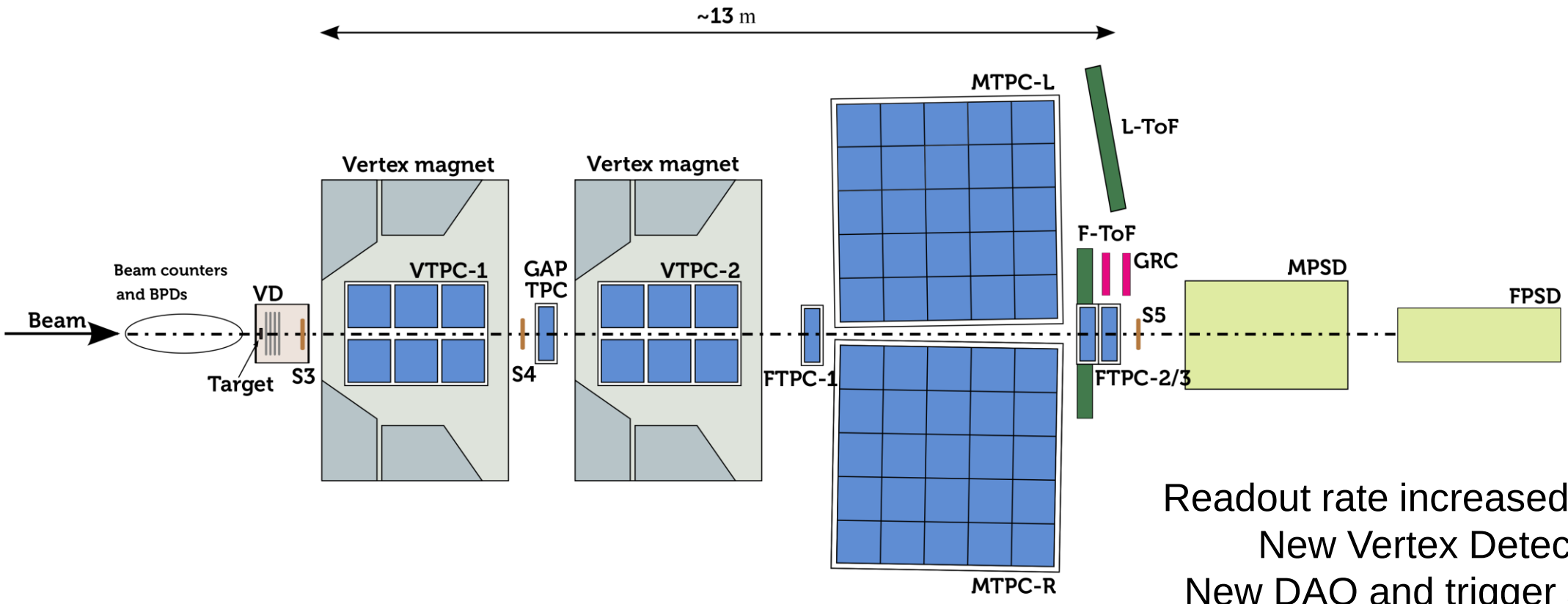
Seweryn Kowalski for the
NA61/SHINE Collaboration
University of Silesia, Poland

Highlights from the NA61/SHINE strong interaction program

upgraded NA61/SHINE detector

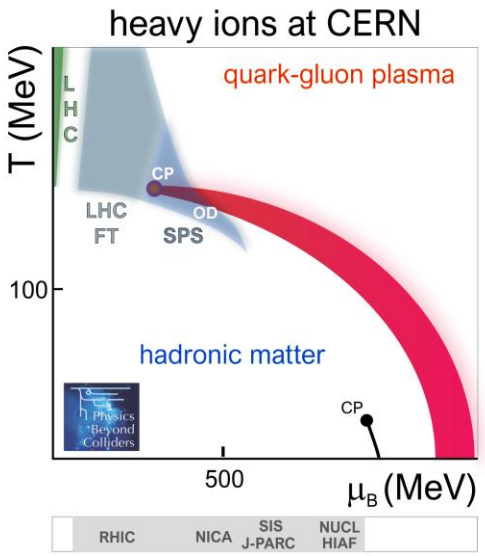
Fixed target experiment located at the CERN SPS accelerator

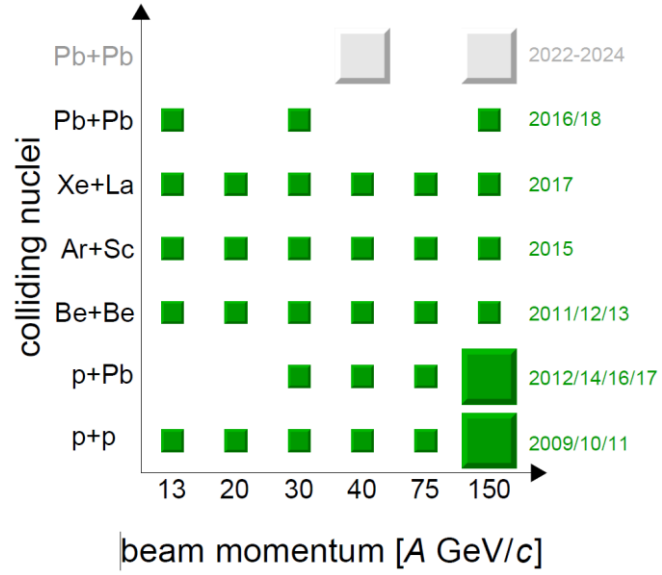


Readout rate increased to 1kHz
New Vertex Detector
New DAQ and trigger system
Upgraded PSD

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

NA61/SHINE - Physics program



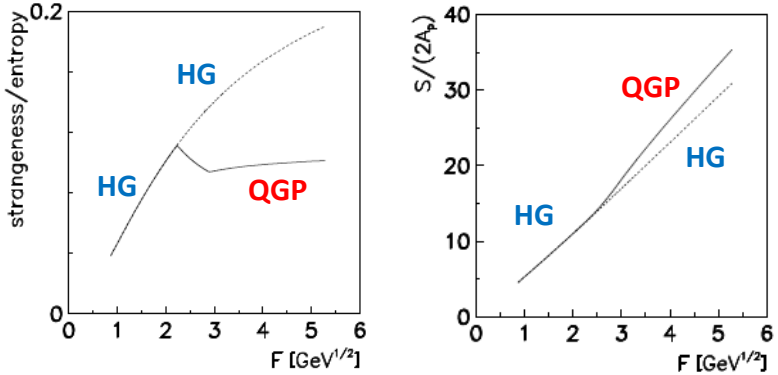


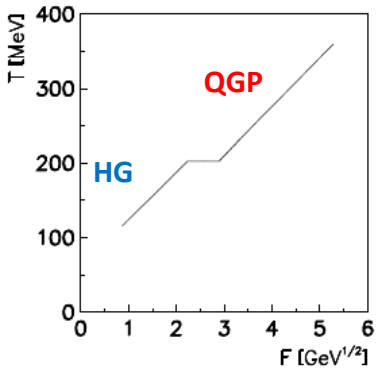
- **Strong interactions program**
  - search for the critical point of strongly interacting matter
  - study of the properties of the onset of deconfinement
- Hadron-production measurements for neutrino experiments
- Hadron-production measurements for cosmic ray experiments

physics results

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

HORN – KINK - STEP

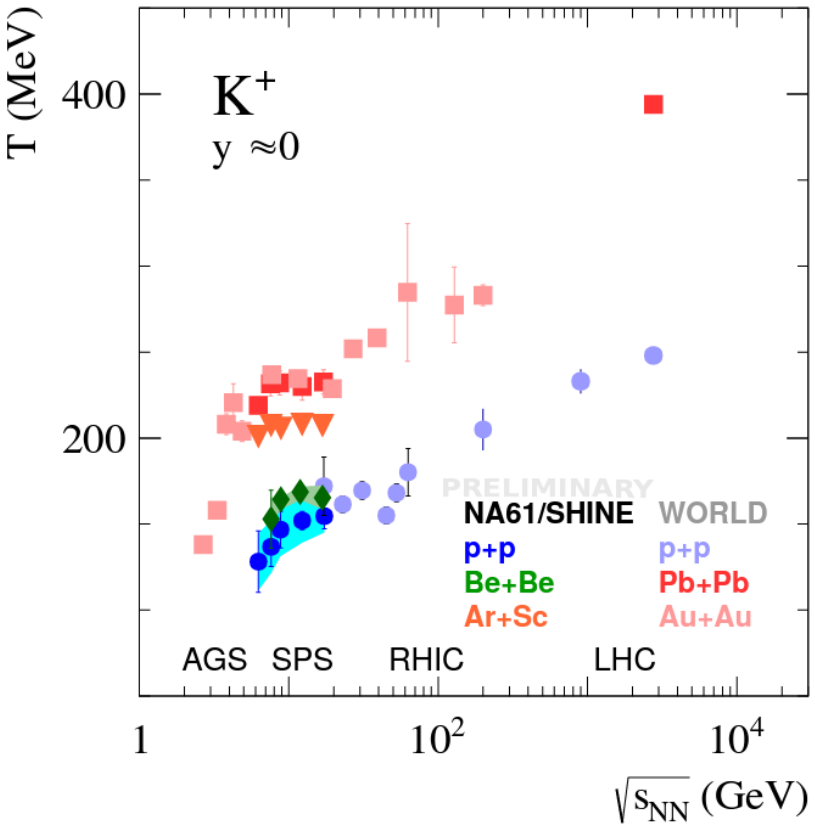


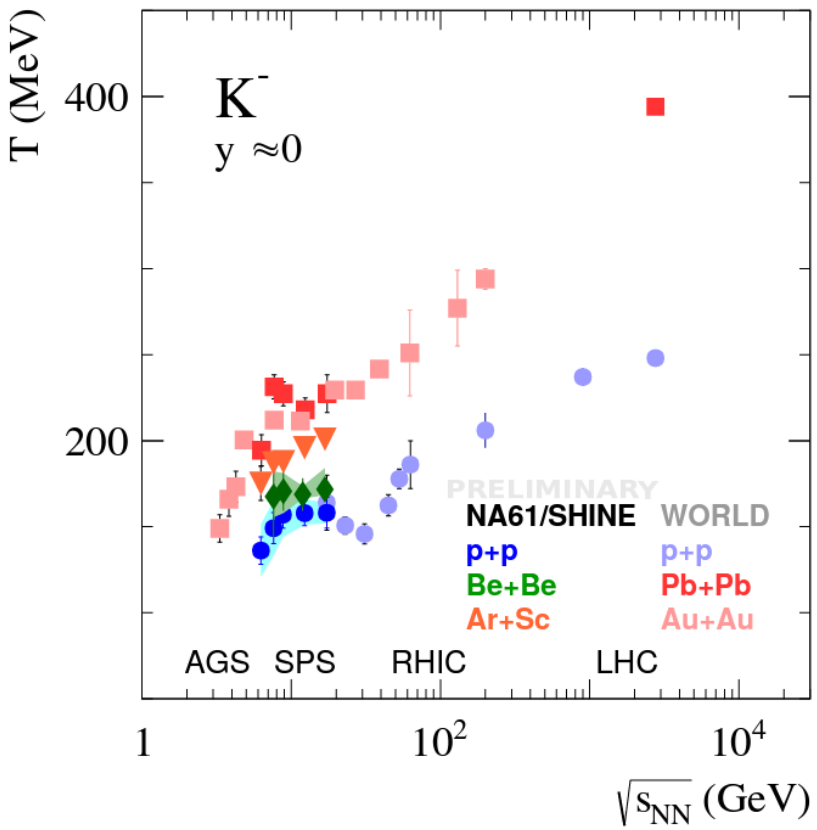


onset of deconfinement

onset of deconfinement: 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





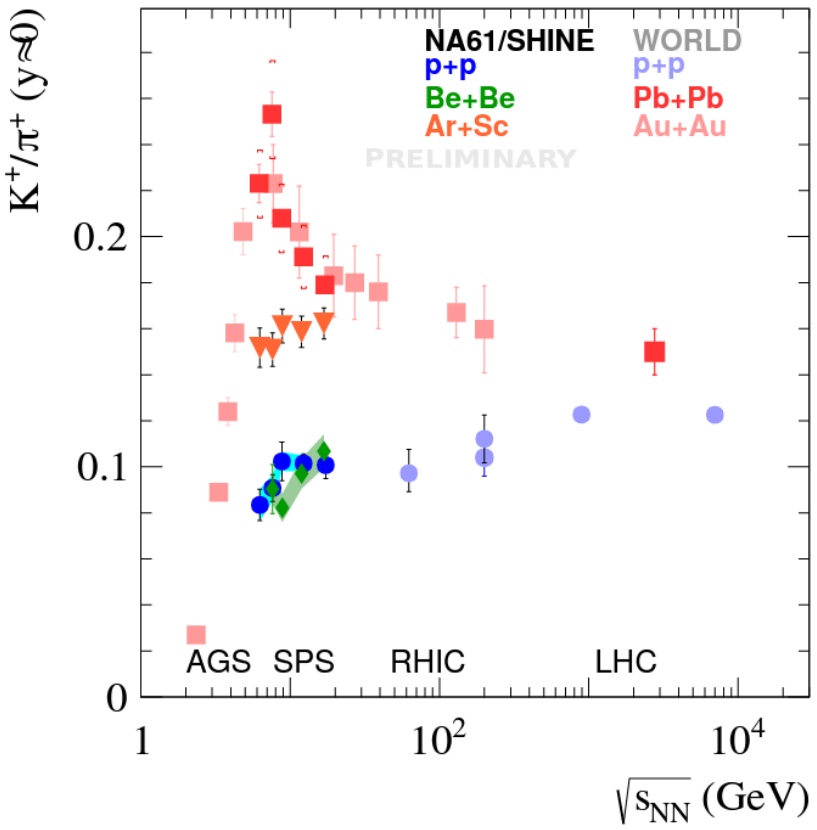
Kaons are only weakly affected by rescattering and resonance decays during the post-hydro phase (at SPS and RHIC energies).

