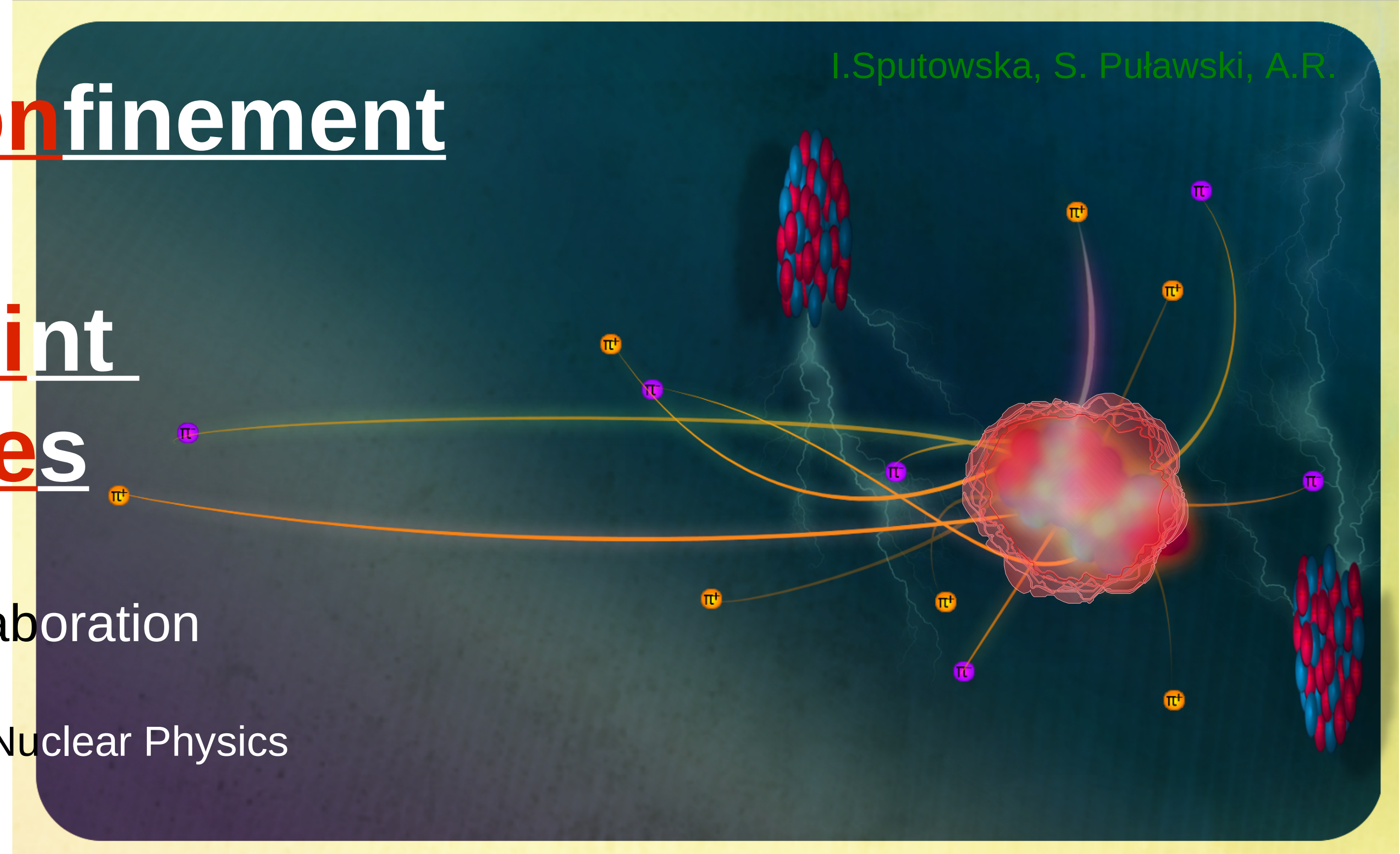
Onset of Deconfinement and the Critical Point at SPS Energies



Andrzej Rybicki
for the NA61/SHINE Collaboration

H. Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences

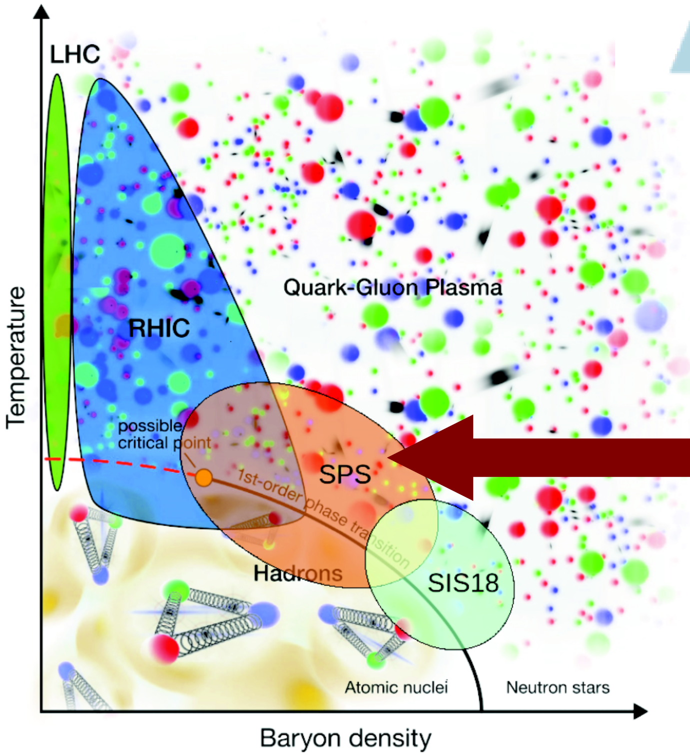
1) **Prologue ;**
2) **The onset of deconfinement ;**
3) **The onset of fireball ;**
4) **The Critical Point ;**
5) **The longitudinal evolution of the system ;**
6) **Summary.**

Note: all hand-made plots courtesy of M. Gazdzicki

WPCF2018

1) Prologue

Motivation for SHINE

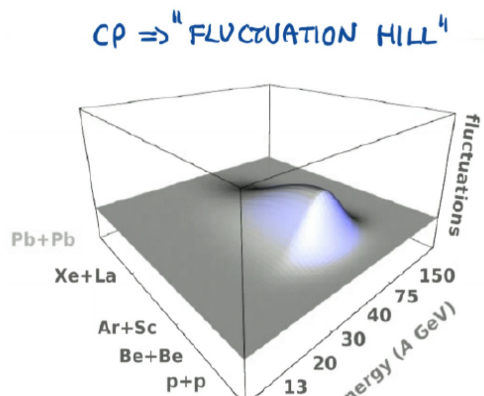


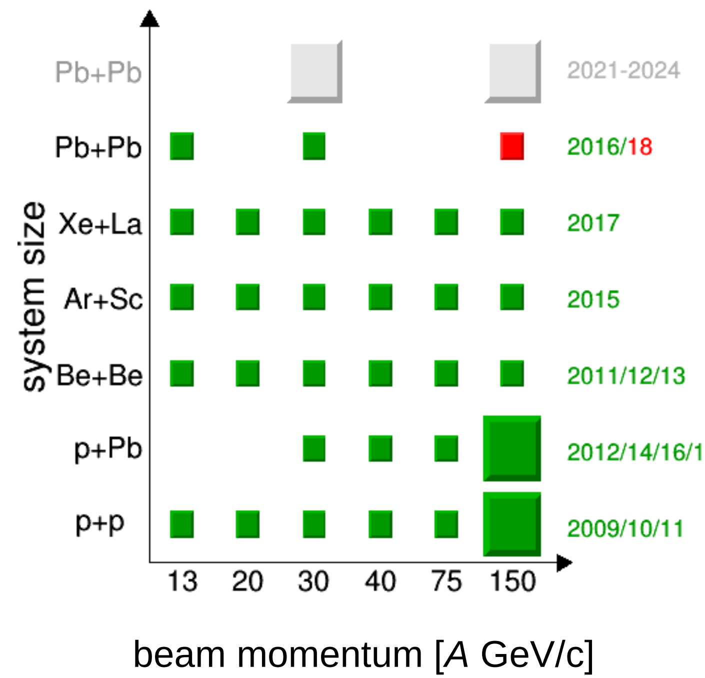
1. Strong interactions;
2. Cosmic rays & neutrinos.

Ad. 1.

- search for the Critical Point (CP);
- study properties of onset of deconfinement;
- but note: there is more than the onset of deconfinement...

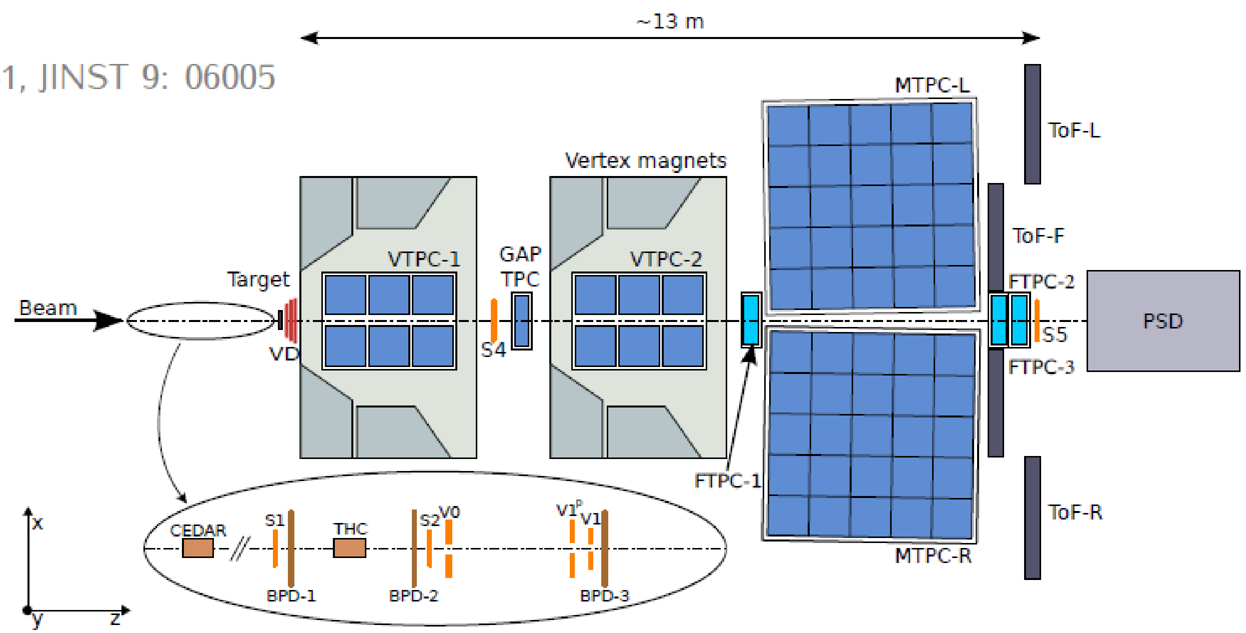
Comprehensive **2D scan** of p+p, p+A, and A+A collisions, as a function of system size and energy





The NA61/SHINE detector

NA61, JINST 9: 06005



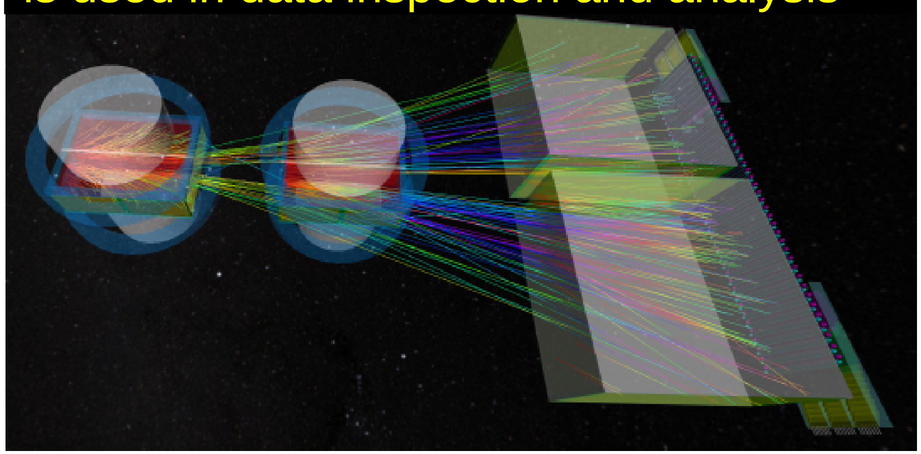
* large acceptance ;

* charged particle
  tracking ;

* PID via dE/dx ;

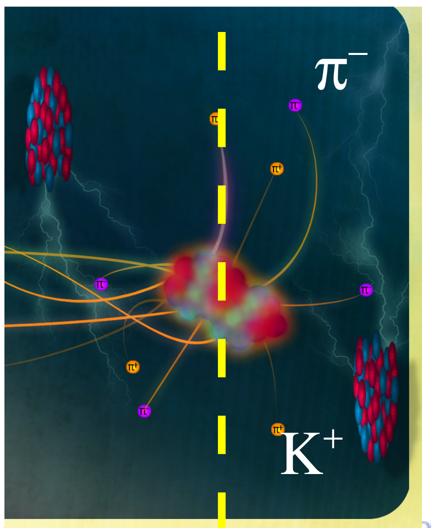
* centrality by **forward** PSD calorimeter.

Virtual reality 3D visualization
is used in data inspection and analysis



NA61/SHINE in virtual reality: http://shine3d.web.cern.ch/shine

Forward
hemisphere
in the
collision
c.m.s.

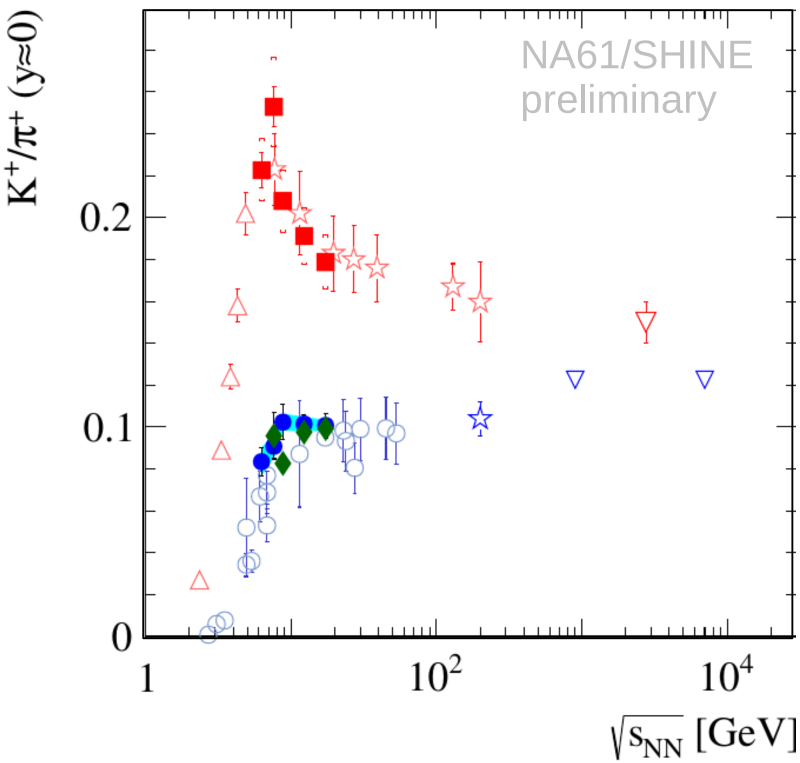


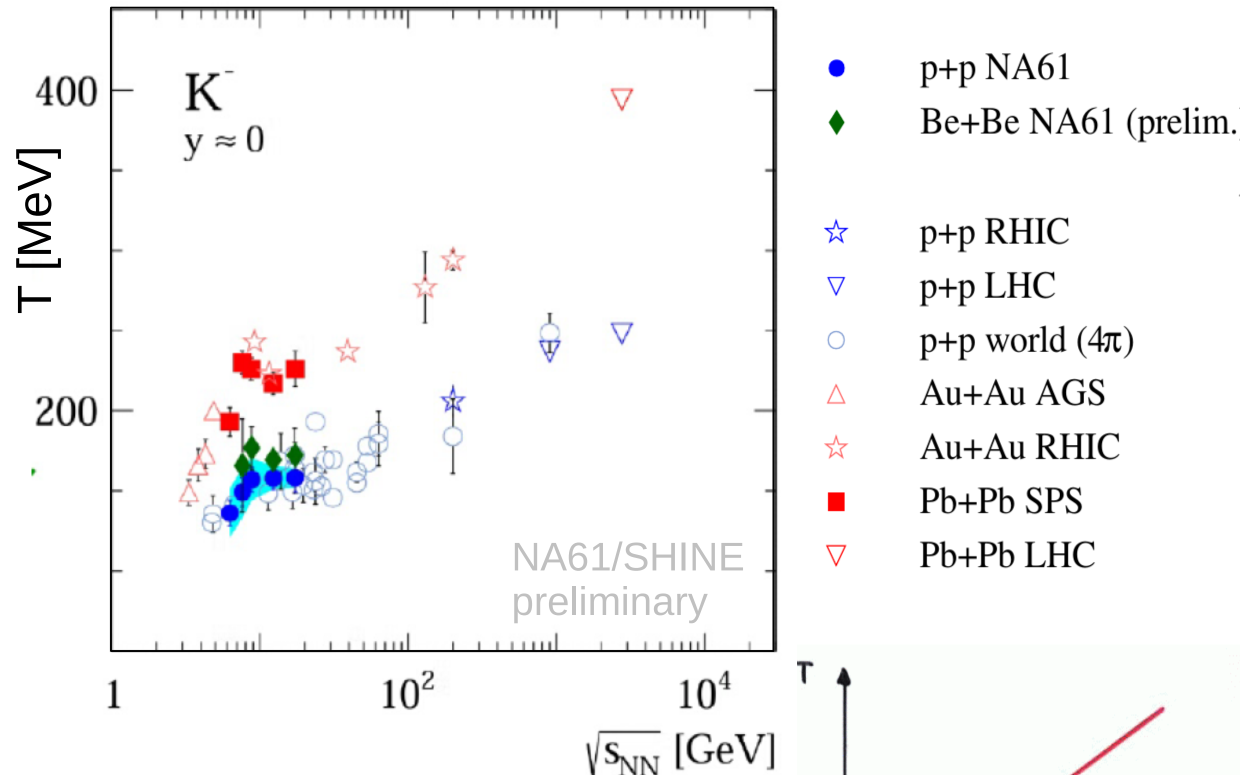
2) The Onset of Deconfinement

Particle ratios and inverse slopes (1)

Rapid changes in **K^+/π^+** (HORN) and a step-like structure in **T** were observed in Pb+Pb collisions. This was predicted within the SMES as a signature of the onset of deconfinement.

