FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

SHINE

Search for critical effects in NA61/SHINE

Magdalena Kuich
for the NA61/SHINE collaboration

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In this presentation...

Introduction to the NA61/SHINE experiment

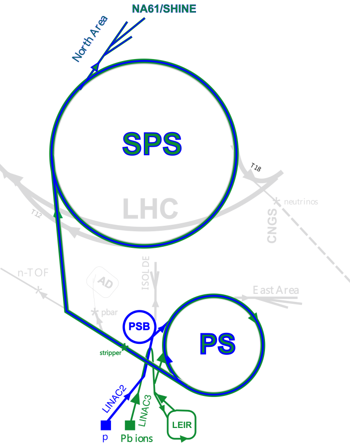
Onset of deconfinement
- **Study of the onset of deconfinement in single particle spectra**
- **Study of the onset of deconfinement in directed flow observation**

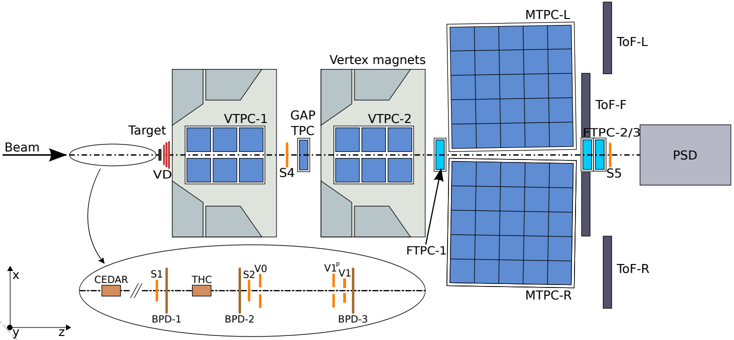
Onset of fireball
- **Observation of the onset of fireball in particle production properties**

Search for critical point
- **Search for critical point in particle production properties**

Summary and outlook

NA61/SHINE – fixed target experiment at the CERN SPS



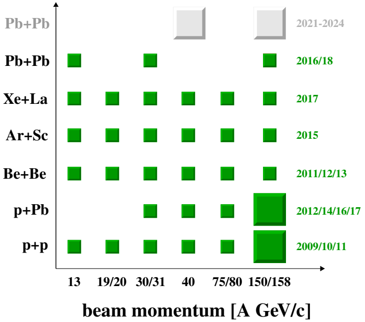


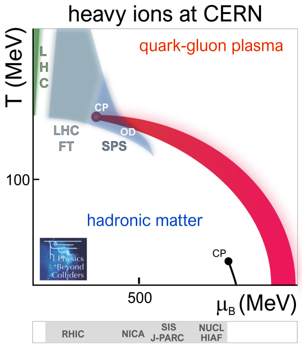
- **Ion** and **hadron** beams, $p_{\text{beam}} = 13A - 150A$ GeV/c (400 GeV/c)
- Full coverage of the forward hemisphere, down to $p_{\text{T}} = 0$
- **Centrality** selection based on **forward energy** measured in PSD

JINST **9** P06005

2D phase-space scan by NA61/SHINE

NA61/SHINE experiment performs 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter in **baryon density and temperature**





Main goals:

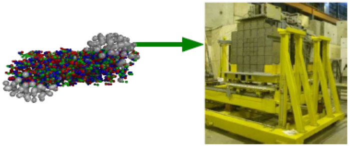
- study of threshold behaviour in HRG-QGP transition:
  →**onset of deconfinement**
  →**onset of fireball**
- search for the **critical point**

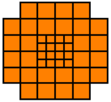
Methodology

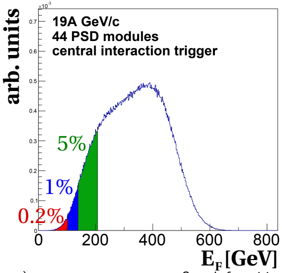
Event selection based on forward energy measurements

