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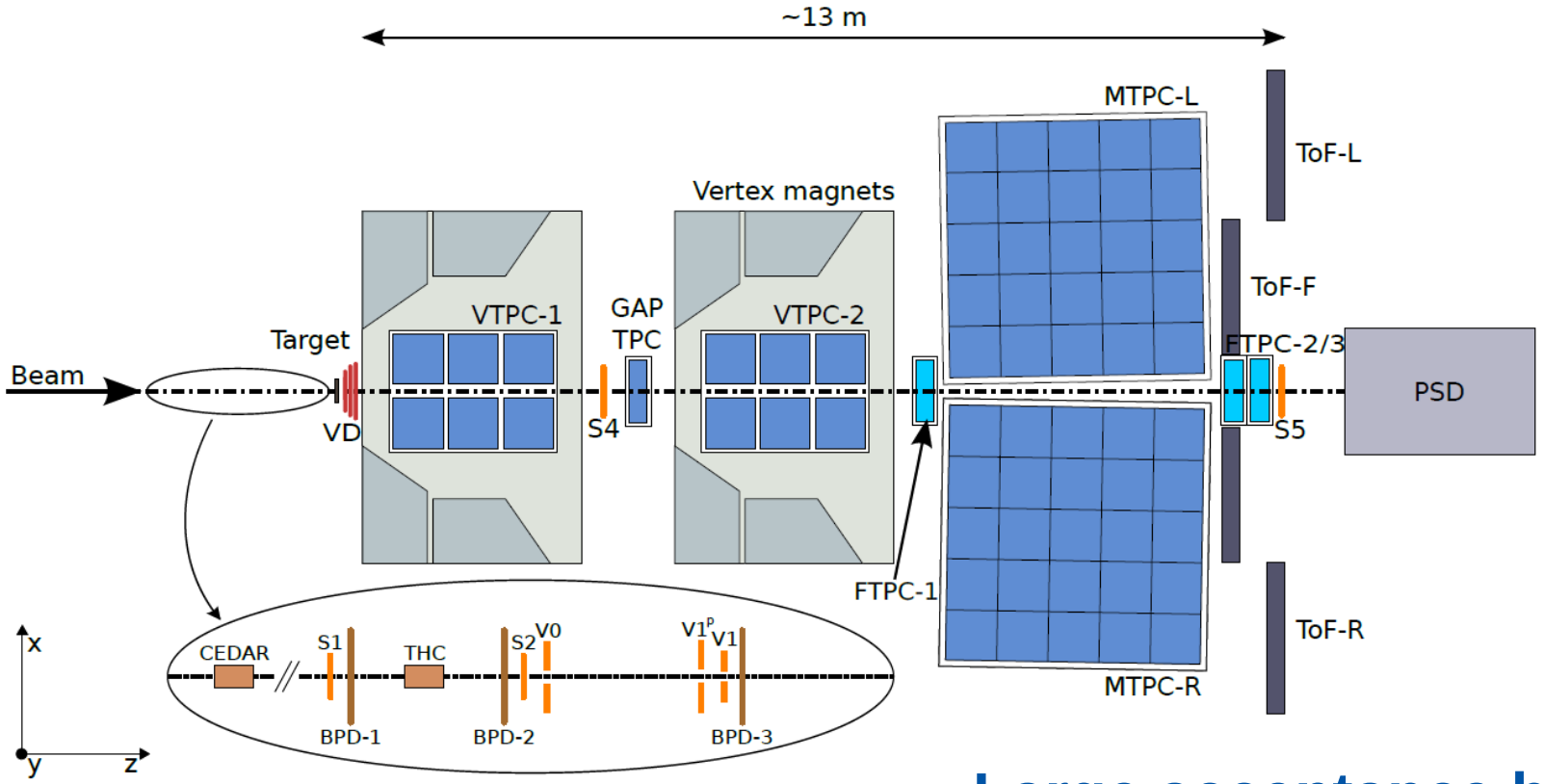
Particle spectra and onset of deconfinement from the NA61/SHINE

Szymon Puławski
for NA61/SHINE

Outline

- **Introduction**
- **Study of the onset of deconfinement**
- **Onset of fireball**
- **Strangeness production in p+p at 158 GeV/c:**
  - **Λ production**
  - **Ξ production**
  - **Search for pentaquark**
  - **$K^*(892)^0$**
- **NA61/SHINE beyond 2020**
- **Summary**

Fixed target experiment located at the CERN SPS accelerator

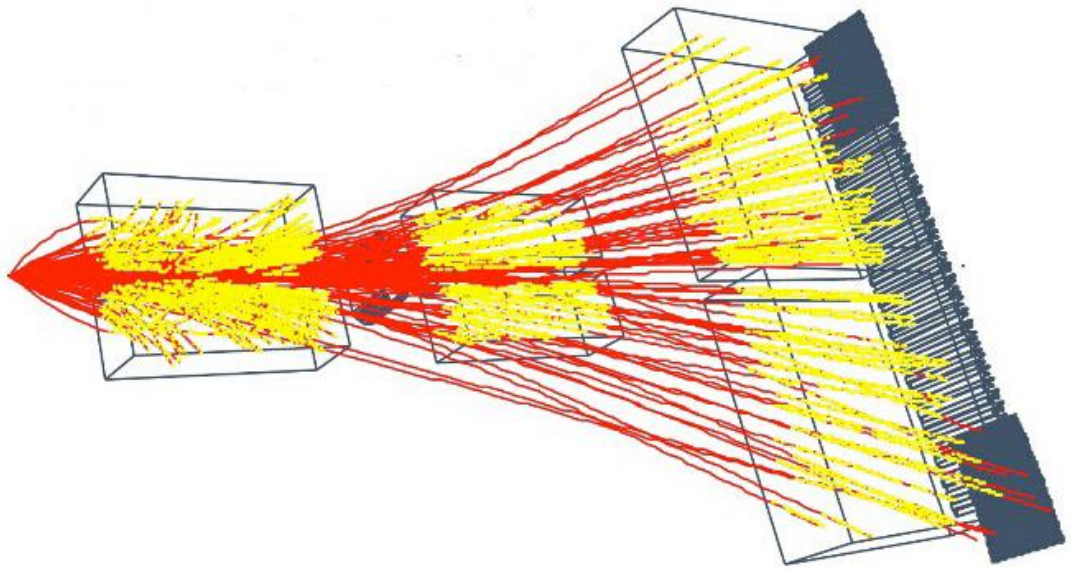


Beams:

- 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

Fixed target experiment located at the CERN SPS accelerator

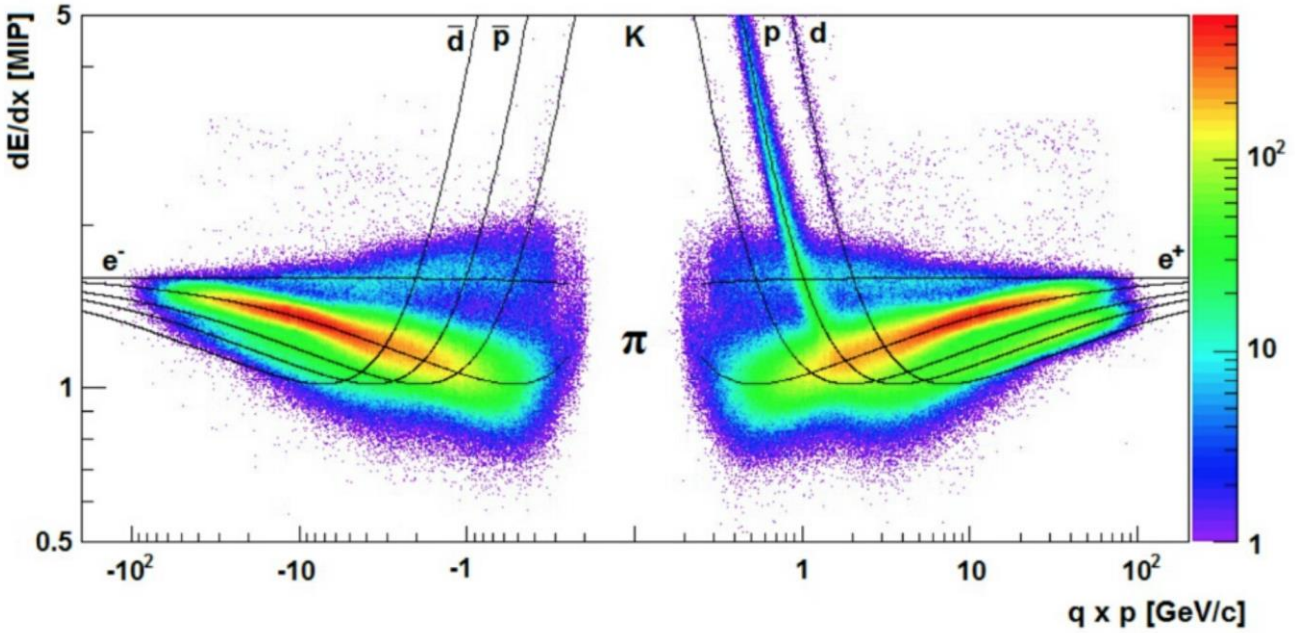


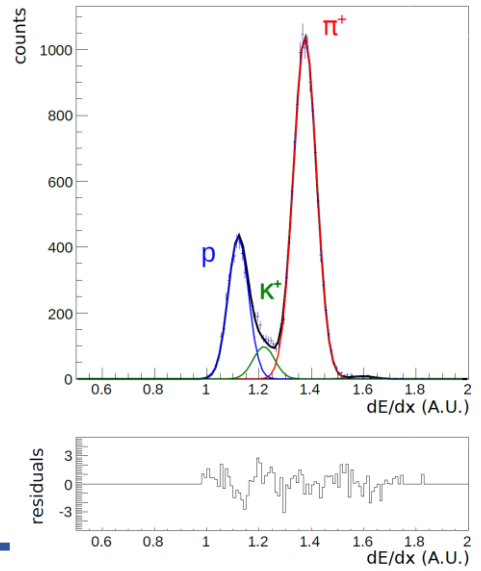
- Large acceptance ≈ 50% of produced particle
- High momentum resolution:
  $\sigma(p)/p^2 \approx 10^{-4}\ (GeV/c)^{-1}$ (at full B=9 T m)
- Particle identyfication based on energy loss (dE/dx) and time-of-flight measurments (tof)
  $\sigma(dE/dx)/ < dE/dx > \approx 0.04$; $\sigma(m_{inv}) \approx 5MeV$
  ToF-L/R: $\sigma(t) \approx 60ps$; $ToF - F : \sigma(t) \approx 120ps$
- High detector efficiency: 95%

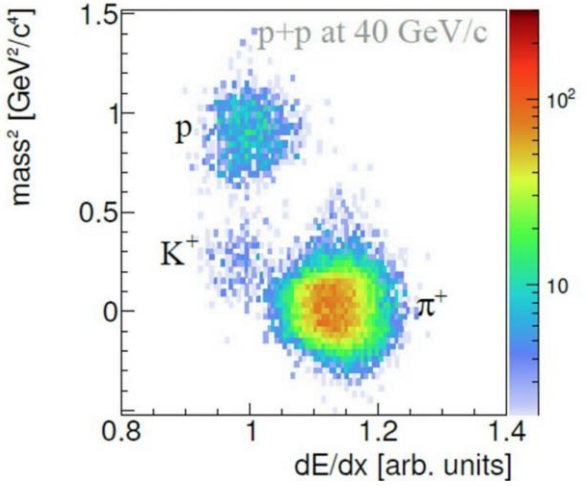
NA61/SHINE – charged particle identification

Final results stand for primary particles produced in strong and electromagnetic processes, they are corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions.

- **h^- analysis** based on the fact that the majority of negatively charged particles are π^- mesons. Contribution of other particles is subtracted using Monte-Carlo models.
- **dE/dx** analysis uses information on energy loss in the TPC gas to identify particles.
- **tof-dE/dx** method estimates number of π, K, p using an energy loss and a particle time of flight measurements.

