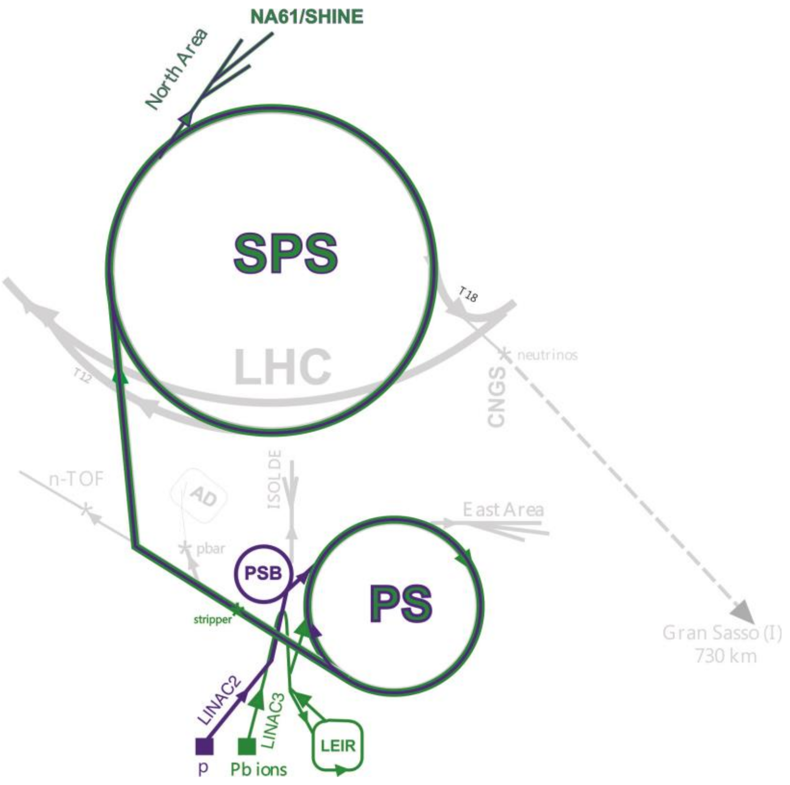
Seweryn Kowalski for the
NA61/SHINE Collaboration
University of Silesia, Poland

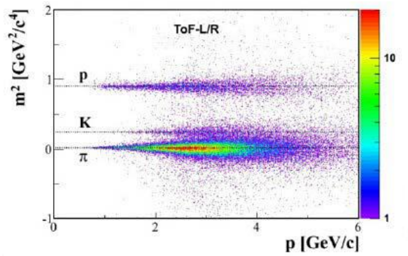
New results from strong interaction measurement program of NA61/SHINE

NA61/SHINE - Acceleration chain

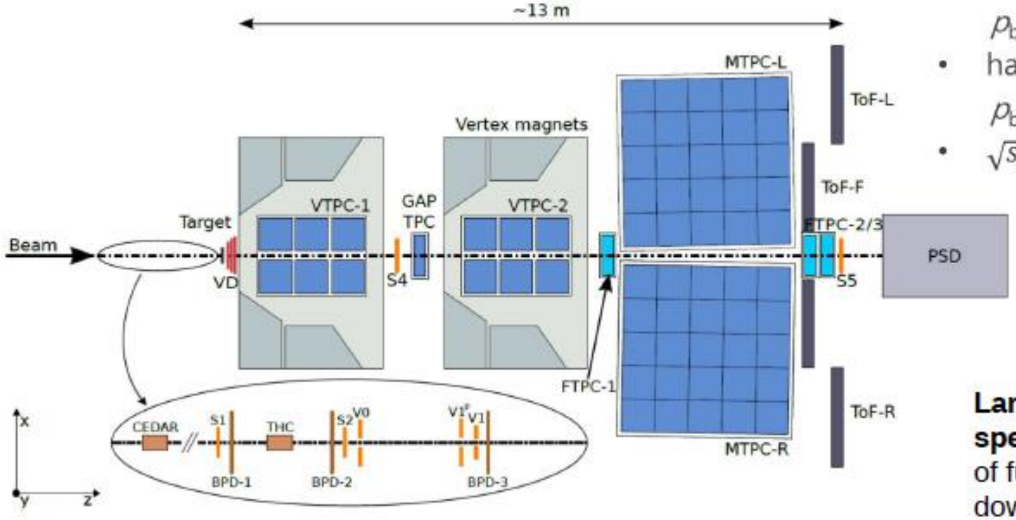


- Primary beams:
  - Protons at 400 GeV/c
  - Ions (Ar, Xe, Pb) at 13A – 150A GeV/c
- Secondary beams:
  - Hadrons ($\boldsymbol{\pi}^{+/-}$, $\boldsymbol{K}^{+/-}$, anty-$\boldsymbol{p}$) at 13 - 400 GeV/c
  - Ions (Be) at 13A - 150A GeV/c

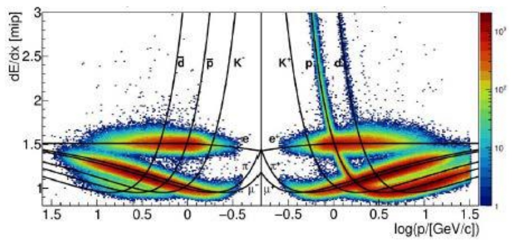
NA61/SHINE - Experimental layout

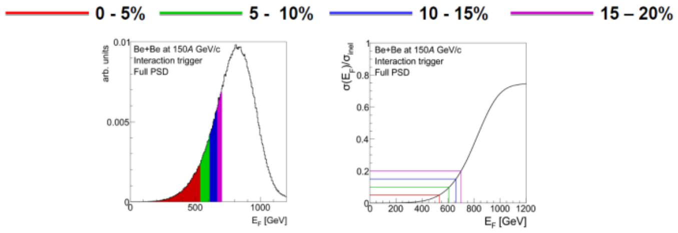


Beams:
- ions (Be, Ar, Xe, Pb)
  p_{beam}=13*A*–150*A* GeV/*c*
- hadrons (π, K, p)
  p_{beam}=13–400 GeV/*c*
- $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV



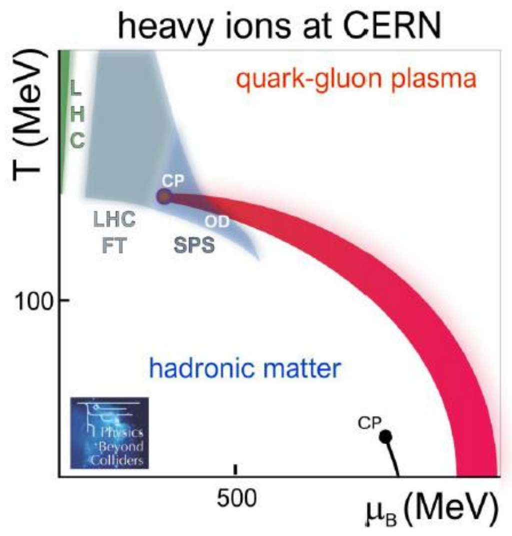
Large acceptance hadron spectrometer – coverage of full forward hemisphere, down to $p_T = 0$

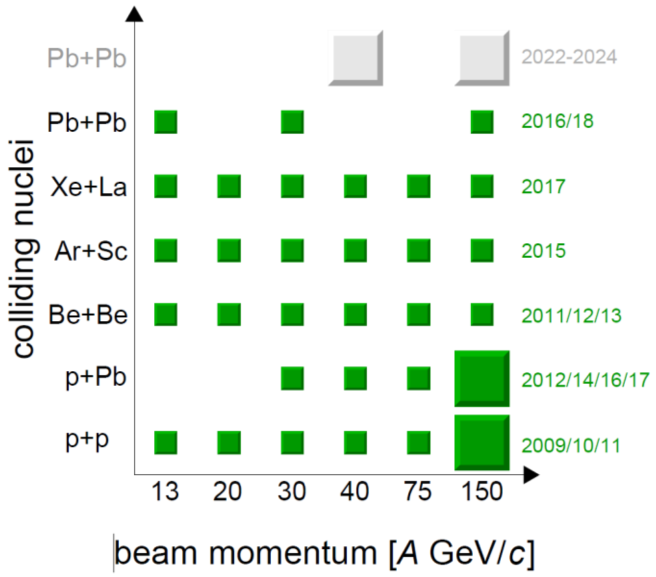




- Large acceptance hadron spectrometer
- Beam particles measured in set of counters and position detectors
- Tracks of charged particles measured in set of TPCs: measurement of *q*, *p* and identification by energy loss measurement
- 3 Time of Flight Walls: identification via time of flight measurement
- Projectile Spectator Detector measures the forward energy which characterizes centrality of collision
- Vertex Detector (open charm measurements)
- Forward TPC-1/2/3

NA61/SHINE - Physics program





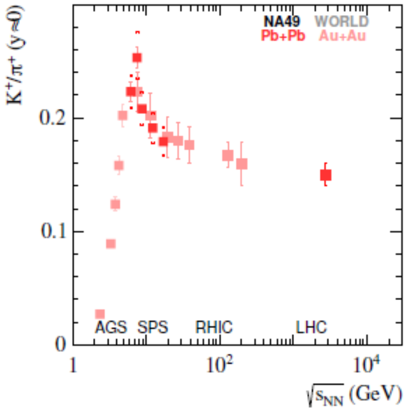
- Strong interactions program
  - search for the critical point of strongly interacting matter
  - study of the properties of the onset of deconfinement
- Hadron-production measurements for neutrino experiments
- Hadron-production measurements for cosmic ray experiments

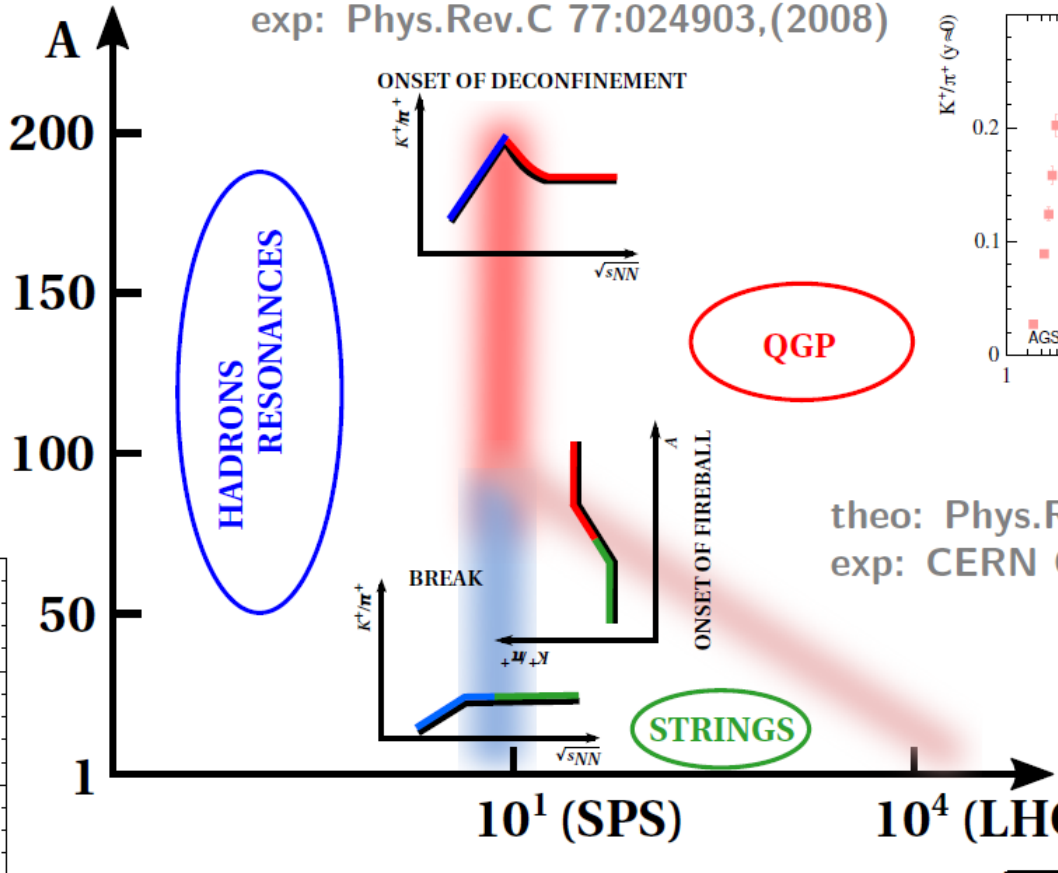
Uniqueness of heavy ion results from NA61/SHINE

NA61/SHINE recorded unique data for:

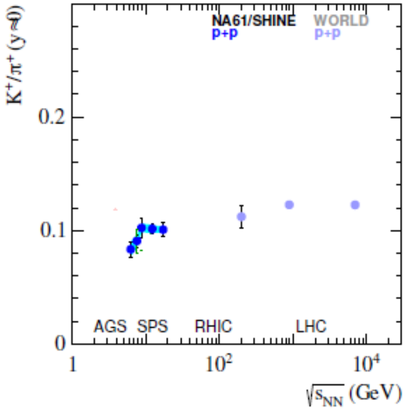
- Onset of deconfinement
- Onset of fireball
- Transition from resonances to strings
- Critical point?

