News from the strong interactions program of NA61/SHINE

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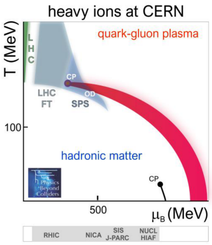
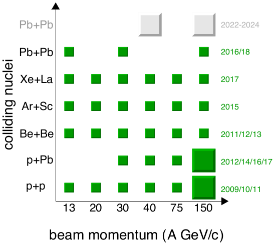
NA61/SHINE experiment

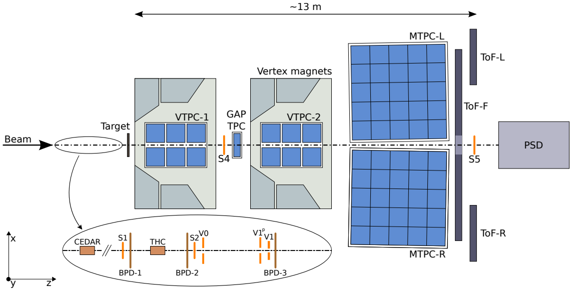
Strong interactions program:

- search for the critical point of strongly interacting matter,
- study of the properties of the onset of deconfinement.

- Fixed-target experiment at CERN SPS.
- Large variety of beams and targets.
- Large acceptance: full forward hemisphere, down to p_T=0.
- Particle identification: dE/dx in Time Projection Chambers, Time of Flight detector.
- Collision centrality measured by forward Projectile Spectator Detector (PSD).

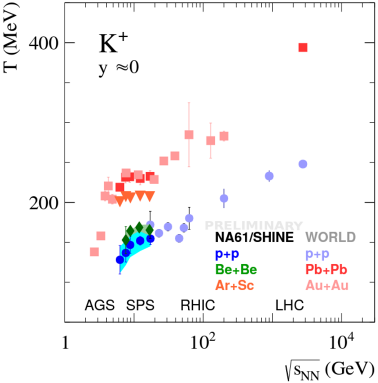


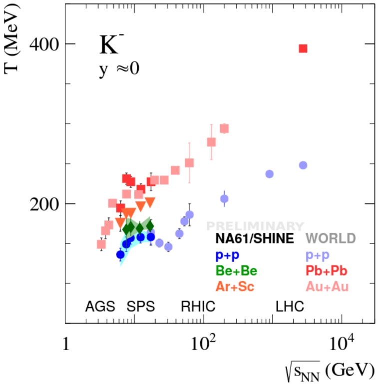


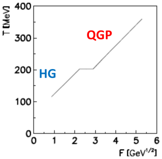


NA61/SHINE, JINST 9, P06005, 2014

Onset of deconfinement: step



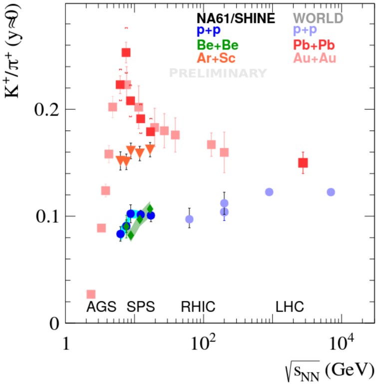


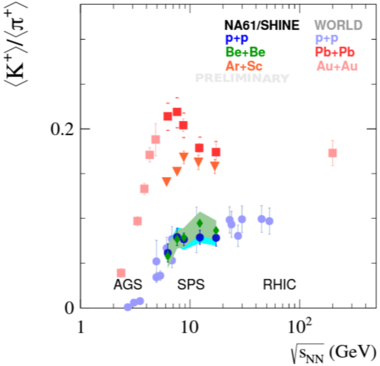


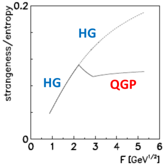
- Qualitatively similar energy dependence is seen in p+p, Be+Be, Ar+Sc and Pb+Pb.
- Magnitude of T increases with the system size.

