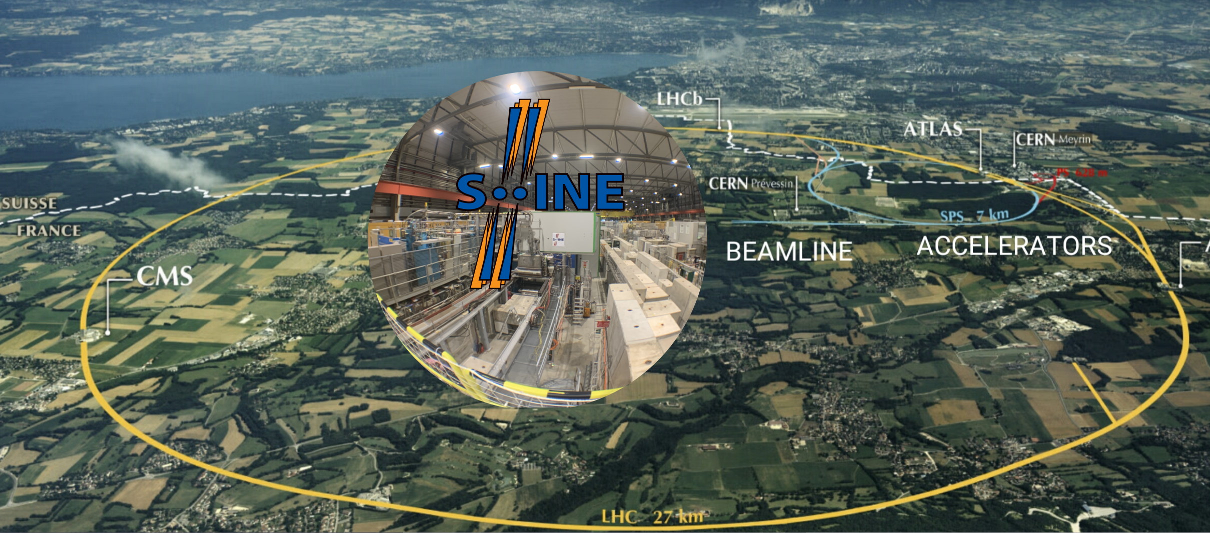
Recent results from NA61/SHINE on the onset of deconfinement studies and particle production

Maja Maćkowiak-Pawłowska
for the NA61/SHINE Collaboration

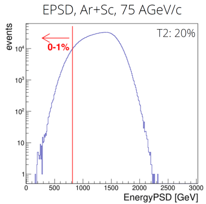
WARSAW UNIVERSITY OF TECHNOLOGY

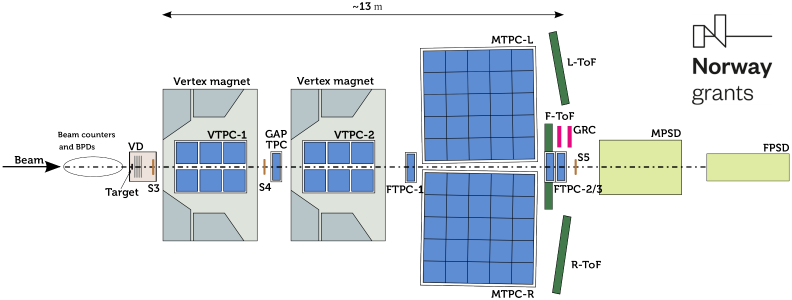
NA61/SHINE - UNIQUE MULTIPURPOSE FACILITY:
Hadron production in hadron-nucleus and nucleus-nucleus collisions at high energies



NA61/SHINE detector setup

- General purpose hadron spectrometer
- Fixed target configuration $\longrightarrow$ large acceptance of produced charged particle (up to 50%) with high tracking efficiency $p_T \gtrsim 0$
- Precise centrality selection based on forward energy measured in Projectile Spectator Detector





Norway grants

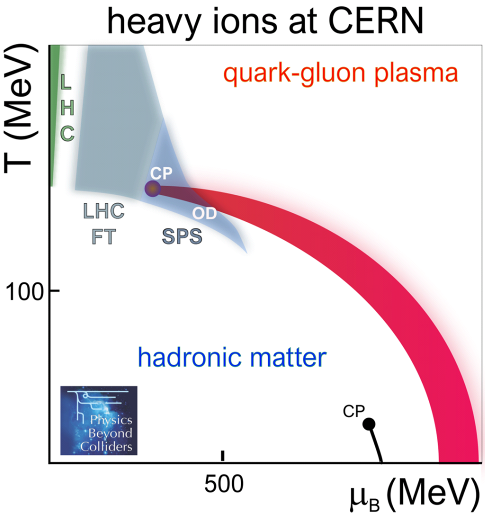
New stage of SHINE!

Setup upgraded in 2022 by set of new detectors as well as new electronics which allow an increase of data rate up to 1.7 kHz

NA61/SHINE program

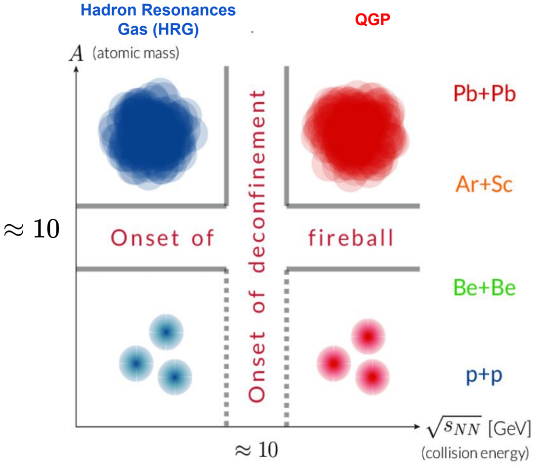
SHINE stands for **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment

