Highlights from NA61/SHINE
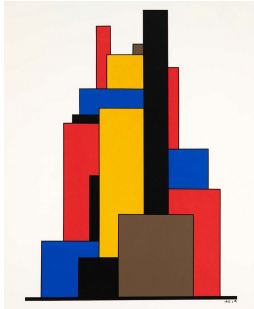
24th Zimányi School,
Winter Workshop on Heavy Ion Physics

Barnabás Pórfy for the NA61/SHINE
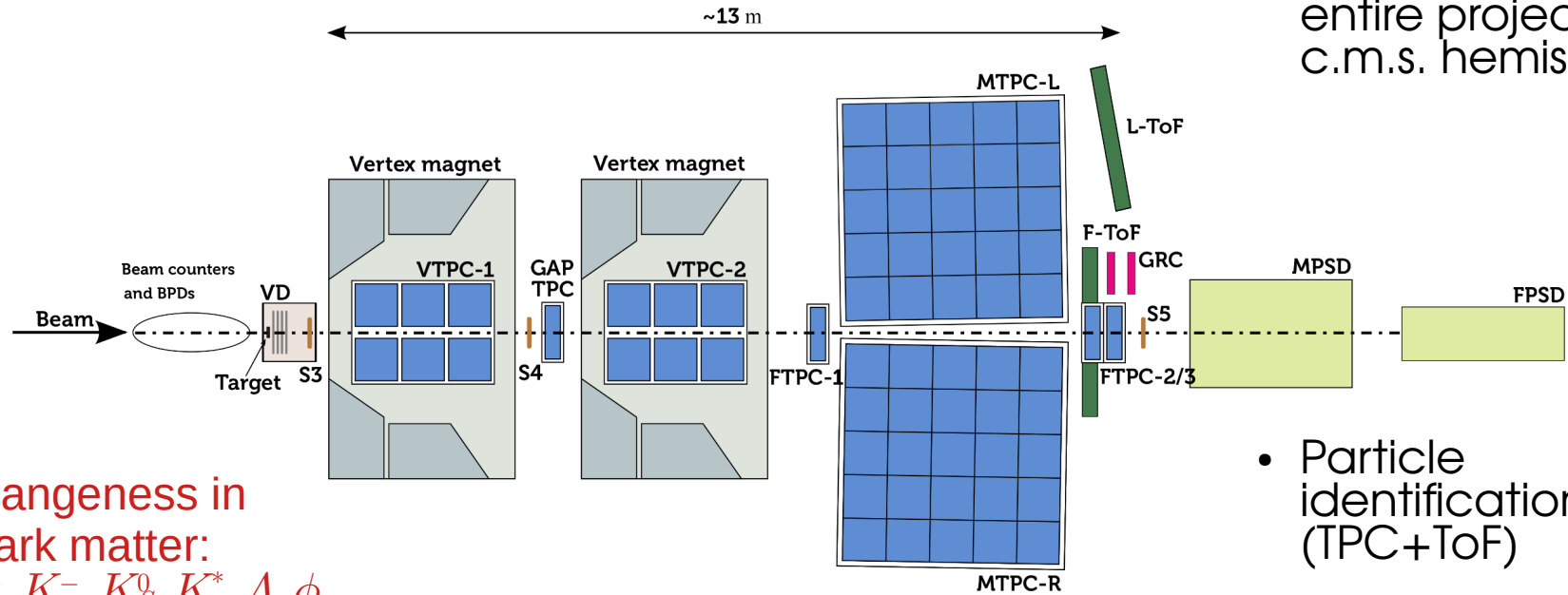HUN-REN Wigner RCP,
Eötvös Loránd University

2024.12.04.

NA61/SHINE at CERN SPS

- Multipurpose fixed-target spectrometer with unique capabilitites

- Coverage of the entire projectile c.m.s. hemisphere

~13 m

MTPC-L

L-ToF

Vertex magnet

Vertex magnet

F-ToF

GRC

MPSD

FPSD

Beam counters and BPDs

VD

VTPC-1

GAP TPC

VTPC-2

S5

Beam

Target

S3

S4

FTPC-1

FTPC-2/3

MTPC-R

- Particle identification (TPC+ToF)

- Strangeness in quark matter:
$K^+, K^-, K^0_S, K^*, \Lambda, \phi$

- Heavy quarks:
D^0 and $\overline{D}^0$

- Correlations, fluctuations, HBT, intermittency...

Barnabás Pórfy for the NA61/SHINE

Research Program of NA61/SHINE

- Strong interaction physics
  - Study the onset of deconfinement
  - Search for the critical point
  - Measurement of open charm

- Neutrino and cosmic-ray physics
  - Measurements for neutrino programs
  - (J-PARC, Fermilab)
  - Measurements for cosmic-ray physics
  - (Pierre-Auger, KASCADE, satellite experiments)

Barnabás Pórfy for the NA61/SHINE
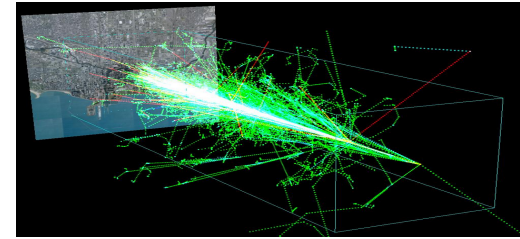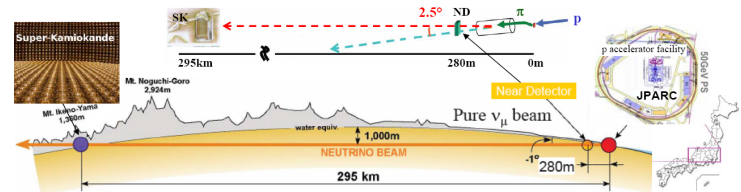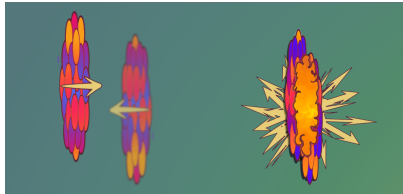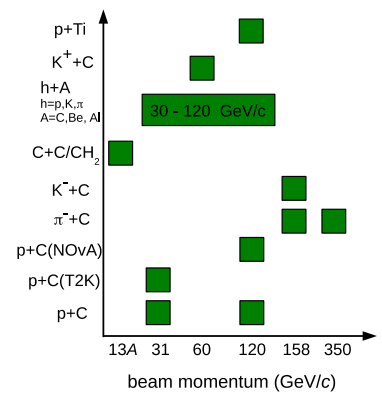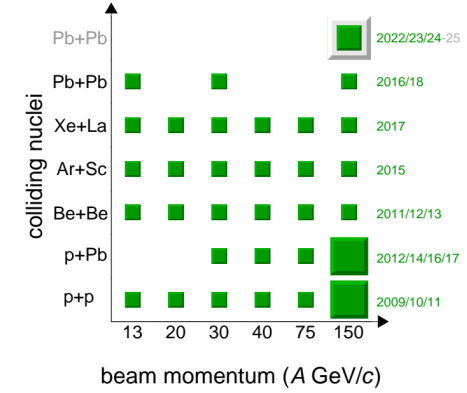
Strong Interaction Program

