Overview of recent measurements by NA61/SHINE at the CERN SPS

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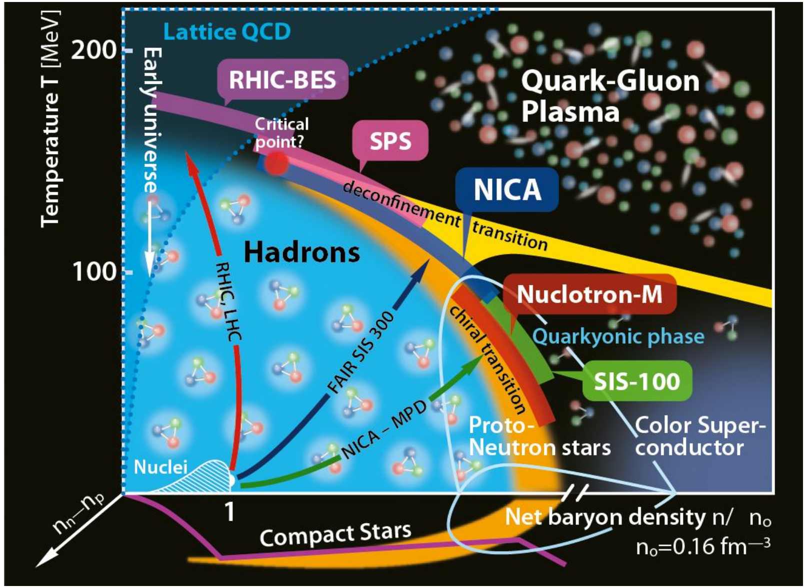
for the NA61/SHINE Collaboration

NUCLEUS-2021 conference, 22/09/2021

NA61/SHINE Collaboration

SHINE - The **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment

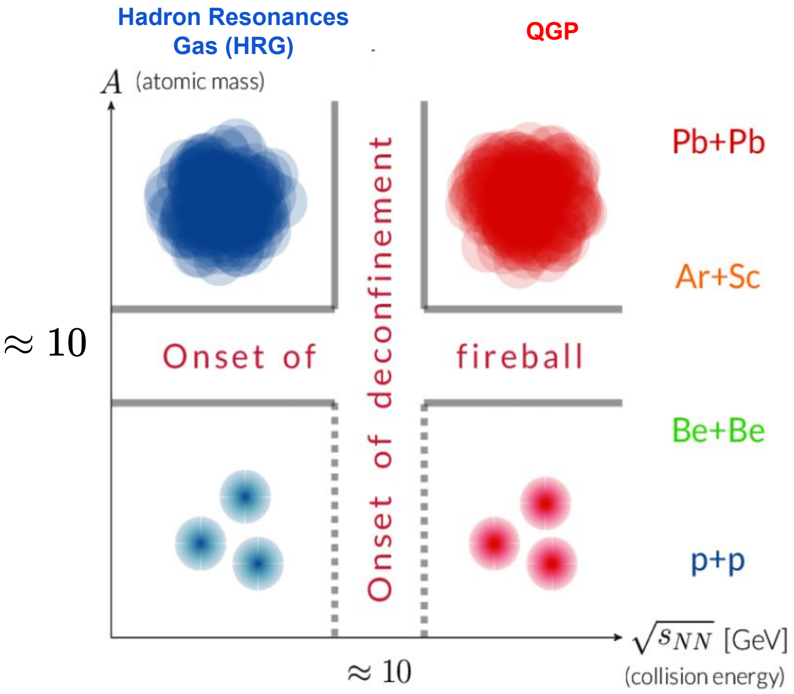
Over 150 physicists from 30 institutions and 15 countries



- Strong interaction
  - Onset of deconfinement & onset of fireball
  - Properties of the QCD matter (EoS)
  - Search for QCD critical point
- Neutrino physics
  - Hadron production cross sections for neutrino flux predictions
- Cosmic rays
  - Hadron production cross sections for air-shower modelling

This talk is focused on results from strong interactions program

Onset of deconfinement & onset of fireball



Onset of deconfinement

QGP formation by heating up the QCD matter with increasing collision energy

- freeze-out temperature (plateau-like structures)
- increase of entropy (new degrees of freedom)
- strangeness enhancement

Onset of fireball

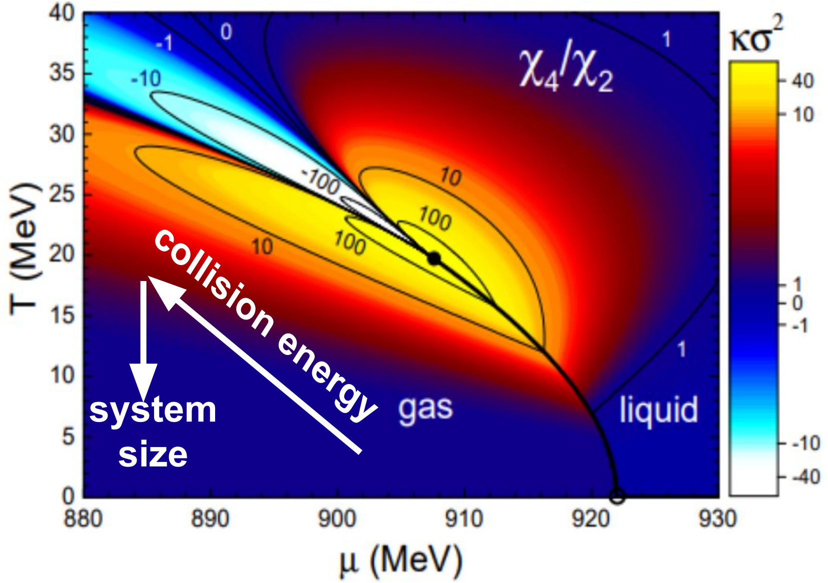
QGP formation as a large equilibrated cluster of the QCD matter with increasing size of colliding nuclei

Observables
(p_T ,*y*, centrality)-differential yields
vs. collision energy & system size

Requires two-dimensional scan in collision energy and system size

Search for QCD critical point

Vovchenko et al. Acta Phys. Polon. Supp. 10,75



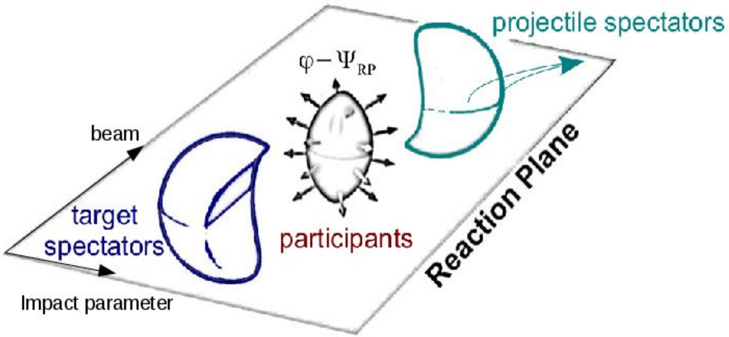
Theoretical predictions for critical point location are model-dependent and have large uncertainties

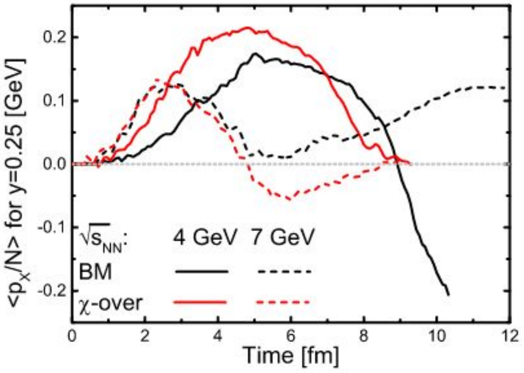
Increased fluctuations at the critical point of conserved charges and particle multiplicities

- Net-charge, net-baryon fluctuations
- Self-similar density fluctuations
    - intermittency
    - femtoscopy

