Recent results from the strong interaction programme of the NA61/SHINE experiment

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for the NA61/SHINE collaboration

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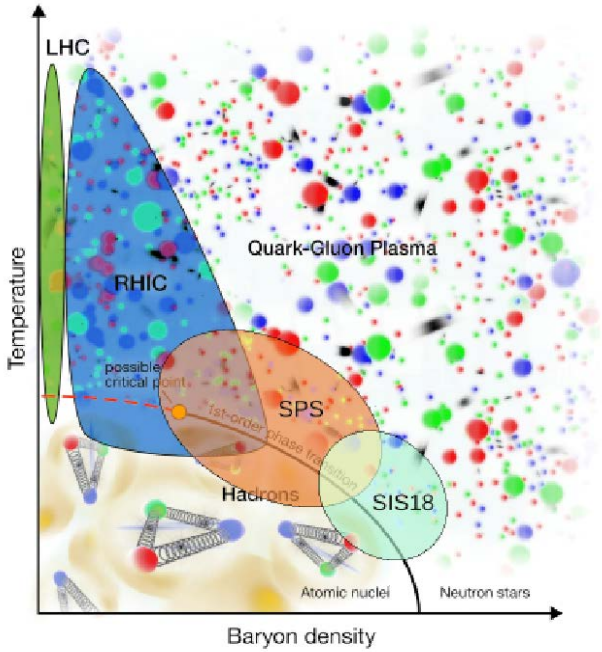
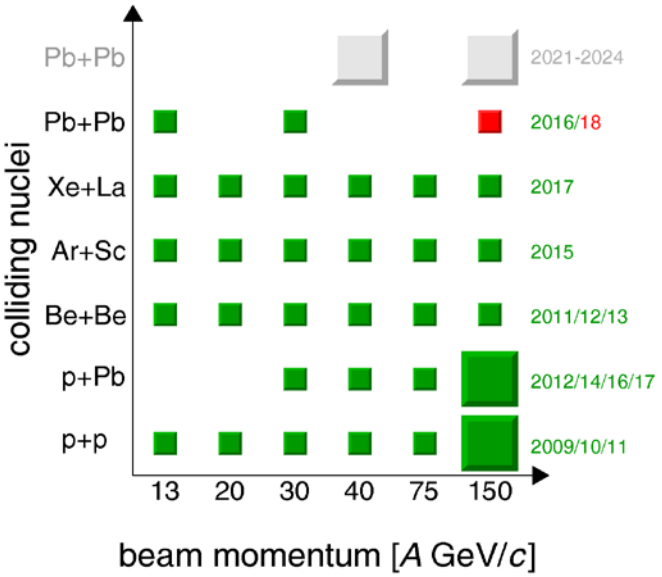
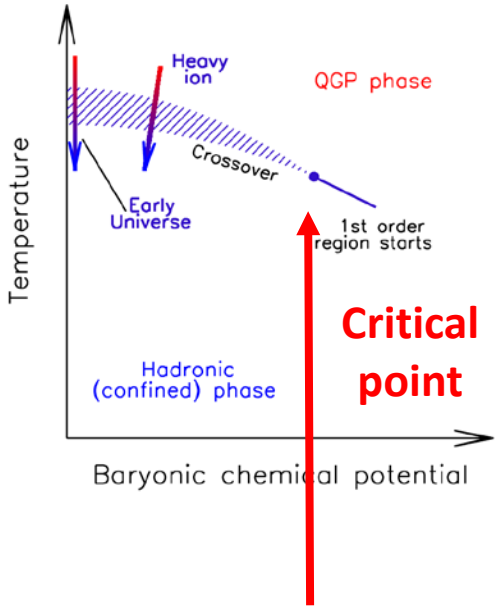
- Motivation
- The onset of deconfinement
- The onset of fireball
- The critical point
- Open charm measurements
- Future plans (beyond 2020)
- Summary

Motivation





N. Brambilla et al.,
arXiv:1404.3723v2 [hep-ph], 2014.



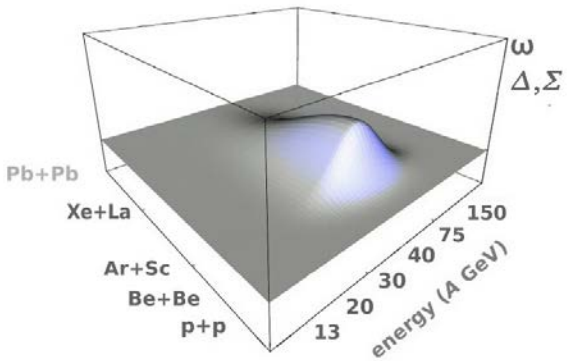
NA61/SHINE programme:

1. Strong interactions

- **Study particle spectra**
- **Study properties of the onset of deconfinement**
- **Search for the critical point (CP)**
- **Charm physics**

