UNIVERSITY OF SILESIA
IN KATOWICE

NA61/SHINE at CERN

Szymon Puławski
for NA61/SHINE

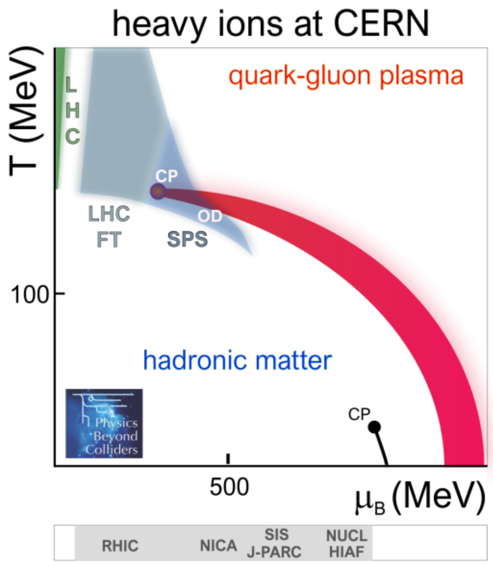
NA61/SHINE physics program

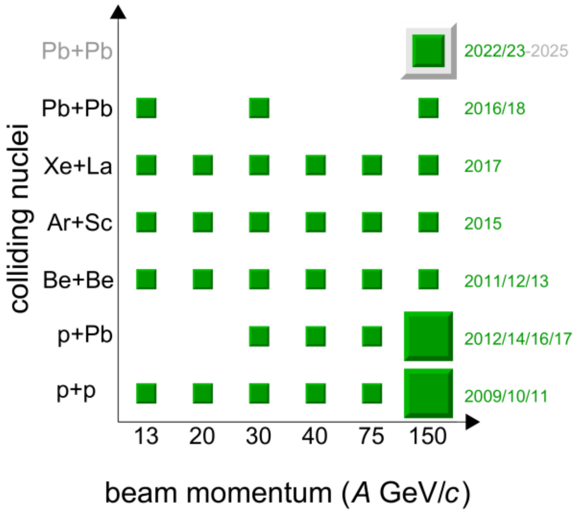
Strong interaction physics:

- study properties of the onset of deconfinement and onset of fireball
- search for the critical point of strongly interacting matter
- direct measurements of open charm

Neutrino and cosmic-ray physics:

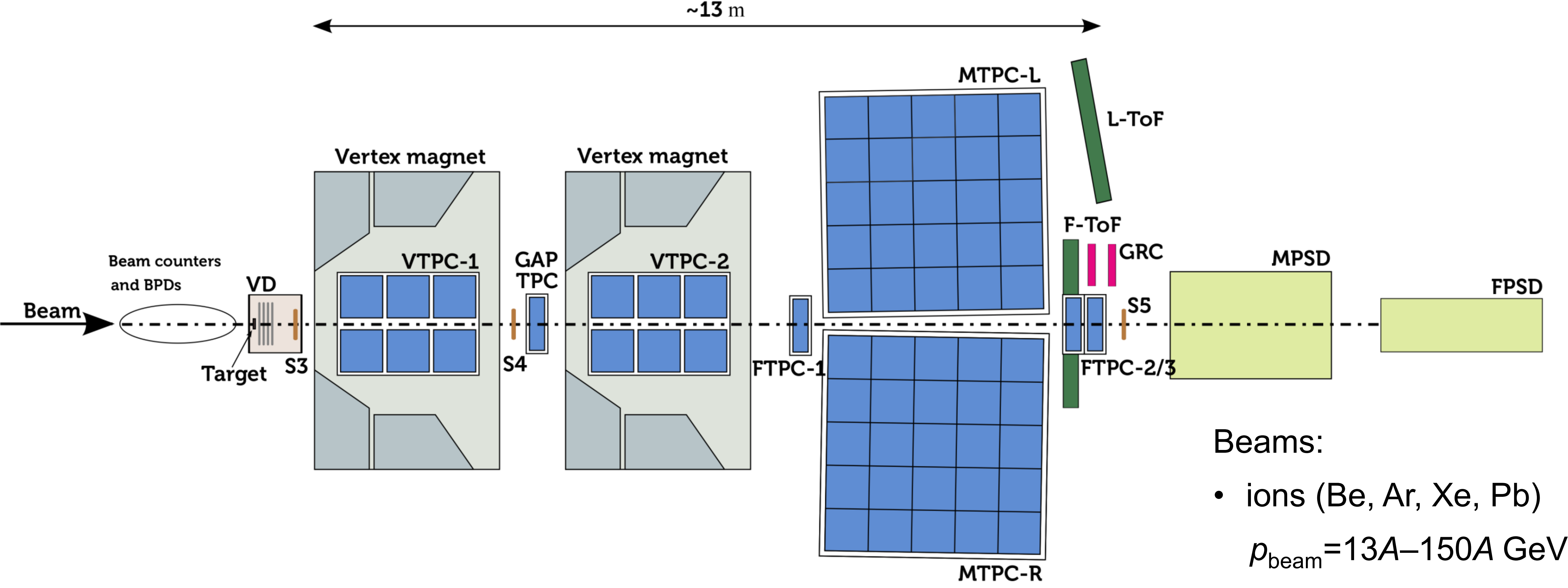
- measurements for neutrino programs at J-PARC and Fermilab
- measurements of hadron production and nuclear fragmentation cross section for cosmic-ray physics





NA61/SHINE detector

Fixed target experiment located at the CERN SPS accelerator



Beams:

- ions (Be, Ar, Xe, Pb)

  p_{beam}=13*A*–150*A* GeV/*c*

- hadrons (π, K, p)

  p_{beam}=13–400 GeV/*c*

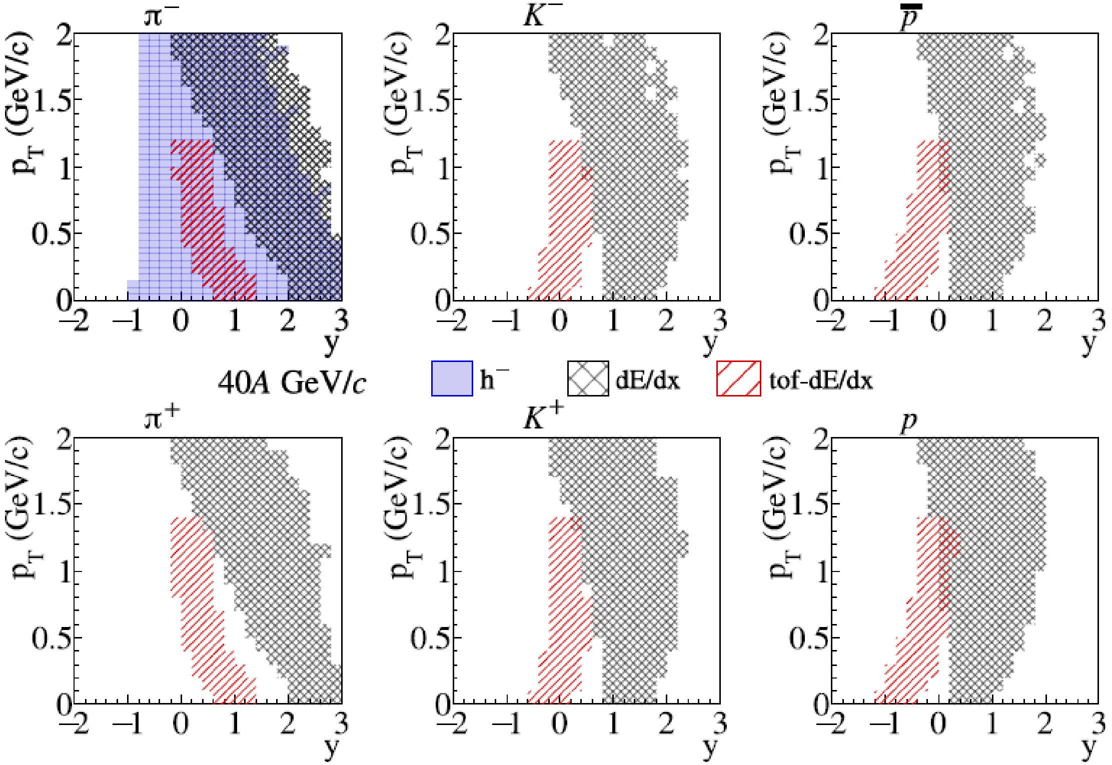
  $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

Large acceptance hadron spectrometer –
coverage of the full forward hemisphere, down to $p_T = 0$

Charged particle identification

Final results stand for primary particles produced in strong and electromagnetic processes, they are corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

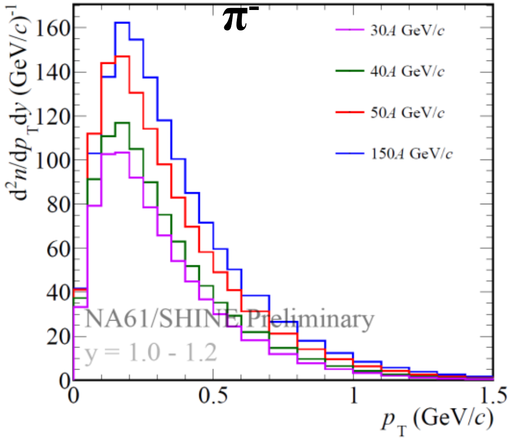
- **h^- analysis** based on the fact that the majority of negatively charged particles are π^- mesons. Contribution of the other particles is subtracted using EPOS Monte-Carlo
- **dE/dx** analysis uses TPC energy loss information to identify particles
- **tof-dE/dx** method estimates number of π, K, p using an energy loss and a particle time of flight measurements

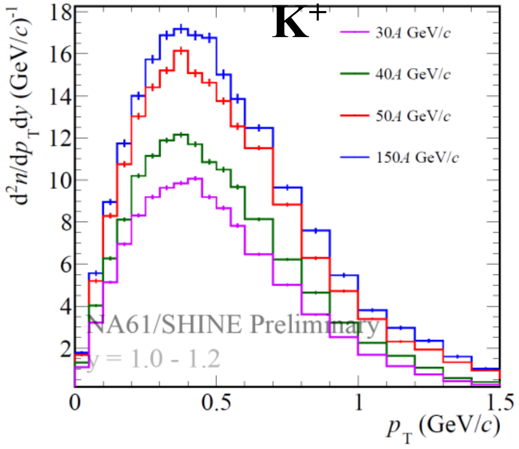


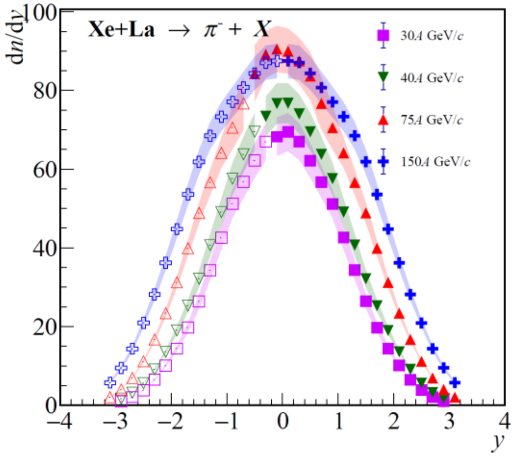
Onset of deconfinement

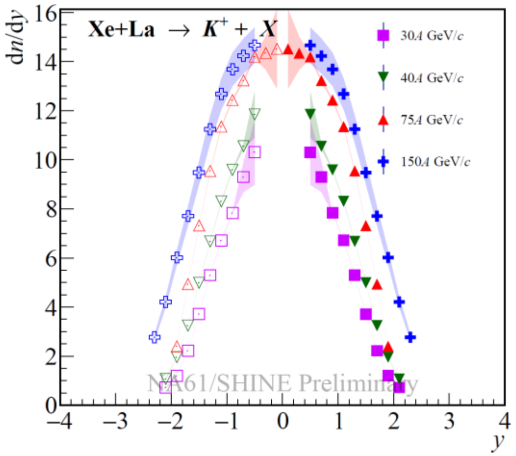
New particle spectra measurements

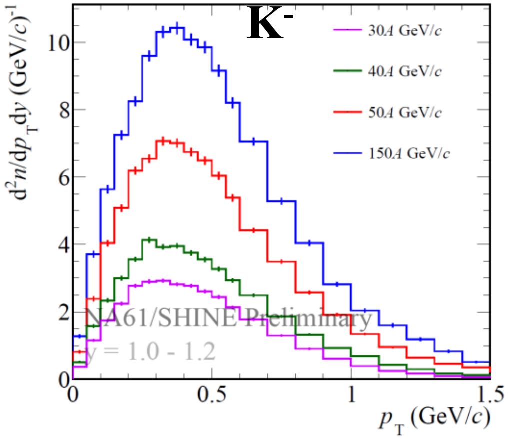
New, preliminary spectra of π^- and $K^\pm$ produced in the 10% most central Xe+La collisions at 30*A*, 40*A*, 75*A* GeV/*c* and in the 20% most central Xe+La collisions at 150*A* GeV/*c* obtained via dE/dx and h$^-$ methods

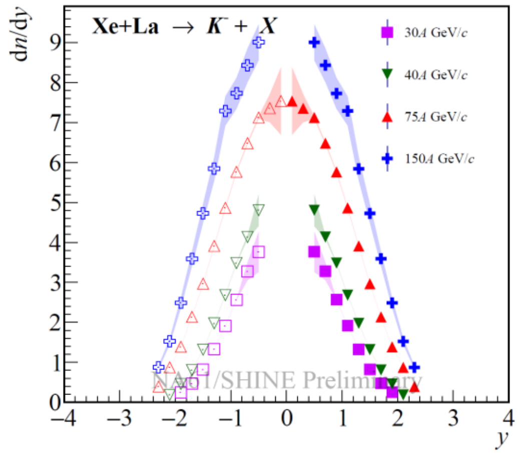






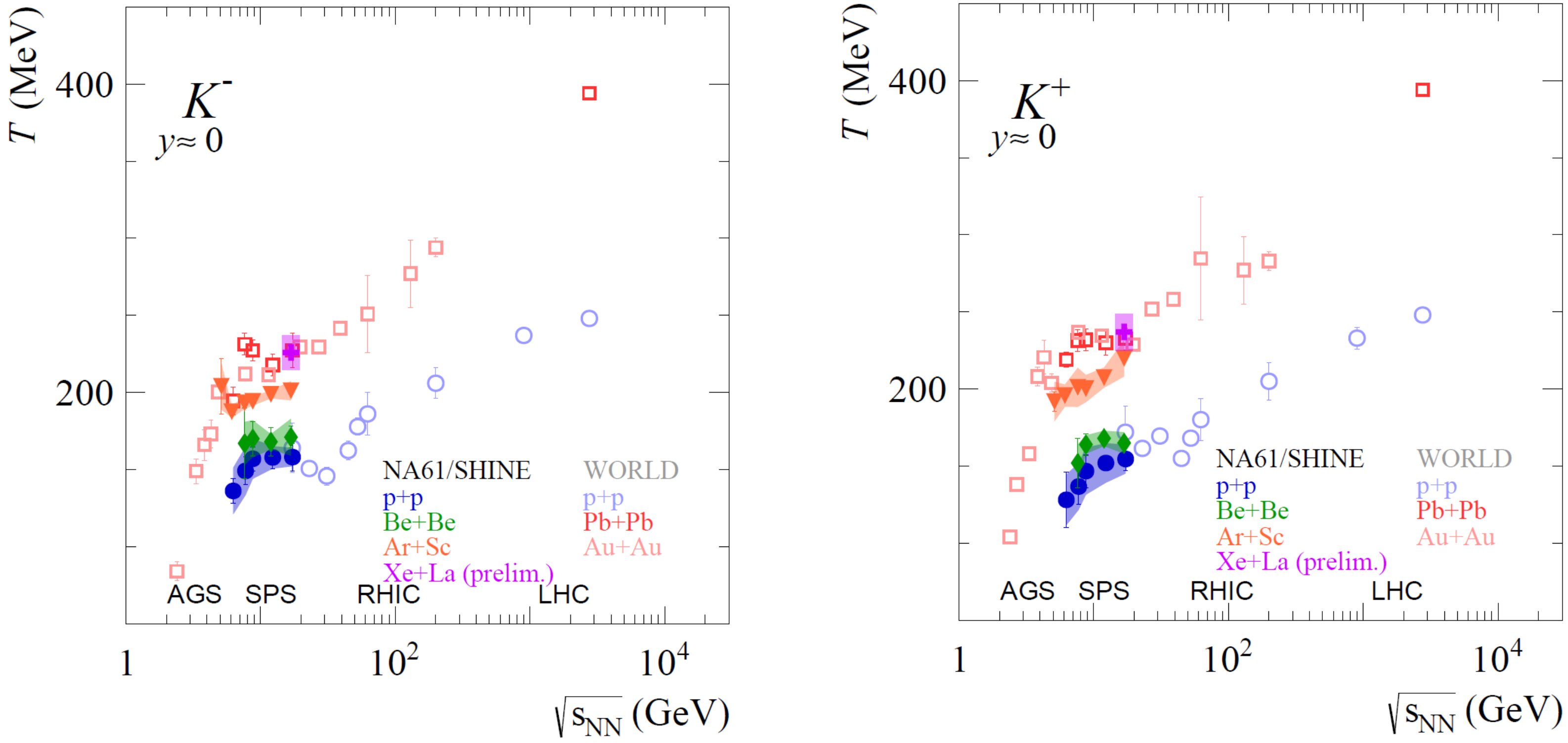






Onset of deconfinement: step

Qualitatively similar energy dependence is seen in p+p, Be+Be, Ar+Sc, and Pb+Pb. Magnitude of T increases with the system size