- NA61/SHINE, EPJC 81, 1, 73, 2021 and Ar+Sc preliminary results, APPB 30, 2705, 1999
- Sensitive to both the temperature and the radial flow.
- Kaons are only weakly affected by re-scattering and resonance decays during the post-hydro phase (at SPS and RHIC energies).
- Connected with the temperature of the freeze-out surface and not the early-stage fireball.

Onset of deconfinement: horn



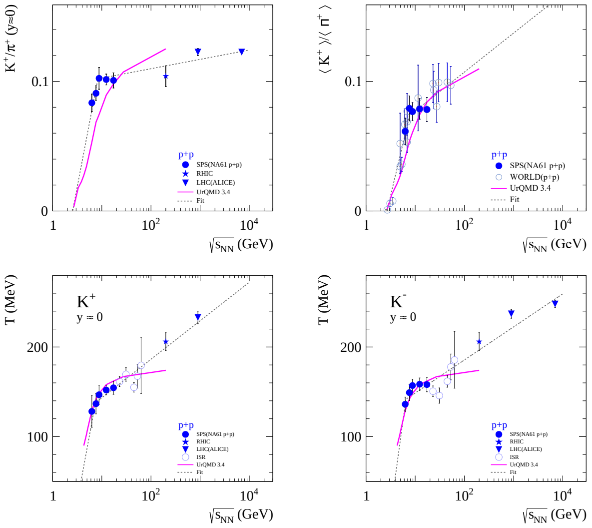




- Be+Be close to p+p in K^+/π^+.
- No horn-like structure in Ar+Sc.

- NA61/SHINE, EPJC 81, 1, 73, 2021 and Ar+Sc preliminary results
- p+p $\approx$ Be+Be $\neq$ Ar+Sc $\ll$ Pb+Pb
- Good measure of the strangeness to entropy ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons) $\rightarrow$ probe of the onset of deconfinement.

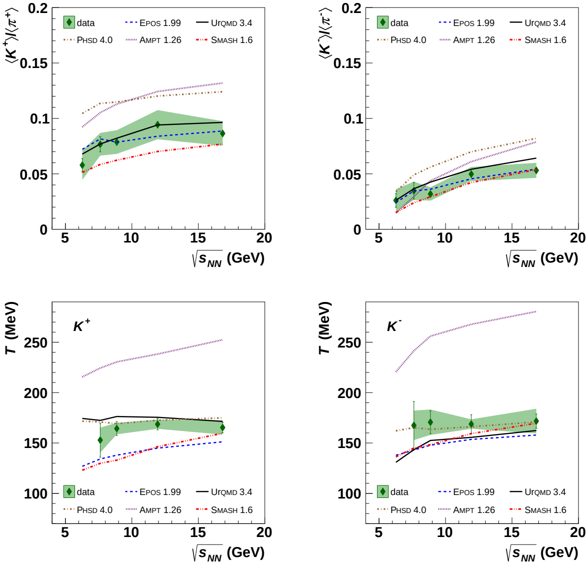
Results for p+p interactions



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

NA61/SHINE, PRC 102, 1, 011901, 2020

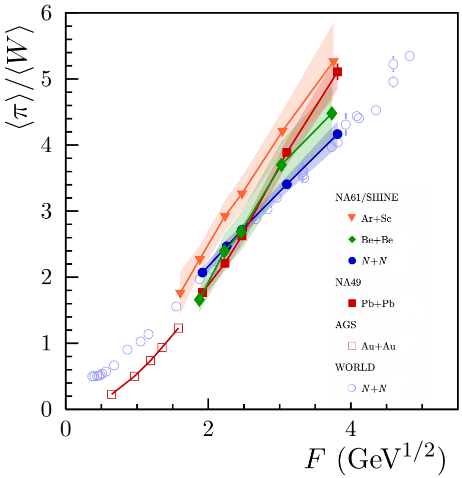
Results for Be+Be interactions



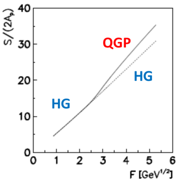
- The first world data for Be+Be collisions.
- No visible sharp break in K^+/π^+ and inverse slope parameter T. Note the limited energy range of data.
- No models which describe all measured quantities.