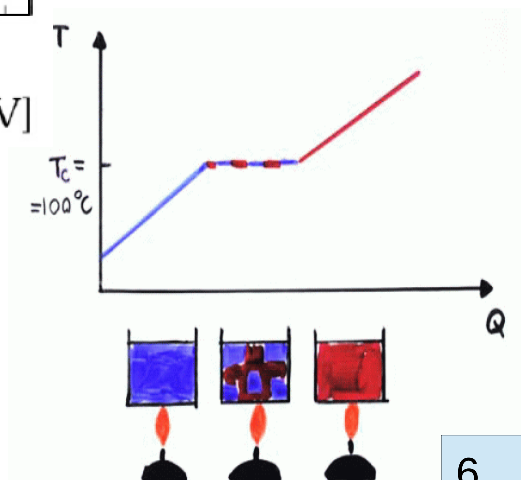
M. Gazdzicki, M. I. Gorenstein, Acta Phys.Polon. B30 (1999) 2705





NEW RESULTS:

- The rapid change in √s-dependence is observed for both p+p and Pb+Pb !
- Be+Be is consistent with p+p.



Particle ratios and inverse slopes (2)

Rapid changes in **K⁺/π⁺** (HORN) and a step-like structure in **T** were observed in Pb+Pb collisions. This was predicted within the SMES as a signature of the onset of deconfinement.

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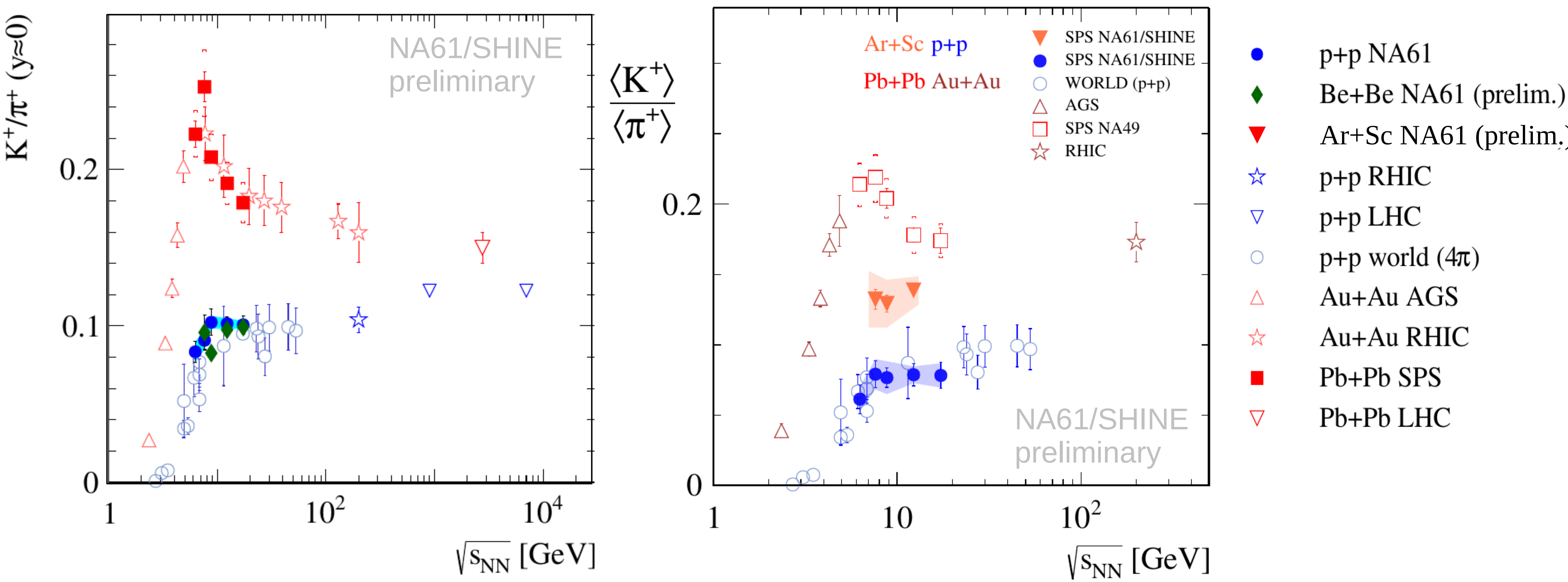
Acta Phys.Polon. B30 (1999) 2705

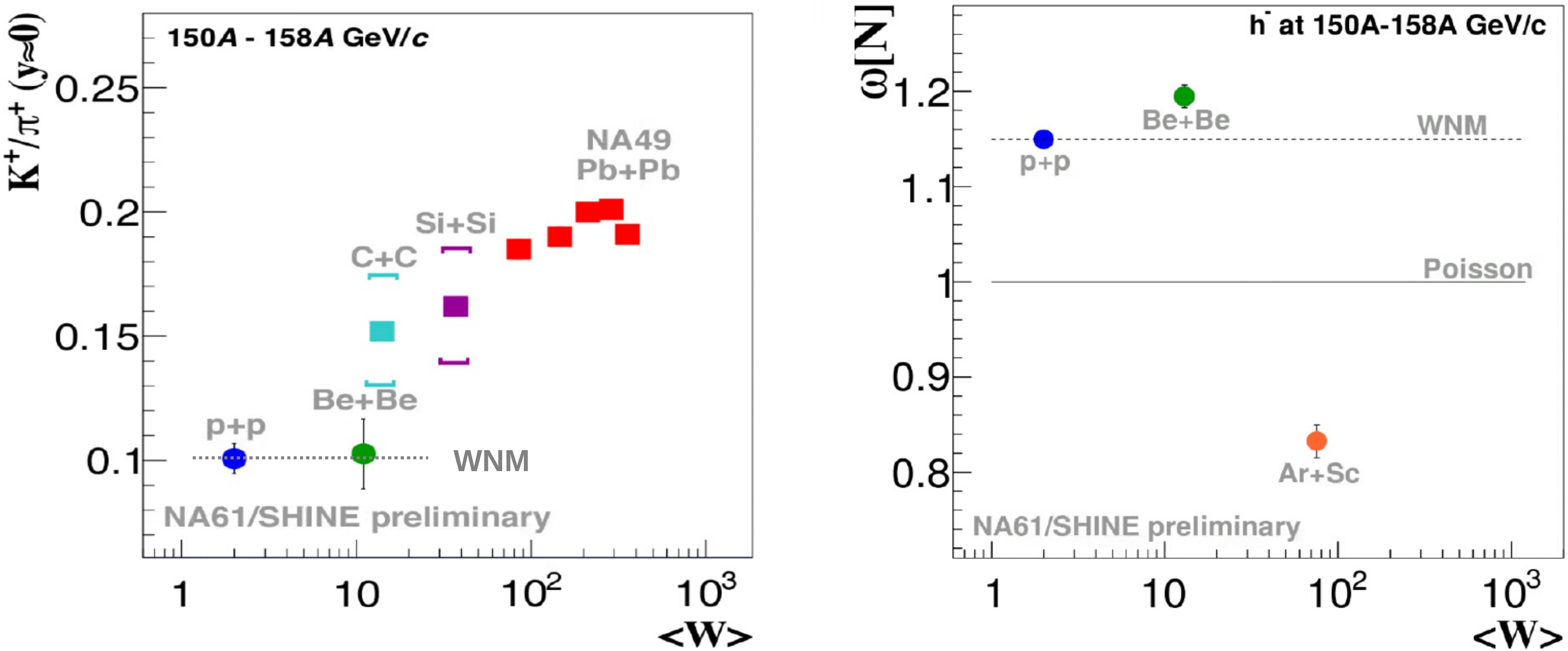


NEW RESULTS:

- The rapid change in √s-dependence is observed for both p+p and Pb+Pb ;
- Be+Be is consistent with p+p.
- <K⁺>/<π⁺> in **Ar+Sc** is **between** p+p, Be+Be and Pb+Pb.

Particle ratios and fluctuations (1)

$\omega[N] = var(N)/<N>$



K^+/π^+ and **multiplicity fluctuations** change rapidly when moving from light (p+p, Be+Be) to intermediate and heavy systems.

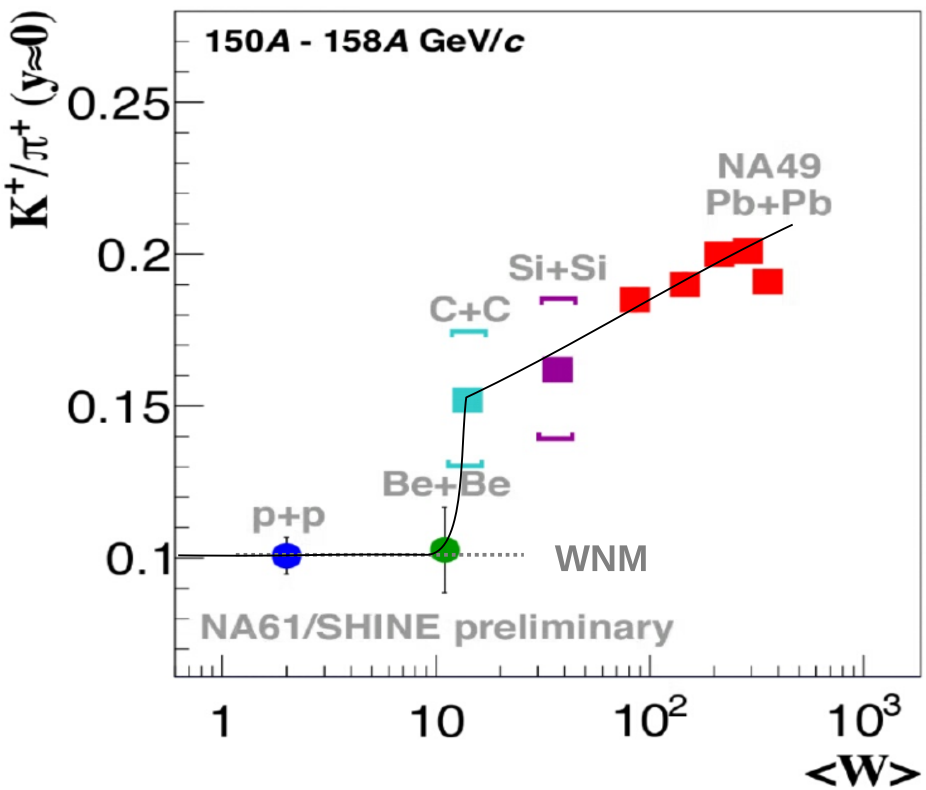
For heavy systems they are closer to predictions of statistical models for **large volumes**.

→ beginning of creation of large clusters of strongly interacting matter ***(onset of fireball)***

(name proposed by E. Shuryak, 2017)

See also: A. Seryakov, E. Andronov, WPCF 2017

Particle ratios and fluctuations (1)



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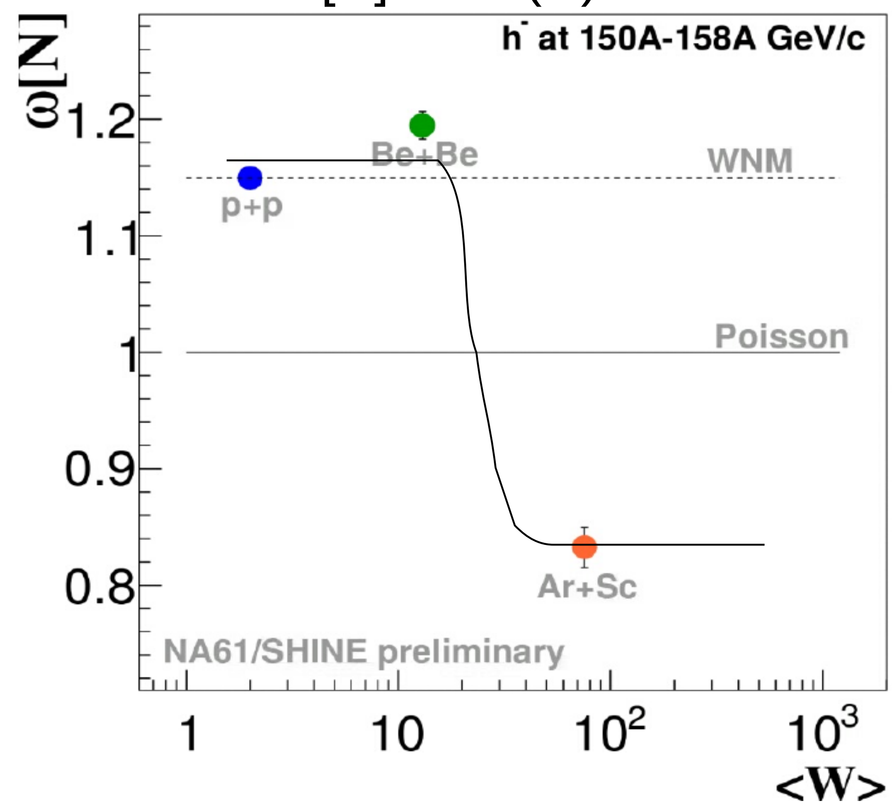

