Recent results from   the NA61/SHINE experiment and physics plans beyond 2020

Roman Płaneta
for the NA61/SHINE Collaboration
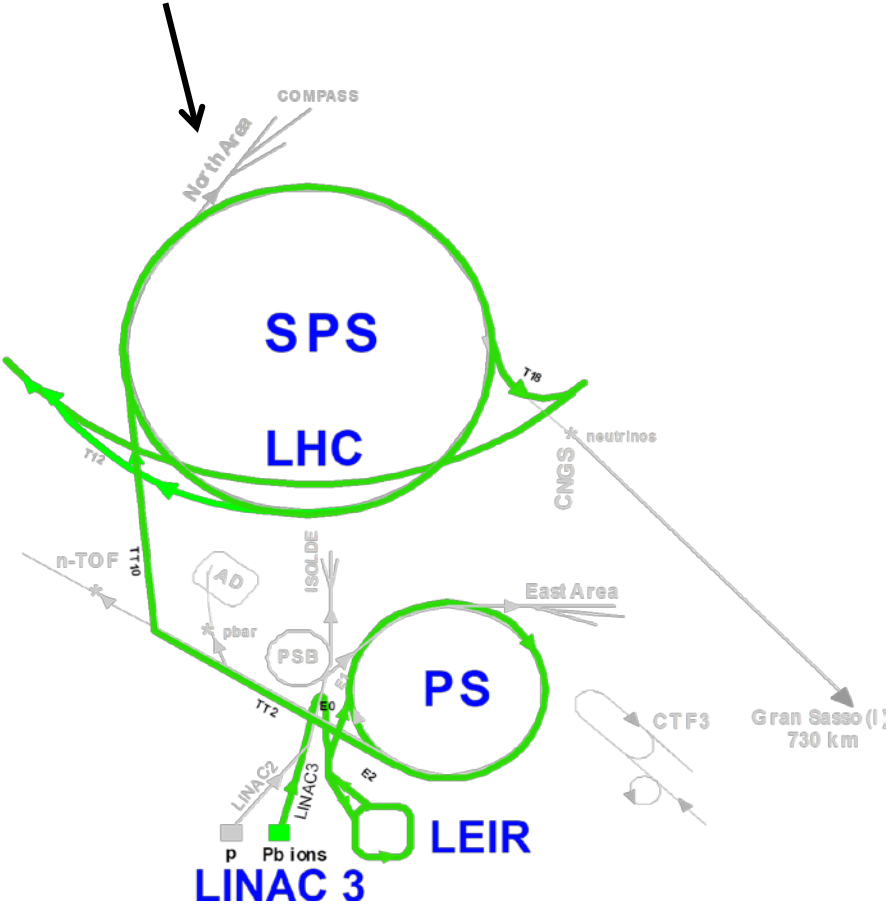**Jagiellonian University**

Outline

- **Experimental setup**

- **Research program**

- **Strong interactions program**
  - **Onset of deconfinement**
  - **Onset of fireball**
  - **Search for critical point**
  - **Open charm measurements**

- **Physics program for 2020+**

NA61/SHINE - Acceleration chain
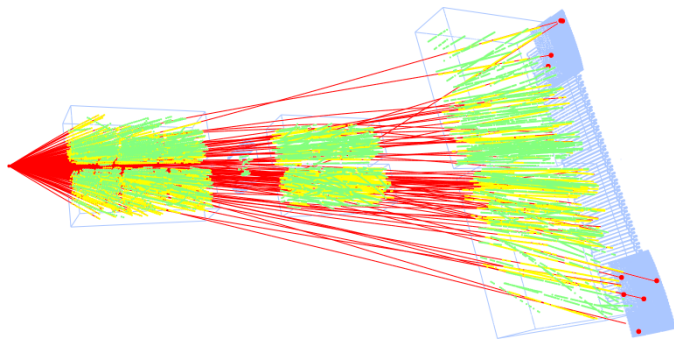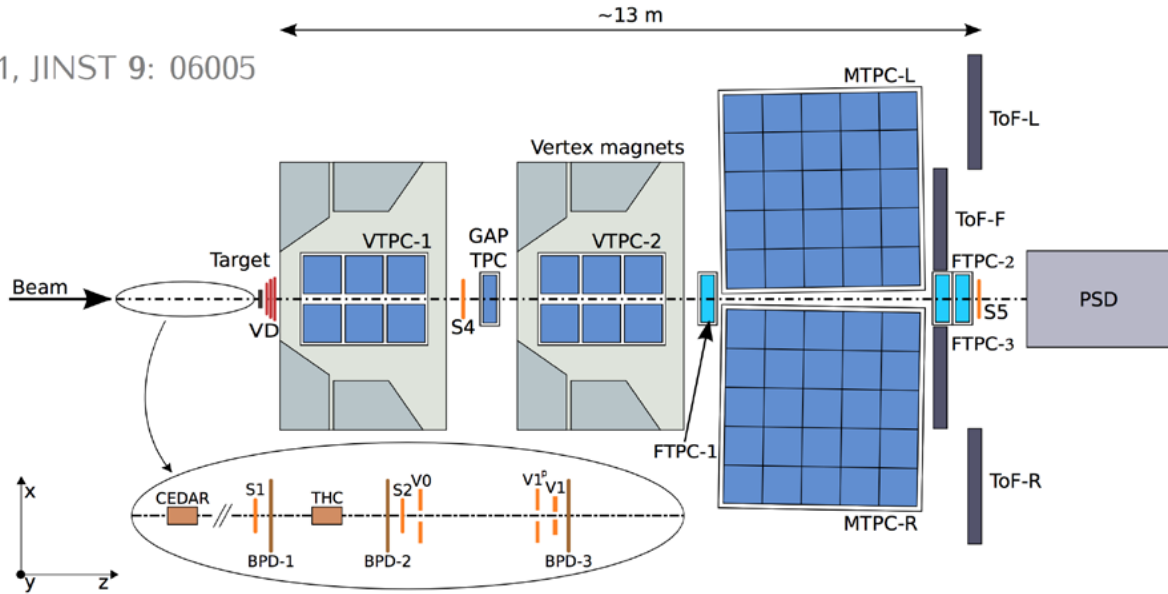
NA61/SHINE facility

Primary beams:
- **Protons at 400 GeV/c**
- **Ions (Ar, Xe, Pb) at 13A – 150A GeV/c**

Secondary beams:
- **Hadrons ($\pi^{+/-}$, $K^{+/-}$, $p/\bar{p}$) at 13 - 400 GeV/c**
- **Ions (Be) at 13A - 150A GeV/c**

NA61/SHINE experiment


NA61, JINST **9**: 06005

- **Large acceptance hadron spectrometer**
- **Beam particles measured in set of counters and position detectors**
- **Tracks of charged particles measured in set of TPCs: measurement of q, p and identification by energy loss measurement**
- **3 Time of Flight Walls: identification via time of flight measurement**
- **Projectile Spectator Detector measures the forward energy which characterises centrality of collision**

Recent upgrades:

- **Vertex Detector (open charm   measurements)**
- **FTPC-1/2/3**

NA61/SHINE facility paper:
JINST 9 (2014) P06005

**Central Pb+Pb collision at 13A GeV/c measured in the NA61/SHINE detector**
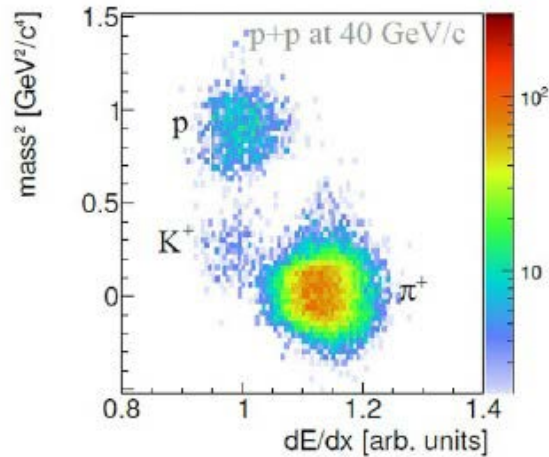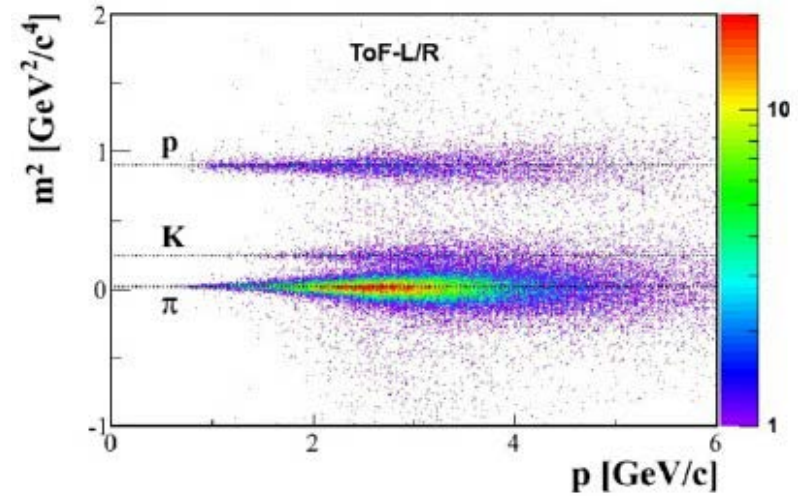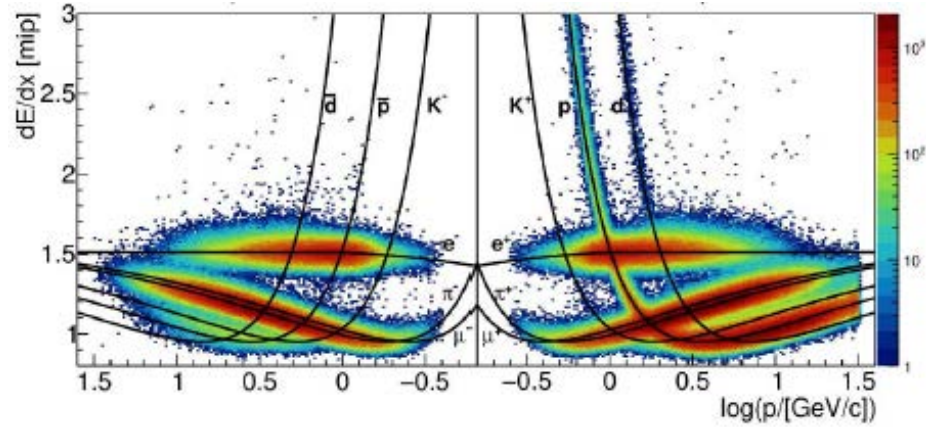
$$\sigma(p)\Big/_{p^2} \approx 10^{-4}(GeV/c)^{-1}$$

$$\sigma(dE/dx) \approx 4\%$$

$$\sigma(ToF) \approx 100\,ps$$

NA61/SHINE program

- **Physics of strongly interacting matter → subject of this talk**

- **Measurements for neutrino experiments**

  ➢ **reference measurements of p + C interactions for the T2K experiment for computing neutrino fluxes from the T2K beam targets**
  ➢ **h + nucleus measurements for the Fermilab neutrino program**

