Strangeness production in NA61/SHINE

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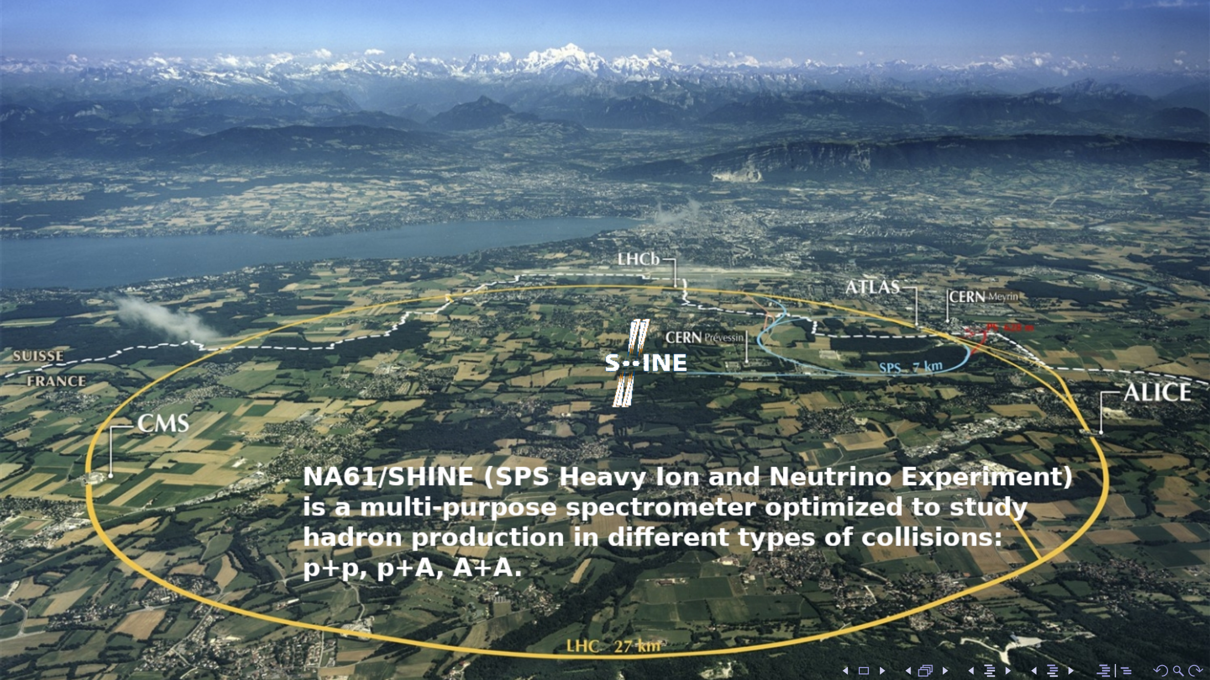
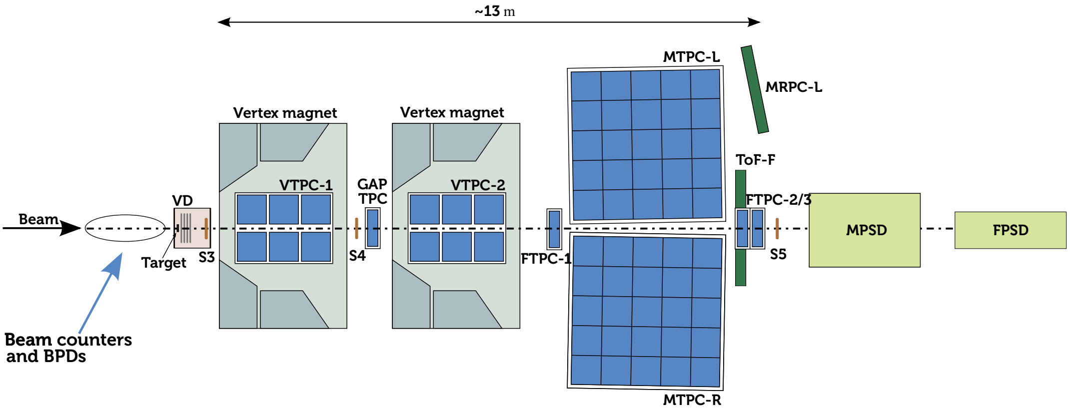


NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a multi-purpose spectrometer optimized to study hadron production in different types of collisions: p+p, p+A, A+A.