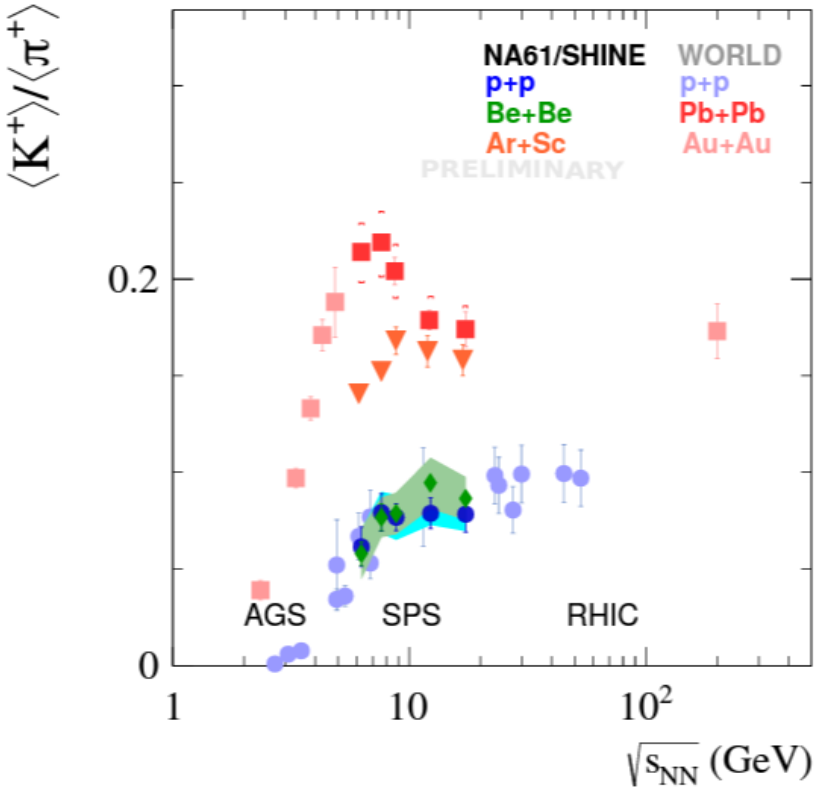
Connected temperature of the freeze-out surface and not the early-stage fireball

onset of deconfinement: horn

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

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

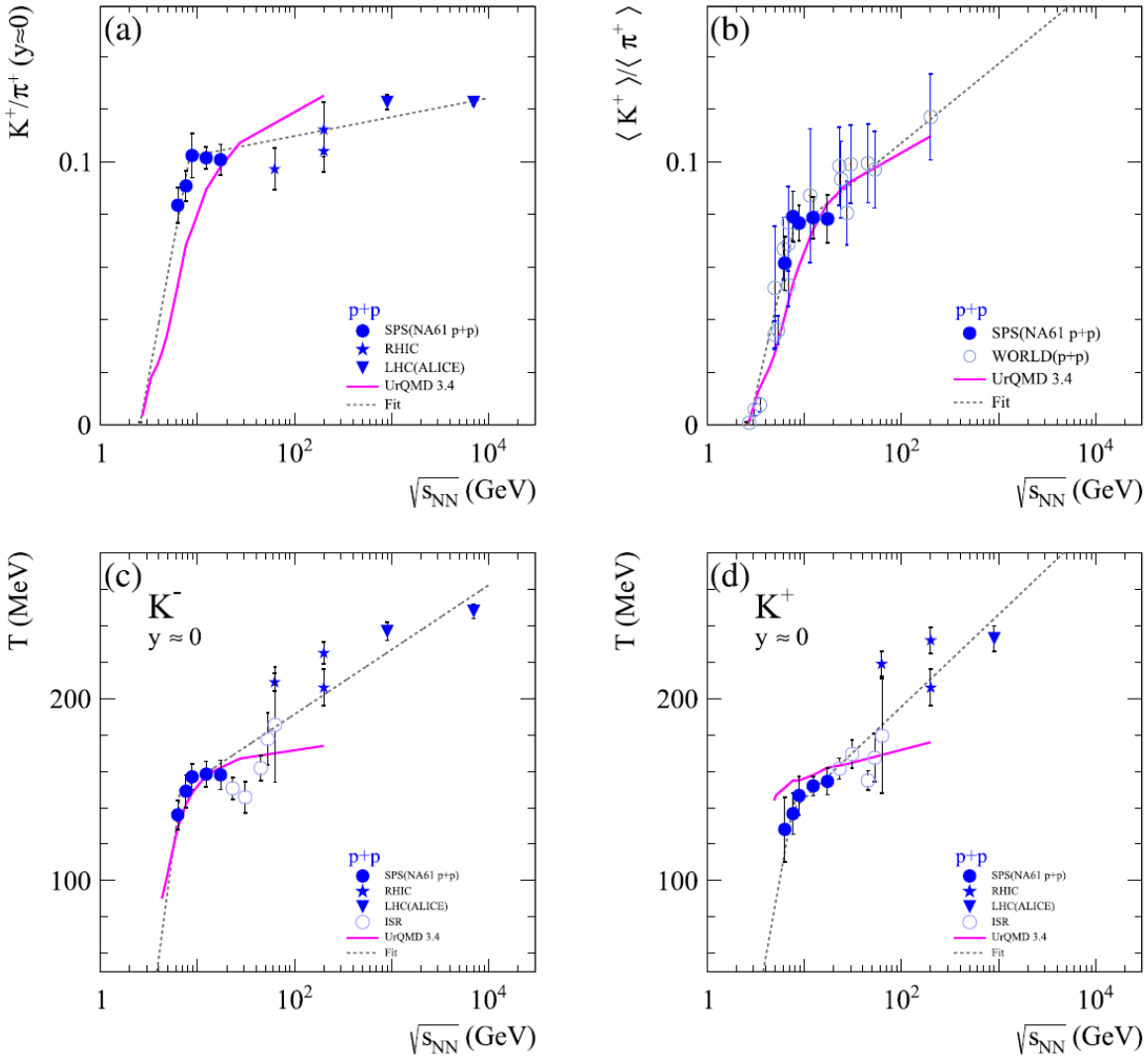




Good measure of the strangeness to entropy ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons).

Probe of the onset of deconfinement.

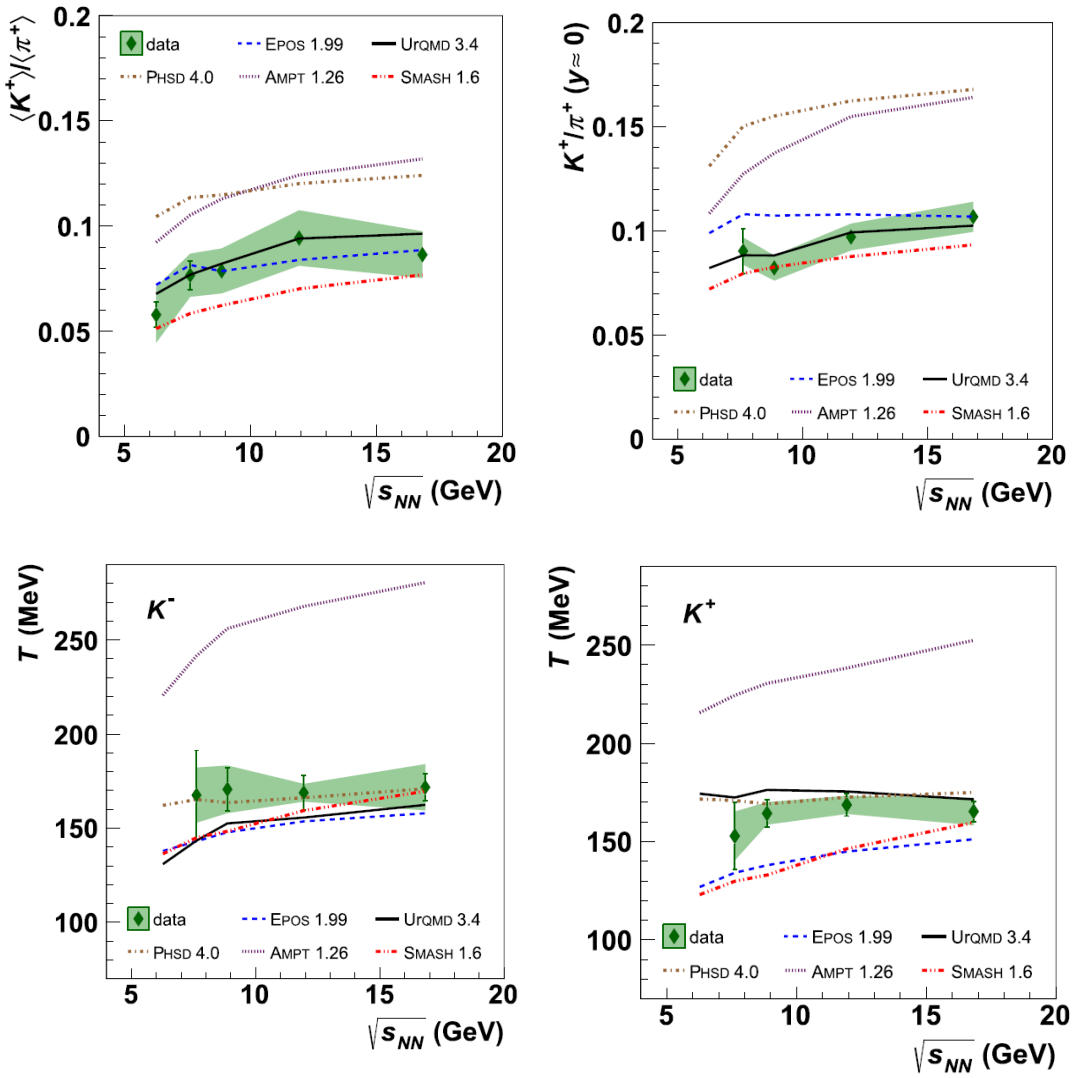
p+p interactions and onset of deconfinement



- 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)

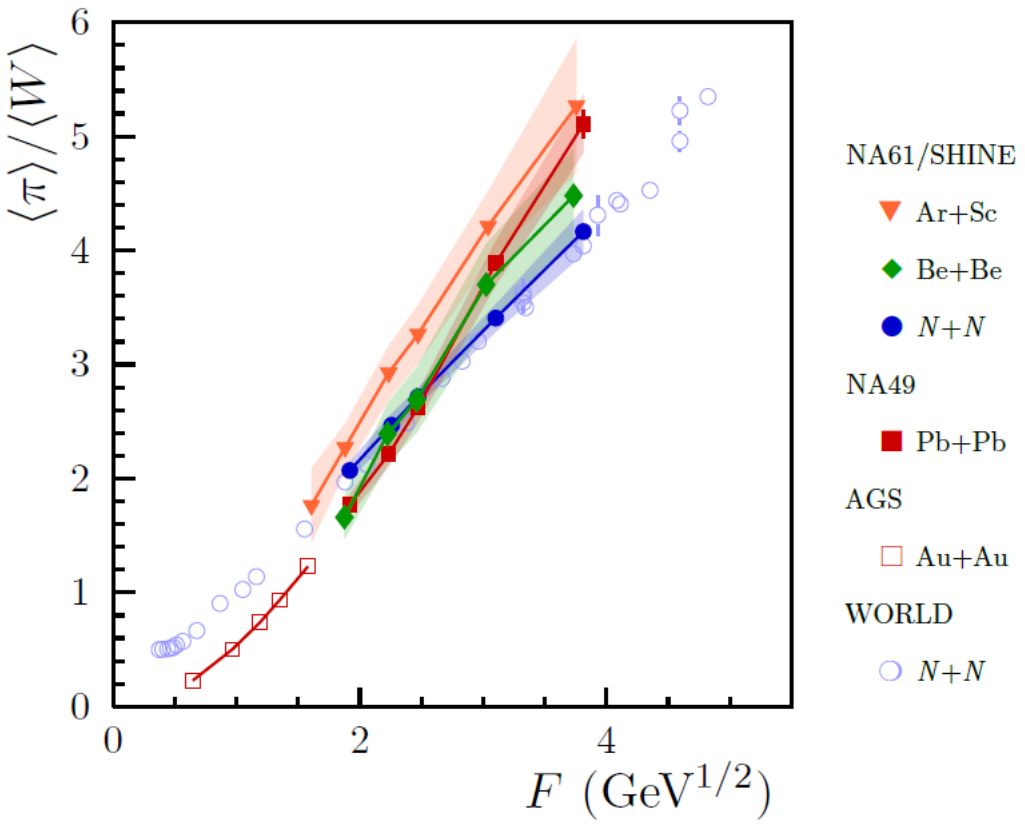
Be+Be collisions and onset of deconfinement