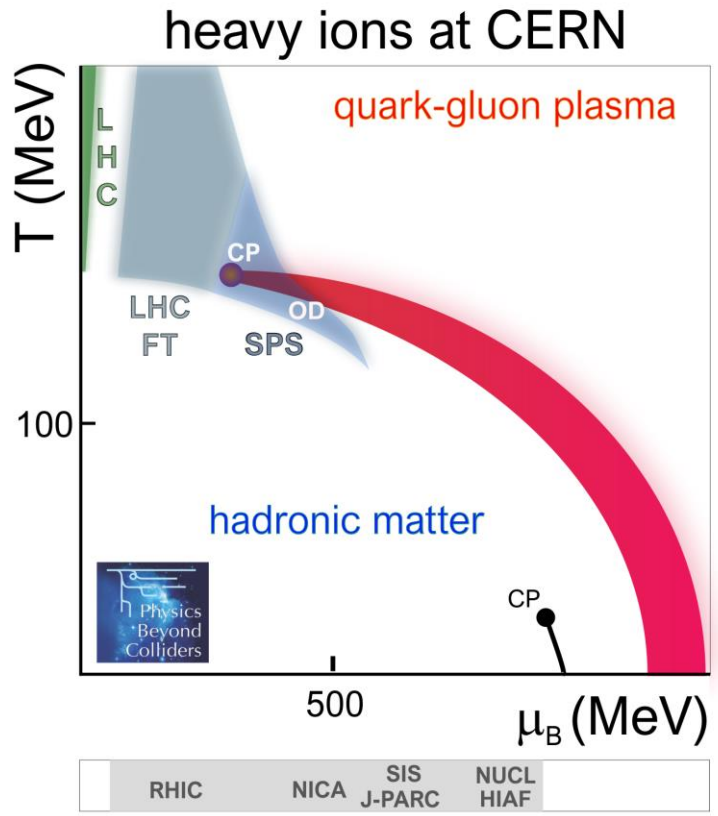


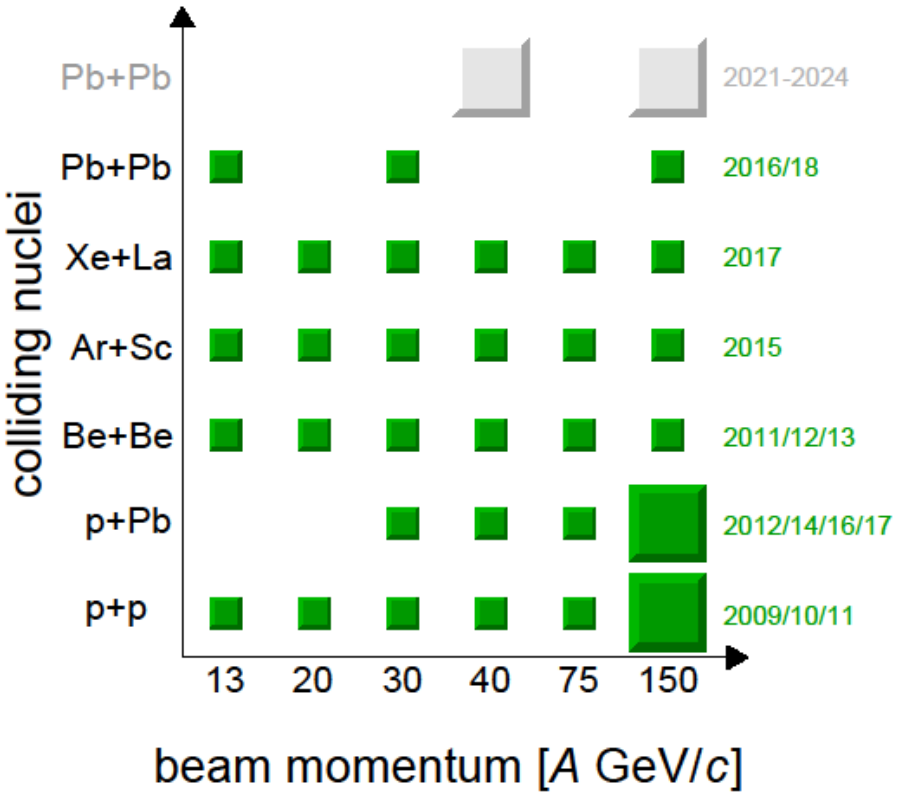




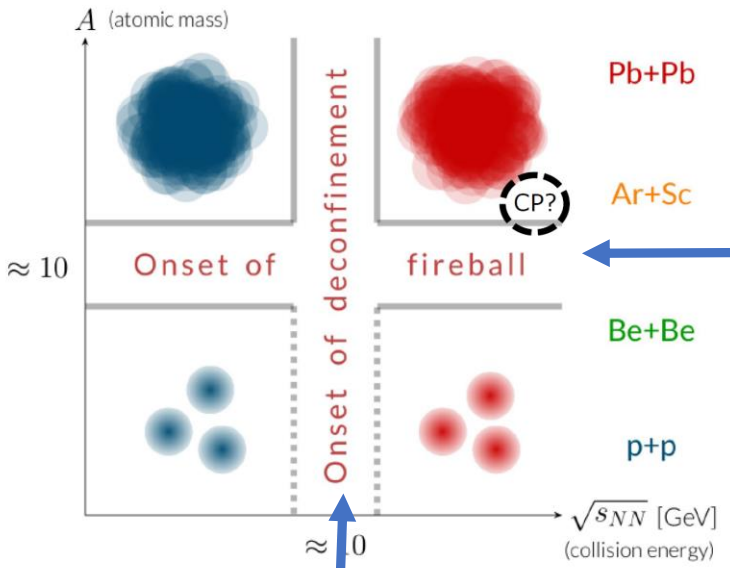
NA61/SHINE 2-dimensional scan

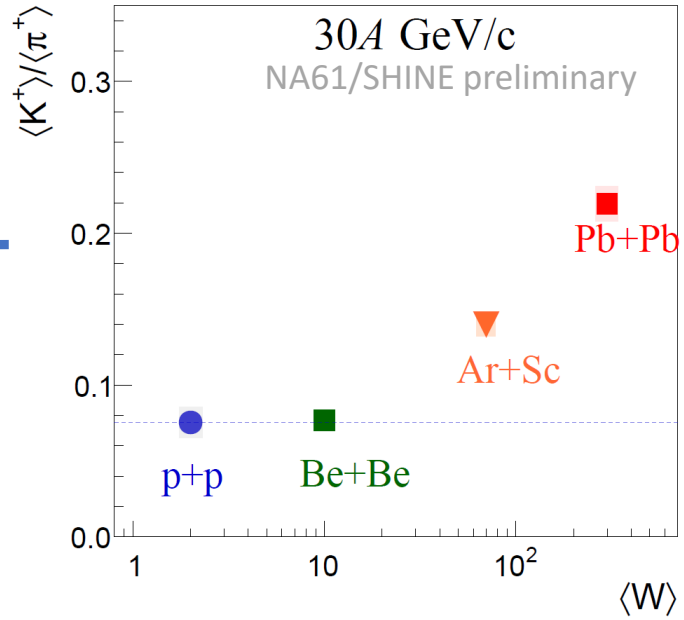
NA61/SHINE performed the 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter

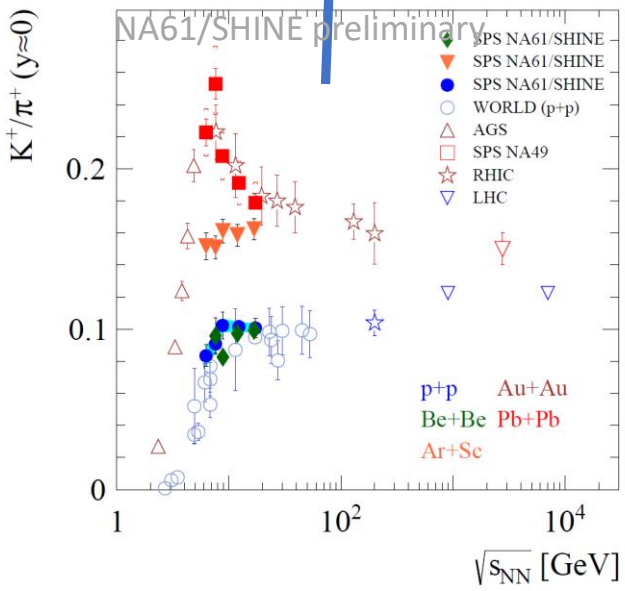




Uniqueness of heavy ion results from NA61/SHINE





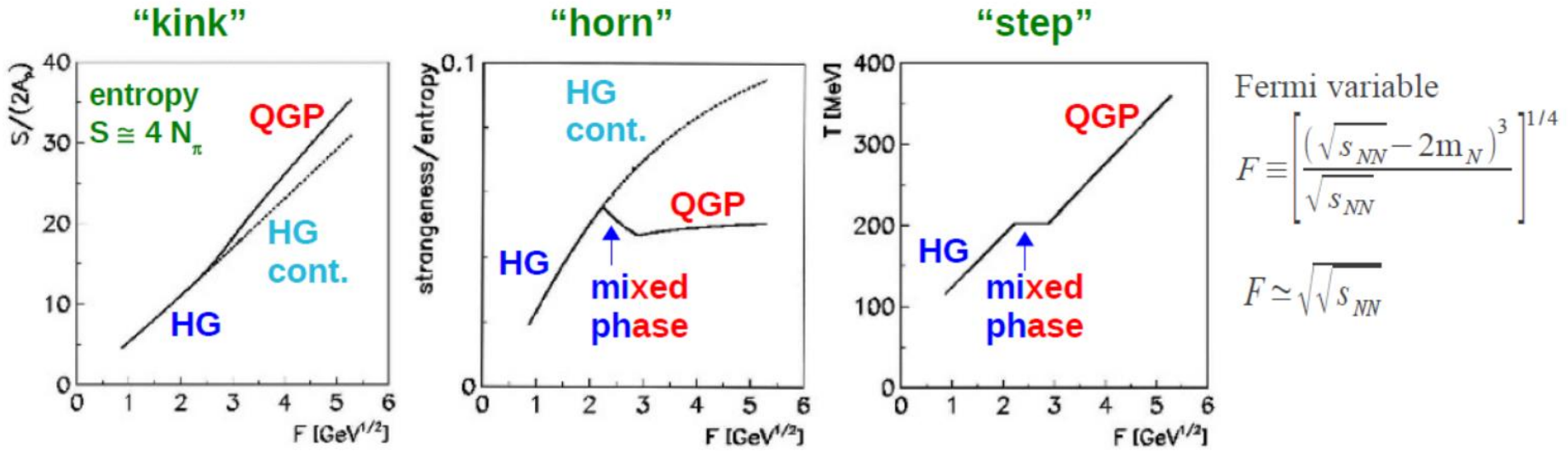


NA61/SHINE recorded unique data for:

- Onset of deconfinement
- Onset of fireball
- …

Study of the onset of deconfinement: Particle production properties

Statistical Model of the Early Stage (SMES)



1st order phase transition to QGP between top AGS and top SPS energies $\sqrt{s_{NN}} \approx 7$ GeV

Number of internal degree of freedom increases HG -> QGP (activation of partonic degrees of freedom)

Total entropy and total strangeness are the same before and after hadronization (cannot decrease QGP -> HG)

Mass of strangeness carries decreases HG->QGP ($m_{\Lambda,K,...} > m_s$)

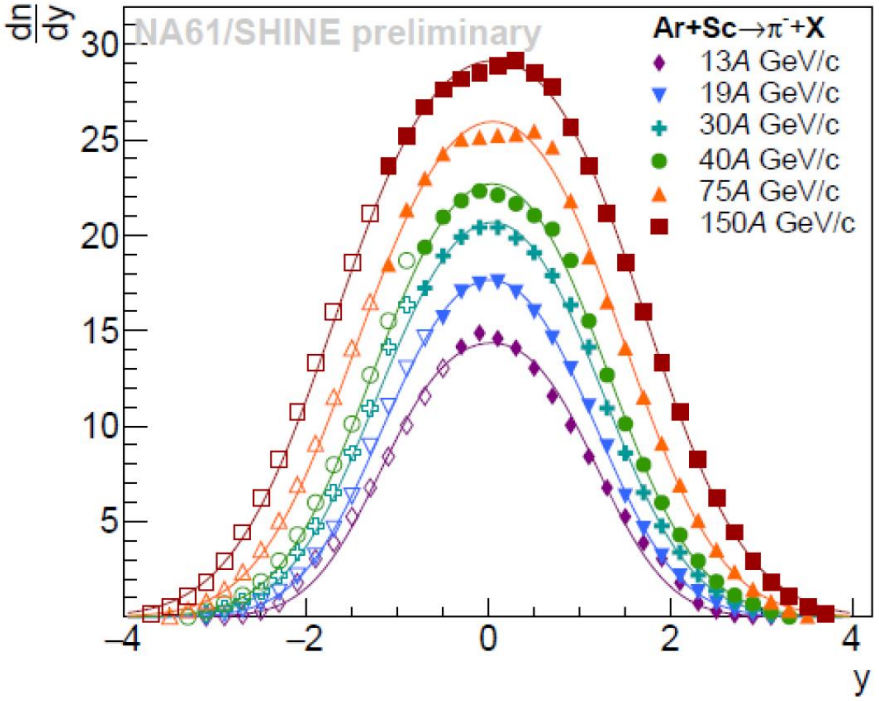
Constant temperature and pressure in mixed phase

Onset of deconfinement: kink

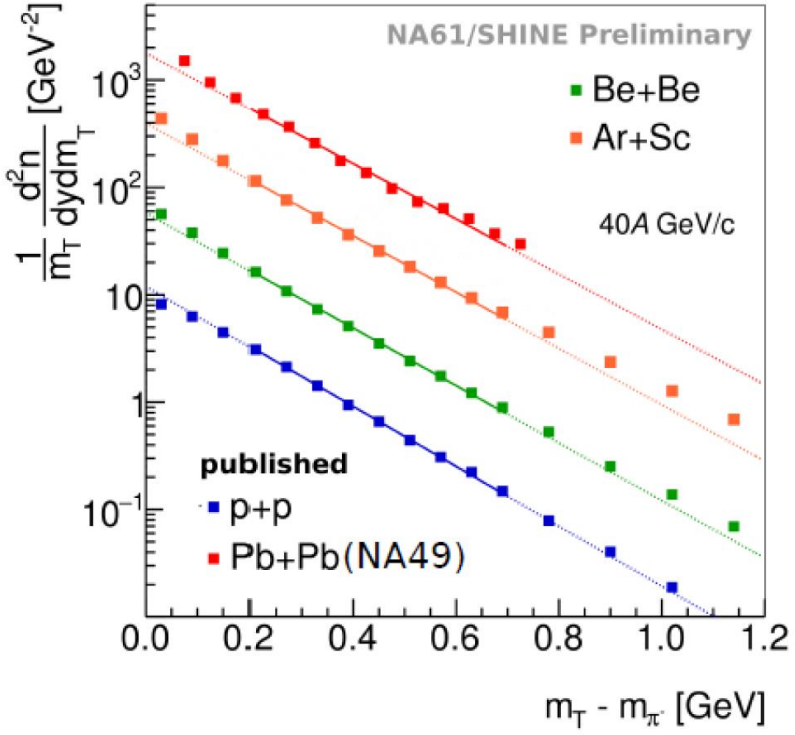
π^- spectra measured in large acceptance:

p_T down to 0, in full forward hemisphere.