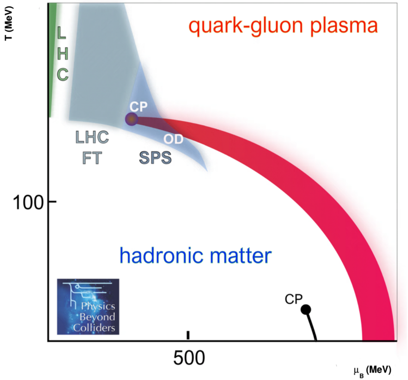
NA61/SHINE detector

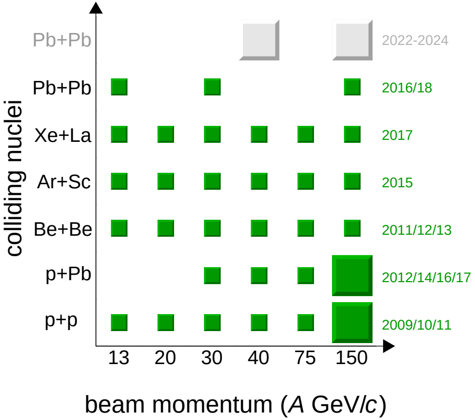


- coverage of the full forward hemisphere, down to $p_T = 0$ GeV/c
- ion (Be, Ar, Xe, Pb) and hadron (π, K, p) beams

NA61/SHINE strong interactions program

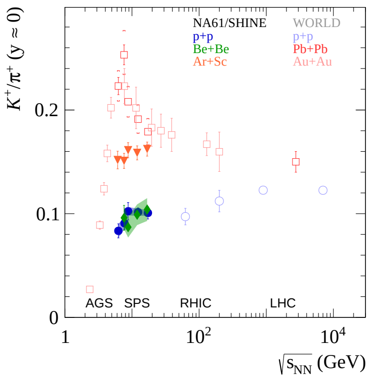
NA61/SHINE explores the phase diagram of strongly interacting matter by performing a 2D scan in collision energy and system size.

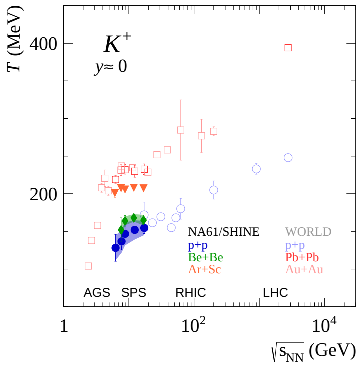




Onset of deconfinement and onset of fireball

K^+/π^+ ratio and inverse slope parameter



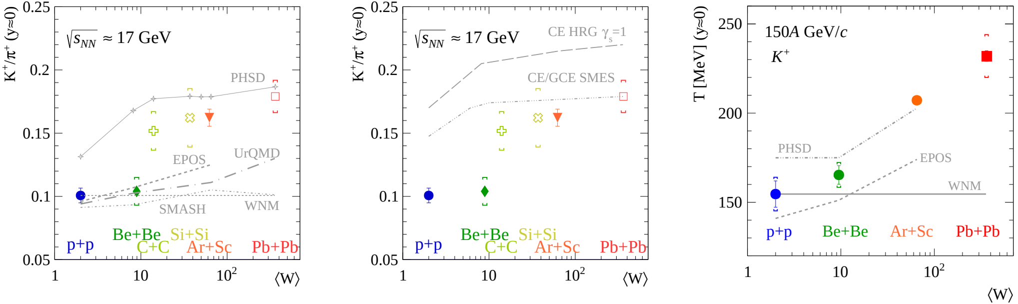


- No horn-like structure in Ar+Sc
- Be+Be close to p+p in K^+/π^+
- Plateau visible in p+p, Be+Be and Ar+Sc
- Ar+Sc significantly above Be+Be

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

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

dynamical models **statistical models**

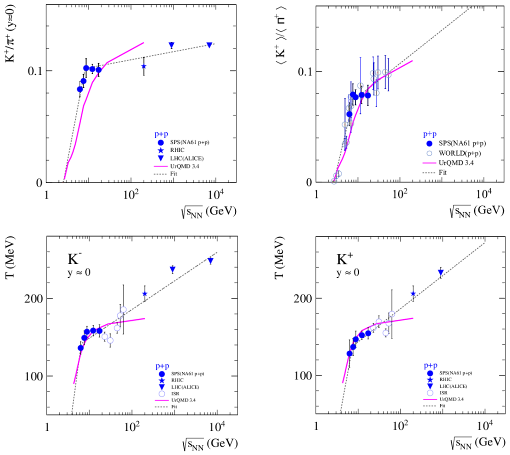


- **Onset of fireball** — rapid change of observables when going from small systems (p+p , Be+Be) to intermediate (Ar+Sc) and large ones (Pb+Pb).
- None of the models reproduces neither K^+/π^+ ratio nor T for whole $\langle W \rangle$ range.