NA61/SHINE, EPJC 81, 1, 73, 2021

Onset of deconfinement: kink



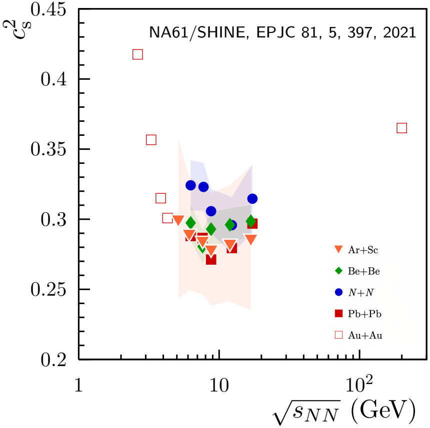
W – wounded nucleons, $F = \left[\frac{(\sqrt{s_{NN}} - 2m_N)^3}{\sqrt{s_{NN}}}\right]^{1/4}$.



- 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.

NA61/SHINE, EPJC 81, 5, 397, 2021

Width of the rapidity distribution



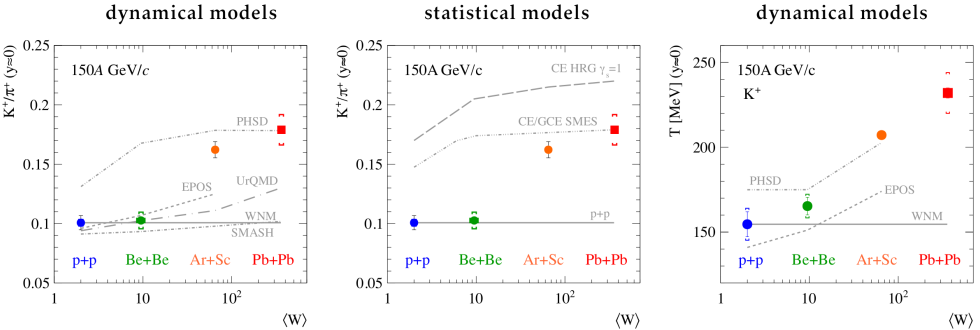
- Collision energy dependence of the width was derived by Shuryak (E. V. Shuryak. Yad.Fiz., 16, 395, 1972) from the Landau hydrodynamical model of high energy collisions:

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

  where c_s denotes the speed of sound.
- 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.

K^+/π^+ and T vs the system size at 150 (158)A GeV/c

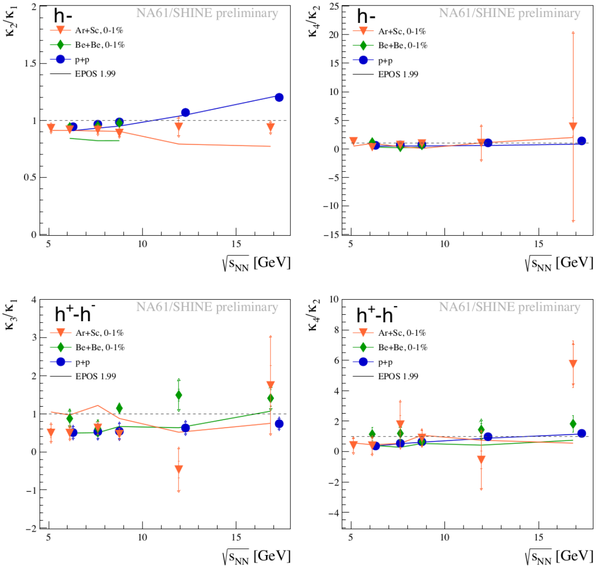


- **Onset of fireball** – rapid change of observables when going from small (p+p, Be+Be) to intermediate (Ar+Sc) and large ones (Pb+Pb) → beginning of the creation of large clusters of strongly interacting matter?
- None of the models reproduce K^+/π^+ ratio nor T for whole $\langle W \rangle$ range.

PHSD: EPJA 56, 9, 223, 2020, arXiv:1908.00451 and private communication;
SMASH: JPG 47, 6, 065101, 2020 and private communication;
UrQMD and HRG: PRC 99, 3, 034909, 2019;
SMES: APPB 46, 10, 1991, 2015

p+p: NA61/SHINE, EPJC 77, 10, 671, 2017;
Be+Be: NA61/SHINE, EPJC 81, 1, 73, 2021;
Ar+Sc: NA61/SHINE preliminary;
Pb+Pb: NA61/SHINE, PRC 66, 054902, 2002.