Collision energy dependence



System size dependence



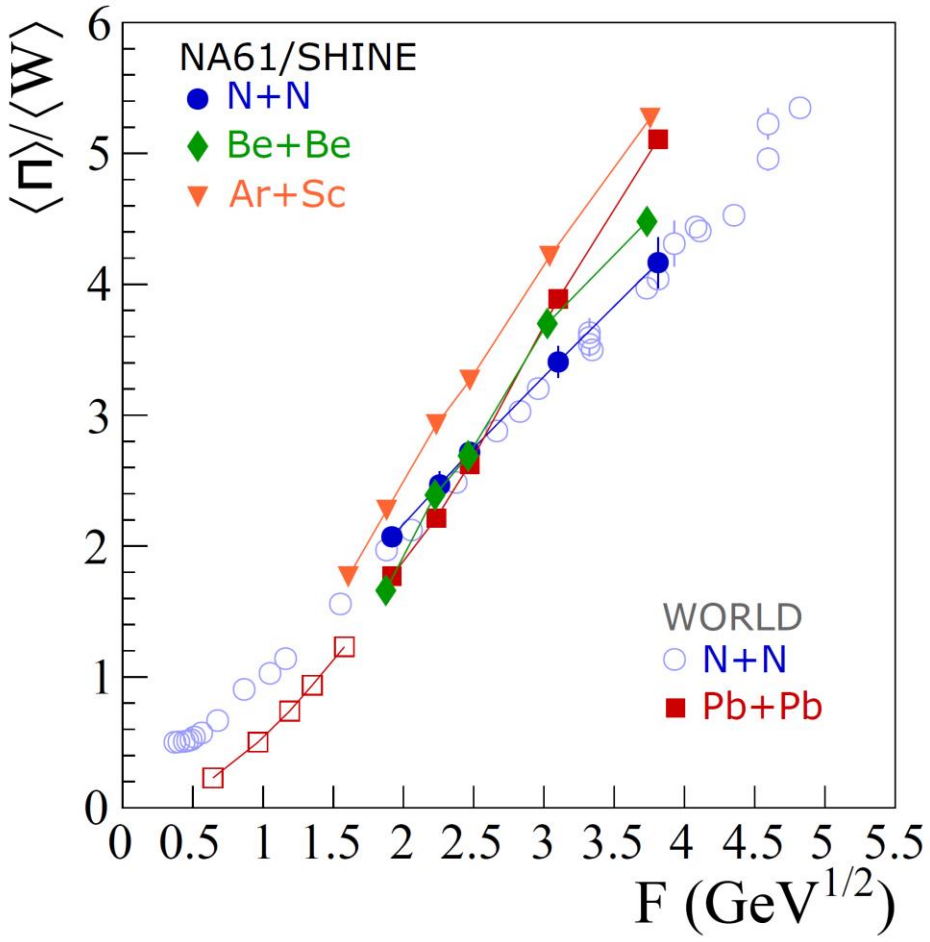
Rapidity spectra ≈ gaussian, independently of collision energy and system size

Large acceptance allows to obtain 4π multiplicity

m_T spectra in p+p are exponential, in larger systems (central collisions) deviate from the exponential shape

Onset of deconfinement: kink

Statistical model with phase transition (SMES) predicts increase of the slope – **KINK** – of <π>/<W> in QGP due to the larger number of degrees of freedom in comparison to HRG.



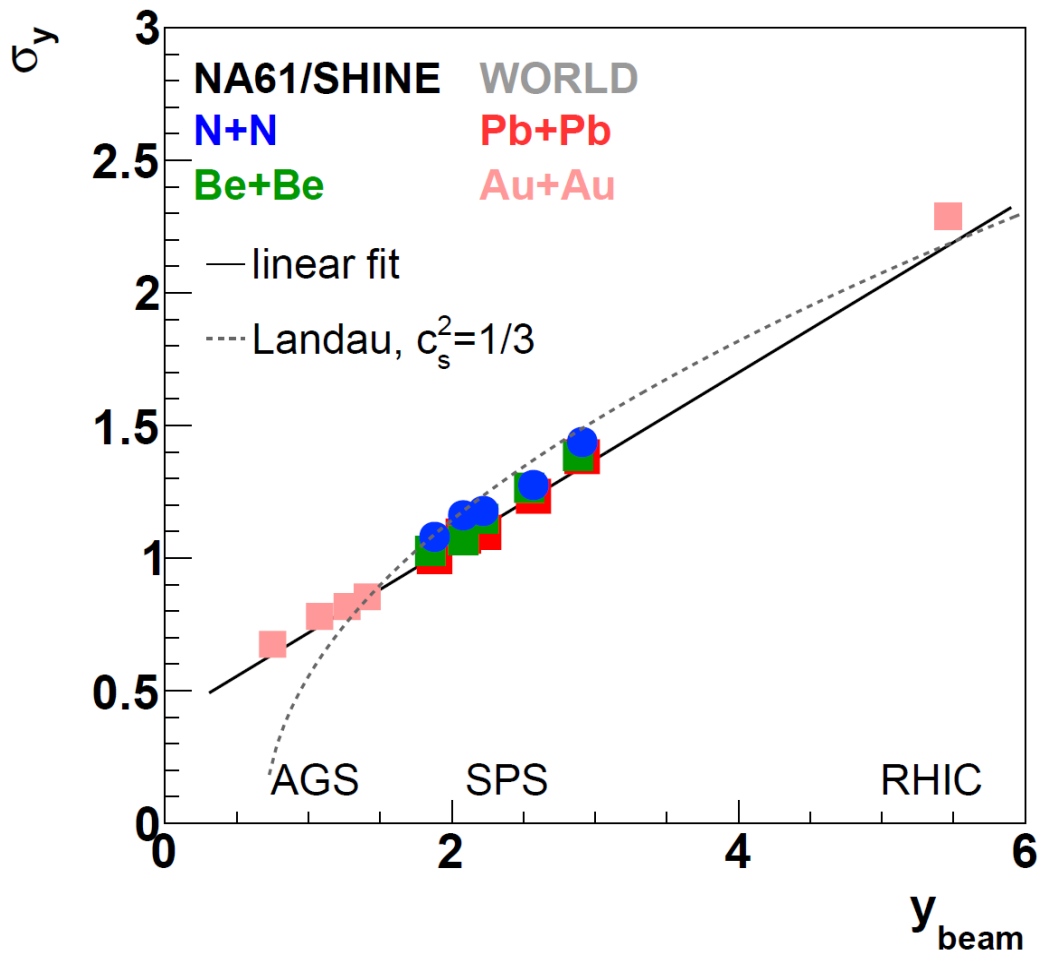
<π> multiplicity at the SPS energies increases faster in central Pb+Pb than in p+p collisions (kink). The two dependences cross at about 40A GeV.

For low SPS energies Be+Be follows the Pb+Pb trend; for top SPS energy Be+Be ratio decreases to the one observed in p+p.

Ar+Sc slope follows Pb+Pb but ratio is systematically higher then one observed in Pb+Pb.

Onset of deconfinement: dale

The collision energy dependence of the rapidity width was derived from the Landau hydrodynamical model:



$$\sigma_y^2(\pi^-) = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right)$$

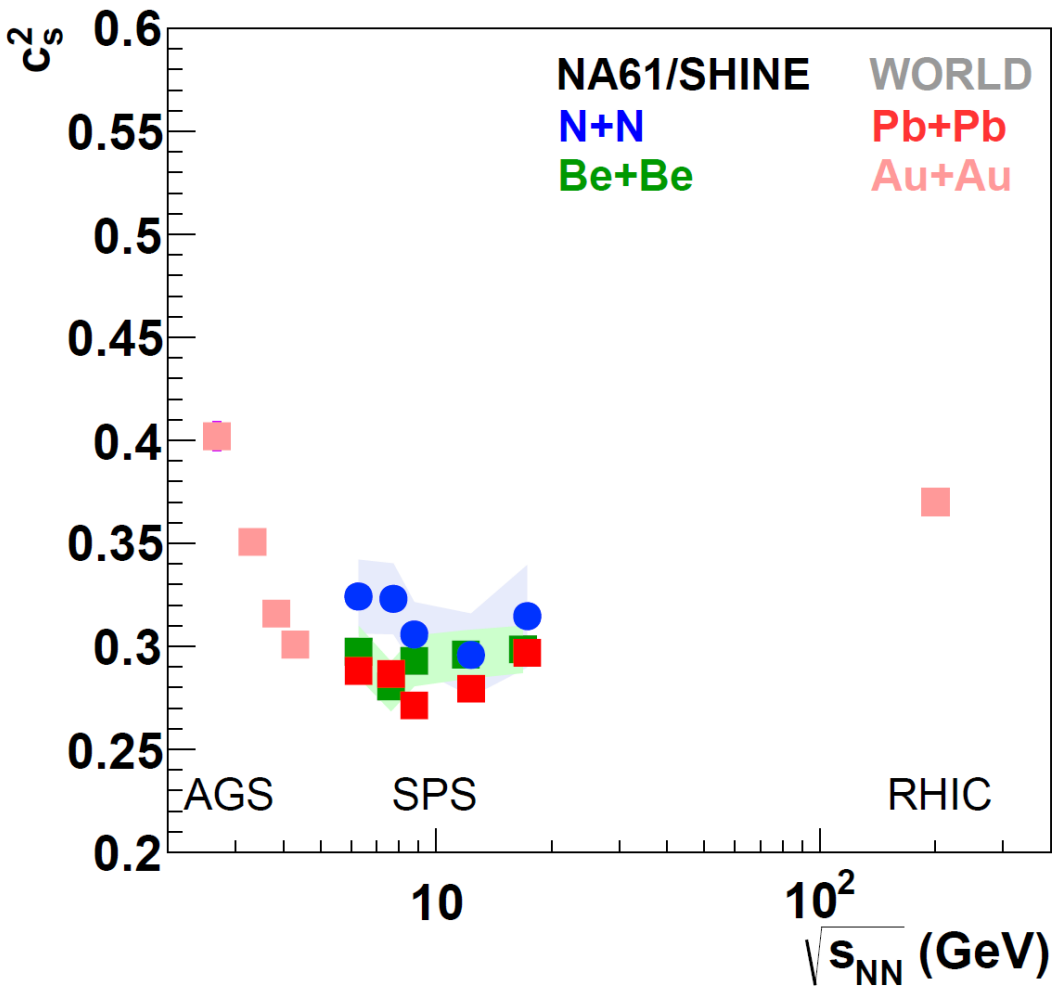
The model calculations are close to the measured dependence on the beam rapidity.

Linear increase with y_{beam} provides a better fit to the measurements.

The measured values of σ_y differ very little between the studied reactions in the SPS energy range.