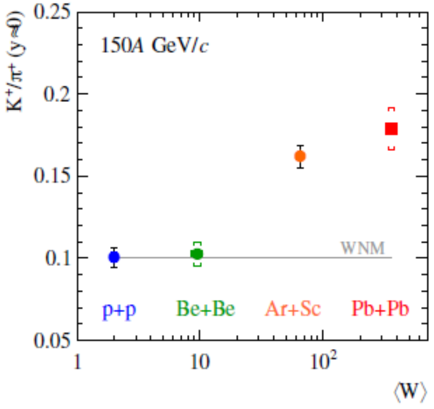
theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)





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



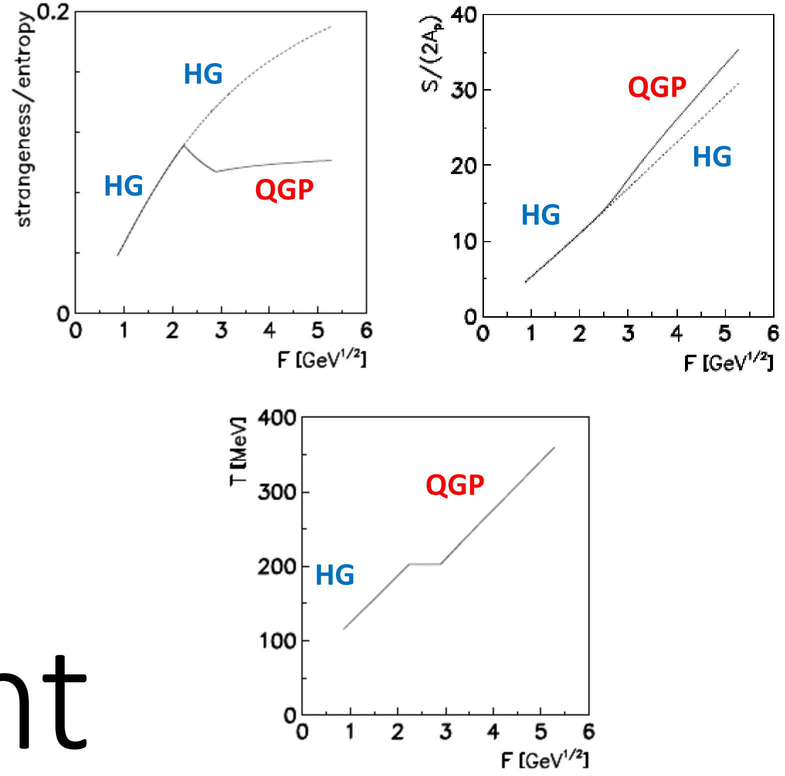


theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

physics results

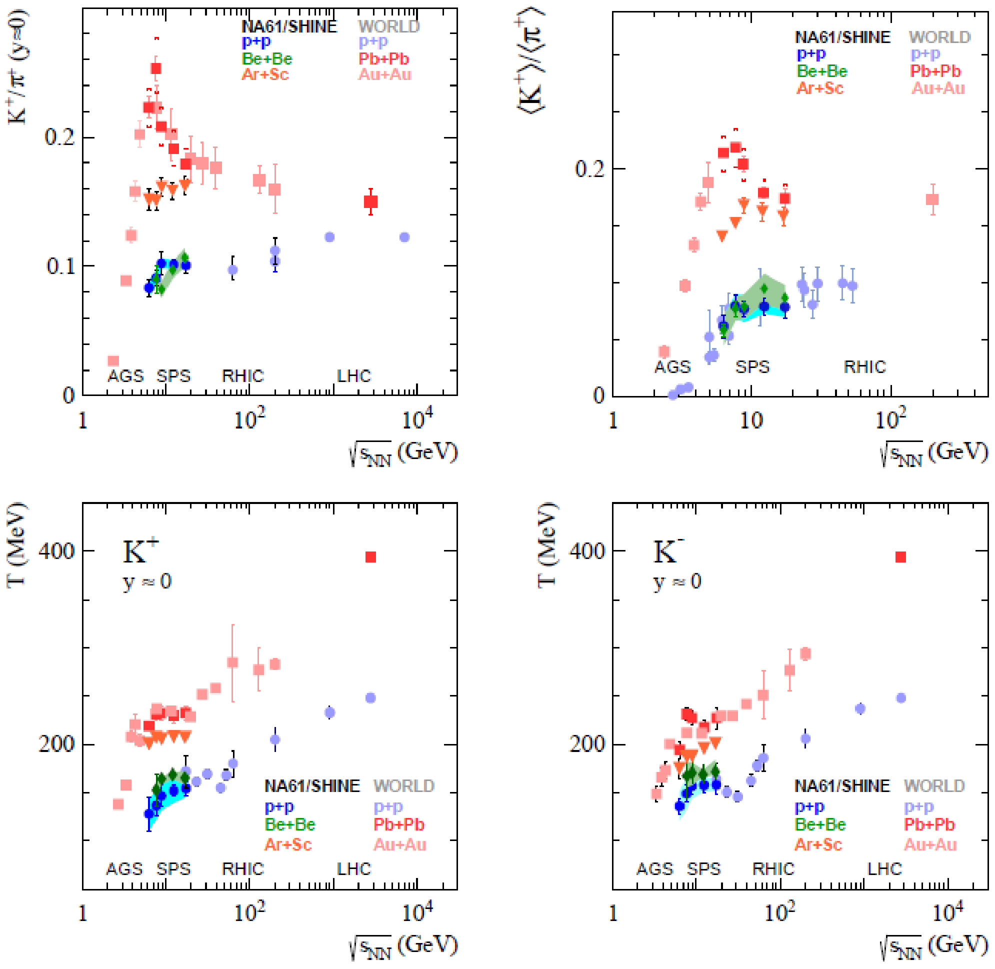
Acta Phys. Pol. B 30, 2705 (1999)

HORN – KINK - STEP



onset of deconfinement

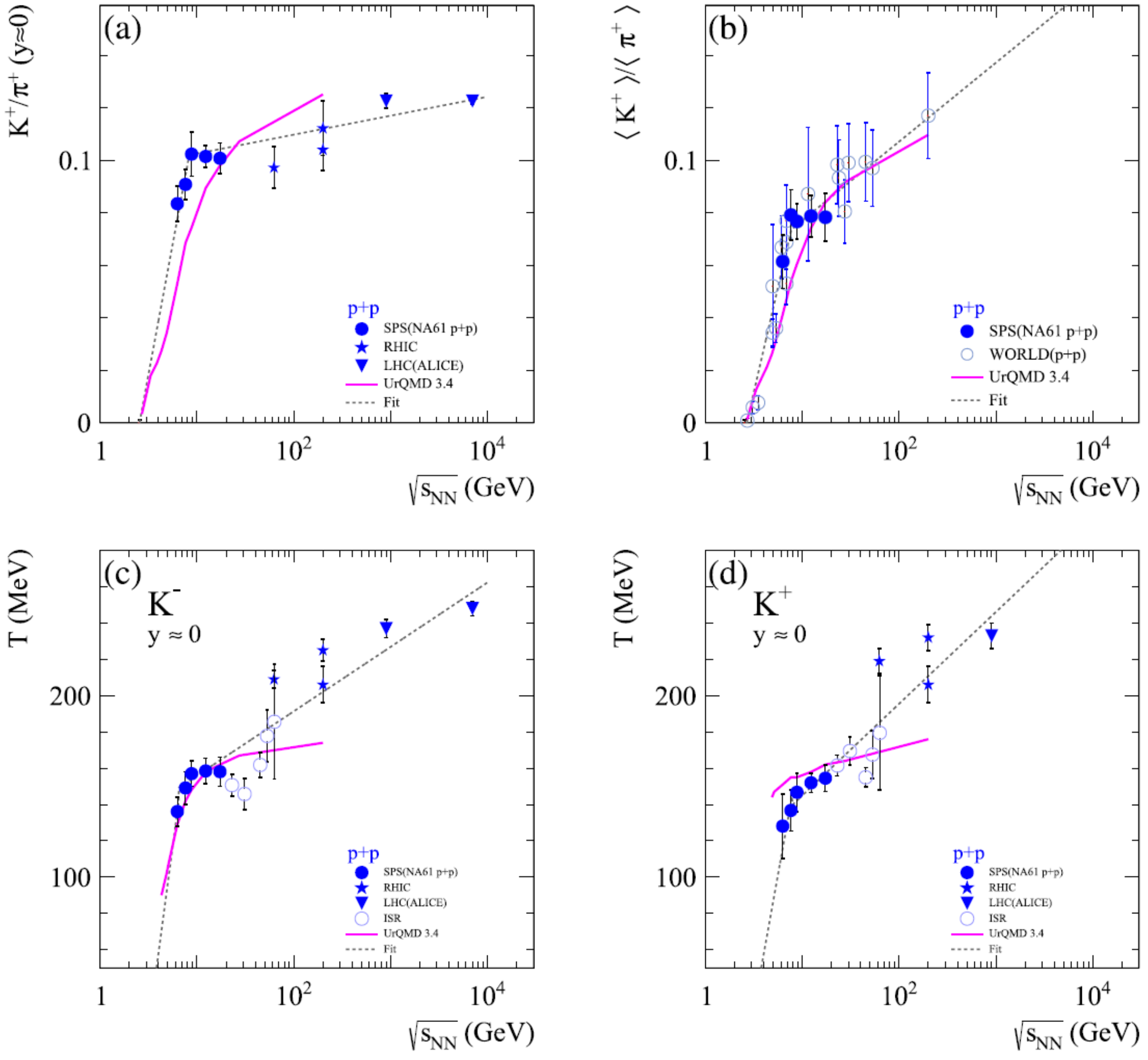
onset of deconfinement



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

- Precise measurements of collision energy dependence for p+p, Be+Be, and Ar+Sc
- K^+/π^+ ratio in inelastic p+p interactions is different from the one in heavy-ion collisions
- No horn structure in Be+Be and Ar+Sc
- The collision energy dependence of the inverse slope parameter of m_T spectra T shows the so-called *step* structure

