Highlights from the NA61/SHINE experiment at the CERN SPS

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IN KATOWICE

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for NA61/SHINE

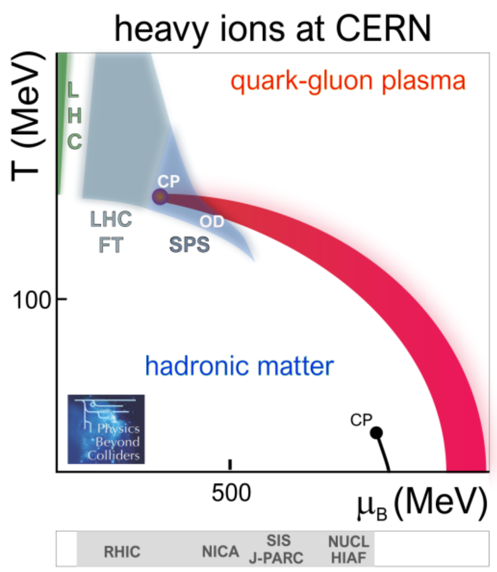
NA61/SHINE physics program

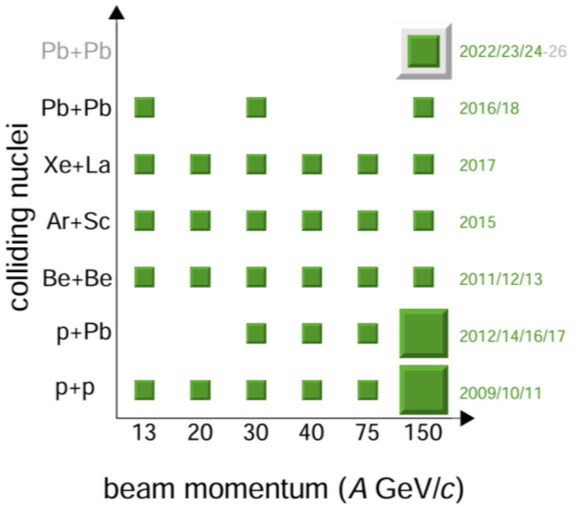
Strong interaction physics:

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

Neutrino and cosmic-ray physics:

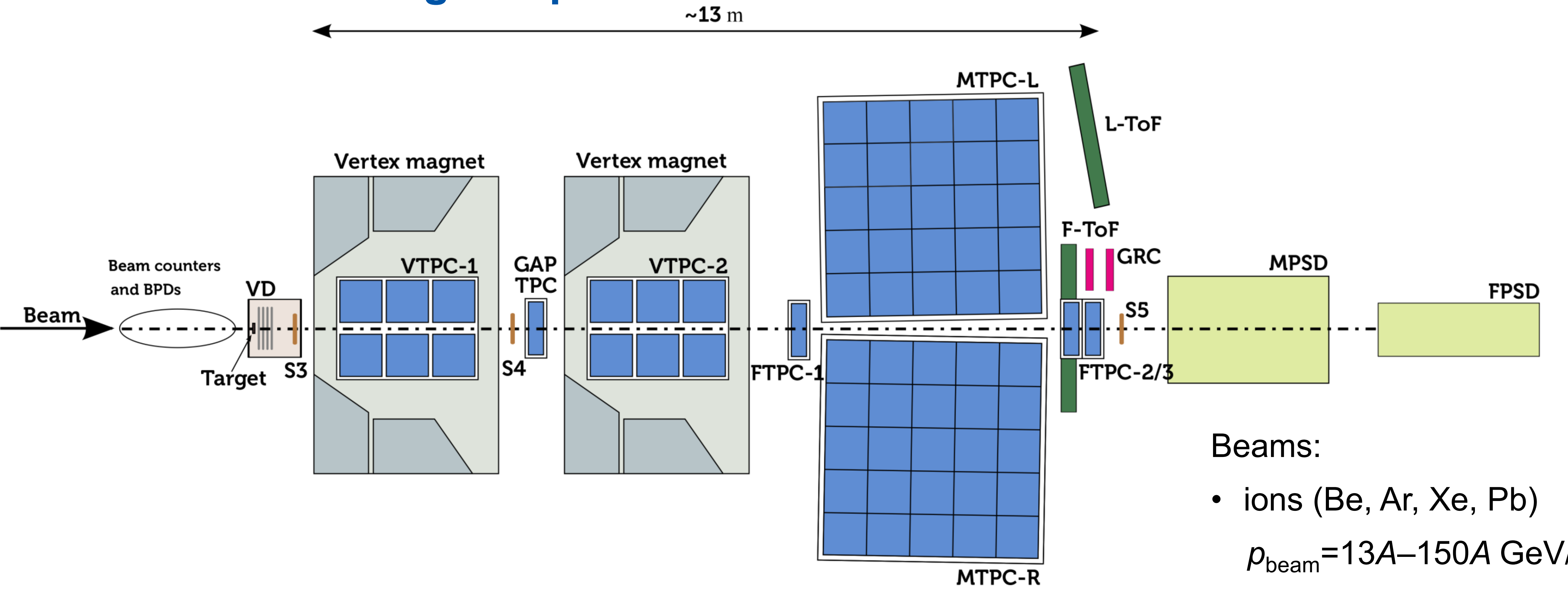
- measurements for neutrino programs at J-PARC and Fermilab
- measurements of hadron production and nuclear fragmentation cross section for cosmic-ray physics





NA61/SHINE detector

Fixed-target experiment located at the CERN SPS accelerator



Beams:

- ions (Be, Ar, Xe, Pb)

  p_{beam}=13A–150A GeV/c

- hadrons (π, K, p)

  p_{beam}=13–400 GeV/c

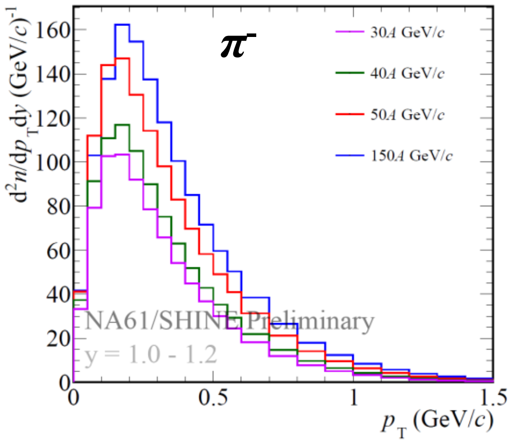
$\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

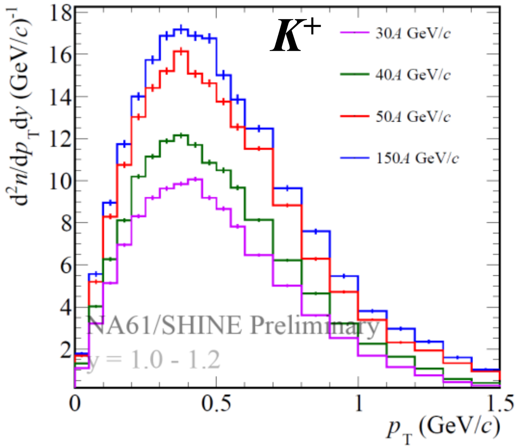
Large acceptance hadron spectrometer –
coverage of the full forward hemisphere, down to p_{T} = 0

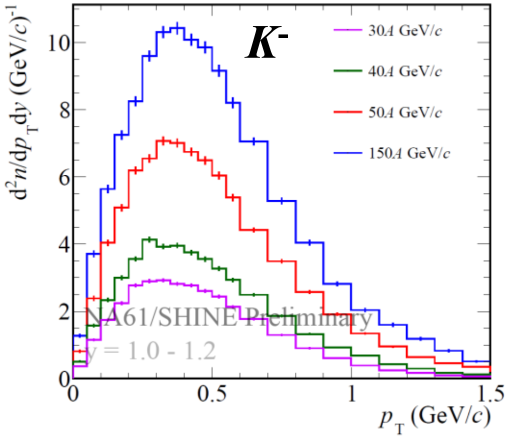
Onset of deconfinement

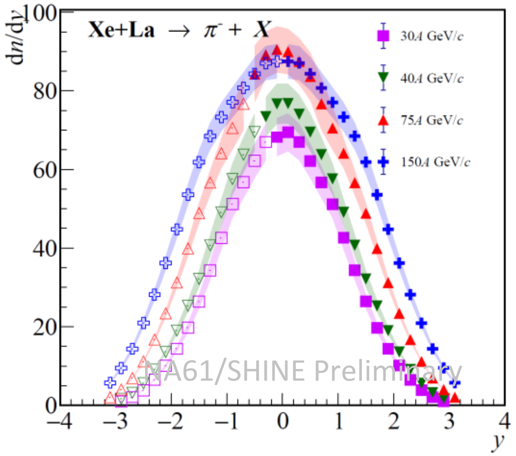
Particle spectra measurements

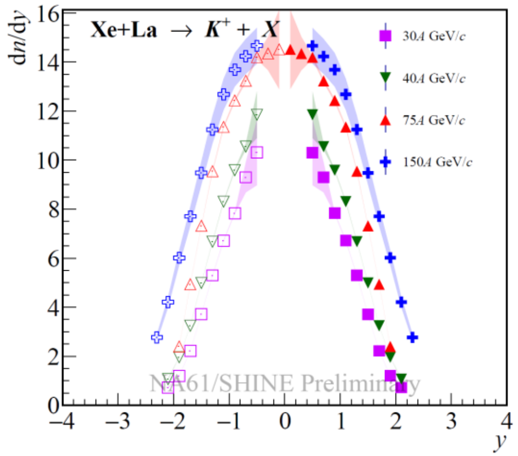
Preliminary spectra of π^- and $K^\pm$ produced in the 10% most central Xe+La collisions at 30*A*, 40*A*, 75*A* GeV/*c* and in the 20% most central Xe+La collisions at 150*A* GeV/*c* obtained via d*E*/d*x* and h^- methods