Onset of deconfinement: dale

The collision energy dependence of the rapidity width was derived from the Landau hydrodynamical model:



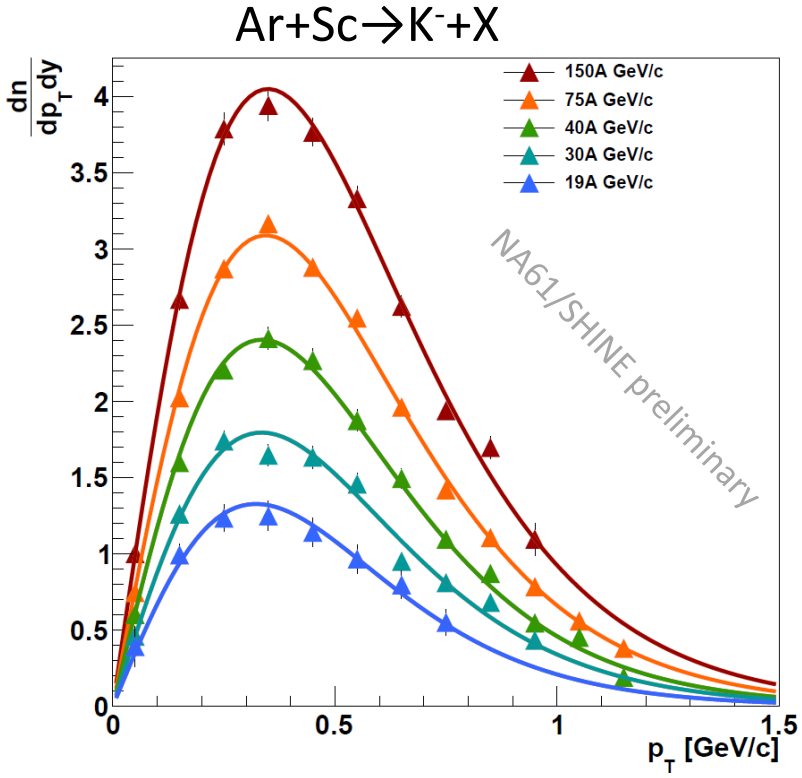
$$\sigma_y^2(\pi^-) = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right)$$

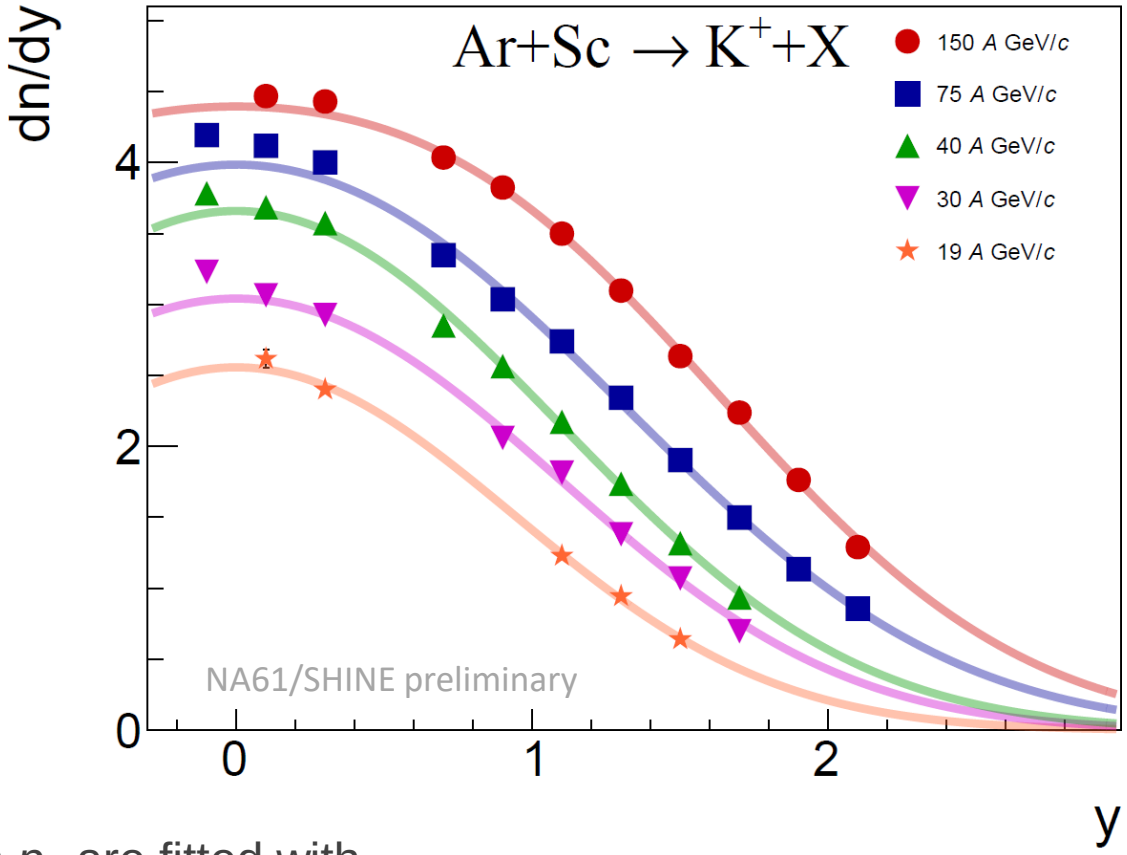
The energy range for results from Be+Be collisions and inelastic p+p reactions is too limited to allow a significant conclusion about a possible minimum.

Data on central Pb+Pb exhibits a clear minimum (the softest point) at $\sqrt{s_{NN}} = 10$ GeV consistent with the reported onset of deconfinement.

Onset of deconfinement: step and horn

2D kaon spectra for central (0-10%) Ar+Sc collisions



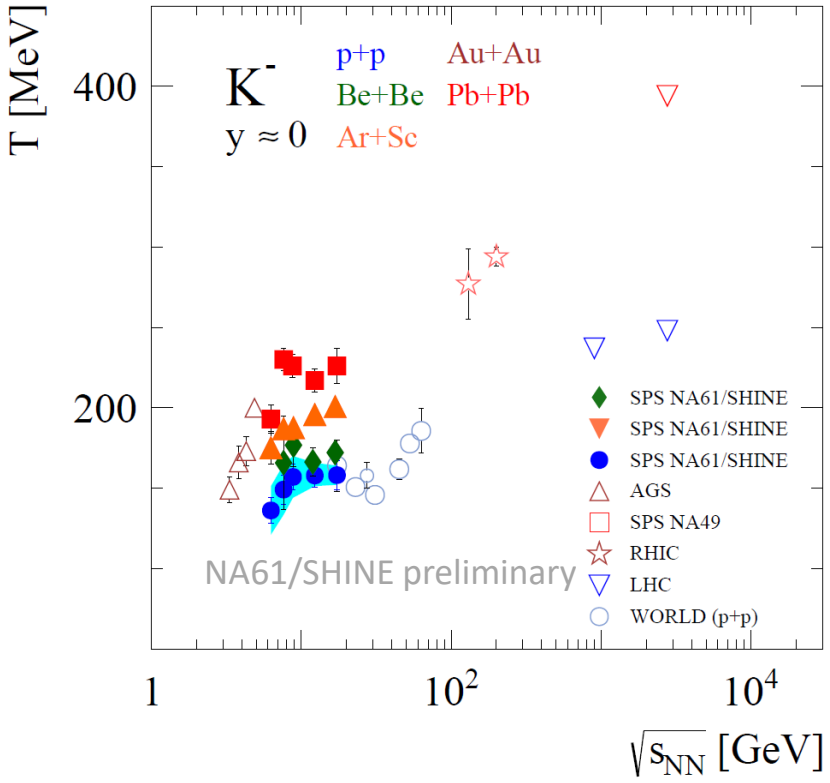


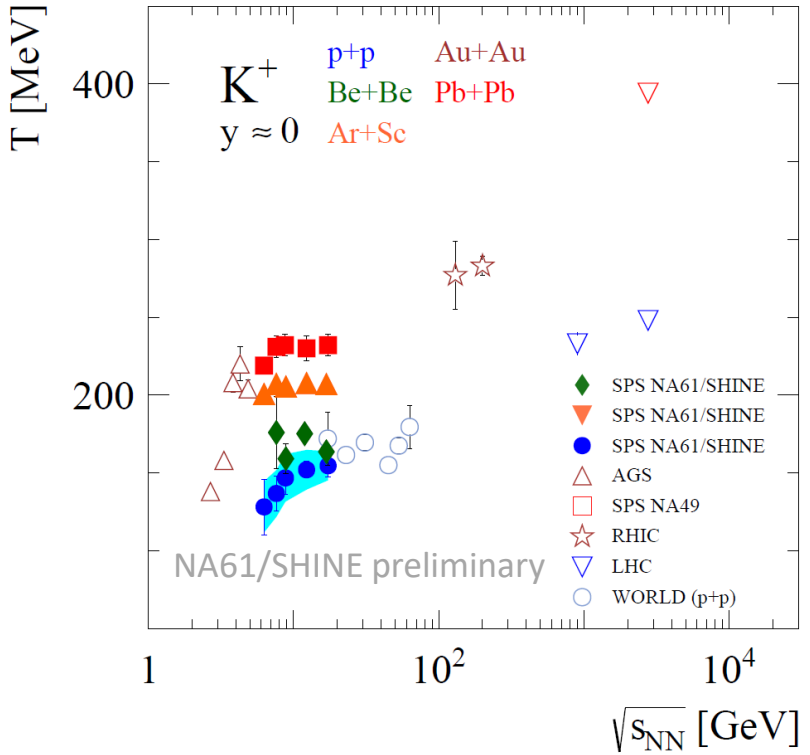
K± spectra in p_T are fitted with

$$\frac{d^2n}{dp_T dy} = \frac{S\ p_T}{T^2 + T\ m_K}\ exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$$

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).





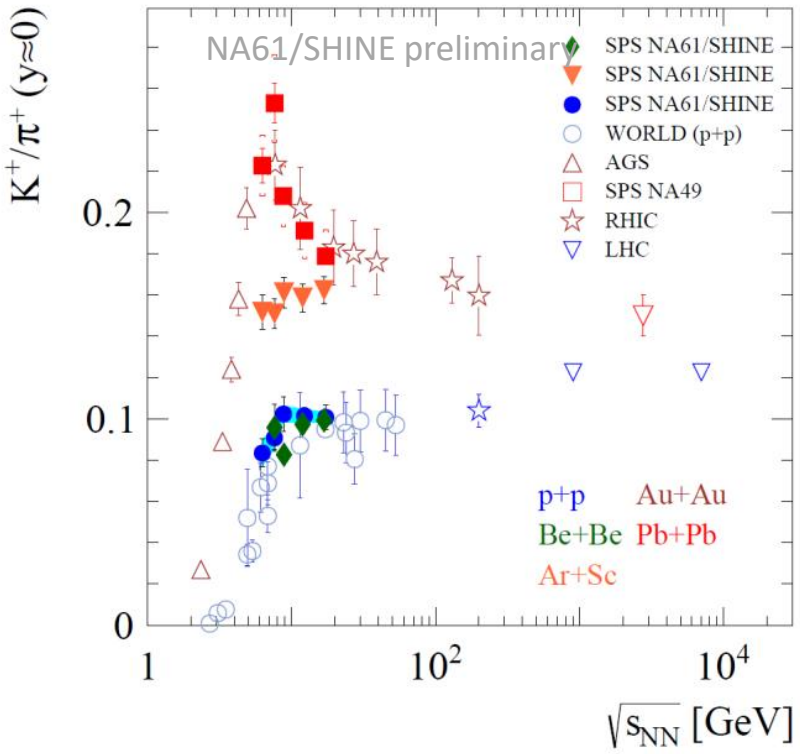
Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions

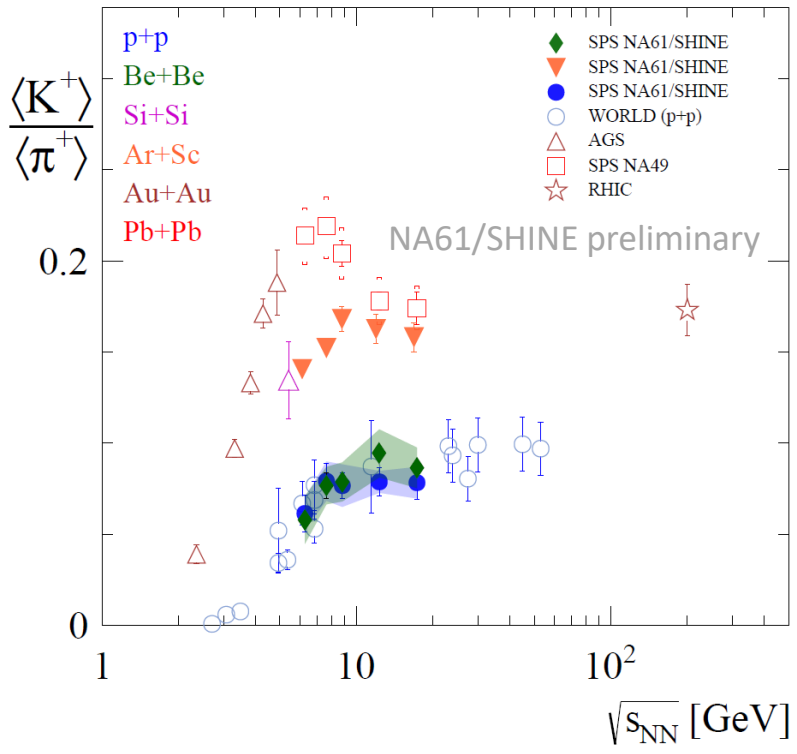
Magnitude of T in Be+Be slightly higher than in p+p

