Recent results from NA61/SHINE

21st International Conference on Strangeness in Quark Matter (SQM 2024), Strasbourg, France

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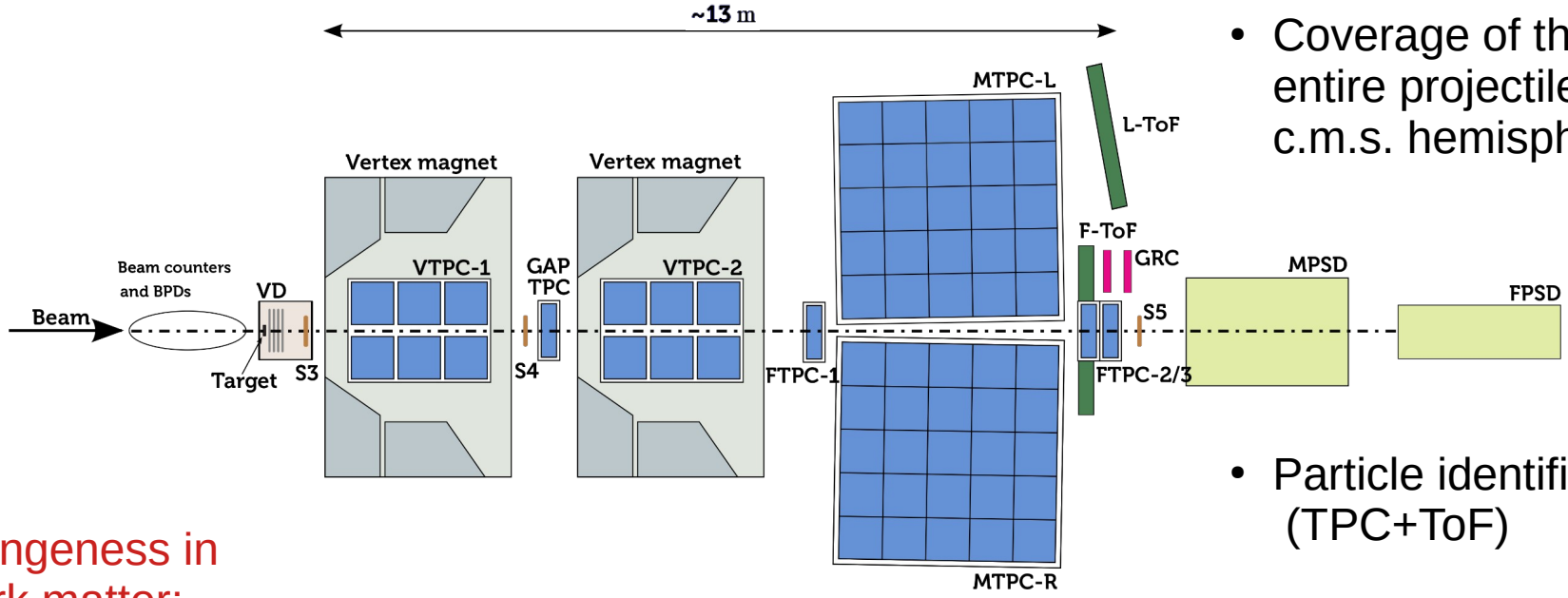
for the NA61/SHINE Collaboration

* Institute of Nuclear Physics, P.A.S., Kraków, Poland

NA61/SHINE at CERN SPS

- Multipurpose fixed-target spectrometer with unique capabilitites



- Coverage of the entire projectile c.m.s. hemisphere
- Particle identification (TPC+ToF)
- Strangeness in quark matter: K^+, K^-, K^0_s, K^*, Λ, ϕ
- Heavy quarks: D^0 and $\overline{D}^0$
- Correlations, fluctuations, HBT, intermittency...

NA61/SHINE – Research program

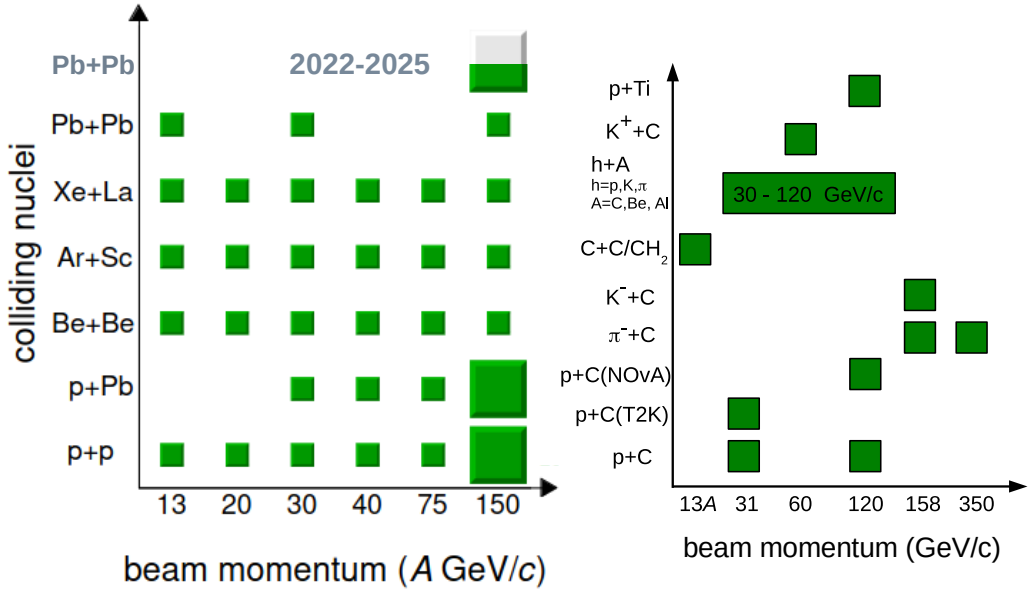
$\sqrt{s_{NN}}$ = 5 – 17 / 27 GeV

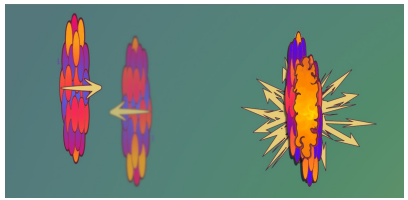
Strong interactions

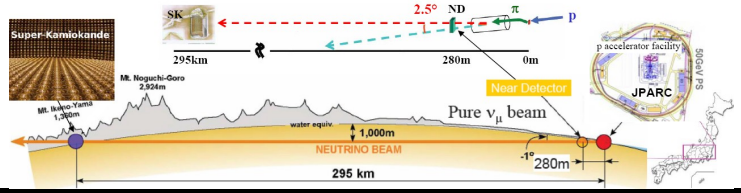
- study the onset of deconfinement
- search for the critical point
- measurement of open charm