- Onset of deconfinement, onset of fireball
  - Beginning of QGP creation in heavy-ion collisions with an increase in collision energy
  - The transition from non-equilibrium strings to QGP with increasing masses of colliding nuclei
- Critical Point
  - The endpoint of first-order phase transition line that has properties of second-order phase transition
- Open charm
  - Direct measurement of open charm at SPS energies
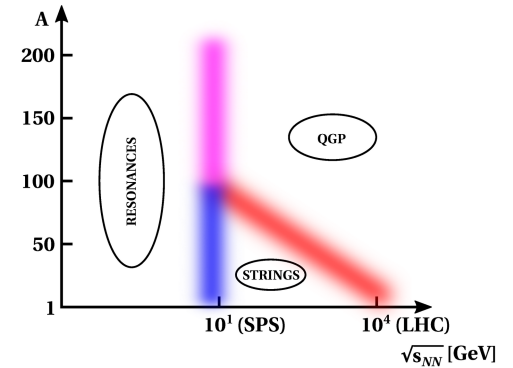
Universe 2023, 9(2), 106
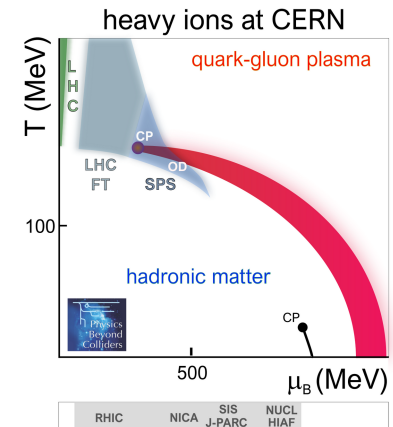
CERN-PBC-REPORT-2018-003

Onset of Deconfinement

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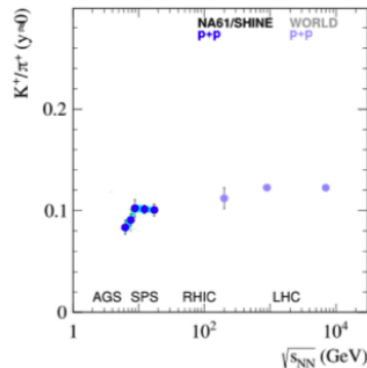
Onset of Deconfinement, Onset of Fireball

- Measured by the ratio of positively-charged kaons and pions at mid-rapidity
- Approx. proportional to the ratio of (anti-)strange quarks to entropy
- By measuring strangeness-to-entropy ratio one can probe the onset of deconfinement

theo: Phys.Part.Nucl. 51 (2020) 3, 337-339

exp: Phys.Rev.C 102 (2020) 011901

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

exp: Phys.Rev.C 77 (2008) 024903

ONSET OF DECONFINEMENT

HADRONS RESONANCES

QGP

BREAK

ONSET OF FIREBALL
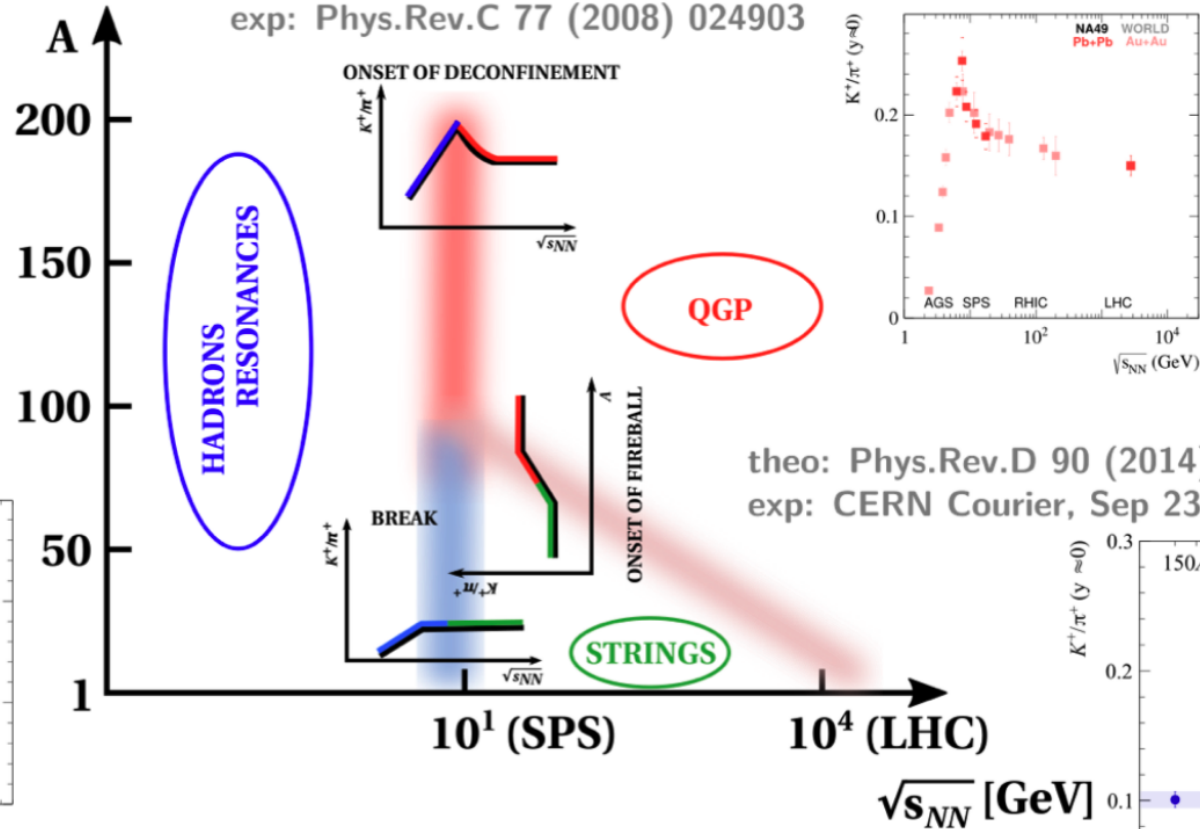
theo: Phys.Rev.D 90 (2014) 025031

exp: CERN Courier, Sep 23rd, 2019

STRINGS

10^1 (SPS) 10^4 (LHC)