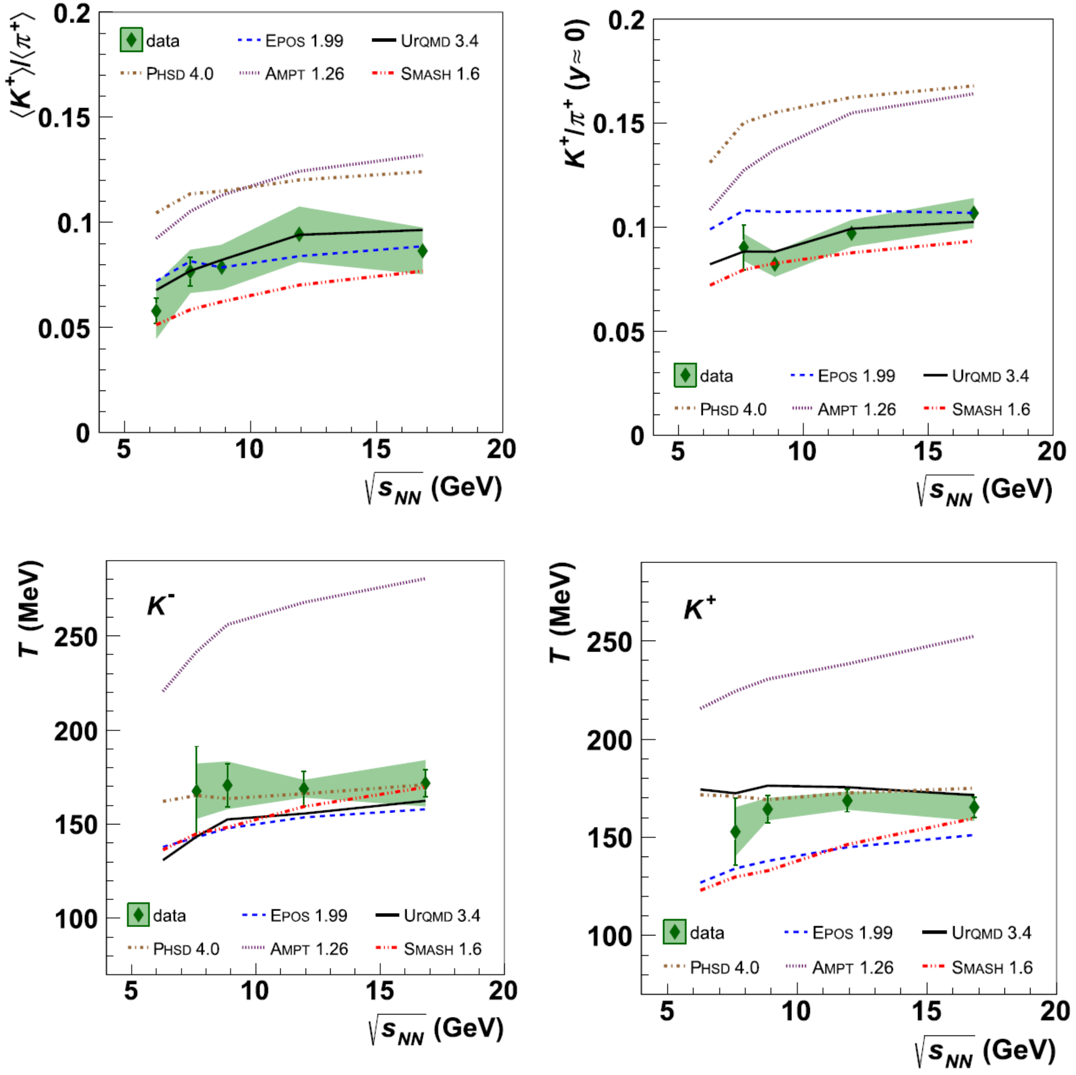
p+p interactions and onset of deconfinement



- 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)

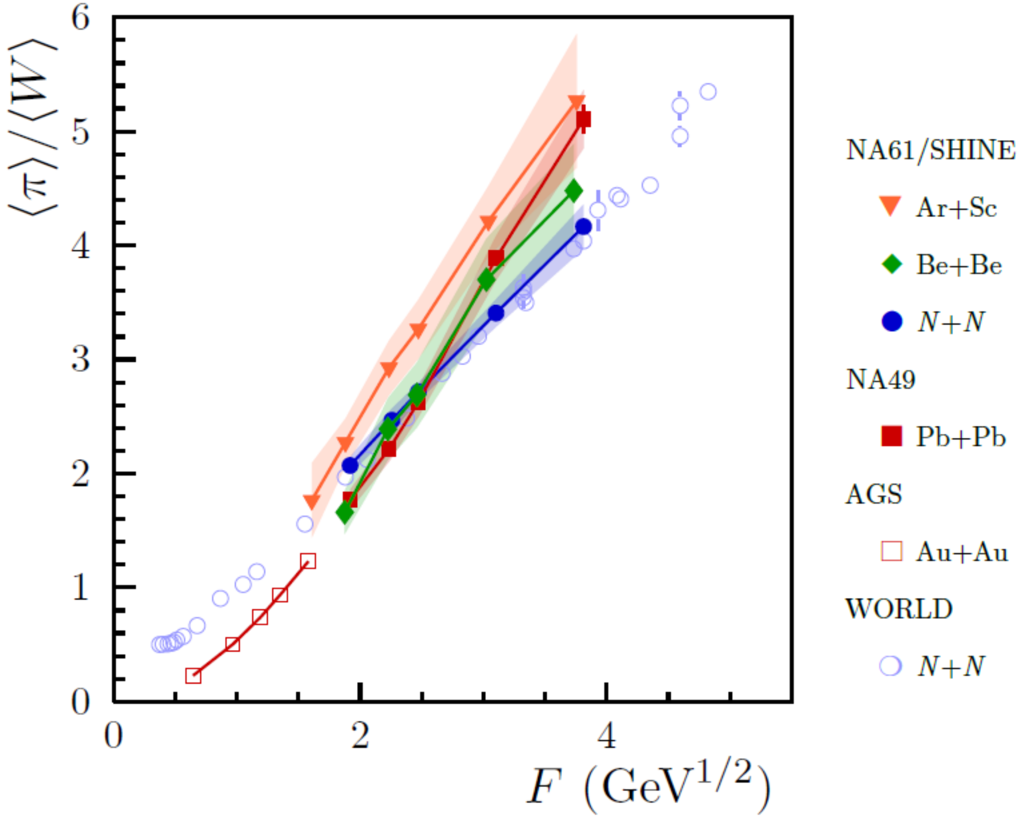
Be+Be collisions and onset of deconfinement