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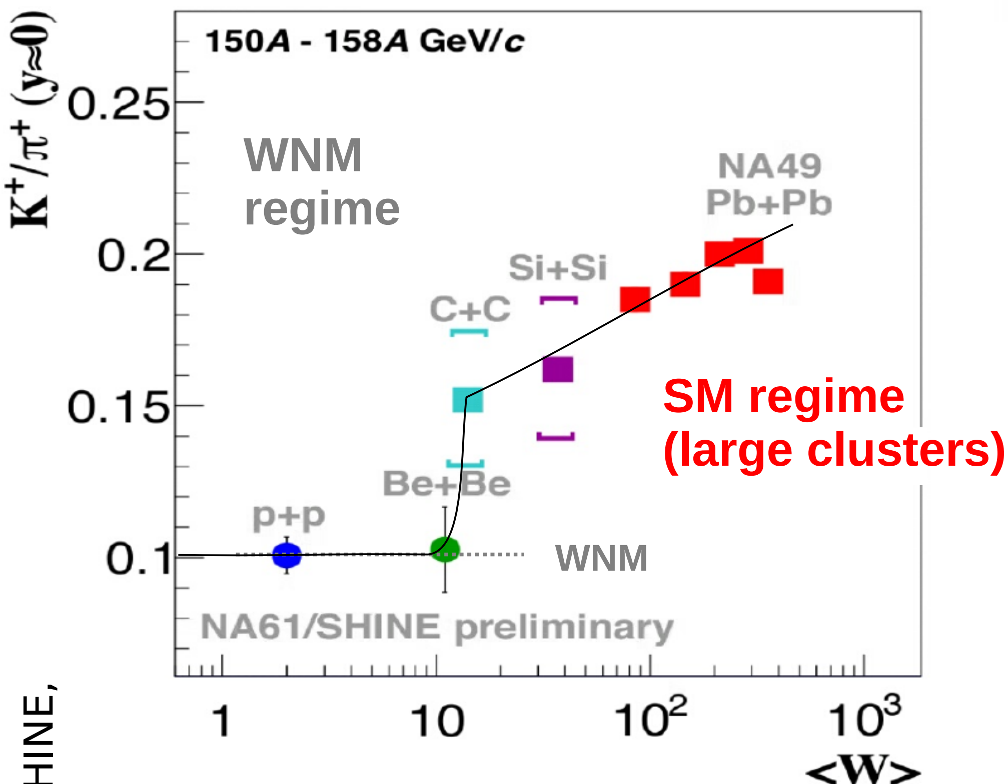
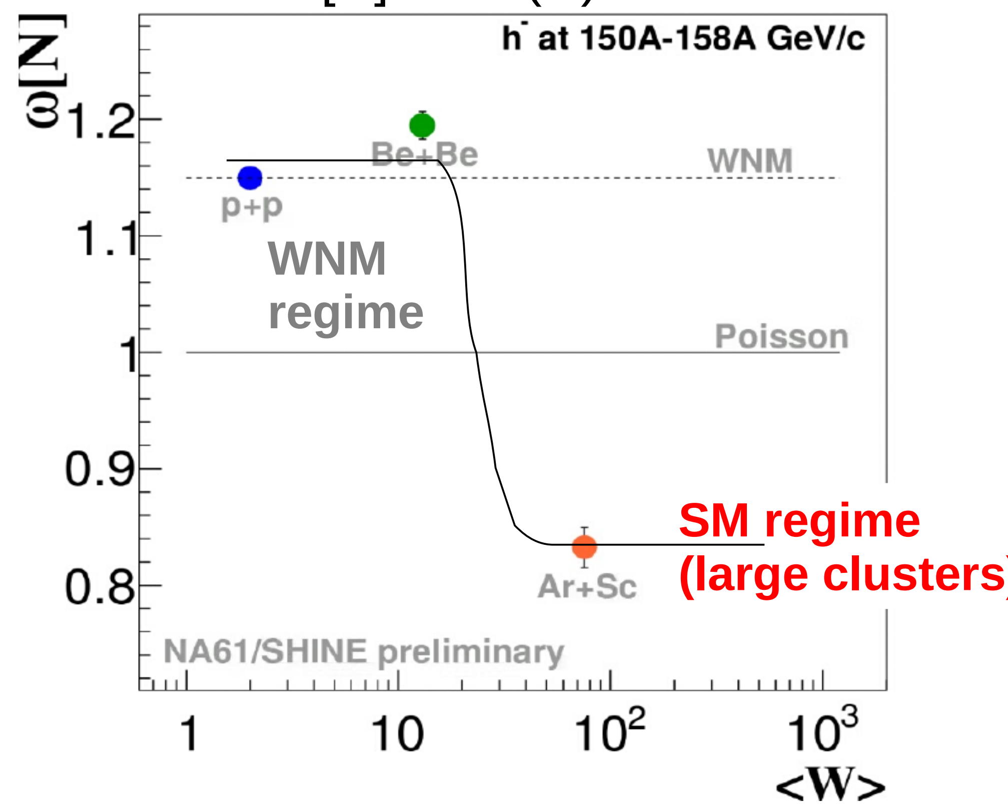
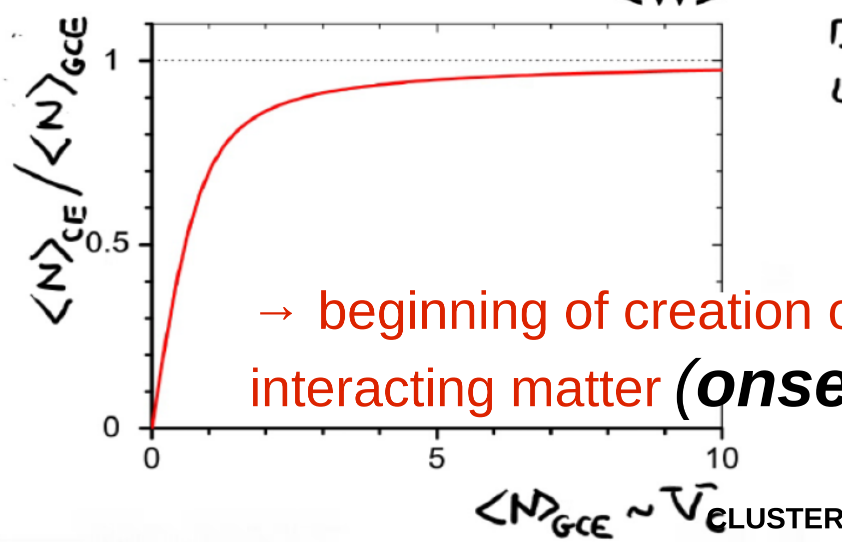
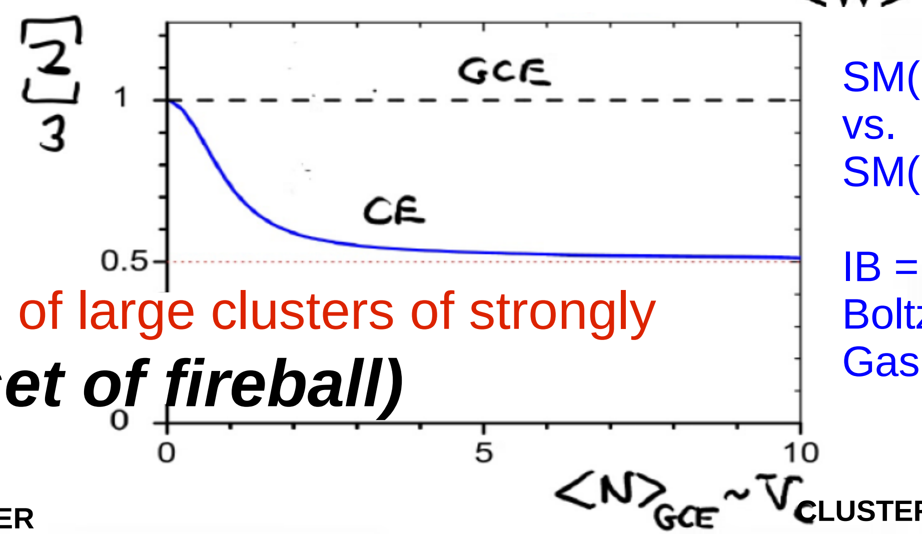
$\omega[N] = \mathrm{var}(N)/\langle N\rangle$









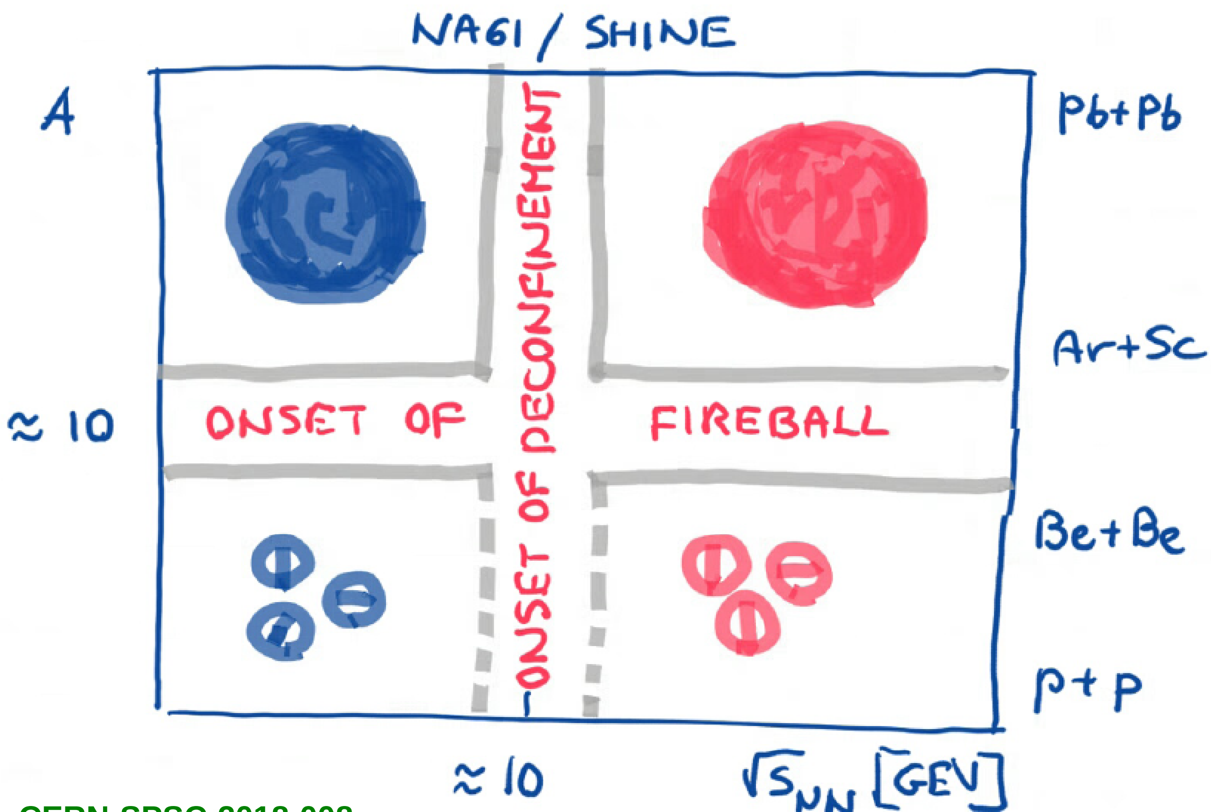
→ beginning of creation of large clusters of strongly interacting matter ***(onset of fireball)***

SM(IB-GCE) vs. SM(IB-CE)

IB = Ideal Boltzmann Gas

M. Gazdzicki for NA61/SHINE, CPOD2017, 1801.00178

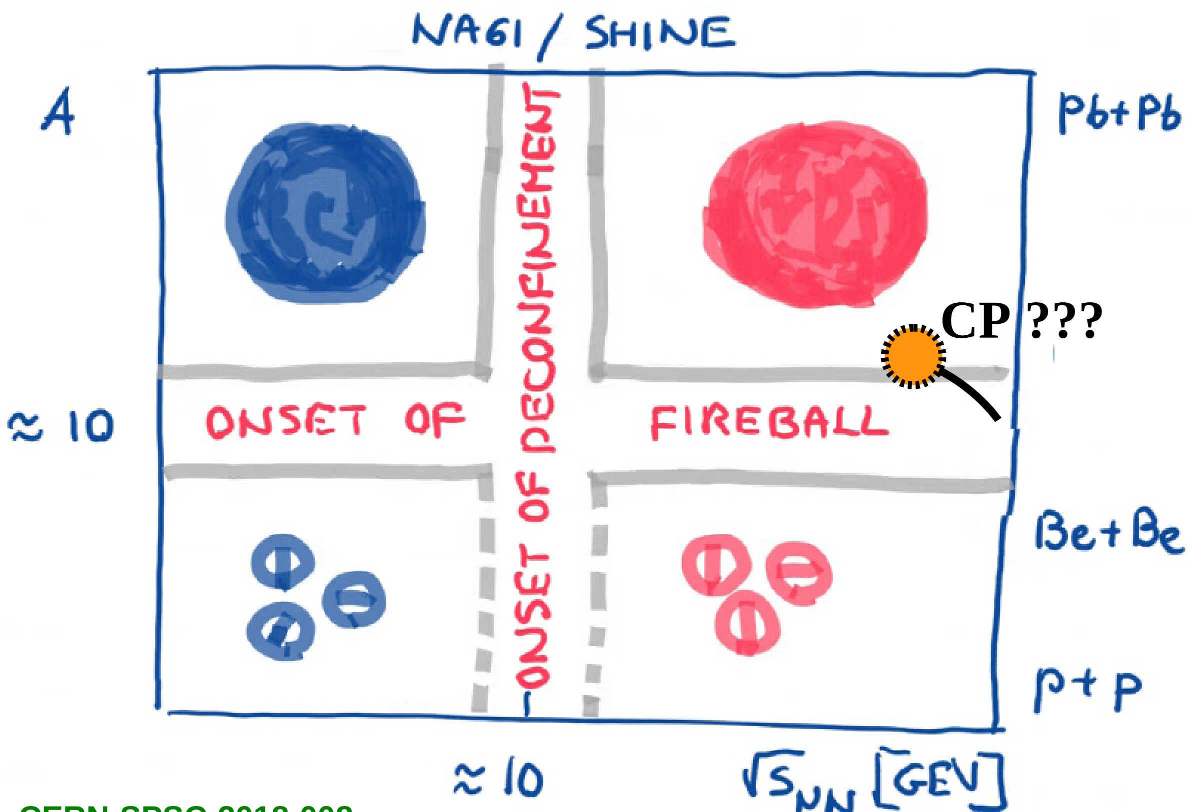
3) The Onset of Deconfinement vs. The Onset of Fireball



NA61/SHINE Collab., CERN-SPSC-2018-008

Figure 4: Two-dimensional scan conducted by NA61/SHINE by varying collision energy and nuclear mass number of colliding nuclei indicates four domains of hadron production separated by two thresholds: the onset of deconfinement and the onset of fireball. The onset of deconfinement is well established in central Pb+Pb(Au+Au) collisions, its presence in collisions of low mass nuclei, in particular, inelastic p+p interactions is questionable.

3) The Onset of Deconfinement vs. The Onset of Fireball



NA61/SHINE Collab., CERN-SPSC-2018-008

Figure 4: Two-dimensional scan conducted by NA61/SHINE by varying collision energy and nuclear mass number of colliding nuclei indicates four domains of hadron production separated by two thresholds: the onset of deconfinement and the onset of fireball. The onset of deconfinement is well established in central Pb+Pb(Au+Au) collisions, its presence in collisions of low mass nuclei, in particular, inelastic p+p interactions is questionable.

4) The Critical Point

independent on system volume...

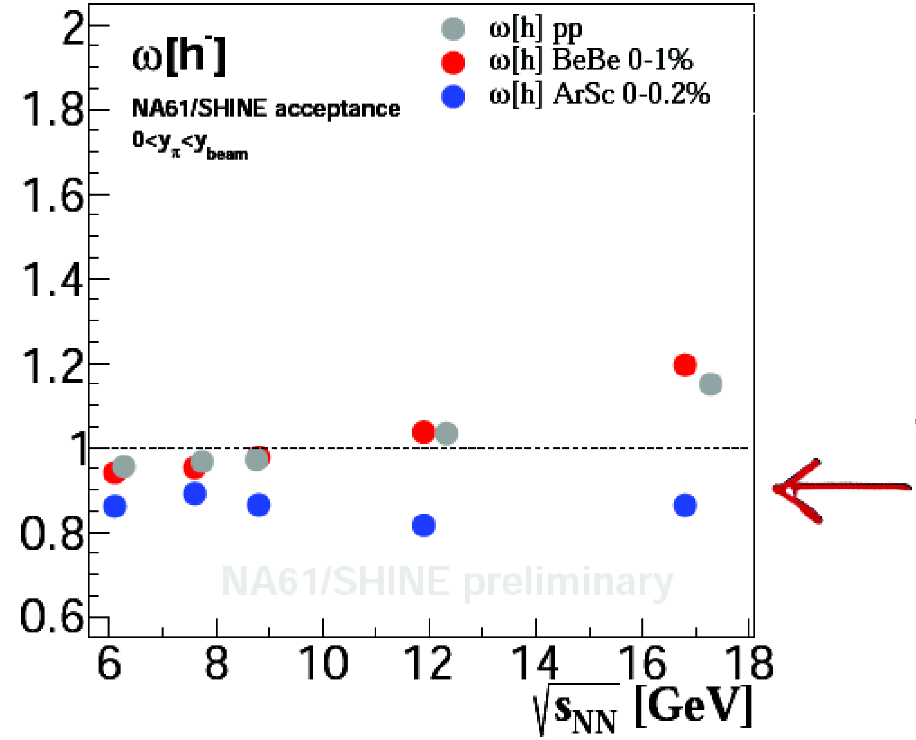
* ω[h-] : intensive ;

... and on its fluctuations.

