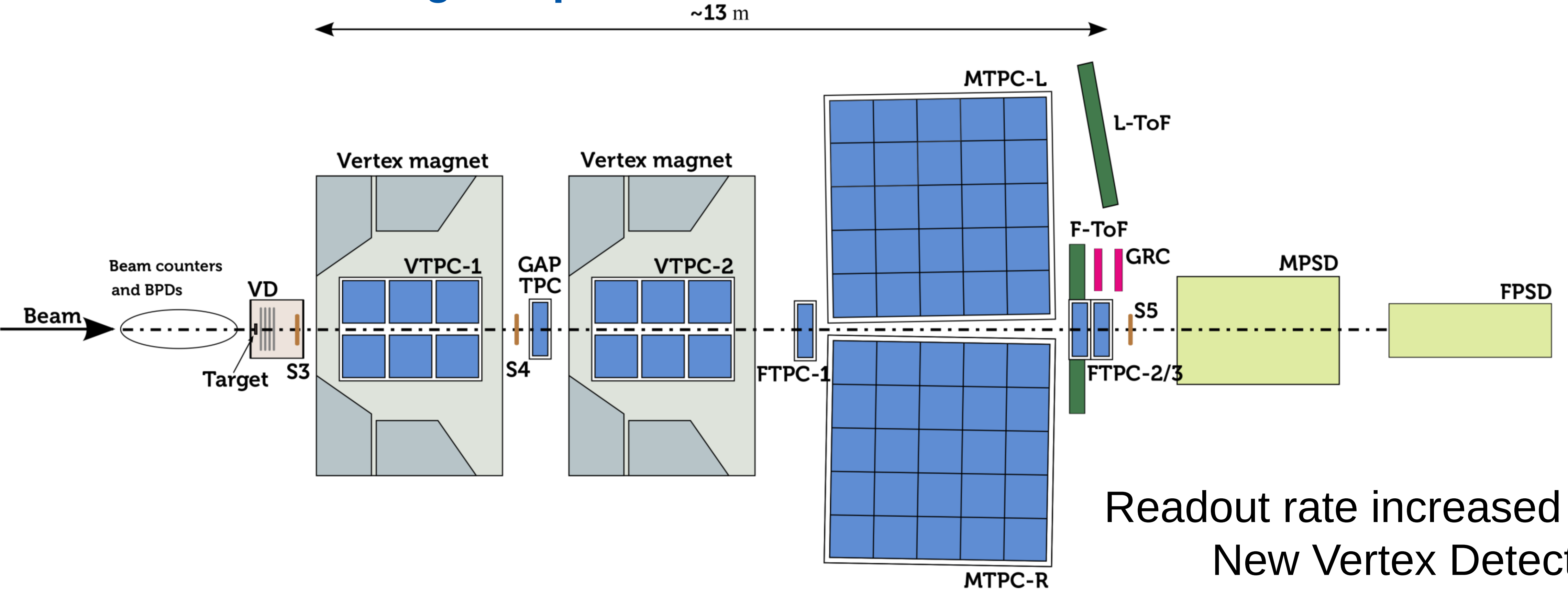
News from strong interaction program of NA61/SHINE experiment at CERN SPS

Szymon Pulawski

for NA61/SHINE

Upgraded NA61/SHINE detector

Fixed target experiment located at the CERN SPS accelerator

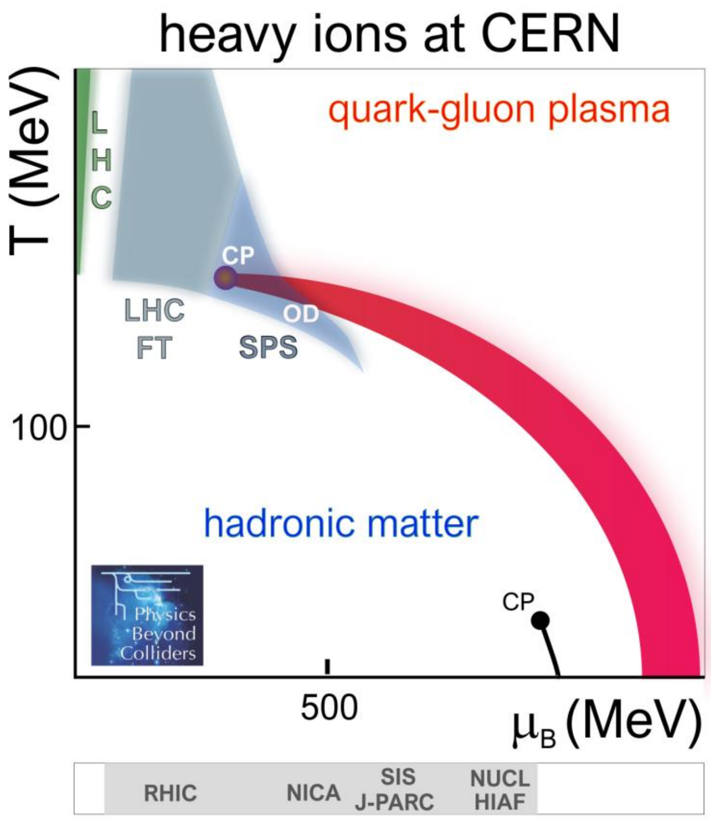


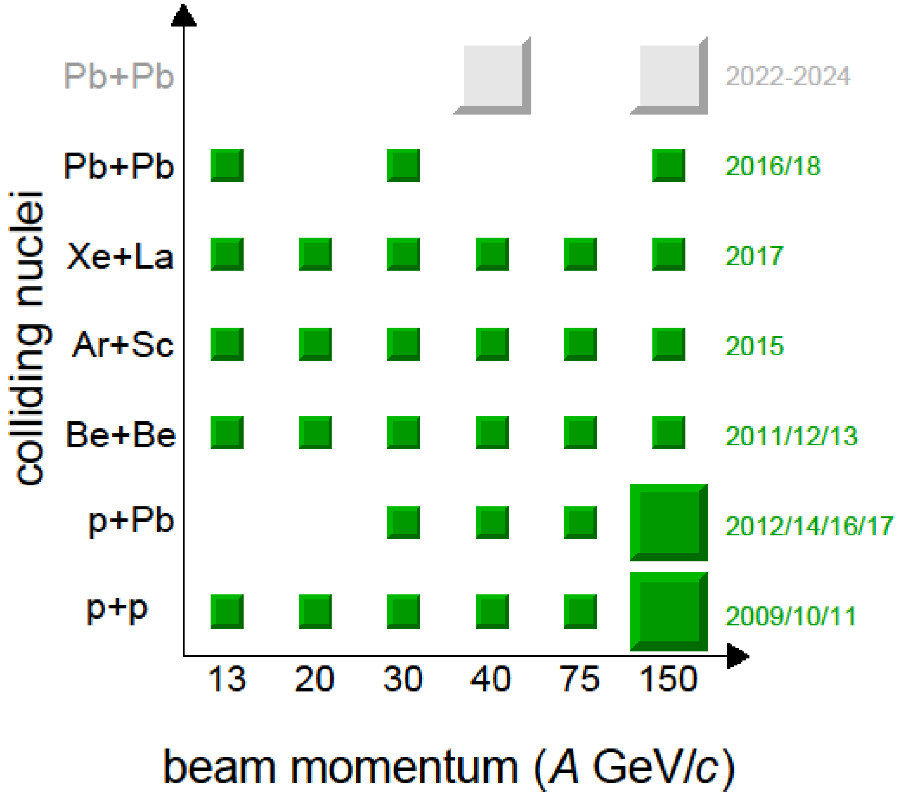
Readout rate increased to 1kHz
New Vertex Detector
New DAQ and trigger system
Upgraded PSD

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

NA61/SHINE 2-dimensional scan

NA61/SHINE performed a 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter



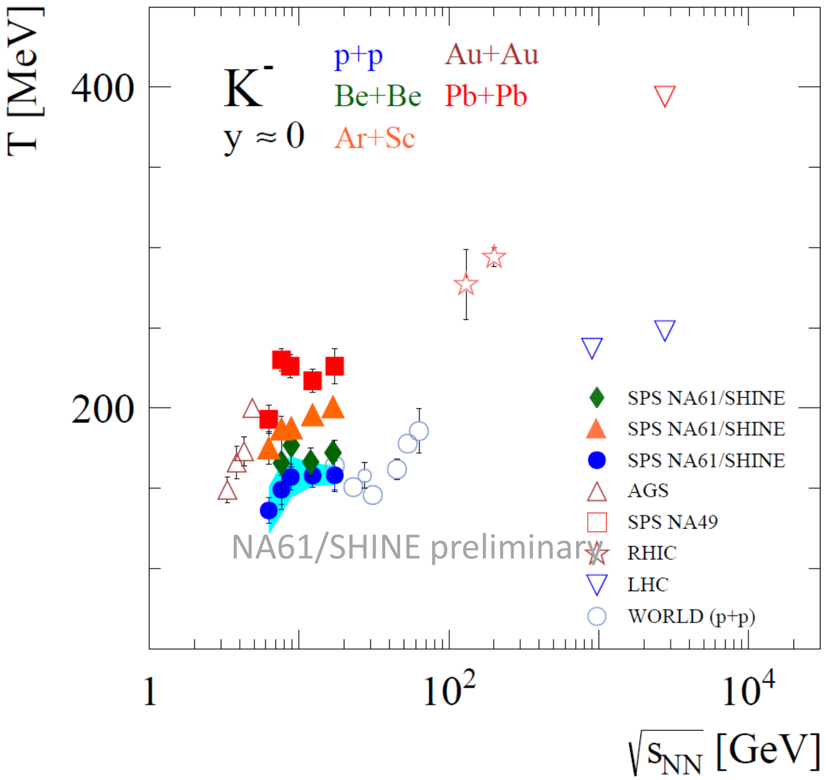


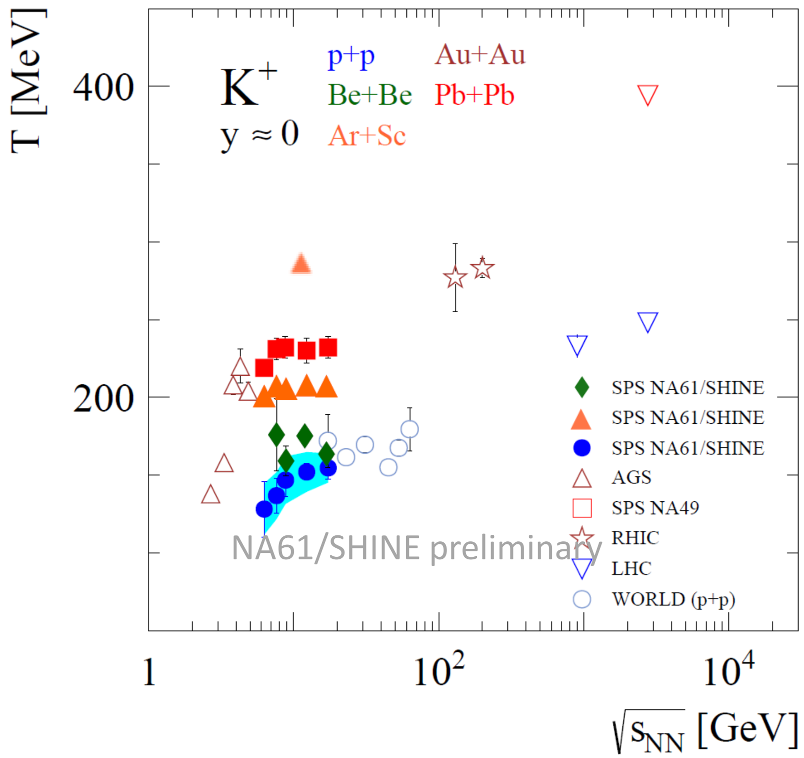
Onset of deconfinement

Onset of deconfinement: step

Qualitatively similar energy dependence is seen in p+p, Be+Be, Ar+Sc and Pb+Pb

Magnitude of T increases with the system size





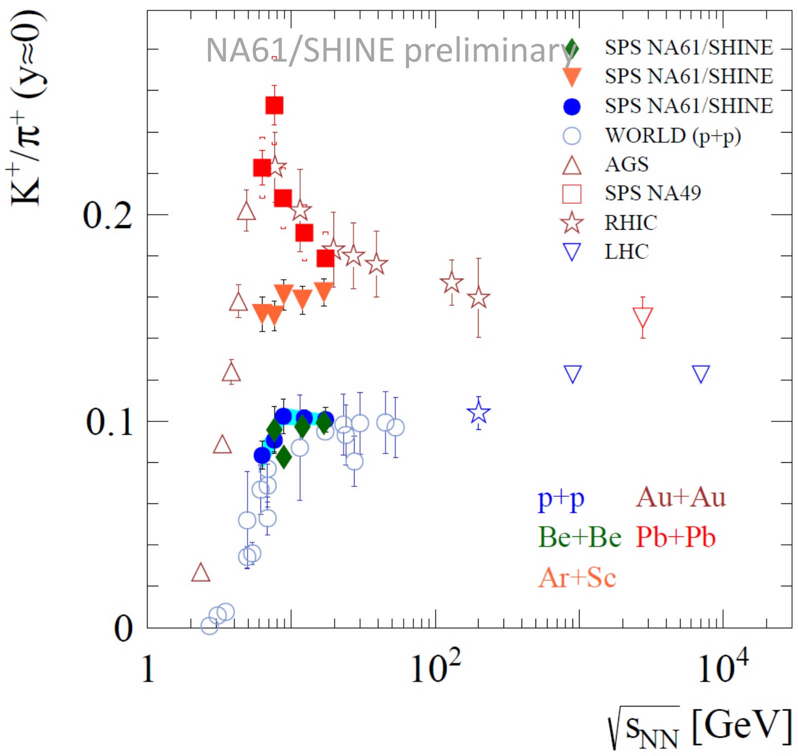
Kaons are only weakly affected by rescattering and resonance decays during the post-hydro phase (at SPS and RHIC energies).

