
# Particle spectra measurements from NA61/SHINE strong interactions program

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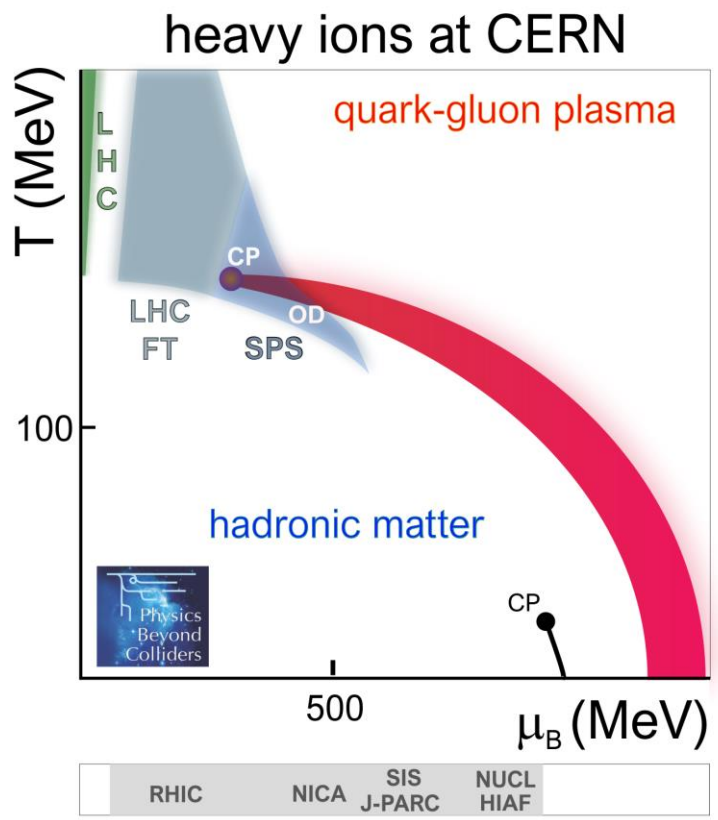
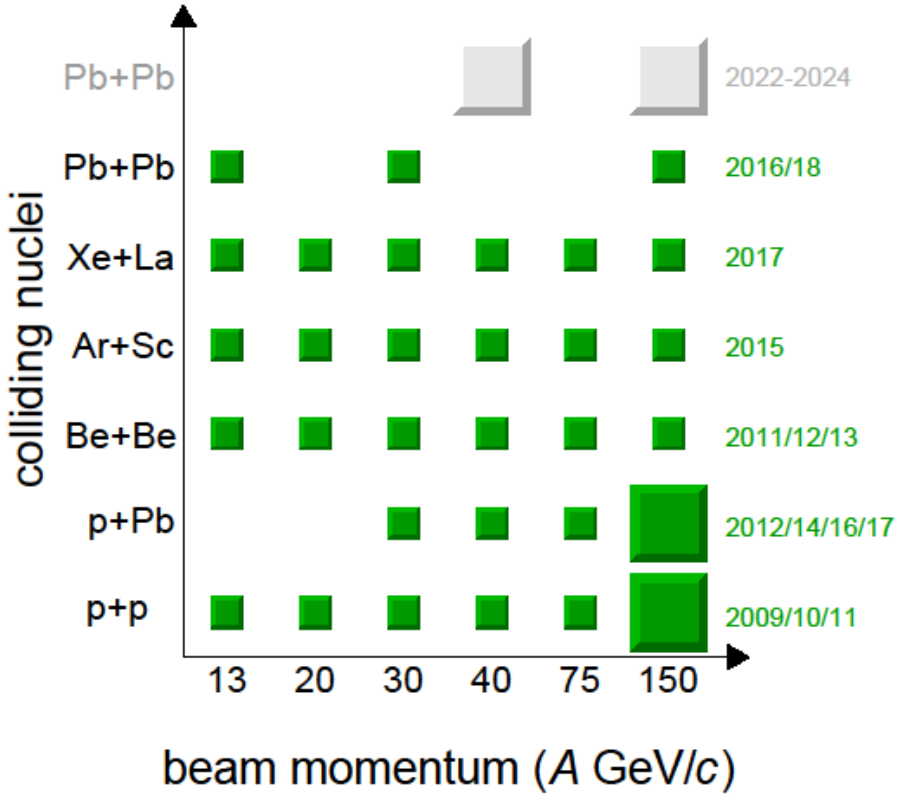
for NA61/SHINE

# NA61/SHINE 2-dimensional scan

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

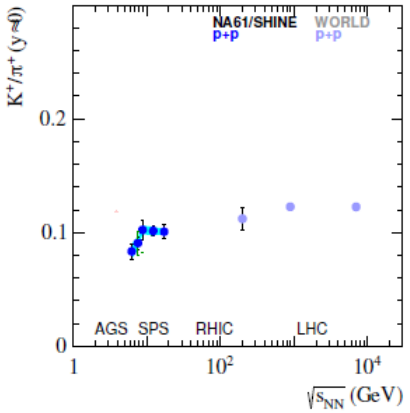


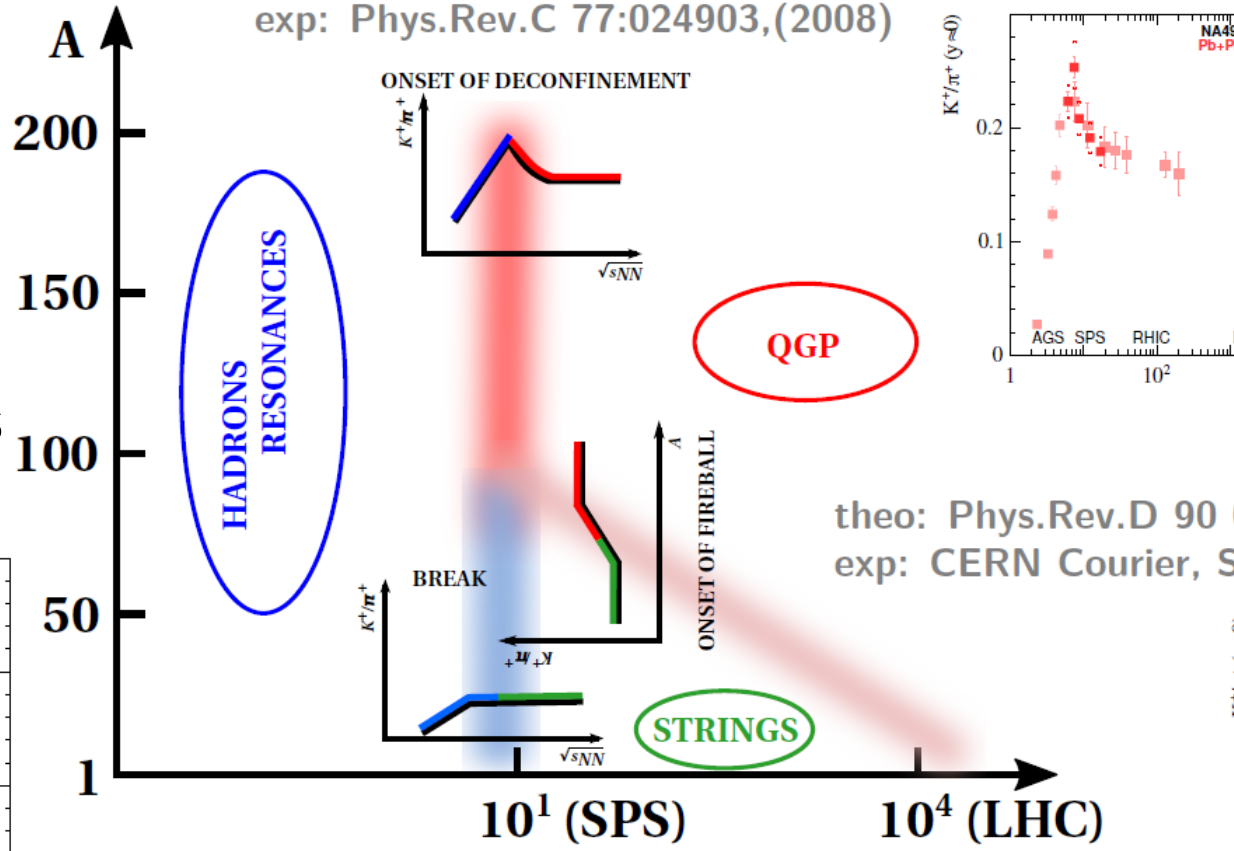



# Uniqueness of heavy ion results from NA61/SHINE

**NA61/SHINE recorded unique data for:**

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

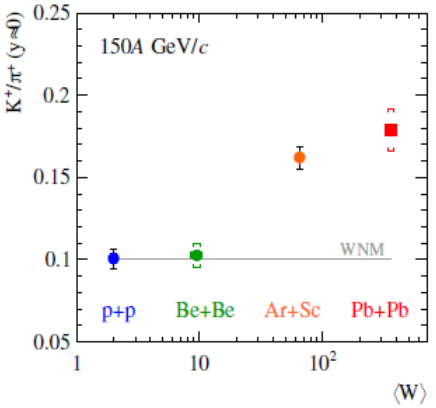



theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)