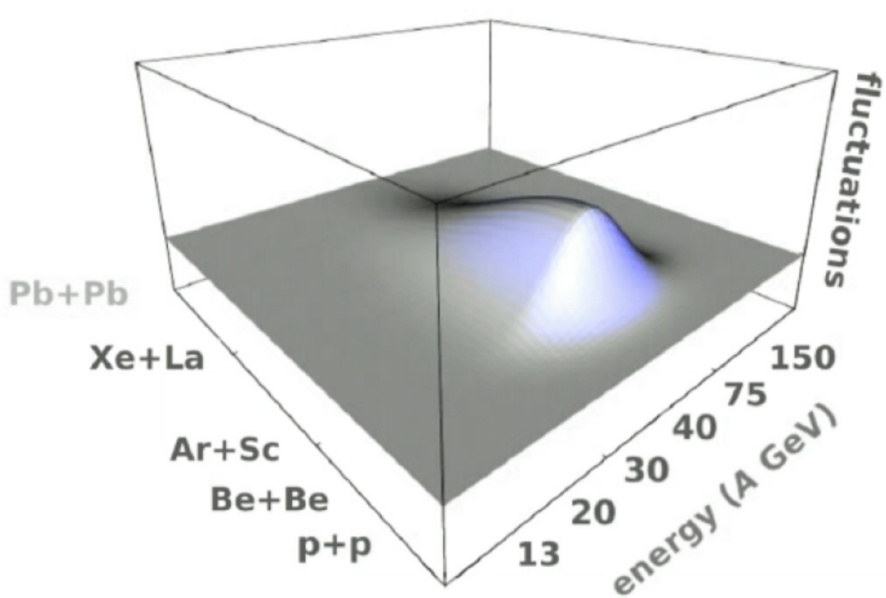
* $\Sigma[P_T, N]$: strongly-intensive ;

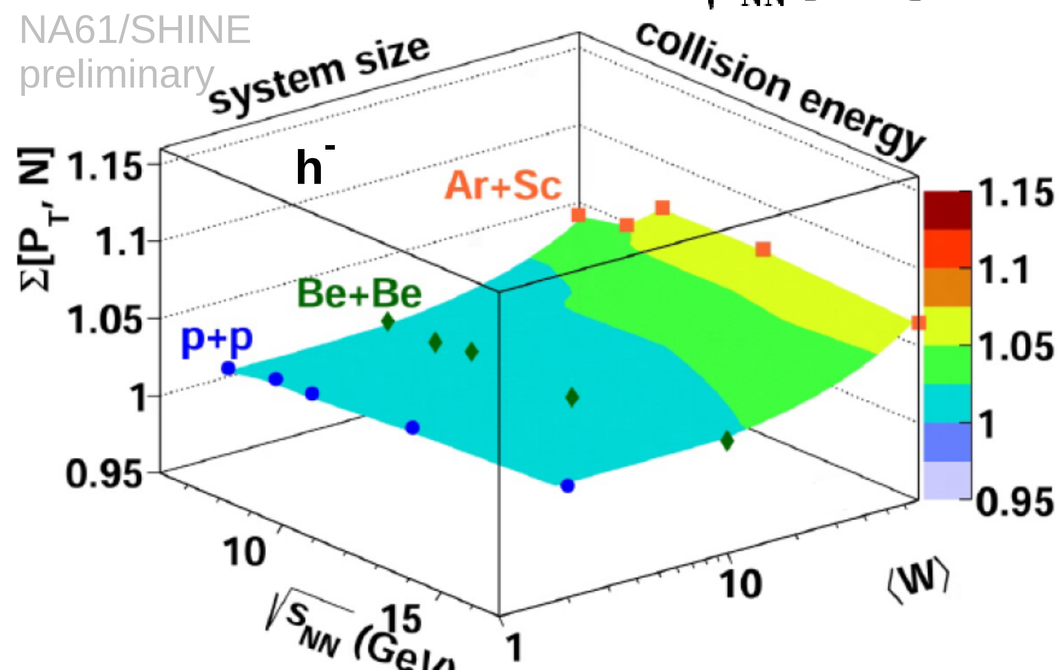
talk by Iwona Sputowska (Wednesday)

* **No signs** that can be clearly associated with the Critical Point.



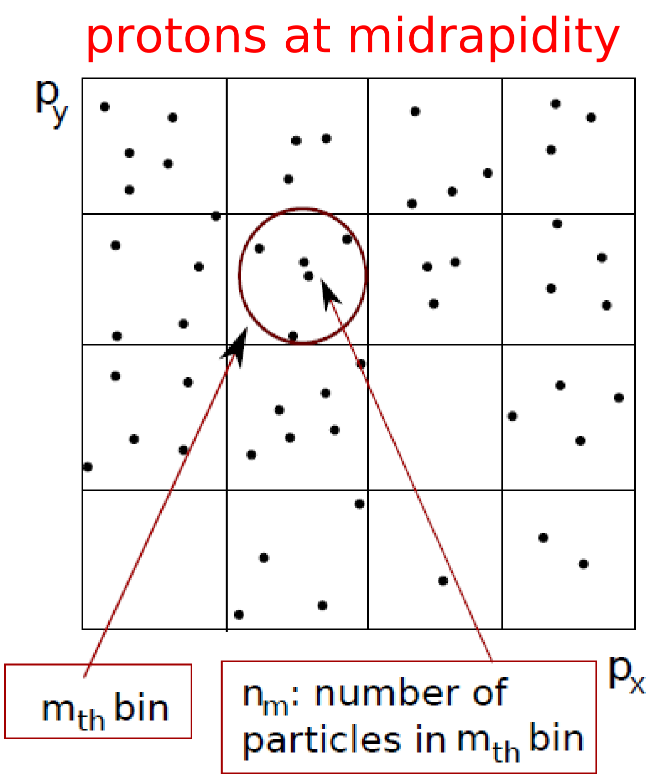
CP ⇒ "FLUCTUATION HILL"





$$\boxed{\Sigma[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left(\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2cov(P_T, N)\right)}$$ where $P_T = \sum_{i=1}^{N} p_{Ti}$

Intermittency analysis of factorial moments (1)



$$F_2(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m - 1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^2}$$

where $\langle \ldots \rangle$ denotes averaging over events.

- We detect local, power-law fluctuations of baryon density by calculating the scaling of 2nd factorial moments $F_2(M)$ with cell size $\Leftrightarrow$ #cells M in (p_x, p_y) space (intermittency).

A. Białas, R. Peschanski, Nucl.Phys. B273 (1986) 703
L. Turko, Phys. Lett. B 227 (1989) 149
F. K. Diakonos et al., PoS (CPOD2006) 010, Florence

- After subtracting non-critical background moments, the correlator:

$$\Delta F_2(M) = F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

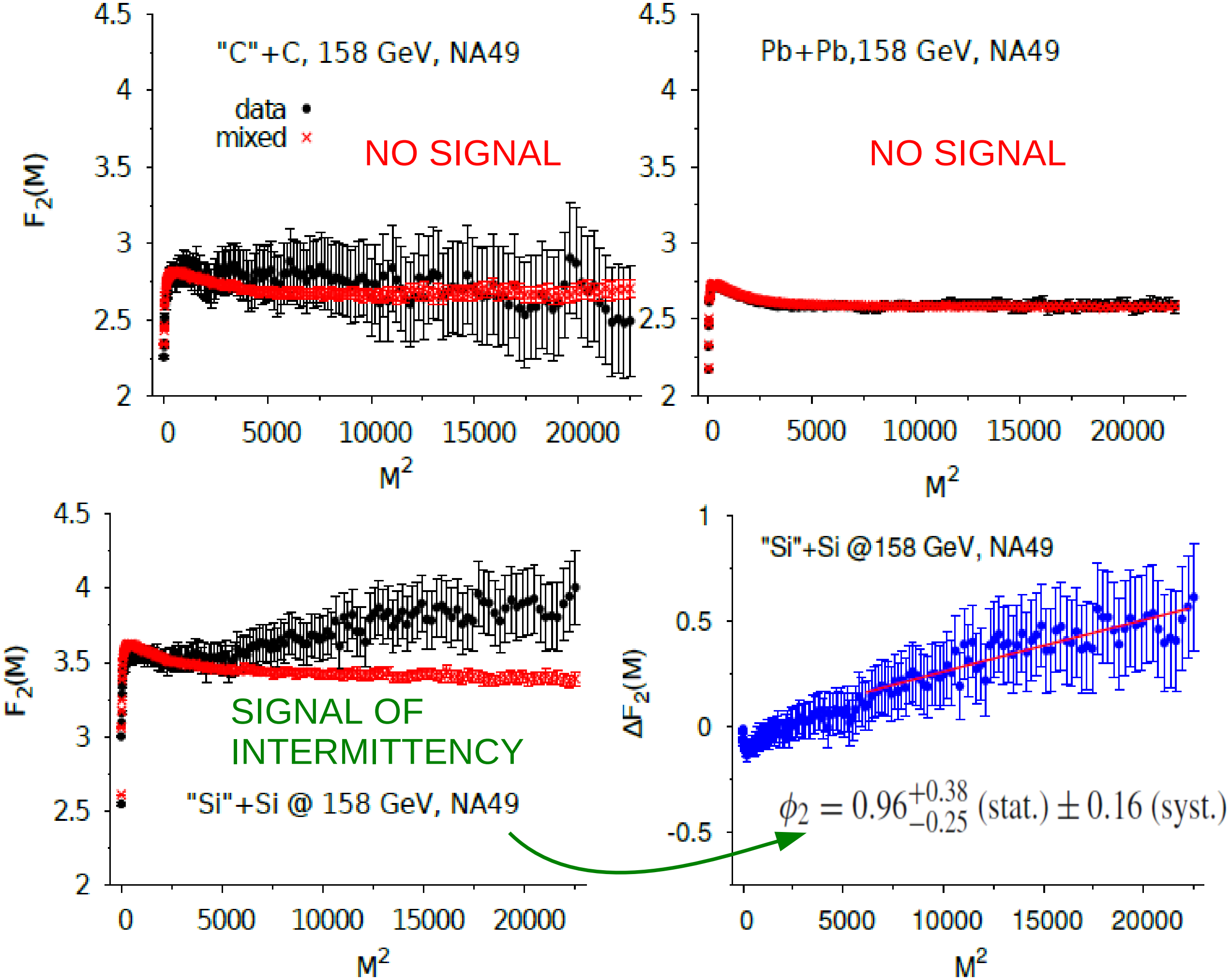
should scale according to a power-law for $M \gg 1$,

$$\Delta F_2(M) \sim (M^2)^{\phi_2},\ \phi_2 = \frac{5}{6}$$

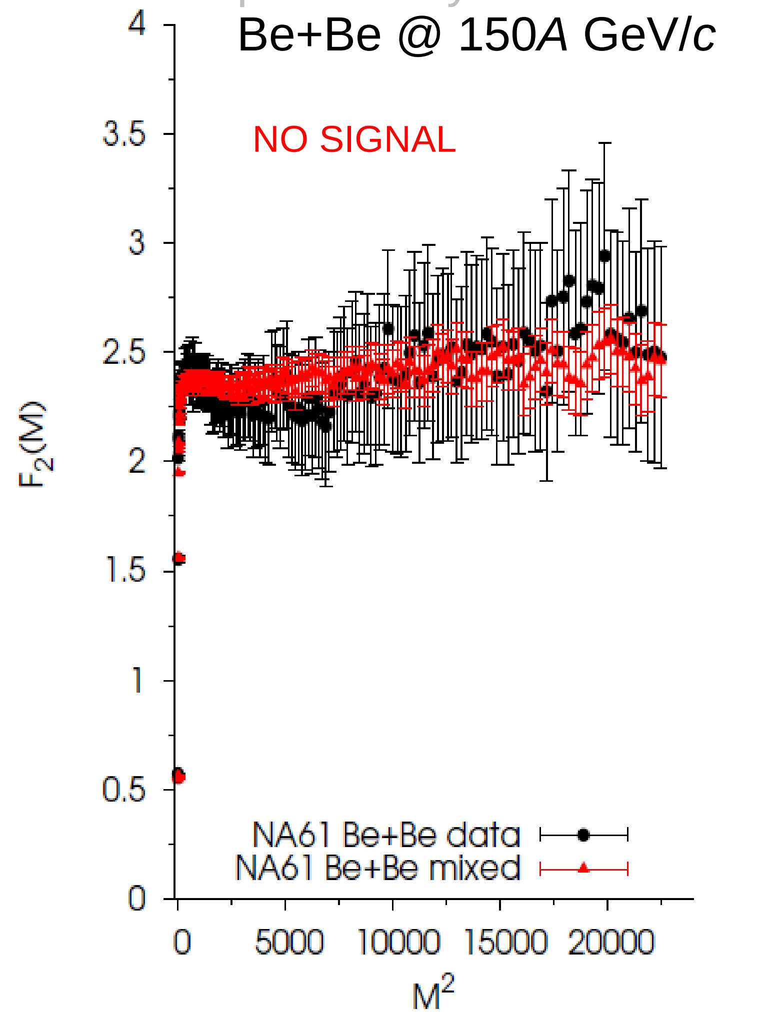
N. G. Antoniou et al., Phys. Rev. Lett. **97**, 032002 (2006)

Intermittency analysis of factorial moments (2)

NA49: T. Anticic et al., Eur. Phys. J. C 75 (2015) 587



NA61/SHINE
preliminary



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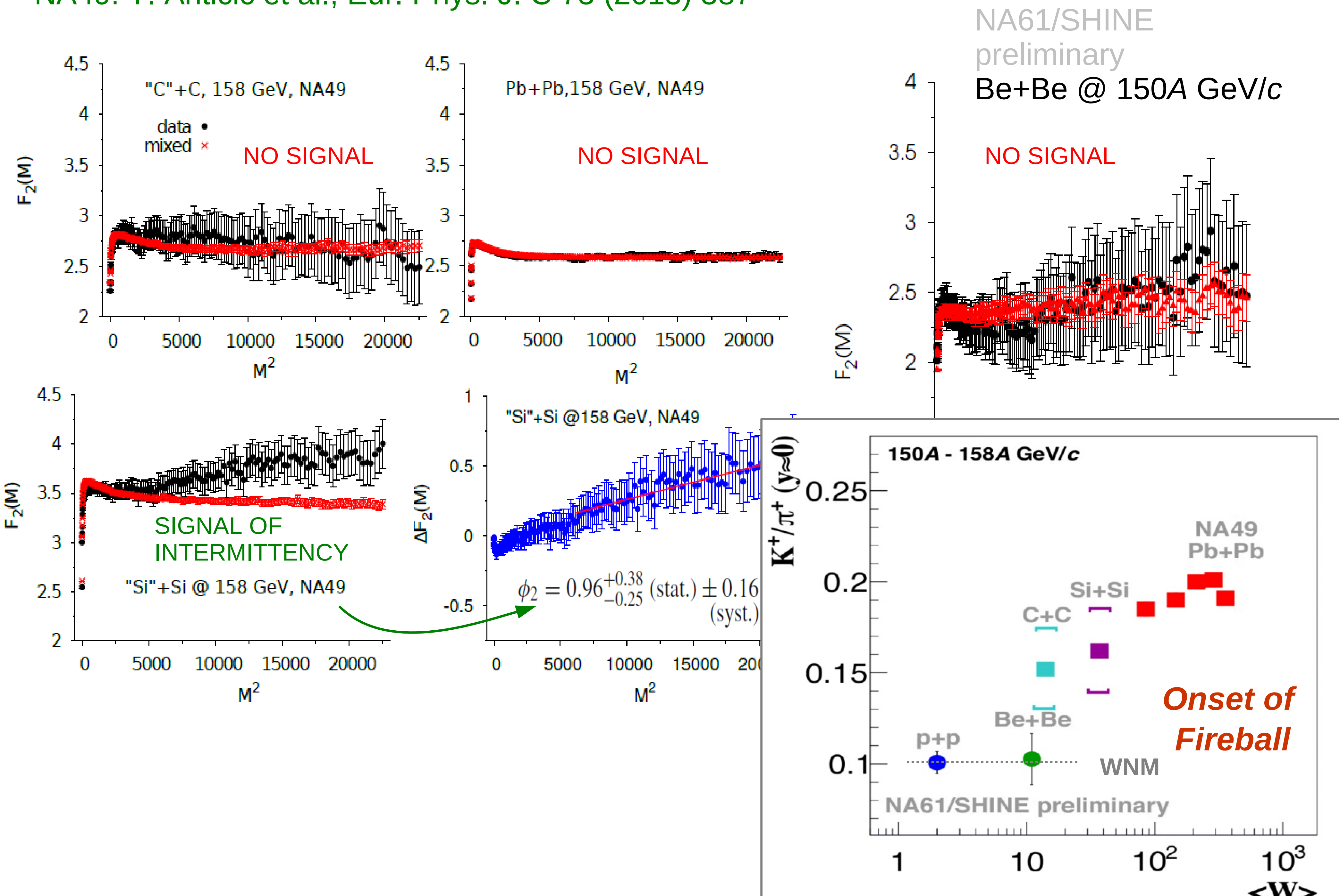