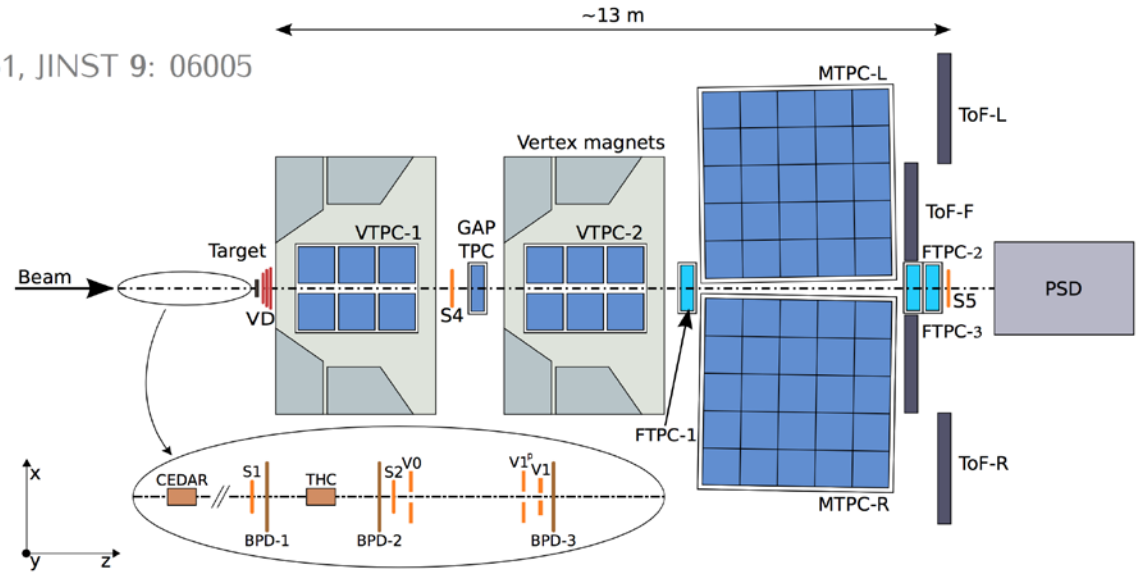
2. Cosmic rays & neutrinos

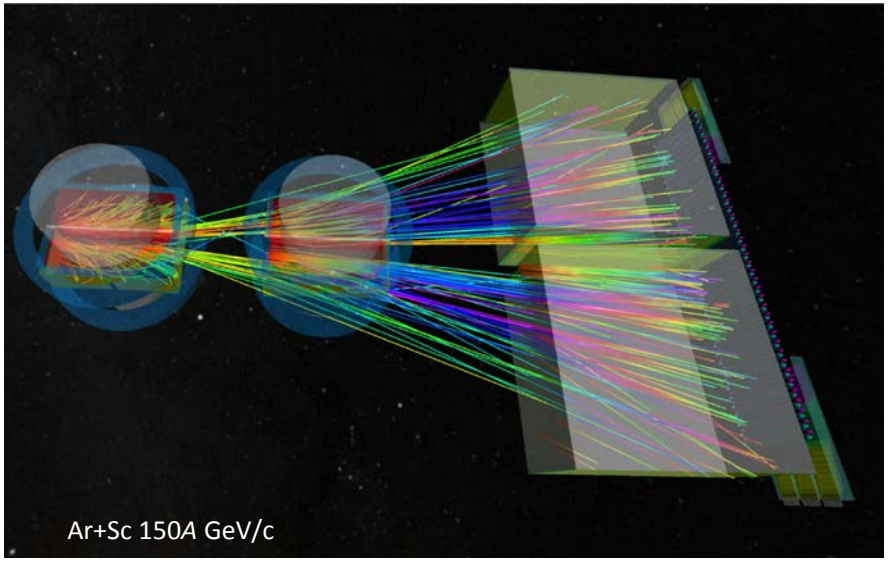
Comprehensive 2D scan of p+p, p+A and A+A collisions, as a function of system size and energy



"fluctuation hill"

NA61/SHINE experiment

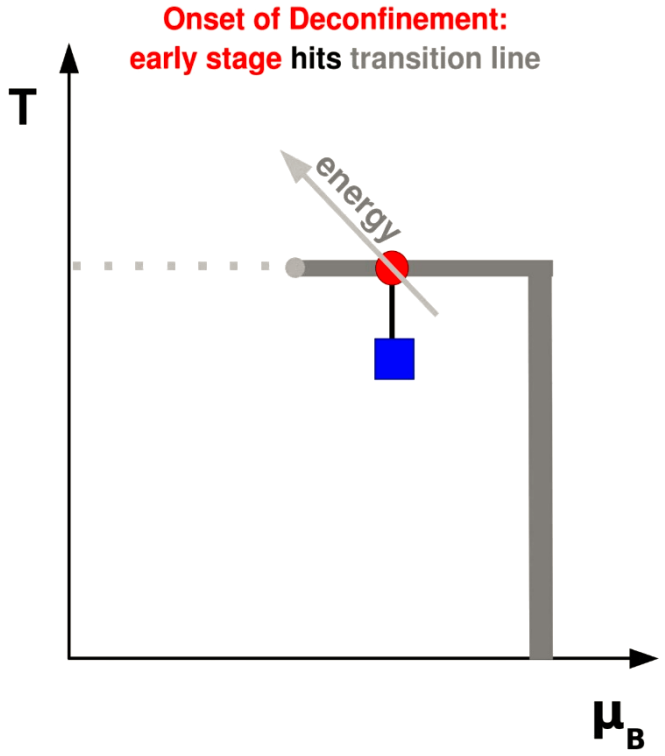


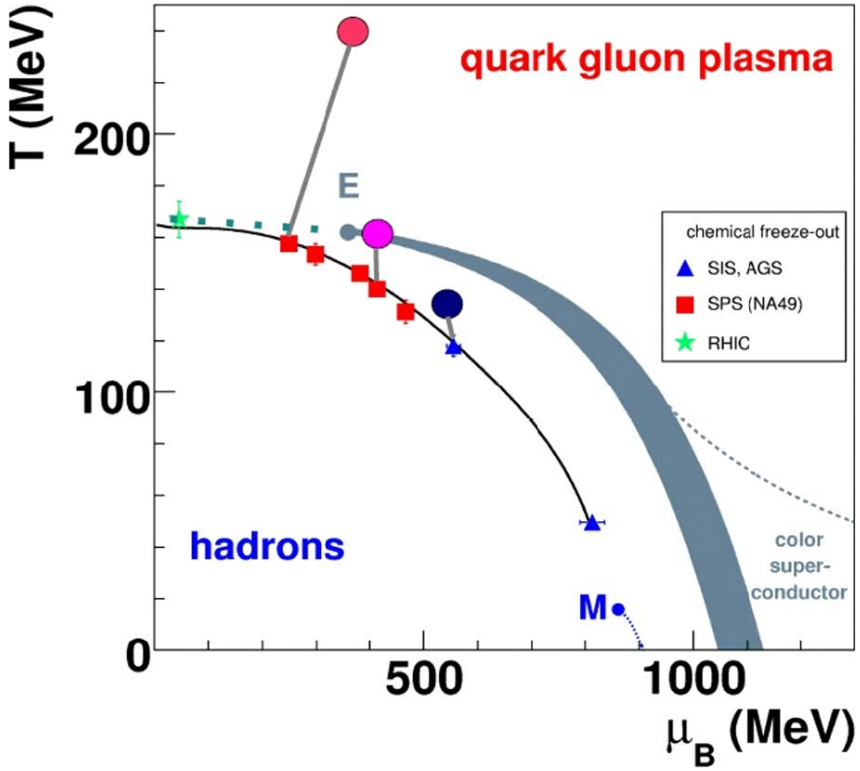


- Large acceptance hadron spectrometer - coverage of the full forward hemisphere, down to $p_T = 0$ GeV/c
- Performs measurements on hadron production in h+p, h+A, A+A at 13A – 150(8)A GeV/c
- Event selection in A+A collisions by measurements of forward energy with PSD
- Recent upgrades:
  - Vertex detector (open charm measurements)
  - FTPC-1/2/3