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

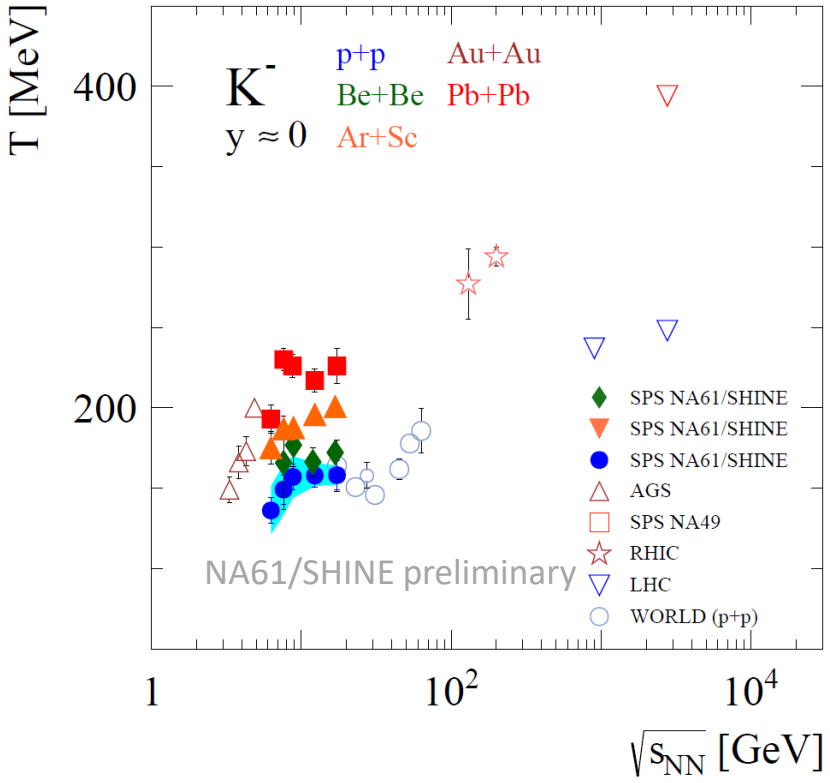


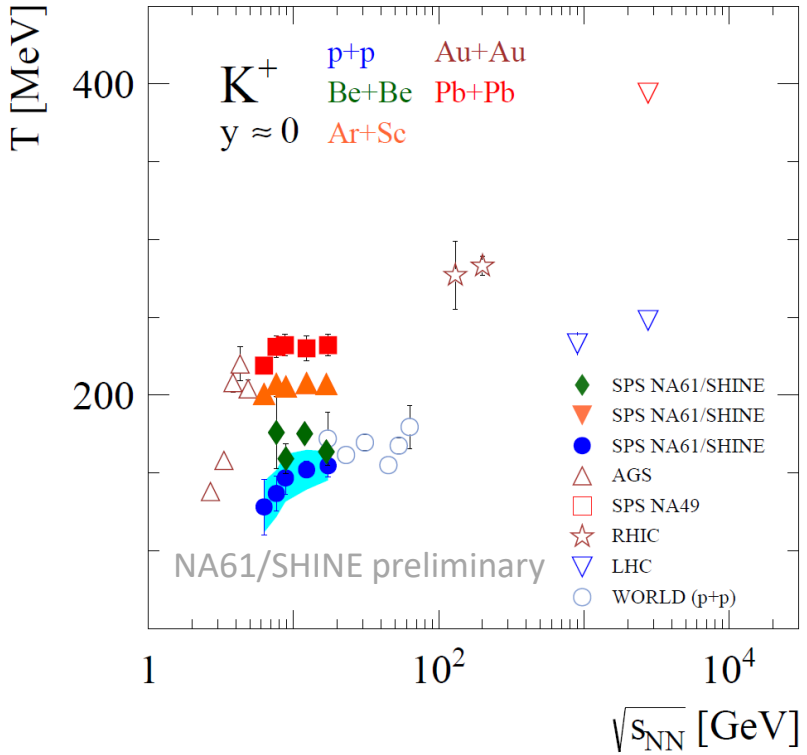

theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

# Study of the onset of deconfinement: Particle production properties

# Onset of deconfinement: step

Plateau – **STEP** – in the inverse slope parameter T of $m_T$ spectra in Pb+Pb collisions observed at SPS energies. This is expected for the onset of deconfinement due to mixed phase of HRG and QGP (SMES).



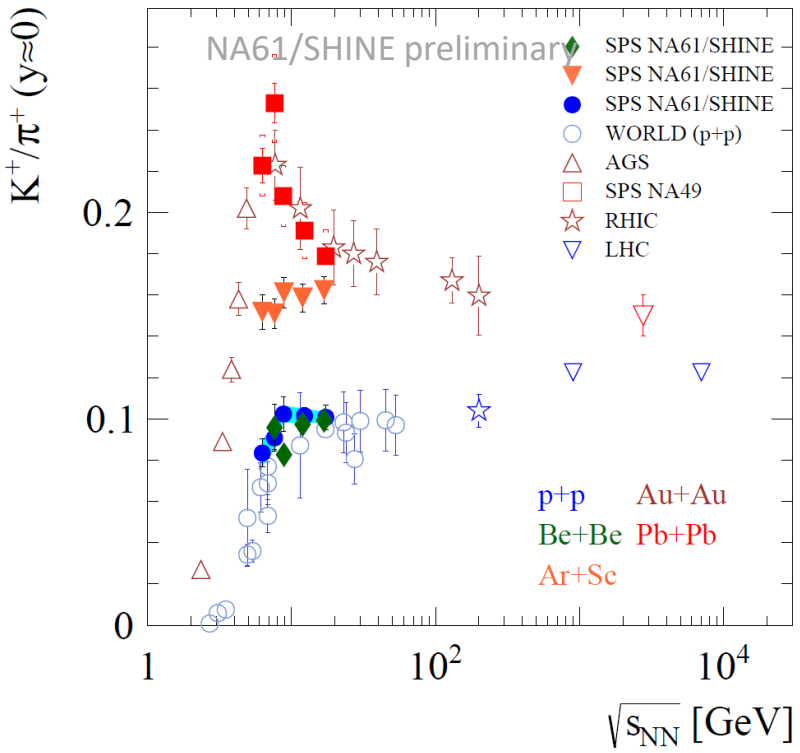

**Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions**

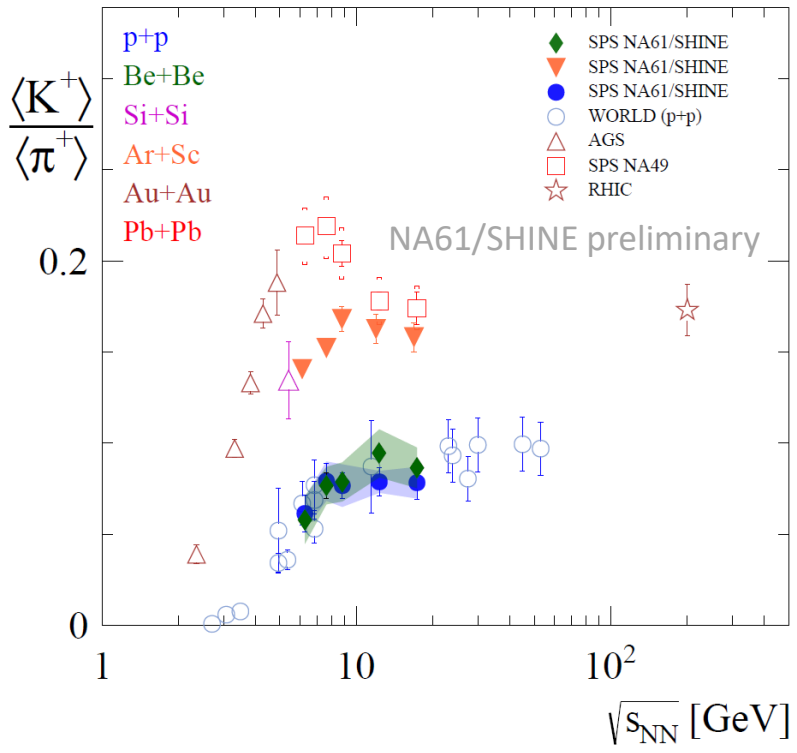
**Magnitude of T in Be+Be slightly higher than in p+p**

**Ar+Sc results between p+p/Be+Be and Pb+Pb**

# Onset of deconfinement: horn

Rapid changes in $K^+/\pi^+$ – **HORN** – were observed in Pb+Pb collisions at SPS energies. This was predicted (SMES) as a signature of onset of deconfinement.




**Plateau like structure visible in p+p**

Be+Be close to p+p

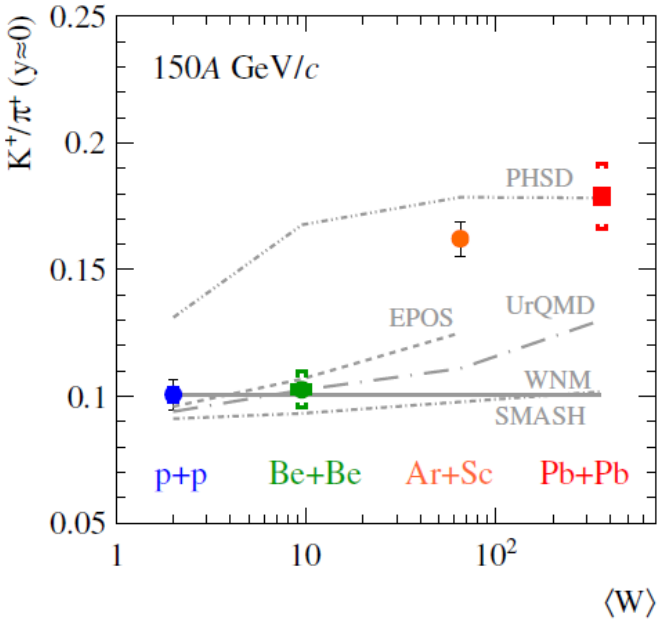
**Ar+Sc is higher than p+p but form of energy dependence is similar to p+p (no horn)**

# Study of the onset of fireball

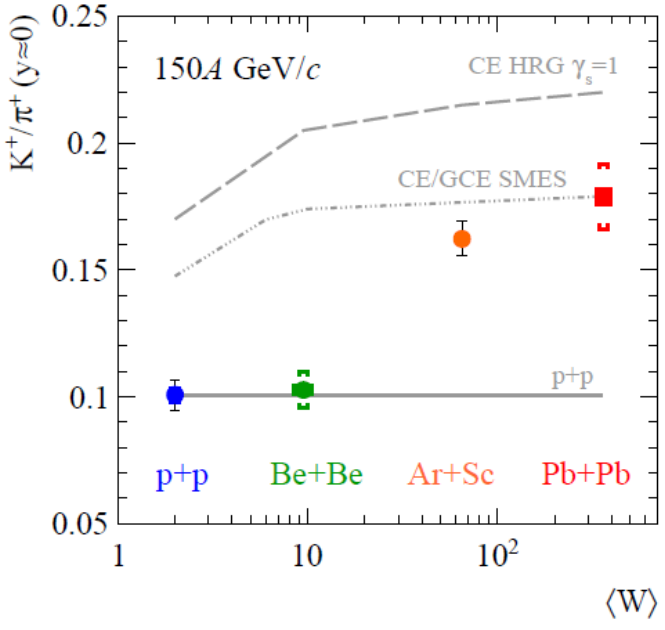
# Onset of fireball

$K^+/\pi^+$

**dynamical models**

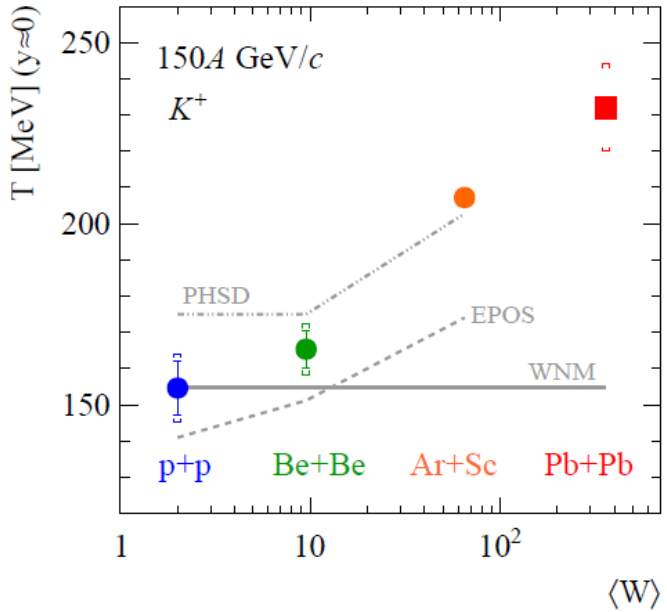



**statistical models**




$T$ parameter

**dynamical models**



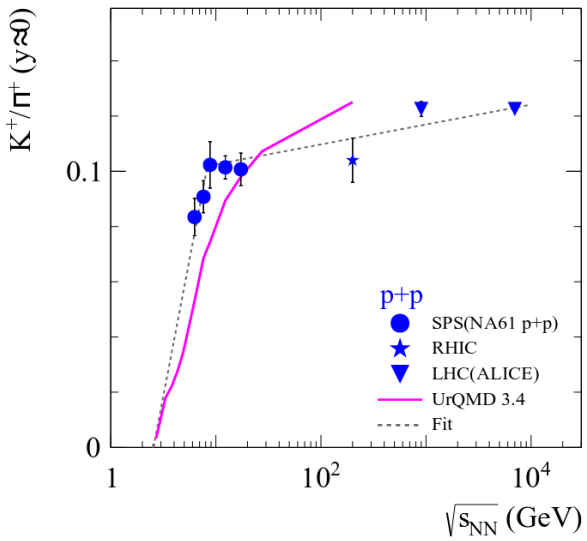

- None of the models reproduce $K^+/\pi^+$ ratio or $T$ for whole $\langle W \rangle$ range