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)

K^+/π^+ ratio and inverse slope parameter in p+p

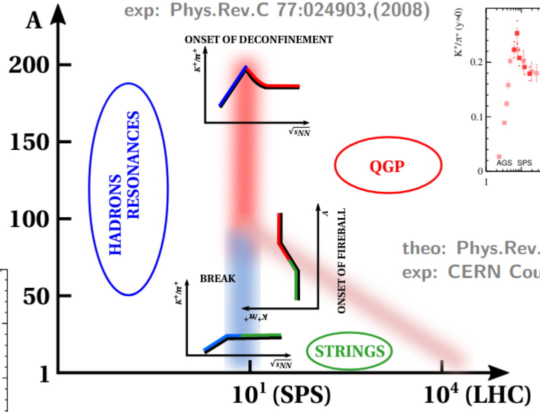


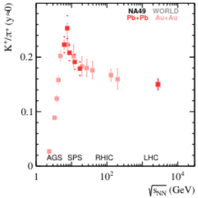
Phys.Rev.C 102 (2020) 1, 011901

- Rates of increase of K^+/π^+ and T change sharply in p+p collisions at SPS energies
- Models assuming change from resonances to string production mechanism follow similar trend

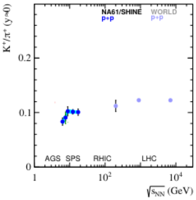
Uniqueness of ion results from NA61/SHINE

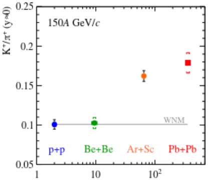
theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)





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

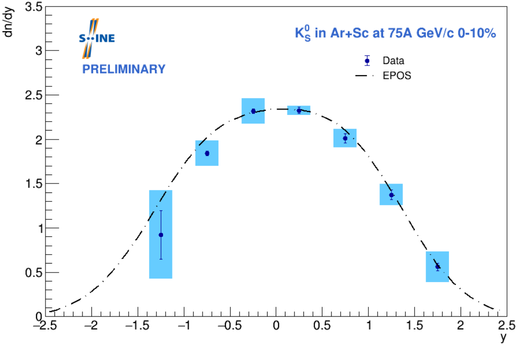


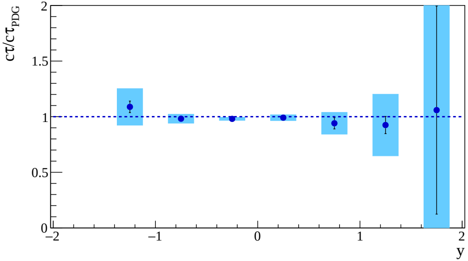


theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Charged/neutral kaon-ratio puzzle

K^0_s production in Ar+Sc at 75A GeV/c

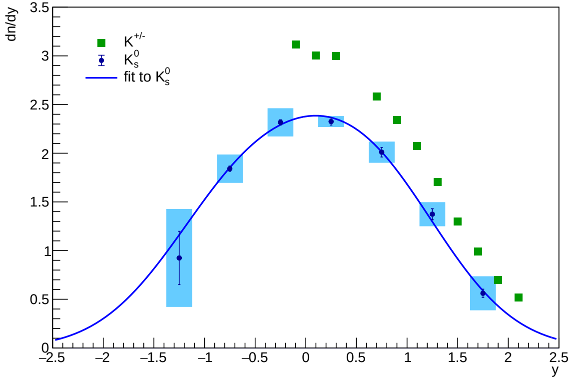




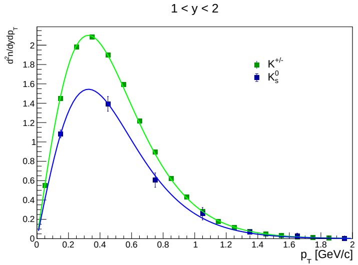
- Mean multiplicity: $\langle K^0_S \rangle = 6.25 \pm 0.09(stat) \pm 0.73(sys)$
- Good agreement with EPOS predictions