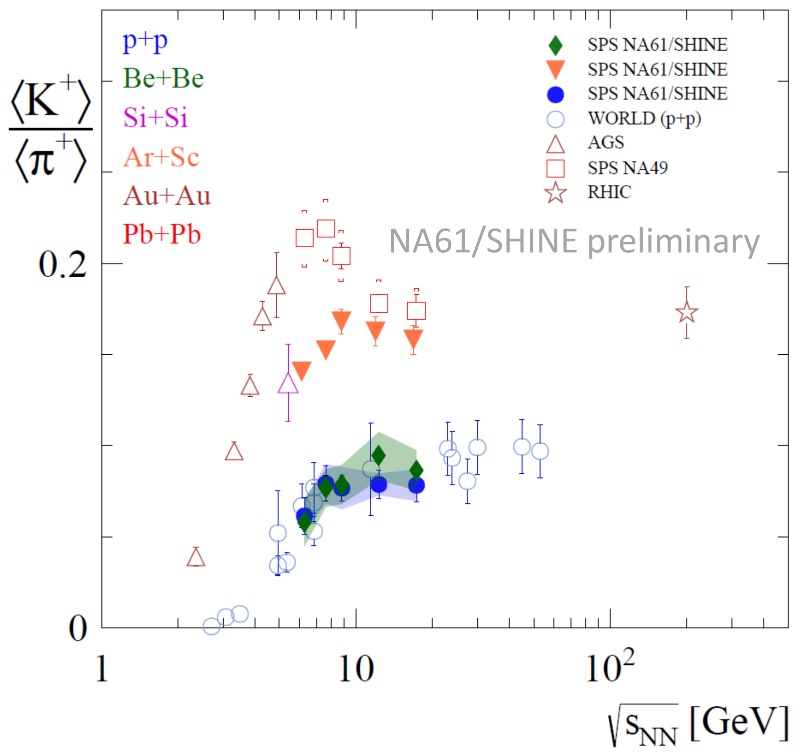
Connected temperature of the freeze-out surface and not the early-stage fireball

Onset of deconfinement: horn

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

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



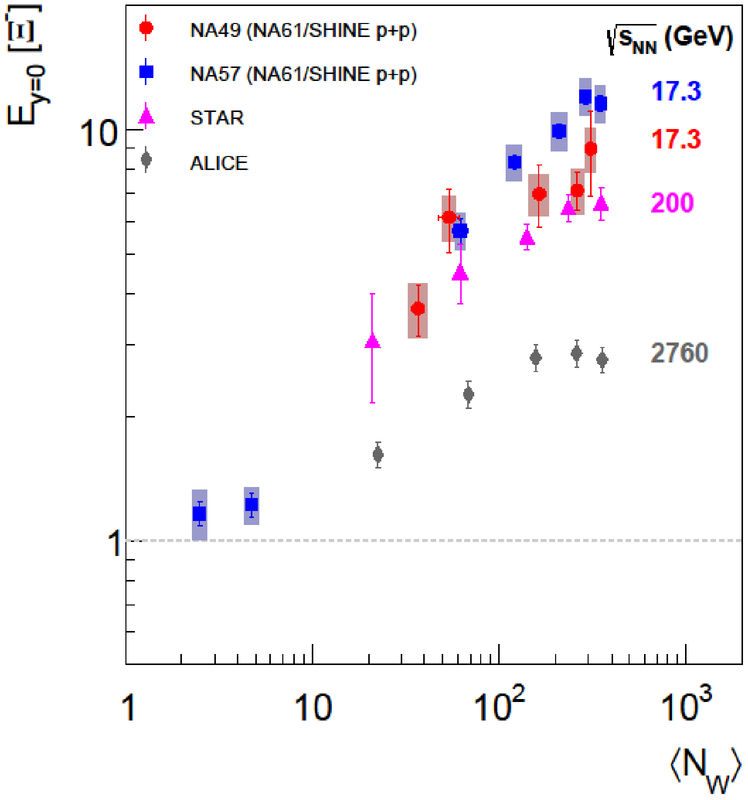


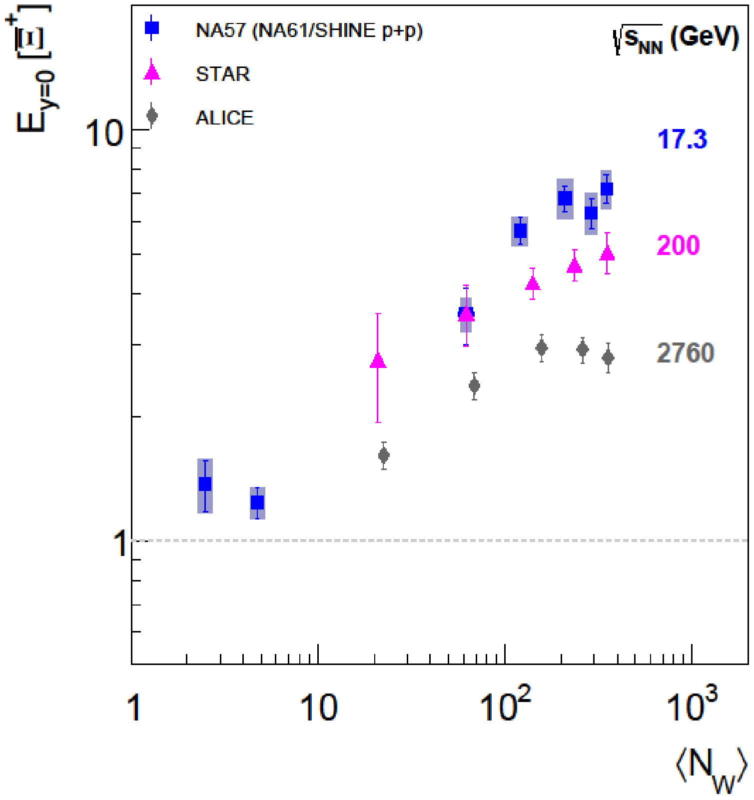
Good measure of the strangeness to entropy ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons).

Probe of the onset of deconfinement.

Strangeness enhancement factors

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





The strangeness enhancement factor:

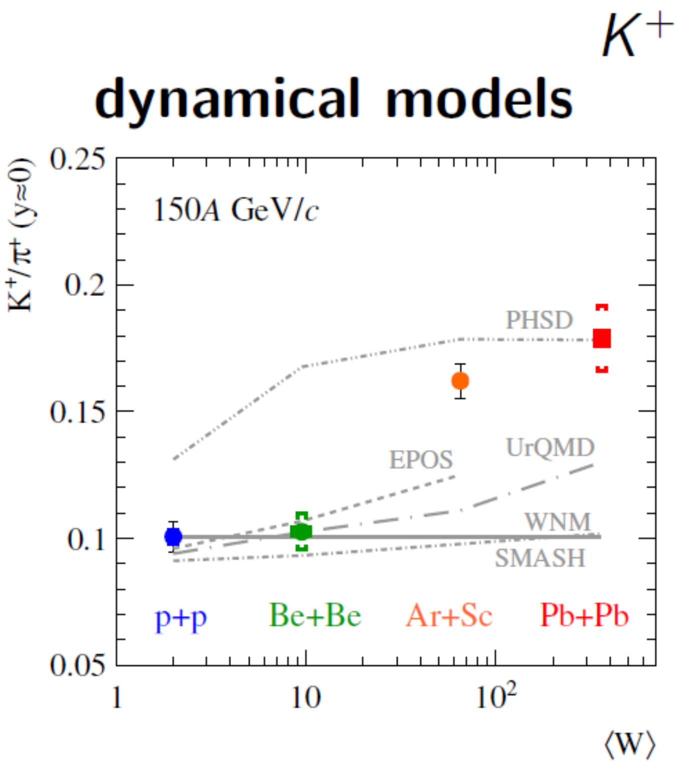
$$E = \frac{2}{\langle N_W \rangle} \frac{{dn}/{dy}\,(A+A)}{{dn}/{dy}\,(p+p)}$$

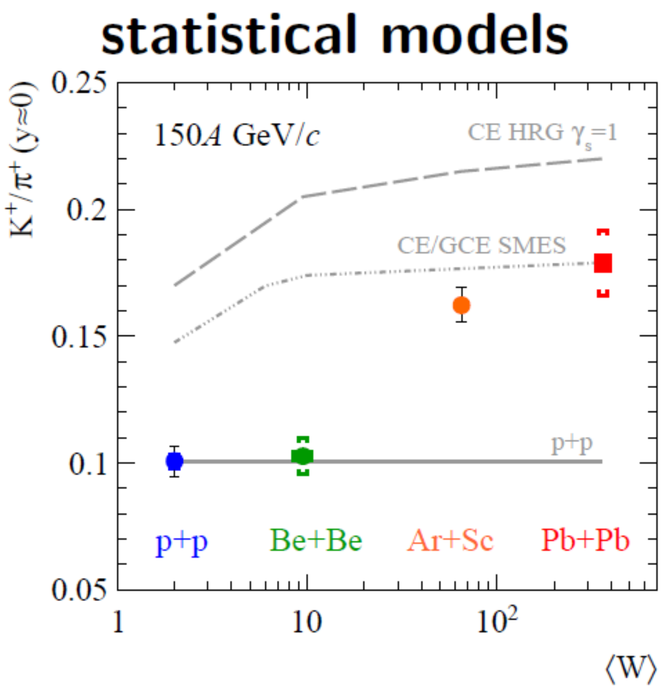
Nucl. Phys. B111 (1976) 461

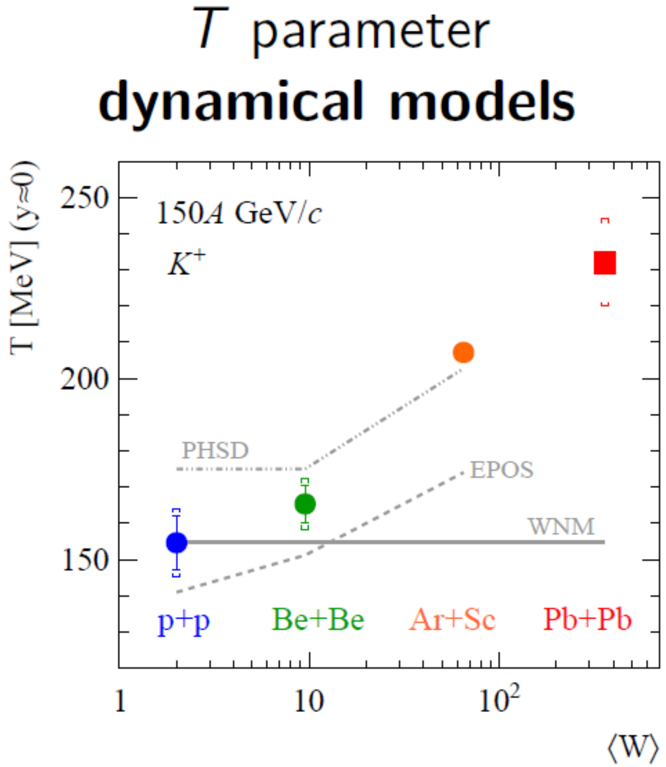
J. Phys. G 32 (2006) 427–442

System size dependence

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







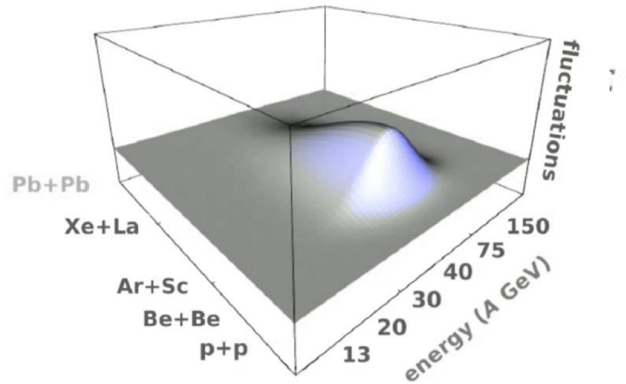
None of the models reproduces K^+/π^+ ratio or T for whole $\langle W \rangle$ range