- **Measurements for cosmic ray experiments**

  ➢ **reference measurements of p + C and π + C interactions for cosmic-ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations**
  ➢ **measurement of Nuclear Fragmentation Cross Sections of intermediate mass nuclei needed to understand the propagation of cosmic rays in our Galaxy (background for dark matter searches with space-based experiments as AMS)**
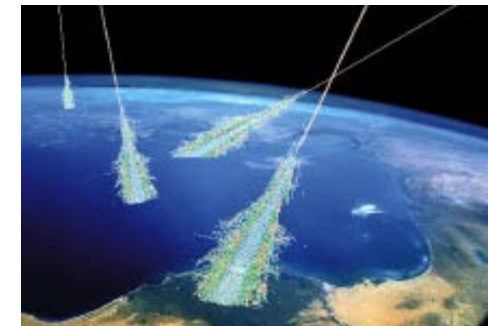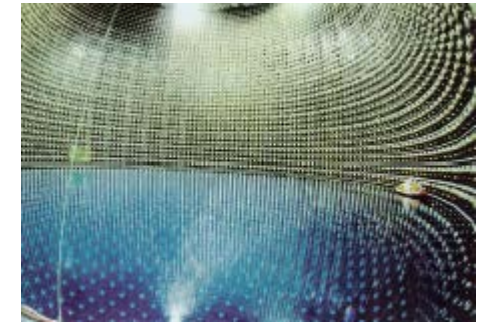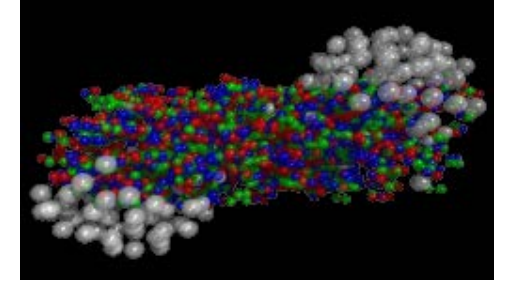
Strong interactions program
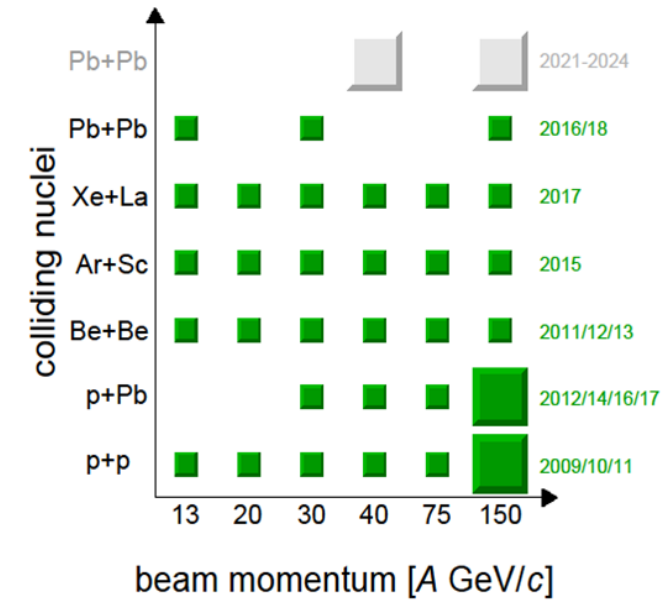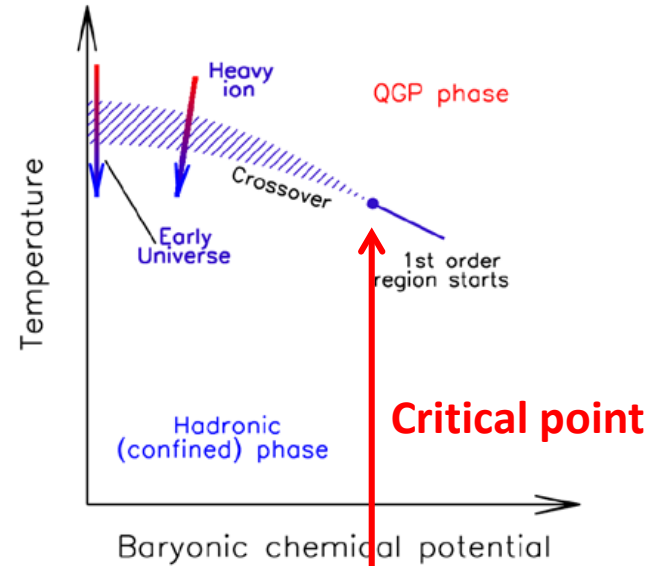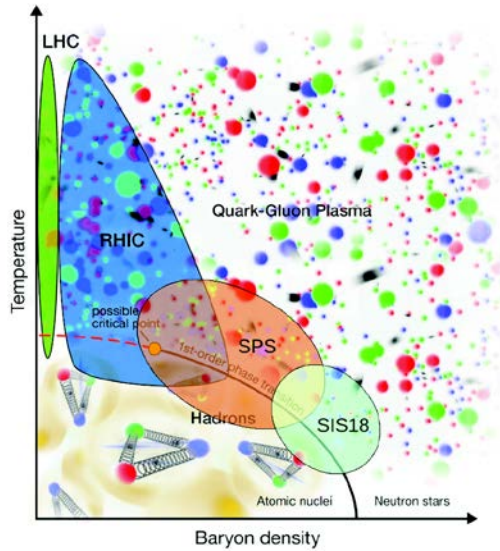
Critical point

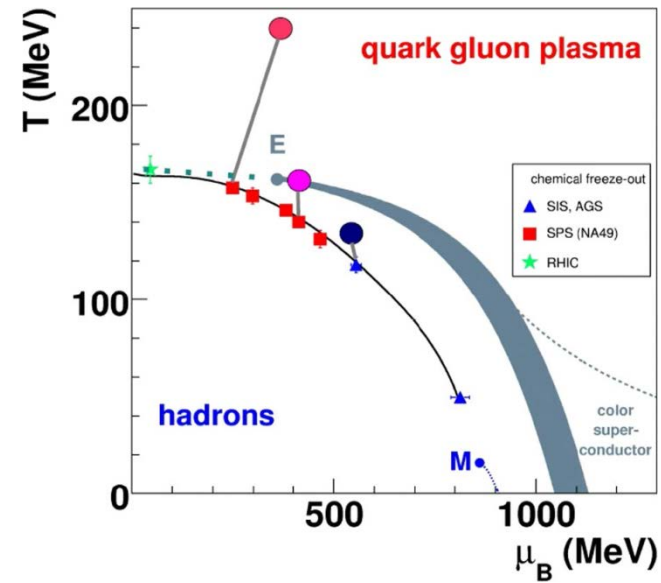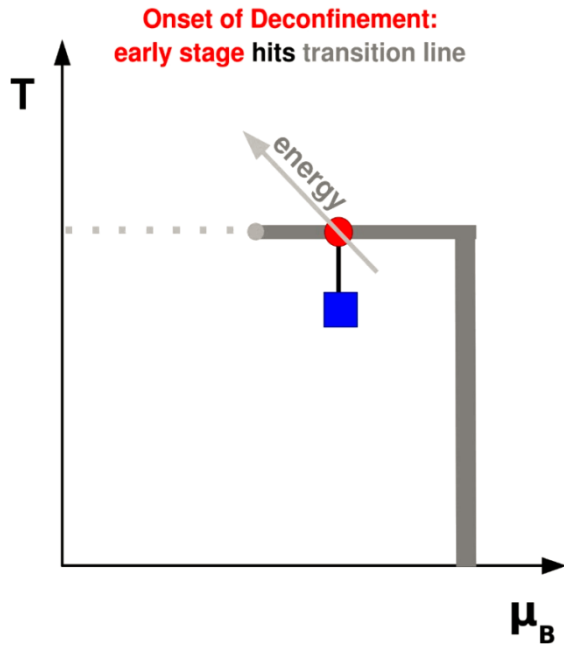- **Study particle spectra**
- **Study properties of the onset of deconfinement**
- **Search for the critical point (CP)**
- **Charm physics**
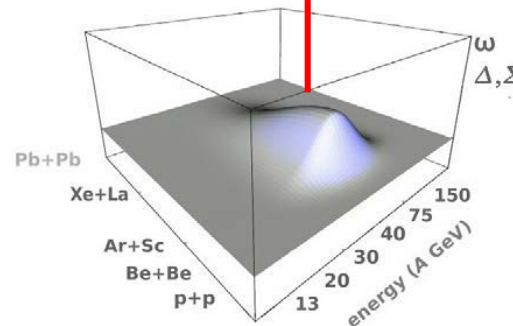
Comprehensive 2D scan of p+p, p+A and A+A collisions, as a function of system size and energy

Onset of deconfinement

Beginning of the creation of quark-gluon plasma (QGP) in nucleus-nucleus (A+A) collisions with increasing collision energy