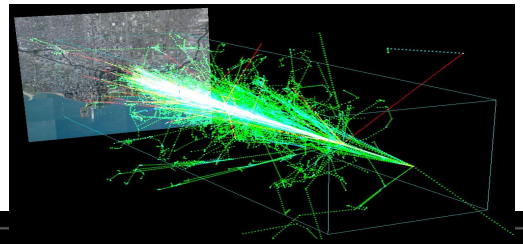
Neutrino and cosmic-ray physics

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

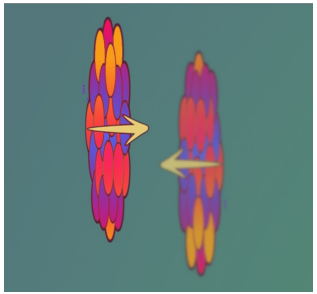


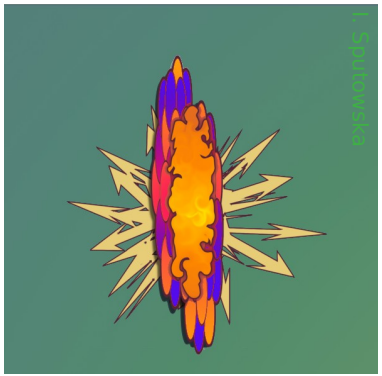






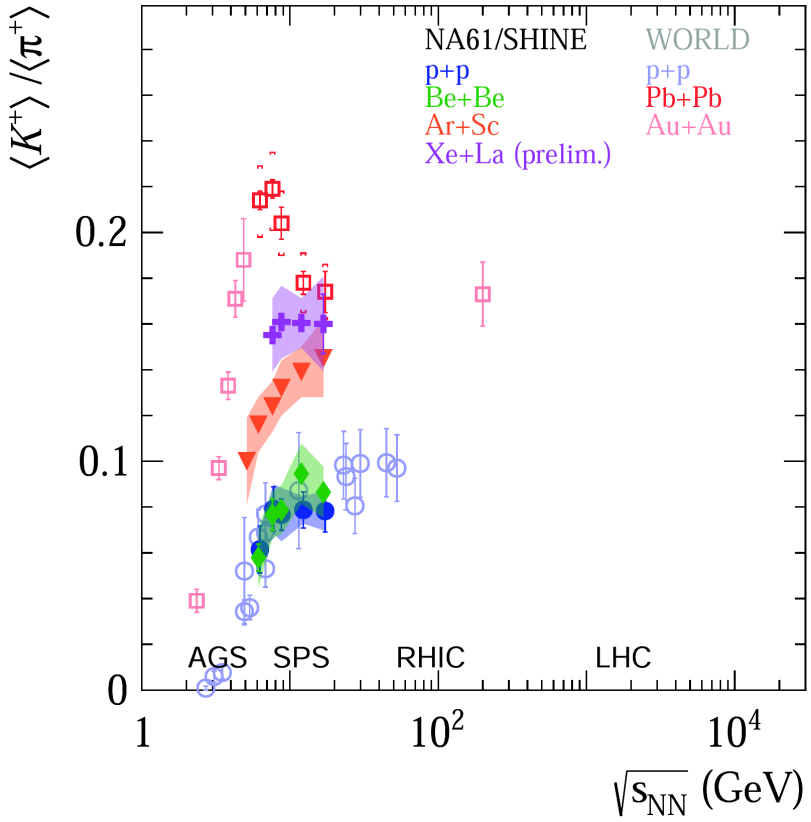
Probing the onset of deconfinement

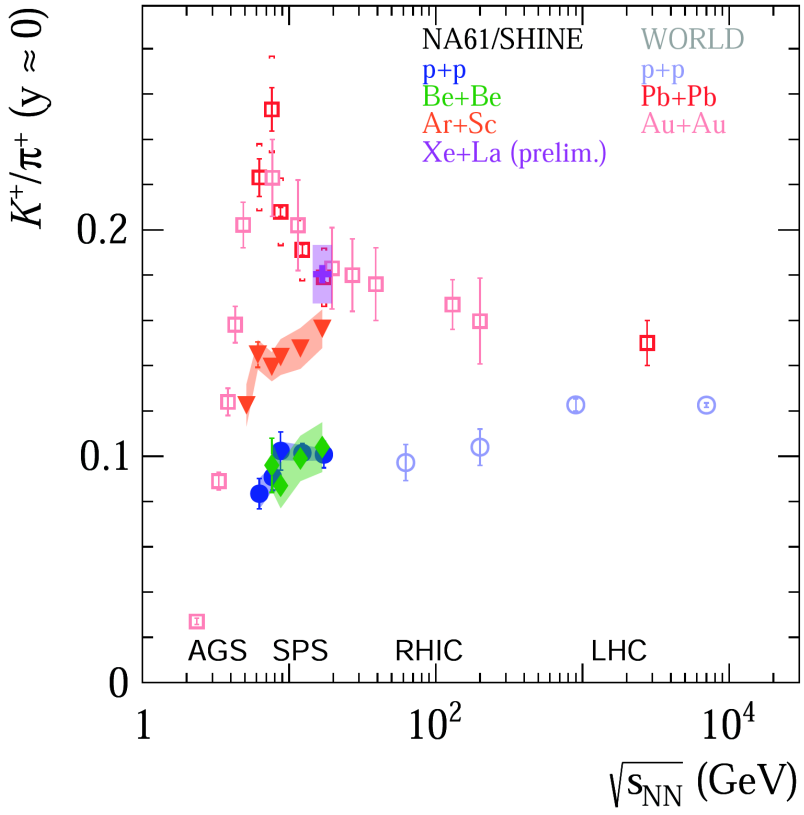




Other NA61/SHINE data: EPJC 77 (2017) 671
EPJC 81 (2021) 73, EPJC 84 (2024) 416

System size dependence of K^+/π^+ ratio





See Poster by Oleksandra Panova

Excess of charged over neutral kaons

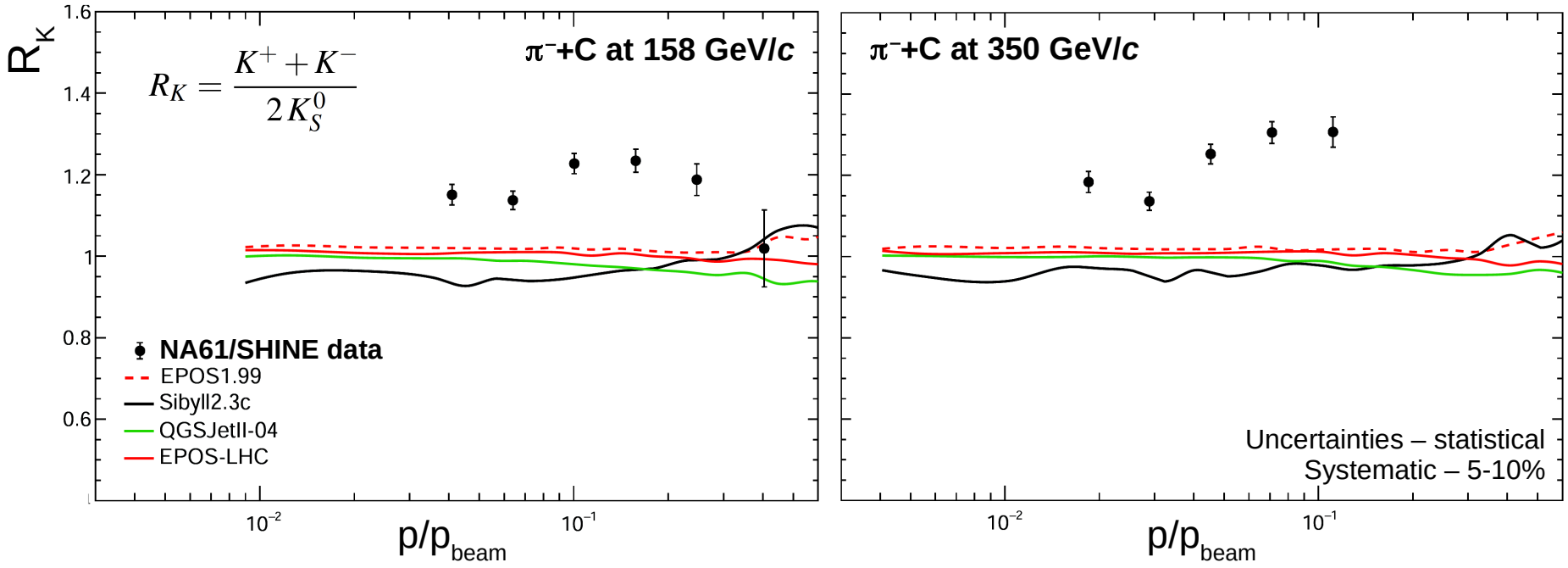
K^+,

K^-,

K^0_S

Ratio of charged-over-neutral kaons as a function of x_F(lab) = p/p_{beam}

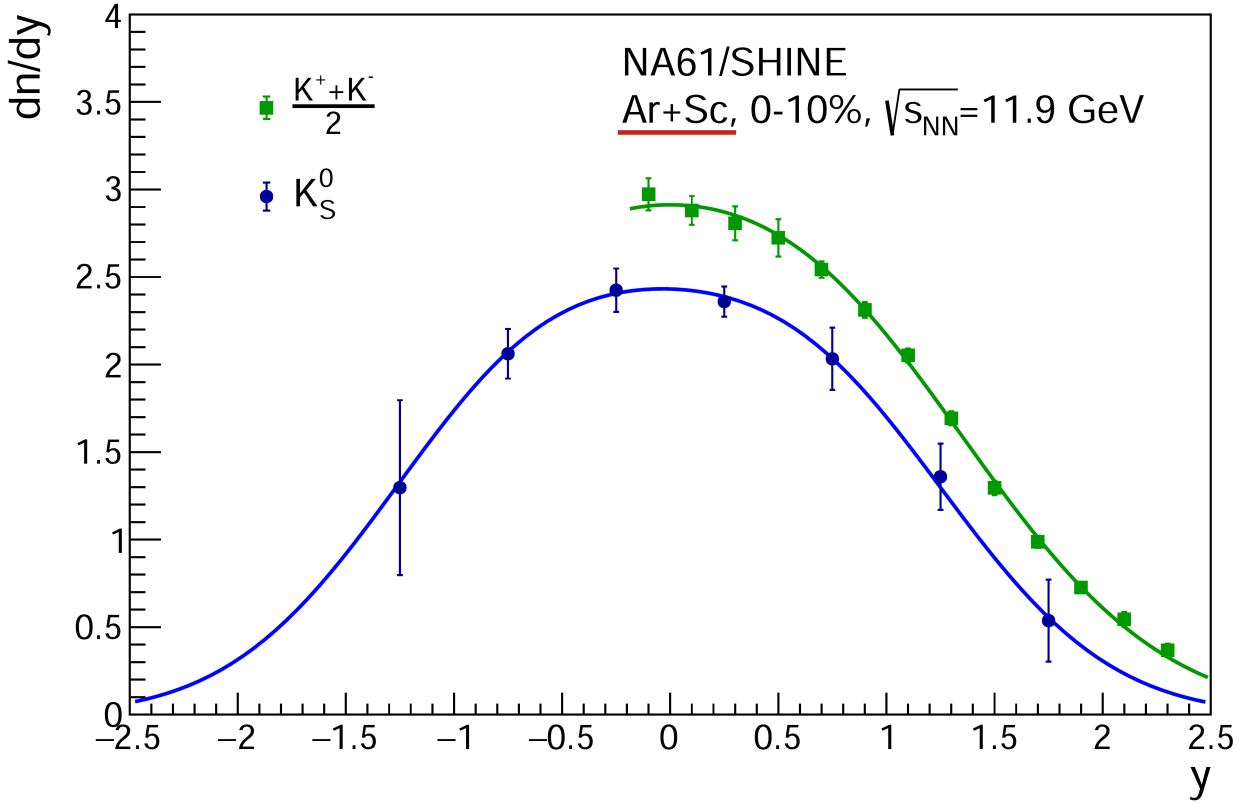
NA61/SHINE, PRD 107 (2023) 062004



- $R_K \approx$ 1.2 – 1.3 ; ● challenging for models ; ● cannot be understood from quark counting

Stepaniak, Pszczel,
EPJC 83 (2023) 10, 928

NA61/SHINE, arXiv:2312.06572



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:

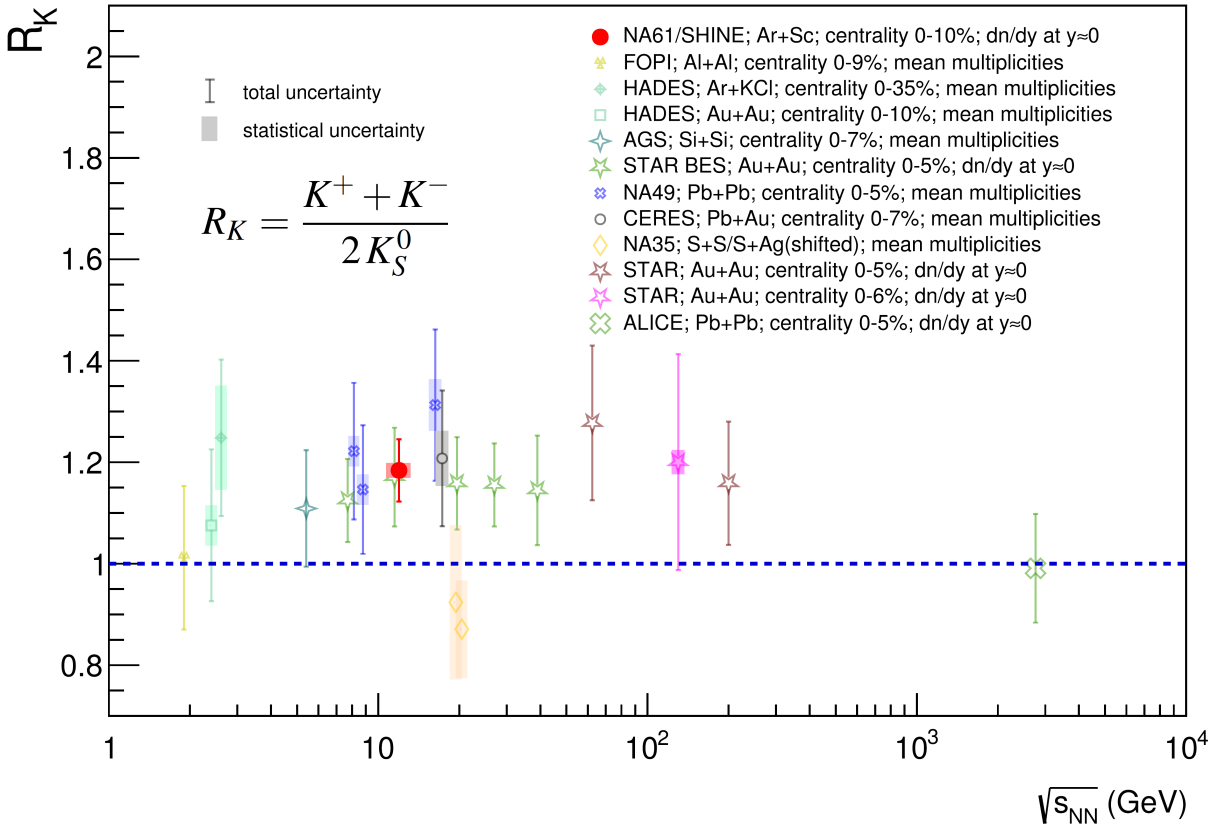
  $K^+ (u \bar{s}) \approx K^0 (d \bar{s})$ $\quad u \leftrightarrow d$