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

Onset of deconfinement: horn

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



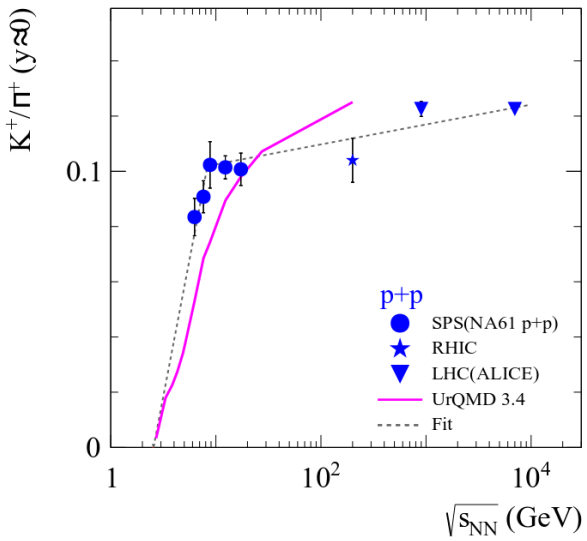


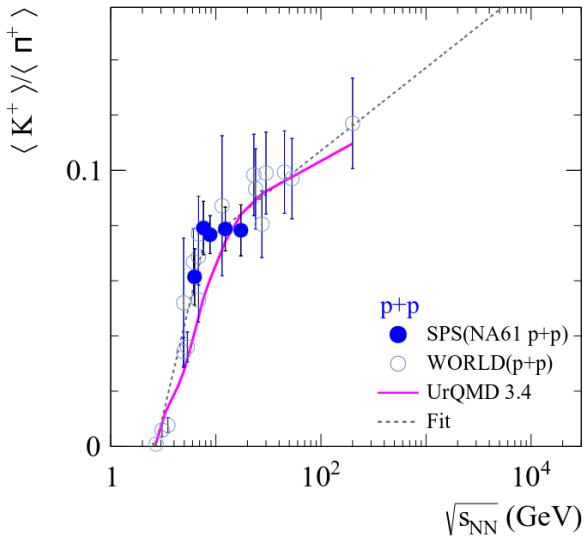
Plateau like structure visible in p+p

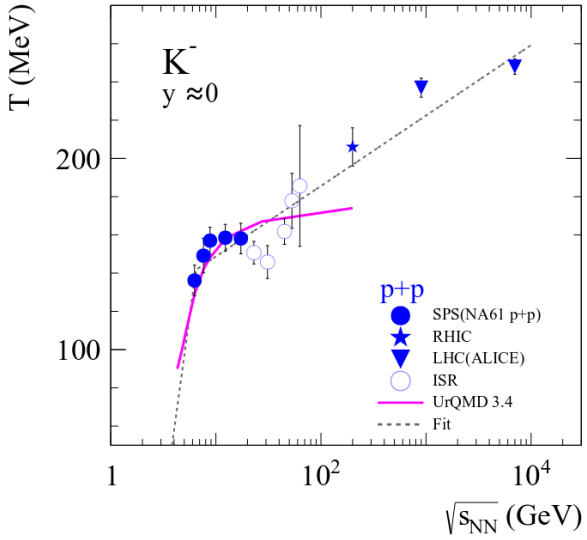
Be+Be close to p+p

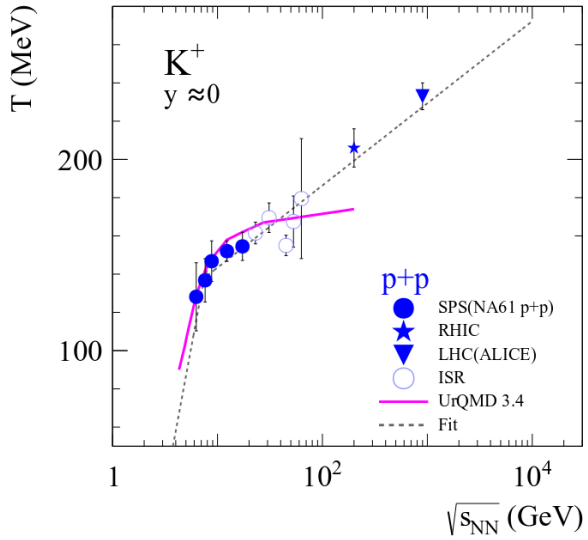
Ar+Sc is higher than p+p but form of energy dependence is similar to p+p (no horn)

Onset of deconfinement: p+p data









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

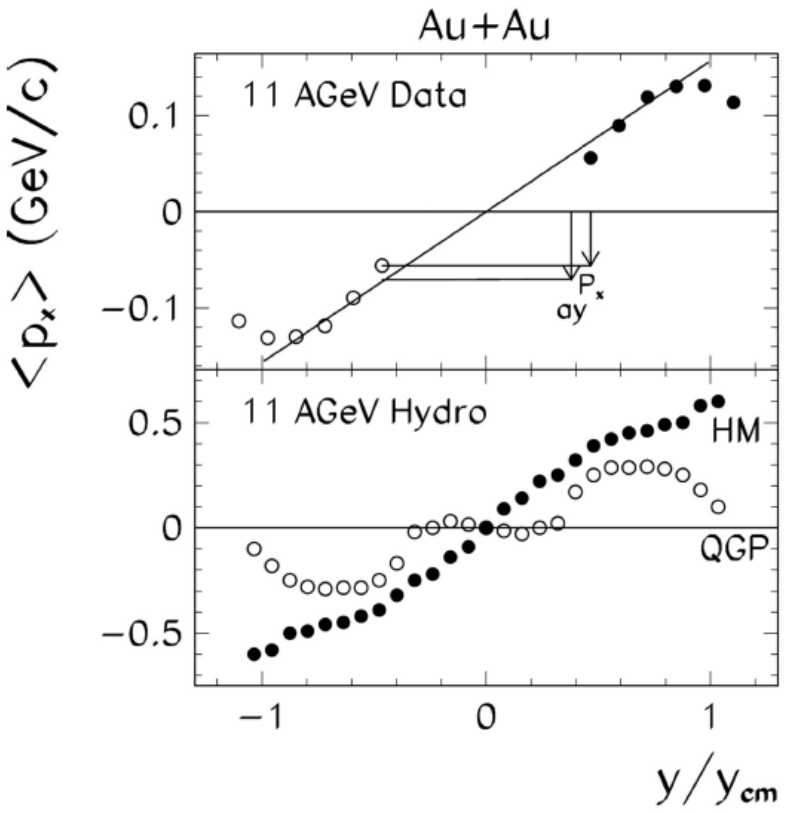
Resonance-string model (UrQMD) fails to reproduce data

Study of the onset of deconfinement: Flow

Directed flow and the onset of deconfinement

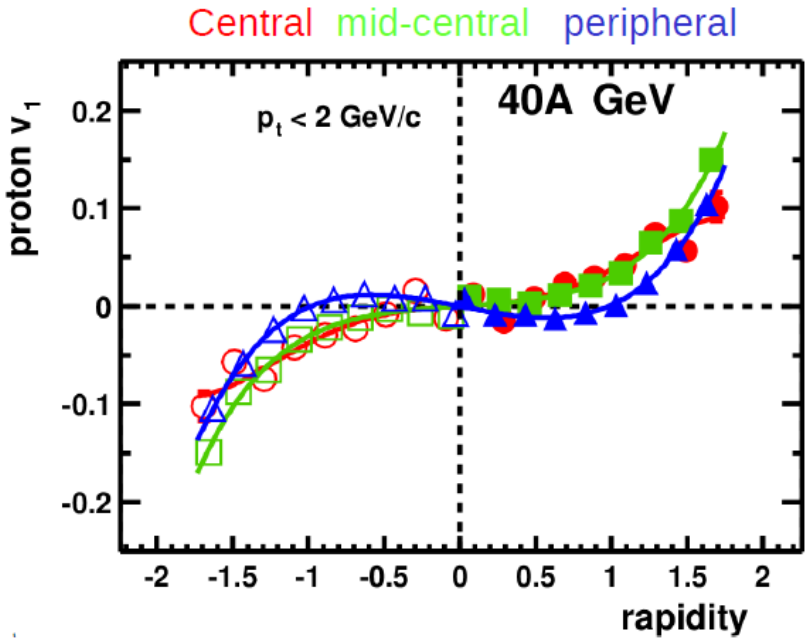
Directed flow v_1 is considered to be **sensitive to 1st order phase transition** (softening of EOS). Expected: **non-monotonic behavior** (positive→negative→positive) **of proton dv_1/dy as a function of beam energy** - "collapse of proton flow"

Predictions of hydrodynamical model:



$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

Directed flow measured by NA49 at middle SPS energy ("anti-flow" of protons at mid-rapidity):



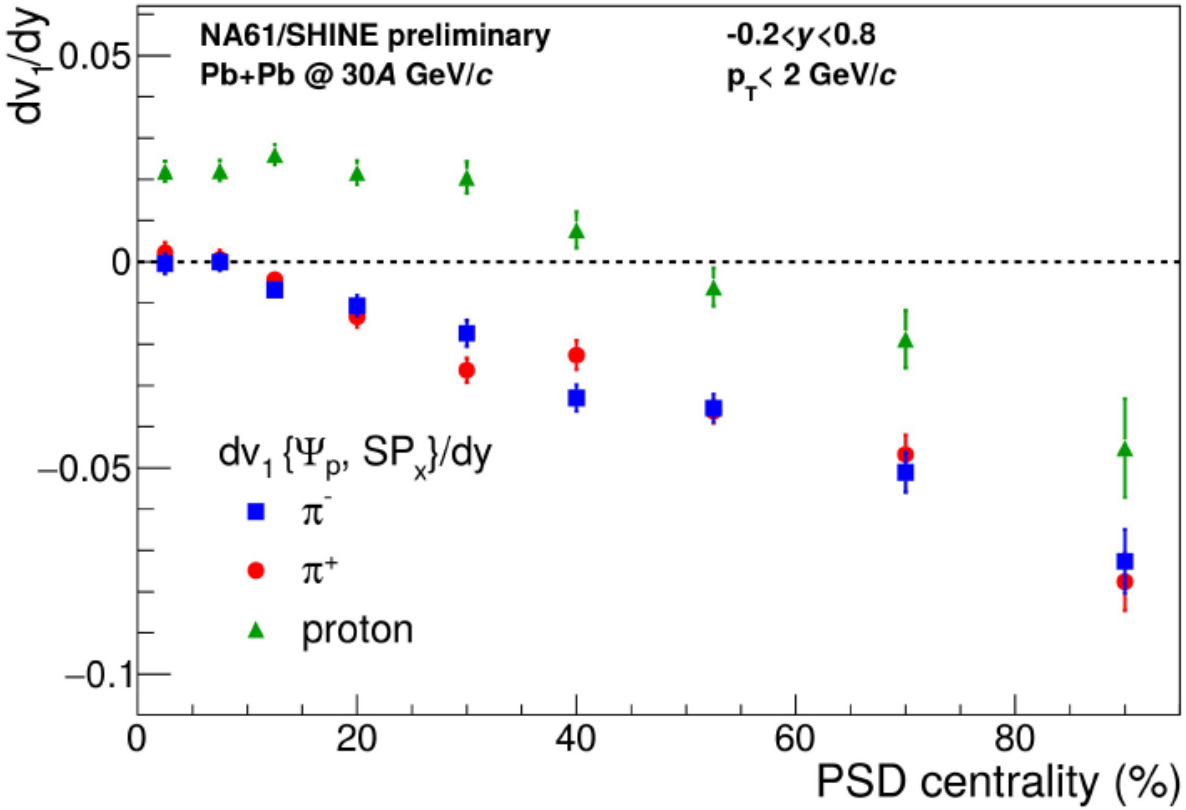
Csernai, Rohrich, PL B458, 454, 1999 H. Stoecker NP 750, 121, 2005

NA49, Phys. Rev. C68, 034903, 2003

Centrality dependence of dv_1/dy in Pb+Pb at $\sqrt{s_{NN}}$ = 7.6 GeV

NA61/SHINE fixed target setup → tracking and particle identification over wide rapidity range

Flow coefficients are measured relative to the **spectator plane estimated with Projectile Spectator Detector** (PSD) → unique for NA61/SHINE