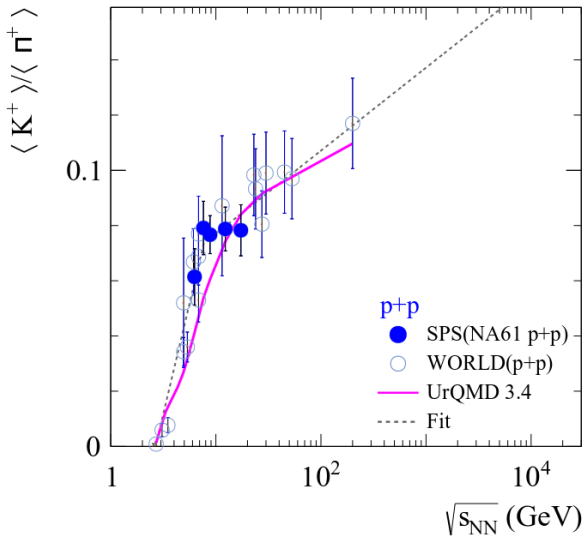
PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private communication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private communication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909
SMES: Acta Phys. Polon. B46 (2015) 10, 1991 - recalculated

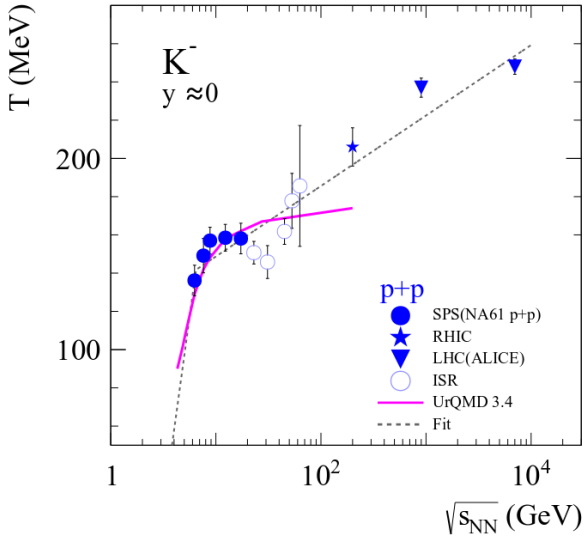
p+p: Eur. Phys. J. C77 (2017) 10, 671
Be+Be: Eur. Phys. J. C81 (2021) 1, 73
Ar+Sc: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C66, 054902 (2002)

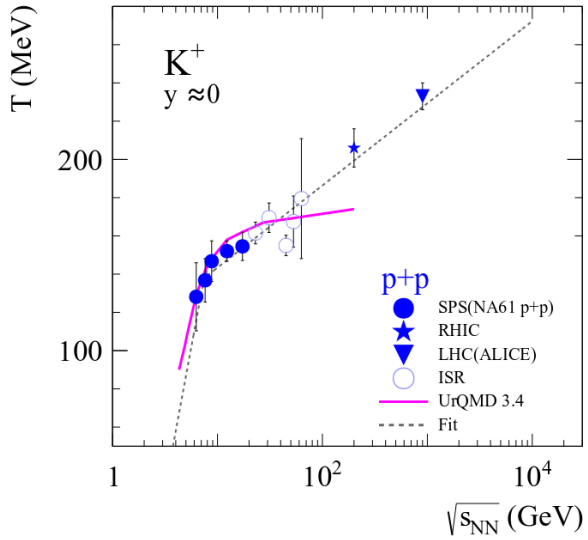
# Transition from resonances to strings

# Transition from resonances to strings




**Rates of increase of $K^+/\pi^+$ and T change sharply in p+p collisions at SPS energies**

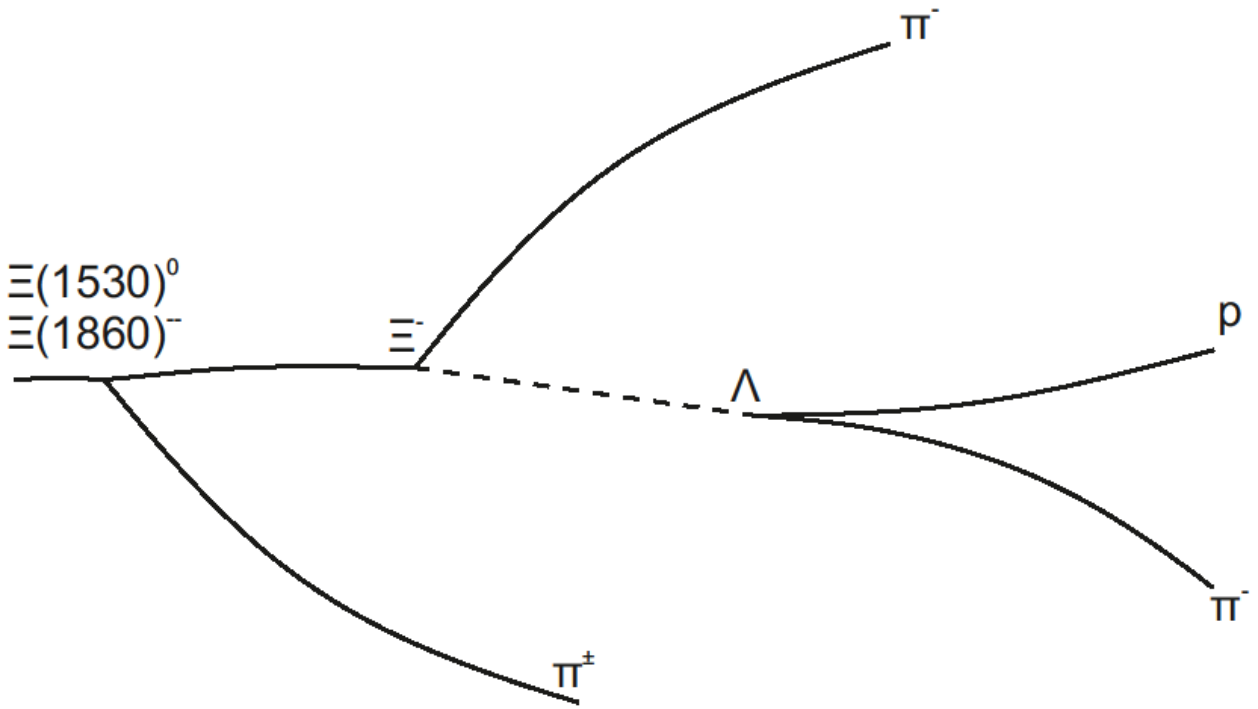
**The fitted change energy is ≈7 GeV - close to the energy of the onset of deconfinement ≈ 8 GeV**

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

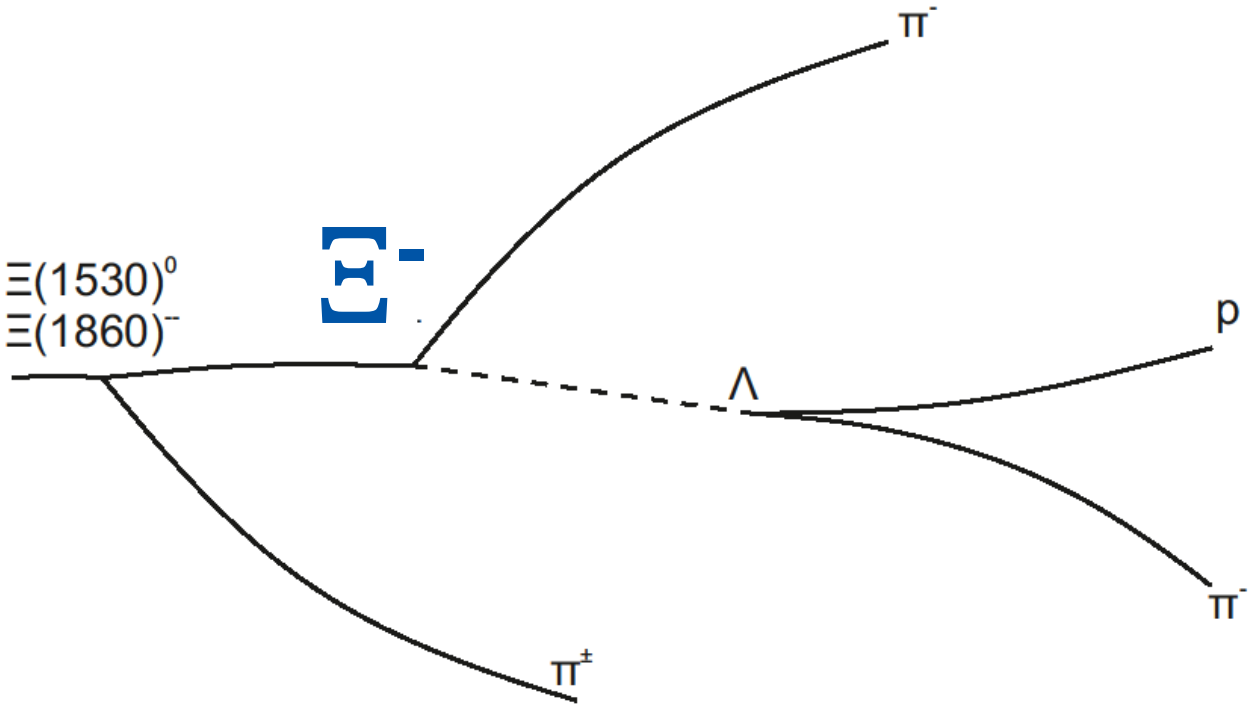
# Multi-strange hadron production in p+p interactions at $\sqrt{s_{NN}}$ =17.3 GeV

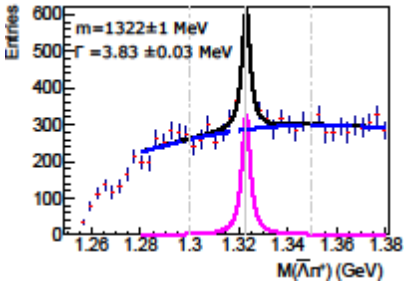
# Multi-strange measurements

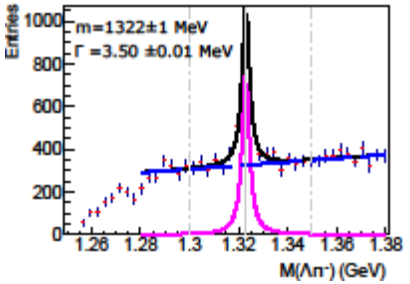
- **Final results** stand for **multi-strange hyperon production in inelastic *p+p* interactions at 158 GeV/c** corresponding to $\sqrt{s_{NN}} = 17.3$ **GeV .**
- Results are corrected for geometrical detector acceptance and reconstruction efficiency and secondary interactions and branching ratios to unmeasured channels**.**
- A total of **33 million** events were analyzed.
- Multi-strange hyperons are identified by their decay topologies**.**