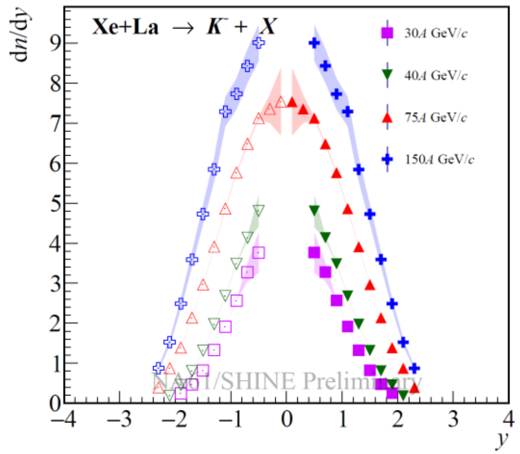






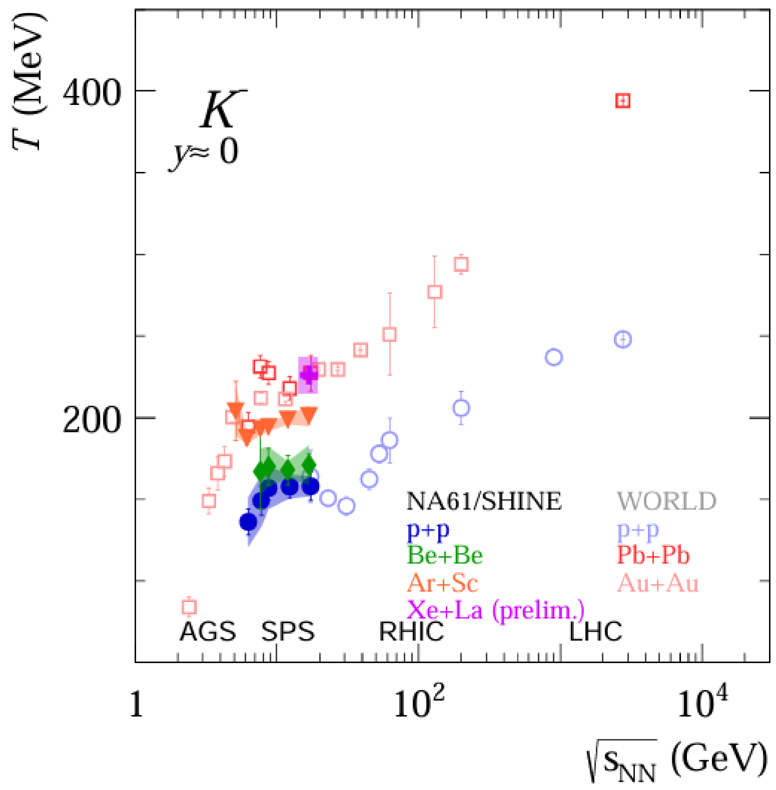


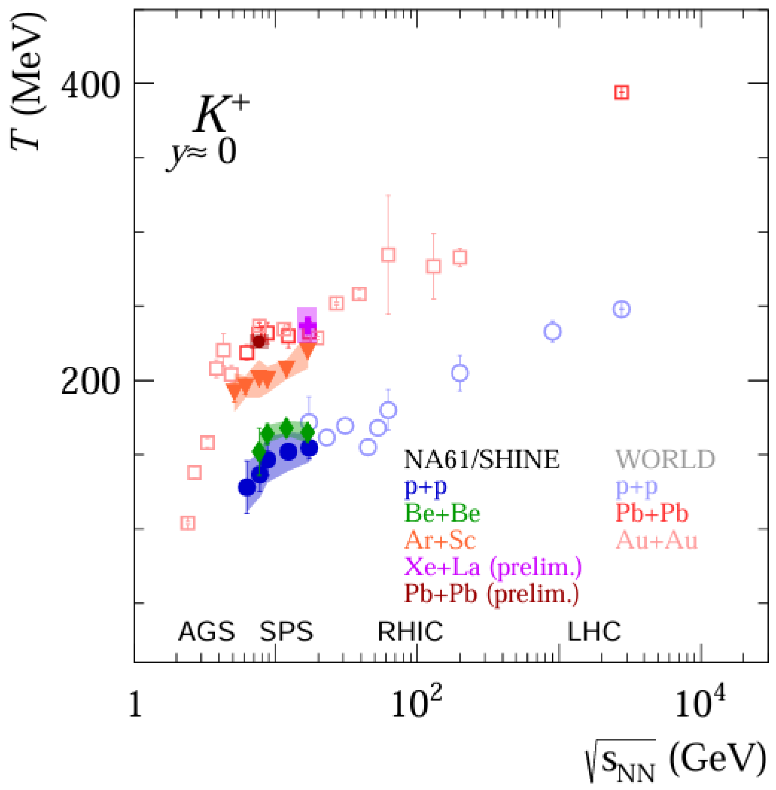




Onset of deconfinement: step

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)

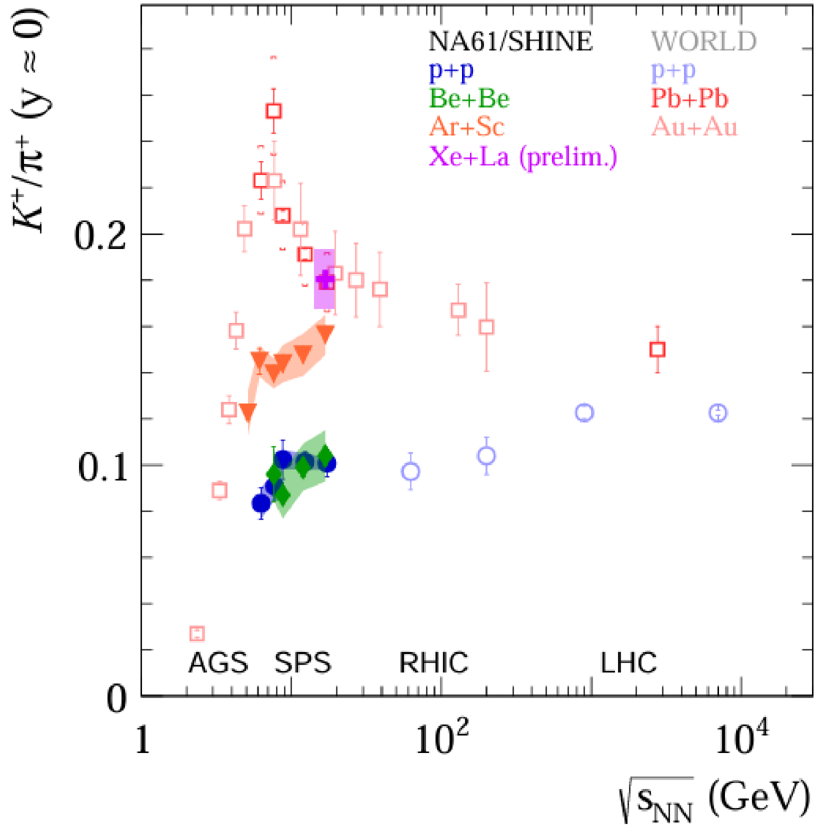
T reflects the thermal freeze-out temperature and the radial flow velocity

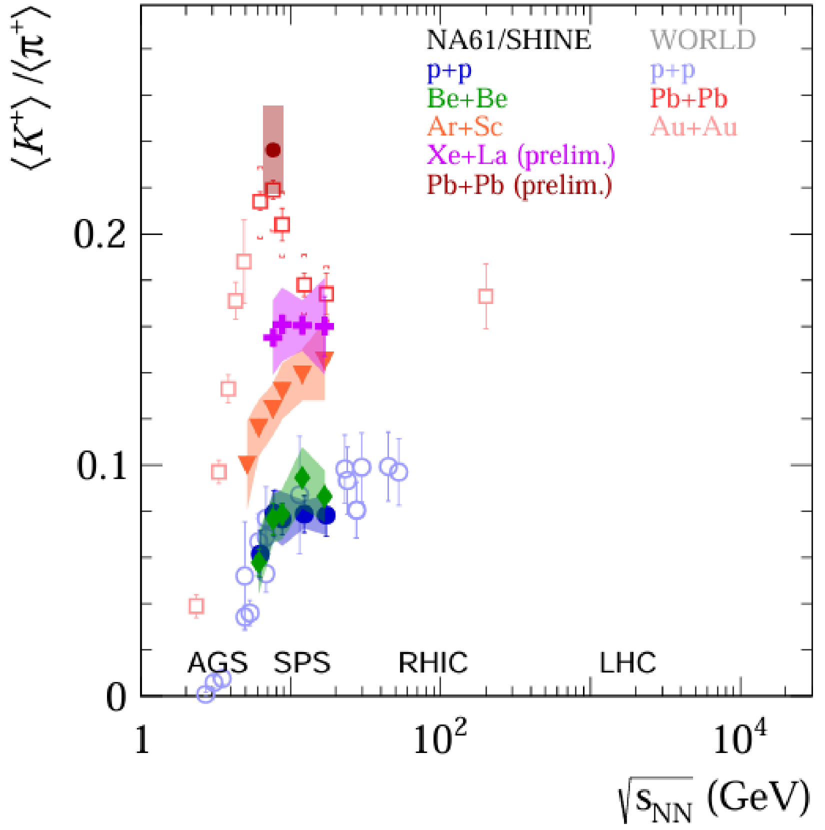
NA61/SHINE: Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p)
see Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc) for references to world data

Onset of deconfinement: horn

Xe+La at lower energies below Pb+Pb,

while higher than Ar+Sc and Be+Be and p+p





K^+/π^+ approx. proportional to 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

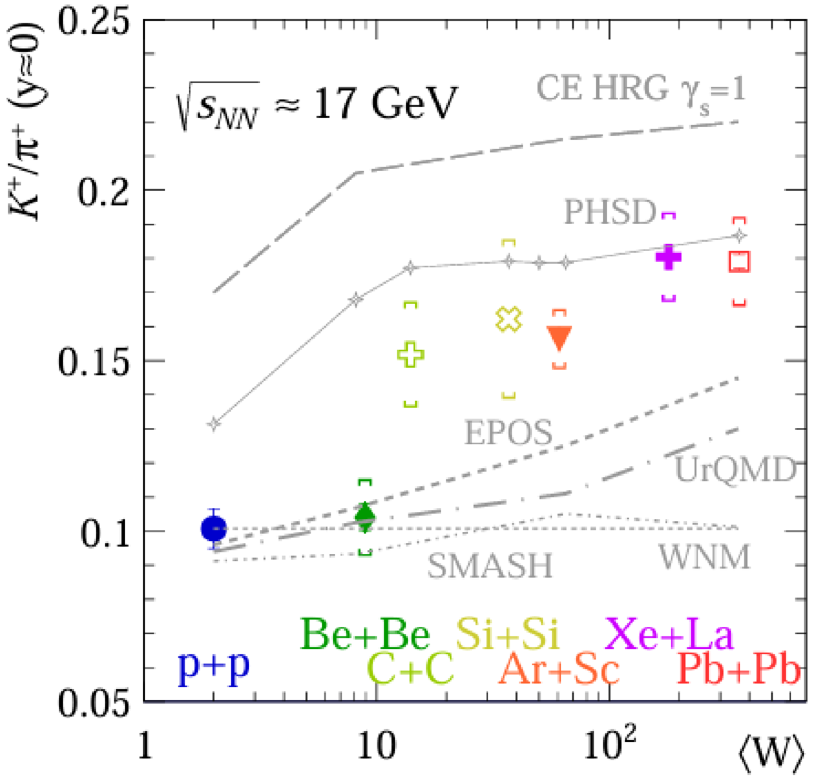
NA61/SHINE: Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p)