$\sqrt{s_{NN}}$ [GeV]

2024.12.04

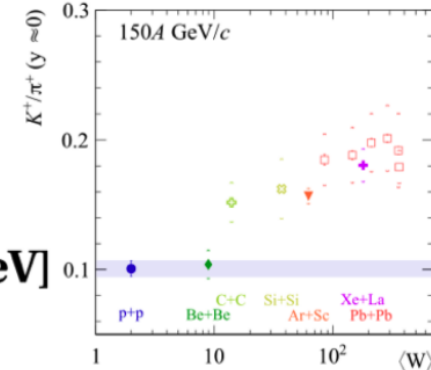# Probing the Onset of Deconfinement

- System size dependence of K^+/π^+ ratio
- Rapid change of ratio signifies onset of deconfinement   Other NA61/SHINE data: EPJC 77 (2017) 671
- <u>Xe+La</u> between intermediate sized (Ar+Sc)   EPJC 81 (2021) 73, EPJC 84 (2024) 416
            and large sized (Pb+Pb) systems
- No indication of horn

Xe+La, preliminary
$\sqrt{s_{NN}} = 7.6\text{-}11.9$ GeV (0-10%)
16.8 GeV (0-20%)

2024.12.04
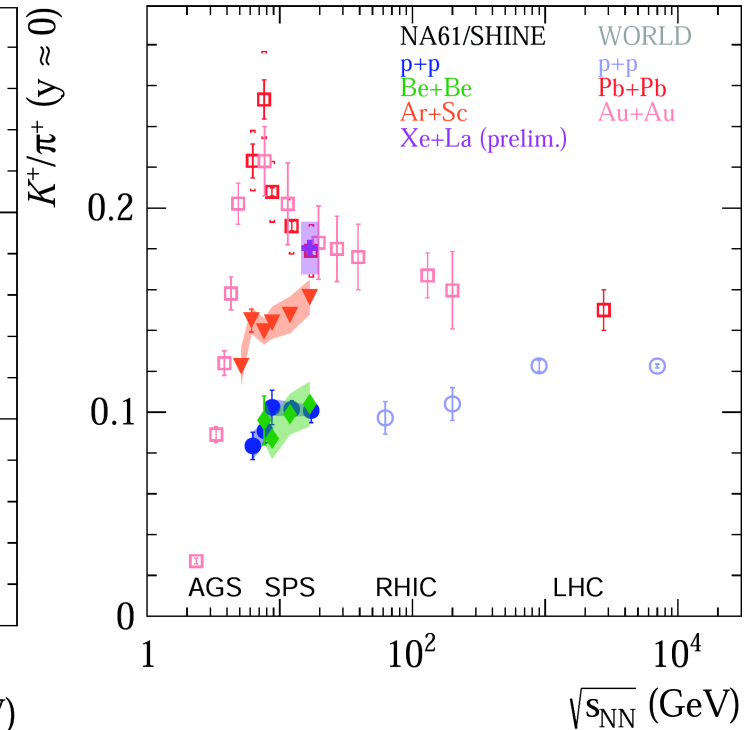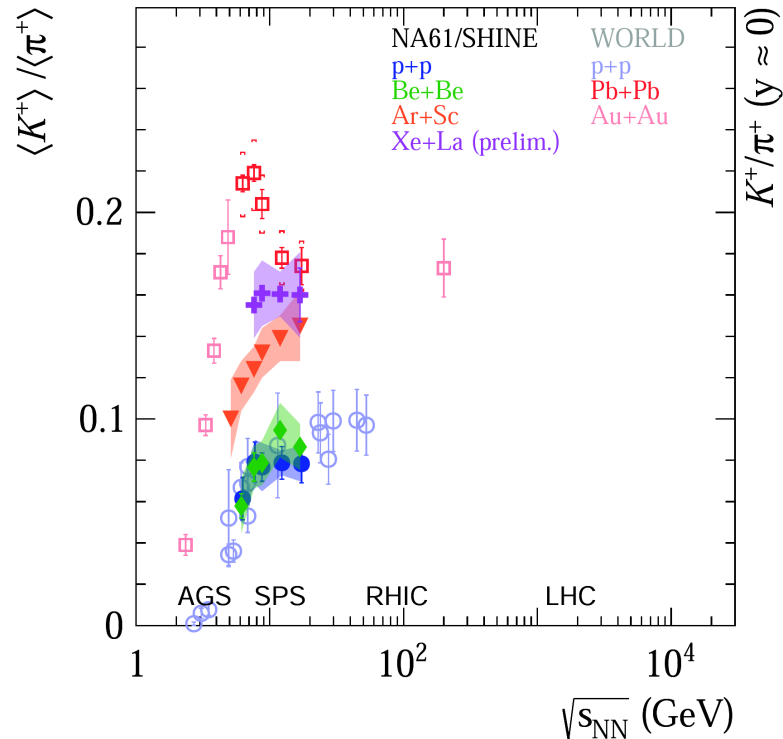
Probing the Onset of Deconfinement

- <u>Pb+Pb</u> measurement at 30A GeV/c
- Good agreement with previous NA49 Pb+Pb results

More details: slides of Uzair Shah, Wednesday, 11:25

Pb+Pb, preliminary
$\sqrt{s_{NN}} = 7.7$ GeV (0-7.2%)