Onset of deconfinement (energy dependence)
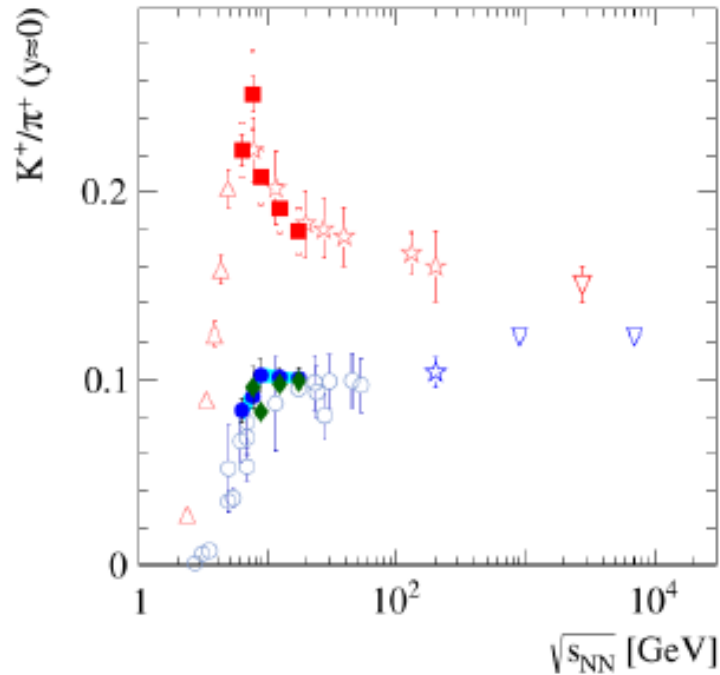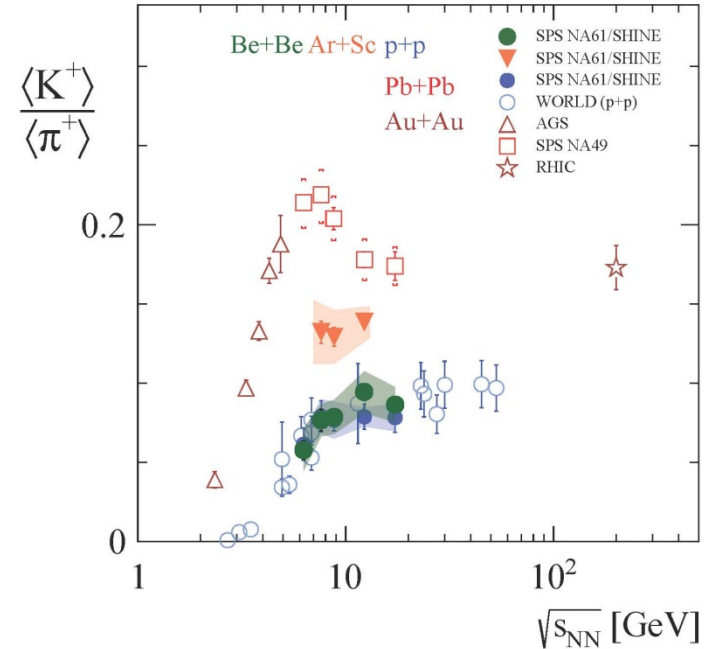
- • **Rapid changes in K+/π+ (HORN) observed in Pb+Pb collisions predicted by SMES as a signature of the onset of deconfinement**
- • **Step seen in p+p interactions**
- • **Be+Be consistent with p+p**
- • **<K+>/<π+> in Ar+Sc between p+p/Be+Be and Pb+Pb**

Statistical Model of the Early Stage (SMES)
M. Gazdzicki, M.I. Gorenstein,
Acta Phys. Pol. B 30, 2705 (1999)
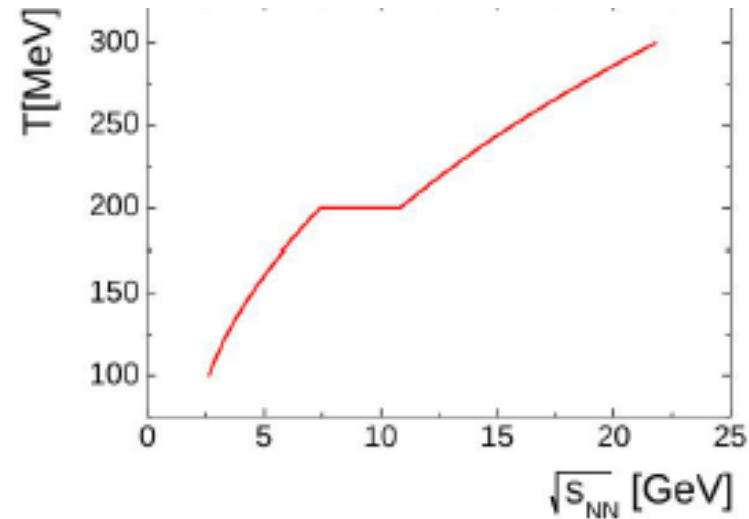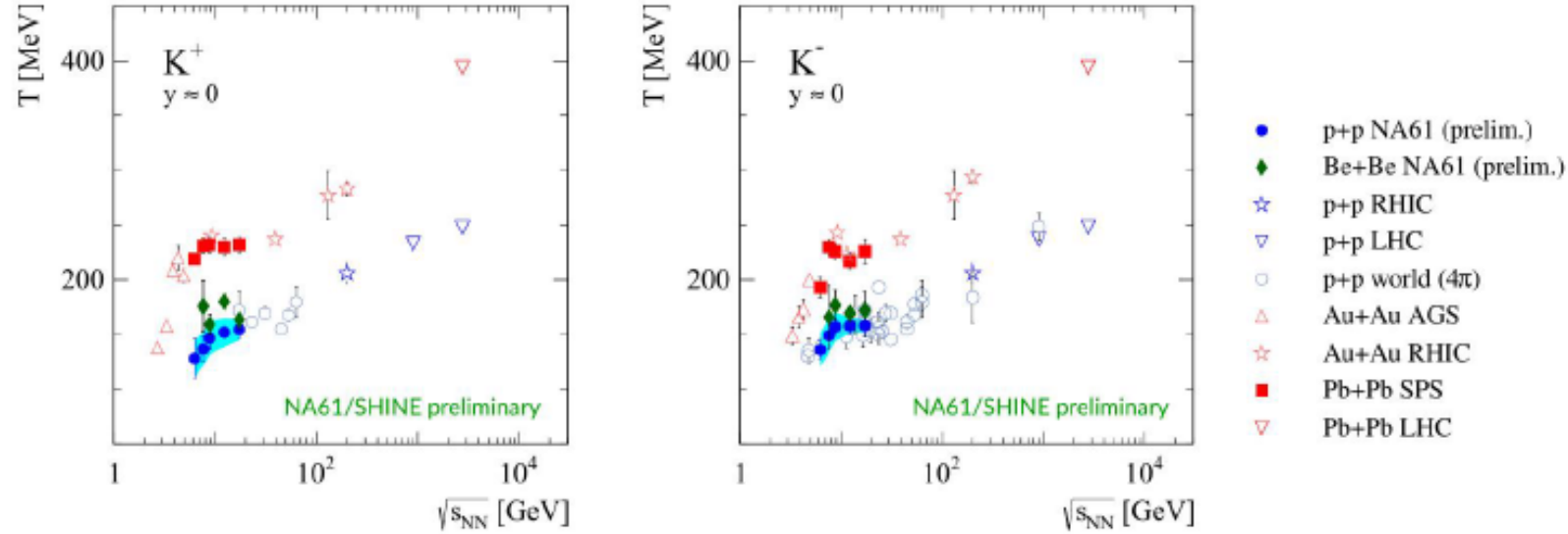
Prediction of Statistical Model of
the Early Stage

- **Changes in T (STEP-like structure), observed in Pb+Pb collisions predicted by SMES model as a signature of the onset of deconfinement**
- **Step is seen in p+p similar to Pb + Pb**
- **Be+Be consistent with p+p**

Onset of fireball

Cluster volume Vc

Small
off-equilibrium
clusters

Large clusters
=
Fireball

mass number *A*
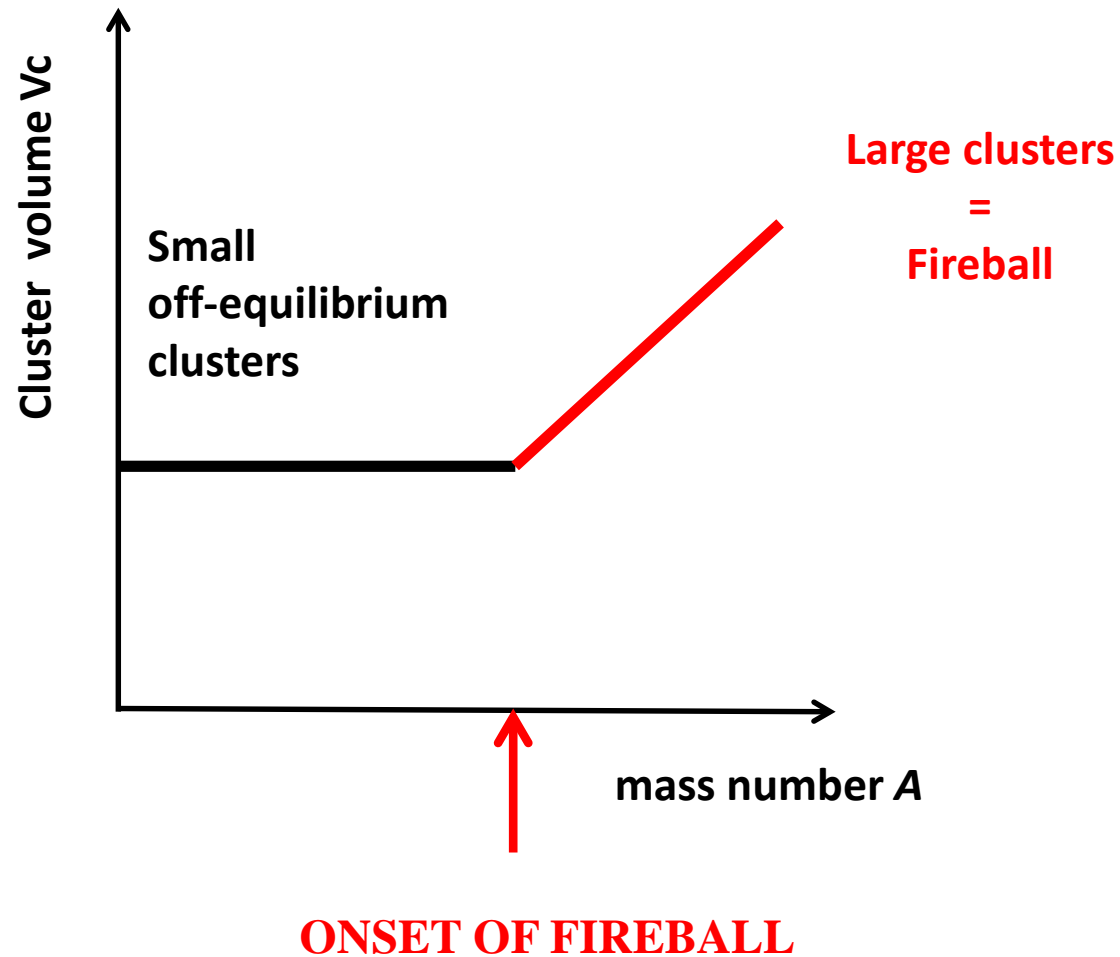
ONSET OF FIREBALL

Beginning of the creation of large clusters of strongly interacting matter in nucleus-nucleus collisions with increasing mass number A.