Requires two-dimensional scan in collision energy and system size

Properties of the QCD matter: EoS & EM effects





Dynamical evolution of the colliding system depends on

- EoS properties:
  - type (presence) of phase transition
  - compressibility of matter

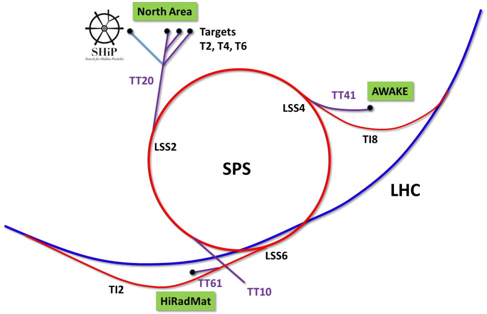
- Dissipative properties e.g. shear viscosity

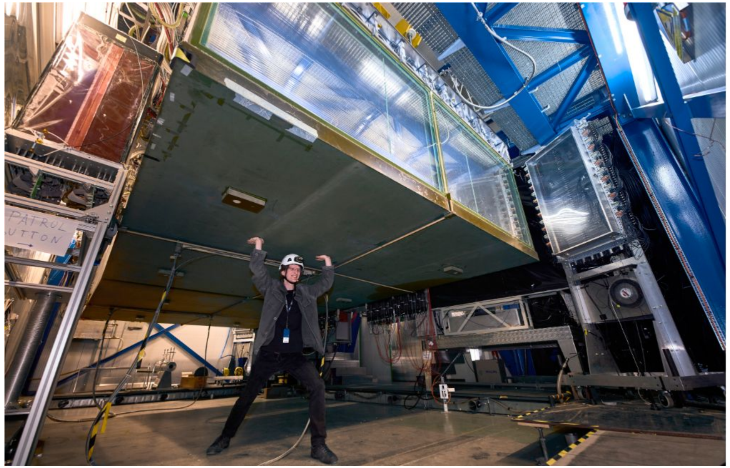
Observables:
collective flow; rapidity width

Large passage time of spectators at SPS energies substantially modify the final state:
- screening of expanding matter
- interaction of produced particles with strong EM fields of charged spectators

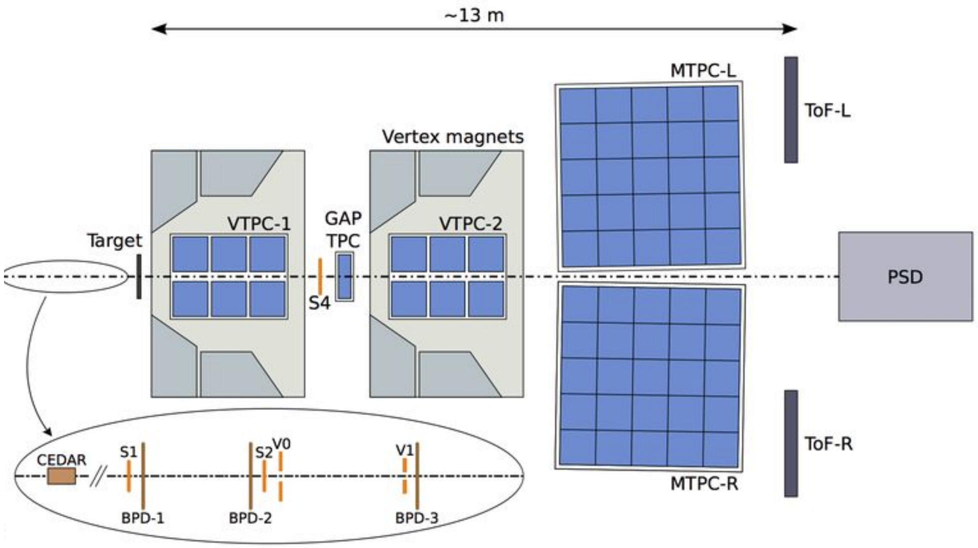
Multi-differential measurements are important

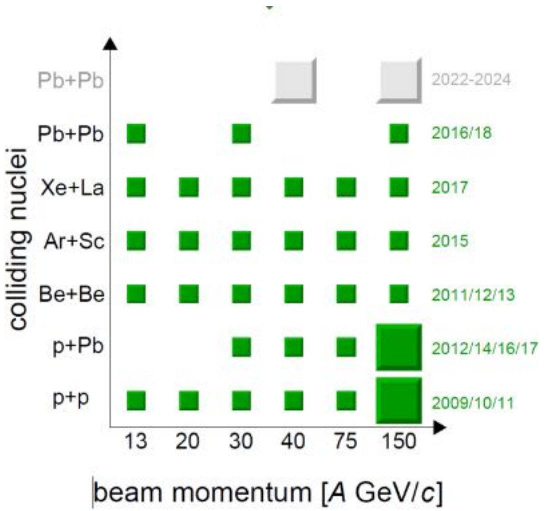
NA61/SHINE facility at North Area @ CERN





NA61/SHINE: subsystems and 2D energy&system size scan

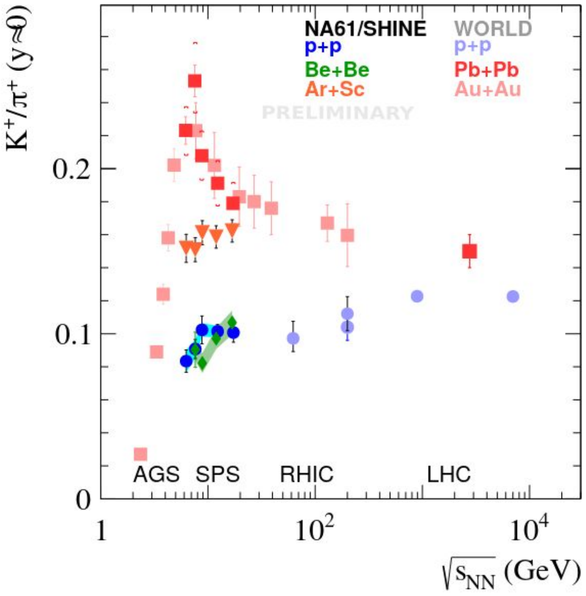


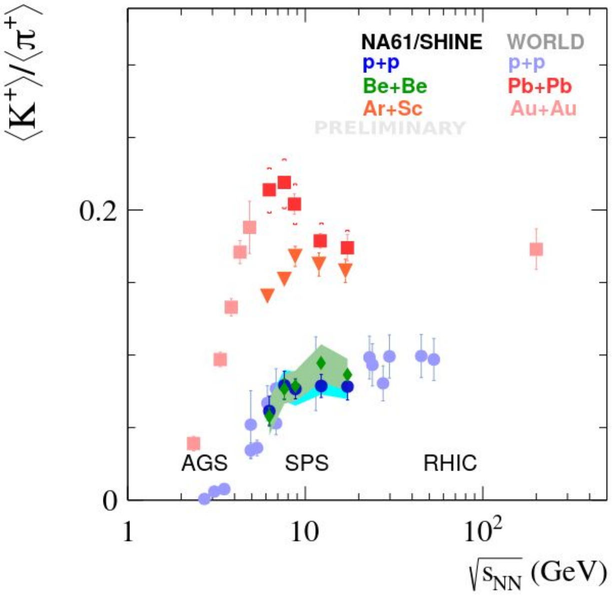


- Full forward hemisphere coverage down to $p_T \sim 0$ and forward rapidities ($y \sim y_{beam}$)
- Measurement of projectile spectators transverse energy with forward calorimeter (PSD)
- Unique 2D scan in system size and collision energy

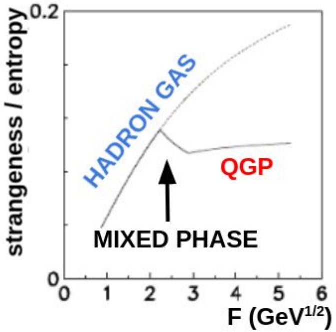
Onset of deconfinement
&
onset of fireball

