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NA61/SHINE Collaboration
University of Silesia, Poland

Highlights from the NA61/SHINE physics program

NA6I/SHINE - UNIQUE MULTIPURPOSE FACILITY:
Hadron production in hadron-nucleus and nucleus-nucleus collisions at high energies

Norway grants

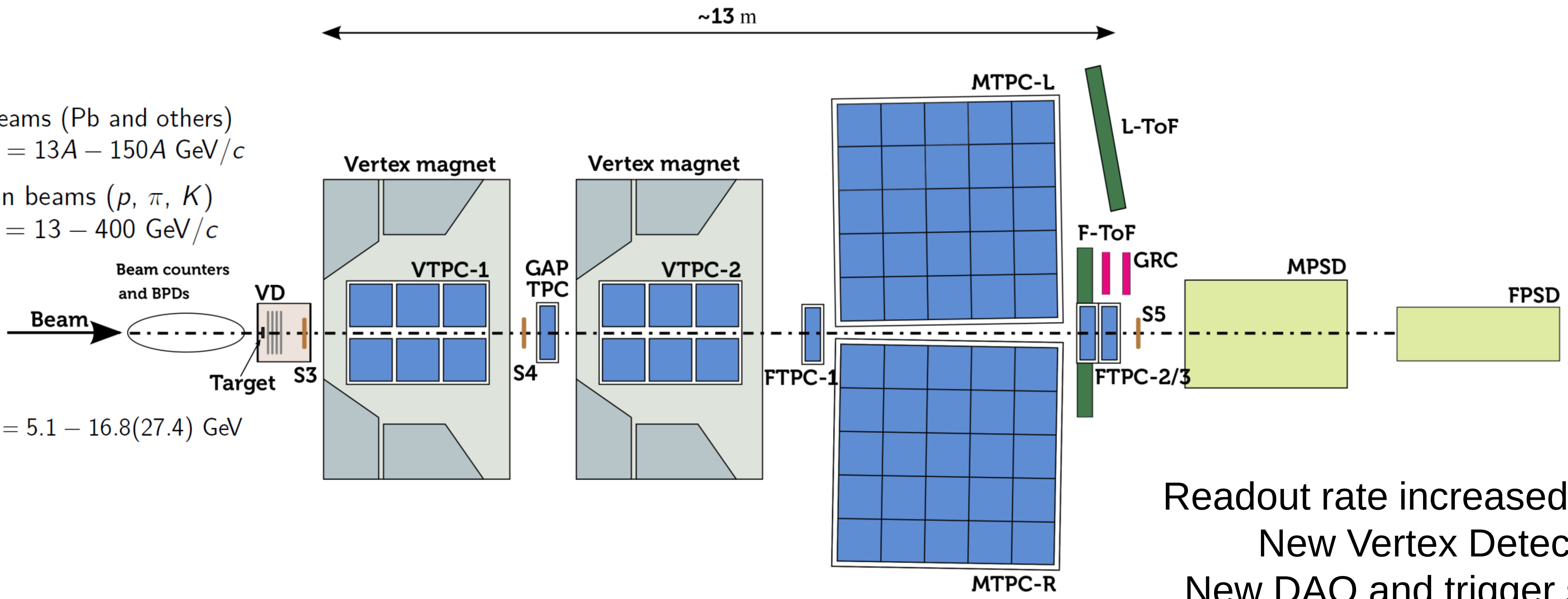
upgraded NA61/SHINE detector

Fixed target experiment located at the CERN SPS accelerator

ion beams (Pb and others)
$p_{beam} = 13A - 150A$ GeV/c

hadron beams (p, π, K)
$p_{beam} = 13 - 400$ GeV/c

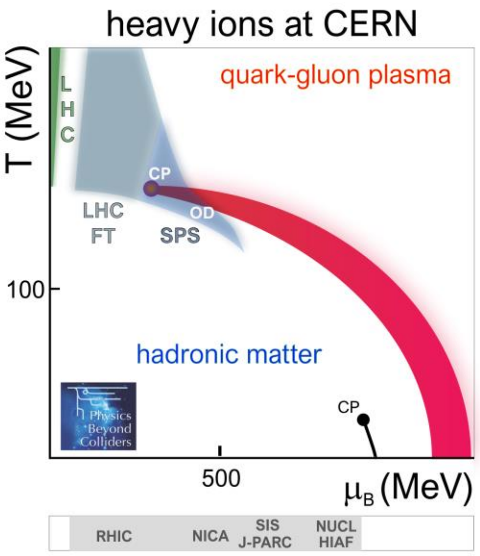
$\sqrt{s_{NN}} = 5.1 - 16.8(27.4)$ GeV

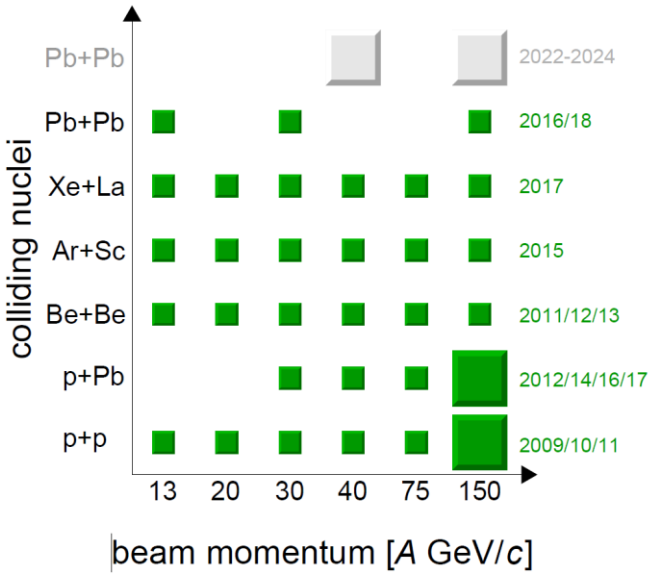


Readout rate increased to 1kHz
New Vertex Detector
New DAQ and trigger system
Upgraded PSD

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

NA61/SHINE - Physics program



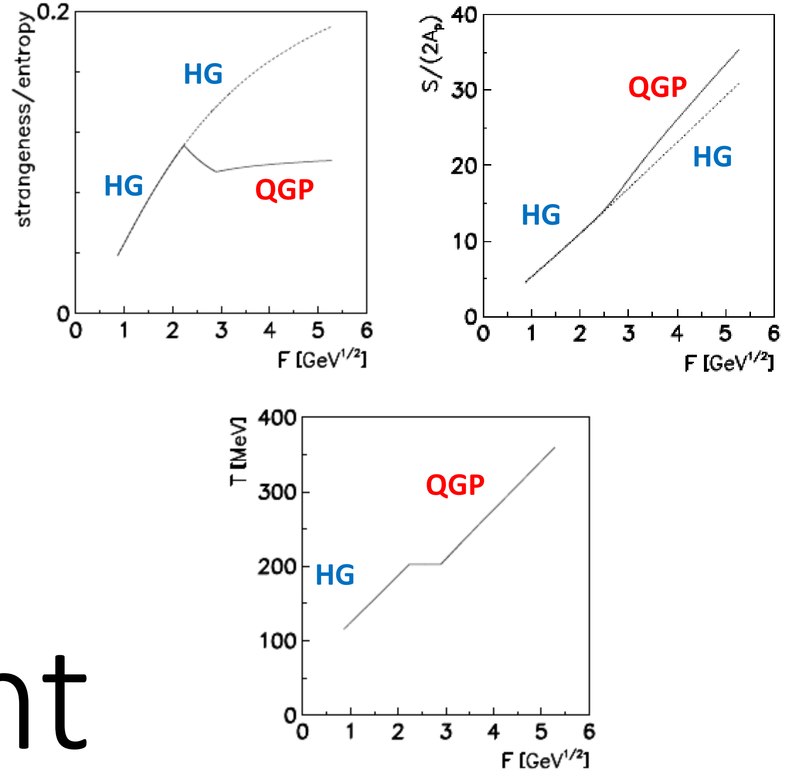


- **Strong interactions program**
  - search for the critical point of strongly interacting matter
  - study of the properties of the onset of deconfinement
  - heavy quarks: direct measurement of open charm at SPS energies
- Hadron-production measurements for neutrino experiments
- Hadron-production measurements for cosmic ray experiments

physics results

Acta Phys. Pol. B 30, 2705 (1999)

HORN – KINK - STEP



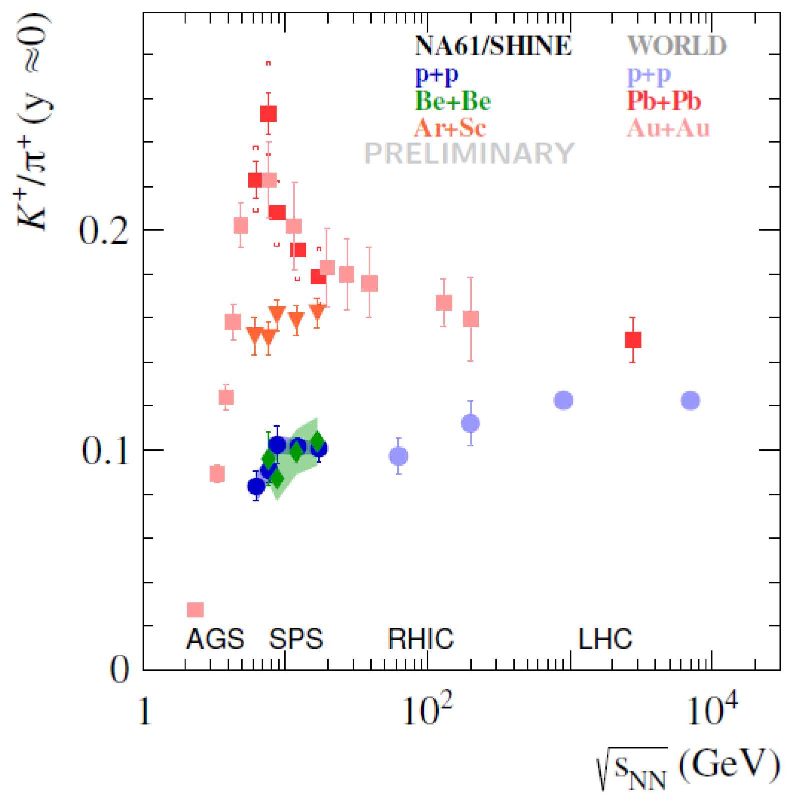
onset of deconfinement

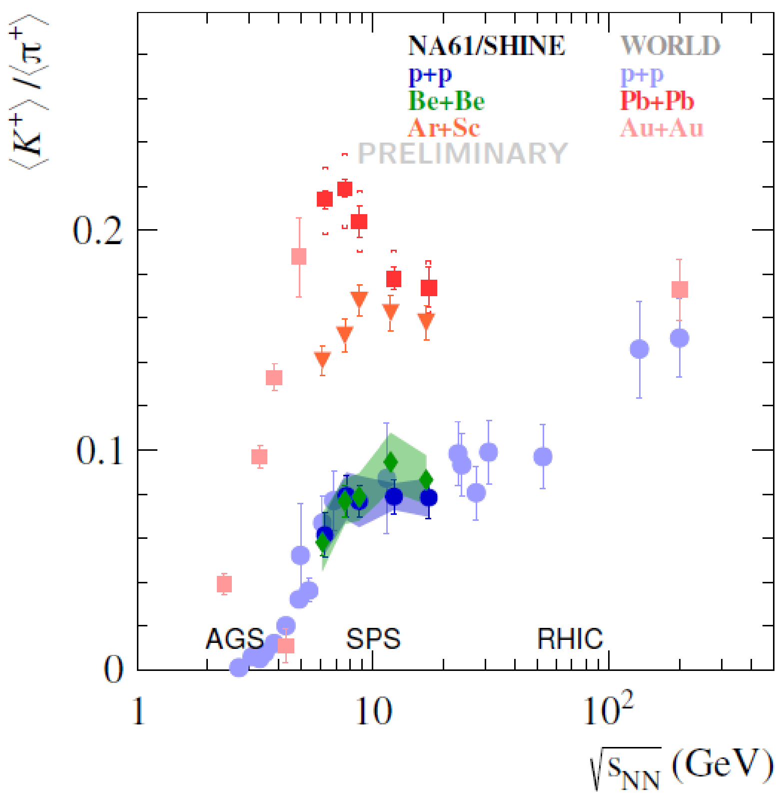
onset of deconfinement: horn

Plateau like structure visible in p+p, Be+Be and Ar+Sc

$p+p \approx \text{Be+Be} \neq \text{Ar+Sc} \leqslant \text{Pb+Pb}$

Ar+Sc is higher than p+p and Be+Be, Ar+Sc – no horn-like structure



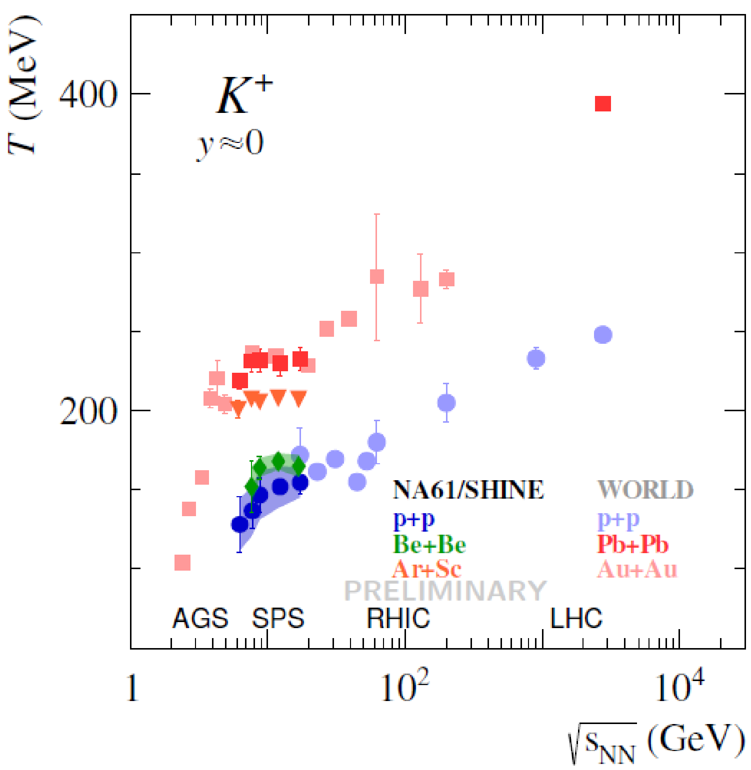


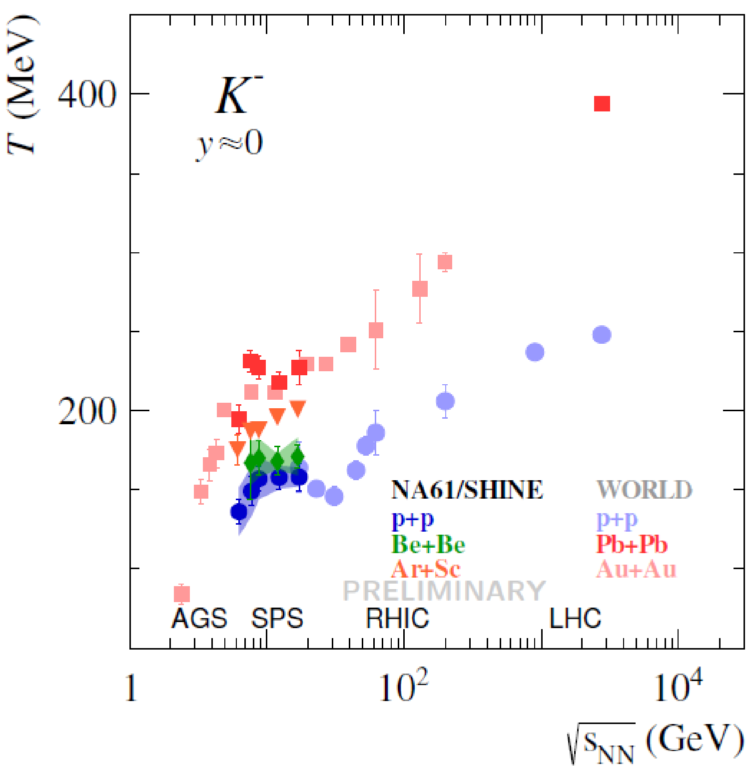
Good measure of the strangeness to entropy ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons).

Probe of the onset of deconfinement.