- 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

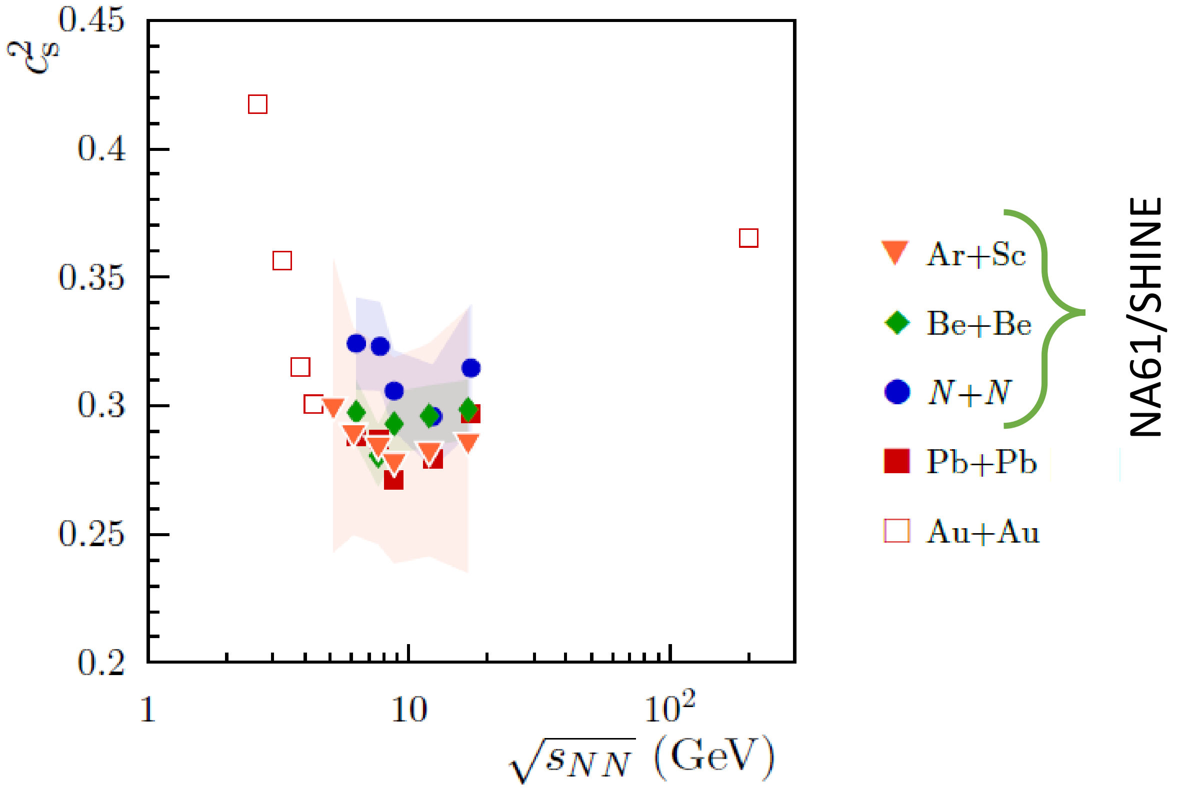


$$F = \left[\left(\sqrt{s_{NN}} - 2m_N\right)^3 / \sqrt{s_{NN}}\right]^{1/4},$$

- 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

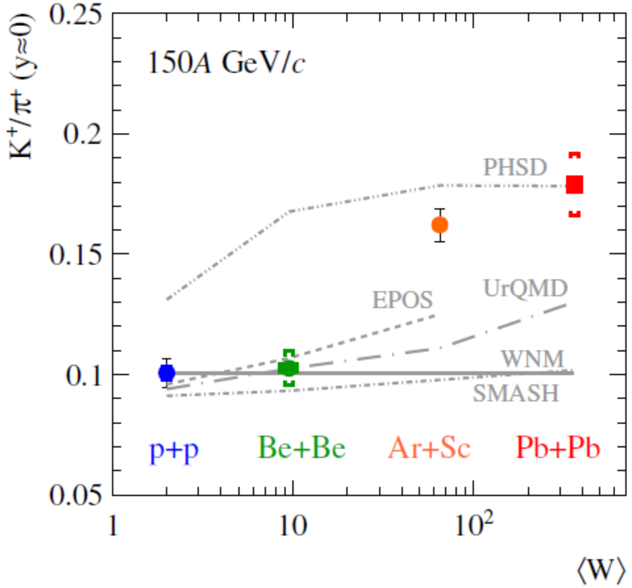
arXiv:2101.08494v2 [hep-ex] 25 Jan 2021

onset of the fireball

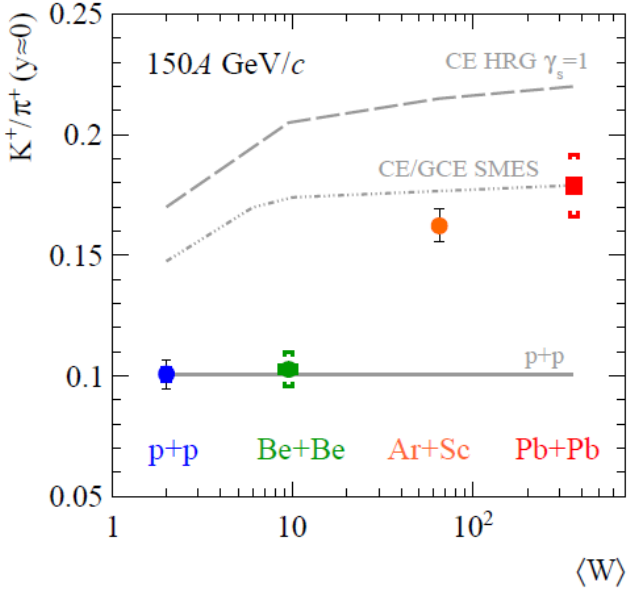
Onset of fireball

K^+/π^+

dynamical models

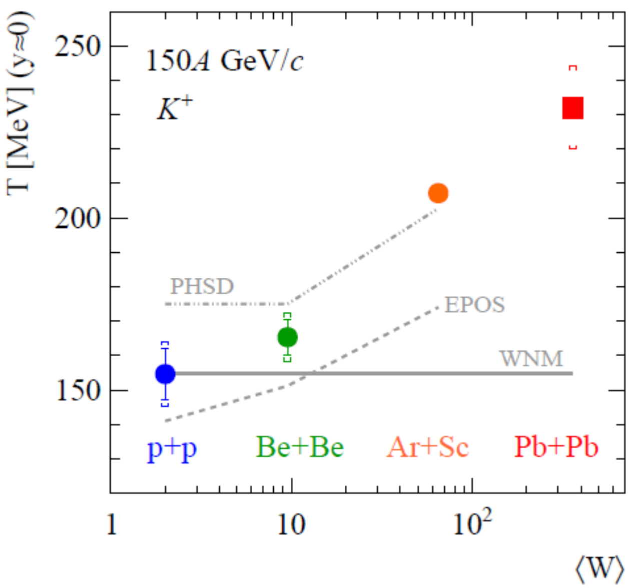


statistical models



T parameter

dynamical models

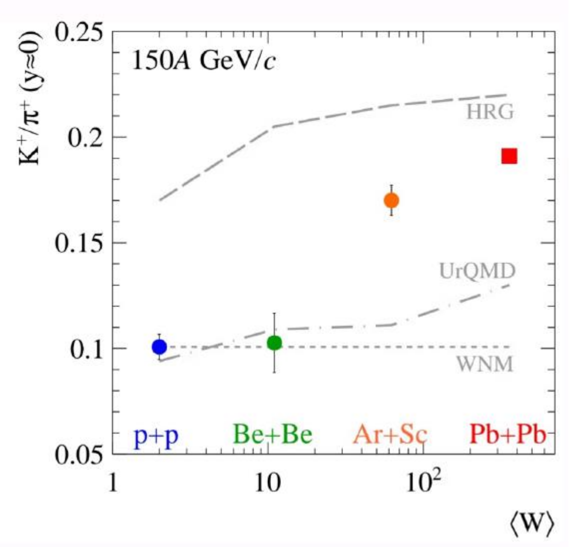


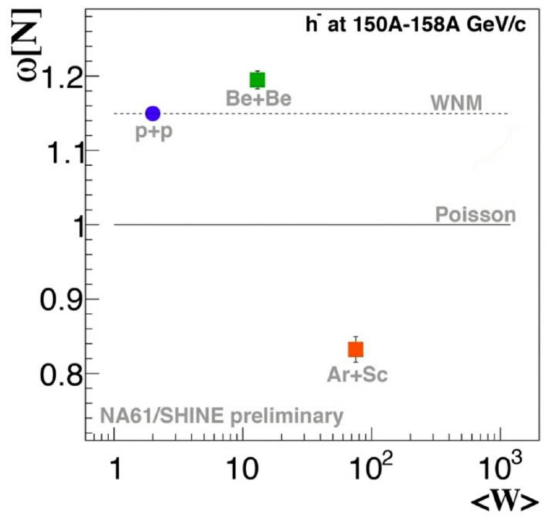
- None of the models reproduce K^+/π^+ ratio or T for whole $\langle W \rangle$ range

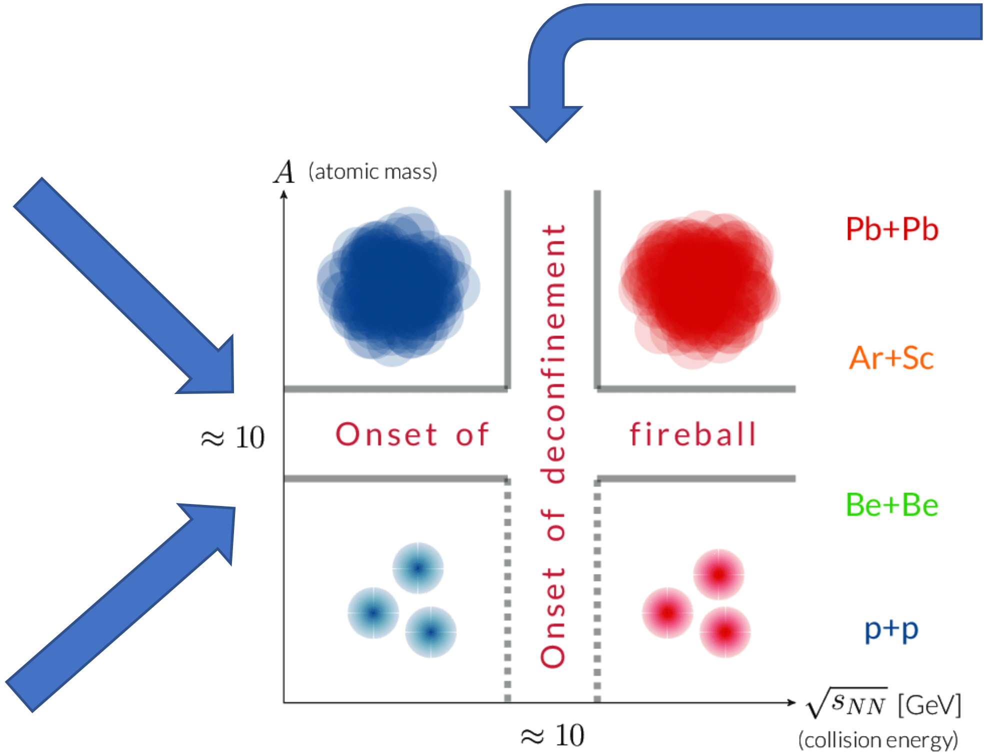
PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private communication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private communication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909
SMES: Acta Phys. Polon. B46 (2015) 10, 1991 - recalculated

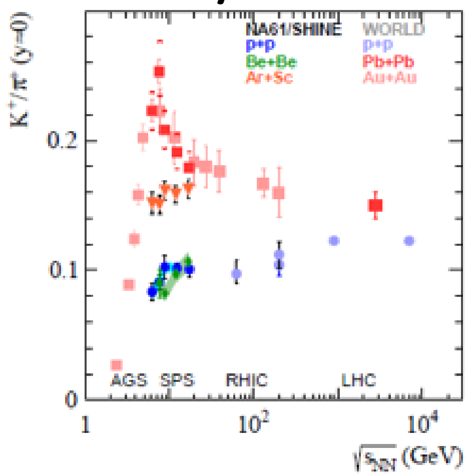
p+p: Eur. Phys. J. C77 (2017) 10, 671
Be+Be: Eur. Phys. J. C81 (2021) 1, 73
Ar+Sc: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C66, 054902 (2002)

Uniqueness of heavy ion results from NA61/SHINE





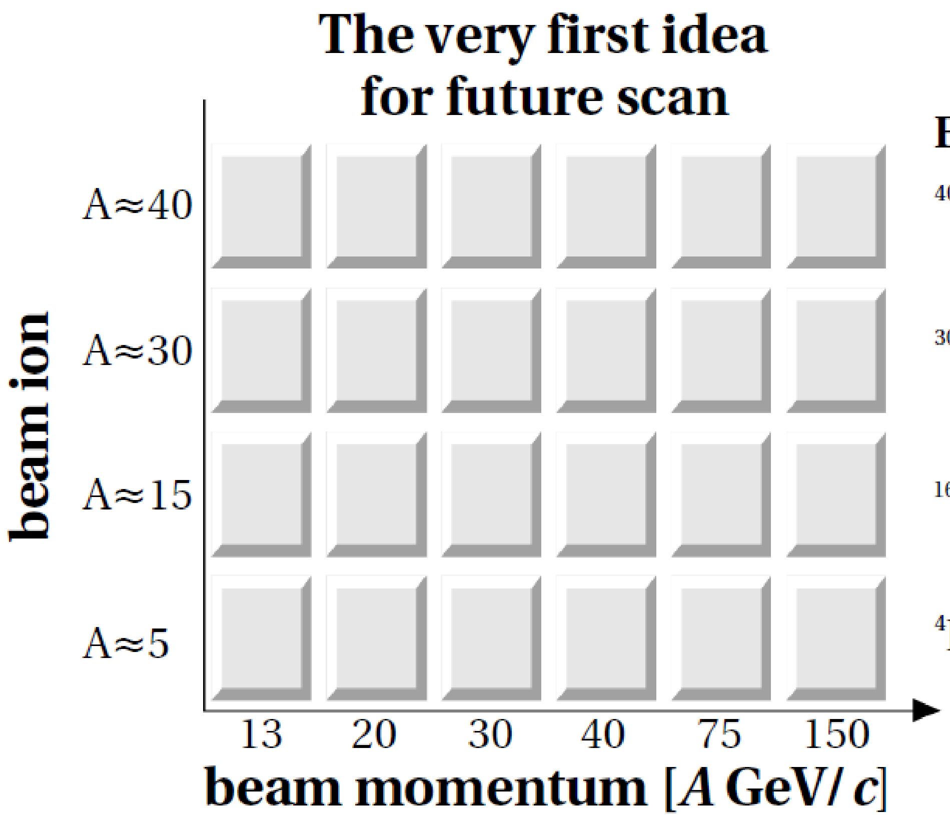




$$p + p \approx Be + Be \quad \neq \quad Ar + Sc$$

- 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

Onset of fireball - measurements after LS3



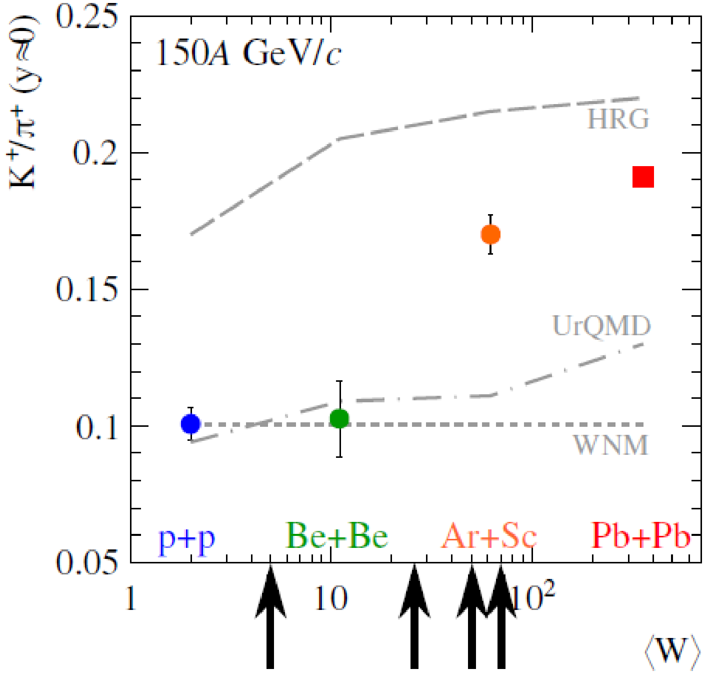
Example ion:

^{40}Ca Synergy with Gamma Factory

^{30}P

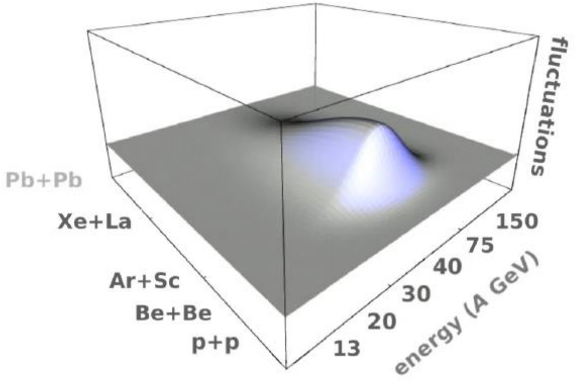
^{16}O Synergy with Cosmic-Ray LHC

^{4}He



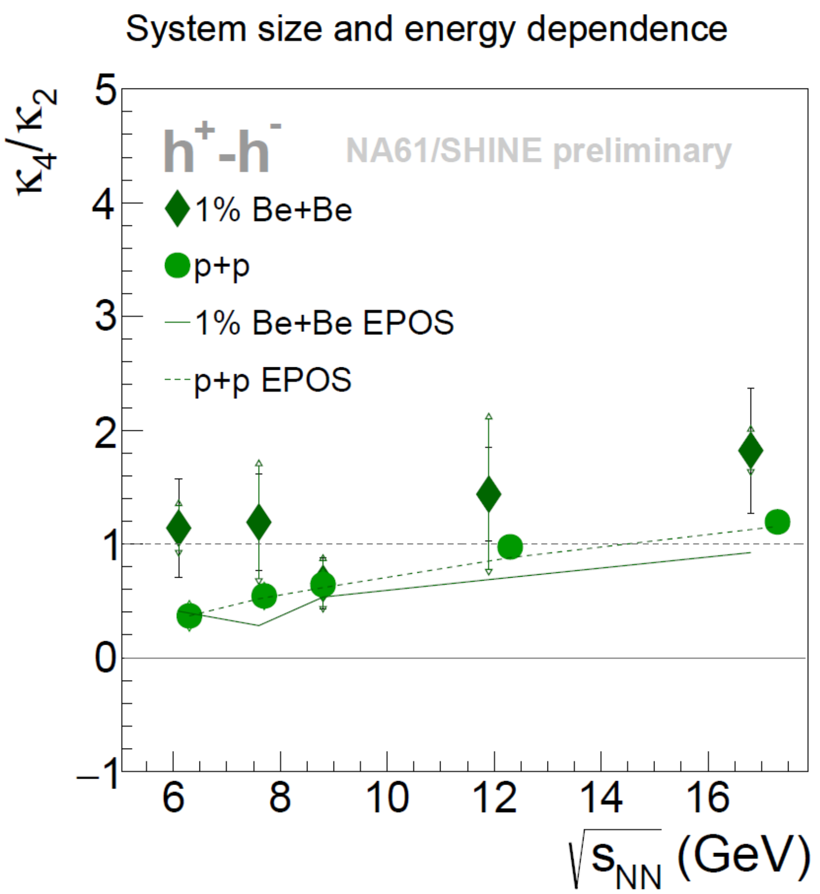
PHYSICAL REVIEW D **60** 114028

Theoretical fluctuations
in presence of critical point



critical point

net-charge fluctuations measured by higher order moments



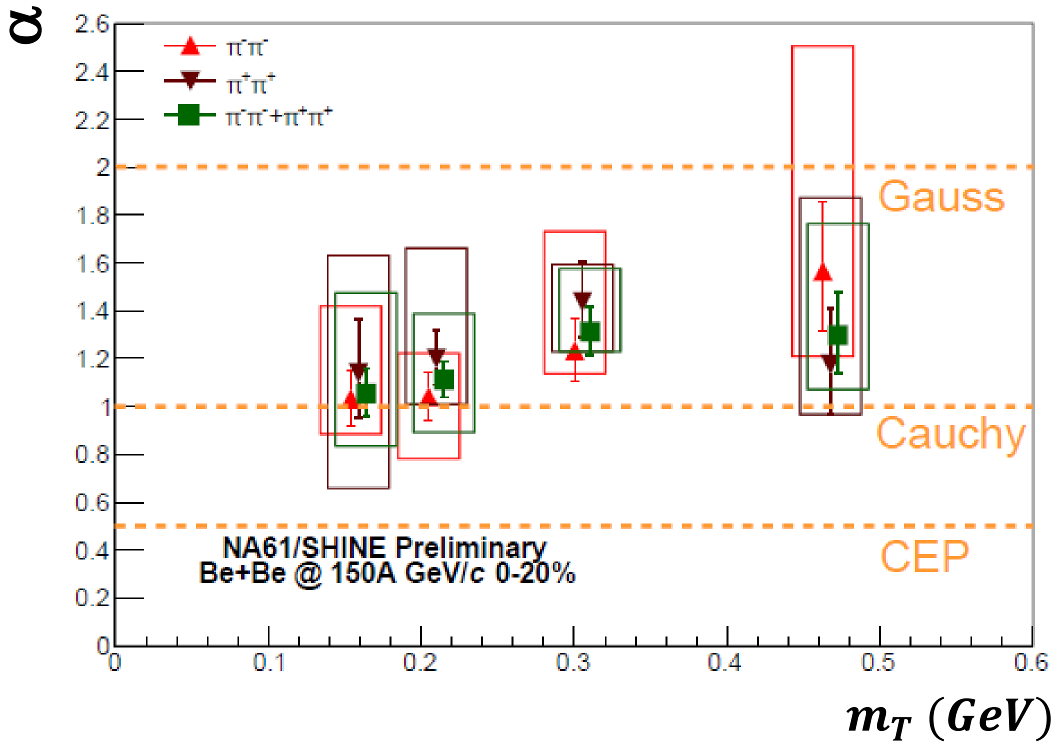
- κ_4/κ_2: p+p≈Be+Be
- EPOS close to the measured data
- No structure indicating critical point

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

N - multiplicity, $\delta N = \langle N - \langle N \rangle \rangle$,
σ - standard deviation, S - skewness
K - kurtosis

two-pion HBT correlation functions

20% Be+Be at 150A GeV/c



Lévy distribution leads to power-law correlation functions

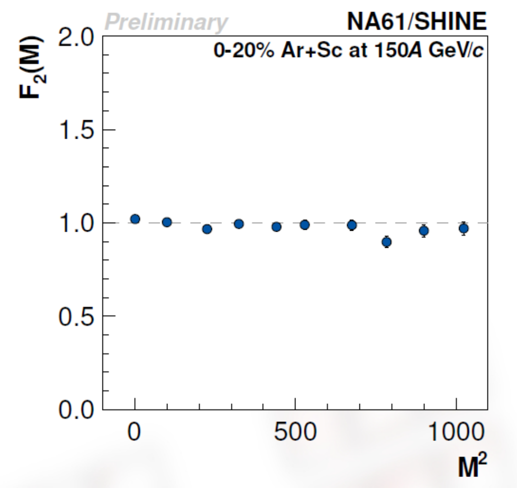
$$C(q) = 1 + \lambda \cdot e^{-(qR)^{\alpha}}$$

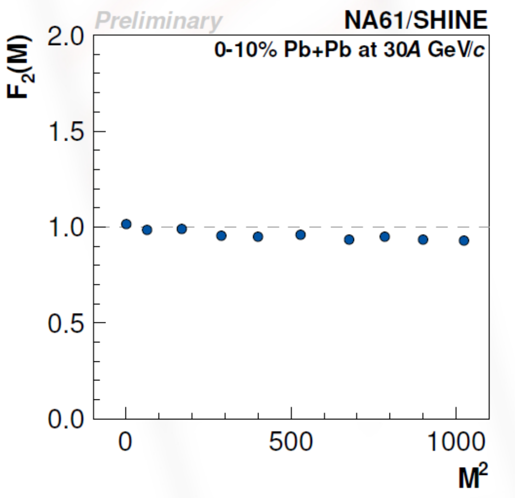
Csörgö et al., EPJC36

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

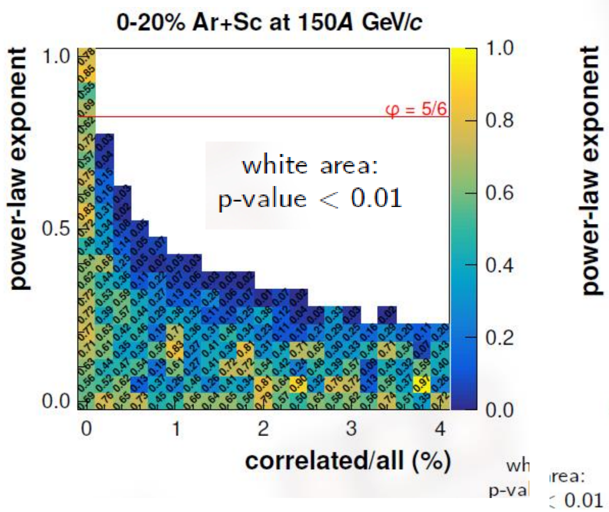
- α between Gaussian or Cauchy shape might be the sign of anomalous diffusion
- α does not indicate the critical point in Be+Be (far above 0.5)

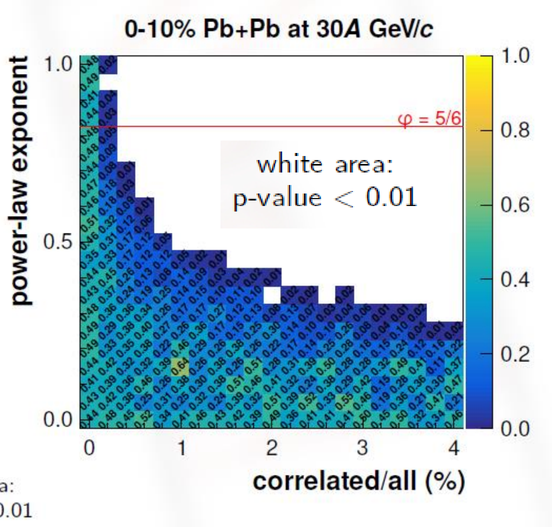
second scaled factorial moments of protons - intermittency analysis





- 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

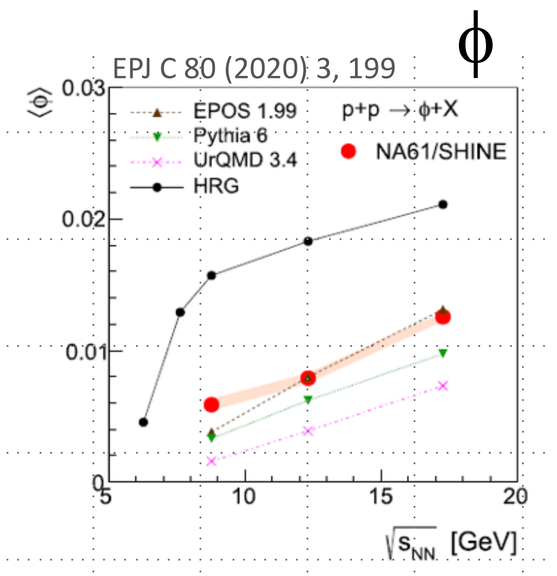


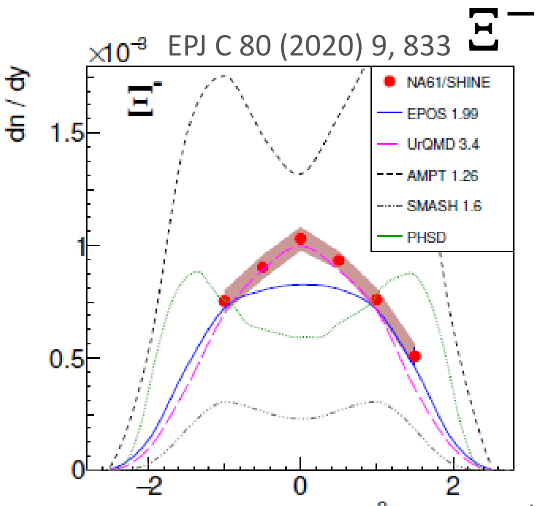


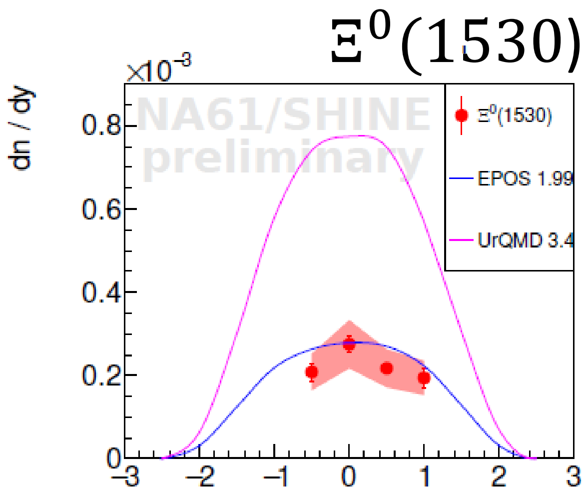
- Exclusion plot
  - predictions for simple power-law model parameters
  - The intermittency index ϕ_2 (power-law component) for a system freezing out at the QCD critical endpoint is expected to be ϕ_2 = 5/6

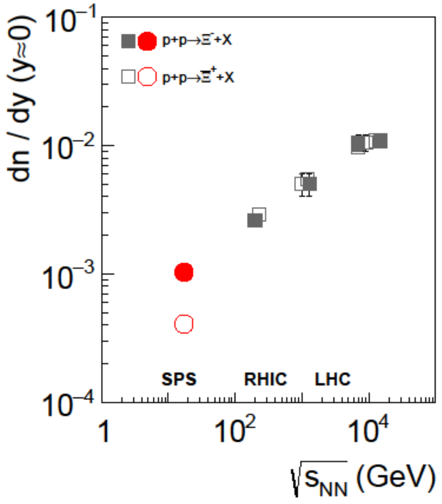
strangeness production in p+p at 158 GeV/c