- **Strong interactions**
  - **Onset of deconfinement & onset of fireball**
  - **Properties of QCD matter (EoS)**
  - QCD critical point – see Haradhan A. poster
- **Neutrino physics**
  - Hadron production cross sections for neutrino flux predictions
- **Cosmic-rays**
  - Hadron production cross sections for air-shower modelling as well as fragmentation cross-section



This talk focuses on the strong-interactions program

Onset of deconfinement & onset of fireball

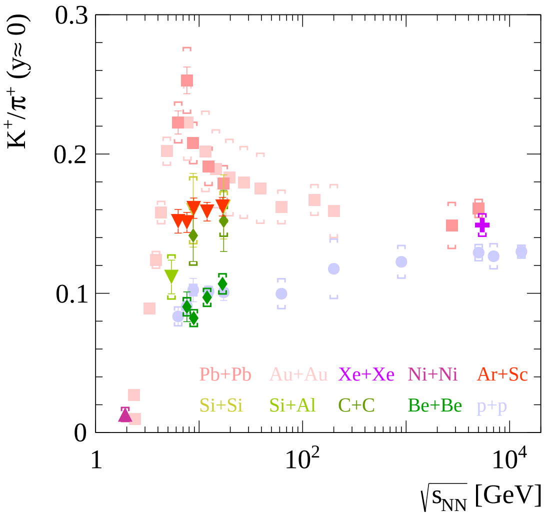


- Onset of deconfinement

  QGP formation by heating up the QCD matter with increasing collision energy
  - temperature (plateau-like structures)
  - increase of entropy (new degrees of freedom)
  - strangeness to entropy (non-monotonic energy dependence)
- Onset of fireball
  QGP formation as a large equilibrated cluster of the QCD matter with increasing size of colliding nuclei

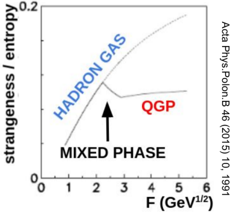
Requires two-dimensional scan in collision energy and system size

Onset of deconfinement: horn



p+p: EPJC 77 (2017) 10,671; Be+Be: EPJC 81 (2021) 1,73
Ar+Sc: M. Kuich, SQM'21; Pb+Pb: PRC 66 (2002) 054902

SMES model

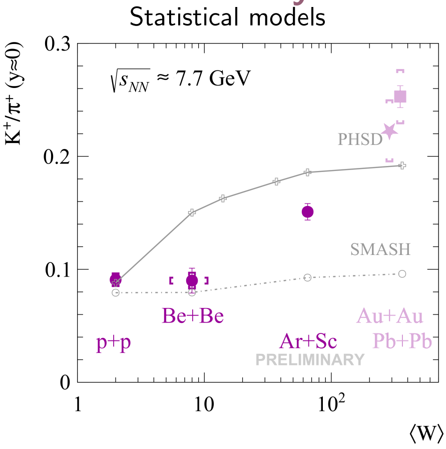


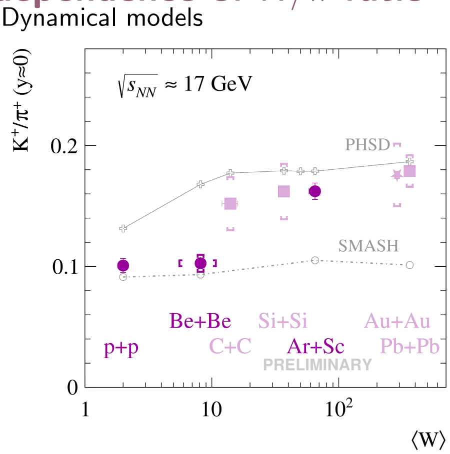
Acta Phys. Polon. B 30 (1999), 2705.

$$F = \frac{(\sqrt{s_{NN}} - 2m_N)^{3/4}}{(\sqrt{s_{NN}})^{1/4}} \approx s_{NN}^{1/4}$$

- Rapid change of K^+/π^+ in Pb+Pb collisions indicated onset of deconfinement in the SPS energy range
- No *horn* structure in Ar+Sc collisions $\longrightarrow$ onset of fireball?
- Be+Be very close to $p + p$

Onset of fireball: system size dependence of K/π ratio



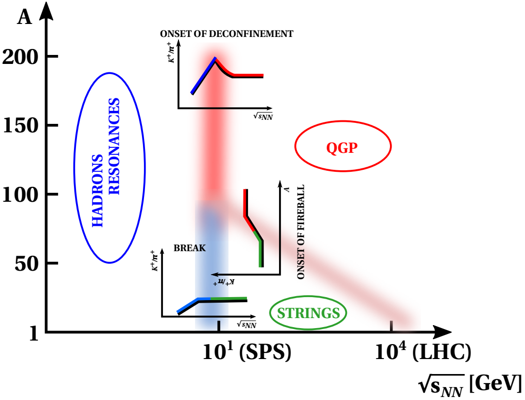


None of the models reproduces K^+/π^+ ratio in the whole $\langle W \rangle$ range

PHSD: EPJA 56 (2020) 9, 223
SMASH: J.Phys.G 47 (2020) 6, 065101

p+p: EPJC 77 (2017) 10,671
Be+Be: EPJC 81 (2021) 1,73
Ar+Sc: M. Kuich, SQM'21
Pb+Pb: PRC 66 (2002) 054902

Possible explanations - references



Onset of strings:

- PHSD: PRC, 78, 034919, 200; and NPA, 831, 215–242, 2009
- SMASH: PRC, 94, 5, 054905, 2016 and J. Phys. G, 47, 6, 065101, 202
- UrQMD: Prog. Part. Nucl. Phys.,41,255–369, 1998 and NPA, 936,1–5, 2015

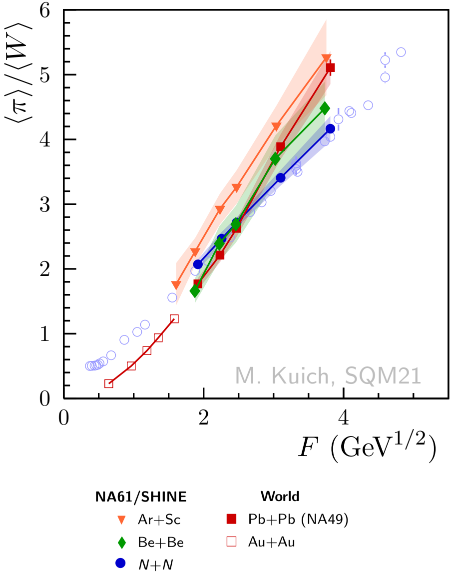
Onset of deconfinement:

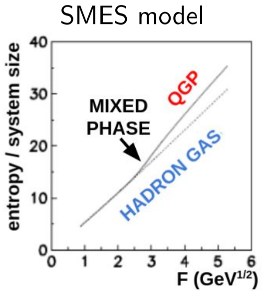
- SMES: Acta Phys.Polon. B30 (1999) 2705; PHSD: PRC, 78, 034919, 200; and NPA, 831, 215–242, 2009

Onset of QGP fireball:

- colour ropes: NPB, 245, 449–468, 1984.
- string fusion: NPB, 390, 542–558, 1993; PLB, 287, 154–158, 1992; EPJA, 51, 4, 44, 2015; Phys. Rep., 599, 1–50, 2015; and PRD, 103, 9, 094029, 2021.
- core fragmentation: PRL., vol. 98, p. 152301, 2007.
- string melting: PRC, 72, 064901, 2005.
- percolation: EPJC, 32, 547–553, 2004; and PLB, 640, 96–100, 2006.
- AdS/CFT duality: PRC, 90, 1, 014901, 2014; PRD, 90, 2, 025031, 2014; PRC, 92, 1, 014011, 2015

Onset of deconfinement/fireball: kink

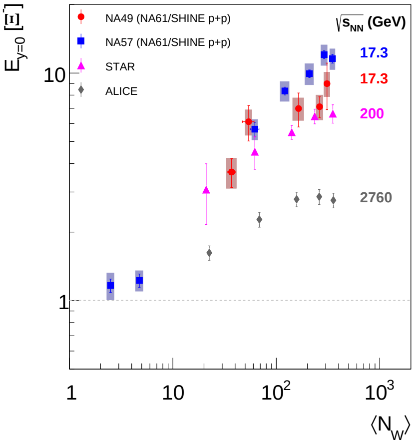




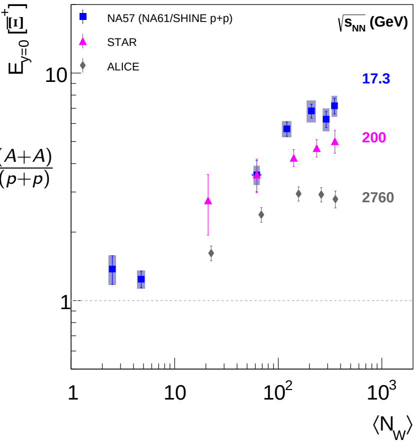
$$F = \frac{(\sqrt{s_{NN}} - 2m_N)^{3/4}}{(\sqrt{s_{NN}})^{1/4}} \approx s_{NN}^{1/4}$$

- Entropy to system's volume should increase when the ndf increases ($\sim ndf^{1/4}$)
- Ar+Sc systematically higher than other systems
- Ar+Sc close to Pb+Pb at higher energies
- Not conclusive with current data uncertainties

Onset of deconfinement: strangeness enhancement factors



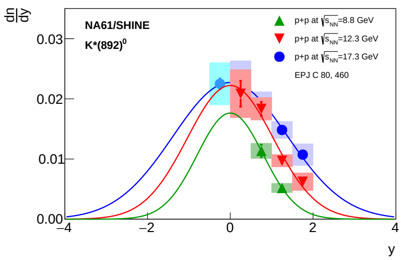
$$E = \frac{2}{\langle N_W \rangle} \frac{dn/dy(A+A)}{dn/dy(p+p)}$$



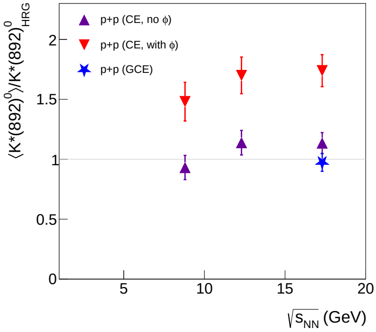
The enhancement based on the new Ξ reference from NA61/SHINE

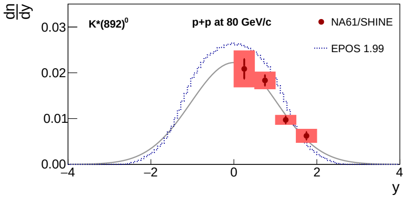
Eur.Phys.J.C 80 (2020) 9, 833; Nucl. Phys. B111 (1976) 461; J. Phys. G 32 (2006) 427-442

K* in p+p at 40-158 GeV/c



Eur. Phys. J. C (2022) 82:322





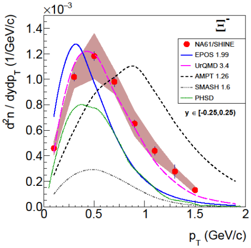
Ratio of K* to K$^-$/K$^+$ sensitive to freeze-out and properties of hadron phase in A+A (p+p - reference):

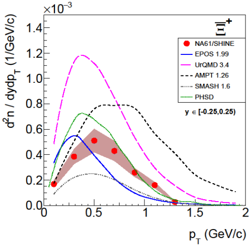
$$\frac{K^*}{K}|_{kinetic}[A+A] = \frac{K^*}{K}|_{chemical}[p+p]$$

Ratio well fitted by GCE whereas CE fits only with ϕ excluded.