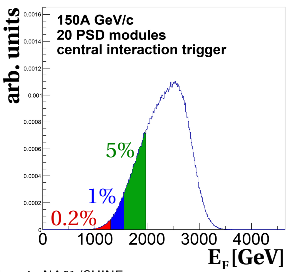
- **Event (centrality) selection** in nucleus-nucleus collisions is done using the measured **forward energy** (E_F) dominated by energy of projectile spectators.
- It **does not bias fluctuation studies** and it is one of the best ways to restrict event-by-event volume fluctuations on the detector level
- Intervals in E_F allow to select different centrality classes
- Examples of event selection using E_F for Ar+Sc:

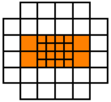
PSD



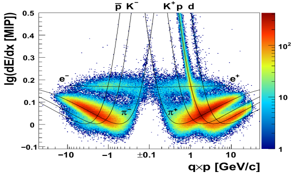


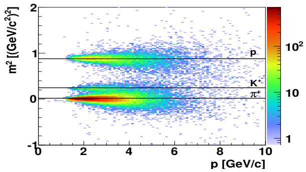


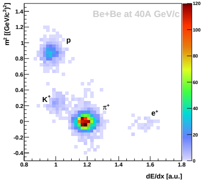




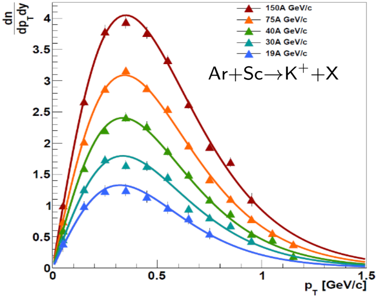
Charged particle identification and spectra

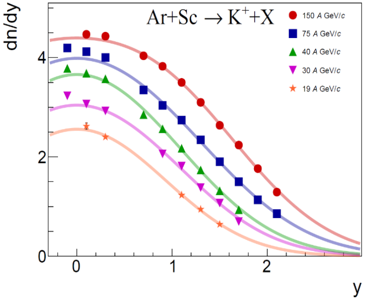






Measured dn/dy yields (≈ 99%) are extrapolated beyond the analysis acceptance





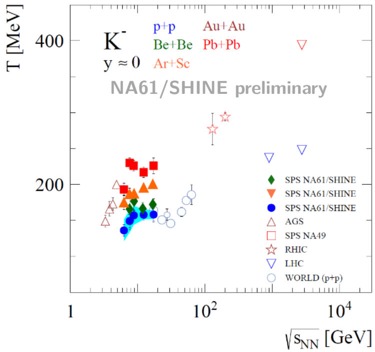
$$\frac{d^2n}{dp_T\,dy} = \frac{Sp_T}{T^2+Tm_K} exp\left(-\frac{\sqrt{p_T^2+m_K^2}}{T}\right)$$

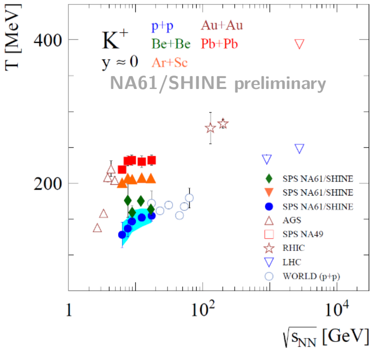
$$\frac{dn}{dy} = \frac{A}{\sigma_0\sqrt{2\pi}} exp\left(-\frac{(y-y_0)^2}{2\sigma_0^2}\right) + \frac{A}{\sigma_0\sqrt{2\pi}} exp\left(-\frac{(y+y_0)^2}{2\sigma_0^2}\right)$$

Study of the onset of deconfinement in single particle spectra

Onset of deconfinement: STEP

Plateau – **STEP** – in the energy dependence of the inverse slope parameter T of m_T spectra in Pb+Pb collisions observed at SPS energies. This is expected for the onset of deconfinement due to mixed phase of HRG and QGP (**S**tatistical **M**odel of the **E**arly **S**tage).