Onset of deconfinement: (K/π) ratio





theory expectation



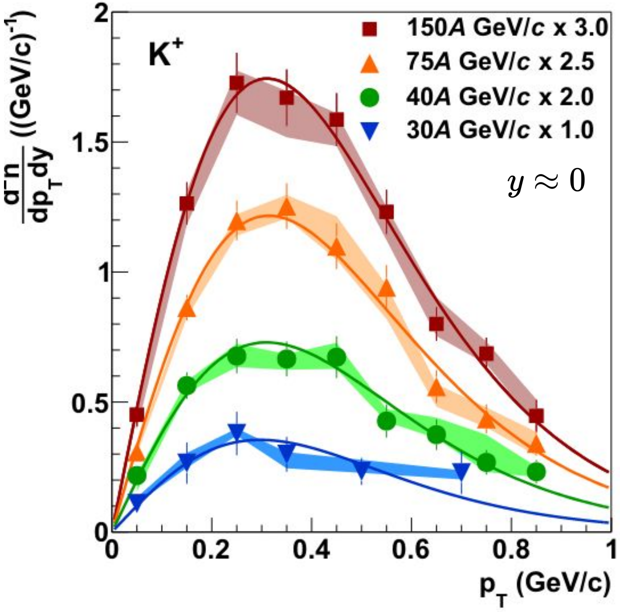
Acta Phys.Polon.B 46 (2015) 10, 1991

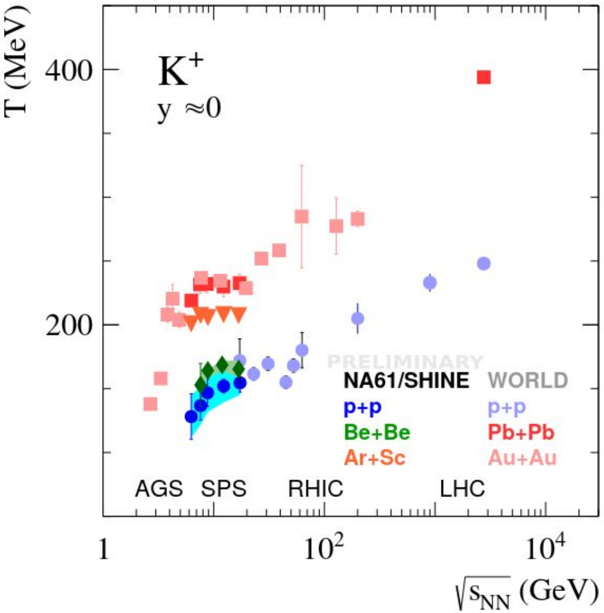
$$F = \frac{(\sqrt{s_{NN}} - 2m_N)^{3/4}}{(\sqrt{s_{NN}})^{1/4}} \approx s_{NN}^{1/4}$$

- Rapid change in the energy dependence of (K/π) ratio in Pb+Pb collisions indicated the onset of deconfinement in the SPS energy range
- No “horn” structure in Ar+Sc - difference between small (p+p and Be+Be) and large systems (Ar+Sc and Pb+Pb)

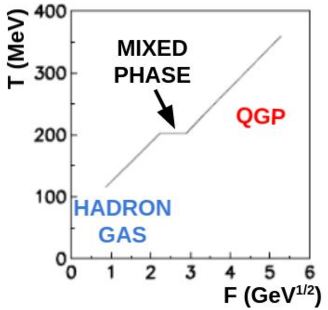
Onset of deconfinement: freeze-out temperature

Be+Be





theory expectation

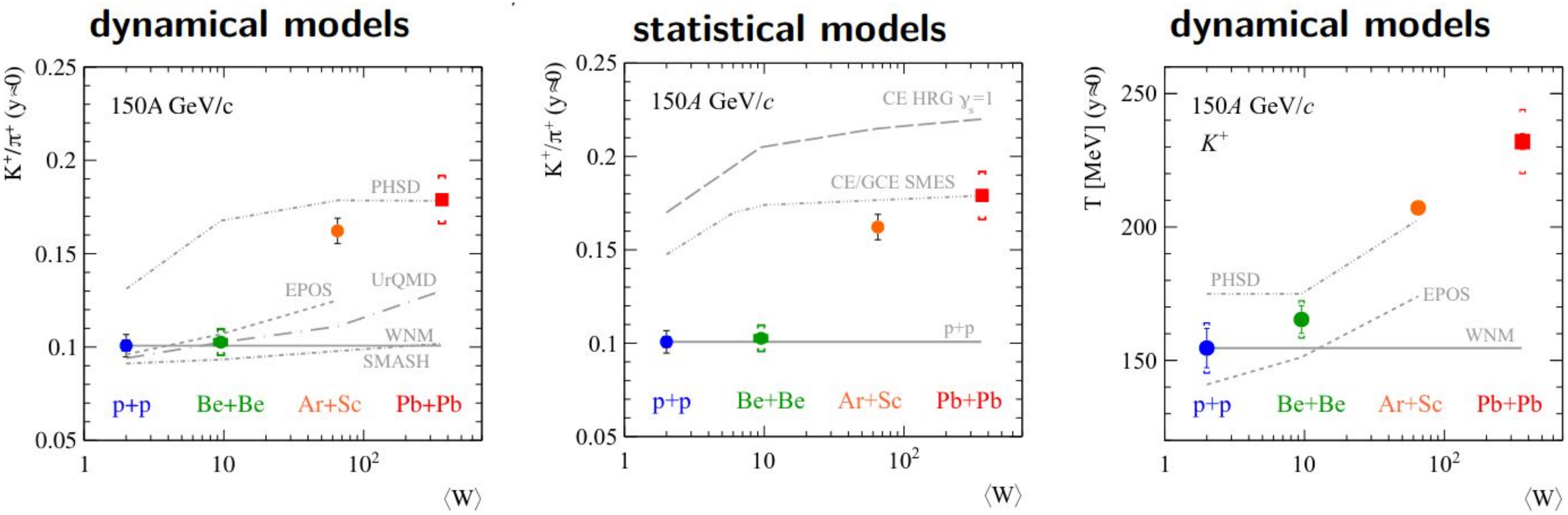


Acta Phys.Polon.B 46 (2015) 10, 1991

$$F = \frac{(\sqrt{s_{NN}} - 2m_N)^{3/4}}{(\sqrt{s_{NN}})^{1/4}} \approx s_{NN}^{1/4}$$

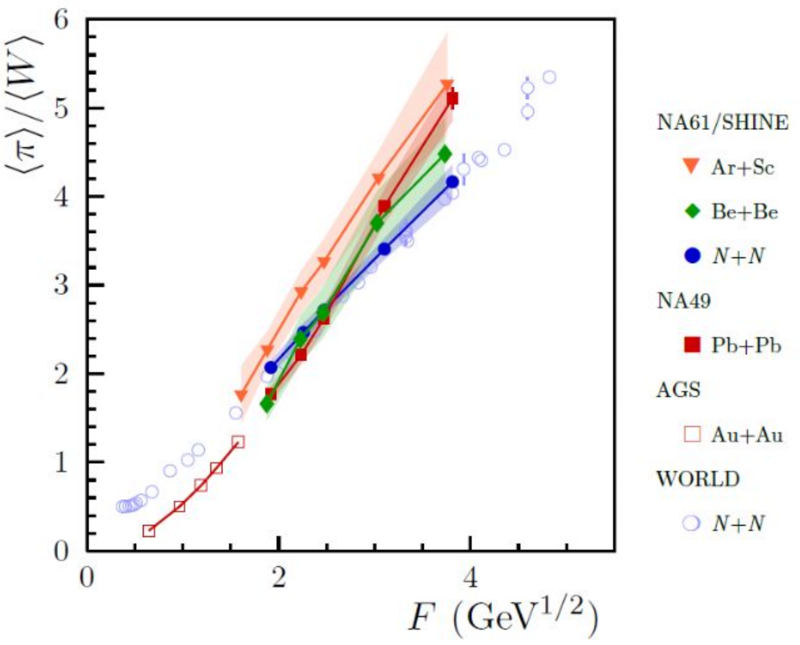
Plateau in the Freeze-out temperature (T) defined by the inverse slope parameter of kaon m_T spectra is expected for mixed phase of hadron gas and QGP

