

NEWS ON
ONSET OF DECONFINEMENT AND CRITICAL
POINT OF STRONGLY INTERACTING MATTER
FROM NAGI/SHINE

M. GAZDZICKI, FRANKFURT, KIELCE
FOR THE NAGI/SHINE COLLABORATION

 VOCABULARY

  ONSET OF FIREBALL

   ONSET OF DECONFINEMENT

    SEARCH FOR CRITICAL POINT





VOCABULARY

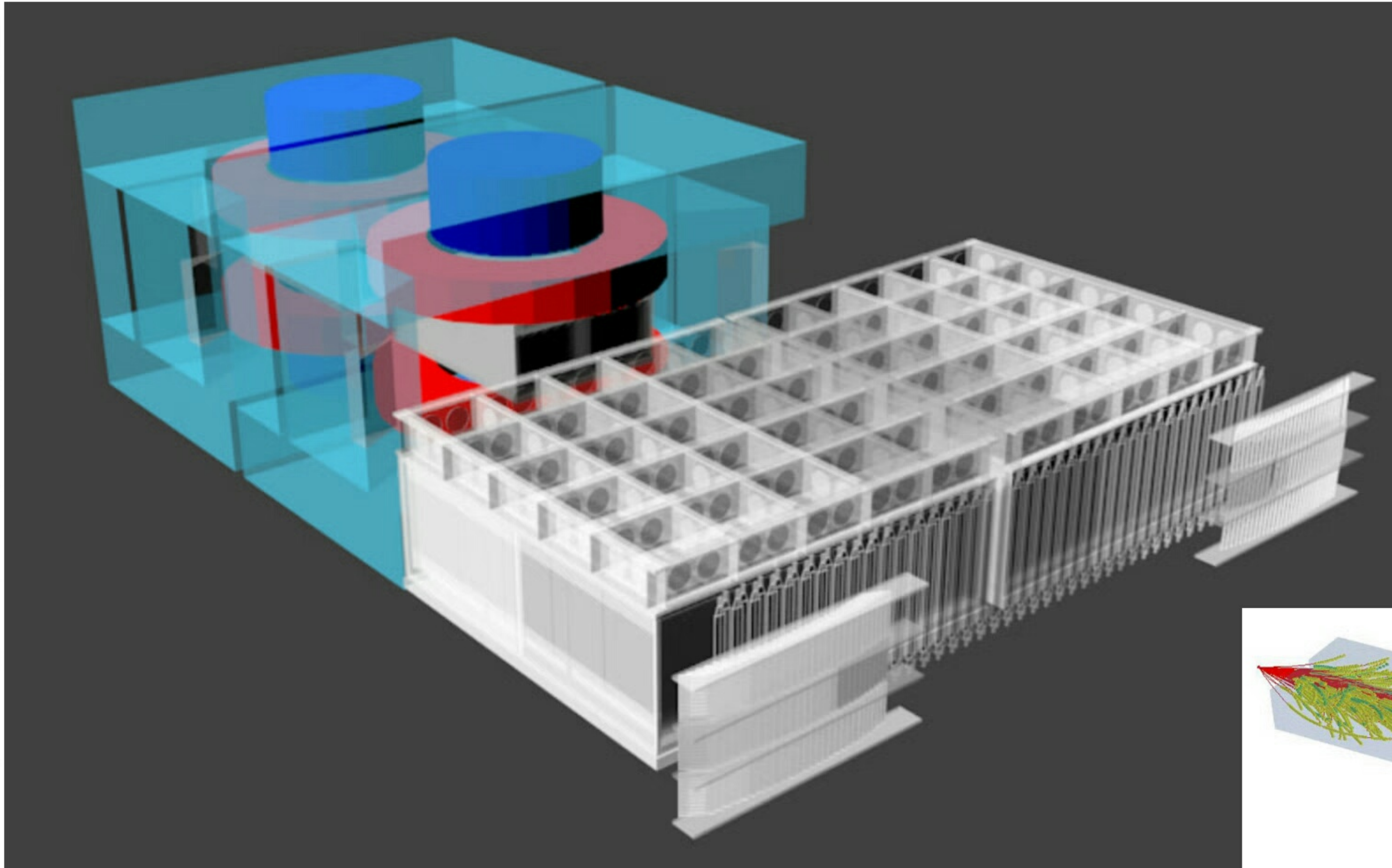
NAGI/SHINE

②

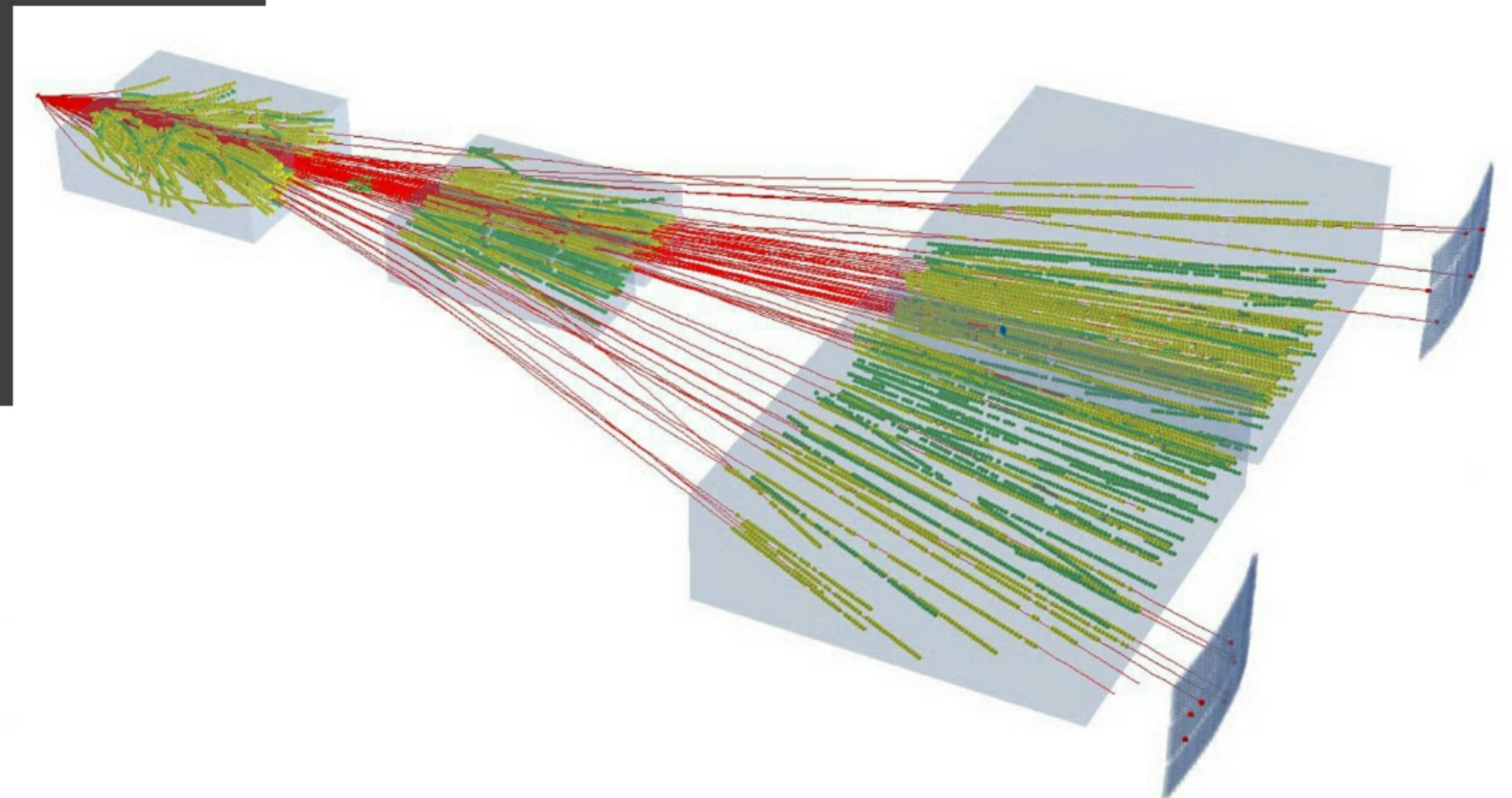
NAGI/SHINE - UNIQUE MULTIPURPOSE EXPERIMENT:
HADRON PRODUCTION IN $h+p$, $h+A$, $A+A$
AT 13A - 150A (400) GeV/c



NAGI / SHINE DETECTOR

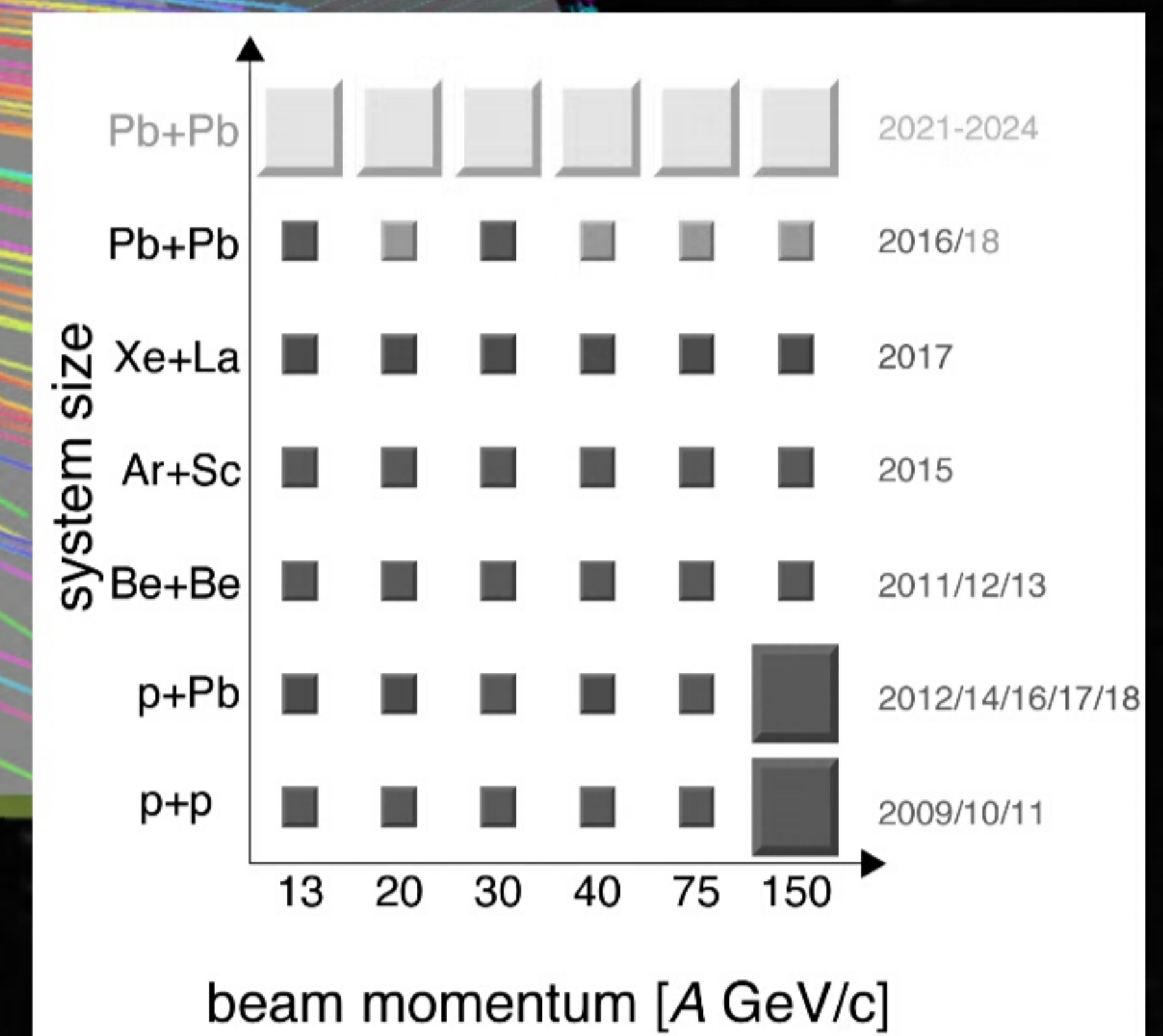


PRECISE MEASUREMENTS
OF PROPERTIES OF
PRODUCED PARTICLES:
ELECTRIC CHARGE, MASS
MOMENTUM VECTOR



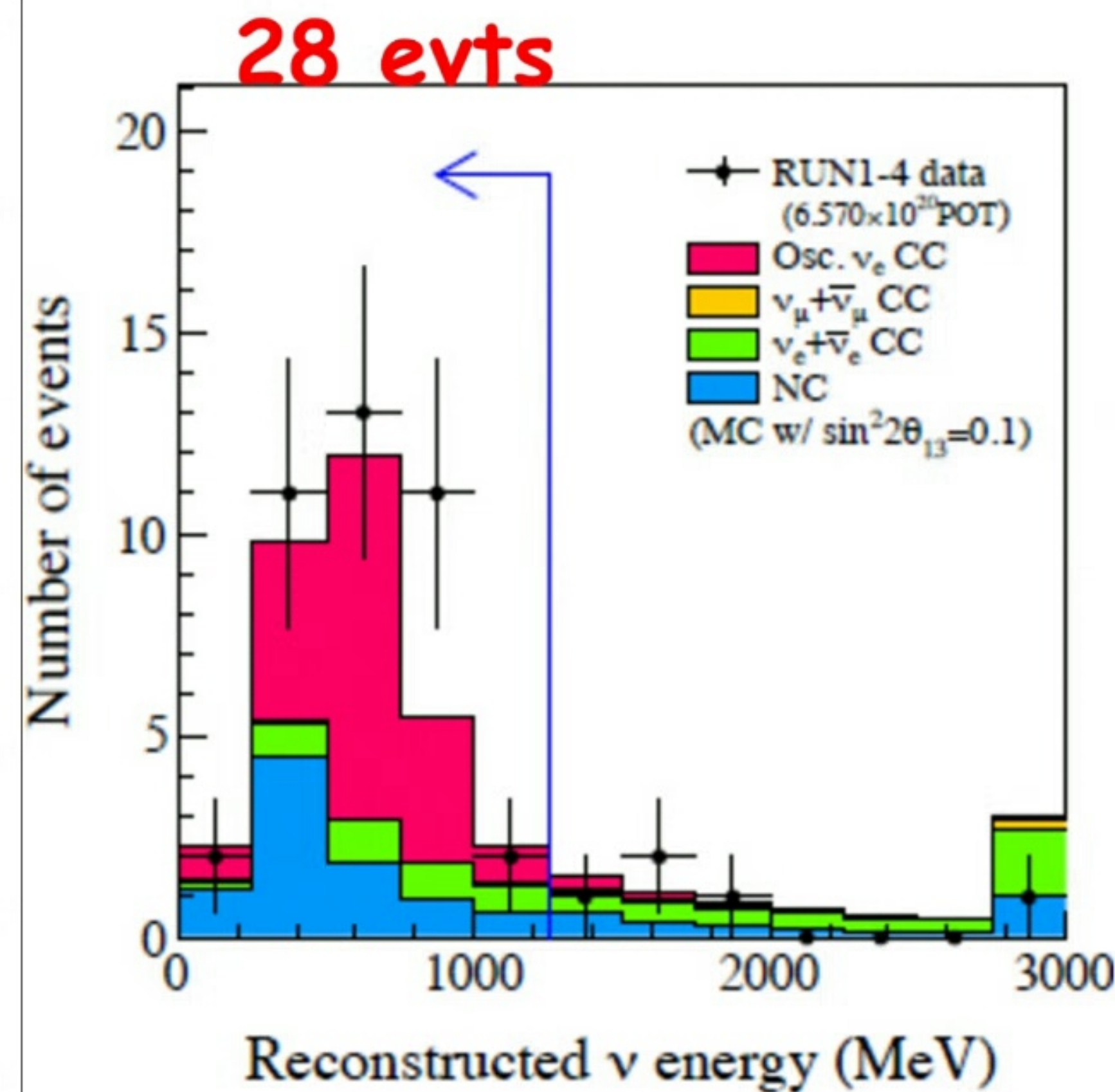
MEASUREMENTS OF HADRON PRODUCTION PROPERTIES FOR