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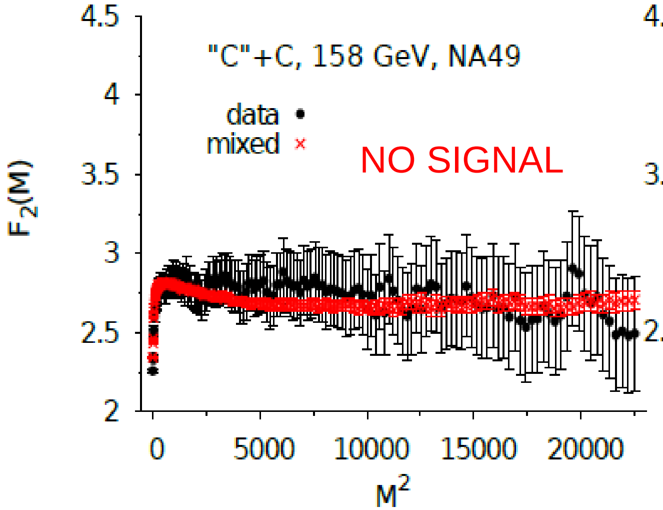
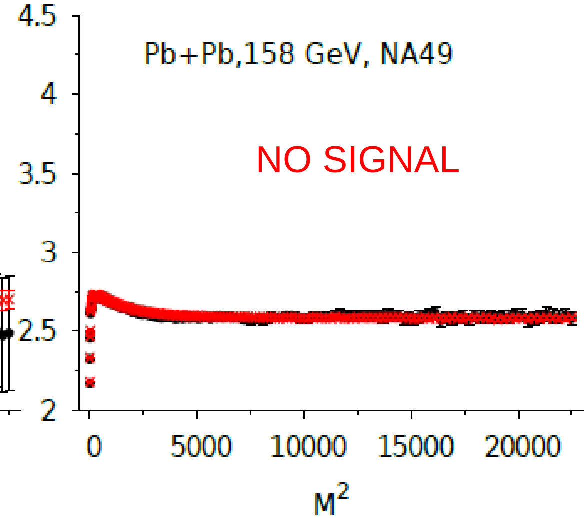
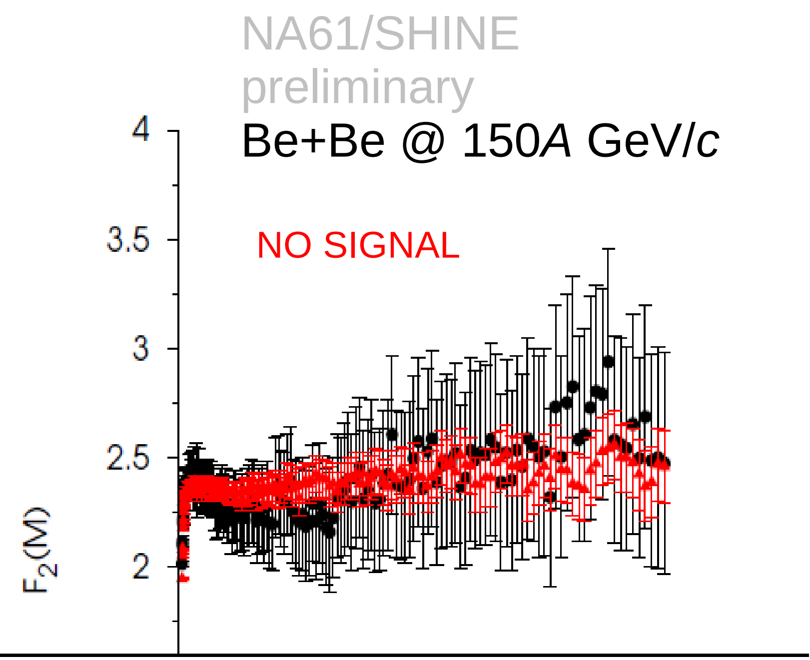
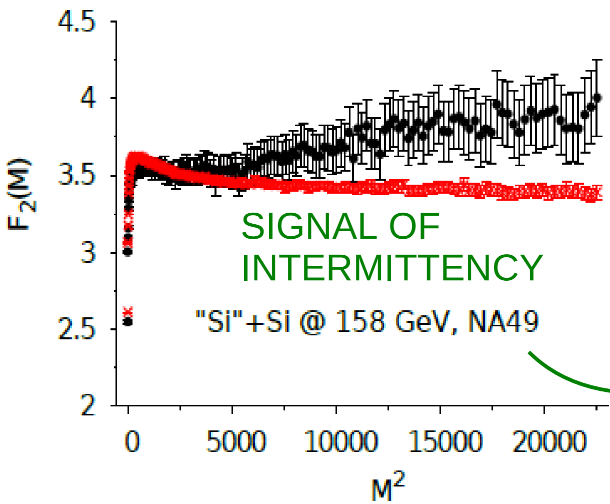
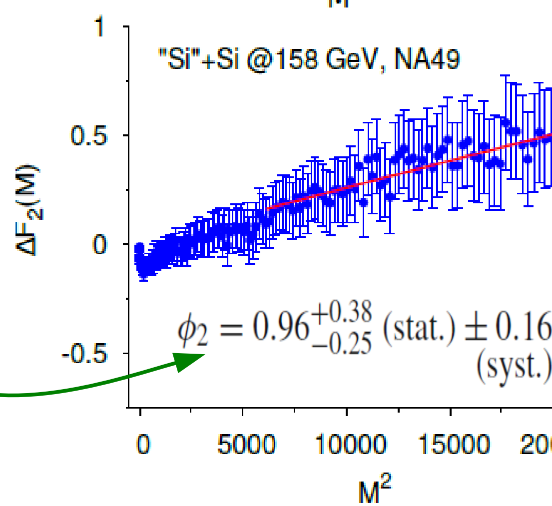
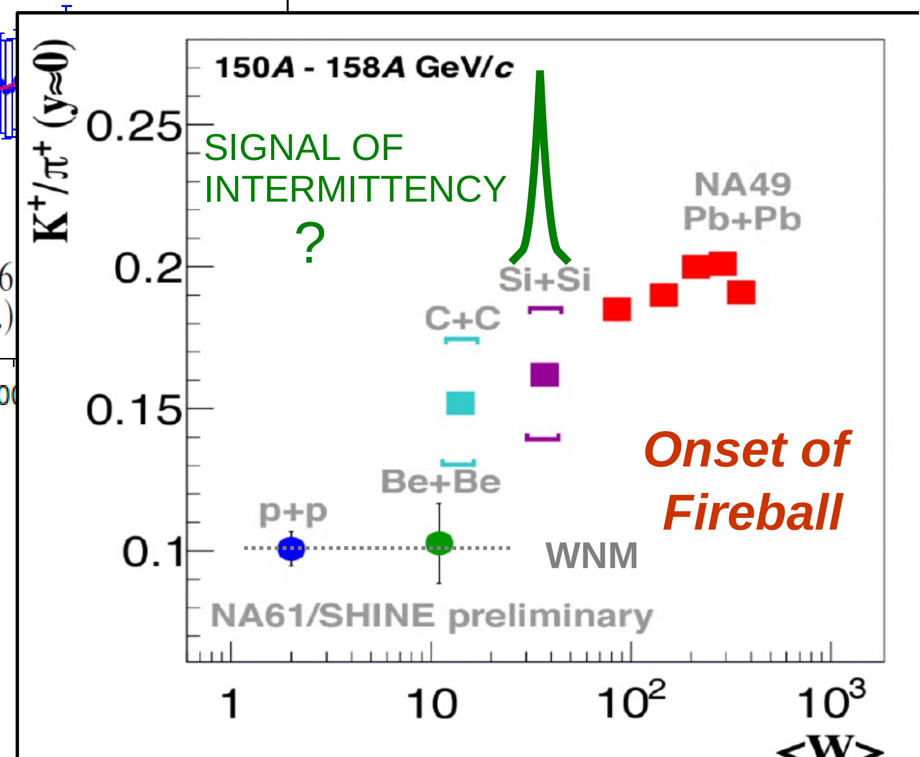










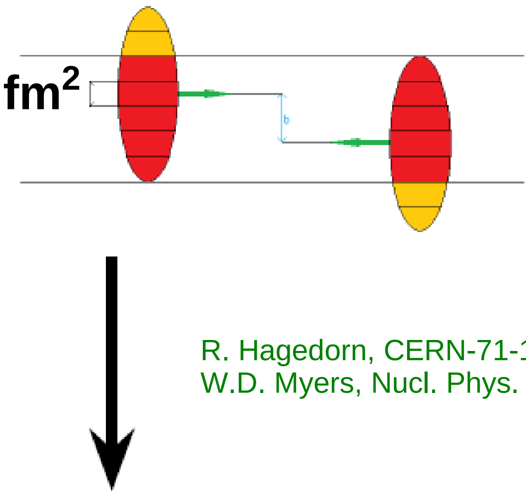


The possible connection of Si+Si intermittent behaviour to the onset of fireball should be further investigated (Turko, Gazdzicki, Davis).

5) The Longitudinal Evolution of the System

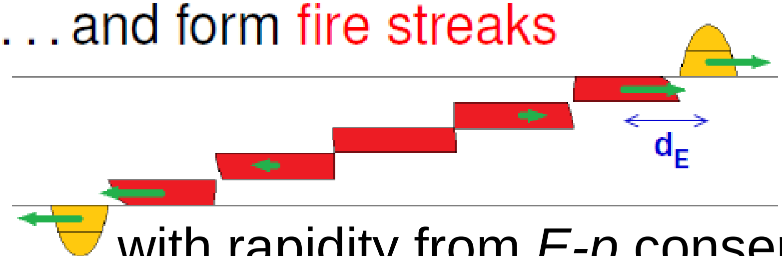
Two nuclei collide ...

1 x 1 fm^2

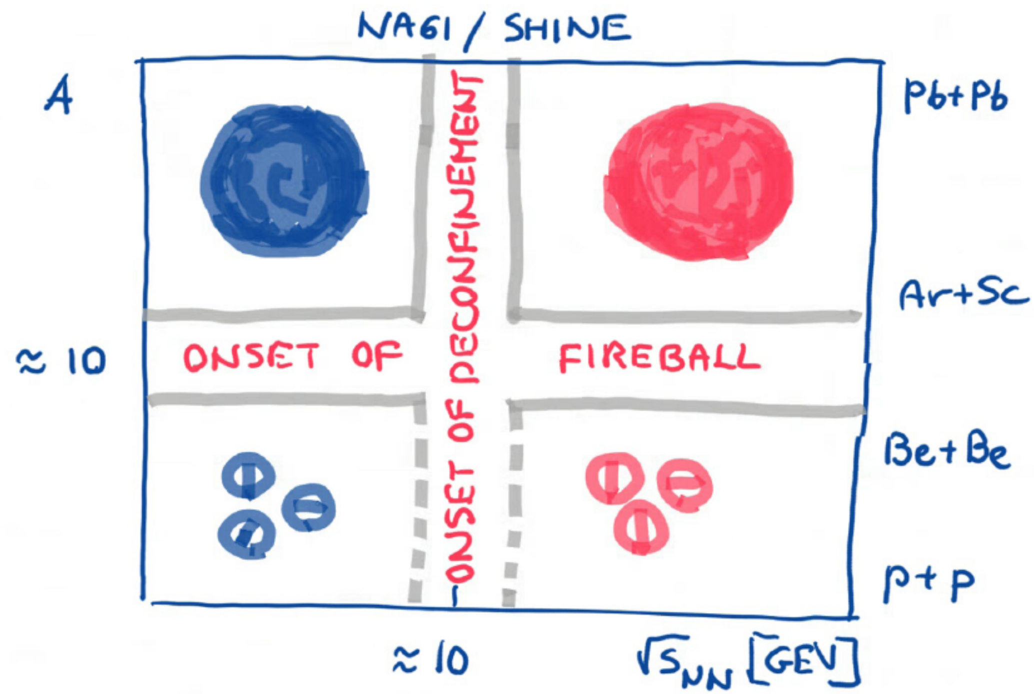


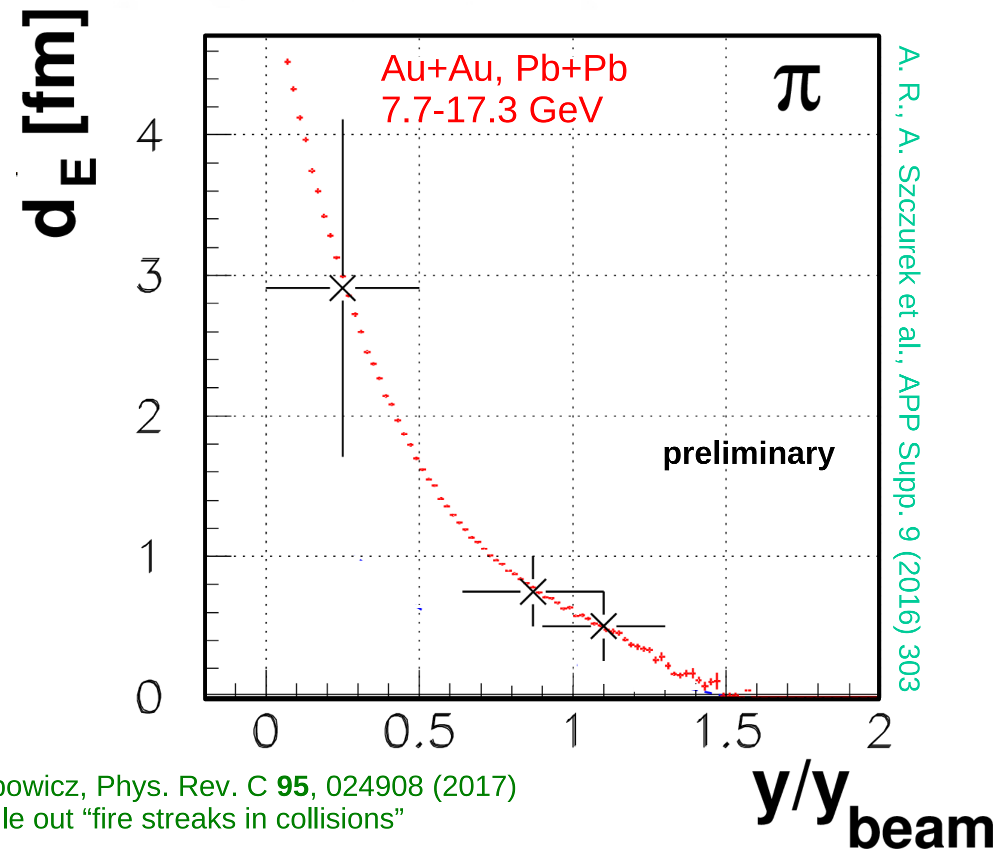
R. Hagedorn, CERN-71-12 (1971)
W.D. Myers, Nucl. Phys. A 296 (1978) 177

. . . and form fire streaks



with rapidity from *E-p* conservation



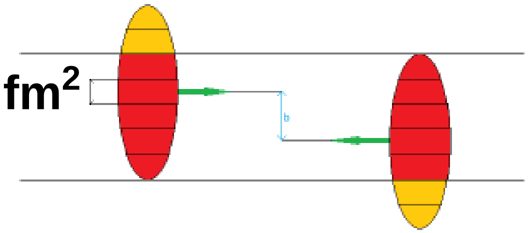


- Inspired by EM effects ;
  - → Iwona Sputowska, Thursday talk ;
  - → Mirek Kiełbowicz, Thursday talk ;
  - → Kasia Mazurek, Thursday talk ;
- (Re)invented by A. Szczurek ;
- Successful for pion spectra at SPS (for now!).

A. Szczurek., A. R., M. Kiełbowicz, Phys. Rev. C **95**, 024908 (2017)
Press release: google out “fire streaks in collisions”

Two nuclei collide ...