- 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

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

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

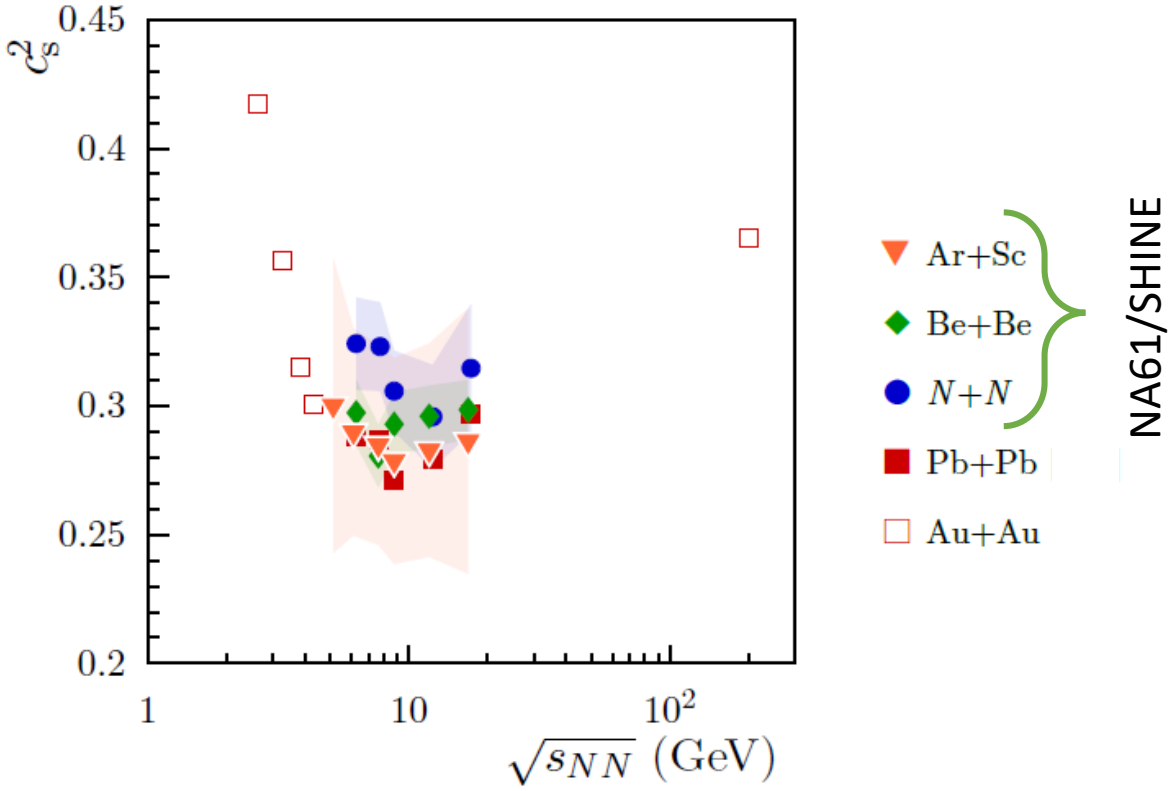


$$F = \left[(\sqrt{s_{NN}} - 2m_N)^3/\sqrt{s_{NN}}\right]^{1/4},$$

- 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 collisions seem to be 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

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

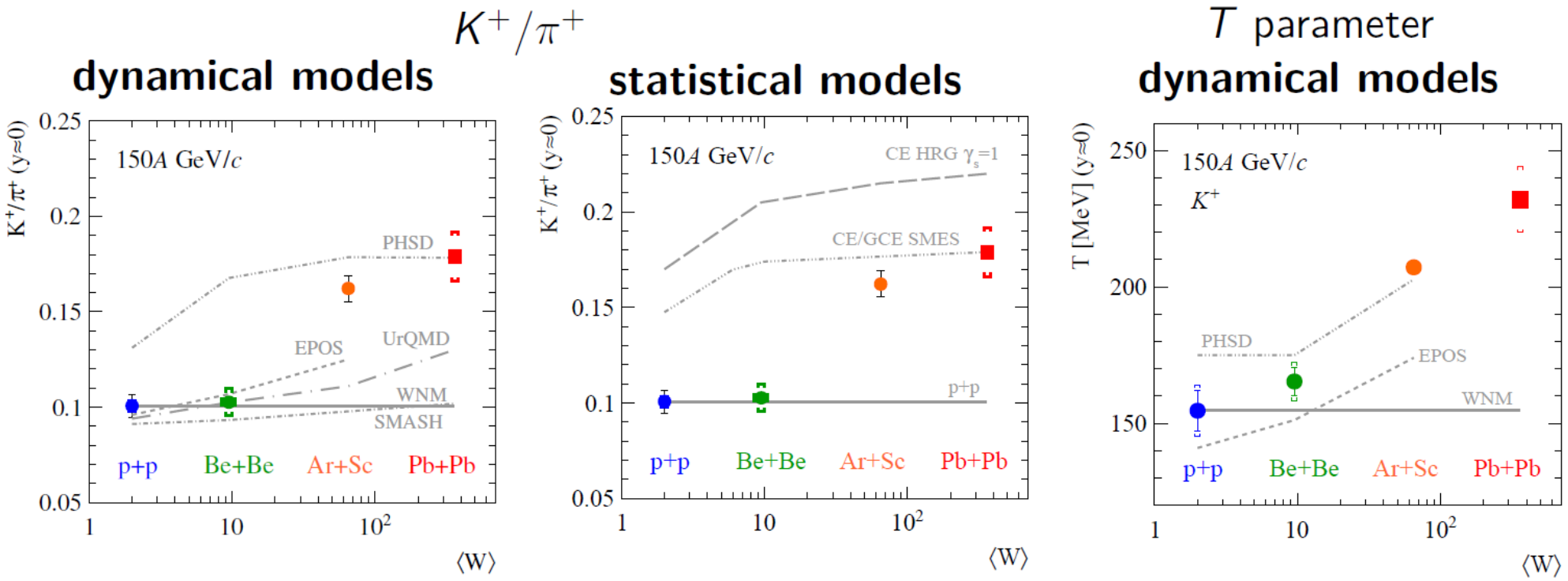
E. V. Shuryak. *Yad.Fiz.*, 16:395–405, 1972.

- 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

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

System size dependence

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

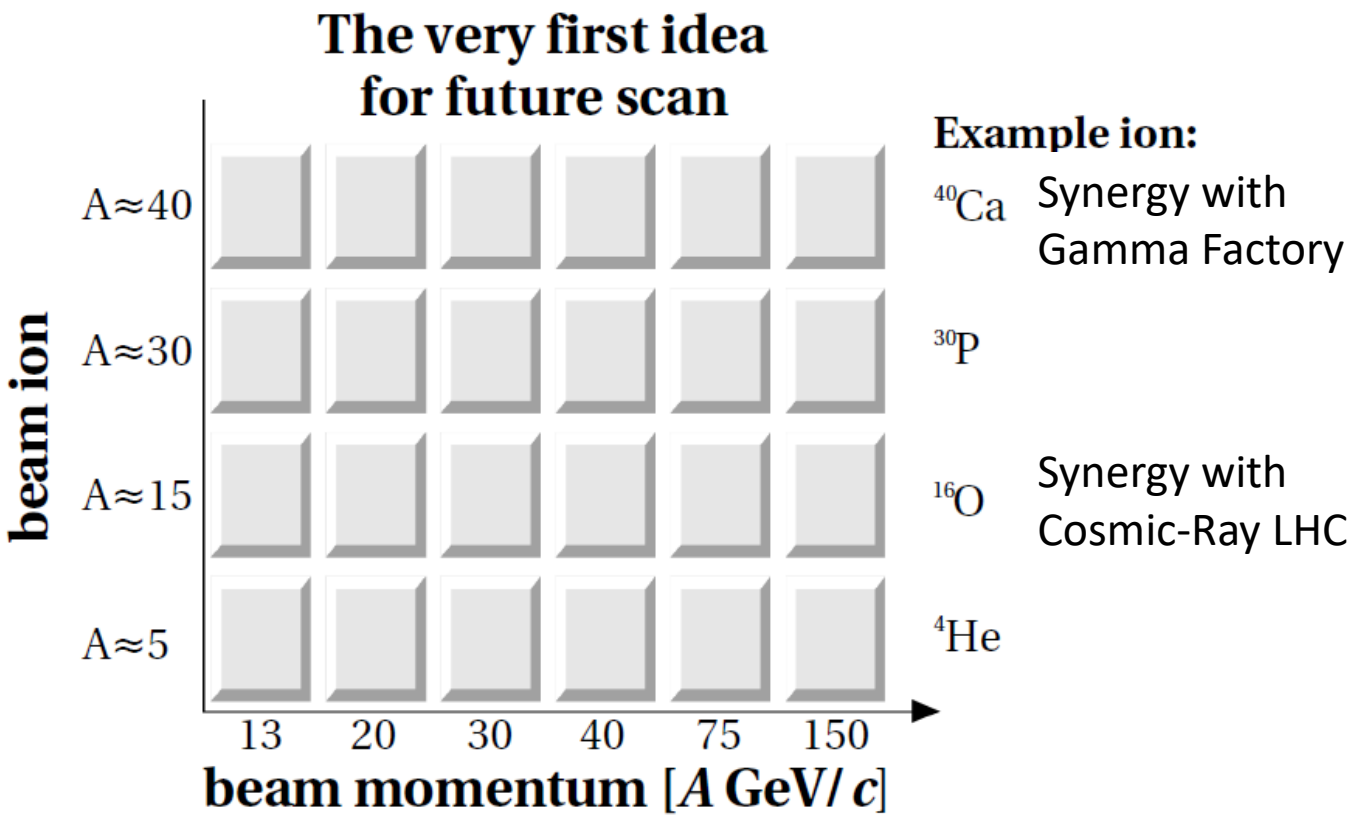


None of the models reproduces K^+/π^+ ratio or T for whole $\langle W \rangle$ range

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

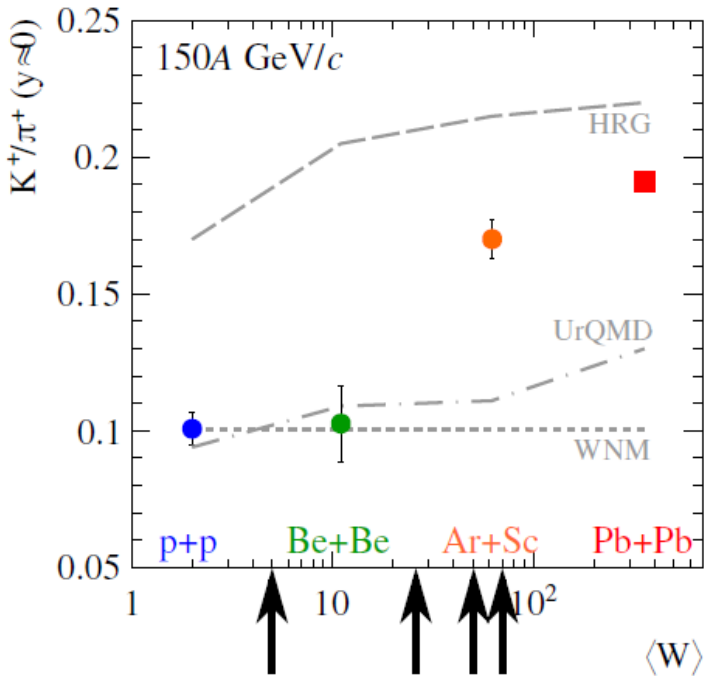
p+p: Eur. Phys. J. C77 (2017) 10, 671
Be+Be: Eur. Phys. J. C81 (2021) 1, 73
Ar+Sc: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C66, 054902 (2002)

measurements after LS3



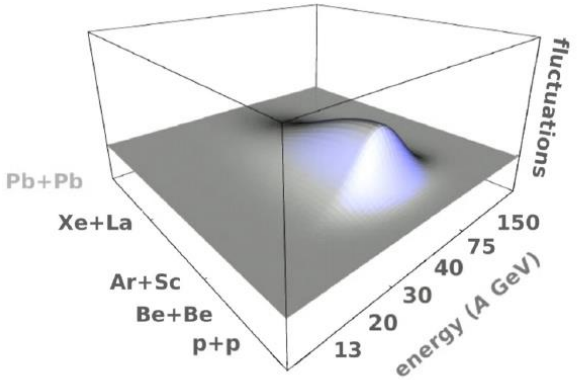
Synergy with Gamma Factory

Synergy with Cosmic-Ray LHC



PHYSICAL REVIEW D **60** 114028

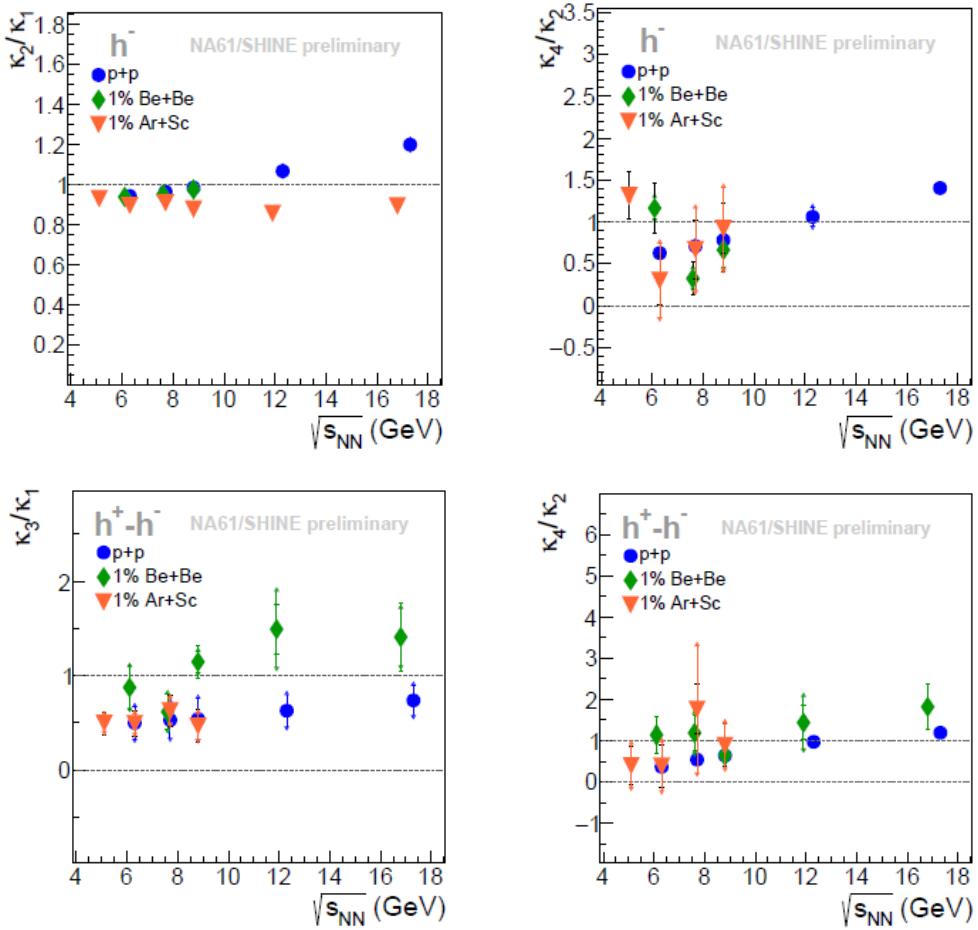
Theoretical fluctuations
in presence of critical point