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

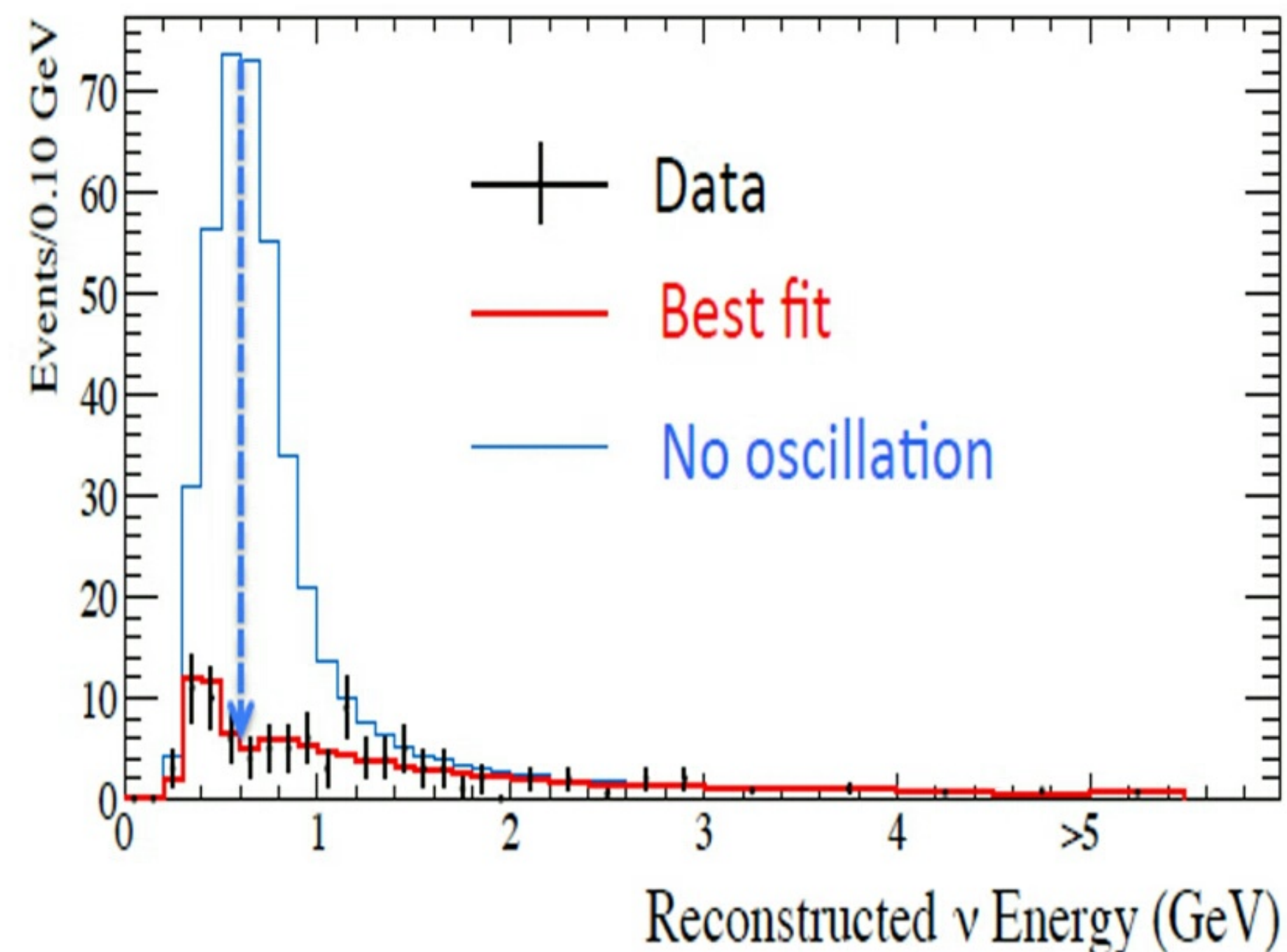


T2K ACHIEVEMENTS AND NAGI/SHINE

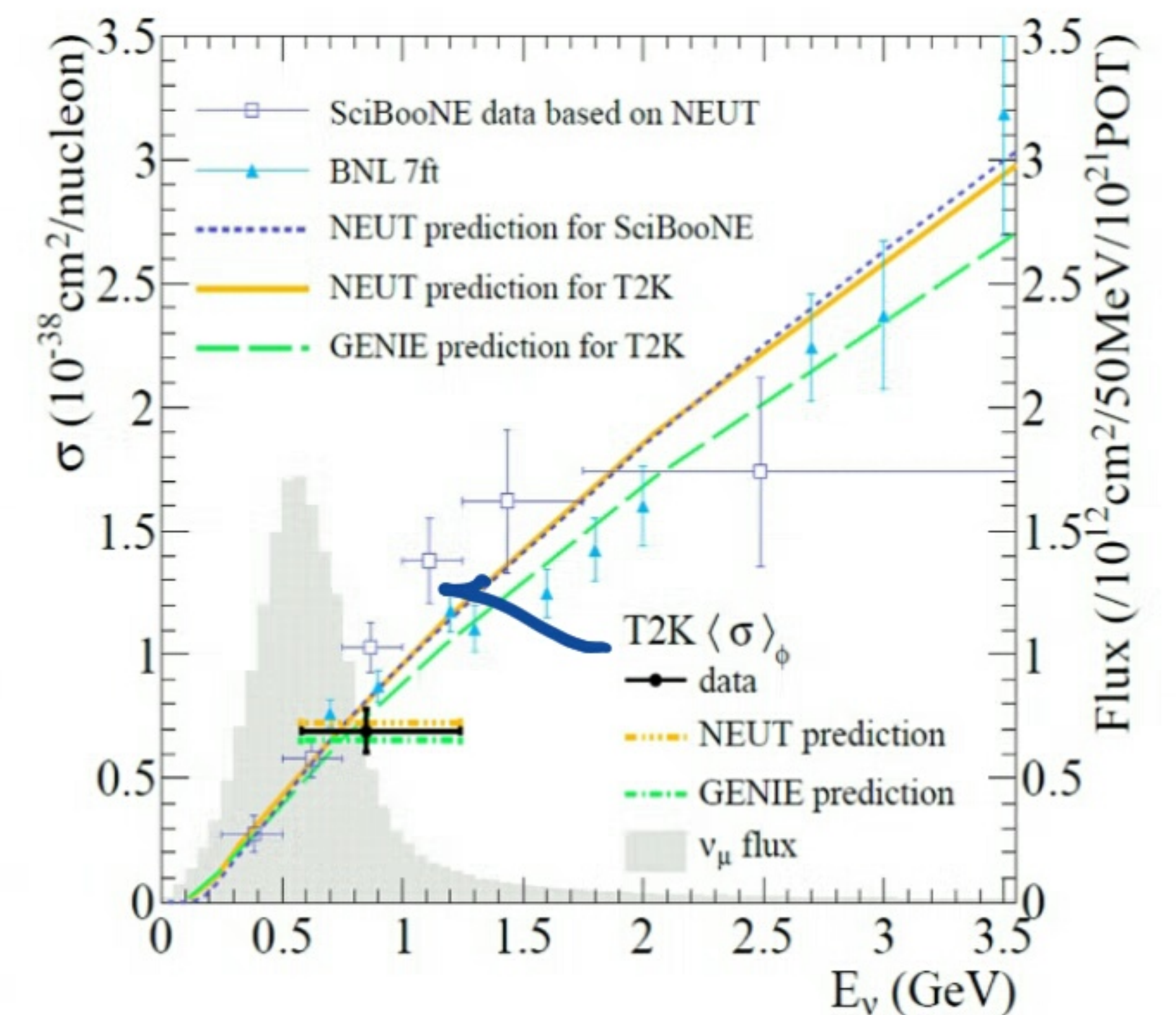
DISCOVERY OF $\nu_\mu \rightarrow \nu_e$ APPEARANCE



ν_μ DISAPPEARANCE



ν_μ CROSS SECTION



INITIAL NEUTRINO FLUX DETERMINATION

NEAR DETECTOR
NAGI / SHINE

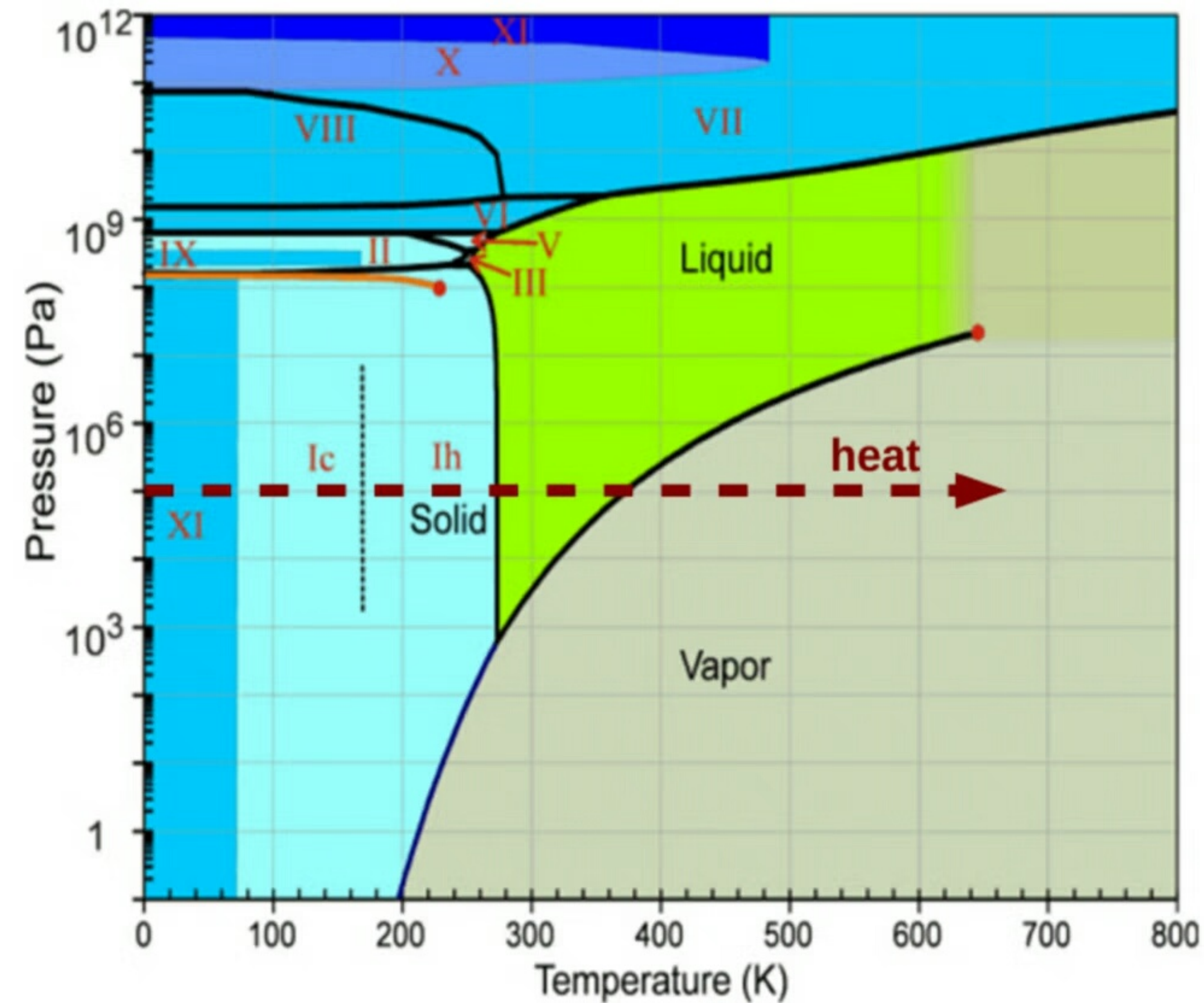
NEAR DETECTOR
NAGI / SHINE

NAGI / SHINE

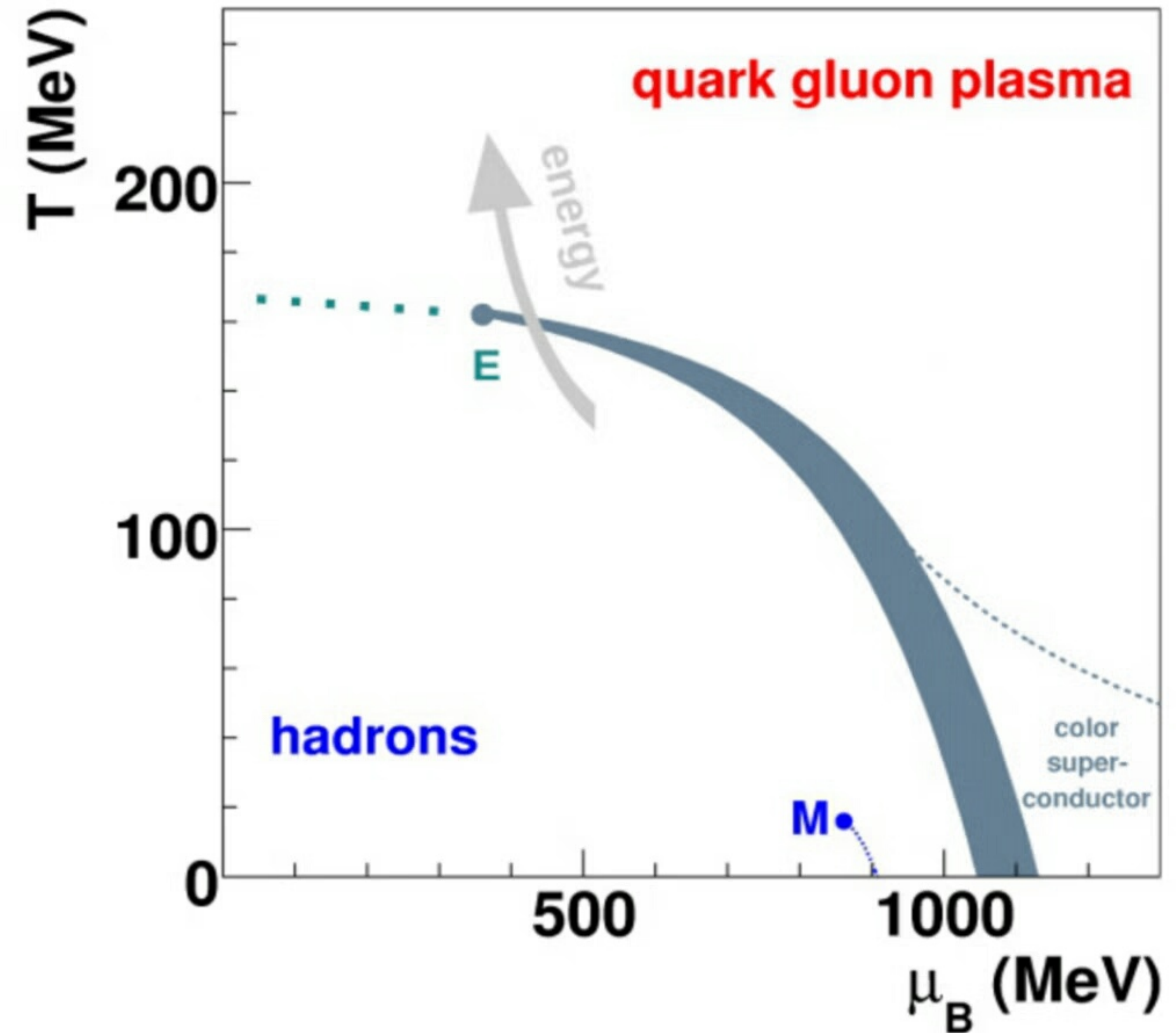
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PHASE DIAGRAM

OF WATER



OF STRONGLY INTERACTING MATTER



NAGI/SHINE:

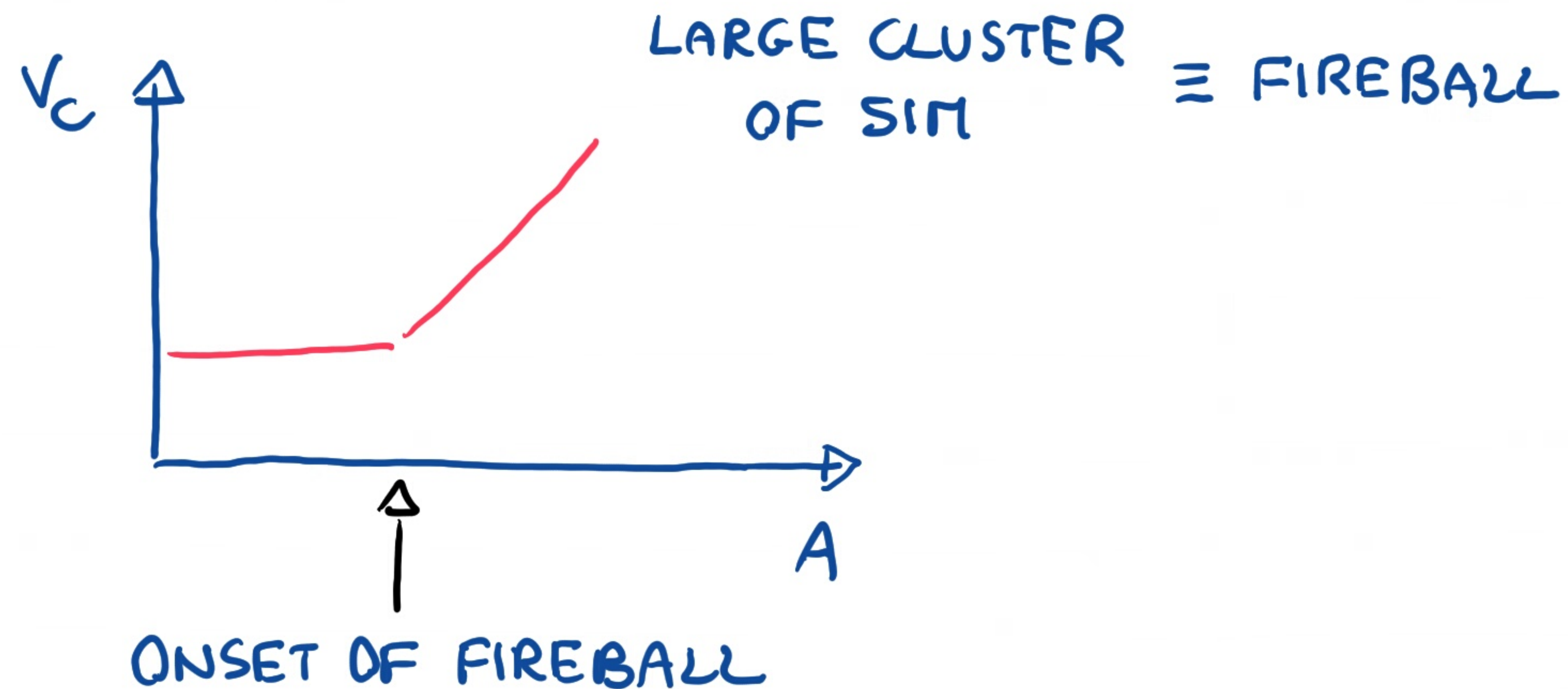
→ PHASE TRANSITION VS VOLUME

→ SEARCH FOR CRITICAL POINT

⑤

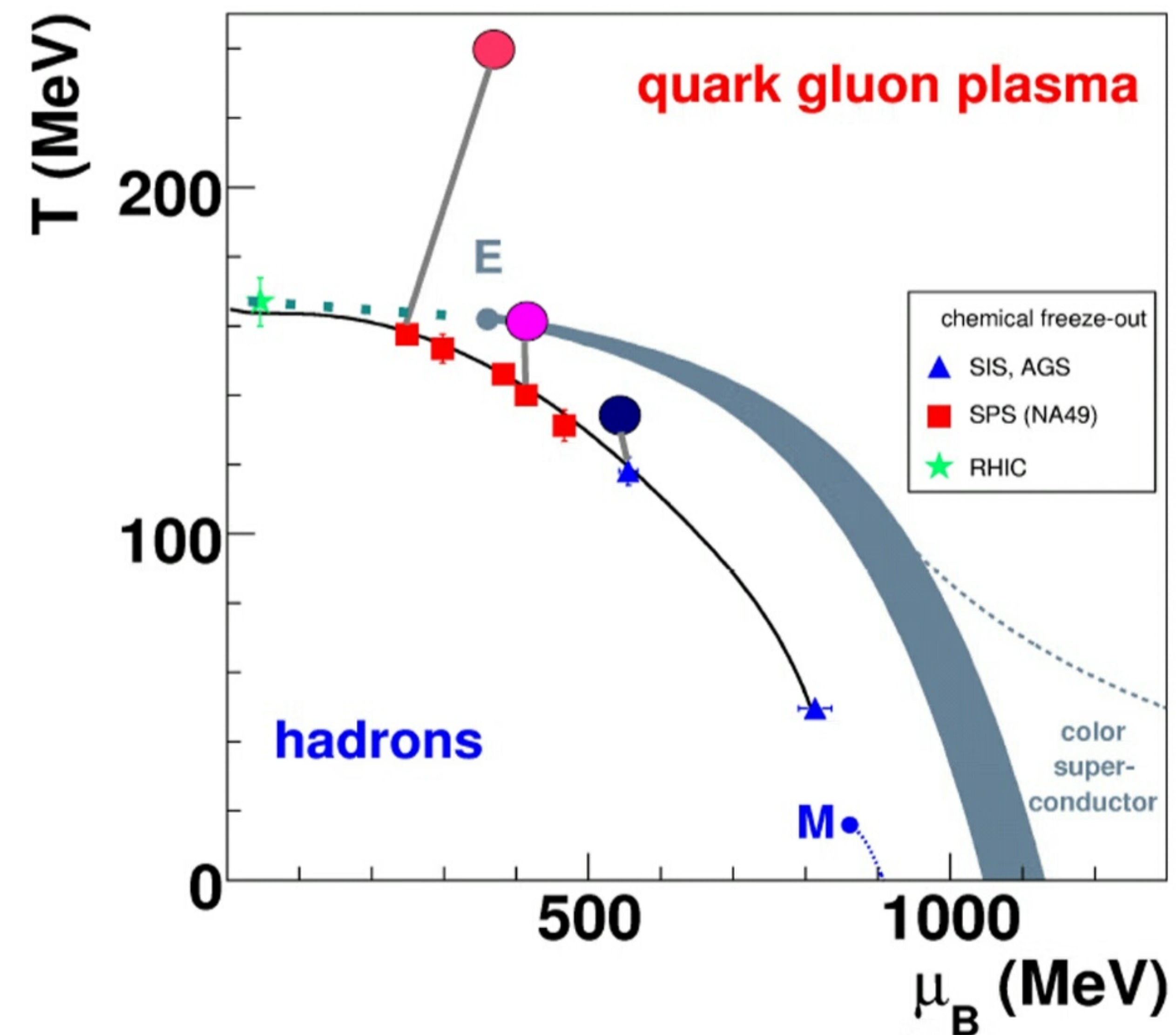
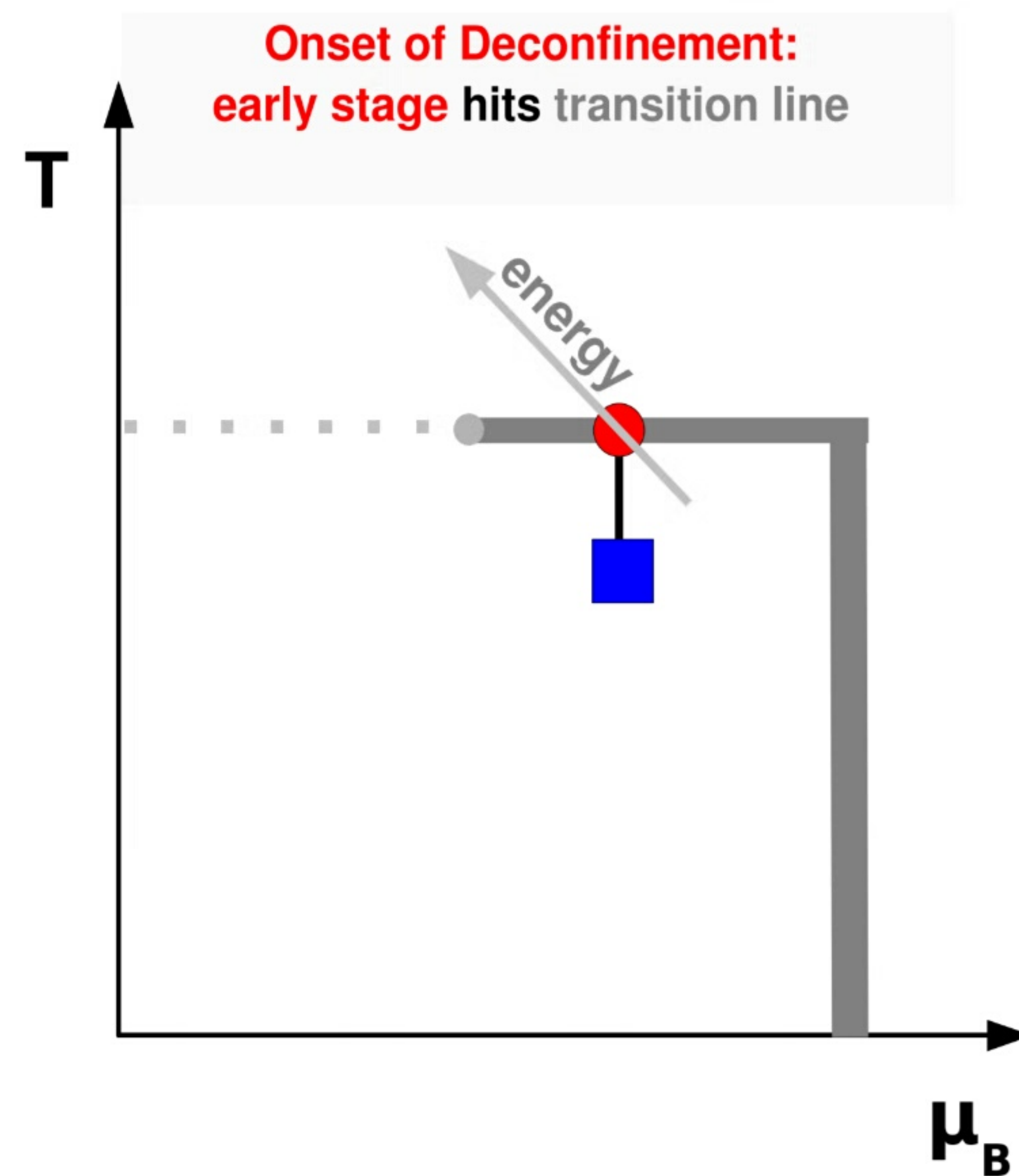
ONSET OF FIREBALL