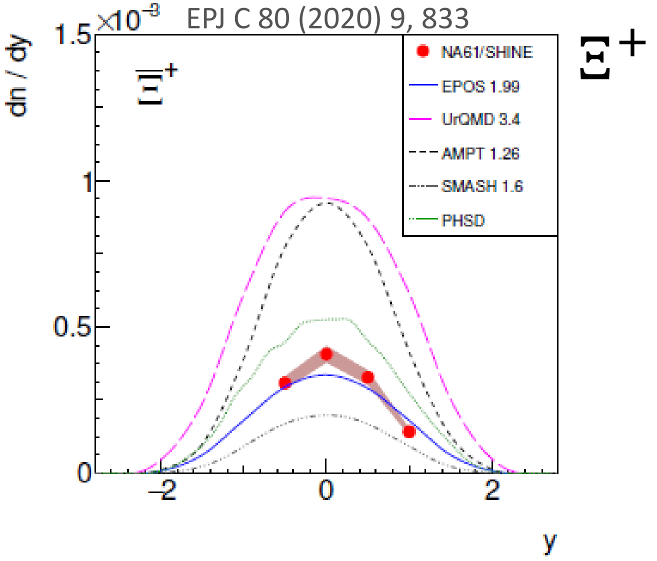
strangeness production in p+p at 158 GeV/c

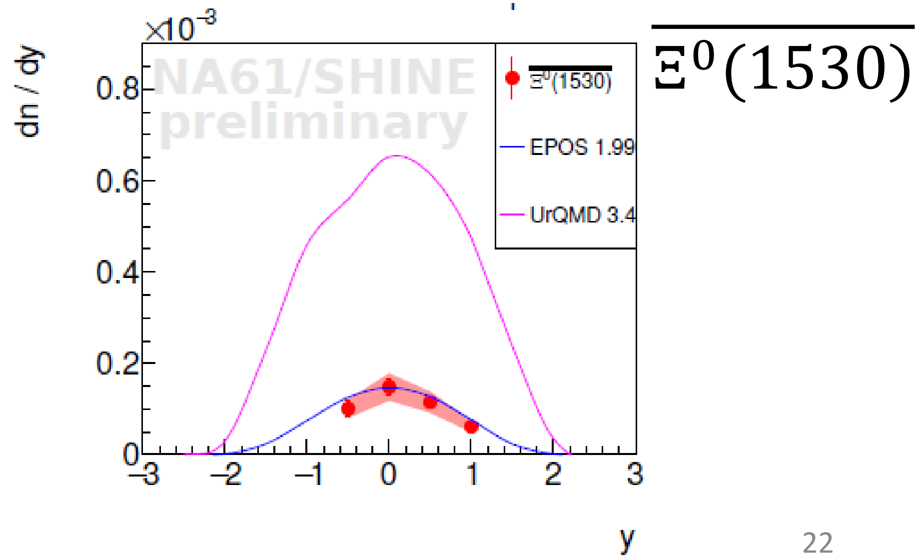










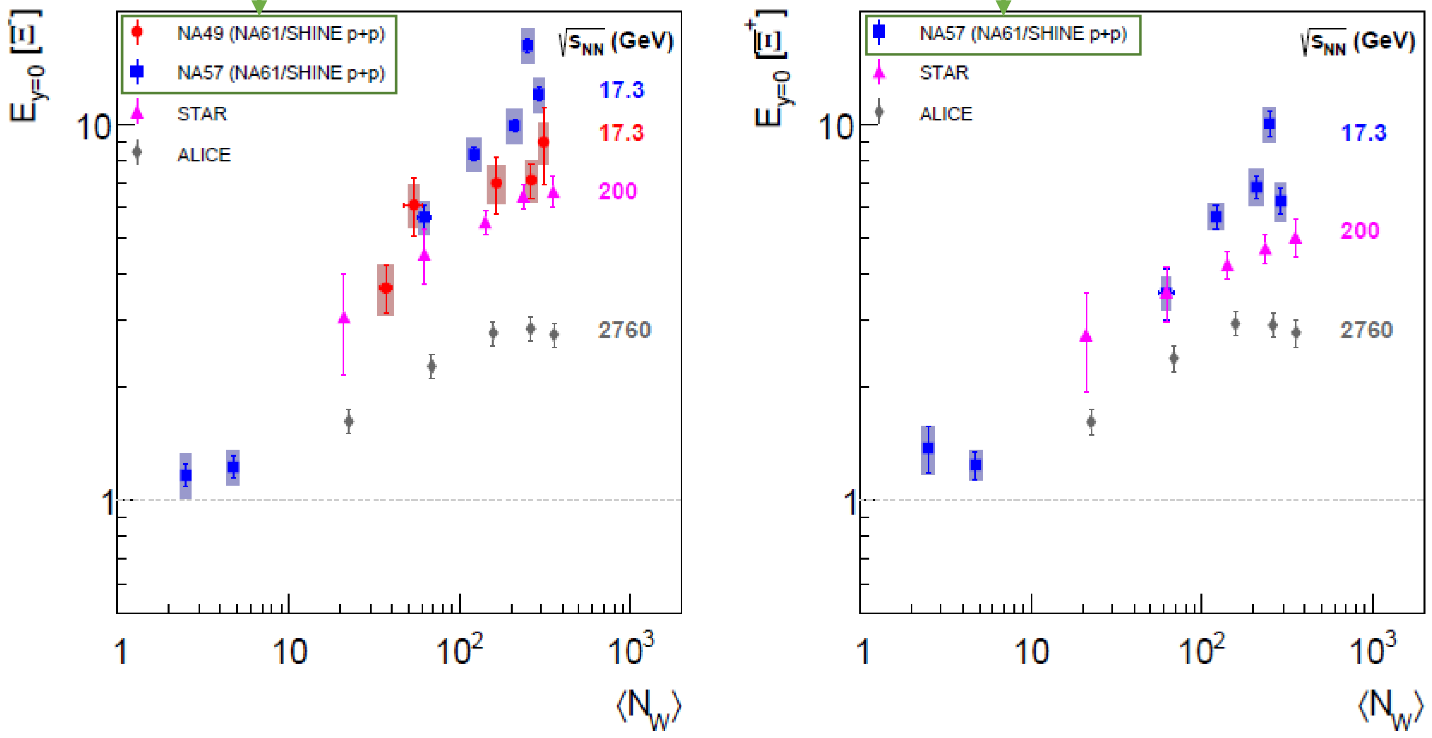


Present theoretical models do not describe the NA61/SHINE results on strange particles production

Details: M. Kuich talk

strangeness enhancement factors

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



The strangeness enhancement factor E

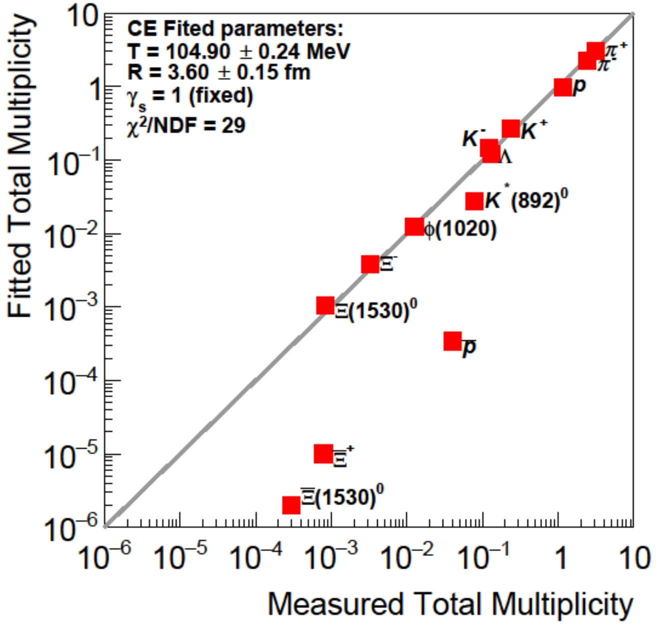
$$E = \frac{2}{\langle N_W \rangle} \frac{dn/dy\,(A+A)}{dn/dy\,(p+p)},$$

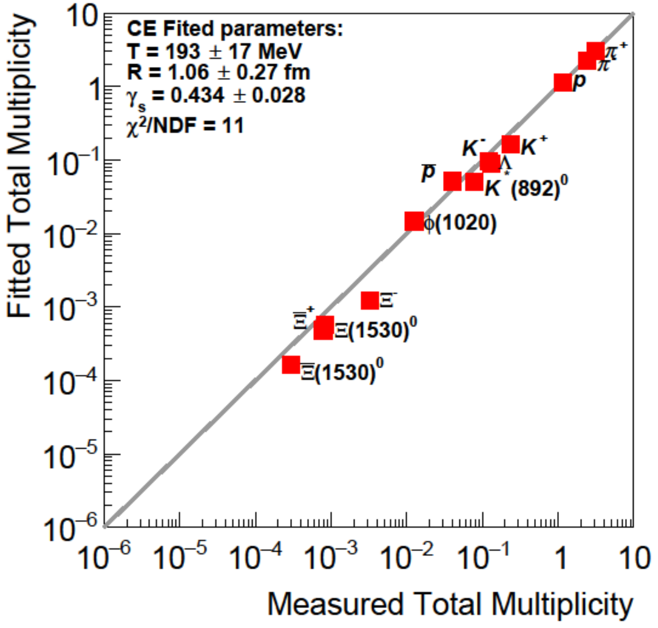
Nucl. Phys. B111 (1976) 461

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

EPJ C 80 (2020) 9, 833

HRG model in the CE formulation and p+p data



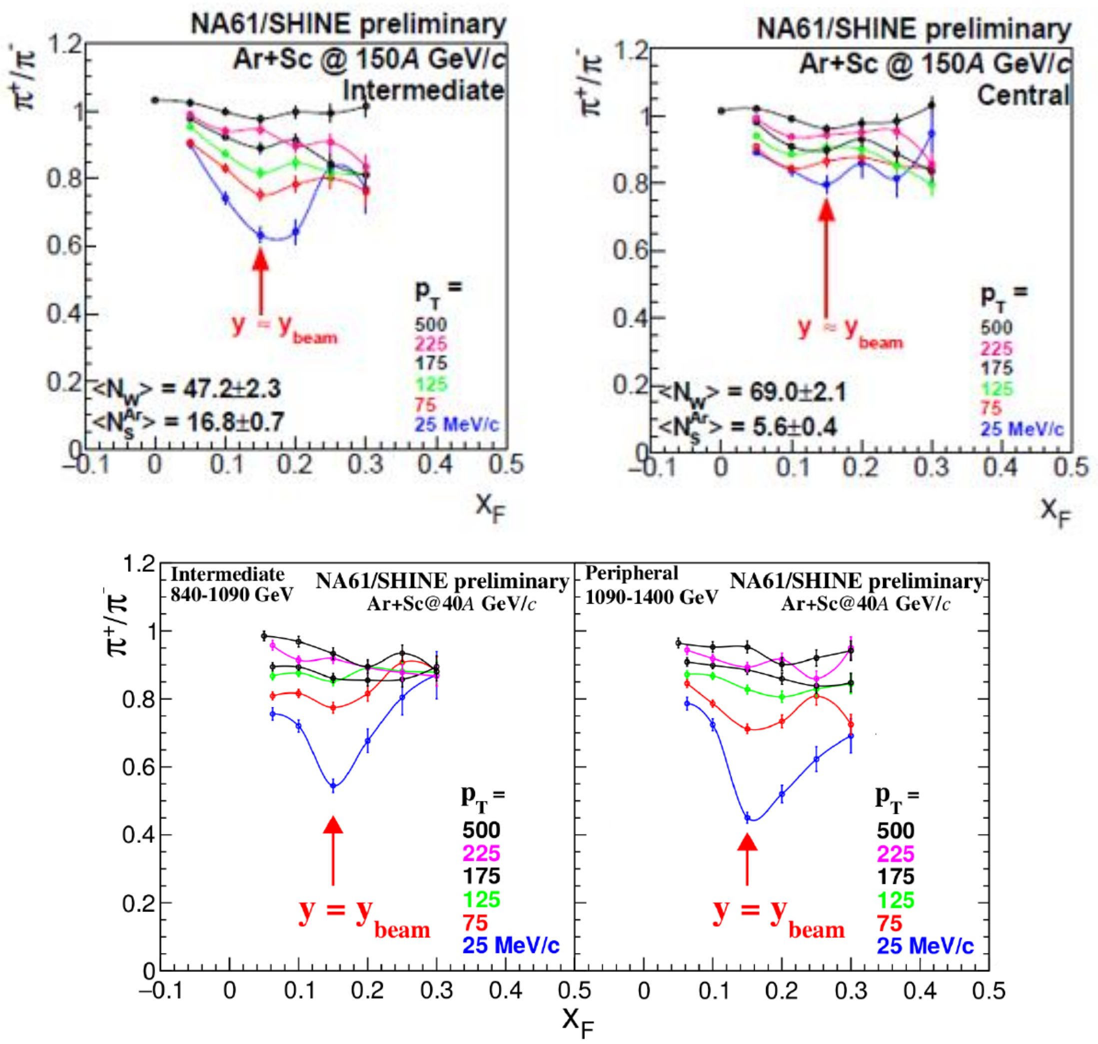


- Fit by different variants of the HRG model (THERMAL-FIST1.3 Comput.Phys.Commun.244(2019)295):
  - **Canonical Ensemble with fixed γ_s=1**
  - **Canonical Ensemble with fitted strangeness saturation parameter γ_s**