2024.12.04

Barnabás Pórfy for the NA61/SHINE
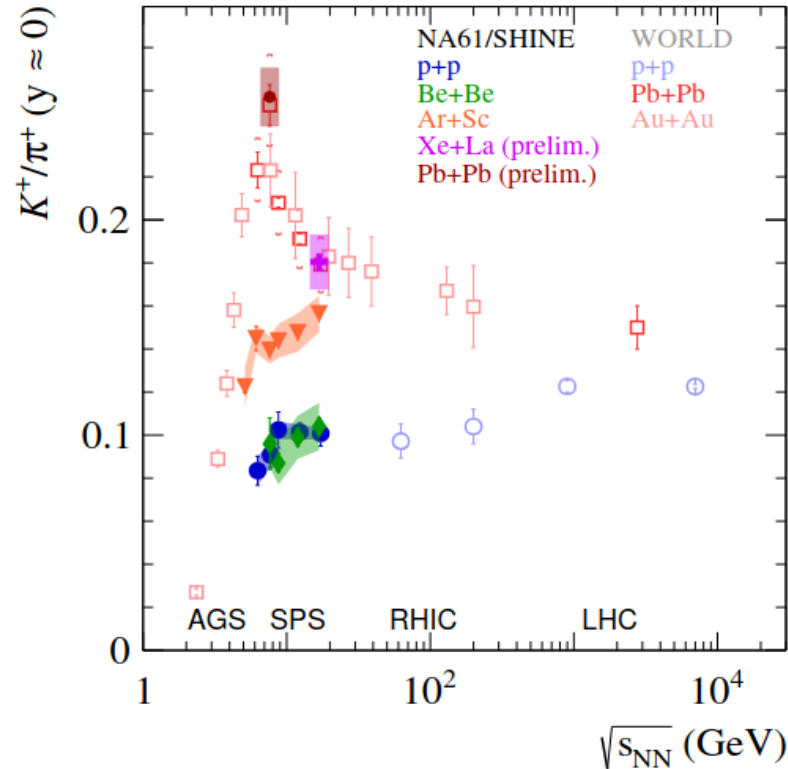
Probing the Onset of Deconfinement

- Similar decline of Λ/π ratio in Ar+Sc and Pb+Pb

- No maximum observed in E_s compared to Pb+Pb

$$E_s = \frac{\langle\Lambda\rangle + \langle K + \overline{K}\rangle}{\langle\pi\rangle}$$

More details: slides of Yuliia Balkova, Wednesday, 16:50

Barnabás Pórfy for the NA61/SHINE

Critical Point Search

Barnabás Pórfy for the NA61/SHINE

Critical Point Search: Intermittency

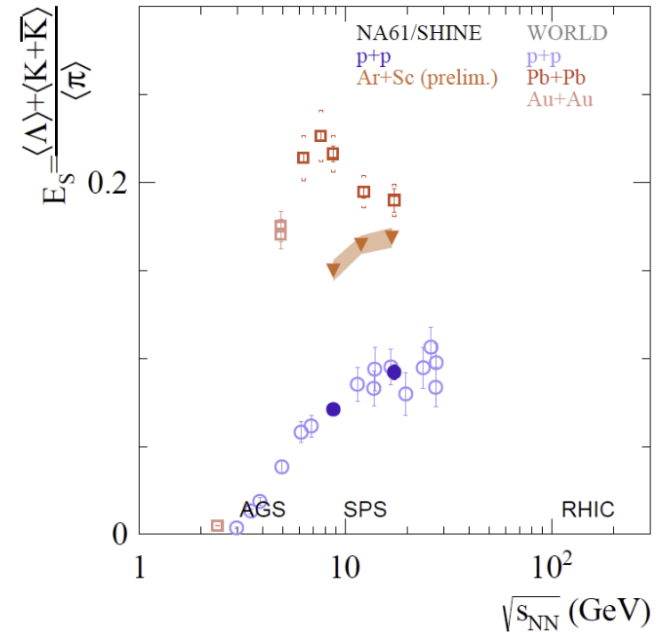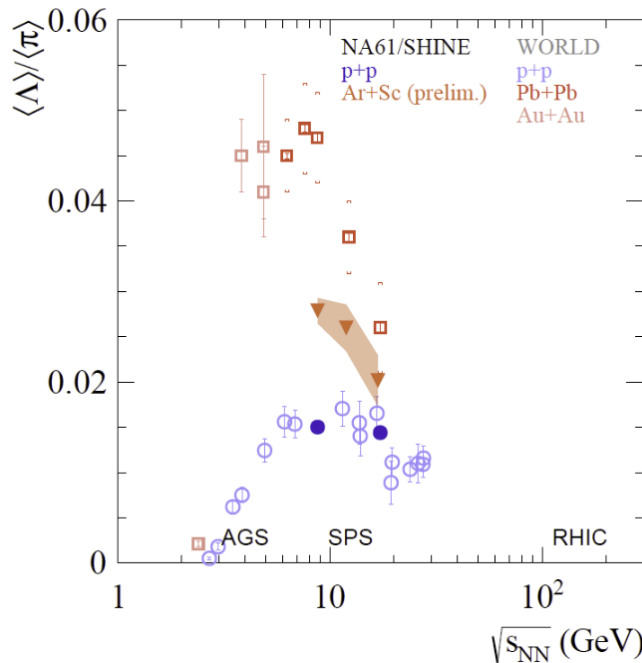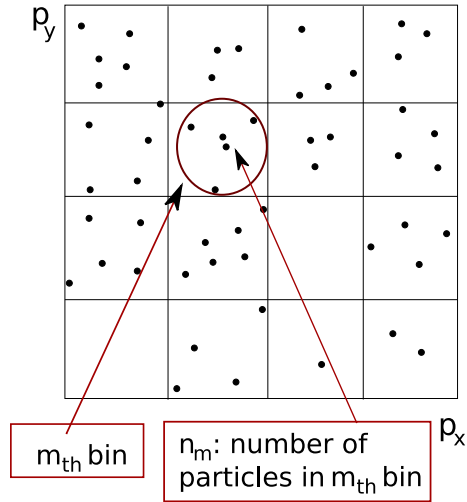p_y

p_x

m$_{th}$ bin

n_m: number of particles in m$_{th}$ bin

- At system freezeing-out near or at CP, its properties expected to be different from an ideal gas

  - System represents a simple fractal

  - Scaled factorial moments $F_r(M)$ are expected to follow a power-law behaviour:

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

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

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

M^D – number of equally sized cells in D dim. space
n_m – number of particles in m^{th} bin
$\langle \dots \rangle$ – averaging over events

Power-law Model
Exponent: 0.75
corr./all: 2%

$F_2(M)$

M^2
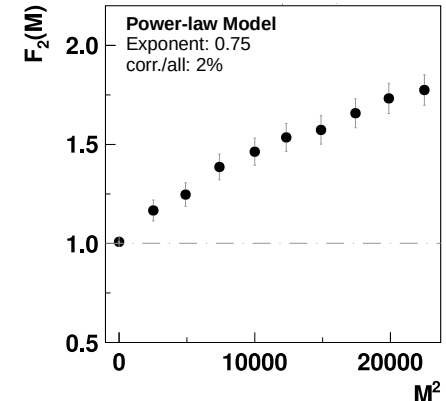
Białas, Peschanski, NPB 273 (1986) 703
Wosiek, APPB 19 (1988) 863
Asakawa, Yazaki, NPA 504 (1989) 668
Barducci et al., PLB 231 (1989) 463
Satz, NPB 326 (1989) 613
Antoniou et al., PRL 97 (2006) 032002
Czopowicz, arxiv:2309.13706

