS POSSIBLE → ONSET OF FIREBALL



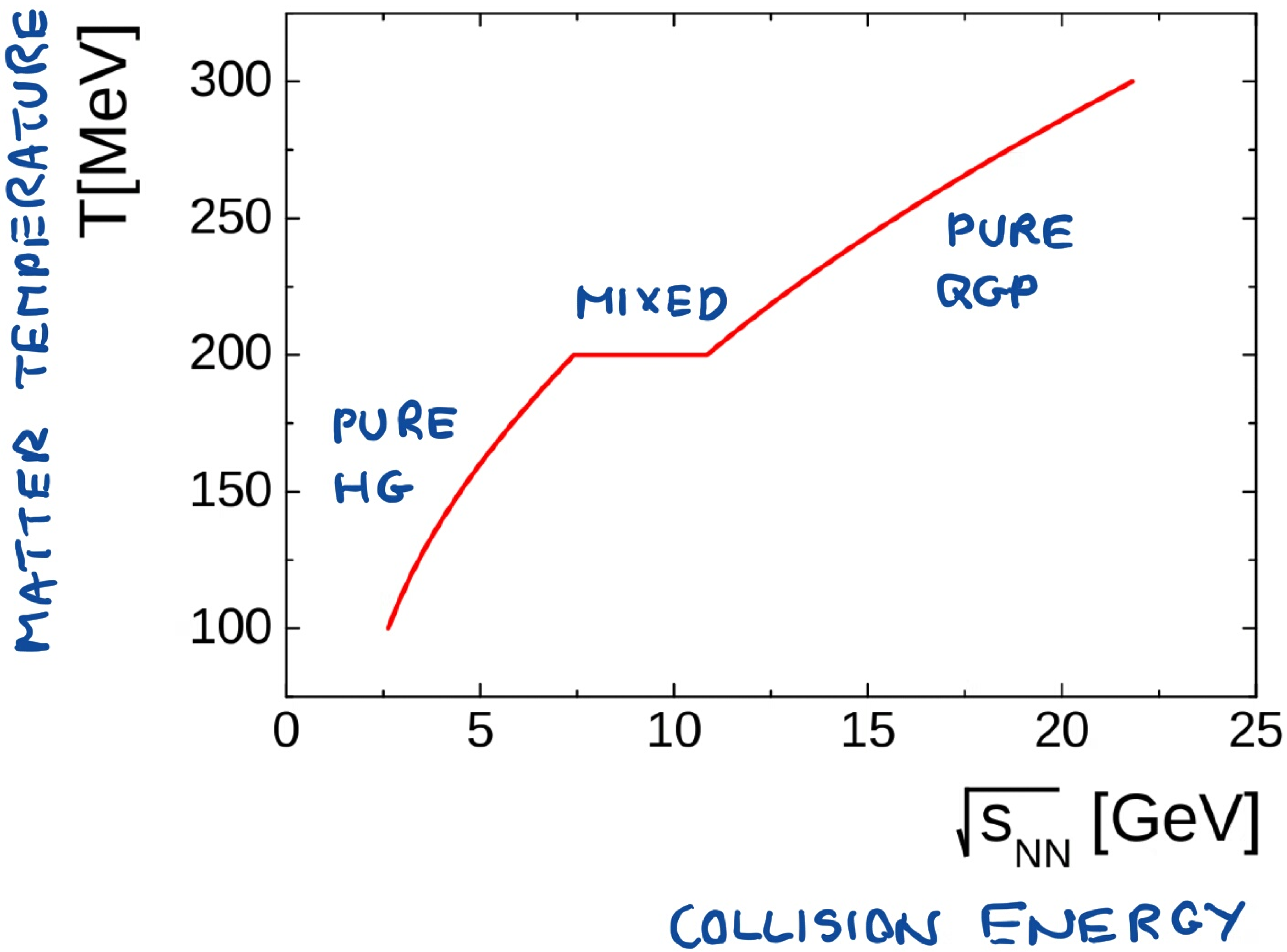
SHURYAK, PROG. PART. NUCL. PHYS. 62 (2009) 48
LIN, SHURYAK PR D79 (2009) 124015

# ONSET OF DECONFINEMENT




RAPID CHANGE OF $\sqrt{s_{NN}}$ - DEPENDECE AT $\sqrt{s_{NN}} \approx 10$ GEV OBSERVED FOR BOTH, FIREBALL AND SMALL CLUSTERS

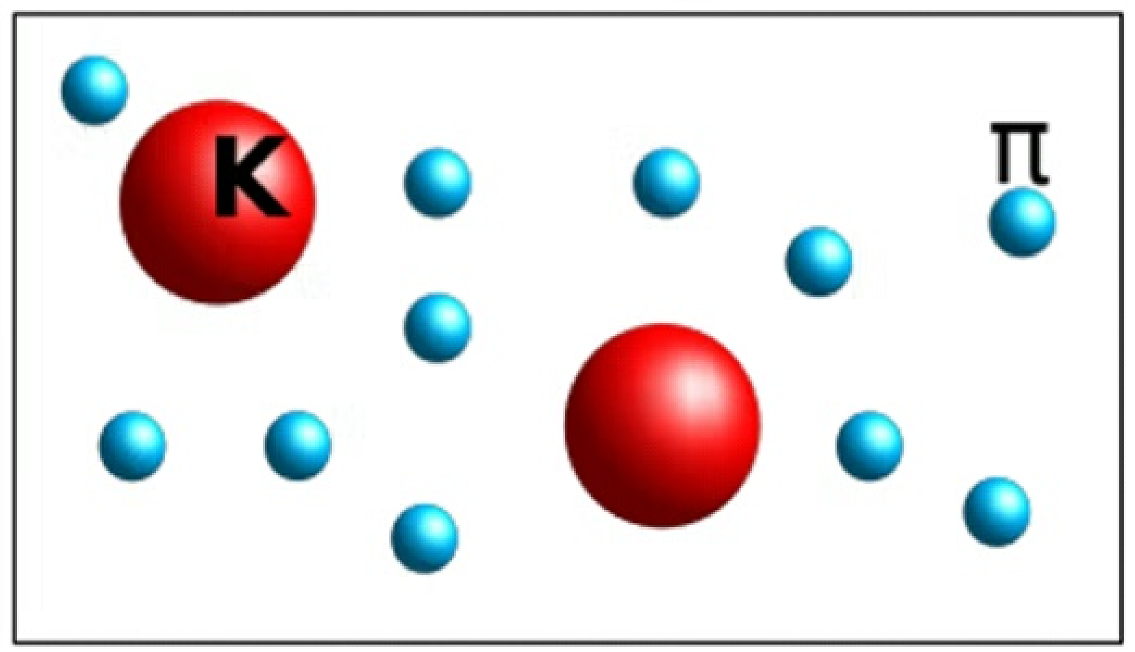
# ONSET OF DECONFINEMENT IN SMES

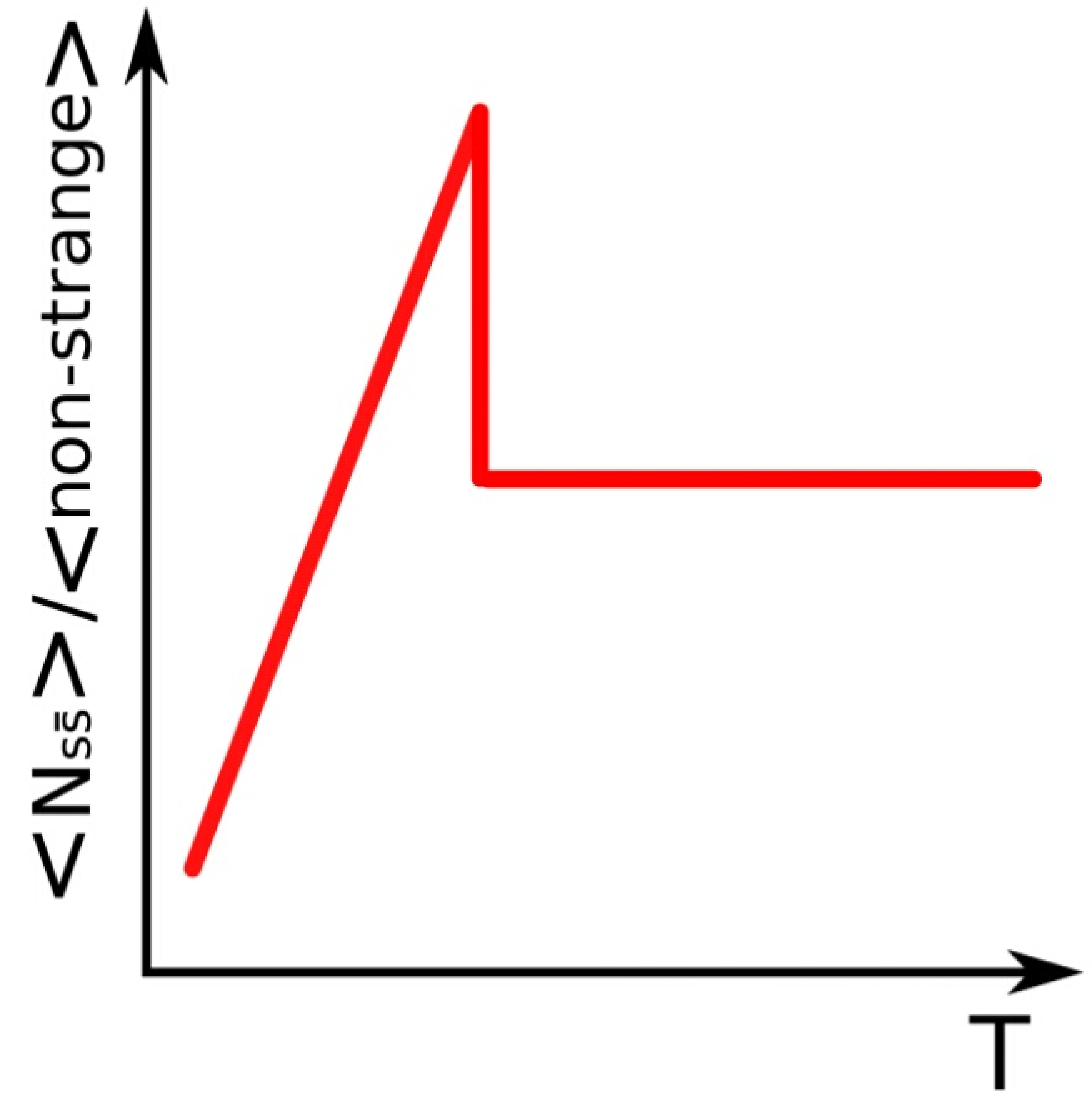


# ONSET OF DECONFINEMENT IN SMES

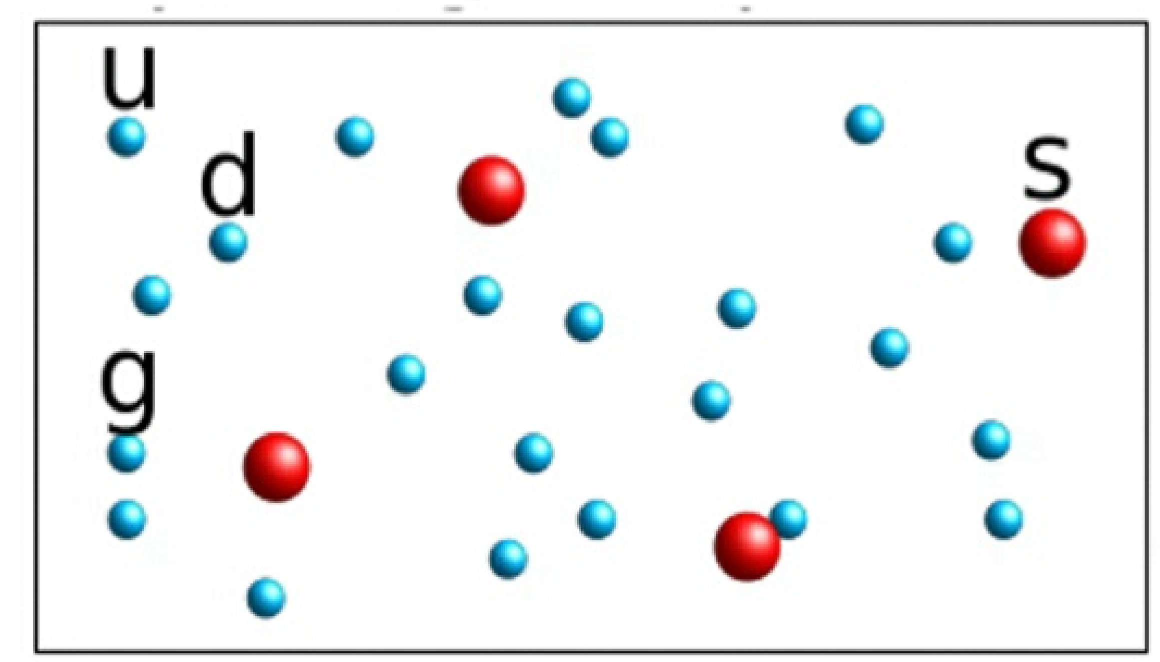
$M_K \approx 500$ MeV $\quad T_c \approx 150$ MeV $\quad M_s \approx 100$ MeV ($\approx 10^{-29}$ kg)