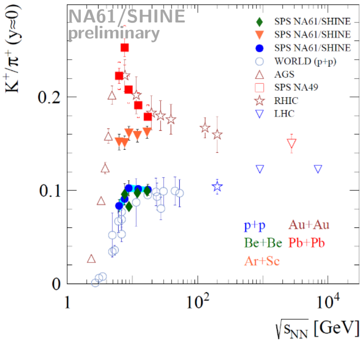
Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions

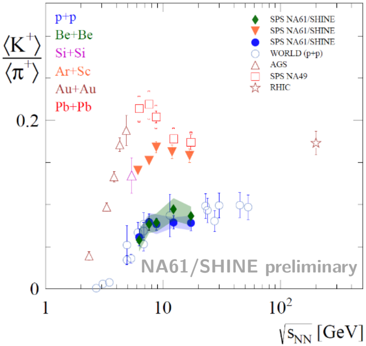
Magnitude of T in Be+Be slightly higher than in p+p

Ar+Sc results between p+p/Be+Be and Pb+Pb results

Onset of deconfinement: HORN

Rapid changes in the energy dependence of the K^+/π^+ ratio – **HORN** – were observed in Pb+Pb collisions at SPS energies. This was predicted (SMES) as a signature of onset of deconfinement.



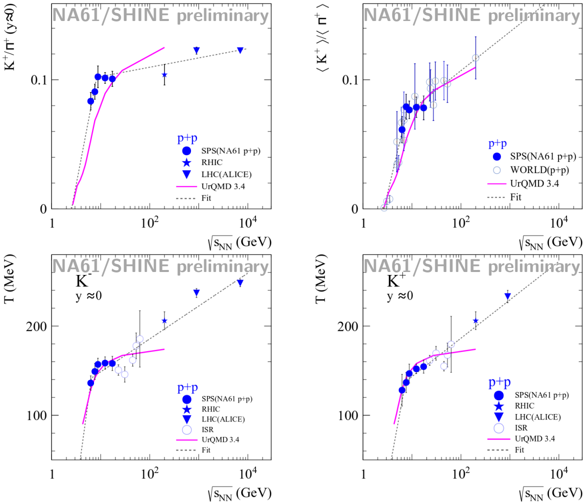


Plateau like structure visible in p+p

Be+Be close to p+p

Ar+Sc is higher than p+p but the energy dependence is similar to p+p (no horn)

Onset of deconfinement: p+p results



Eur. Phys. J. C77, 671 (2017)

Rates of increase with energy of the K^+/π^+ ratio and T change sharply in results from p+p interactions at SPS energies.

The fitted change energy is ≈7 GeV – close to the energy of the onset of deconfinement ≈ 8 GeV.

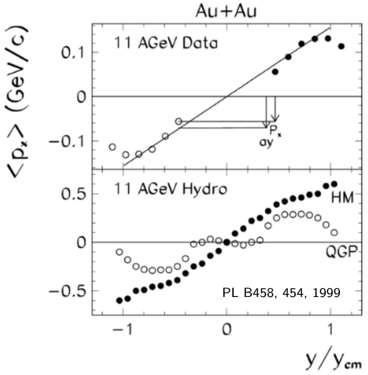
Resonance-string model (UrQMD) fails to reproduce data

Study of the onset of deconfinement in directed flow observation

Directed flow and the onset of deconfinement

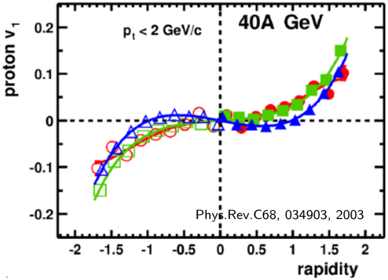
Directed flow v_1 is considered to be **sensitive to 1^{st} order phase transition** (softening of EOS).
Expected: **non-monotonic behavior** (positive→negative→positive) **of proton dv_1/dy as a function of beam energy** - "collapse of proton flow"

Predictions of hydrodynamical model:



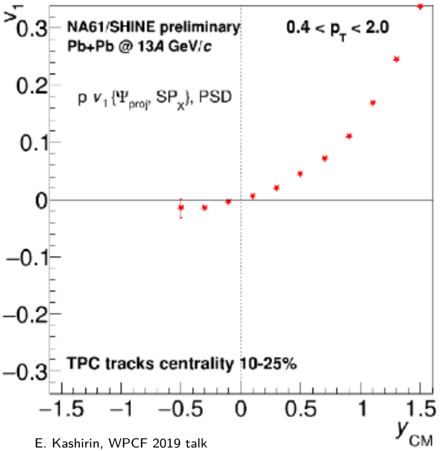
Directed flow measured by NA49
at middle SPS energy
("anti-flow" of protons at mid-rapidity):