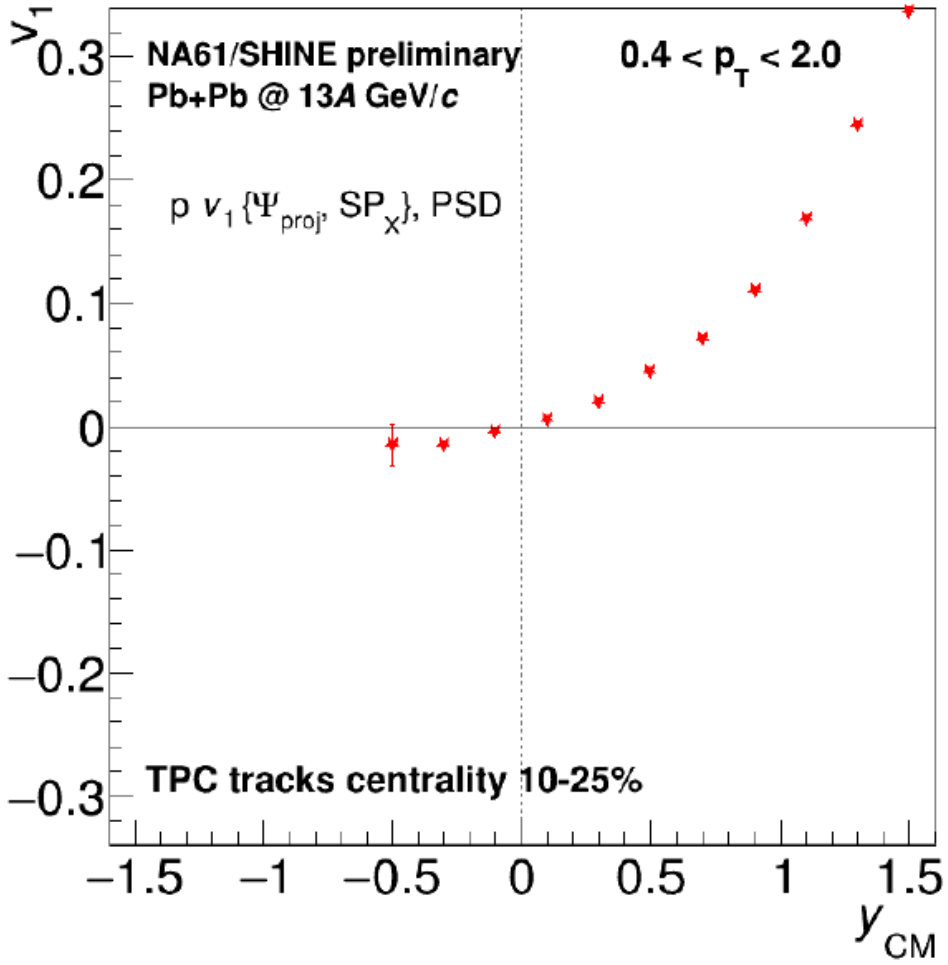
Close to mid-rapidity (-0.2 < y < 0.8)

- slope of pion v_1 is negative for all centralities

- slope of proton v_1 changes sign at centrality of about 50%

Proton directed flow vs rapidity

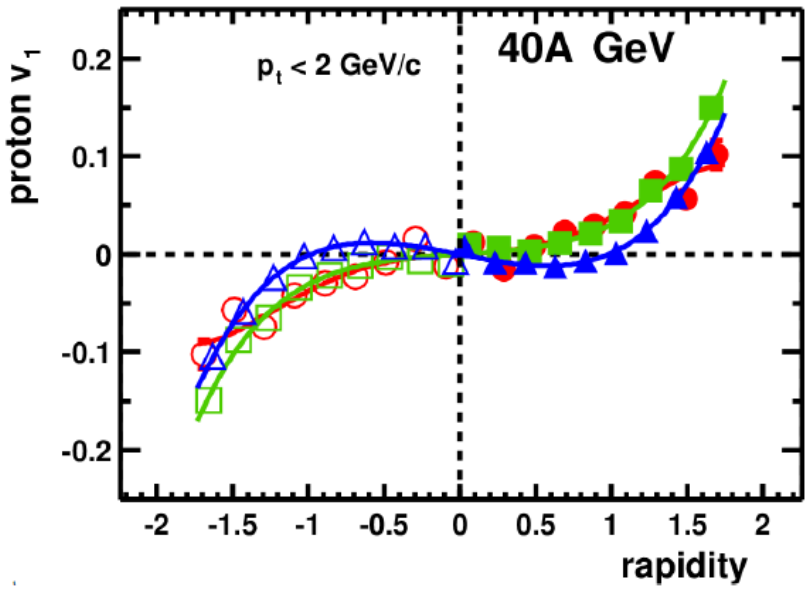
NA61 Pb+Pb at 13*A* GeV/c



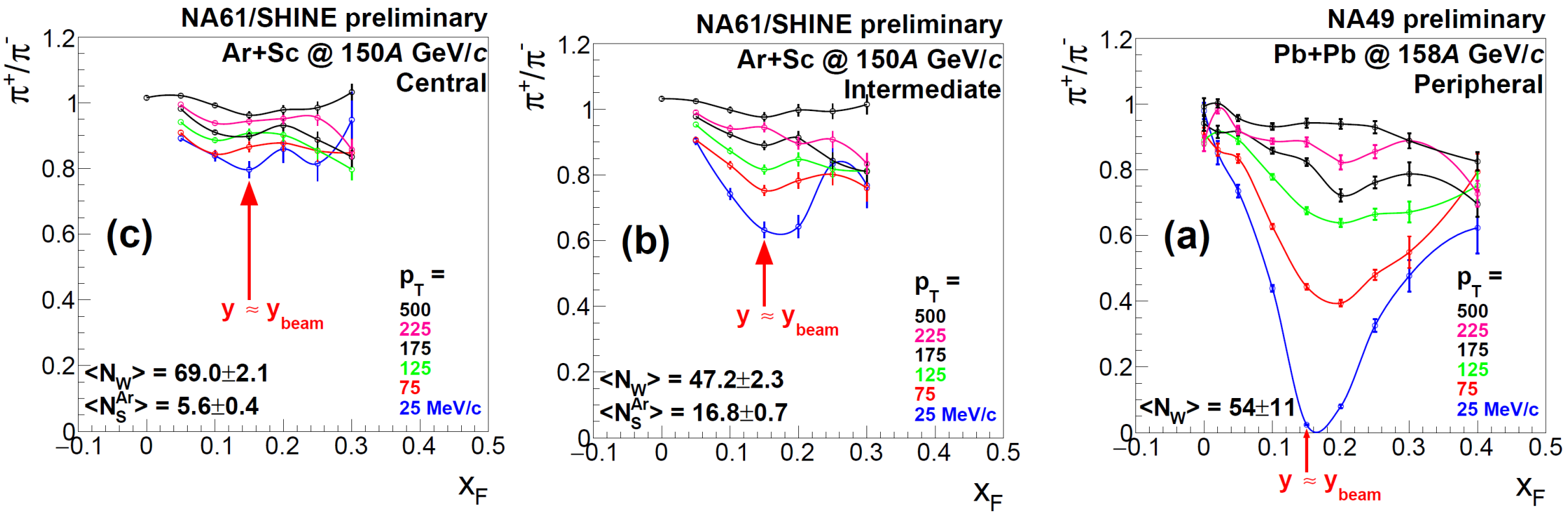
No evidence for the collapse of proton directed flow in Pb+Pb at 13*A* GeV/c

Directed flow measured by NA49 at middle SPS energy ("anti-flow" of protons at mid-rapidity):

Central mid-central peripheral



Spectator-induced electromagnetic effects



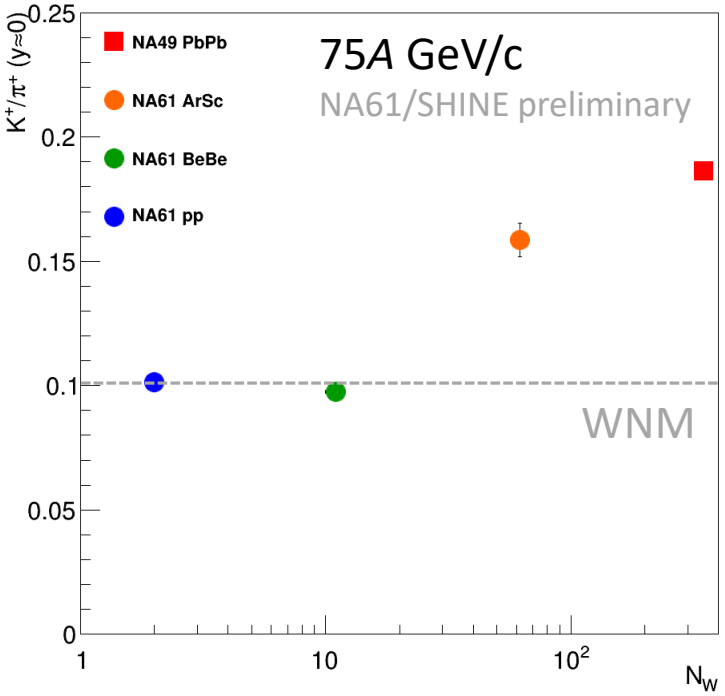
EM-repulsion of π^+ and attraction of π^- is the strongest for pions with rapidities close to spectator (beam) rapidity and with low p_T

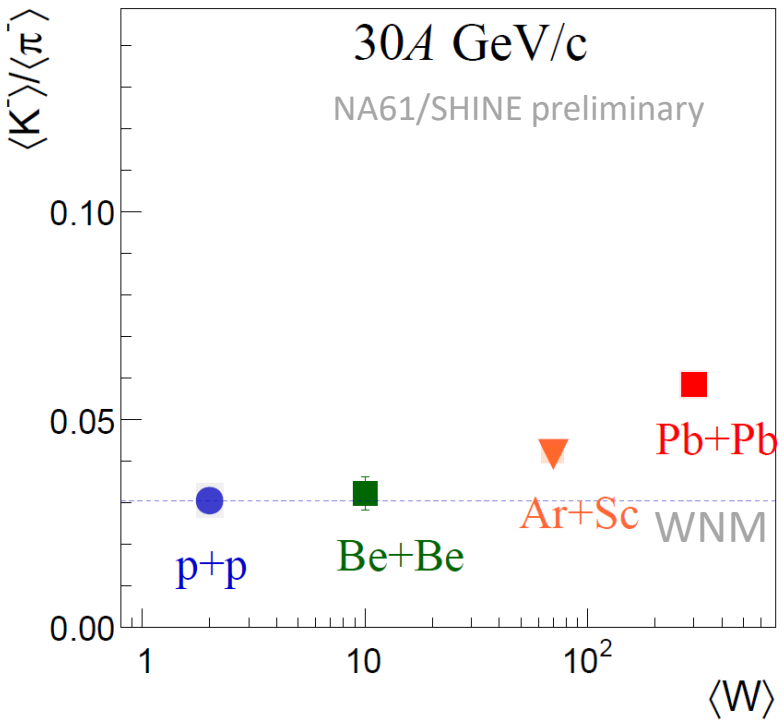
First observation of spectator induced EM effects in small systems at SPS

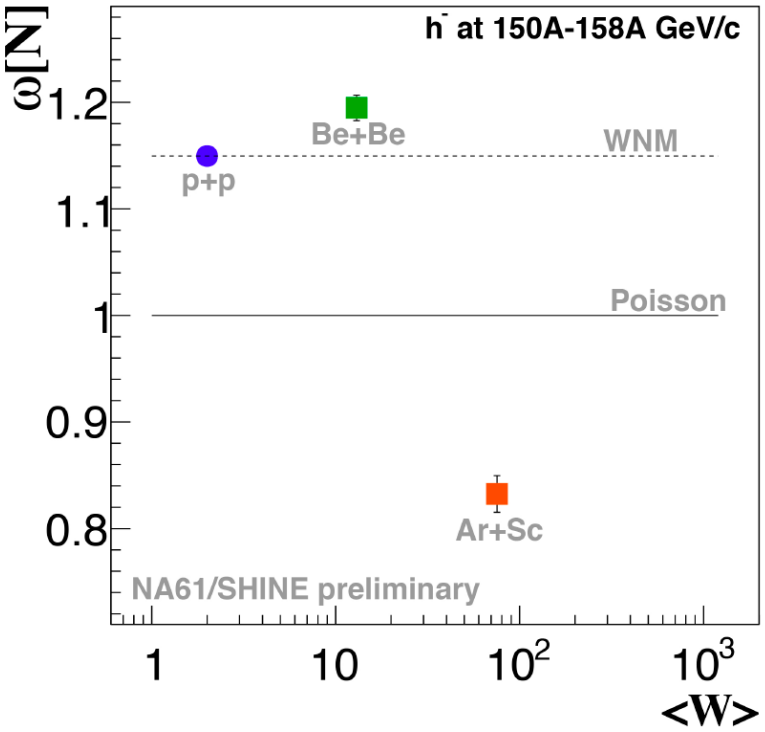
Similar effect seen in intermediate centrality Ar+Sc (NA61/SHINE) and peripheral Pb+Pb (NA49)