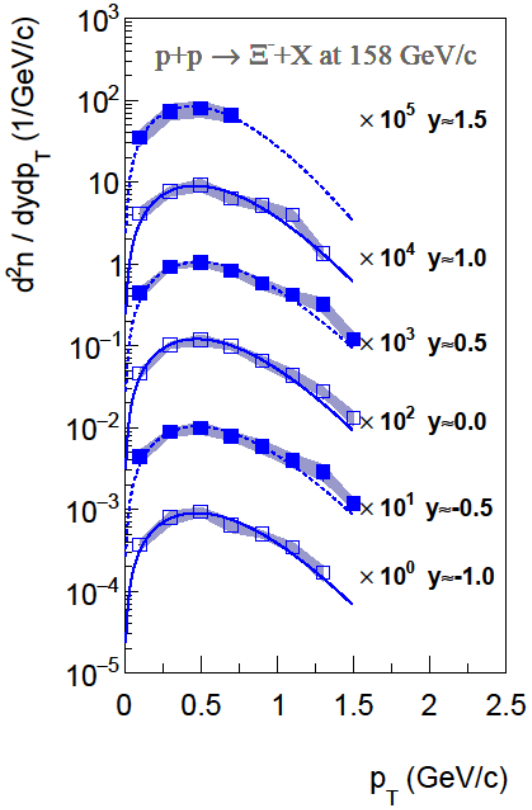
# Ξ production in *p+p* at 158 GeV/*c*

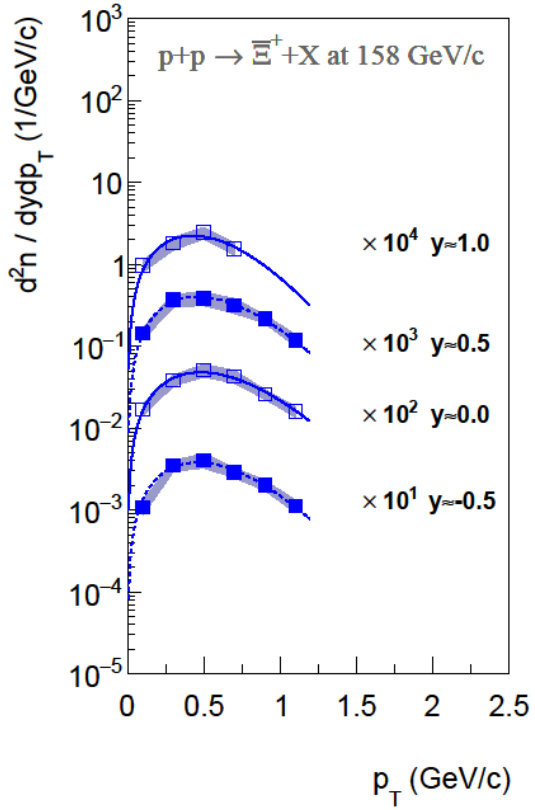


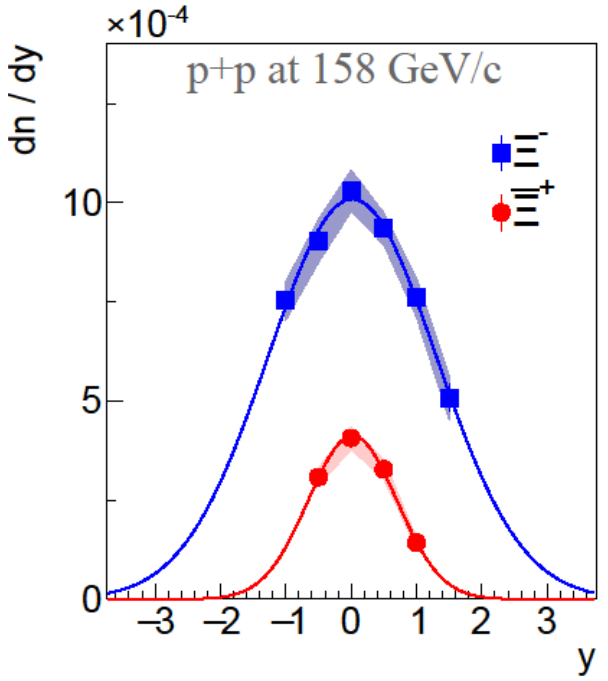



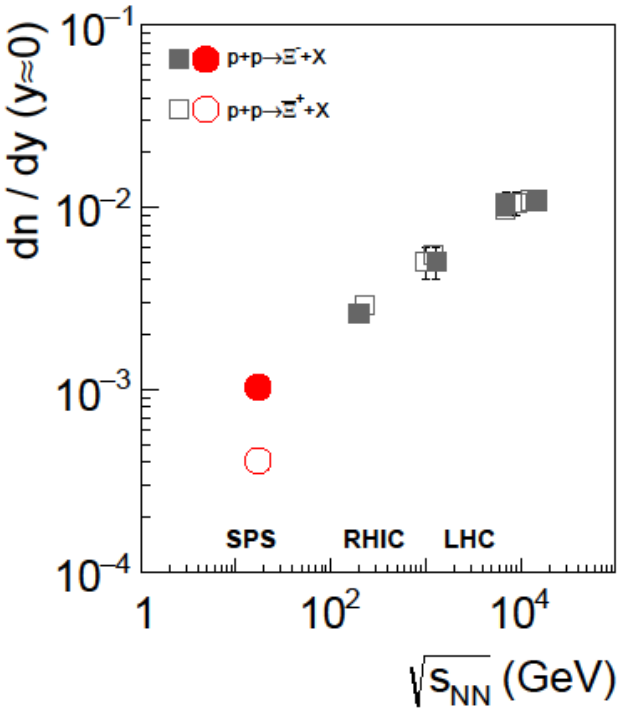



# Ξ production in inelastic *p*+*p* collisions at 158 GeV/*c*



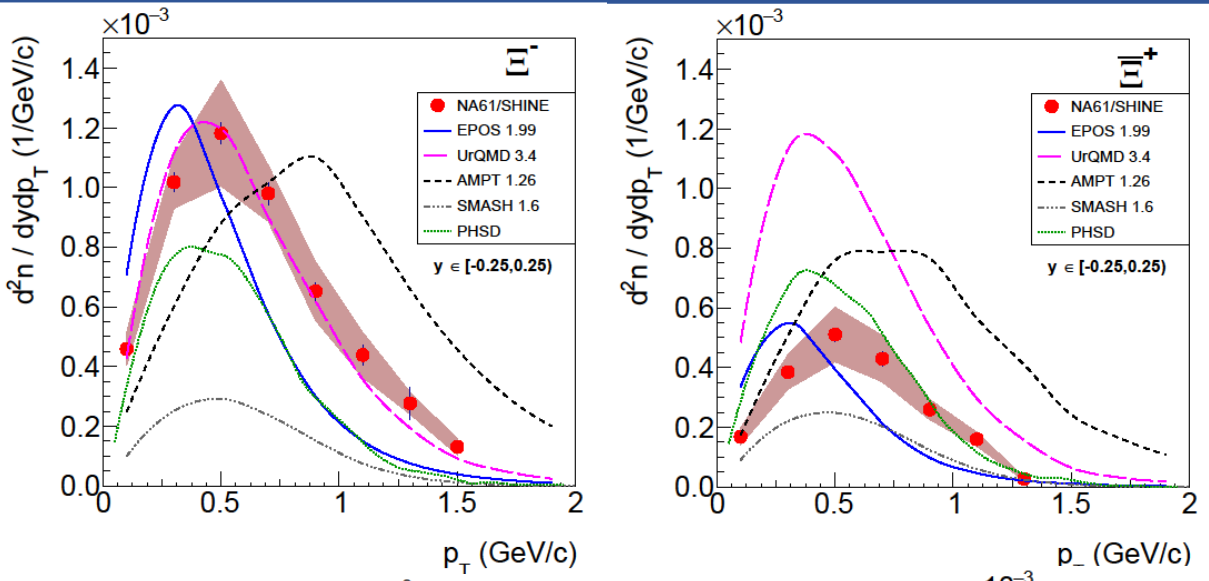




- **The only results on $\Xi^-$ and $\bar{\Xi}^+$ production in *p*+*p* at the SPS energy**
- **Strong suppression of $\bar{\Xi}^+$ production: $\langle\bar{\Xi}^+\rangle$ / $\langle\Xi^-\rangle$= 0.24 ± 0.01 ± 0.05**

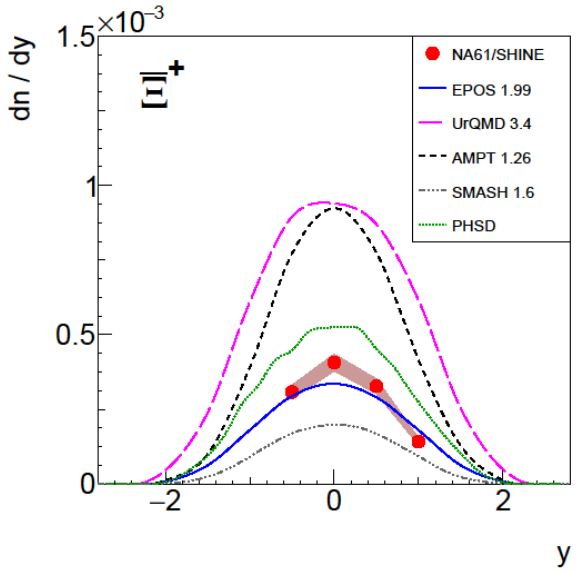
# Ξ production in inelastic *p*+*p* collisions – model comparison

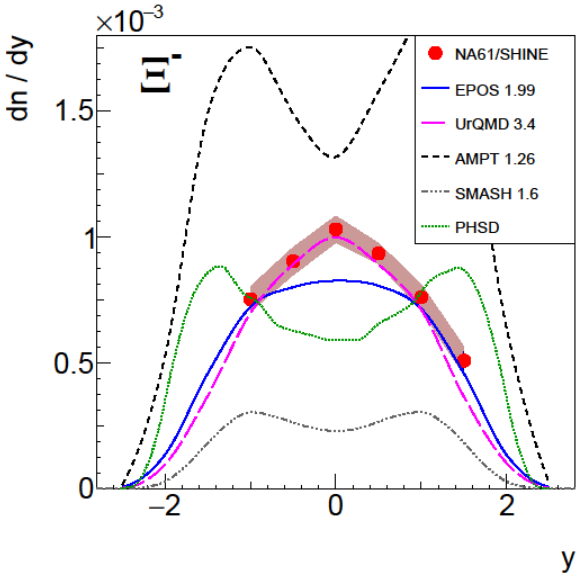


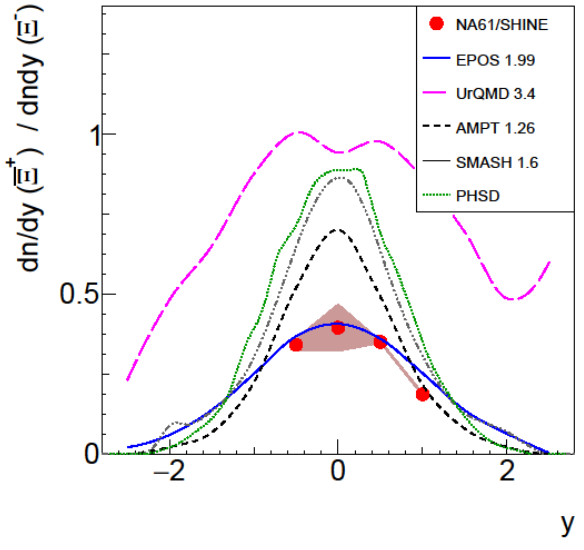




- Transport models **fail** to describe the NA61/SHINE results on Ξ production in *p*+*p* collisions