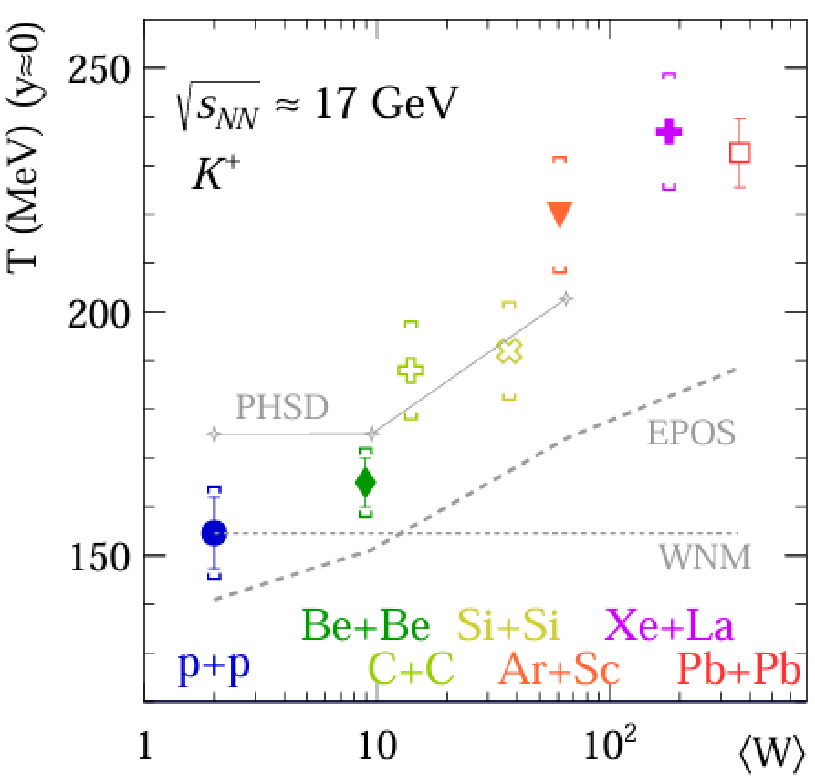
see Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc) for references to world data

System size dependence

K/π and T vs system size

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





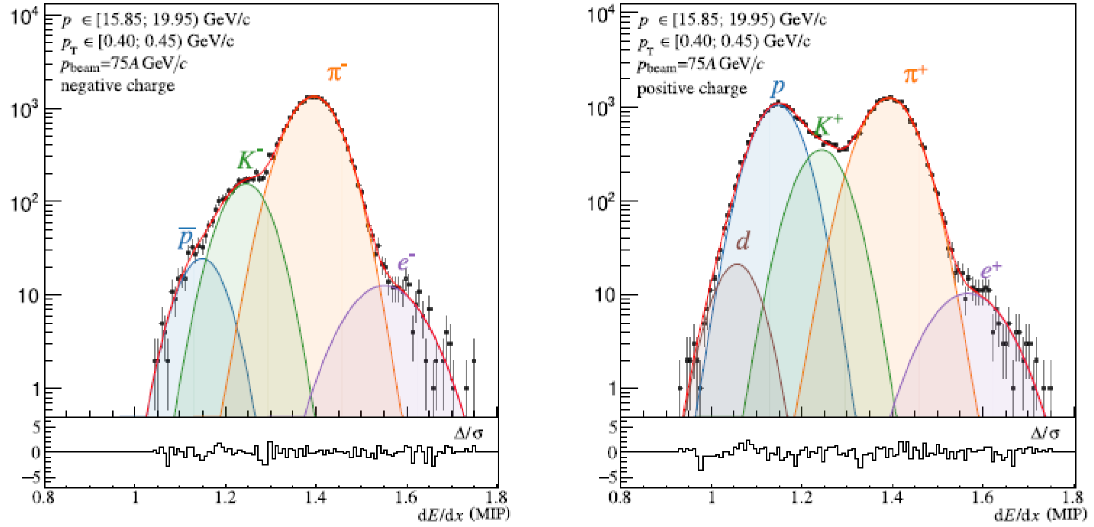
None of the models reproduces
K^+/π^+ratio and T for whole $\langle W \rangle$ range

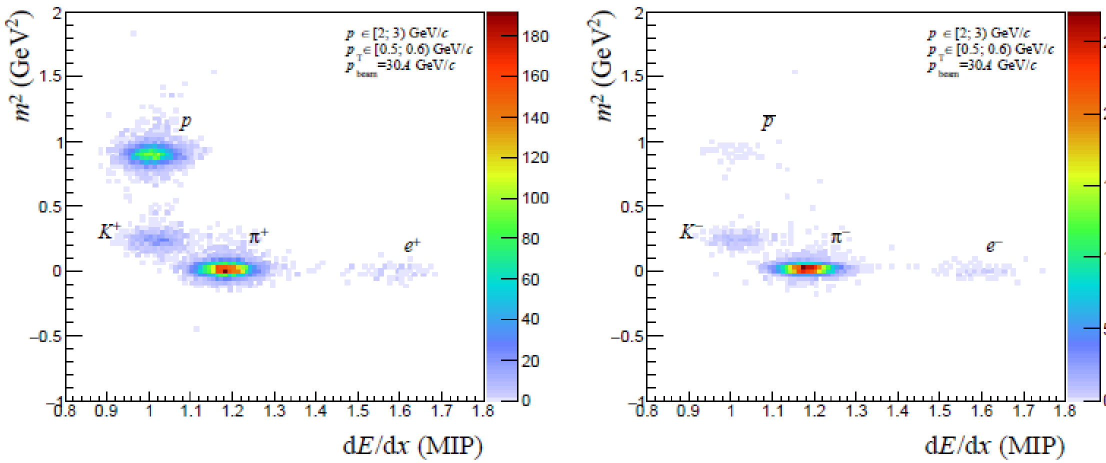
PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private communication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private communication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909;

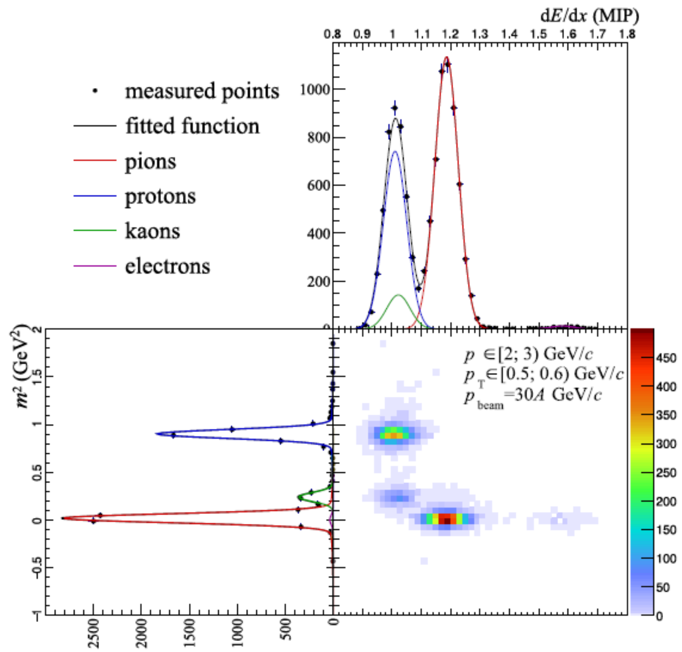
NA61/SHINE: Preliminary (Xe+La); Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc); Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be); Eur.Phys.J.C 77 (2017) 10, 671 (p+p); see Eur.Phys.J.C 84 (2024) 4, 416 (Ar+Sc) for references to world data