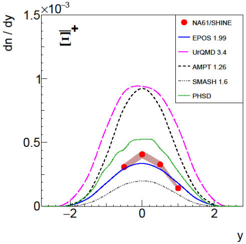
Ξ in p+p

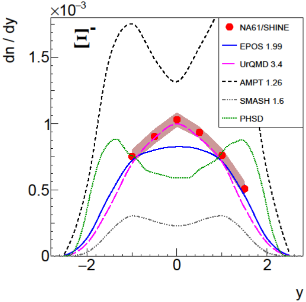
Many transport models fail to describe NA61/SHINE results on Ξ production in p+p

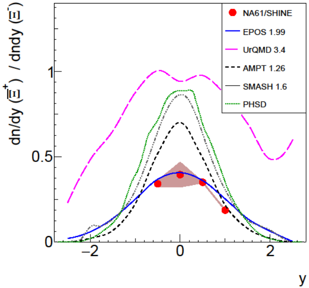




NA61/SHINE, Eur.Phys.J.C 80 (2020) 9, 833

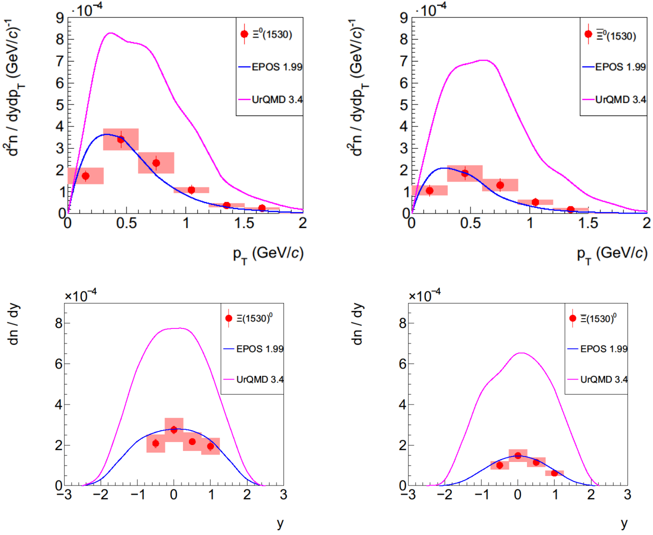






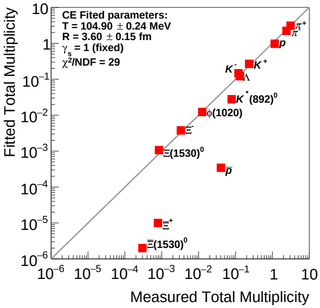
$\Xi(1530)^0$ in p+p

Considerable differences between models. Data ($\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$) is described by EPOS but not UrQMD.

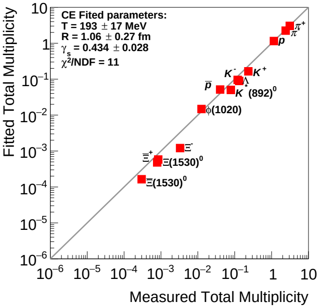


Eur.Phys.J.C 81 (2021) 10, 911

HRG model in the CE formulation and p + p data



Canonical Ensemble with fixed $\gamma_S = 1$

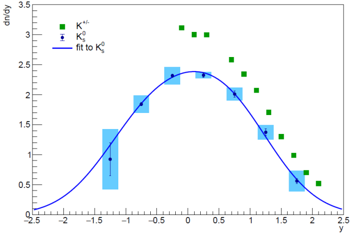


Canonical Ensemble with fitted strangeness saturation parameter γ_S

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

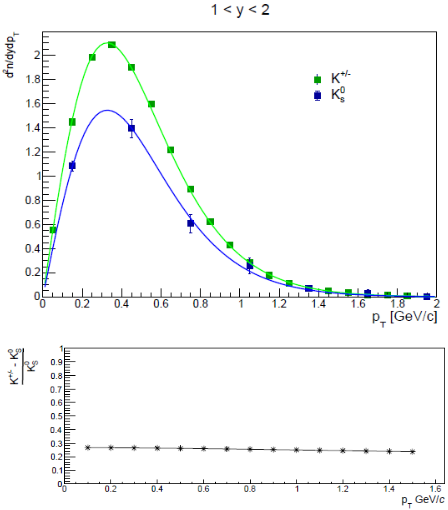
The statistical model fails when fixed γ_S. The fit with free γ_S finds 0.434±0.028 and reproduces the measurements well - a suppression of strange particle production in p+p collisions at CERN SPS energies

Charged/neutral kaon-ratio puzzle in Ar+Sc

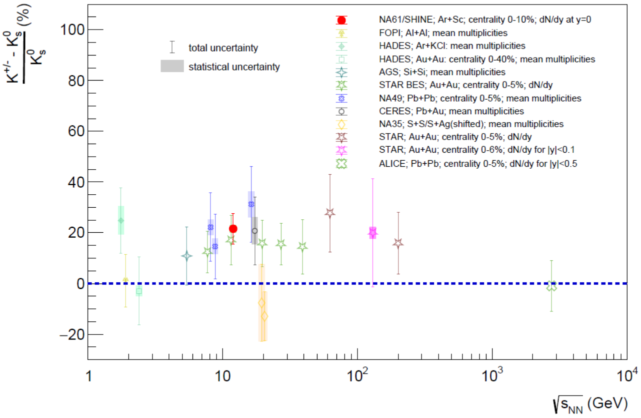


$$\langle K^0_S \rangle = 6.25 \pm 0.09 \pm 0.073$$
in Ar+Sc at 75*A* GeV/*c*

Around 25% difference between charged and neutral kaons in forward rapidity and whole p_T range.