Study of the onset of fireball

Onset of fireball: system size dependence







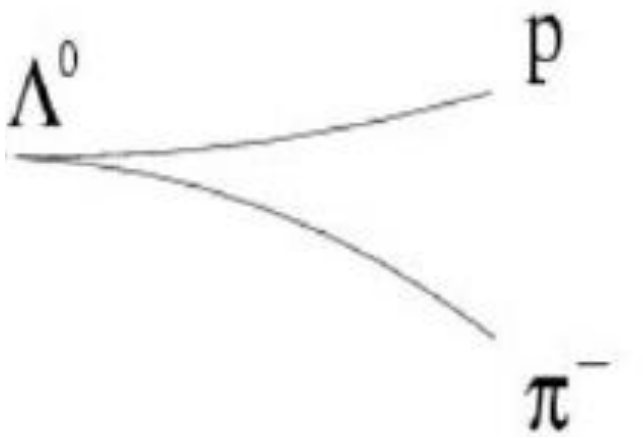
Change between

p+p ≈ Be+Be and Ar+Sc, Pb+Pb results

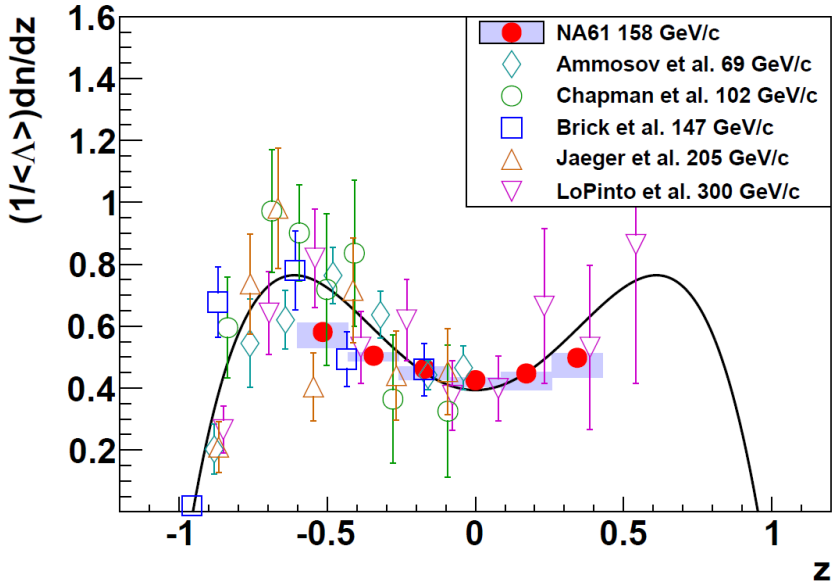
- p+p data are corrected for experimental biases, systematic uncertainty ~0.1 [EPJ.C76:635]
- 0-1% Be+Be data is uncorrected, experimental bias is ~10-15%
- 0-0.2% Ar+Sc data is uncorrected, experimental bias is ~5-7%

Strangeness production in p+p : Λ production

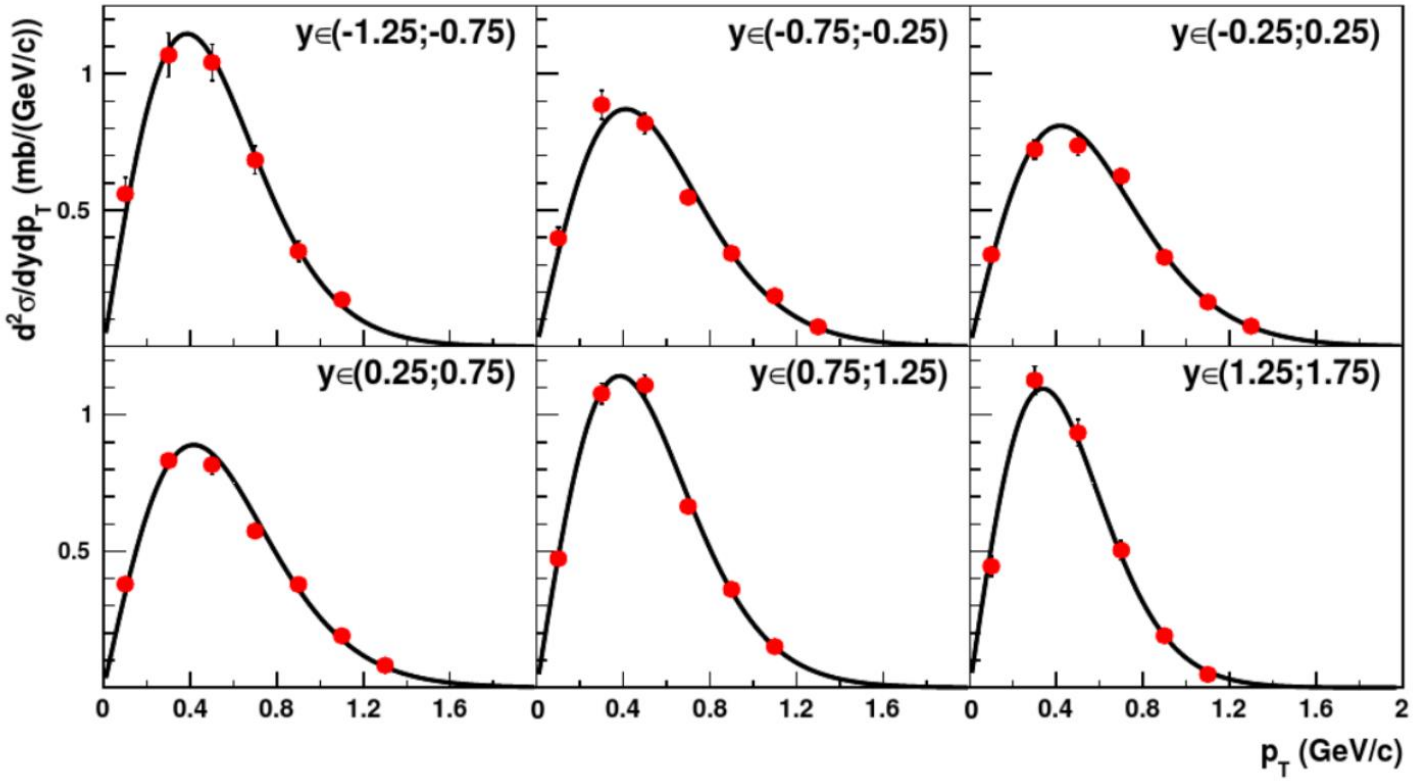
Λ production in inelastic p+p



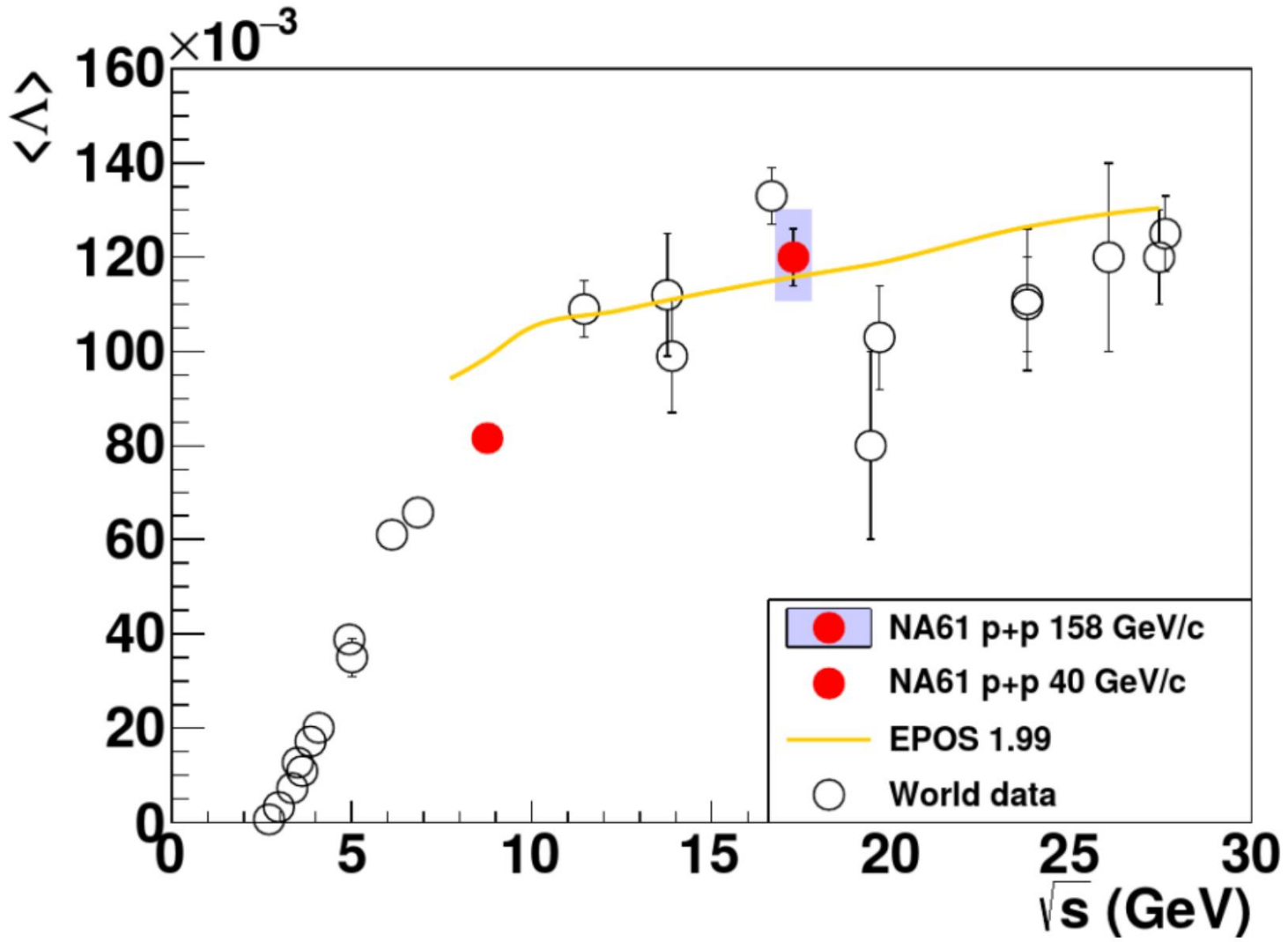
p + p at 158 GeV/c



p + p at 40 GeV/c

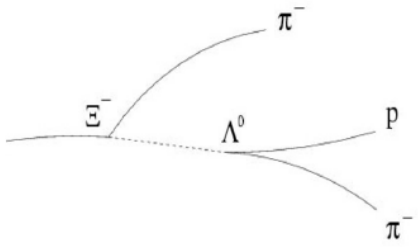


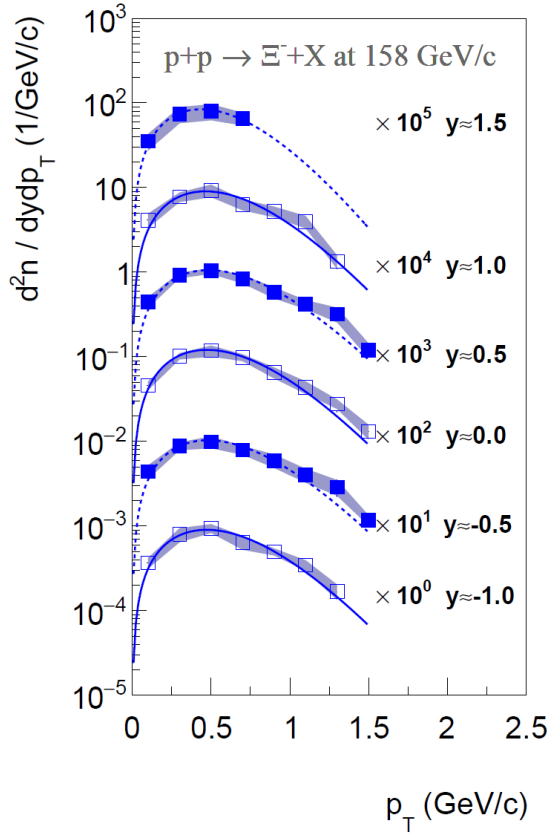
Λ production in inelastic p+p – excitation function