K_s^0 – comparison with K^+ and K^-

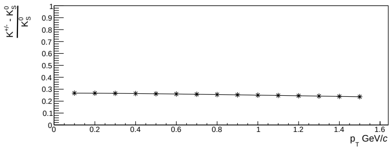
$$K^{+/-} = \frac{K^+ + K^-}{2}$$



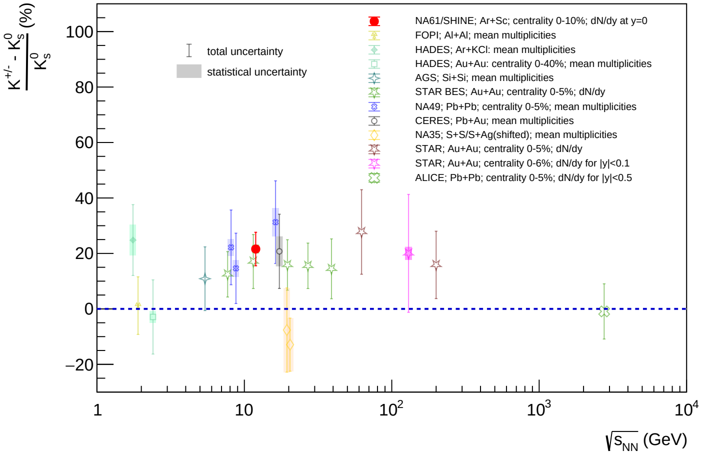
Around 25% difference in forward rapidity.



Around 25% difference for the whole p_T range.



K^0_s – comparison with K^+ and K^- – summary



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

Comparison of isospin asymmetry for D mesons and kaons

$D^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.66 \pm 0.05$ MeV
Mean life $\tau = (1033 \pm 5) \times 10^{-15}$ s
$c\tau = 309.8\ \mu$m

D^0

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1864.84 \pm 0.05$ MeV
$m_{D^{\pm}} - m_{D^0} = 4.822 \pm 0.015$ MeV
Mean life $\tau = (410.3 \pm 1.0) \times 10^{-15}$ s
$c\tau = 123.01\ \mu$m

Mass difference: $\Delta m \approx 5$ MeV
Multiplicity: $\langle D^+ + D^- \rangle < \langle D^0 + \overline{D}^0 \rangle$

$K^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [a] (S = 2.8)
Mean life $\tau = (1.2380 \pm 0.0020) \times 10^{-8}$ s (S = 1.8)
$c\tau = 3.711$ m

K^0

$I(J^P) = \frac{1}{2}(0^-)$

50% K_S, 50% K_L
Mass $m = 497.611 \pm 0.013$ MeV (S = 1.2)
$m_{K^0} - m_{K^{\pm}} = 3.934 \pm 0.020$ MeV (S = 1.6)

Mass difference: $\Delta m \approx -4$ MeV
Multiplicity: $\langle K^+ + K^- \rangle > \langle K^0 + \overline{K}^0 \rangle$

Isospin asymmetry for D mesons

S··INE

$D^{\pm}$

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$c\tau = 123.01$ μm

Mass difference: Δm ≈ 5 MeV
Multiplicity: ⟨$D^+ + D^-$⟩ < ⟨$D^0 + \overline{D^0}$⟩

$D^*(2007)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2006.85 \pm 0.05$ MeV (S = 1.1)
$m_{D^{*0}} - m_{D^0} = 142.014 \pm 0.030$ MeV (S = 1.5)
Full width $\Gamma < 2.1$ MeV, CL = 90%

$D^*(2007)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^0$	(64.7 ± 0.9) %	43
$D^0\gamma$	(35.3 ± 0.9) %	137
$D^0 e^+ e^-$	$(3.91 \pm 0.33) \times 10^{-3}$	137

$D^*(2010)^{\pm}$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2010.26 \pm 0.05$ MeV
$m_{D^*(2010)^+} - m_{D^+} = 140.603 \pm 0.015$ MeV
$m_{D^*(2010)^+} - m_{D^0} = 145.4258 \pm 0.0017$ MeV
Full width $\Gamma = 83.4 \pm 1.8$ keV

$D^*(2010)^-$ modes are charge conjugates of the modes below.

$D^*(2010)^{\pm}$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^+$	(67.7 ± 0.5) %	39
$D^+\pi^0$	(30.7 ± 0.5) %	38

- Simple explanation according to Adv.Ser.Direct.High Energy Phys. 15 (1998) 609-706: "A simple model for estimating the charged-to-neutral D cross section ratio is the following. One assumes isospin invariance in the c→D and c→D* transition. Furthermore, one assumes that the D cross section is one third of the D* cross section, due to the counting of polarization states. Using then the published values of the D* →D branching ratios [R.M. Barnett et al., Phys. Rev. D54(1996)1], the result is roughly $\frac{\sigma(D^+)}{\sigma(D^0)} \approx 0.32$."