1 x 1 fm^2



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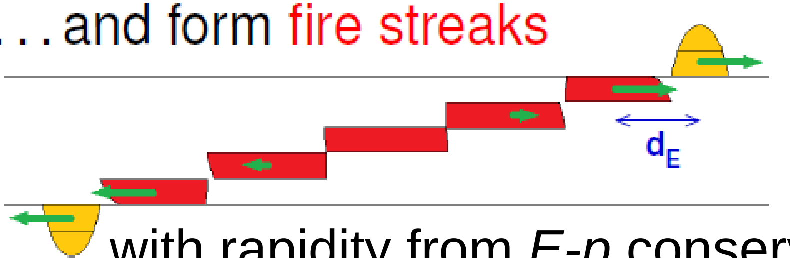
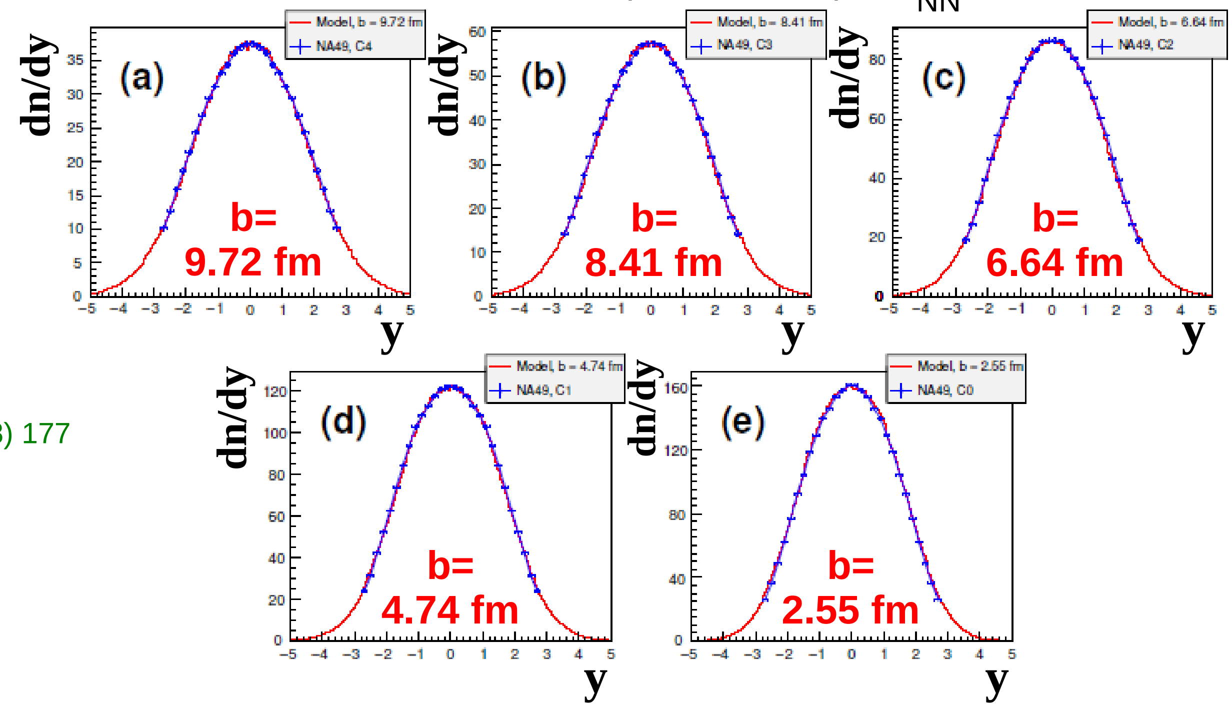


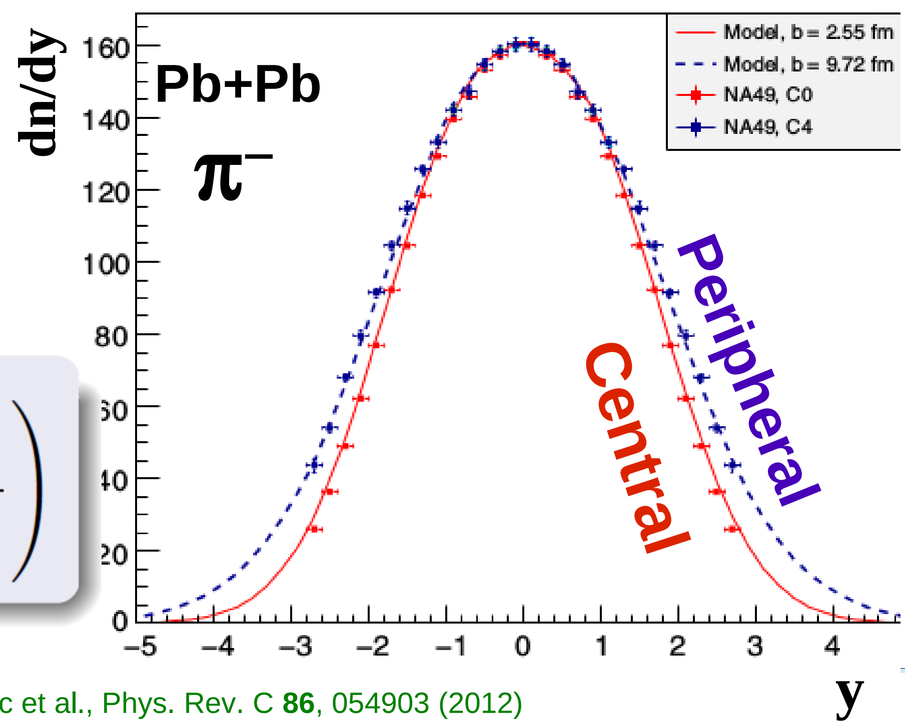
with rapidity from *E*-*p* conservation

Each fire streak decays into pions

$$\frac{\mathrm{d}n}{\mathrm{d}y} \sim A \cdot (E_s^* - m_s) \cdot \exp\left(- \frac{\left[(y - y_s)^2 + \epsilon^2\right]^{\frac{n}{2}}}{n\sigma_y^n} \right)$$

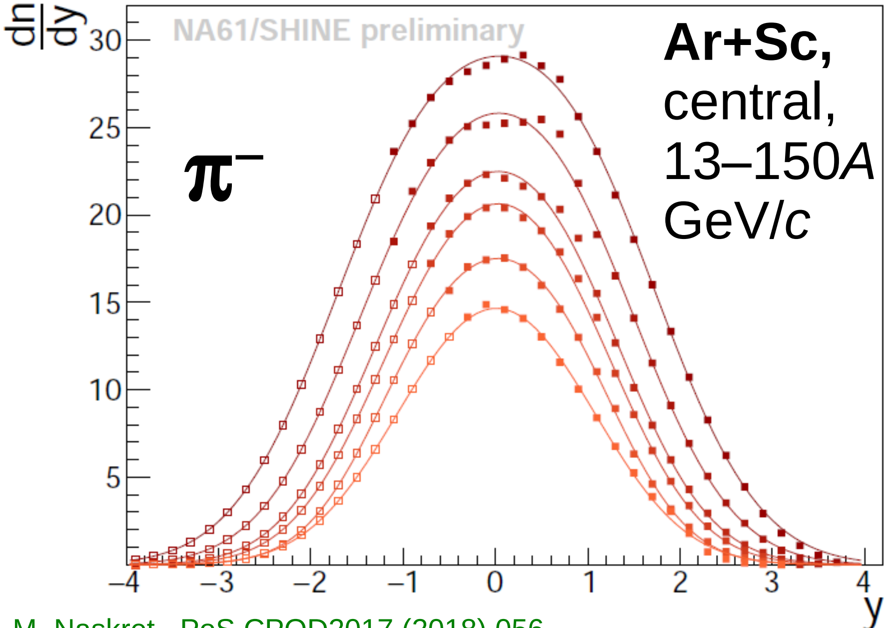
π^-, Pb+Pb, $\sqrt{s_{NN}}$ = 17.3 GeV



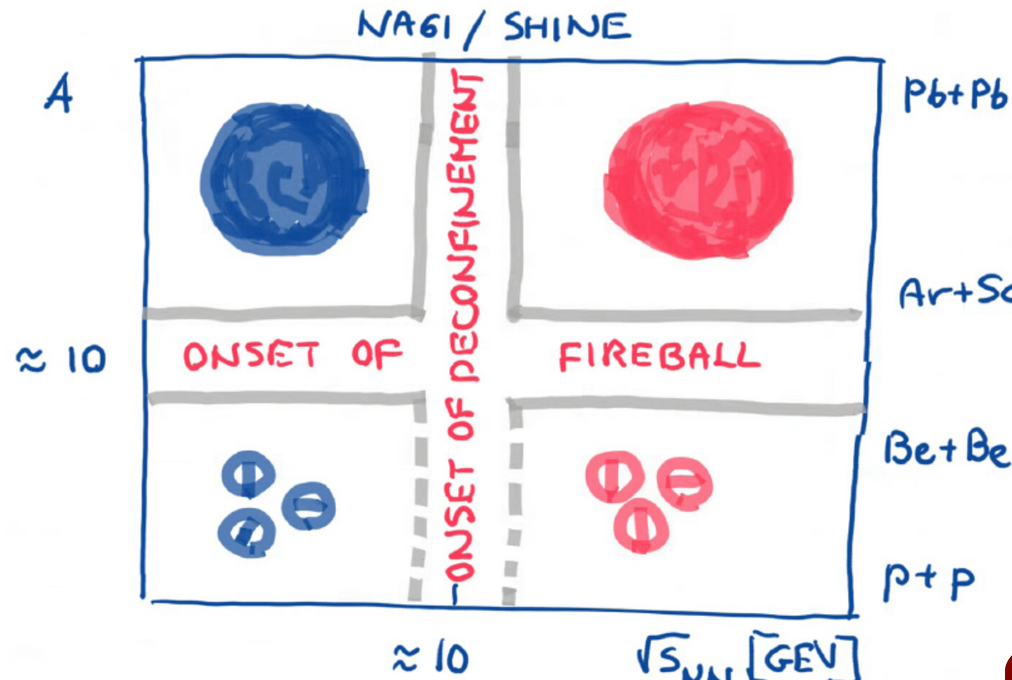


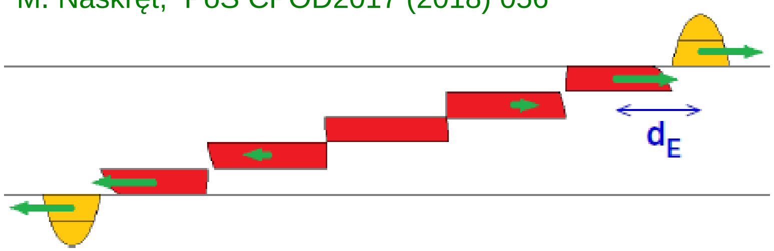
A. Szczurek., A. R., M. Kiełbowicz, Phys. Rev. C **95**, 024908 (2017)

data points from: **NA49**, T. Anticic et al., Phys. Rev. C **86**, 054903 (2012)



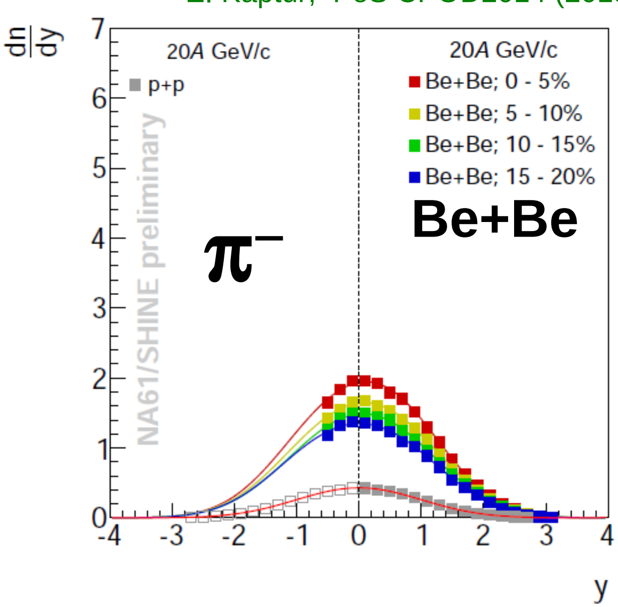
M. Naskręt, PoS CPOD2017 (2018) 056

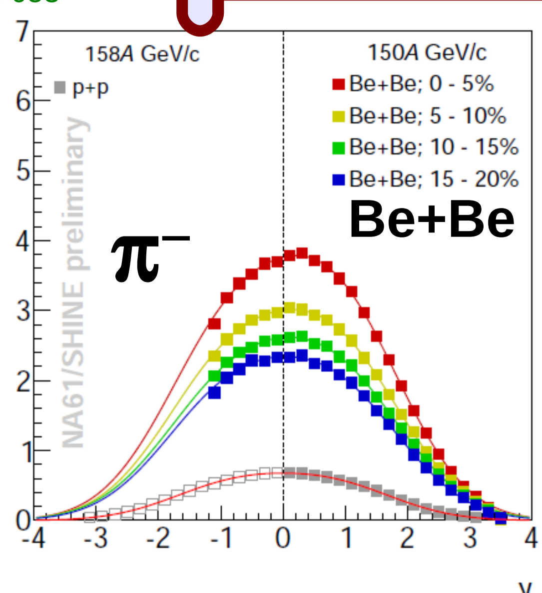


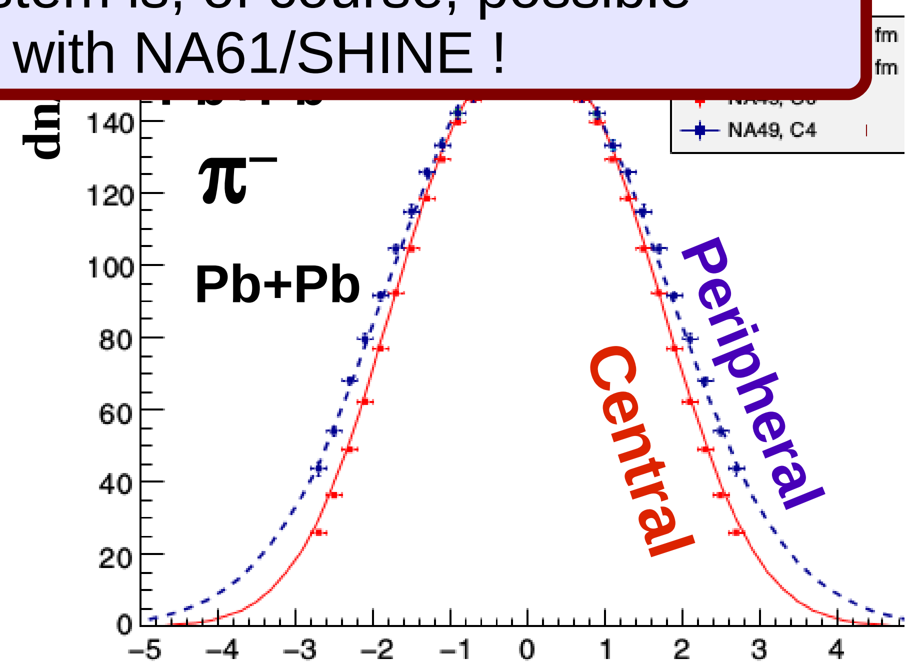


E. Kaptur, PoS CPOD2014 (2015) 053

A **2D scan** of the longitudinal evolution of the system is, of course, possible - with NA61/SHINE !

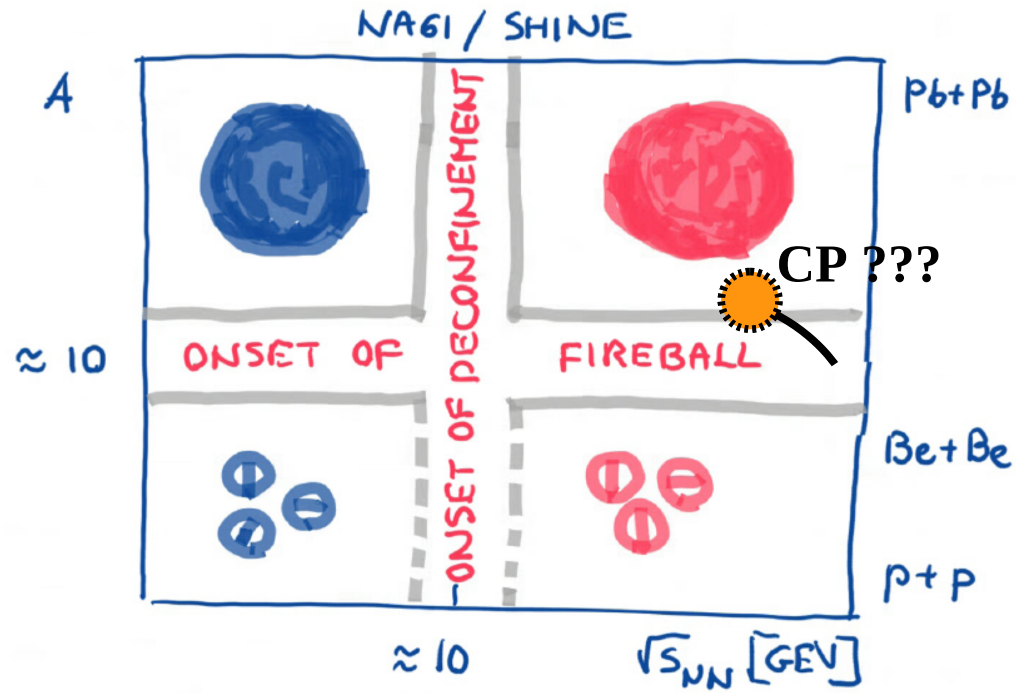






Phys. Rev. C **86**, 054903 (2012)

6) Summary



- NA61/SHINE is a gold mine.
- Tentative conclusion from 2D scan:
  four domains of hadron production
  separated by **two** thresholds:
  the onset of deconfinement
  and
  the onset of fireball.
- In this situation, the search for the Critical Point becomes a challenging task. What is the role of the intermittency signal ?
- Exploitation of the mine goes on.
  New options, including flow (Evgeny), HBT (Barnabas), EM effects (Mirek), and the longitudinal evolution of the system, open up like flowers in the sun…

Thank you!