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

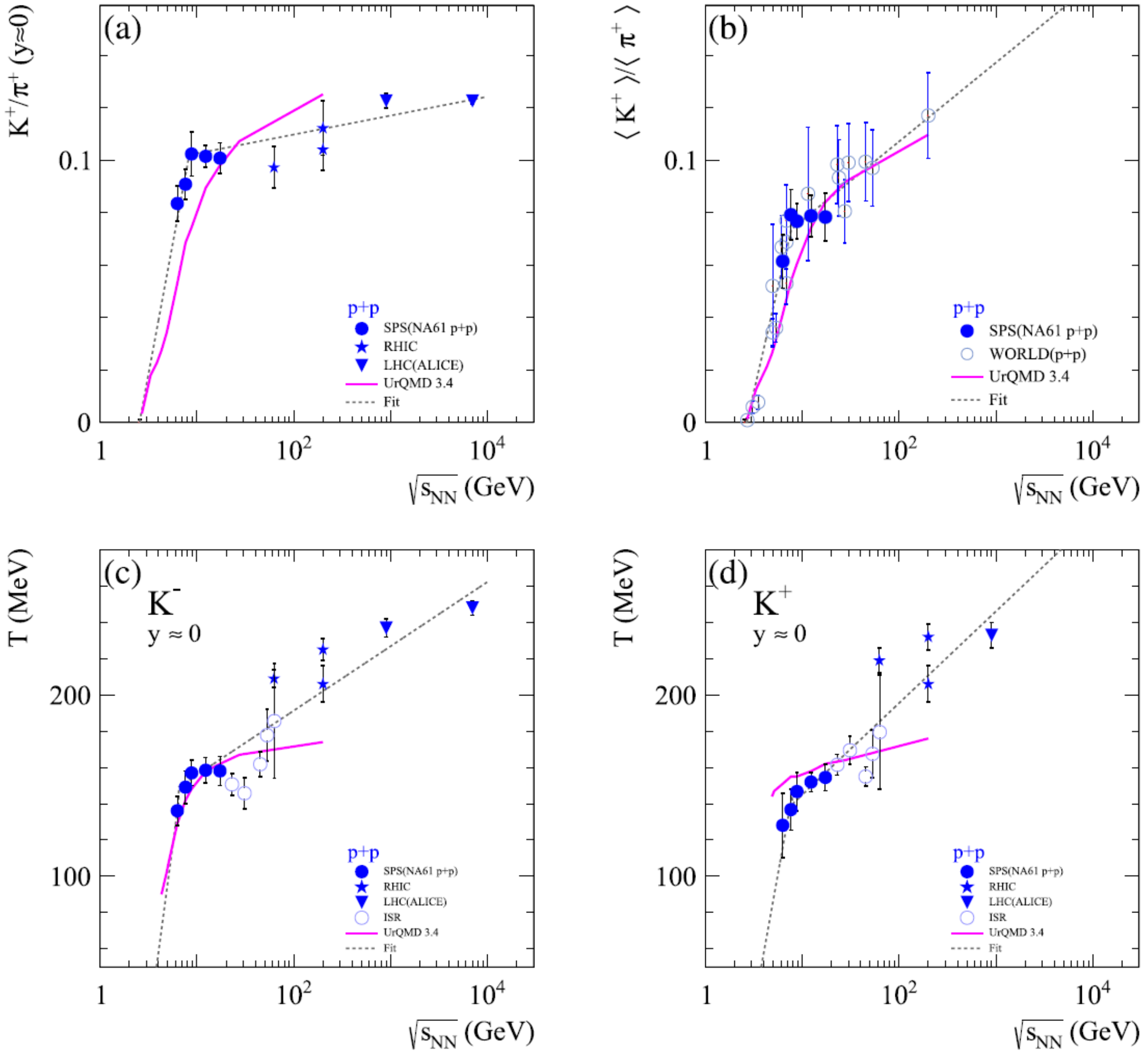




Kaons are only weakly affected by rescattering and resonance decays during the post-hydro phase (at SPS and RHIC energies).

Connected temperature of the freeze-out surface and not the early-stage fireball

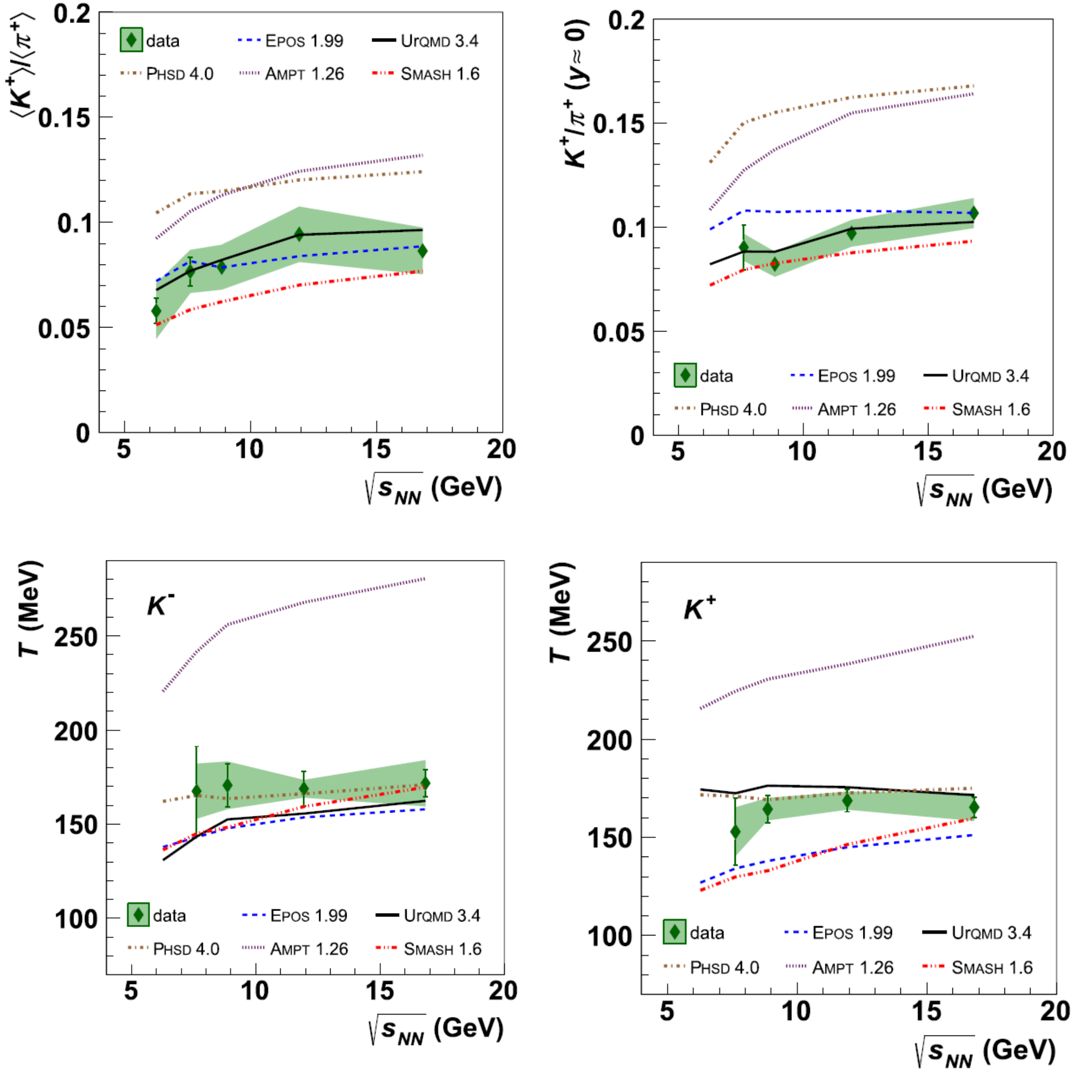
p+p interactions and onset of deconfinement



- The sharp break in K^+/π^+ and inverse slope parameter T in p+p collisions at SPS energies
- The break energy is ≈7 GeV - close to the energy of the onset of deconfinement ≈8 GeV
- The UrQMD model does not reproduce the sharpness of the break

Phys. Rev. C 102, 011901(R)

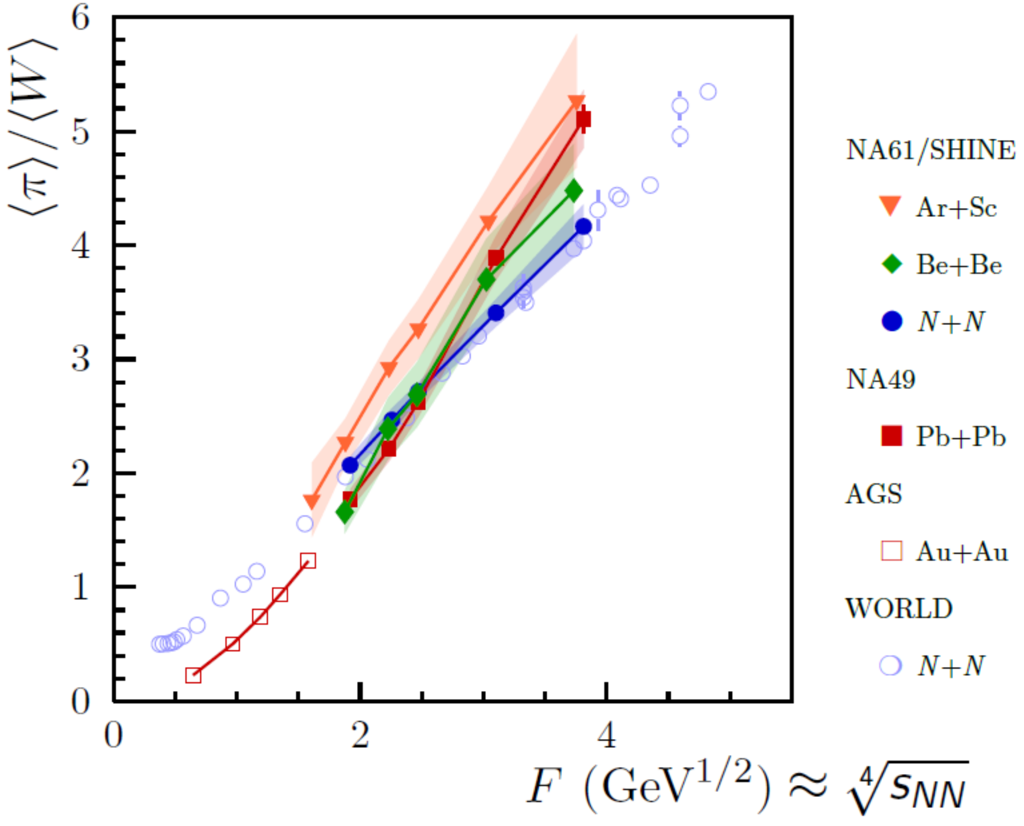
Be+Be collisions and onset of deconfinement



- NA61/SHINE – the only world data for Be+Be collisions
- No visible sharp break in K^+/π^+ and inverse slope parameter T. Note the limited energy range of data
- No models which describe all measured quantities
- Results available only in the SPS energy range

Eur.Phys.J.C 81 (2021) 1, 73

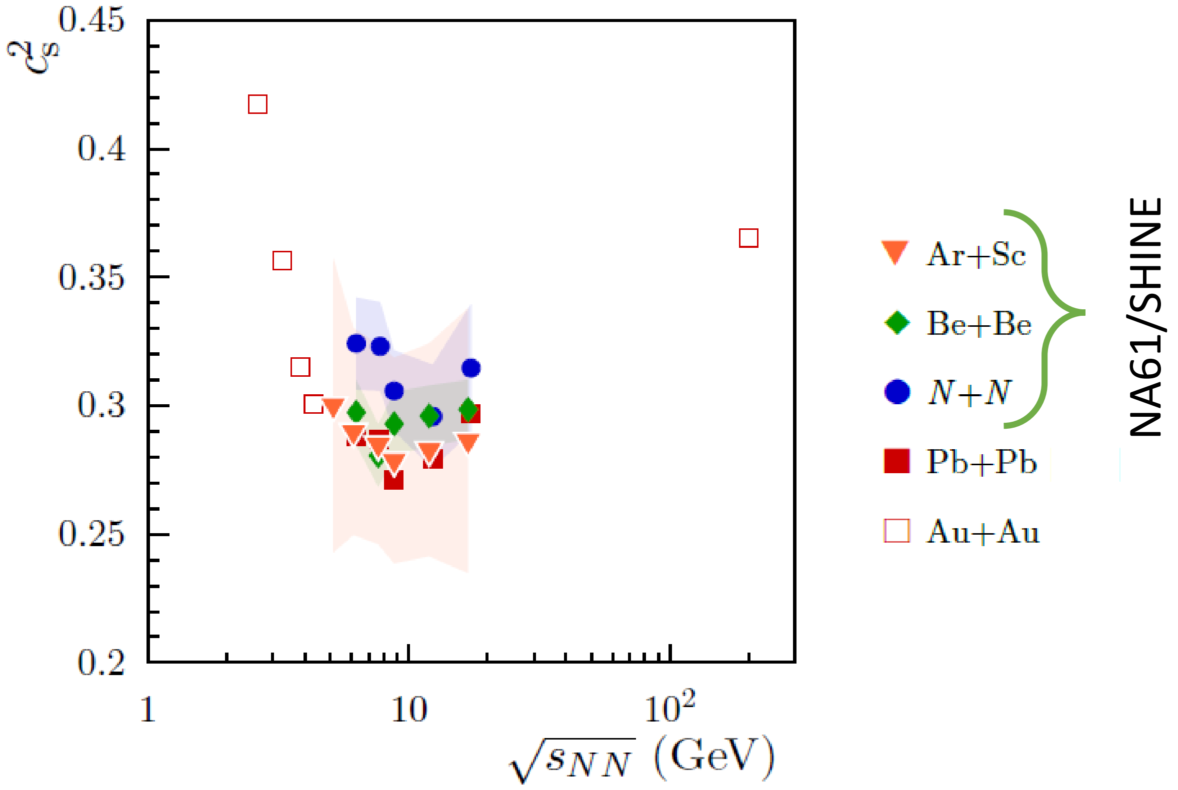
update of the “kink” plot – pion multiplicity per number of wounded nucleons



- The NA61/SHINE results
  - *N*+*N* interactions agree well with the world data
  - Be+Be collisions are mostly between measurements from *N*+*N* and Pb+Pb collisions.
  - Ar+Sc results systematically higher than the results for *N*+*N*, Be+Be and Pb+Pb collisions at the lower energies
  - Ar+Sc close to the Pb+Pb results at the highest energies.

arXiv:2101.08494v2 [hep-ex] 25 Jan 2021

width of the rapidity distribution - speed of sound



- The collision energy dependence of the rapidity distribution width is associated with the speed of sound c_S

$$\sigma^2 = \frac{8}{3} \cdot \frac{c_s^2}{1 - c_s^4} \cdot \ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right)$$

E. V. Shuryak. *Yad.Fiz.*, 16:395–405, 1972.

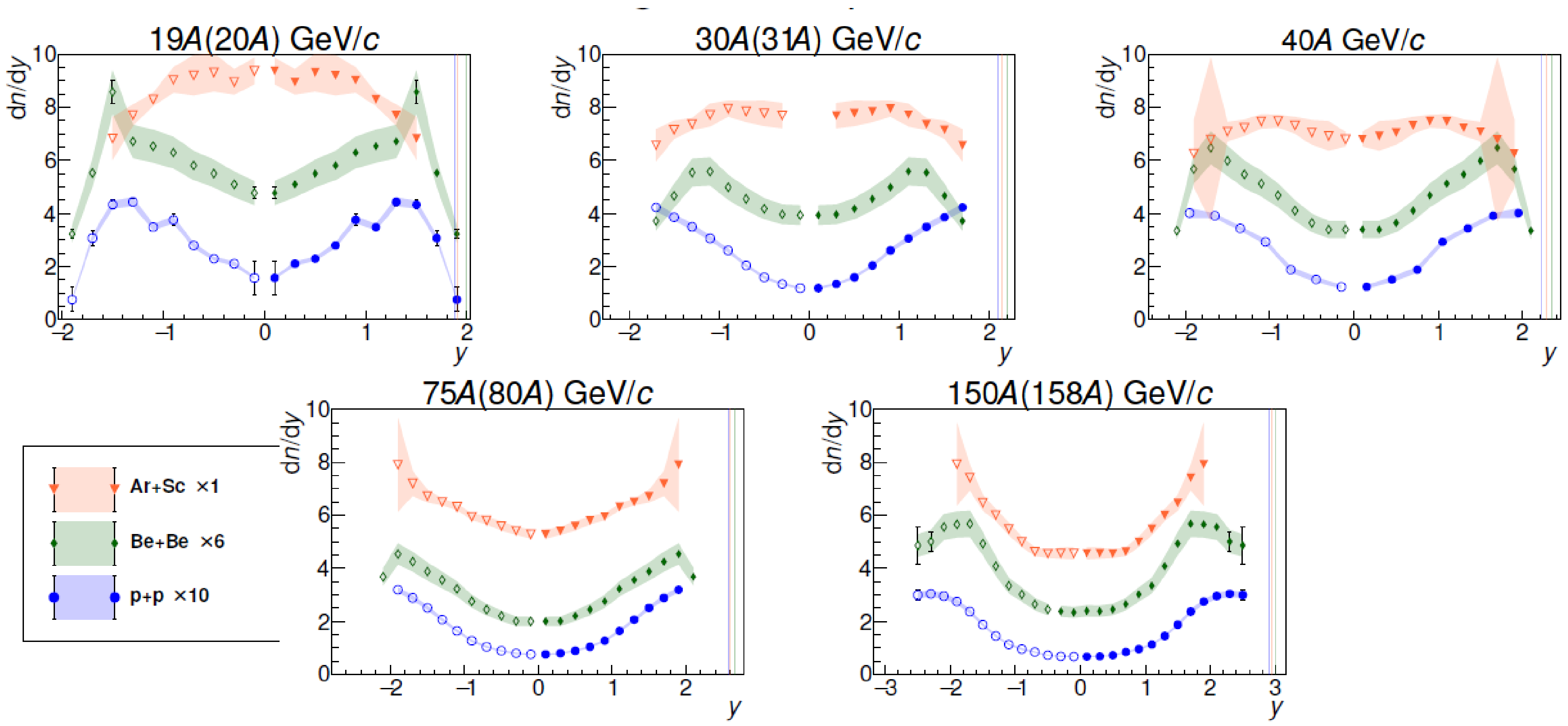
- The dense matter produced in the collisions was predicted to show a minimum in the speed of sound energy dependence around the collision energy of the onset of deconfinement
- Confirmed by Pb+Pb data in combination with results from central Au+Au collisions
- The results of NA61/SHINE from *central* Ar+Sc, Be+Be collisions, and inelastic *N+N* reactions need to be extended to lower end energies for conclusion about a possible minimum