Isospin asymmetry for D mesons

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Mean life $\tau = (1033 \pm 5) \times 10^{-15}$ s
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- $m(D^+) + m(\pi^-) = 1869.66$ MeV $+ 139.57039$ MeV $= 2009.23039$ MeV $> m(D^*(2007)^0)$ – decay not possible
- $m(D^0) + m(\pi^0) = 1864.84$ MeV $+ 134.9768$ MeV $= 1999.8168$ MeV $< m(D^*(2007)^0)$

Isospin asymmetry for kaons

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Mean life $\tau = (1.2380 \pm 0.0020) \times 10^{-8}$ s $(S = 1.8)$
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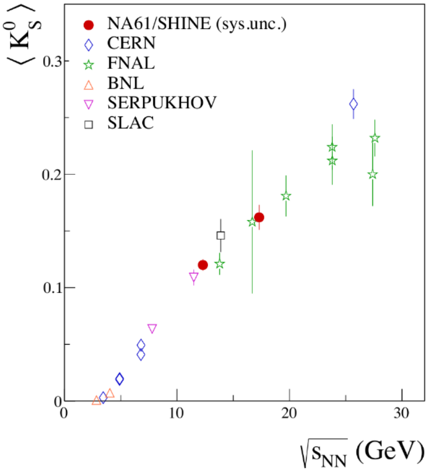
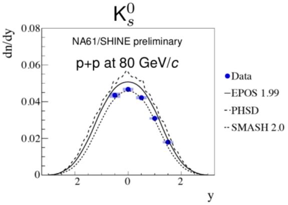
Mass difference: $\Delta m \approx -4$ MeV
Multiplicity: $\langle K^+ + K^- \rangle > \langle K^0 + \overline{K^0} \rangle$

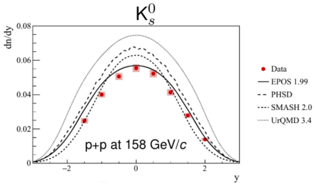
- For any state going to kaons, there is always a bit more K^+ and K^- because of mass difference.
- But masses of kaon resonances are much larger than sum of decay products (the higher mass of decaying resonance, the smaller difference between charged and neutral kaons).
- First preliminary estimation using statistical model gives the asymmetry $< 5\%$ (thanks to Francesco Giacosa).

(Multi-)strange hadron production in p+p interactions at $\sqrt{s} = 17.3$ GeV

K^0_S meson production in $p+p$ interactions

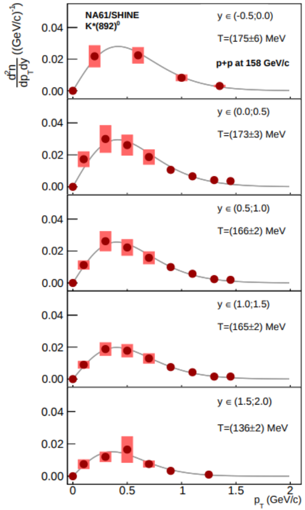


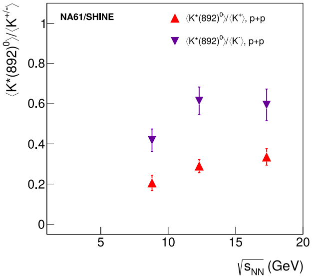




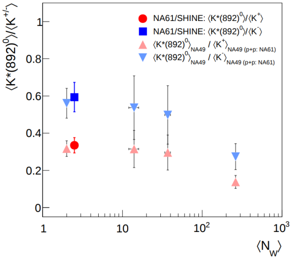
- EPJC 82, 96, 2022 (158A GeV/c) and preliminary results (80A GeV/c).
- New high-precision measurements of K^0_S in p+p interactions at 80A and 158A GeV/c.

$K^*(892)^0$ meson production in $p{+}p$ interactions



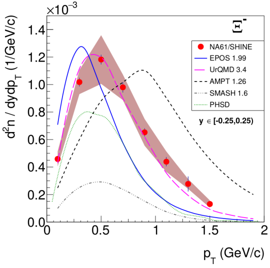


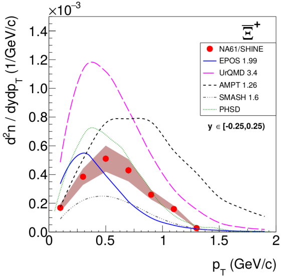
Eur.Phys.J.C 80 (2020) 5, 460
Eur.Phys.J.C 82 (2022) 4, 322

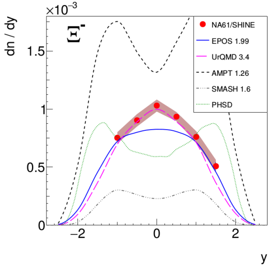


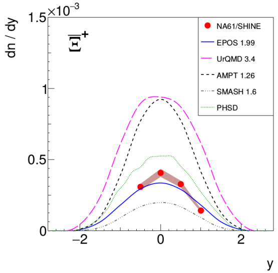
- **Results on $K^*(892)^0$ mass and width were included in PDG**
- time between chemical and kinetic freezeouts at 158 GeV/c estimated to be $\Delta t \sim 5.3 fm/c$
- $\Delta t_{\mathrm{SPS}} > \Delta t_{\mathrm{RHIC}} \rightarrow$ lifetime of hadronic phase longer at SPS and/or regeneration more important at RHIC energies