Charged/neutral kaon-ratio - world data



CERES: M. Kalisky, PhD thesis 2007,
https://cds.cern.ch/record/1497739
STAR BES: Phys. Rev. C **102** (2020) no.3, 034909
Phys. Rev. C **96** (2017) no.4, 044904
STAR: Phys. Lett. B **595** (2004), 143-150
Phys. Rev. C **83** (2011), 024901
Phys. Rev. Lett. **108** (2012), 072301
Phys. Rev. C **79** (2009), 034909
ALICE: Phys. Rev. Lett. **111** (2013), 222301
Phys. Rev. C **88** (2013), 044910
AGS and NA35: Z. Phys. C **71** (1996), 55-64
Z. Phys. C **64** (1994), 195-207
Z. Phys. C **58** (1993), 367-374
NA49: C. Strabel, PhD thesis 2006,
https://edms.cern.ch/document/2693436/1
HADES: H. Schuldes, PhD thesis 2016,
https://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/42489
Phys. Lett. B **793** (2019), 457-463
Phys.Rev.C 80 (2009) 025209
Phys.Rev.C 82 (2010) 044907
FOPI: Eur.Phys.J.A 52 (2016) 6, 177
Phys.Rev.C 81 (2010) 061902

$\frac{K^{\pm}-K^0_S}{K^0_S}$ ratio significantly higher than 1 – unexpected isospin symmetry violation?

Summary

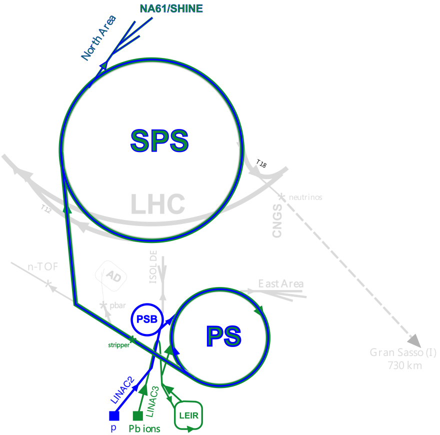
- Unique 2D scan in system size and the collision energy is completed (keep in touch as analysis are still ongoing)
- Large difference between small (p+p and Be+Be) and large systems (Ar+Sc)
- Unexpected system-size dependence was revealed - onset of (QGP) fireball?
  - **p+p** $\approx$**Be+Be** $\neq$ **Ar+Sc** $\leq$ **Pb+Pb**
  - further studies needed
- So-called horn structure does not appear in p+p, Be+Be, and Ar+Sc
- Unique results on multi-strange baryons production in p + p interactions in SPS
- None of the present theoretical models can explain results from NA61/SHINE
- Charged/neutral kaon-ratio puzzle indicates unexpected isospin symmetry violation.

Thank you

Supported by WUT ID-UB

NA61/SHINE detector setup@CERN

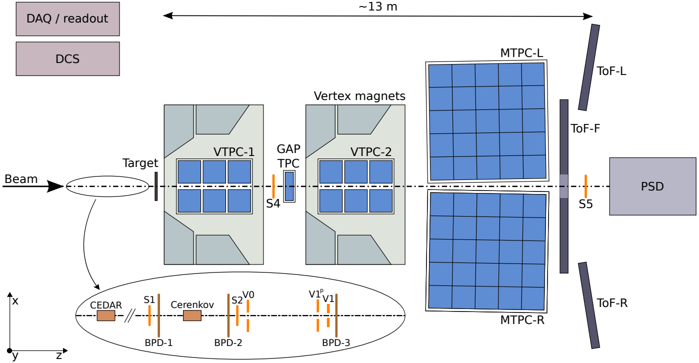
https://shine.web.cern.ch/



NA61/SHINE, JINST 9 (2014) P06005

NA stands for **N**orth **A**rea of the CERN accelerator complex connected with SPS accelerator.

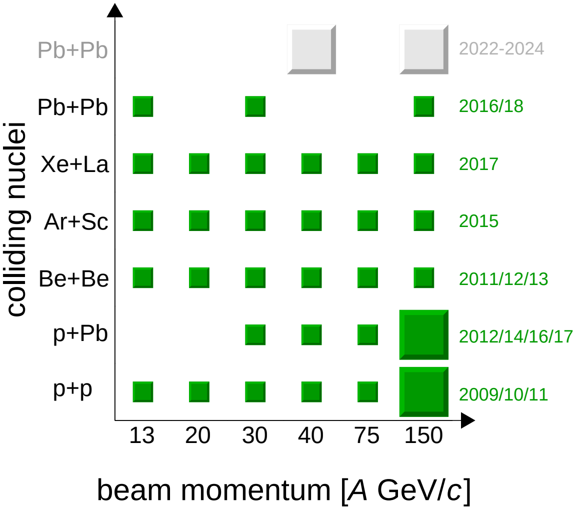
NA61/SHINE: detector layout



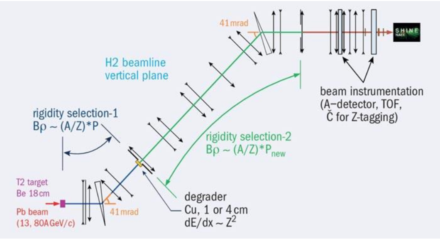
https://shine.web.cern.ch/
NA61/SHINE, JINST 9 (2014) P06005