  $K^- (\bar{u} s) \approx \bar{K}^0 (\bar{d} s)$ $\quad \bar{u} \leftrightarrow \bar{d}$

  $$\frac{K^+ + K^-}{2} \approx \frac{K^0 + \bar{K}^0}{2} = K^0_S$$ | neglecting CP violation
- Data - excess of charged over neutral kaons:

  $$\frac{K^+ + K^-}{2} > K^0_S$$
- Indication of violation of isospin symmetry

NA61/SHINE, arXiv:2312.06572 → see references for numerical values used to calculate R_K as a function of $\sqrt{s_{NN}}$

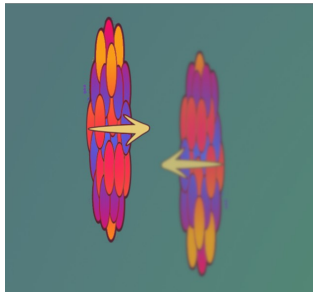


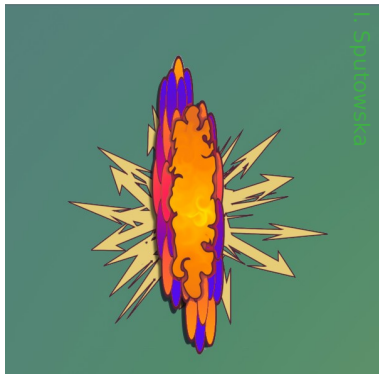
- Unexpected excess of charged over neutral kaon production in A+A collisions
- Up to now, not understood by known effects

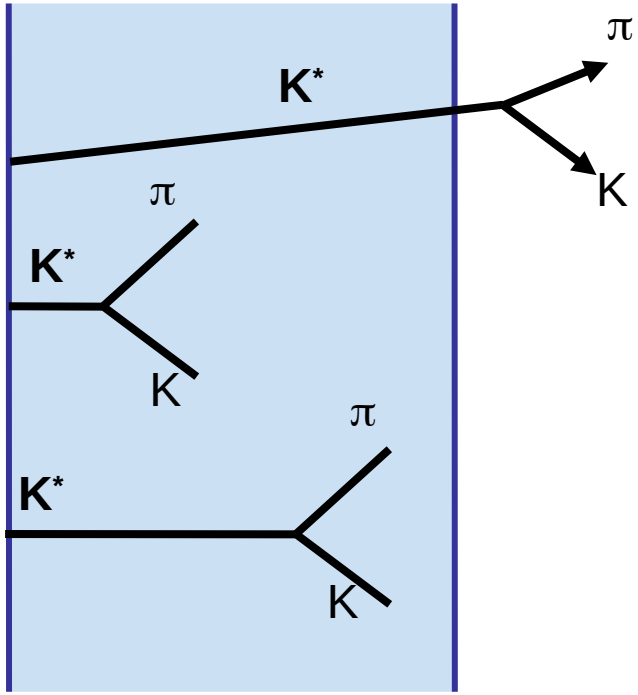
➔ See talk by Francesco Giacosa (TH) **Tomorrow 8:50 AM**

➔ See talk by Tanja Šuša (EXP) **Wednesday 12:00 AM**

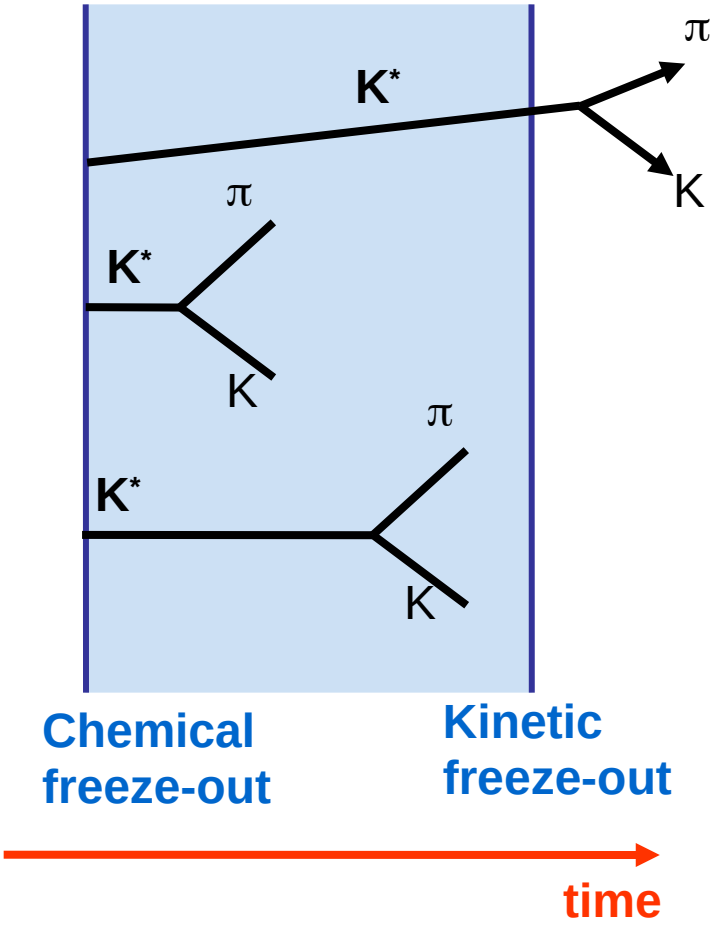
Strange resonances







K*(892)^0



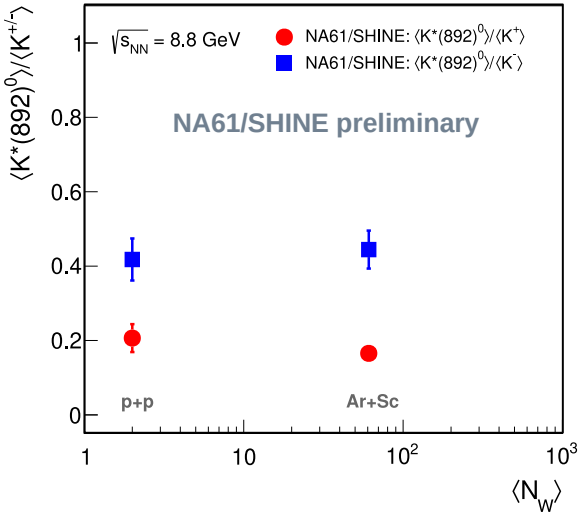
- K* lifetime (≈ 4 fm/*c*) is comparable with the time between two freeze-outs
- Some K* resonances may decay inside the fireball
- Suppression of observed K* yield
- Assuming no regeneration processes (Fig.) the time Δt between freeze-outs can be determined from (STAR, PRC71, 064902, 2005):

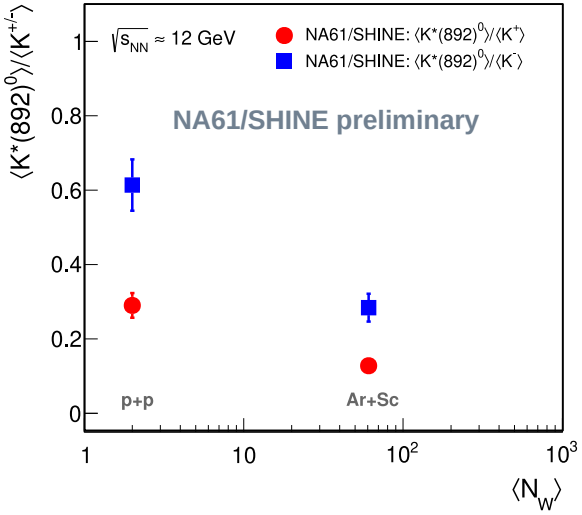
$$\frac{K^*}{K}(\text{kinet}) = \frac{K^*}{K}(\text{chem}) \cdot e^{\frac{-\Delta t}{\tau}}$$

K* lifetime

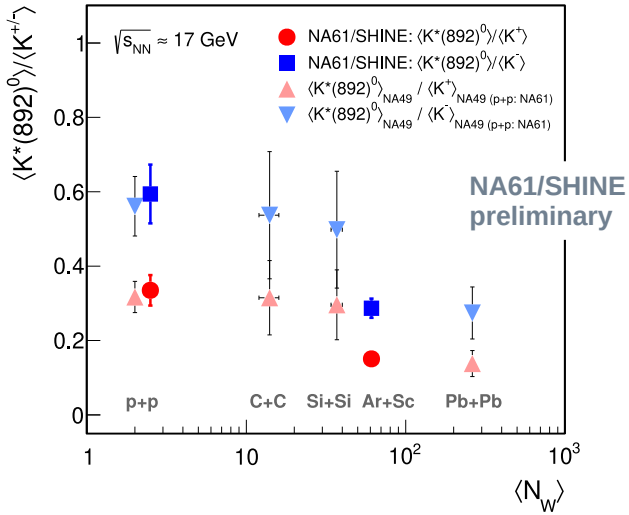
use Pb+Pb or Au+Au ratio

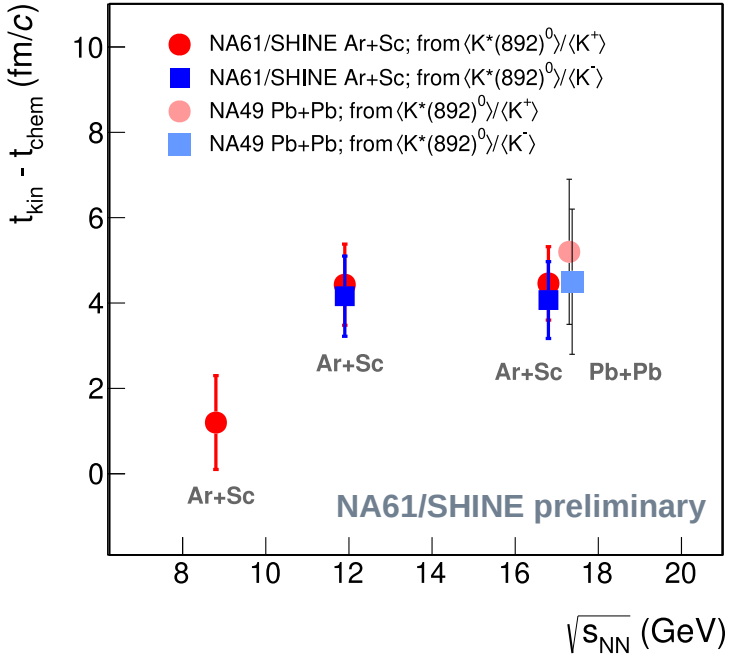
use p+p ratio





- New data on K* production in 0-10% central Ar+Sc collisions
- Ar+Sc ≈ Pb+Pb at $\sqrt{s_{NN}} \approx 17$ GeV
- No K* suppresion in Ar+Sc at $\sqrt{s_{NN}} = 8.8$ GeV ?