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

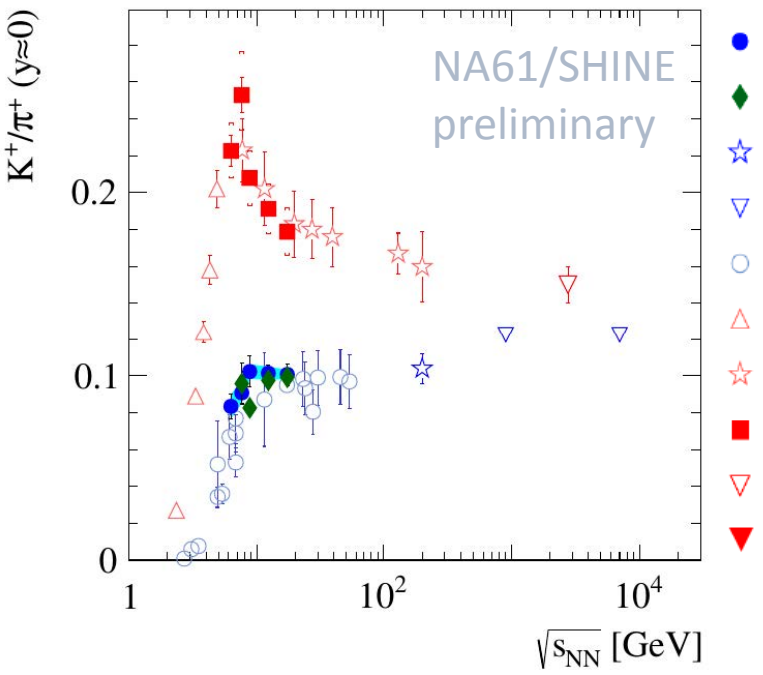
Onset of deconfinement

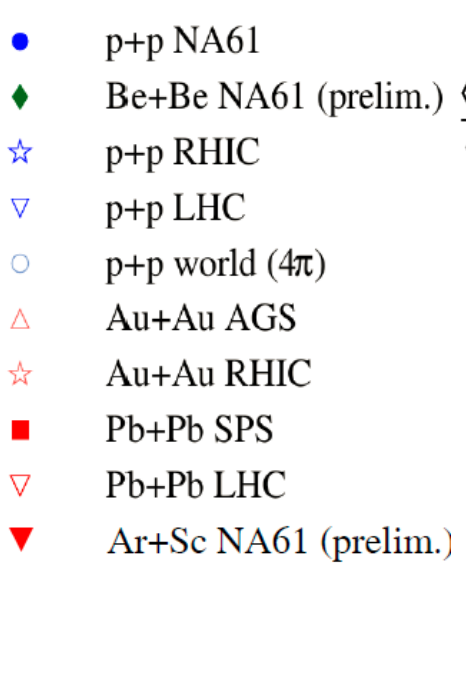


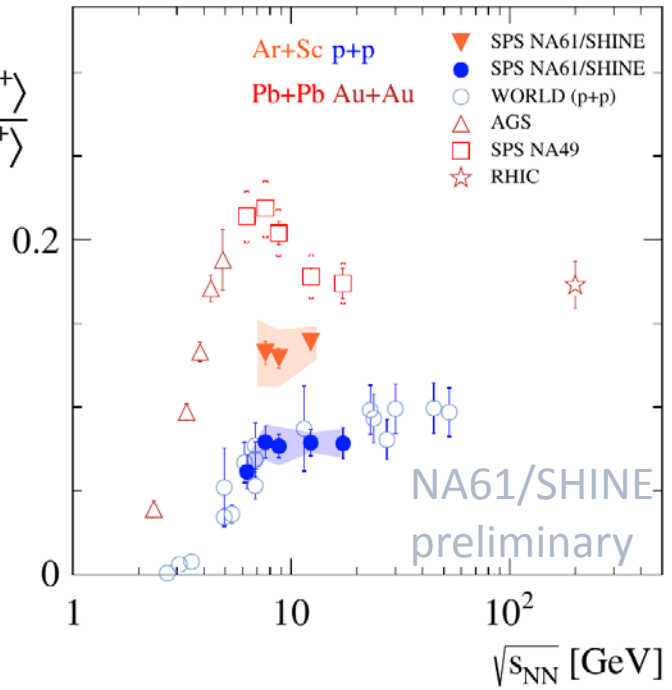


- Beginning of the creation of quark-gluon plasma (QGP) in nucleus-nucleus (A+A) collisions with increasing collision energy $\sqrt{s_{NN}}$.

Onset of deconfinement (energy dependence)