- 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

electromagnetic effects

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



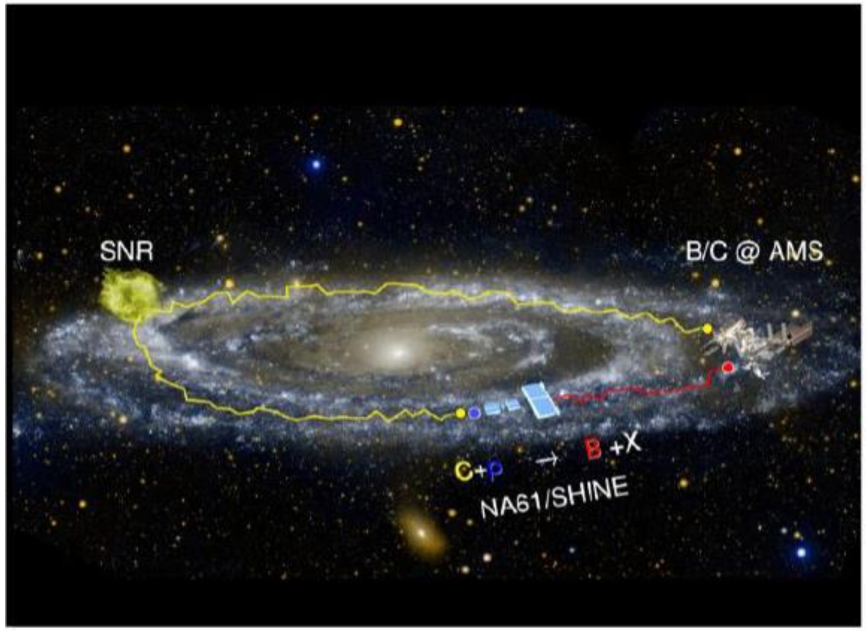
- Charged pion trajectories can be modified by electromagnetic interactions (repulsion for π^+ and attraction for π^-) with the spectators → the effect is sensitive to the space-time evolution the system

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
- First time ever observation of the spectator-induced electromagnetic effects in small systems Ar+Sc at 150*A* GeV/c and 40*A* GeV/c

Cosmic ray and neutrino physics program

Reference measurements: Nuclear fragmentation cross section for cosmic ray experiments



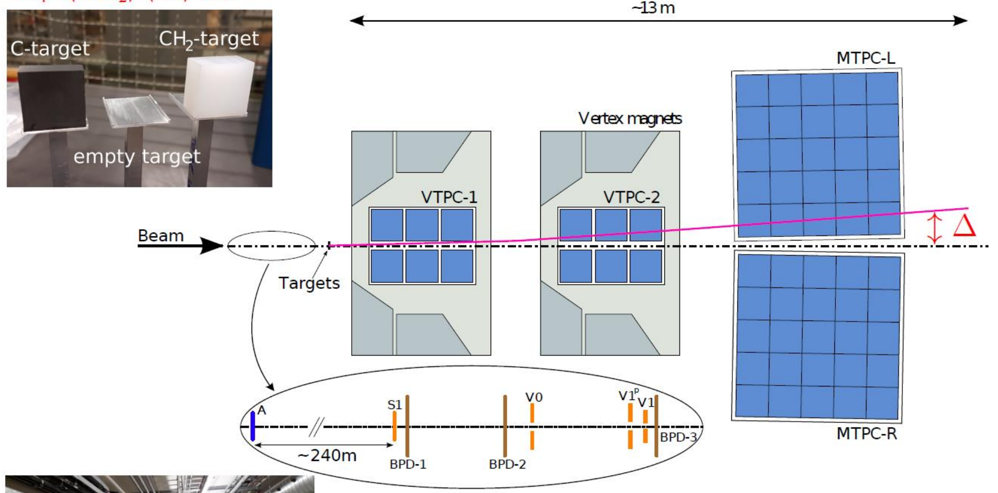
- Primary cosmic rays from supernova remnants
- Secondary cosmic rays from interactions with interstellar matter during propagation e.g.
  $^{12}C + p \xrightarrow{frag.} B + X$
  $^{12}C + p \xrightarrow{frag.} {}^{11}C + p \xrightarrow{decay} B + Y$
- Primary-to-secondary ratios (e.g. B/C) → traversed mass density
- Unstable-to-stable ratios (e.g. $^{10}Be/^{9}Be$) → traversed distance
- Important for the understanding of origin of Galactic cosmic rays and backgrounds for DM searches

Understanding of cosmic ray propagation limited by uncertainties of fragmentation cross sections

NA61/SHINE will significantly reduce the uncertainties (from 20% to 0.5%)

Test measurement - nuclear fragmentation cross section

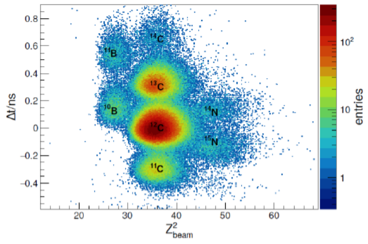
"C+p = (C+CH$_2$) - (C+C) - OUT"



ToF(A to S1) + dE/dx(S1) → (A, Z^2)$_{beam}$

Δ + dE/dx(MTPC) → (A, Z^2)$_{fragment}$

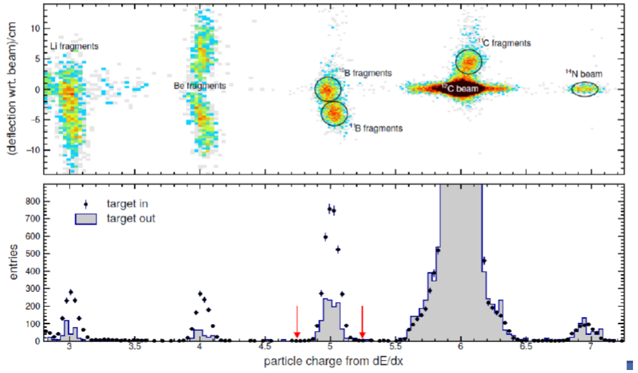
^{12}C beam:



^{12}C purity: 99.2%

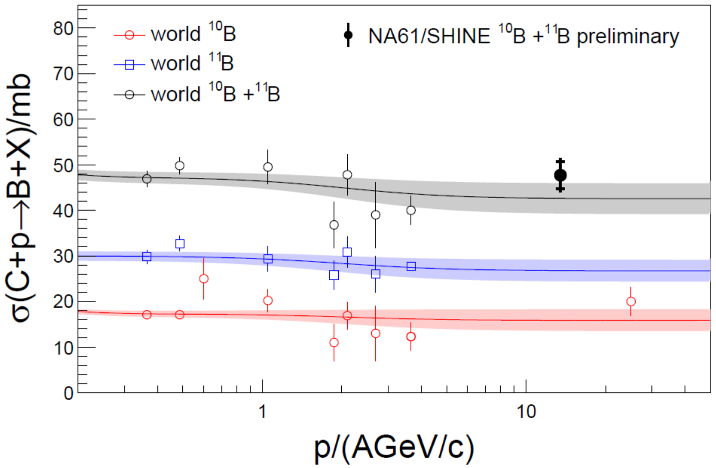
B contamination: < 0.1%

Identification of Isotopes Produced in Target



$$\sigma(^{12}\mathrm{C}+\mathrm{p}\rightarrow^{10}\mathrm{B}+X)+\sigma(^{12}\mathrm{C}+\mathrm{p}\rightarrow^{11}\mathrm{B}+\mathrm{X}) =$$

$$47.7 \pm 3.0\ (\mathrm{stat.}) \pm 2.3\ (\mathrm{syst.})\ \mathrm{mb}$$

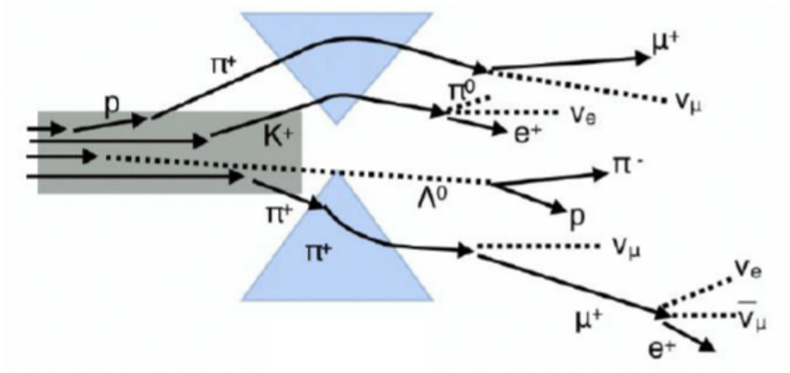


Reference measurements: Hadron production for neutrino experiments

Proton beam

Jungle of h+A interactions and decays

Neutino beam



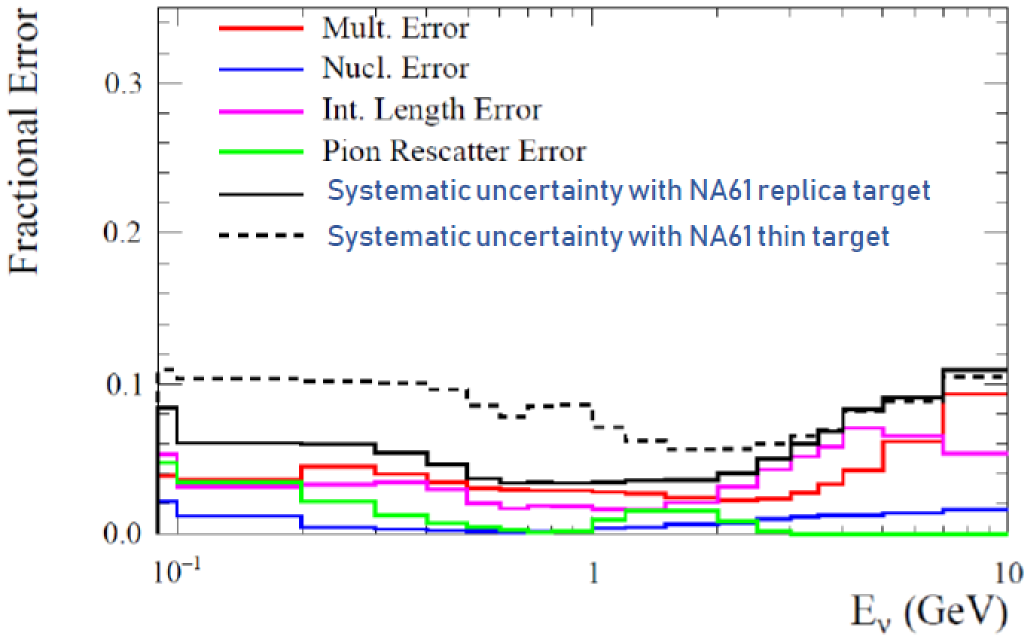
- Further improvement of the precision of measurements for the currently used T2K replica target,
- Measurements for a new target material (super-sialon) for T2K-II and Hyper-Kamiokande,
- Study of the possibility of measurements with beams <12 GeV/c for improved predictions of atmospheric and accelerator ν fluxes,
- Ultimate hadron production measurements with prototypes of Hyper-Kamiokande and DUNE targets.