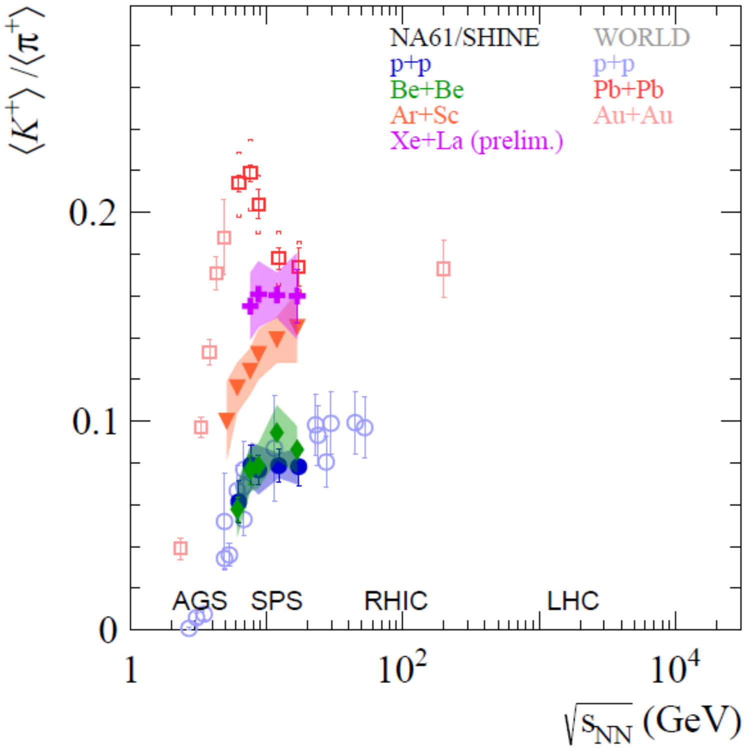
Kaons are only weakly affected by rescattering and resonance decays during the post-hydro phase (at SPS and RHIC energies)

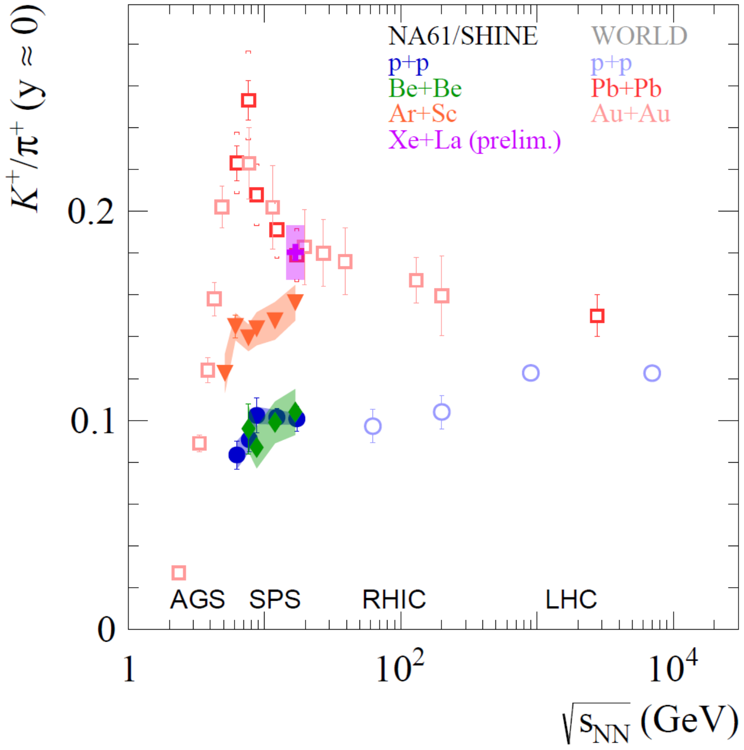
T reflects the thermal freeze-out temperature and the radial flow velocity

NA61/SHINE: Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

Onset of deconfinement: horn

Xe+La below Pb+Pb, while higher than Ar+Sc and Be+Be and p+p





Good measure of the strangeness to entropy ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons)

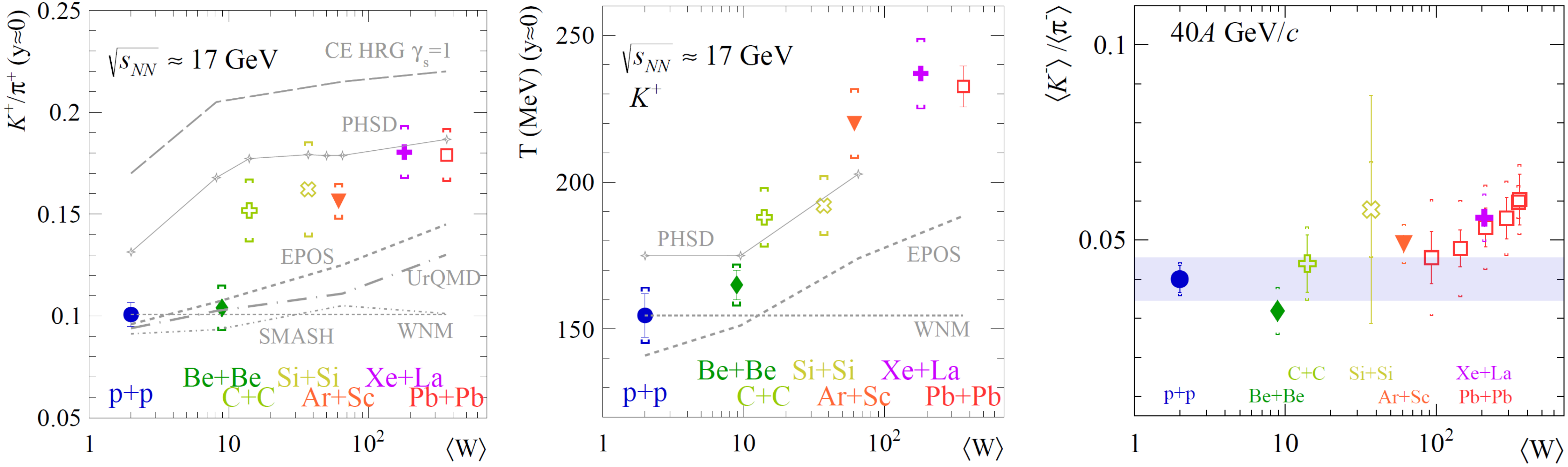
Probe of the onset of deconfinement

NA61/SHINE: Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

System size dependence

K/π and T vs the system size

(p+p ≈ Be+Be) ⩽ Ar+Sc ⩽ (Xe+La ≈ Pb+Pb)



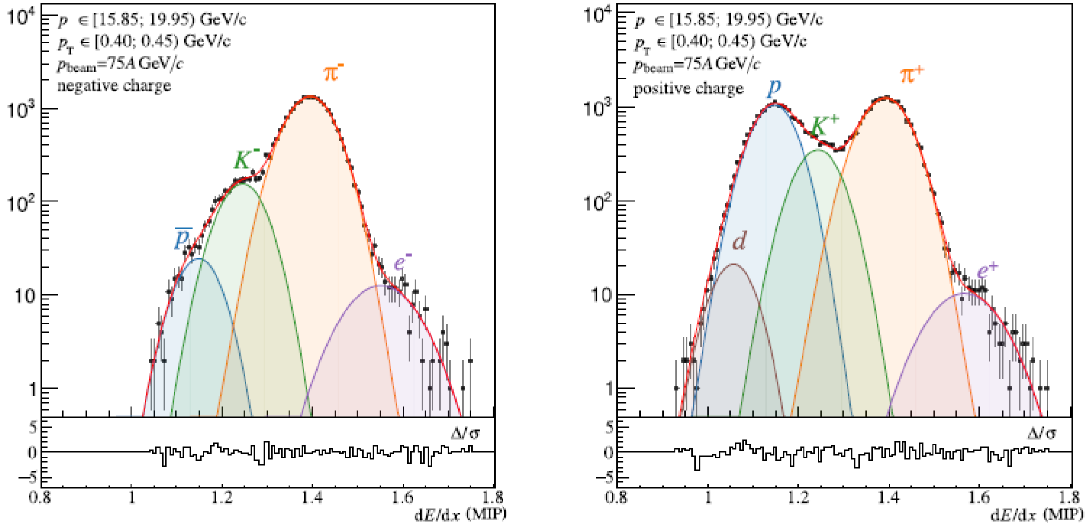
None of the models reproduces
K^+/π^+ratio and T for whole ⟨W⟩ range

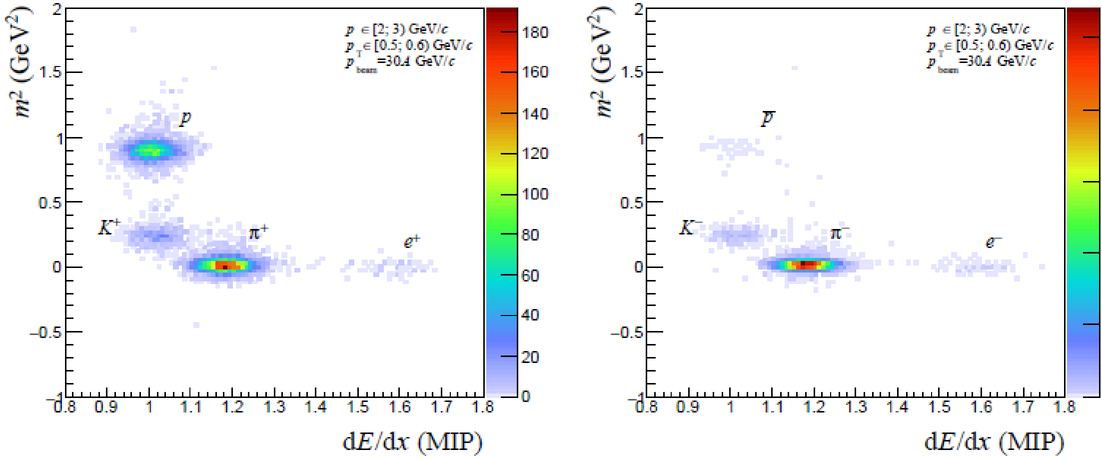
PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private communication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private communication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909;

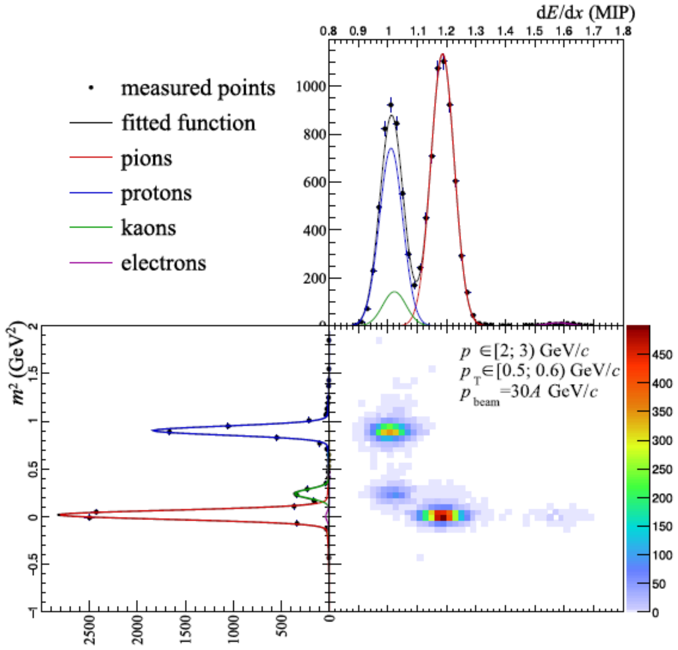
NA61/SHINE: Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