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



ONSET OF DECONFINEMENT

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



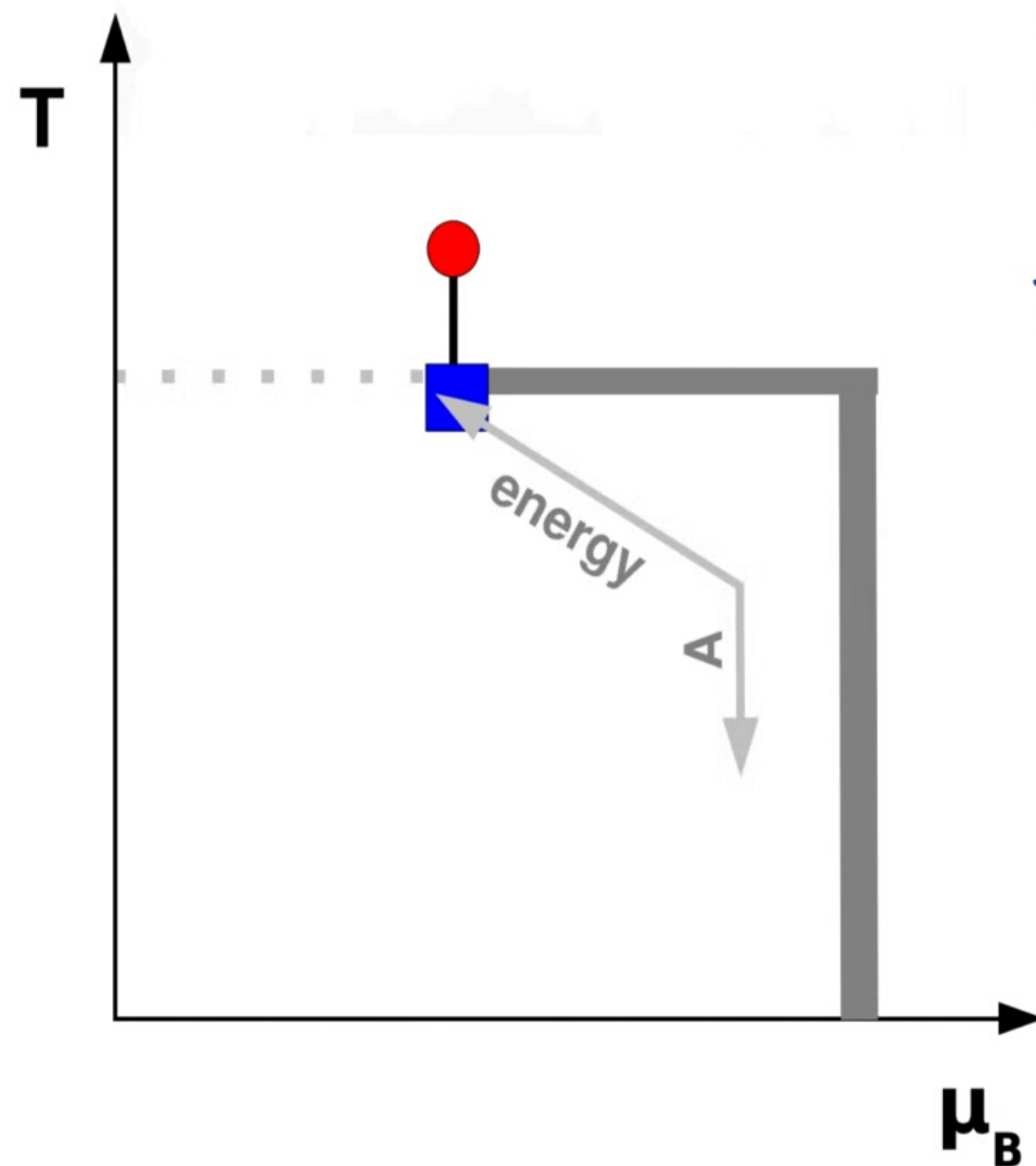
⑧

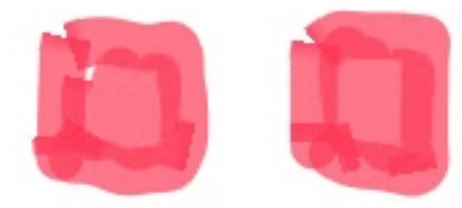
CRITICAL POINT OF SIM

≡ 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

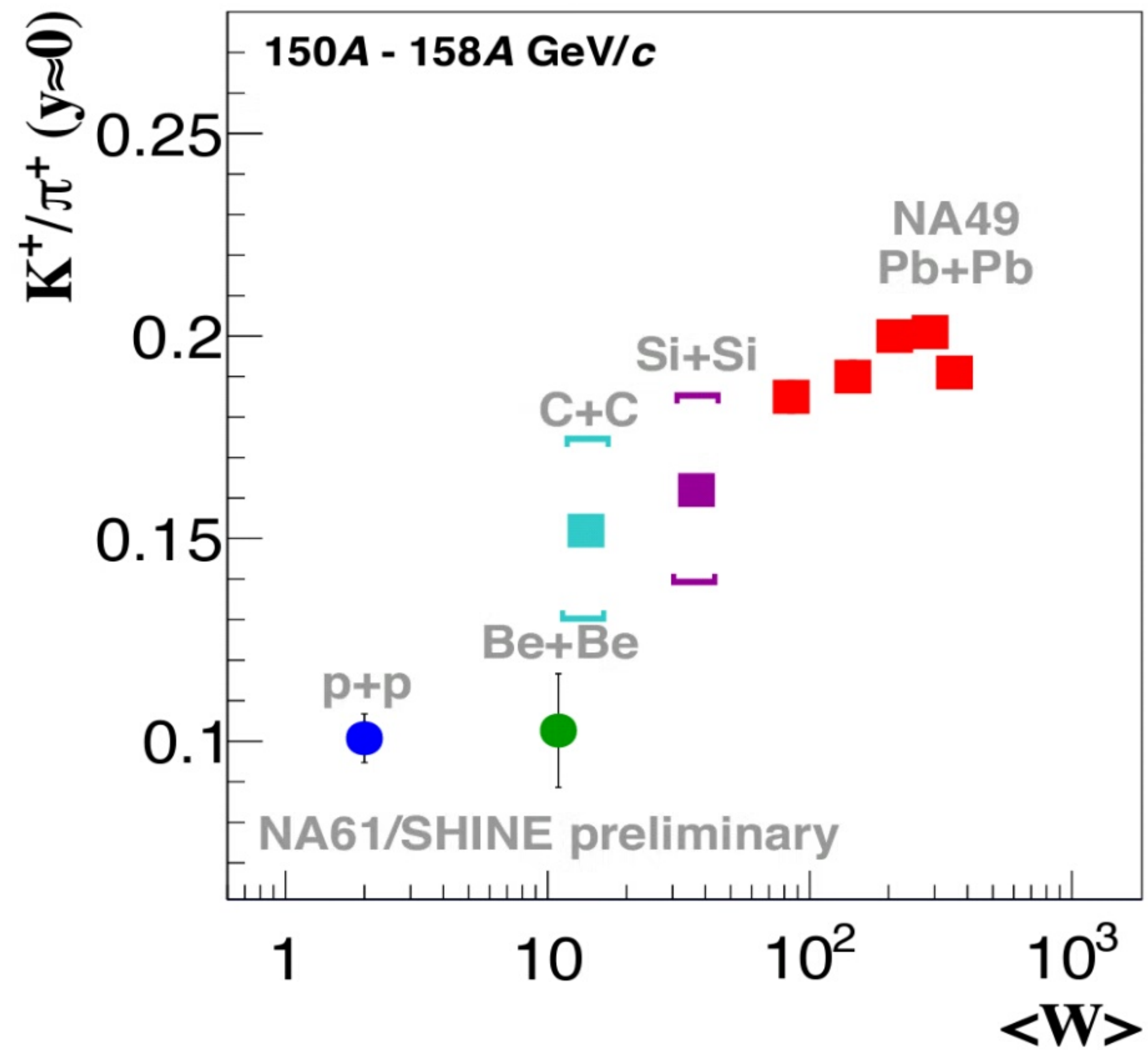
≡ SCAN IN $\sqrt{s_{NN}}$ AND A TO POSITION
FREEZE-OUT POINT CLOSE TO CP



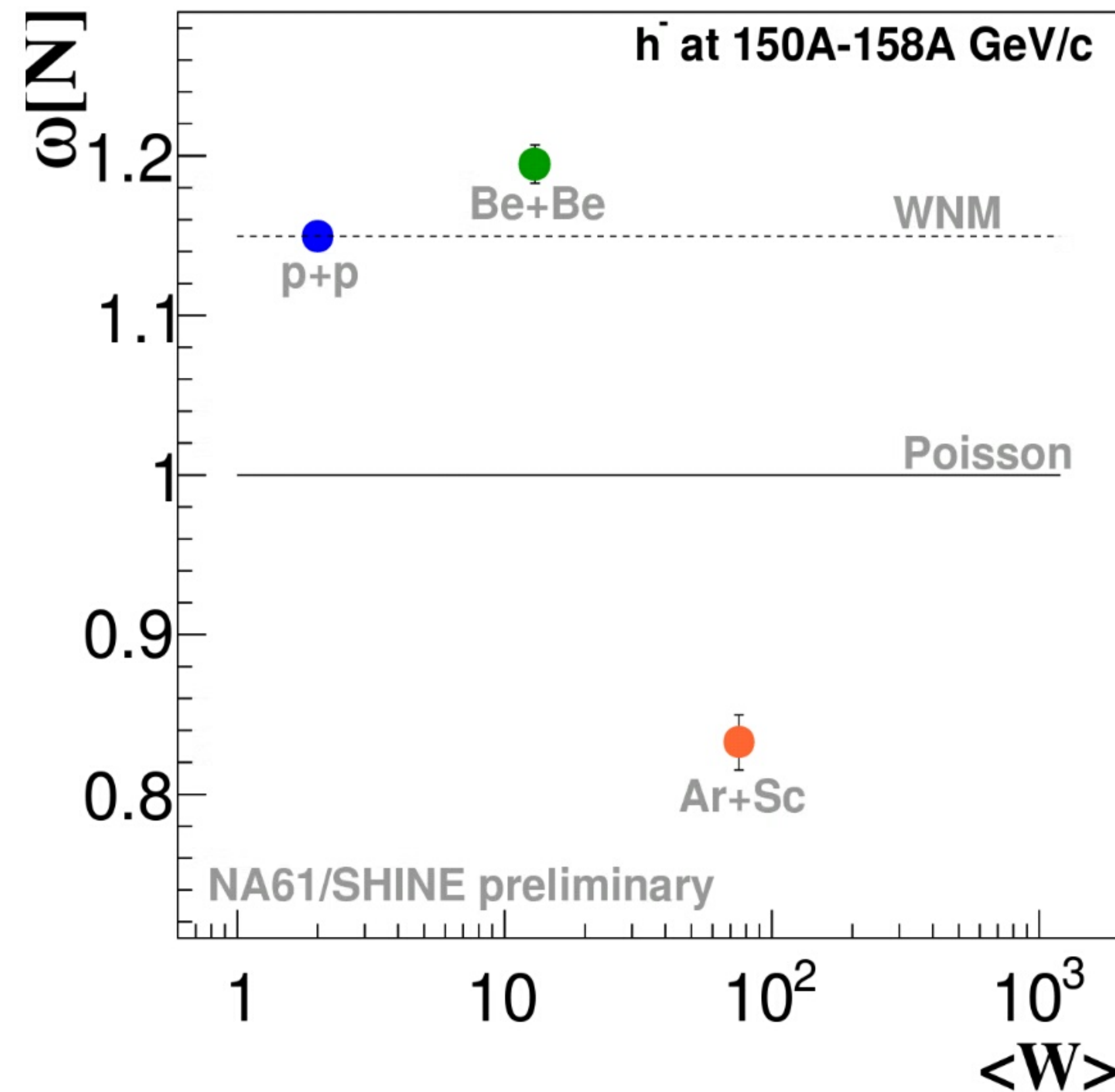


ONSET OF FIREBALL

MEAN MULTIPLICITY RATIO



MULTIPLICITY FLUCTUATIONS



$$w[N] \equiv \frac{\text{Var}[N]}{\langle N \rangle}$$

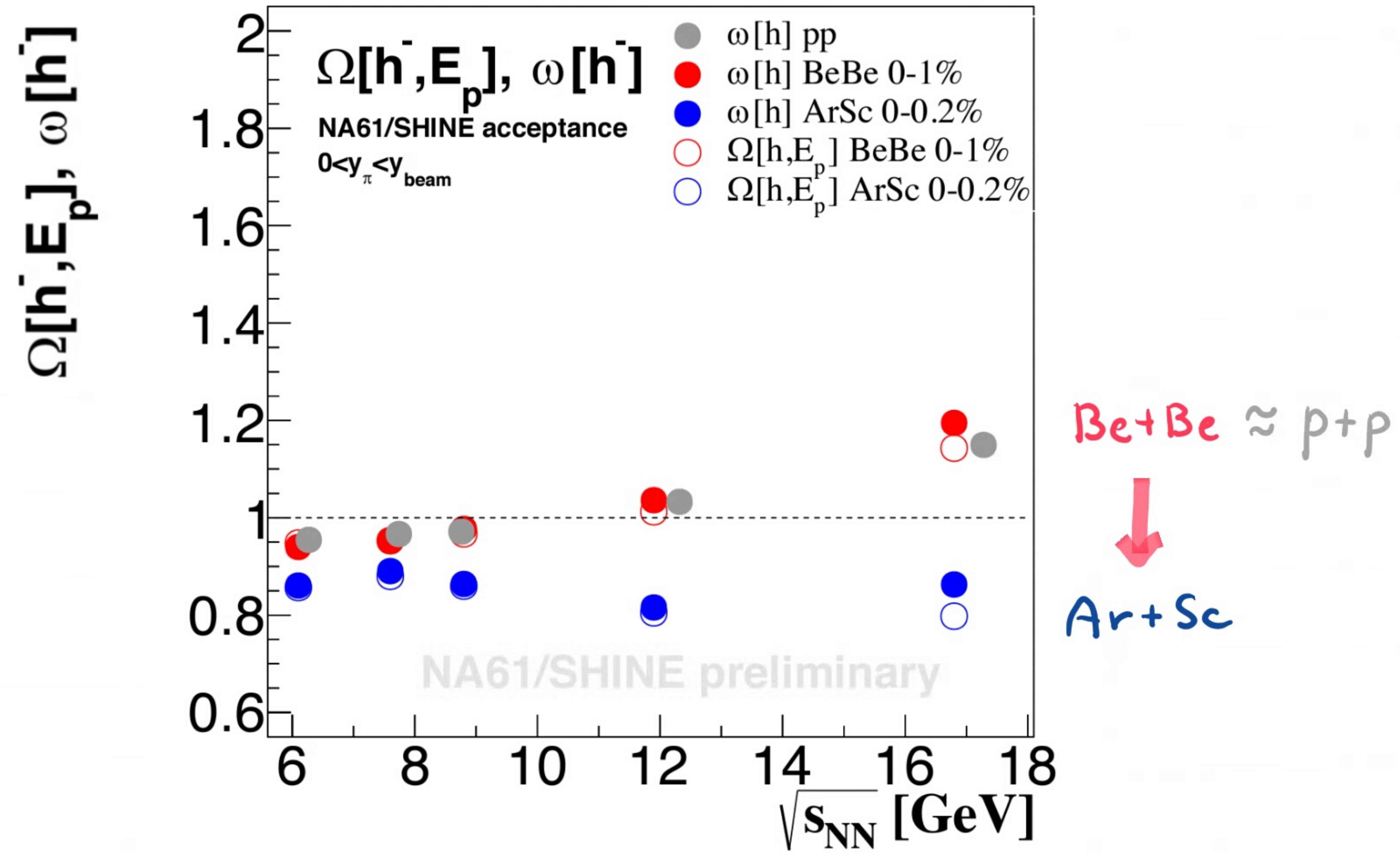


ONSET OF FIREBALL?



(NUMBER OF WOUNDED NUCLEONS)