Onset of fireball: system size dependence of (K/π) ratio

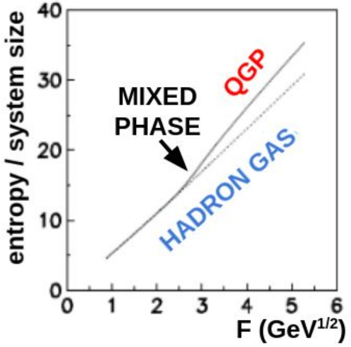


- Difference between small & large systems - transition between Be+Be and Ar+Sc collisions
- Models do not reproduce the NA61/SHINE data

Onset of deconfinement: New degrees of freedom & entropy increase



theory expectation



Acta Phys.Polon.B 46 (2015) 10, 1991

$$F = \frac{(\sqrt{s_{NN}} - 2m_N)^{3/4}}{(\sqrt{s_{NN}})^{1/4}} \approx s_{NN}^{1/4}$$

Not conclusive yet as data uncertainties are too large

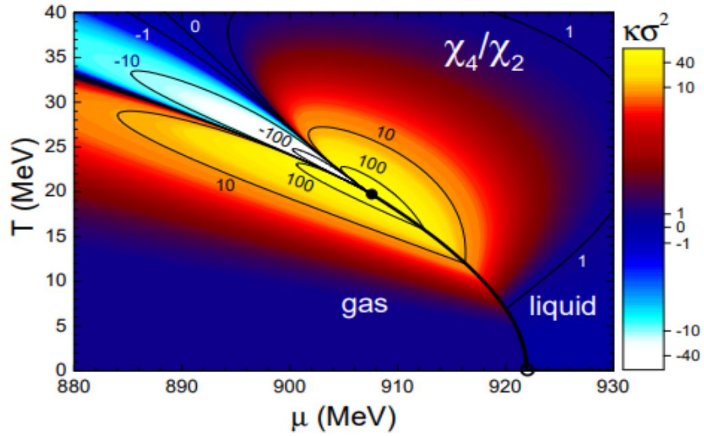
Search for QCD critical point

Search for QCD critical point: net-charge fluctuations

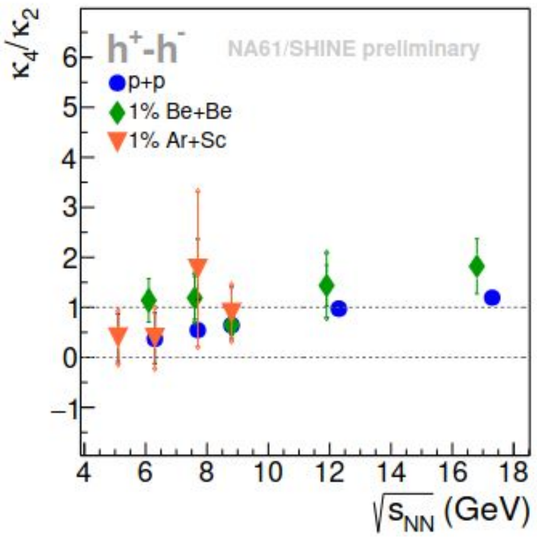
Intensive (independent on system size) quantities:

$$\frac{\kappa_2}{\kappa_1} = \omega[N] \qquad \frac{\kappa_3}{\kappa_2} = S\sigma \qquad \frac{\kappa_4}{\kappa_2} = \kappa\sigma^2$$

$$\kappa_1 = \langle N \rangle$$
$$\kappa_2 = \left\langle (\delta N)^2 \right\rangle = \sigma^2$$
$$\kappa_3 = \left\langle (\delta N)^3 \right\rangle = S\sigma^3$$
$$\kappa_4 = \left\langle (\delta N)^4 \right\rangle - 3\left\langle (\delta N)^2 \right\rangle^2 = \kappa\sigma^4$$



Vovchenko et al. Acta Phys. Polon. Supp. 10,75



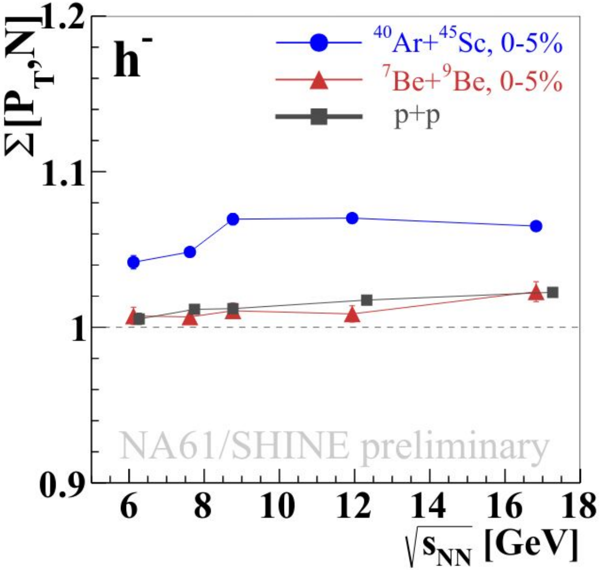
- No specific hill / dip structures that could be related to the critical point are observed so far
- Intensive quantities still sensitive to system-size fluctuations

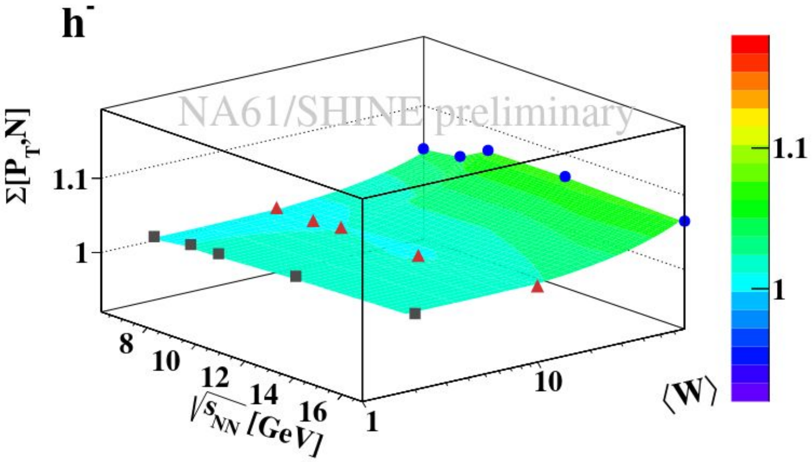
Search for QCD critical point: strongly intensive quantities

$$\Sigma[N, P_T] = \frac{1}{C}(\omega[N]\langle P_T\rangle + \omega[B]\langle N\rangle - 2(\langle NP_T\rangle - \langle P_T\rangle\langle N\rangle))$$

$$P_T = \sum_{i=1}^{N} p_T \qquad C = \langle N \rangle$$

Insensitive to system-size fluctuations





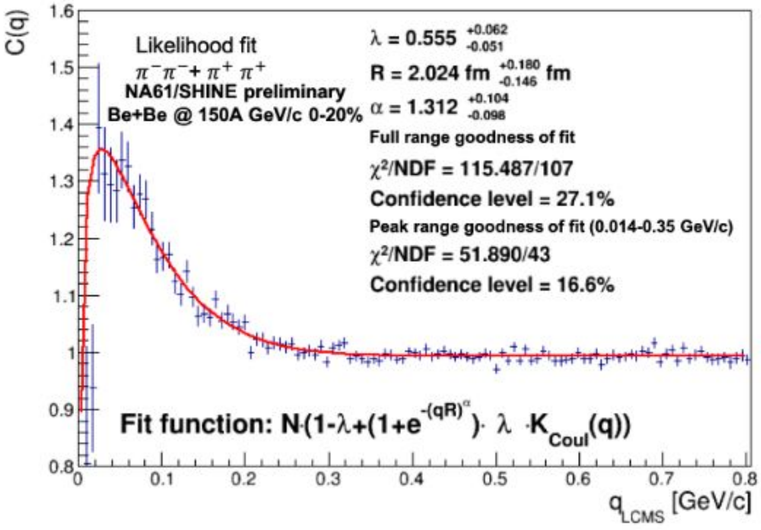
No specific hill / dip structures structures that could be related to the critical point are observed so far