Ξ^- and $\overline{\Xi}^+$ production in $p+p$ interactions at 158 GeV/c

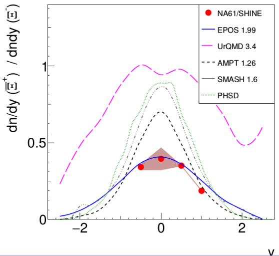








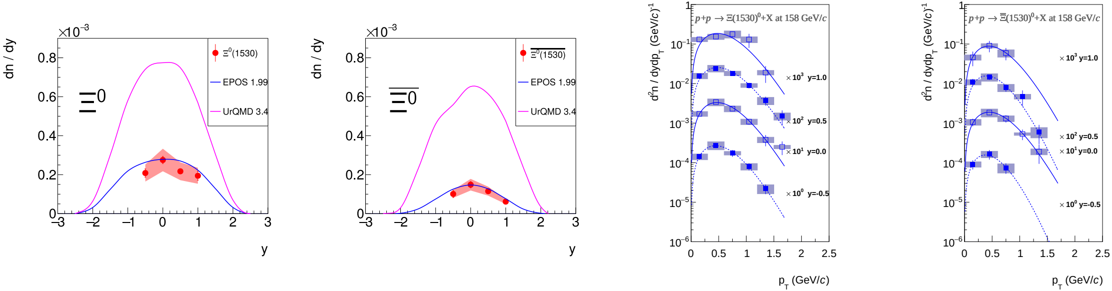
- The only existing results on Ξ^- and $\overline{\Xi}^+$ production in SPS energy range in $p+p$ interactions
- Strong suppression of $\overline{\Xi}^+$: $\langle \overline{\Xi}^+ \rangle / \langle \Xi^- \rangle = 0.24 \pm 0.01 \pm 0.05$
- Transport models fail to describe the results on Ξ production in $p+p$ collisions



Eur.Phys.J.C 80 (2020) 9, 833, Erratum: Eur.Phys.J.C 82 (2022) 2, 174

$\Xi^0(1530)$ and $\bar{\Xi}^0(1530)$ production in $p+p$ interactions at 158 GeV/c

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



- The first results on $\Xi^0(1530)$ production in $p+p$ in SPS energy range
- The second result on $\Xi^0(1530)$ production in $p+p$ (other measurement was provided by ALICE at 7 TeV Eur.Phys.J.C 75 (2015) 1)
- Suppression of $\bar{\Xi}^0(1530)$: $\langle\bar{\Xi}^0(1530)\rangle / \langle\Xi^0(1530)\rangle \approx 0.40 \pm 0.03 \pm 0.05$

Summary

- NA61/SHINE 2D scan in system size and energy is completed.
- NA61/SHINE data delivered rich information related to the onset of deconfinement.
- Unexpected system size dependence was revealed – onset of fireball.
- Observation of $\frac{K^{+/-}}{K^0_S}$ ratio to be significantly higher than 1 in Ar+Sc at 75A GeV/c – unexpected isospin symmetry violation.
- Unique and precise results on strange baryons production in p+p interactions.

Thank you!

wobrylin@cern.ch

Have a SHINY day!

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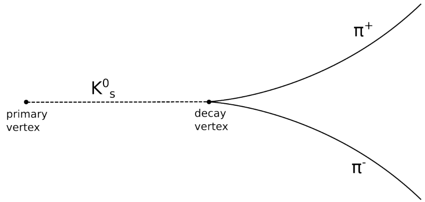
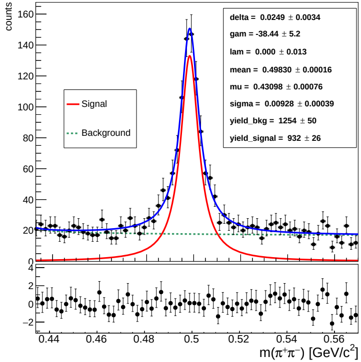
Backup