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

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

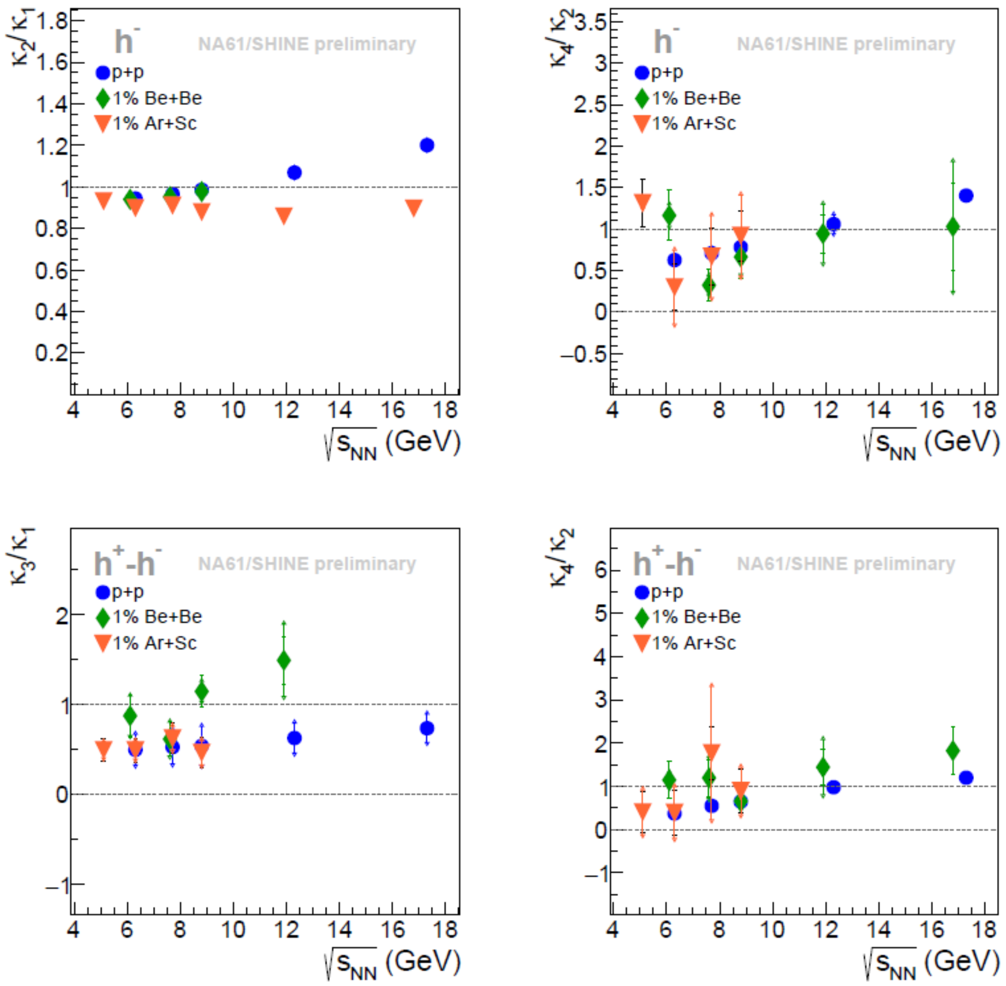
Search for critical point

Expected: non-monotonic behavior of CP signatures



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

No structure indicating critical point



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

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

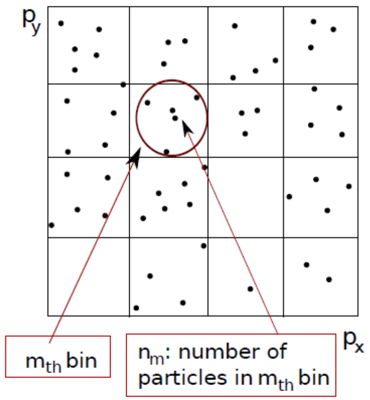
Negatively charge κ_2/κ_1: increasing difference between small systems (p+p and Be+Be) and a heavier system (Ar+Sc) with collision energy

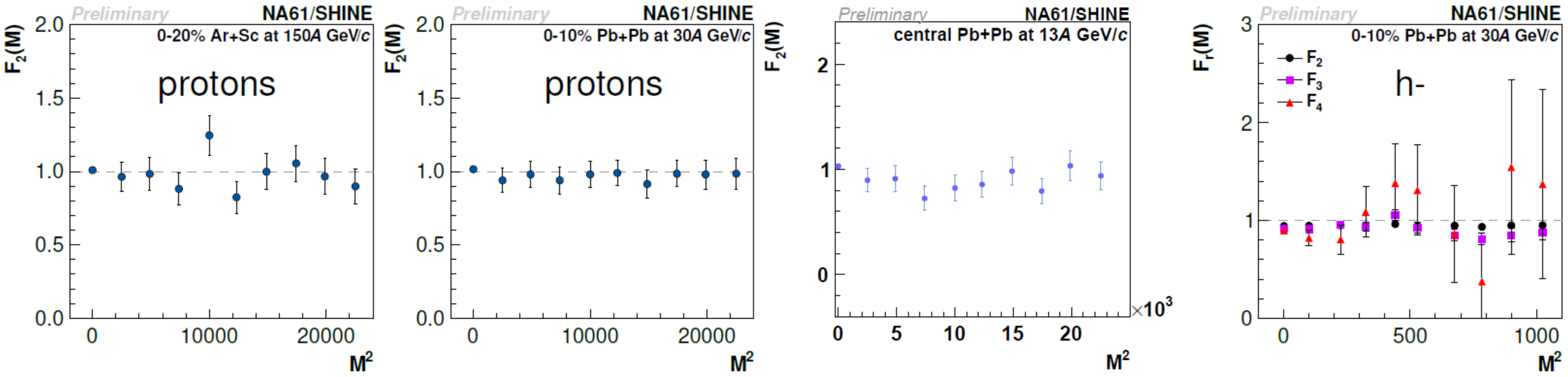
Net-charge κ_3/κ_1:increasing difference between Be+Be and other systems (p+p and Ar+Sc) with collision energy

κ_4/κ_1 : consistent values for all measured systems at given collision energy

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

No structure indicating critical point





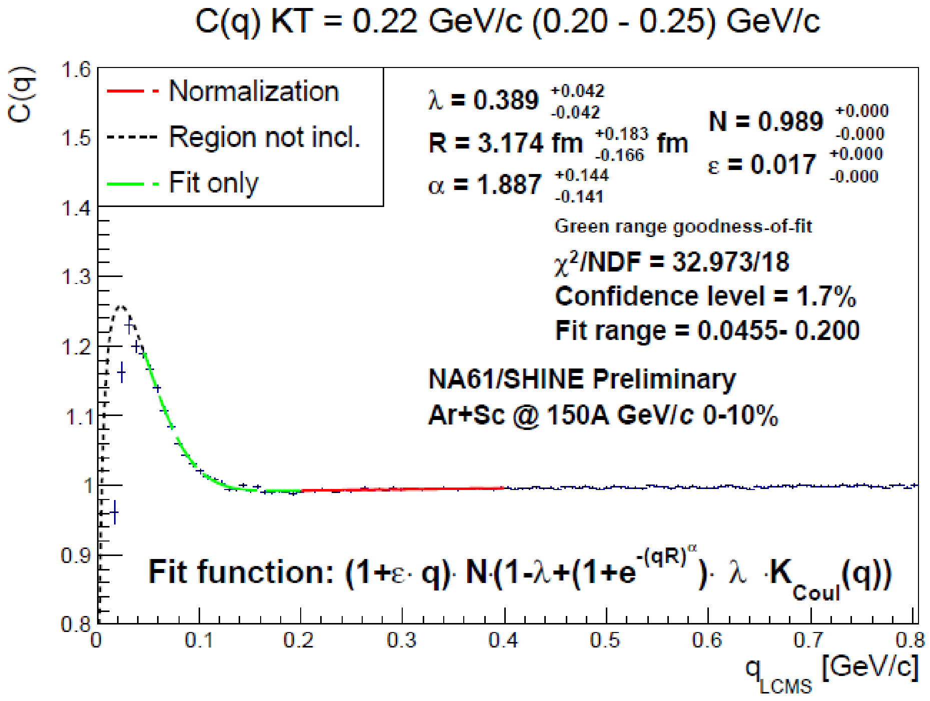
$$F_r(M) = \frac{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m(n_m-1)\ldots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M} \sum_{m=1}^{M} n_m \right\rangle^r},$$

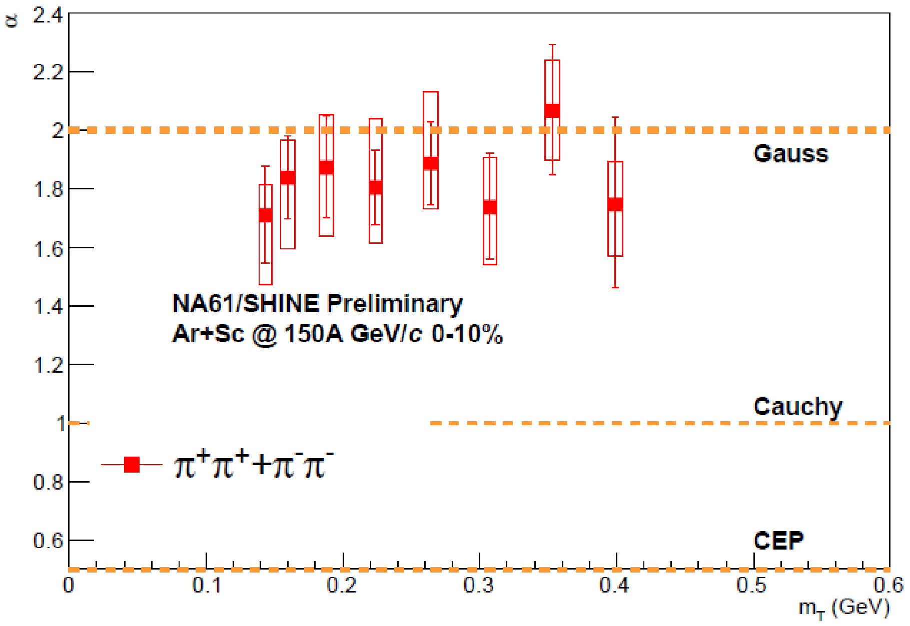
where $\langle \ldots \rangle$ denotes averaging over events, M the number of cells

Statistically independent points, cumulative variables

No indication of critical point in these analyses (power-law scaling $F_r(M) \sim M^{\phi_r}$)

Symmetric Levy HBT correlations



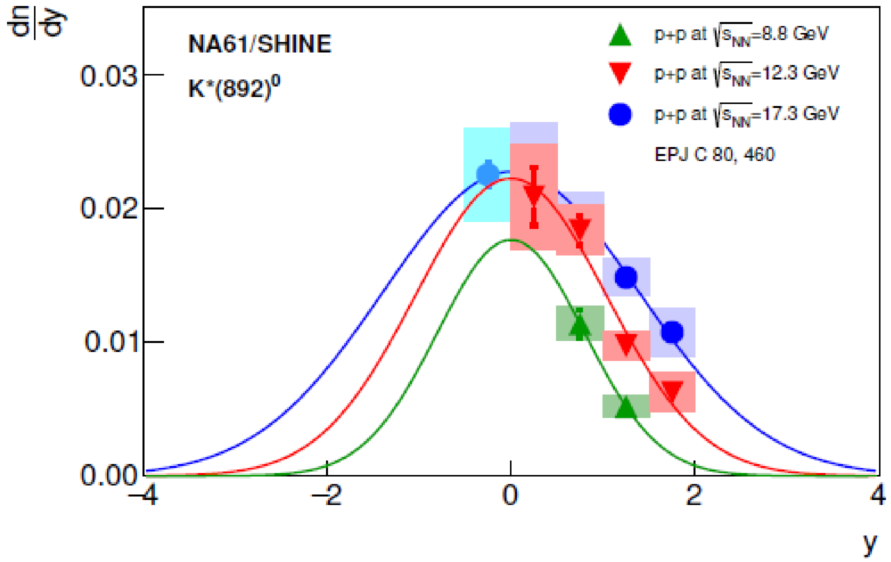


The Levy stability parameter α describes shape of the source

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

Highlights from strangeness production in p+p

$K^*(892)^0$ in p+p at 40-158 GeV/c



K^*/K^- or $K^*/K^+ \longrightarrow$ time between chemical and kinetic freeze-outs, properties of hadron gas phase

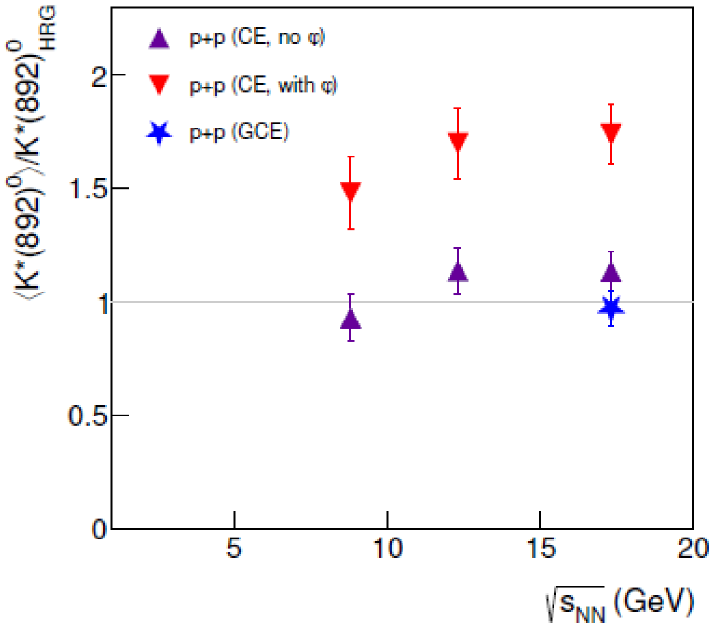
STAR, PR C71, 064902, 2005;
C. Blume, APP B43, 577, 2012