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
- Net-charge κ_3/κ_1:increasing difference between Be+Be and other systems (p+p and Ar+Sc) with collision energy
- κ_4/κ_1 : consistent values for all measured systems at given collision energy

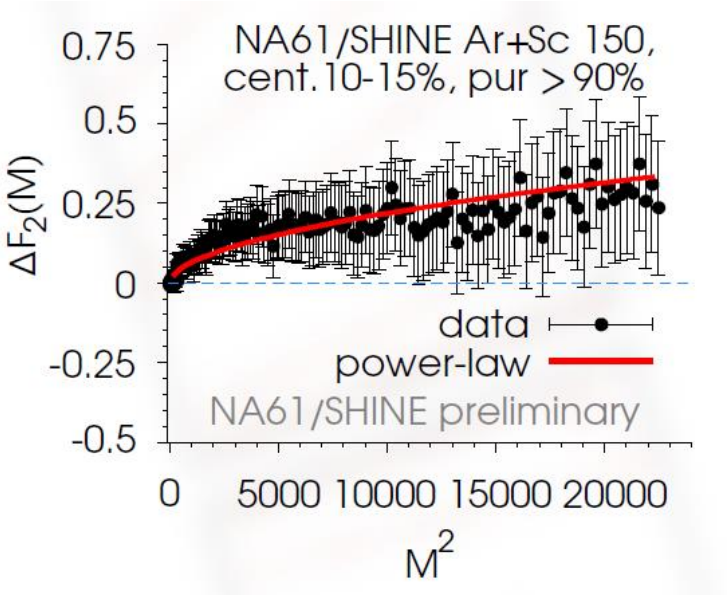
second scaled factorial moments - intermittency analysis

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

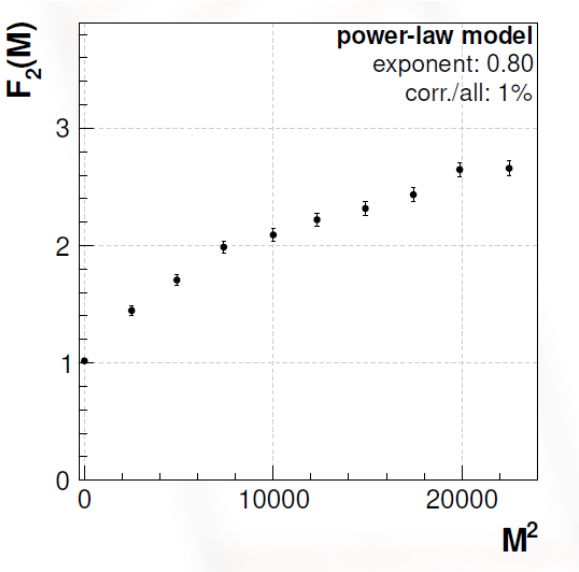
δ - size of each of the $M = \frac{\Delta}{\delta}$ subdivision intervals of the momentum phase-space region Δ

n_i - number of particles in i-th bin

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



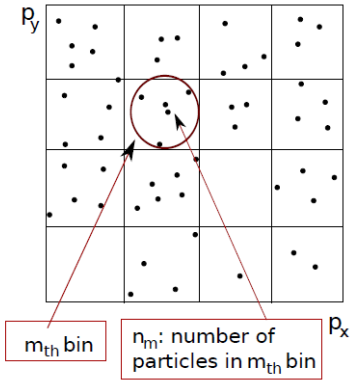
If the system freezes-out in the vicinity of the critical point, $F_2(M)$ should reveal a power-law dependence.

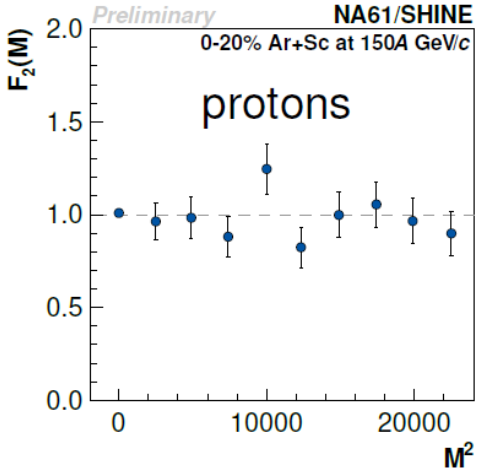


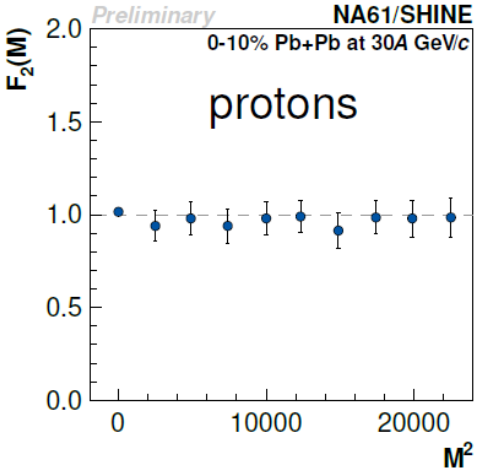
- A deviation of ΔF_2 from in mid-central Ar+Sc?
- The data points are correlated which makes the interpretation difficult.

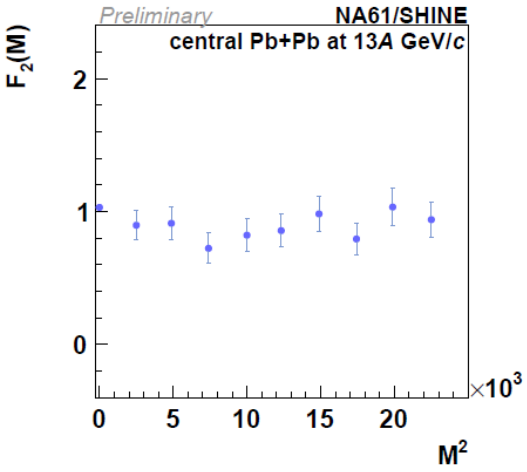
proton and charge hadron intermittency in Ar+Sc and Pb+Pb collisions

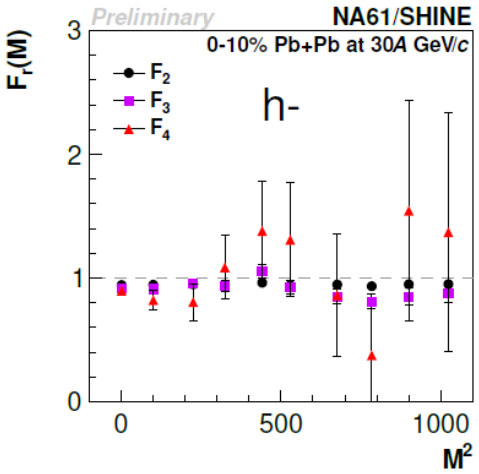
No structure indicating critical point











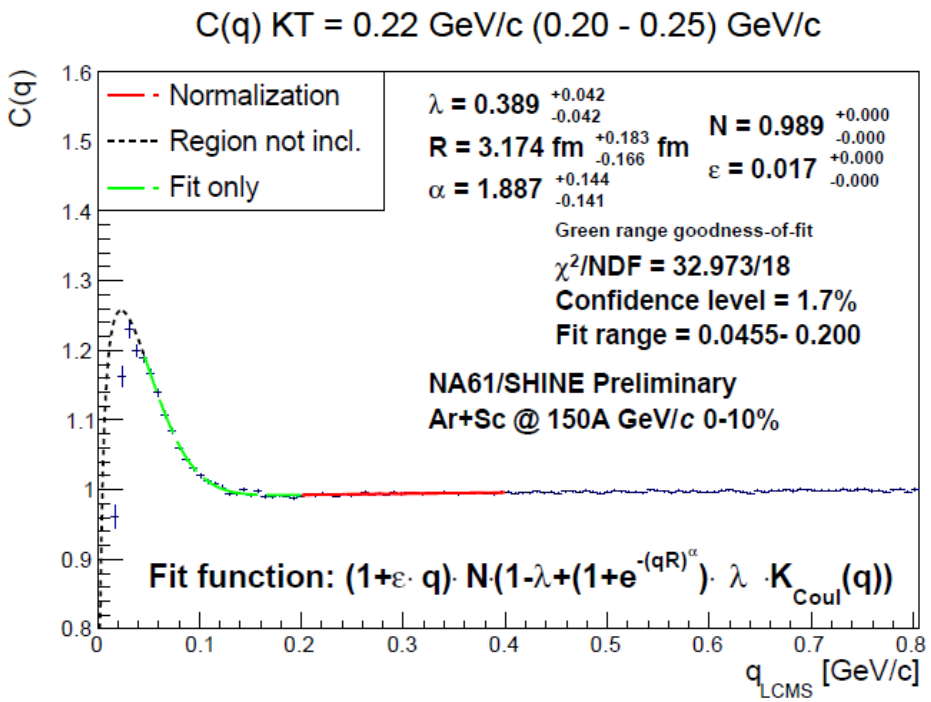
$$F_r(M) = \frac{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m(n_m-1)\ldots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m \right\rangle^r},$$

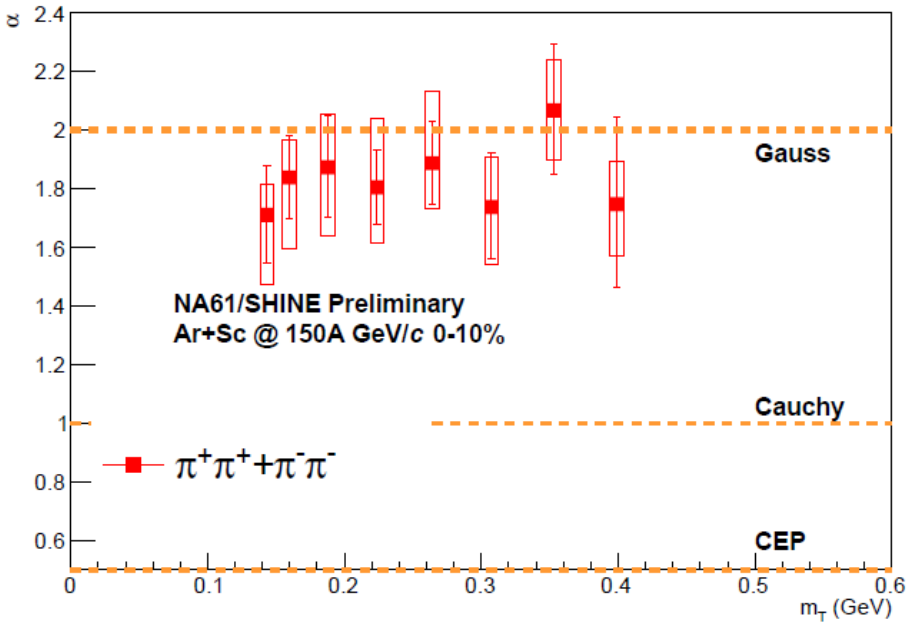
where $\langle \ldots \rangle$ denotes averaging over events, M the number of cells