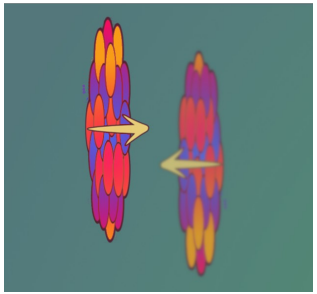
K*(892)⁰ data in Ar+Sc: NA61/SHINE preliminary

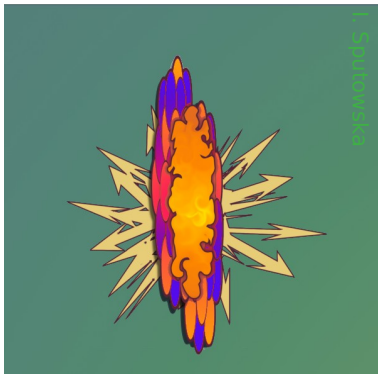
Other data: NA61/SHINE, EPJC 84 (2024) 416
EPJC 82 (2022) 322
EPJC 80 (2020) 460
EPJC 77 (2017) 671

Uncertainties: total (stat, syst)

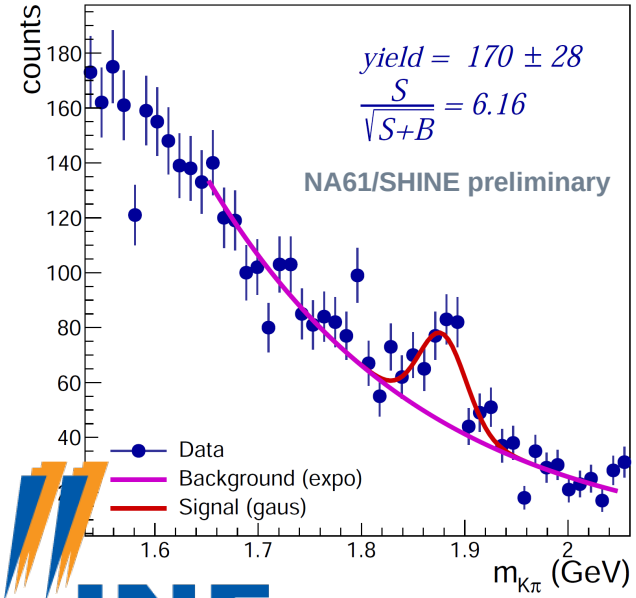
NA49, PRC 84 (2011) 064909
PRL 94 (2005) 052301
PRC 66 (2002) 054902

Charm





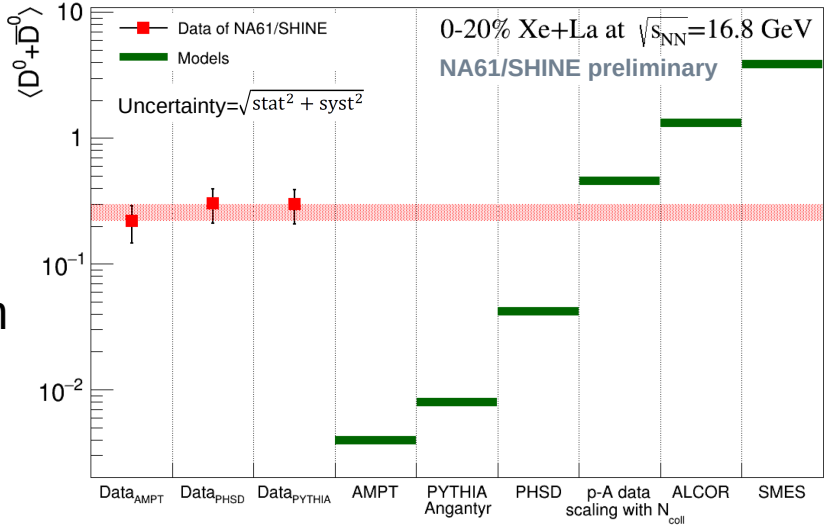
0-20% Xe+La $\sqrt{s_{NN}}$=16.8 GeV



NA61/SHINE preliminary

Correction made with:	Yield in 4π ⟨D⁰ +$\overline{D}^0$⟩
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)

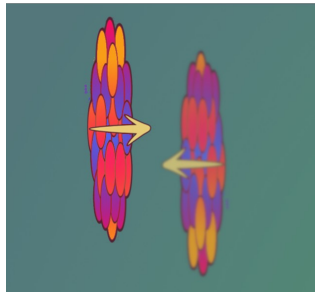
Comparison of ⟨D⁰ +$\overline{D}^0$⟩ with models

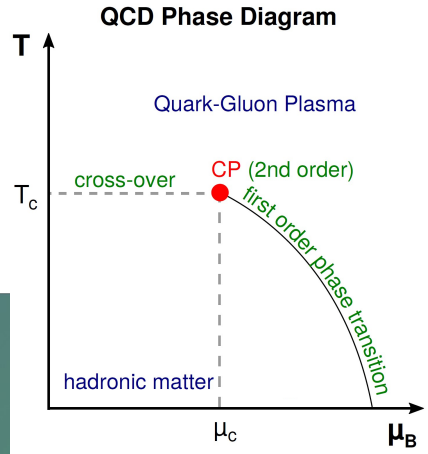


- First-ever direct measurement of open charm production in A+A collisions at SPS energies
- Result from Pb+Pb collisions will follow from NA61/SHINE

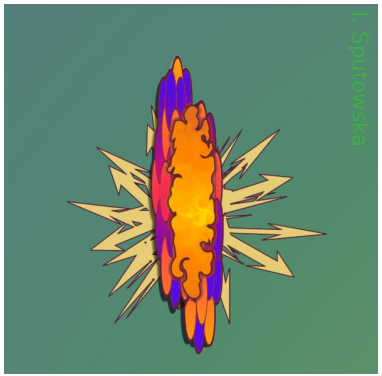
Tomorrow, 10:40 AM → See talk by Anastasia Merzlaya for NA61/SHINE

The critical point



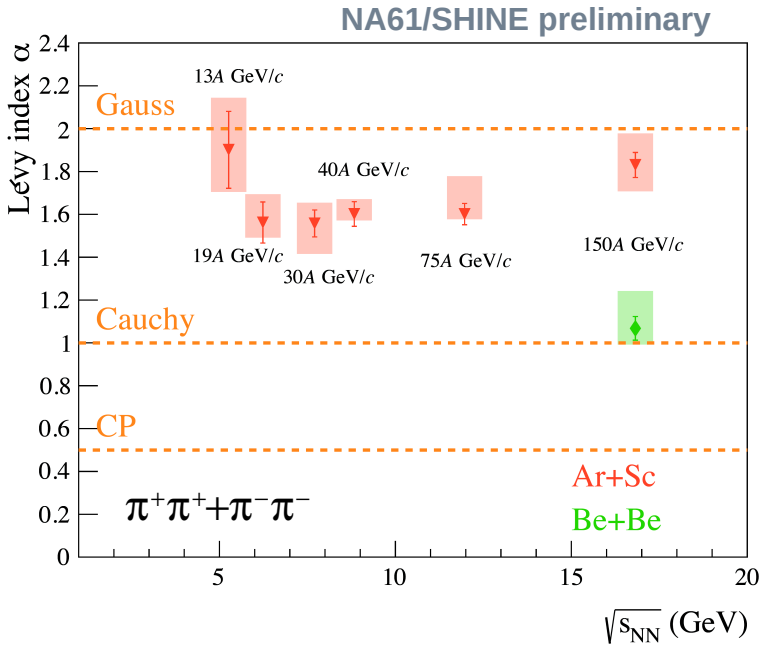


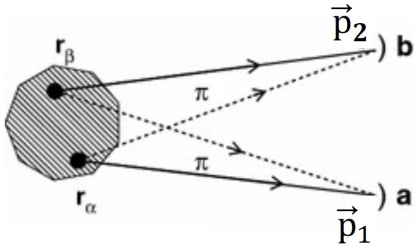
Sketch by N. Davis



I. Sputowska

Search for the critical point in NA61/SHINE (1): femtoscopy analysis in central Ar+Sc collisions





Lévy source:

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

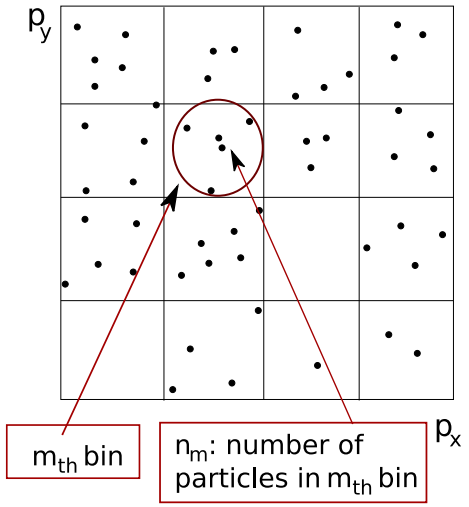
$$q = |\vec{p}_1 - \vec{p}_2|$$

- Bose-Einstein correlations (femtoscopy) reveal the space-time structure of hadron production
- The Lévy parameter α describes the shape of the source and is sensitive to the system freezing out at the CP
- The new Ar+Sc results are close to Gaussian, and **far from the CP**

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

Ar+Sc, 0-10% central, NA61/SHINE preliminary
Be+Be, 0-20% central, NA61/SHINE, EPJC 83 (2023) 919

Search for the critical point in NA61/SHINE (2): proton intermittency

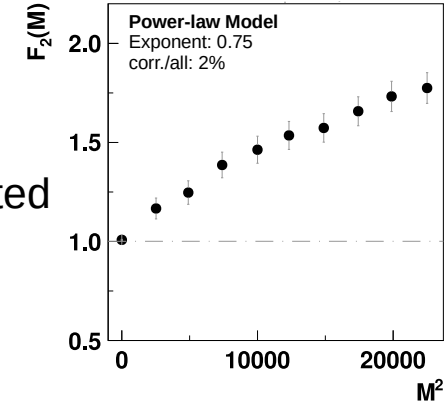


- When the system freezes out at CP, the scaled factorial moments $F_r(M)$ are expected to follow a power-law behaviour:

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

- For protons and $r = 2$, $\phi_2 = 5/6$ is expected

Czopowicz, 2309.13706



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

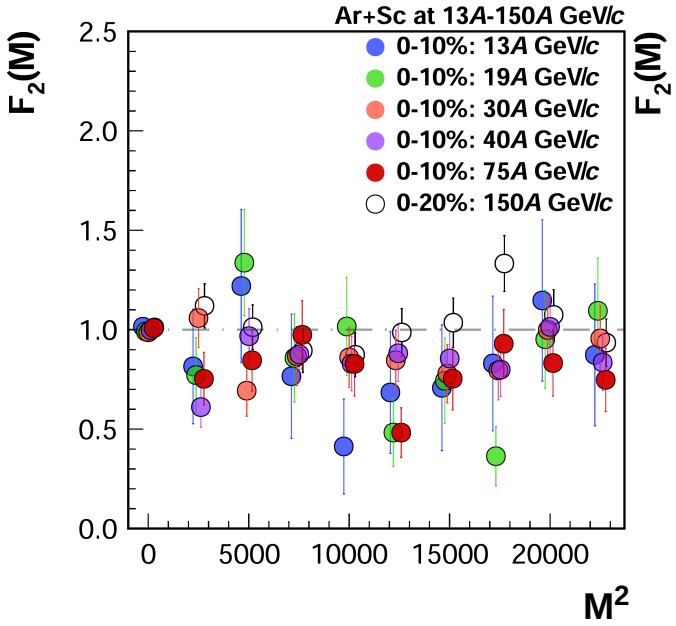
$$F_r(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m - 1)...(n_m - r + 1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^r}$$

M^2 – number of bins; $\langle ... \rangle$ – averaging over events

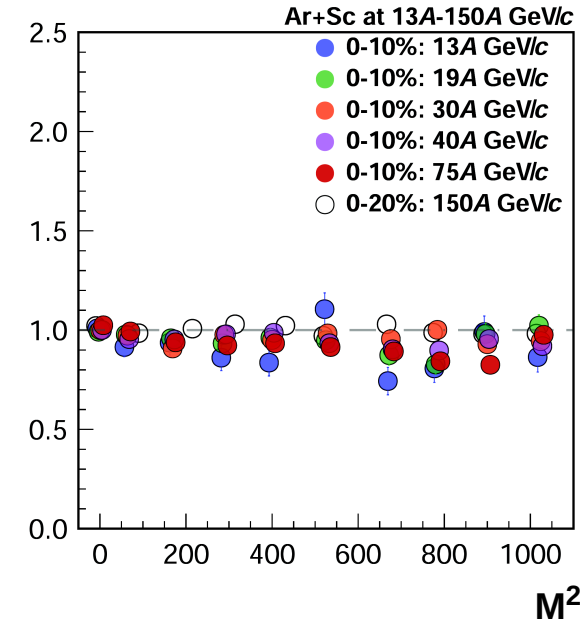
The analysis is made for:

- *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

No signal indicating the critical point

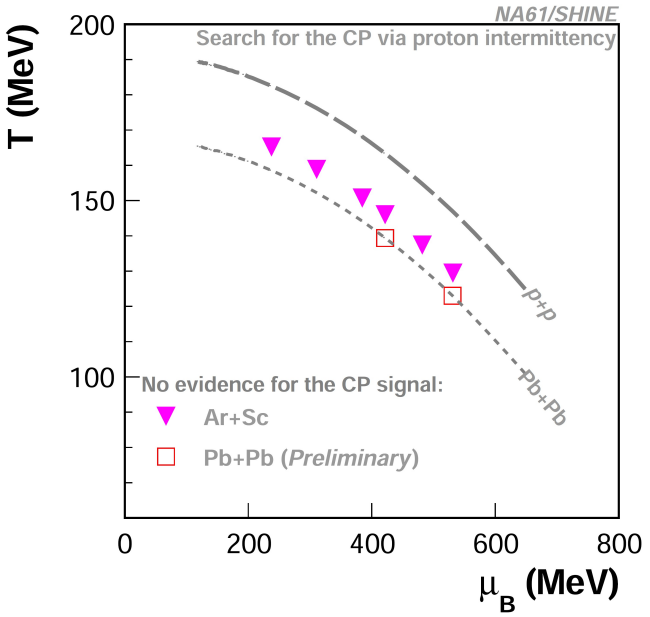


$1^2 \le M^2 \le 150^2$



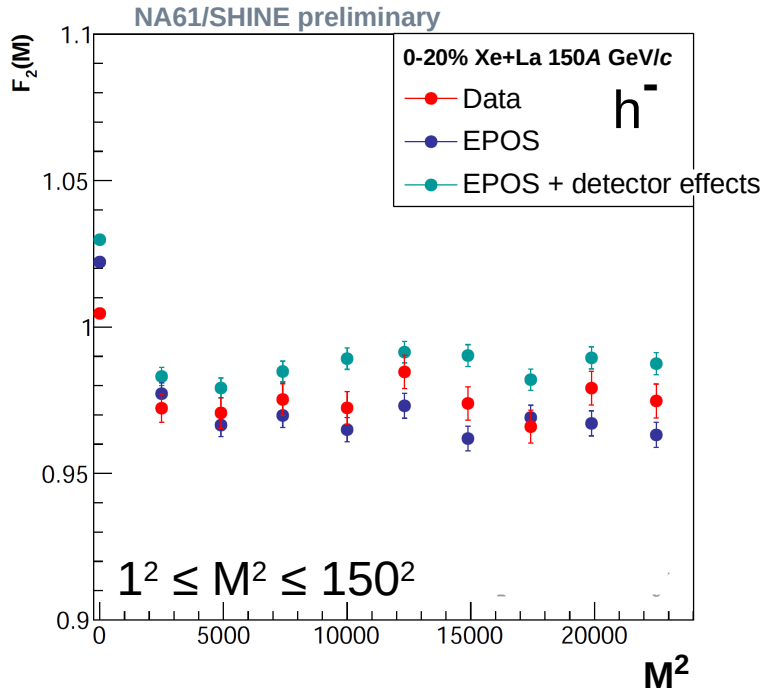
$1^2 \le M^2 \le 32^2$

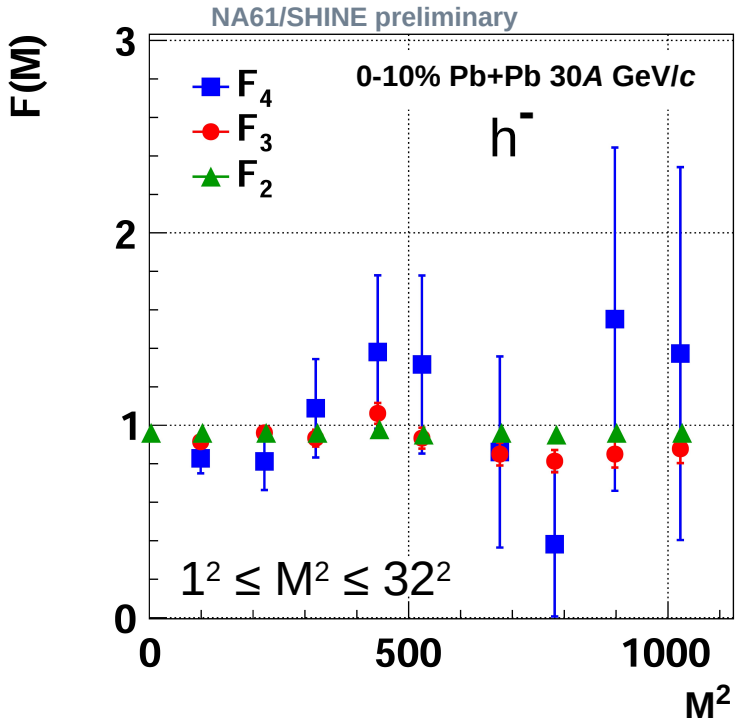
number of subdivisions in cumulative transverse momentum space



NA61/SHINE, EPJC 83 (2023) 881
NA61/SHINE, arXiv:2401.03445

Search for the critical point in NA61/SHINE (3): intermittency of negatively charged hadrons





No signal indicating the critical point

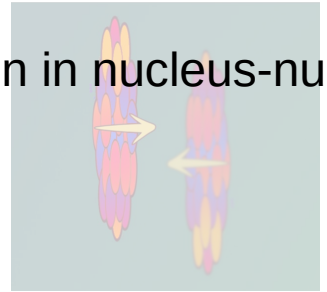
News from NA61/SHINE:

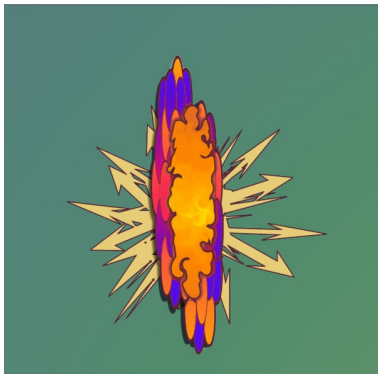
1. Unexpected excess of charged-over-neutral kaon production in Ar+Sc collisions

   → indication for violation of isospin symmetry

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

3. No sign of critical point





Thank you

Merci beaucoup

NA61/SHINE at SQM 2024

Posters (Tuesday, 6:30 PM, Hall Schweitzer, ground floor)

- **Bartosz Kozłowski**, K*/K ratio and the time between freeze-outs for intermediate-mass Ar+Sc system at the SPS energy range **[strange resonances]**
- **Yuliia Balkova**, Λ baryon production in heavy-ion collisions at the NA61/SHINE experiment **[strange baryons]**
- **Oleksandra Panova**, News on identified hadron production in central nucleus-nucleus collisions from NA61/SHINE at CERN SPS **[onset of deconfinement]**

Talks

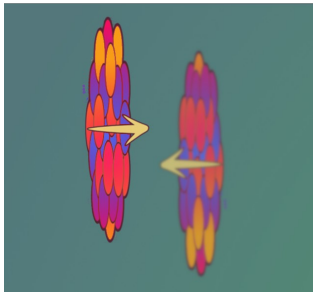
Not addressed in this talk, unfortunately!