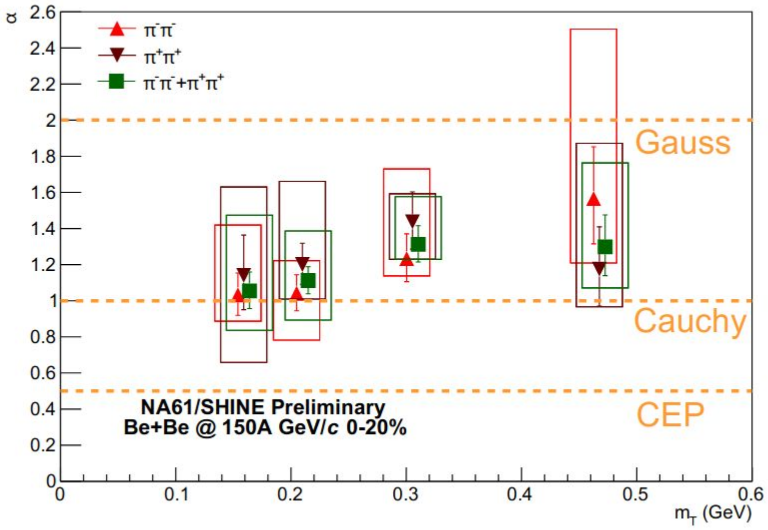
Search for QCD critical point: femtoscopic correlations

Levy-stable distribution: $\mathcal{L}(\alpha, R, r) = \frac{1}{2\pi} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^{\alpha}}$

3D Ising model: α = 0.5 ± 0.05 at critical point

H.Rieger Phys. Rev. B. 32 (1992) 6659





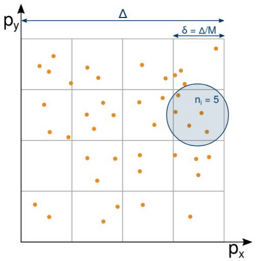
- α is between 1 and 2 - no indication of critical point in Be+Be at 150*A* GeV/*c*
- Extension to heavy systems is needed

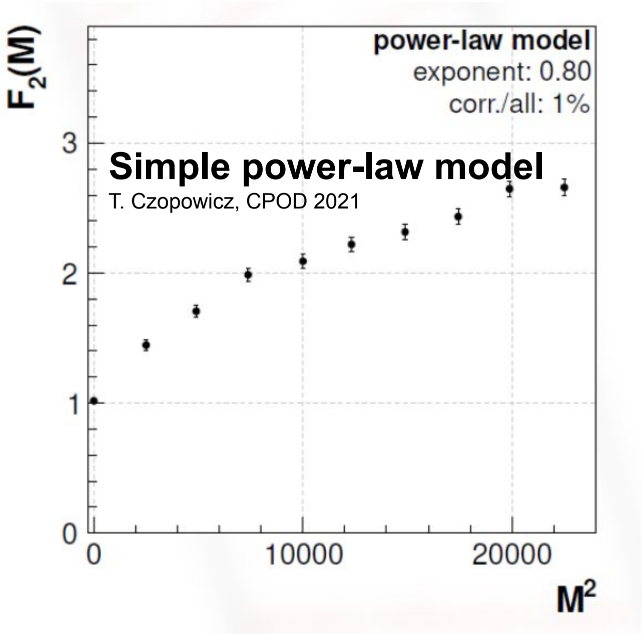
Search for QCD critical point: proton intermittency

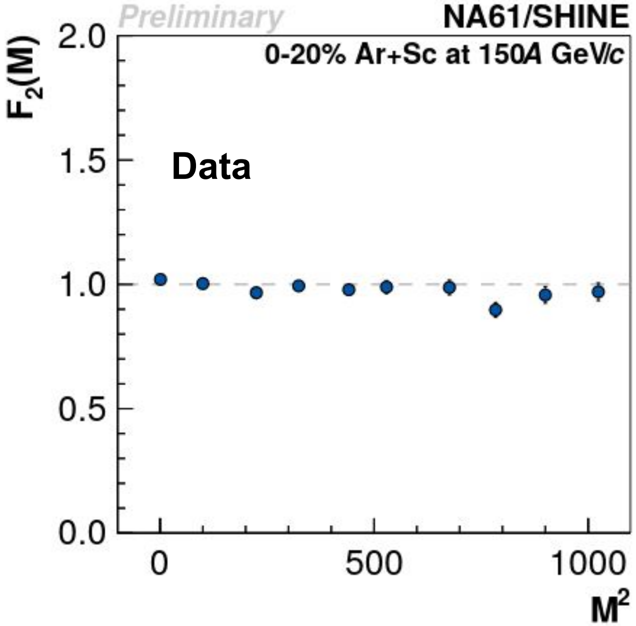
Second factorial moment as function of momentum bin size

At critical point predicted: $F_2(M) \sim (M^2)^{\phi_2}$ with ϕ_2 = 5/6 from 3D Ising model

N. G. Antoniou et al., Nucl. Phys. A 761, 149–161 (2005)







No indication for power-law increase with a bin size

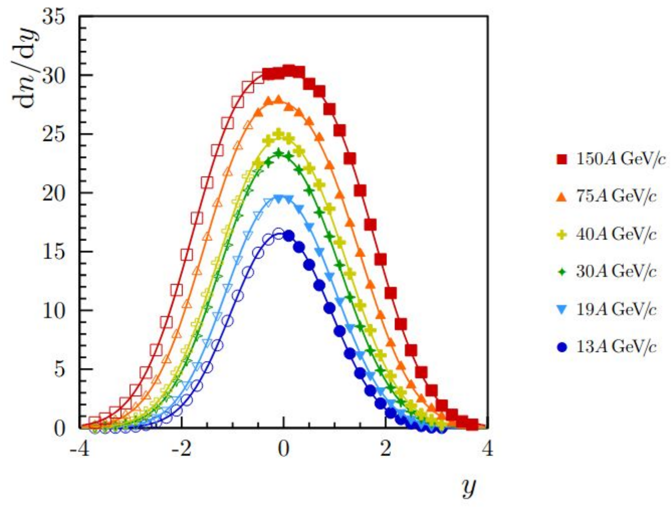
Properties of the QCD matter

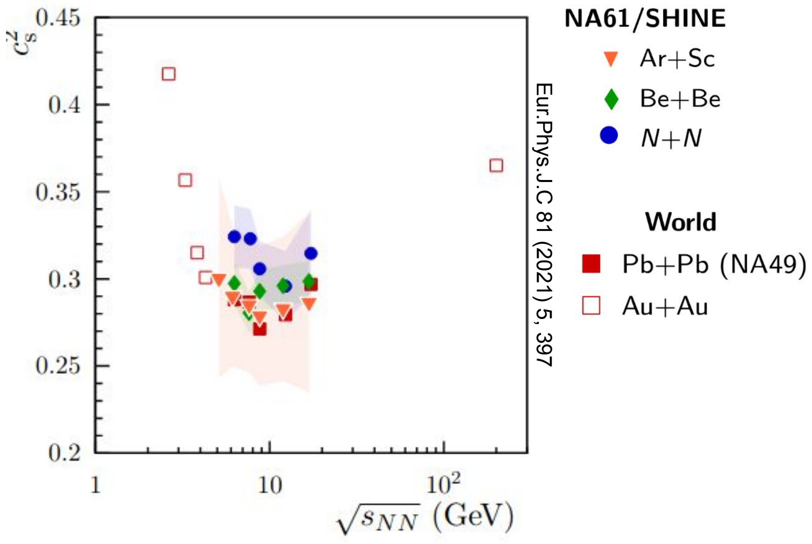
Properties of the QCD matter: softening of EoS