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

A+A p+p

Mean multiplicity of $K^*(892)^0$

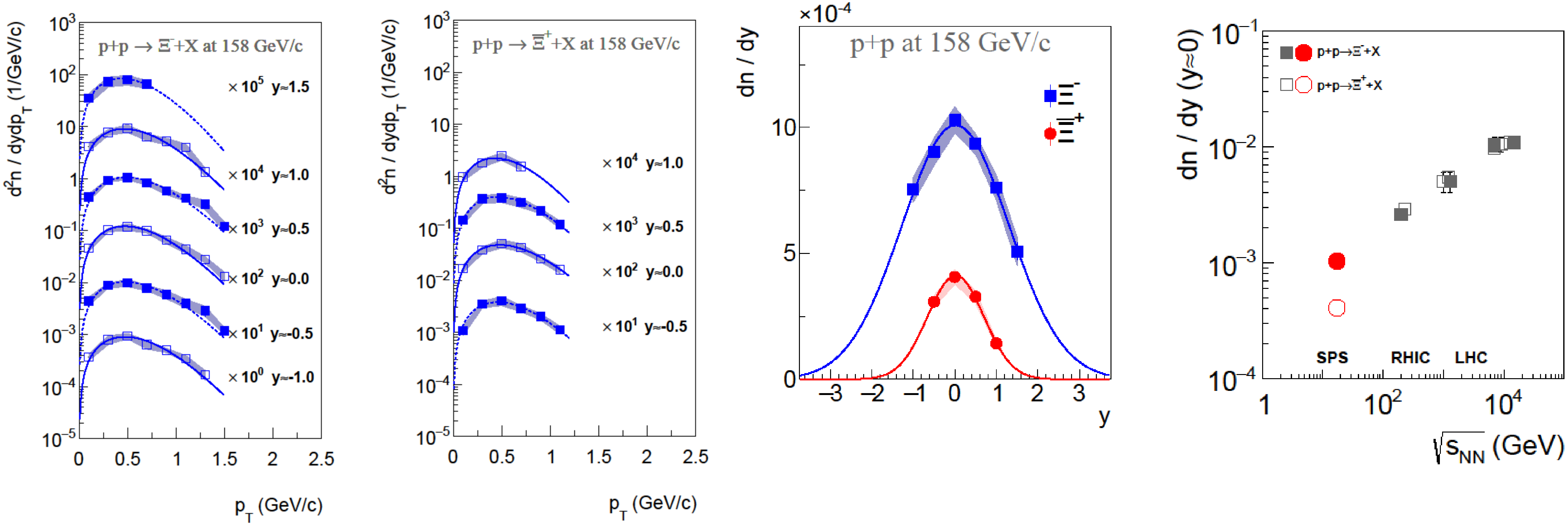
$\sqrt{sNN}$	NA61	NA49 (PR C84, 064909, 2011)
8.8	$(35.1 \pm 1.3 \pm 3.6)\cdot 10^{-3}$	-
12.3	$(58.3 \pm 1.9 \pm 4.9)\cdot 10^{-3}$	-
17.3	$(78.44 \pm 0.38 \pm 6.0)\cdot 10^{-3}$	$(74.1 \pm 1.5 \pm 6.7)\cdot 10^{-3}$



GCE: good fit (unexpectedly!)

CE: good fit only with ϕ meson excluded

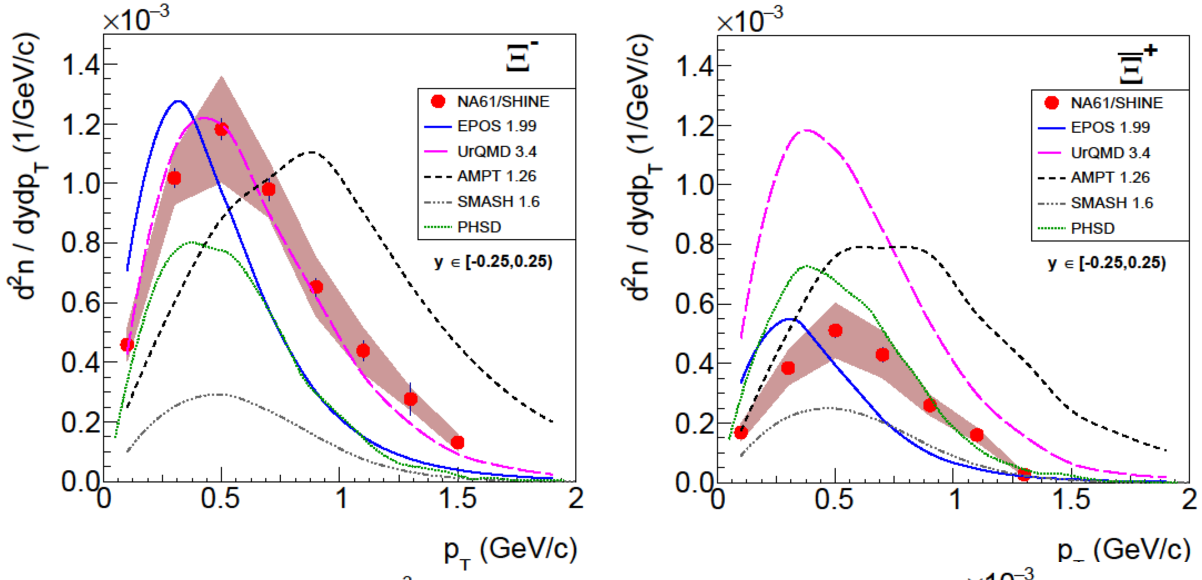
Ξ production in inelastic *p*+*p* collisions at 158 GeV/*c*



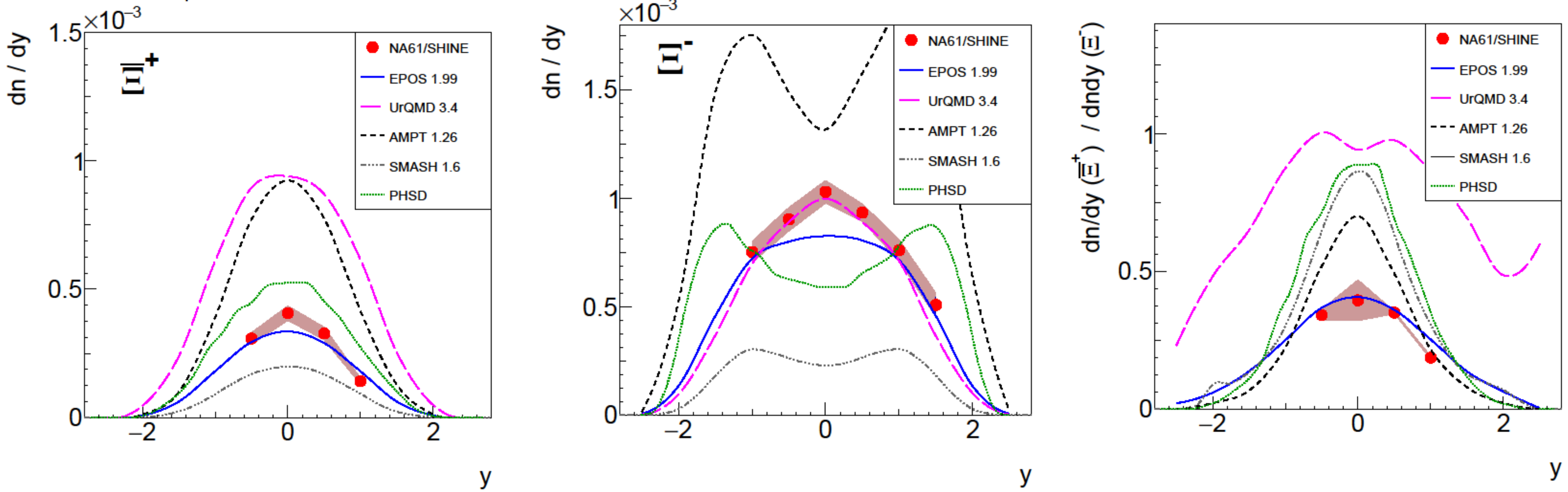
The only results on Ξ^- and $\bar{\Xi}^+$ production in *p*+*p* at SPS energy

Suppression of $\bar{\Xi}^+$ production: $\langle\bar{\Xi}^+\rangle / \langle\Xi^-\rangle = 0.24 \pm 0.01 \pm 0.05$

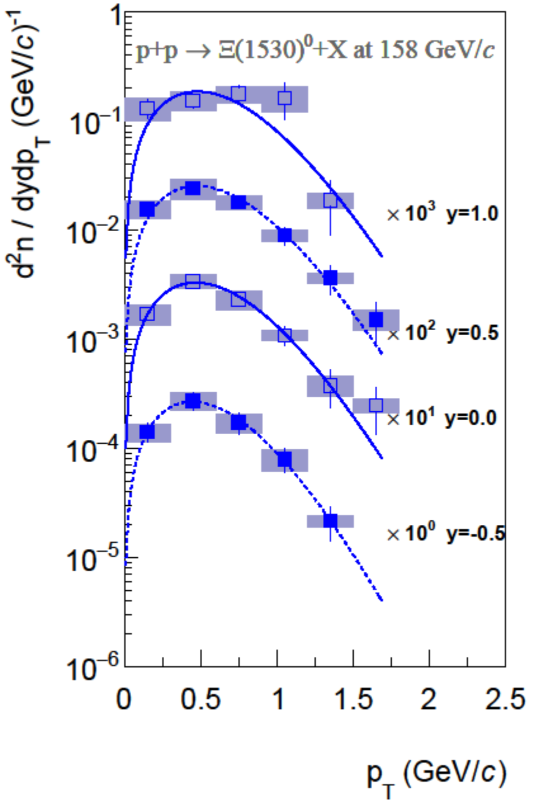
Ξ production in inelastic p+p collisions – model comparison

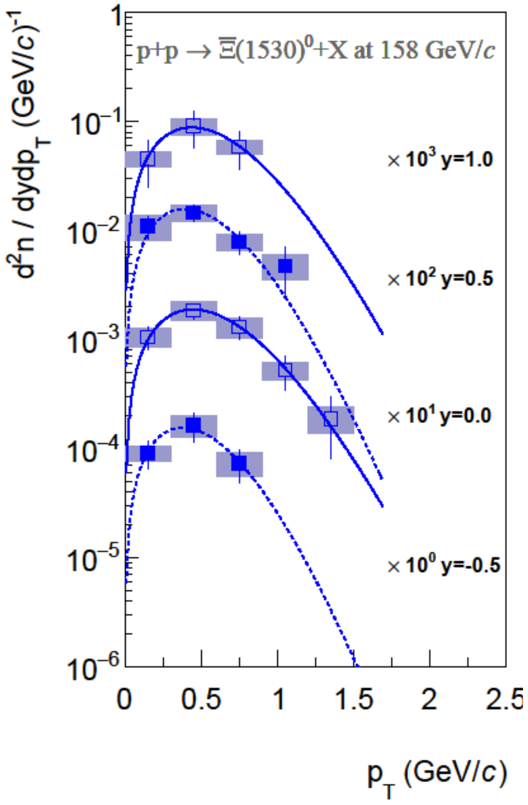


Transport models **fail** to describe the NA61/SHINE results on Ξ production in p+p collisions