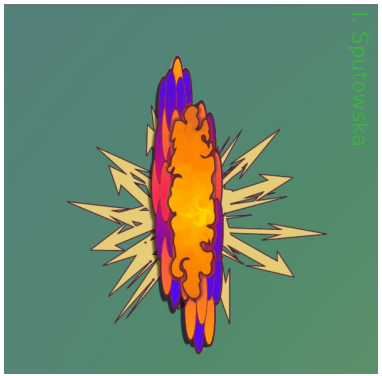
- **Anastasia Merzlaya**, First $D^0+\overline{D}^0$ measurement in heavy-ion collisions at SPS energies with NA61/SHINE, Tuesday, 10:40 AM, Room Rome **[charm]**
- **Łukasz Rozpłochowski**, Energy dependence of $\phi(1020)$ meson production in nucleus-nucleus collisions at the CERN SPS, Wednesday, 9:50 AM, Room Londres 1 **[hidden strangeness]**
- **Tatjana Šuša**, Measurement of charged and neutral kaons in Ar+Sc collisions at NA61/SHINE experiment, Wednesday, 12:00 PM, Room Madrid **[charged kaon excess]**

Recommended by NA61/SHINE :)

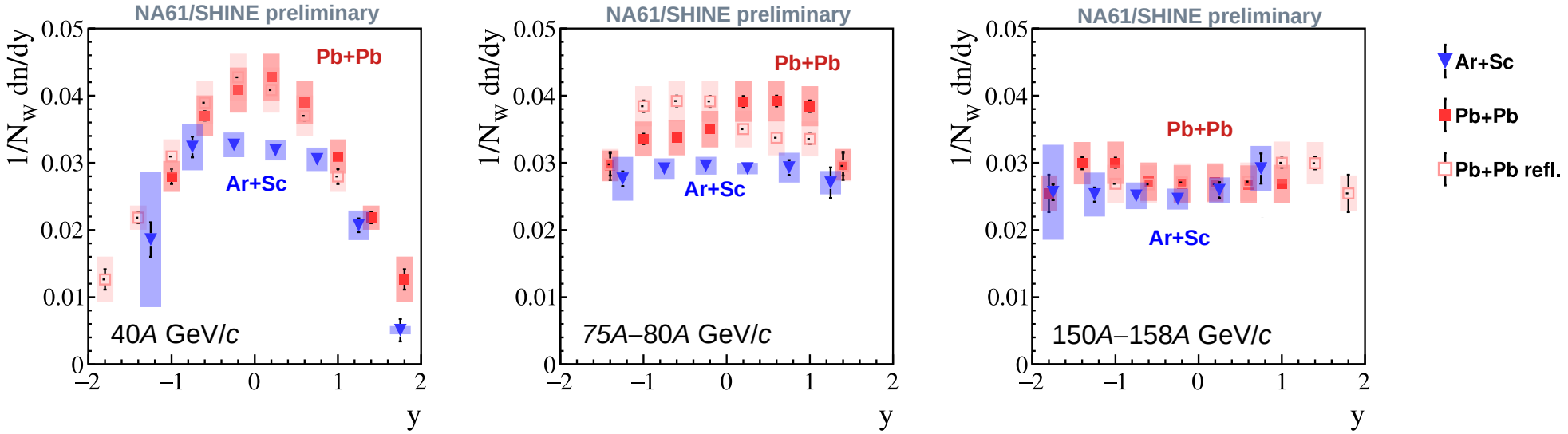
- **Francesco Giacosa** (TH), Large isospin symmetry breaking in kaon production at high energies, Tuesday, 8:50 AM, Room Madrid **[charged kaon excess]**
- **Piotr Podlaski**, SPS Upgrades and prospects, Friday, 12:00 PM, Room Curie **[prospects]**

Extra slides





Λ baryon production per wounded nucleon:

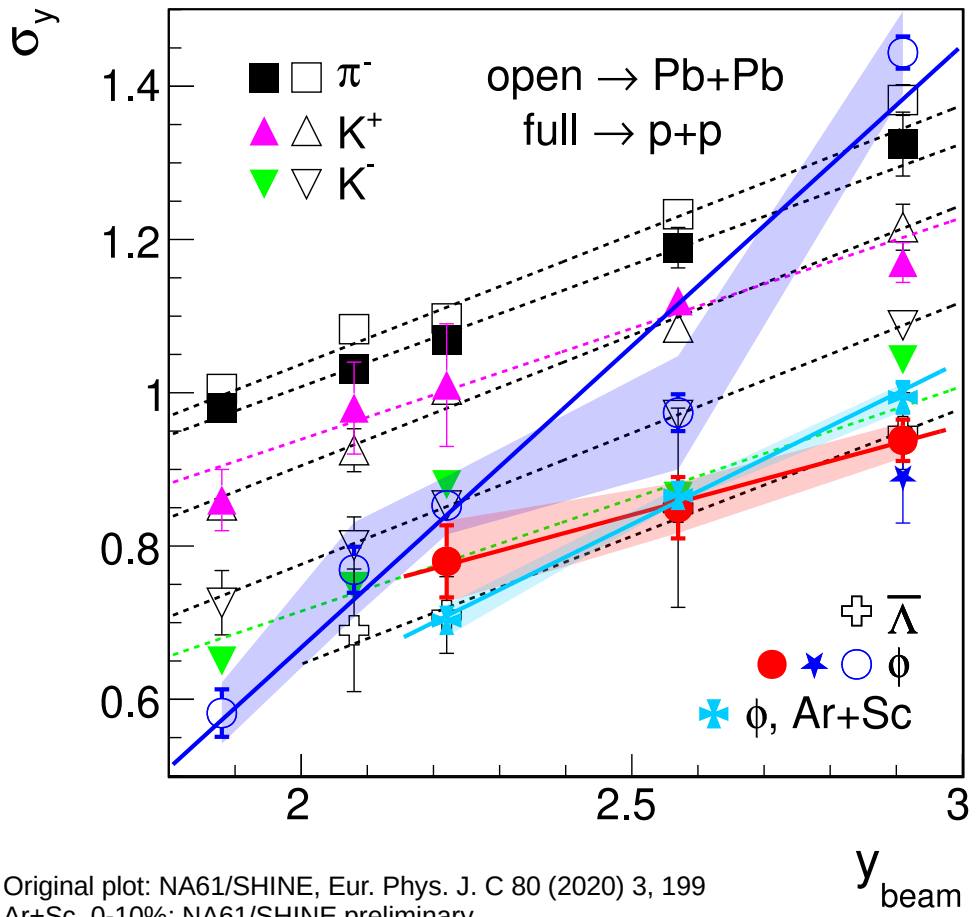


- Transition from baryon “stopping” to baryon “transparency”, similar in central Ar+Sc and Pb+Pb collisions
- Mid-rapidity density of the Λ baryon in Ar+Sc collisions reaches the Pb+Pb value at top SPS energy

Ar+Sc, 0-10%, 40*A*, *75A*, 150*A* GeV/*c*: NA61/SHINE preliminary
Pb+Pb, 0-10%, 40*A*, 80*A*, 158*A* GeV/*c*: NA49, PRC 78 (2008) 034918

See Poster by Yuliia Balkova

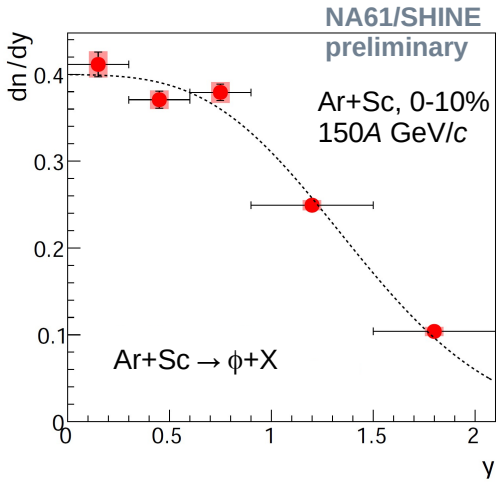
Width of rapidity distribution of the ϕ meson



σ_y(Pb+Pb)

σ_y(Ar+Sc)

σ_y(p+p)

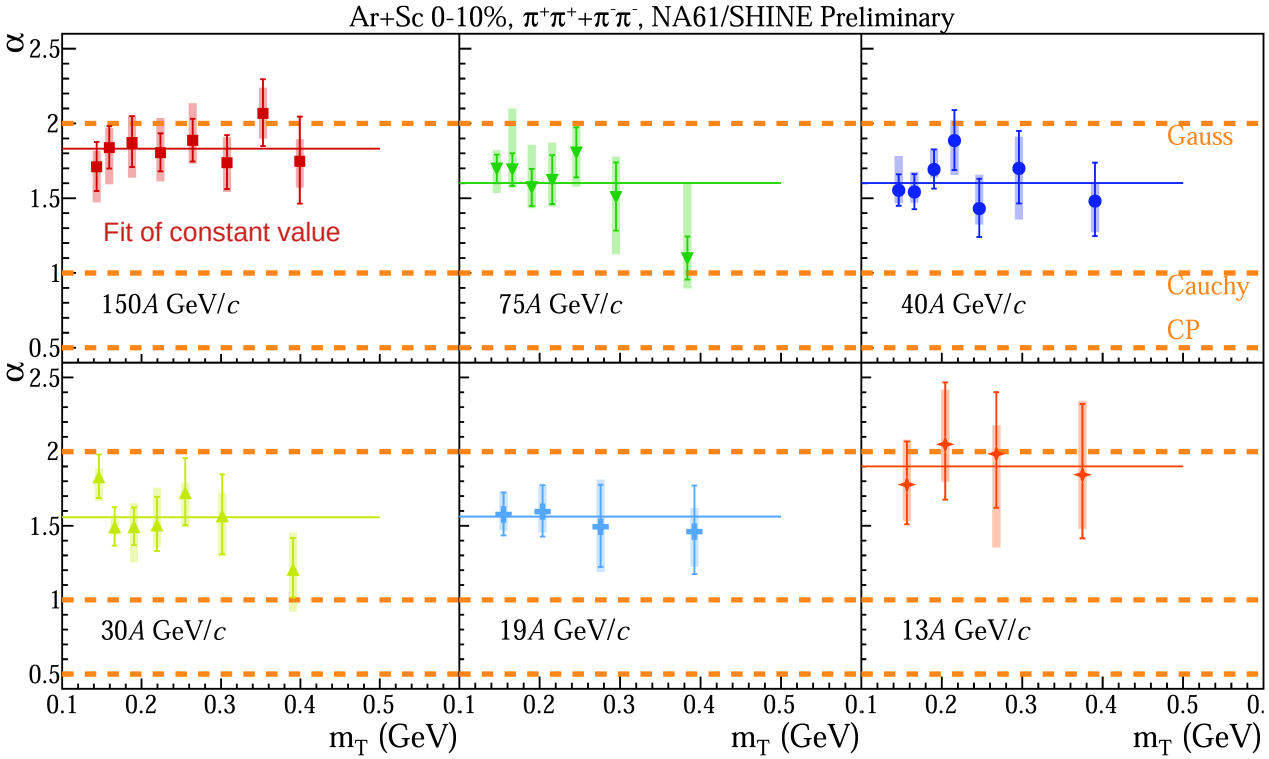


- New data on ϕ(1020) production in central Ar+Sc collisions
- Similar width of the rapidity distribution to p+p reactions
- ➔ See talk by Łukasz Rozpłochowski