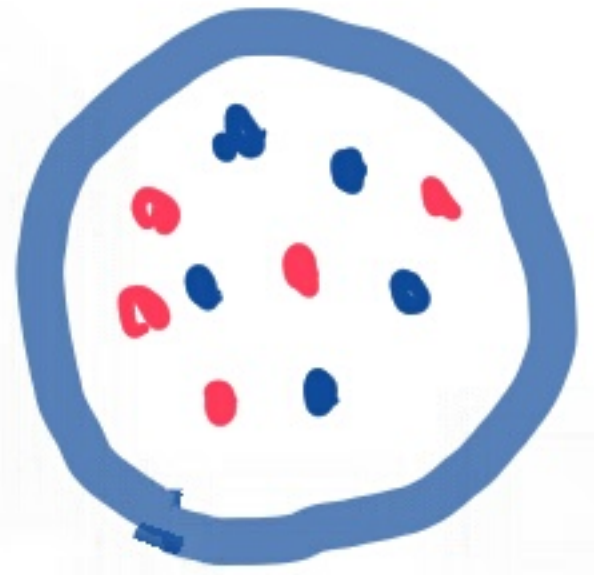
MULTIPLICITY FLUCTUATIONS



RAPID CHANGE OF A-DEPENDENCE AT $A \approx 10$
OBSERVED AT ALL SPS COLLISION ENERGIES

VOLUME DEPENDENCE OF $\langle N \rangle$ AND $w[N]$

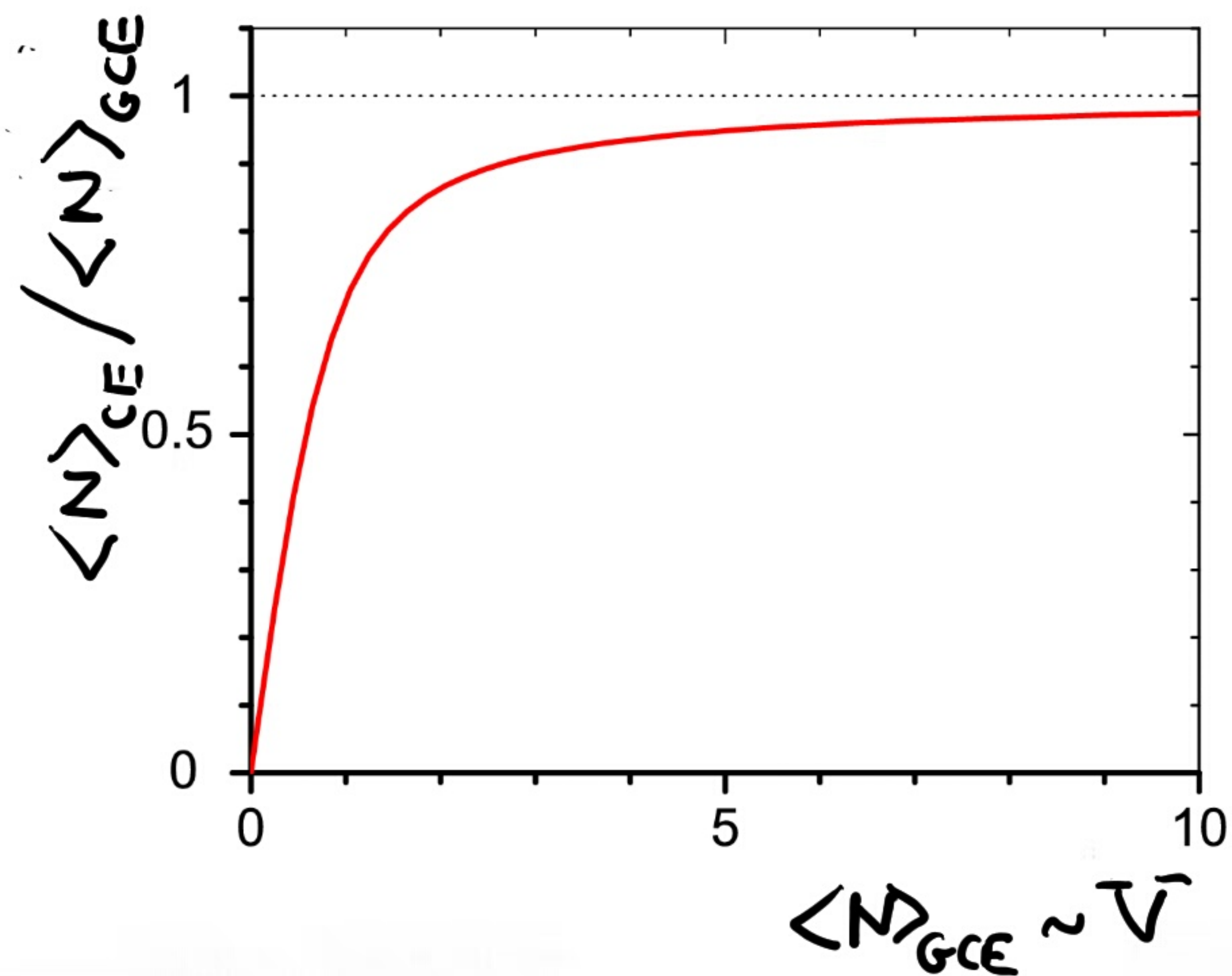
V, T
 $Q=0$



IDEAL BOLTZMANN (IB)
ENSEMBLE (CE) $\rightarrow$

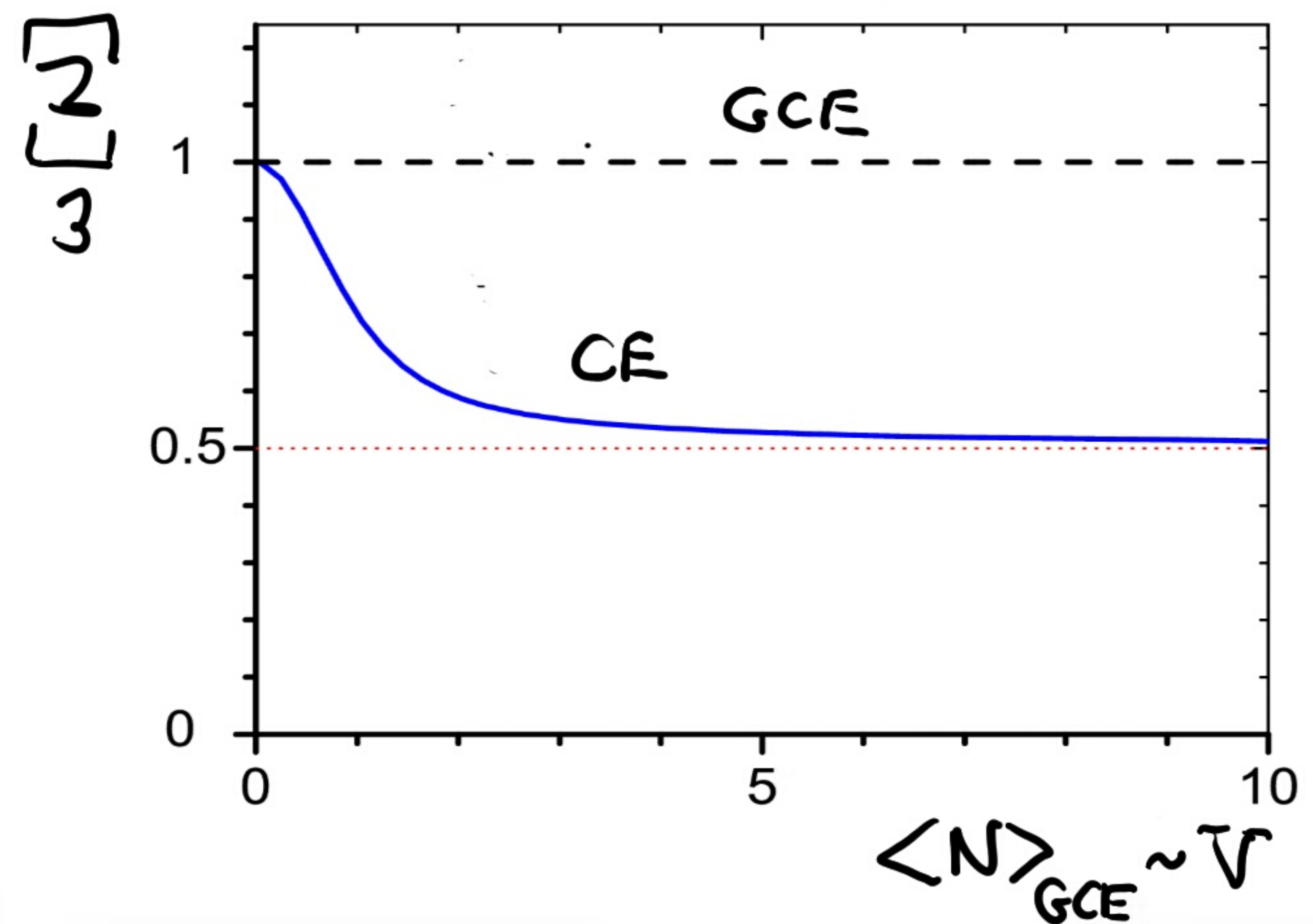
GAS WITHIN CANONICAL
NON-TRIVIAL DEPENDENCE OF
 $\langle N \rangle$ AND $w[N]$ ON V

"CANONICAL SUPPRESSION"
OF $\langle N \rangle$



DANOS, RAFELSKI

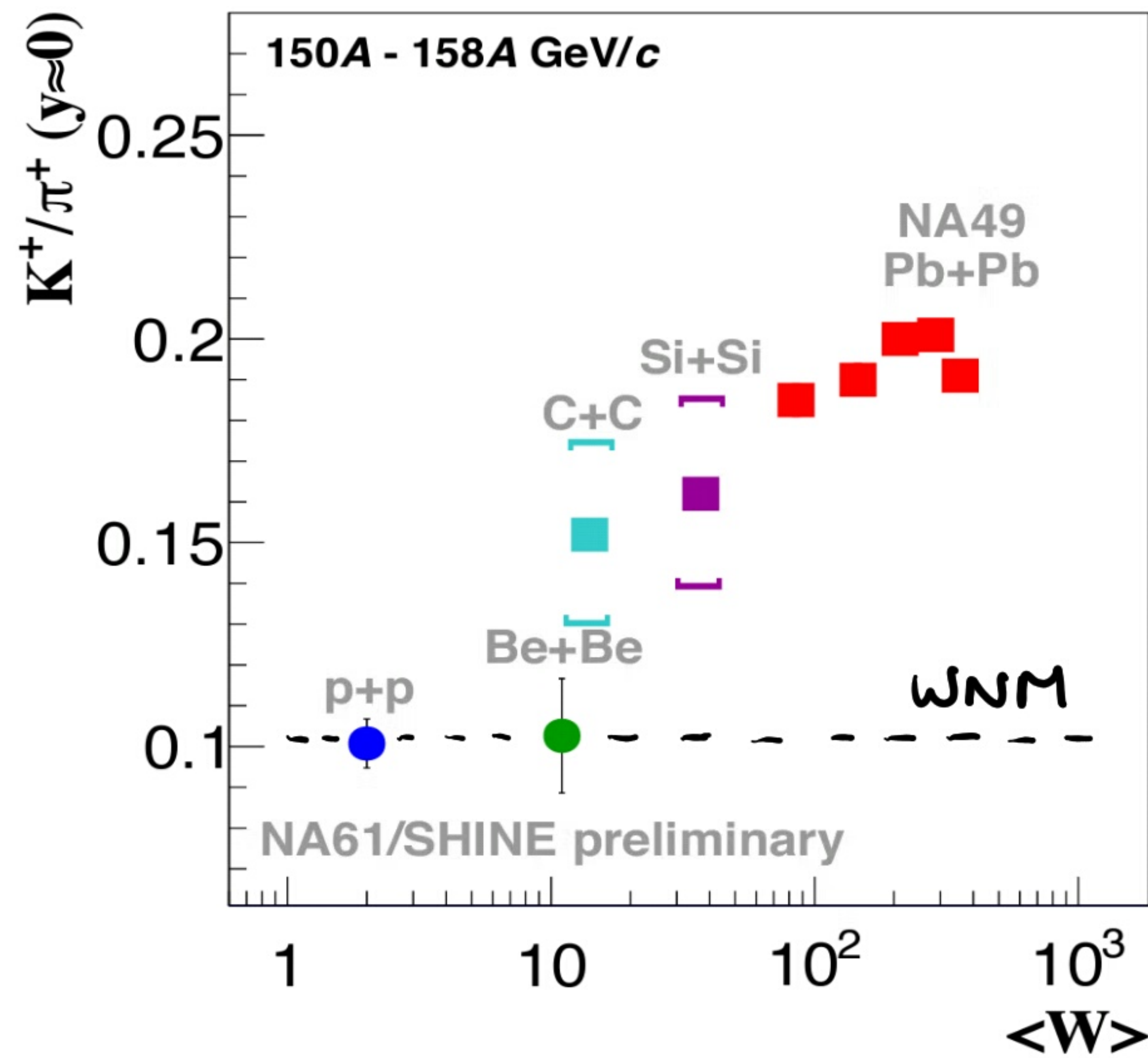
"CANONICAL ENHANCEMENT"
OF $w[N]$



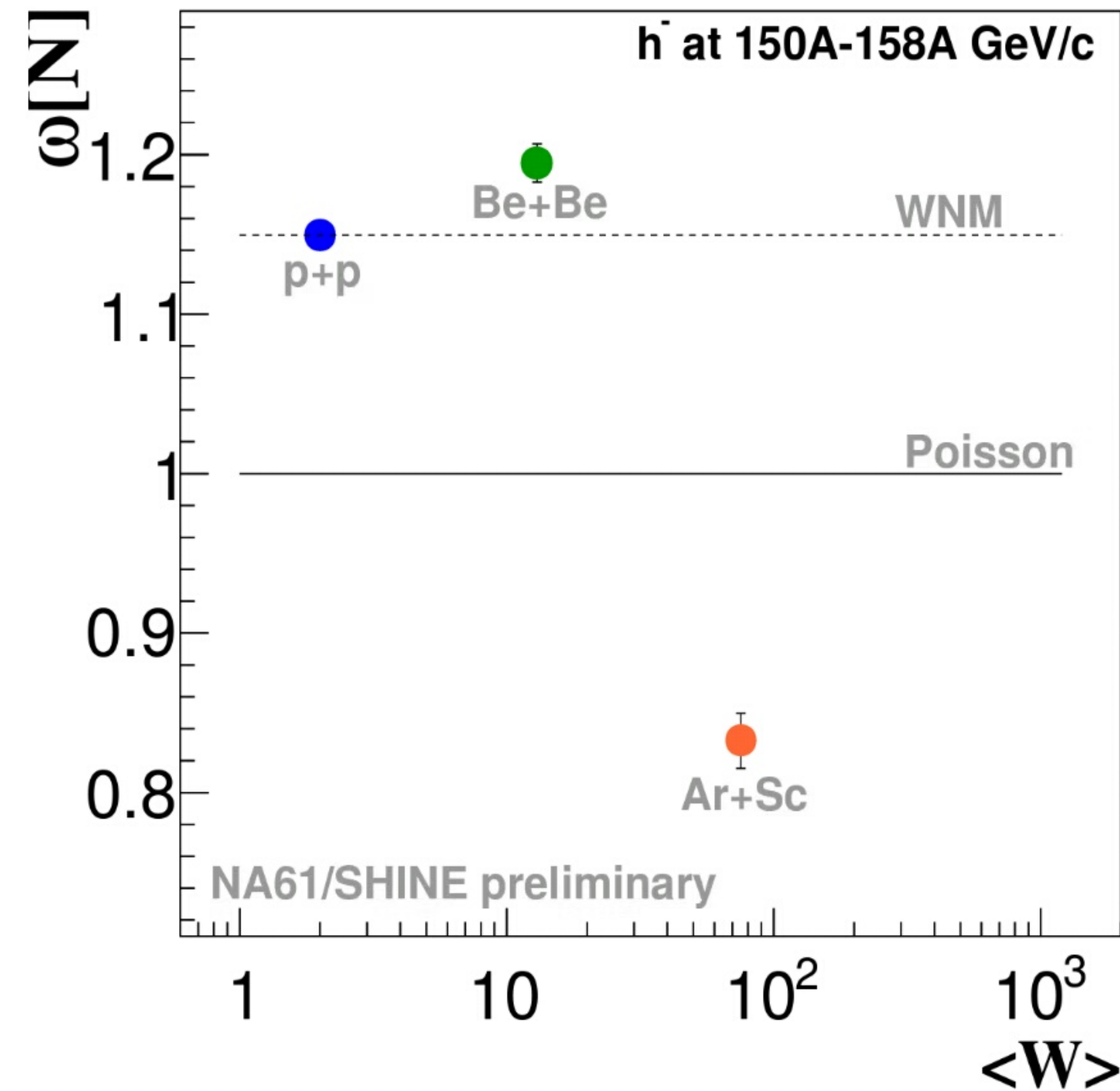
BEGUN, MG, GARENSTEIN, ZOZULYA

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

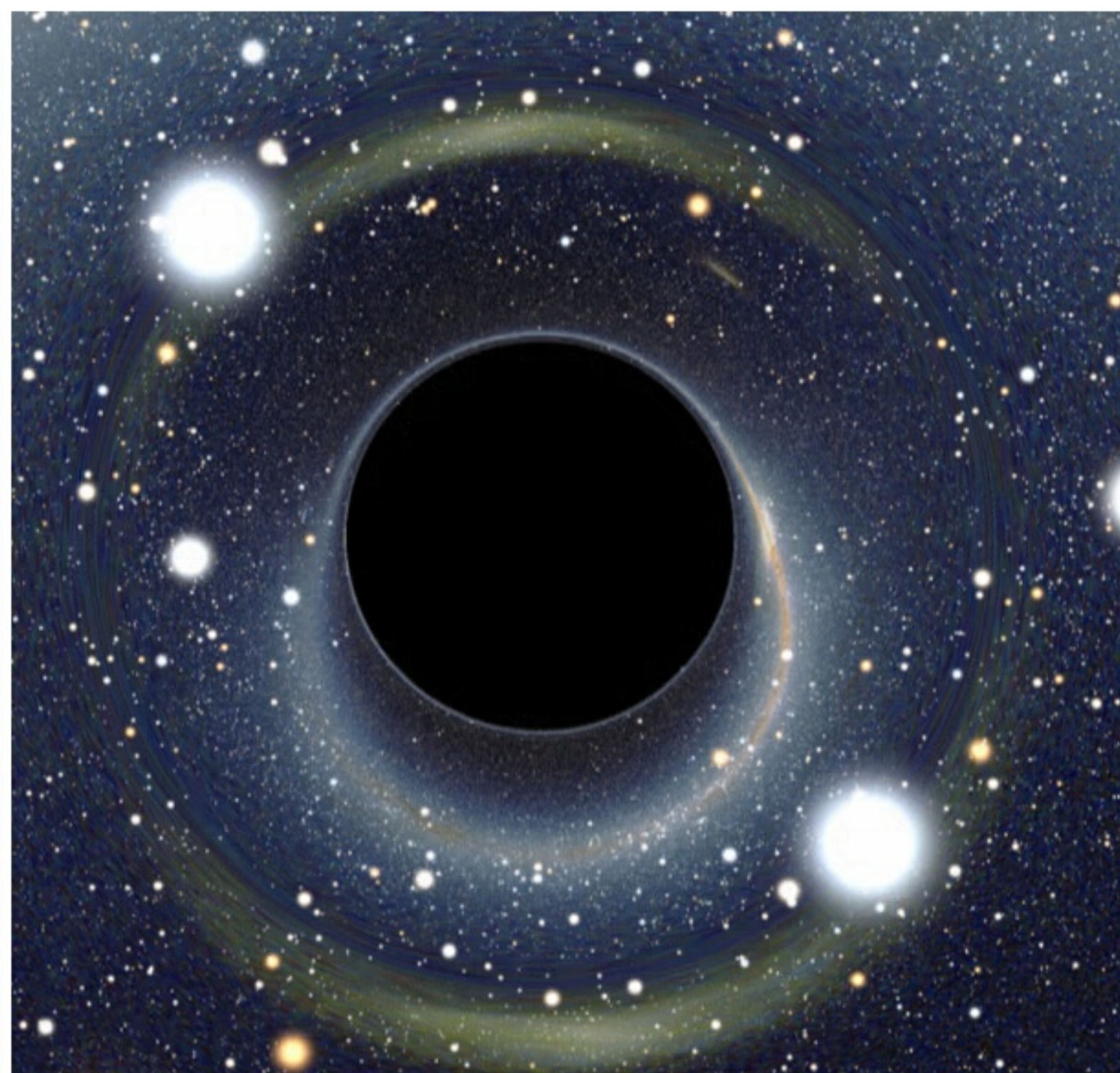
CUNQUEIRO, FERREIRO, MORAL, PAJARES PRC75 (05) 024902

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 SURFACE) TAKES PLACE WHEN CRITICAL VALUES OF MODEL PARAMETERS ARE REACHED.