Anomaly in charged/neutral kaon production

Charged kaon measurments in Ar+Sc

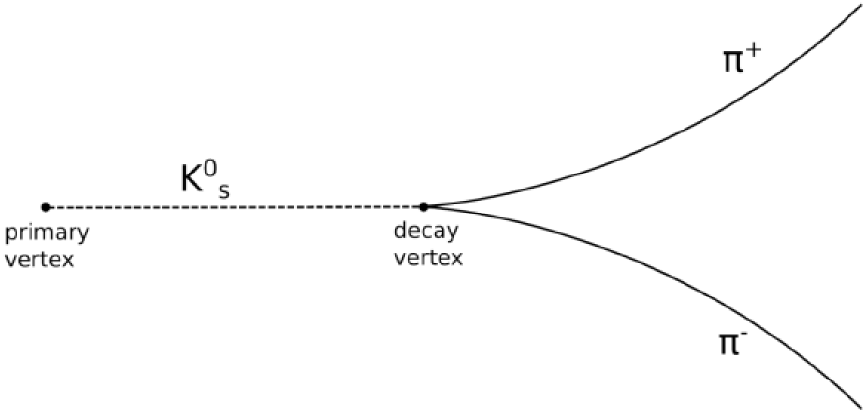


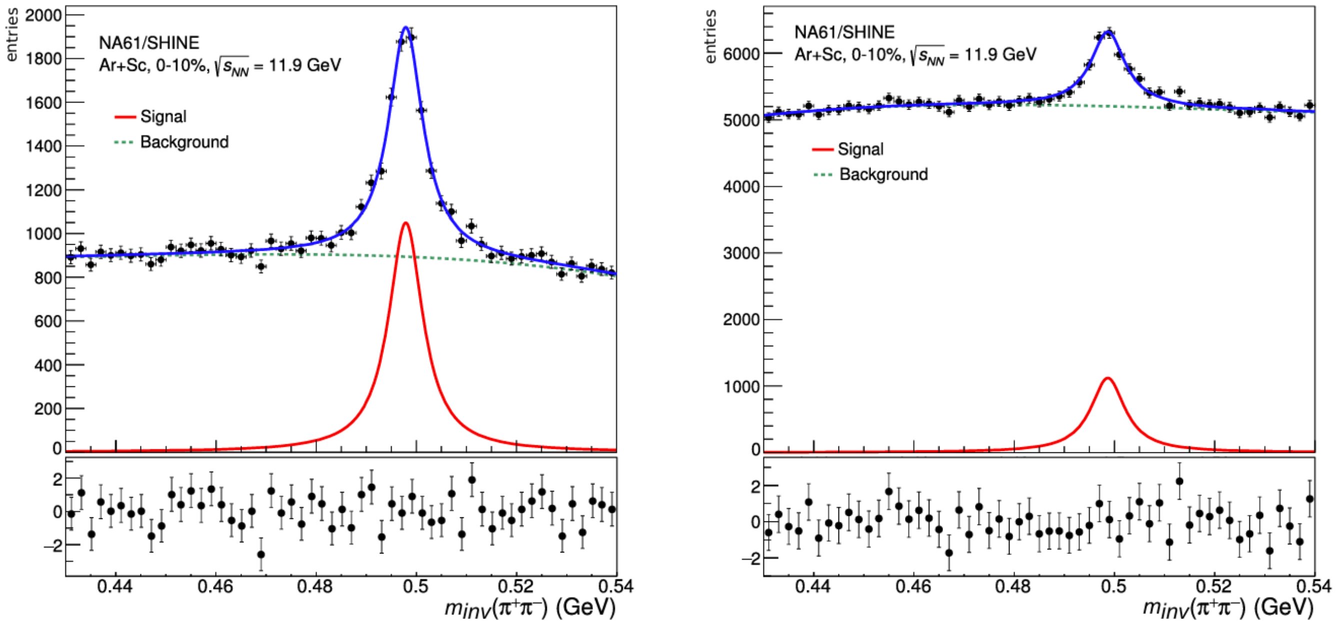




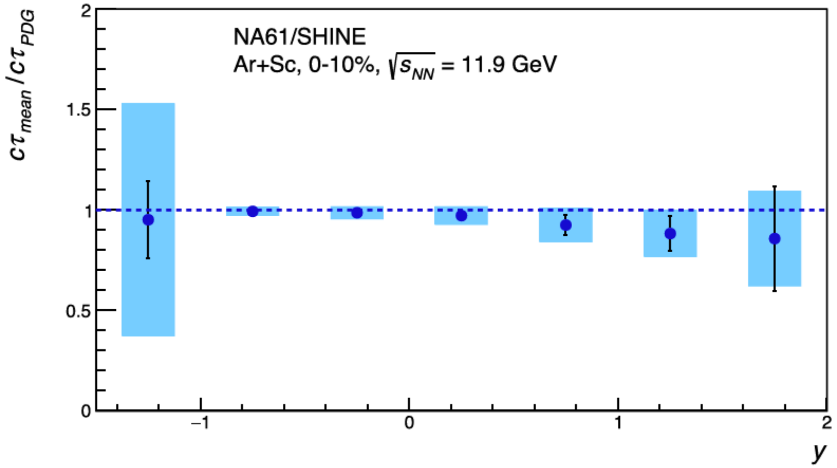
- Measurement based on **d*E*/dx** and ***tof*-d*E*/dx**
- Probability method
- Corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

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

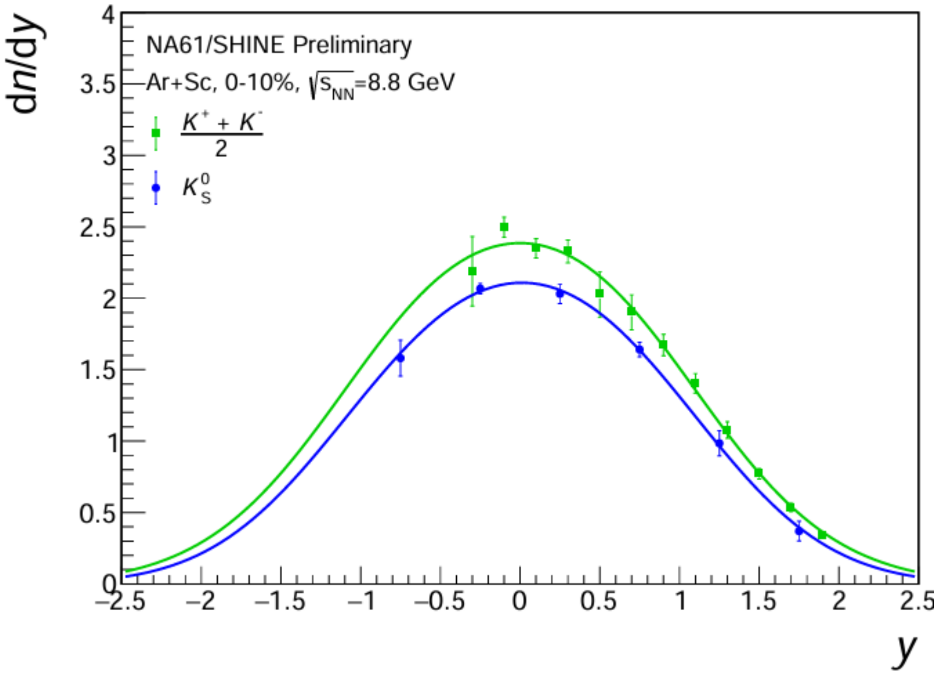


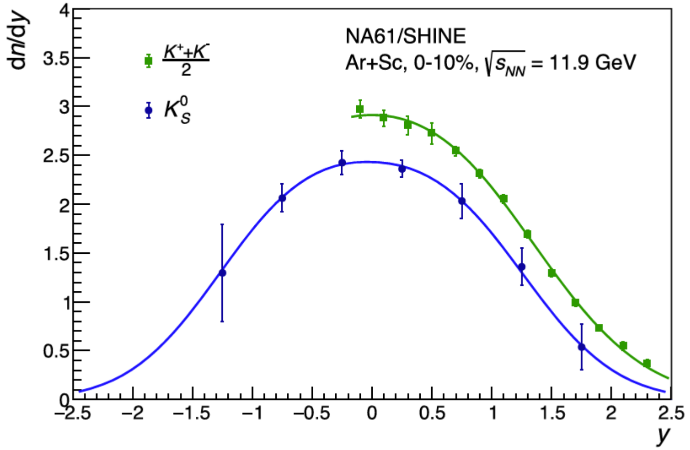


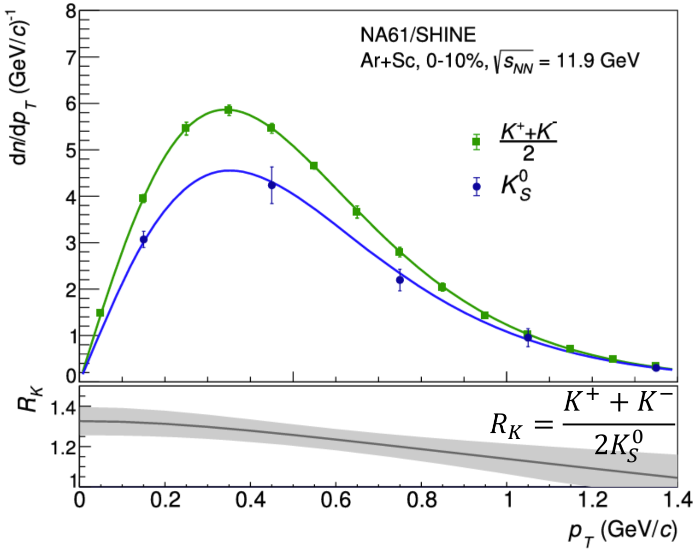
- Reconstruction based on decay topology
- K_s^0 decays into π+ and π− with BR≈69.2%
- Breit-Wigner function is used to describe the signal



K_s^0 production in Ar+Sc







For exact isospin symmetry and *Z=N* collisions

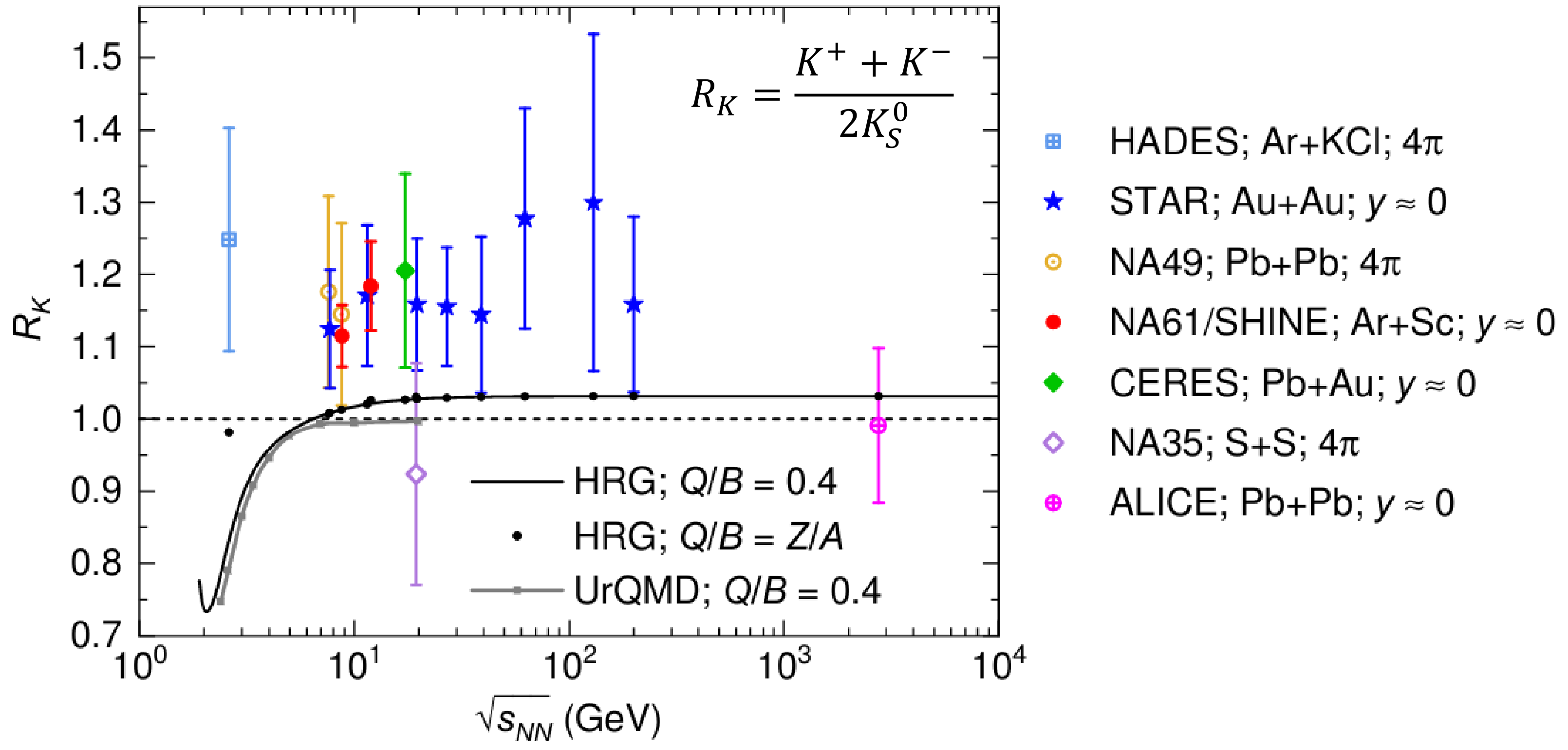
$$\langle K^+(u\bar{s})\rangle = \langle K^0(d\bar{s})\rangle \text{ and } \langle K^-(\bar{u}s)\rangle = \langle \bar{K}^0(\bar{d}s)\rangle;$$

$$\langle K_s^0\rangle = \frac{1}{2}\langle K^0\rangle + \frac{1}{2}\langle \bar{K}^0\rangle = \langle K_L^0\rangle$$