Wednesday
9:50 AM

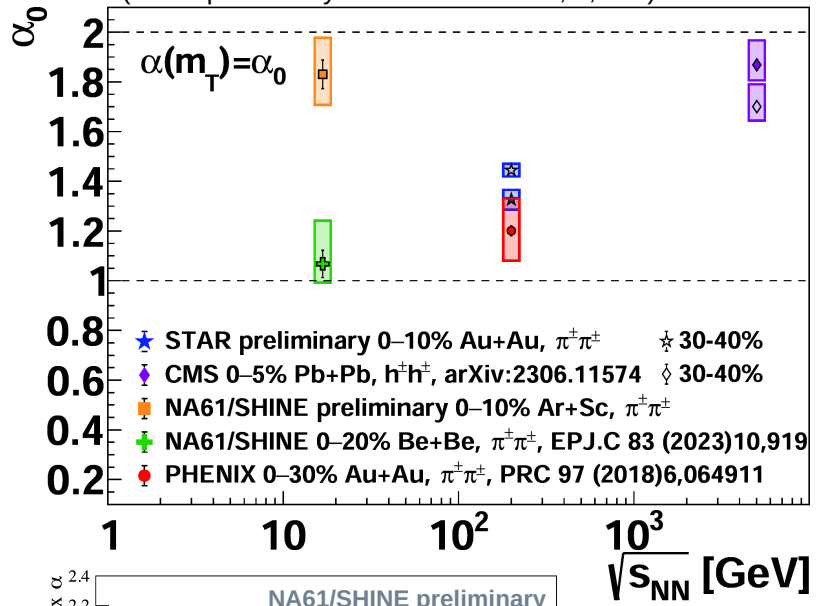
Original plot: NA61/SHINE, Eur. Phys. J. C 80 (2020) 3, 199
Ar+Sc, 0-10%: NA61/SHINE preliminary

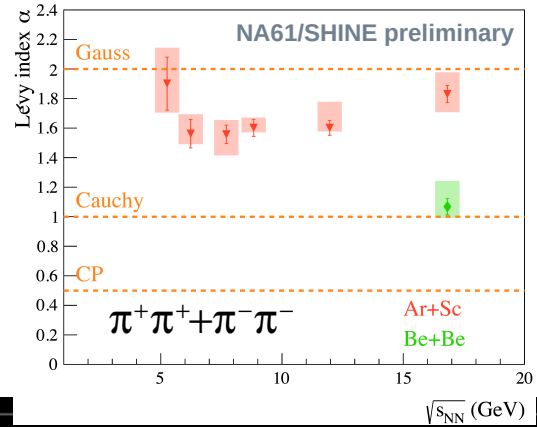
Femtoscopy analysis NA61/SHINE: Lévy stability index α



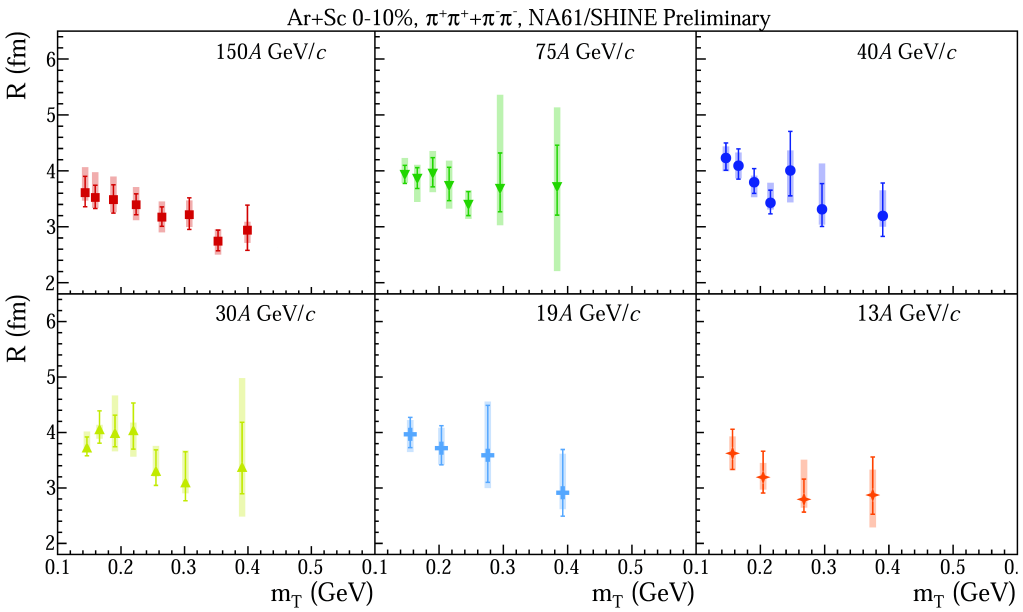
Ar+Sc, 0-10% central, NA61/SHINE preliminary
Be+Be, 0-20% central, NA61/SHINE, EPJC 83 (2023) 919

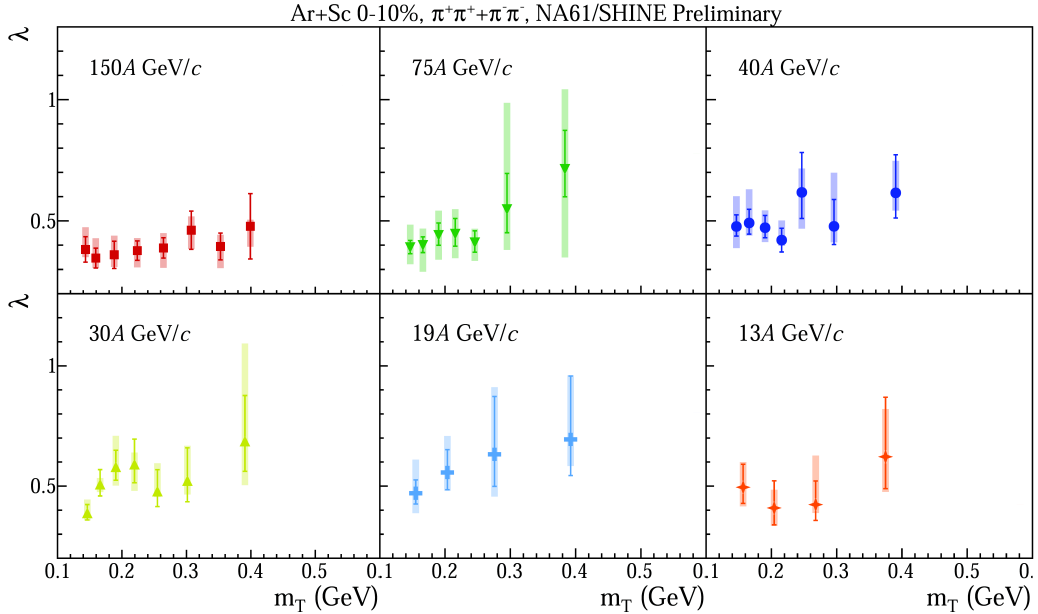
M. Csanád, D. Kincses, Universe 10 (2024) 2, 54
(STAR preliminary: Universe 10 2024, 3, 102)





Femtoscopy analysis NA61/SHINE: Lévy scale parameter R and correlation strength λ





Lévy scale R:

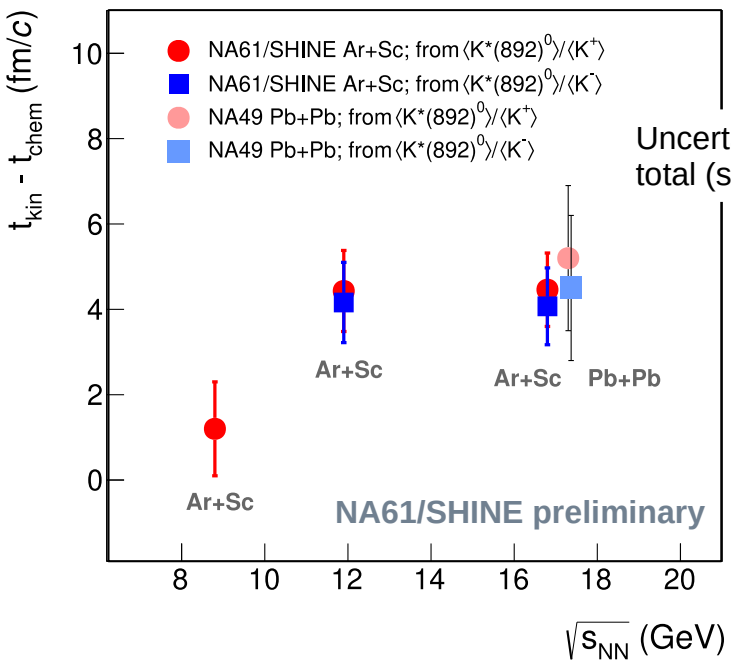
- Describes length of homogeneity
- Visible m_T dependence (sign of transverse flow)

Correlation strength λ:

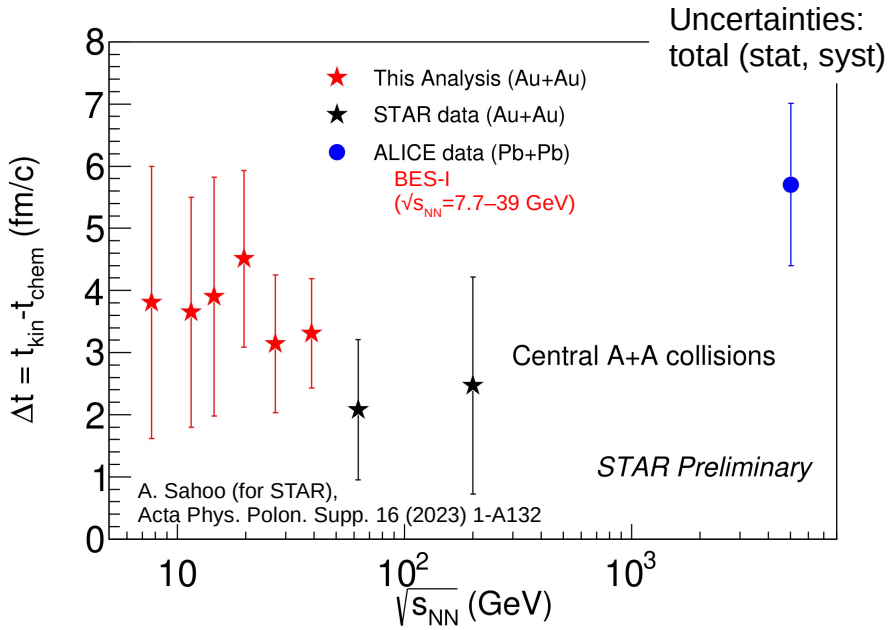
- Describes core-halo ratio
- Shows no m_T dependence