Onset of fireball (system size dependence)
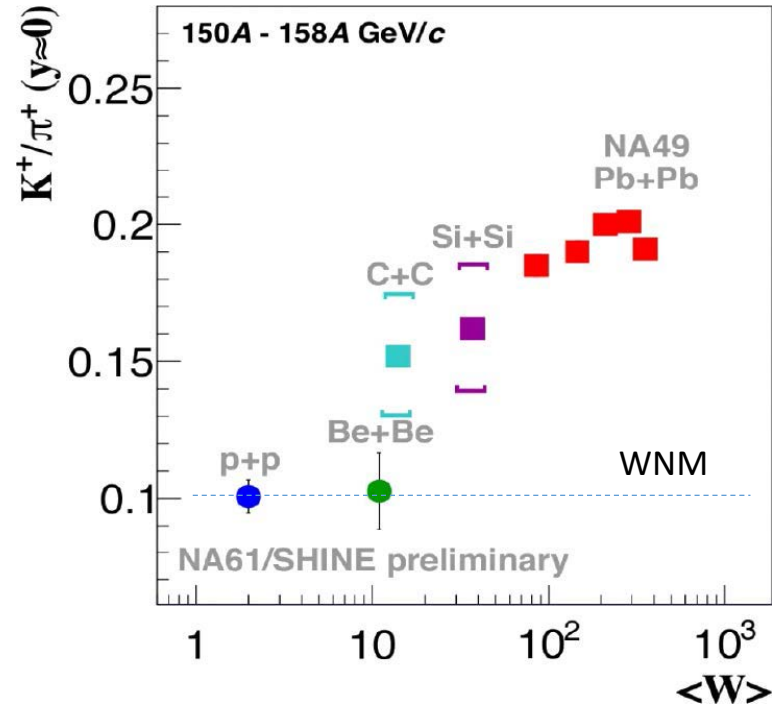
$$\omega[N] = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$

Scaled variance of
multiplicity distributions
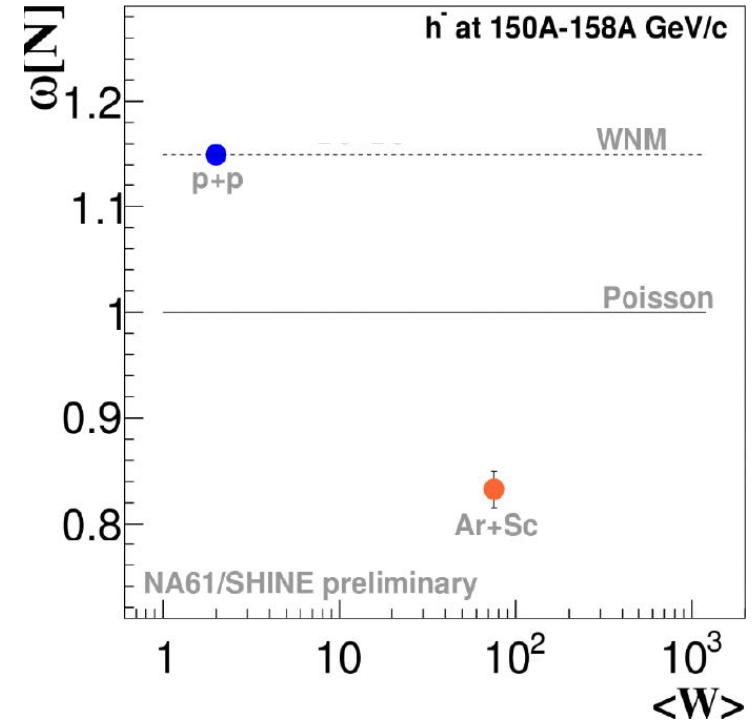
- **Rapid changes in K+/π+ and multiplicity fluctuations when moving from light (p+p, central Be+Be) to intermediate and heavy systems (central Pb+Pb)**
- **Heavy systems closer to predictions of statistical models for large volumes**

<W> -number of wounded nucleons

→ **begining of creation of large clusters of strongly interacting matter in intermediate systems (onset of fireball)**

Onset of deconfinement vs onset of fireball
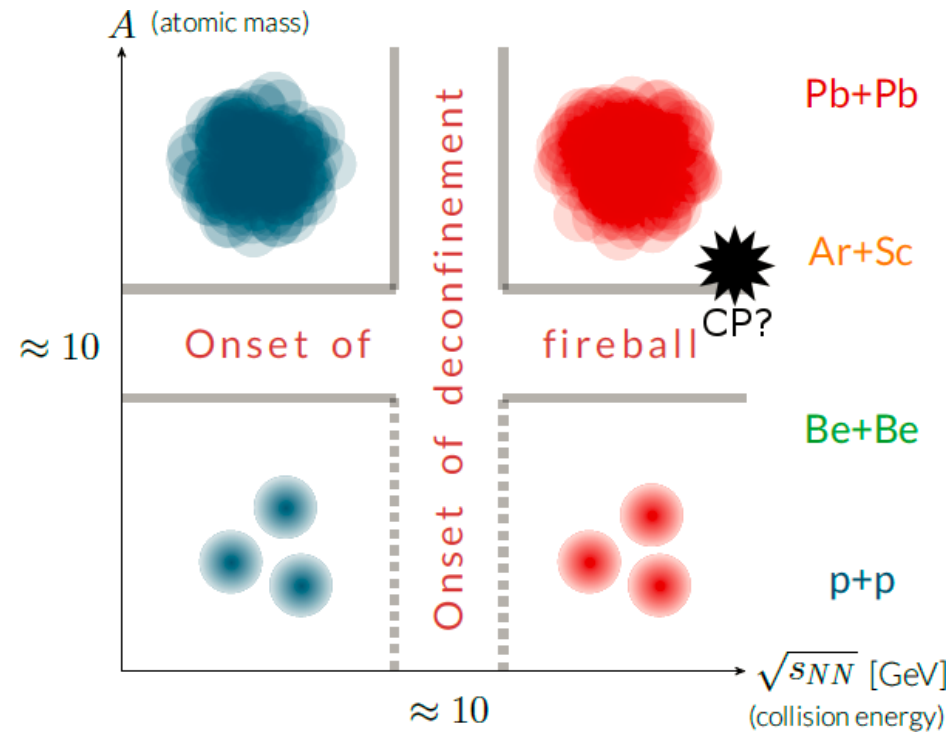
2D scan conducted by varing collision energy and system size indicated two thresholds:

- **Onset of deconfinement**
- **Onset of fireball**

Four domains of hadron production

Critical point and critical fluctuations

Event-by-event fluctuation measures
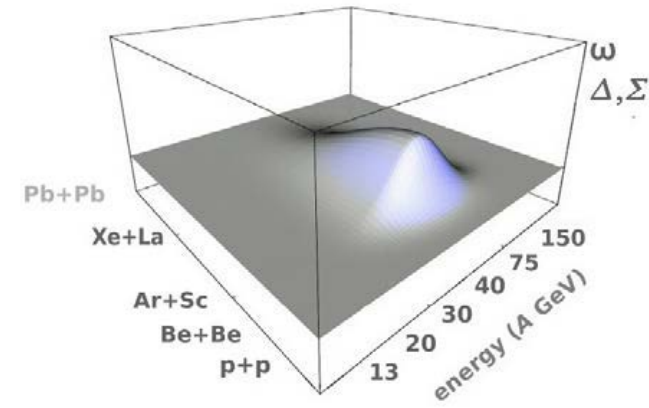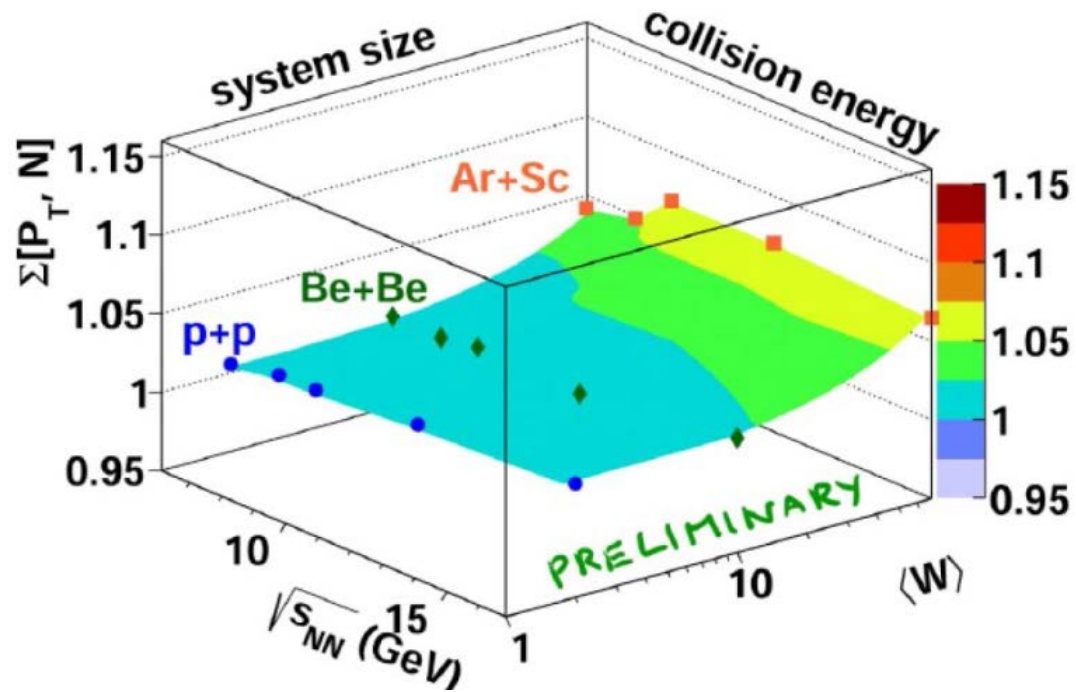
$\sum[\boldsymbol{P_T}, \boldsymbol{N}]$ - strongly intensive (*independent on system volume and its fluctuations, insensitive to material conservation laws*)

no fluctuation hill associated with the critical point

Critical point and critical fluctuations

Intermittency analysis of 2-nd factorial moments

subject of the next talk presented by Nikolaos Davis

Open charm measurements (motivation)

HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17, 1367, 2008;
Song, private communication

pQCD
Gavai, et al., IJMP A10, 2999, 1995
Braun-Munzinger, Stachel, PL B490, 196, 2000

Quark Coalesc. Dyn.
Levai et al. JP G27, 703, 2001

HRG; Quark Coalesc. Stat.
Kostyuk et al. PL B531, 195, 2002

SMES
Gazdzicki, Gorenstein, APP B30, 2705, 1999
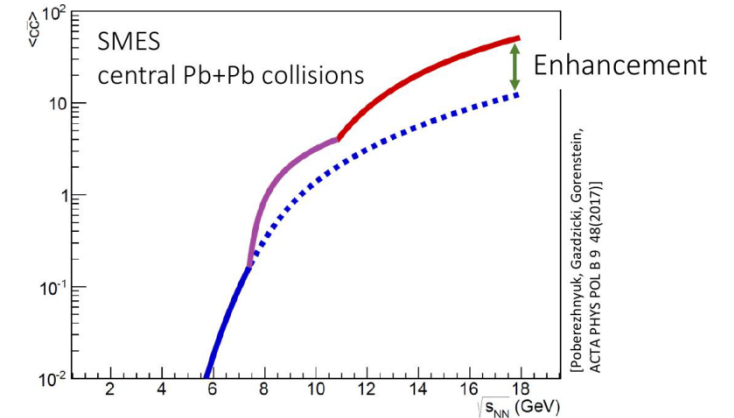
Model predictions by a factor up to 50 for Pb+Pb collisions at top SPS energy
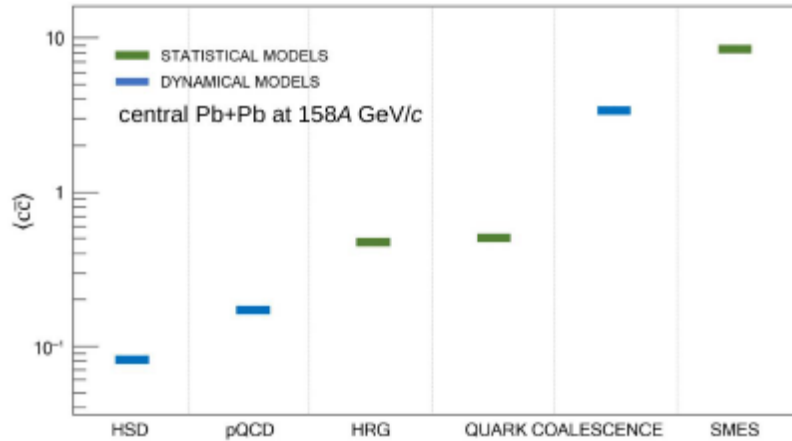
Enhancement in $\langle c\bar{c} \rangle$ production predicted by SMES

- **What is the mechanism of open charm and J/ψ production ?**
- **How does the onset of deconfinement impact open charm production ?**
- **How does the formation of quark-gluon plasma impact J/ψ production ?**

➢ **Mesurement of both J/ψ and $\langle c\bar{c} \rangle$ are needed to calculate probability of hadronization**
➢ **Production in full phase space required to discriminate models**

Up to now corresponding experimental data for $\langle c\bar{c} \rangle$ production does not exist. Only NA61/SHINE can perform it in the near future.

Open charm measurements
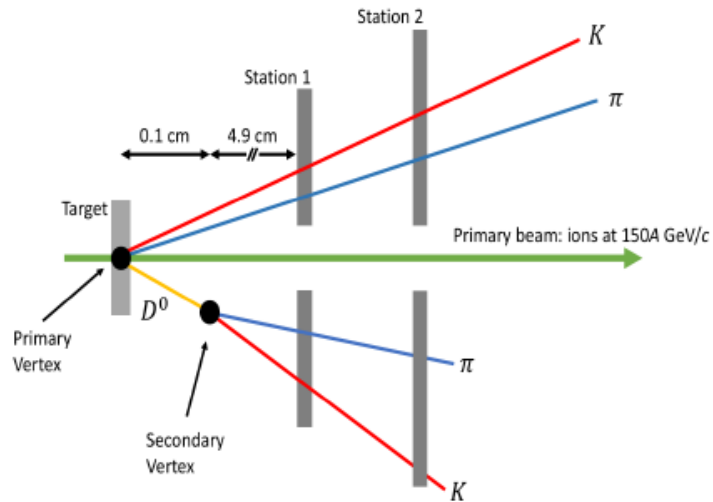
→ Vertex Detector project of the NA61/SHINE experiment

$\sigma_{D0} = 14.6 \pm 3.2$ MeV
yield = 62
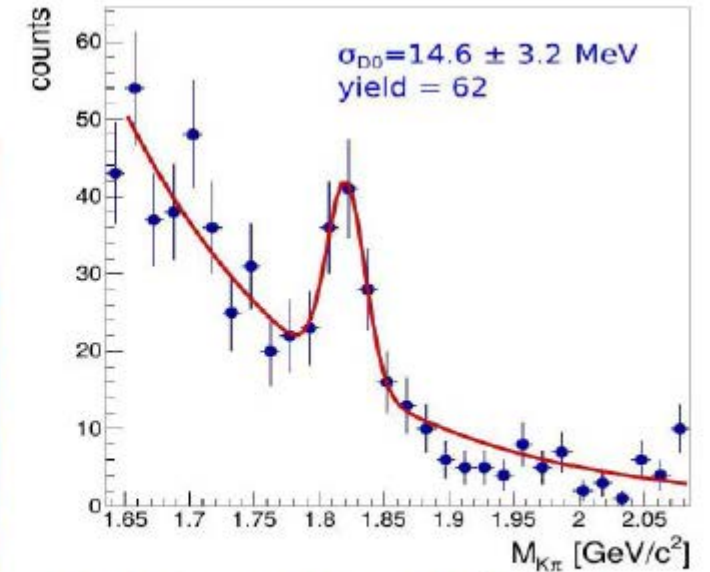
First observation of D^0 peak in Pb+Pb collisions at SPS energies

Vertex detector is needed to reconstruct primary vertex and secondary vertexes with high precision

- **The analysis of pilot data on Pb+Pb collisions at 150A Gev/c (low statistics - 140k events) proved the measurement of D^0 production by Small Acceptance Vertex Detector is possible**
- **Pb+Pb and Xe+La data with higher statistics are under analysis**
- **Detailed studies require Large Acceptance VD and high statistics data**

Physics program for 2020+

Measurement plans:

✓ precise open charm studies in Pb+Pb collisions at 150A and 40A GeV/c with Large Acceptance Vertex Detector

✓ reference measurements of nuclear fragmentation cross-section for cosmic ray experiments (DAMPE, PAMELA, CALET, GAPS) to decrease uncertainties on cosmic ray propagation from 20% to 0.5%

✓ reference measurements of hadron production for neutrino experiments T2K-II, Hyper-Kamionkande to decrease systematical uncertainty for neutrino flux from 10% to 3-4%

Detector upgrade during LS2

Construction of Vertex Detector (VD) for D^0, $\overline{D^0}$ decay reconstruction

Replacement of the TPC read-out electronics to increase data rate to 1 kHz

New Time-of-Flight detectors (stage 2)

New trigger and data acquisition system

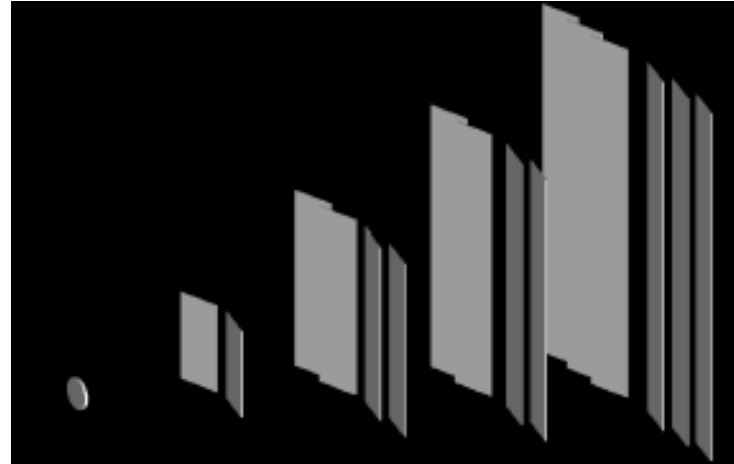**Upgrade of Projectile Spectator Detector**
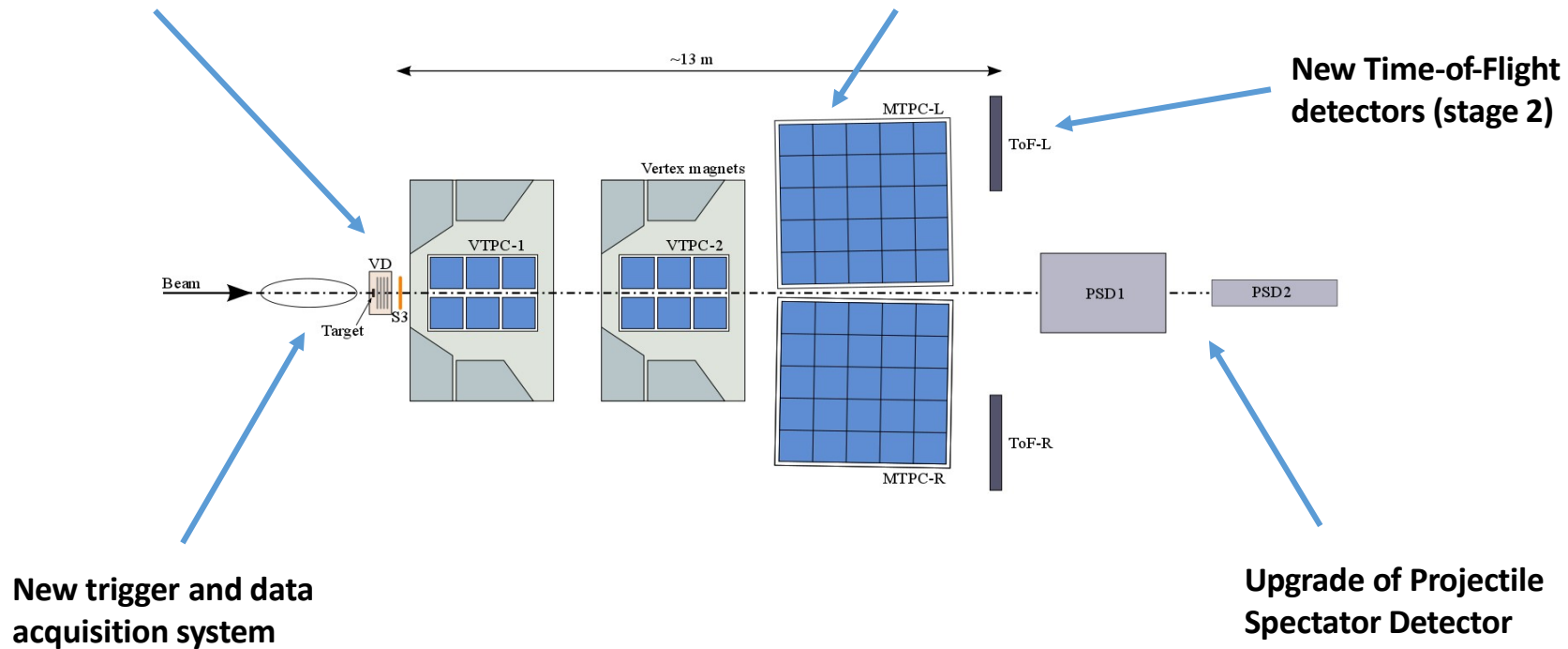
In total 850k CHF (Hardware only, stage 1) Moderate costs thanks to collaboration with ALICE (TPC, VD) and CBM (PSD)