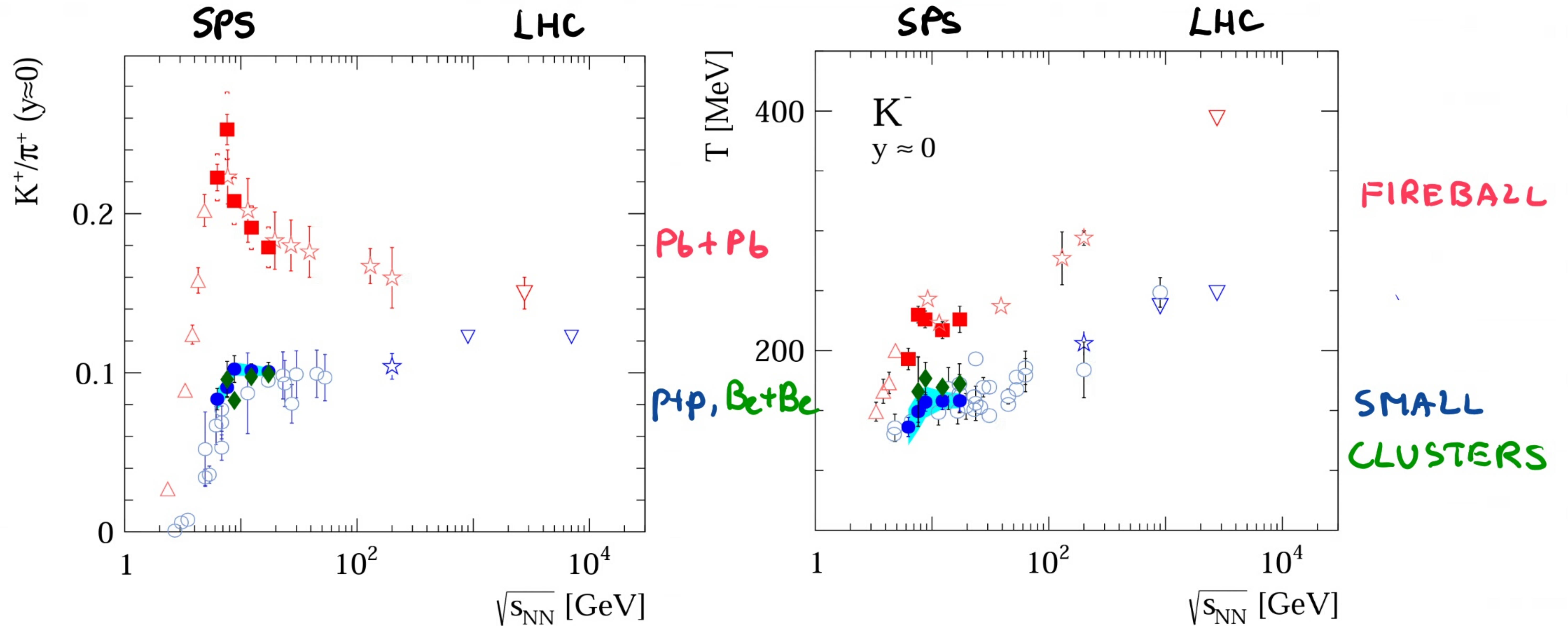
CFT (QCD): ONLY STARTING FROM A SUFFICIENTLY LARGE NUCLEAR MASS NUMBER THE FORMATION OF THE TRAPPING SURFACE IN A+A COLLISIONS IS POSSIBLE $\rightarrow$ ONSET OF FIREBALL



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



ONSET OF DECONFINEMENT

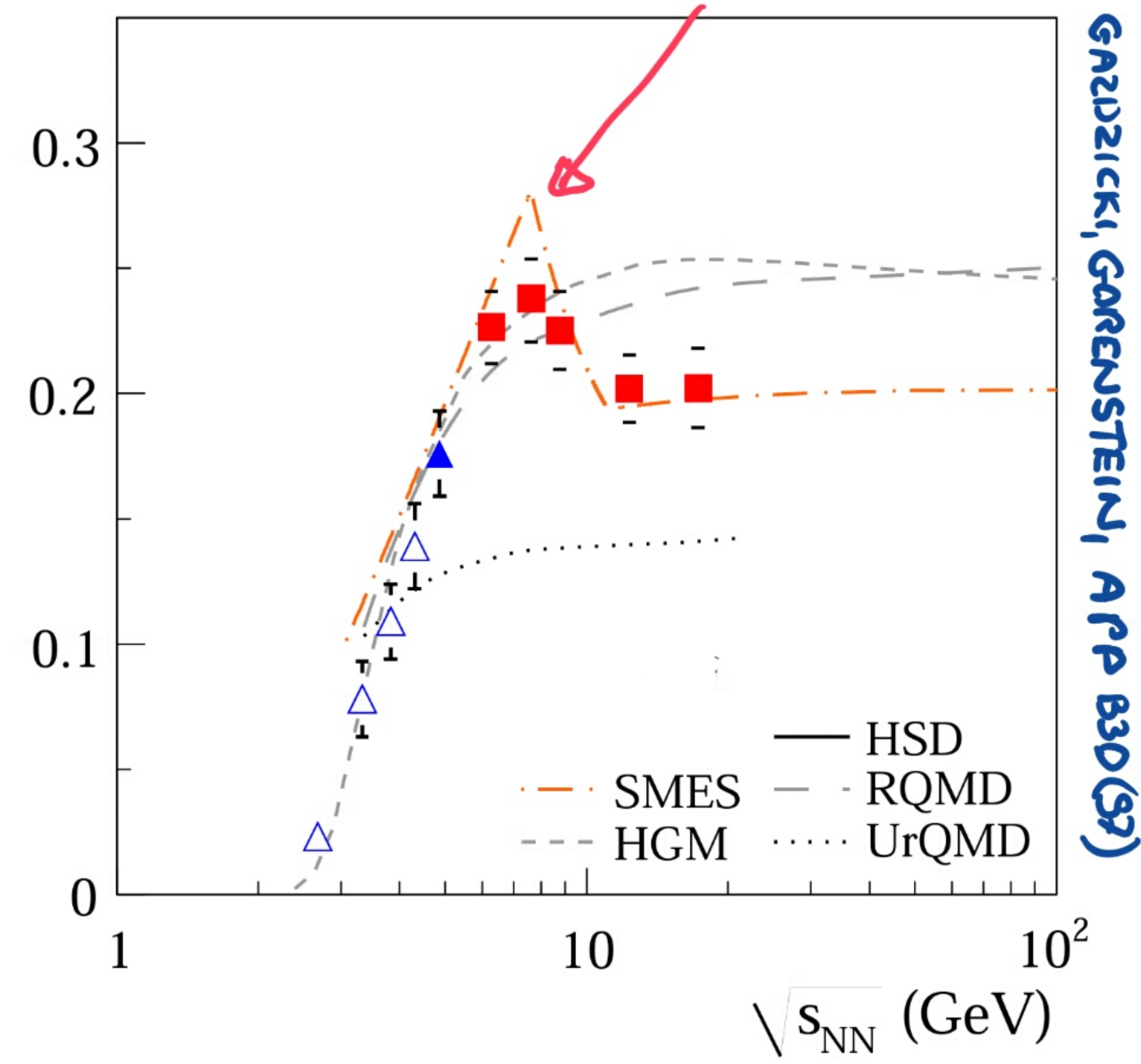


RAPID CHANGE OF $\sqrt{s_{NN}}$ -DEPENDENCE AT $\sqrt{s_{NN}} \approx 10$ GEV
OBSERVED FOR BOTH, FIREBALL AND SMALL CLUSTERS

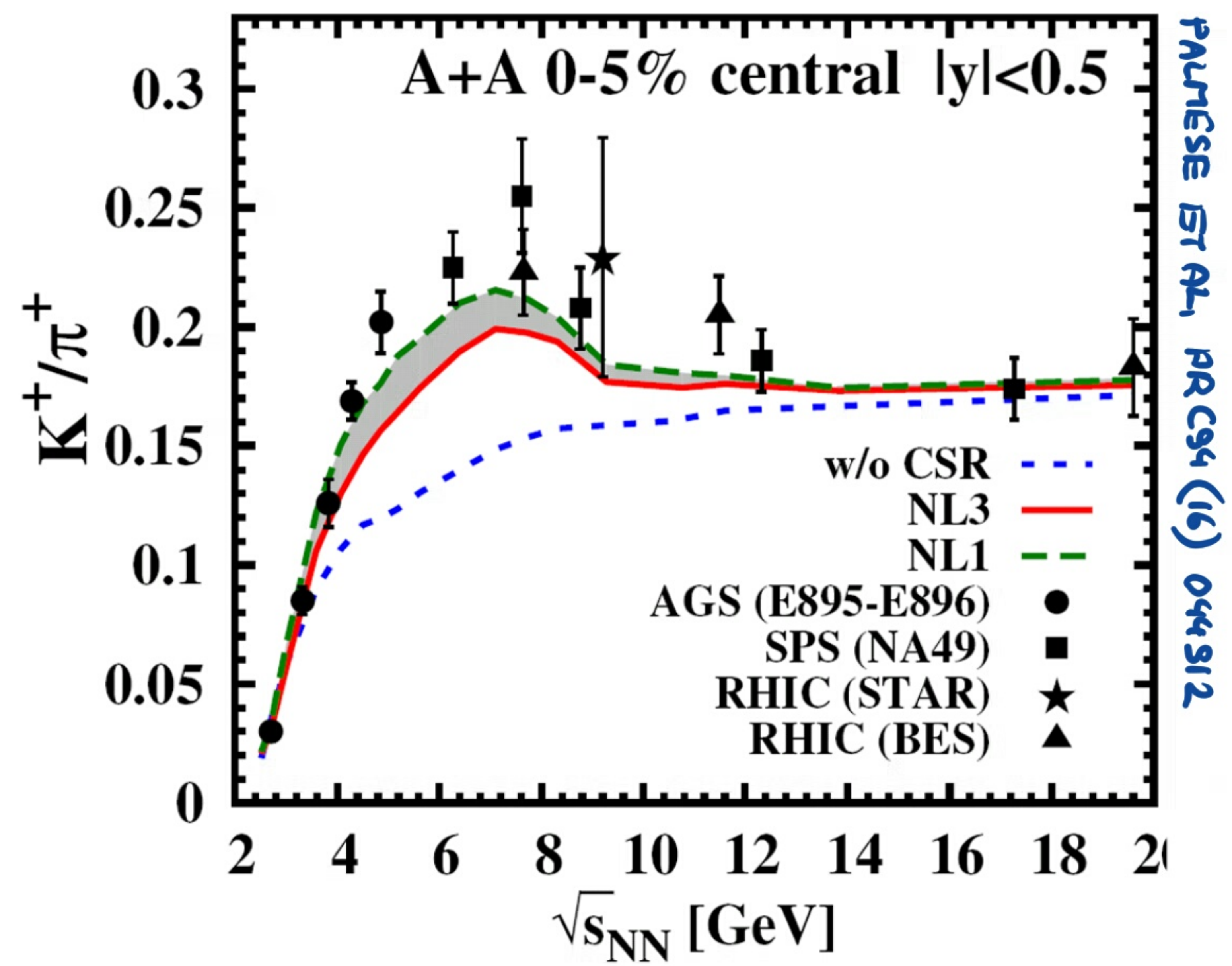
ONSET OF DECONFINEMENT IN MODELS

$$E_s \approx \frac{\langle K + \bar{K} \rangle + \langle \pi \rangle}{\langle \pi \rangle}$$

STATISTICAL: SMES

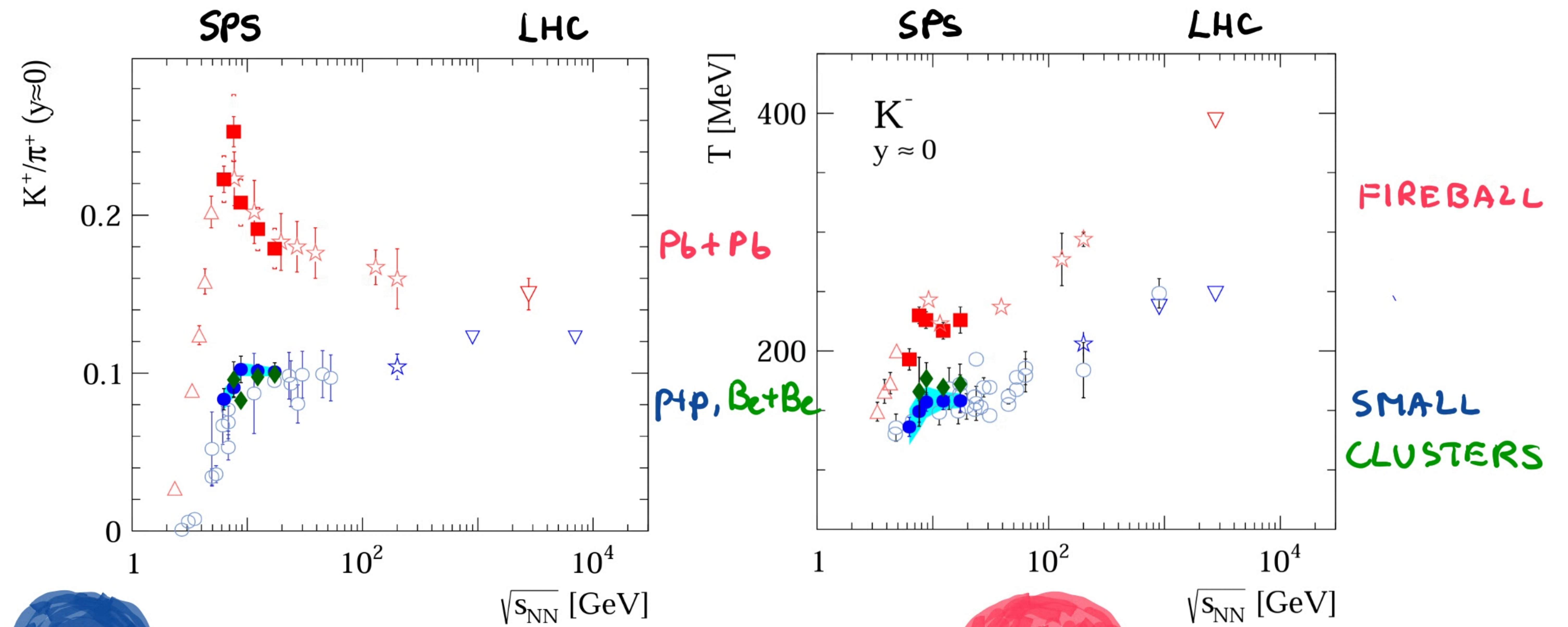


DYNAMICAL: pHSD



STATISTICAL AND DYNAMICAL MODELS WITH CHIRAL SYMMETRY RESTORATION AND DECONFINEMENT FIT P_b+P_b DATA (BUT BOTH FAIL TO REPRODUCE SMALL SYSTEMS)

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

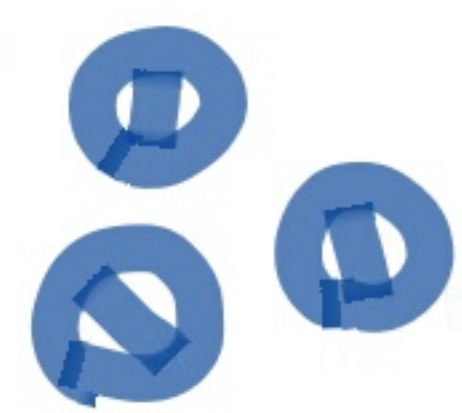
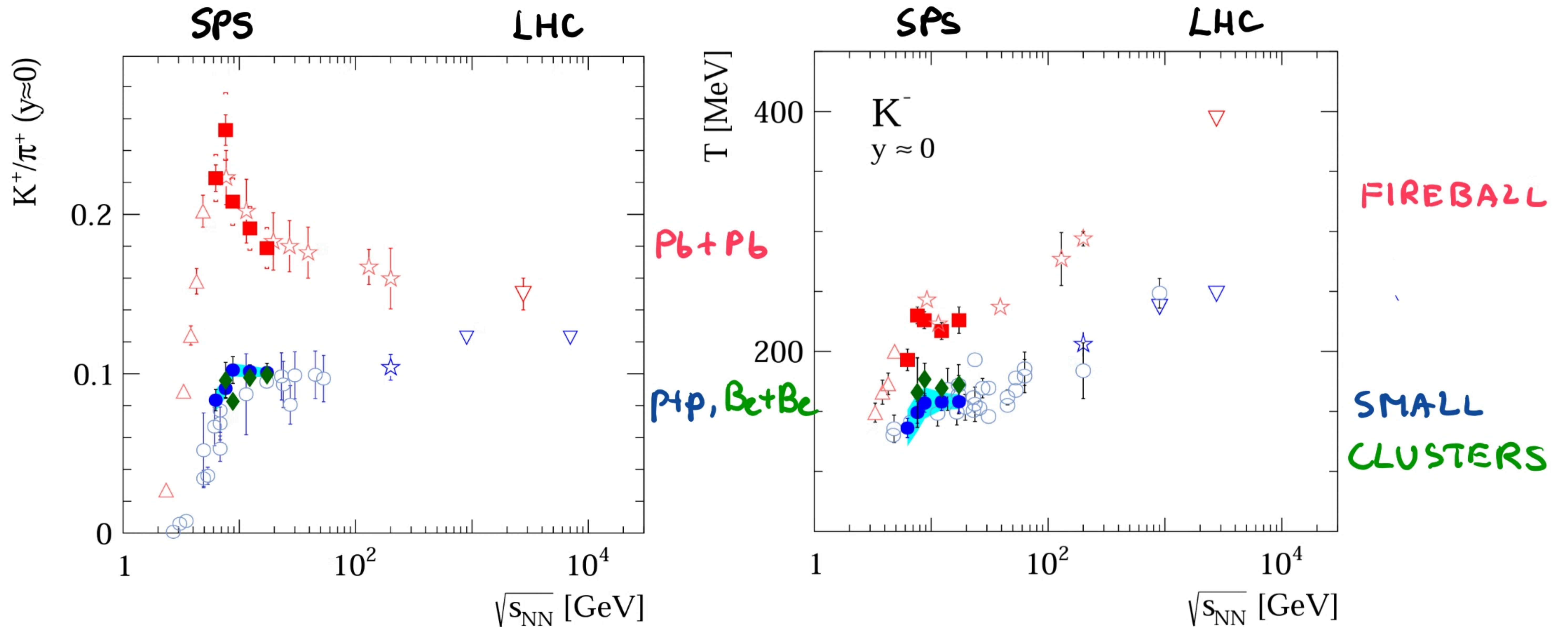


↑ ONSET OF DECONFINEMENT ↑

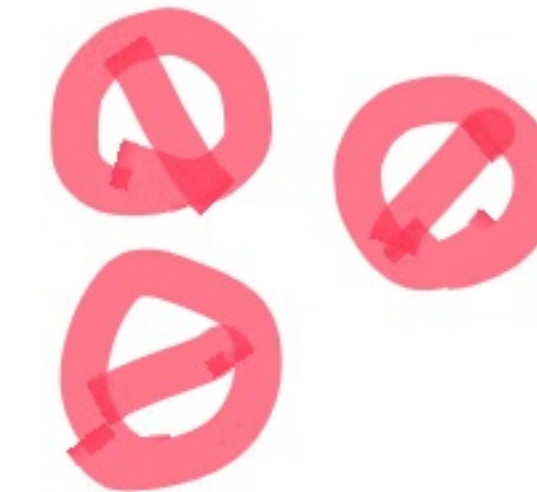


Pb+Pb CLOSE TO EQUILIBRIUM

EVIDENCE FOR ONSET OF DECONFINEMENT CHALLENGE TO UNDERSTAND pTP AND Be+Be DATA

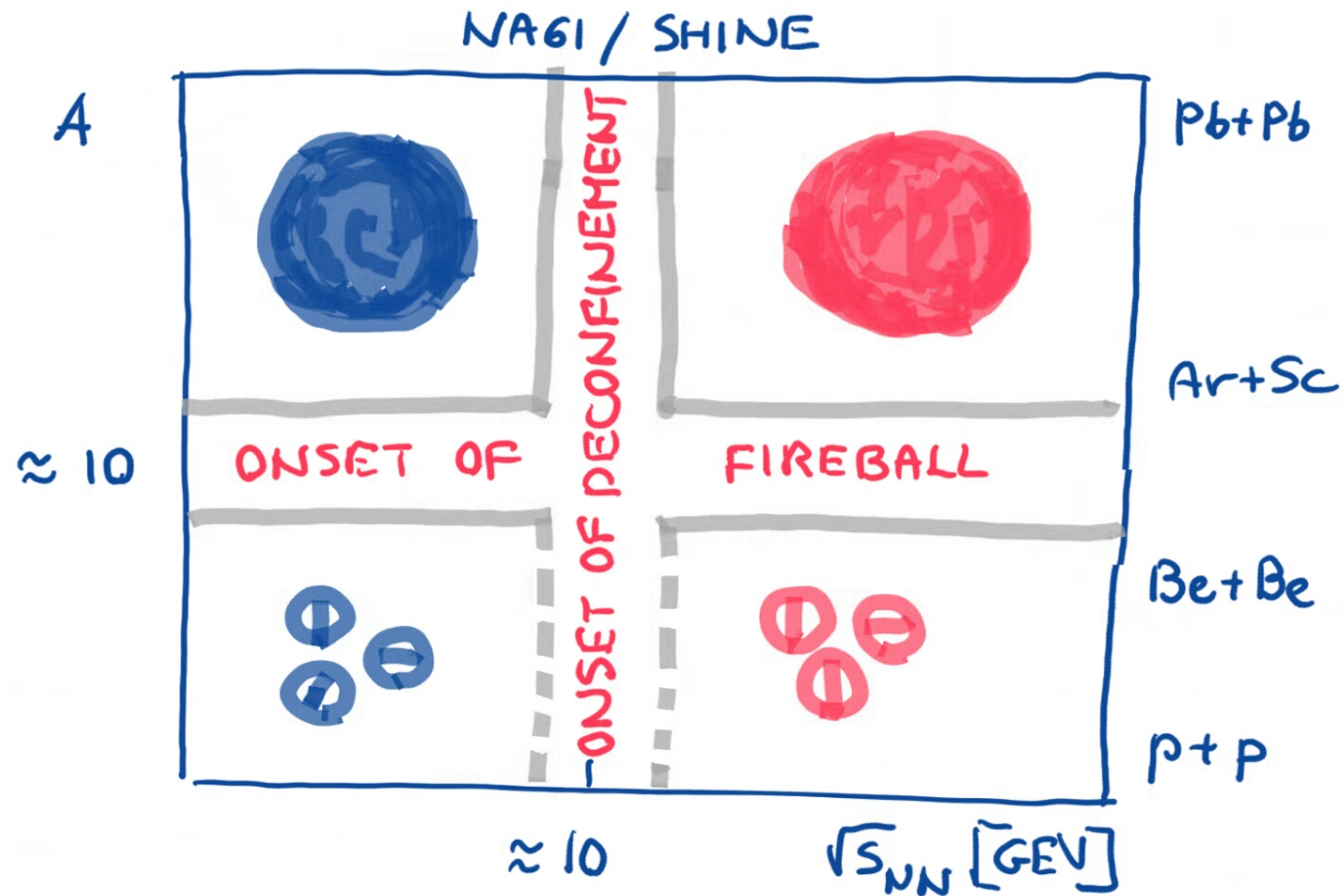


↑ ONSET OF DECONFINEMENT? ↑



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:

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



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

WITH $C \equiv \langle N \rangle \cdot w[P_T]$, $P_T = \sum_i^N p_T^i$

IB - GCE AND
IB - CE WITH V FLUCTUATIONS



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

CONSERVATION LAWS AND CRITICAL POINT

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WITHIN IB-CE (MATERIAL CONSERVATION) WITH VOLUME FLUCTUATIONS:

$$\begin{array}{l} \Sigma [N, P_T] = 1 \\ \Delta [N, P_T] = 1 \end{array} \quad \left| \begin{array}{l} \text{IB-CE:} \\ \leftarrow f_N(\bar{P}_1, \bar{P}_2, \dots, \bar{P}_N) = f(\bar{P}_1) f(\bar{P}_2) \dots f(\bar{P}_N) \end{array} \right.$$

AND THUS ARE EQUAL TO $\Sigma [N, P_T]$, $\Delta [N, P_T]$ IN IB-GCE. THEY ARE INDEPENDENT OF MATERIAL CONSERVATION LAWS.