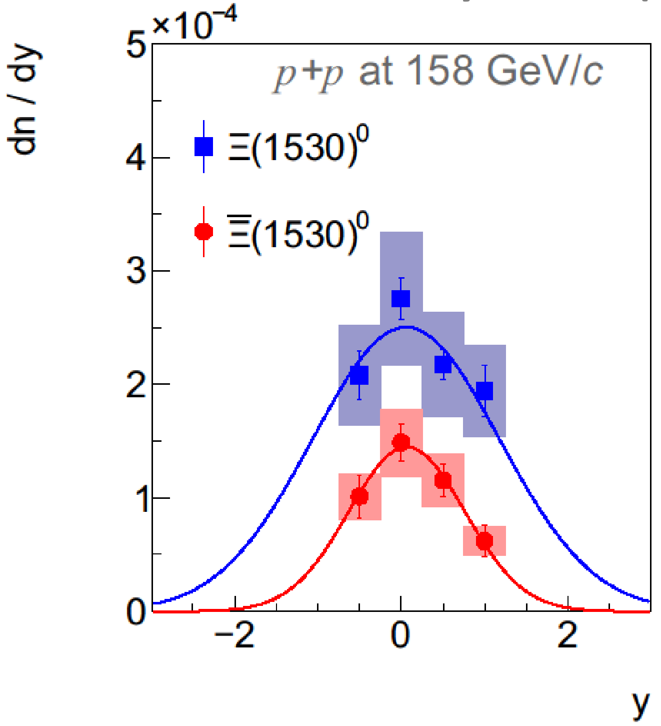


$\Xi(1530)^0$ production in inelastic *p*+*p* collisions at 158 GeV/*c*





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

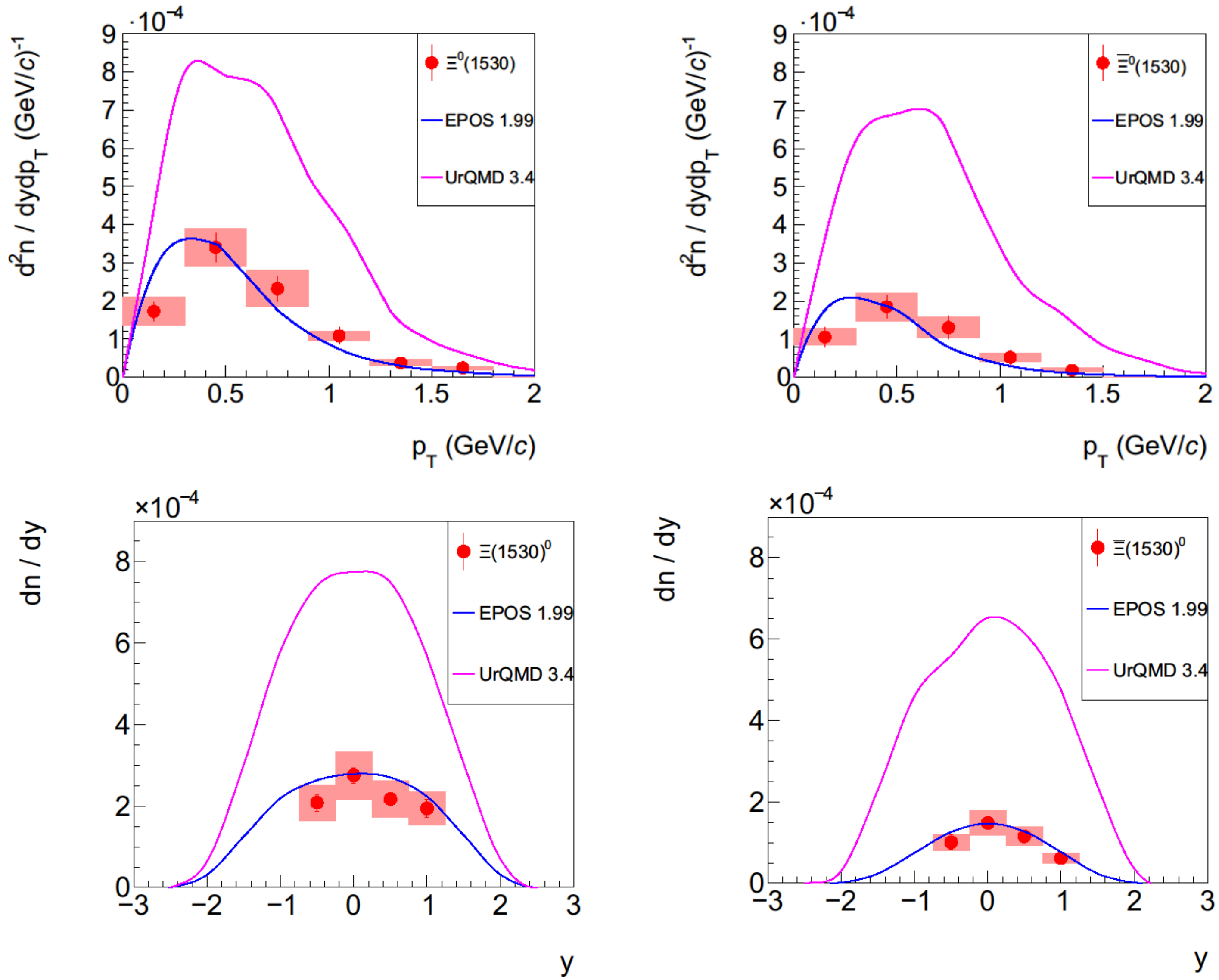


The only results on $\Xi(1530)^0$production in *p+p* at the SPS energy

The second result on $\Xi(1530)^0$ production in *p*+*p* (ALICE at 7 TeV Eur.Phys.J.C 75 (2015) 1)

Suppression of $\overline{\Xi}(1530)^0$ production: $\langle\overline{\Xi}(1530)^0\rangle / \langle\Xi(1530)^0\rangle = 0.40 \pm 0.03 \pm 0.05$

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



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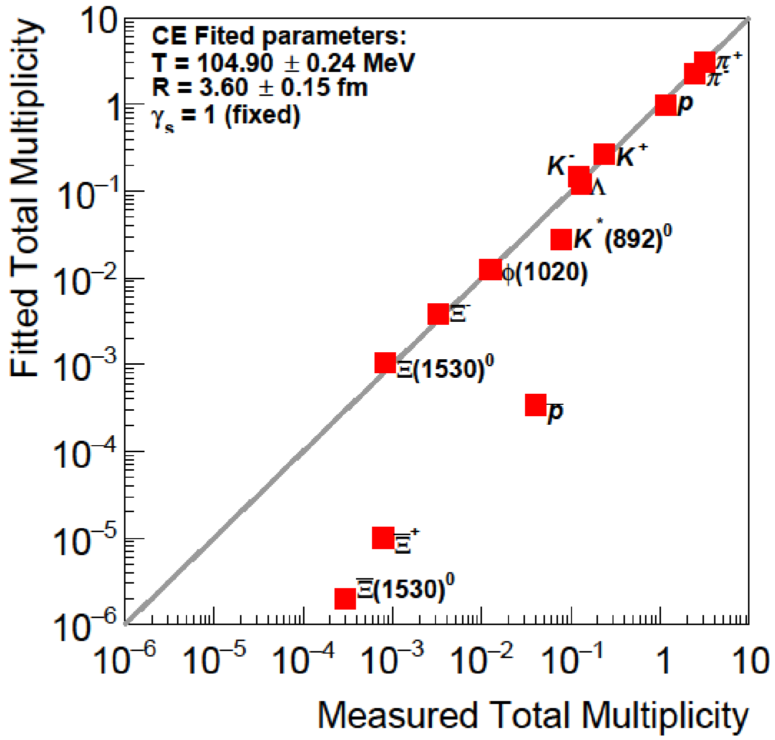
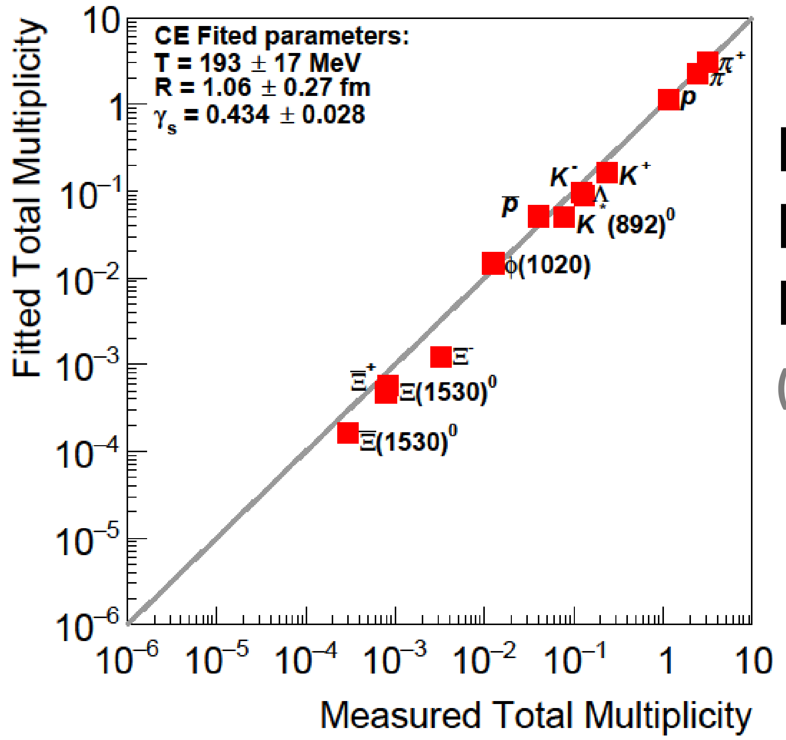
EPOS describes well transverse momentum and rapidity distributions of $\Xi(1530)^0$ and $\overline{\Xi}(1530)^0$

UrQMD significantly overestimates all spectra of $\Xi(1530)^0$ and $\overline{\Xi}(1530)^0$ hyperons

HRG model in the CE formulation and *p+p* data





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

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

- ❑ Canonical Ensemble with fixed 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

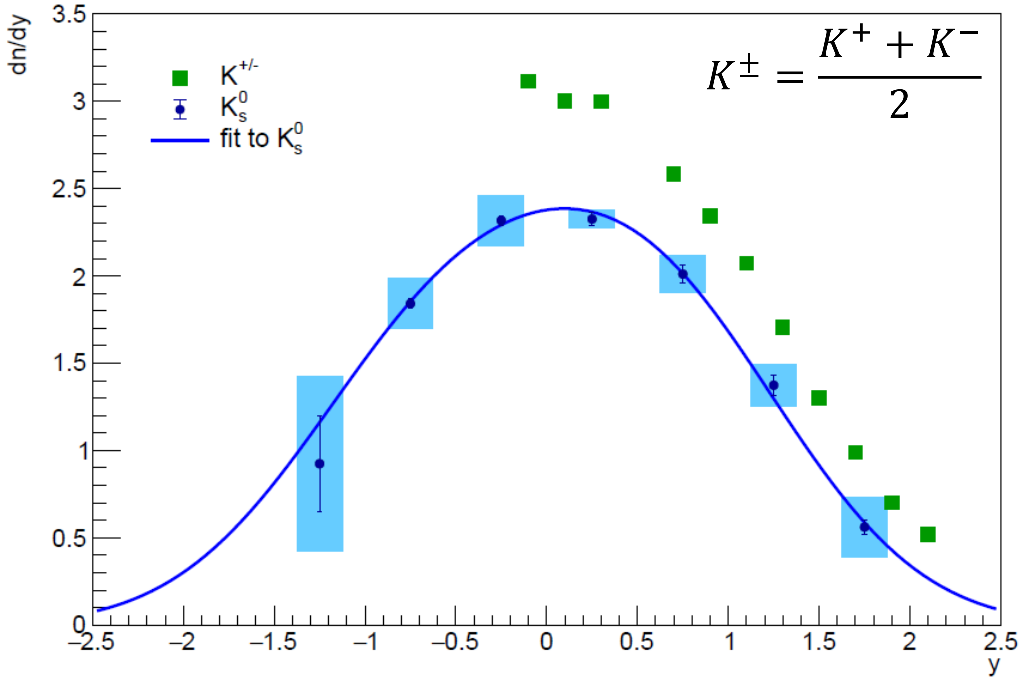
The fit with free γ_s finds γ_s =0.434±0.028 and reproduces the measurements well - a suppression of strange particle production in *p+p* collisions at CERN SPS energies

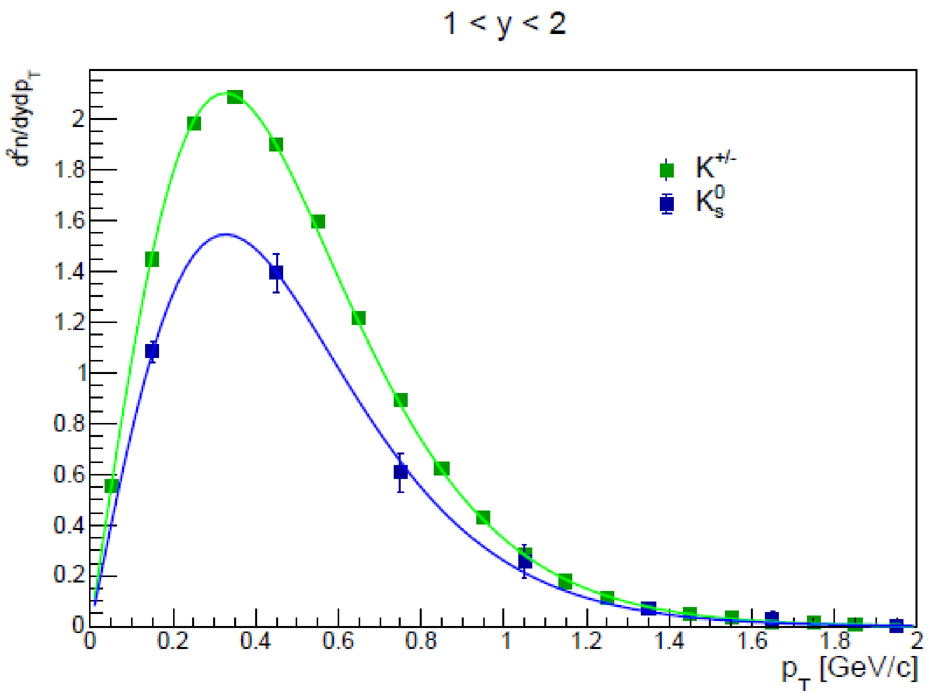
Eur.Phys.J.C: 74 (2014) 2794; 77 (2017) 671; 80 (2020) 460; 80 (2020) 199; 76 (2016) 198, 80 (2020) 833