- beams: hadrons and ions with $p_{beam} = 13(8)A - 400$ GeV$/c$
- large acceptance detector which coverages full forward hemisphere from $p_T \approx 0$
- precise centrality selection based on forward energy

Unprecedented scan in system size and energy



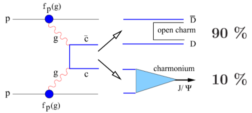
- primary *Ar*, *Xe* and *Pb*
  - *Ar* beam in parallel, in SPS, with protons for LHC
  - NA61/SHINE requested *Xe* which went up to LHC
- secondary and fragmented beams (p, Be)

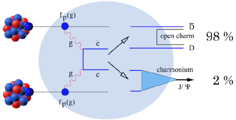


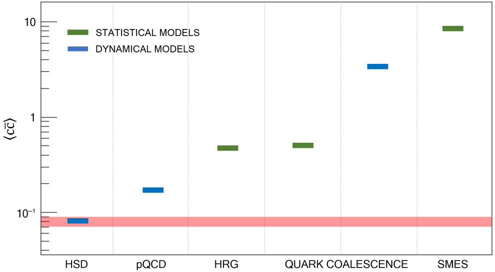
D. Manglunki

NA61/SHINE in 2022-2024: motivation

- 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?







- first measurement of open charm at SPS energies
- large discrepency between models

$\longleftarrow$ expected data precision (magenta band)

Fluctuations - Intensive quantities

Independent of volume V in Ideal Boltzmann Grand Canonical Ensemble (IB-GCE)

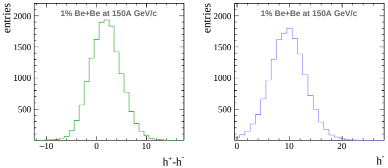
$$\omega[N] = \frac{\kappa_2[N]}{\kappa_1[N]}, \quad S\sigma[N] = \frac{\kappa_3[N]}{\kappa_2[N]}, \quad \kappa\sigma^2[N] = \frac{\kappa_4[N]}{\kappa_2[N]}$$

where κ_i stands for $i'th$ order cumulant of the distribution

There are **two reference values**:

- 1 for Poisson distribution (e.g. IB-GCE)
- 0 for no fluctuations

Begun and MMP, arxiv:1705.01110[nucl-th]



MMP, CPOD'21

Experimentally we are only able to narrow centrality of the registered events and consider events from a given centrality class. Thus, intensive quantities contain also fluctuations of the system size e.g. *Gazdzicki et al.*, arXiv:2102.11186

- For **net-charge reference** distribution is **Skellam** not Poisson $\longrightarrow$
- Centrality selection differs between experiments and for not the most central events it leads to different sets of events
- The simplest dependence is for $\omega[N] = \omega[N]_V + \langle n \rangle \frac{Var[V]}{\langle V \rangle}$, where n stands for particle density

Intensive for net-charge

$$\frac{\kappa_2[h^+ - h^-]}{(\kappa_1[h^+] + \kappa_1[h^-])}, \quad \frac{\kappa_3[h^+ - h^-]}{\kappa_1[h^+ - h^-]}$$

Data and analysis acceptance

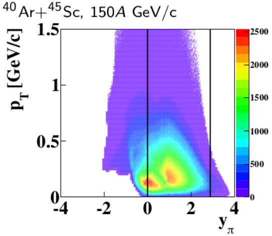
Presented results refers to charged hadrons produced in strong and electromagnetic processes in:

- **p+p – inelastic interactions** corrected for trigger bias, detector inefficiency and feed-down
  ω - NA61/SHINE, EPJC(2016)76:635; MMP, CPOD2016
- **Be+Be – 1% most central collisions** uncorrected with estimate of systematic bias (e.g. feed-down, detector ineffciency, beam and target impurity)
  ω - Seryakov, WPCF2017

All considered results have statistical uncertainty obtained either via sub-sample or bootstrap methods.

Acceptance: **forward rapidity with $p_T < 1.5$ GeV/c:**

- p+p acceptance - full acceptance of NA61/SHINE
  https://edms.cern.ch/document/1549298/1
- Be+Be acceptance: acceptance with additional rapidity cut:
  $0 < y_\pi < y_{beam}$.
  https://edms.cern.ch/document/2487456/1



Accepted fraction of particles

$$x[h^-] = \frac{h^-_{accepted}}{h^-_{4\pi}} \longrightarrow$$

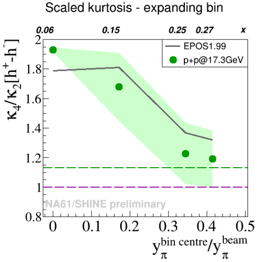
$\sqrt{s_{NN}}$ (GeV)	6.1	7.6	8.7	11.9	16.8
$x[h^-]$	0.27	0.3	0.3	0.4	0.5

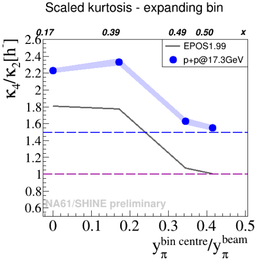
Note: non-uniform acceptance in ϕ

Search for QCD critical point: baseline fluctuations

When measured fluctuations are grand-canonical?