EPJC 81 (2021) 5, 397

Protons and the onset of deconfinement

Proton rapidity distributions are suggested to be sensitive to the onset of deconfinement due to softening of the equation of state

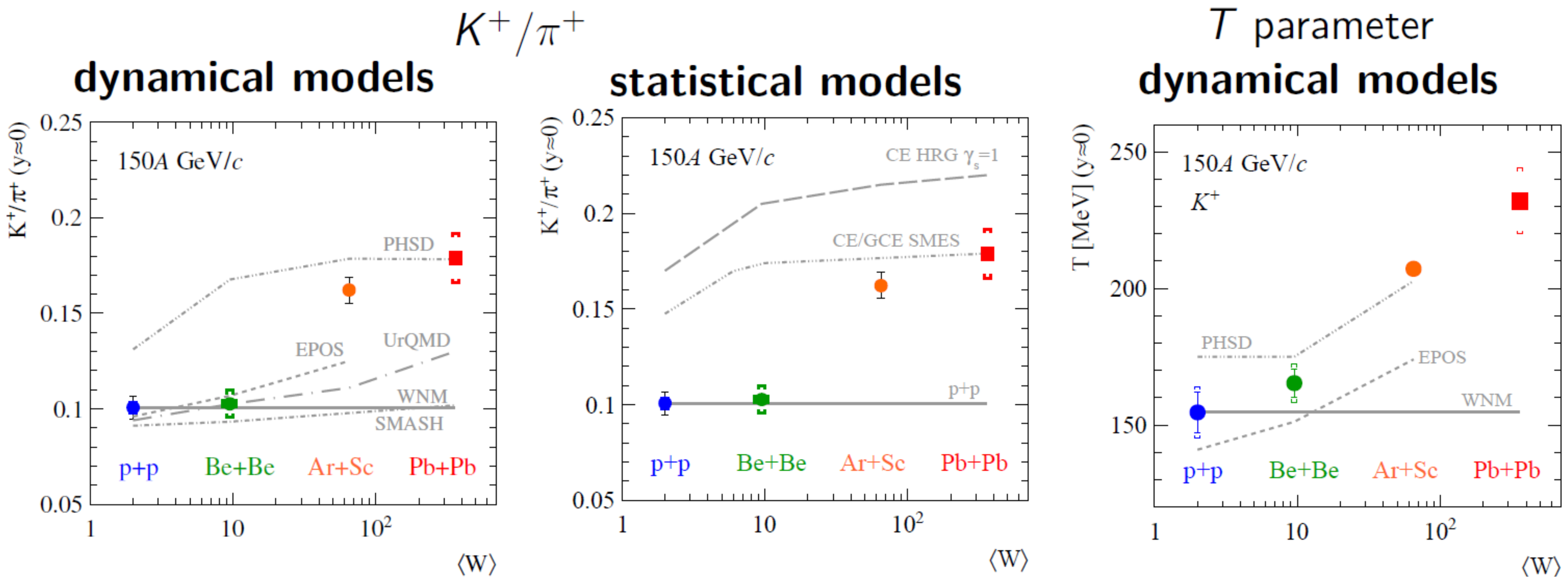
Ivanov, PLB 690 (2010) 358



“Dip” for p+p and Be+Be. “Peak-dip” transition for Ar+Sc.

System size dependence

Onset of fireball
K^+/π^+ and T vs the system size at 150A GeV/c

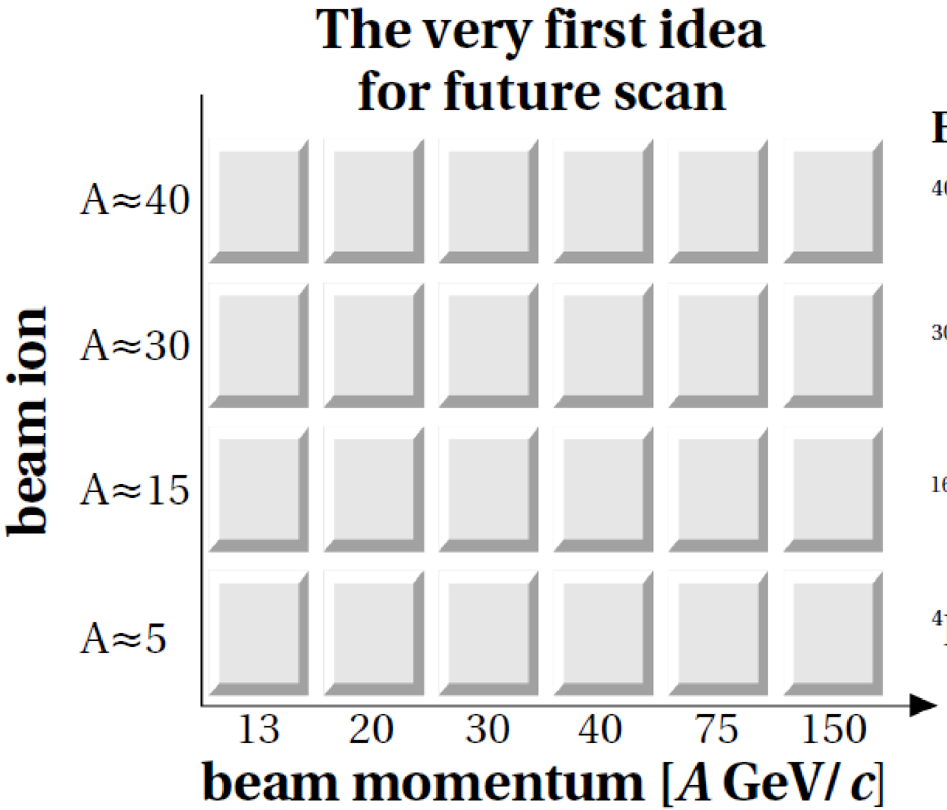


None of the models reproduces K^+/π^+ ratio or T for whole $\langle W \rangle$ range

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
SMES: Acta Phys. Polon. B46 (2015) 10, 1991 - recalculated

p+p: Eur. Phys. J. C77 (2017) 10, 671
Be+Be: Eur. Phys. J. C81 (2021) 1, 73
Ar+Sc: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C66, 054902 (2002)

measurements after LS3



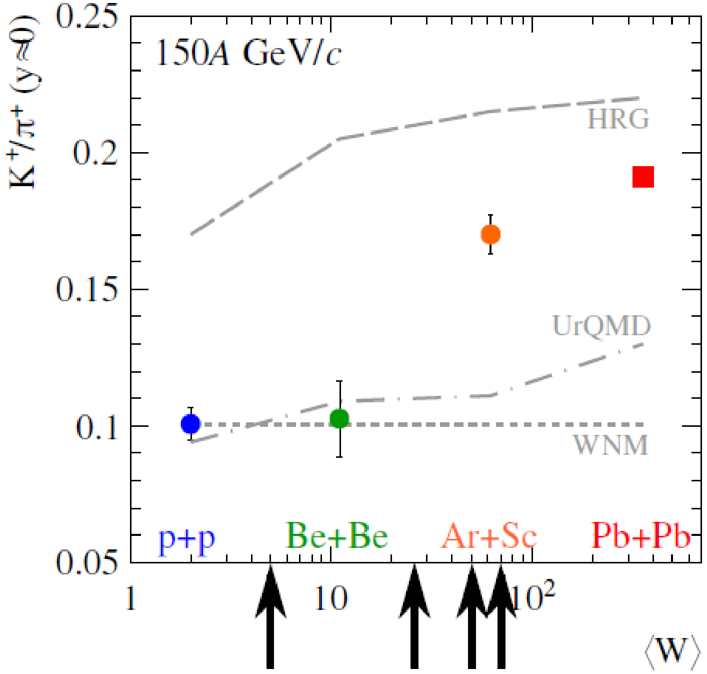
Example ion:

^{40}Ca Synergy with Gamma Factory

^{30}P

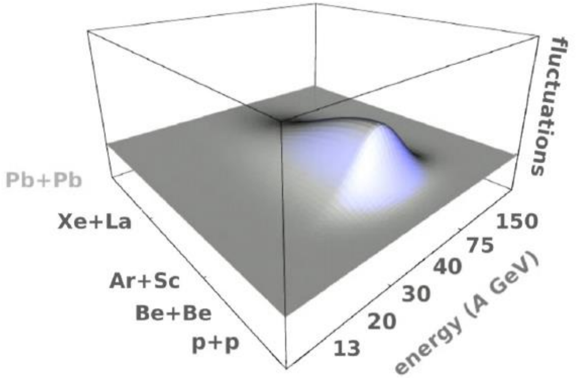
^{16}O Synergy with Cosmic-Ray LHC

^{4}He



PHYSICAL REVIEW D **60** 114028

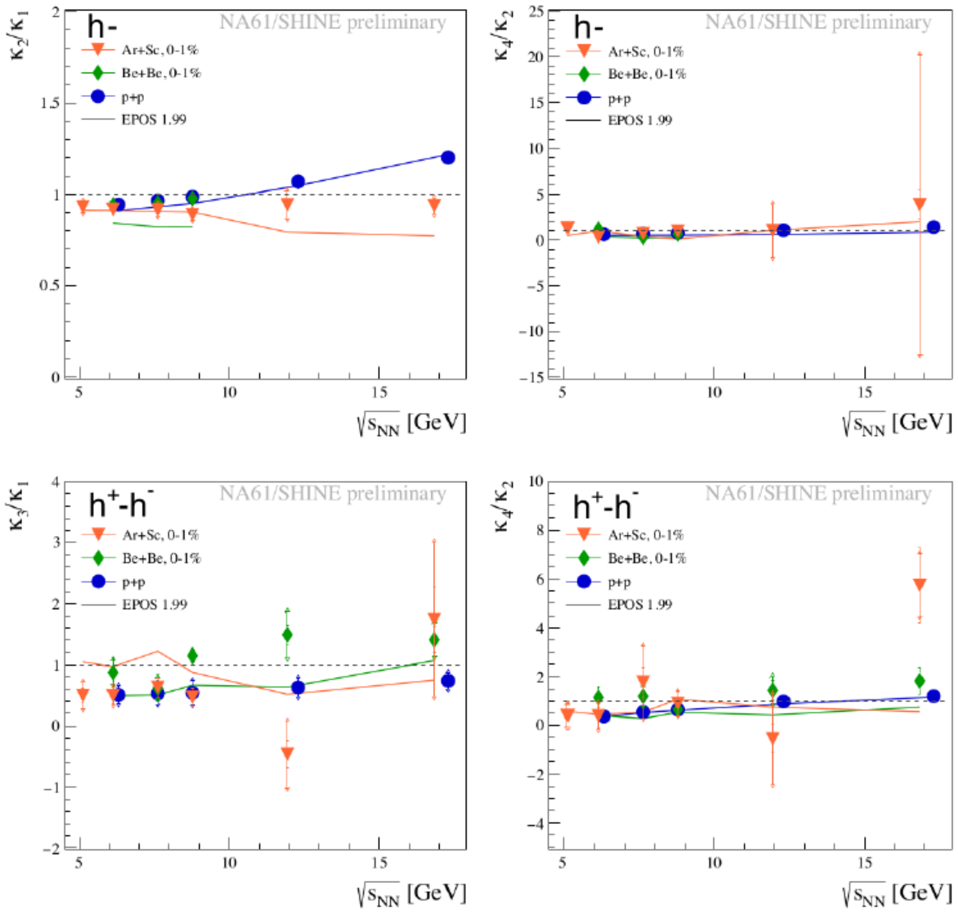
Theoretical fluctuations
in presence of critical point



critical point

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

No structure indicating critical point



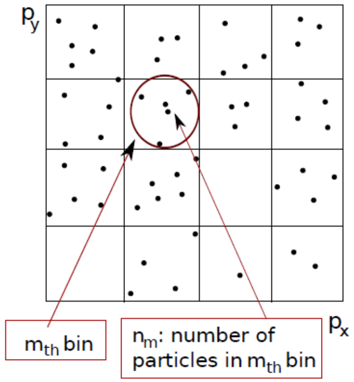
$$\kappa_1 = \langle N \rangle$$
$$\kappa_2 = \langle (\delta N)^2 \rangle = \sigma^2$$
$$\kappa_3 = \langle (\delta N)^3 \rangle = S\sigma^3$$
$$\kappa_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 = K\sigma^4$$

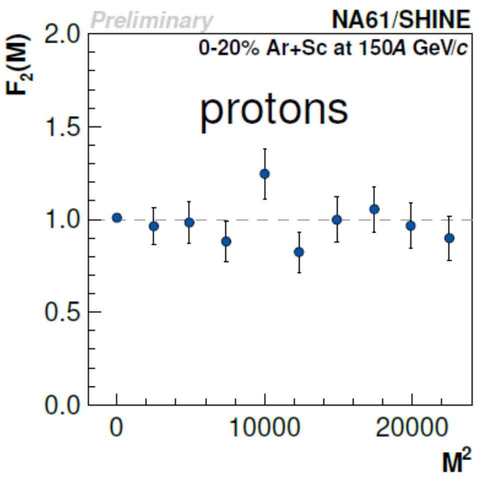
where:
N – multiplicity; $\delta N = N - \langle N \rangle$
σ – standard deviation
S – skewness; K – kurtosis

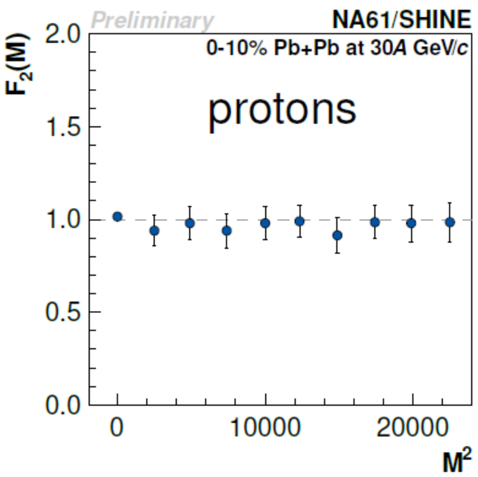
- Negatively charge κ_2/κ_1: increasing difference between small systems (p+p and Be+Be) and a heavier system (Ar+Sc) with collision energy
- In case of net-electric charge, the scaled skewness and scaled kurtosis indicate non-monotonic behavior within sizeable systematic uncertainties

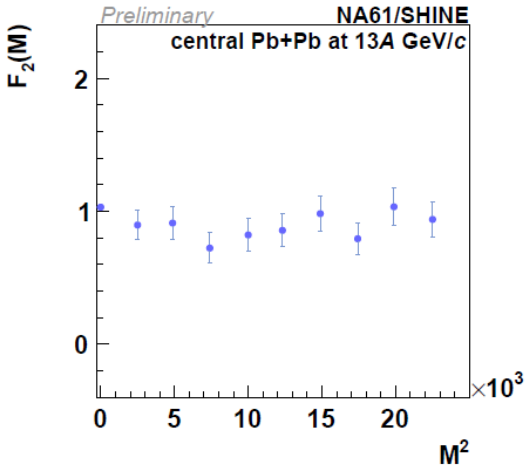
proton and charge hadron intermittency in Ar+Sc and Pb+Pb collisions

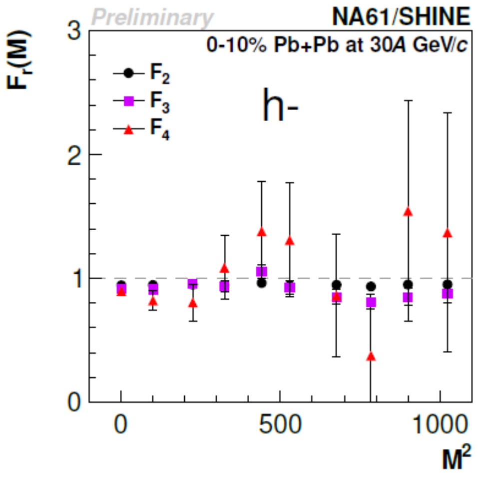
No structure indicating critical point







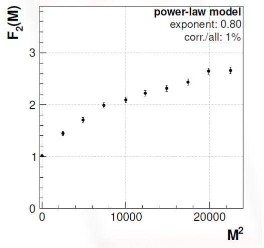




$$F_r(M) = \frac{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m(n_m-1)\ldots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m \right\rangle^r},$$

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

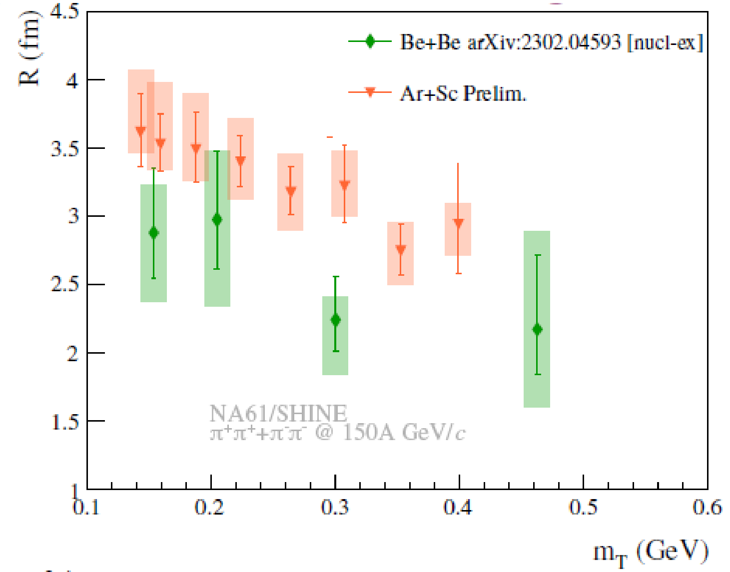
If the system freezes-out in the vicinity of the critical point, $F_2(M)$ should reveal a power-law dependence