Barnabás Pórfy for the NA61/SHINE

Critical Point Search: Intermittency

- Cumulative quantities (p_x, p_y are transformed to obtain a uniform 2D distribution) Białas, Gazdzicki, PLB 252 (1990) 483
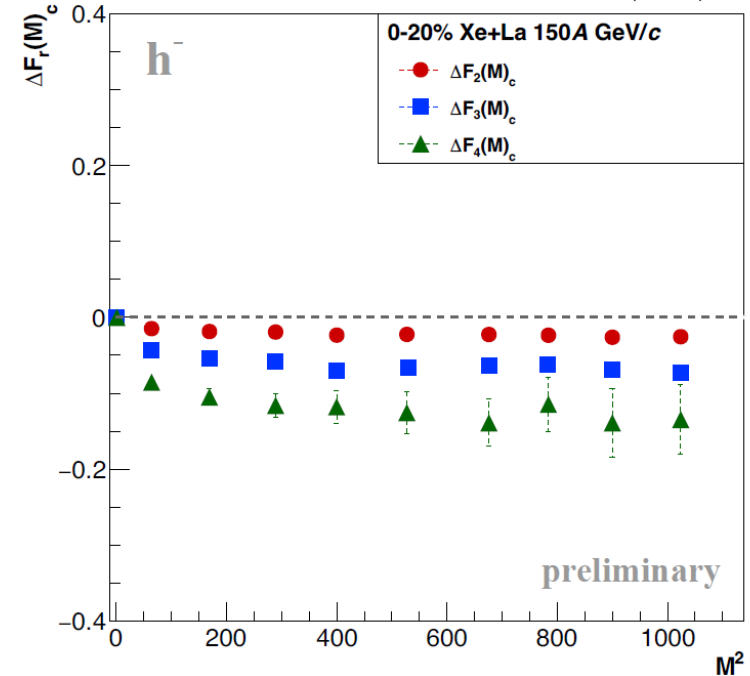
- Statistically independent data points NA61/SHINE, EPJC 83 (2023) 881

- Number of subdivisions in cumulative transverse momentum space

$$1^2 \leq M^2 \leq 32^2$$

- Xe+La central (0-20%) at 150A GeV/c, h^- intermittency no signal indication of the critical point using cumulative p_T binning

More details: talk of Valeria Zelina Reyna Ortiz Wednesday, 11:40

Barnabás Pórfy for the NA61/SHINE

Critical Point Search: Femtoscopy
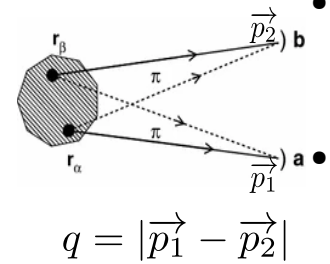
- Bose-Einstein correlations: tool to measure spatial correlations in heavy ion collisions

D. A. Brown and P. Danielewicz. Phys. Lett. B 398 (1997), pp. 252–258.
S. S. Adler et al., PHENIX Coll. Phys. Rev. Lett. 98 (2007), p. 132301

- Using symmetric Lévy stable distributions we can measure:

Csörgő, Hegyi, Novák, Zajc, AIP Conf. Proc. 828 (2006) 525

$$q = |\vec{p_1} - \vec{p_2}|$$

  - Shape of the source

  - Proximity to the CP
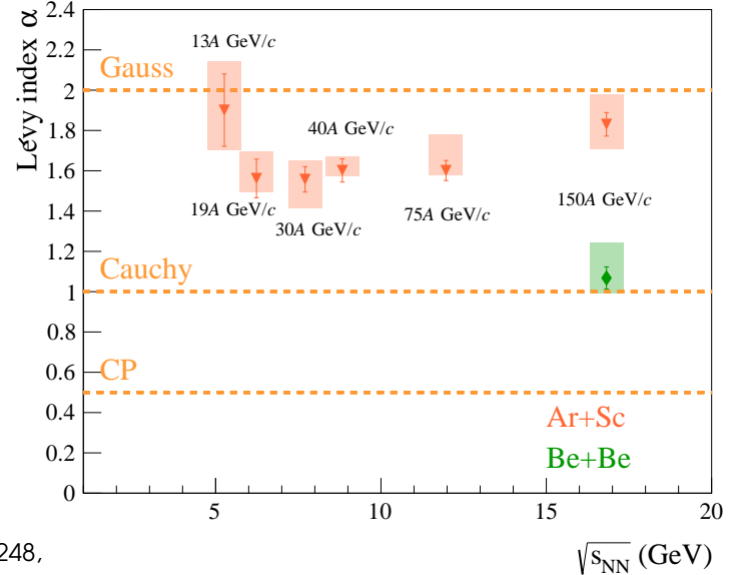
- Correlation function using Lévy source + FSI

$$C(Q) = 1 - \lambda + \left(1 + e^{-|QR|^{\alpha}}\right) \cdot \lambda \cdot K_{\text{Coul}}(Q; \alpha, R)$$

Yu. Sinyukov et al., Phys.Lett.B432 (1998) 248,
M.G. Bowler Phys.Lett.B270 (1991) 69

- Ar+Sc central (0-10%) results show small non-monoticity, **far from CP**, close to Gaussian

Ar+Sc, 0-10% central, NA61/SHINE preliminary, Universe 9 (2023) 7, 298; arXiv:2406.02242, 2410.13975
**Be+Be**, 0-20% central, NA61/SHINE, EPJC 83 (2023) 919

More details: my poster and flash talk Thursday, 13:32

Barnabás Pórfy for the NA61/SHINE

Strange Resonances

Barnabás Pórfy for the NA61/SHINE

Strange Resonances

- Study of $K^*(892)^0$ production in 0-10% central Ar+Sc at 40A, 75A and 150A GeV/c
- K^* lifetime (≈ 4 fm/c) comparable with the time between two freeze-outs