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



$\kappa_1 = \langle N \rangle$

$\kappa_2 = \langle (\delta N)^2 \rangle = \sigma^2$

$\kappa_3 = \langle (\delta N)^3 \rangle = S\sigma^3$

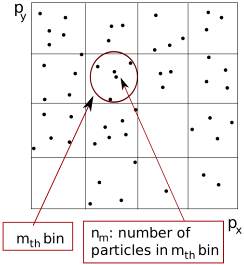
$\kappa_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 = K\sigma^4$

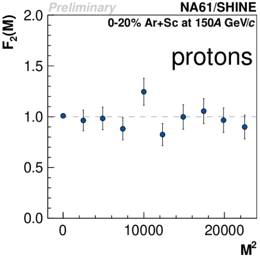
where:

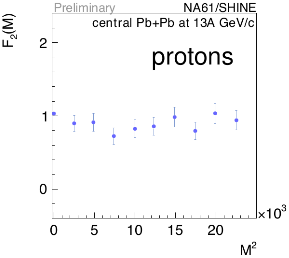
N – multiplicity; $\delta N = N - \langle N \rangle$; σ – standard deviation; S – skewness; K – kurtosis.

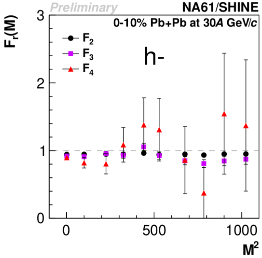
- In case of h-, only the scaled variance show significant differences between heavier and lighter systems.
- In case of net-electric charge, the scaled skewness and scaled kurtosis indicate non-monotonic behaviour.
- Currently, analysis is focused on reducing the considerable systematic uncertainties.

Proton and charged hadron intermittency in Ar+Sc and Pb+Pb collisions







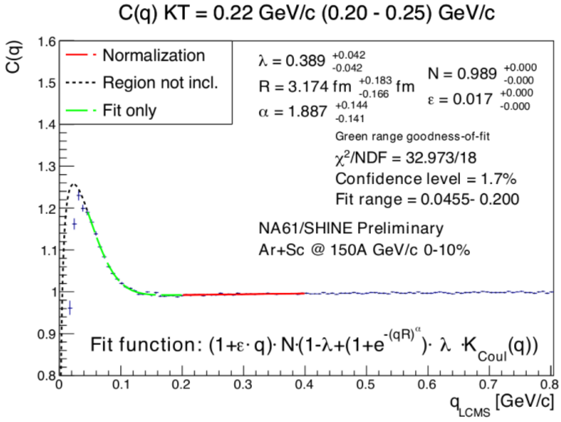


$$F_r(M) = \frac{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m(n_m-1)\dots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m \right\rangle^r},$$

where $\langle \dots \rangle$ denotes averaging over events, M is the number of cells.

- Statistically independent points, cumulative variables.
- If the system freezes-out in the vicinity of the critical point, $F_2(M)$ should reveal a power-law dependence $\rightarrow$ not observed in these analyses.
- Work on more advanced methodology ongoing.

Symmetric Lévy HBT correlations



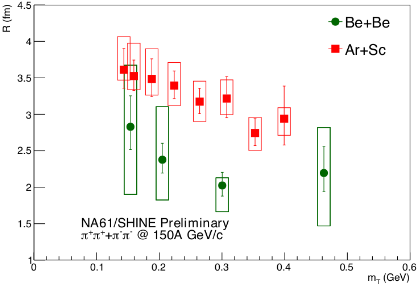
- $A(q)$ – pairs of pions from same event,
- $B(q)$ – pairs of pions from mixed events,
- $C(q) = A(q)/B(q)$,
- $q = |p_1 - p_2|$