Central mid-central peripheral



$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

Directed flow as a function of rapidity



E. Kashirin, WPCF 2019 talk

Flow coefficients are measured relative to the spectator plane estimated with Projectile Spectator Detector (PSD) → unique for NA61/SHINE

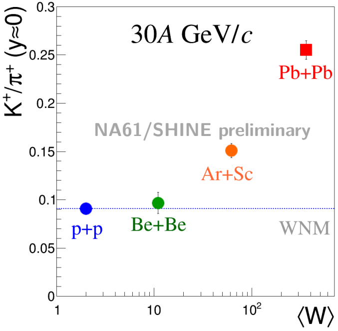
No evidence for the collapse of proton directed flow in semi-central Pb+Pb collisions at 13*A* GeV/*c*

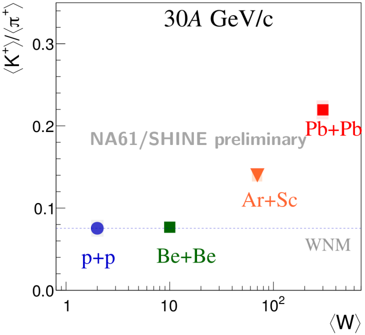
Results from Pb+Pb collisions at 30*A* and 150*A* GeV/*c* soon!

Observation of the onset of fireball in particle production properties

Onset of fireball: system size dependence of particle spectra

Rapid enhancement of the K^+/π^+ ratio with the system size was predicted due to formation of the droplet of strongly interacting matter (SMES).





Experimental results suggest:

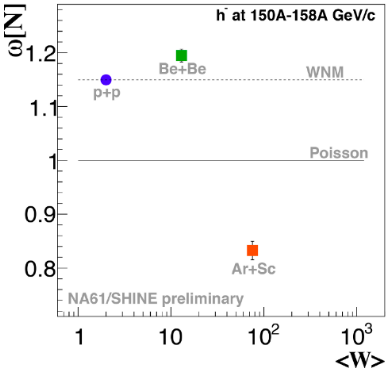
- **p+p ≈ Be+Be**
- **visible change between light and intermediate or heavy systems**
- effect manifests in mid-rapidity and full acceptance

Onset of fireball: system size dependence in particle multiplicity fluctuations

Scaled variance defined as:

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

is significantly larger for p+p interactions and central Be+Be collisions than for central Ar+Sc collisions and suggest non-negligible change between light and intermediate systems.



p+p data are corrected for experimental biases, systematic uncertainty ∼0.1 [EPJ.C76:635]; 0-1% Be+Be data is uncorrected, experimental bias is ∼10-15%; 0-0.2% Ar+Sc data is uncorrected, experimental bias is ∼5-7%

Search for critical point in particle production properties

Search for critical point in strongly intensive measures: event-by-event fluctuations

Intensive quantities: a ratio of two extensive quantities ($\sim$ volume) is an intensive quantity e.g.:

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

where A stands for an extensive event quantity.

- independent of V
- depends on fluctuations of V
- $\omega = 1$ for Poisson distribution

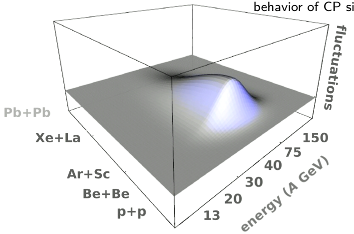
In statistical model (IB-GCE) $\omega_i = \frac{Var(a)}{\langle a\rangle} + \langle a\rangle \frac{Var(V)}{\langle V\rangle}$, where a - particles produced in a system with fixed V

Strongly intensive quantities: special combination of extensive quantities, e.g.:

$$\Sigma[A,B] = \frac{1}{C_\Sigma}\left[\langle B\rangle\omega_A + \langle A\rangle\omega_B - 2\Big(\langle AB\rangle - \langle A\rangle\langle B\rangle\Big)\right]$$