$K^*(892)^0$

Chemical freeze-out   **Kinetic freeze-out**
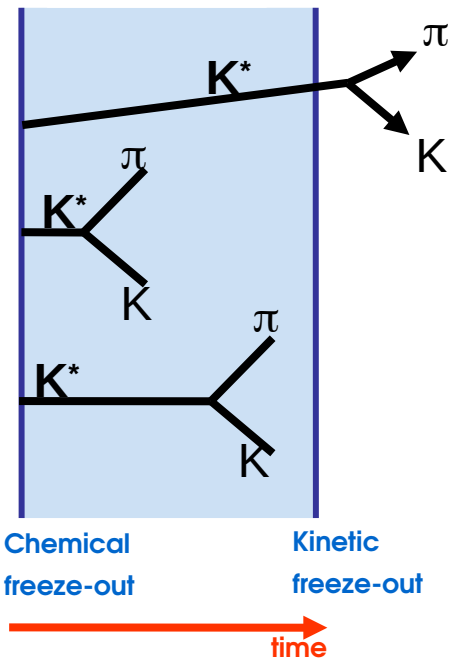
time

- K^* resonances may decay inside fireball
- Suppression of observed K^* yield
- Assuming no regeneration processes
  the **Δt** between freeze-outs can be determined   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

2024.12.04   Barnabás Pórfy for the NA61/SHINE

Strange Resonances

- No K^* suppression in Ar+Sc $\sqrt{s_{NN}} = 8.8$ GeV?
- Ar+Sc $\approx$ Pb+Pb at $\sqrt{s_{NN}} \approx 17$ GeV
- Time between freeze-outs Ar+Sc $\approx$ Pb+Pb at $\sqrt{s_{NN}} \approx 17$ GeV

NA61/SHINE preliminary
arXiv:2409.20229

2024.12.04

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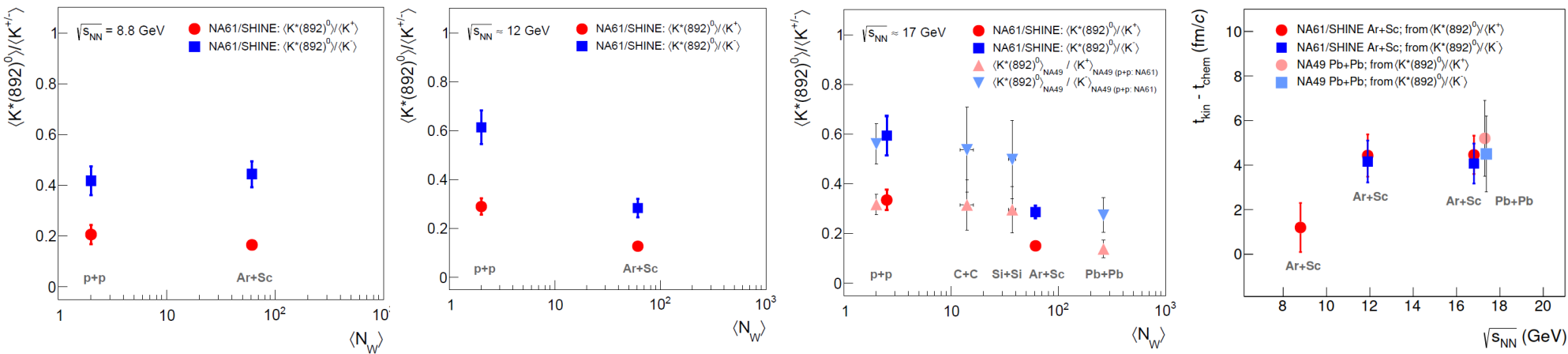
Strange Resonances

- Production of $\phi(1020)$ meson

  – Lightest meson with hidden strangeness

  – Constrains hadron production models

  – Comparison to Pb+Pb and p+p results

- Preliminary results in Ar+Sc at $\sqrt{s_{NN}} \approx 8.8, 12, 17$ GeV
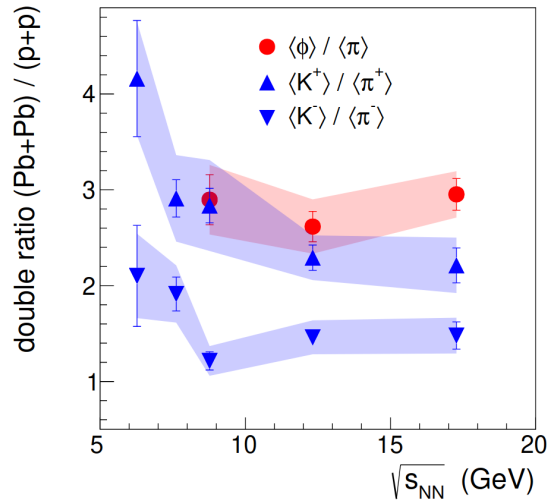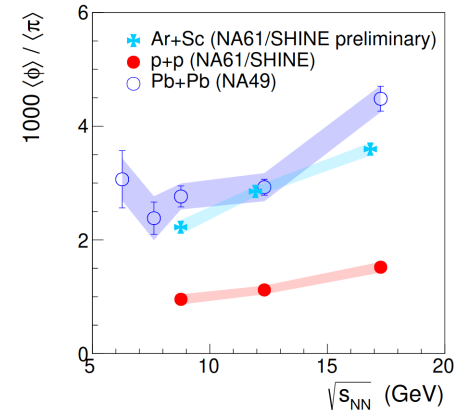
NA61/SHINE, Eur.Phys.J.C 80 (2020) 3, 199

- ϕ / π :
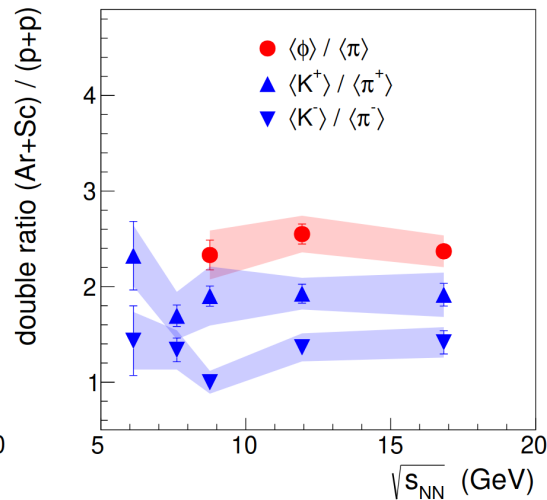
  – Ar+Sc $\leq$ Pb+Pb

  – Ar+Sc $\gg$ p+p

- ϕ production $>$ K

  – Independent of $\sqrt{s_{NN}}$ (in the observed range)