Upgrade of Vertex Detector

Small Acceptance Vertex Detector
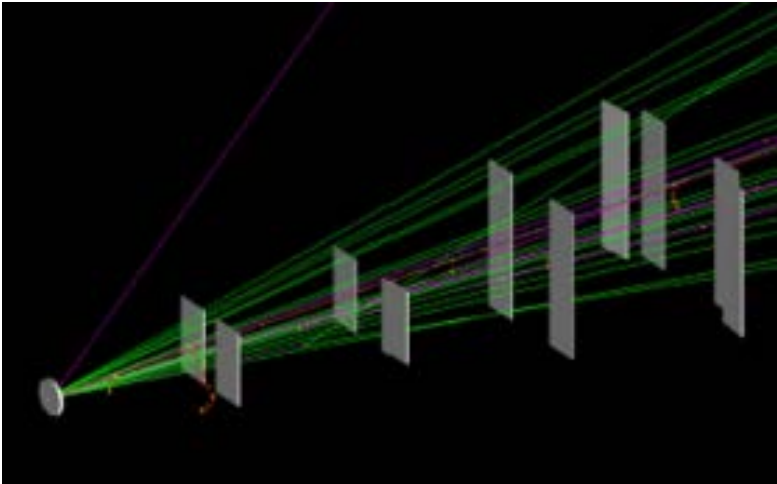
Large Acceptance Vertex Detector

	SAVD	Future VD
Sensor	MIMOSA-26	ALPIDE
№ sensors	16	46
Active surface	$32cm^2$	$190cm^2$
Spatial resolution	$3.5\mu m$	$5\mu m$
Time resolution	$115.2\mu s$	$10\mu s$

Mimosa 26AHR sensors will be replaced by ALPIDE sensors developed for ALICE-ITS
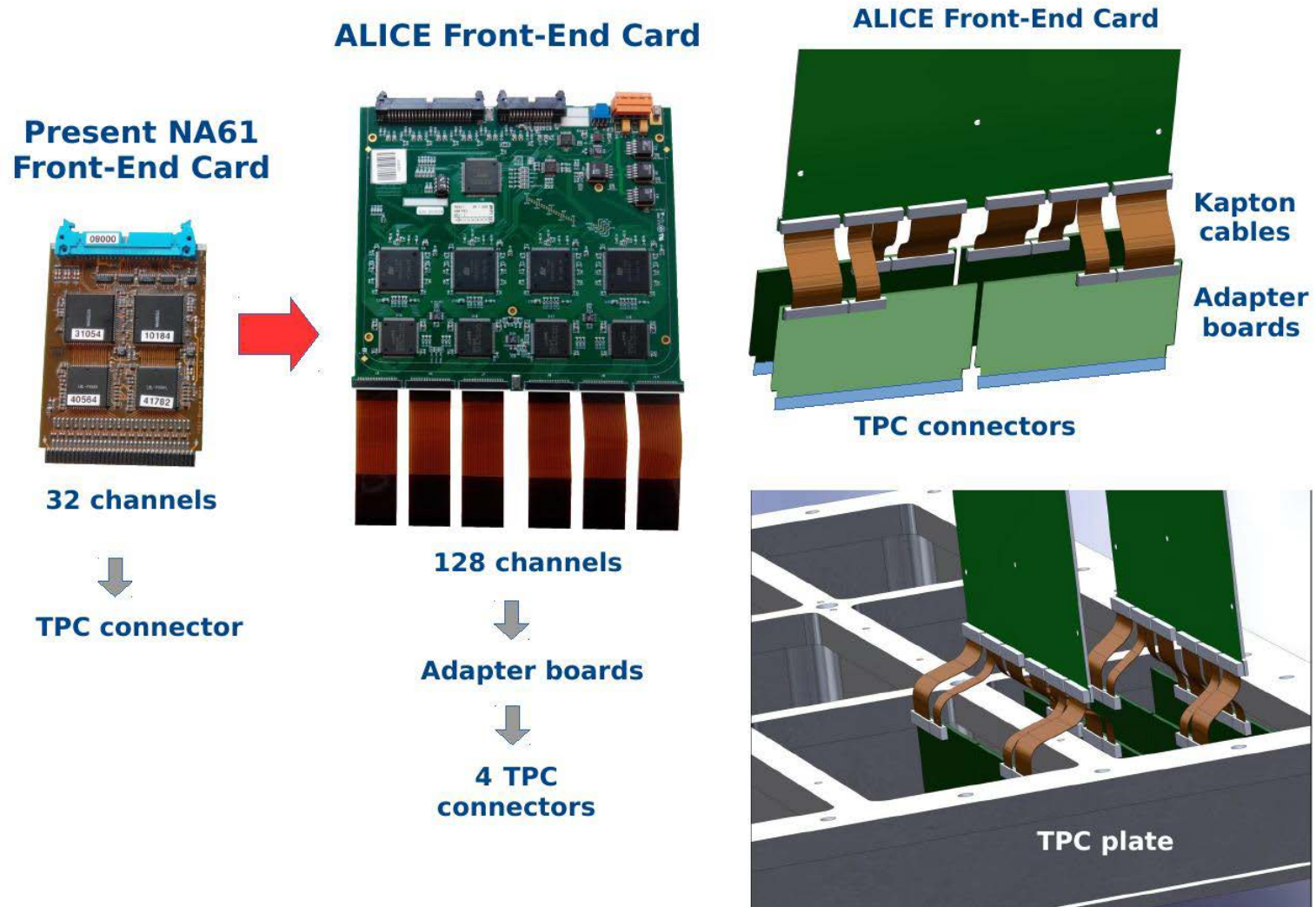
Summary

- **Changes in hadron production as a function of energy (HORN, STEP) observed in central Pb+Pb collisions (NA49) as a signature of deconfinement**

- **p+p/Be+Be collisions similar; Ar+Sc data lie between p+p/Be+Be and Pb+Pb**

- **Dependence of particle ratios and fluctuations on the system size suggests existence of the onset of fire ball ie. the beginning of creation of large clusters**

- **Four domains of hadron production with two thresholds**

- **No clear fluctuation signal atributed to the critical point although intermittency analysis suggests the increase of fluctuations in Ar + Sc collisions**

- **First observation of D^0 peak in Pb+Pb collisions at SPS energies**

- **New NA61/SHINE results for Ar+Sc, Xe+La and Pb+Pb collisions expected soon**
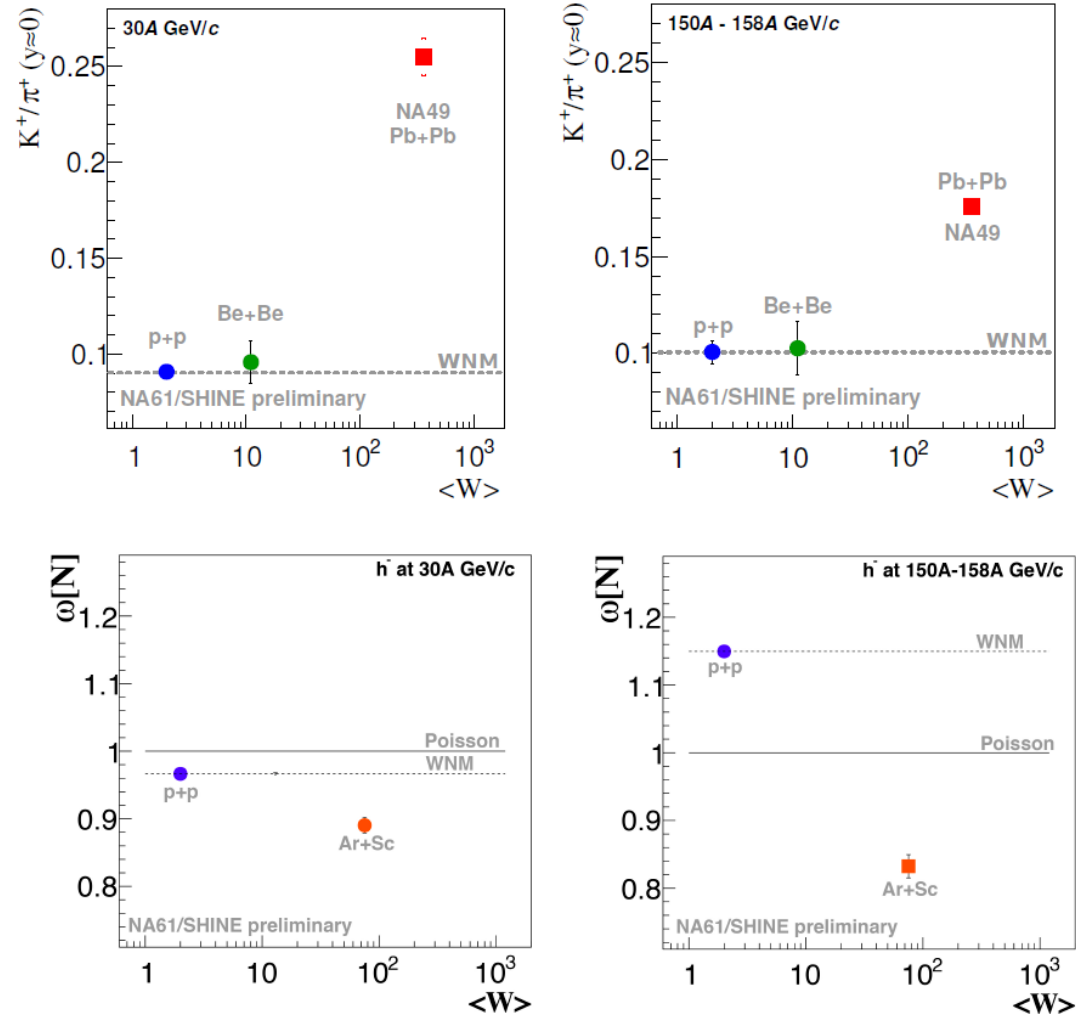
- **Ambitious program of measurements beyond 2020**