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



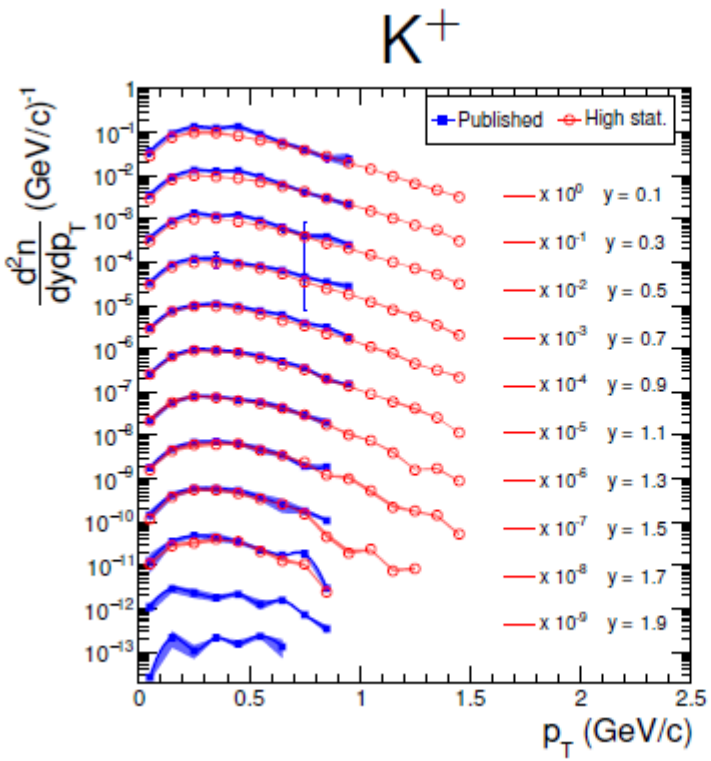


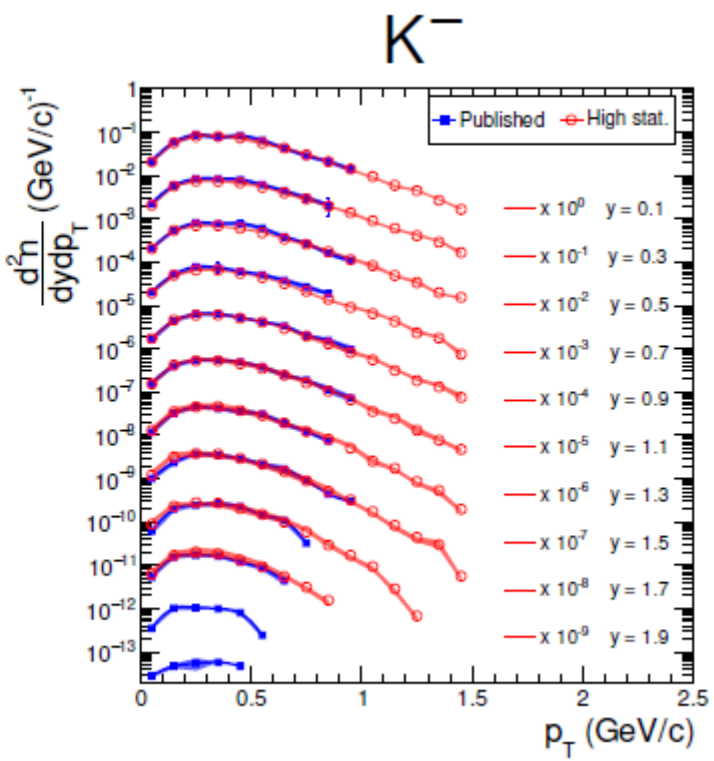
The Levy stability parameter α describes shape of the source

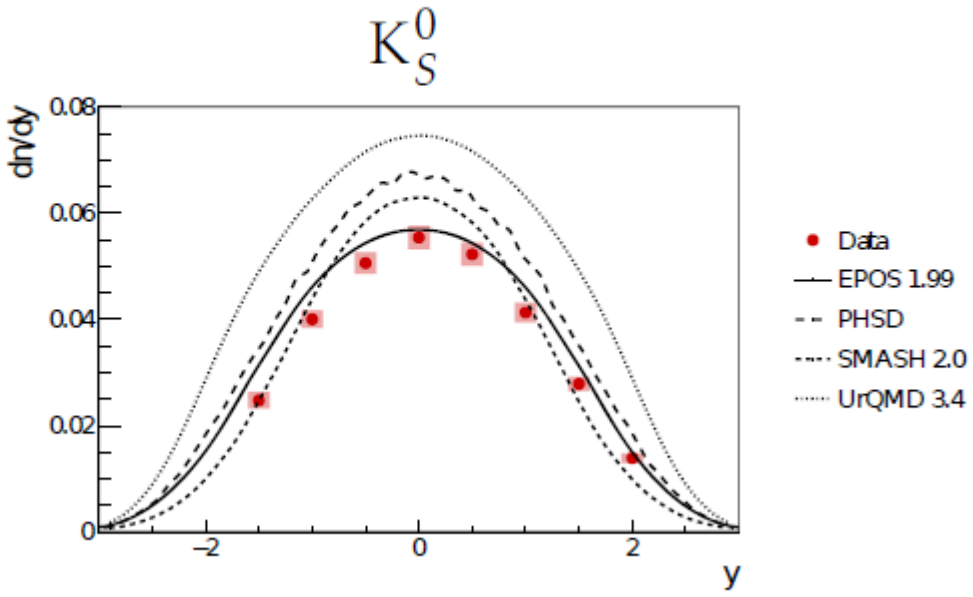
3D Ising model with random external field predicts $\alpha = 0.5 \pm 0.05$ at critical point

strangeness production in p+p

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







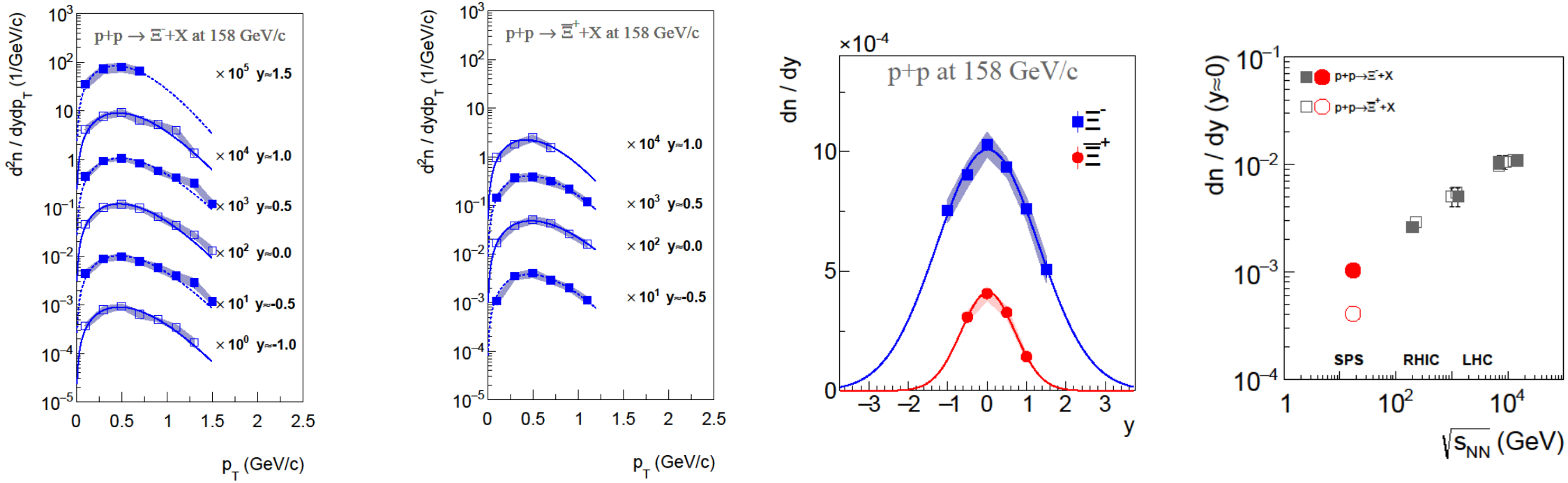
New results on K⁺, K⁻ (preliminary) and K_S^0 from high statistic p+p data

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

K_S^0 mean multiplicity: 0.162±0.001±0.011

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

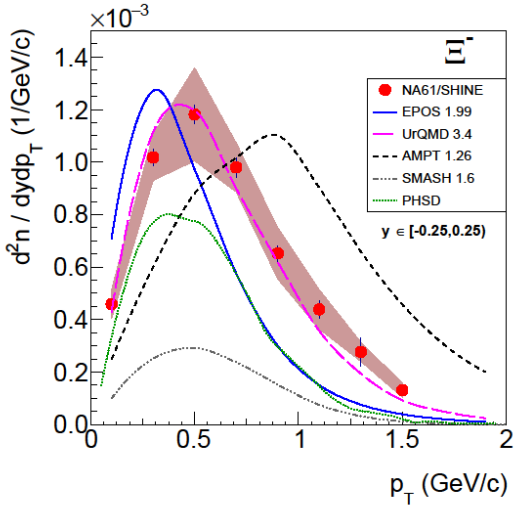
Ξ production in inelastic p+p collisions at 158 GeV/c

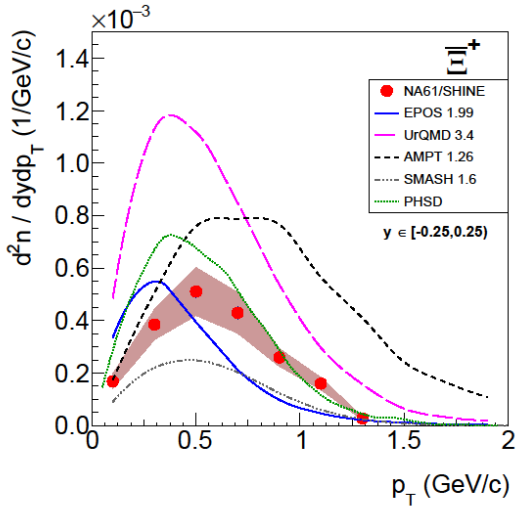


- **The only results on Ξ⁻ and Ξ̄⁺ production in *p+p* at SPS energy**
  - Strong suppression of Ξ̄⁺ production: ⟨Ξ̄⁺⟩ / ⟨Ξ⁻⟩= 0.24 ± 0.01 ± 0.05

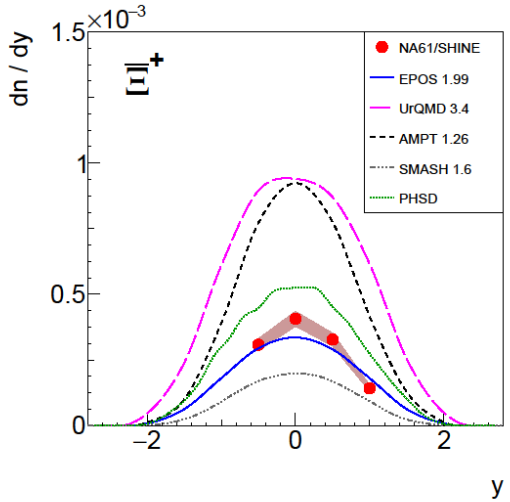
Eur.Phys.J.C 80 (2020) 9, 833

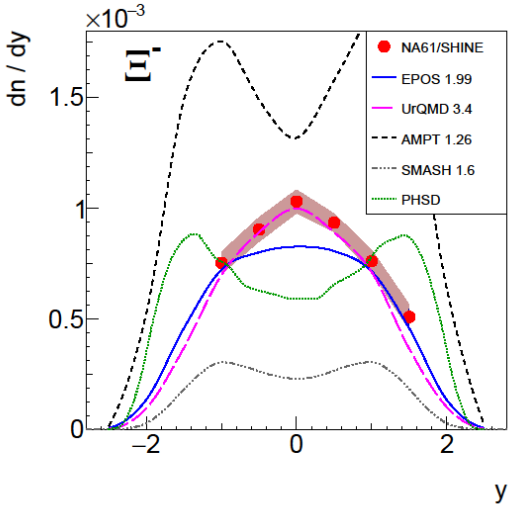
Ξ production in inelastic p+p collisions – model comparison

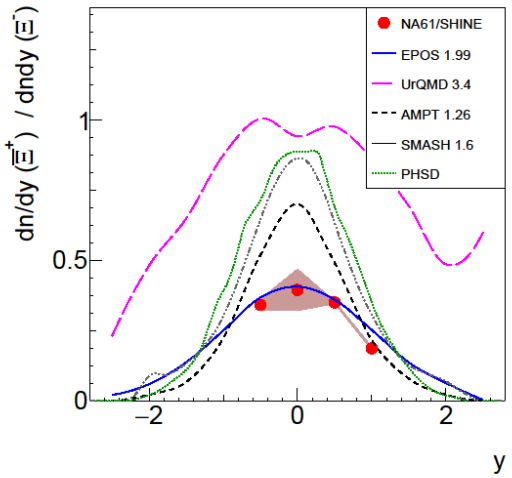




- Transport models **fail** to describe the NA61/SHINE results on Ξ production in p+p collisions