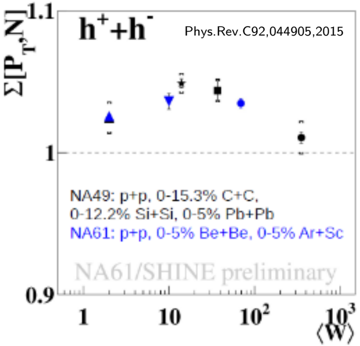
- independent of V and fluctuations of V
- normalization chosen such that $\Sigma[A,B] = 1$ for independent particle model and quantity is dimensionless
- $\Sigma[A,B] = 0$ in the absence of fluctuations
- note: Σ can be sensitive to several physics effects in different ways

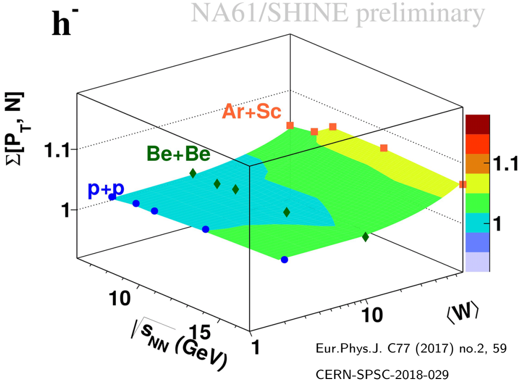
Expected: non-monotonic behavior of CP signatures



Critical point: strongly intensive measures $\Sigma[P_T, N]$

Comparison to NA49 A+A at 158A GeV/c
within NA49 two different acceptances





System size dependence of $\Sigma[P_T, N]$ at 150/158A GeV/c: **NA49 and NA61/SHINE points show consistent trends**

So far there are no prominent structures which could be related to critical point

Critical point: proton intermittency as signal of CP

Critical point as 2^{nd} order phase transition → scale invariance → characteristic dependence of fluctuations on size δ of subdivision intervals of momentum space Δ (power-law form of correlation function for large distances/small momentum transfer)

- **Net protons** used as proxy for **net baryons** (same critical fluctuations)
- Transverse momentum space is partitioned into M^2 cells, $M^2 = (\Delta/\delta)^2$
- Second factorial moments $F_2(M)$ as a function of cell size are defined:

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

$$\Delta F_2(M) \equiv F_2^{data}(M) - F_2^{mixed}(M)$$

(background subtraction)

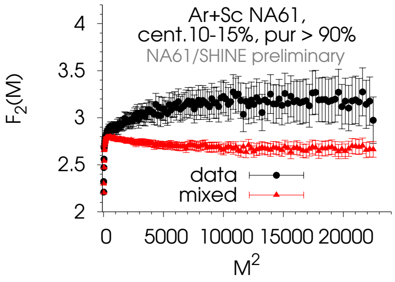
At critical point power law dependence is expected:

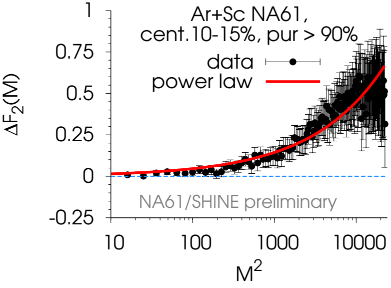
$$\Delta F_2(M) \sim (M^2)^{\varphi_2}$$

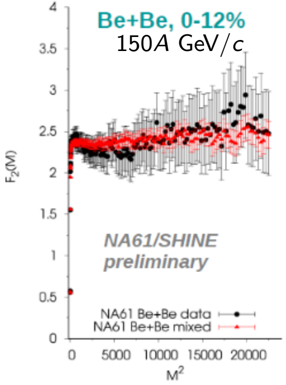
prediction for intermittency index for critical point: $\varphi_2 = 5/6$

Phys. Rev. Lett. 97, 032002 (2006)

Critical point: proton intermittency in Ar+Sc and Be+Be







$F_2(M^2)$ moments are higher in data than in mixed events in

Ar+Sc collisions @ 150*A* GeV/*c*.

Possible hint of the intermittency effect???