Relation between rapidity width and sound velocity: $\sigma^2 = \frac{8}{3}\frac{c_S^2}{1-c_S^4} ln(\frac{\sqrt{s_{NN}}}{2m_p})$

E.V.Shuryak, Yad.Fiz., 16, 395–405, 1972
M. Bleicher, PoS CPOD 2006, 025 (2006)

negative pions 5% most central Ar+Sc

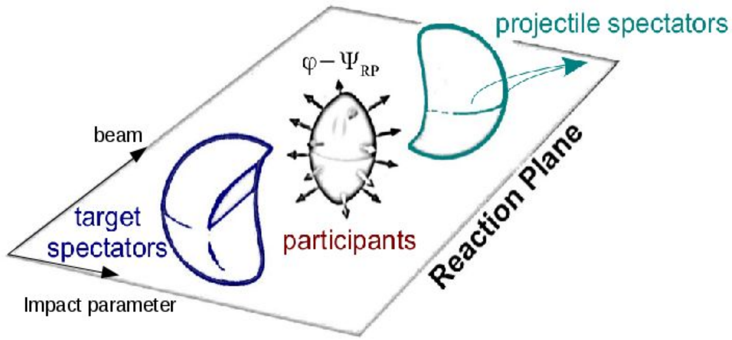




- Minimum in energy dependence indicate possible softening of EoS
- Need to extend data to lower energies

Properties of the QCD matter: collective flow

In non-central collision spatial azimuthal asymmetry of initial state is converted to azimuthal asymmetry of produced particles in momentum space.



$$\rho(\phi) = \frac{1}{2\pi}[1+2\sum_{n=1}^{\infty} v_n \cos(n(\phi-\Psi_s))]$$

$$v_n = \langle \cos(n[\phi-\Psi_s]) \rangle$$

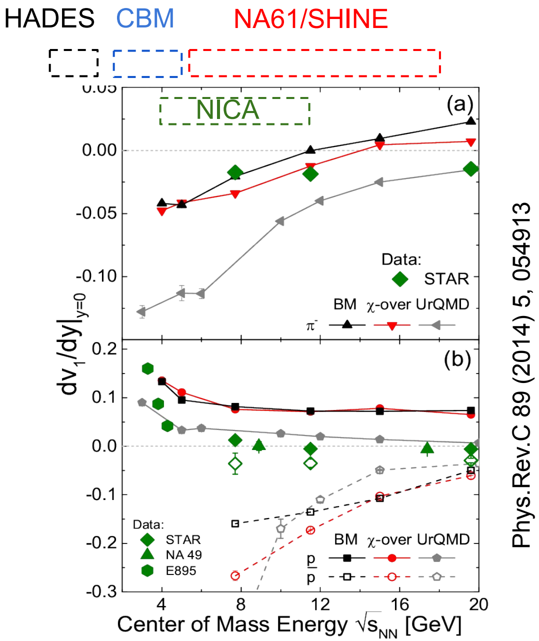
Azimuthal angle of identified particles

Symmetry plane from projectile spectators

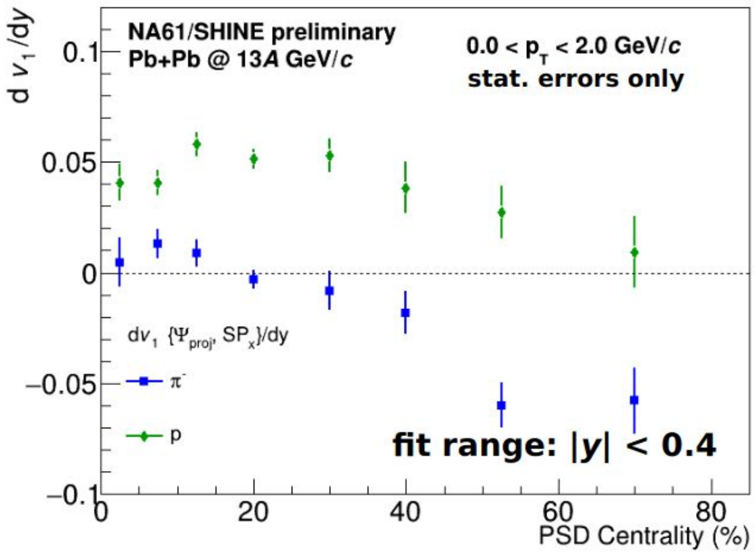
NA61/SHINE features:

- measurements in forward rapidity (up to y_{beam})
- differential measurements
- interplay between produced particles and spectators

Slope of the directed flow (v_1) at midrapidity

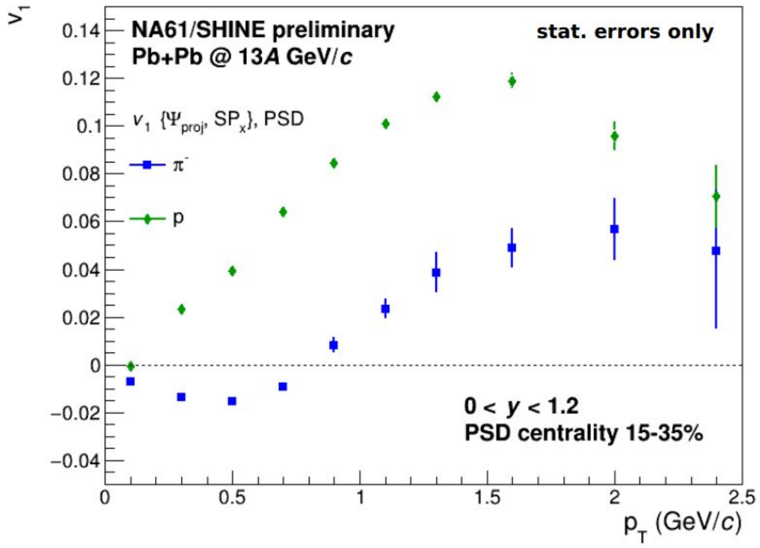


$\sqrt{s_{NN}}$ = 5.1 GeV/c



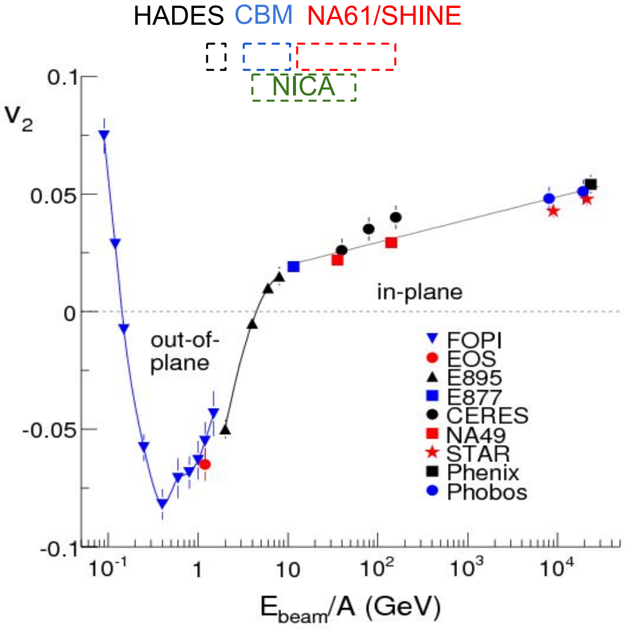
- Slope of directed flow strongly depends on centrality
- Change of sign for pions in midcentral collisions