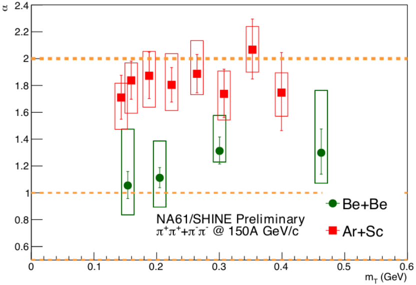
- Bose-Einstein correlations are sensitive to spatial extension of particle source.
- Usually correlation function assumes Gaussian source but it can be generalized by Lévy-shaped:

$$C(q) = 1 + \lambda \cdot e^{-(qR)^{\alpha}} \quad (2)$$

where:
$\alpha = 0.50 \pm 0.05$ – conjectured value at the critical point (CP),
$\alpha < 2$ – anomalous diffusion,
$\alpha = 2$ – Gaussian (EPJC 36, 67, 2004).

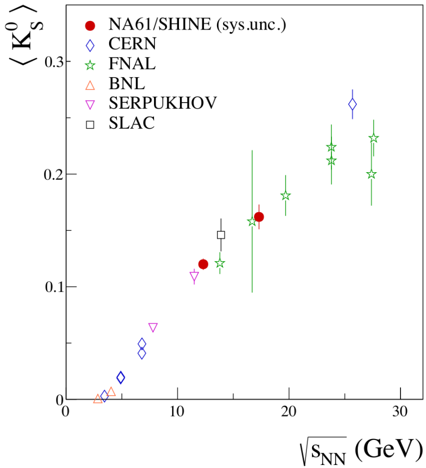
Symmetric Lévy HBT correlations

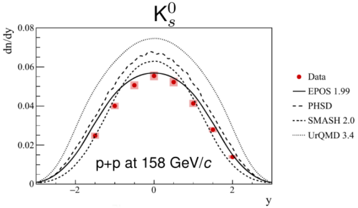


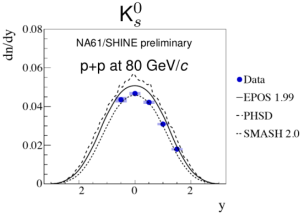


- R Lévy-scale parameter:
  - describes length of homogeneity,
  - from hydro: $R \sim 1/\sqrt{m_T}$ (For Gaussian source) PRC 54, 1390, 1996,
  - visible m_T dependence – sign of transverse flow.
- Lévy-stability index α:
  - shape of spatial correlation,
  - α does not indicate CP in Be+Be and Ar+Sc (far from 0.5),
  - α between Gaussian or Cauchy shape might be the sign of anomalous diffusion.

New data on hadron spectra in p+p reactions

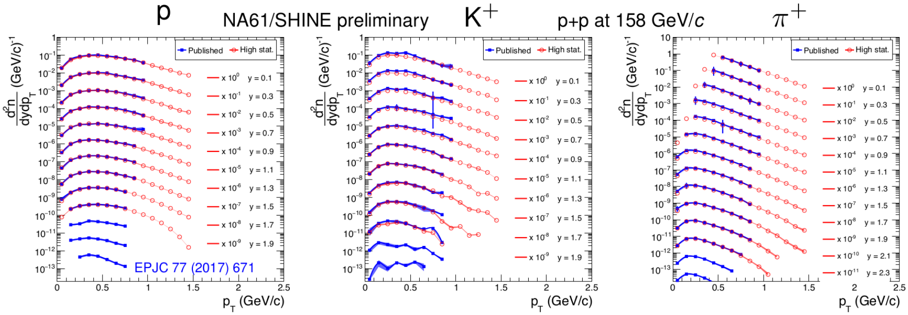


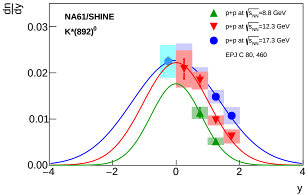


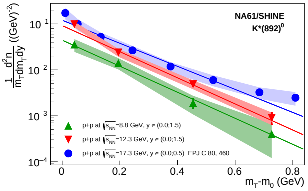


- EPJC 82, 96, 2022 (158 GeV/c) and preliminary results (80 GeV/c).
- New K^0_S data for p+p interactions at 80 and 158 GeV/c.
- The best decription of rapidity spectra is given by SMASH 2.0 (for 80 GeV/c) or EPOS 1.99 (for 158 GeV/c).