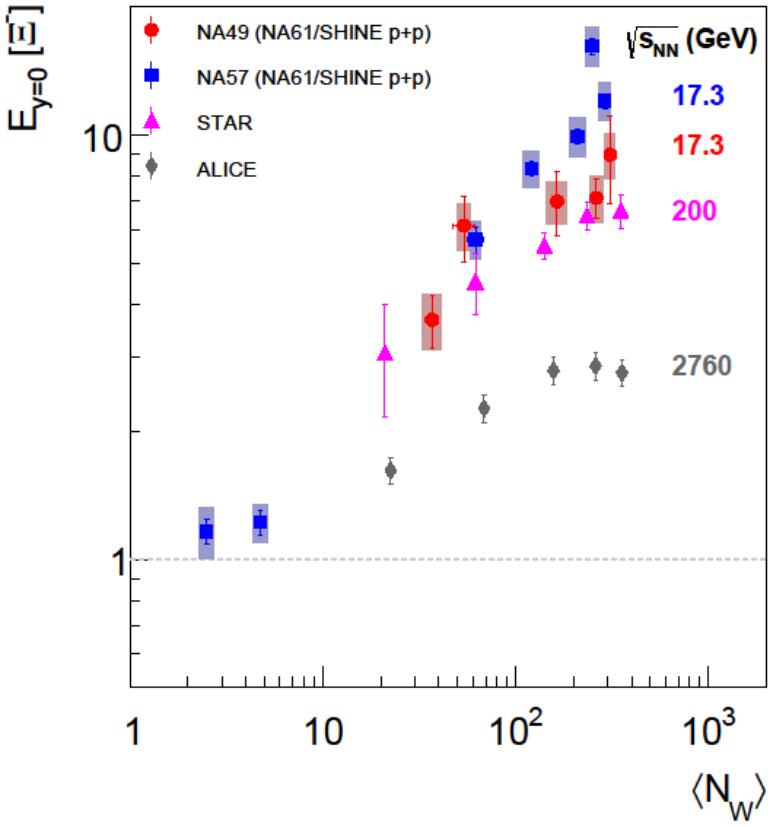



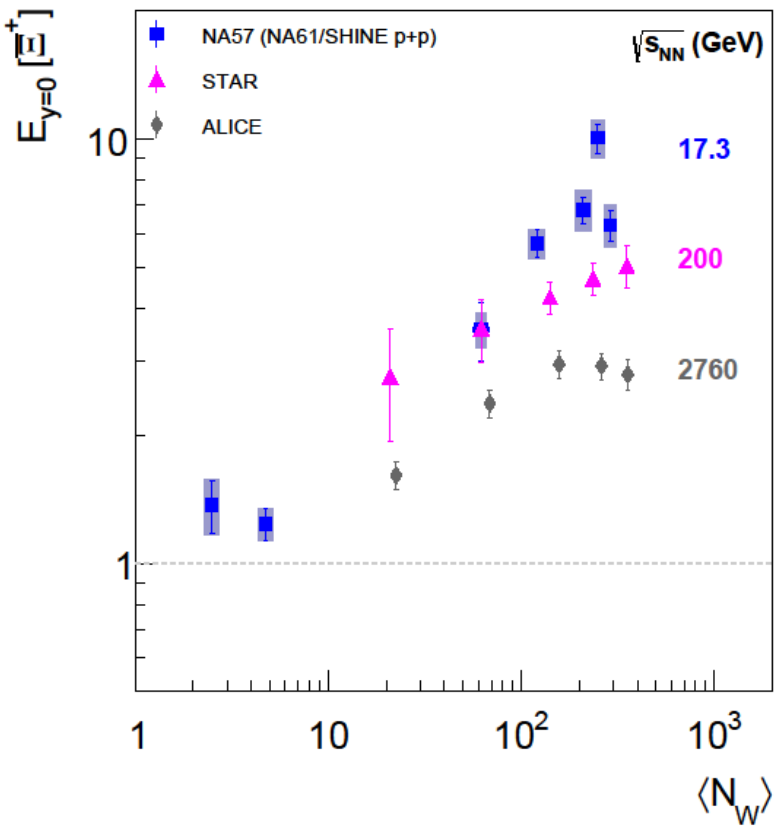




Eur.Phys.J.C 80 (2020) 9, 833

# Strangeness enhancement factors - Ξ production

- **The enhancement recalculated based on the NA61/SHINE data**




- 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

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

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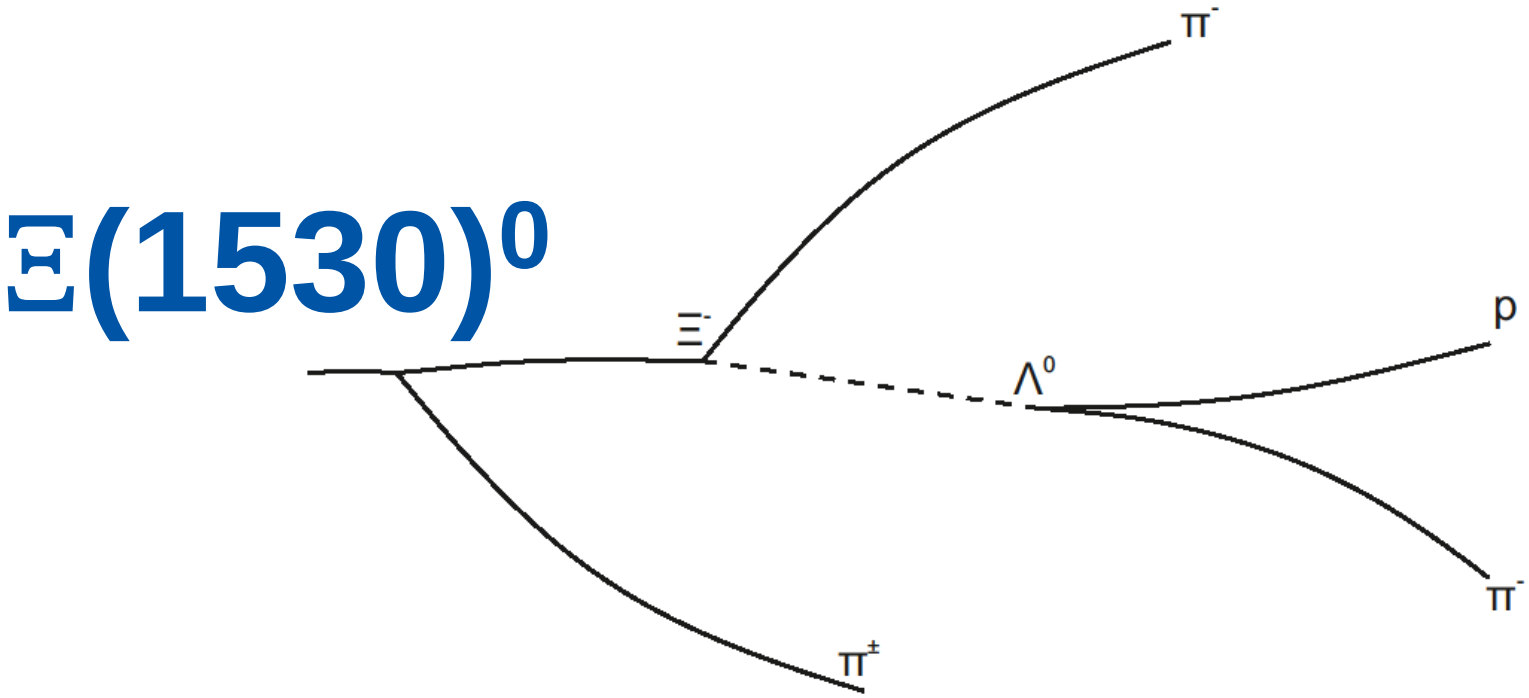
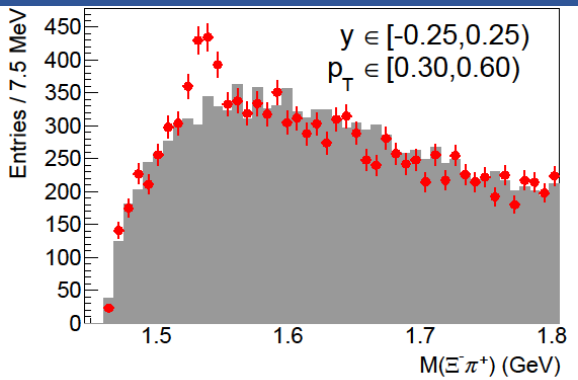
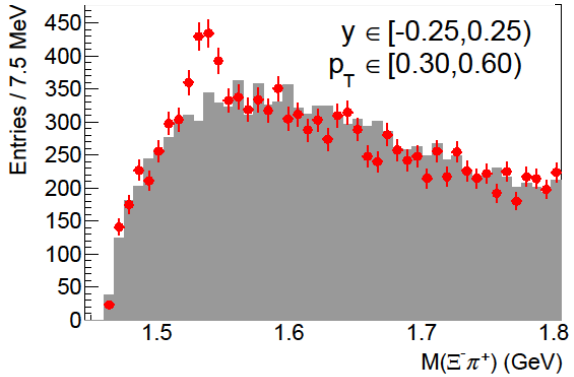
# $\Xi(1530)^0$ production in *p+p* at 158 GeV/*c*