For details, see B. Porfy for NA61/SHINE, Procs. WPCF 2023, arXiv:2405.01061

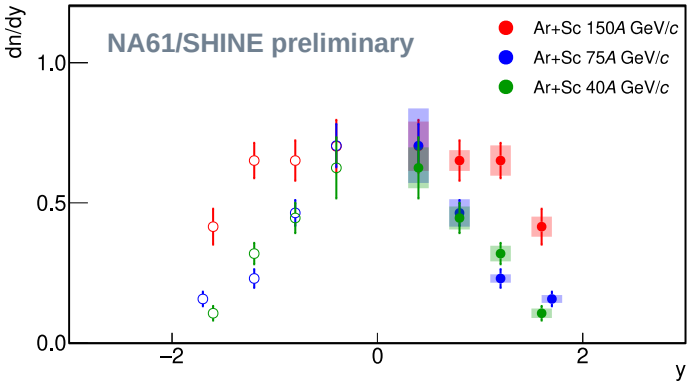
$K^*(892)^0$

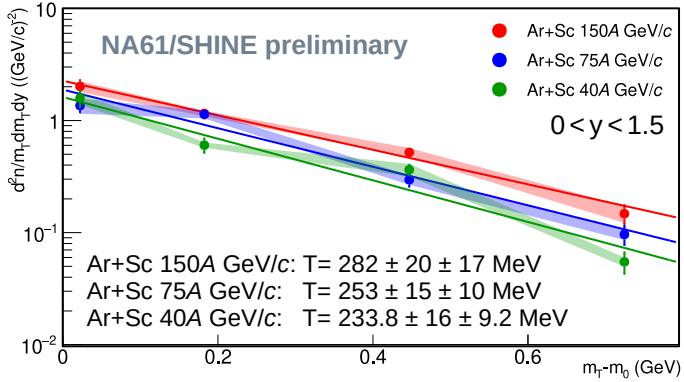


Uncertainties:
total (stat, syst)



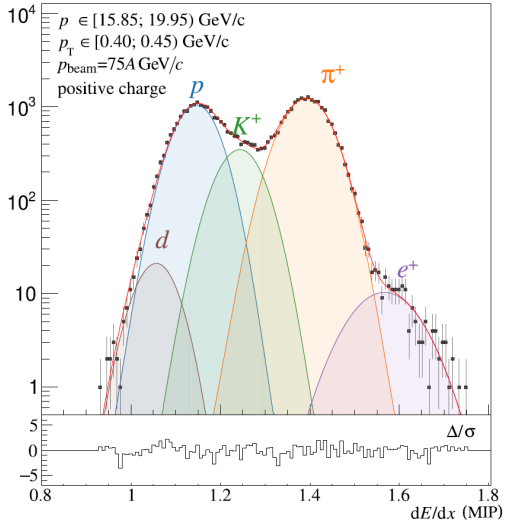
Uncertainties:
total (stat, syst)

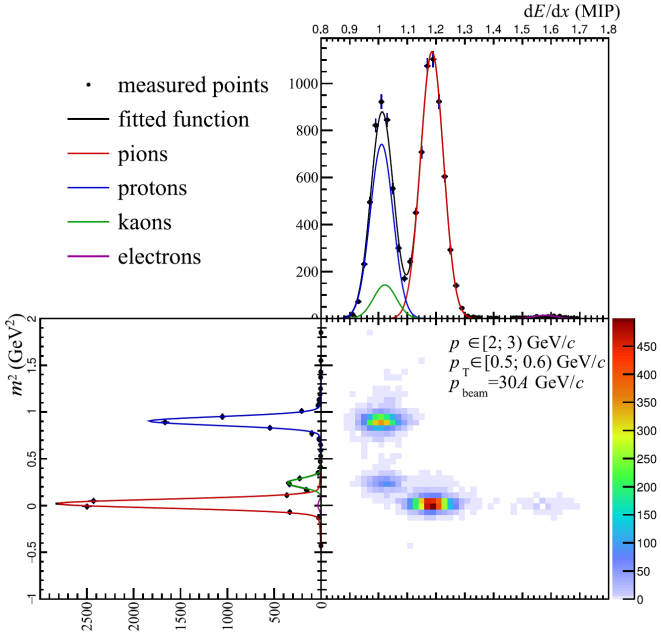




See Poster by
Bartosz Kozłowski

Measurement of identified charged particles in Ar+Sc reactions

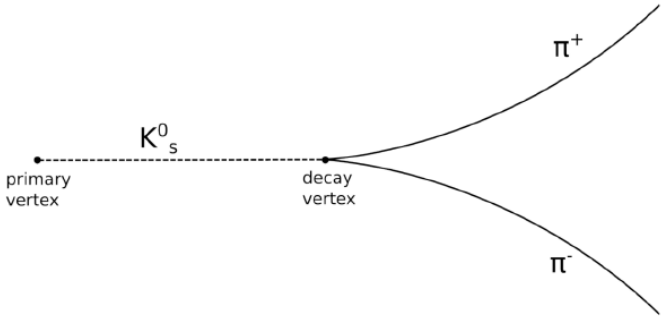




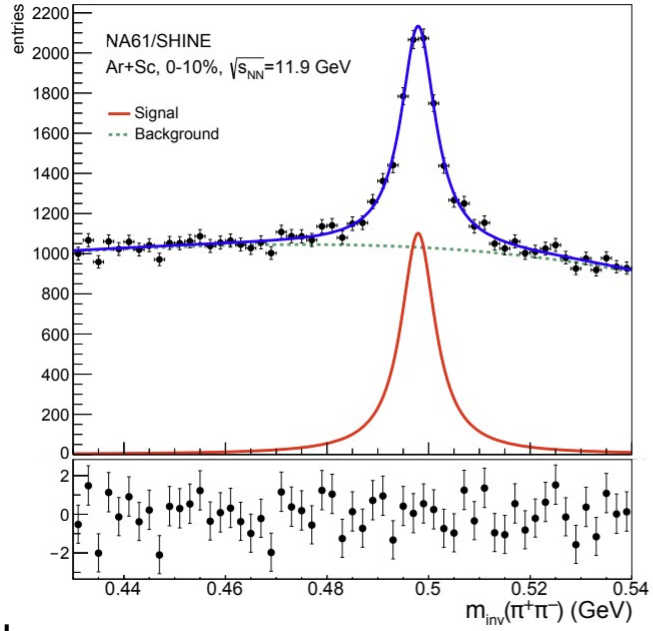
- Measurement based on **dE/dx** and **tof-dE/dx**
- Probability method
- Corrected for detector geometrical acceptance and reconstruction efficiency, as well as weak decays and secondary interactions

Both figures from:
NA61/SHINE, Eur.Phys.J.C 84 (2024) 4, 416

K^0_s measurement in Ar+Sc reactions



NA61/SHINE, arXiv:2312.06572

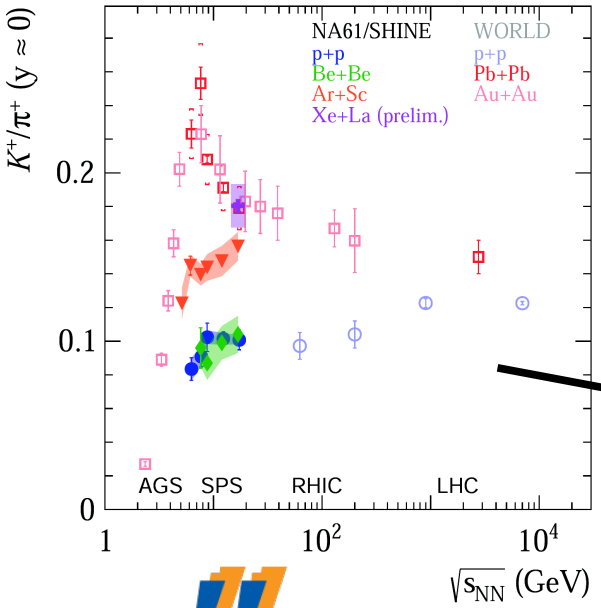


- Reconstruction based on decay topology
- K^0_s decays into π^+ and π^- with BR≈69.2%
- Lorentzian function is used to describe the signal
- Corrected for detector geometrical acceptance and reconstruction efficiency, as well as secondary interactions

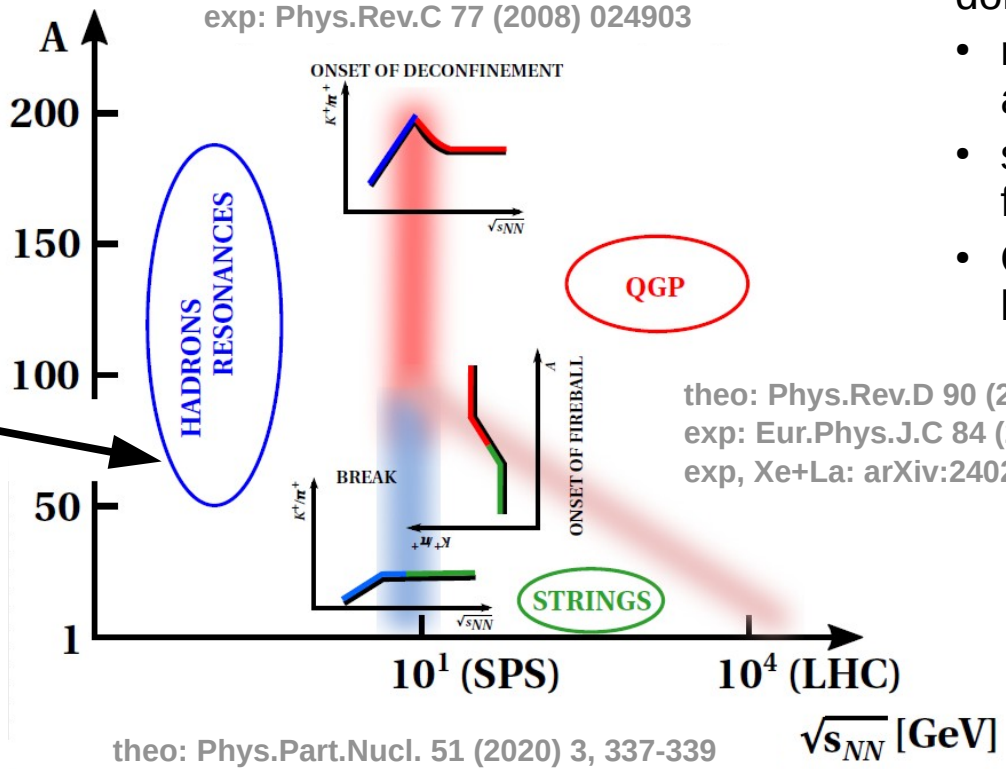
See talk by Tanja Šuša

Wednesday 12:00 AM

Diagram of high-energy nuclear collisions



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

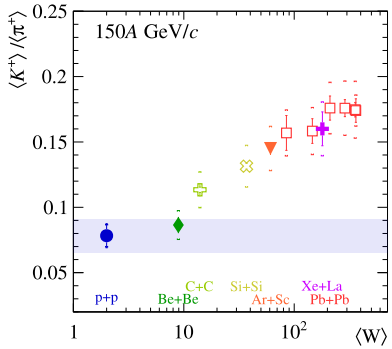


theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Hypothetical domains of hadron production, dominated by:

- resonance creation and decay
- string creation and fragmentation
- QGP formation and hadronisation

theo: Phys.Rev.D 90 (2014) 2, 025031
exp: Eur.Phys.J.C 84 (2024) 4, 416
exp, Xe+La: arXiv:2402.10973 [nucl-ex]



Kaon inverse slope *T*

Other NA61/SHINE data: EPJC 77 (2017) 671
EPJC 81 (2021) 73, EPJC 84 (2024) 416