(detailed investigation of significance of this result – in progress)

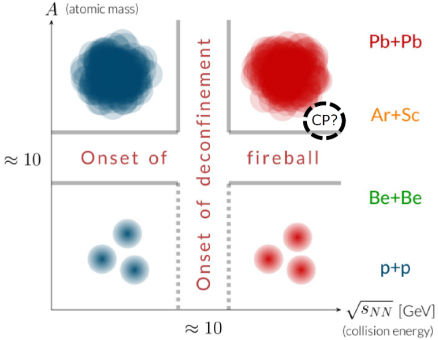
No signal visible in Be+Be

NA61/SHINE: PoS(CPOD2017) 054

Summary and outlook

Summary

- 2D scan in system size and collision energy was completed in 2017 with Xe+La data
- Analysis ongoing for p+p, Be+Be, Ar+Sc, Xe+La and Pb+Pb data
- No horn in Ar+Sc
- Unexpected system size dependence: (p+p $\approx$ Be+Be) $\neq$ (Ar+Sc $\neq$ Pb+Pb)
- No convincing indication of CP, proton intermittency signal in Ar+Sc is under scrutiny
- Plans to extend NA61/SHINE program with measurements of open charm production in 2021-2024



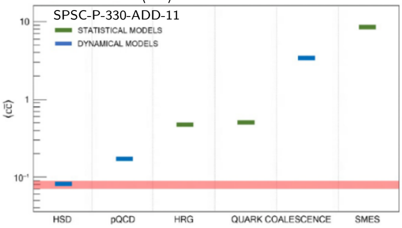
NA61/SHINE programme for 2021-2024

Open questions:

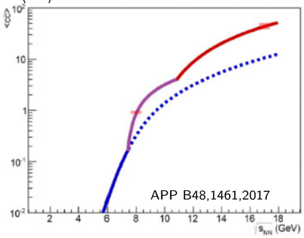
- **What is the mechanism of $\langle c\overline{c}\rangle$ production?**
- **How does the onset of deconfinement impact $\langle c\overline{c}\rangle$ production?**
- **How does the formation of quark gluon plasma impact $\langle J/\Psi\rangle$ production?**

To answer these questions **mean number of charm quark pairs**, $\langle c\overline{c}\rangle$, produced in A+A collisions has to be known. Up to now corresponding **experimental data does not exist** and **only NA61/SHINE can perform this measurement in the near future**.

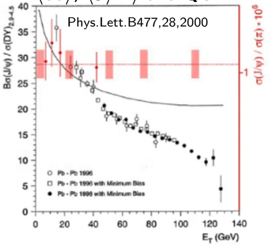
$\langle c\overline{c}\rangle$ and models



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



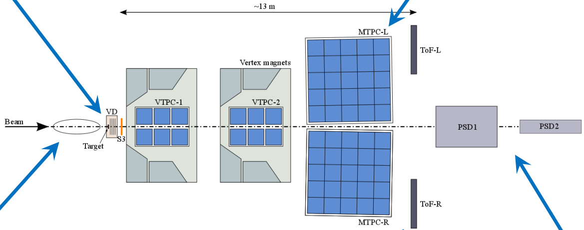
$\langle c\overline{c}\rangle$, $\langle J/\Psi\rangle$ and QGP



Detector upgrade during LS2

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

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



New trigger and data acquisition system

New Time-of-Flight detectors

Upgrade of Projectile Spectator Detector

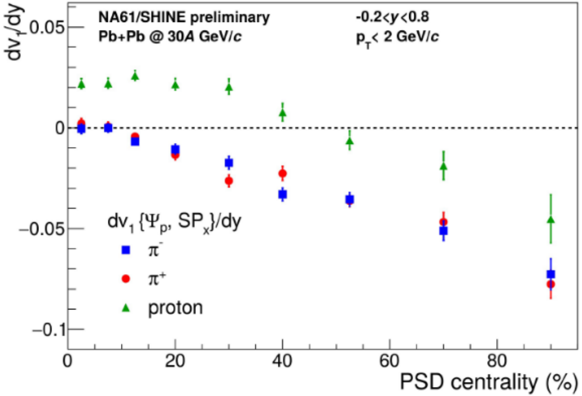
Stay tuned!