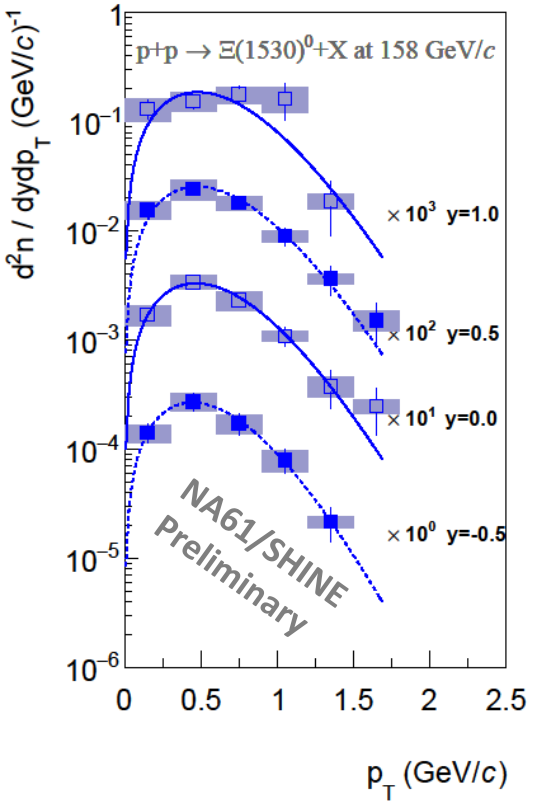
$\Xi(1530)^0$

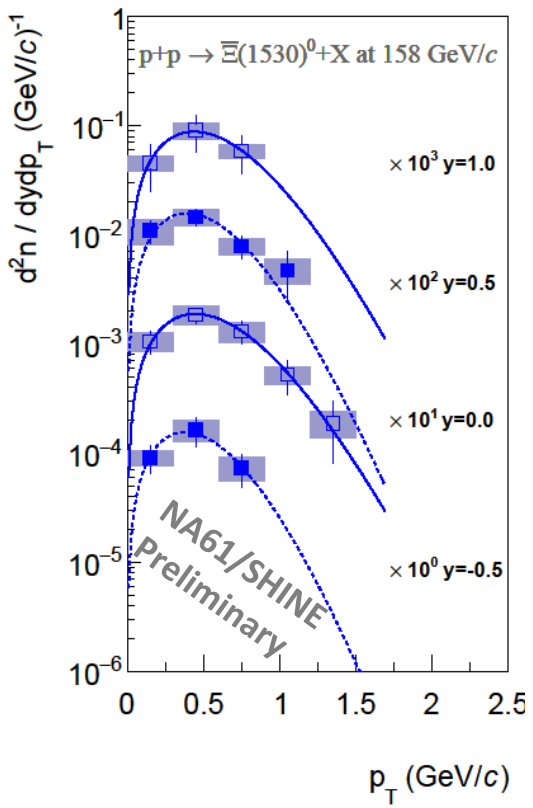


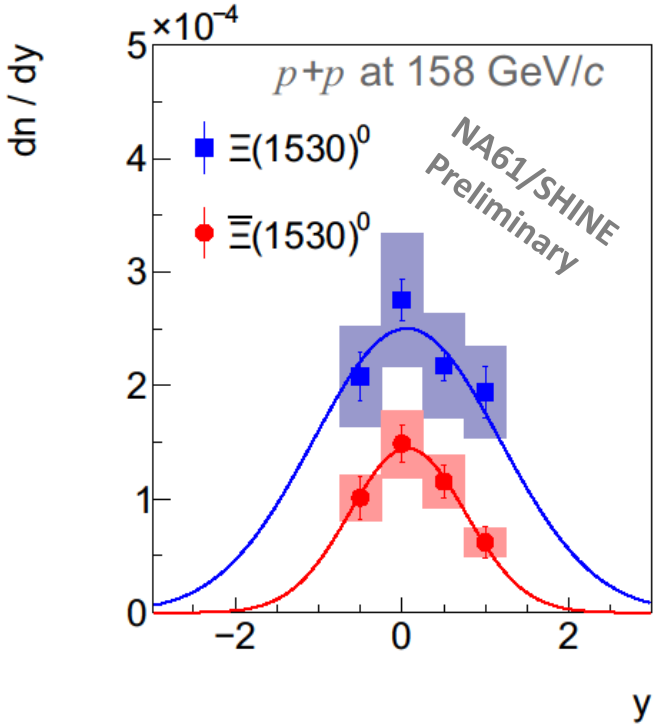



# $\Xi(1530)^0$ production in inelastic *p+p* collisions at 158 GeV/*c*

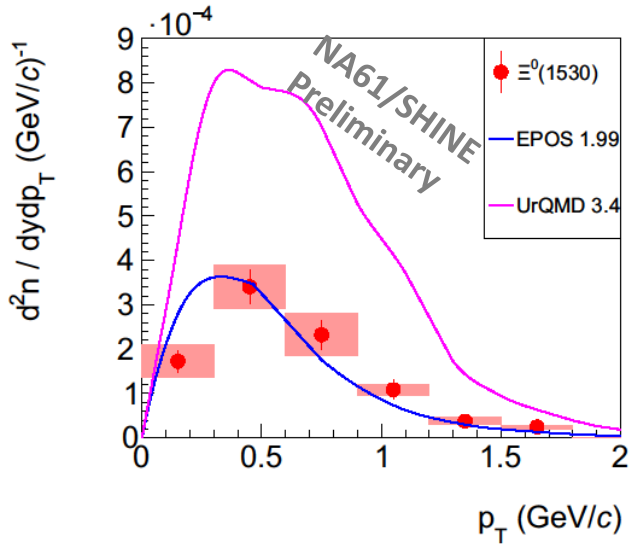


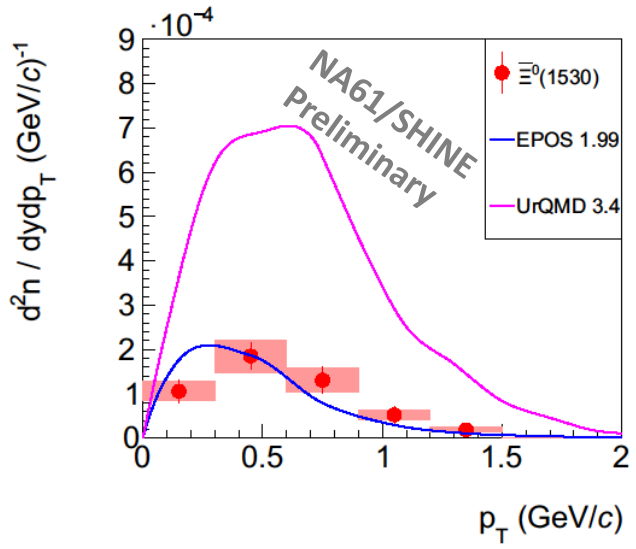



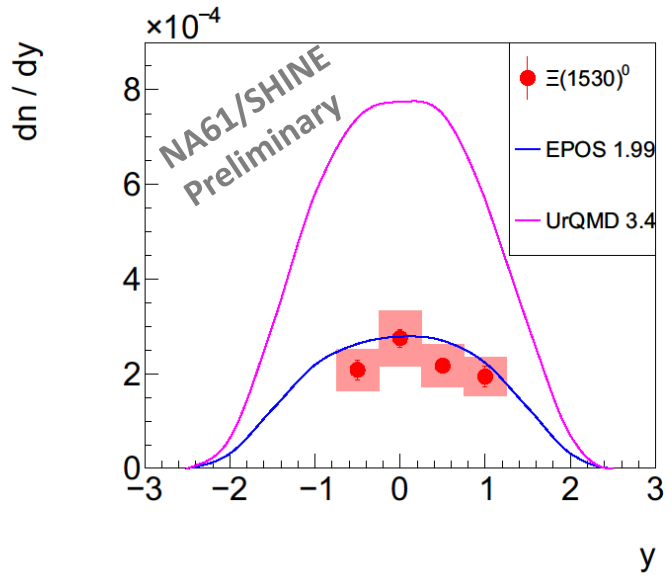



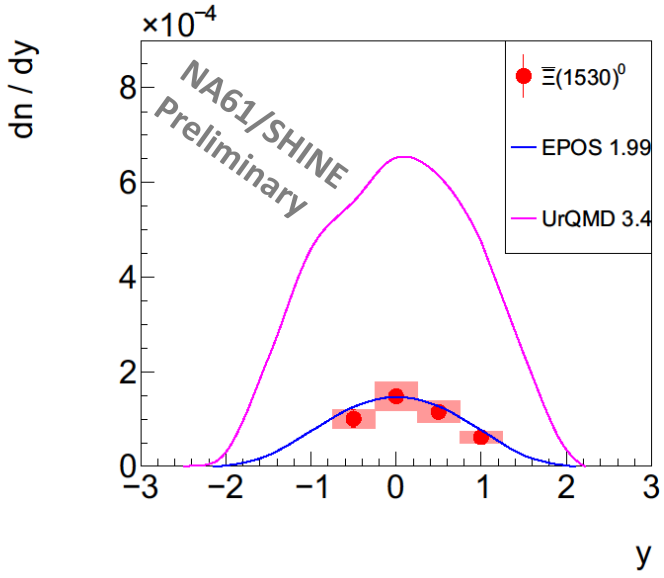

- **The only results on $\Xi(1530)^0$production in *p+p* at the SPS energy**
- The second result on $\Xi(1530)^0$ production in *p+p* (ALICE at 7 TeV Eur.Phys.J.C 75 (2015) 1)
- **Suppression of $\bar{\Xi}(1530)^0$ production: $\langle\bar{\Xi}(1530)^0\rangle$ / $\langle\Xi(1530)^0\rangle$= 0.35 ± 0.04 ± 0.05**

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



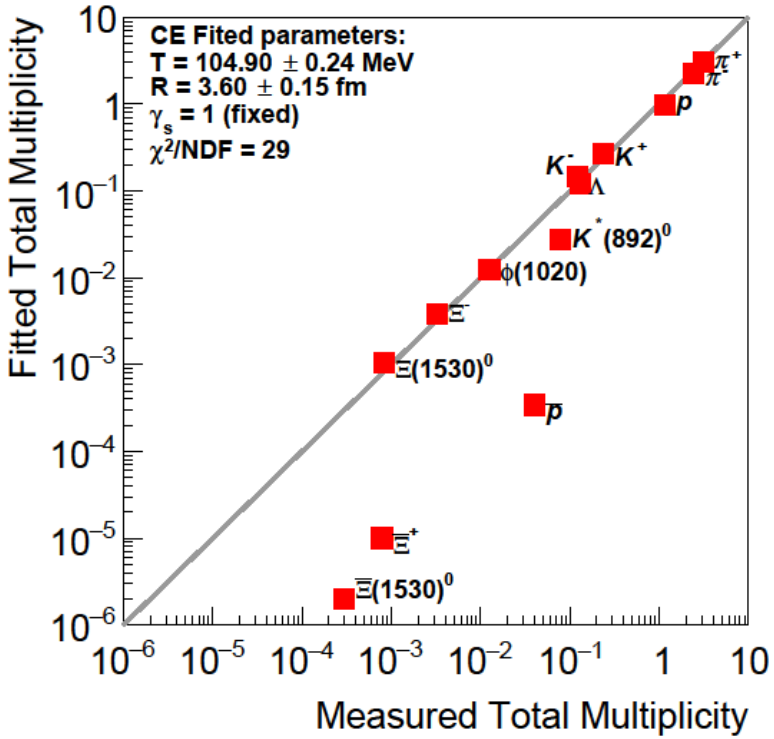



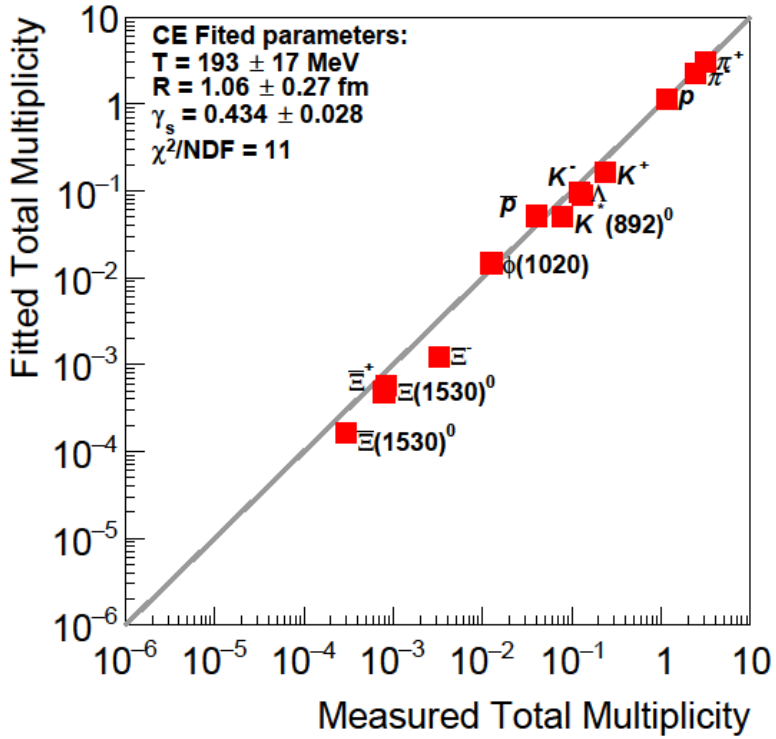




- **EPOS describes well transverse momentum and rapidity distributions of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$**
- **UrQMD significantly overestimates all spectra of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ hyperons**