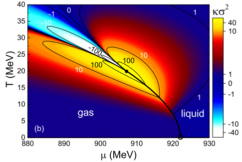
- Fluctuations of particle number in acceptance ΔY_{accept} *around midrapidity*
- Scales: ΔY_{accept} - analysis acceptance; ΔY_{total} - full space; $\Delta Y_{kick,corr}$ - diffusion and smearing
- ideal case: $\Delta Y_{total} >> \Delta Y_{accept} >> \Delta Y_{kick,corr}$
- NA61/SHINE as large acceptance experiment ideal for such studies
- p+p interactions as a reference for A+A studies $\longrightarrow$
- Note redefinition of intensive quantity to $\kappa_4/\kappa_2[h^-]$





A. Borucka, Lomonosov Conf. '21

Search for QCD critical point: net-charge fluctuations

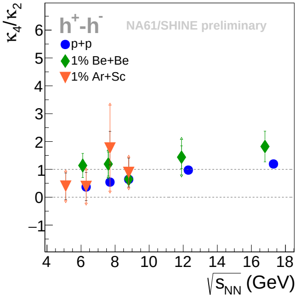


- $\langle N^2 \rangle \sim \xi^2 \quad \langle N^4 \rangle \sim \xi^7$

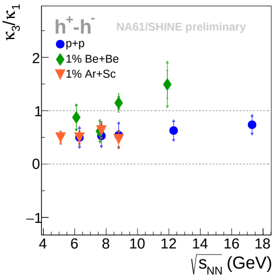
Special interest is devoted to net-charges as:

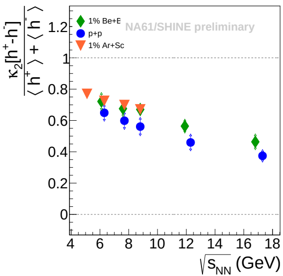
Cumulant generating function $\longrightarrow$ $\kappa_n \propto \frac{\delta^n (ln Z^{gce})}{\delta \mu^n}$ $\longleftarrow$ Grand partition function

In order to study fluctuations in systems of different size one needs intensive quantities: $\frac{\kappa_2[h^+ - h^-]}{\kappa_1[h^+] + \kappa_1[h^-]}$, $\frac{\kappa_3}{\kappa_1}[h^+ - h^-]$, $\frac{\kappa_4}{\kappa_2}[h^+ - h^-] = \kappa\sigma^2$

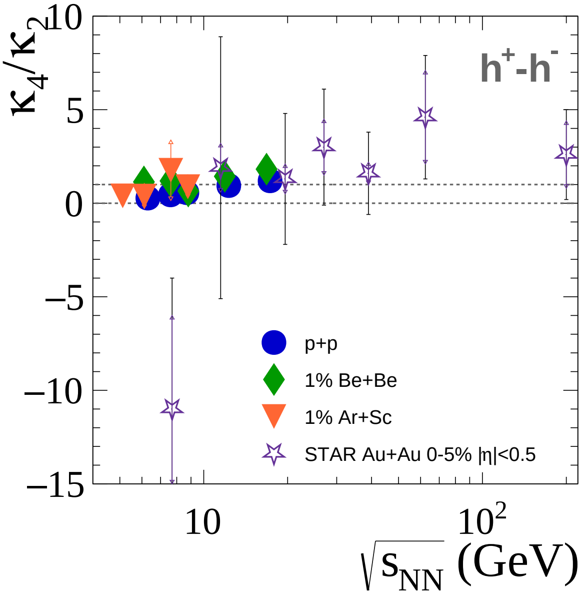


MMP, PANIC2021





Search for QCD critical point: net-charge fluctuations



- no non-monotonic signal observed
- qualitative agreement with STAR data
- Note: different acceptance and centrality determination

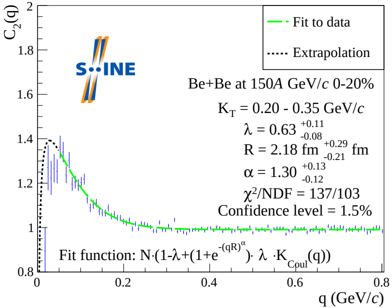
Search for QCD critical point: femtoscopic correlations

Measurements suggest Gaussian $\longrightarrow$ Lévy-stable source distribution

$$\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

- From generalization of Gaussian, power-law tail: $\sim r^{-(d-2+\alpha)}$
- The shape of the correlation function with Lévy source: $C(q) = 1 + \lambda e^{-(qR)^\alpha}$, where $\alpha = 1 \longrightarrow$ exponential and $\alpha = 2 \longrightarrow$ Gaussian
- We expect spatial power-law correlations at the CP ($\sim r^{-(d-2+\eta)}$) $\longrightarrow$ Lévy-exponent α identical to correlation exponent η

Csorgo, Hegyi, Zajc, EPJC36 (2004) 67

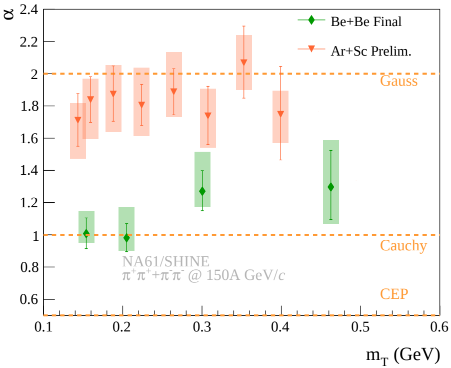


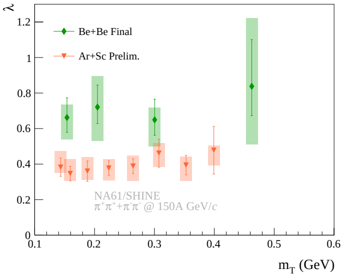
arXiv:2302.04593

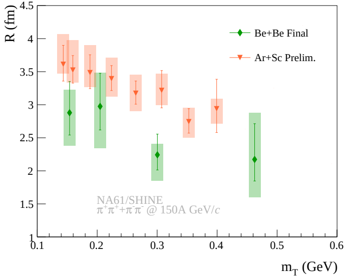
- Fit function: Bowler-Sinyukov $C(q) = 1-\lambda+1(1+e^{-|qR|^\alpha})\cdot\lambda\cdot K(q)$