hadron gas




quark-gluon plasma



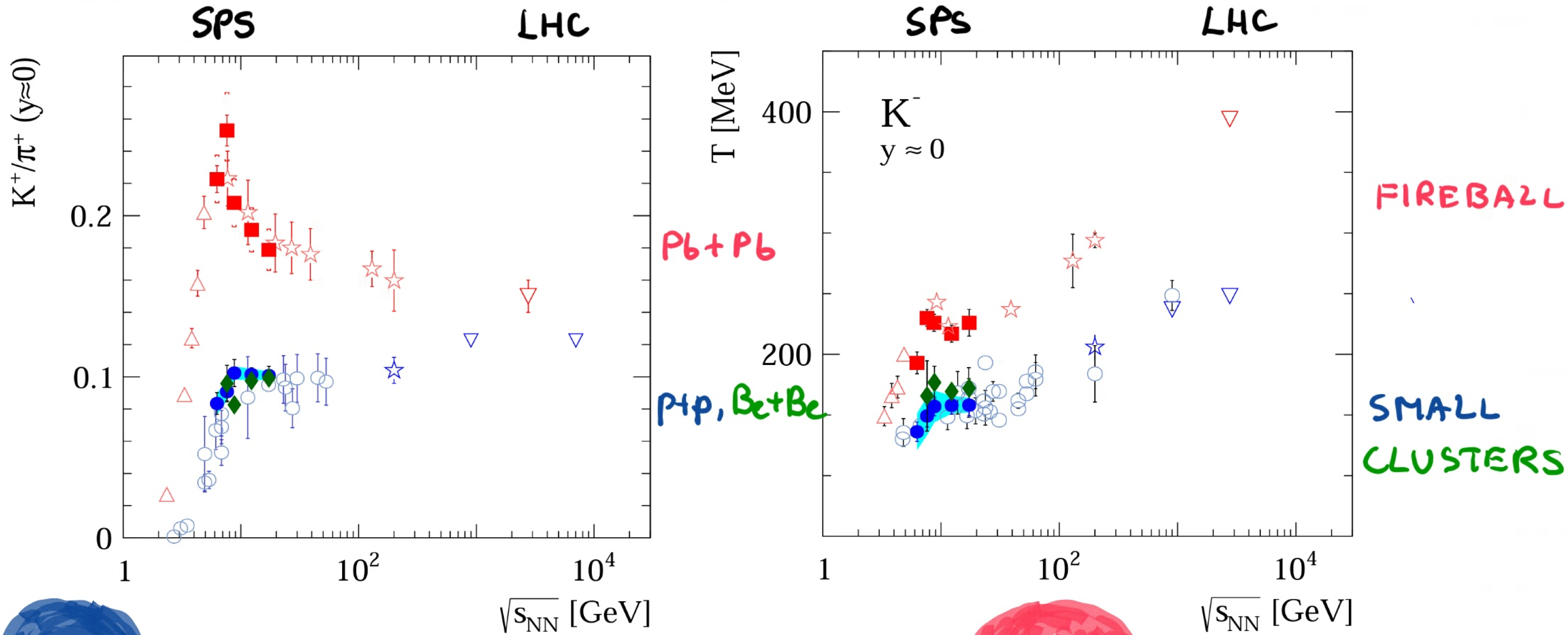

$$\frac{\langle K\rangle}{\langle \pi\rangle} \propto \frac{MT^{3/2}}{T^3} \cdot e^{-M/T}$$

$$\frac{\langle s\rangle}{\langle u+d+g\rangle} \propto \frac{T^3}{T^3} = const(T)$$

$$\langle n\rangle = \frac{g\cdot V}{(2\pi)^3}\int d^3p \, \frac{1}{e^{E/T}\pm 1} \approx g\cdot V \frac{2\pi^2}{4.45} T^3 \quad \text{FOR } M \ll T$$

$$\approx g\cdot V \left(\frac{M\cdot T}{2\pi}\right)^{3/2} e^{-M/T} \quad \text{FOR } M \gg T$$

# EVIDENCE FOR ONSET OF DECONFINEMENT IN Pb+Pb (FIREBALL)

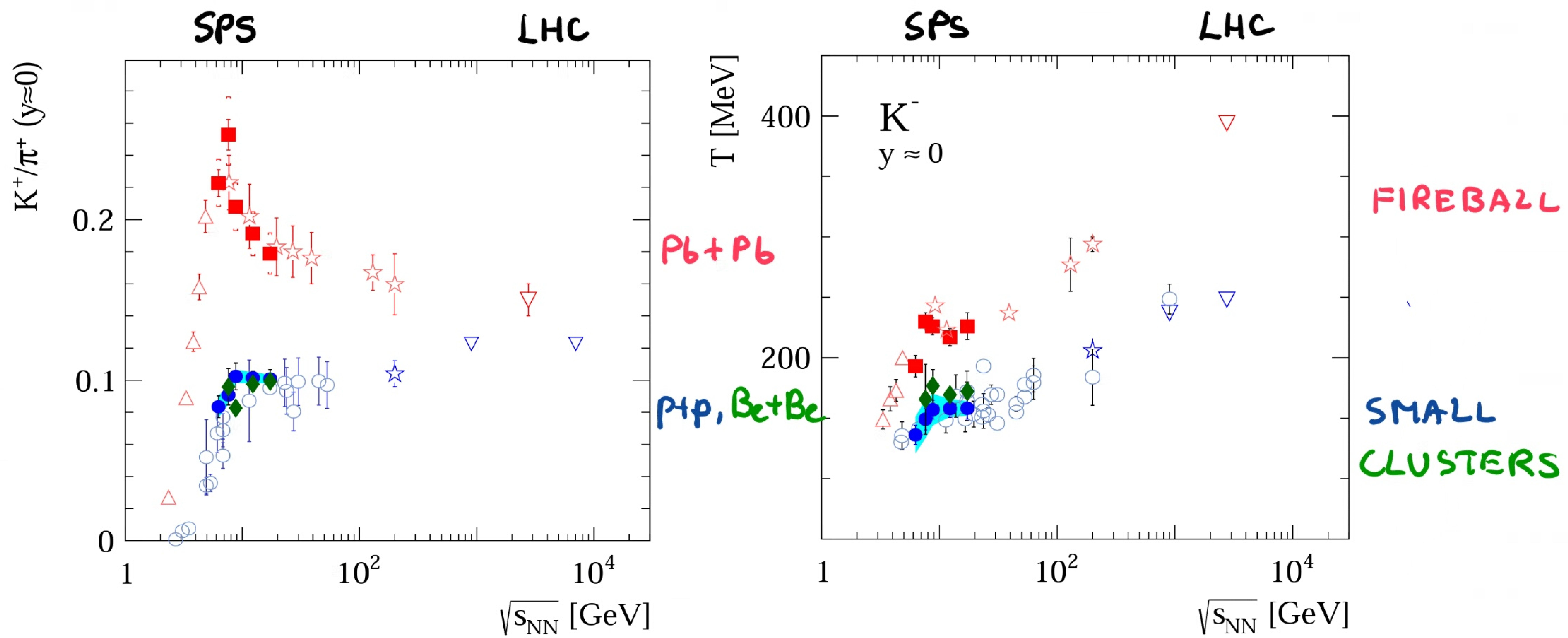


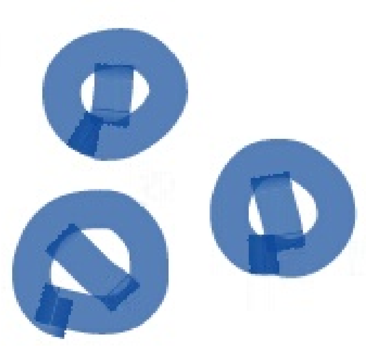

↑ ONSET OF DECONFINEMENT ↑

Pb+Pb CLOSE TO EQUILIBRIUM

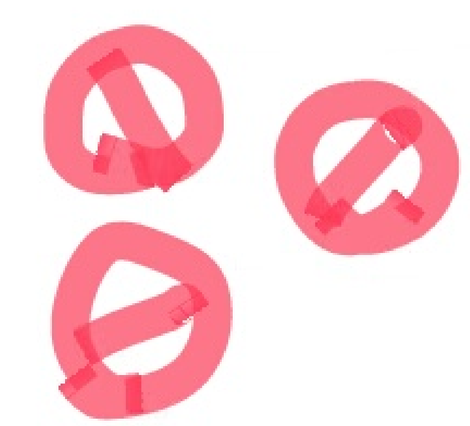
# EVIDENCE FOR ONSET OF DECONFINEMENT

## CHALLENGE TO UNDERSTAND p+p AND Be+Be DATA



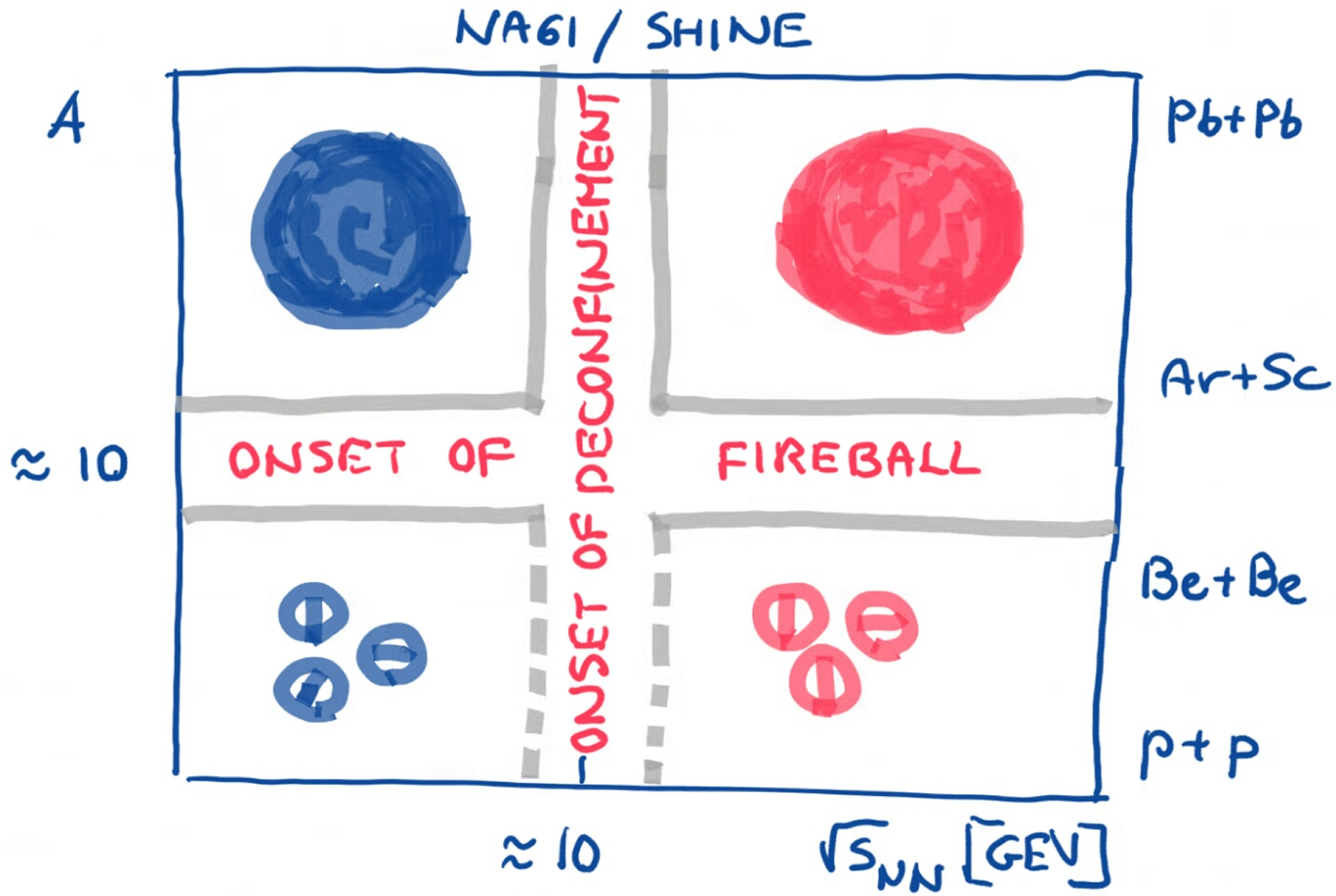



↑ ONSET OF DECONFINEMENT ? ↑



p+p, Be+Be FAR FROM EQUILIBRIUM

# RESULTS ON ONSET OF FIREBALL AND ONSET OF DECONFINEMENT SUGGEST FOUR DOMAINS IN A – $\sqrt{s_{NN}}$ PLANE



# SEARCH FOR CRITICAL POINT

## FLUCTUATIONS VS $\sqrt{s_{NN}}$ AND A

USE QUANTITIES INSENSITIVE TO VOLUME FLUCTUATIONS AND MATERIAL CONSERVATION LAWS:

⇓

STRONGLY INTENSIVE QUANTITIES WITH PROPER SELECTION OF EXTENSIVE QUANTITIES:

$$\Sigma[N, P_T] \equiv C^{-1}\left[\langle P_T\rangle \omega[N] + \langle N\rangle \cdot \omega[P_T] - 2(\langle N \cdot P_T\rangle - \langle N\rangle\langle P_T\rangle)\right]$$

$$\Delta[N, P_T] \equiv C^{-1}\left[\langle P_T\rangle \omega[N] - \langle N\rangle \cdot \omega[P_T]\right]$$

WITH $C \equiv \langle N\rangle \cdot \omega[P_T]$, $\quad P_T = \sum_1^N p_T^i$

IB-GCE AND IB-CE WITH V FLUCTUATIONS

⇓

$$\Sigma[P_T, N] = \Delta[P_T, N] = 1$$

MG, MROWCZYNSKI

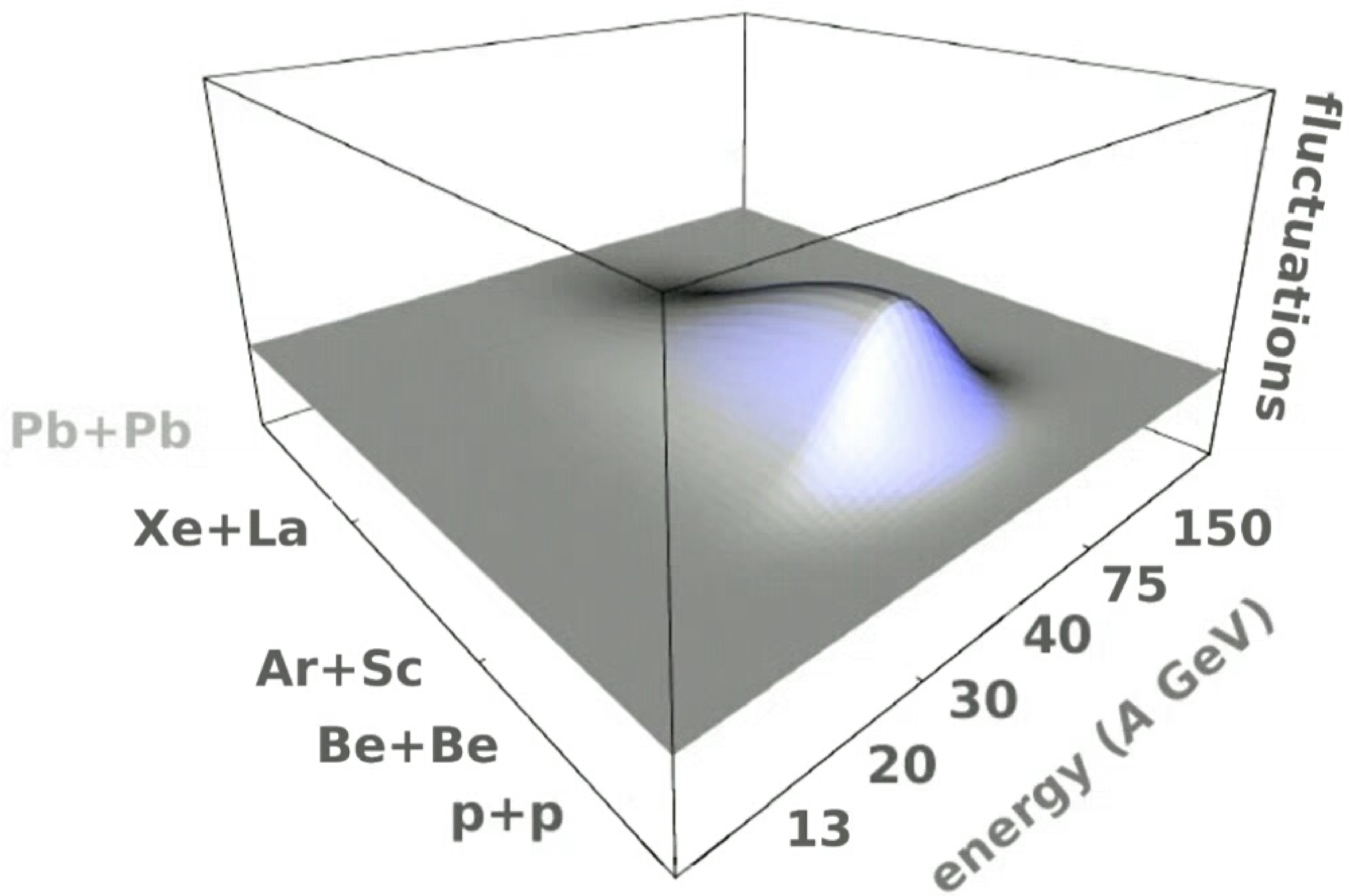
MG, GORENSTEIN

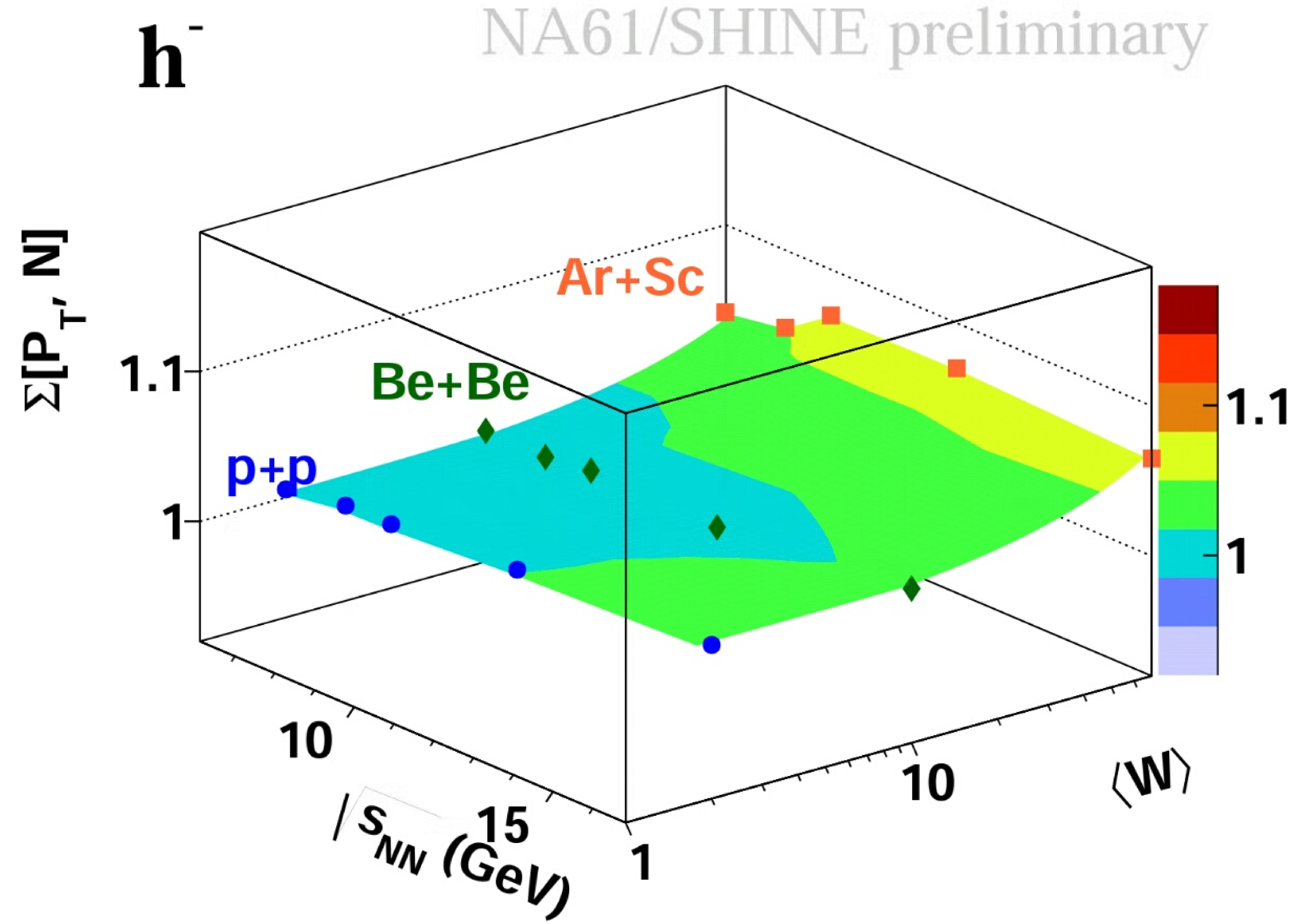
SANGELINE

# SEARCH FOR CRITICAL POINT: FLUCTUATIONS VS $\sqrt{s_{NN}}$ AND A



CP ⇒ "FLUCTUATION HILL"




NO INDICATION FOR CRITICAL POINT SO FAR

# SEARCH FOR CRITICAL POINT : FLUCTUATIONS VS M
## "INTERMITTENCY ANALYSIS"

SECOND ORDER PHASE TRANSITION → SCALE INVARIANCE → CHARACTERISTIC DEPENDENCE OF FLUCTUATIONS ON SIZE $\delta$ OF SUBDIVISION INTERVALS OF MOMENTUM SPACE $\Delta$

$M = \Delta / \delta$ – NUMBER OF INTERVALS

$$F_2(M) \equiv \sum_{i=1}^{M} \langle N_i (N_i - 1) \rangle \Big/ \sum_{i=1}^{M} \langle N_i \rangle^2$$

WHERE $N_i$ – PARTICLE NUMBER IN BIN $i$,
$\langle .. \rangle$ – AVERAGING OVER EVENTS