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

Replacement of TPC read-out electronics

Present NA61 Front-End Card

32 channels

TPC connector

ALICE Front-End Card

128 channels

Adapter boards

4 TPC connectors

ALICE Front-End Card

Kapton cables
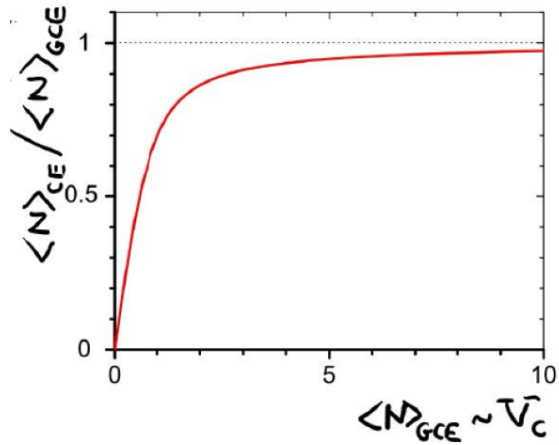
Adapter boards

TPC connectors

TPC plate

System size dependence as a function energy

Onset of fireball
(system size/cluster volume dependence)
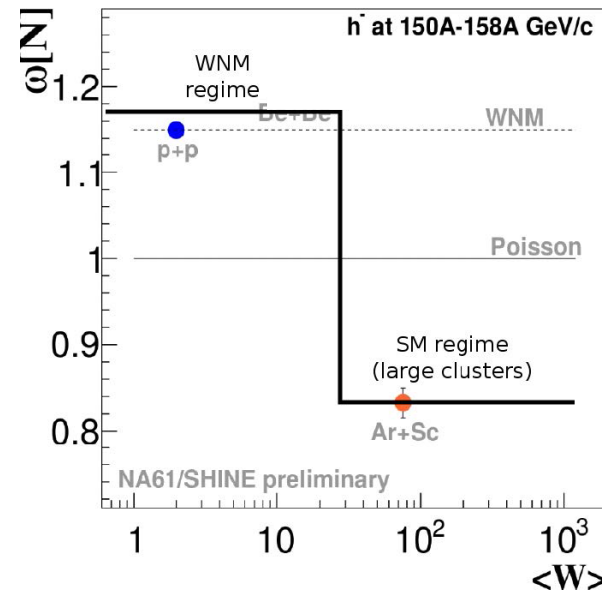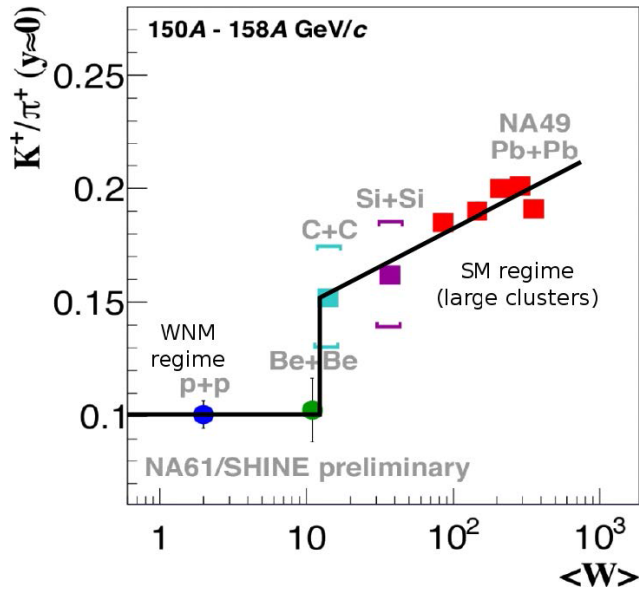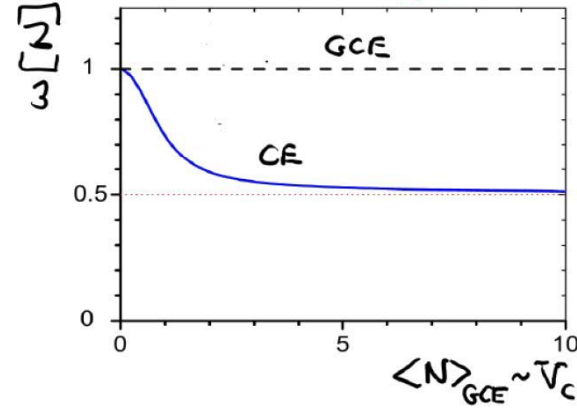

"CANONICAL SUPPRESSION" OF $\langle N \rangle$

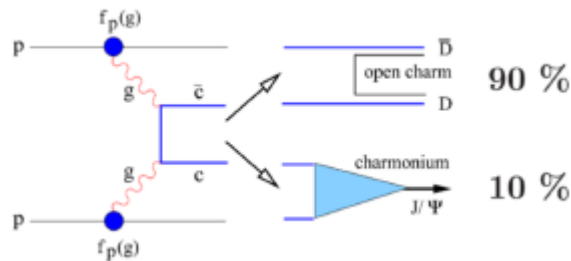Statistical Models with an Ideal Boltzmann gas within

Canonical Ensemble (CE)

and

Grand Canonical Ensemble (GCE)

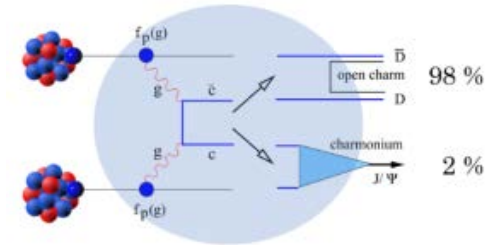"CANONICAL ENHANCEMENT" OF $\omega[N]$

Open charm measurements (motivation)

H. Satz, Adv. High En. Phys. (2013) 2429

Below LHC energies in p+p 90% of $c\bar{c}$ pairs convert to open charm, remaining 10% form charmonia states.


In A+A color screening reduces charmonia production → reduction of fraction of $c\bar{c}$ pairs going into charmonia in respect to p+p at the same energy

Due to shadowing, parton energy loss etc., the number of $c\bar{c}$ pairs produced in A+A may well be less than the scaled number from p+p
→ initial state effects can reduce charmonium production rate in A+A relative to p+p collisions.
→ the effect of the medium on $c\bar{c}$ binding can only be determined by comparing the ratio of $\langle J/\psi\rangle/\langle\, c\bar{c}\,\rangle$ in A+A to that in proton-proton collisions.
→ measurements of open charm in A+A are needed!!!

Onset of deconfinement (energy dependence)
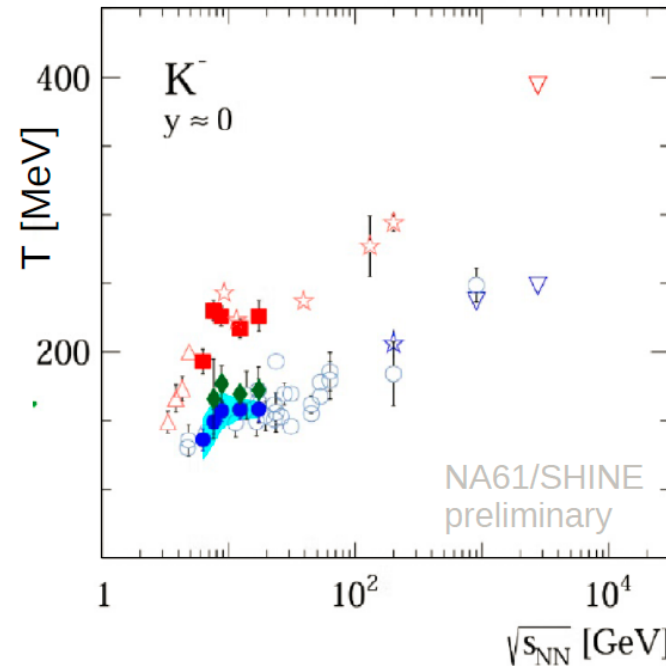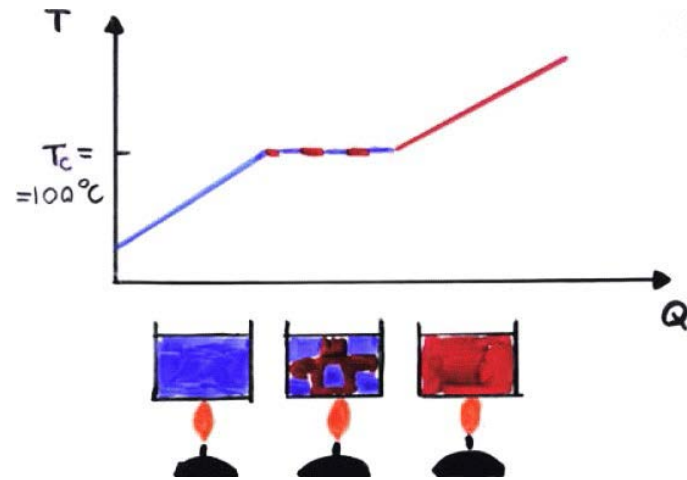
- **Changes in T (STEP-like structure), observed in Pb+Pb collisions predicted by SMES model as a signature of the onset of deconfinement**
- **"Shadow" of HORN seen for p+p interactions**
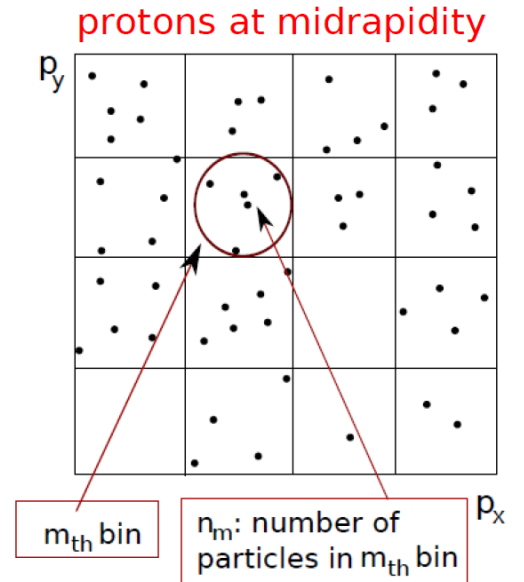- **Be+Be consistent with p+p**