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

NA61/SHINE: Nature Commun. 16 (2025) 1, 2849; Eur.Phys.J.C 84 (2024) 4, 416

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

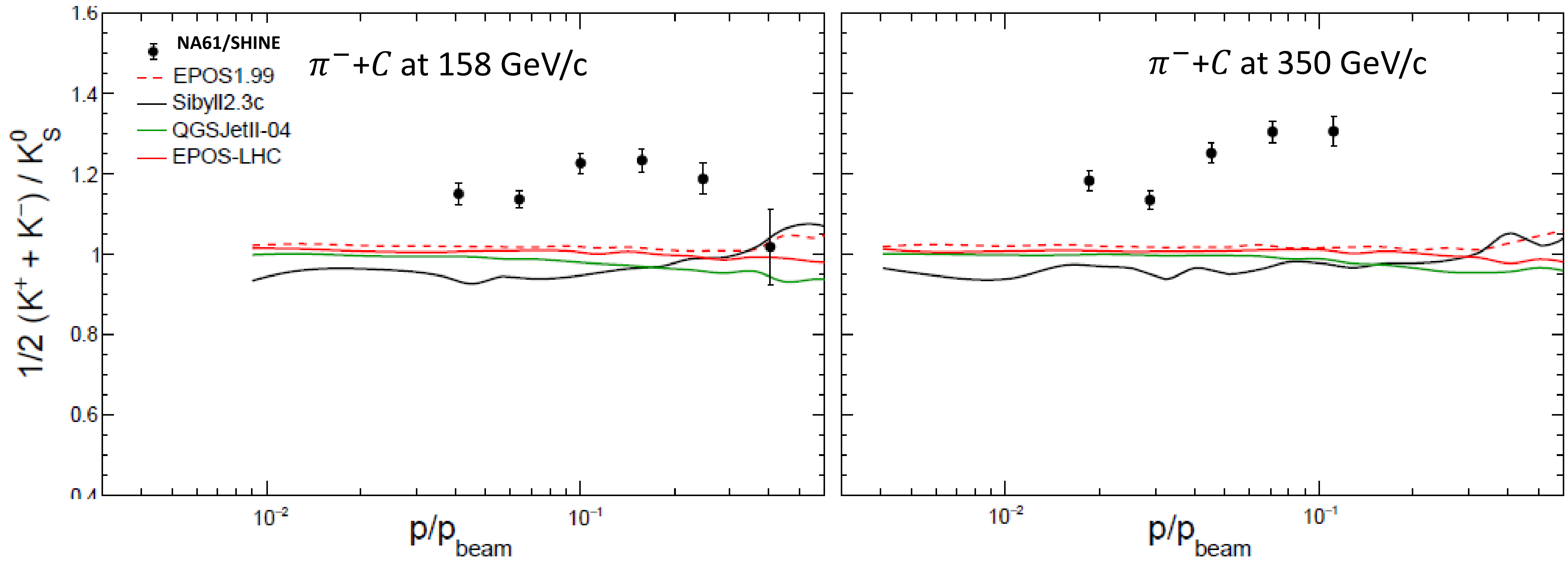


R_K significantly higher than 1

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.

Excess of charged over neutral K meson production, at the level of 12%, was also observed in central Ar+Sc collisions at 8.8 GeV.

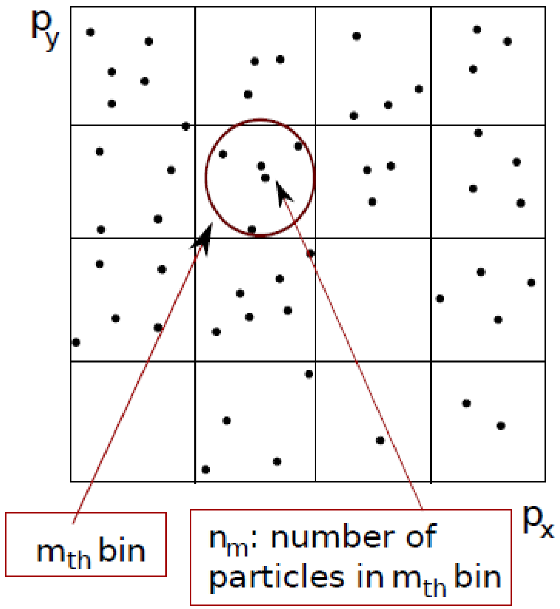
K_s^0 comparison with K^+ and K^- in $\pi^- + C$ at 158 and 350 GeV/c



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

Search for critical point

Proton and charged hadron intermittency



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

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

$$F_r(M) \sim (M^2)^{\phi_r}$$

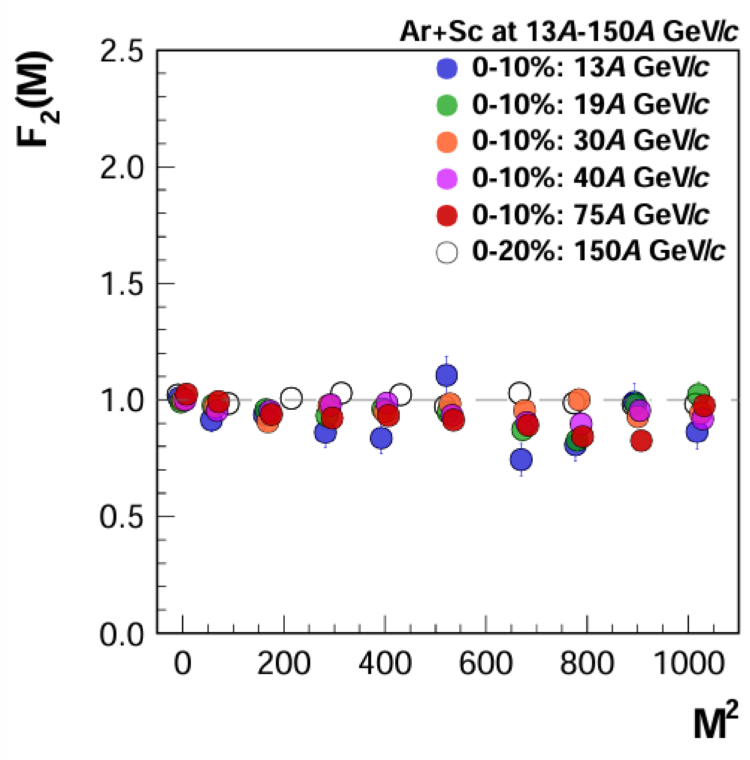
For a pure system exhibiting critical fluctuations and for $r = 2$, a value of $\phi_2 = {}^5/_6$ is expected for protons

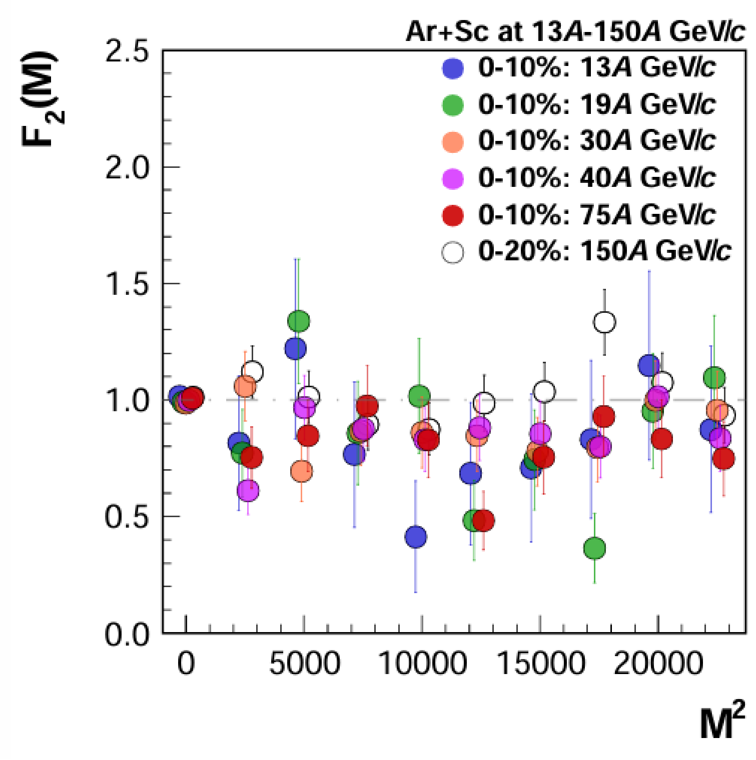
[Antoniou et al., Phys.Rev.Lett. 97 (2006) 032002]

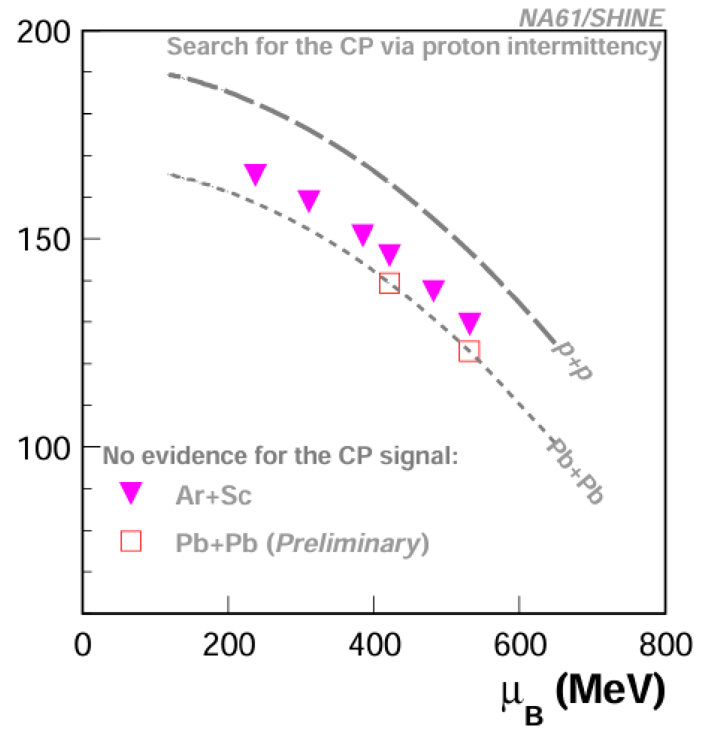
NA61/SHINE used in intermittency analysis:

- Statistically independent points
- Cumulative variables [Białas, Gaździcki, Phys.Lett.B 252 (1990) 483; NA61, Eur.Phys.J.C 83 (2023) 881]