NA61/SHINE will decrease systematic uncertainties on neutrino fluxes (for T2K-II, Hyper-K from 10% to 3%)

Neutrino-related accomplishments from NA61/SHINE first phase

NA61/SHINE took thin and thick target data with 31 GeV/c protons specifically for T2K in 2007, 2009 and 2010

T2K flux predictions (Phys.ReV.D87 2013 no.1, 012001) currently uses thin target data and incorporation of thick target data is in progress



2016/17 data collection:

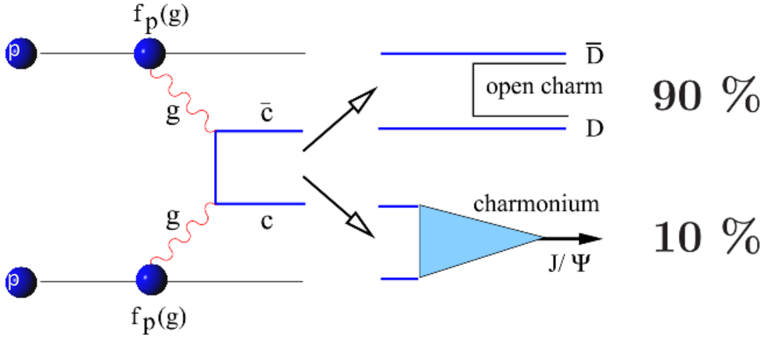
- Thin target measurements with p and π beams at C, Be, Al targets at 30, 60 and 120 GeV/c

2018 data collection:

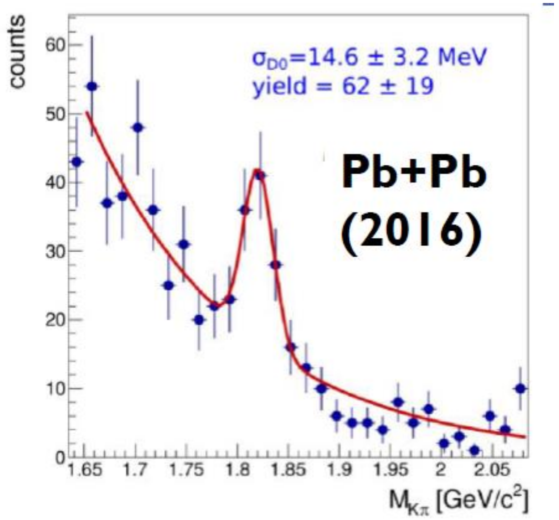
- 120 GeV/c p on NOvA replica target provided by Fermilab
- 18M events recorded

NA61/SHINE beyond LS2

charm production and the onset of deconfinement

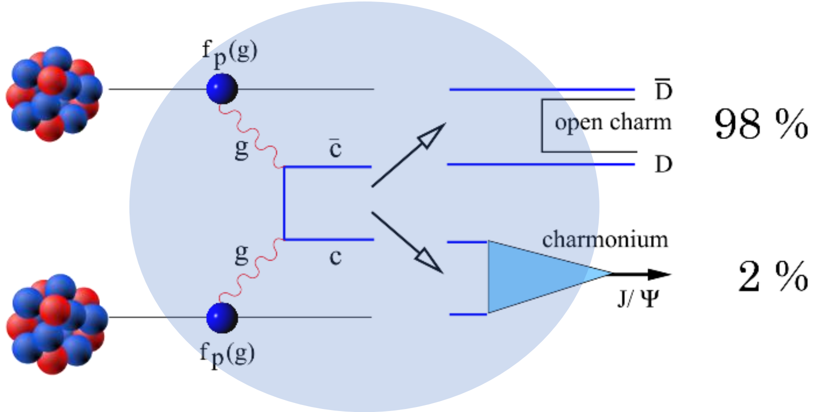


Open charm and J/ψ production
within Matsui-Satz model
[PL B178 416]



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?

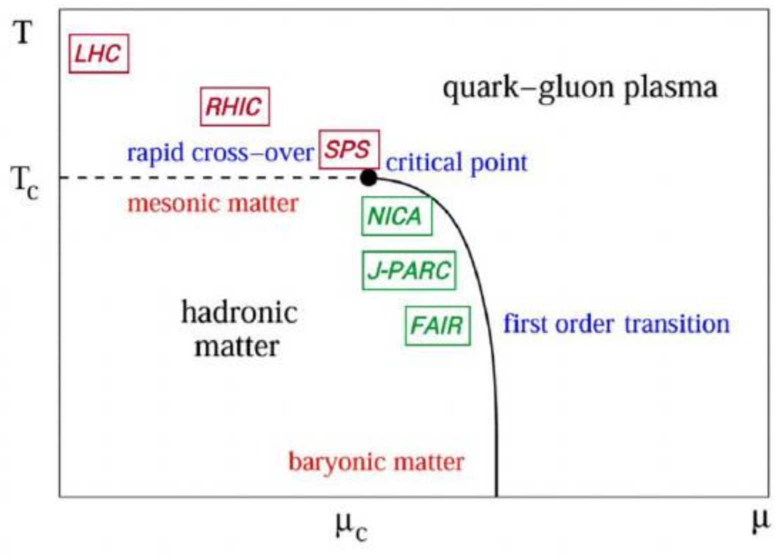
Medium reduces probability of J/ψ production

$$P(c\bar{c} \to J/\psi) \equiv \frac{< J/\psi >}{< c\bar{c} >} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$$

$$P_{\text{vacuum}}(c\bar{c} \to J/\psi) \quad > \quad P_{\text{medium}}(c\bar{c} \to J/\psi)$$

Uniqueness of NA61 open charm program

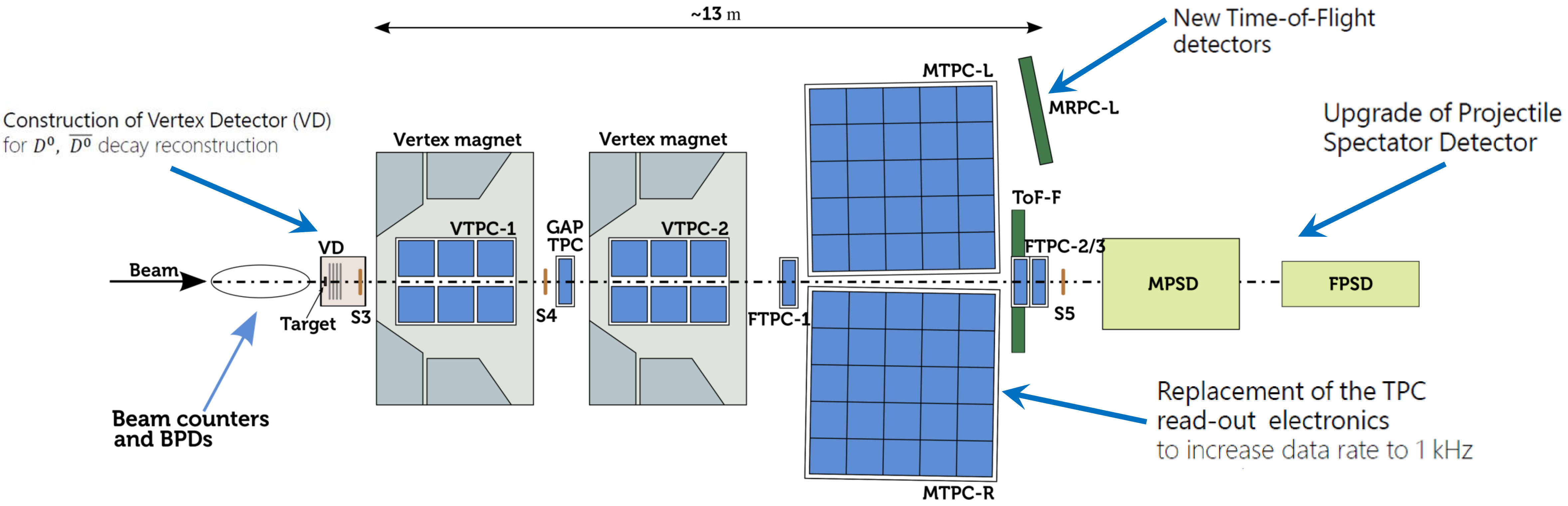
Landscape of present and future heavy ion experiments



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

Detector upgrade during LS2



Summary

- Measurements within the 2D scan in system size and the collision energy are completed
- 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
- 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- 2024

Thank You

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second scaled factorial moments - intermittency analysis

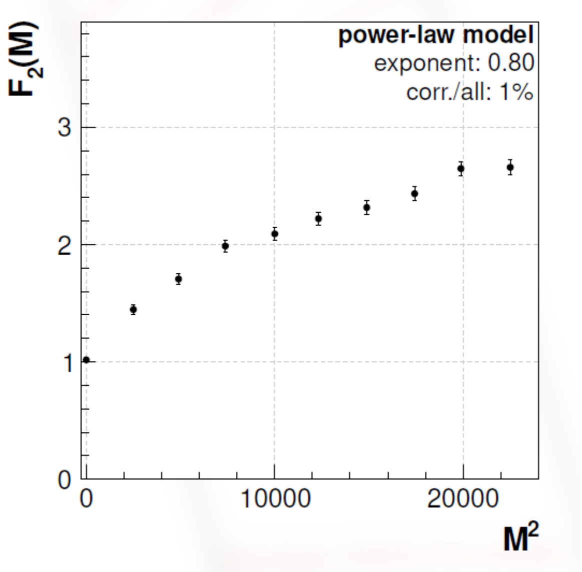
$$F_2(\delta) = \frac{\left\langle \frac{1}{M}\sum_{i=1}^{M} n_i(n_i-1)\right\rangle}{\left\langle \frac{1}{M}\sum_{i=1}^{M} n_i\right\rangle^2}$$

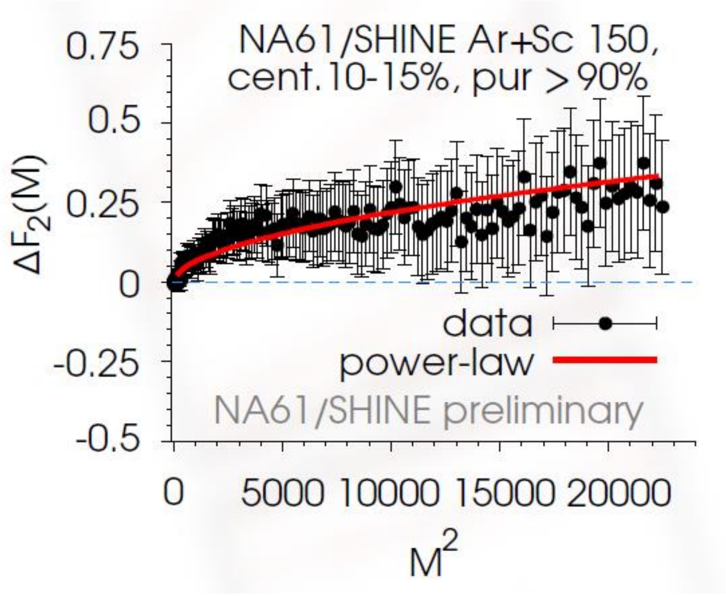
δ - size of each of the $M = \frac{\Delta}{\delta}$ subdivision intervals of the momentum phase-space region Δ

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.