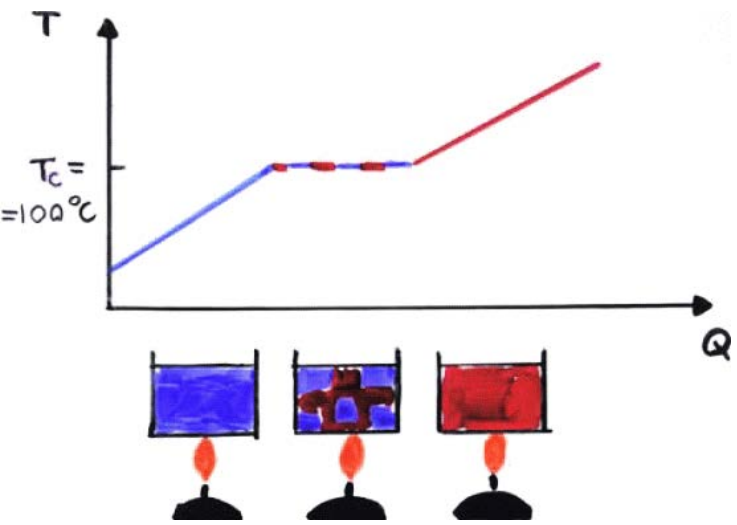


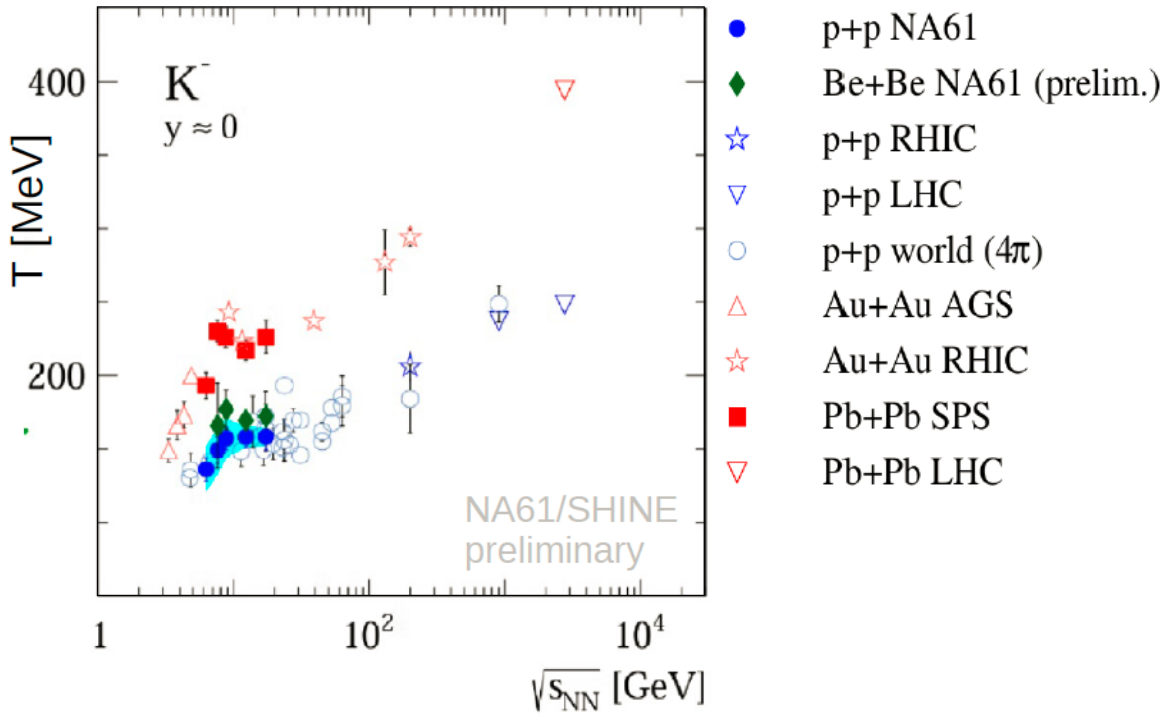




- Rapid changes in K^+/π^+ (HORN) observed in Pb+Pb collisions predicted by the Statistical Model of Early Stage (SMES) as a signature of the onset of deconfinement
- ”Shadow” of HORN seen for p+p interactions
- Be+Be close to p+p
- $\langle K^+ \rangle / \langle \pi^+ \rangle$ in Ar+Sc between p+p/Be+Be and Pb+Pb

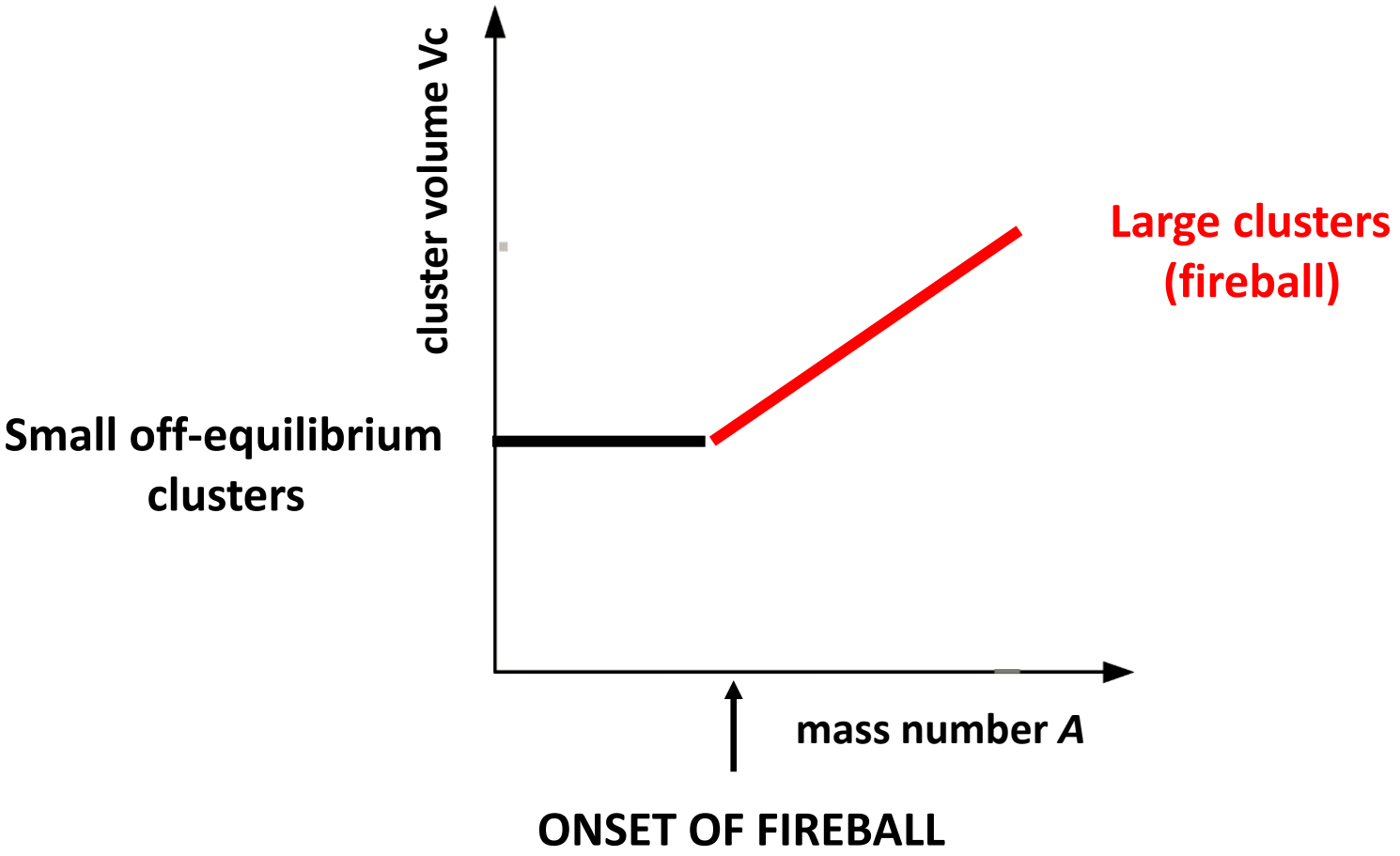
Onset of deconfinement (energy dependence)