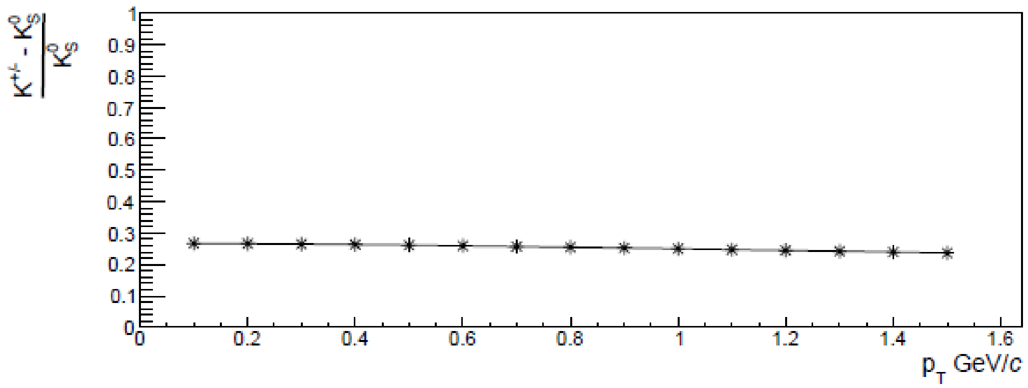
Charged/neutral kaon-ratio puzzle

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

Mean multiplicity: $\langle K_s^0 \rangle = 6.25\ \pm 0.09\ \pm 0.73$

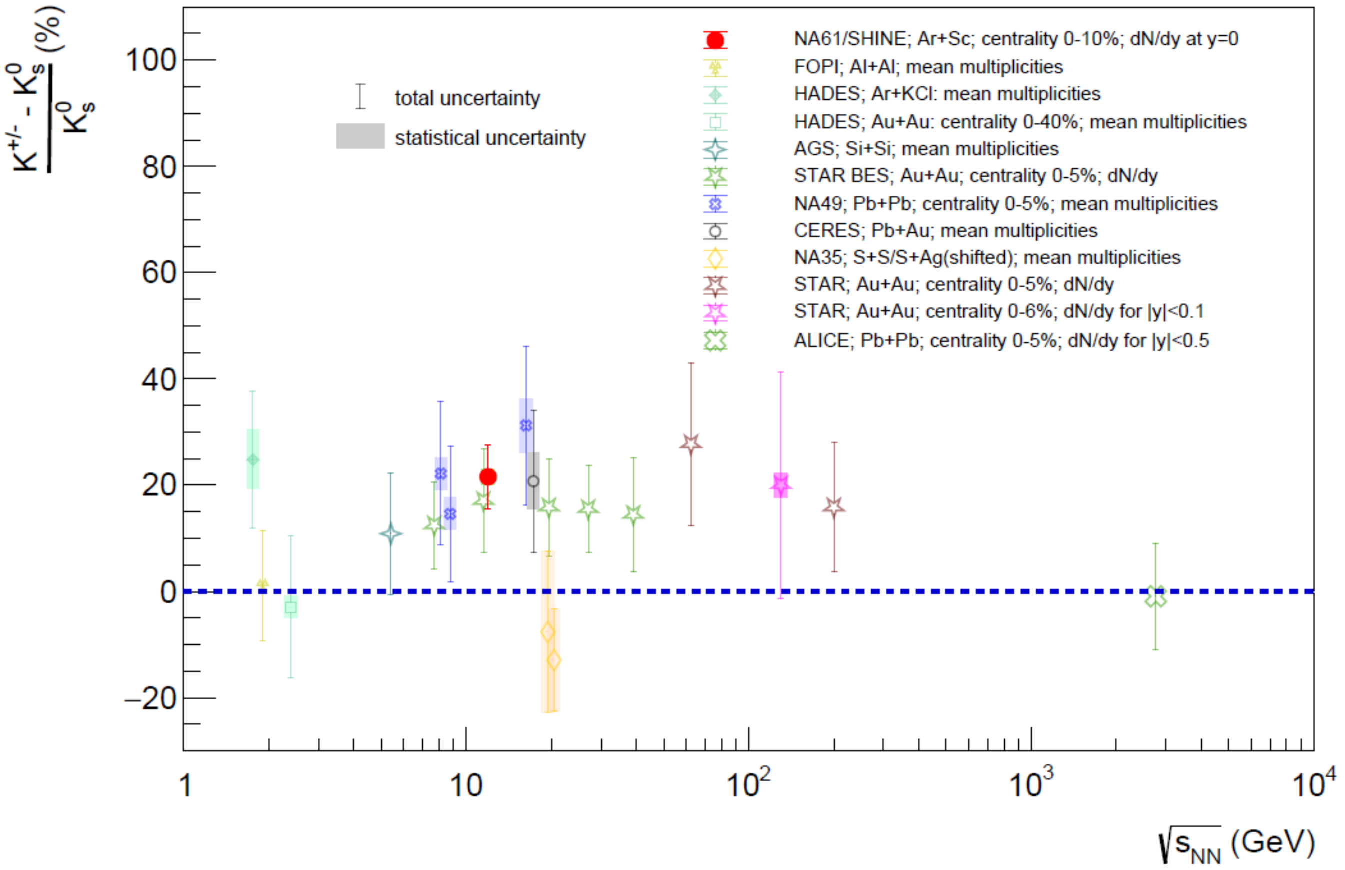






Around 25% difference between charged and neutral kaons in forward rapidity and whole p_T range

K_s^0 comparison with K+ and K- - 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

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

NA61/SHINE in 2022-2025

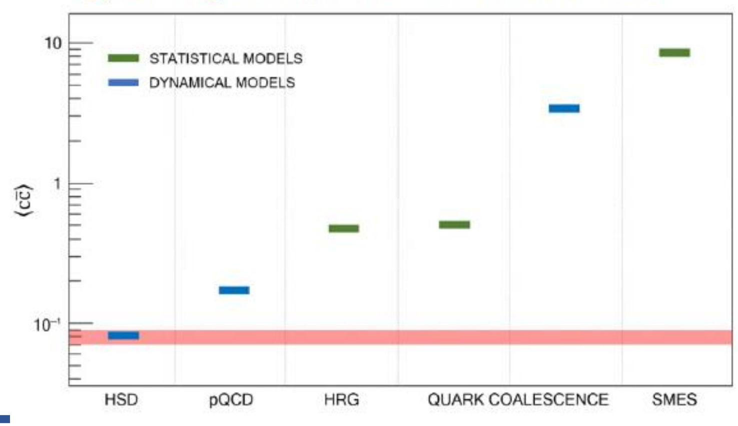
NA61/SHINE program for 2022-2024

Upgrade completed
First Pb+Pb data taking in autumn 2022

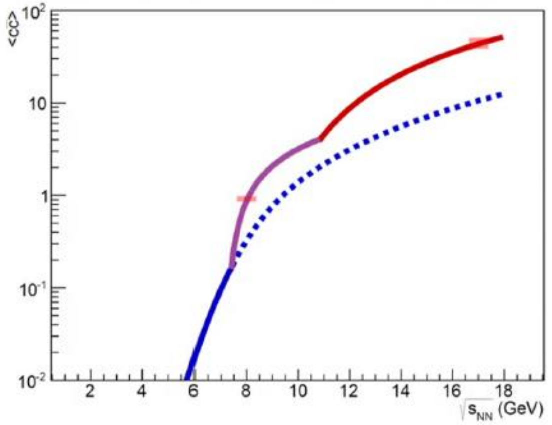
What is the mechanism of open charm production?
How does the onset of deconfinement impact open charm production?
How does the formation of quark gluon plasma impact J/ψ production?

To answer these questions the mean number of charm quark pairs, $\langle c\bar{c}\rangle$, produced in A+A collisions has to be known. Up to now the corresponding experimental data does not exist and NA61/SHINE will perform this measurement in the near future.

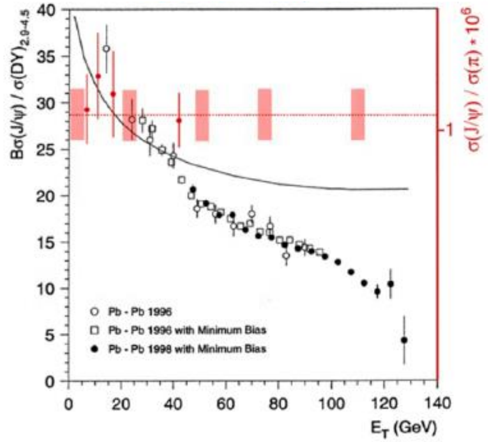
$\langle c\bar{c}\rangle$ and models



$\langle c\bar{c}\rangle$ and onset of deconfinement



$\langle c\bar{c}\rangle, \langle J/\psi\rangle$ and QGP



Summary

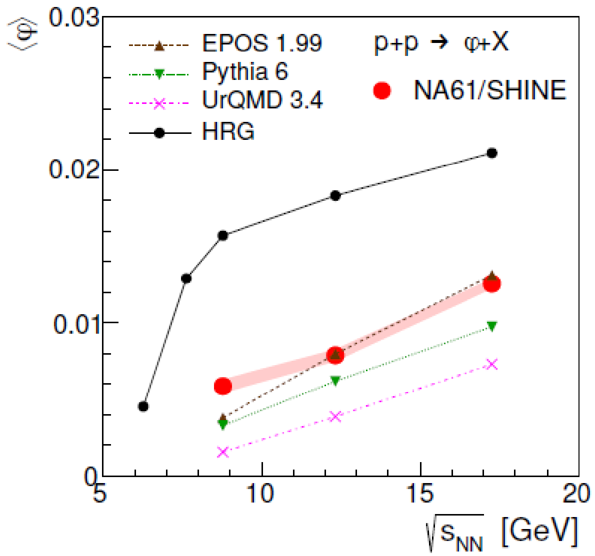
- 2D scan in system size and collision energy was completed in 2017 with Xe+La data. Analysis ongoing for p+p, Be+Be, Ar+Sc, Xe+La and Pb+Pb data
- NA61/SHINE data delivered rich information related to the onset of deconfinement.
- Unexpected system size dependence: (p+p ≈ Be+Be) ≠ (Ar+Sc ≠ Pb+Pb)
- No convincing indication of CP
- Unique results on strange baryons production in p+p interactions
- $\frac{K^{\pm}-K_s^0}{K_s^0}$ ratio significantly higher than 1 in Ar+Sc at 75A GeV/c
- NA61/SHINE program with measurements of open charm production in 2022-2025

NA61/SHINE at SQM conference

- P. Podlaski, Tuesday 15:20, „Results on system size dependence of strangeness production in the CERN SPS energy range from NA61/SHINE"
- N. Davis , Wednesday 9:40, „Assessing critical point signatures through proton intermittency in NA61/SHINE"
- Posters:
  - T. Czopowicz, „Search for critical point in NA61/SHINE (POS-BLK-11)"
  - A. Tefelska, „Mesonic strange resonances in p+p collisions at SPS energies (POS-RES-04)"
  - A. Shukla, „Identified hadron spectra in high-statistics p+p collisions at 158 GeV/c (POS-OTH-02)"

Thank you

Strangeness production in p+p at 158 GeV/c



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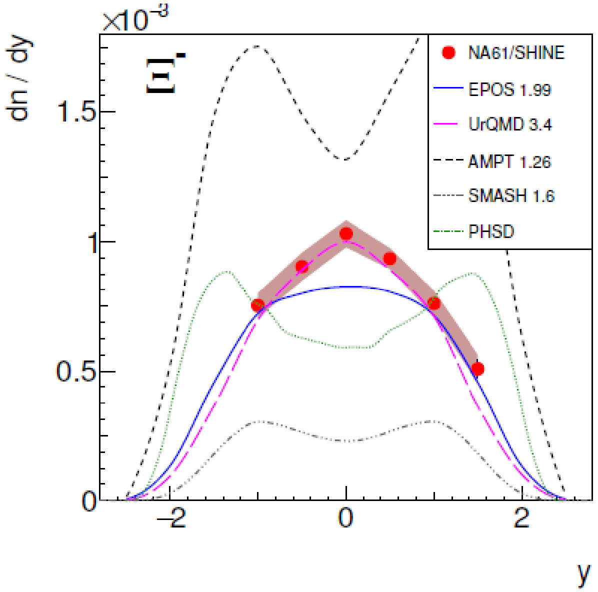
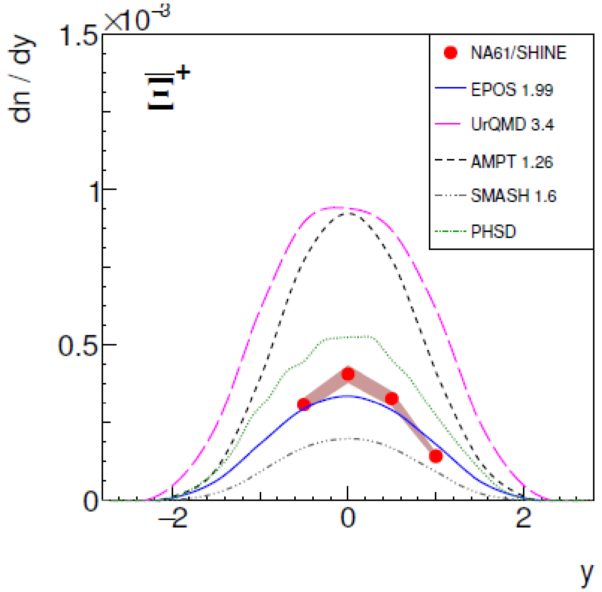
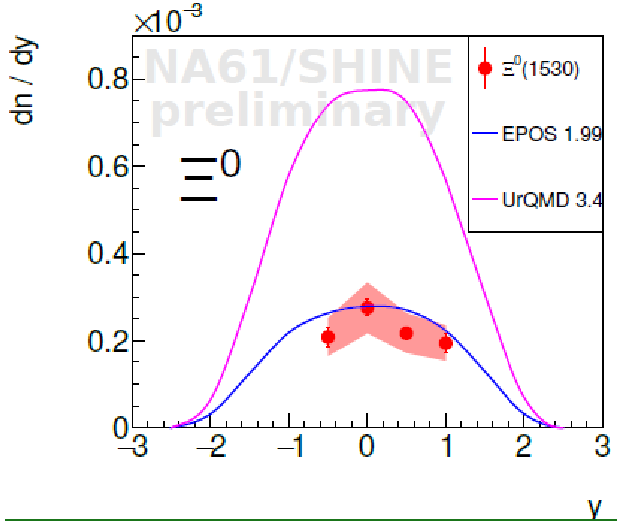
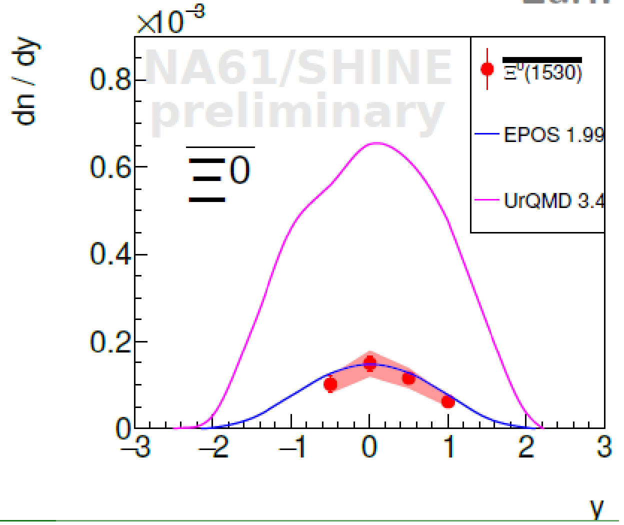