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

Search for QCD critical point: femtoscopic correlations







- **α: far from CP prediction (0.5)**
  Rieger, Phys.Rev.B52 (1995) 6659
  Be+Be $\alpha \sim 1.5 \longrightarrow$ anomalous diffusion
  Ar+Sc $\alpha \approx 2$ Gaussian source?
- R: Visible m_T dependence - sign of transverse flow
- λ: no m_T dependence

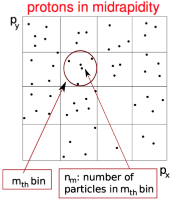
arXiv:2302.04593

Search for QCD critical point: proton intermittency

Second factorial moment as function of momentum bin size

CP $\longrightarrow$ scale invariance $\longrightarrow$ power-law form of correlation function for large distances $\Leftrightarrow$ small momentum transfer $\Delta\vec{k}$

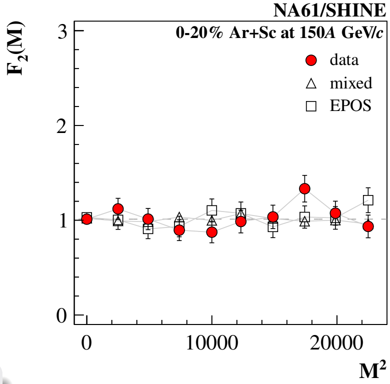
Wosiek ,Acta Phys. Polon.B 19,863-869; Bialas and Hwa,PLB 253,436-438; Diakonos et al., PoS (CPOD2006)010; Hatta and Stephanov, PRL91, 102003



$$F_2(M) = \langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \rangle \Big/ \langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_m \rangle^2,$$

where $\langle ... \rangle$ indicates averaging over events

power-law dependence on M:
$F_2(M) \sim (M^2)^{\phi_2}$

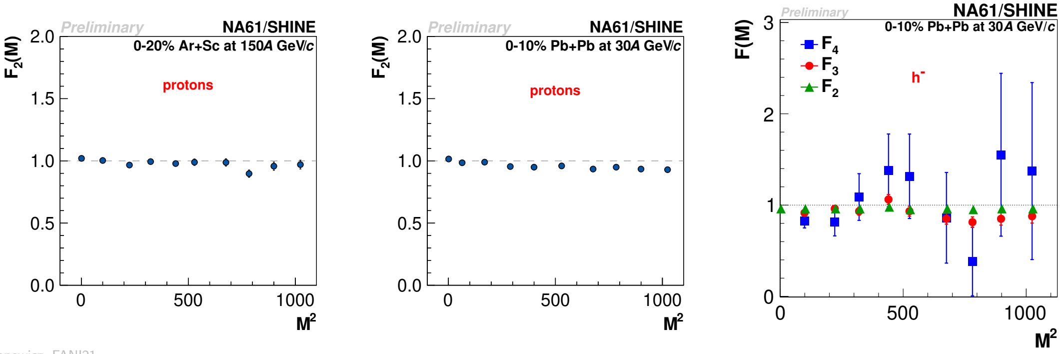


arXiv:2305.07557

Expected intermittency index ϕ_2 at CP is 5/6 assuming the 3-D Ising universality class of QCD.

No indication for power-law increase with bin size

Search for QCD critical point: proton intermittency



Czopowicz, FANI21

No indication for power-law increase with bin size

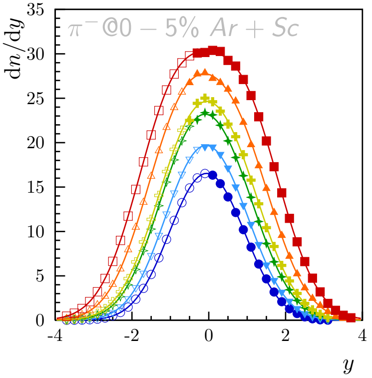
There is a disagreement between NA61/SHINE and STAR measurements J. Wu, ISMD'21 - comparison of analysis procedures ongoing

Properties of the QCD matter: softening of EoS

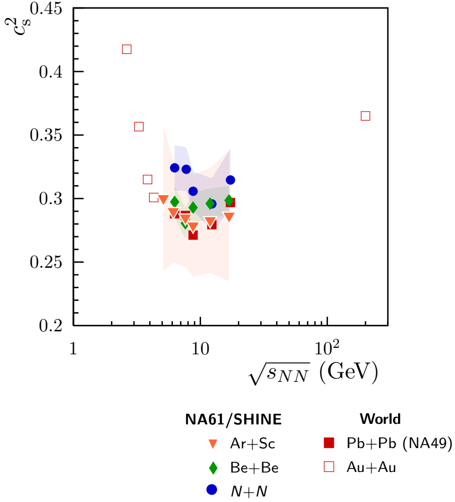
Relation between rapidity width and sound velocity: $\sigma^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4} ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right)$

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

M. Bleicher, PoS CPOD 2006, 025 (2006)



NA61/SHINE, Eur.Phys.J.C 81 (2021) 5, 397



Minimum in energy dependence indicate possible softening of EoS

Need to extend data to lower energies