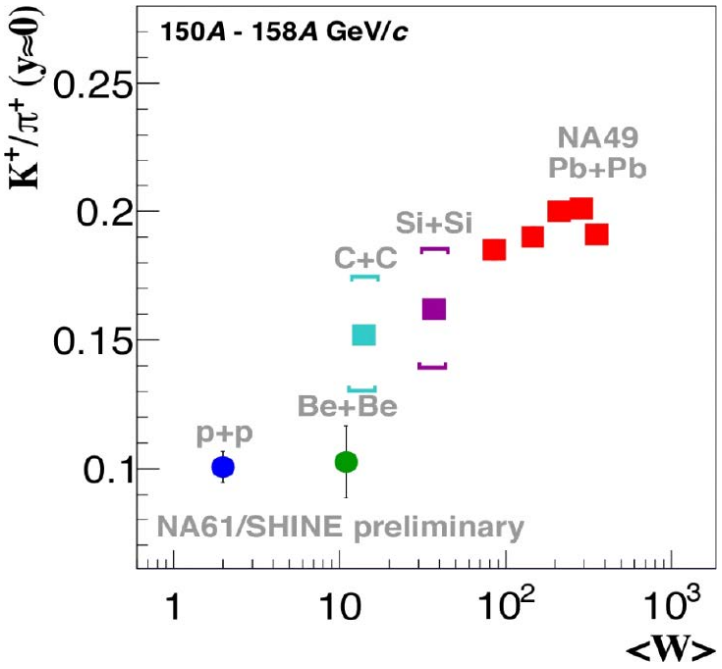
- Changes in T (STEP-like structure), observed in Pb+Pb collisions predicted by SMES model as a signature of the onset of deconfinement
- ”Shadow” of STEP seen for p+p interactions
- Be+Be close to p+p

Onset of fireball



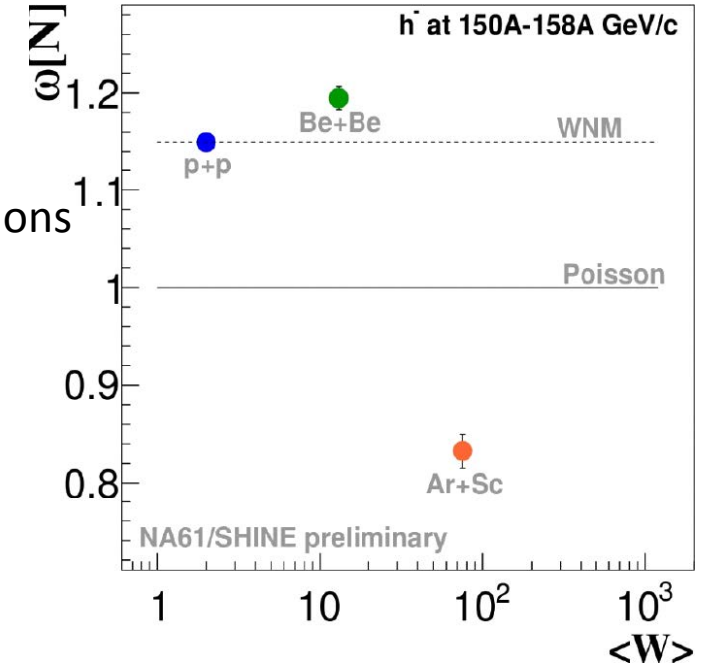
- Beginning of the creation of large clusters of strongly interacting matter (SIM) in nucleus-nucleus collisions with increasing mass number *A*.

Onset of fireball (system size dependence)



Scaled variance
of multiplicity distributions

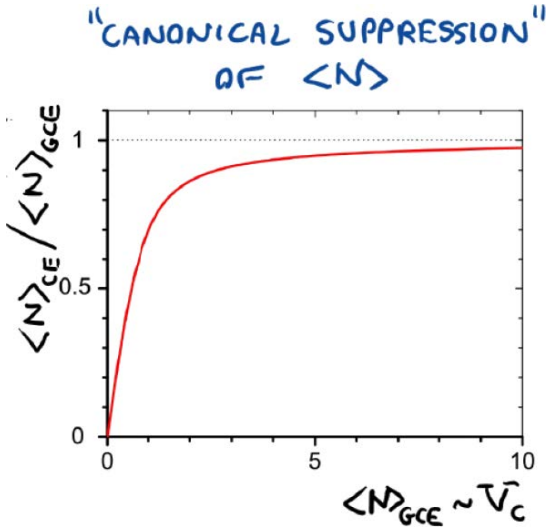
$$\omega[N] = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$



- 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

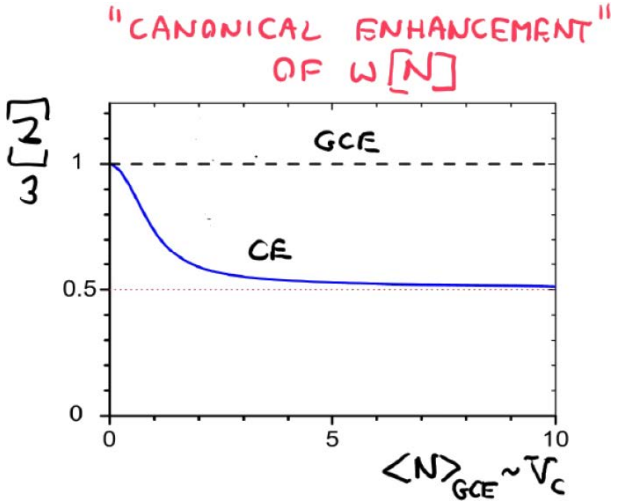
→ beginning of the creation of large clusters of strongly interacting matter in intermediate systems - **onset of fireball ?**

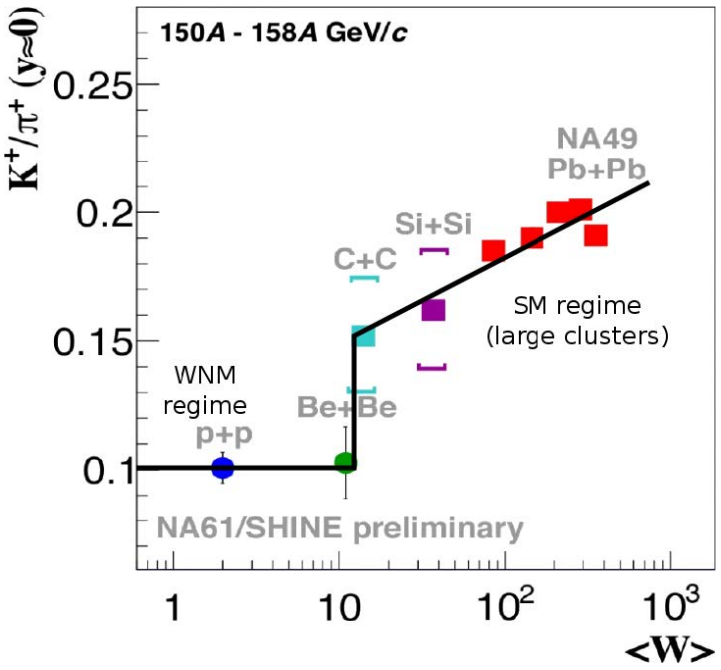
Onset of fireball (system size/cluster volume dependence)