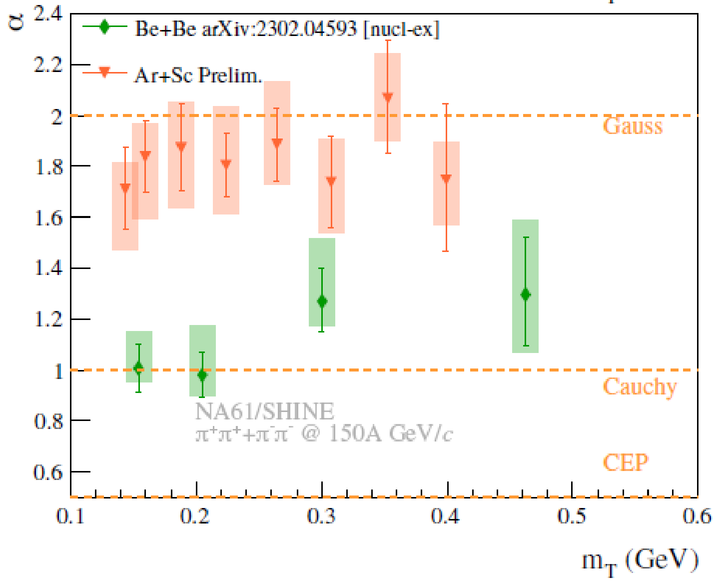


Statistically independent points, cumulative variables

No indication of critical point in these analyses (power-law scaling $F_r(M) \sim M^{\phi_r}$)

two-pion - symmetric Levy HBT correlations



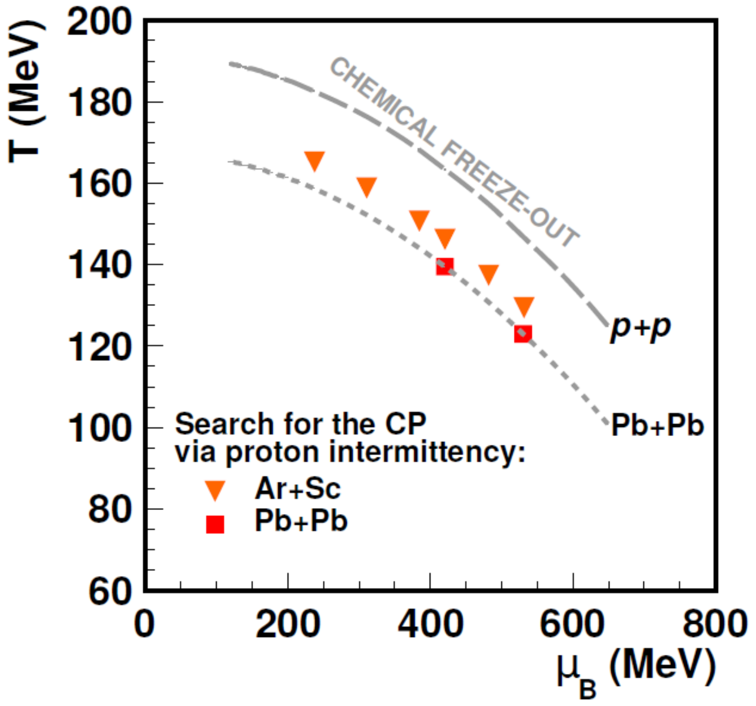


- Bose-Einstein correlations are sensitive to spatial extension of particle source
- Usually correlation function assumes Gaussian source but it can be generalized by Lévy-shaped

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

- R Lévy-scale parameter:
  - describes length of homogeneity
  - from hydro: R $1/mT$ (For Gaussian source)
  - visible mT dependence -> sign of transverse flow
- Lévy-stability index :
  - describes shape of spatial correlation
  - α does not indicate CP in Be+Be and Ar+Sc
  - α between Gaussian or Cauchy shape compatible with symmetric Lévy assumption

Summary of NA61/SHINE critical point search



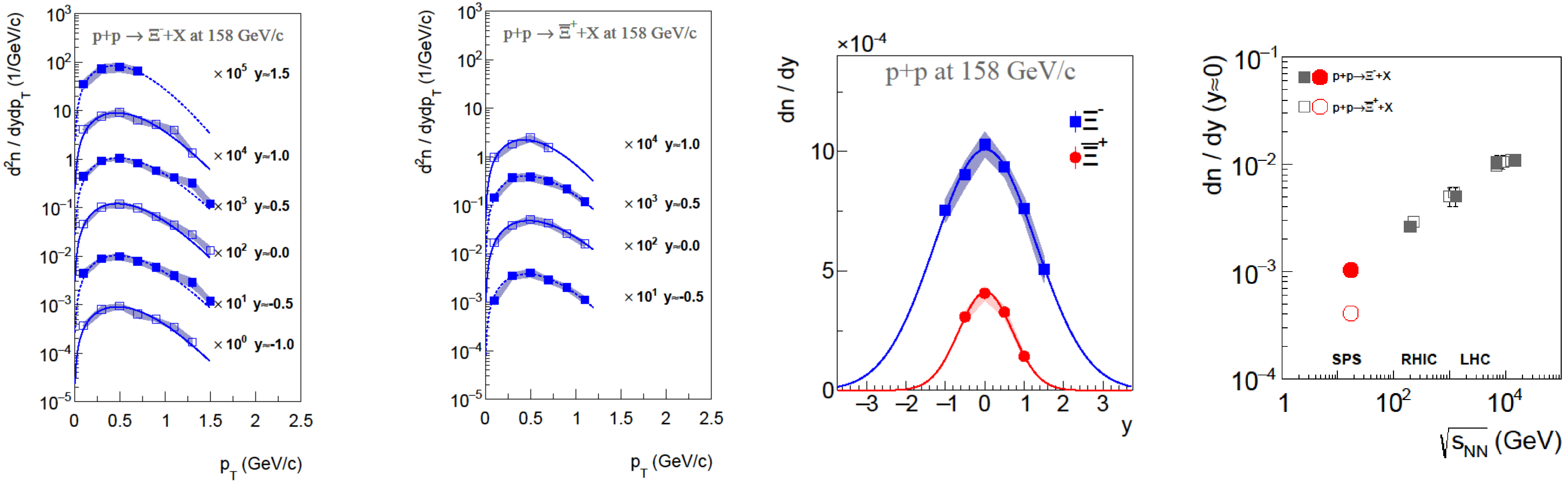
Work in progress on intermittency analysis for Xe+La collisions

- Summarize NA61/SHINE critical point search via proton intermittency on the diagram of chemical freeze-out temperature and chemical potential
- Dashed line indicates parameters in p+p interactions
- Dotted line in central Pb+Pb collisions
- Color points mark reactions in the $T - \mu_B$ phase diagram for which search for the critical point was conducted
- Freeze-out points in the $T - \mu_B$ achieved by simple parabolic fit within the statistical hadronization model supplemented with the hydrodynamical expansion of the matter

F. Becattini, J. Manninen and M. Gazdzicki, Phys.Rev. C73 (2006) 044905

strangeness production in p+p

Ξ production in inelastic p+p collisions at 158 GeV/c

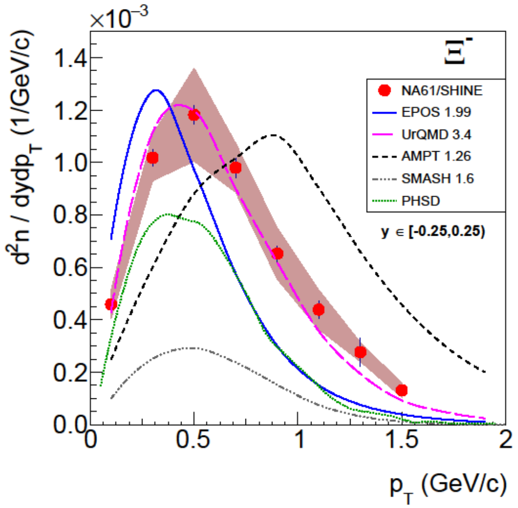


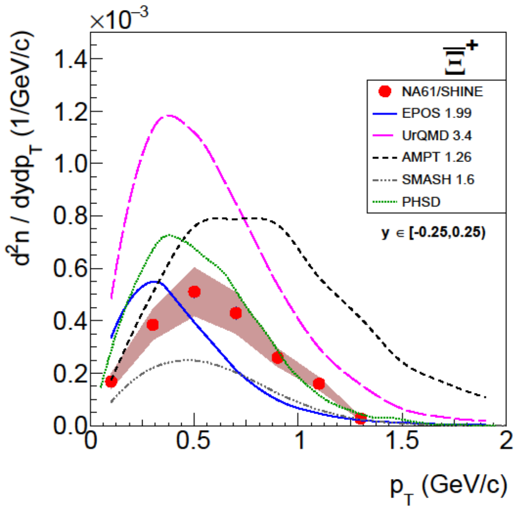
The only results on Ξ^- and $\bar{\Xi}^+$ production in *p+p* at SPS energy

Suppression of $\bar{\Xi}^+$ production: $\langle\bar{\Xi}^+\rangle / \langle\Xi^-\rangle = 0.24 \pm 0.01 \pm 0.05$

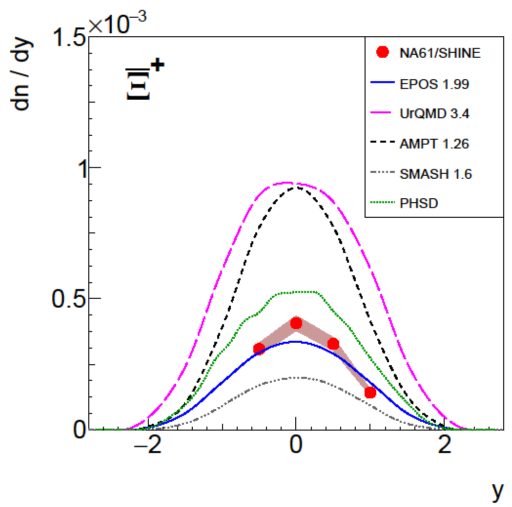
Eur.Phys.J.C 80 (2020) 9, 833

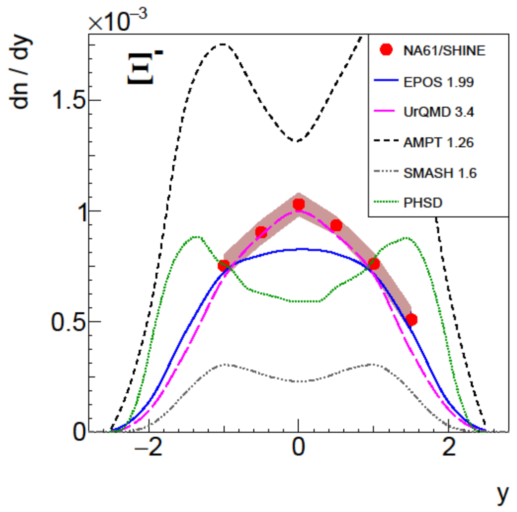
Ξ production in inelastic p+p collisions – model comparison

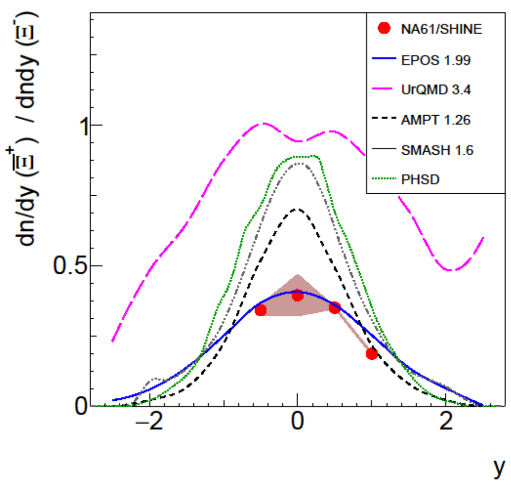




- Transport models **fail** to describe the NA61/SHINE results on Ξ production in p+p collisions



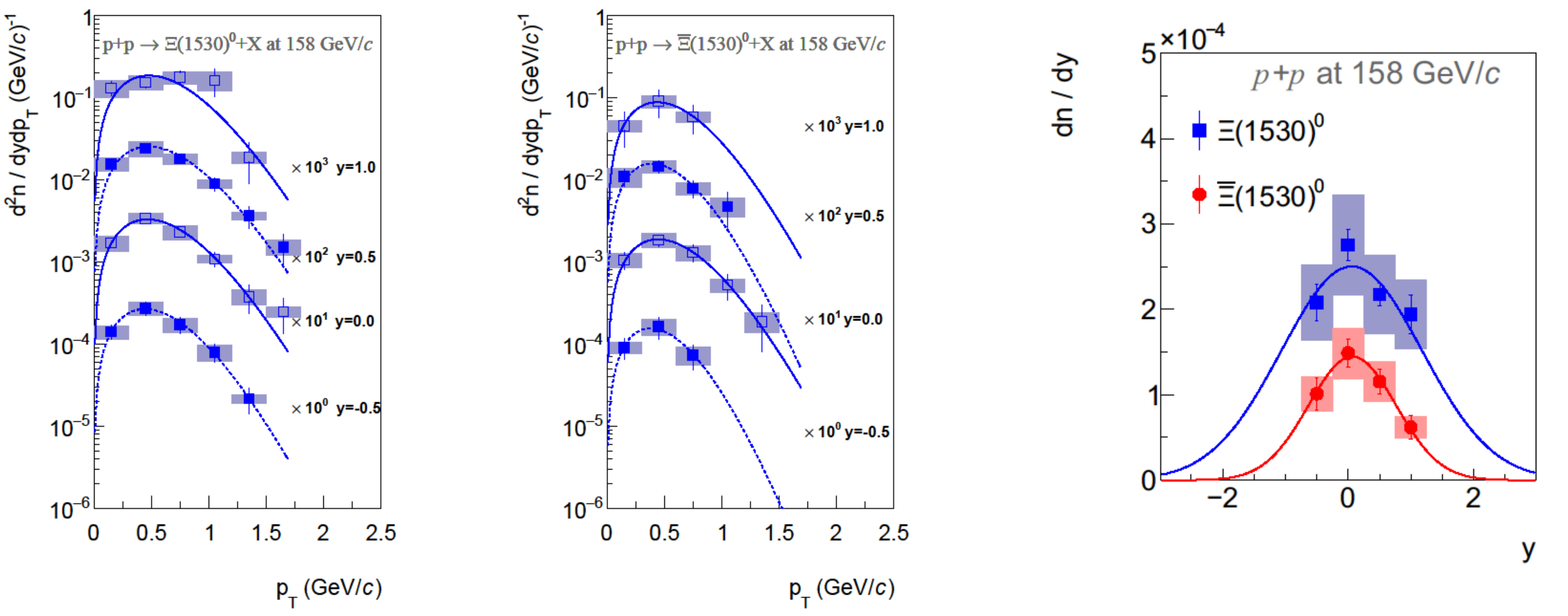




Eur.Phys.J.C 80 (2020) 9, 833

$\Xi(1530)^0$ production in inelastic p+p collisions at 158

Eur.Phys.J.C 81 (2021) 10, 911



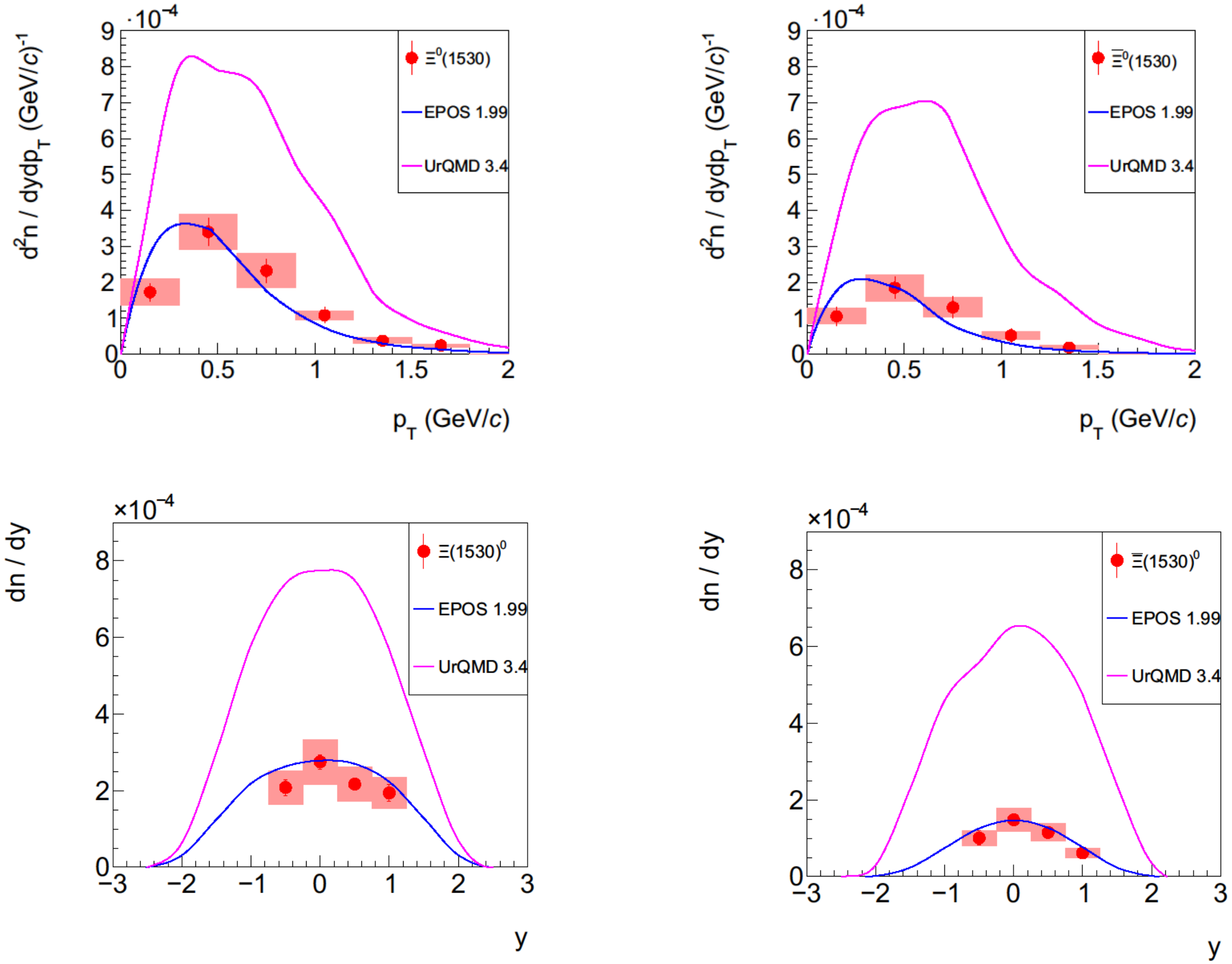
The only results on $\Xi(1530)^0$ production in *p+p* at the SPS energy