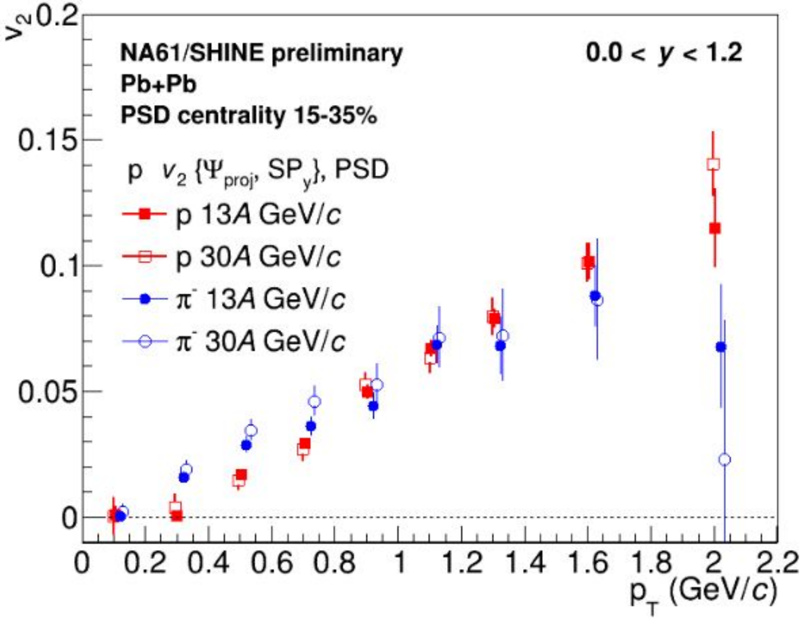
Directed flow vs transverse momentum



- Mass dependence of directed flow
- Directed flow of pions changes sign at $p_T \sim 1$ GeV/*c*

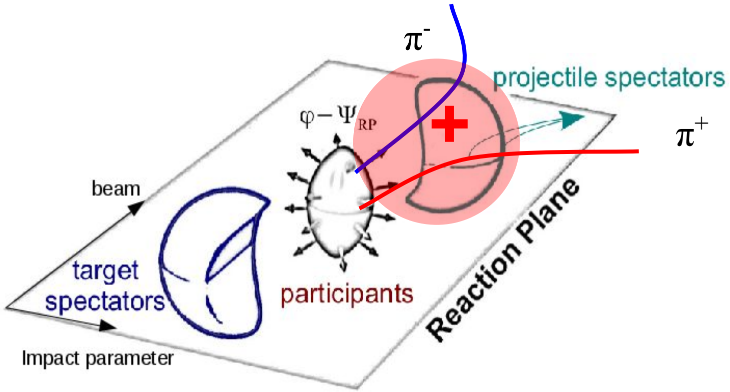
Elliptic flow (v_2) vs collision energy

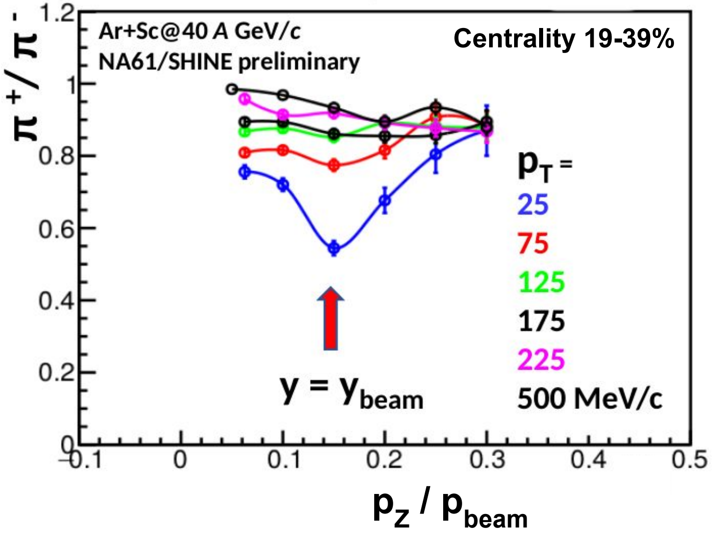




- Mass dependence of elliptic flow
- Weak energy dependence of the elliptic flow

EM effects: (π^+ / π^-) ratio in Ar+Sc @ 40A GeV/c





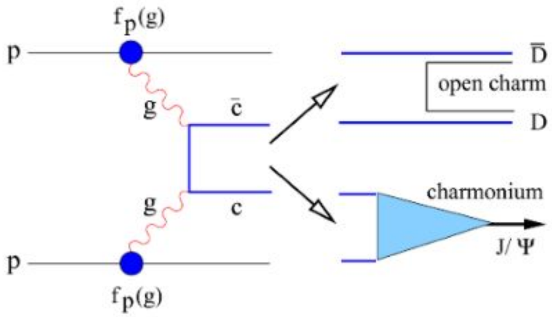
- Charged pions are deflected by EM field produced by charged spectators
- EM distortion is sensitive to the distance between the pion formation zone and the spectator system; creation time scales of pions
- Dip in π+/π- ratio appears close to the rapidity of spectators and is maximal for low transverse momentum pions

A.Marcinek et al., Acta Phys. Pol. B 50, 1127 (2019)
V.Ozvenchuk et al., Phys. Rev. C 102 (2020) 1, 014901

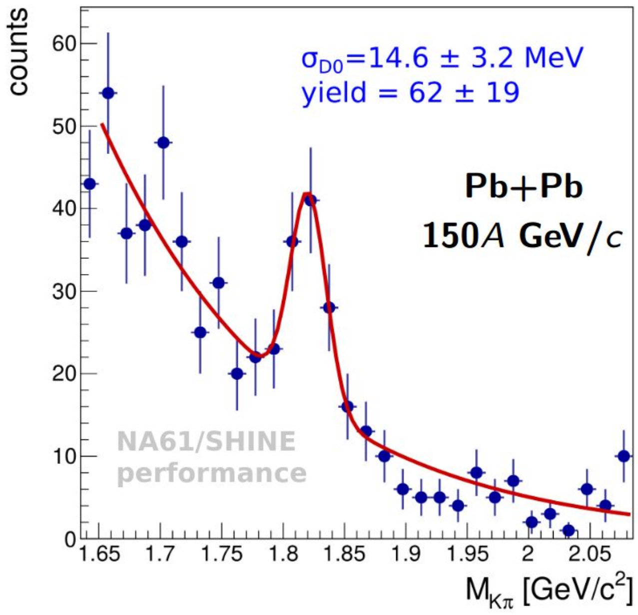
Open charm

Pilot NA61/SHINE measurements

Open charm and J /ψ production
within Matsui-Satz model PL B178 416



	in vacuum	in medium
open charm	90%	98%
charmonium	10%	2%



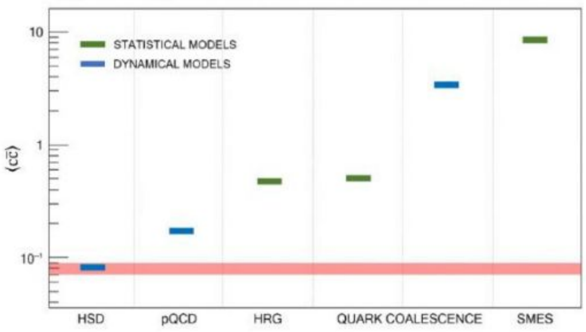
First observation of D^0
inv. mass peak in Pb+Pb data