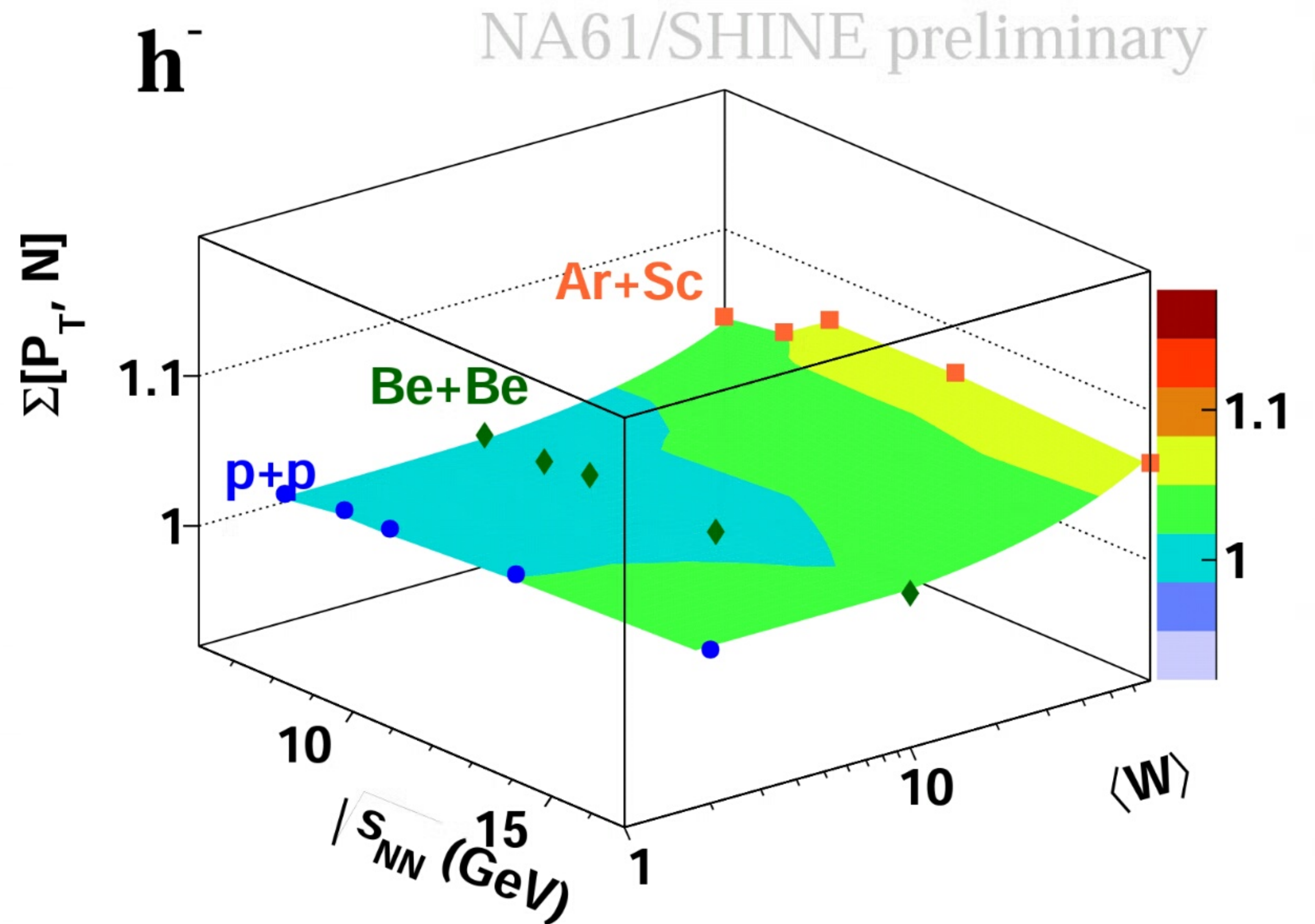
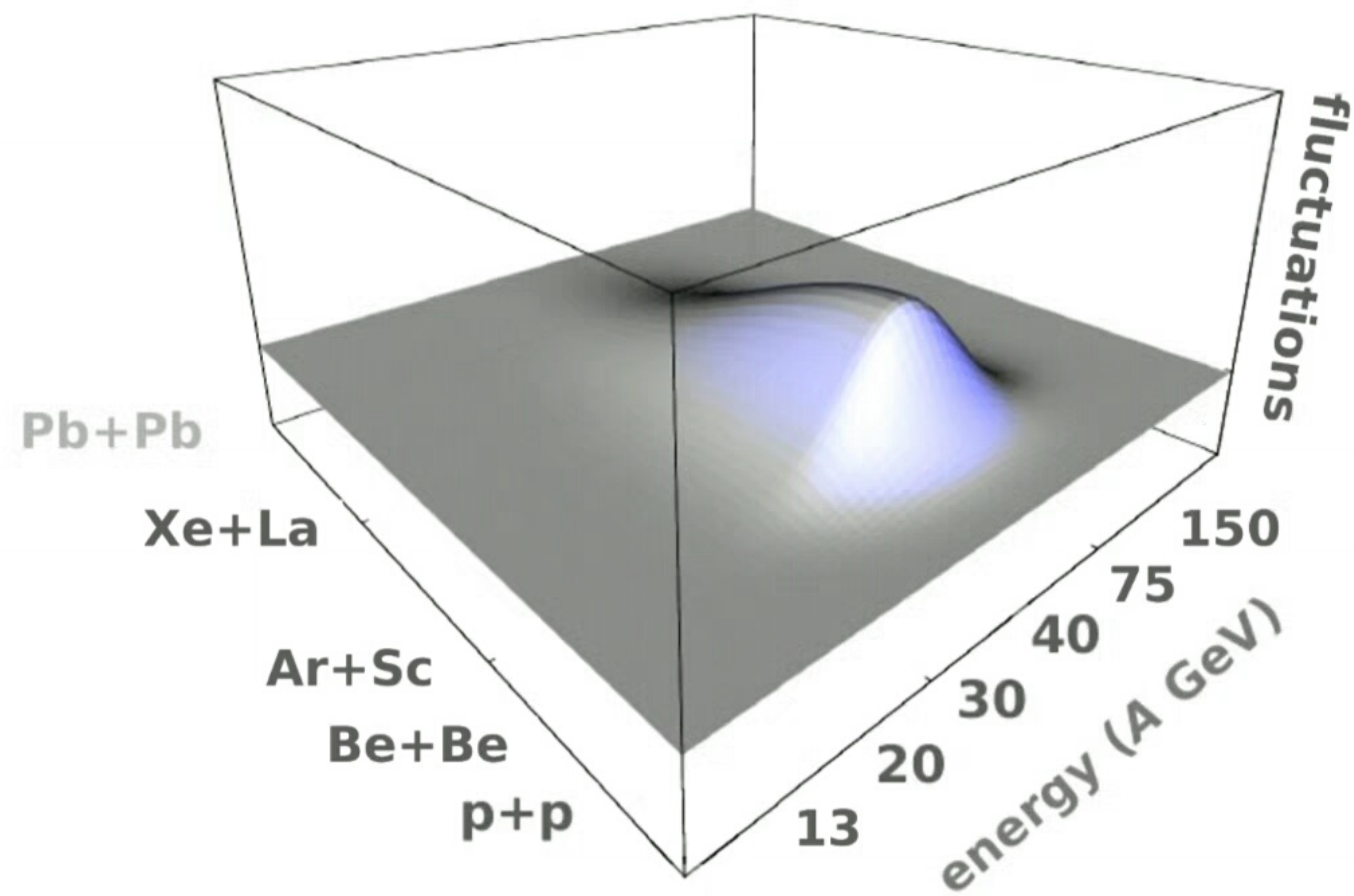
HOPE** THAT CRITICAL POINT WILL CORRELATE PARTICLES IN MOMENTUM SPACE $(f_N(\bar{P}_1, \bar{P}_2, \dots, \bar{P}_N) \neq f(\bar{P}_1) f(\bar{P}_2) \dots f(\bar{P}_N))$ AND THUS IT WILL LEAD TO ANOMALIES IN DEPENDENCE OF Σ AND Δ ON $\sqrt{s_{NN}}$ AND A .

* MG, GARENSTEIN, MACKOWIAK

** BIALAS, HWA
STEPHANOV, RAJAGOPAL, SHURYAK

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

CP $\Rightarrow$ "FLUCTUATION HILL"



NO INDICATION FOR CRITICAL POINT
SO FAR

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

SECOND ORDER PHASE TRANSITION $\rightarrow$ SCALE INVARIANCE $\rightarrow$
CHARACTERISTIC DEPENDENCE OF FLUCTUATIONS ON SIZE δ OF
SUBDIVISION INTERVALS OF MOMENTUM SPACE Δ
 $M = \Delta/\delta$ - NUMBER OF INTERVALS

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

WHERE N_i - PARTICLE NUMBER IN BIN i ,
 $\langle \dots \rangle$ - AVERAGING OVER EVENTS

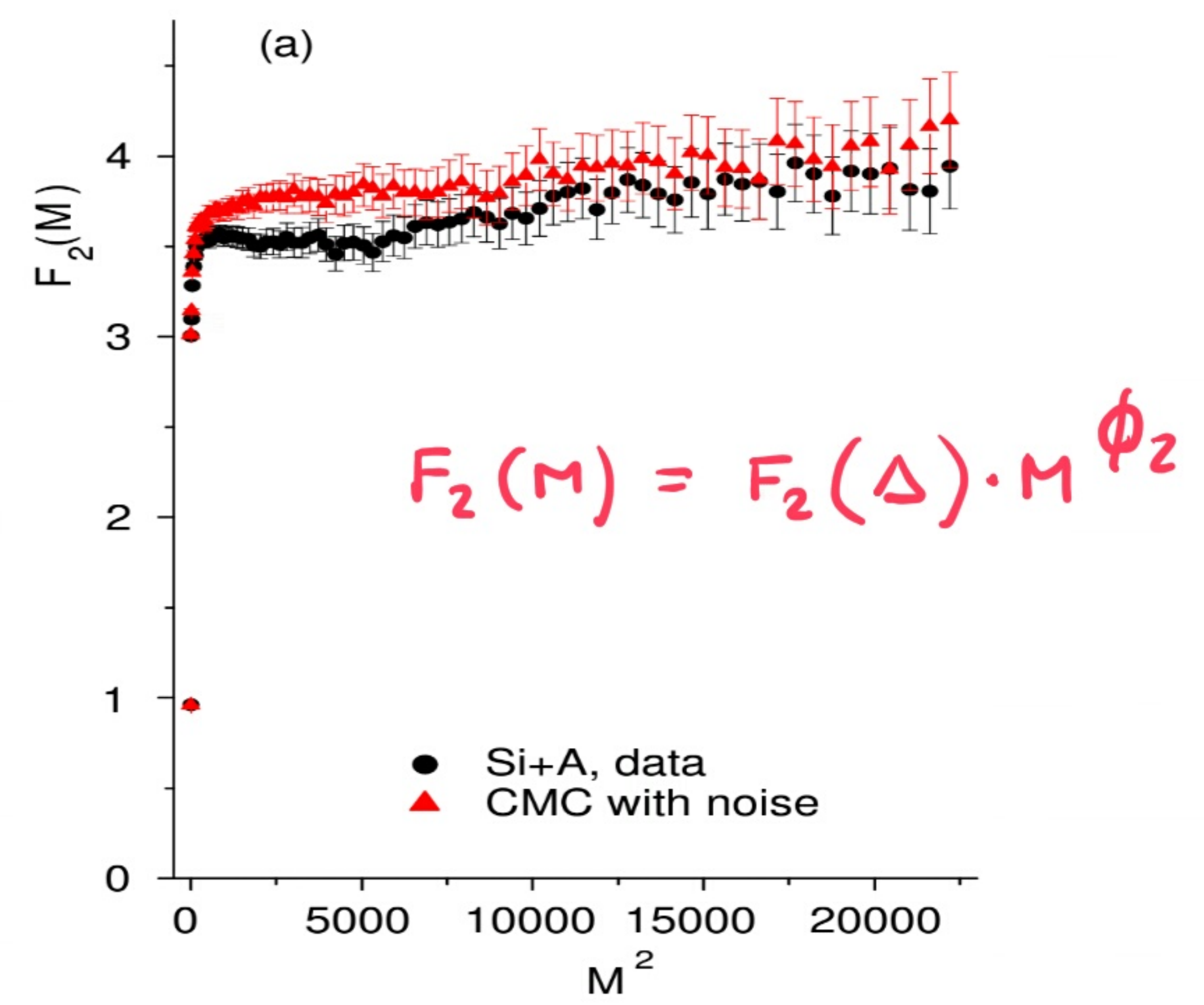
AT CRITICAL POINT POWER LAW DEPENDENCE IS EXPECTED