The second result on $\Xi(1530)^0$ production in *p+p* (ALICE at 7 TeV Eur.Phys.J.C 75 (2015) 1)

Suppression of $\bar{\Xi}(1530)^0$ production: $\langle\bar{\Xi}(1530)^0\rangle$ / $\langle\Xi(1530)^0\rangle$= 0.40 ± 0.03 ± 0.05

$\Xi(1530)^0$ production in inelastic p+p collisions at 158 GeV/c

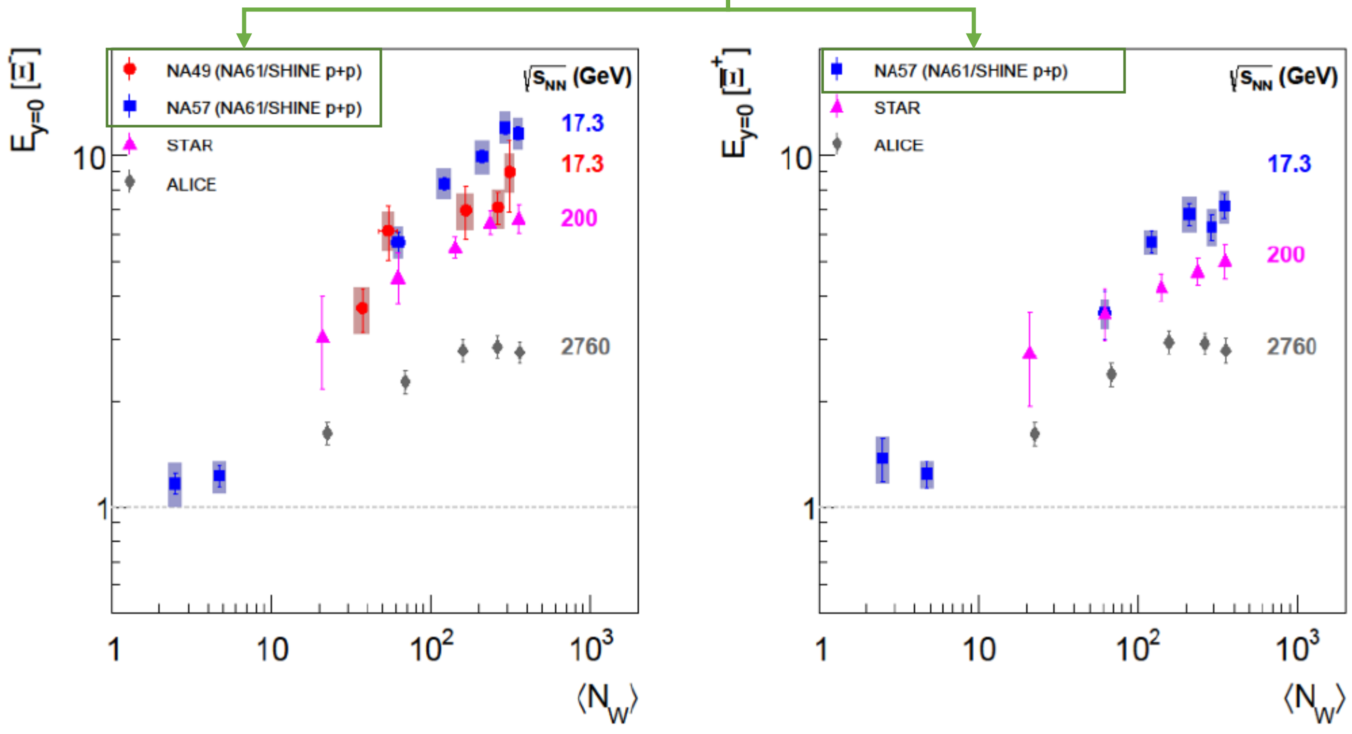
Eur.Phys.J.C 81 (2021) 10, 911



- EPOS describes well transverse momentum and rapidity distributions of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$
- UrQMD significantly overestimates all spectra of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ hyperons

strangeness enhancement factors

the recalculation of the enhancement based on the NA61/SHINE data



The strangeness enhancement factor E

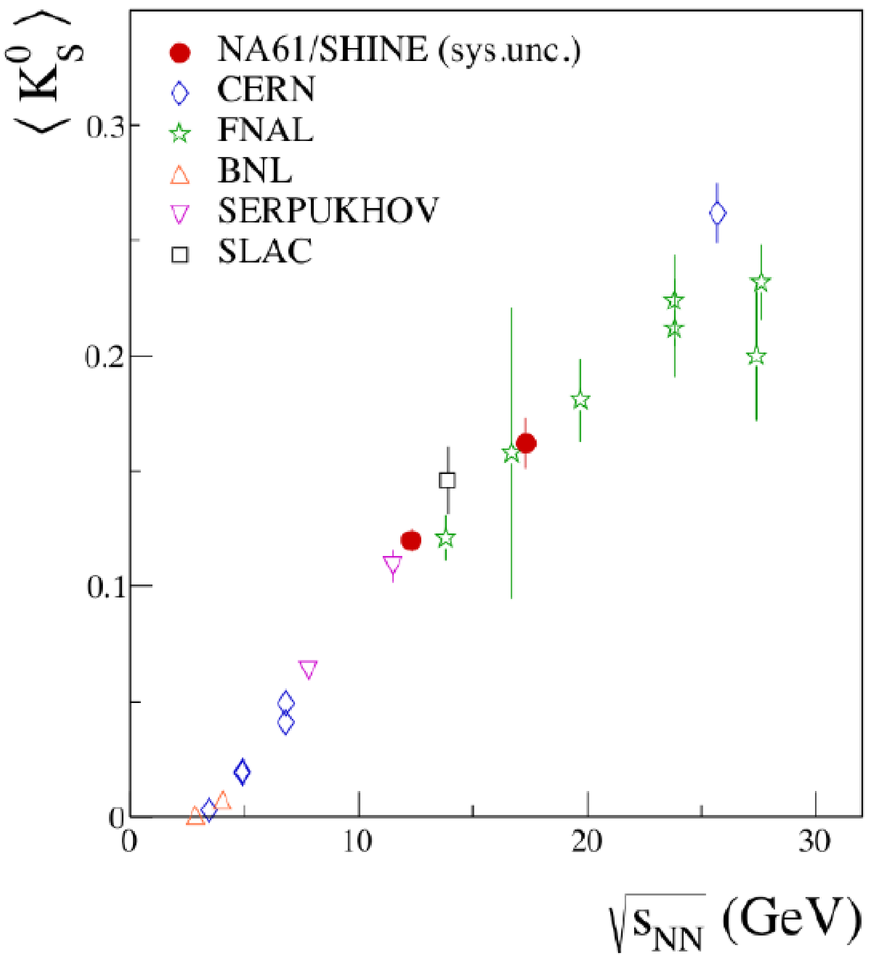
$$E = \frac{2}{\langle N_W \rangle} \frac{dn/dy\,(A+A)}{dn/dy\,(p+p)},$$

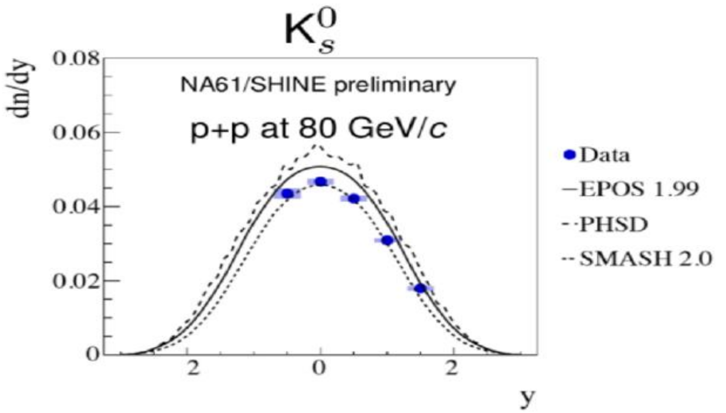
Nucl. Phys. B111 (1976) 461

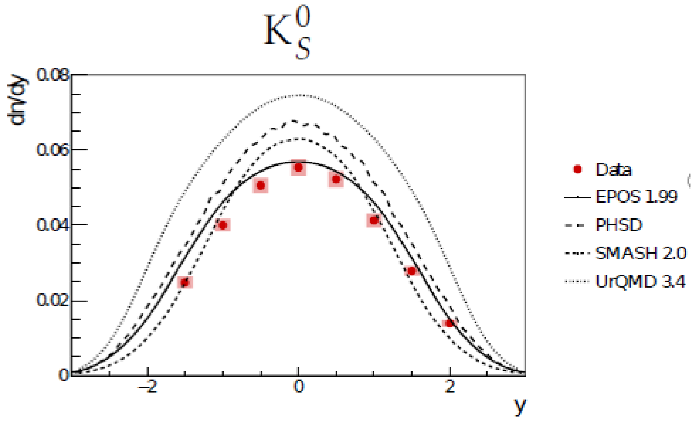
Thanks to the NA61/SHINE p+p data new baseline for Ξ^- and Ξ^+ production at 158 GeV/c was set

Eur.Phys.J.C 80 (2020) 9, 833

K_S^0 meson production in *p+p* interactions

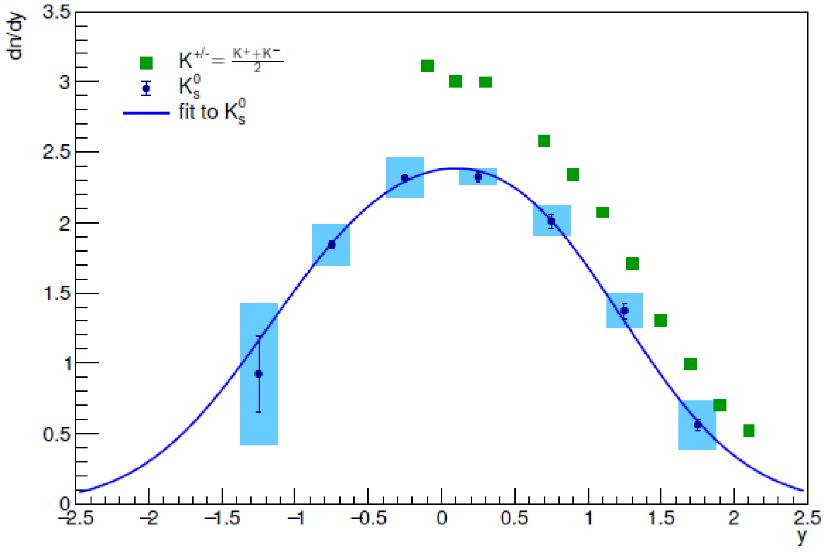


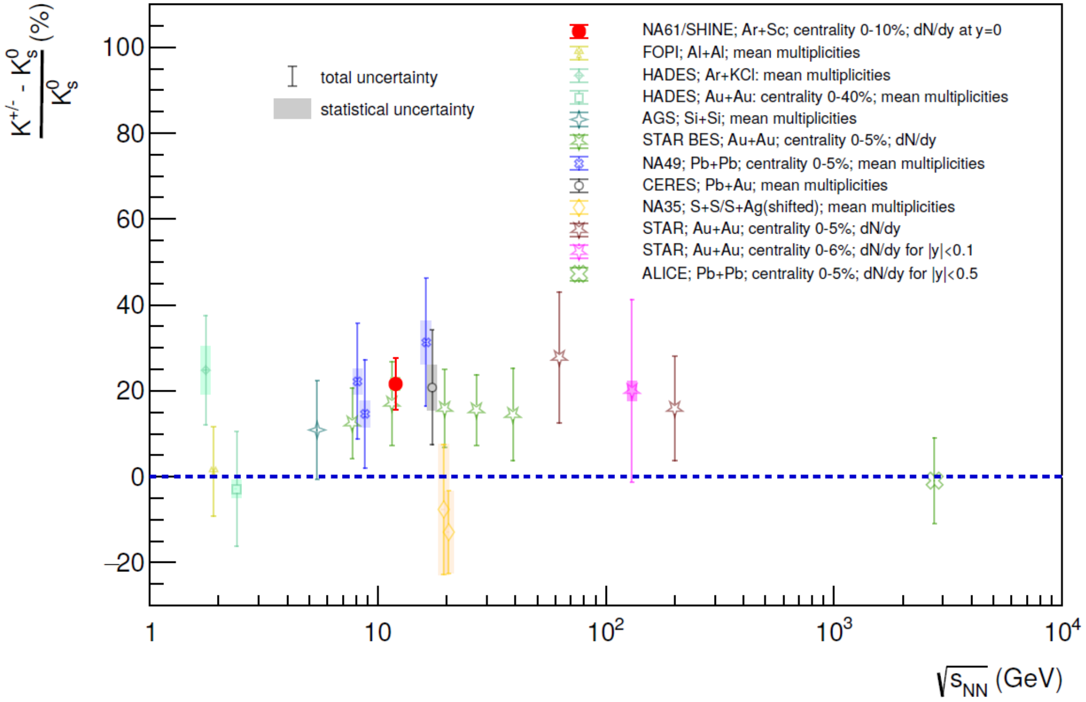




- EPJC 82, 96, 2022 (158*A* GeV/*c*) and preliminary results (80*A* GeV/*c*).
- New high-precision measurements of K_S^0 in p+p interactions at 80*A* and 158*A* GeV/*c*.
- Model predictions deviate by up to 20% from the measurements

K_S^0 spectra from Ar+Sc at 75*A* GeV/*c*





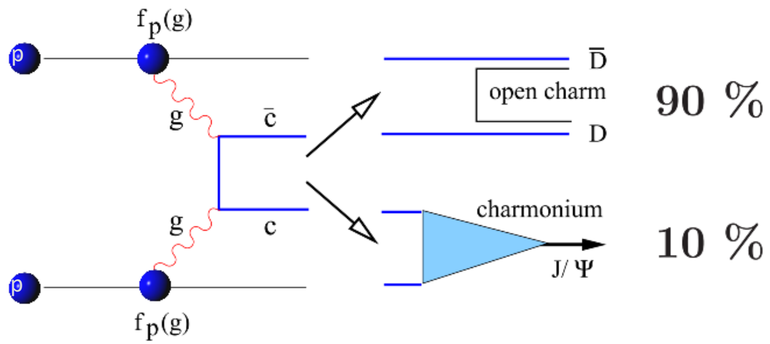
First measurements od K_S^0 spectra in Ar+Sc collisions

Mean multiplicity: $\langle K_S^0 \rangle$ = 6.25 ± 0.09 (stat) ±0.73 (sys)

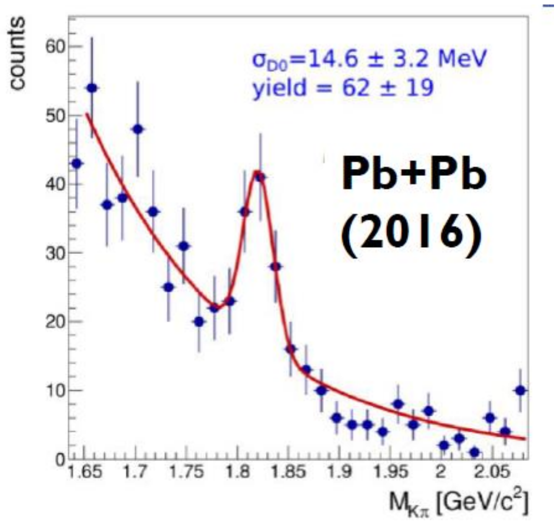
$K^{\pm}/_{K_S^0}$ ratio significantly higher than 1 in Ar+Sc at 75*A* GeV/c -> large isospin symmetry violation

NA61/SHINE in 2022-2025

charm production and the onset of deconfinement

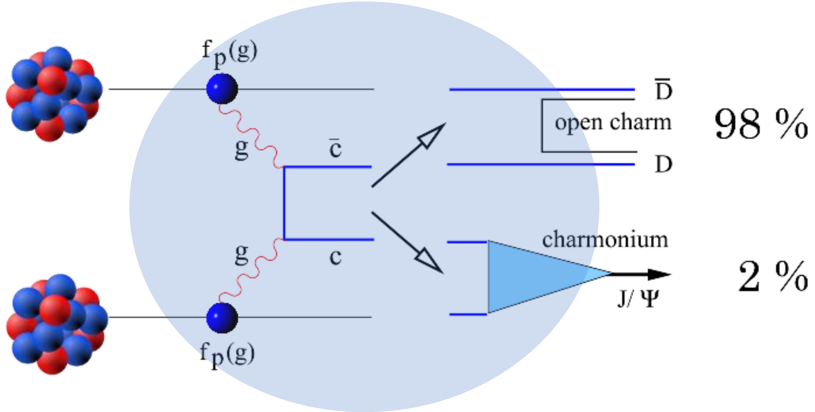


Open charm and J/ψ production within Matsui-Satz model [PL B178 416]



NA61/SHINE pilot measurements
open charm signal in Pb+Pb at 150 A GeV/c

Pb+Pb with QGP



- 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 the mean number of charm quark pairs, $\langle c\bar{c} \rangle$, produced in A+A collisions has to be known. Up to now the corresponding experimental data does not exist and NA61/SHINE will perform this measurement in the near future.