More results from the NA61/SHINE soon

Additional slides

Directed flow as a function of centrality

NA61/SHINE fixed target setup → tracking and particle identification over wide rapidity range



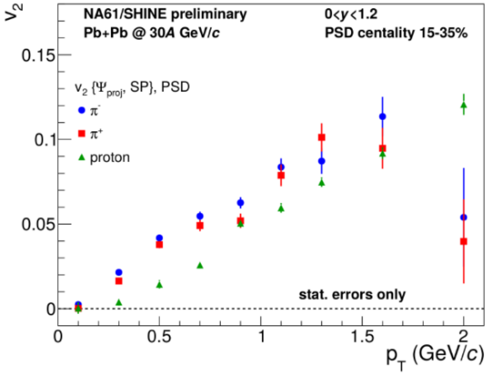
Nucl.Phys.A982, 439,2019

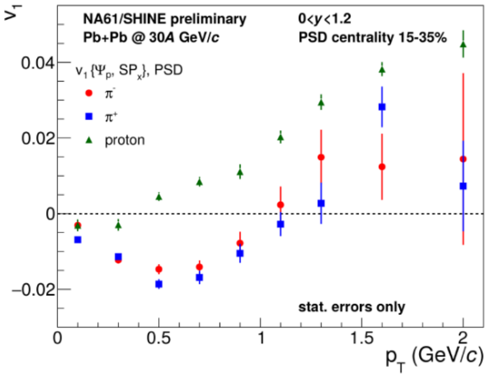
Flow coefficients are measured relative to the **spectator plane estimated with Projectile Spectator Detector** (PSD) → unique for NA61/SHINE

Close to mid-rapidity (-0.2<y<0.8):

- **slope of pion v_1 is always negative**
- **slope of proton v_1 changes sign at centrality of about 50%**

Particle type dependence of elliptic and directed flow



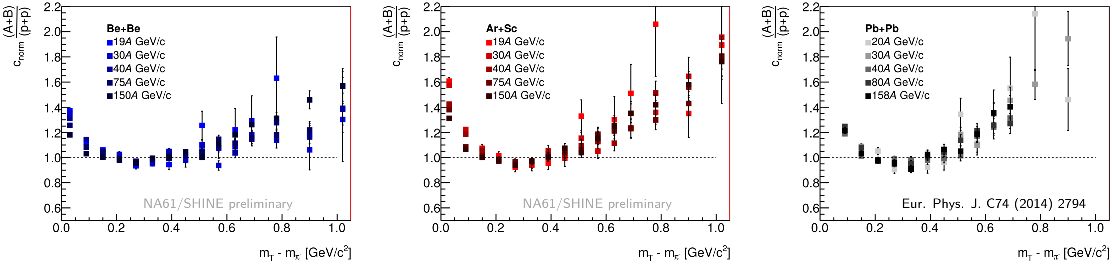


Clear mass hierarchy of v_2 - radial flow
Difference between v_2 for π^+ and π^- is small

Significant mass dependence of v_1
Difference between v_2 for π^+ and π^- is sensitive to electromagnetic effects

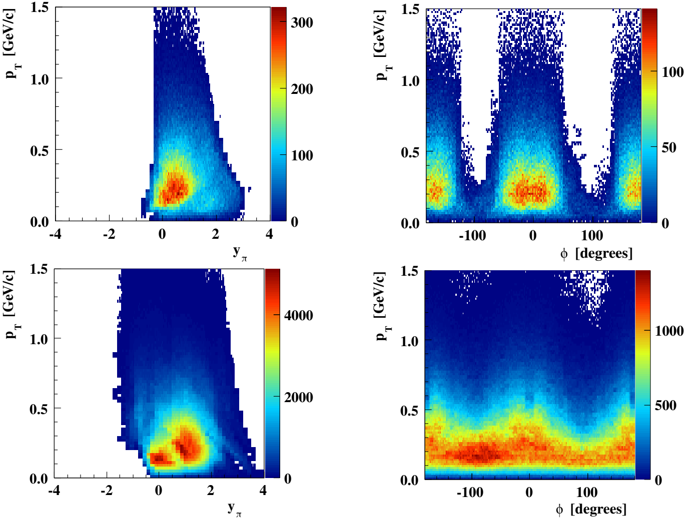
A. Rybicki and A. Szczurek, Phys. Rev. C87, 054909 (2013)