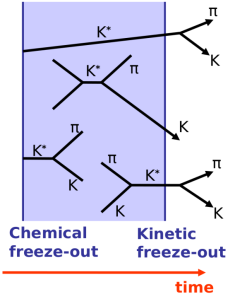
K_s^0 production in Ar+Sc at 75A GeV/c

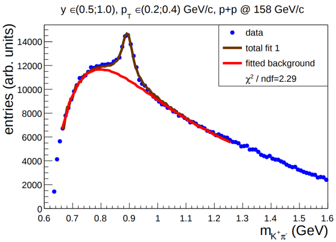


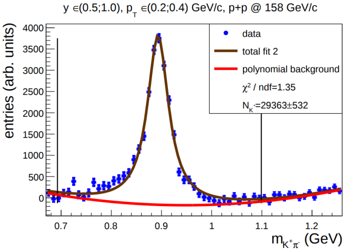
- Reconstruction based on decay topology
- K_s^0 decays into π^+ and π^- with BR≈69.2%
- A set of quality cuts is imposed onto K_s^0 candidates to improve SNR
- Lorentz function is used to describe signal



$K^*(892)^0$ meson production in $p+p$ interactions



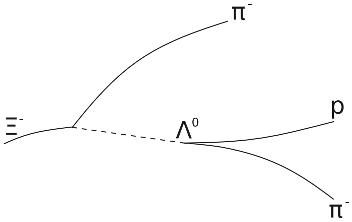


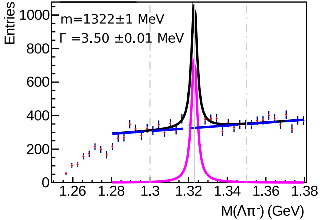


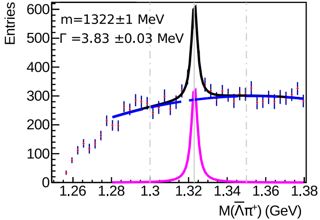
- $K^*(892)^0$ was reconstructed in $K^* \to K^+ + \pi^-$ channel
- The resonance yield is affected by regeneration and rescattering processes
- We have observable sensitive to time between chemical and kinetic freezouts Δt:

$$\left.\frac{K^*}{K^\pm}\right|_{kinetic} = \left.\frac{K^*}{K^\pm}\right|_{chemical} \cdot e^{-\Delta t/\tau}, \qquad \tau = 4.17\ \mathrm{fm}/c$$

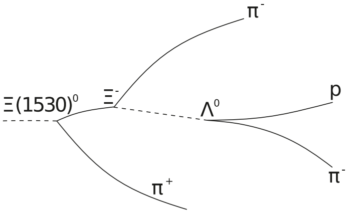
Ξ^- and $\bar{\Xi}^+$ production in $p+p$ interactions at 158 GeV/c

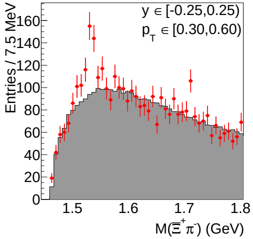


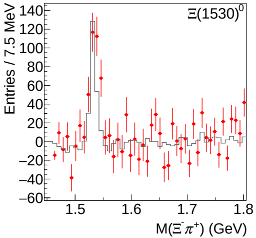




- Reconstruction based on decay topology
- $\Xi^{\pm}$ decays into $\pi^{\pm}$ and $\Lambda(\bar{\Lambda})$ with BR≈99.9%
- A set of quality cuts is imposed onto Ξ candidates to improve SNR
- Breit–Wigner function is used to describe signal







- Reconstruction based on decay topology
- $\Xi^0(1530)$ decays into Ξ and π exclusively
- A set of quality cuts is imposed onto Ξ candidates to improve SNR
- Breit–Wigner function is used to describe signal

HRG model and $p+p$ data

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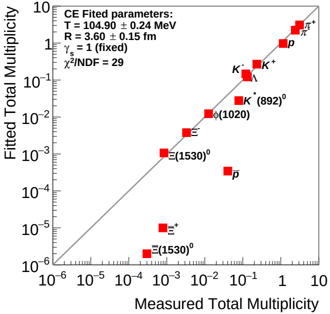
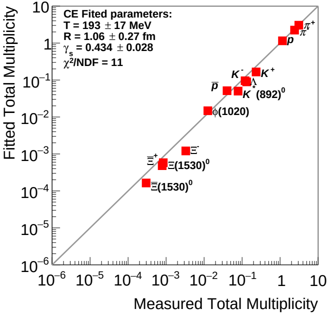




Fit done with different variants of HRG (THERMAL_FIST1.3):

- Canonical Ensemble with fixed $\gamma_s = 1$
- Canonical Ensemble with fitted γ_s

- Statistical model fails when strangeness saturation parameter γ_s is fixed
- The fit with free γ_s finds $\gamma_s = 0.434 \pm 0.028$
- Disagreement between model predictions and data is slightly reduced by allowing for out-of-equilibrium strangeness production

Onset of deconfinement

Strangeness – key property for key goal of NA61/SHINE

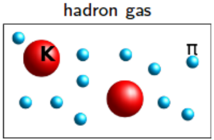
produced strangeness – number of pairs of strange and anti-strange particles