Summary

- 2D scan in system size and the collision energy was completed in 2017 with Xe+La data
- NA61/SHINE delivers reach information related to the onset of deconfinement in the light and medium-size system
  - the collision energy dependence of the inverse slope T parameter shows the so-called *step* structure in p+p, Be+Be, and Ar+Sc
  - the sharp break in K^+/π^+ and inverse slope T parameter in p+p collisions is visible
  - the *horn* structure does not appear in p+p, Be+Be, and Ar+Sc
  - for Ar+Sc collisions, the ratio of mean pion multiplicity to the number of wounded nucleons and its collision energy dependence at the highest SPS energies are close to the ones for central Pb+Pb collisions and higher than the corresponding results for *N+N* and Be+Be interactions.
  - the velocity of sound extracted from the width of rapidity distribution from *central* Ar+Sc, Be+Be collisions, and inelastic *N+N* reactions is consistent with results for central Pb+Pb but too limited to allow a significant conclusion about a possible minimum in the speed of sound energy dependence
  - “Peak-dip transition observed for Ar+Sc within SPS energy range
- Unexpected system size dependence
  - (p+p = Be+Be) ≠ (Ar+Sc)
  - the idea of new measurements after LS3
- So far, no convincing indication of the critical point in:
  - net-charge fluctuations measured by the higher-order moments
  - two-pion HBT correlation functions
  - second scaled factorial moments of protons
- New and unique results on K+, K-, $\boldsymbol{K_S^0}$, K*, $\Xi-$, $\overline{\Xi}^+$, $\Xi(1530)0$ and $\overline{\Xi}(1530)^0$ production in p+p interactions
  - None of the theoretical models can explain strangeness production in p+p NA61/SHINE data
- NA61/SHINE measure open charm production in 2022- 2024

Thank You

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Backup

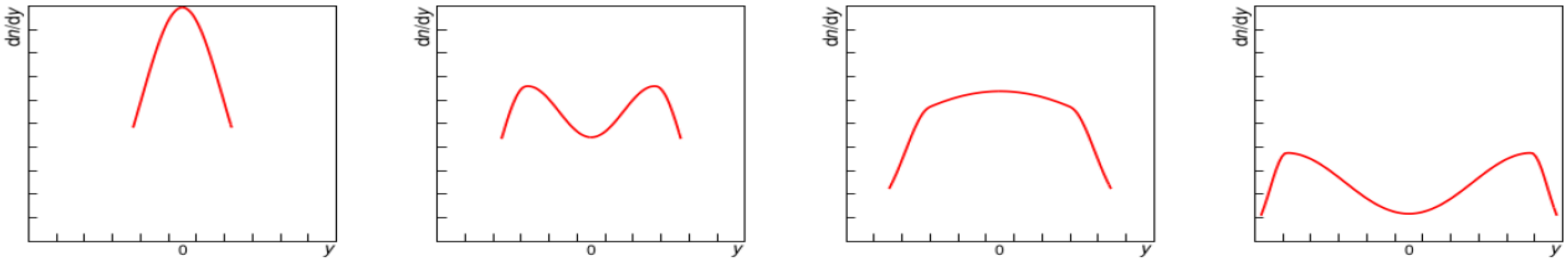
”Peak-dip-peak-dip“ irregularity in p rapidity spectra

Reason of irregularity – onset of deconfinement!

For the EoS with a phase transition:

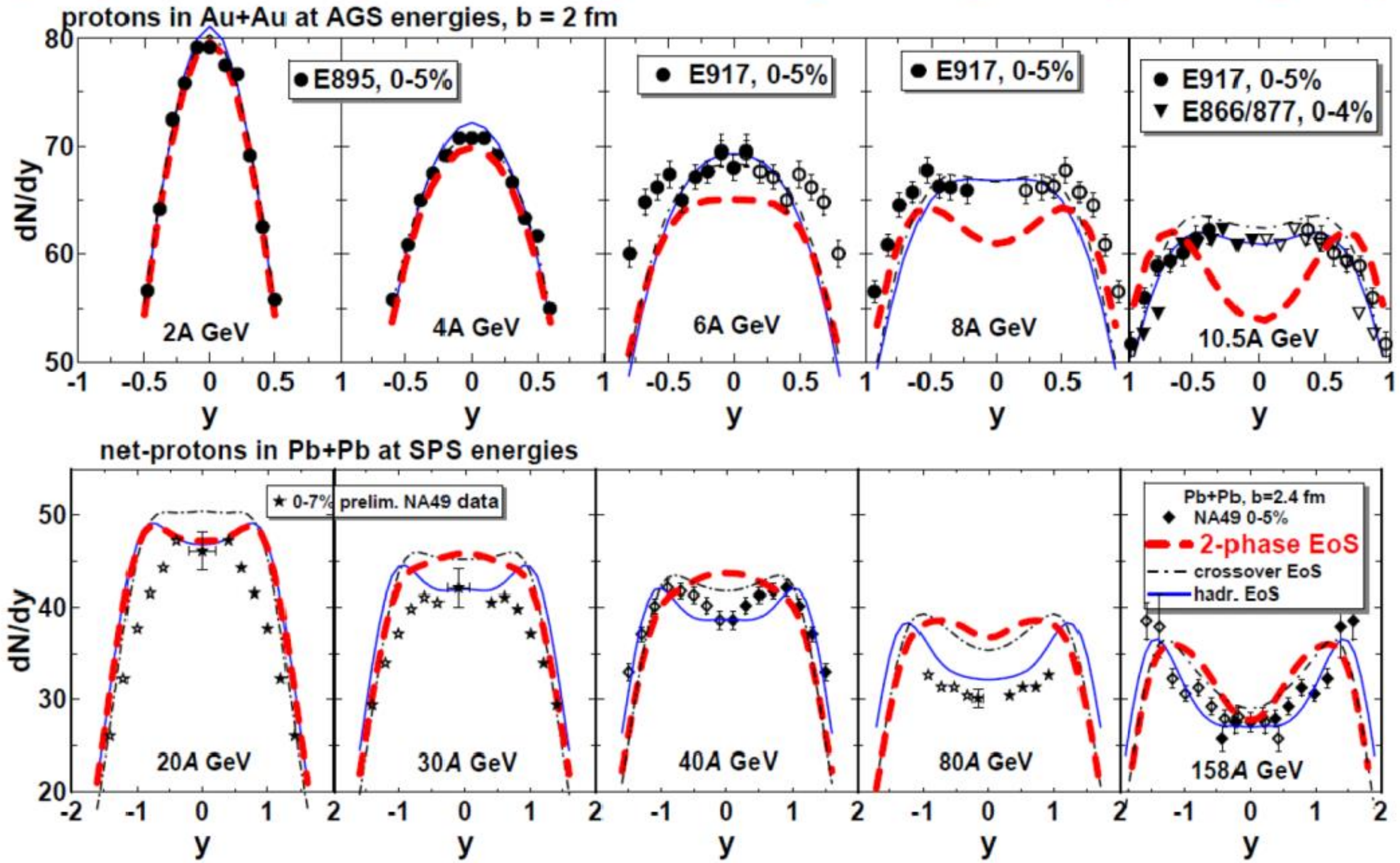
$\sqrt{s_{NN}}_1 < \sqrt{s_{NN}}_2 < \sqrt{s_{NN}}_3 < \sqrt{s_{NN}}_4$

peak	dip	peak	dip



stiff EoS – spherical fireball	softest point region of the EoS – deformed fireball	stiffness of the EoS grows – less deformed fireball	kinetic pressure overcomes stiffness of the EoS – deformed fireball

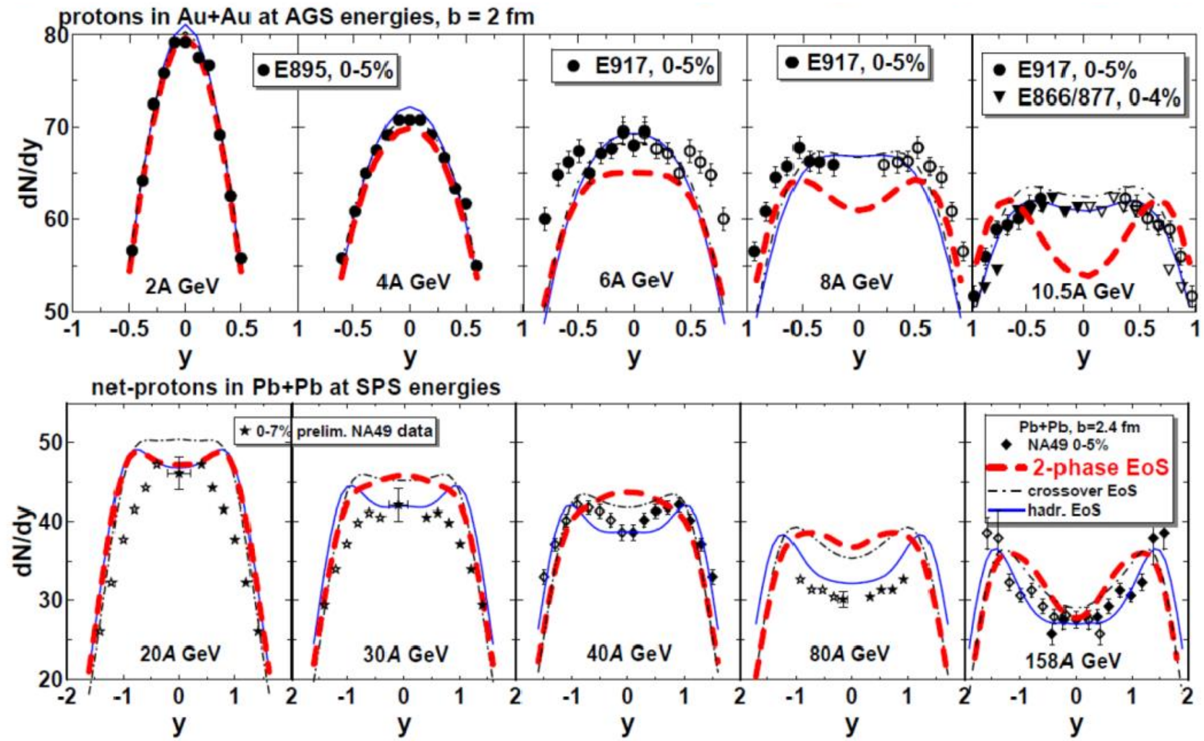
"Peak-dip-peak-dip" irregularity in p rapidity spectra



"Peak-dip-peak-dip" irregularity exists for experimental proton spectra.

Ivanov, Blaschke, EPJ A (2016) 52: 237

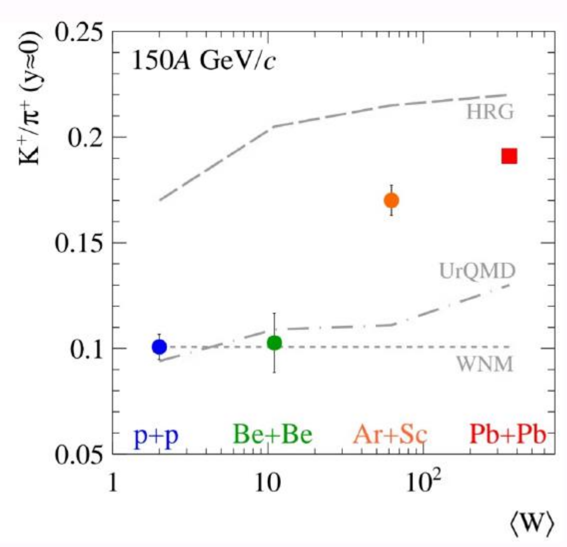
”Peak-dip-peak-dip“ irregularity in p rapidity spectra

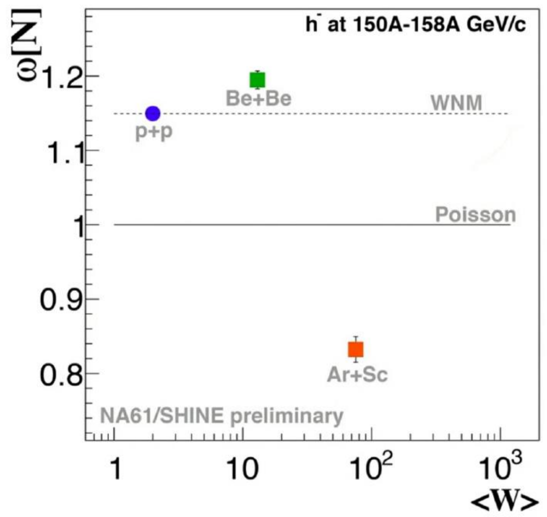


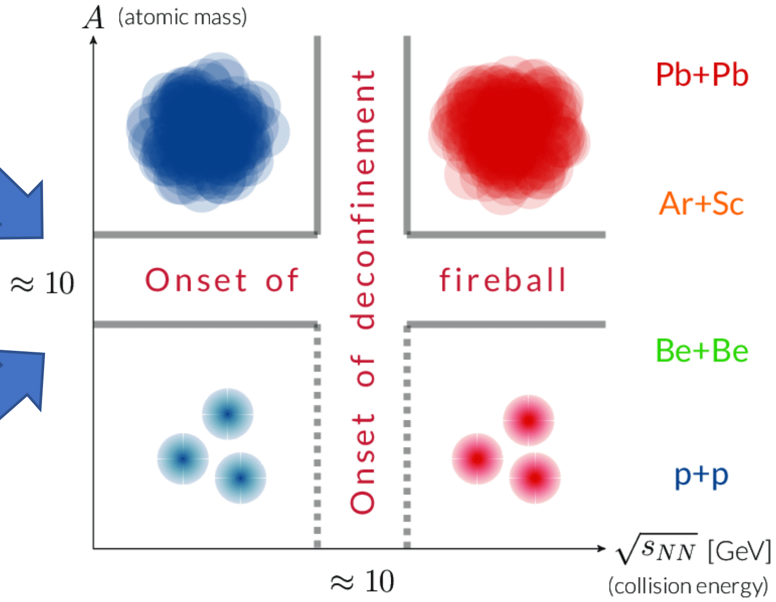
“Peak-dip-peak-dip” irregularity exists for experimental proton spectra.

Ivanov, Blaschke, EPJ A (2016) 52: 237

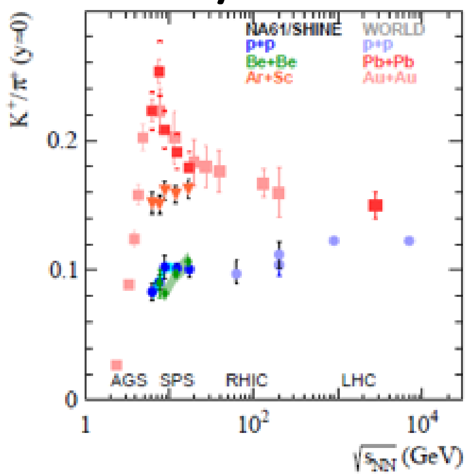
Uniqueness of heavy ion results from NA61/SHINE





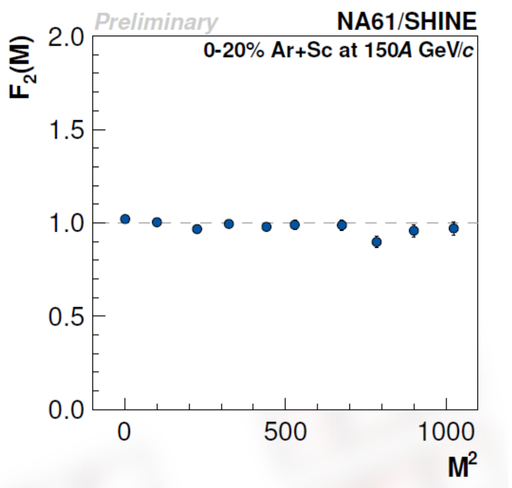


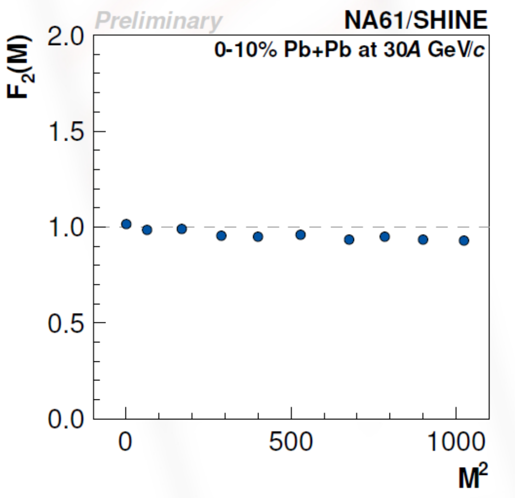
$$p + p \approx Be + Be \quad \neq \quad Ar + Sc$$