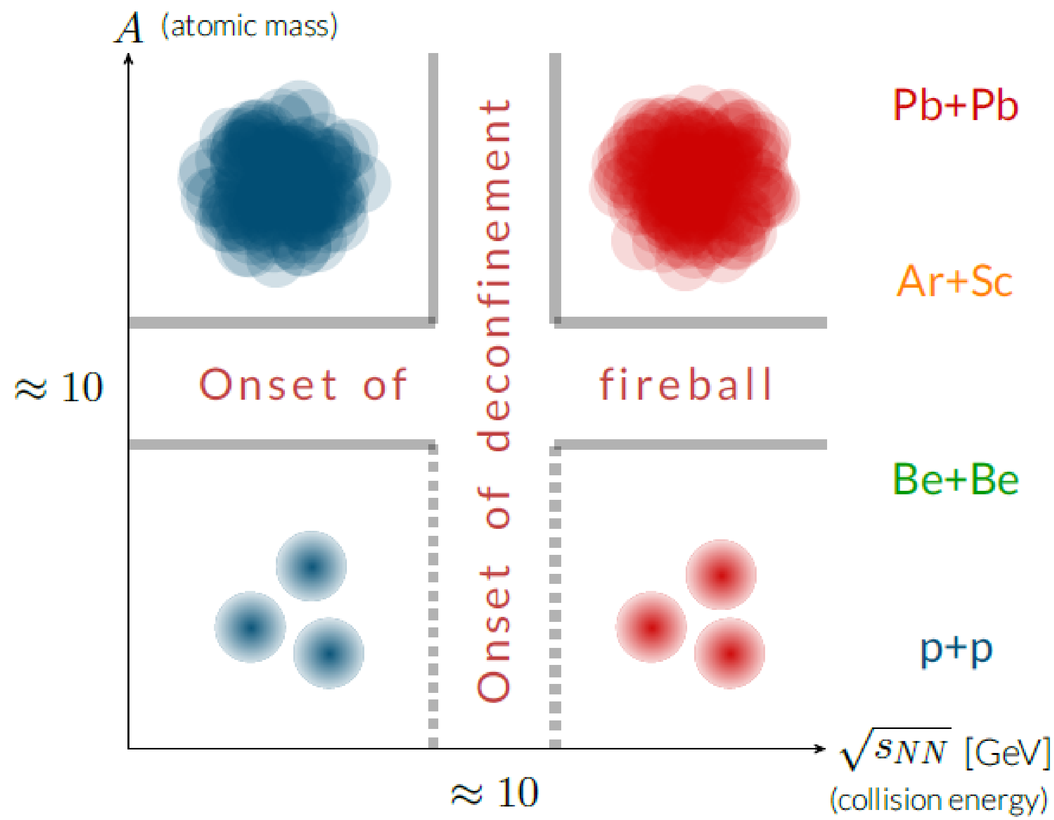
Acknowledgments.

This work was supported by the National Science Centre, Poland

(grant no. 2014/14/E/ST2/00018).

Extra slides

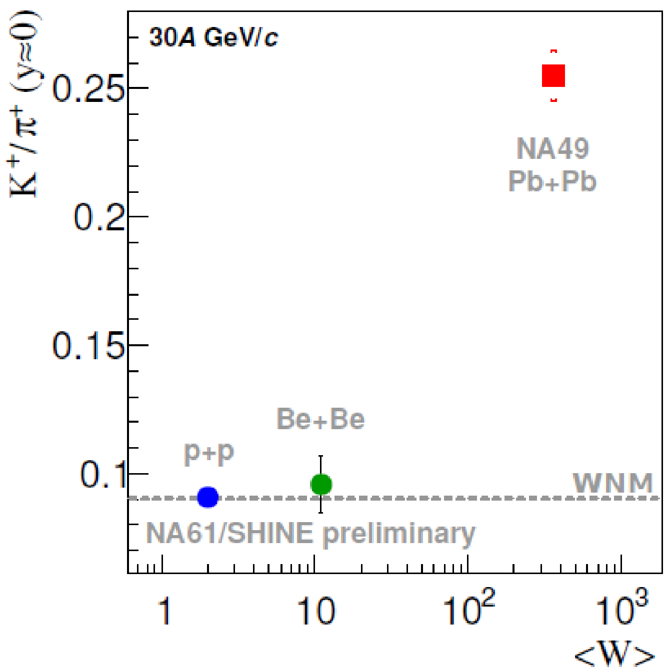
The Onset of Deconfinement vs. The Onset of Fireball (official version)

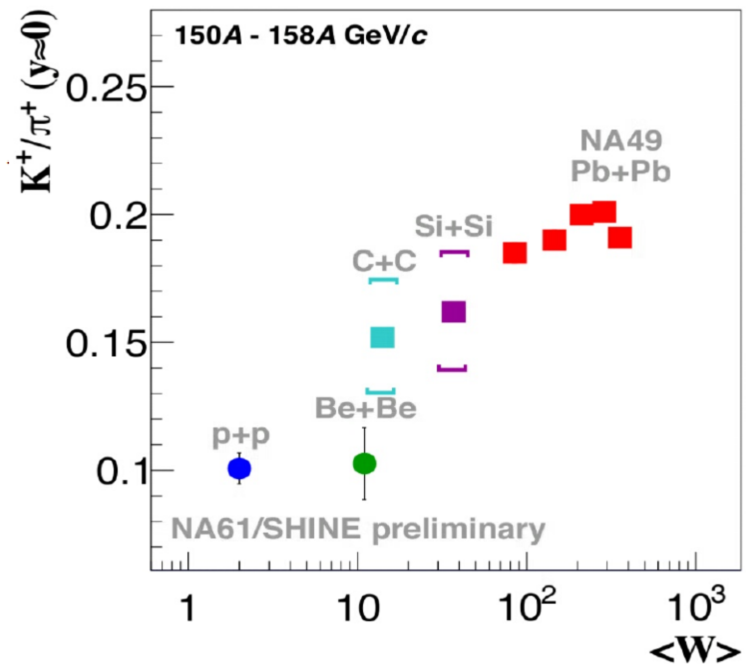


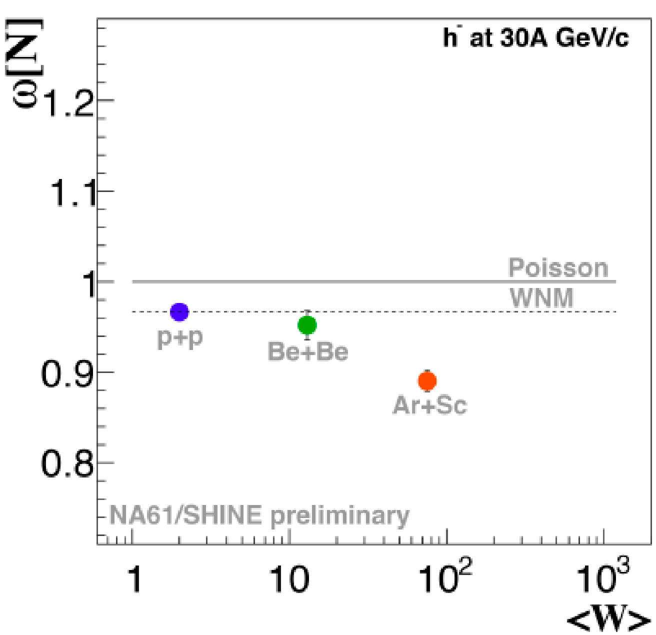
NA61/SHINE Collab., CERN-SPSC-2018-008

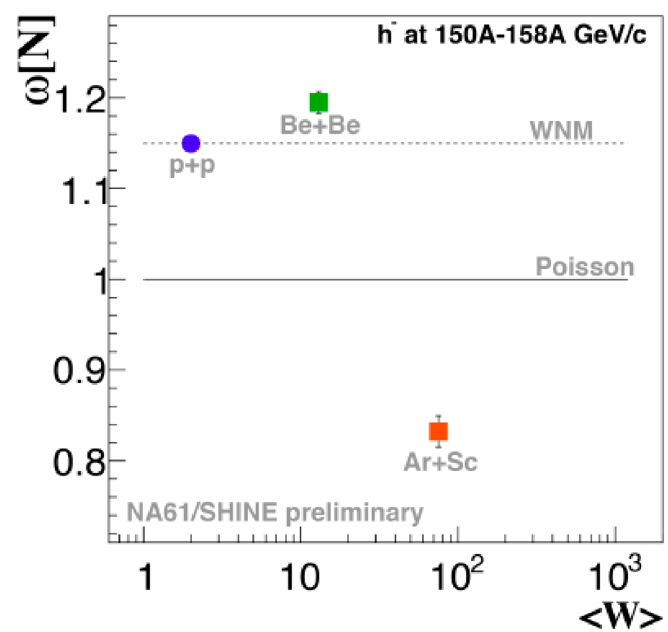
Figure 4: Two-dimensional scan conducted by NA61/SHINE by varying collision energy and nuclear mass number of colliding nuclei indicates four domains of hadron production separated by two thresholds: the onset of deconfinement and the onset of fireball. The onset of deconfinement is well established in central Pb+Pb(Au+Au) collisions, its presence in collisions of low mass nuclei, in particular, inelastic p+p interactions is questionable.

System size dependence as a function energy





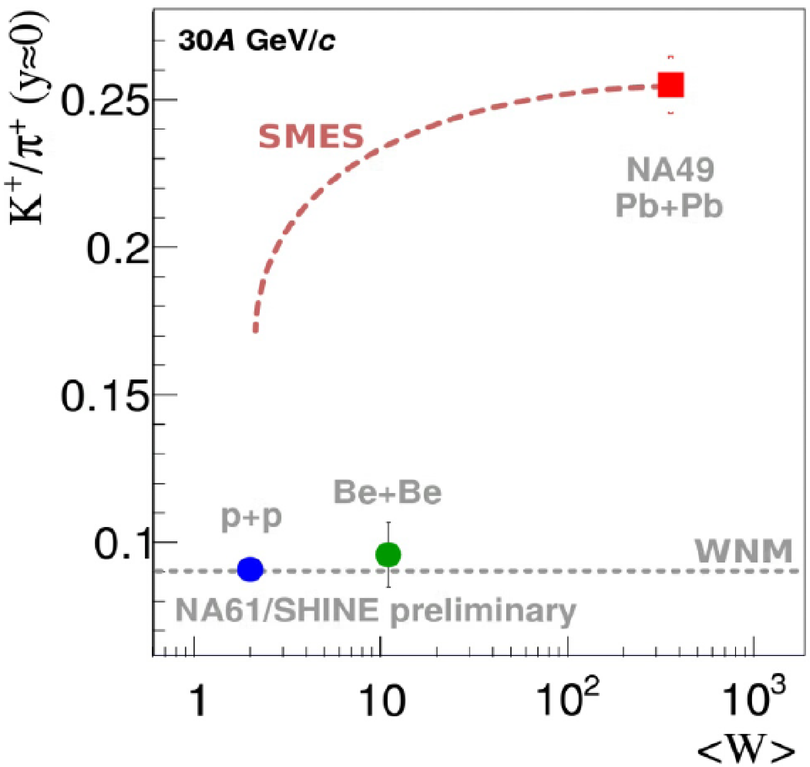


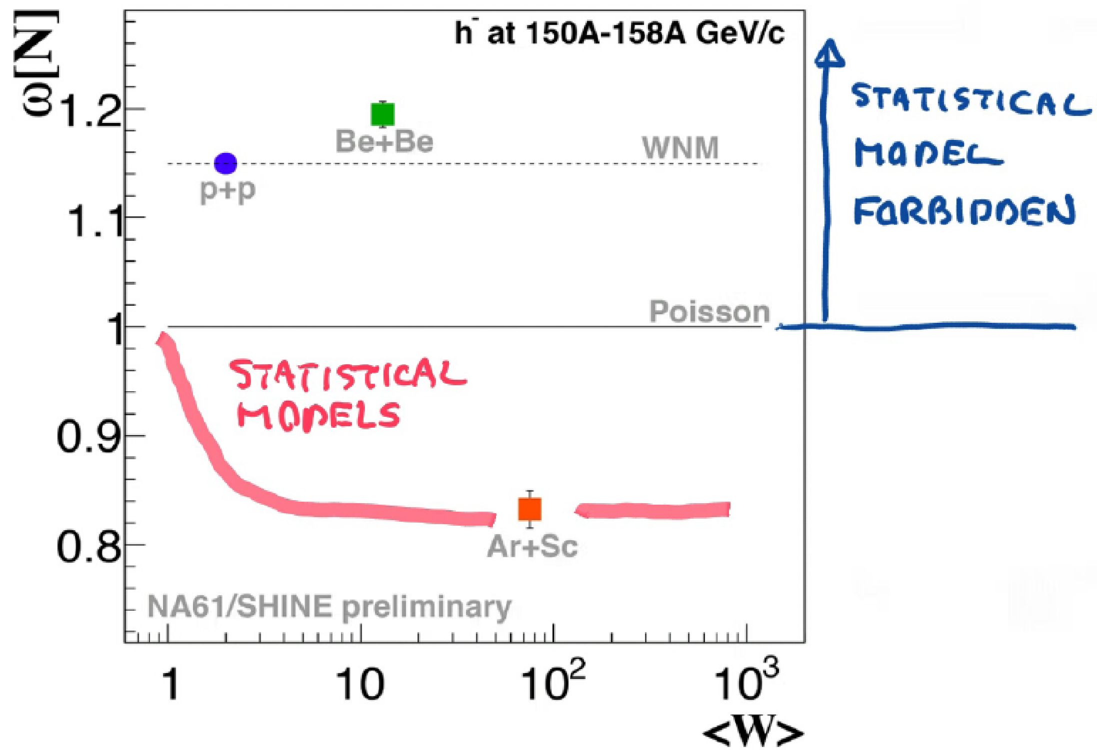


Statistical models vs. NA61/SHINE data

(more realistic version)

p+p AND Be+Be SUPPERPOSITION OF "NON-STATISTICAL CLUSTERS" (11)





Ar+Sc AND Pb+Pb ≈ LARGE VOLUME CLUSTER OF SIM ?