2024.12.04

Barnabás Pórfy for the NA61/SHINE

Excess of charged over neutral kaons

Barnabás Pórfy for the NA61/SHINE

Excess of charged over neutral kaons

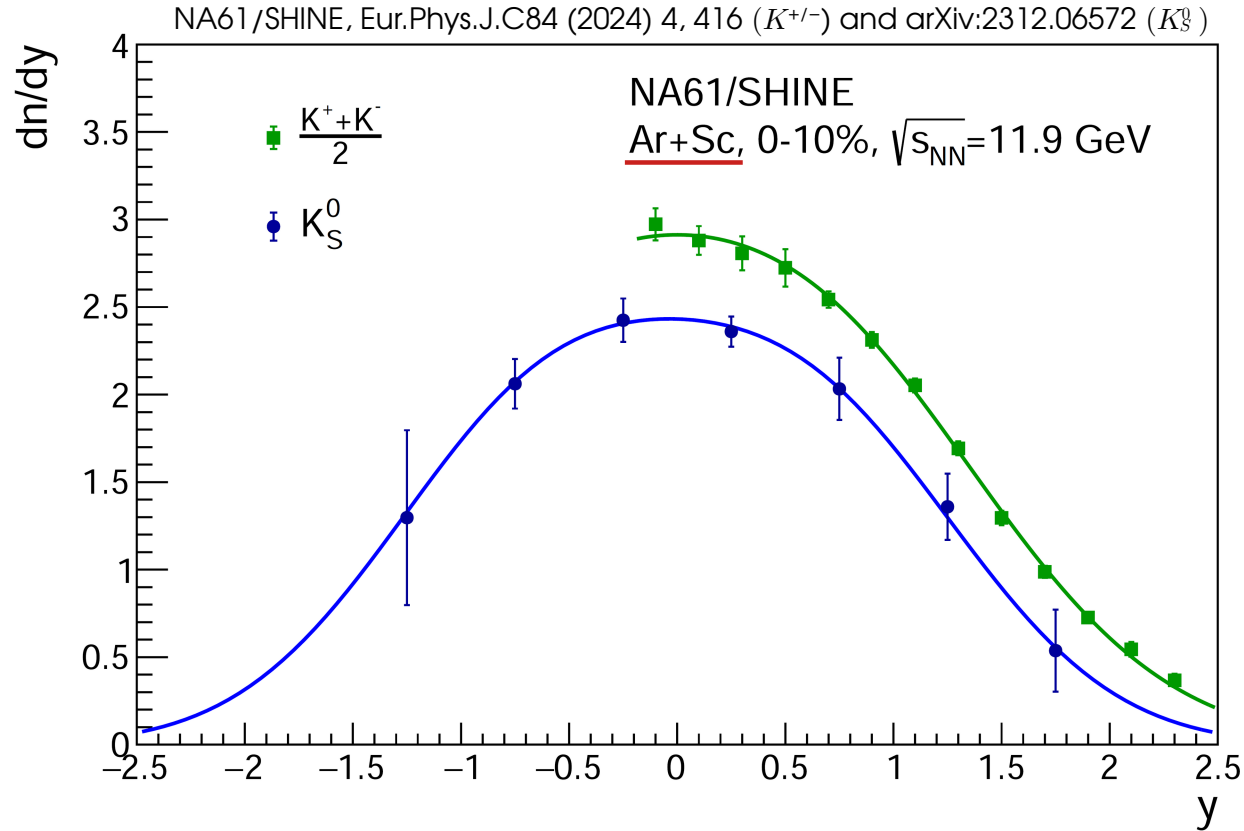NA61/SHINE, Eur.Phys.J.C84 (2024) 4, 416 ($K^{+/-}$) and arXiv:2312.06572 (K_S^0)

NA61/SHINE
Ar+Sc, 0-10%, $\sqrt{s_{NN}}$=11.9 GeV

$\frac{K^+ + K^-}{2}$

K_S^0

Uncertainties:
total (stat, syst)

(unexpected violation of flavour
symmetry between u and d quarks)

- Ar, Sc nuclei are nearly isospin-symmetric
  (valence **u ≈ d** within 6%)

- We expect:

$$K^+(u\overline{s}) \approx K^0(d\overline{s}), \quad u \leftrightarrow d$$
$$K^-(\overline{u}s) \approx \overline{K}^0(\overline{d}s), \quad \overline{u} \leftrightarrow \overline{d}$$
$$\downarrow$$
$$\frac{K^+ + K^-}{2} \approx \frac{K^0 + \overline{K}^0}{2} = K_s^0$$

| neglecting
| CP
| violation

- Data - excess of charged over neutral kaons:

$$\frac{K^+ + K^-}{2} > K_s^0$$

- Indication of violation of isospin symmetry

Barnabás Pórfy for the NA61/SHINE

Excess of charged over neutral kaons

$$R_K = \frac{K^+ + K^-}{2 K_S^0}$$

- HADES; Ar+KCl; 4π
- STAR; Au+Au; $y \approx 0$
- NA49; Pb+Pb; 4π
- NA61/SHINE; Ar+Sc; $y \approx 0$
- CERES; Pb+Au; $y \approx 0$
- NA35; S+S; 4π
- ALICE; Pb+Pb; $y \approx 0$