Critical point and critical fluctuations

Intermittency analysis of 2-nd factorial moments

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

Second order factorial moment for M^2 cells in transverse momentum space

M^2 – number of bins
(M bins in p_x and M bins in p_y)

protons at midrapidity

m_{th} bin n_m: number of particles in m_{th} bin

Combinatorial background subtracted (by mixed events)
2nd factorial moment should scale according to power-law for M ≫ 1

$$\Delta F_2(M) \sim (M^2)^{\Phi_2}$$
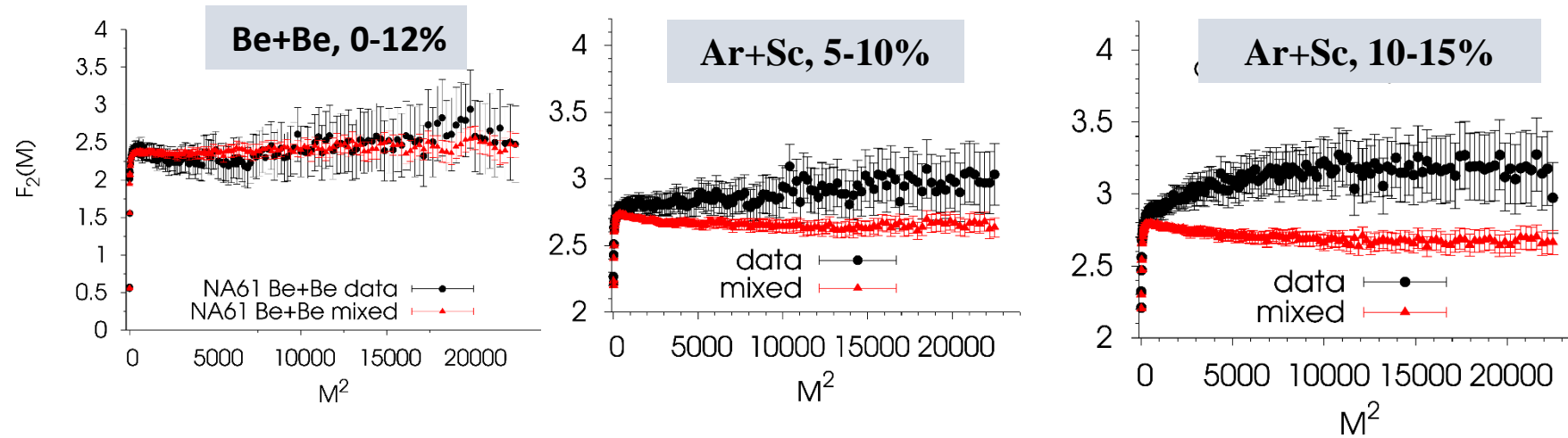
Białas, Peschanski, NP B273, 703, 1986;
Turko, PL B227, 149, 1989;
Diakonos et al., PoS, CPOD2006, 010, 2010

$\phi_2 = 5/6$ for CP, Antoniou et al., PRL 97,032002, 2006

Proton intermittency – comparison at 150(8) A GeV/c

NA61

Be+Be, 0-12%

Ar+Sc, 5-10%

Ar+Sc, 10-15%

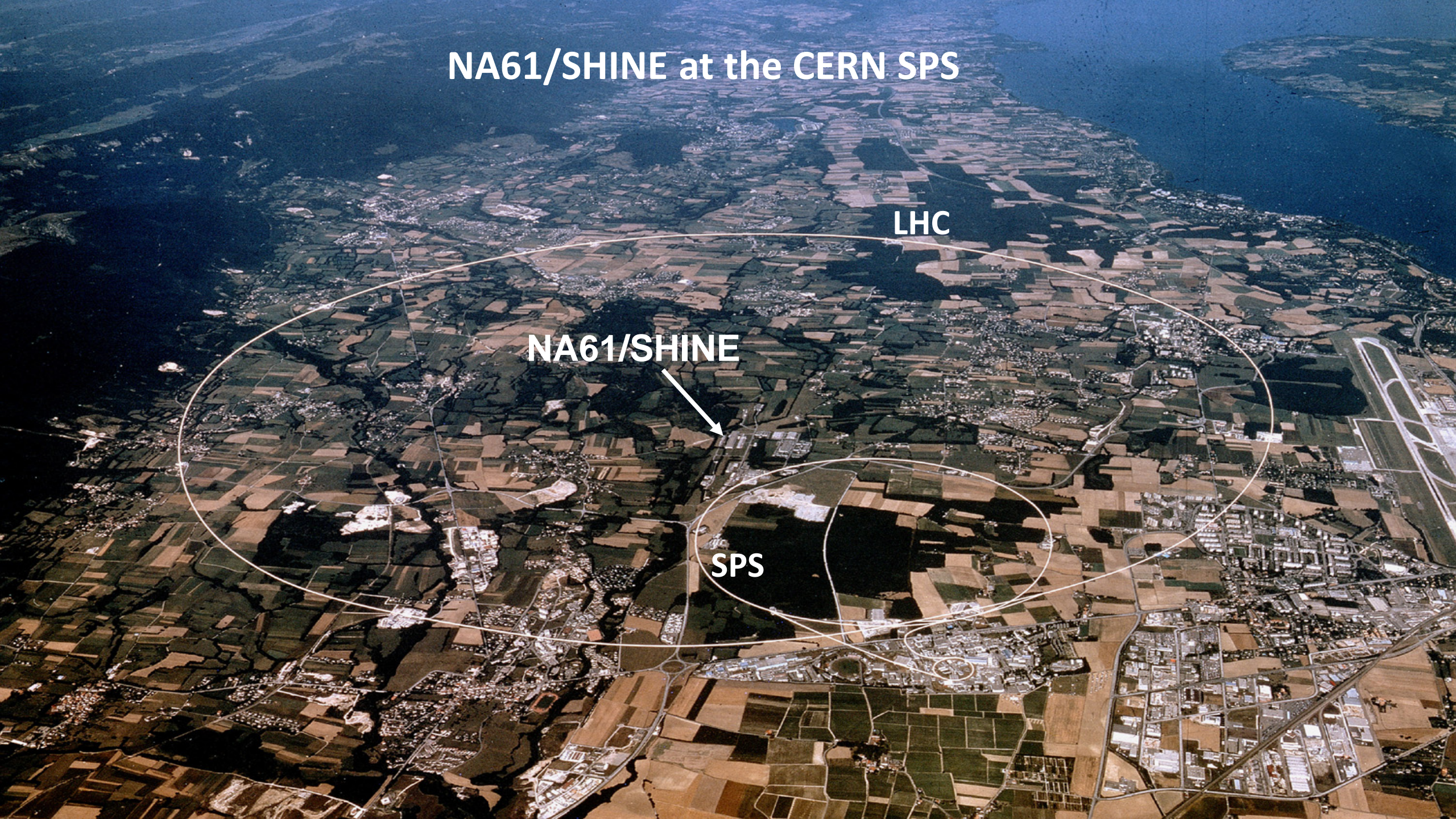**NA49**

C+C, 0-12%

Si+Si, 0-12%

Pb+Pb, 0-10%
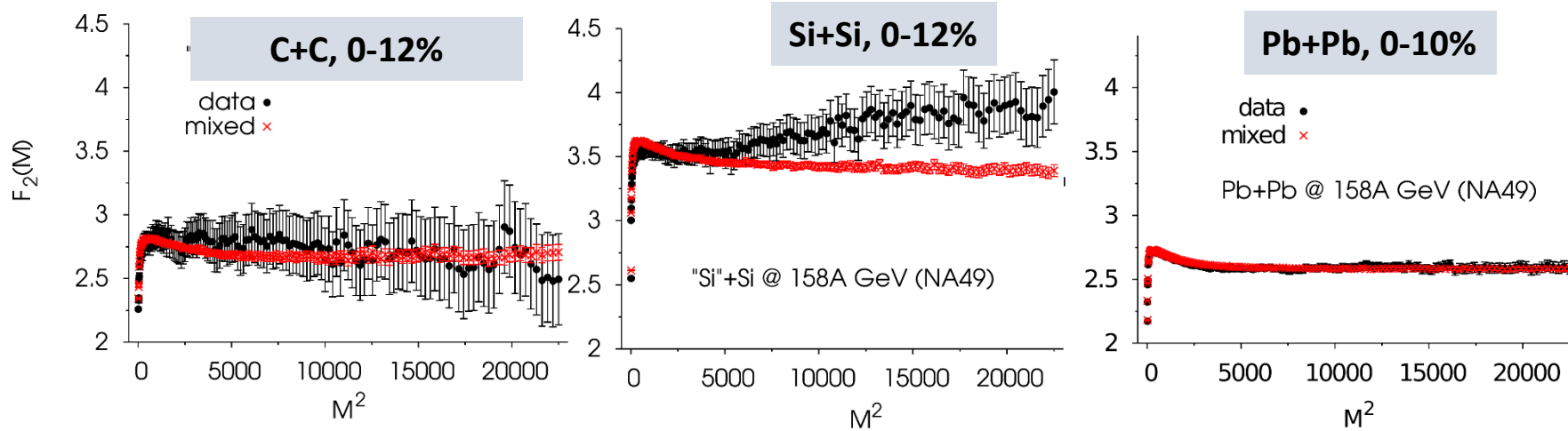
Indication of CP in Ar+Sc data at 150 GeV/c

NA61/SHINE at the CERN SPS

LHC

NA61/SHINE

SPS