Anomaly in charged/neutral kaon production

Charged kaon measurments in Ar+Sc



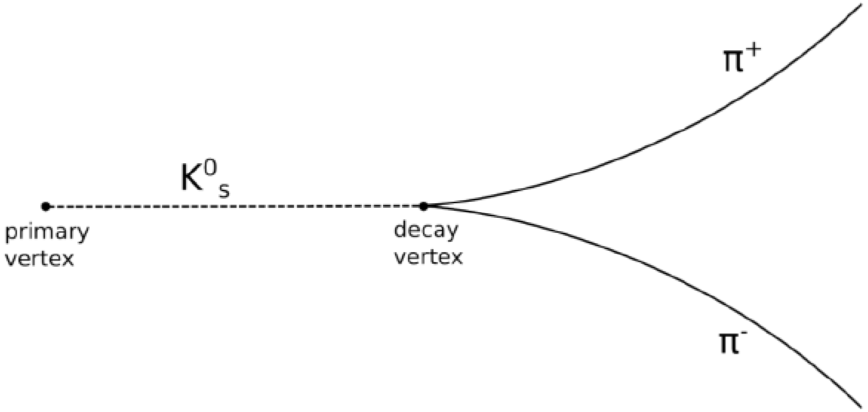


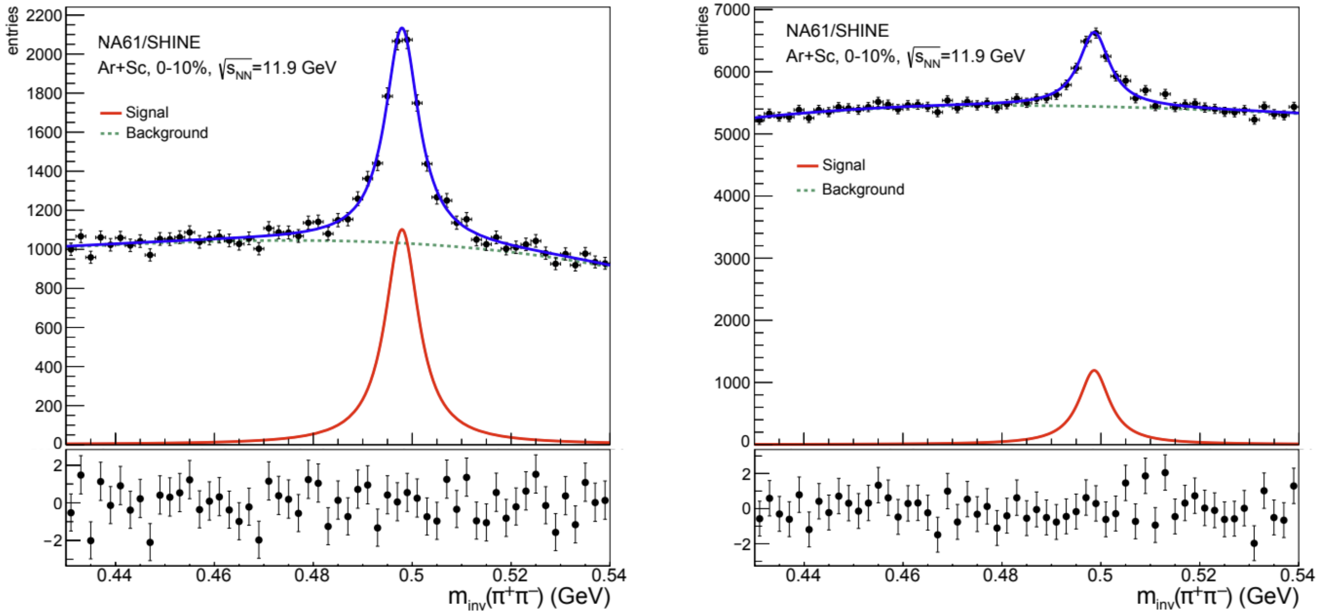


- Measurement based on **dE/dx** and **tof-dE/dx**
- Probability method
- Corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

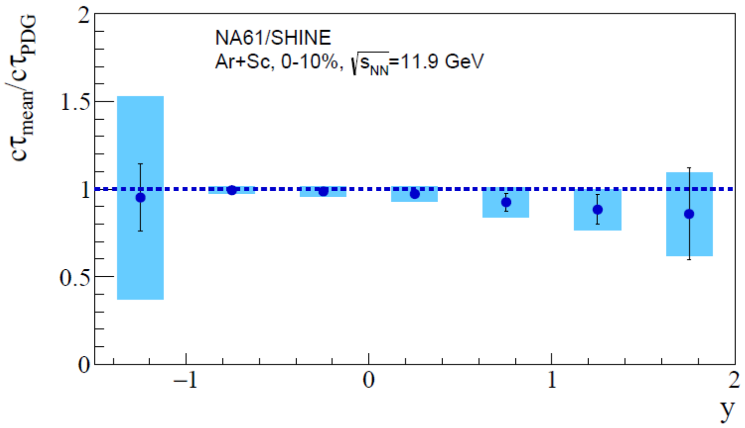
NA61/SHINE, Eur.Phys.J.C 84 (2024) 4, 416

K_s^0 production in Ar+Sc at 75*A* GeV/*c*



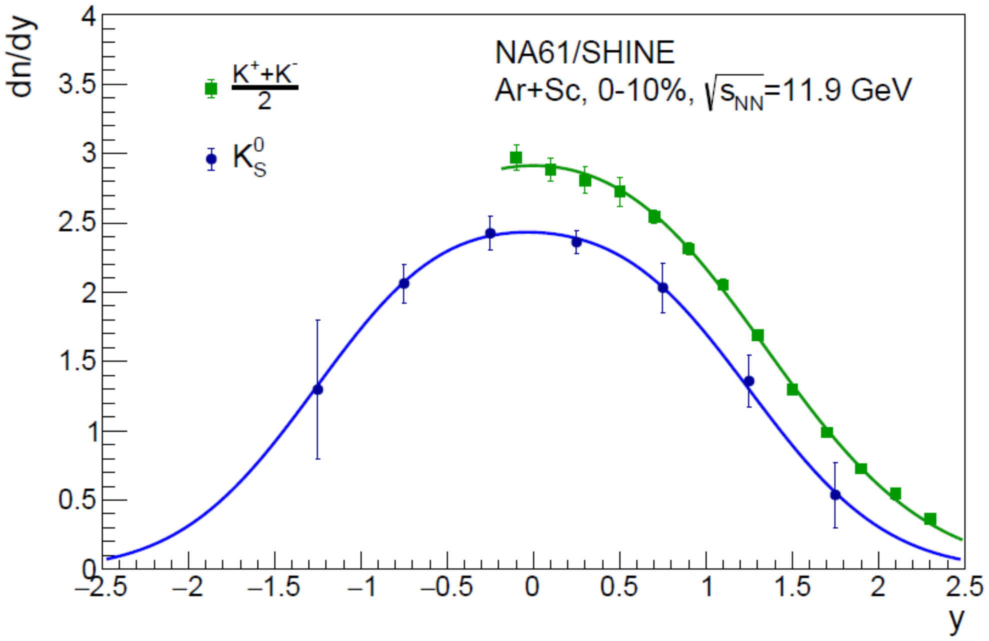


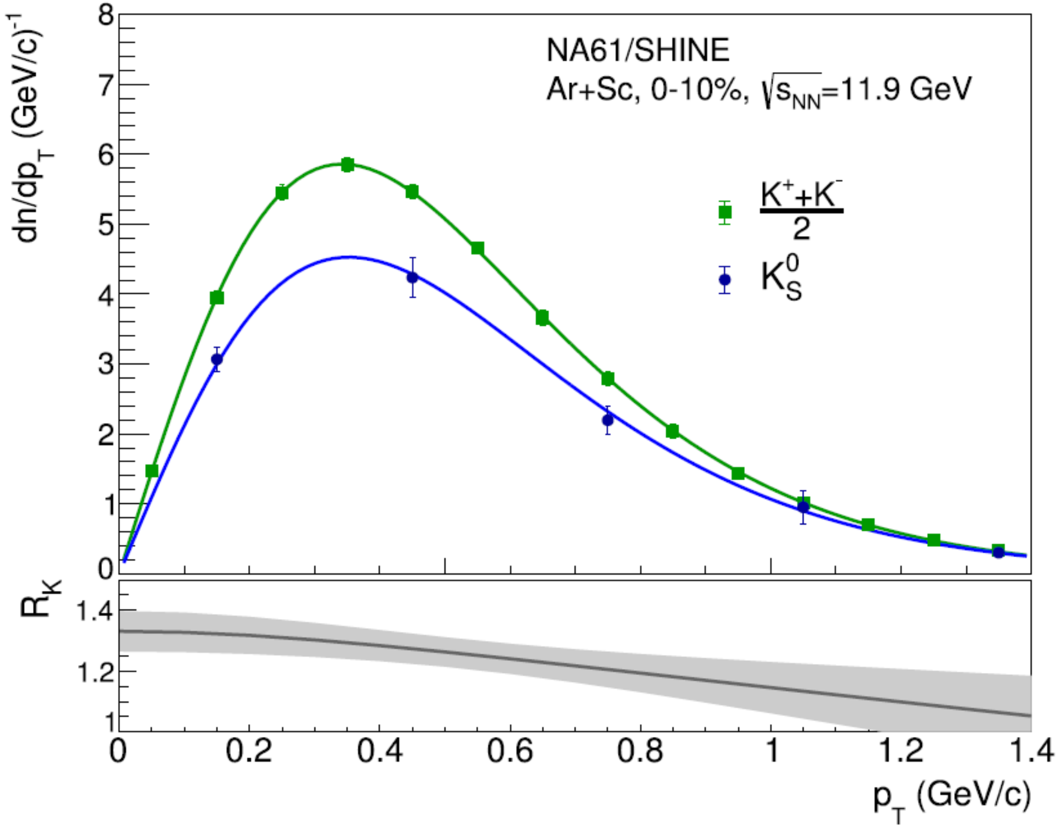
- Reconstruction based on decay topology
- K_s^0 decays into π+ and π− with BR≈69.2%
- Breit-Wigner function is used to describe the signal



NA61/SHINE, arxiv:2312.06572

K_s^0 production in Ar+Sc at 75A GeV/c

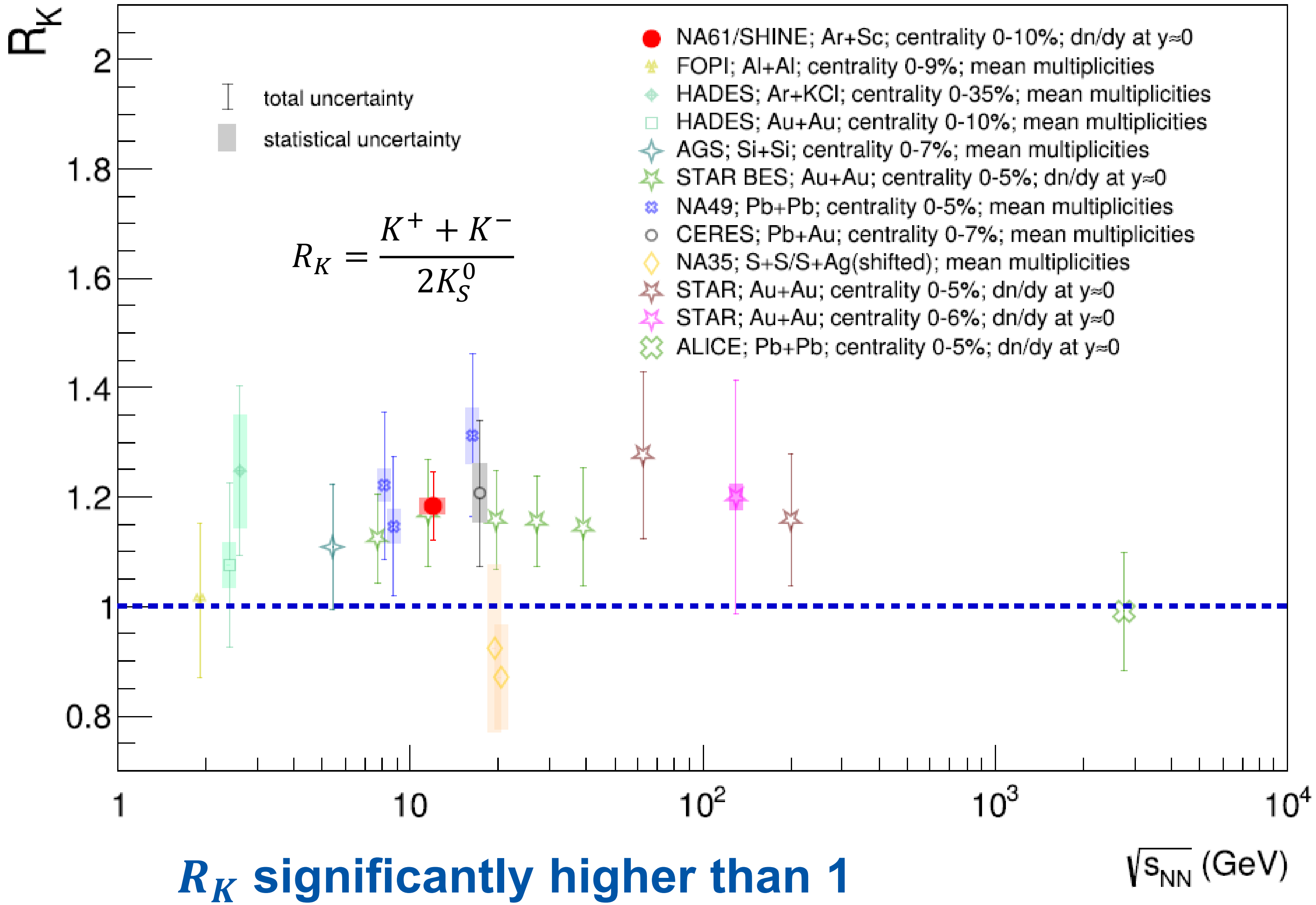




Excess of charged to neutral kaons in the whole rapidity and transverse momentum range

NA61/SHINE: arxiv:2312.06572; Eur.Phys.J.C 84 (2024) 4, 416

K_S^0 comparison with K$^+$ and K$^-$ - world data



R_K significantly higher than 1

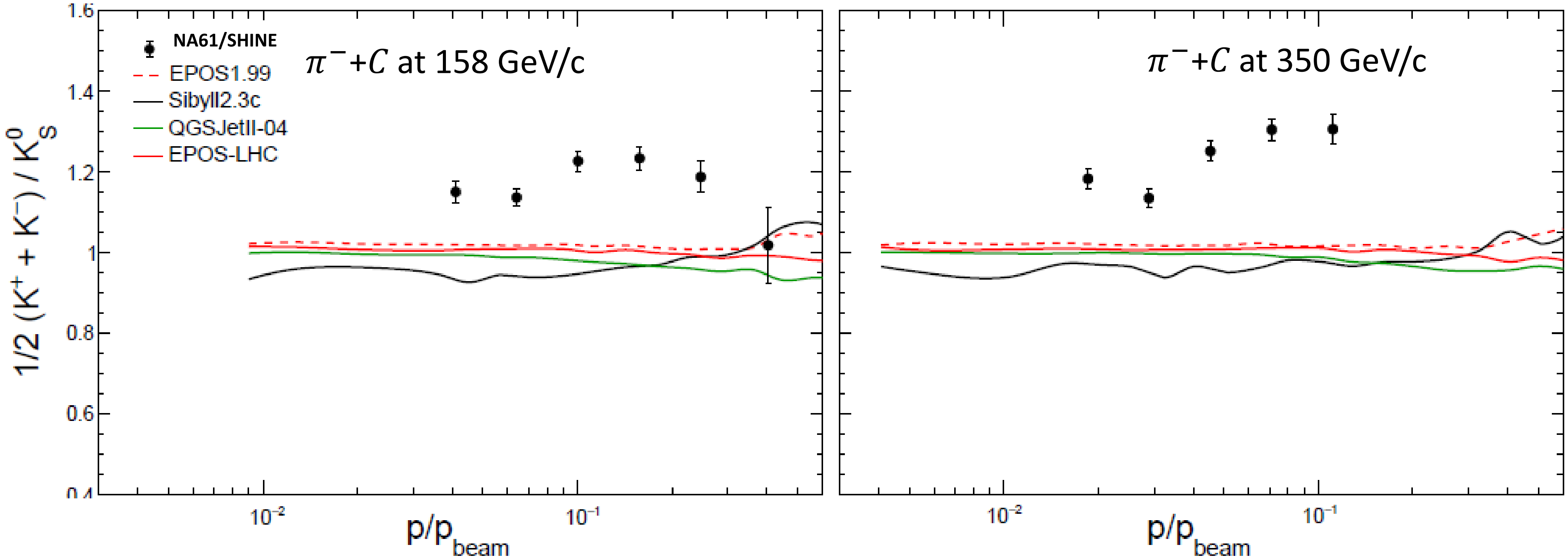
Unexpected excess of charged over neutral K meson production in central Ar+Sc collisions at 11.9 GeV center-of-mass energy per nucleon pair

Measured excess corresponds to about four additional K$^+$ or K$^-$ mesons produced per central Ar+Sc collision