— HRG; Q/B = 0.4
· HRG; Q/B = Z/A
— UrQMD; Q/B = 0.4
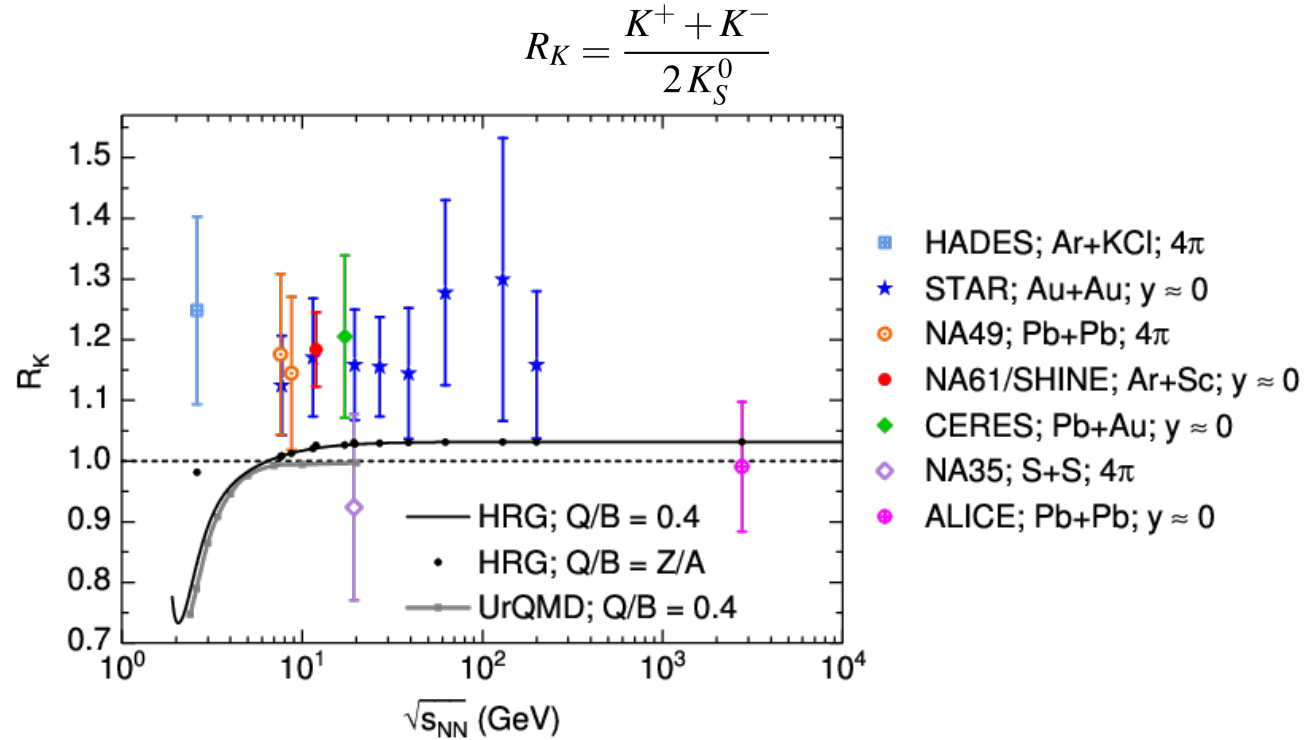
- Unexpected excess of charged over neutral kaon production in A+A collisions
- HRG model does not reproduce experimental results
- Up to now, not understood by known effects

Theor. details: Francesco Giacosa, Wednesday, 11:05

2024.12.04

Barnabás Pórfy for the NA61/SHINE

Open Charm

Barnabás Pórfy for the NA61/SHINE

Open Charm

- First-ever direct measurement of open charm production in A+A collisions at SPS energies! NA61/SHINE preliminary arXiv:2410.24014

- Results from Pb+Pb collisions will soon follow from NA61/SHINE

Barnabás Pórfy for the NA61/SHINE
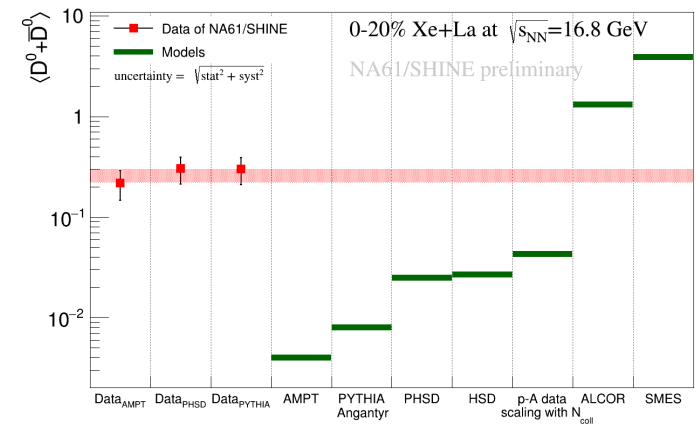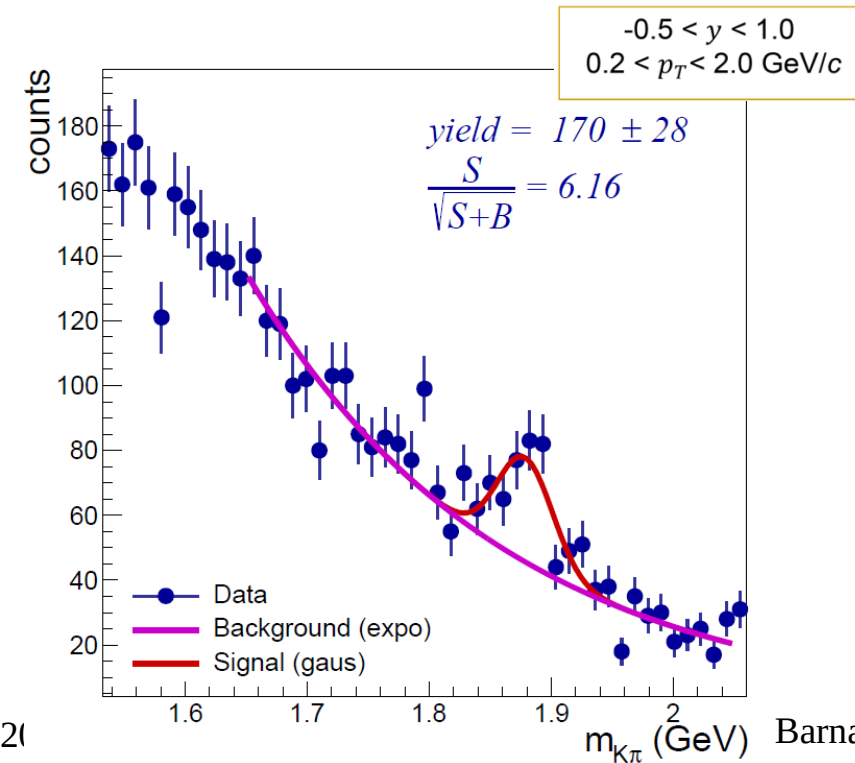
Correction made with:	Yield in 4π $\langle D^0 + \overline{D}^0 \rangle$
AMPT	**0.218** ± 0.039(stat) ± 0.060(syst)
PHSD	**0.303** ± 0.054(stat) ± 0.074(syst)
PYTHIA/Angantyr	**0.300** ± 0.052(stat) ± 0.075(syst)

Summary

- No indication of horn in Ar+Sc or Xe+La

- No sign of critical point

- Unexpected excess of charged-over-neutral kaon production in Ar+Sc collisions

- First-ever direct measurement of open charm production in nucleus-nucleus collisions at SPS energies

Barnabás Pórfy for the NA61/SHINE

Thank you!

Barnabás Pórfy for the NA61/SHINE