NA61/SHINE in 2022-2024

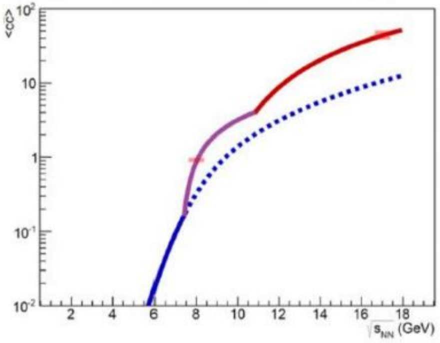
NA61/SHINE program for 2022-2024

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

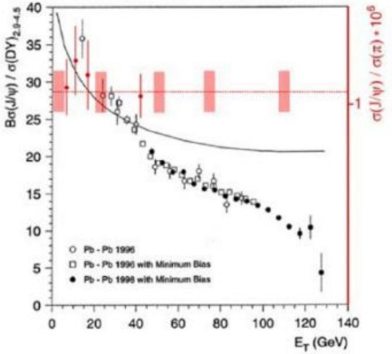
$\langle c\bar{c} \rangle$ and models



$\langle c\bar{c} \rangle$ and onset of deconfinement

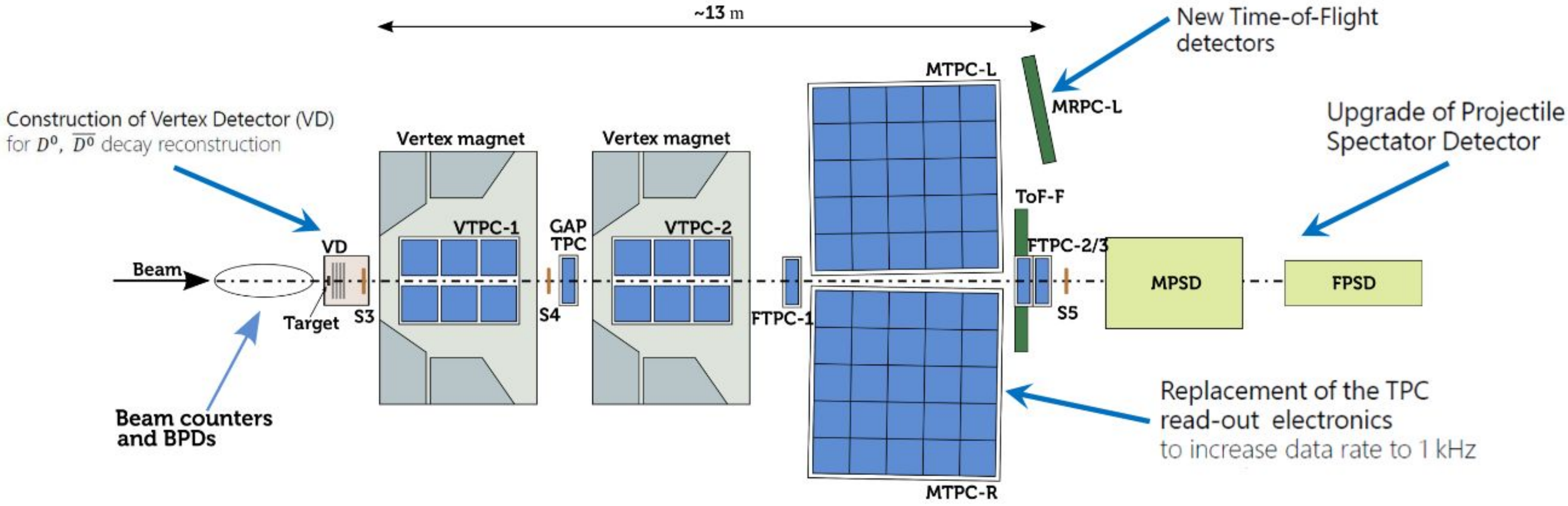


$\langle c\bar{c} \rangle$, $\langle J/\psi \rangle$ and QGP

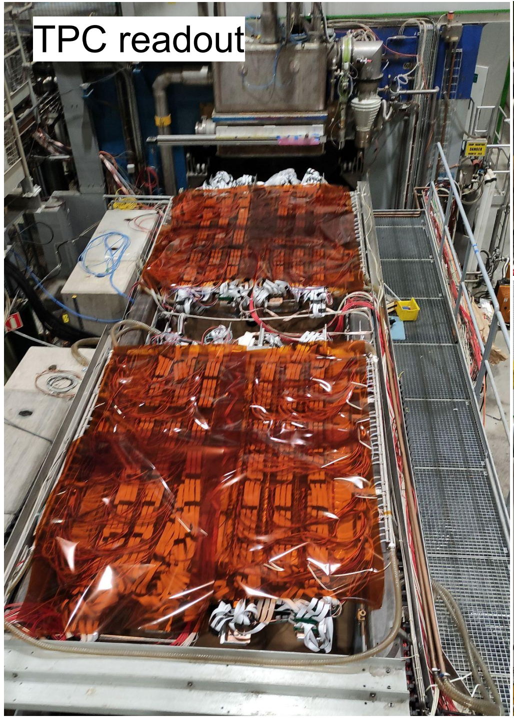


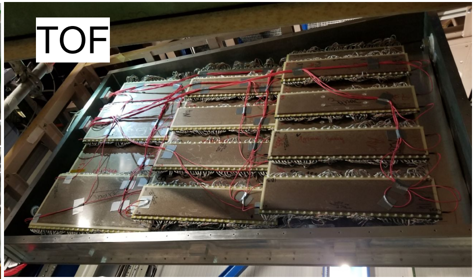
- Foreseen NA61/SHINE resolution is sufficient to answer addressed questions

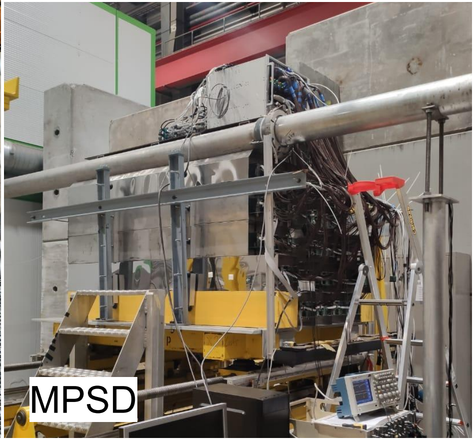
Detector upgrade during LS2



Current upgrade status







Plans for 2021 beamtime

(October - November):

- Finish installation of the detector
- Commissioning & tests

Conclusions

- **Onset of deconfinement**
  - Sharp peak on K+/pi+ ratio for Pb+Pb, no “horn”-like structures in Ar+Sc
  - Plateau in the inverse slope parameter T of kaon m_T spectra - possible indication of onset of deconfinement
  - Entropy vs collision energy - systematic uncertainties too large to make conclusion
- **Probing EoS properties:**
  - Collective flow in Pb+Pb @ 13*A* GeV/*c*:
    - v_1: strong mass dependence; $v_1(p_T)$ of negative pions changes sign
    - v_2: strong mass dependence, weak energy dependence
    - Differential measurements and comparisons with models are needed (ongoing)
  - EM effects: pion distribution is altered by collision spectators in Ar+Sc @ 40*A* GeV/*c*
  - Velocity of sound: results need to be extended to lower energies for conclusion about a possible minimum (EoS softening)
- **Onset of fireball:** Profound difference between small and big colliding systems in K+/pi+ ratio & inverse slope parameter
- **Search for critical point**
  - Fluctuations: no indication of CP, extension to heavier systems is needed
  - HBT in Be+Be @ 150*A* GeV/*c*: no indication of CP - extension to heavy systems is needed (stay tuned)
  - Intermittency in Pb+Pb @ 30A GeV/c & Ar+Sc @ 150A GeV/c: no indication of CP

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BACKUP