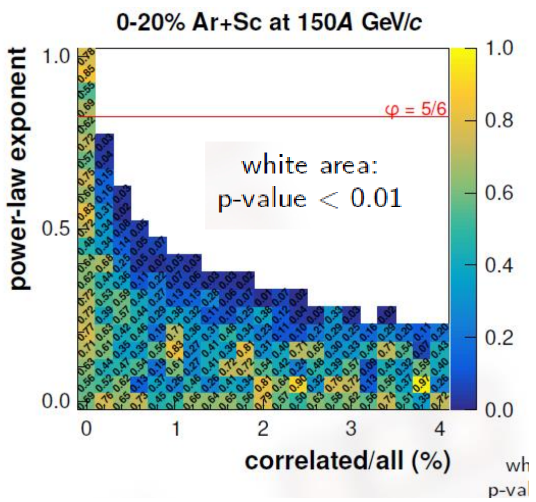


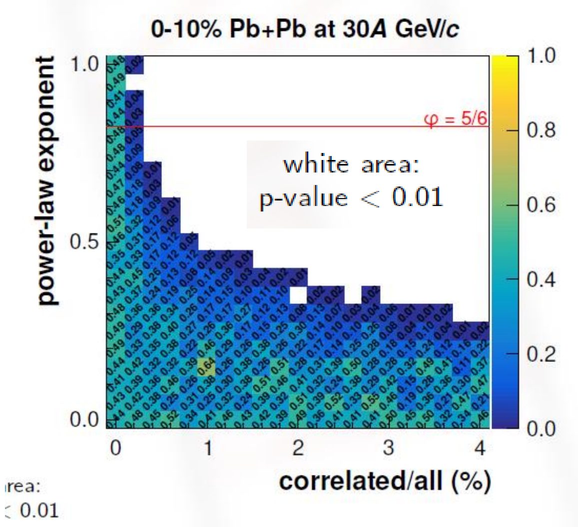
- Two onsets in nucleus-nucleus collisions
- Onset of deconfinement - beginning of QGP formation
- Onset of fireball - beginning of formation of a large cluster which decays statistically

second scaled factorial moments of protons - intermittency analysis









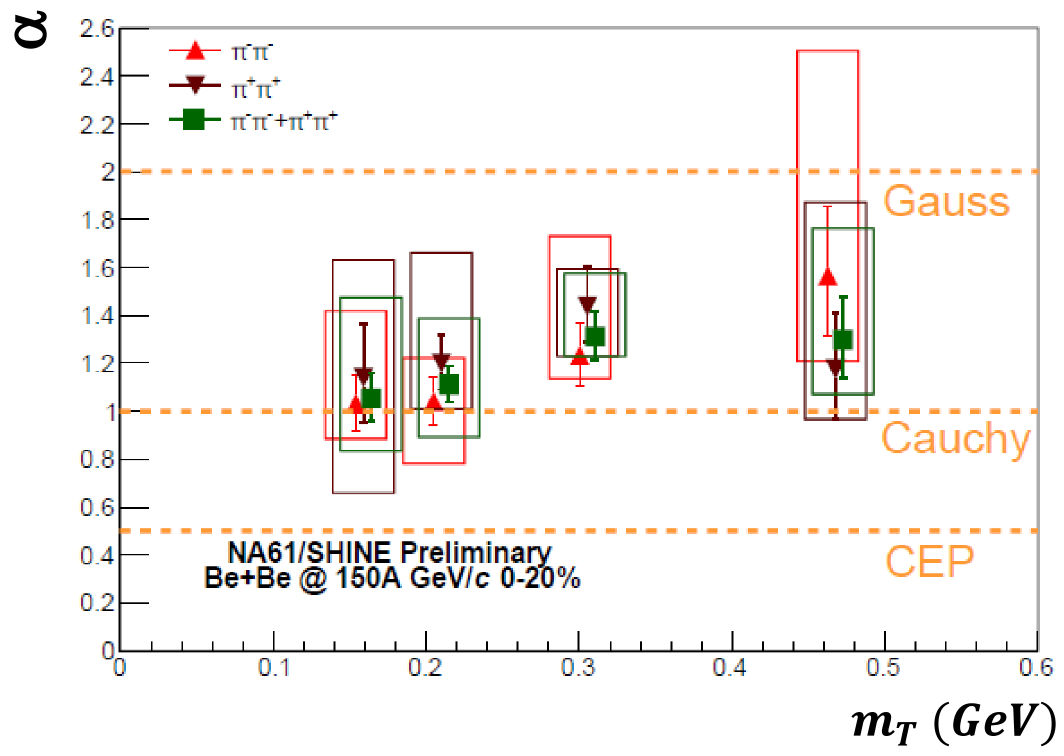
- Results for :
  - statistically independent points
  - cumulative quantities
  - M = 1 … 32 bins in p_x and p_y
- second scaled factorial moments of protons for Ar+Sc at 150*A* GeV/*c* and Pb+Pb at 30*A* GeV/*c* shows no indication for power-law increase with a bin size

- Exclusion plot
  - predictions for simple power-law model parameters
  - The intermittency index ϕ_2 (power-law component) for a system freezing out at the QCD critical endpoint is expected to be ϕ_2 = 5/6

Details: T. Czopowicz talk

two-pion HBT correlation functions

20% Be+Be at 150A GeV/c



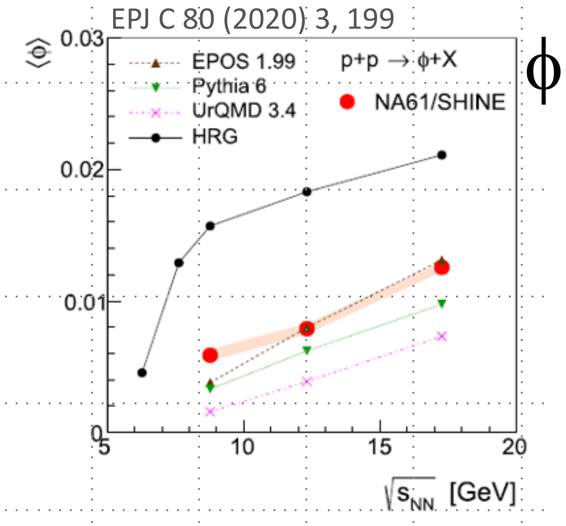
Lévy distribution leads to power-law correlation functions

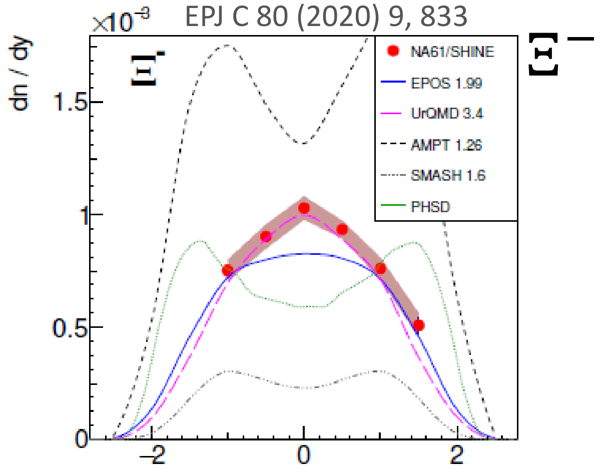
$$C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}$$ Csörgö et al., EPJC36

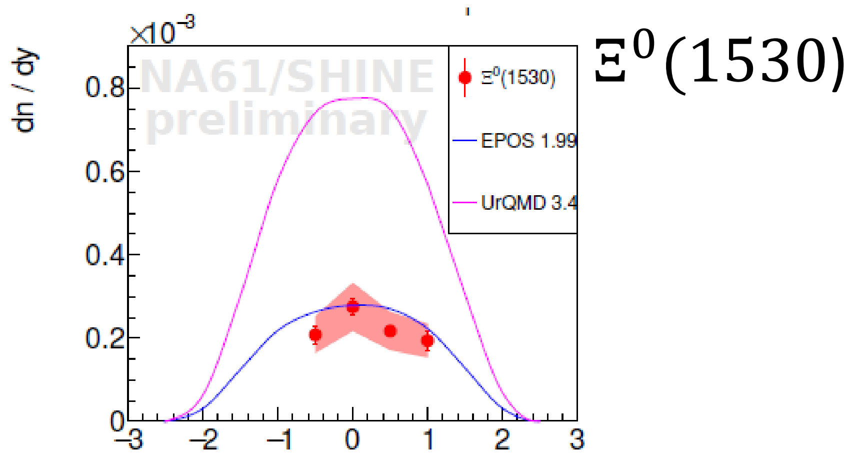
Lévy-exponent $\alpha \approx 0.5$ for the critical point

- α between Gaussian or Cauchy shape might be the sign of anomalous diffusion
- α does not indicate the critical point in Be+Be (far above 0.5)

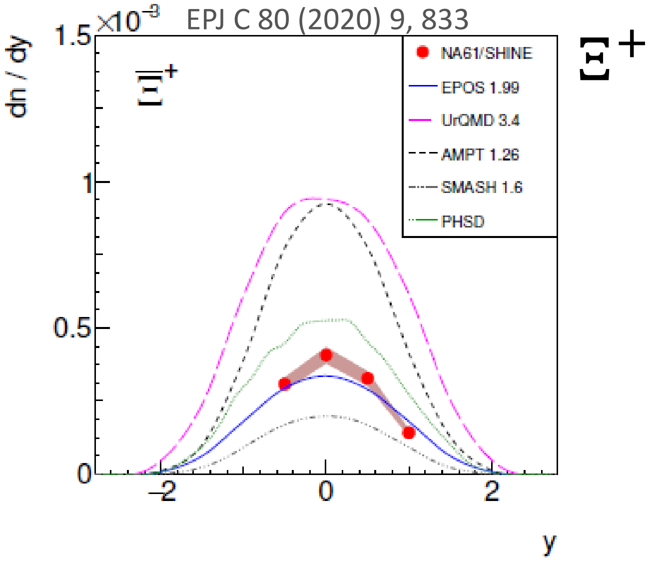
strangeness production in p+p at 158 GeV/c

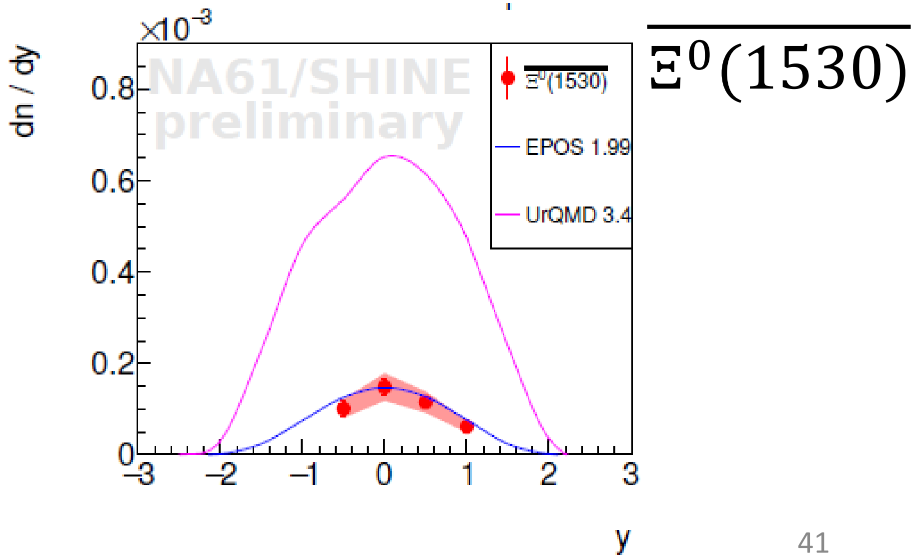




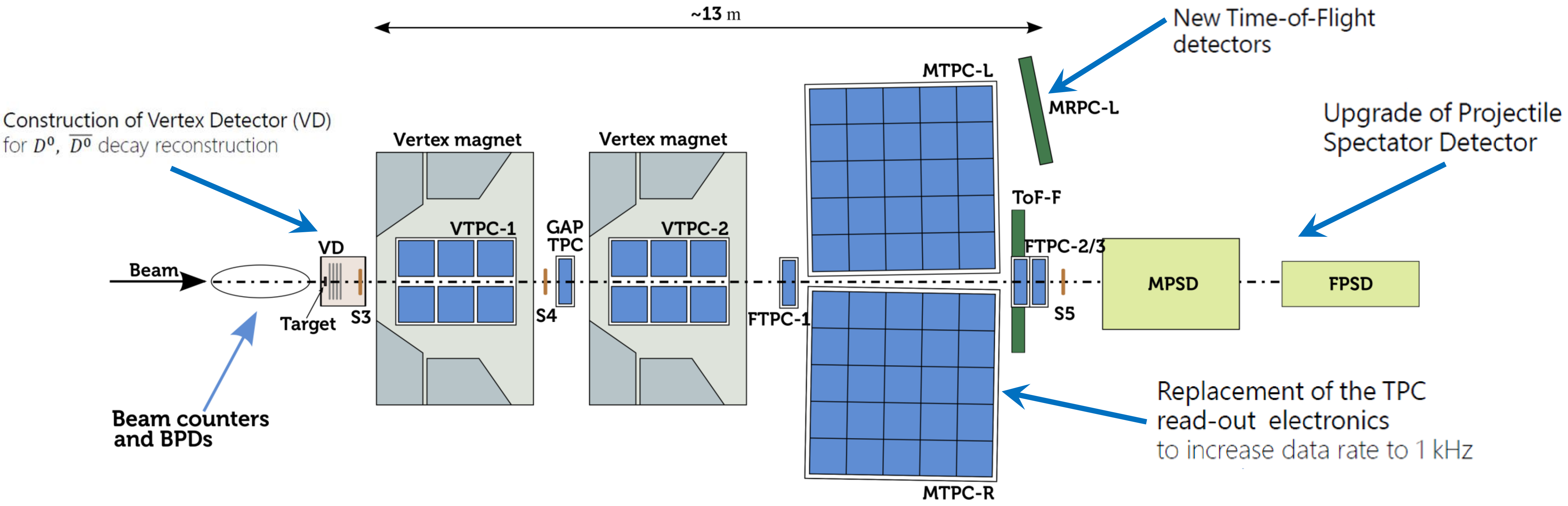


Present theoretical models do not describe the NA61/SHINE results on strange particles production



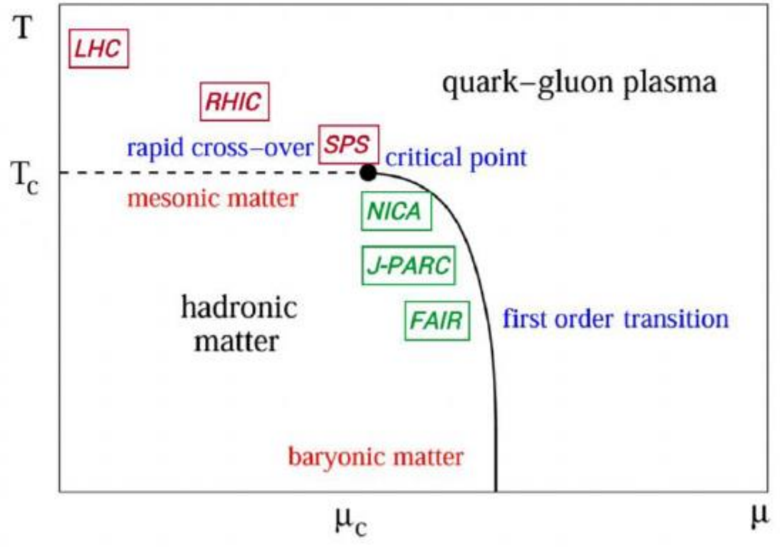


Detector upgrade during LS2



Uniqueness of NA61 open charm program

Landscape of present and future heavy ion experiments

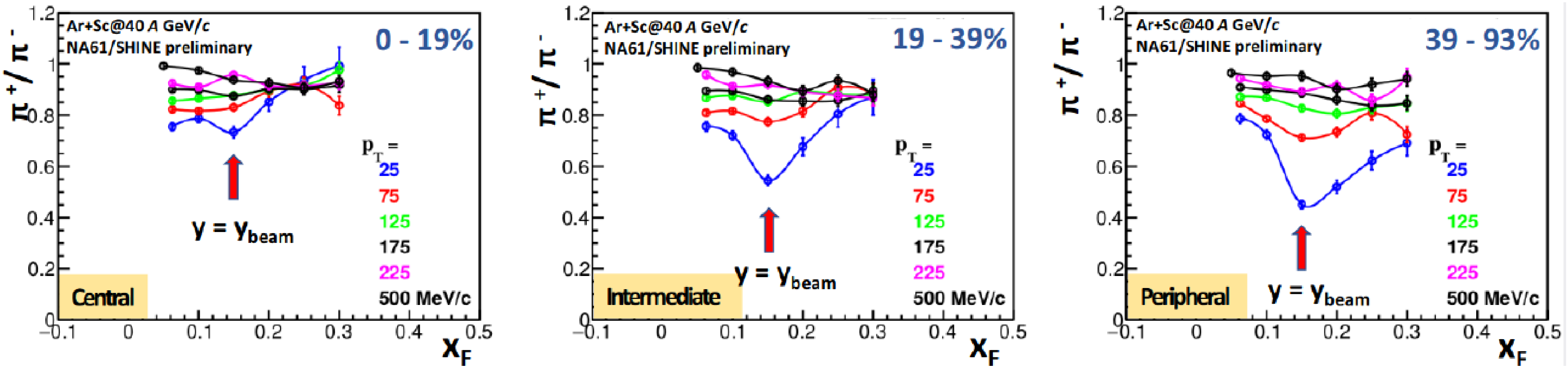


Only NA61/SHINE is able to measure open charm production in heavy ion collisions in full phase space in the near future