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




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

- Significant discrepancies of the fitted parameters
- **The statistical model fails when fixed $\gamma_s$**
- The fit with free $\gamma_s$ finds **$\gamma_s$ =0.434±0.028** and reproduces the measurements well -

a **suppression of strange particle production in *p*+*p* collisions** at CERN SPS energies

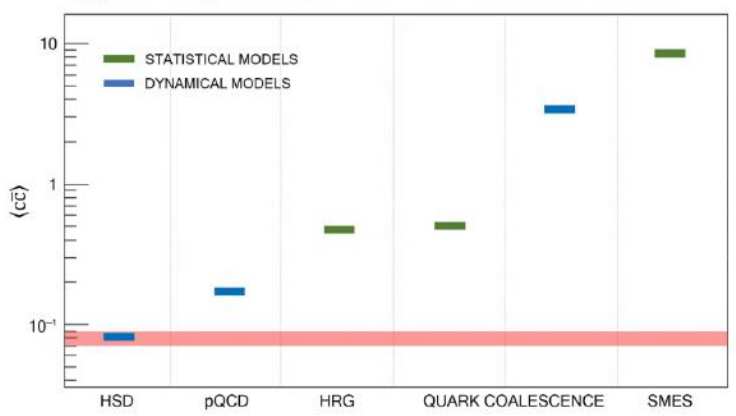

# NA61/SHINE in 2021-2024

# NA61/SHINE program for 2021-2024

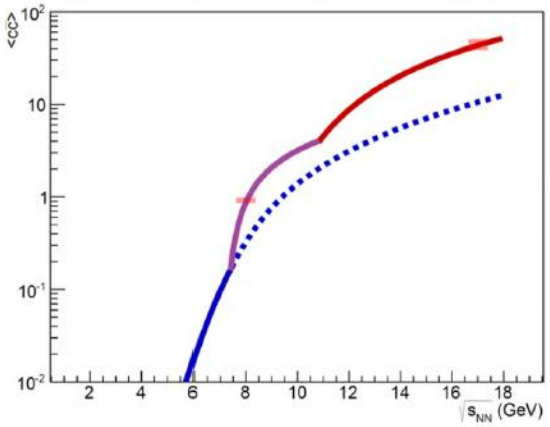
- **What is the mechanism of open charm production?**
- **How does the onset of deconfinement impact open charm production?**
- **How does the formation of quark gluon plasma impact $J/\psi$ production?**

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**.

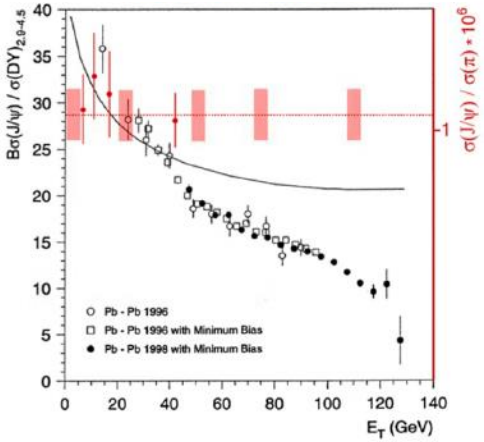
**$\langle c\bar{c}\rangle$ and models**




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




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

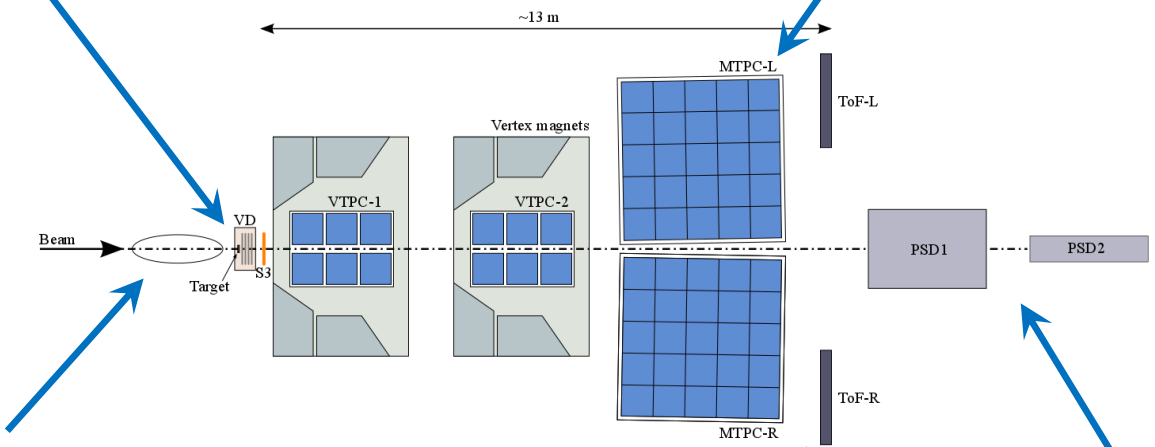



**Foreseen NA61/SHINE resolution is sufficient to answer addressed questions**

# 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

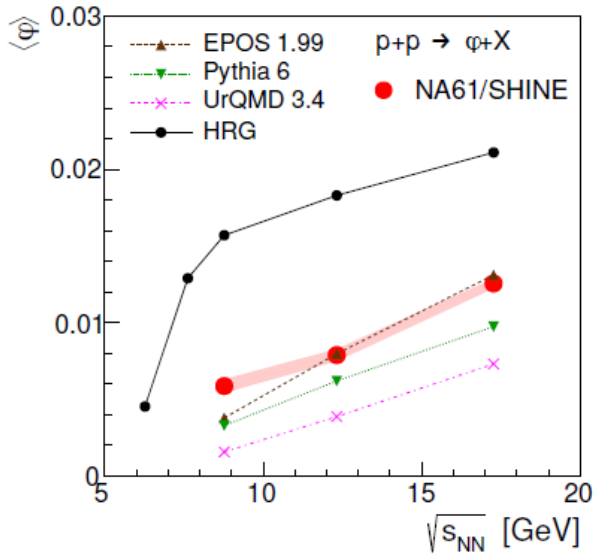
Upgrade of Projectile
Spectator Detector

# 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
- No horn in Ar+Sc collisions
- Unexpected system size dependence: (p+p ≈ Be+Be) ≠ (Ar+Sc ≠ Pb+Pb)
- New and unique results on $\Xi^-$ and $\bar{\Xi}^+$, $\Xi(1530)0$ and $\bar{\Xi}(1530)^0$ production in p+p interactions at 158 GeV/c
- NA61/SHINE program with measurements of open charm production in 2021-2024
- The Canonical Ensemble HRG fit with free $\gamma_S$ finds $\gamma_S = 0.434 \pm 0.028$ and reproduces the measurements well - suppression of strange particle production in p+p collisions at CERN SPS energies


# Thank you

# Strangeness production in p+p at 158 GeV/*c*

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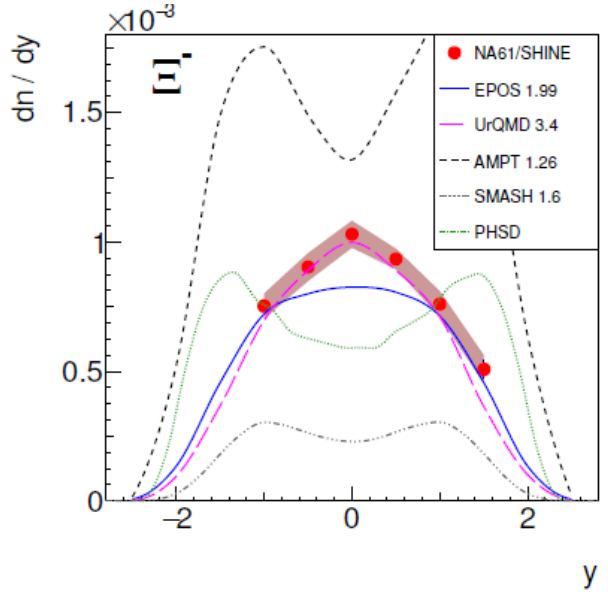


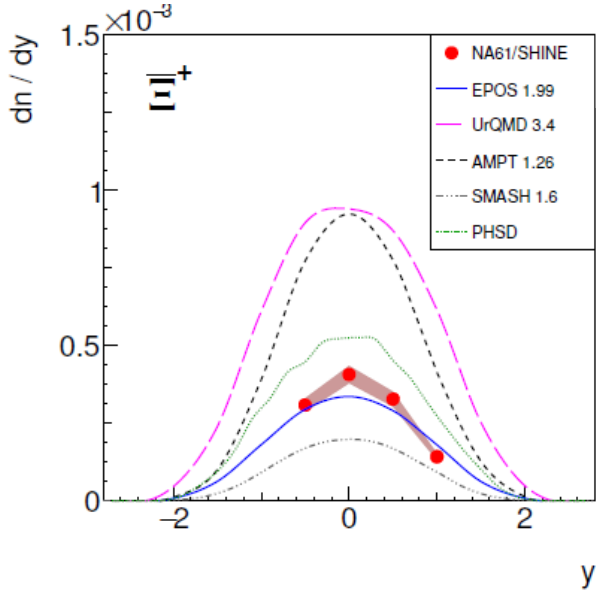


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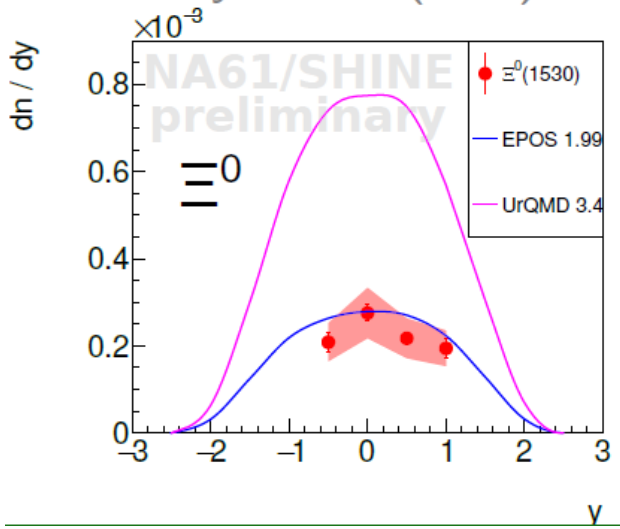