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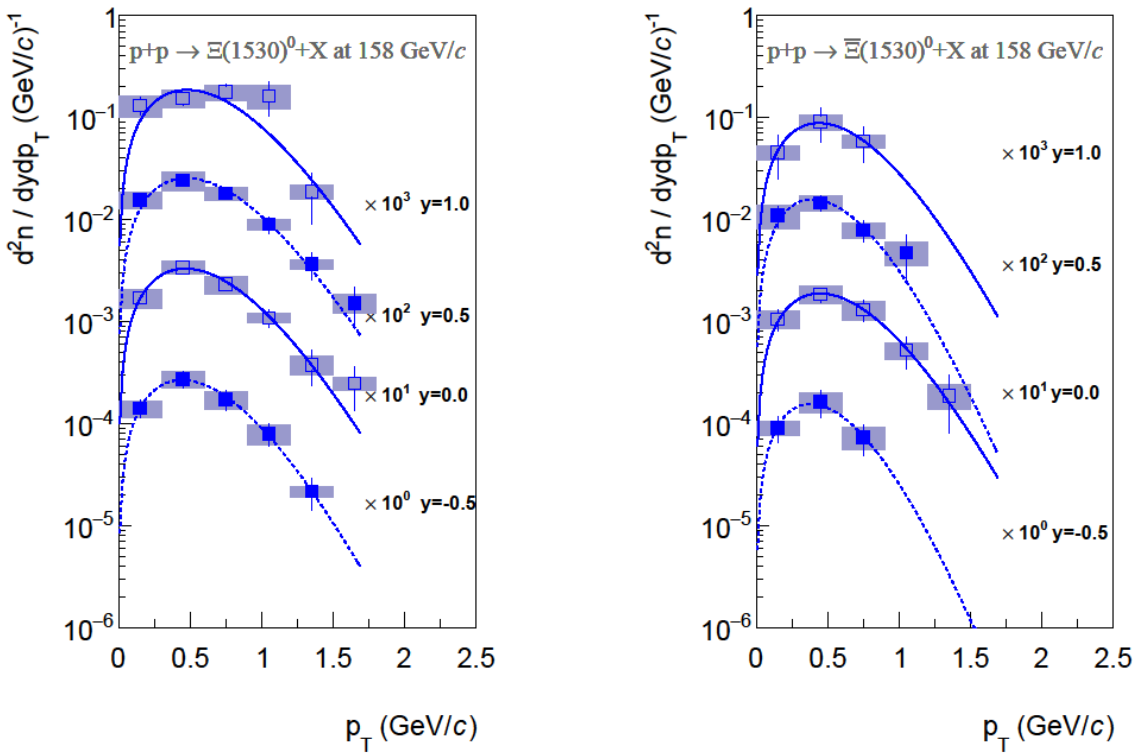
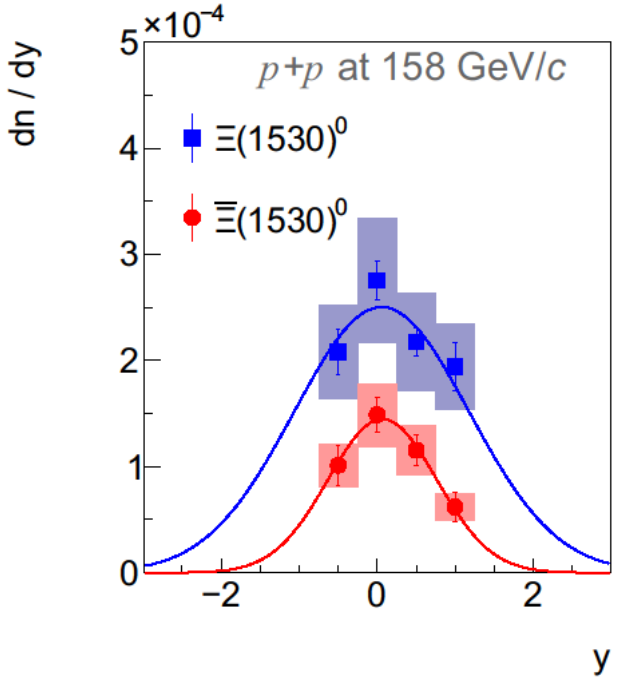
$\Xi(1530)^0$ production in inelastic p+p collisions at 158

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

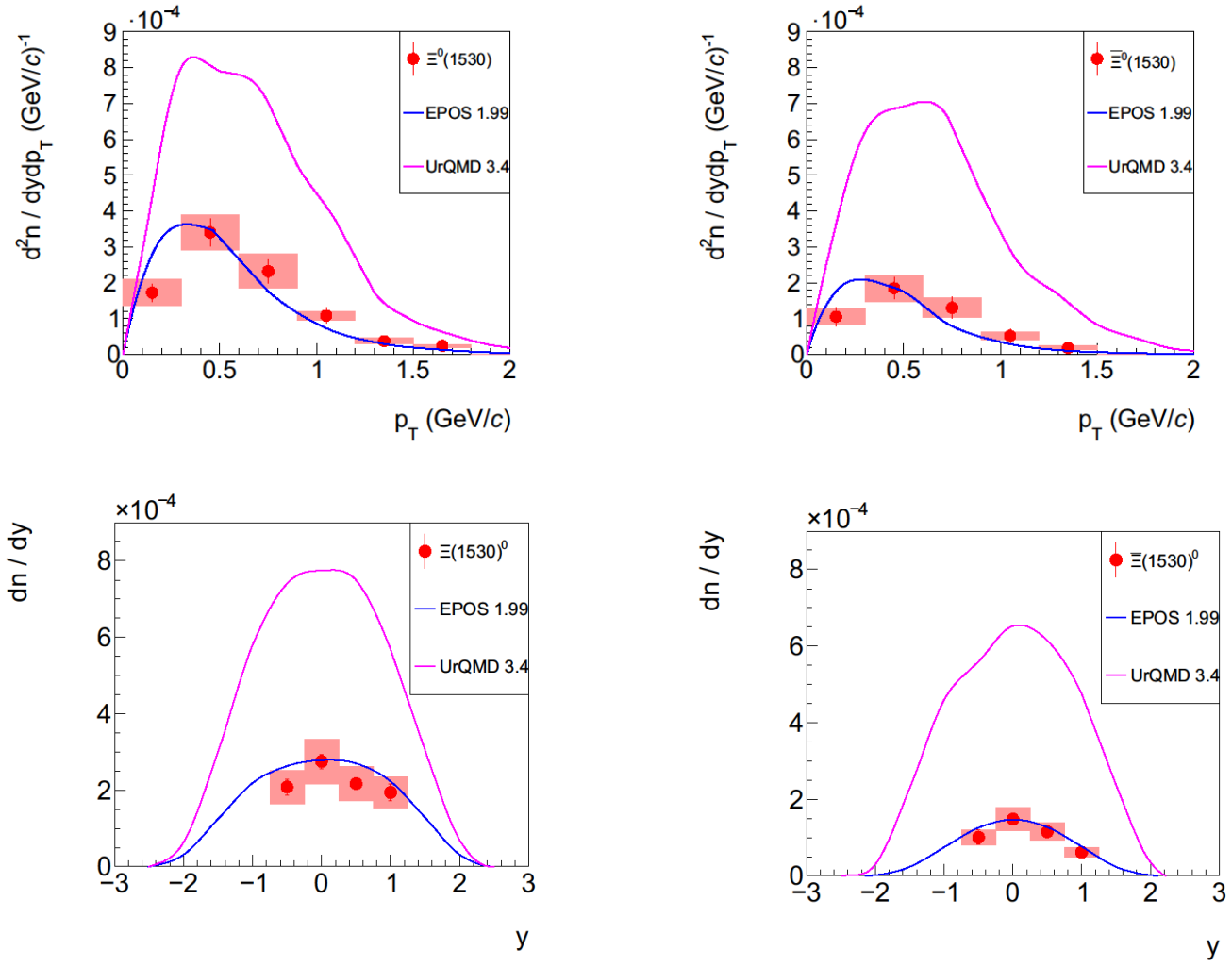




- **The only results on $\Xi(1530)^0$ production in *p+p* at the SPS energy**
- The second result on $\Xi(1530)^0$ production in *p+p* (ALICE at 7 TeV Eur.Phys.J.C 75 (2015) 1)
  - Suppression of $\bar{\Xi}(1530)^0$ production: $\langle\bar{\Xi}(1530)^0\rangle$ / $\langle\Xi(1530)^0\rangle$= 0.40 ± 0.03 ± 0.05

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

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

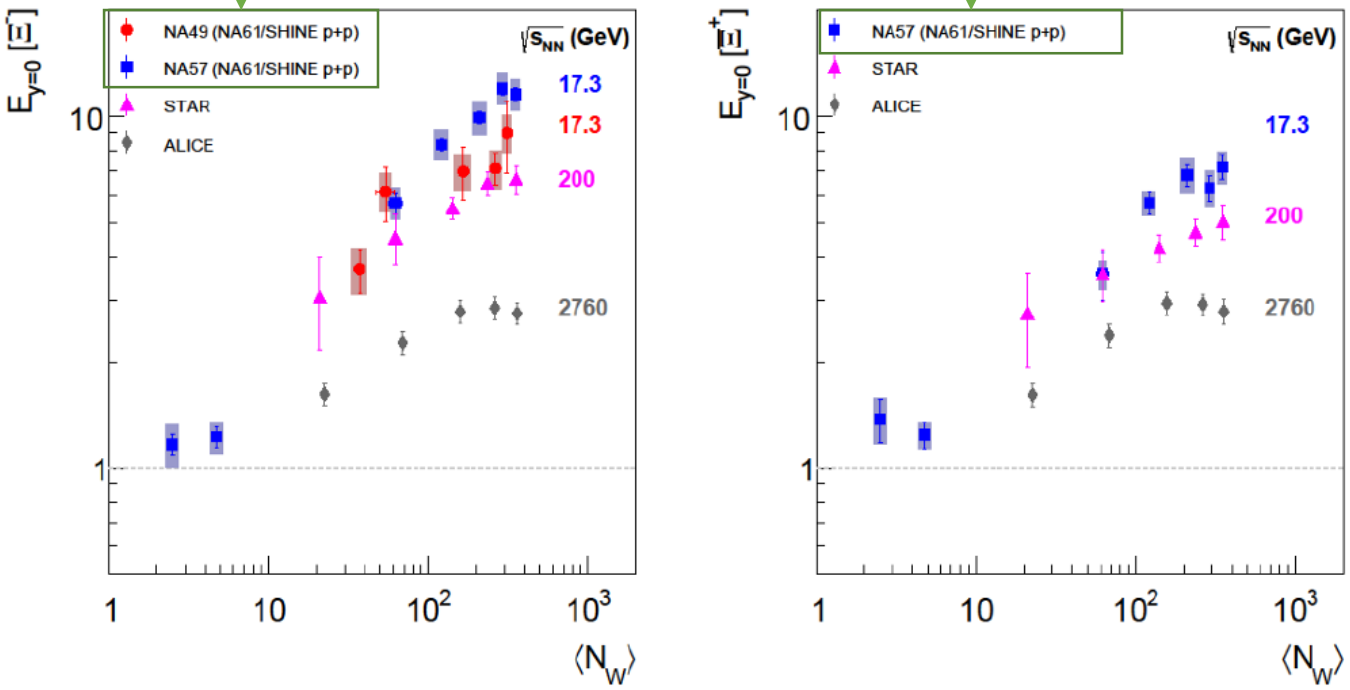


- EPOS describes well transverse momentum and rapidity distributions of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$

- 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

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

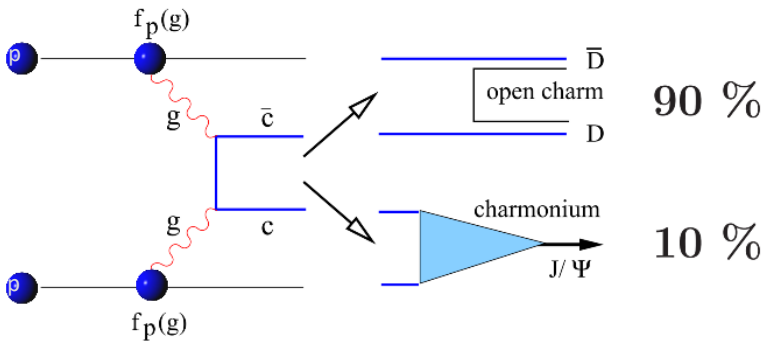
Nucl. Phys. B111 (1976) 461

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

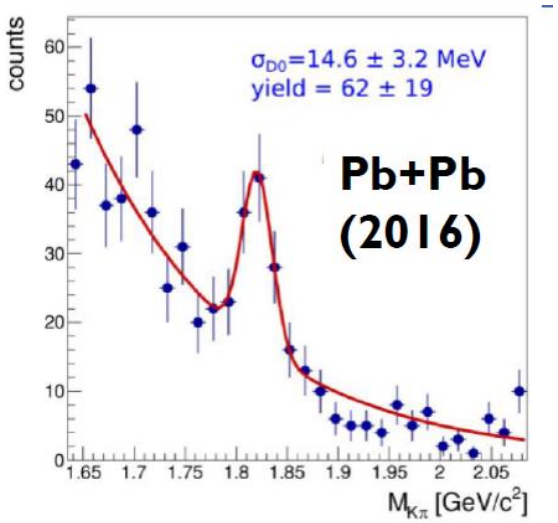
Eur.Phys.J.C 80 (2020) 9, 833

NA61/SHINE in 2022-2025

charm production and the onset of deconfinement

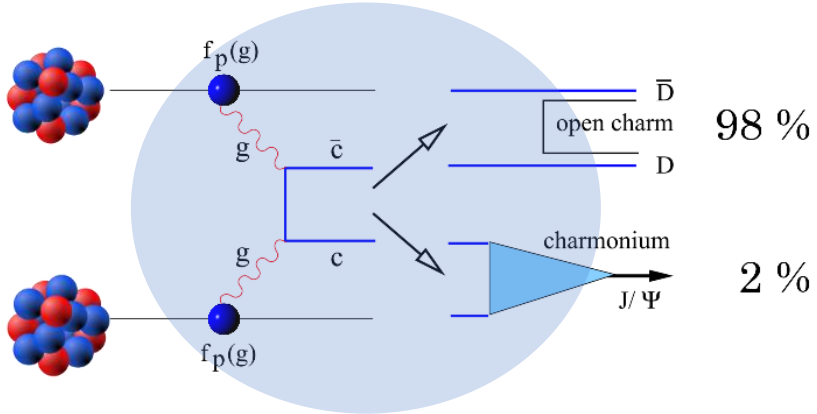


Open charm and J/ψ production within Matsui-Satz model
[PL B178 416]