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

WOSIEK (1988)
BIALAS, PESZANSKI
SATZ
ANTONIDU, DIAKONDS, KAPOYANIS

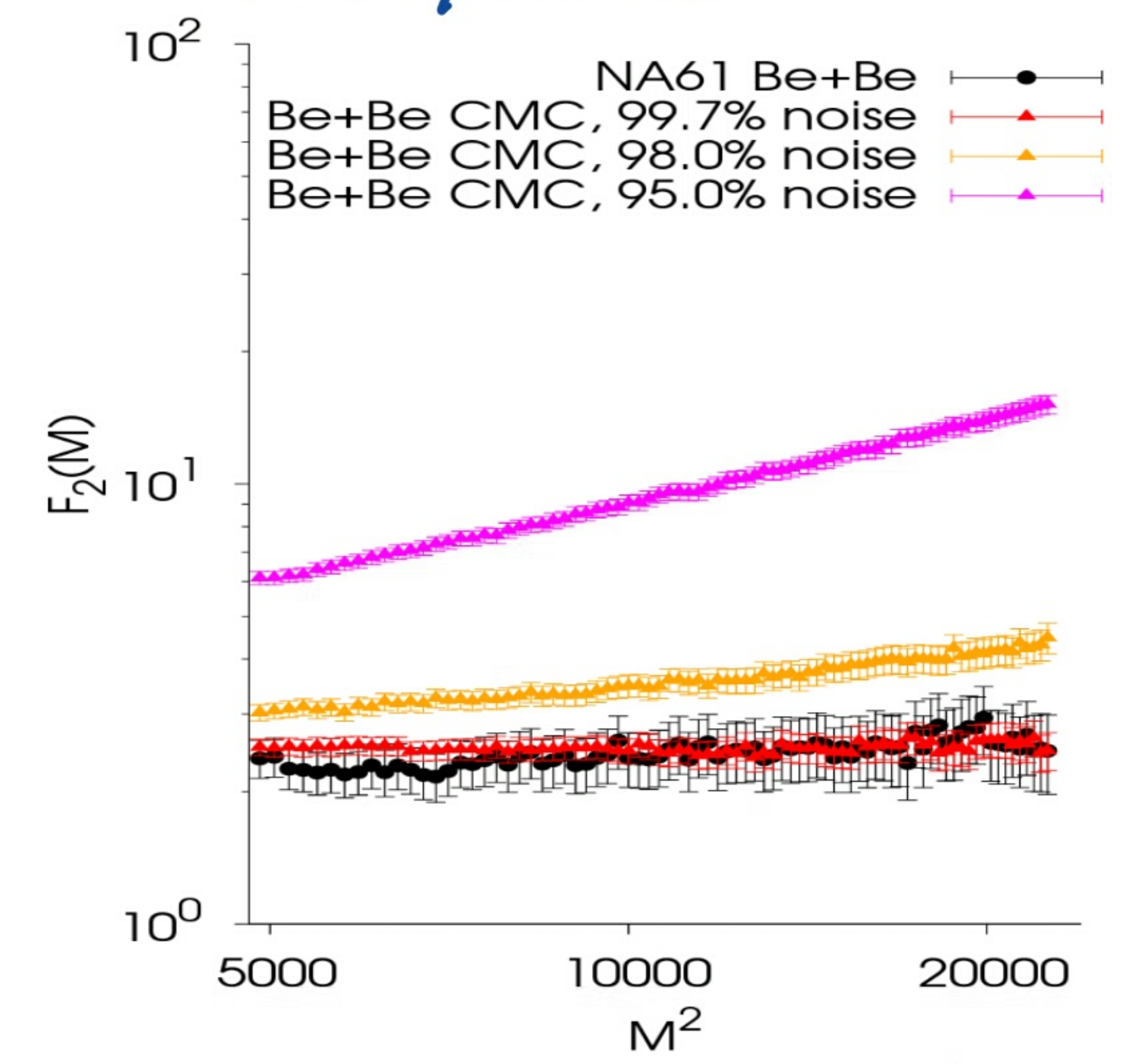
SEARCH FOR CRITICAL POINT : FLUCTUATIONS VS M PROTONS

Si+A AT 158A GEV/c
NA49



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

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

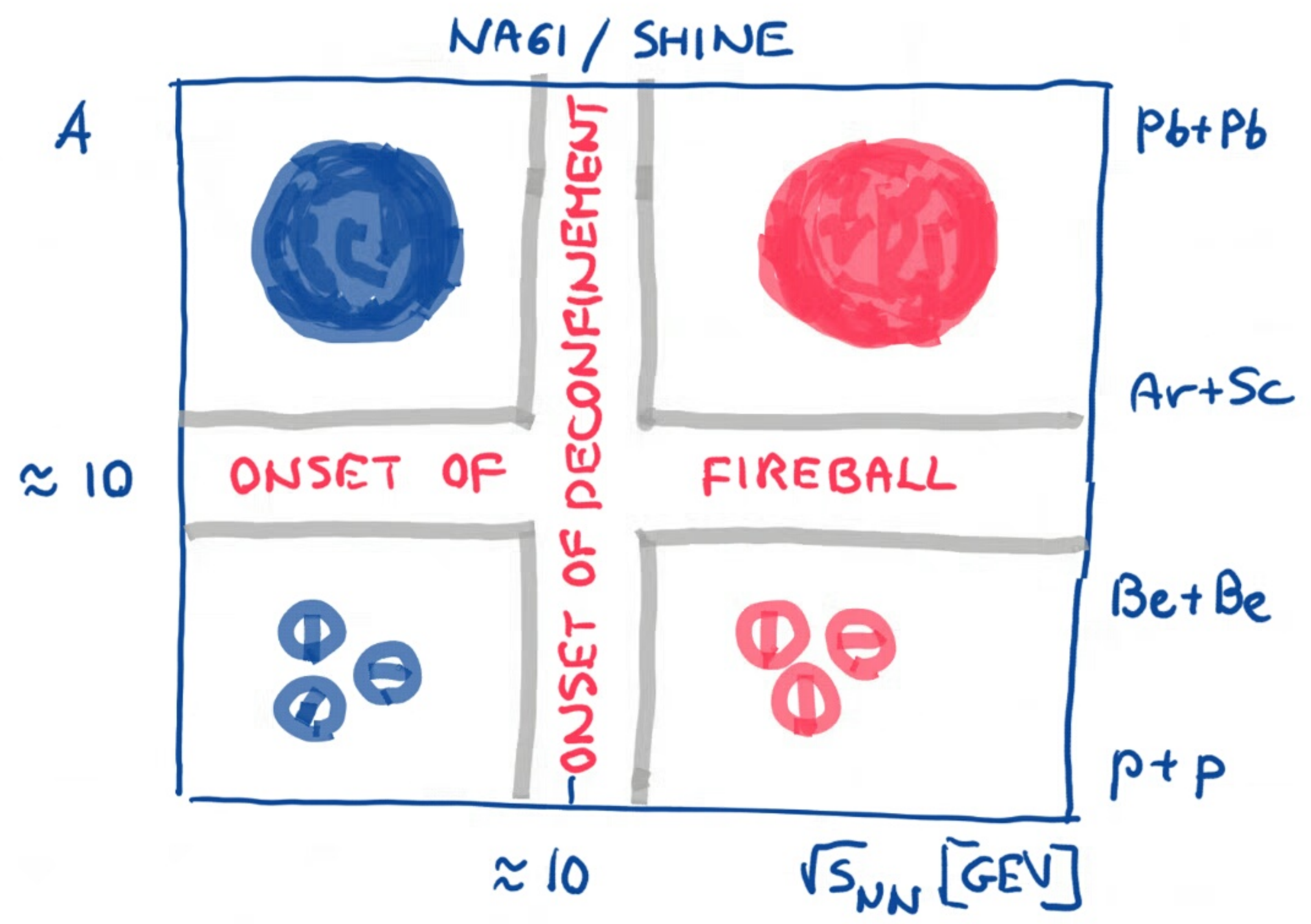


UPPER LIMIT OF "CRITICAL"
PROTONS $\approx 0.3\%$

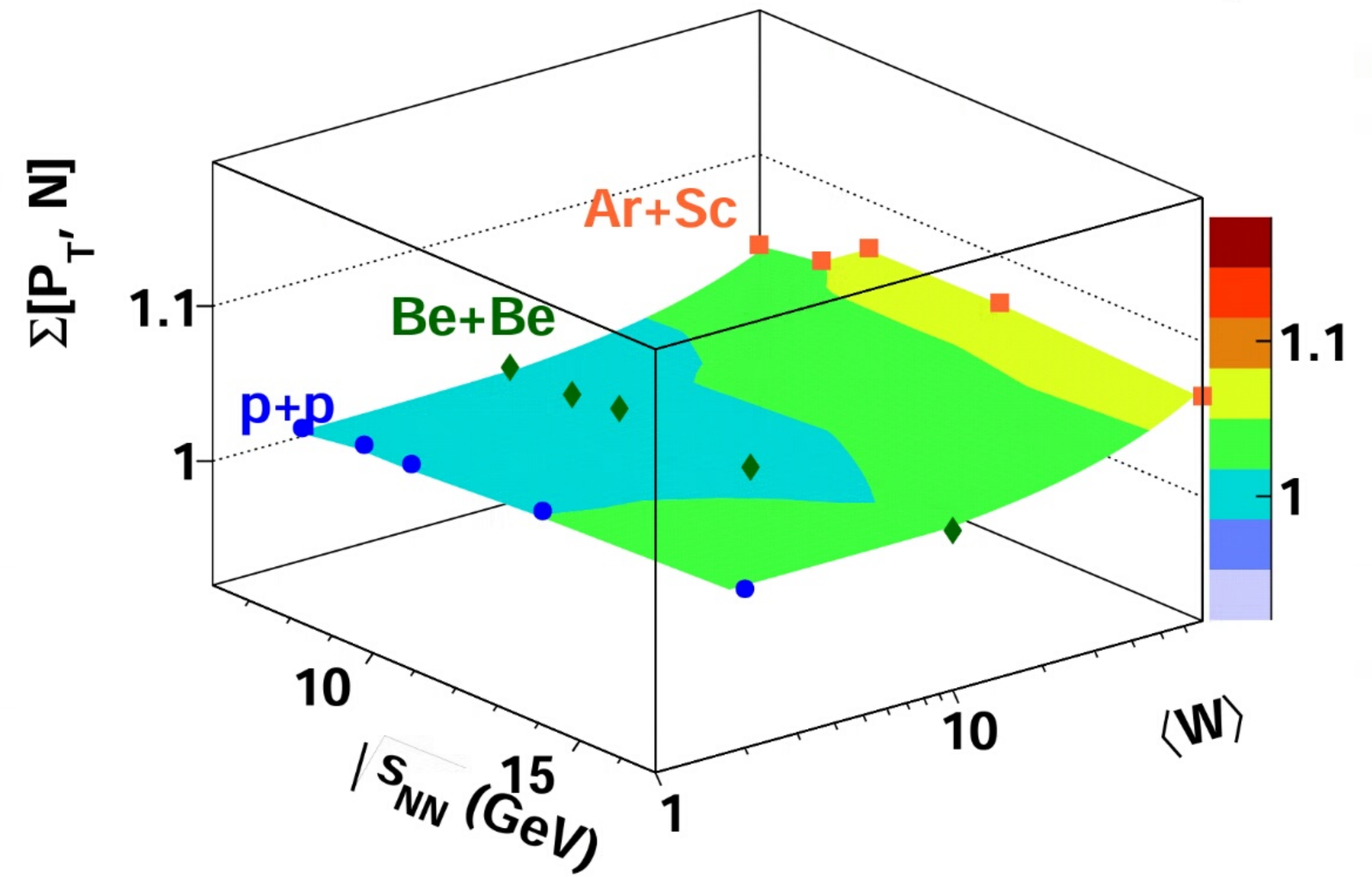
SUMMARY

- INDICATION FOR ONSET OF FIREBALL
→ MORE DATA ON COLLISIONS OF LIGHT NUCLEI
MAY BE NEEDED
- EVIDENCE FOR ONSET OF DECONFINEMENT IN $Pb+Pb$
→ CHALLENGE TO UNDERSTAND $p+p$, $Be+Be$
- NO EVIDENCE FOR CRITICAL POINT SO FAR
→ ANALYSIS IN PROGRESS

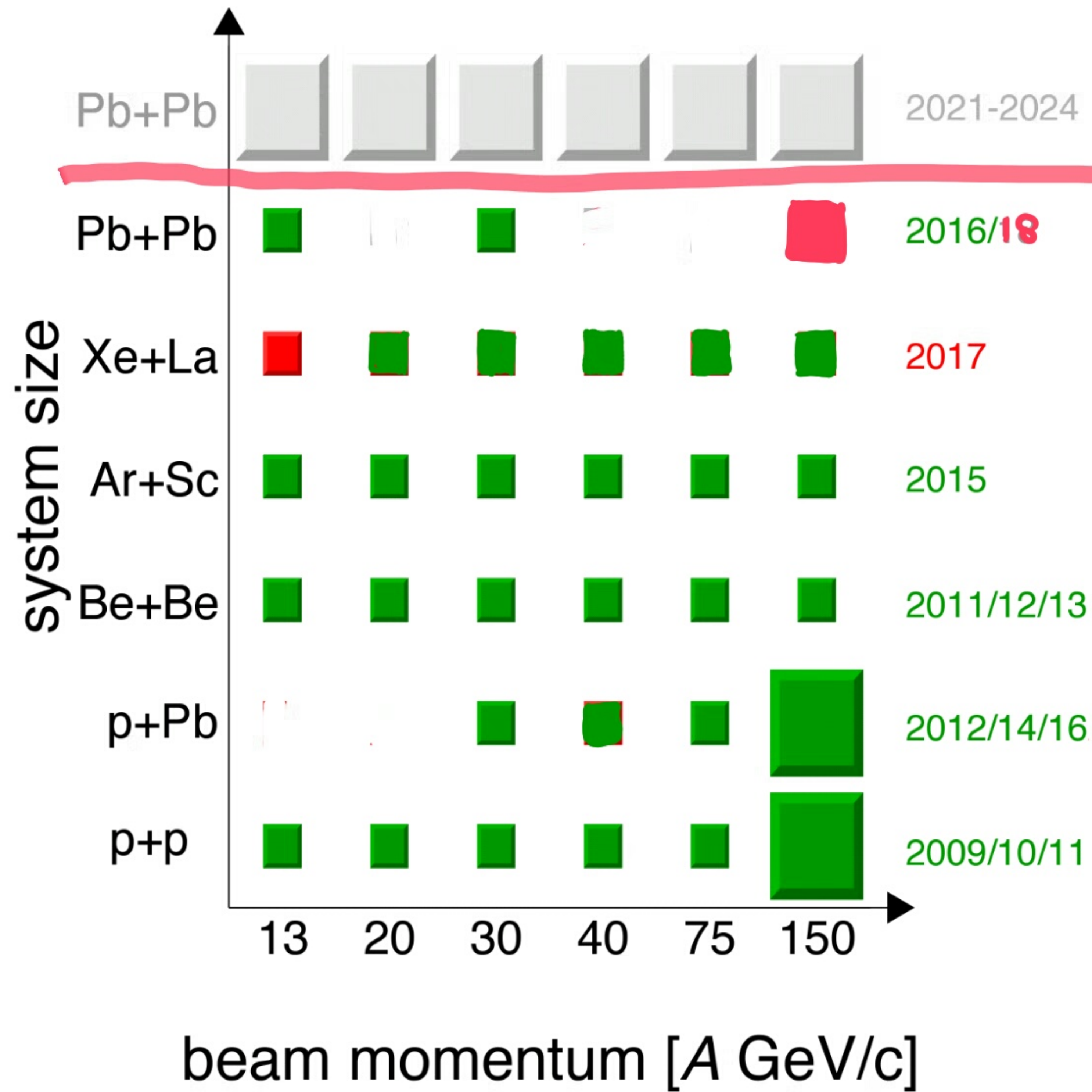
ONSETS



CRITICAL POINT



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

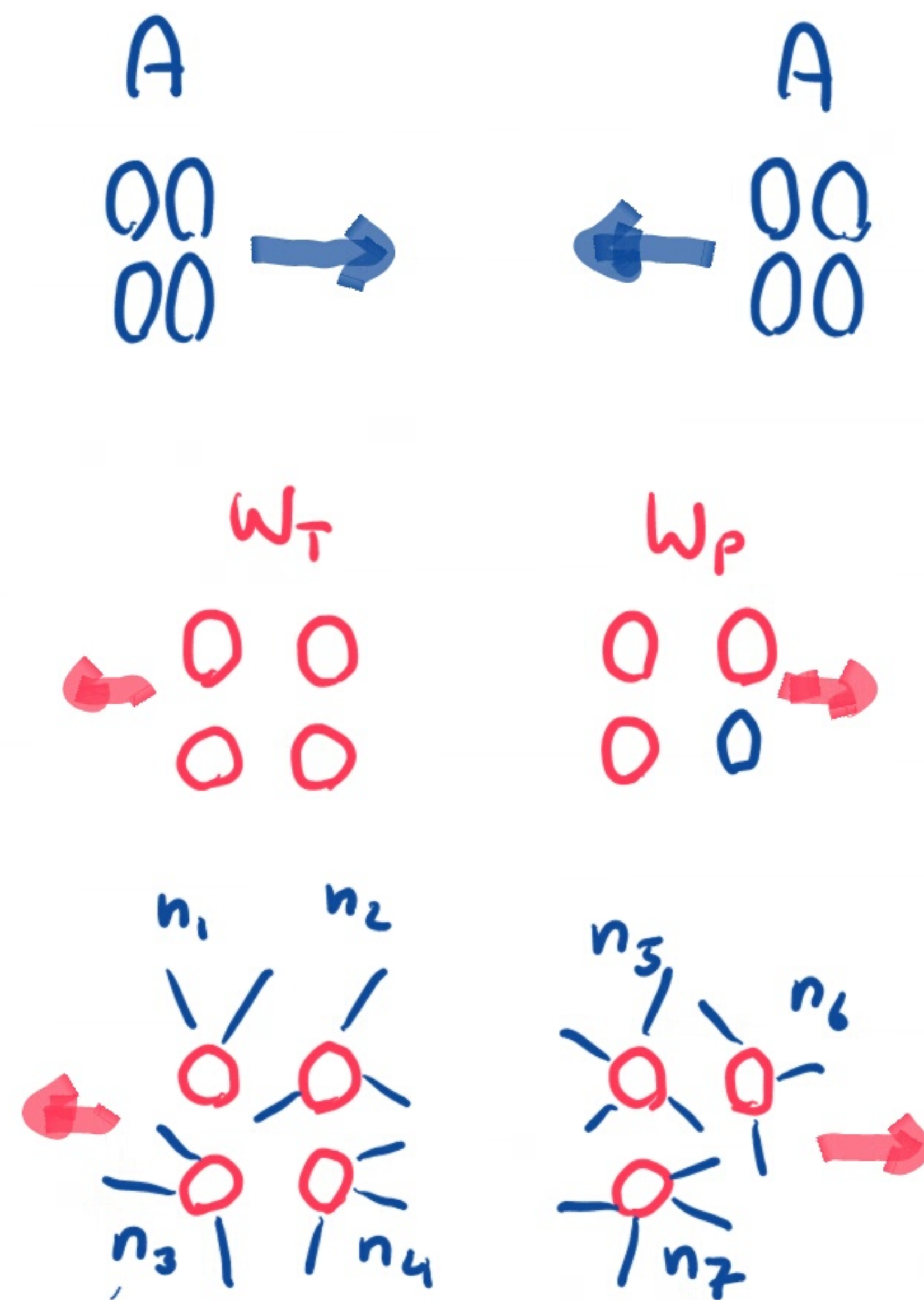
~150 physicists from ~30 institutes



ADDITIONAL SLIDES

REMOVING VOLUME FLUCTUATIONS

REFERENCE MODEL: WOUNDED NUCLEON MODEL:



$$N = \sum n_i$$

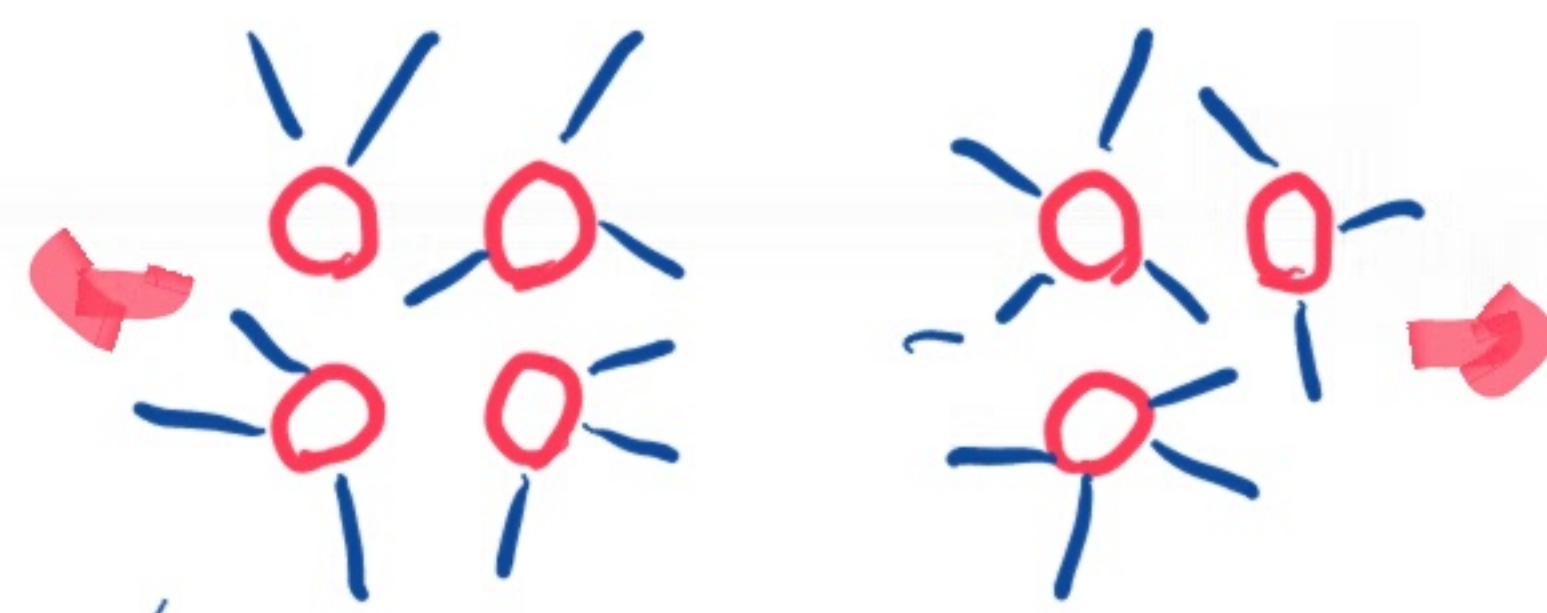
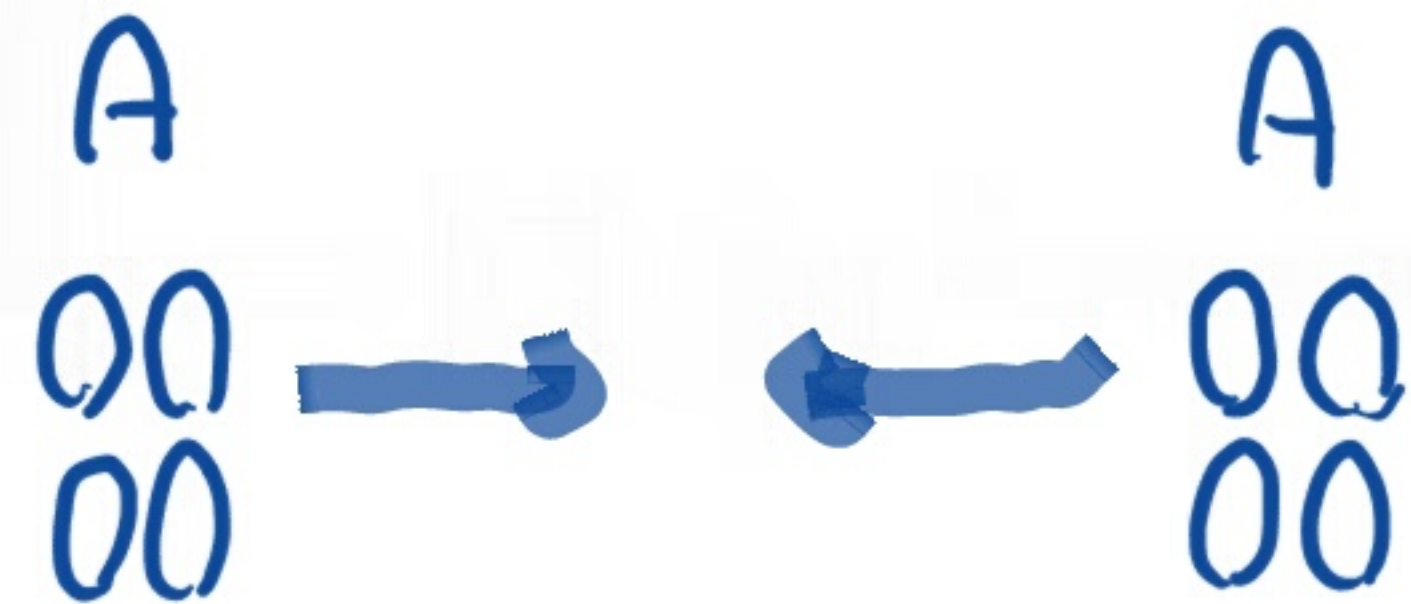
NUMBERS OF PROJECTILE (W_P) AND TARGET (W_T) NUCLEONS THAT INTERACTED INELASTICALLY (**WOUNDED NUCLEONS**) ARE CALCULATED ASSUMING STRAIGHT LINE TRAJECTORIES ($W = W_P + W_T$).

WOUNDED NUCLEONS IN $A_P + A_T$ COLLISIONS HAVE PROPERTIES THE SAME AS WOUNDED NUCLEONS IN $N+N$ ($\approx p+p$) INTERACTIONS AT THE SAME $\sqrt{s_{NN}}$.