Proton intermittency in Ar+Sc





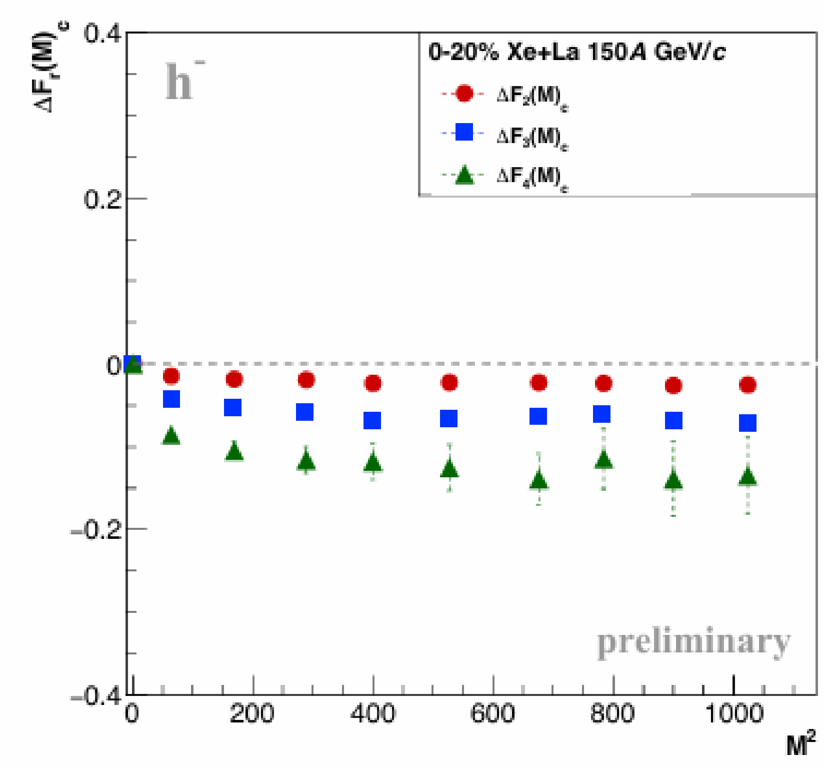


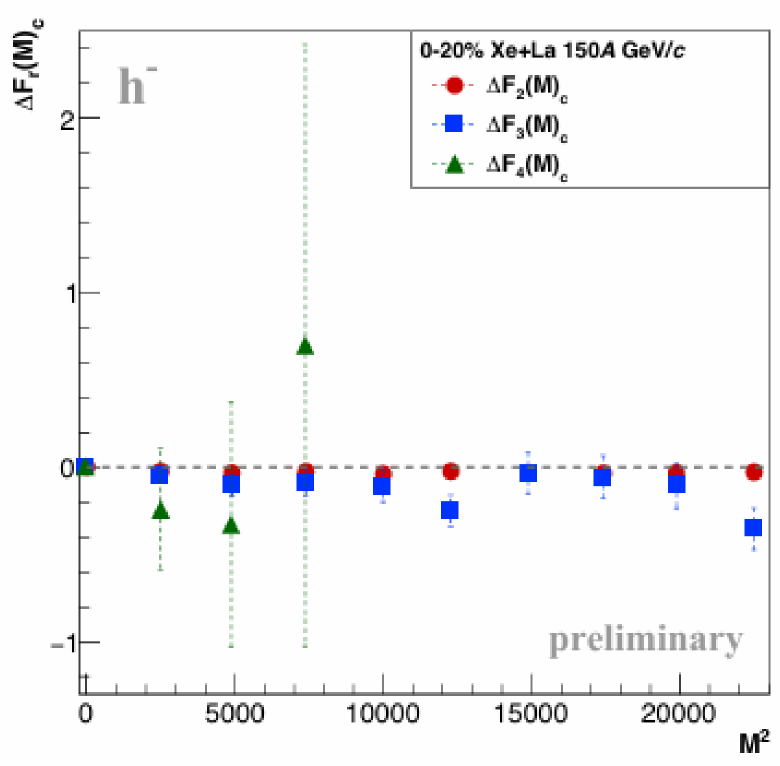
Calculated for number of subdivisions in cumulative transverse momentum space for $1^2 \leq M^2 \leq 32^2$ (left) and $1^2 \leq M^2 \leq 150^2$ (center)

No signal indicating critical point

Negatively charged hadron intermittency

No signal indicating critical point in Xe+La at 150*A* GeV/*c*



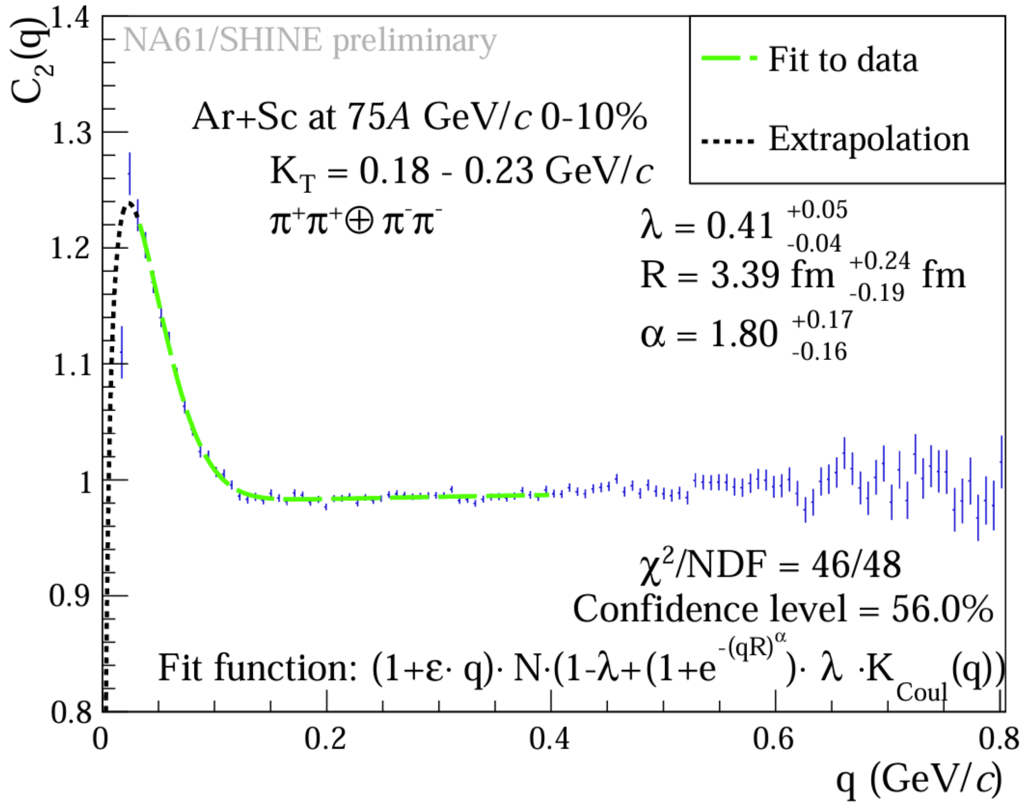


Note that results in cumulative quantities are sensitive to CP and insensitive to SR HBT-like correlations

Calculated for independent sub-sample for each *M* points

Presented using $\Delta F_r\,(M)_c = F_r\,(M) - F_r\,(1)$ where $F_r\,(M)$ and $F_r\,(1)$ are also computed by employing cumulative p_{T} binning; $F_r\,(1) = F_r\,(M)$ for uncorrelated particles in p_{T}

Symmetric Lévy HBT correlations



Two-particle Bose-Einstein 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

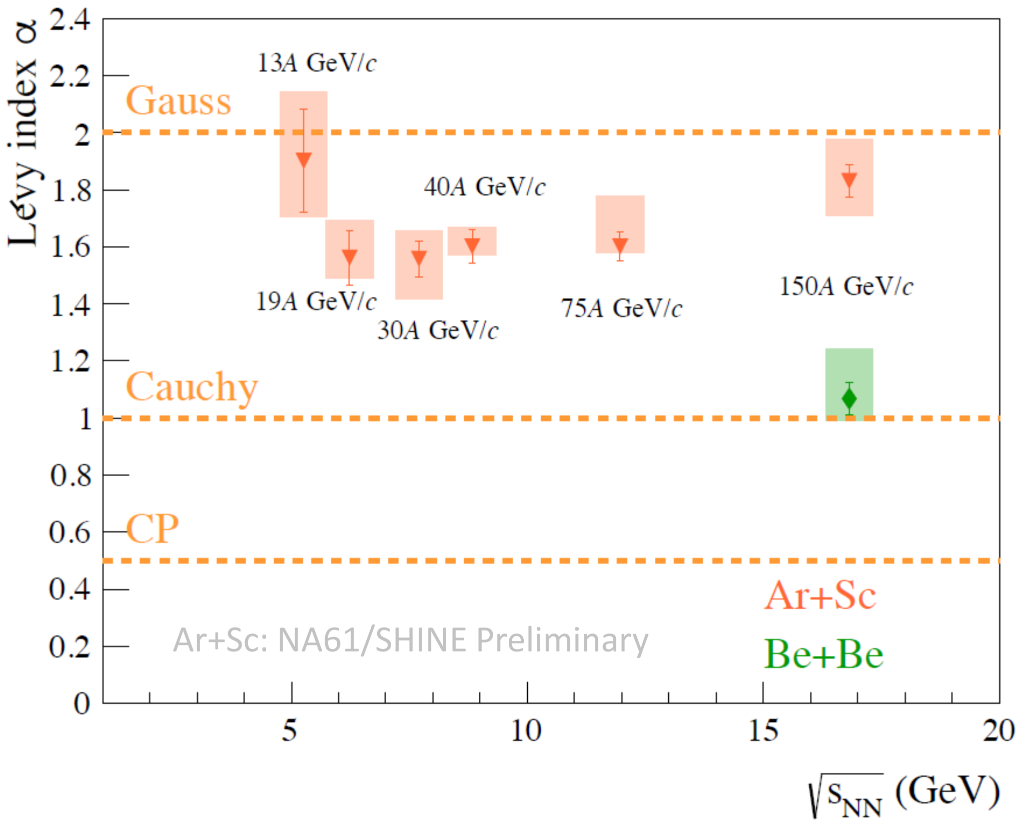
$\alpha < 2$: Generalized central limit theorem

$\alpha \leq 0.5$: Conjectured value at CP (3D Ising model)

[H. Rieger, Phys. Rev. B 52, (1995) 6659, NA61 Eur. Phys. J. C 83, (2023) 919]

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)

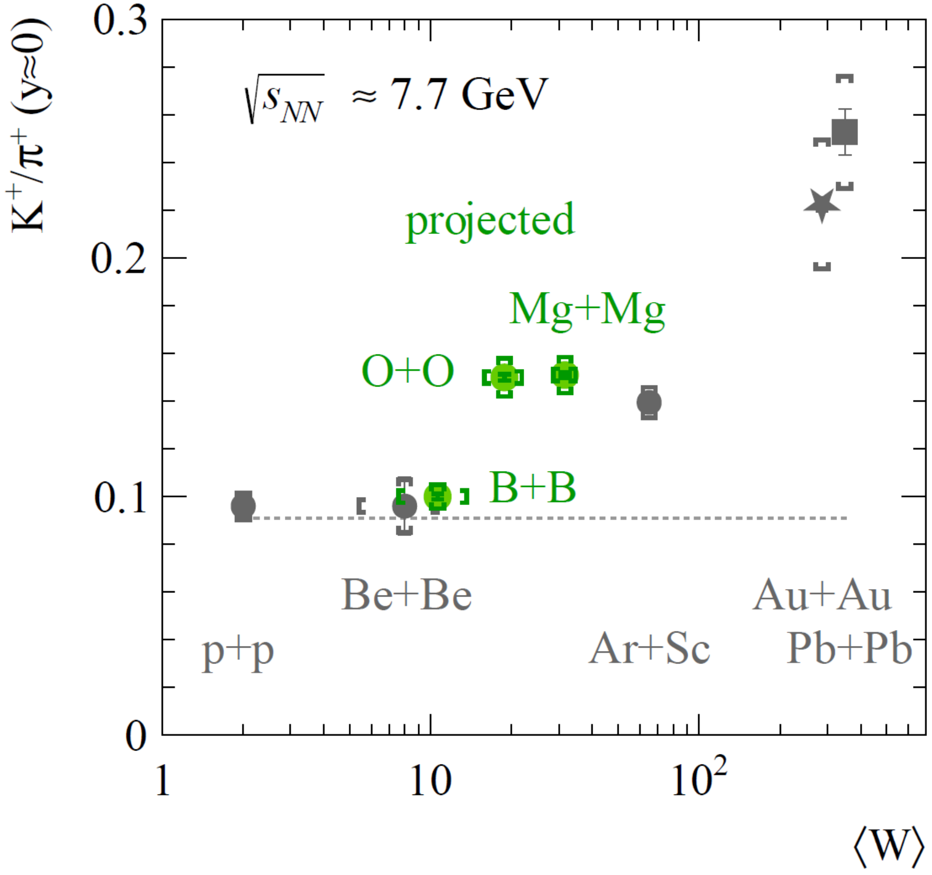
Ar+Sc:
far from Cauchy,
decreases from "close to Gaussian"
at middle SPS energies