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 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
- The onset of Fireball - 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 present theoretical models can explain strangeness production in p+p NA61/SHINE data
- NA61/SHINE will measure open charm production in 2022- 2025

Thank You

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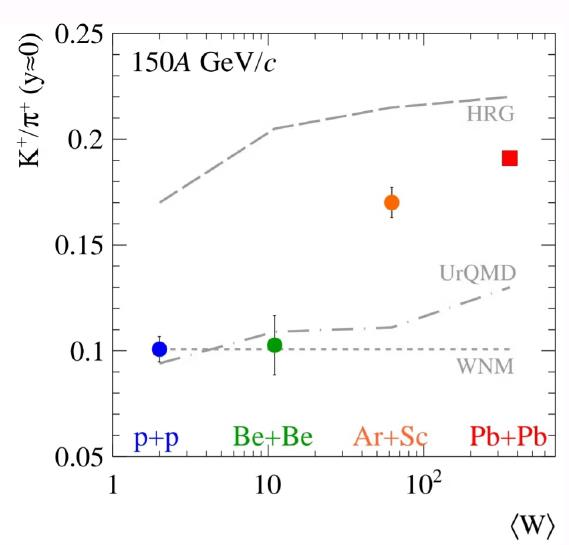
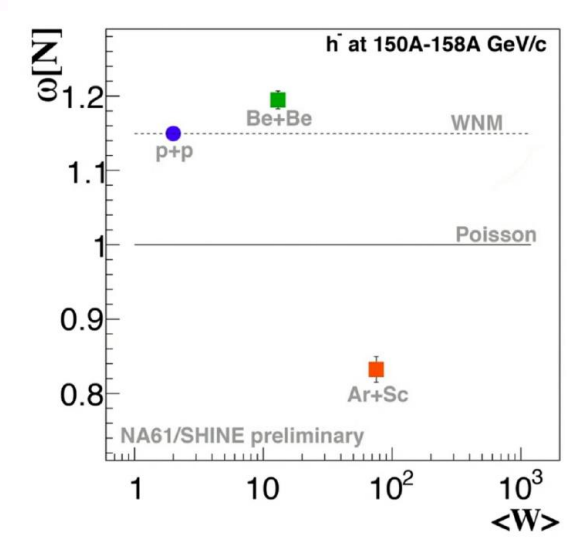
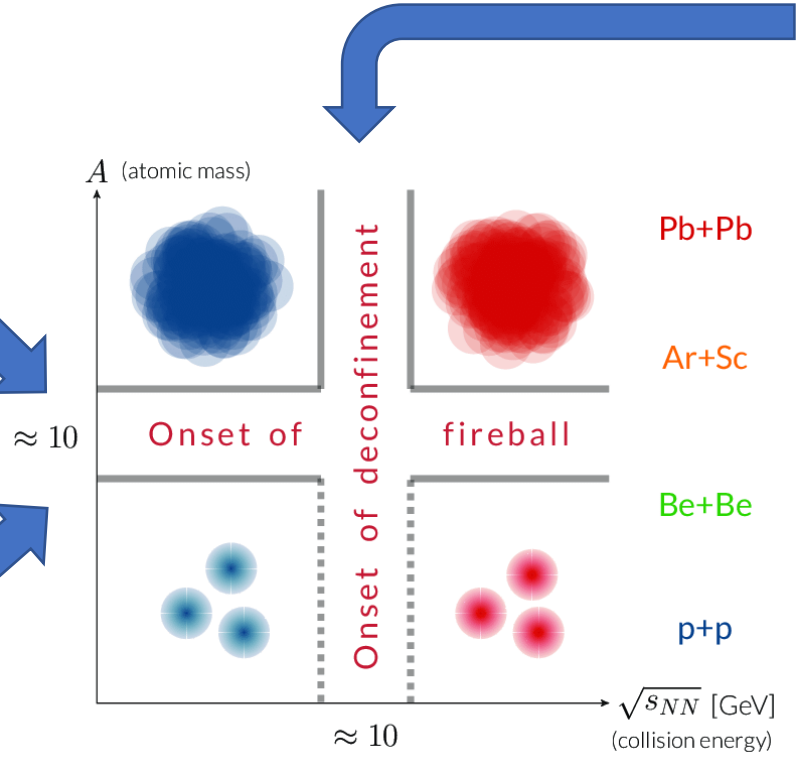
Backup

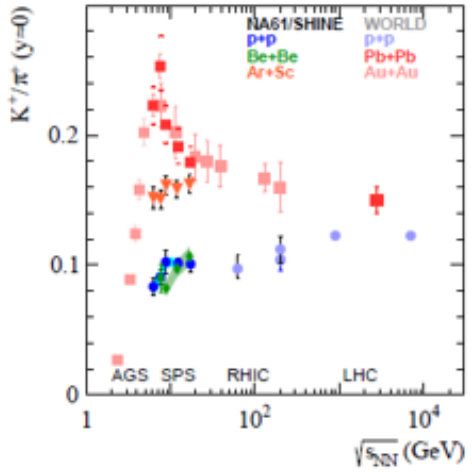
Uniqueness of heavy ion results from NA61/SHINE





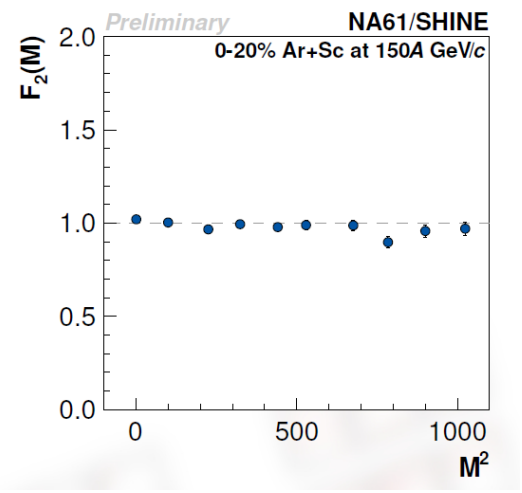


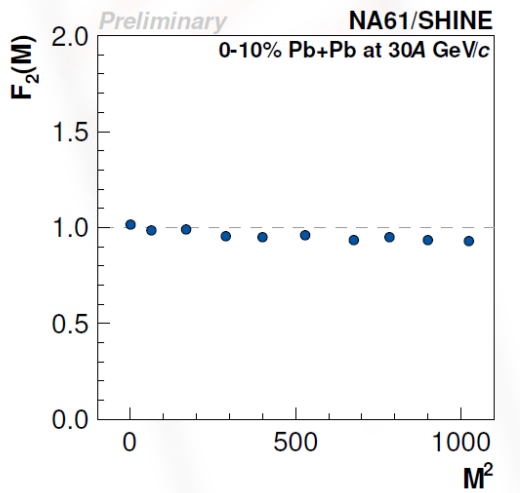
$p + p \approx Be + Be \neq Ar + Sc$

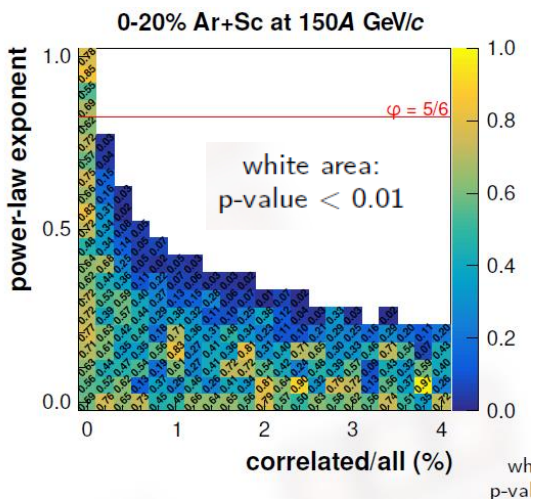


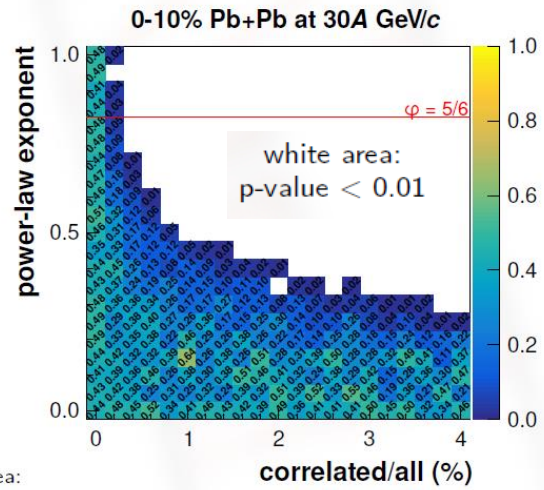
- Two onsets in nucleus-nucleus collisions
- Onset of deconfinement - beginning of QGP formation
- Onset of fireball - beginning of formation of a large cluster which decays statistically

second scaled factorial moments of protons - intermittency analysis





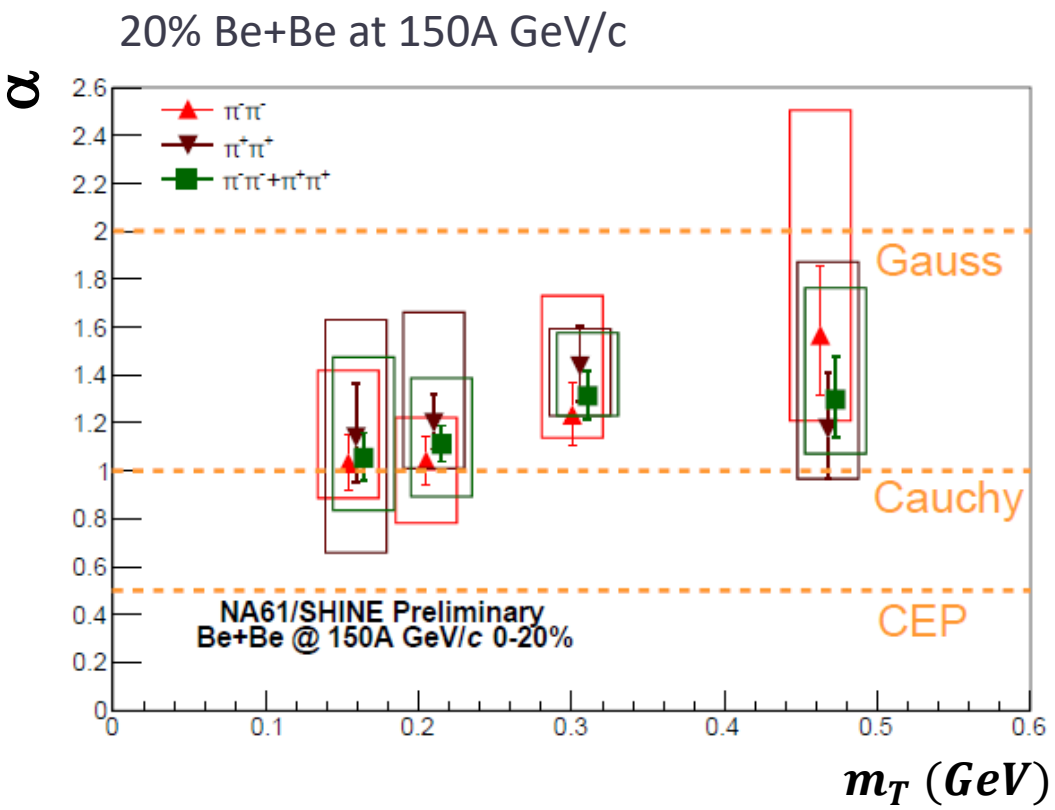




- Results for :
  - statistically independent points
  - cumulative quantities
  - M = 1 … 32 bins in p_x and p_y
- second scaled factorial moments of protons for Ar+Sc at 150*A* GeV/*c* and Pb+Pb at 30*A* GeV/*c* shows no indication for power-law increase with a bin size
- Exclusion plot
  - predictions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



Lévy distribution leads to power-law correlation functions

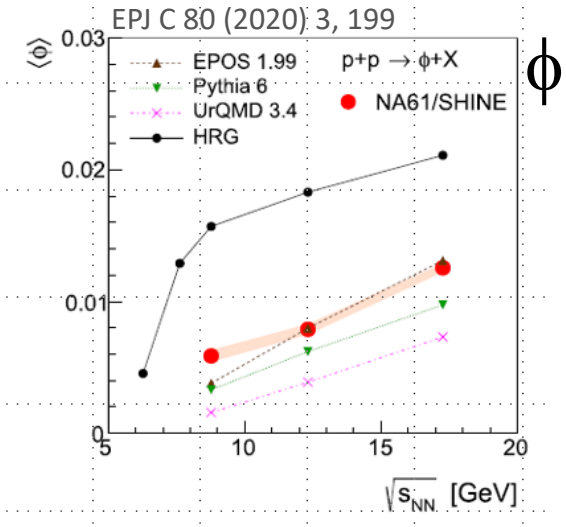
$$C(q) = 1 + \lambda \cdot e^{-(qR)^{\alpha}}$$

Csörgö et al., EPJC36

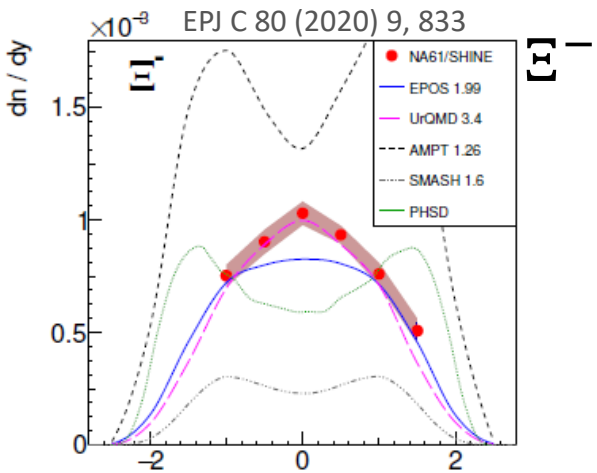
Lévy-exponent $\alpha \approx 0.5$ for the critical point