BIALAS, BLESZYNSKI, CZYZ

②

MULTIPLICITY FLUCTUATIONS IN WNM:



LET $\bar{W}$ VARY ACCORDING TO $P(\bar{W})$

$$\text{Var}[N] = \langle (N - \langle N \rangle)^2 \rangle =$$

$$= \text{Var}[n] \langle W \rangle + \langle n^2 \rangle \text{Var}[W]$$

DEPENDS ON $\langle W \rangle$ AND $\text{Var}[W]$

SIMILAR RELATIONS ARE VALID FOR STATISTICAL MODELS IN IDEAL BOLTZMANN GAS WITHIN GCE (WOUNDED NUCLEONS $\rightarrow$ VOLUME ELEMENTS, v , $W = V/v$)

③

MULTIPLICITY FLUCTUATIONS IN $\bar{W}$ NM:

$$\omega[N] = \underbrace{\omega[N]_W}_P + \underbrace{\langle N \rangle / \langle \bar{W} \rangle}_{UNWANTED} \cdot \omega[\bar{W}]$$

$$\omega[A] \equiv \text{Var}[A] / \langle A \rangle$$

$$\omega[A]_W \equiv \omega[A] \text{ AT FIXED } W$$

TWO METHODS TO REMOVE THE UNWANTED TERM:

(i) SELECT EVENTS WITH $\bar{W} = \text{CONST} \Rightarrow \omega(\bar{W}) = 0$

$\Rightarrow$ SELECTION USING PROJECTILE SPECTATORS

(ii) DEFINE FLUCTUATION QUANTITIES TO BE INDEPENDENT OF $P(W)$

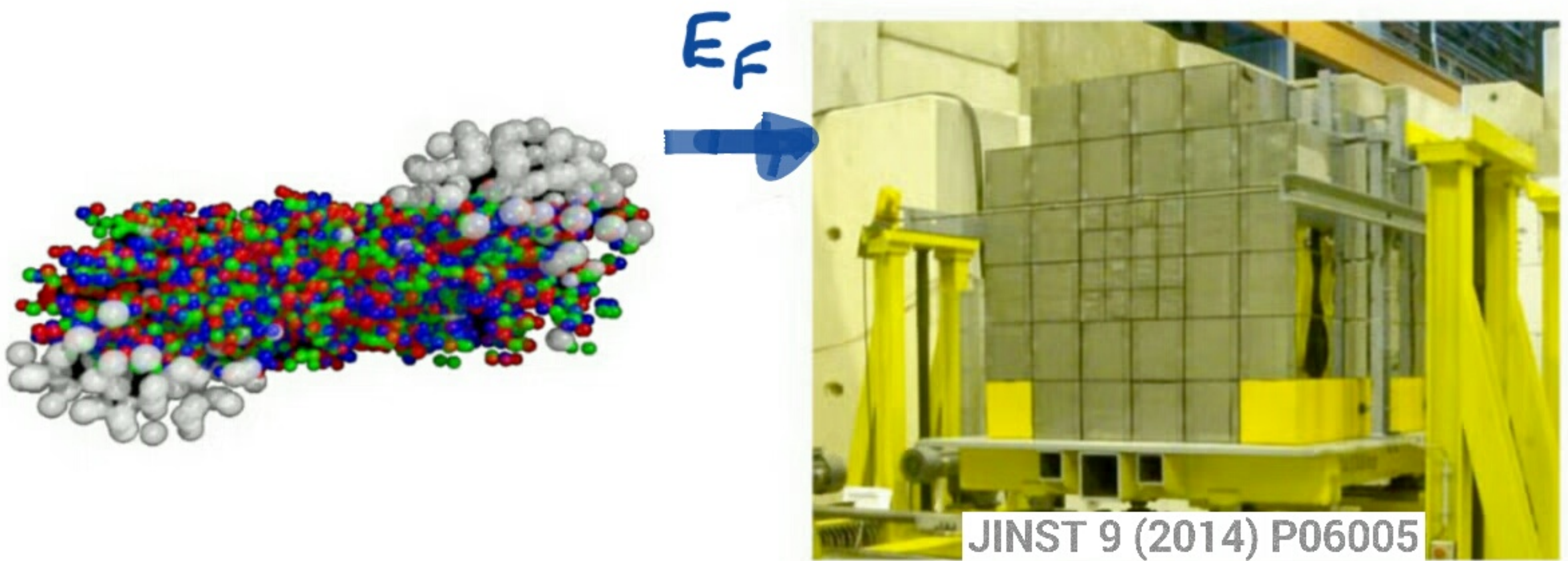
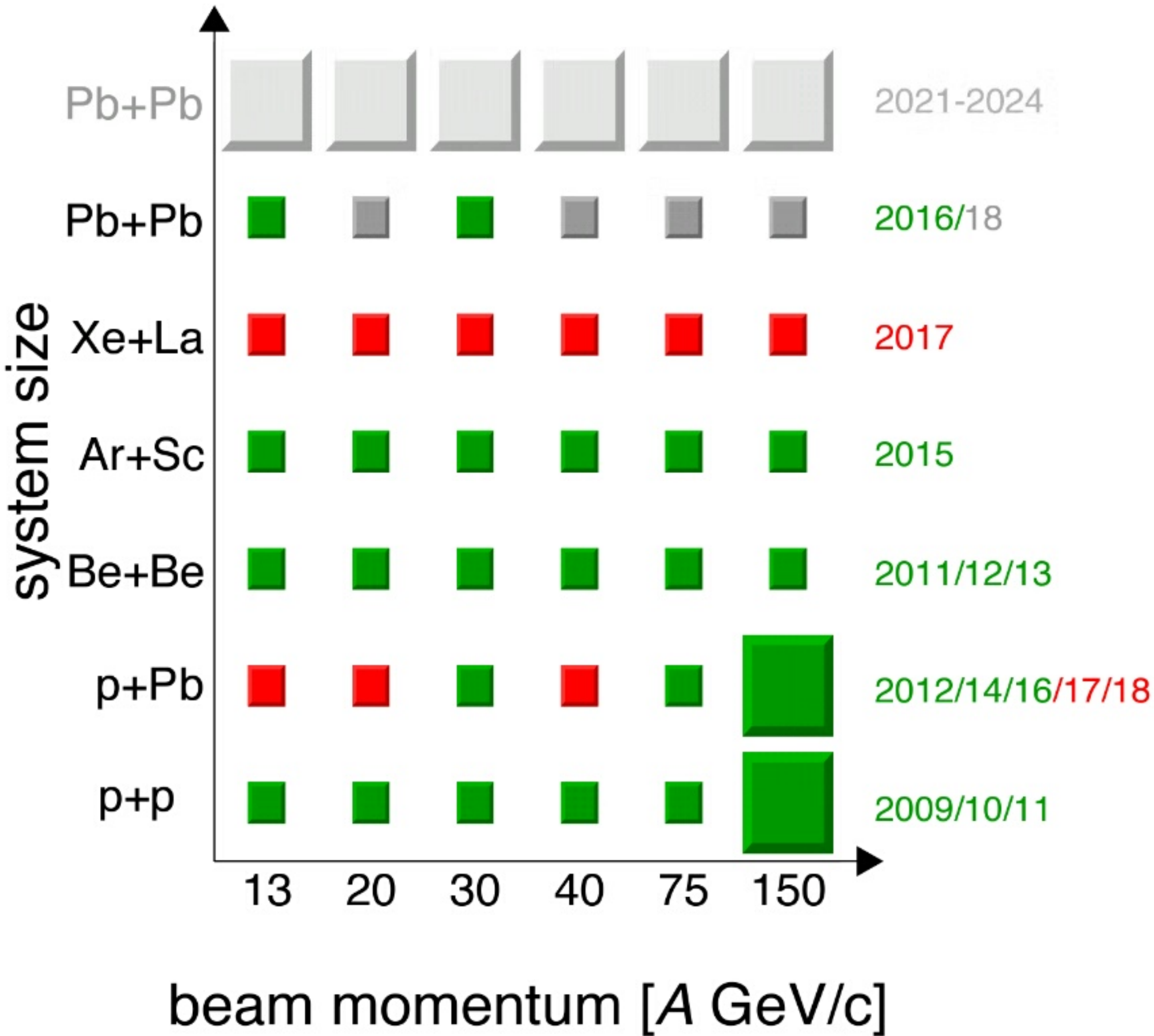
$\Rightarrow$ STRONGLY INTENSIVE QUANTITIES

NAGI/SHINE SELECTION OF VIOLENT EVENTS

COLLISIONS OF
SIMILAR SIZE NUCLEI



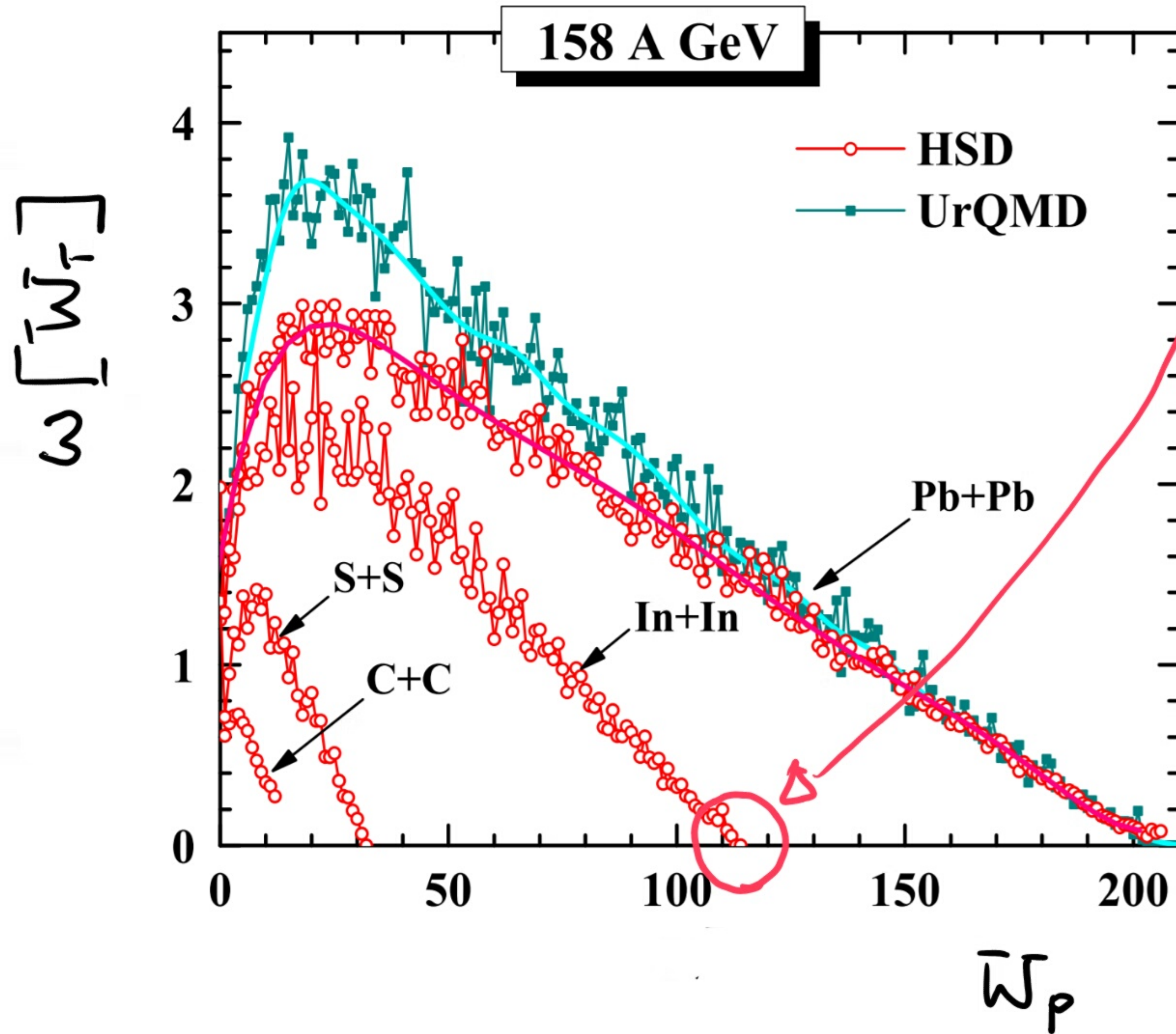
SELECTION OF EVENTS WITH SMALL
NUMBER OF PROJECTILE SPECTATORS



COST AND TIME EXPENSIVE BUT
REWARDING PROCEDURE

⑤

NAGI/SHINE SELECTION OF VIOLENT EVENTS



EXAMPLE FOR In+In (Xe+La):

FOR $\bar{W}_P \approx A$ (113) $\omega[\bar{W}_T] \approx 0$
 AND $\bar{W}_T \approx A$

$\Downarrow$
 $\omega[\bar{W} = \bar{W}_P + \bar{W}_T] \approx 0$

$$\omega[N] = \omega[N]_W + \frac{\langle N \rangle}{\langle \bar{W} \rangle} \cdot \omega[\bar{W}]$$

P
WANTED

~~P
UNWANTED~~

KANCHAKOVSKI, LUNGWITZ, GORENSTEIN BRATKOUSKAYA

⑥

STRONGLY INTENSIVE QUANTITIES

FLUCTUATION MEASURES THAT ARE INDEPENDENT OF $P(\bar{W})$
WITHIN $\bar{W}NM$. (IB-GCE)

FOR EXAMPLE:

$$\Omega[N, E_p] \equiv \omega[N] - \frac{\langle N \cdot E_p \rangle - \langle N \rangle \langle E_p \rangle}{\langle E_p \rangle} \approx \omega[N]_W = \omega[n]$$

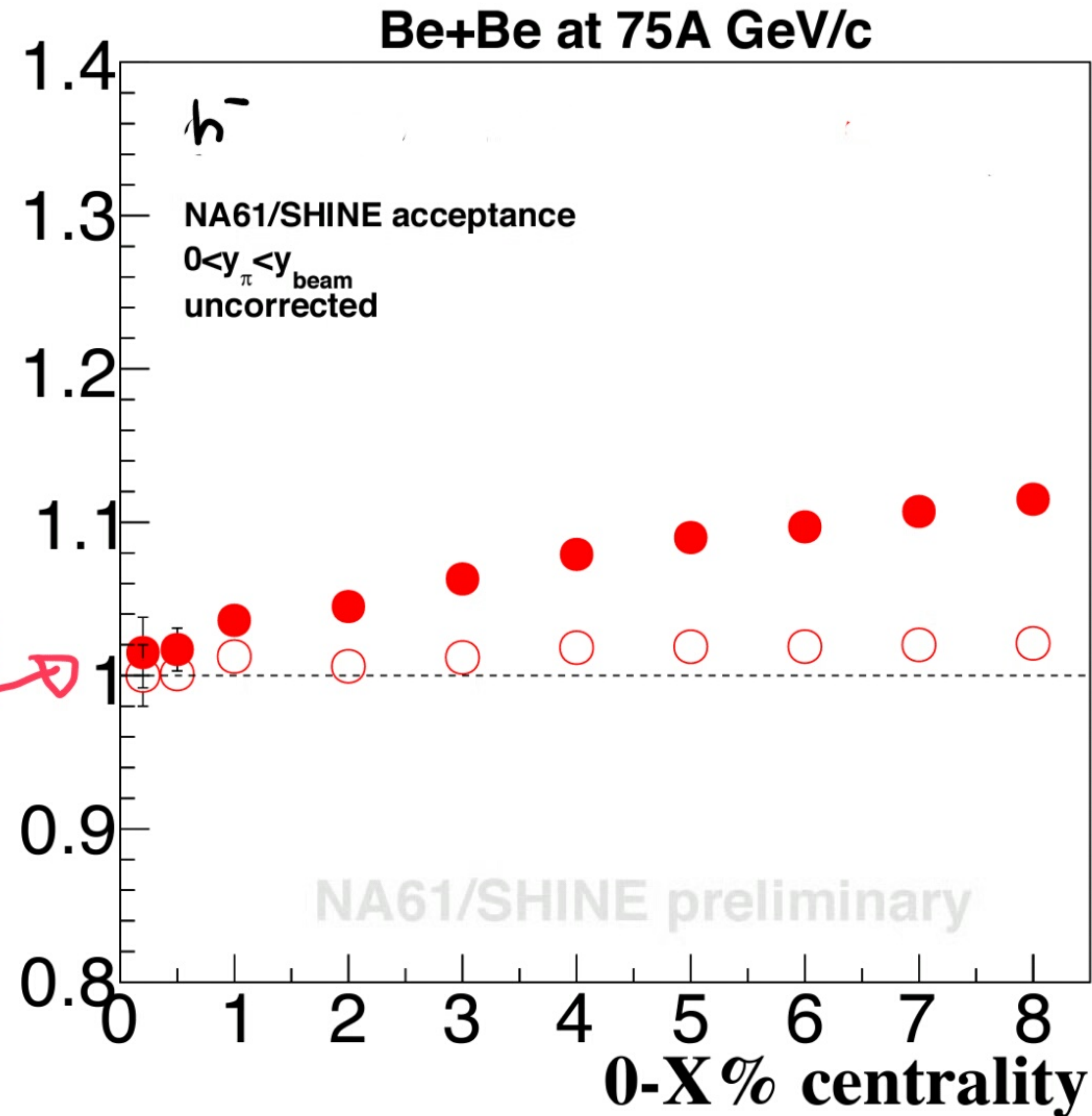
WHERE $E_p = E_{\text{BEAM}} - E_F$

$$\begin{aligned} \langle N \cdot E_p \rangle_W &\approx \langle N \rangle_W \langle E_p \rangle_W \\ \langle E_p \rangle_W &\sim \bar{W} \end{aligned}$$

VIOLENT A+A COLLISIONS

MG, MRDOWCZYNSKI
MG, GORENSTEIN
SANGELINE

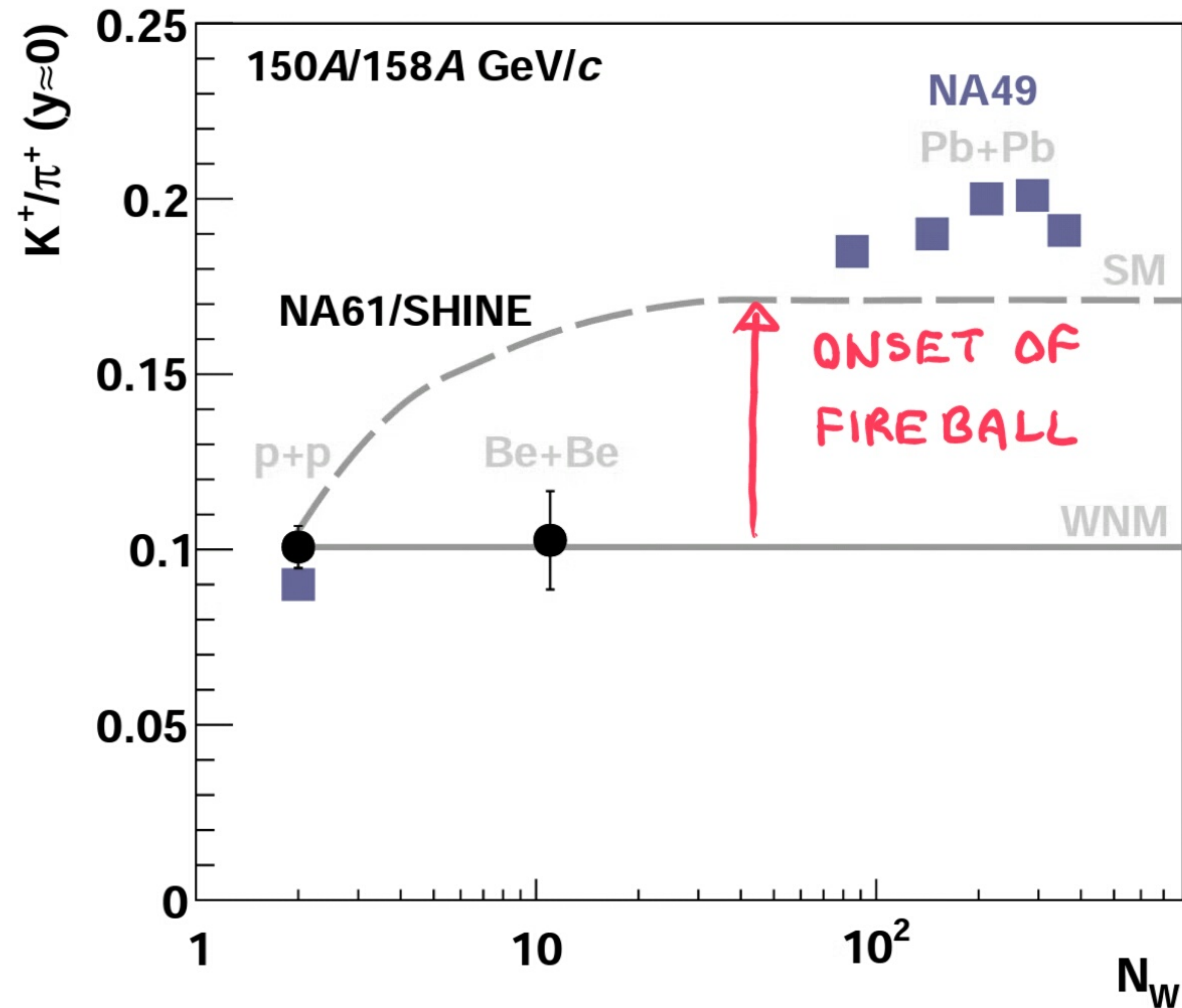
REMOVING VOLUME FLUCTUATIONS: EXPERIMENTAL CROSS-CHECK



$\Omega[N]$ FOR MOST
VIOLENT COLLISIONS

← STRONGLY
INTENSIVE
 $\Omega[N, E_p]$

ONSET OF FIREBALL VS STATISTICAL MODELS



CANONICAL STRANGENESS
SUPPRESSION IN TWO-FIREBALL
HADRON GAS

SOLLFRANK, BECATTINI
REDLICH, SATZ, nucl-th/980204

WOUNDED NUCLEON MODEL

BIALAS, BLESZYNSKI, CZYZ