New data on hadron spectra in p+p reactions

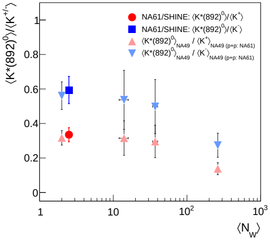




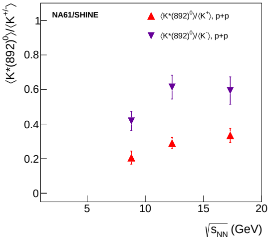


NA61/SHINE, EPJC 82, 4, 322, 2022.

System size dependence of $K^*(892)^0$ to charged kaon ratio



NA61/SHINE, EPJC 80, 5, 460, 2020



NA61/SHINE, EPJC 82, 4, 322, 2022

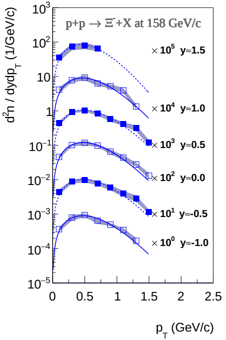
- K^*/K^- or $K^*/K^+ \rightarrow$ **time between chemical and kinetic freeze-outs** (STAR, PRC 71, 064902, 2005; C. Blume, APPB 43, 577, 2012):

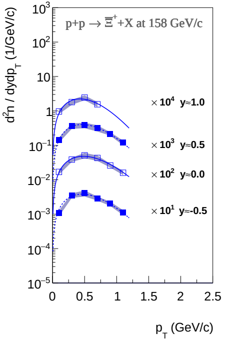
$$\left.\frac{K^*}{K}\right|_{kinetic} = \left.\frac{K^*}{K}\right|_{chemical} e^{-\frac{\Delta t}{\tau}} \qquad (3)$$

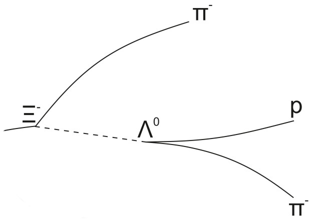
  Assumption: no regeneration processes; ratio for kinetic freeze-out from Pb+Pb interactions; ratio for chemical freeze-out from p+p interactions.

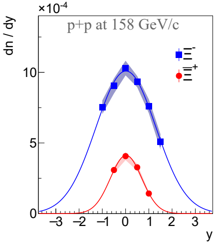
- Lorentz boosted time interval between chemical and kinetic freeze-outs for Pb+Pb at 158A GeV/c:
  - 5.3 fm/c for $K^*(892)^0/K^+$, 4.6 fm/c for $K^*(892)^0/K^-$
- **Δt at SPS $>$ Δt at RHIC** (at corresponding centrality) NA61/SHINE, EPJC 80, 5, 460, 2020 $\rightarrow$ regeneration effects may be significant at higher energies
- Regeneration effects may exist also at SPS $\rightarrow$ obtained **Δt is a lower limit of time between freeze-outs**
- Reference ion data are needed to estimate Δt at lower energies ($K^*/K^\pm$ for p+p data already exist – left plot).

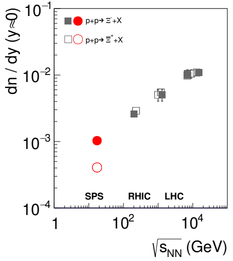
Ξ production in inelastic p+p collisions at 158 GeV/c