For theoreticality see: Francesco Giacosa talk Tuesday at 3 pm

NA61/SHINE, arxiv:2312.06572

K_s^0 comparison with K$^+$ and K$^-$ - $\pi^- + C$ at 158 and 350 GeV/c

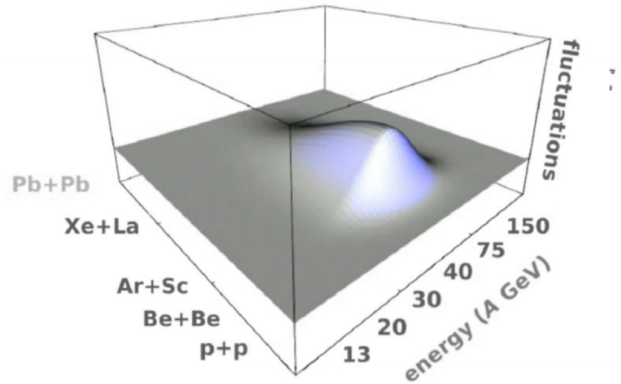


Models fail to describe ratio of charged to neutral kaons even for small asymmetric systems

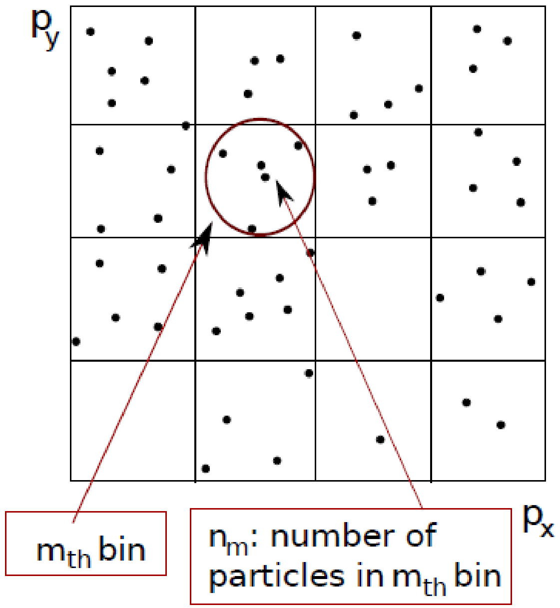
NA61/SHINE, Phys.Rev.D 107 (2023) 6, 062004

Search for critical point

Expected: non-monotonic behavior of CP signatures



Proton and charge hadron intermittency



$$F_r(M) = \frac{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m(n_m-1)\ldots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m \right\rangle^r},$$

where $\langle \ldots \rangle$ denotes averaging over events, M the number of cells

If the system freezes out near CP, its properties are expected to be different from those of an ideal gas. Such a system represents a simple fractal and $F_r(M)$ follows a power-law dependence

$$F_r(M) = F_r(\Delta) \cdot (M^D)^{\varphi_r}$$

For a pure system exhibiting critical fluctuations, $d = \varphi_2 = 5/6$ is expected for protons

NA61/SHINE used in intermittency analysis:

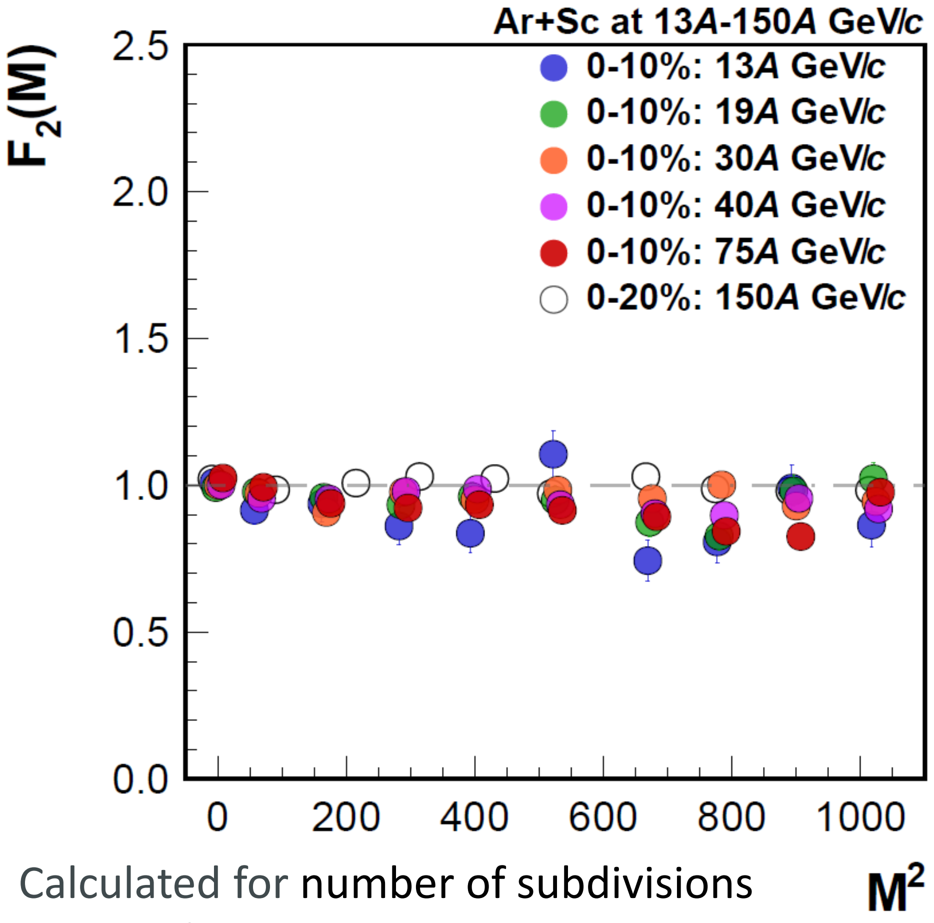
- Statistically independent points
- Cumulative variables

For details see: Tobiasz Czopowicz talk Tuesday at 4:20 pm and Valeria Reyna talk Tuesday at 4:40 pm

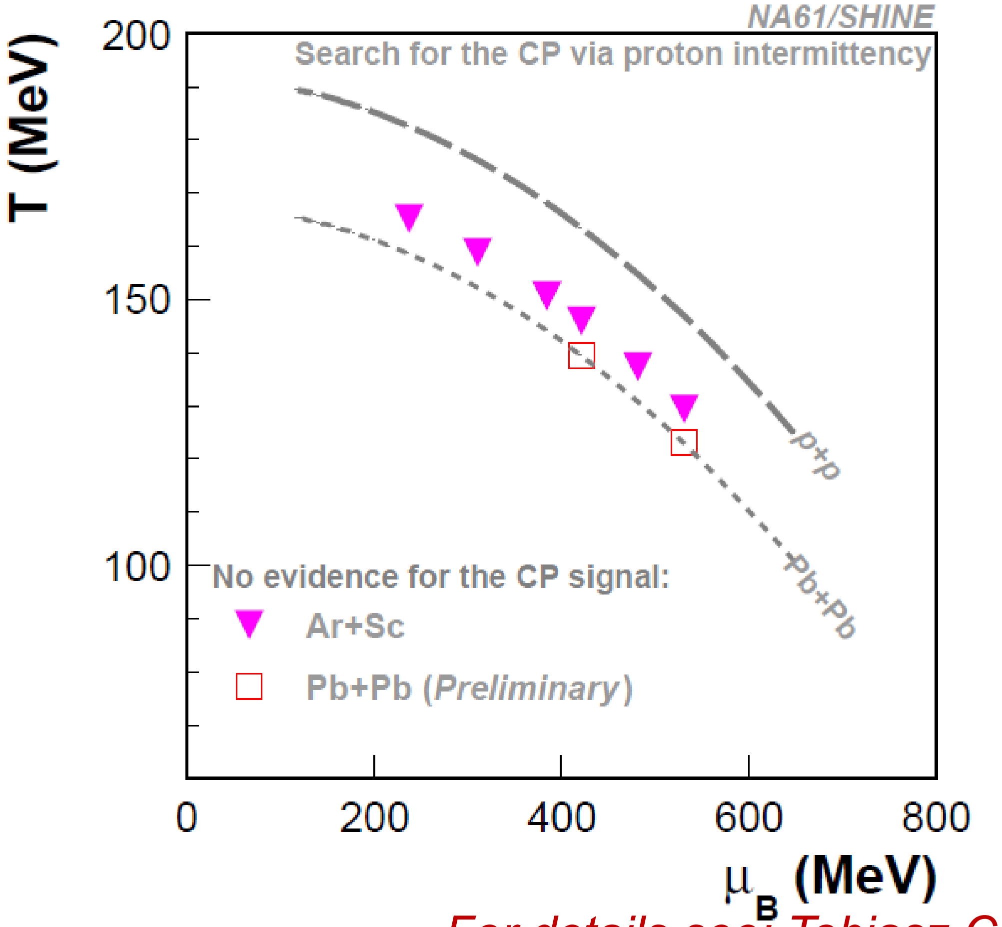
NA61/SHINE: Eur.Phys.J.C 83 (2023) 9, 881; arxiv:2401.03445

Proton intermittency in Ar+Sc

No signal indicating critical point



Calculated for number of subdivisions in cumulative transverse momentum space for $1^2 \leq M^2 \leq 32^2$

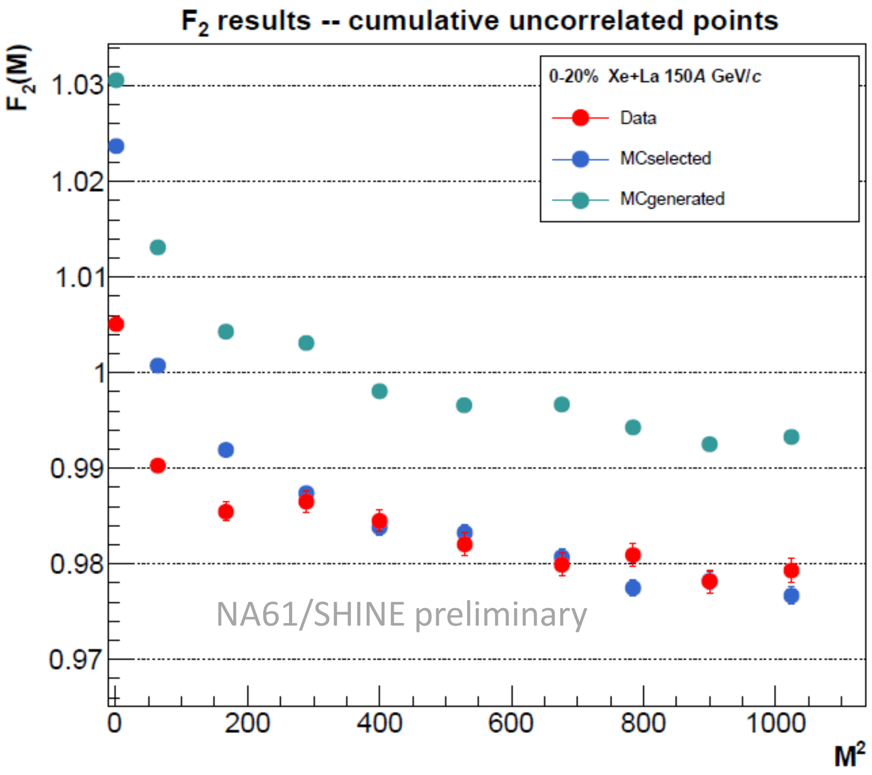


For details see: Tobiasz Czopowicz talk Tuesday at 4:20 pm

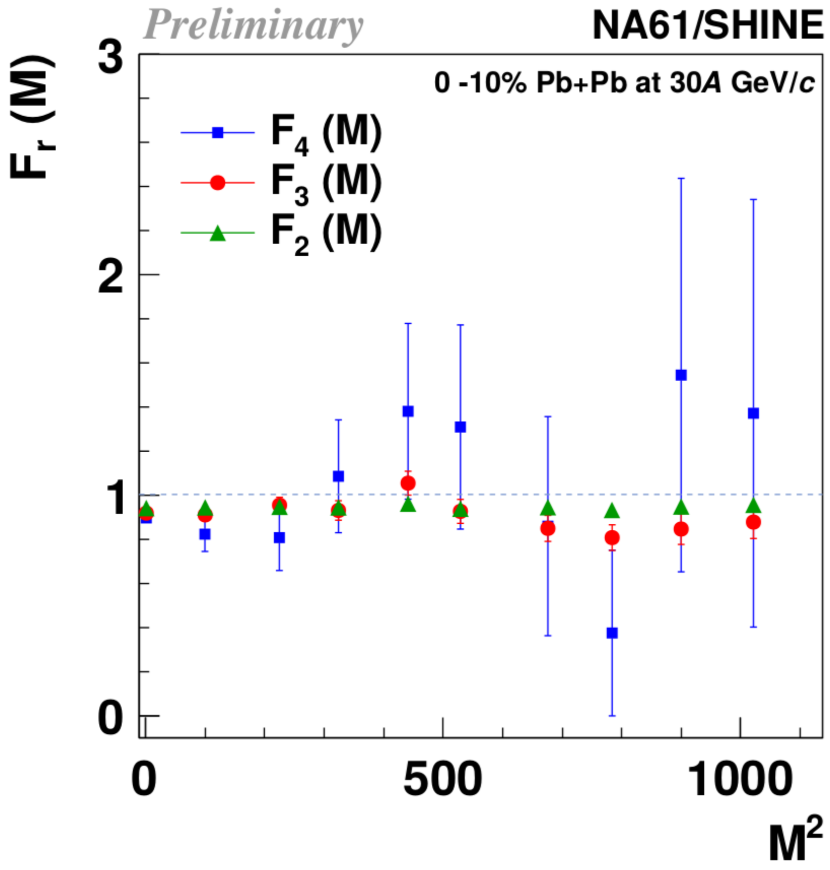
NA61/SHINE: Eur.Phys.J.C 83 (2023) 9, 881; arxiv:2401.03445; arxiv:2211.10504 (Pb+Pb)

Negatively charged hadron intermittency

No signal indicating critical point

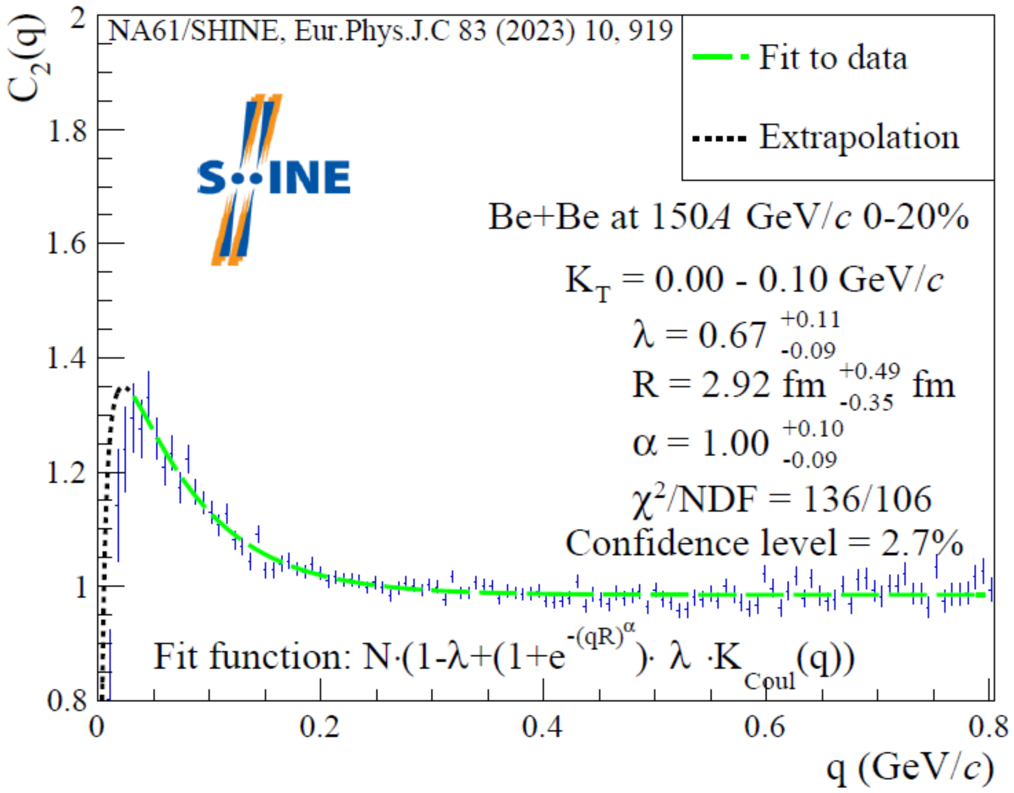


Calculated for independent sub-sample for each M points
1, 10, 15, 18, 21, 23, 26, 28, 30, 32