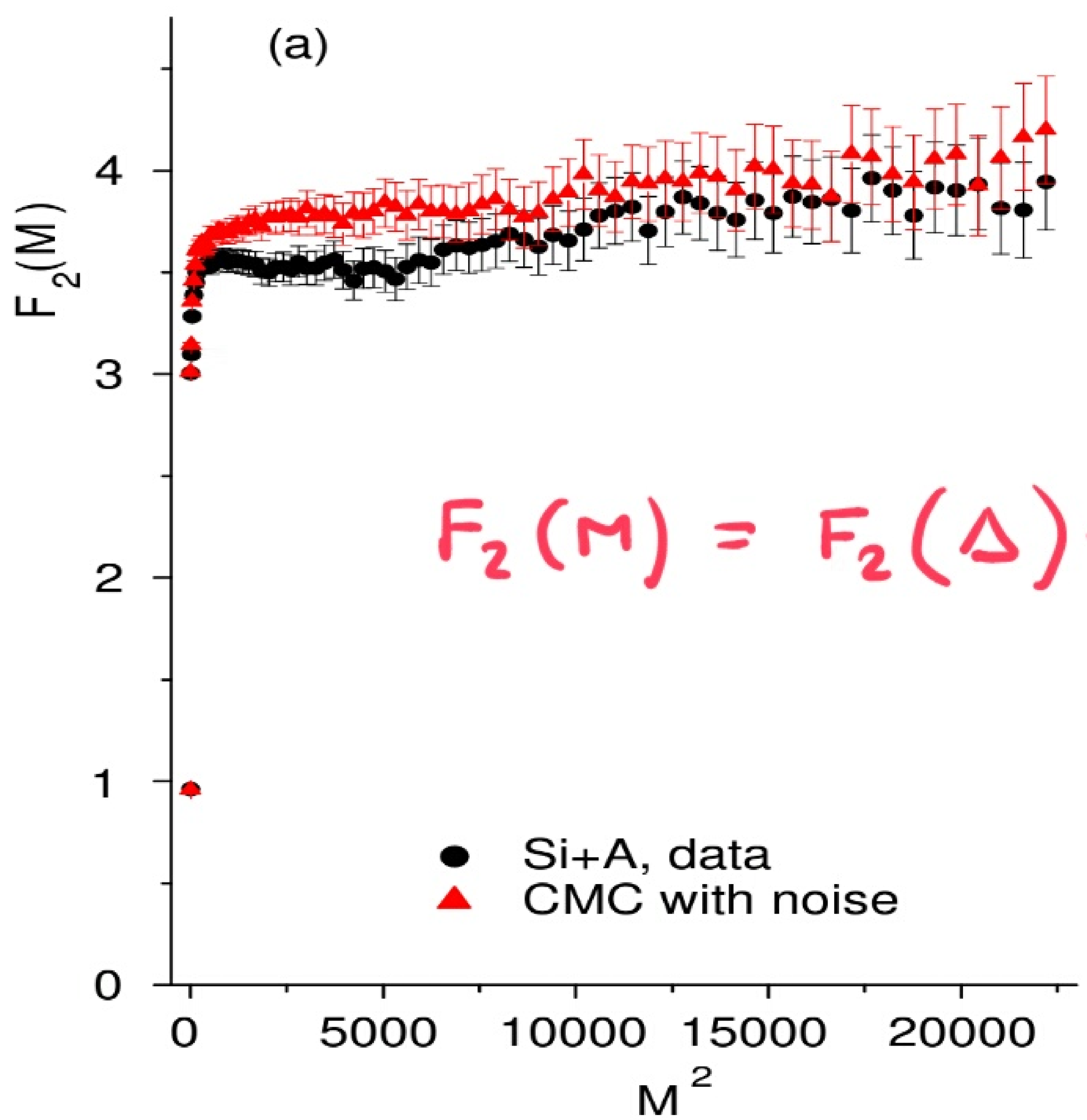
AT CRITICAL POINT POWER LAW DEPENDECE IS EXPECTED