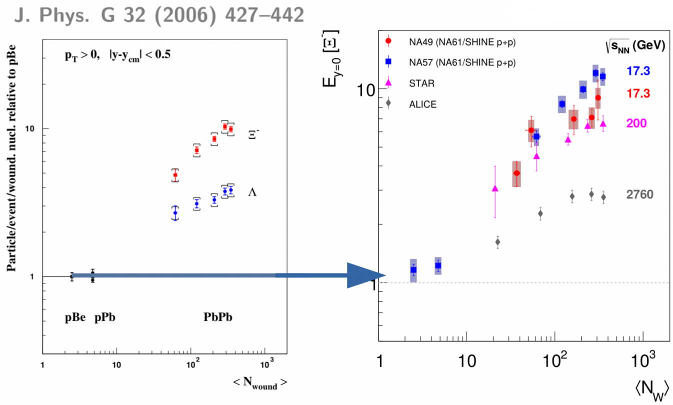






- Mean multip. $\langle \overline{\Xi}^+ \rangle / \langle \Xi^- \rangle = 0.24 \pm 0.01 \pm 0.05$.
- The only results on Ξ^- and $\overline{\Xi}^+$ production in p+p at the SPS energy (NA61/SHINE, EPJC 81, 10, 911, 2021).
- Suppression of $\overline{\Xi}^+$ production at mid-rapidity.

Strangeness enhancement factors - Ξ production



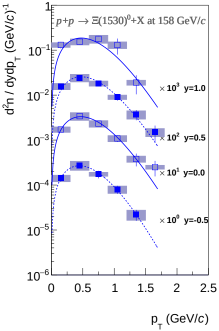
EPJC 80, 9, 833, 2020;
Erratum: EPJC 82, 174, 2022.

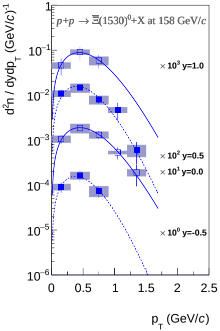
- The enhancement recalculated based on the NA61/SHINE data.
- The strangeness enhancement factor (NPB 111, 461, 1976)):

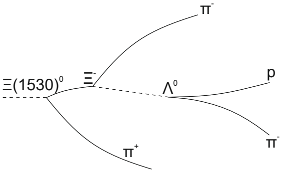
$$E = \frac{2}{\langle N_W \rangle} \frac{dn/dy\,(A+A)}{dn/dy\,(p+p)}, \qquad (4)$$

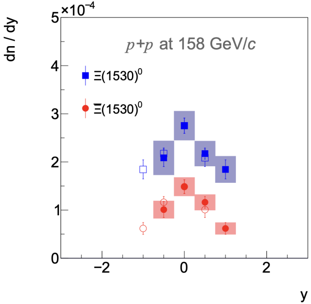
- The NA61/SHINE p+p data is new baseline for Ξ production at 158A GeV/c.

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







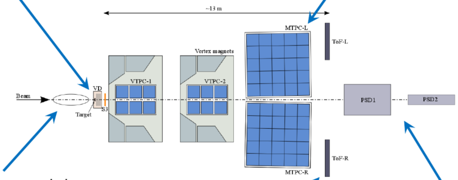


- Mean multip. $\langle\overline{\Xi}(1530)^0\rangle/\langle\Xi(1530)^0\rangle = 0.40 \pm 0.03 \pm 0.05$.
- The only results on $\Xi(1530)^0$ production in p+p at the SPS energy (NA61/SHINE, EPJC 81, 10, 911, 2021).
- The second result on $\Xi(1530)^0$ production in p+p (ALICE at 7 TeV – EPJC 75, 1, 2015).

NA61/SHINE upgrade

Construction of Vertex Detector (VD) for D^0, $\overline{D^0}$ decay reconstruction

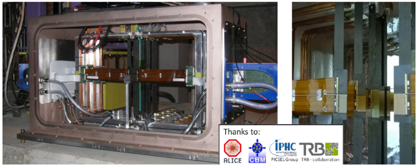
Replacement of the TPC read-out electronics to increase data rate to 1 kHz



New trigger and data acquisition system

New Time-of-Flight detectors

Upgrade of Projectile Spectator Detector



- Main goal: first ever open charm measurements at SPS. Open questions:
  - 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 mean number of charm quark pairs $\langle c\bar{c}\rangle$ produced in the full phase space in A+A collisions has to be known.

Summary

- 2D scan in system size and collision energy was completed in 2017 with Xe+La.
- NA61/SHINE delivers reach information related to the onset of deconfinement in the light and medium-size system.
- The onset of fireball - unexpected system size dependence.
- So far no convincing indication of the critical point.
- Detector upgrade almost done, open charm measurements starting this year.

Thank you!

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