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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) 024907

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(14)

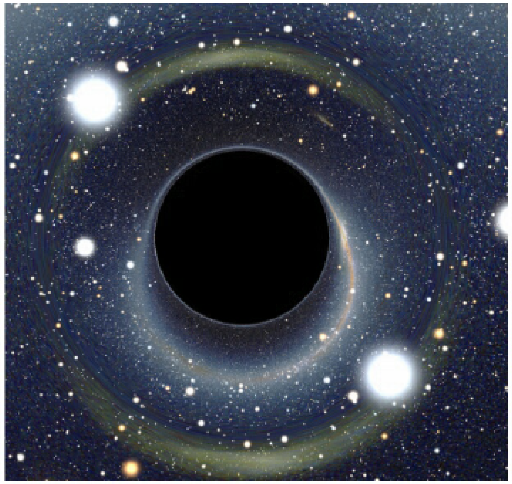
ON INTERPRETATION OF ONSET OF FIREBALL:

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

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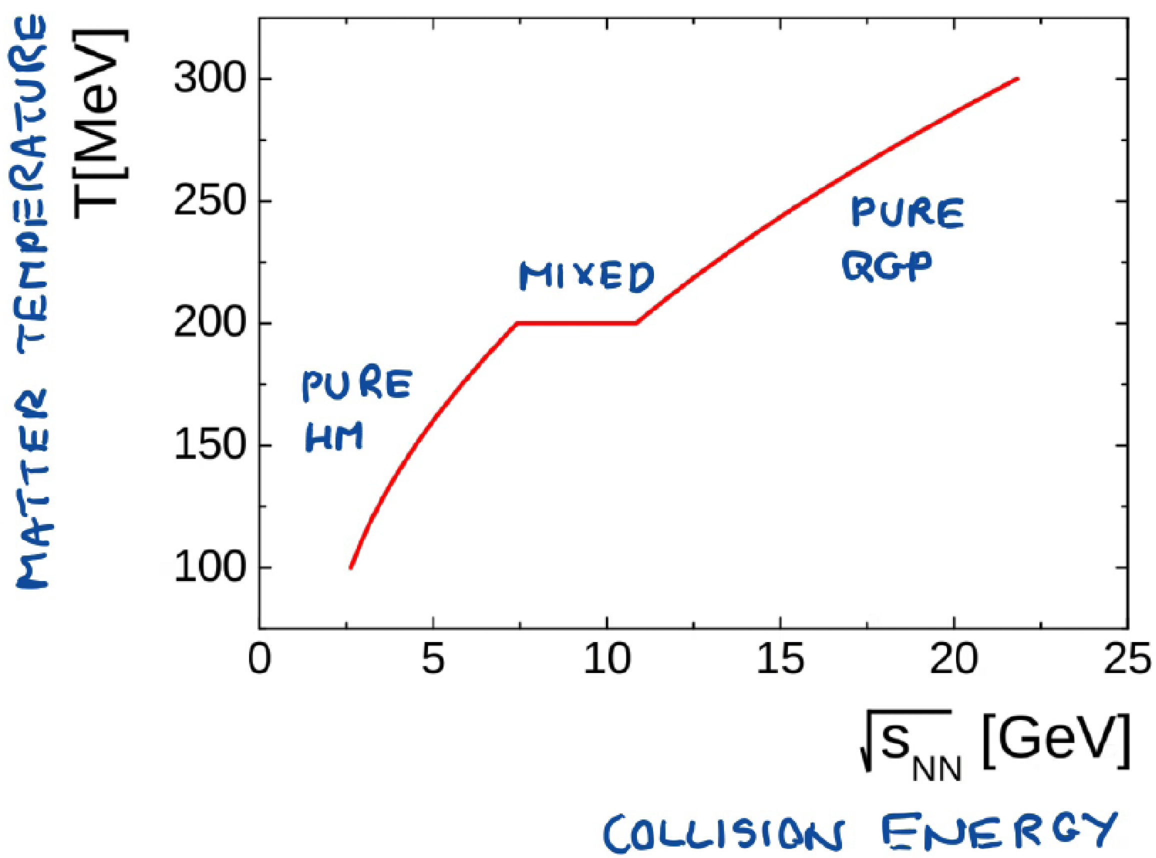
ONSET OF DECONFINEMENT IN SMES

16



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ONSET OF DECONFINEMENT IN SMES

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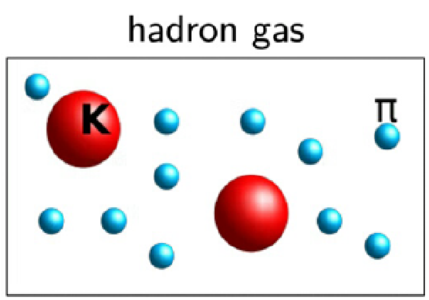
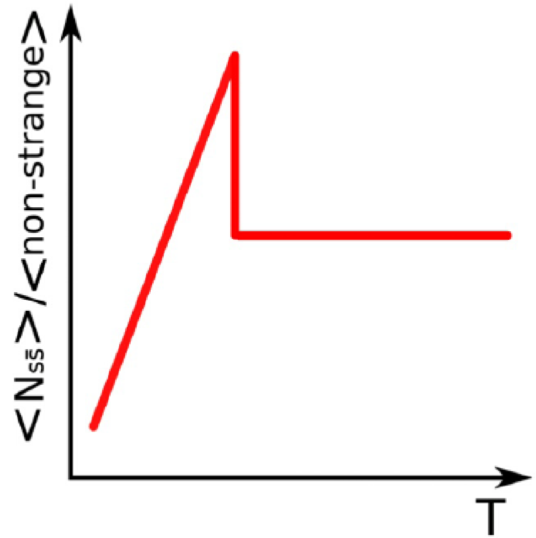
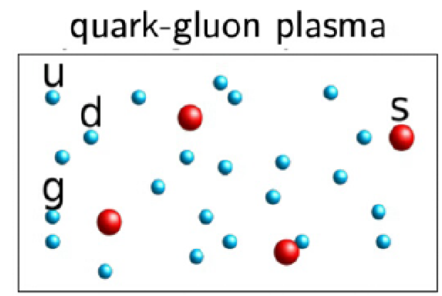
$M_K \approx 500$ MeV $\qquad T_c \approx 150$ MeV $\qquad M_s \approx 100$ MeV ($\approx 10^{-29}$ kg)



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





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

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

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

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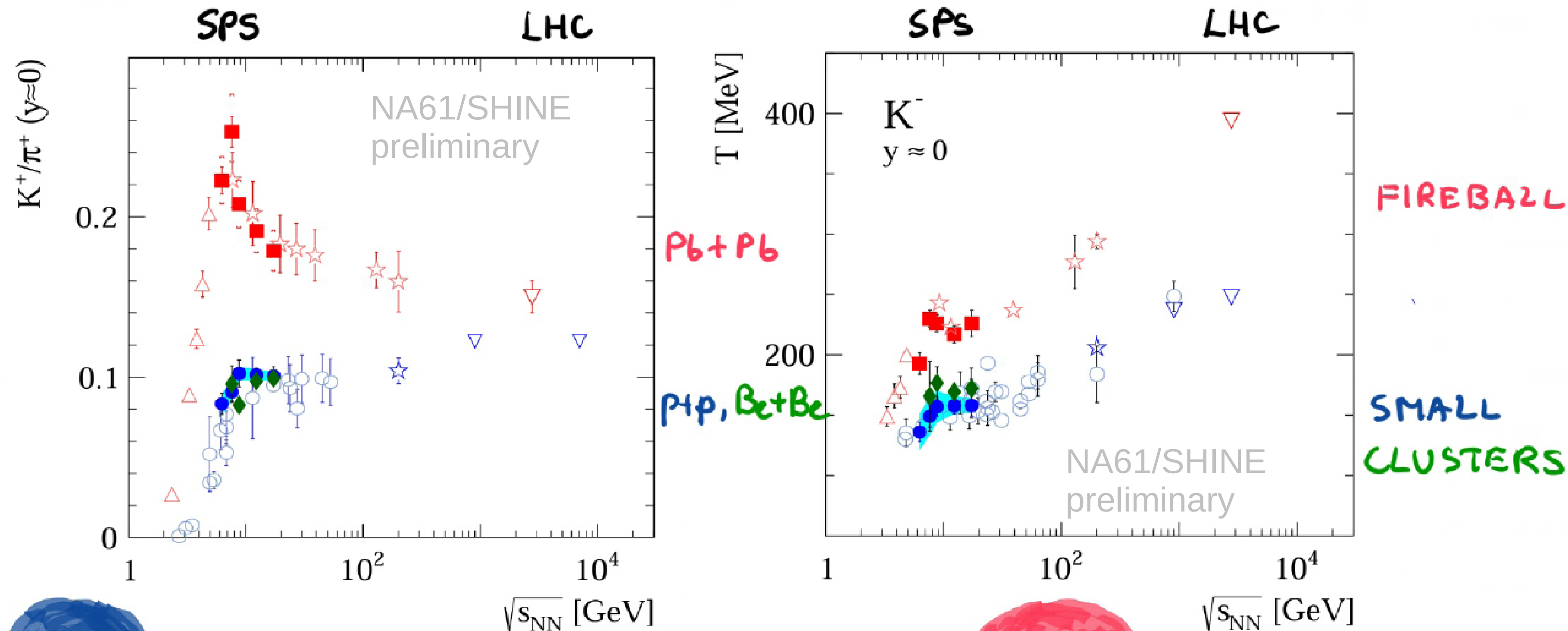
EVIDENCE FOR ONSET OF DECONFINEMENT IN Pb+Pb (FIREBALL)



↑ ONSET OF DECONFINEMENT ↑

Pb+Pb CLOSE TO EQUILIBRIUM

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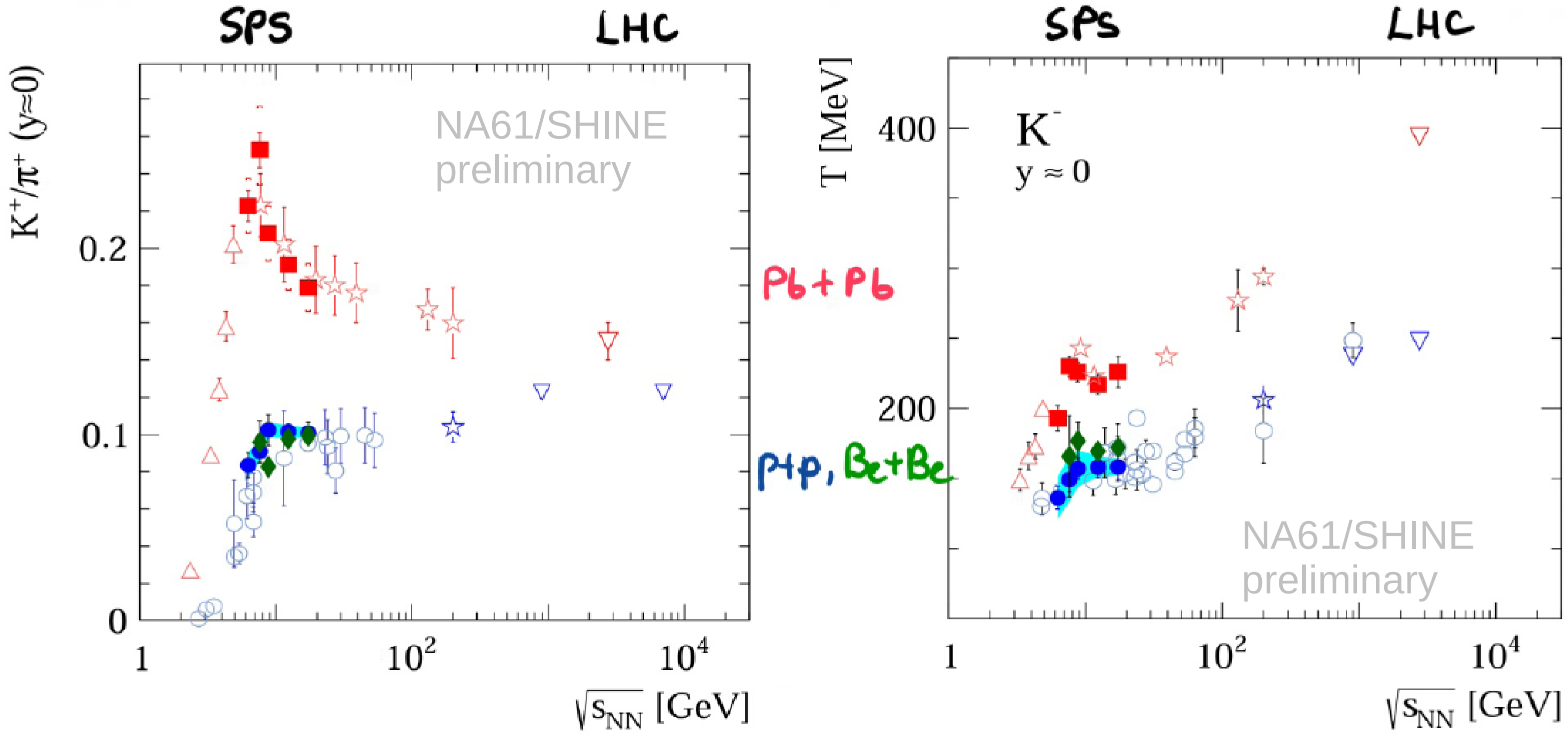
EVIDENCE FOR ONSET OF DECONFINEMENT

CHALLENGE TO UNDERSTAND p+p AND Be+Be DATA



Pb+Pb

p+p, Be+Be

FIREBALL

SMALL CLUSTERS

↑ ONSET OF DECONFINEMENT ? ↑

p+p, Be+Be FAR FROM EQUILIBRIUM

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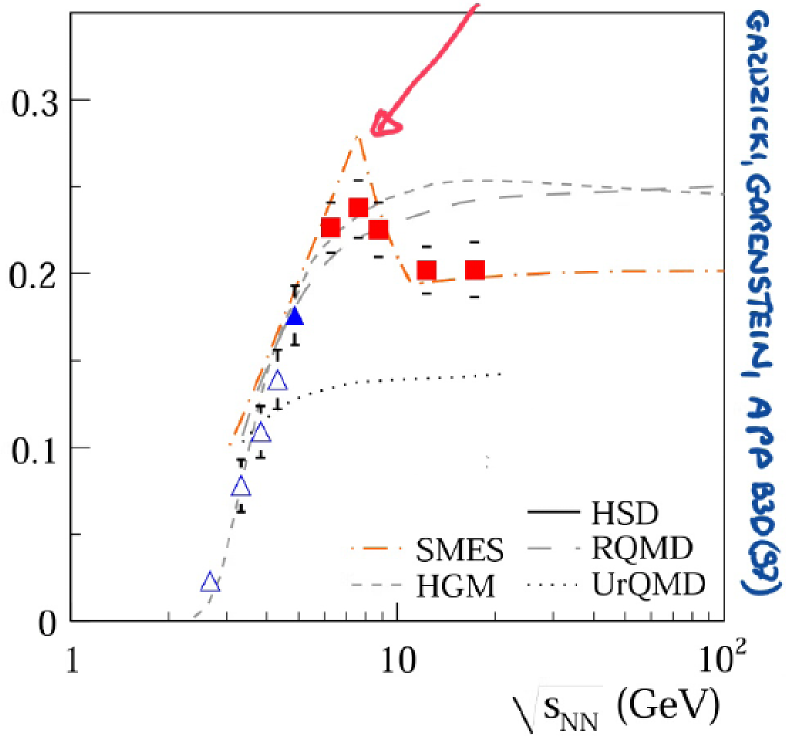
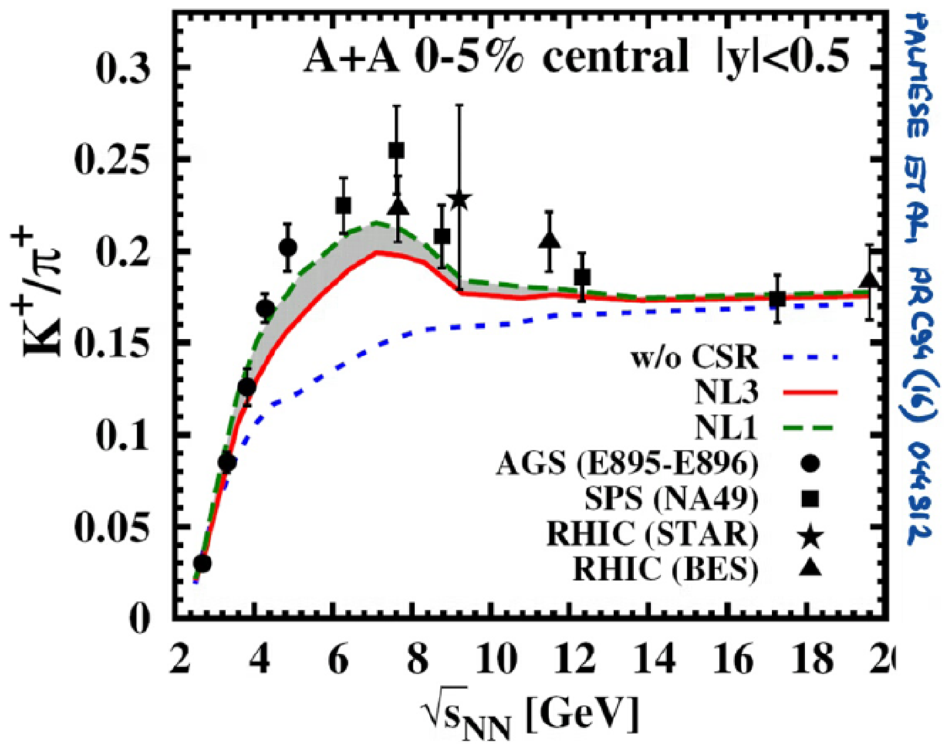
ONSET OF DECONFINEMENT IN MODELS

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

STATISTICAL: SMES



DYNAMICAL: pHSD



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

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