Energy and system size dependence of the m_T spectra of π^-



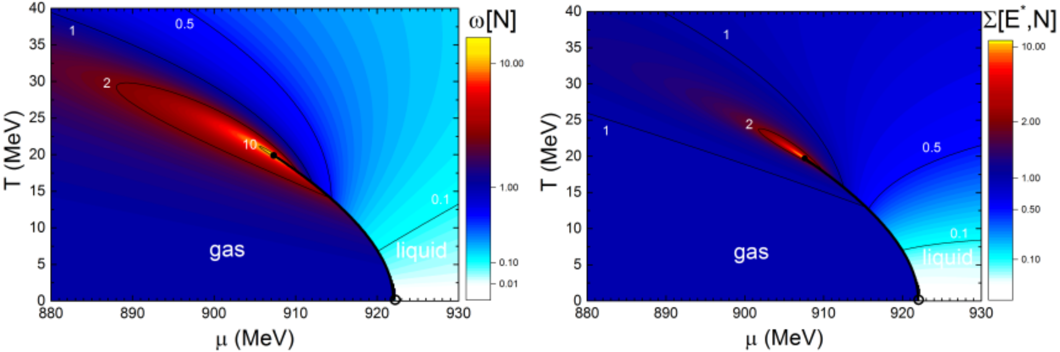
- m_T spectra shape differs significantly between p+p and A+A results
- clear system size dependence with small energy dependence
- the effect possibly associated to transverse collective flow

Example of acceptance maps



- TOP ROW $\rightarrow$ acceptance map example for $p_{beam} = 19A$ GeV$/c$
- BOTTOM ROW $\rightarrow$ acceptance map example for $p_{beam} = 150A$ GeV$/c$
- acceptance studied with MC simulation
- only region with registration efficiency $\geq 99\%$ selected for fluctuation analysis

Event-by-event fluctuations – model predictions

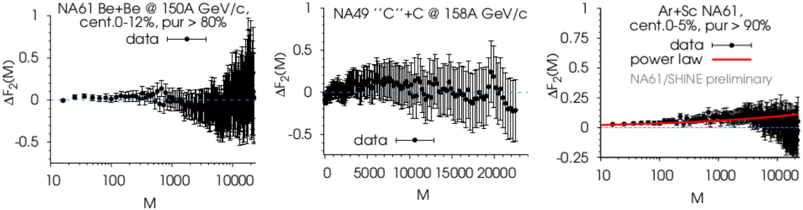


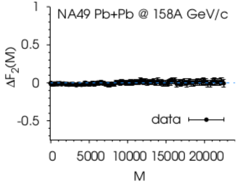
Vovchenko, Anchishkin, Gorenstein, Poberezhnyuk, Stoecker, Acta Phys.Polon.Supp. 10 (2017) 753

Fluctuations as a function of momentum bin size

Experimental results

ΔF_2 for mid-rapidity protons at 17 GeV





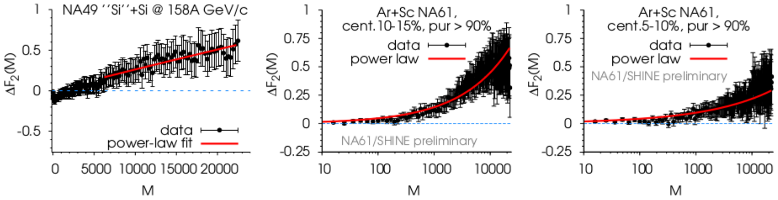
No signal visible in central Be+Be, C+C, Ar+Sc and Pb+Pb

NA49: EPJC 75 (2015) 587
NA61/SHINE: PoS(CPOD2017) 054

Fluctuations as a function of momentum bin size

Experimental results

ΔF_2 for mid-rapidity protons at 17 GeV



A deviation of ΔF_2 from zero seems apparent in central Si+Si and mid-central Ar+Sc

NA49: EPJC 75 (2015) 587
NA61/SHINE: PoS(CPOD2017) 054

Proton intermittency vs background