$$F_2(M) = F_2(\Delta) \cdot M^{\phi_2}$$

WOSIEK (1988)
BIALAS, PESZANSKI
SATZ
ANTONIOU, DIAKONOS, KAPOYANIS

# SEARCH FOR CRITICAL POINT : FLUCTUATIONS VS M
## PROTONS

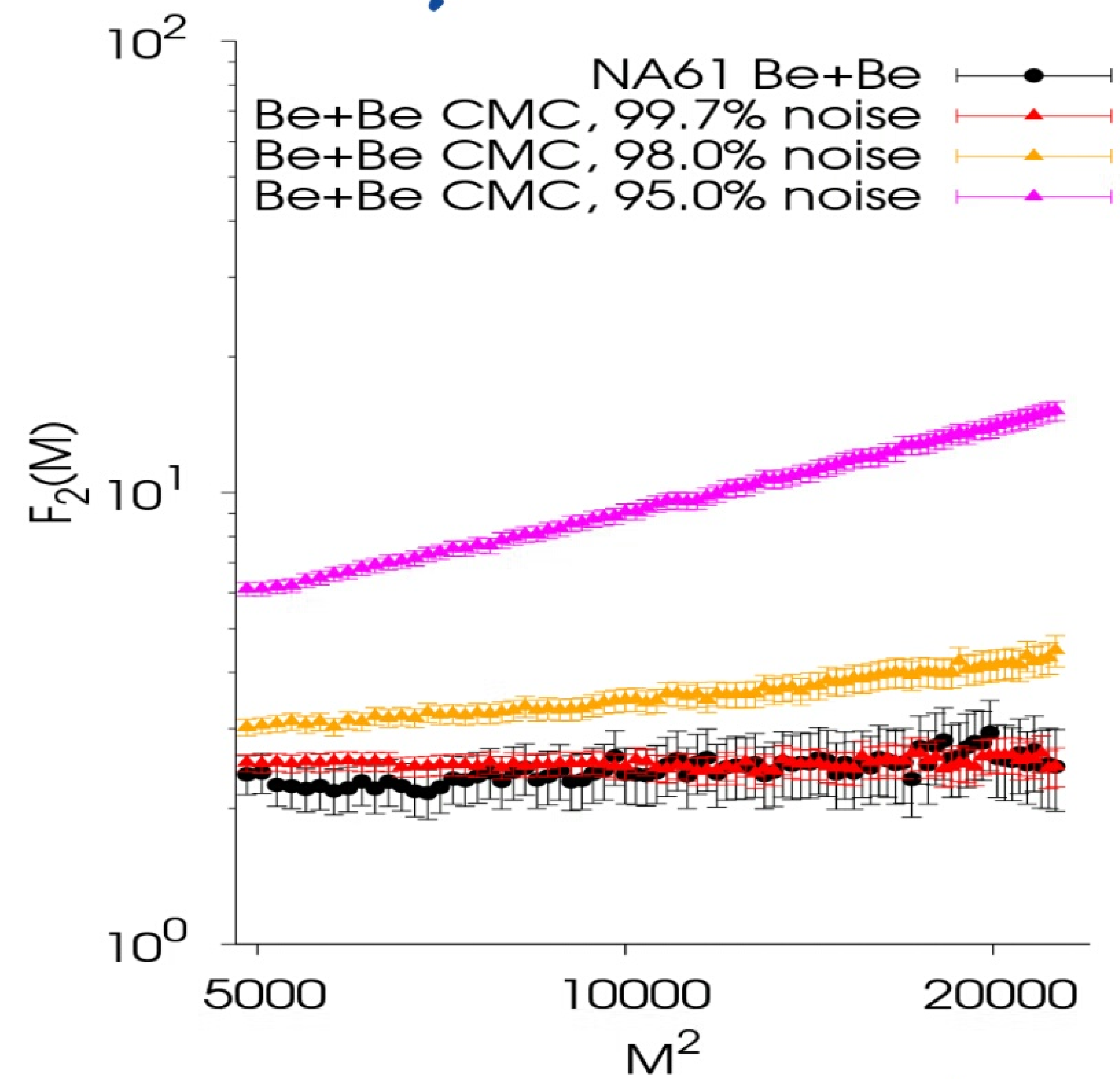
**Si+A AT 158A GEV/c**
**NA49**




$$F_2(M) = F_2(\Delta) \cdot M^{\phi_2}$$

NA49: RESULTS CONSISTENT WITH ≈1 % OF "CRITICAL" PROTONS, $\phi_2 \approx 1$

**Be+Be AT 150A GEV/c**
**NA61/SHINE**




UPPER LIMIT OF "CRITICAL" PROTONS ≈ 0.3%

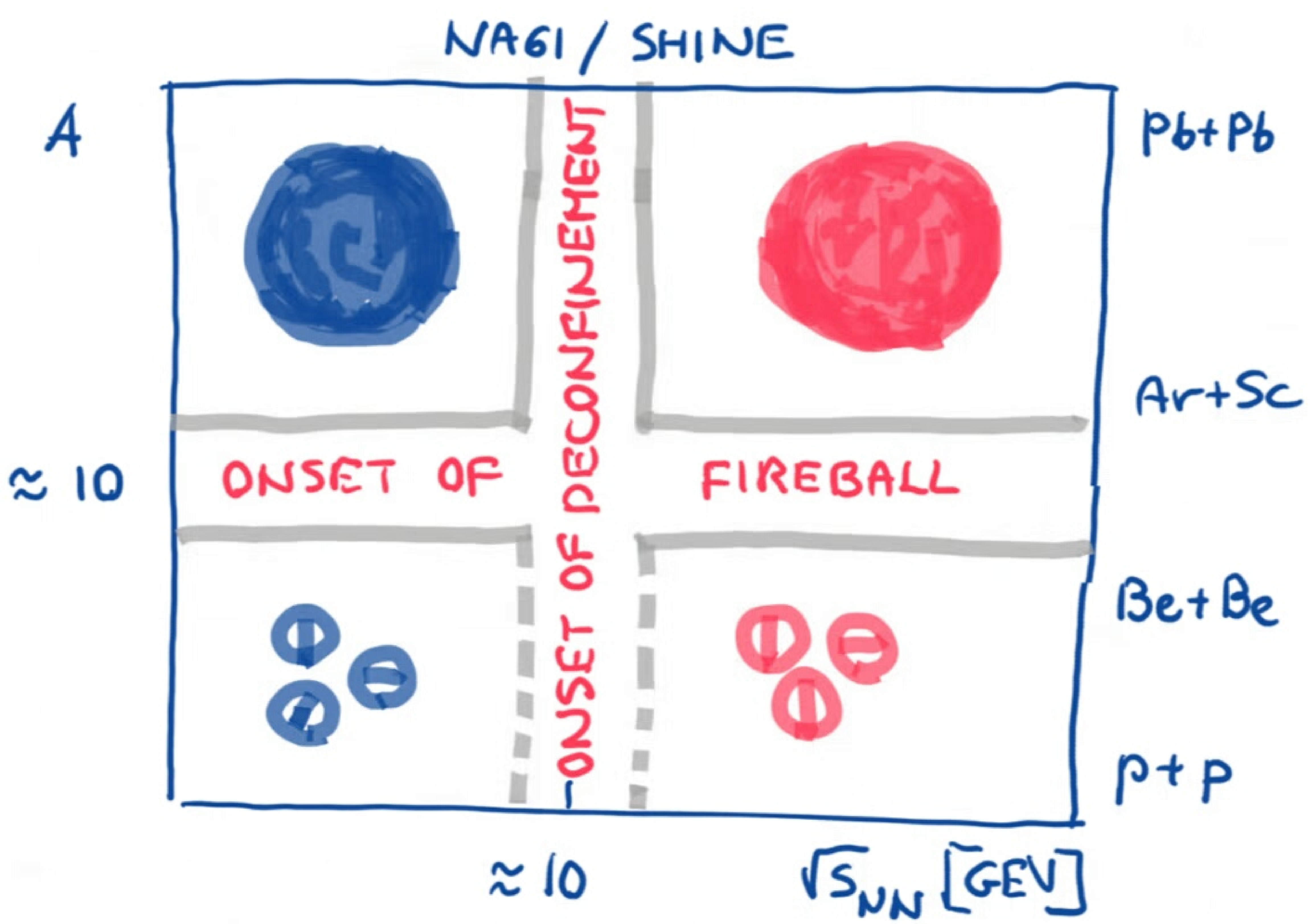
# SUMMARY

- INDICATION FOR ONSET OF FIREBALL
  → MORE DATA ON COLLISIONS OF LIGHT NUCLEI MAY BE NEEDED

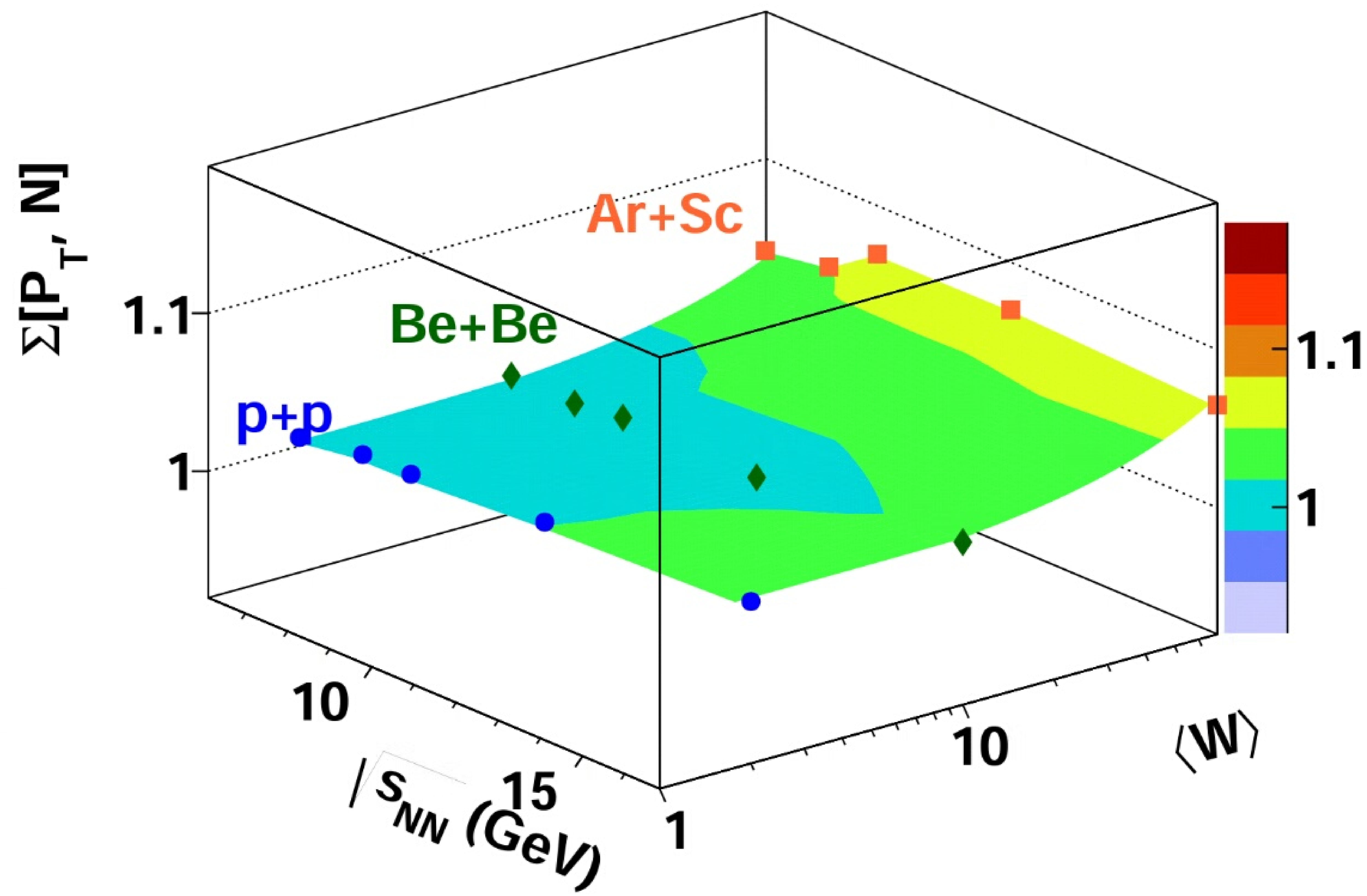
- EVIDENCE FOR ONSET OF DECONFINEMENT IN Pb+Pb
  → CHALLANGE TO UNDERSTAND p+p, Be+Be

- NO EVIDENCE FOR CRITICAL POINT SO FAR
  → ANALYSIS IN PROGRESS

## ONSETS

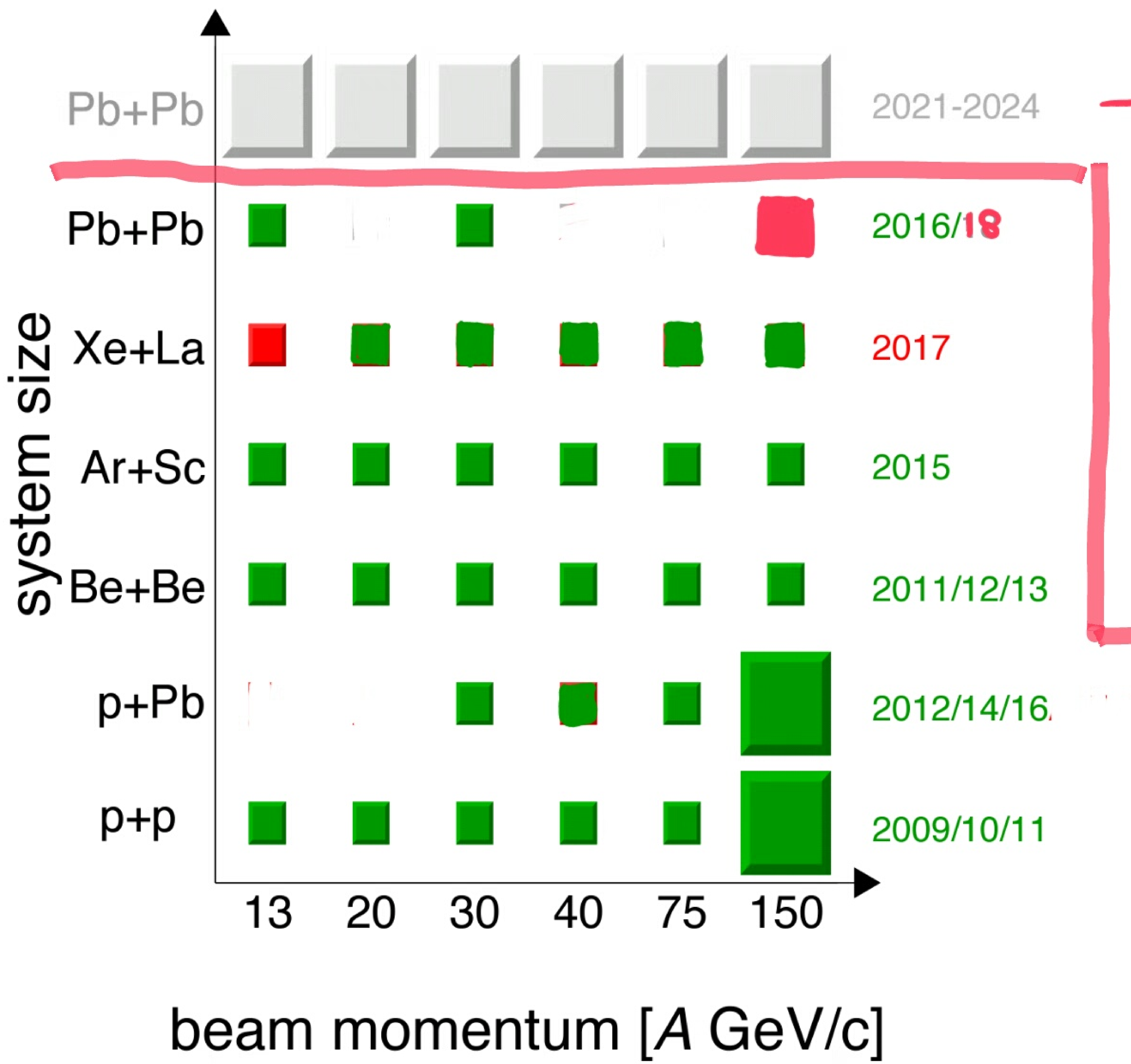



## CRITICAL POINT



# ADDITIONAL SLIDES

# FUTURE PLANS



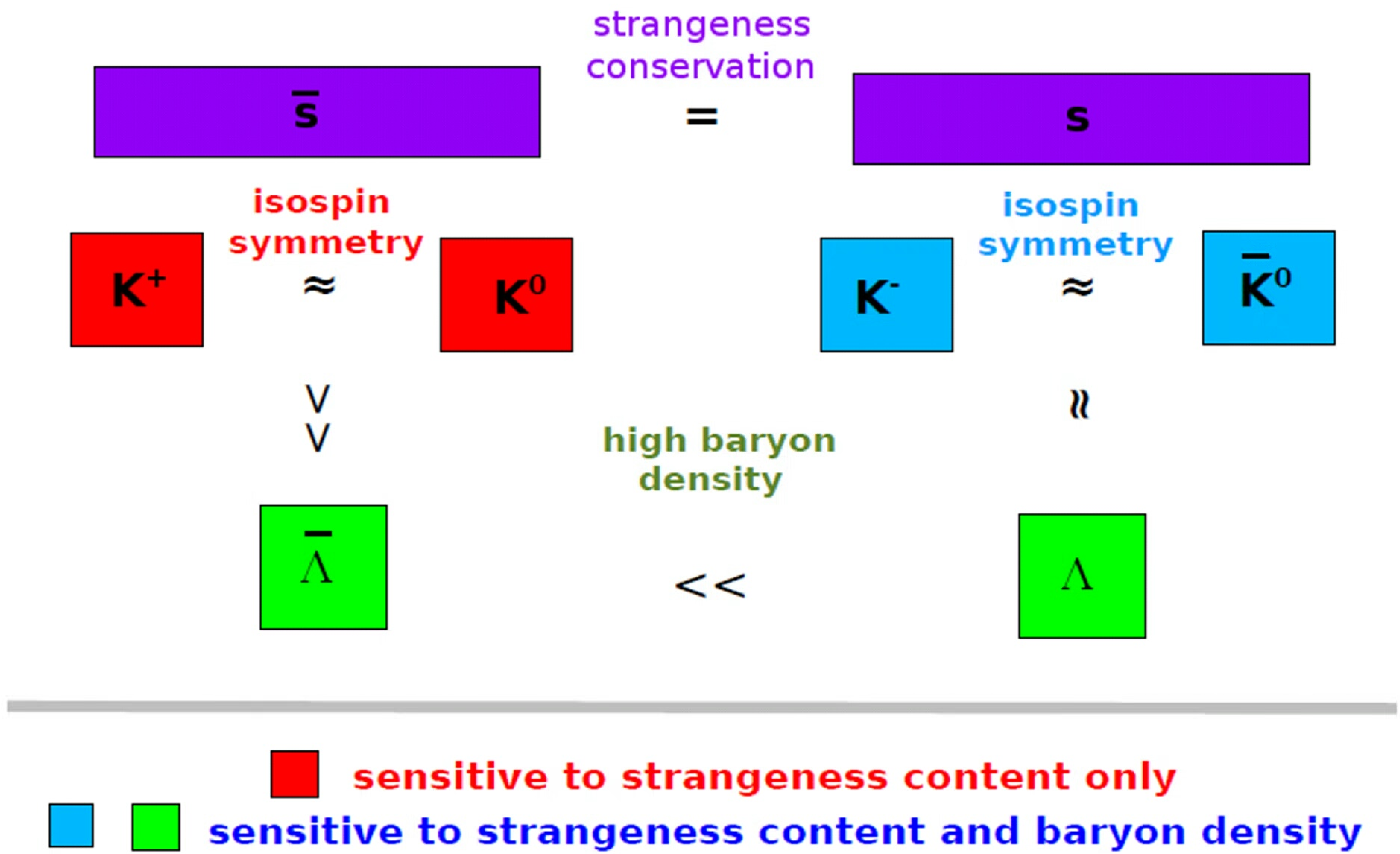

→ OPEN CHARM FOR ONSET OF DECONFINEMENT

ALSO ENERGY SCAN WITH WITH COLLISIONS OF LIGHT IONS (E.G. C+C, Mg+Mg) MAY BE NEEDED FOR ONSET OF FIREBALL

# NA61/SHINE Collaboration

- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- Hungary
  - Wigner RCP, Budapest
- Japan
  - KEK Tsukuba, Tsukuba
- Norway
  - University of Bergen, Bergen
- Poland
  - UJK, Kielce
  - NCBJ, Warsaw
  - University of Warsaw, Warsaw
  - WUT, Warsaw
  - Jagiellonian University, Kraków
  - IFJ PAN, Kraków
  - AGH, Kraków
  - University of Silesia, Katowice
  - University of Wrocław, Wrocław
- Russia
  - INR Moscow, Moscow
  - JINR Dubna, Dubna
  - SPBU, St.Petersburg
  - MEPhI, Moscow
- Serbia
  - University of Belgrade, Belgrade
- Switzerland
  - ETH Zürich, Zürich
  - University of Bern, Bern
  - University of Geneva, Geneva
- USA
  - University of Colorado Boulder, Boulder
  - LANL, Los Alamos
  - University of Pittsburgh, Pittsburgh
  - FNAL, Batavia
  - University of Hawaii, Manoa