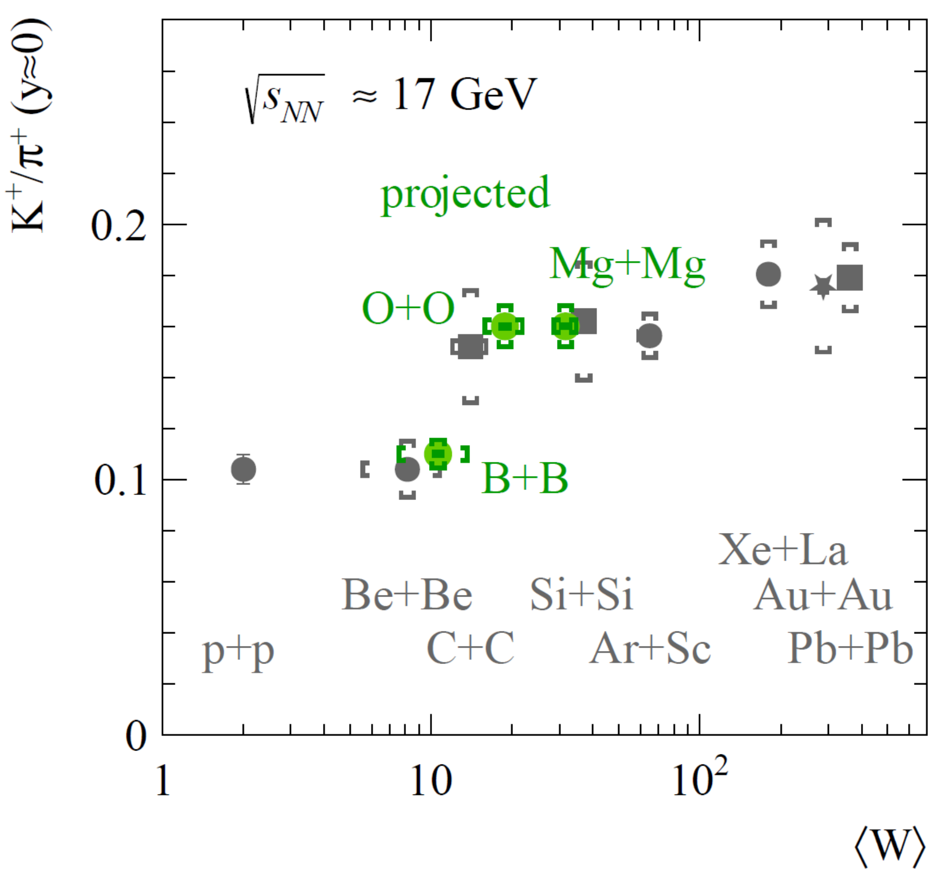
NA61/SHINE: Eur.Phys.J.C 83 (2023) 10, 919 (Be+Be); B. Porfy, PoS ICHEP2024 (2025) 603

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

Note: presented Ar+Sc results were preliminary

Summary

- Unique 2D scan in collision energy and system size is completed
- New preliminary results from Xe+La and Pb+Pb 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+)

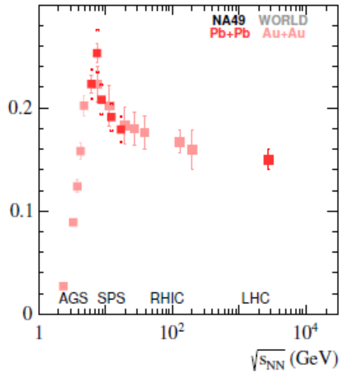
Thank you

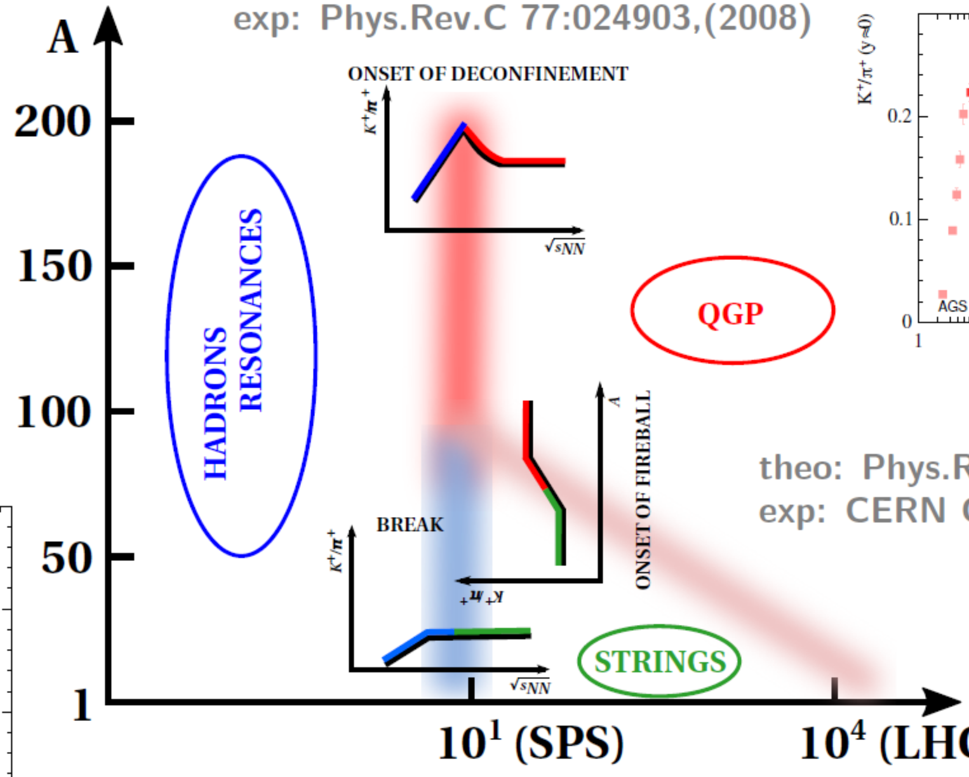
Diagram of high-energy nuclear collisions

Hypothetical domains of hadron-production dominated by:

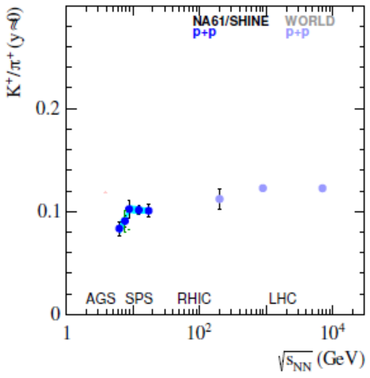
- resonance creation and decays
- string creation and decays
- quark-gluon plasma formation and hadronisation

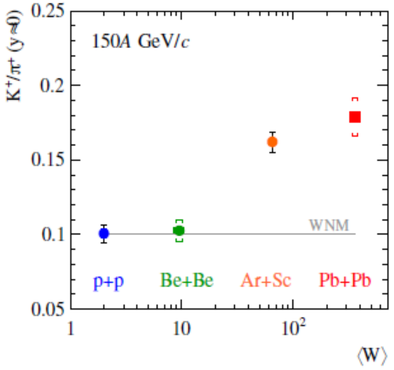
theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)