Eur.Phys.J.C 80 (2020) 9, 833



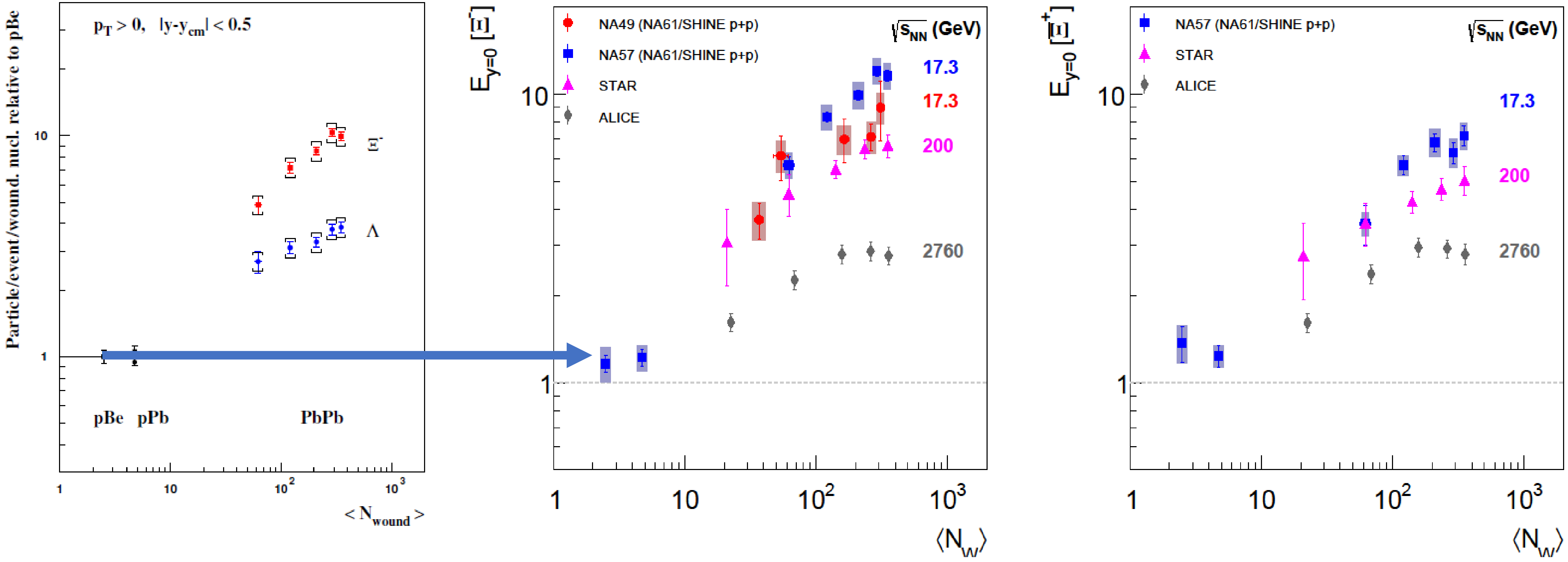


Present theoretical models do not describe the NA61/SHINE results on strange particles production in p+p interactions

Strangeness enhancement factors

J. Phys. G 32 (2006) 427–442

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

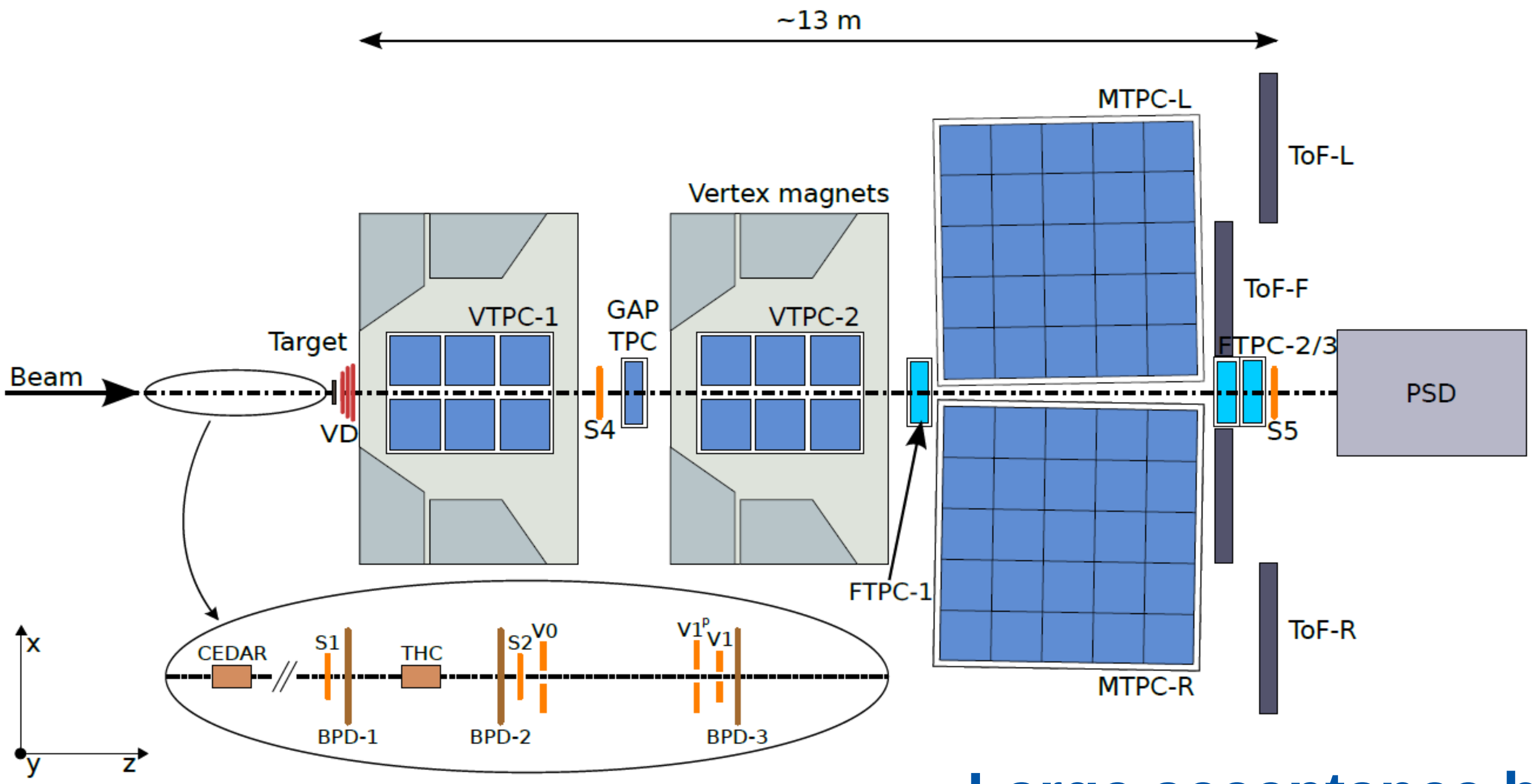


$$E_{\Xi_s} = \frac{2}{\langle N_W \rangle} \frac{dn/dy(A+A)}{dn/dy(p+p)}$$

NA61/SHINE results give new base-line for strangeness enhancement study in SPS energy range

NA61/SHINE

Fixed target experiment located at the CERN SPS accelerator



Beams:

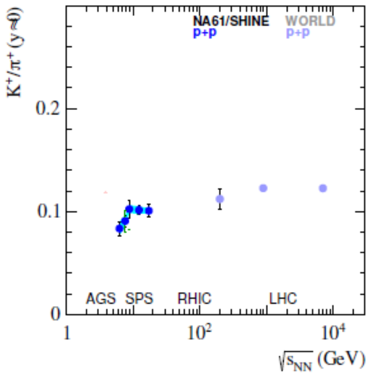
- ions (Be, Ar, Xe, Pb)
  p_{beam}=13A–150A GeV/c
- hadrons (π, K, p)
  p_{beam}=13–400 GeV/c
- $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

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

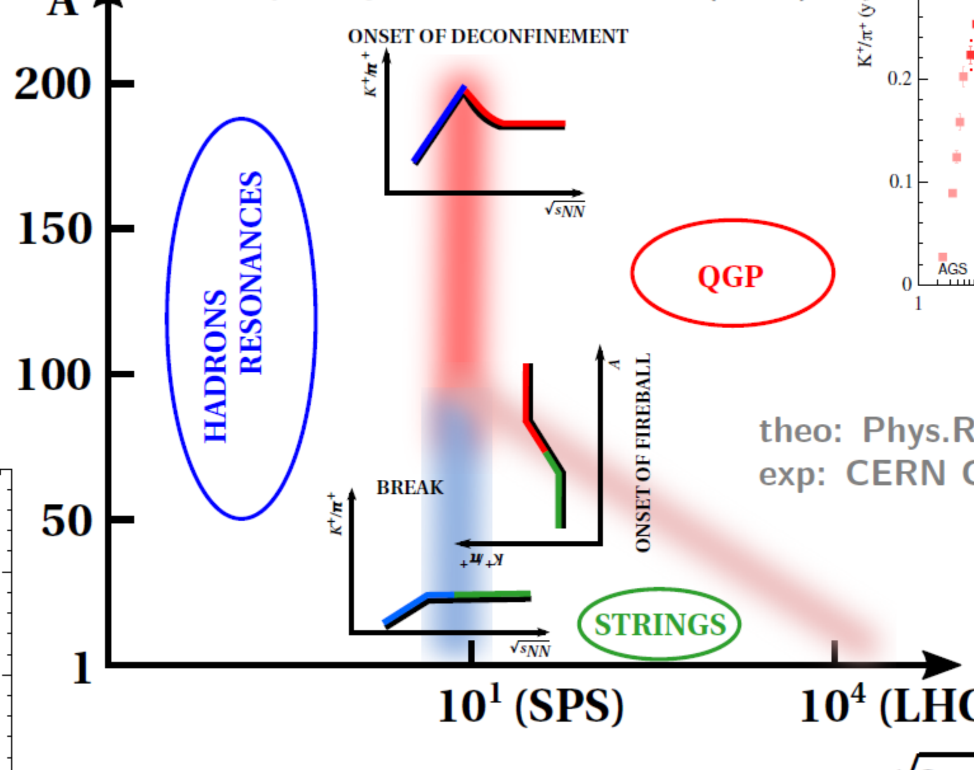
Diagram of high-energy nuclear collisions

Hypothetical domains of hadron-production dominated by:

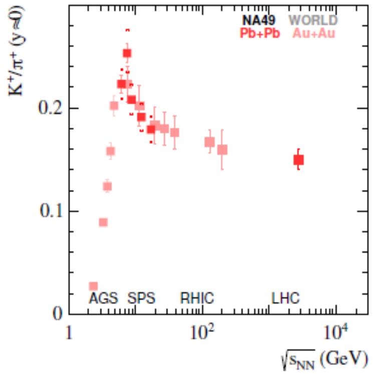
- resonance creation and decays
- string creation and decays
- quark-gluon plasma formation and hadronisation



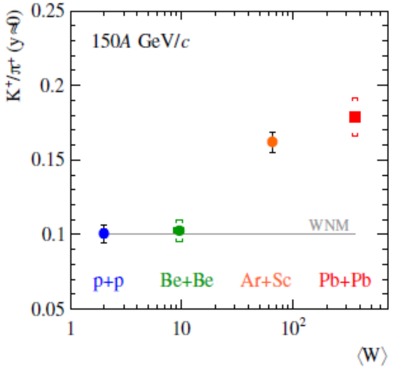
theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)



$\sqrt{s_{NN}}$ [GeV]