For details see: Valeria Reyna talk Tuesday at 4:40 pm

Symmetric Lévy HBT correlations



Shape of correlation function with Lévy source:

$$C(q) = 1 + \lambda e^{-(qR)^{\alpha}}$$

where:

$q = |\boldsymbol{p}_1 - \boldsymbol{p}_2|$

R - Lévy-scale parameter (length of homogeneity)

λ - correlation strength

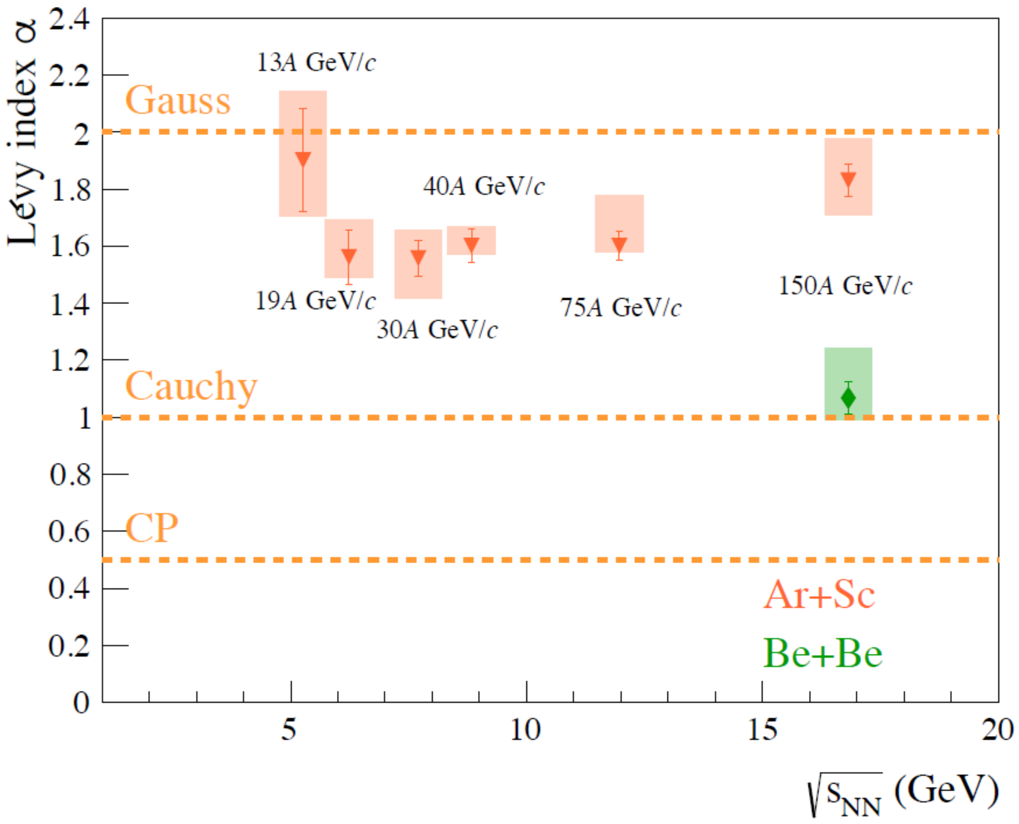
α - Lévy-stability index

- $\alpha = 2$: Gauss shape
- $\alpha < 2$: Generalized central limit theorem
- $\alpha \leq 0.5$: Conjectured value at CP (3D Ising model)

Barnabas Porfy, PhD under preparation; Universe 9 (2023) 7, 298

Lévy-stability index α

No indication of critical point (α far from CP predictions)



Be+Be:
far from Gaussian (α = 2),
close to Cauchy (α = 1)

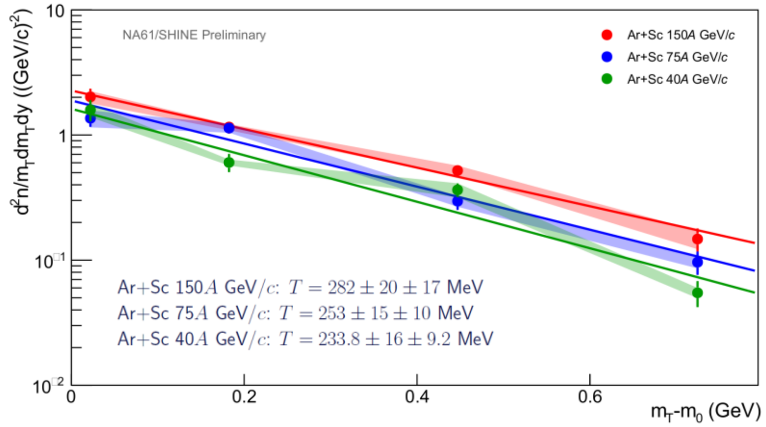
Ar+Sc:
far from Cauchy,
decreases from "close to Gaussian"

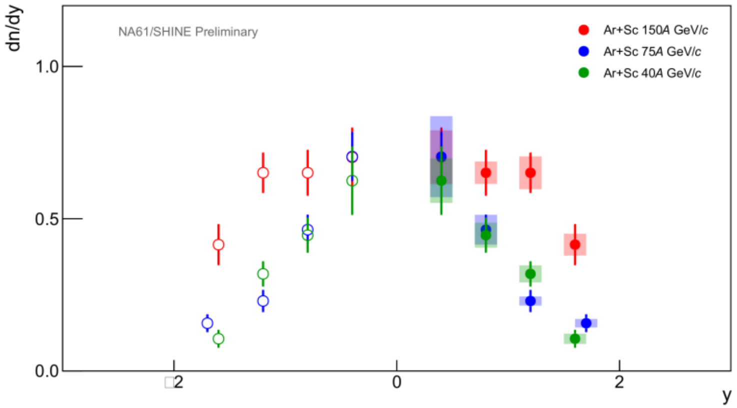
For details see: Tobiasz Czopowicz
talk Tuesday at 4:20 pm

NA61/SHINE: Eur.Phys.J.C 83 (2023) 10, 919 (Be+Be); Universe 9 (2023) 7, 298

$K^{*}(892)^{0}$ production in Ar+Sc

$K^*(892)^0$ in Ar+Sc at 40-158*A* GeV/*c*





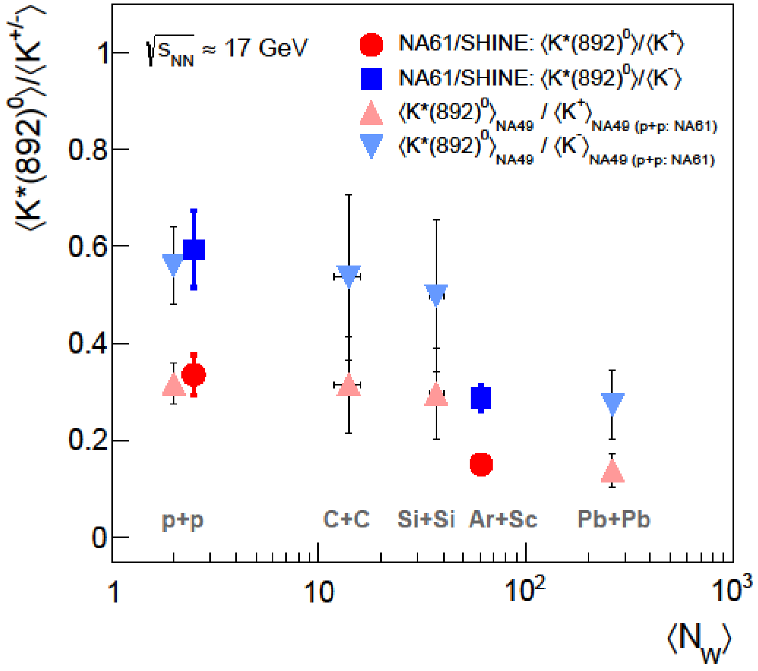
K^*/K allows to estimate time between chemical and kinetic freeze-outs

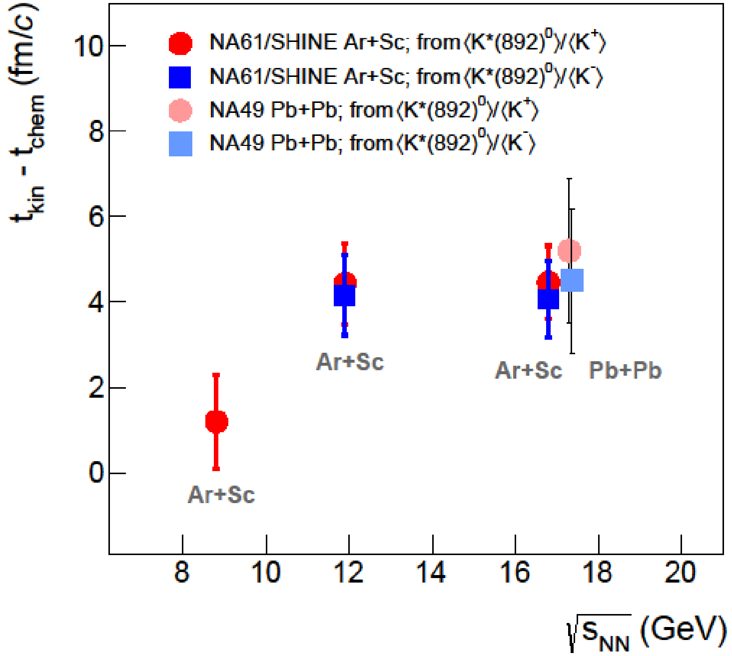
STAR, PR C71, 064902, 2005;
C. Blume, APP B43, 577, 2012

$$\left.\frac{K^*}{K}\right|_{kinetic} = \left.\frac{K^*}{K}\right|_{chemical} e^{-\frac{\Delta t}{\tau}}$$

A+A

p+p





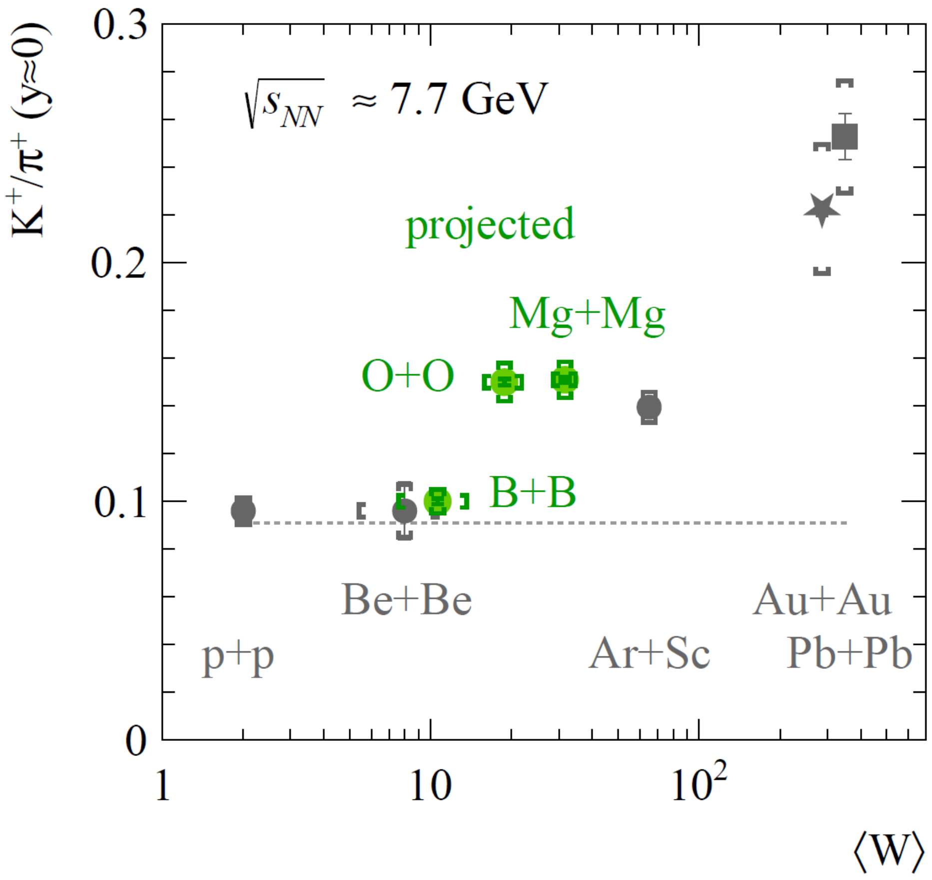
NA61: Eur.Phys.J.C 80 (2020) 5, 460; Eur.Phys.J.C 82 (2022) 4, 322; Eur.Phys.J.C 77 (2017) 10, 671, Eur.Phys.J.C 84 (2024) 4, 416

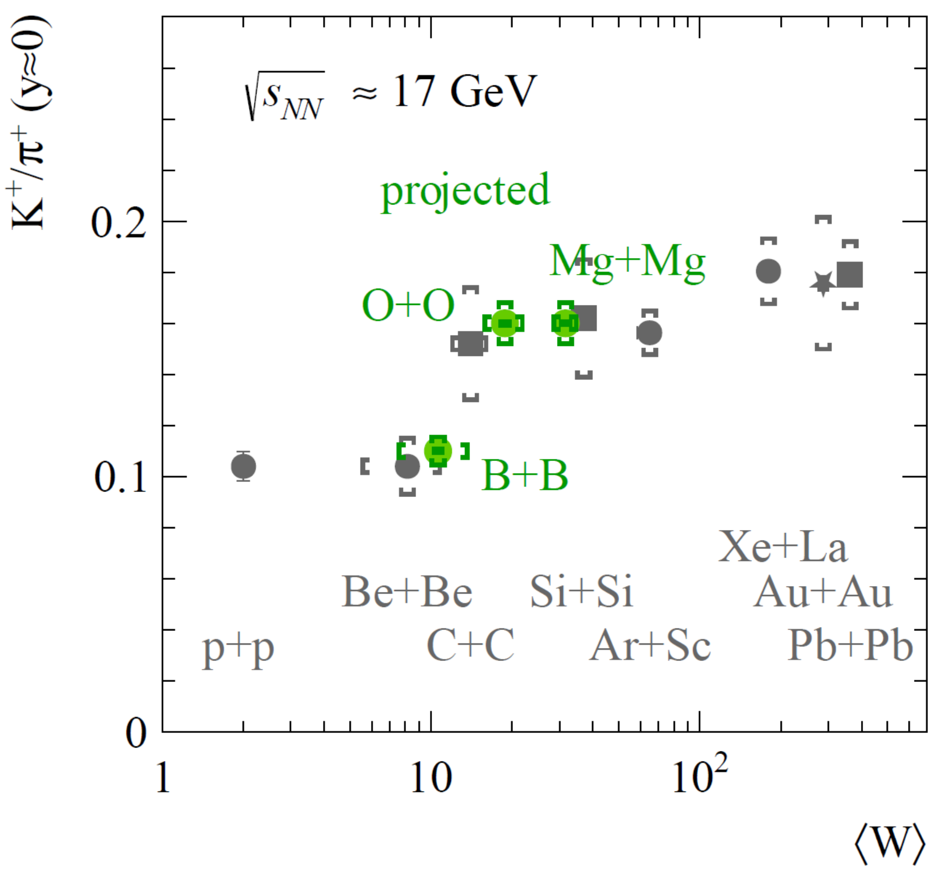
NA49: Phys.Rev.C 84 (2011) 064909, Phys.Rev.Lett. 94 (2005) 052301, Phys.Rev.C 66 (2002) 054902