- LHC and RHIC at high energies: measurements of open charm are performed in a significantly limited acceptance; this limitation is due to the collider kinematics and related to the detector geometry
- RHIC BES collider ($\sqrt{s_{NN}} = 7.7\ GeV\ - 39\ GeV$): measurement not considered in the current program, this may likely be due to difficulties related to collider geometry and kinematics as well as the low charm production cross-section
- RHIC BES fixed-target ($\sqrt{s_{NN}} = 3\ GeV\ - 7.7\ GeV$): not considered in the current program
- NICA ($\sqrt{s_{NN}} =< 11\ GeV$): measurements during stage 2 (after 2023) are under consideration
- J-PARC-HI ($\sqrt{s_{NN}} \lesssim 6\ GeV$): under consideration, may be possible after 2025
- FAIR SIS-100 ($\sqrt{s_{NN}} \lesssim 5\ GeV$): not possible due to the very low cross-section at SIS-100, systematic charm measurements are planned with SIS-300 (($\sqrt{s_{NN}} \lesssim 7\ GeV$) which is part of the FAIR project, but not of the start version

electromagnetic effects

π^+/π^- ratio and spectator-induced electromagnetic effects



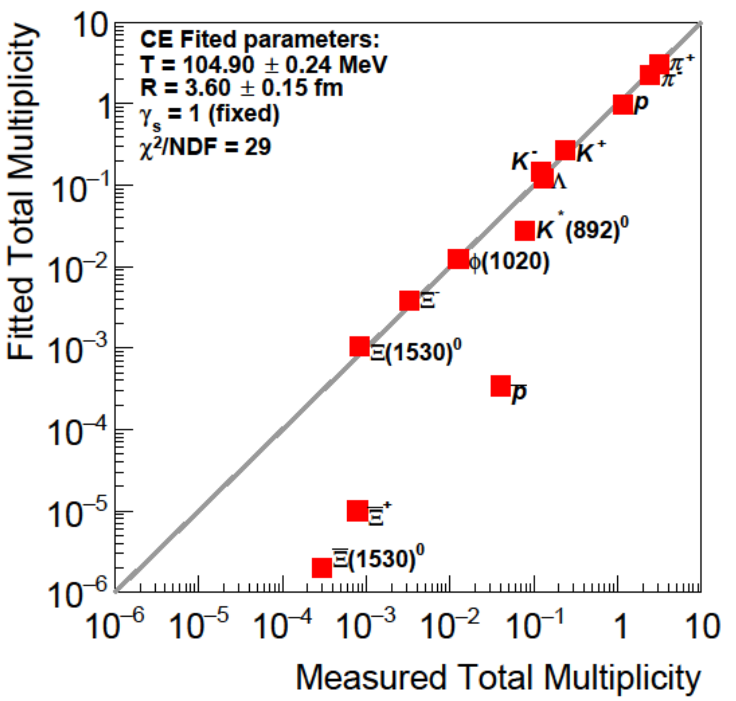
First time ever observation of the spectator-induced electromagnetic effects in peripheral small systems: Ar+Sc at 40A GeV/c

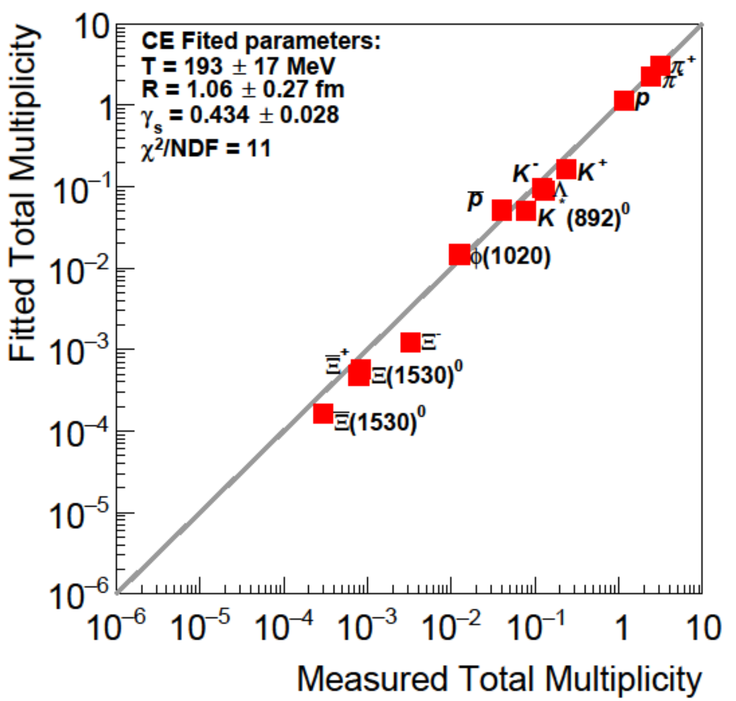
- Charged pion trajectories can be modified by electromagnetic interactions (repulsion for π^+ and attraction for π^-) with the spectators → the effect is sensitive to the space-time evolution the system

Phys.Rev.C 75 (2007) 054903
Phys.Rev.C 87 (2013) 5, 054909
Phys.Rev.C 102 (2020) 1, 014901

- Spectator - induced electromagnetic effects are stronger with rapidity closer to the spectator rapidity and with low p_T
- The effect was observed in Pb+Pb 150*A* GeV/c collision by NA49

HRG model in the CE formulation and p+p data





Eur.Phys.J.C 81 (2021) 10, 911

Fit by different variants of the HRG model (THERMAL-FIST1.3 Comput.Phys.Commun.244 (2019)295):

- Canonical Ensemble with fixed γs=1
- Canonical Ensemble with fitted strangeness saturation parameter γs

Significant discrepancies of the fitted parameters

The statistical model fails when fixed γ_s

The fit with free γ_s finds γ_s =0.434±0.028 and reproduces the measurements well – a suppression of strange particle production in *p+p* collisions at CERN SPS energies

Eur.Phys.J.C: 74 (2014) 2794; 77 (2017) 671; 80 (2020) 460; 80 (2020) 199; 76 (2016) 198, 80 (2020) 833

second scaled factorial moments - intermittency analysis

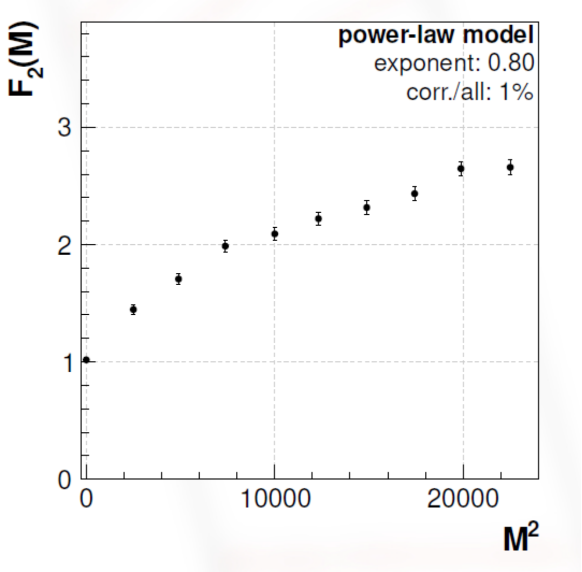
$$F_2(\delta) = \frac{\left\langle \frac{1}{M}\sum_{i=1}^{M} n_i(n_i-1)\right\rangle}{\left\langle \frac{1}{M}\sum_{i=1}^{M} n_i\right\rangle^2}$$

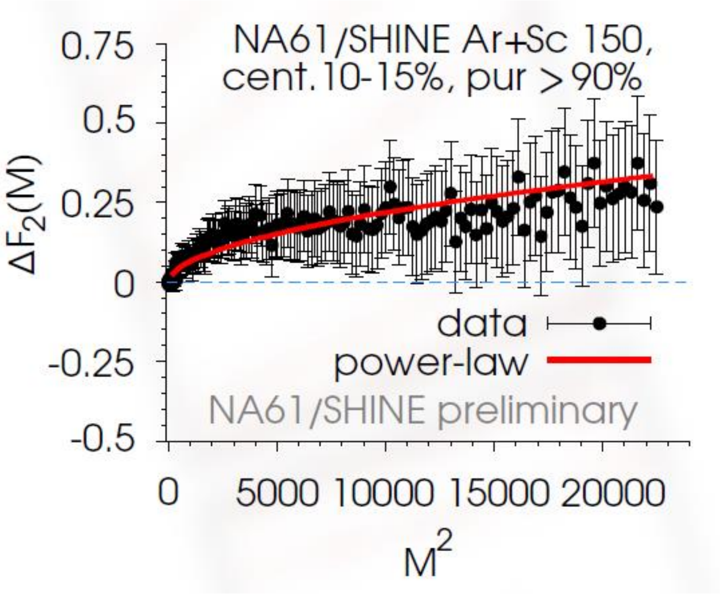
δ - size of each of the $M = \frac{\Delta}{\delta}$ subdivision intervals of the momentum phase-space region Δ

n_i - number of particles in i-th bin

$\langle\dots\rangle$ - averaging over events

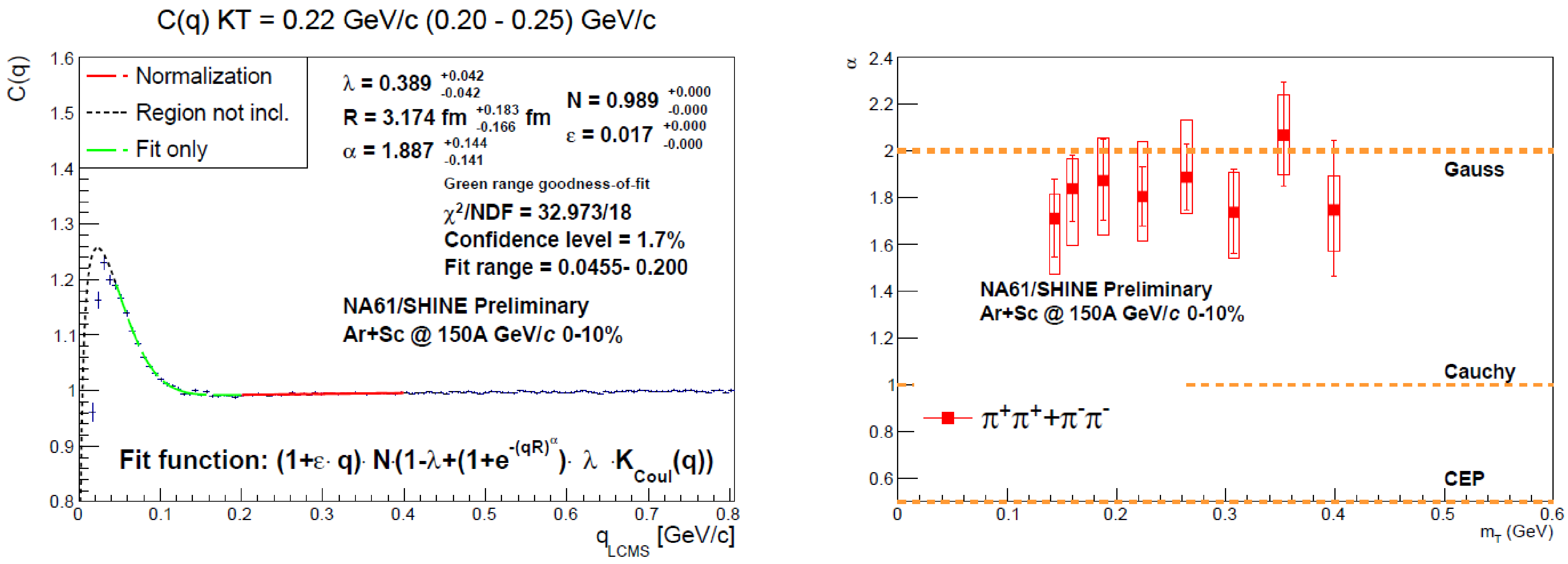
If the system freezes-out in the vicinity of the critical point, $F_2(M)$ should reveal a power-law dependence.





- A deviation of ΔF_2 from in mid-central Ar+Sc?
- The data points are correlated which makes the interpretation difficult.

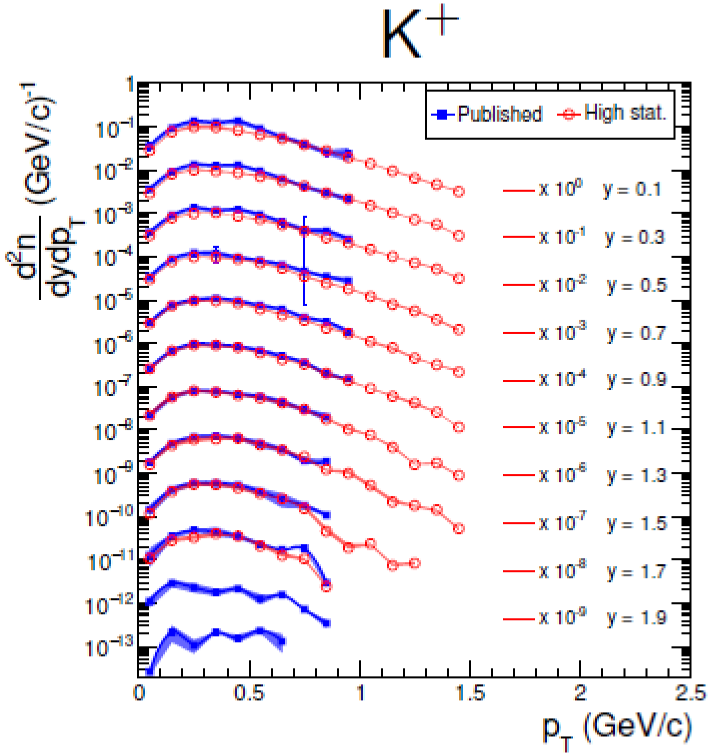
two-pion - symmetric Levy HBT correlations

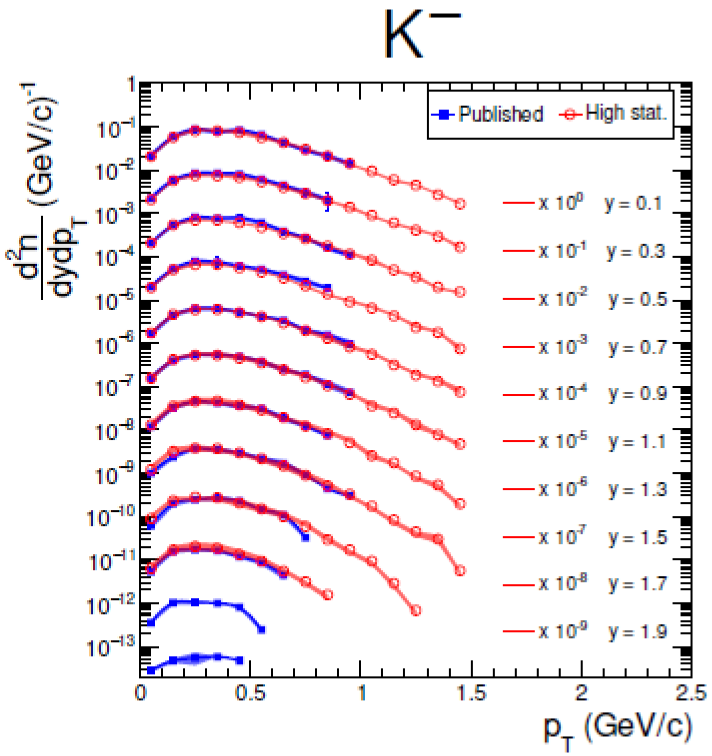


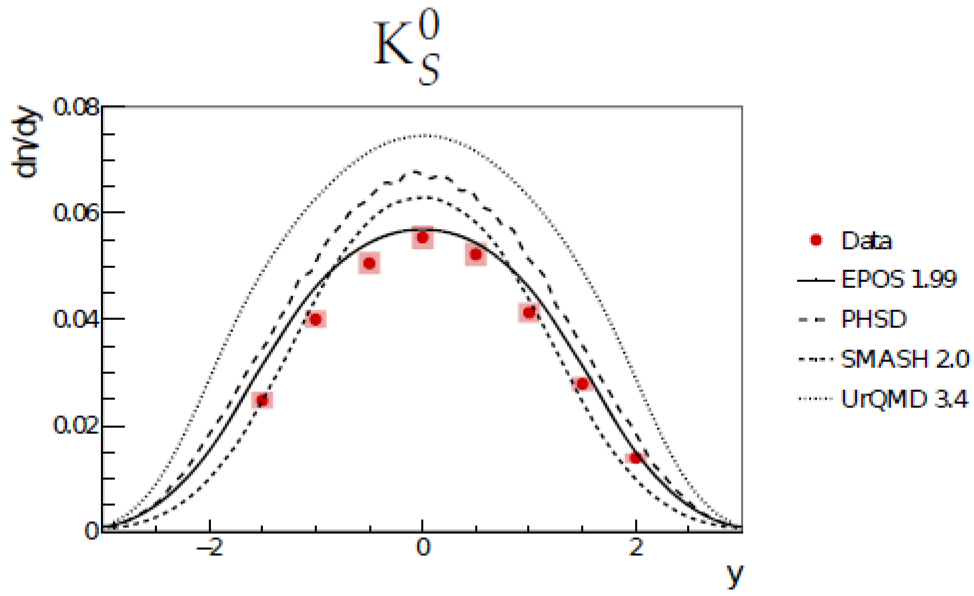
The Levy stability parameter α describes shape of the source

3D Ising model with random external field predicts $\alpha = 0.5 \pm 0.05$ at critical point

K production in inelastic p+p collisions at 158 GeV/c







New results on K⁺, K⁻ (preliminary) and K^0_S from high statistic p+p data

$K^{\pm}$: almost 20 times larger dataset than previously published results (**Eur.Phys.J.C 77 (2017), 671**)

K^0_S mean multiplicity: 0.162±0.001±0.011

Model predictions deviate by up to 20% from the measurements — best predictions from EPOS 1.99.