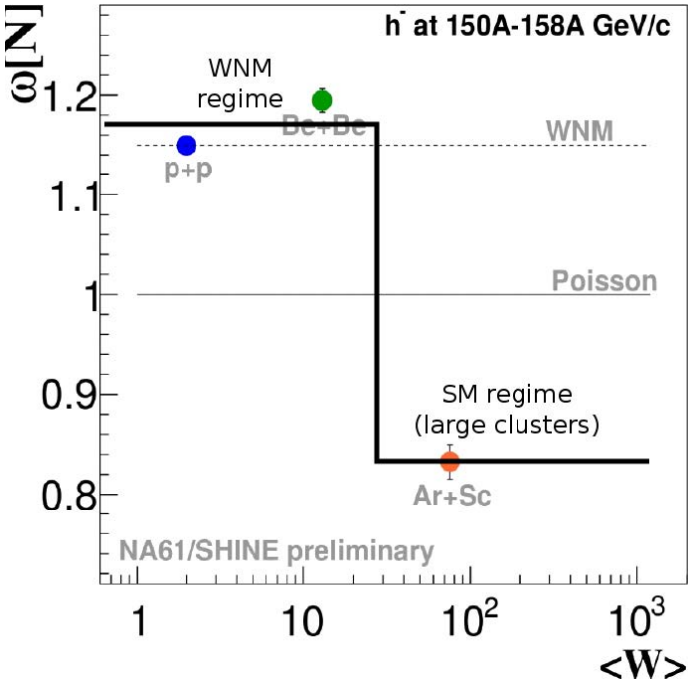


Statistical Models with an Ideal Boltzmann gas within
Canonical Ensemble (CE)
and
Grand Canonical Ensemble (GCE)

M.Gazdzicki, PoS – CPOD2017, 1801.00178

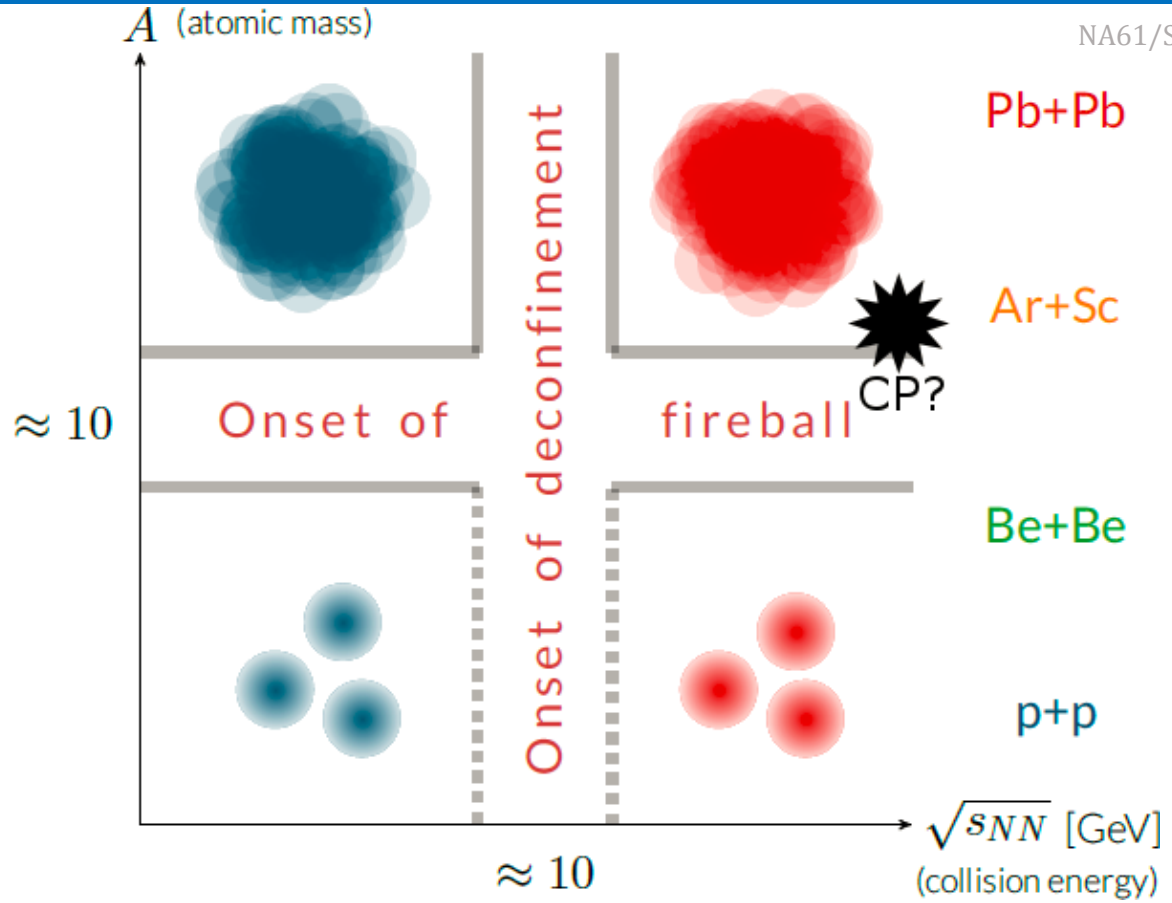






Onset of deconfinement vs onset of fireball

NA61/SHINE: CERN-SPSC-2018-008



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

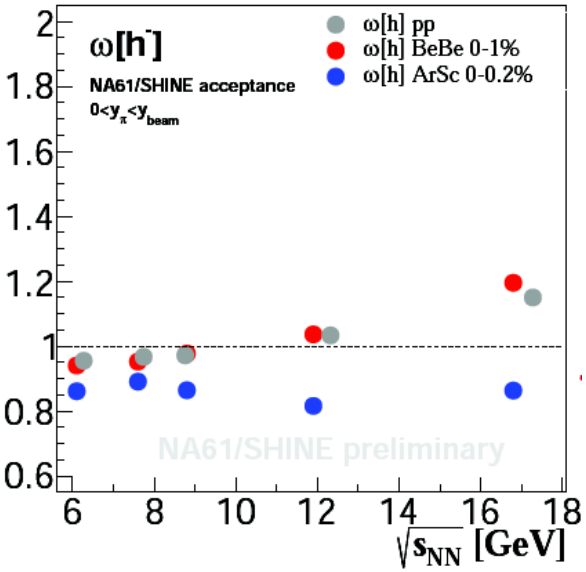
→ four domains of hadron production

Critical point and critical fluctuations

Event-by-event fluctuation measures:

- $\omega[h^-]$: **intensive** (*independent on system volume, dependent on its fluctuations, sensitive to material conservation laws)*