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

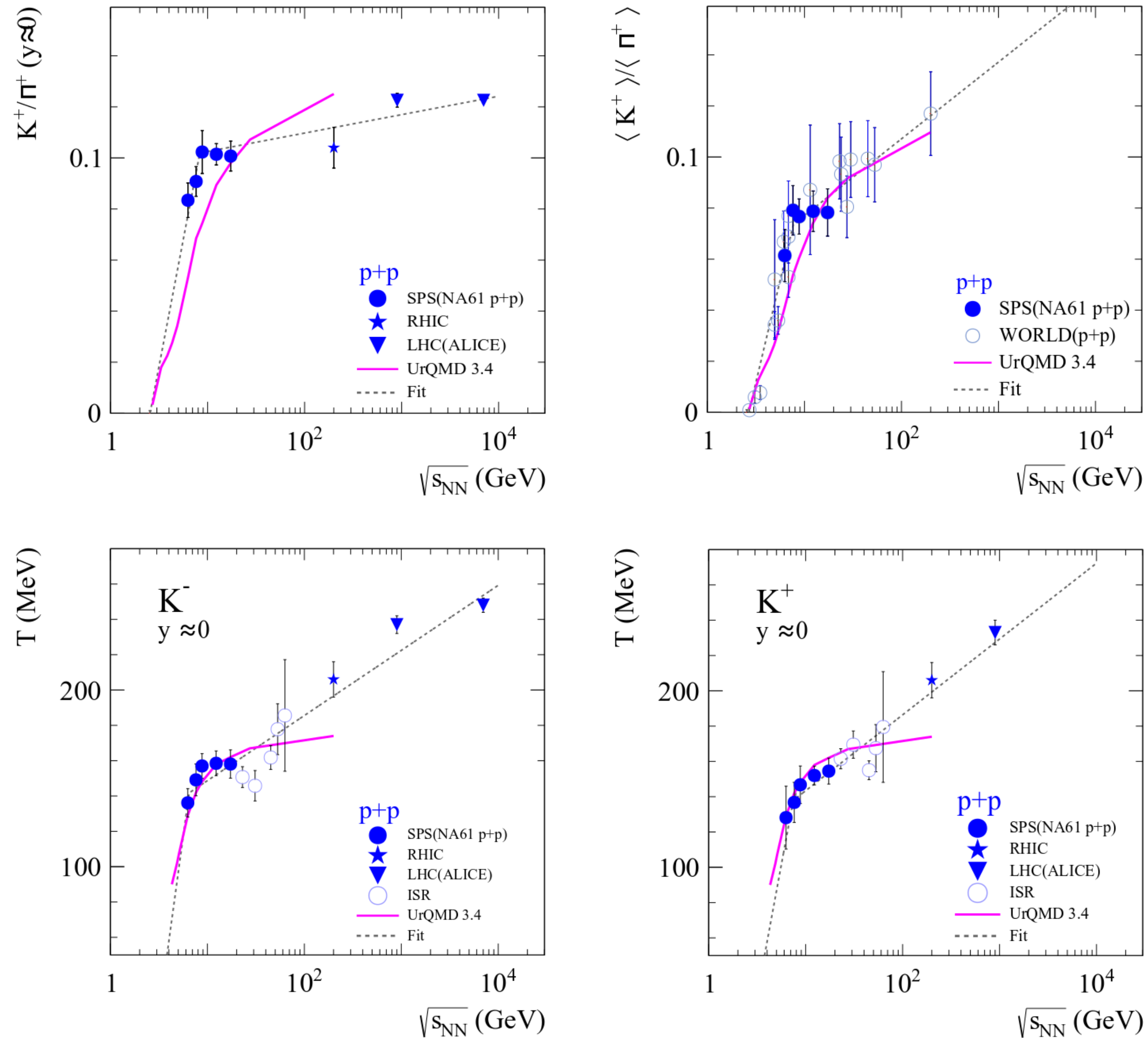




theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

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

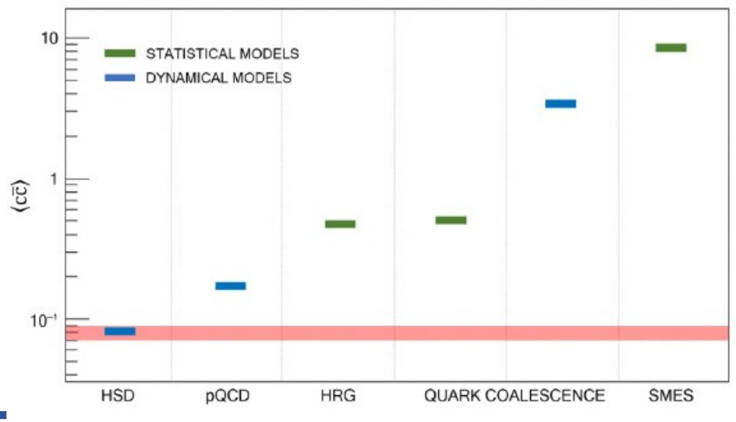
NA61/SHINE in 2022–2026

NA61/SHINE program for 2022–2026

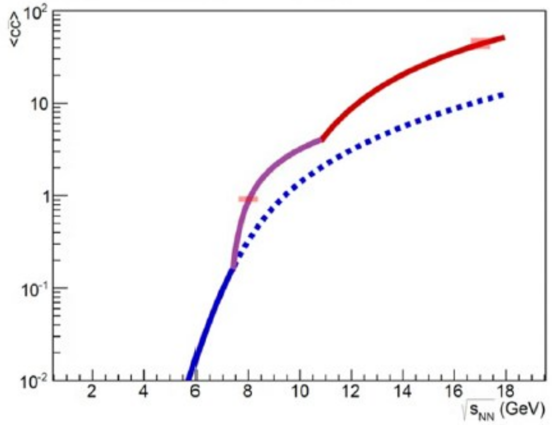
- **What is the mechanism of open charm production?**
- **How does the onset of deconfinement impact open charm production?**
- **How does the formation of quark gluon plasma impact J/ψ production?**

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**.

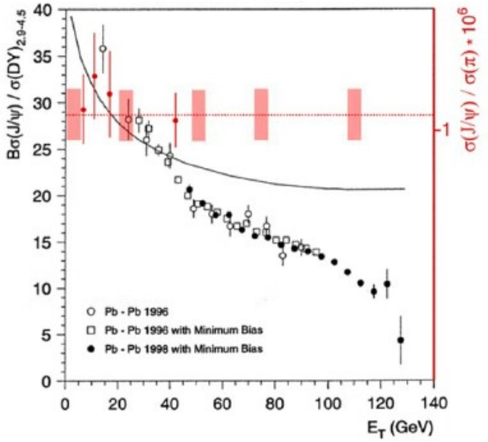
$\langle c\bar{c}\rangle$ and models



$\langle c\bar{c}\rangle$ 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
$c\tau = 309.8\ \mu$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: $\langle D^+ + D^- \rangle < \langle D^0 + \overline{D^0} \rangle$

$D^*(2007)^0$ $I(J^P) = \frac{1}{2}(1^-)$
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

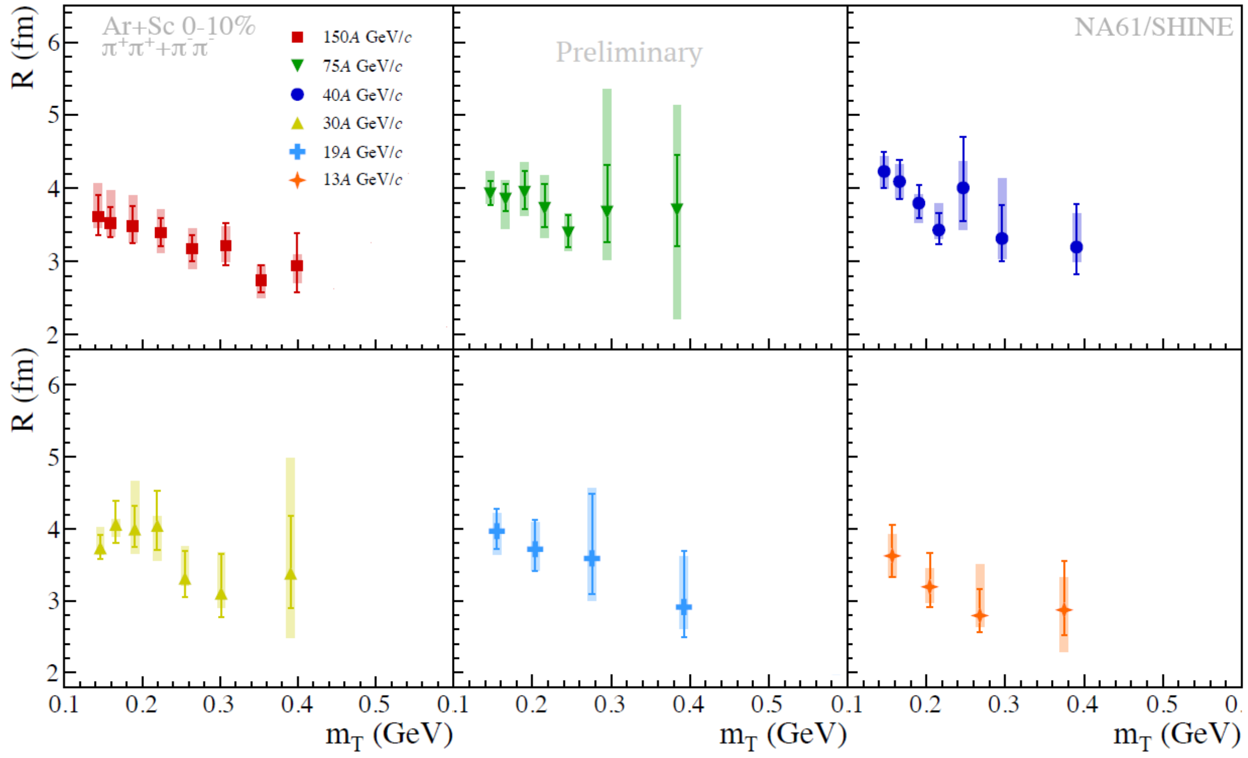
$\boxed{K^0}$ $I(J^P) = \frac{1}{2}(0^-)$

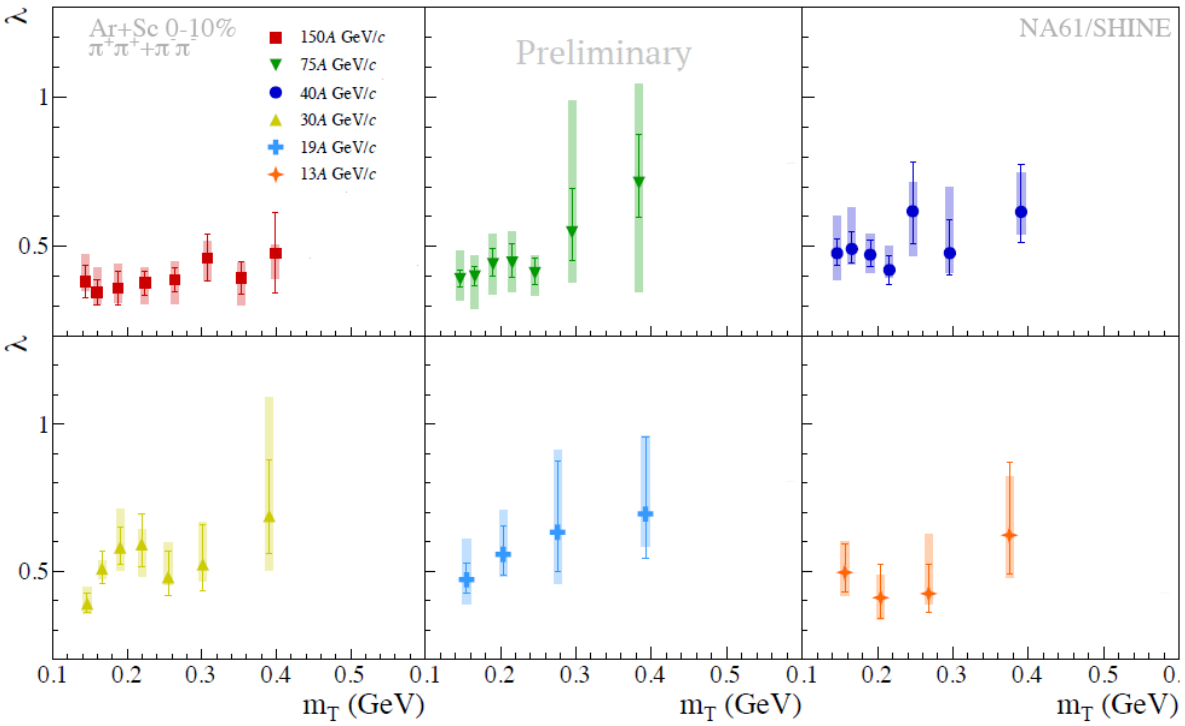
50% K_S, 50% K_L
Mass $m = 497.611 \pm 0.013$ MeV $(S = 1.2)$
$m_{K^0} - m_{K^{\pm}} = 3.934 \pm 0.020$ MeV $(S = 1.6)$

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).

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

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
- d*E*/d*x* analysis uses TPC energy loss information to identify particles
- *tof-*d*E*/d*x* method estimates number of π, K, p using an energy loss and a particle time of flight measurements