**~150 physicists from ~30 institutes**

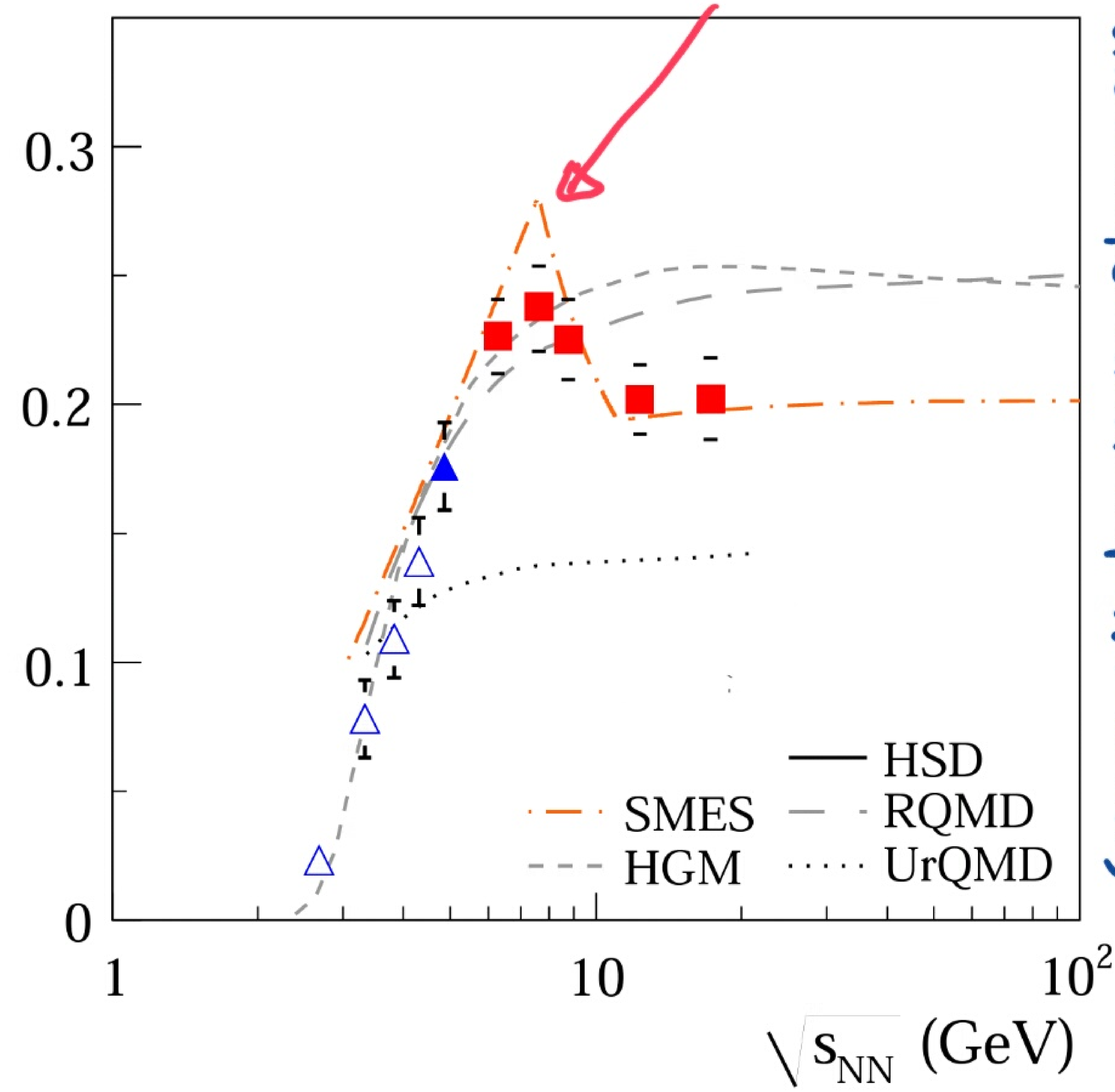


strangeness conservation
$\bar{s}$ = s
isospin symmetry
$K^+$ ≈ $K^0$
isospin symmetry
$K^-$ ≈ $\bar{K}^0$
high baryon density
$\bar{\Lambda}$ << $\Lambda$
sensitive to strangeness content only
sensitive to strangeness content and baryon density

# ONSET OF DECONFINEMENT IN MODELS

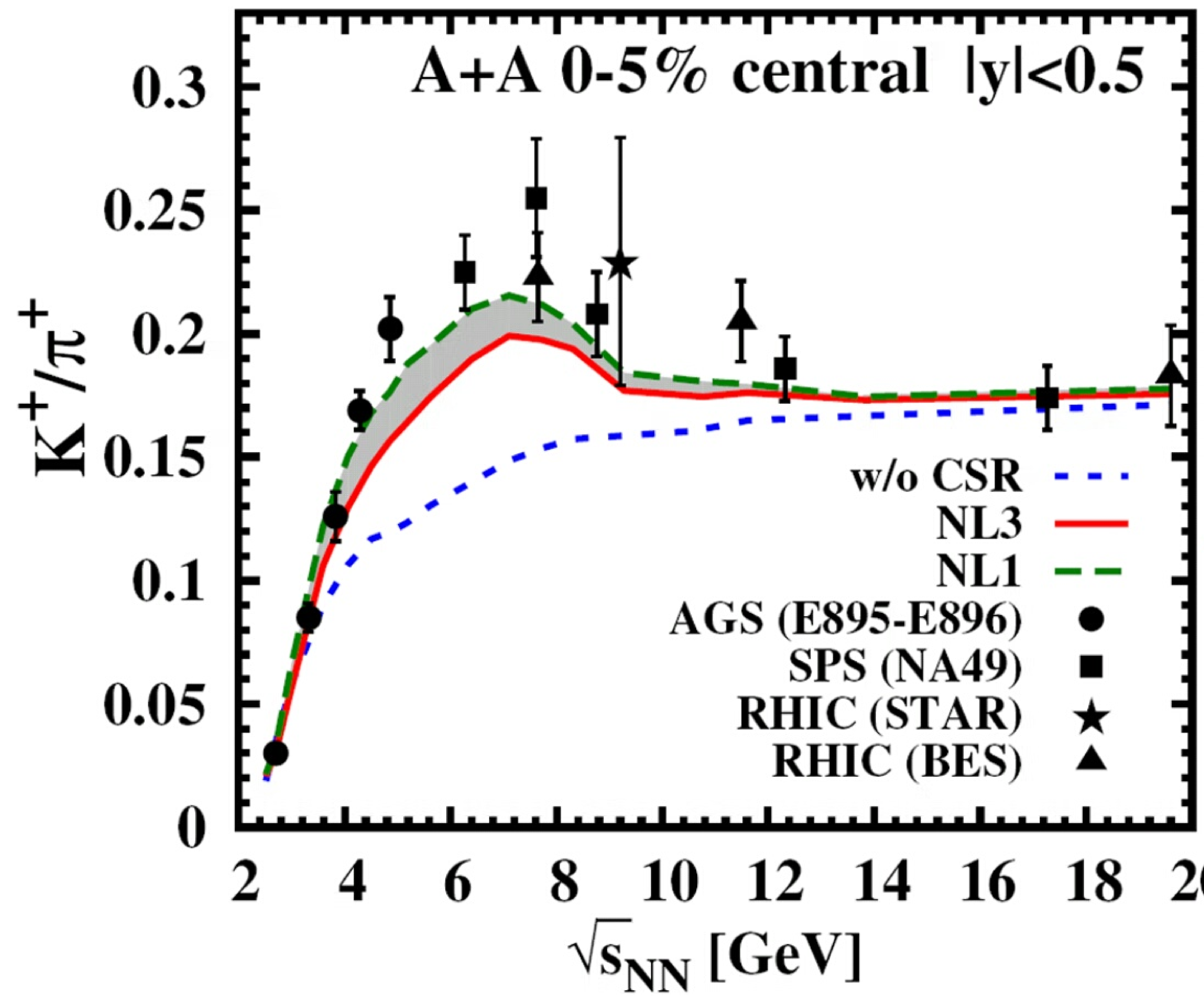
$E_S \equiv \frac{\langle K+\bar{K}\rangle + \langle \Lambda \rangle}{\langle \pi \rangle}$

## STATISTICAL: SMES




GAZDZICKI, GORENSTEIN, APP B30 (99)

## DYNAMICAL: pHSD




PALMESE ET AL, PR C94 (16) 044912

STATISTICAL AND DYNAMICAL MODELS WITH CHIRAL SYMMETRY RESTORATION AND DECONFINEMENT FIT Pb+Pb DATA

(BUT BOTH FAIL TO REPRODUCE SMALL SYSTEMS)

# FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

**Leptons** spin = 1/2

| Flavor | | Mass GeV/$c^2$ | Electric charge |
|---|---|---|---|
| $\nu_e$ | electron neutrino | $<1\times10^{-8}$ | 0 |
| e | electron | 0.000511 | −1 |
| $\nu_\mu$ | muon neutrino | <0.0002 | 0 |
| $\mu$ | muon | 0.106 | −1 |
| $\nu_\tau$ | tau neutrino | <0.02 | 0 |
| $\tau$ | tau | 1.7771 | −1 |

**Quarks** spin = 1/2

| Flavor | | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|---|
| u | up | 0.003 | 2/3 |
| d | down | 0.006 | −1/3 |
| c | charm | 1.3 | 2/3 |
| s | strange | 0.1 | −1/3 |
| t | top | 175 | 2/3 |
| b | bottom | 4.3 | −1/3 |

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = $1.05\times10^{-34}$ J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60\times10^{-19}$ coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/$c^2$ (remember $E = mc^2$), where 1 GeV = $10^9$ eV = $1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/$c^2$ = $1.67\times10^{-27}$ kg.

# BOSONS

force carriers
spin = 0, 1, 2, ...

| Unified Electroweak spin = 1 | | |
|---|---|---|
| Name | Mass GeV/$c^2$ | Electric charge |
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | –1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

| Strong (color) spin = 1 | | |
|---|---|---|
| Name | Mass GeV/$c^2$ | Electric charge |
| g gluon | 0 | 0 |

### Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** $qqq$.

### Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

# PROPERTIES OF THE INTERACTIONS

| Property \ Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong: Fundamental | Strong: Residual |
|---|---|---|---|---|---|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | $\gamma$ | Gluons | Mesons |
| Strength relative to electromag for two u quarks at: $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | Not applicable to quarks |
| Strength relative to electromag for two u quarks at: $3\times10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | |
| for two protons in nucleus | $10^{-36}$ | $10^{-7}$ | 1 | Not applicable to hadrons | 20 |

## Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin |
|---|---|---|---|---|---|
| $p$ | proton | uud | 1 | 0.938 | 1/2 |
| $\bar{p}$ | anti-proton | $\bar{u}\bar{u}\bar{d}$ | –1 | 0.938 | 1/2 |
| $n$ | neutron | udd | 0 | 0.940 | 1/2 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
| $\Omega^-$ | omega | sss | –1 | 1.672 | 3/2 |