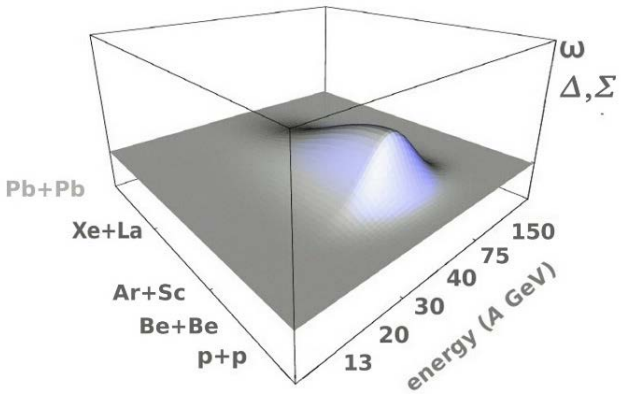
$\omega[h^-]$: different energy dependence for p+p/Be+Be (increase) and Ar+Sc (constant)



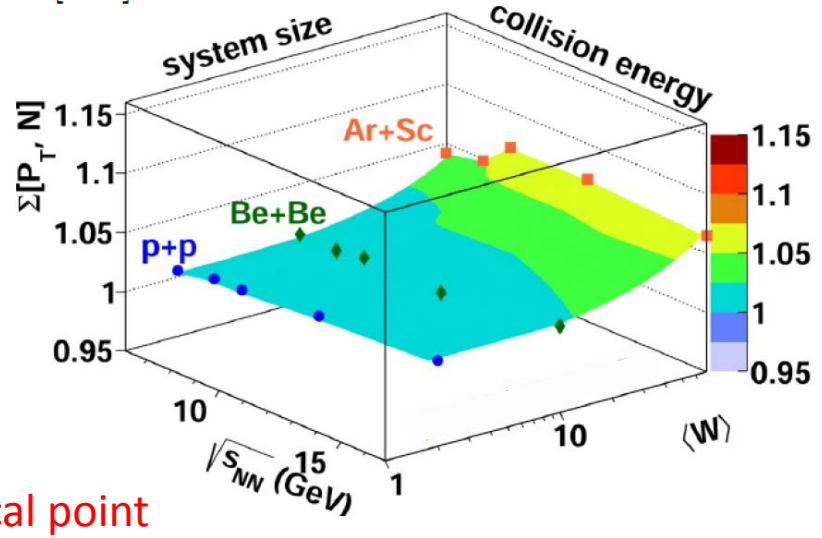
- $\Sigma[P_T,N]$: **strongly intensive** (*independent on system volume and its fluctuations, insensitive to material conservation laws*

$$\Sigma[P_T,N]=\left(\langle N\rangle\omega[P_T]+\langle P_T\rangle\omega[N]-2\mathrm{cov}(P_T,N)\right)\frac{1}{\langle N\rangle\omega[p_T]}$$

$P_T=\sum_i^N p_{Ti}$; $\omega[p_T]$ - *for inclusive* p_T *distribution*



NA61/SHINE preliminary



$\Sigma[P_T,N]$: no fluctuation hill associated with the critical point

Critical point and critical fluctuations

Intermittency analysis of 2-nd factorial moments

- $F_2(M)$: *second factorial moment for M^2 cells in transverse momentum space*

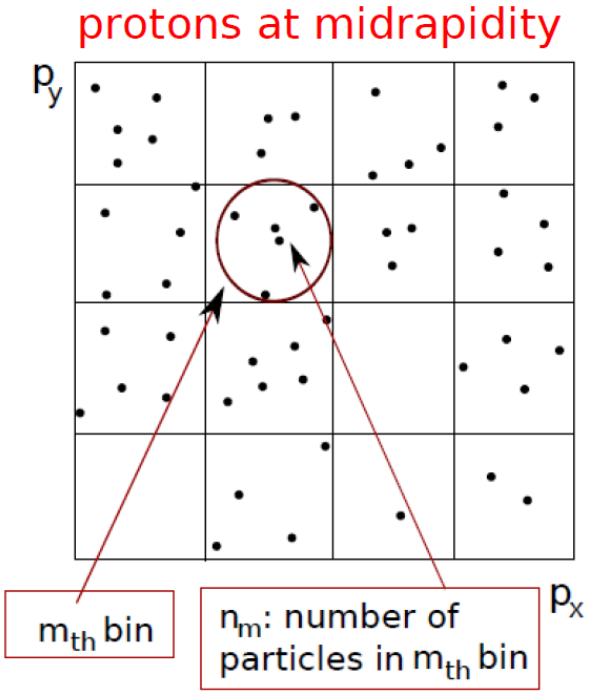
$$F_2(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m - 1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^2}$$

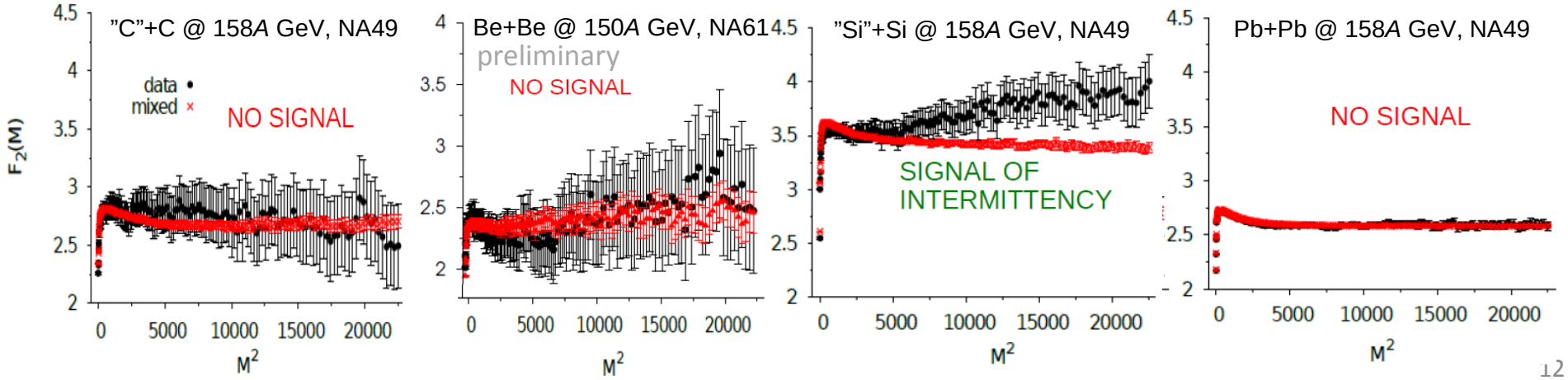
N. G. Antoniou et al., Phys. Rev. Lett. 97, 032002 (2006)

- $\Delta F_2(M) = F_2^{data}(M) - F_2^{mix}(M)$: *correlator after subtraction of non-critical background moments*