Phase Transition: $T_c \approx 150$ MeV

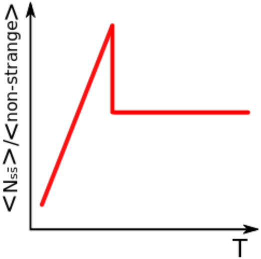
confined matter	$\longrightarrow$	quark-gluon plasma
K mesons	$\longrightarrow$	(anti-)strange quarks
$g_K = 4$	$\longrightarrow$	$g_s = 12$
$2M \approx 2 \cdot 500$ MeV	$\longrightarrow$	$2m \approx 2 \cdot 100$ MeV

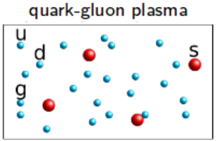
Thanks to these properties of strange mesons and strange quarks the strangeness production is sensitive to phase transition!

Statistical Model of Early Stage



$\frac{\langle K \rangle}{\langle \pi \rangle} \propto \frac{MT^{3/2}}{T^3} \cdot e^{-M/T}$





$\frac{\langle s \rangle}{\langle u+d+g \rangle} \propto \frac{T^3}{T^3} = const(T)$

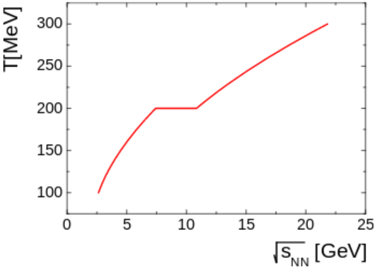
$$\langle n \rangle = \frac{gV}{(2\pi)^3} \int d^3p \frac{1}{e^{E/T} \pm 1} \approx gV \frac{2\pi^2}{4 \cdot 45} T^3 \quad \text{for light particles}$$

$$\approx gV \left(\frac{MT}{2\pi} \right)^{3/2} e^{-M/T} \quad \text{for heavy particles}$$

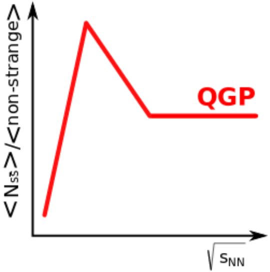
Gaździcki, Gorenstein, Acta Phys.Polon. B30 (1999) 2705

Statistical Model of Early Stage

In SMES temperature depends on collision energy as follows:

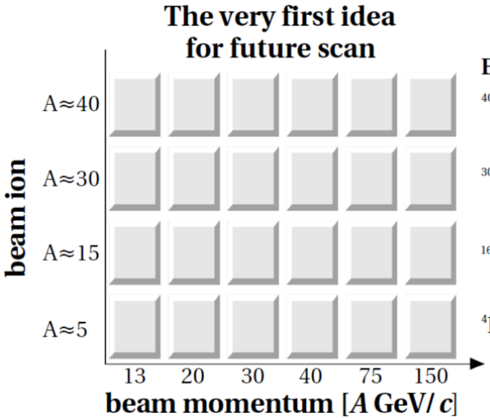


Then, the strange/non-strange particle ratio looks as follows:



- Crossing the phase transition leads to a decrease of the strange/non-strange particle ratio – the **horn-like structure**

Onset of fireball – measurements after LS3



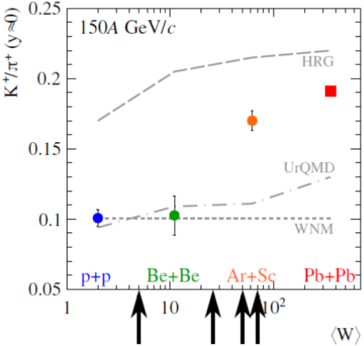
Example ion:

^{40}Ca Synergy with Gamma Factory

^{30}P

^{16}O Synergy with Cosmic-Ray LHC

^{4}He



$K^{\pm}$ spectra parametrisation

- In order to obtain the dn/dy yields, the data is extrapolated beyond the detector acceptance
- Exponential dependence in p_T is assumed:

$$f(p_T) = S \cdot p_T \cdot \exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$$

- To obtain mean multiplicity of produced particles rapidity distribution is fitted with following function:

$$f_{fit}(y) = \frac{A}{\sigma_0\sqrt{2\pi}} exp\left(-\frac{(y-y_0)^2}{2\sigma_0^2}\right) + \frac{A}{\sigma_0\sqrt{2\pi}} exp\left(-\frac{(y+y_0)^2}{2\sigma_0^2}\right)$$

- A, y_0 and σ_0 parameters are fitted