## Mesons $q\bar{q}$

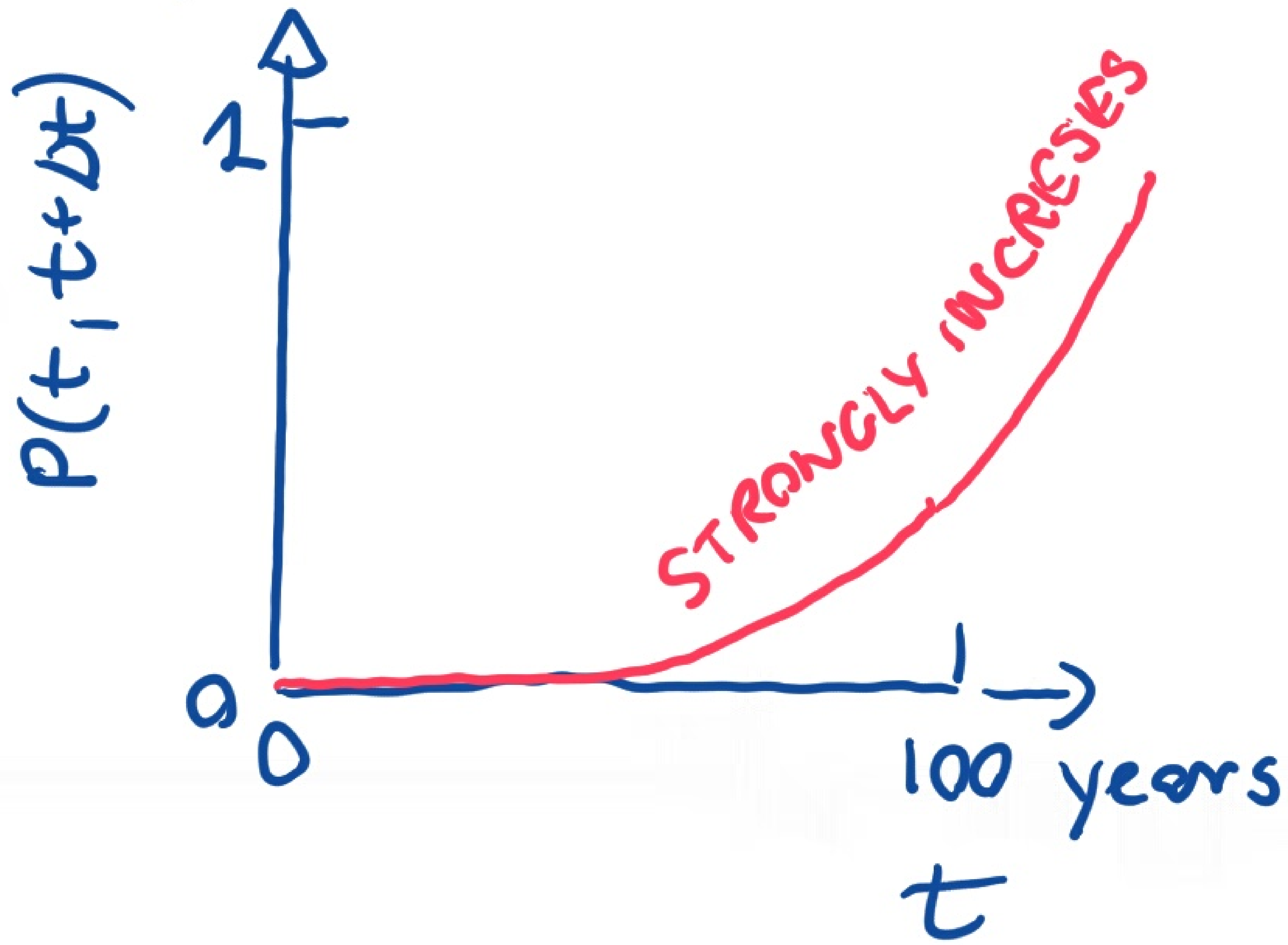
Mesons are bosonic hadrons.
There are about 140 types of mesons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin |
|---|---|---|---|---|---|
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | –1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.770 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | eta-c | $c\bar{c}$ | 0 | 2 .980 | 0 |

# PARTICLES ARE YOUNG FOREVER

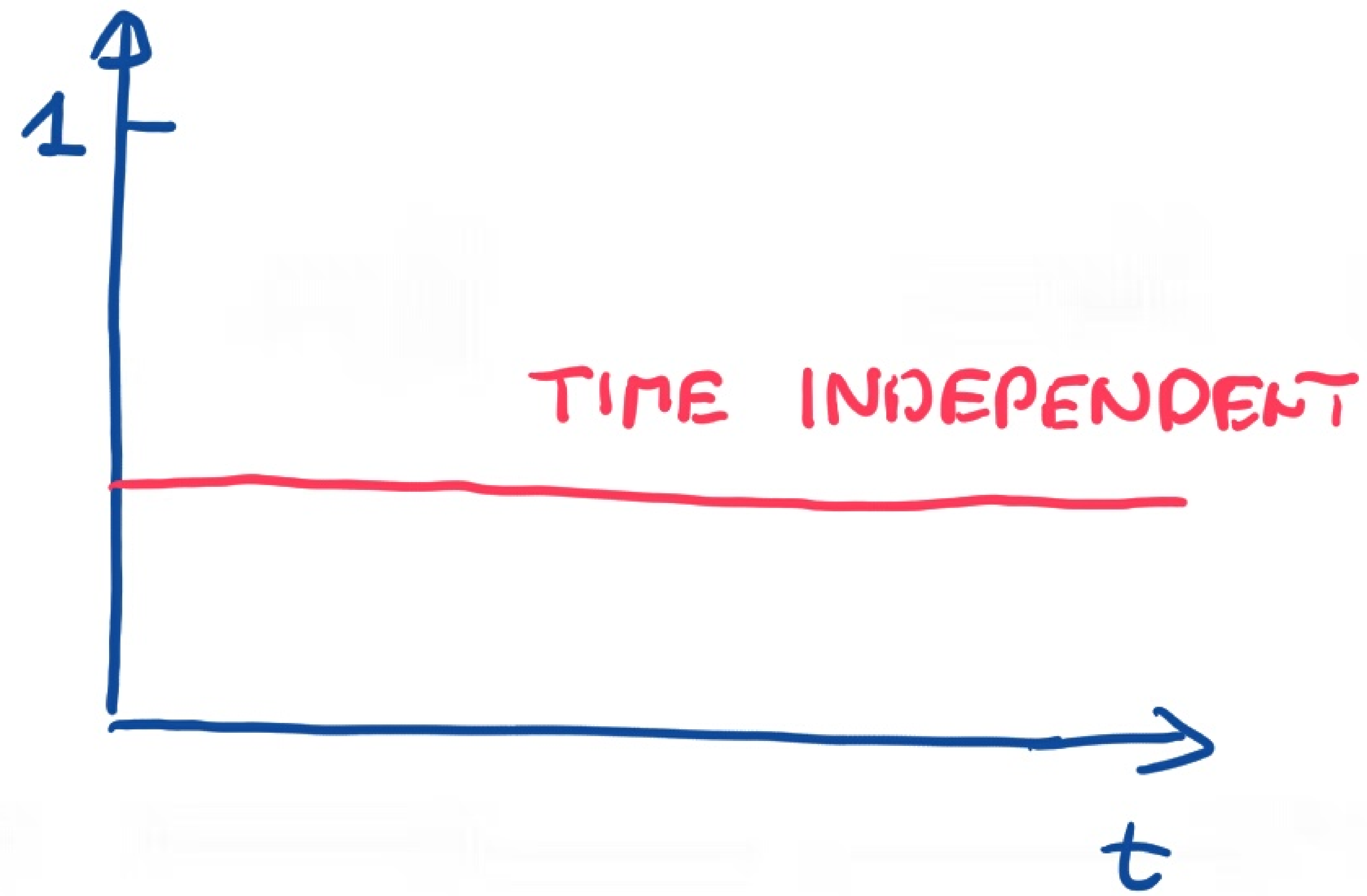
PROBABILITY TO DECAY (DIE) IN A TIME INTEVAL $(t, t+\Delta t)$