- $\Delta F_2(M) \sim (M^2)^{\phi_2}$, $\varphi_2 = 5/6$ (protons): *critical fluctuations*

T. Anticic et al., Eur. Phys. J. C75, 587 (2006)





Open charm measurements

Motivation:

- **What is the mechanism of open charm production ?**

HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367

pQCD
Gavai et al. IJMP A 10 2999
Braun-Munzinger, J. Stachel, PLB 490, 196

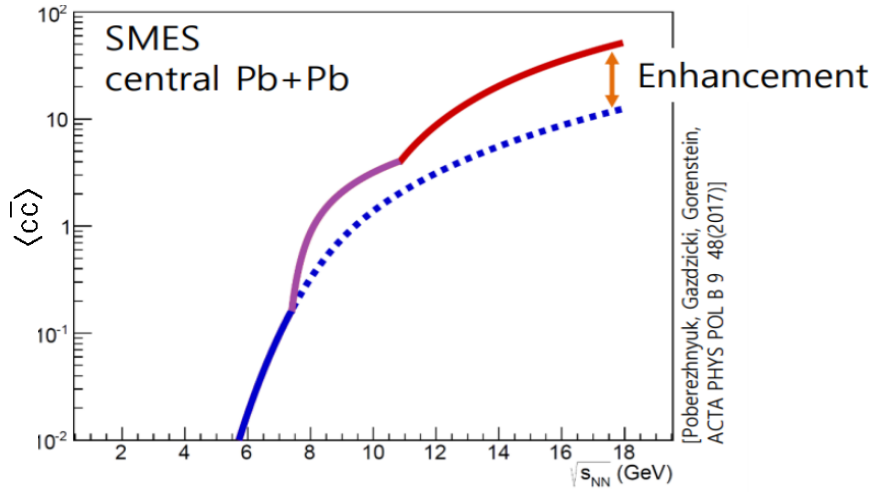
HRG, Quark Coalesc. Stat.
Gavai et al. IJMP A10 2999
Braun-Munzinger, J. Stachel, PLB 490, 196

Quark Coalesc. Dyn.
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G27, 703

SMES
Gazdzicki, Gorenstein, APP B30, 2705

- Model predictions differ by a factor up to 50 for central Pb+Pb collisions at top SPS energy
- Production in full phase space required to discriminate models

- **How does the onset of deconfinement impact charm production** ?

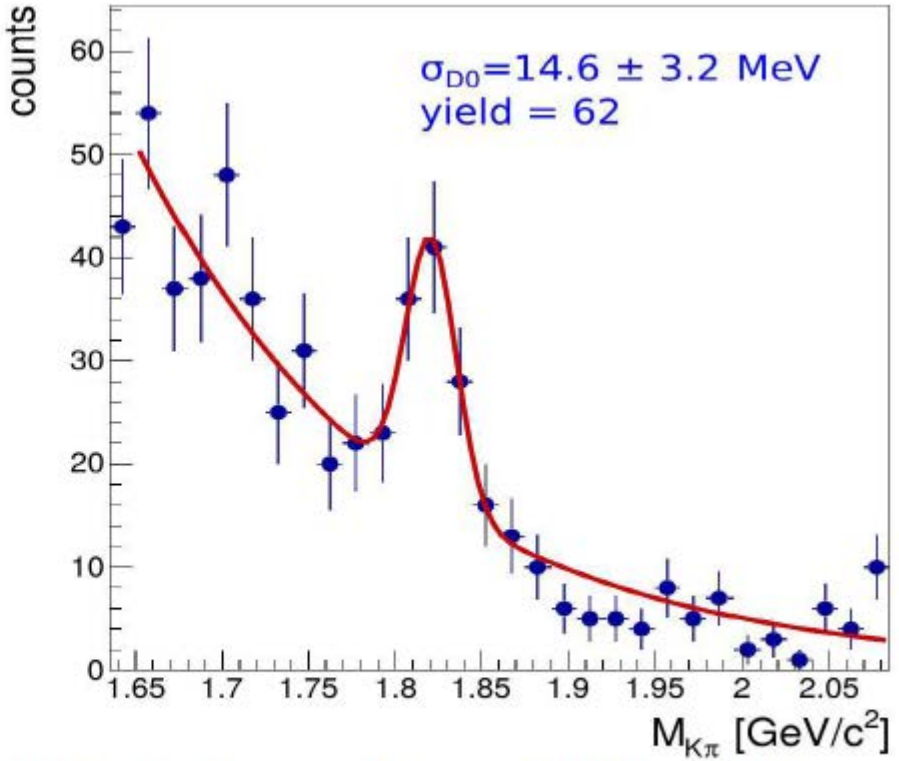


- Different charm carriers in deconfined (c quarks) and confined (D mesons) matter
- Enhancement of $\langle c\bar{c} \rangle$ production predicted by the SMES
- Mesurement of both J/ψ and $\langle c\bar{c} \rangle$ required to calculate probability of $\langle c\bar{c} \rangle$ to J/ψ hadronization

- **How does the formation of quark-gluon plasma impact J/ψ production ?**

Open charm measurements

→ Vertex Detector project of the NA61/SHINE experiment



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

- The analysis of pilot data on Pb+Pb collisions at 150*A* 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

Future plans (beyond 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 from 20% to 0.5%

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

- NA61/SHINE detector upgrade:

  - construction of Large Acceptance Vertex Detector for D^0, anti-D^0 decay reconstruction

  - new trigger and data acquisition system

  - replacement of the TPC readout electronics to increase data rate to 1 kHz

  - upgrade of Projectile Spectator Detector

  - new Time-of-Flight detectors

Summary

- Changes in hadron production as a function of energy (HORN, STEP) observed in central Pb+Pb collisions (NA49) as signatures of deconfinement
- Shadow of HORN observed in p+p/Be+Be
- STEP structure also observed in light nuclei collisions p+p/Be+Be
- Dependence of particle yeald ratios and multiplicity fluctuations on the system size suggests existence of the onset of fireball - the beginning of creation of large clusters
- Four domains of hadron production with two thresholds
- No fluctuation signal attributed to the critical point
- The increase of fluctuations in Si+Si collisions (NA49) from intermittency analysis
- First observation of D^0 peak in central Pb+Pb collisions at SPS energies
- New NA61/SHINE results for Ar+Sc, Xe+La and Pb+Pb collisions expected soon
- Ambitious programme of measurements beyond 2020

Thank you for your attention !

- 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, Moscov
  - JINR Dubna, Dubna
  - SPBU, St.Petersburg
  - MEPhI, Moscow

~150 physicists from ~30 institutes

- 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