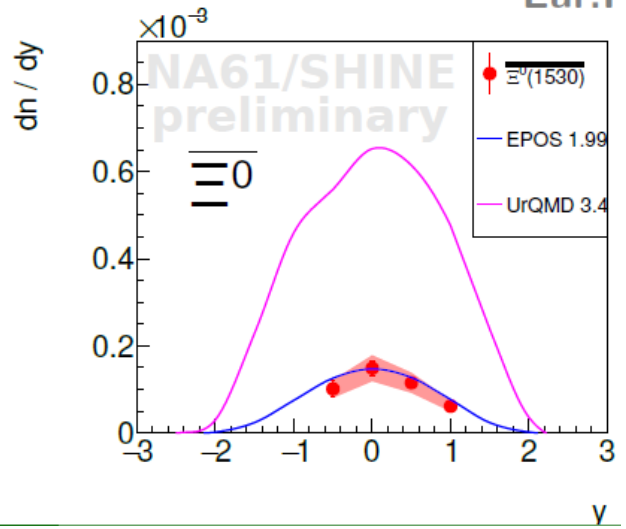


**Present theoretical models do not describe the NA61/SHINE results on strange particles production in p+p interactions**

# Strangeness enhancement factors

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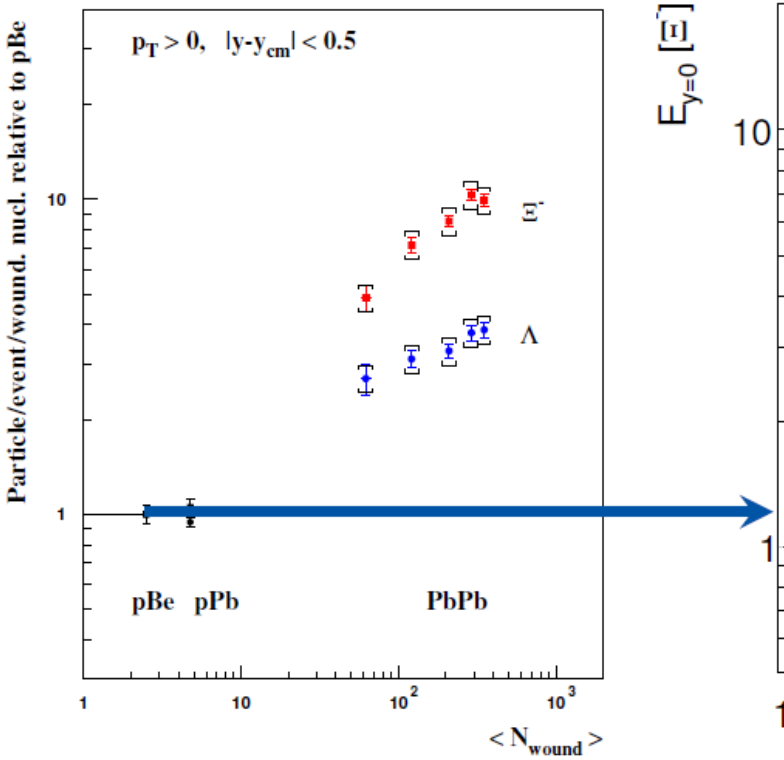


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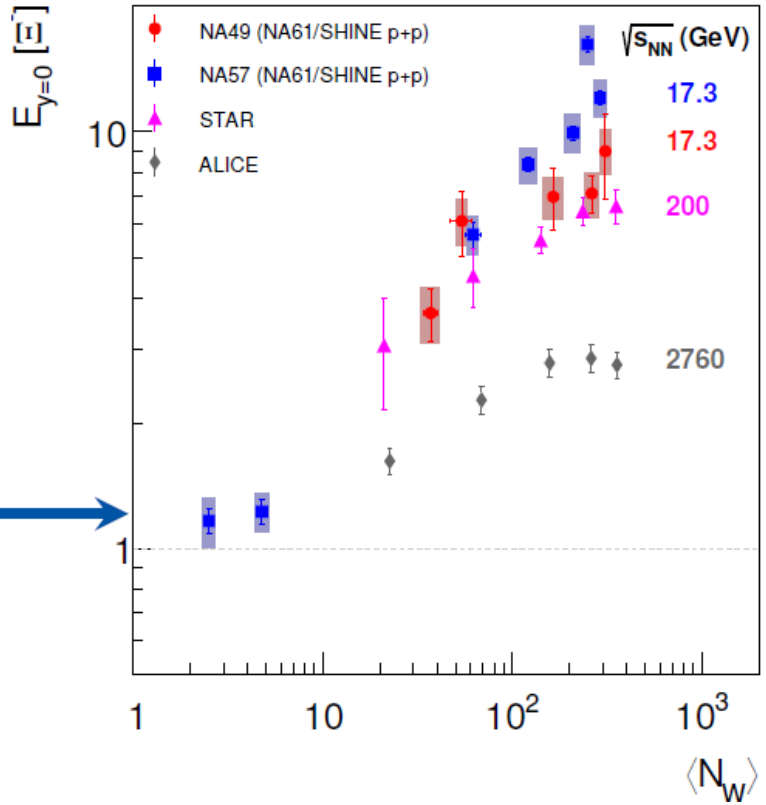
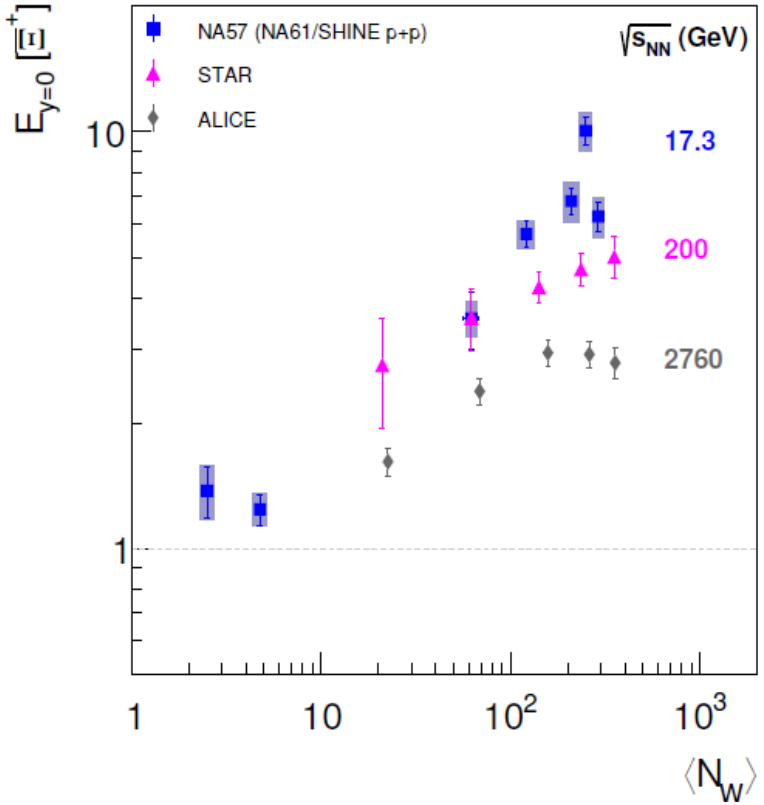
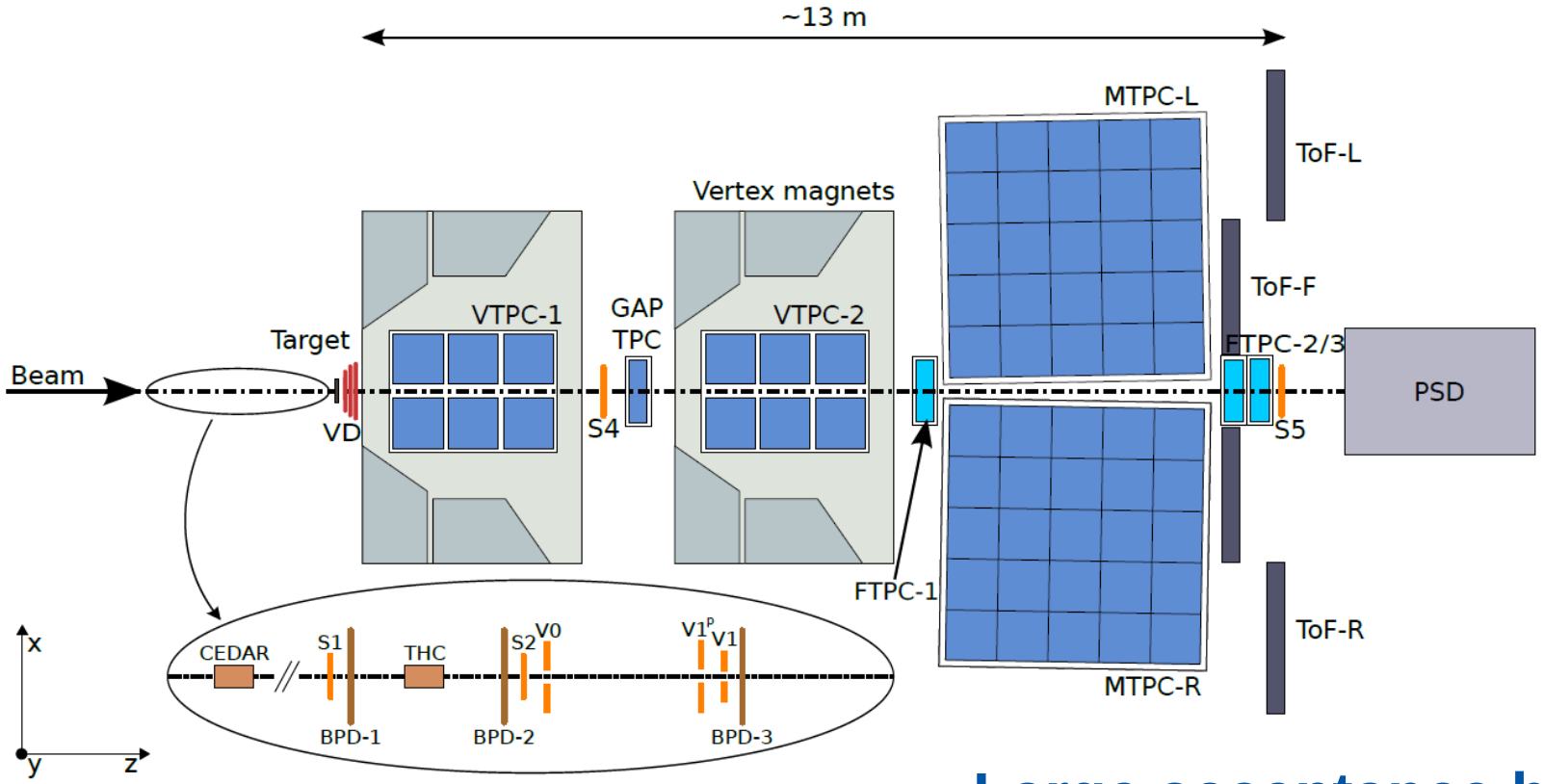



$$E_{\Xi_s} = \frac{2}{\langle N_W \rangle} \frac{dn/dy(A+A)}{dn/dy(p+p)}$$

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

## Fixed target experiment located at the CERN SPS accelerator




Beams:

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

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