Future of NA61/SHINE

NA61/SHINE after CERN LS3 (2028+)

Continuation of 2D scan with B+B, O+O and Mg+Mg collisions





See NA61/SHINE: addendum SPSC-P-330-ADD-14

Summary

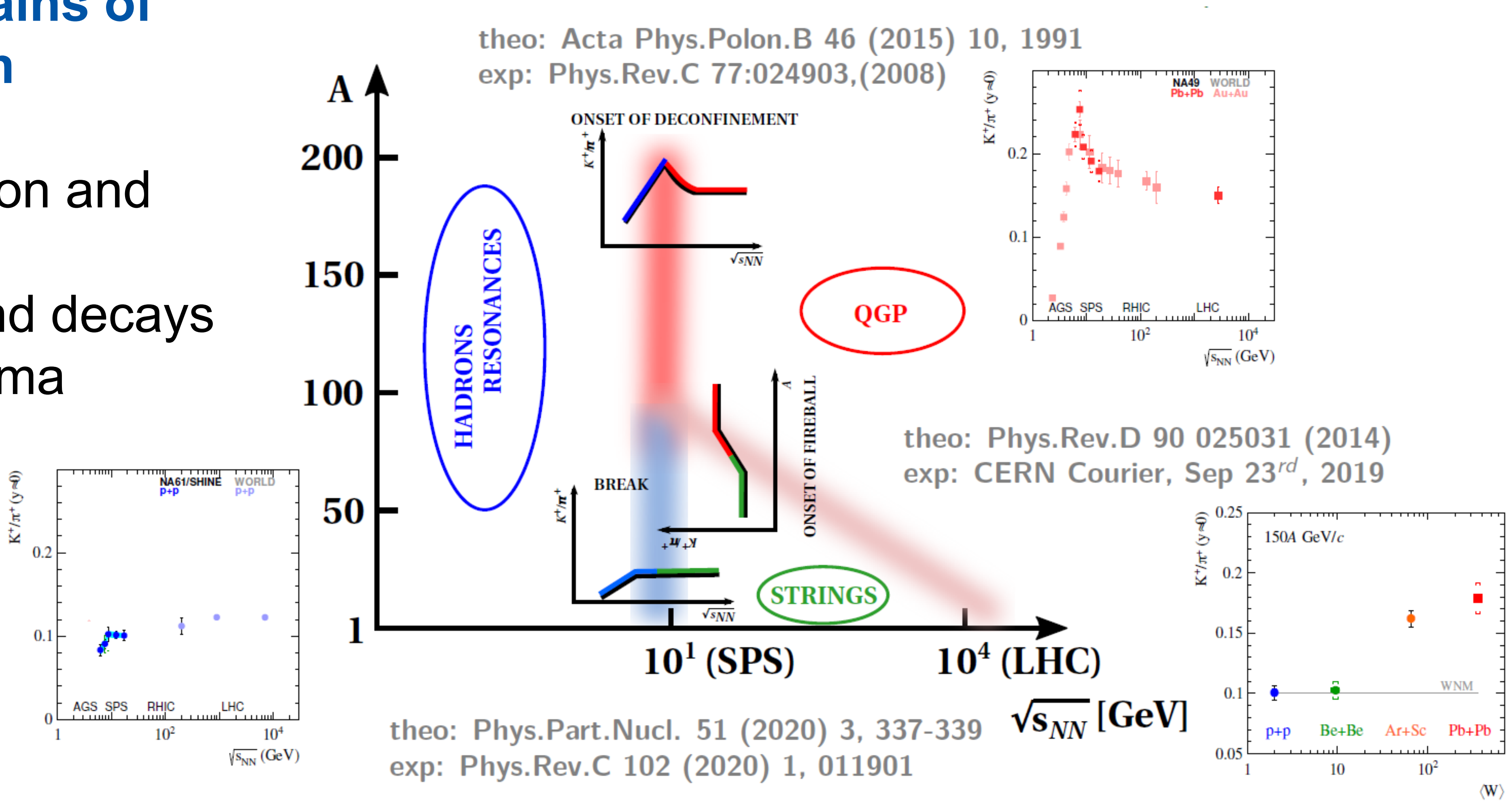
- Unique 2D scan in collision energy and system size is completed
- New preliminary results from Xe+La released
- Unexpected system size dependence: (p+p ≈ Be+Be) < (Ar+Sc ≤ Xe+La ≤ Pb+Pb)
- Observed anomaly in charged over neutral K meson production in high-energy collisions of atomic nuclei
- So far no indication of the critical point
- Plans for new measurements with light-ion beams (B, O, Mg) beyond CERN LS3 (2028+)

Thank you

Diagram of high-energy nuclear collisions

Hypothetical domains of hadron-production dominated by:

- resonance creation and decays
- string creation and decays
- quark-gluon plasma formation and hadronisation



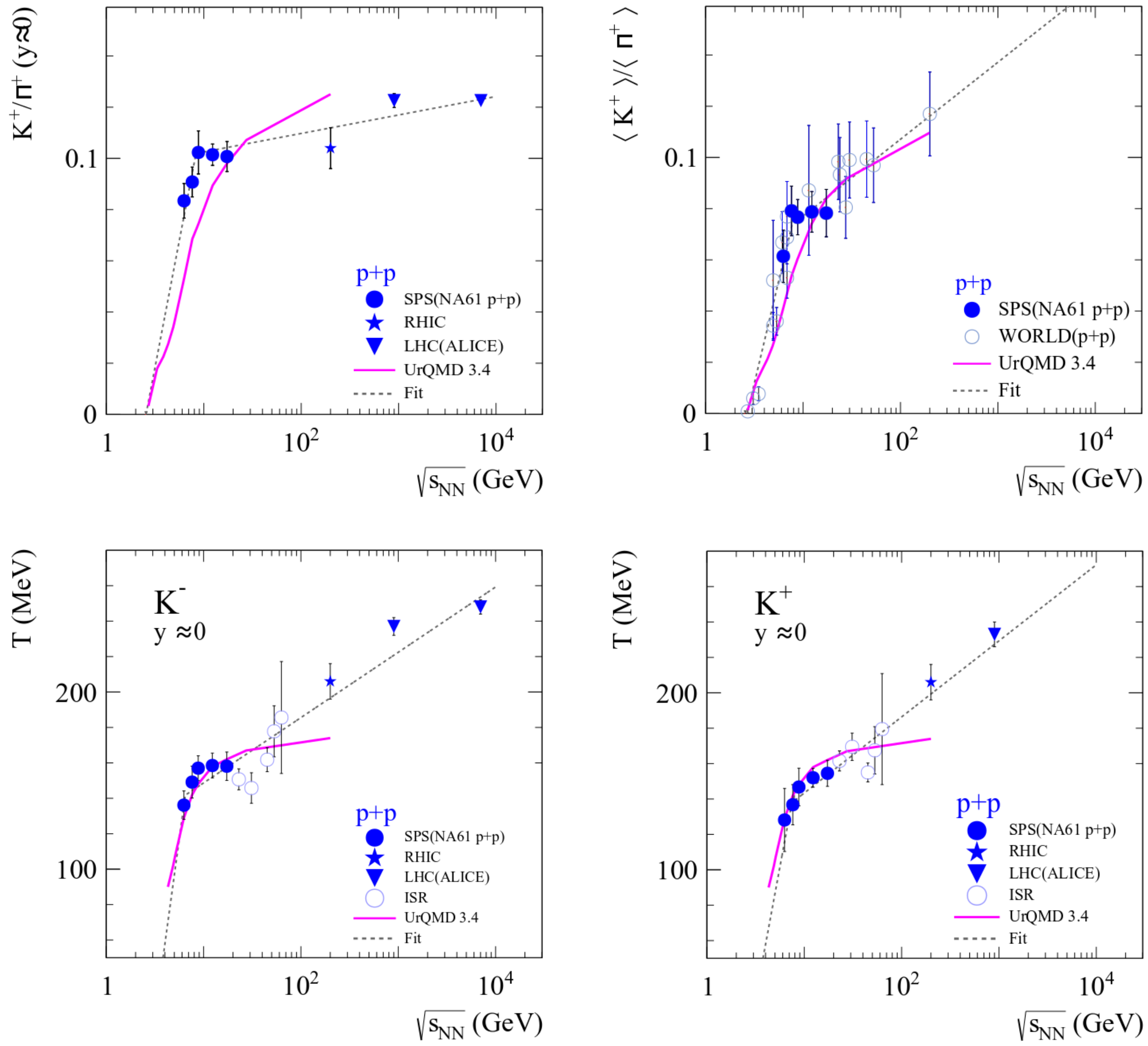
theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)

theo: Phys.Rev.D 90 025031 (2014)
exp: CERN Courier, Sep 23^{rd}, 2019

theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Transition from resonances to strings

Transition from resonances to strings



Rates of increase of K^+/π^+ and T change sharply in p+p collisions at SPS energies

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

Models assuming change from resonances to string production mechanism show similar trend

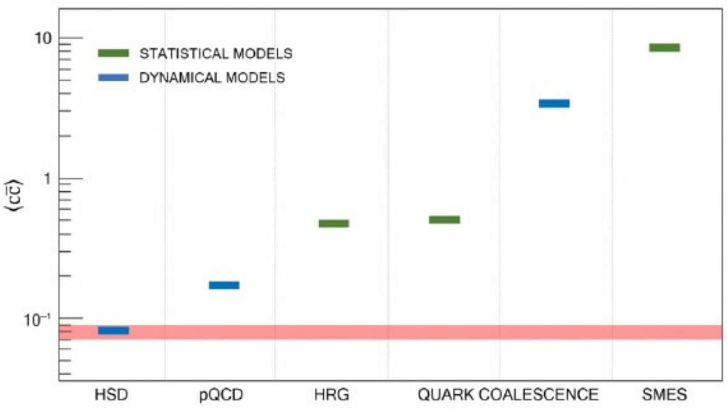
NA61/SHINE in 2022-2025

NA61/SHINE program for 2021-2024

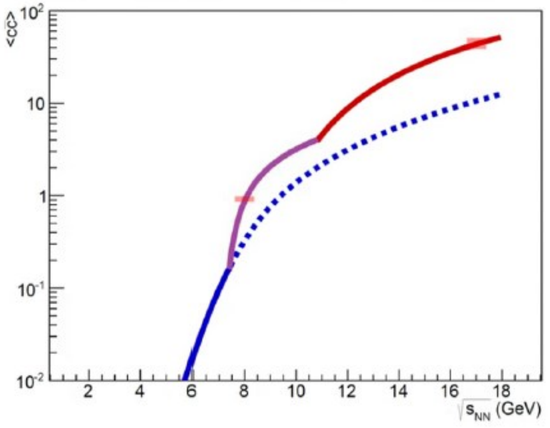
- **What is the mechanism of open charm production?**
- **How does the onset of deconfinement impact open charm production?**
- **How does the formation of quark gluon plasma impact J/ψ production?**

To answer these questions **mean number of charm quark pairs**, $\langle c\bar{c}\rangle$, 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**.

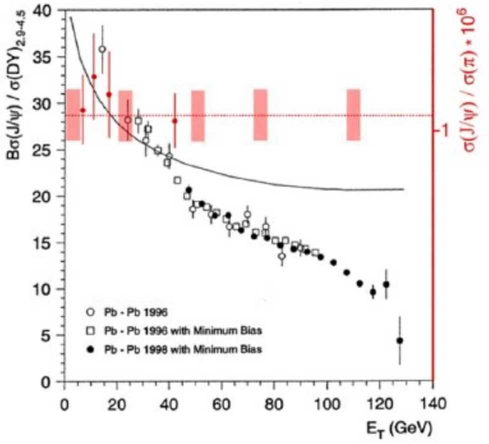
$\langle c\bar{c}\rangle$ and models



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



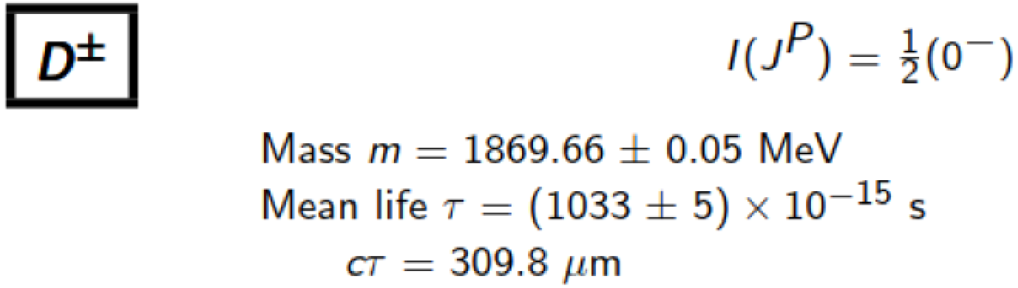
$\langle c\bar{c}\rangle, \langle J/\psi\rangle$ and QGP



Foreseen NA61/SHINE resolution is sufficient to answer addressed questions

Charged/neutral kaon-ratio puzzle

Comparison of isospin asymmetry for D mesons and kaons



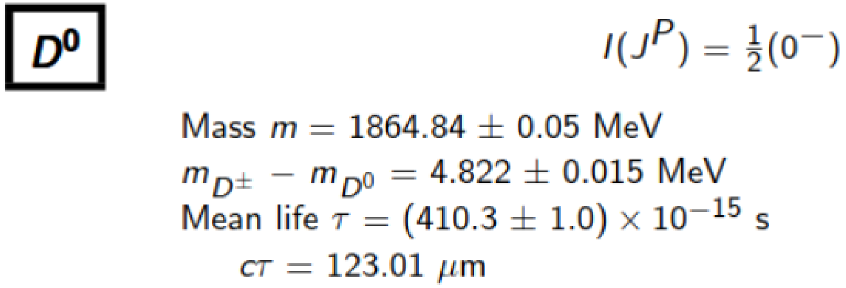
$D^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.66 \pm 0.05$ MeV