HUMAN



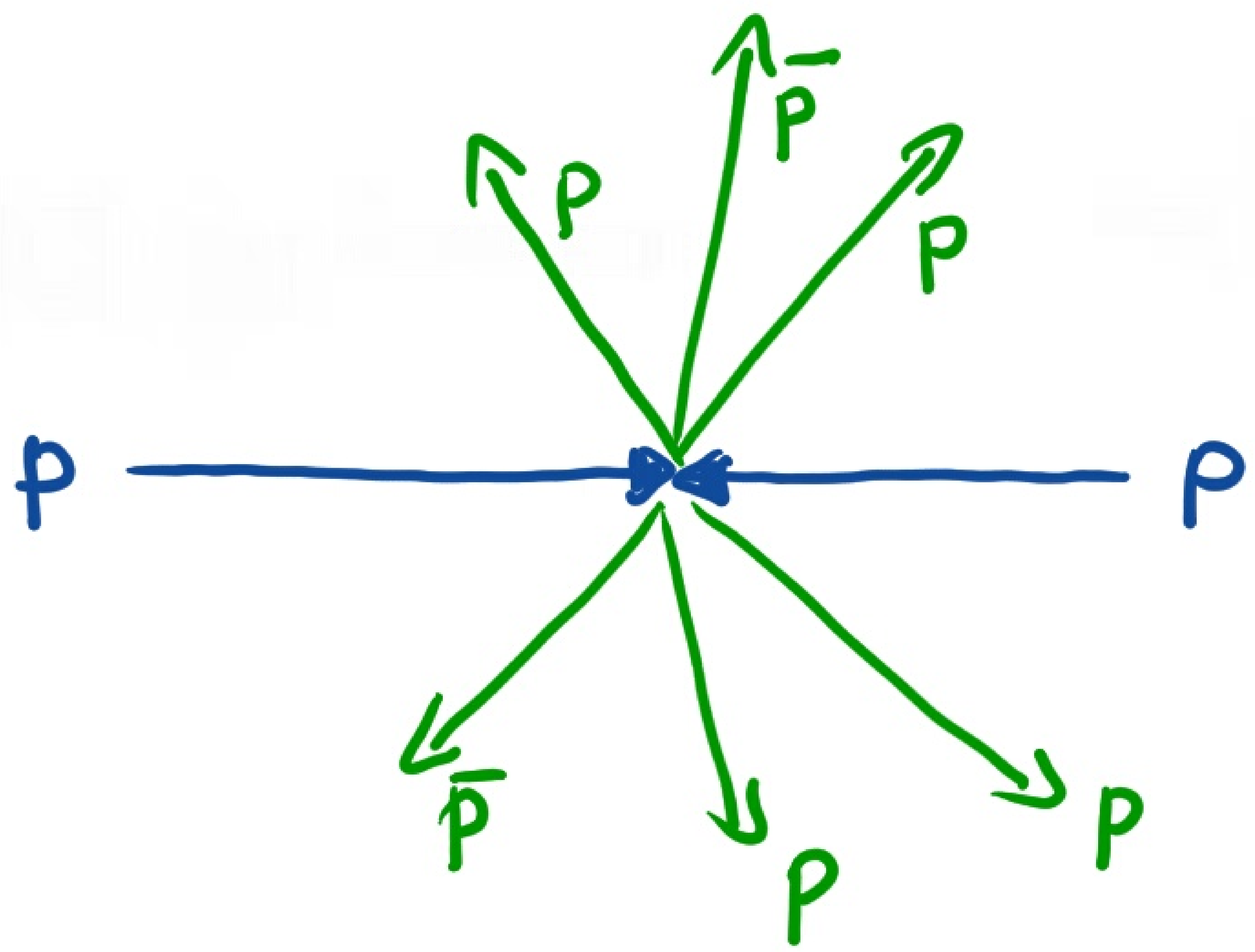

$\Delta t = 1$ year

PARTICLE

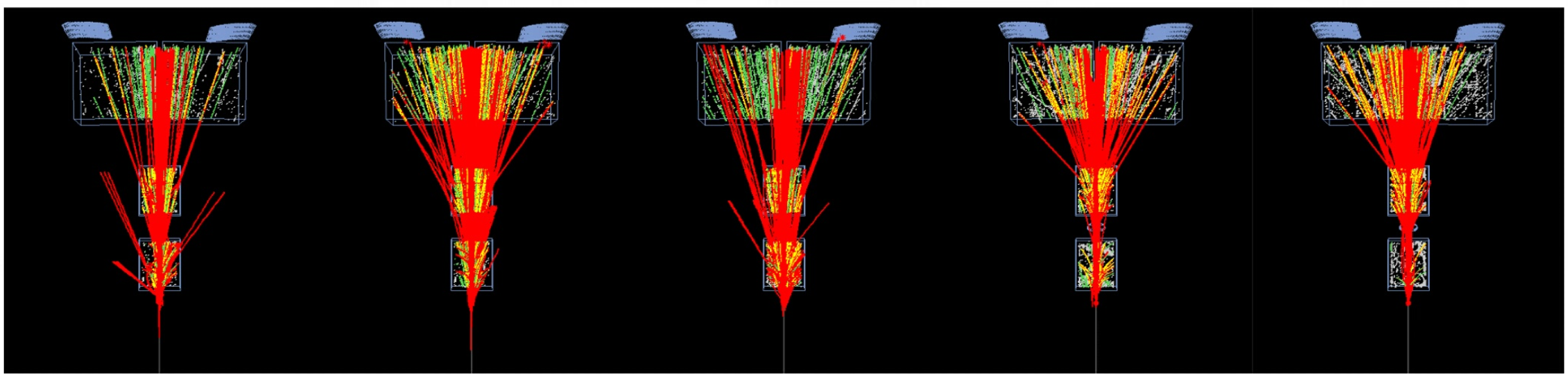



(VERY) DIFFERENT PROBABILITIES
FOR DIFFERENT PARTICLE TYPES

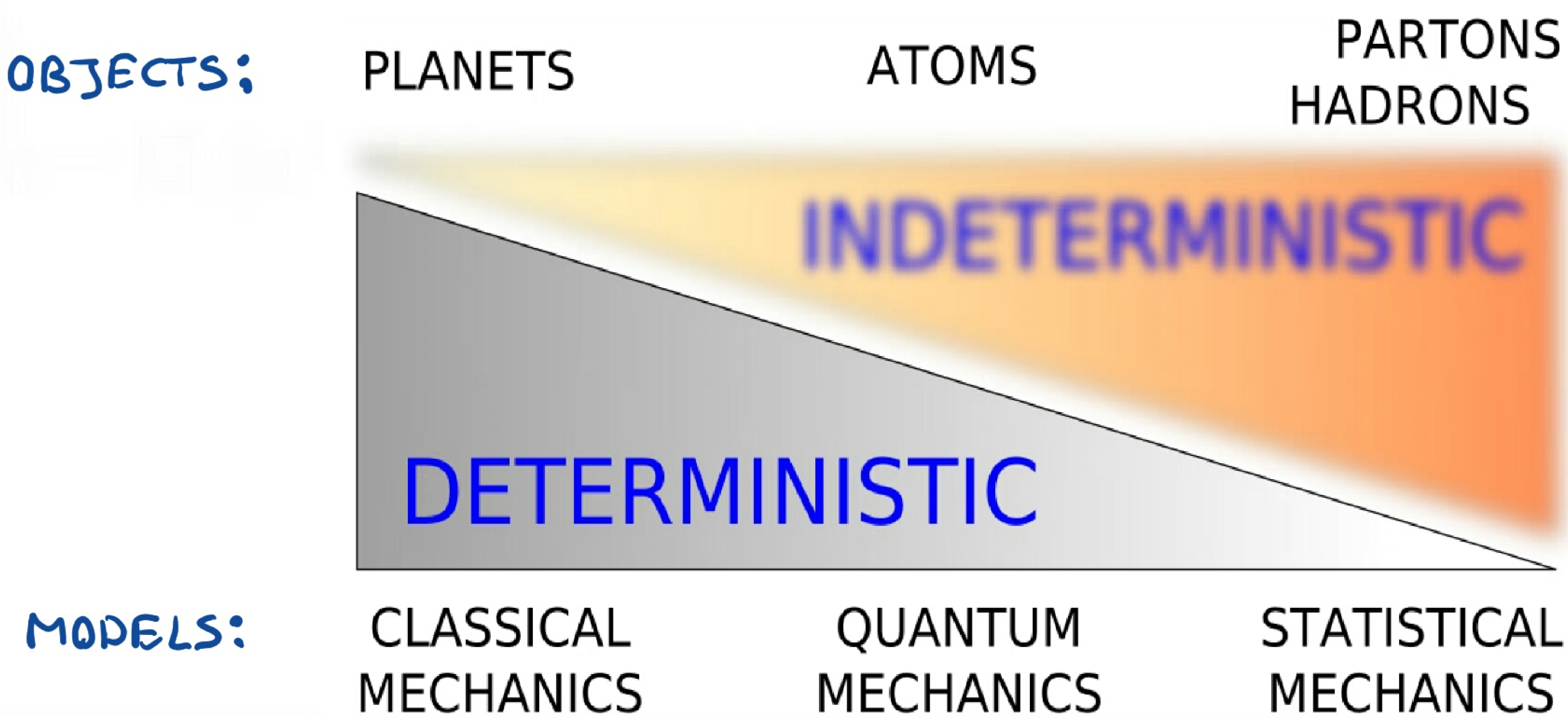
# PARTICLE NUMBER CHANGES

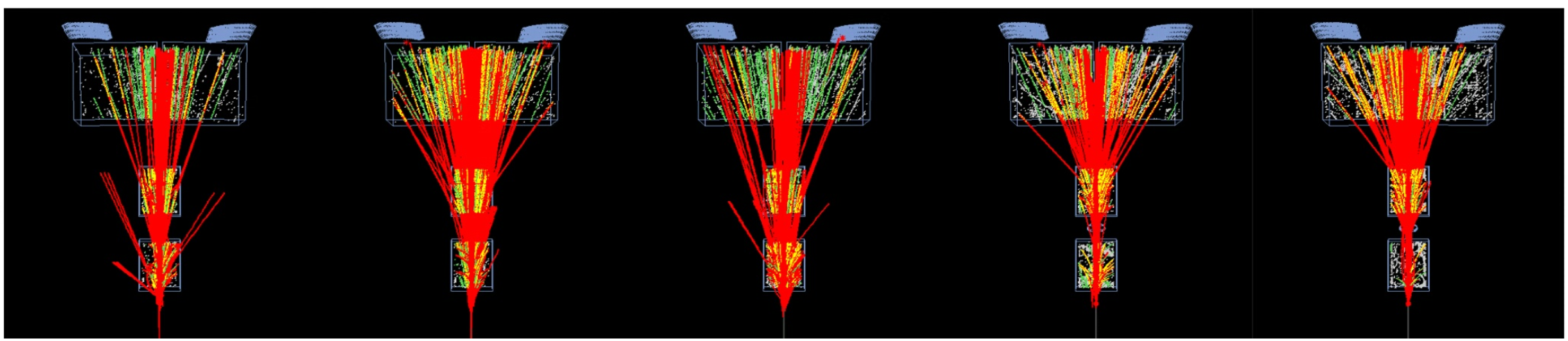


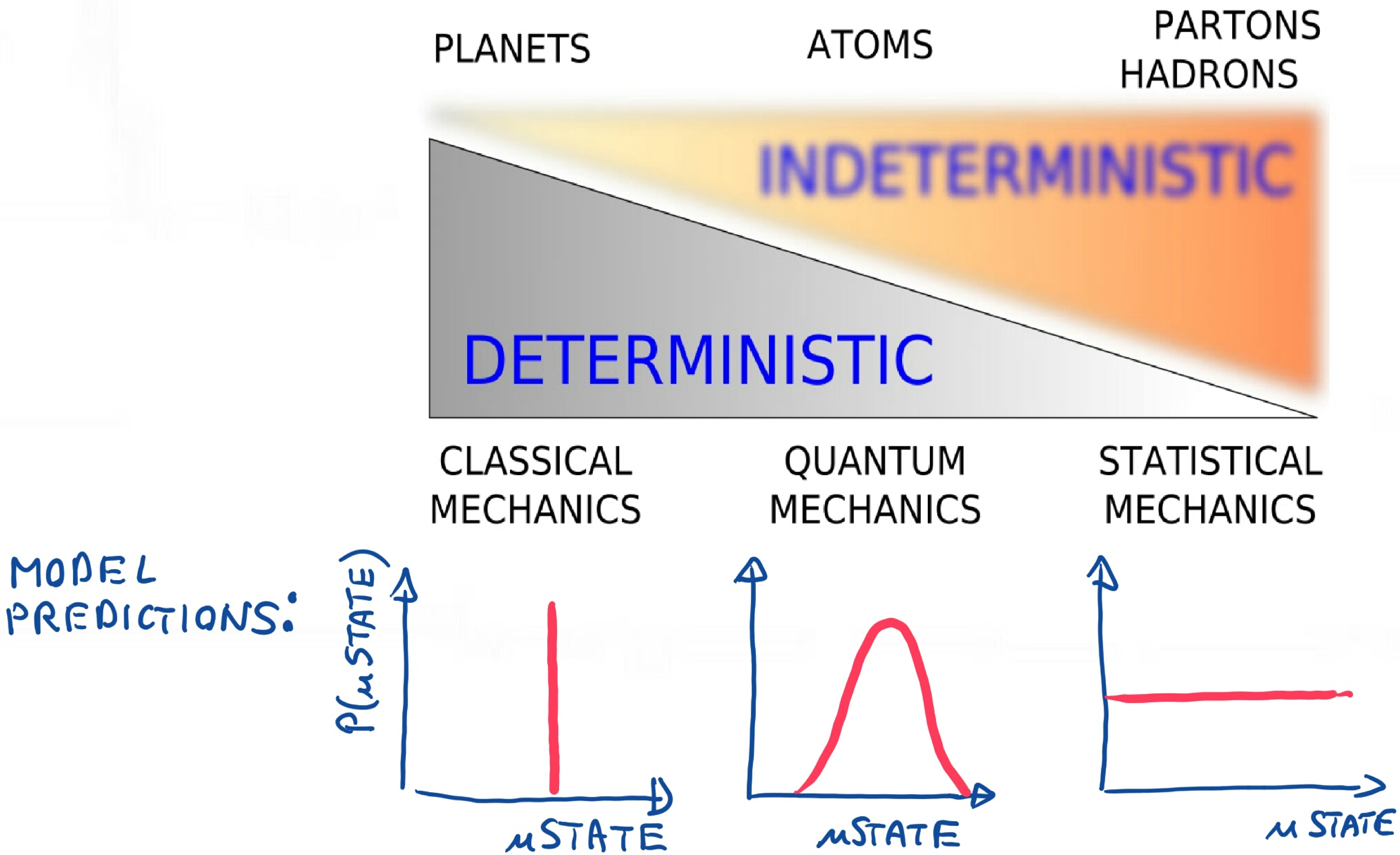

E.G. INTERACTION OF TWO PROTONS CAN PRODUCE FOUR PROTONS AND TWO ANTIPROTONS



# NATURE IS INDETERMINISTIC

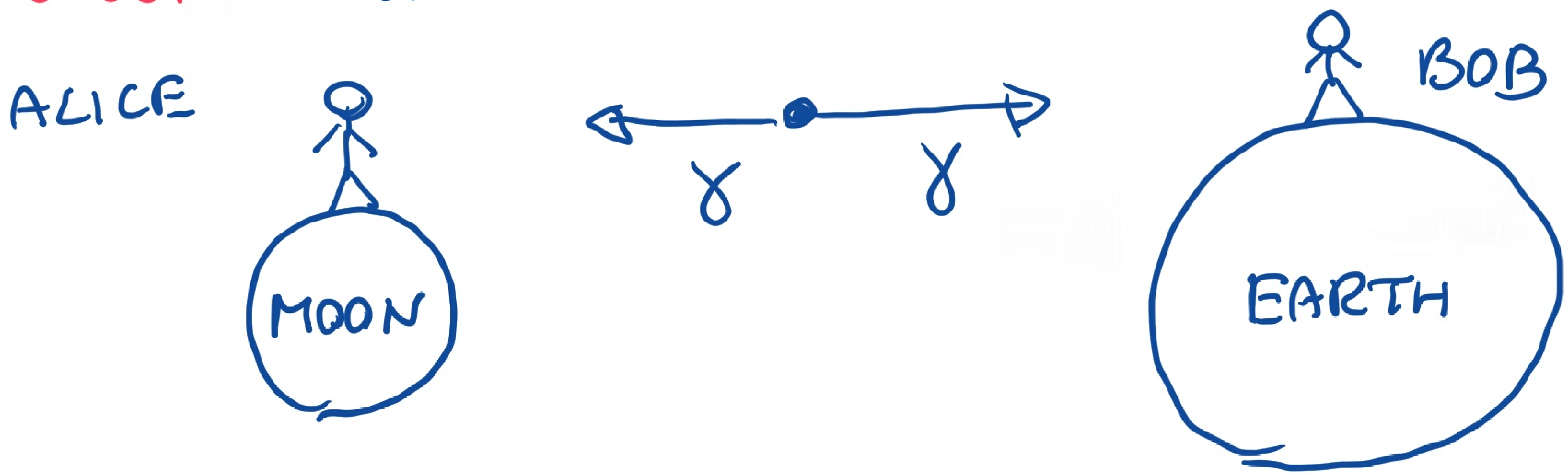



PLANETS
ATOMS
PARTONS
HADRONS
INDETERMINISTIC
DETERMINISTIC
CLASSICAL MECHANICS
QUANTUM MECHANICS
STATISTICAL MECHANICS
MODEL PREDICTIONS:
P(μSTATE)
μSTATE
μSTATE
μ STATE

# NATURE IS NON-LOCAL

REMOTE EVENTS ARE CORRELATED BY INSTANTENOUS "GHOST" INTERACTIONS




ALICE'S RESULTS ARE CORRELATED WITH BOB'S RESULTS (STILL NO-WAY TO TRANSFER INFORMATION WITH $v > c$)