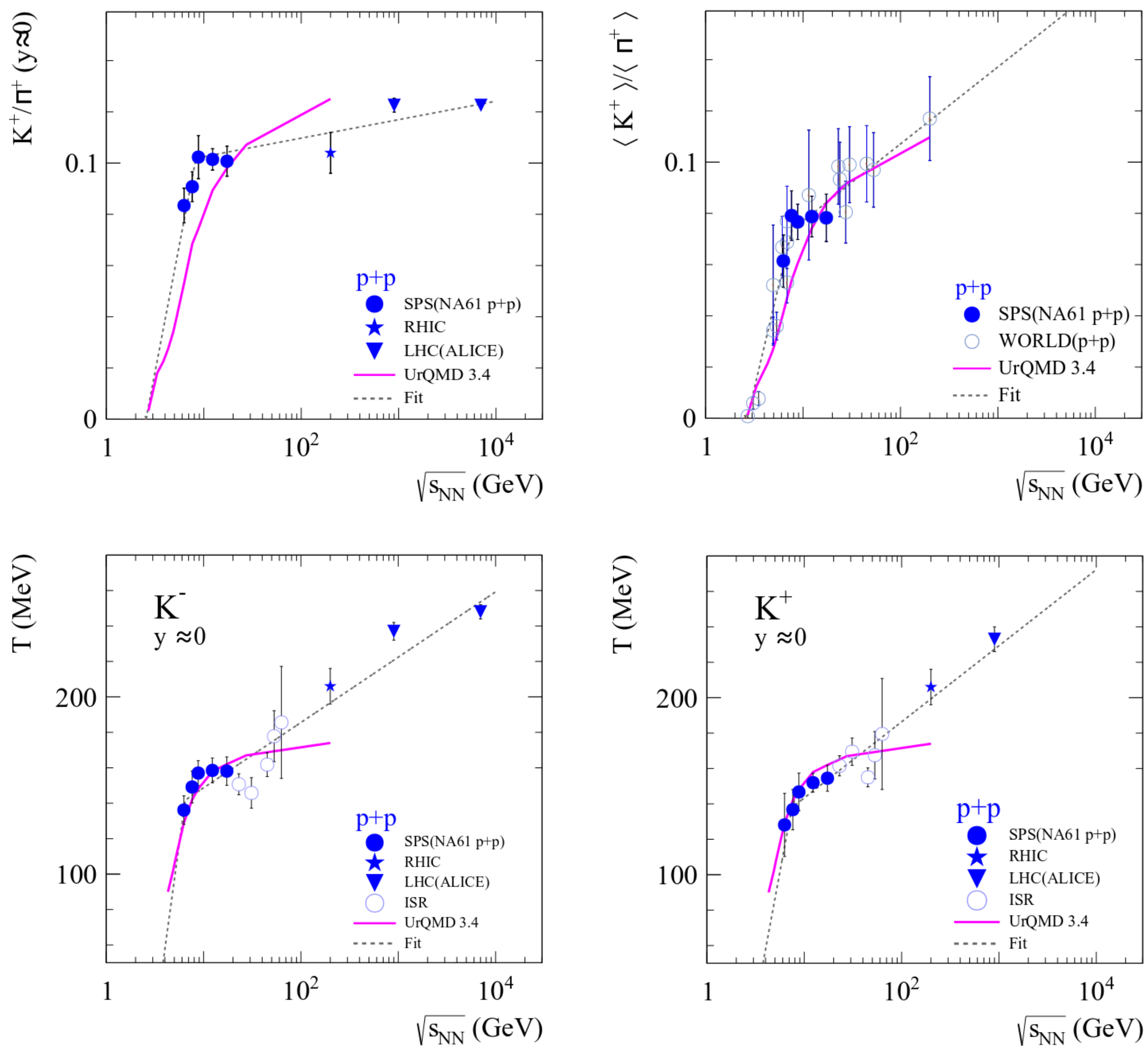
theo: Phys.Rev.D 90 025031 (2014)
exp: CERN Courier, Sep 23rd, 2019



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

Transition from resonances to strings

Transition from resonances to strings



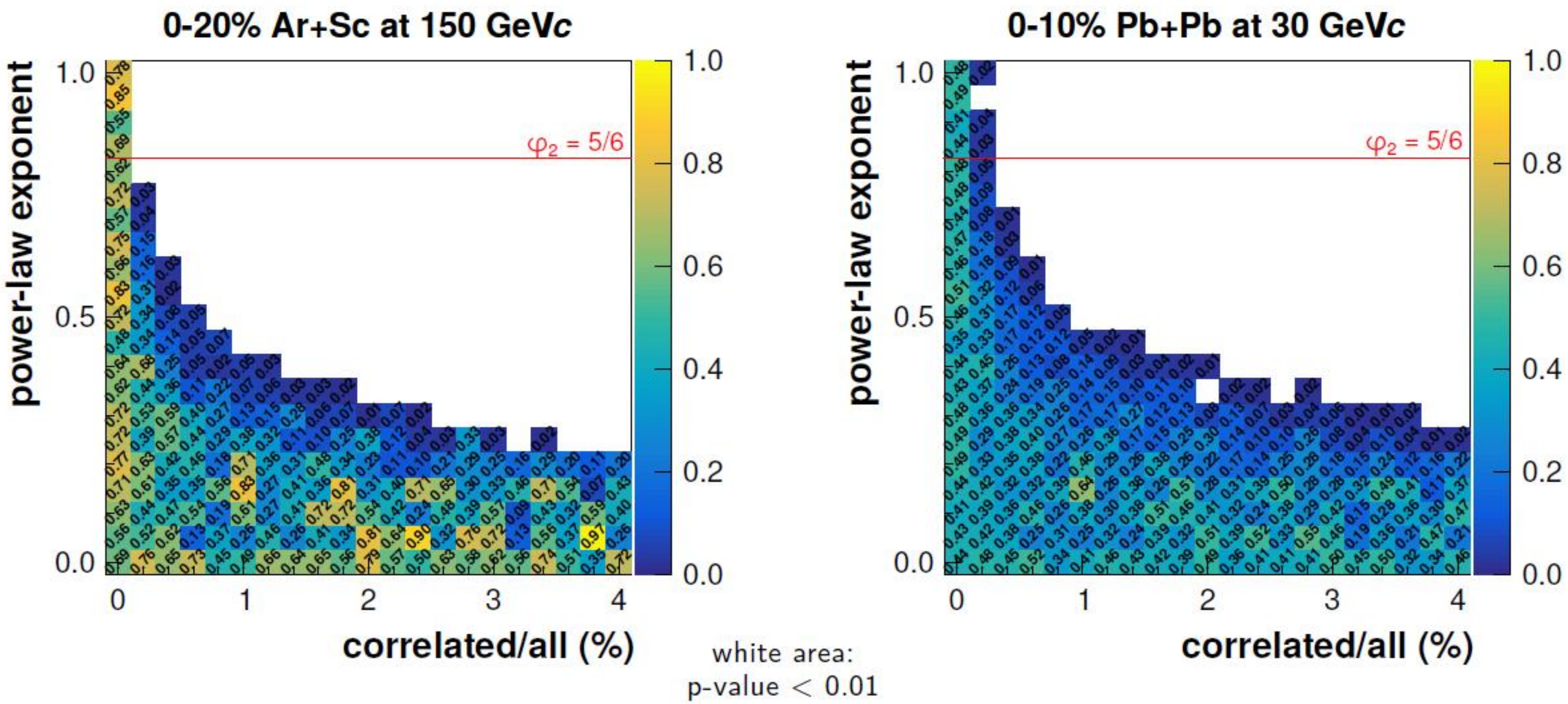
Rates of increase of K^+/π^+ and T change sharply in p+p collisions at SPS energies

The fitted change energy is ≈7 GeV - close to the energy of the onset of deconfinement ≈ 8 GeV

Models assuming change from resonances to string production mechanism show similar trend

Exclusion plots for parameters of simple power-law model

using statistically independent points and cumulative variables



The predicted intermittency index for a system freezing out at the QCD critical endpoint corresponds to the 3-D Ising universality class, to which the phase transition is expected

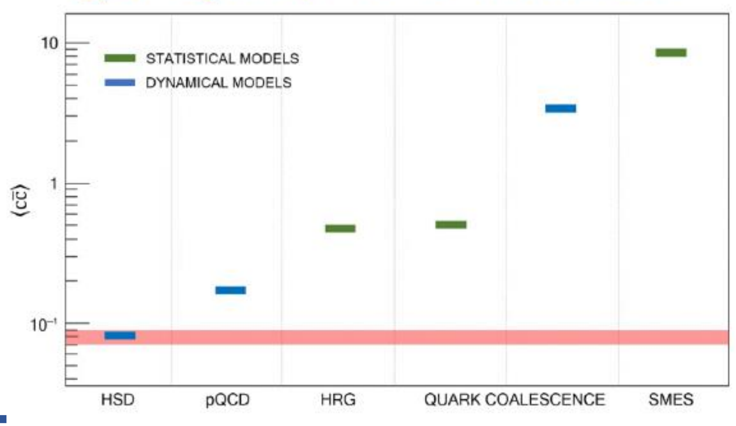
NA61/SHINE in 2021-2024

NA61/SHINE program for 2021-2024

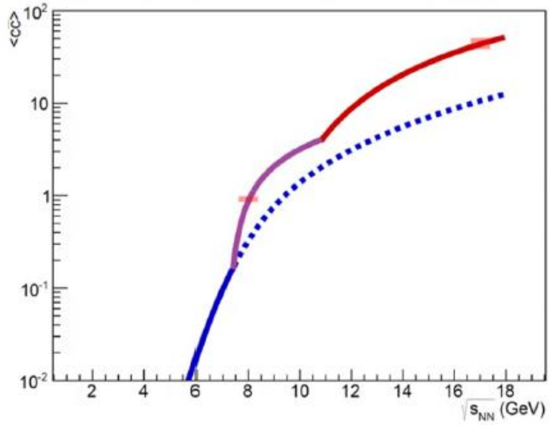
- **What is the mechanism of open charm production?**
- **How does the onset of deconfinement impact open charm production?**
- **How does the formation of quark gluon plasma impact J/ψ production?**

To answer these questions **mean number of charm quark pairs**, $\langle c\bar{c}\rangle$, produced in A+A collisions has to be known. Up to now corresponding experimental **data does not exist** and **only NA61/SHINE can perform this measurement in the near future**.

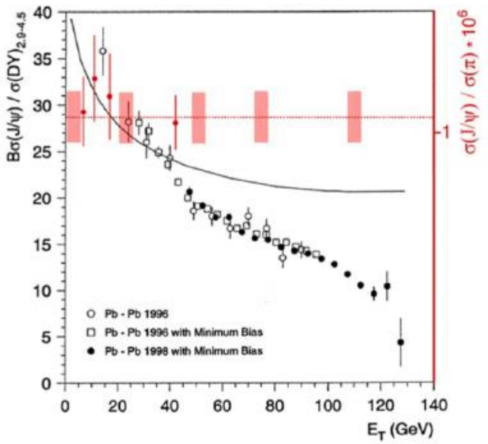
$\langle c\bar{c}\rangle$ and models



$\langle c\bar{c}\rangle$ and onset of deconfinement



$\langle c\bar{c}\rangle$, $\langle J/\psi\rangle$ and QGP

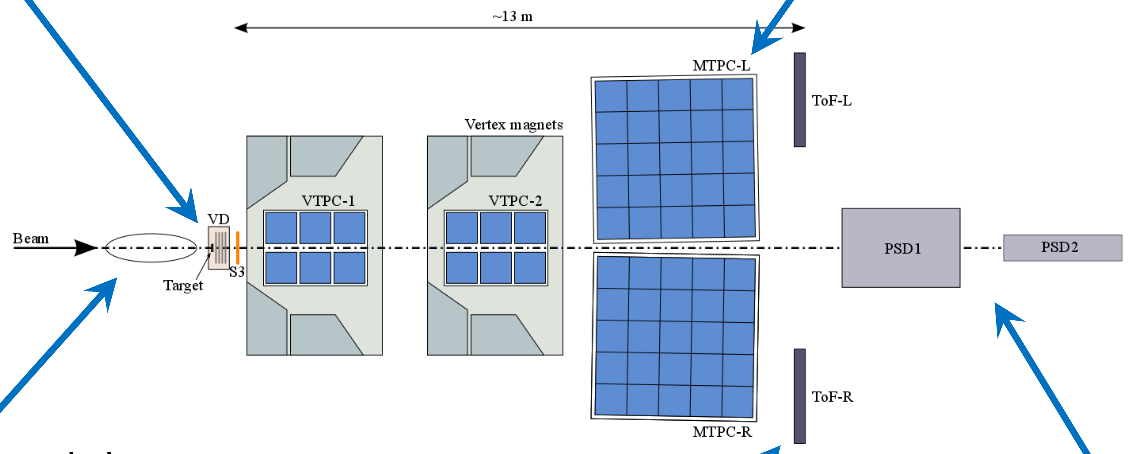


Foreseen NA61/SHINE resolution is sufficient to answer addressed questions

Detector upgrade during LS2

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

Charged/neutral kaon-ratio puzzle

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
$c\tau = 309.8$ μm

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
$c\tau = 123.01$ μm

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

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

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$D^*(2007)^0$ $I(J^P) = \frac{1}{2}(1^-)$
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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Isospin asymmetry for kaons

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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).