Mean life $\tau = (1033 \pm 5) \times 10^{-15}$ s

$c\tau = 309.8\ \mu$m



D^0

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1864.84 \pm 0.05$ MeV

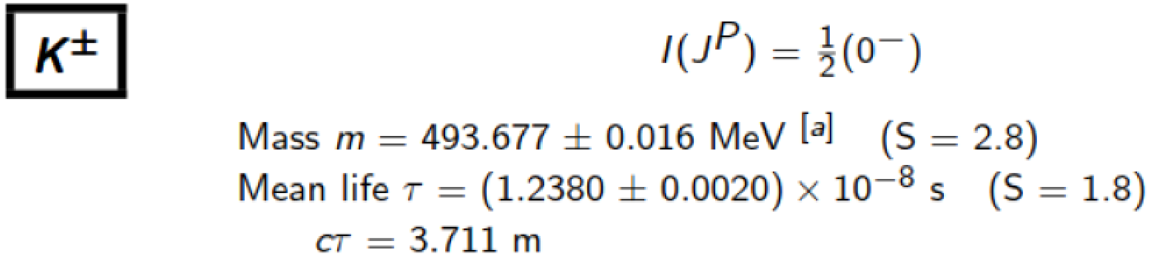
$m_{D^{\pm}} - m_{D^0} = 4.822 \pm 0.015$ MeV

Mean life $\tau = (410.3 \pm 1.0) \times 10^{-15}$ s

$c\tau = 123.01\ \mu$m

Mass difference: $\Delta m \approx 5$ MeV

Multiplicity: $\langle D^+ + D^- \rangle < \langle D^0 + \overline{D^0} \rangle$



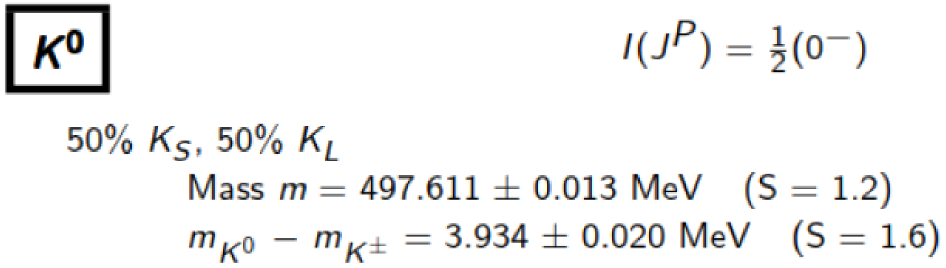
$K^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [a] (S = 2.8)

Mean life $\tau = (1.2380 \pm 0.0020) \times 10^{-8}$ s (S = 1.8)

$c\tau = 3.711$ m



K^0

$I(J^P) = \frac{1}{2}(0^-)$

50% K_S, 50% K_L

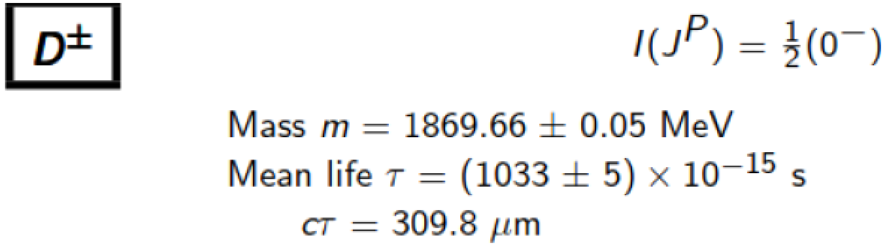
Mass $m = 497.611 \pm 0.013$ MeV (S = 1.2)

$m_{K^0} - m_{K^{\pm}} = 3.934 \pm 0.020$ MeV (S = 1.6)

Mass difference: $\Delta m \approx -4$ MeV

Multiplicity: $\langle K^+ + K^- \rangle > \langle K^0 + \overline{K^0} \rangle$

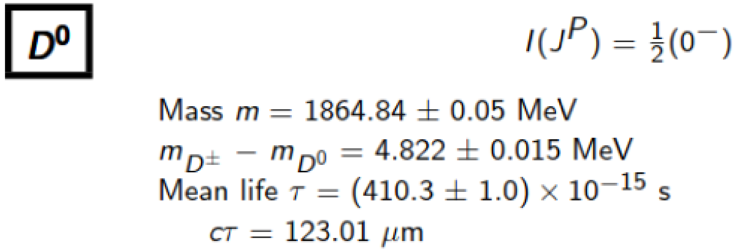
Isospin asymmetry for D mesons



$D^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.66 \pm 0.05$ MeV
Mean life $\tau = (1033 \pm 5) \times 10^{-15}$ s
$c\tau = 309.8$ μm

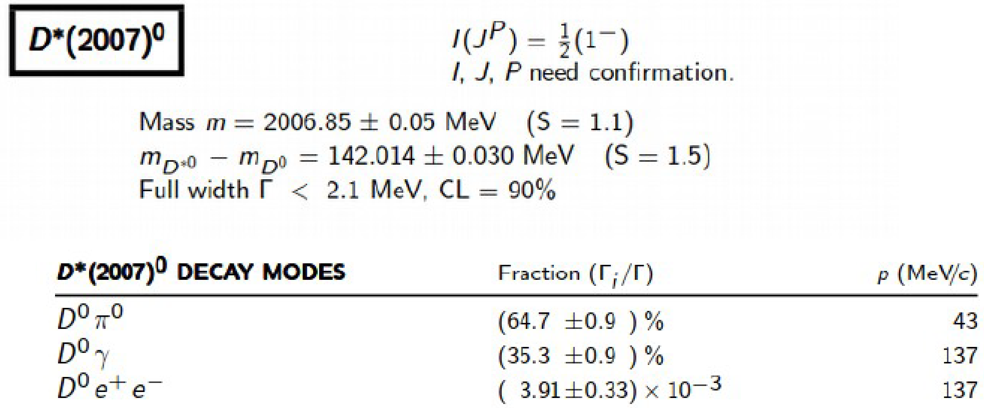


D^0

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1864.84 \pm 0.05$ MeV
$m_{D^{\pm}} - m_{D^0} = 4.822 \pm 0.015$ MeV
Mean life $\tau = (410.3 \pm 1.0) \times 10^{-15}$ s
$c\tau = 123.01$ μm

Mass difference: $\Delta m \approx 5$ MeV
Multiplicity: $\langle D^+ + D^- \rangle < \langle D^0 + \overline{D^0} \rangle$

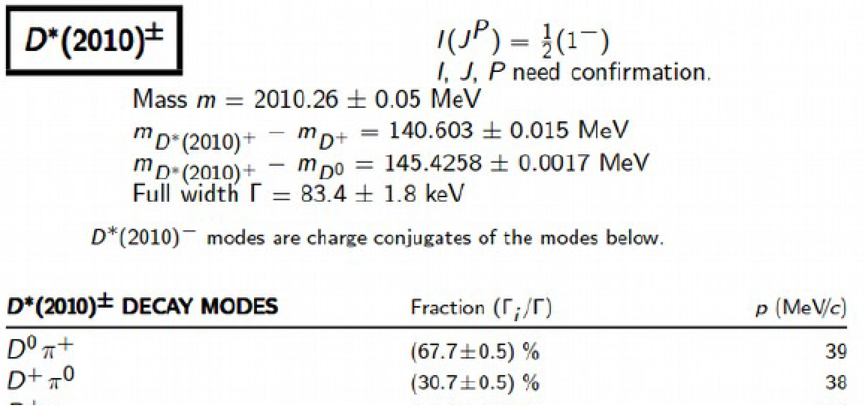


$D^*(2007)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2006.85 \pm 0.05$ MeV (S = 1.1)
$m_{D^{*0}} - m_{D^0} = 142.014 \pm 0.030$ MeV (S = 1.5)
Full width $\Gamma < 2.1$ MeV, CL = 90%

$D^*(2007)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^0$	(64.7 ± 0.9) %	43
$D^0\gamma$	(35.3 ± 0.9) %	137
$D^0 e^+ e^-$	$(3.91 \pm 0.33) \times 10^{-3}$	137



$D^*(2010)^{\pm}$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

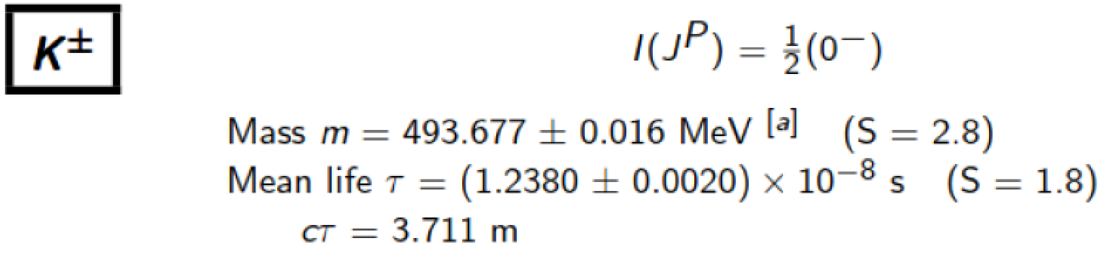
Mass $m = 2010.26 \pm 0.05$ MeV
$m_{D^*(2010)^+} - m_{D^+} = 140.603 \pm 0.015$ MeV
$m_{D^*(2010)^+} - m_{D^0} = 145.4258 \pm 0.0017$ MeV
Full width $\Gamma = 83.4 \pm 1.8$ keV

$D^*(2010)^-$ modes are charge conjugates of the modes below.

$D^*(2010)^{\pm}$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^+$	(67.7 ± 0.5) %	39
$D^+\pi^0$	(30.7 ± 0.5) %	38

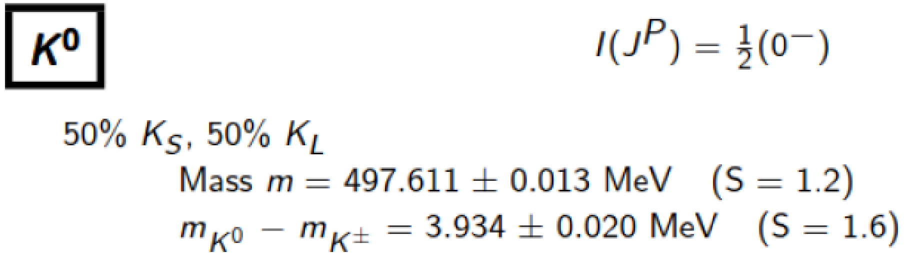
- Simple explanation according to Adv.Ser.Direct.High Energy Phys. 15 (1998) 609-706: "A simple model for estimating the charged-to-neutral D cross section ratio is the following. One assumes isospin invariance in the c→D and c→D* transition. Furthermore, one assumes that the D cross section is one third of the D* cross section, due to the counting of polarization states. Using then the published values of the D* →D branching ratios [R.M. Barnett et al., Phys. Rev. D54(1996)1], the result is roughly $\frac{\sigma(D^+)}{\sigma(D^0)} \approx 0.32$."

Isospin asymmetry for kaons



$\boxed{K^{\pm}}$ $I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [a] (S = 2.8)
Mean life $\tau = (1.2380 \pm 0.0020) \times 10^{-8}$ s (S = 1.8)
$c\tau = 3.711$ m



$\boxed{K^0}$ $I(J^P) = \frac{1}{2}(0^-)$

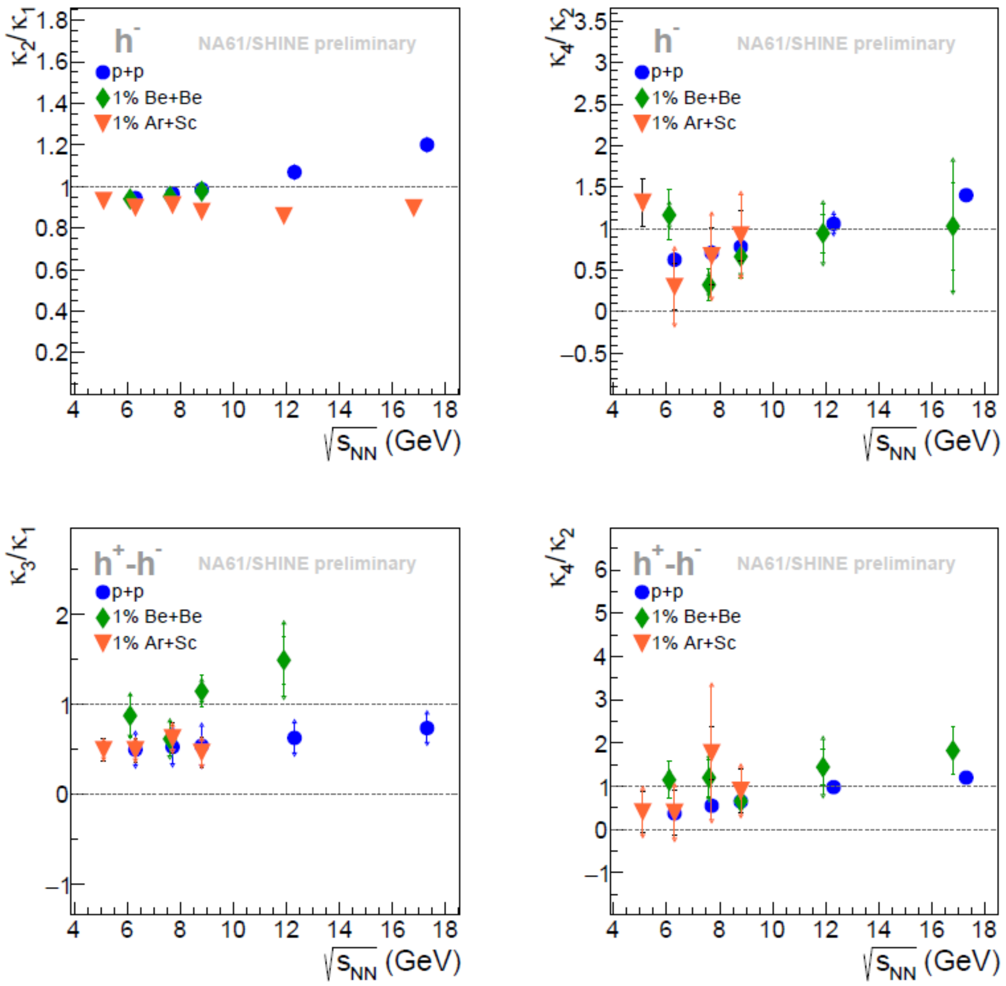
50% K_S, 50% K_L
Mass $m = 497.611 \pm 0.013$ MeV (S = 1.2)
$m_{K^0} - m_{K^\pm} = 3.934 \pm 0.020$ MeV (S = 1.6)

Mass difference: $\Delta m \approx -4$ MeV
Multiplicity: $\langle K^+ + K^- \rangle > \langle K^0 + \overline{K^0} \rangle$

- For any state going to kaons, there is always a bit more K^+ and K^- because of mass difference.
- But masses of kaon resonances are much larger than sum of decay products (the higher mass of decaying resonance, the smaller difference between charged and neutral kaons).
- First preliminary estimation using statistical model gives the asymmetry $< 5\%$ (thanks to Francesco Giacosa).