- 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)

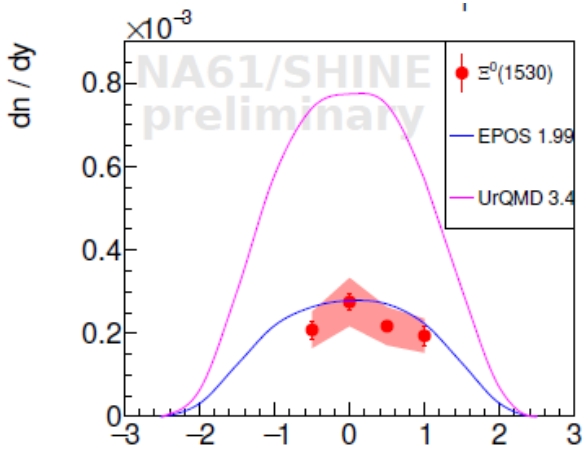
strangeness production in p+p at 158 GeV/c



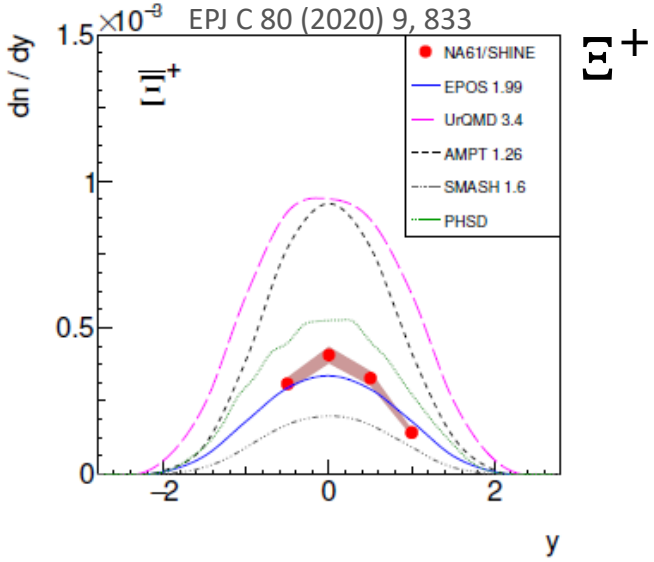
ϕ



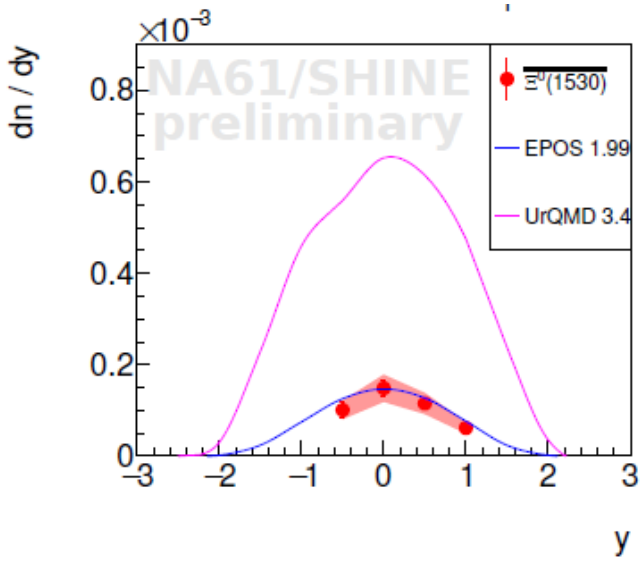
Ξ^-



$\Xi^0(1530)$



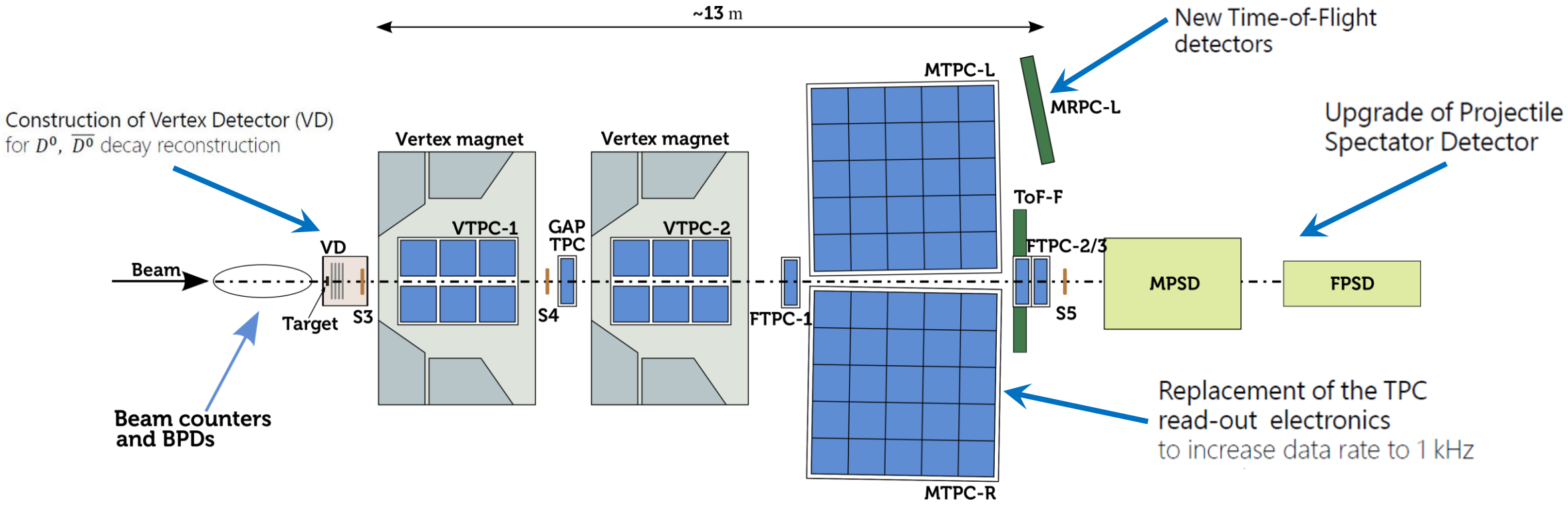
Ξ^+



$\overline{\Xi^0(1530)}$

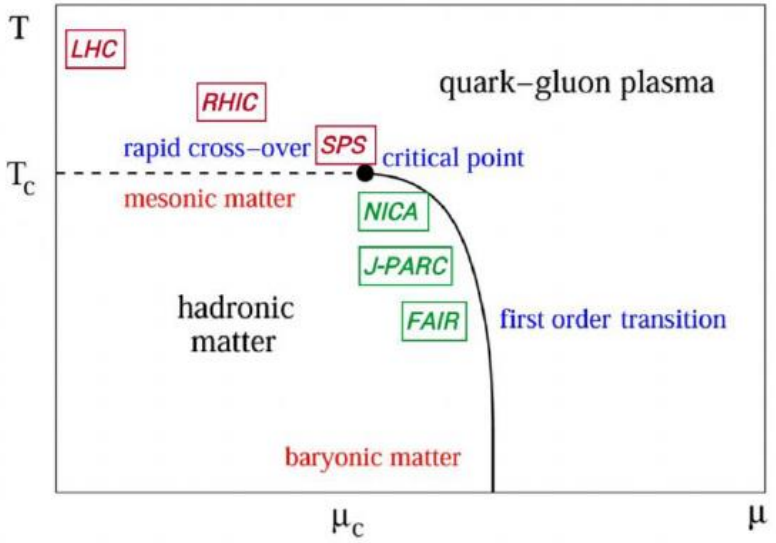
Present theoretical models do not describe the NA61/SHINE results on strange particles production

Detector upgrade during LS2



Uniqueness of NA61 open charm program

Landscape of present and future heavy ion experiments

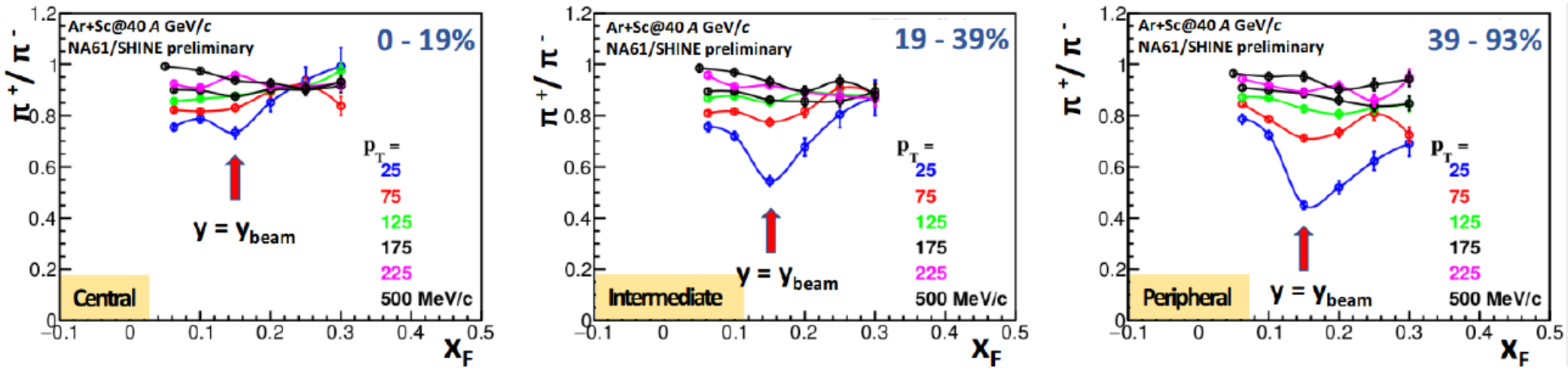


Only NA61/SHINE is able to measure open charm production in heavy ion collisions in full phase space in the near future

- 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



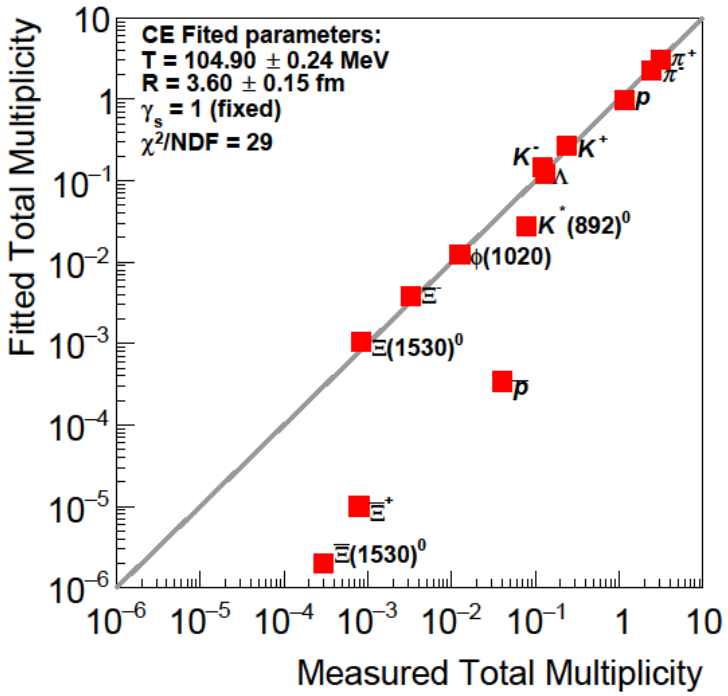
First time ever observation of the spectator-induced electromagnetic effects in peripheral small systems: Ar+Sc at 40A GeV/c

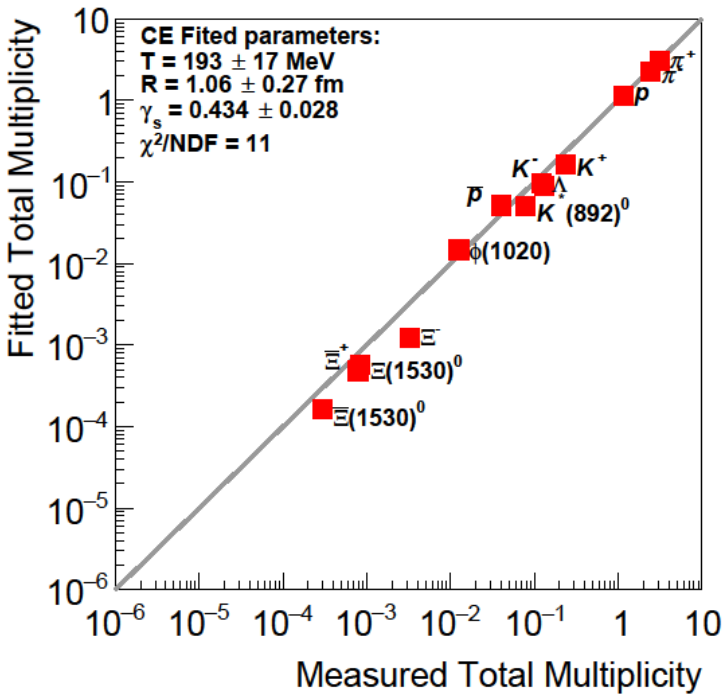
- Charged pion trajectories can be modified by electromagnetic interactions (repulsion for π^+ and attraction for π^-) with the spectators → the effect is sensitive to the space-time evolution the system

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