Multiplicity and net-charge fluctuations in p+p, Be+Be and Ar+Sc

No structure indicating critical point



$$
\begin{aligned}
\kappa_1 &= \langle N \rangle \\
\kappa_2 &= \langle (\delta N)^2 \rangle = \sigma^2 \\
\kappa_3 &= \langle (\delta N)^3 \rangle = S\sigma^3 \\
\kappa_4 &= \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 = K\sigma^4
\end{aligned}
$$

where:

N – multiplicity; $\delta N = N - \langle N \rangle$

σ – standard deviation

S – skewness; K – kurtosis

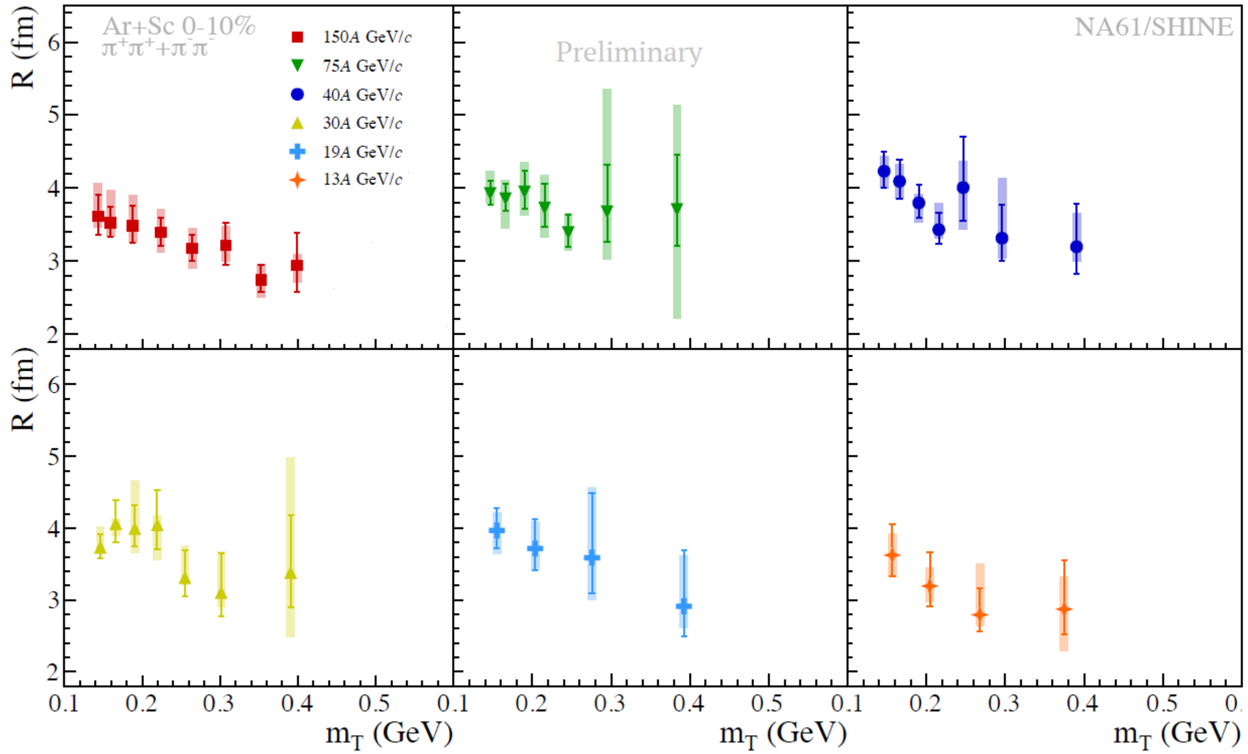
Negatively charge κ_2/κ_1: increasing difference between small systems (p+p and Be+Be) and a heavier system (Ar+Sc) with collision energy

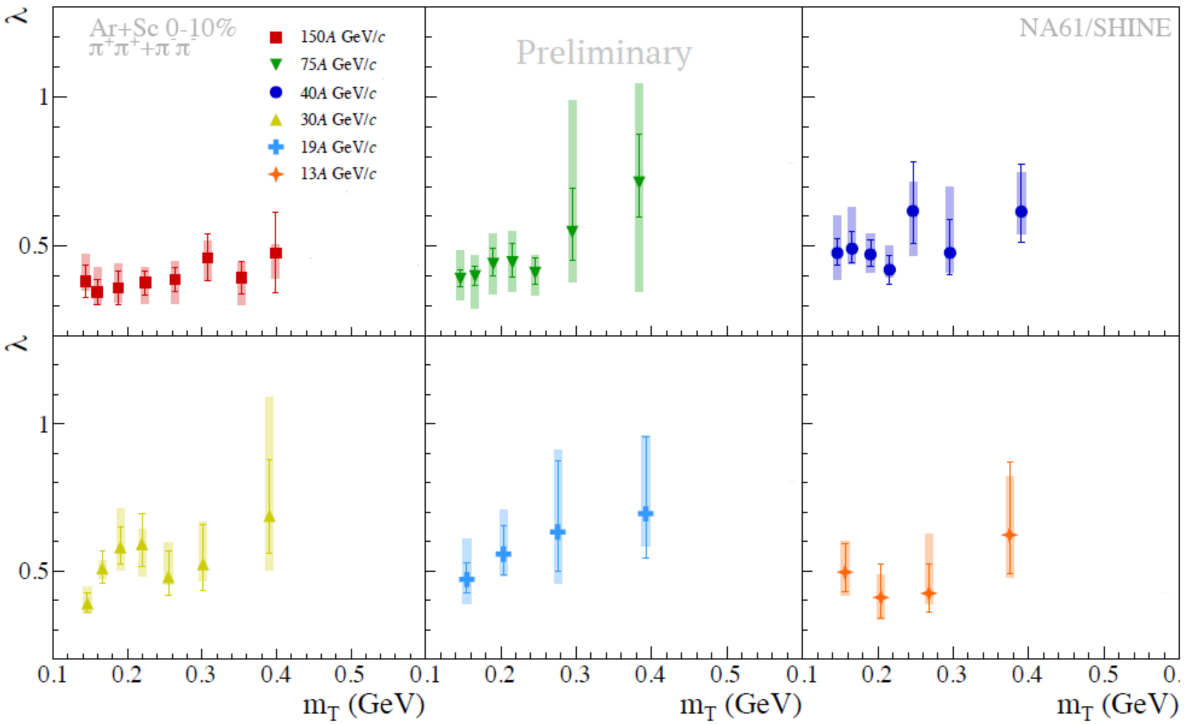
Net-charge κ_3/κ_1:increasing difference between Be+Be and other systems (p+p and Ar+Sc) with collision energy

κ_4/κ_1 : consistent values for all measured systems at given collision energy

see NA61/SHINE, arxiv:2312.13706 for final p+p results

Lévy-scale parameter R and Correlation Strength λ





Lévy scale R:

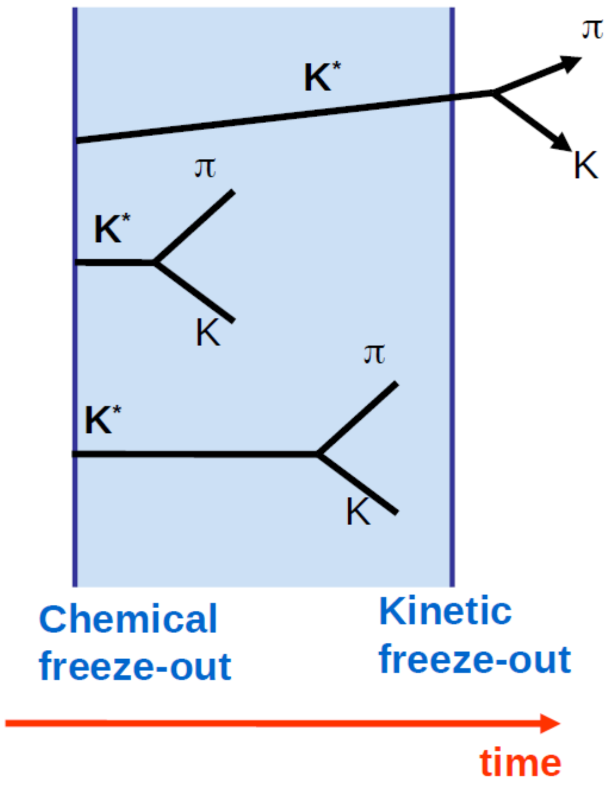
- Describes length of homogeneity
- Visible m_T dependence sign of transverse flow

λ correlation strength:

- Describes core-halo ratio
- Shows no m_T dependence

see NA61/SHINE, Eur.Phys.J.C 83 (2023) 10, 919 for Be+Be results

Time between freezeouts



- K* lifetime (≈ 4 fm/*c*) is comparable with the time between two freeze-outs
- Some K* resonances may decay inside the fireball
- Suppression of observed K* yield
- Assuming no regeneration processes (Fig.) the time **Δt** between freeze-outs can be determined from (STAR, PRC71, 064902, 2005):

$$\frac{K^*}{K}(\text{kinet})=\frac{K^*}{K}(\text{chem})\cdot e^{\frac{-\Delta t}{\tau}}$$

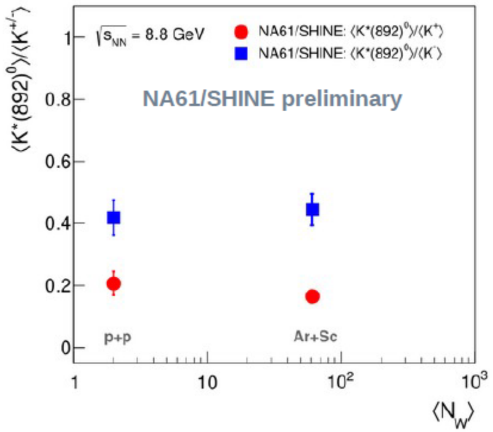
K* lifetime

use Pb+Pb or Au+Au ratio

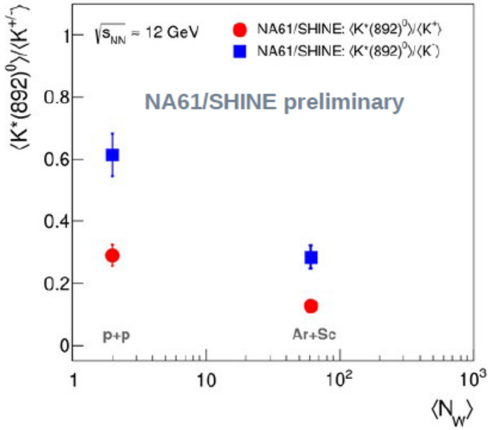
use p+p ratio

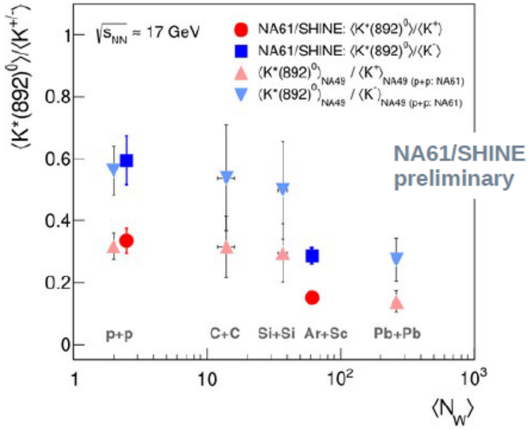
see NA61/SHINE, Eur.Phys.J.C 83 (2023) 10, 919 for Be+Be results

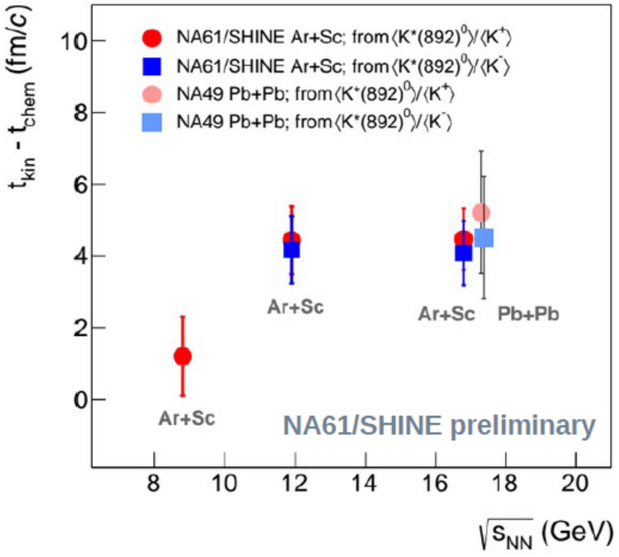
Time between freezeouts



- New data on K* production in 0-10% central Ar+Sc collisions
- Ar+Sc ≈ Pb+Pb at $\sqrt{s_{NN}}$=16.8 GeV
- No K* suppresion at $\sqrt{s_{NN}}$=8.8 GeV ?







$K^{*}(892)^{0}$ data in Ar+Sc: NA61/SHINE preliminary

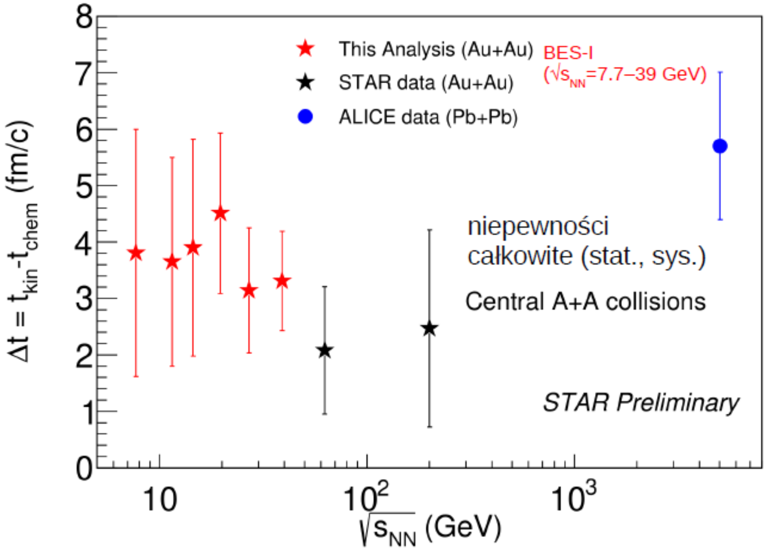
Other data: NA61/SHINE, EPJC 84 (2024) 416
EPJC 82 (2022) 322
EPJC 80 (2020) 460
EPJC 77 (2017) 671

NA49, PRC 84 (2011) 064909
PRL 94 (2005) 052301
PRC 66 (2002) 054902

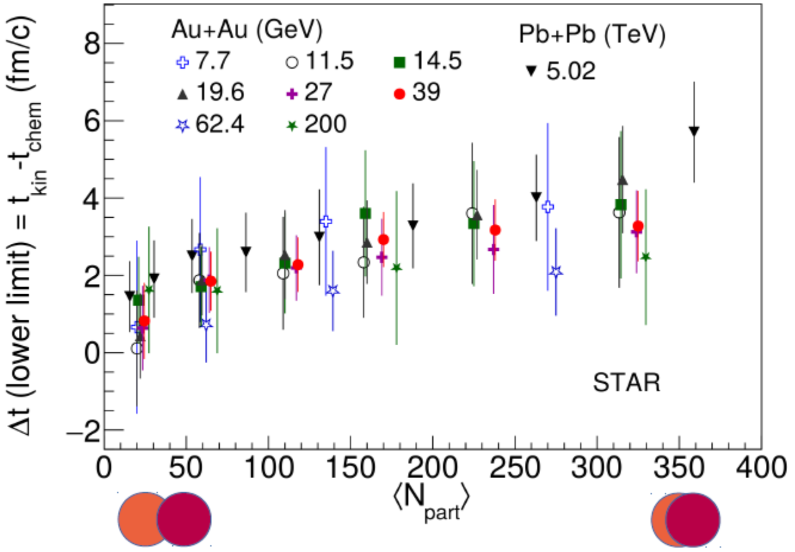
see NA61/SHINE, Eur.Phys.J.C 83 (2023) 10, 919 for Be+Be results

Time between freezeouts

A. Sahoo (for STAR), Acta Phys. Polon. Supp. 16 (2023) 1-A132



STAR, Phys. Rev. C 107 (2023) 3, 034907



see NA61/SHINE, Eur.Phys.J.C 83 (2023) 10, 919 for Be+Be results