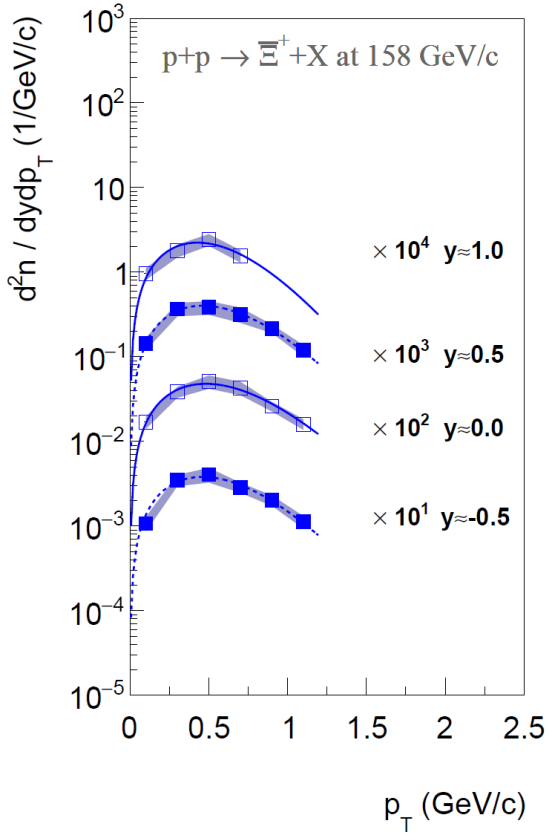


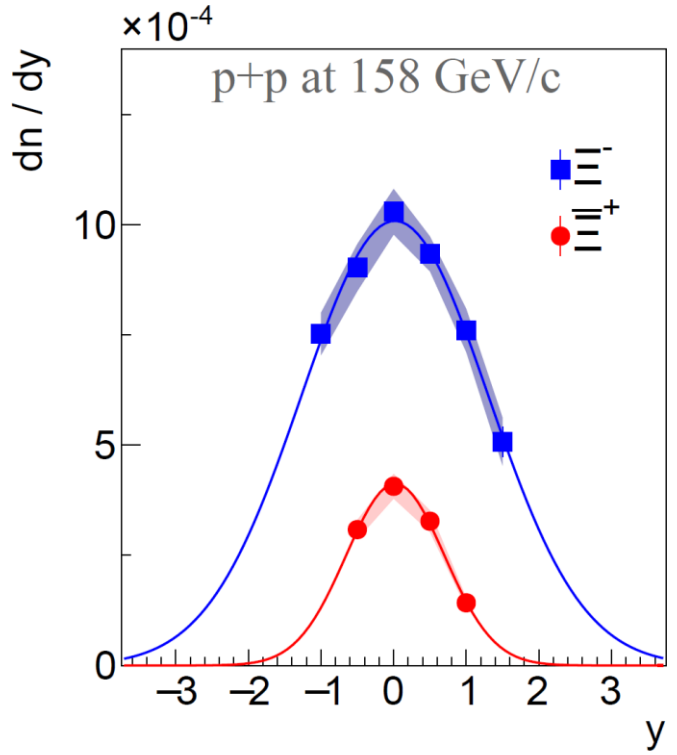
Strangeness production in p+p at 158 GeV/*c*.
Ξ production

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





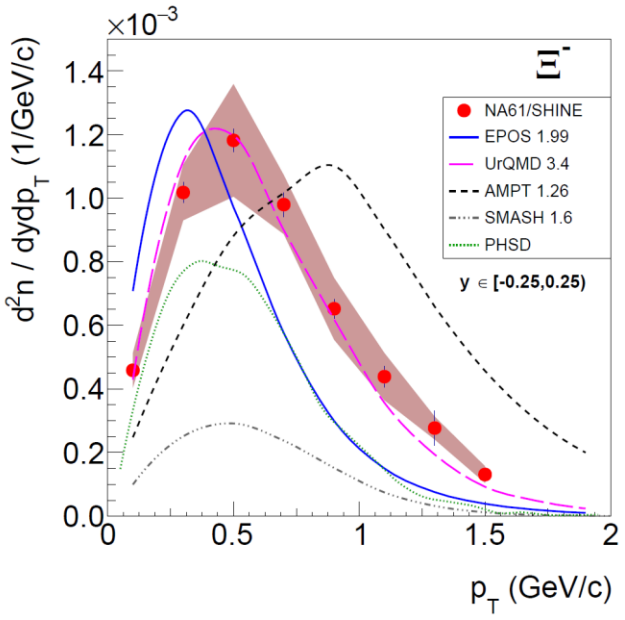


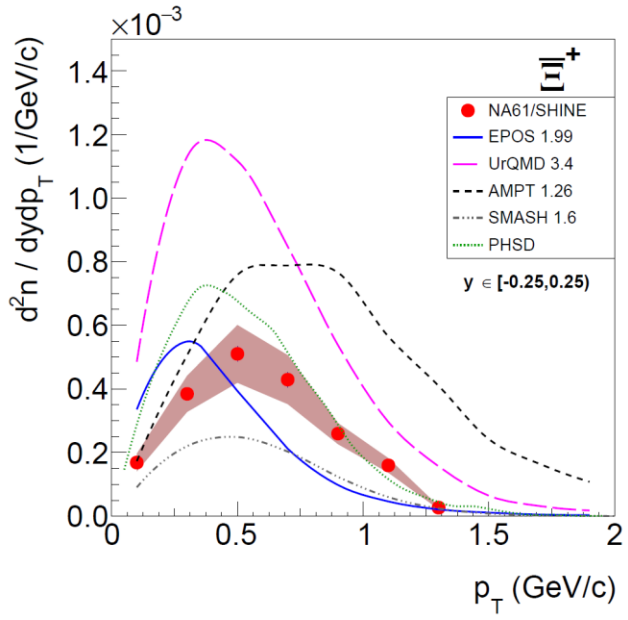


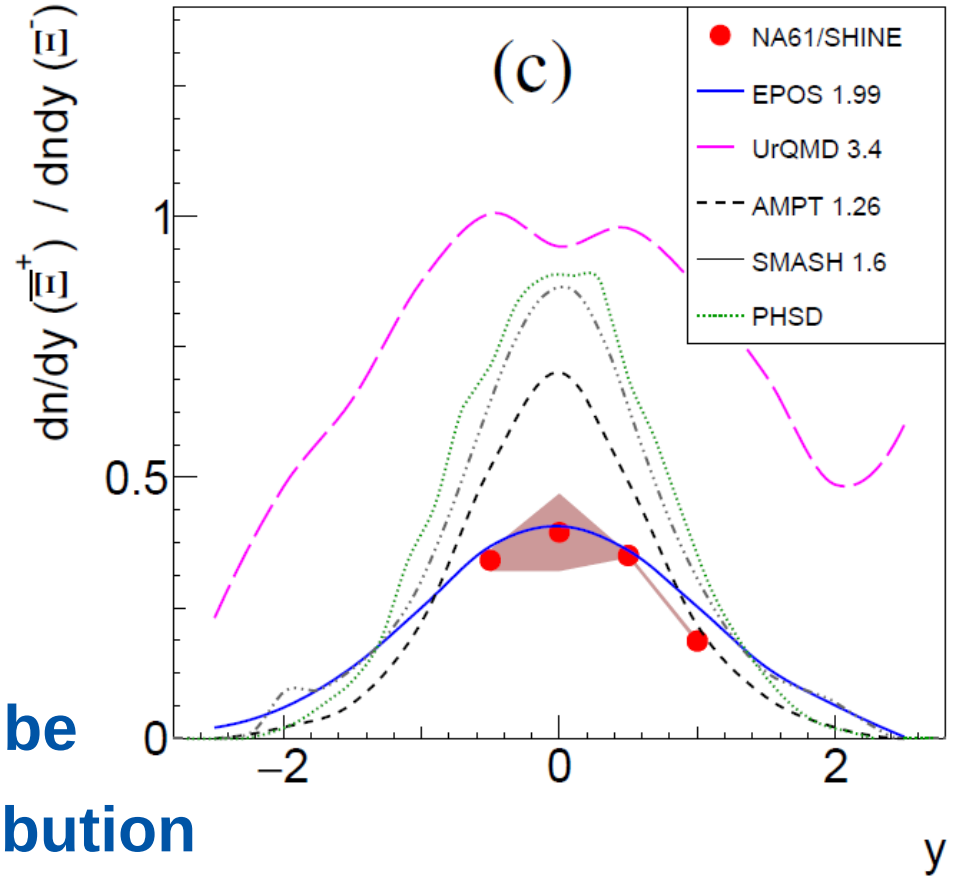
$$\langle \Xi^- \rangle = (3.3 \pm 0.1 \pm 0.6) \times 10^{-3}$$

$$\langle \bar{\Xi}^+ \rangle = (7.9 \pm 0.2 \pm 1.0) \times 10^{-4}$$

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





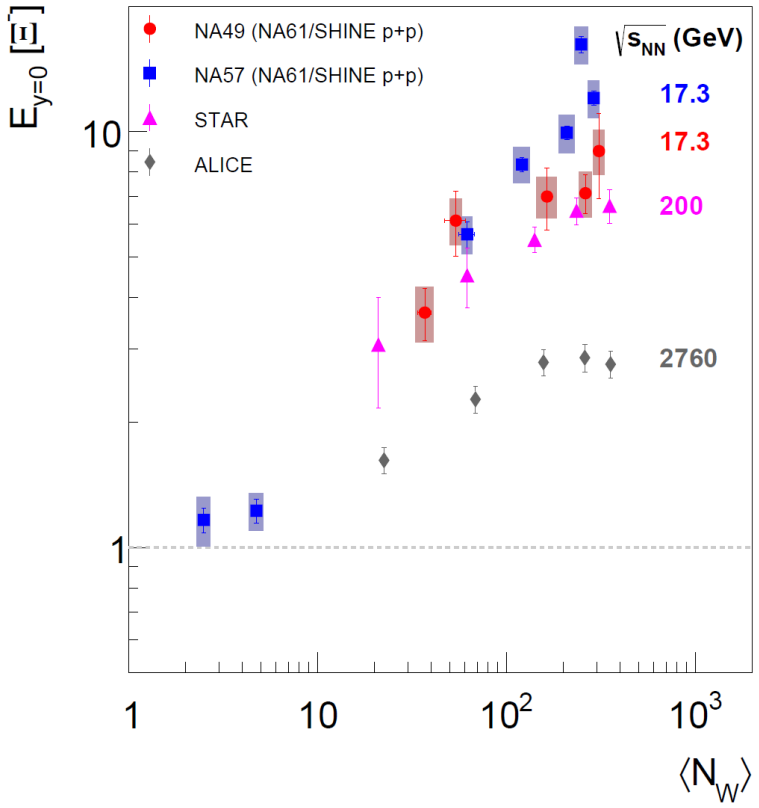


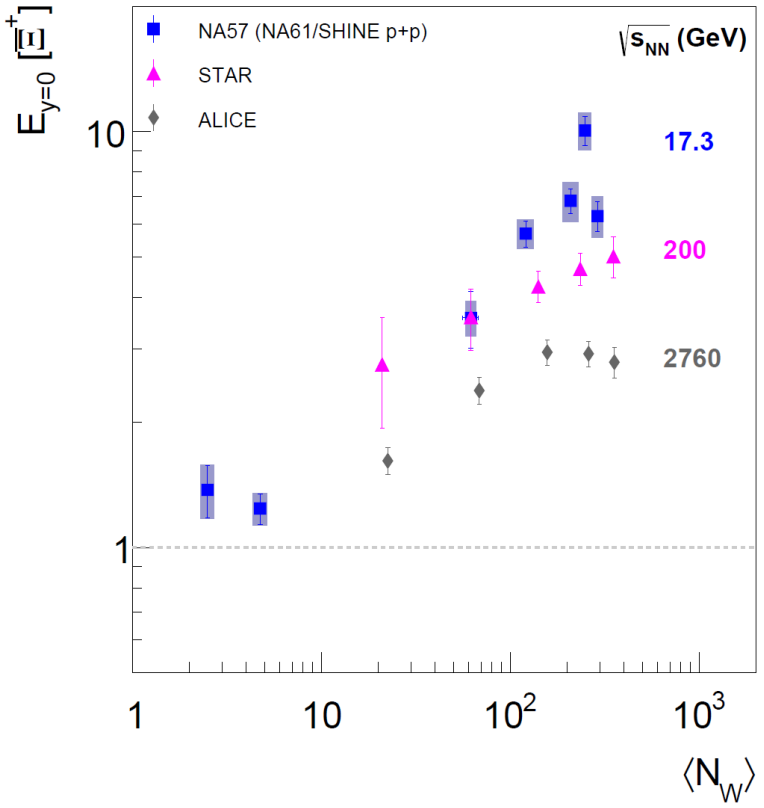
UrQMD, AMPT, PHSD, SMASH fails to describe $\bar{\Xi}^+/\Xi^-$ ratio and transverse momentum distribution

EPOS describes rapidity distributions of $\bar{\Xi}^+, \Xi^-$ and their ratio, but not shape of transverse momentum spectrum.

Ξ production: enhancement factor

The predicted enhancement of strangeness production in nucleus-nucleus collisions relative to proton-proton reactions was established experimentally 30 years ago





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

The enhancement factor at SPS increases approximately linearly from 3.5 in C+C to 9 in central Pb+Pb collisions.

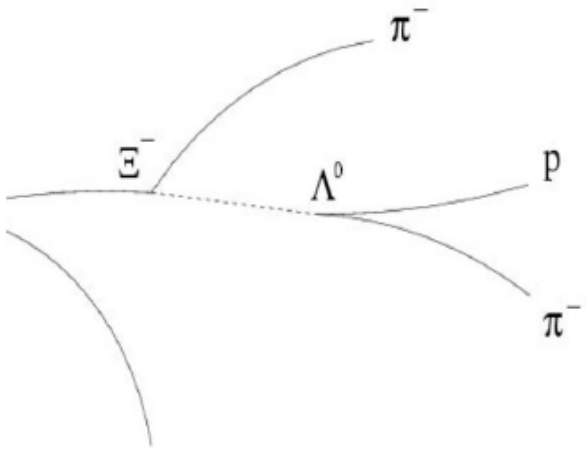
The STAR data show a slightly lower enhancement, but the enhancement observed by ALICE is significantly lower

Strangeness production in p+p at 158 GeV/*c*. Search for $\Xi^{--}(1860)$ pentaquark

$\Xi^{--}(1860)$ pentaquark search in NA61/SHINE - motivation

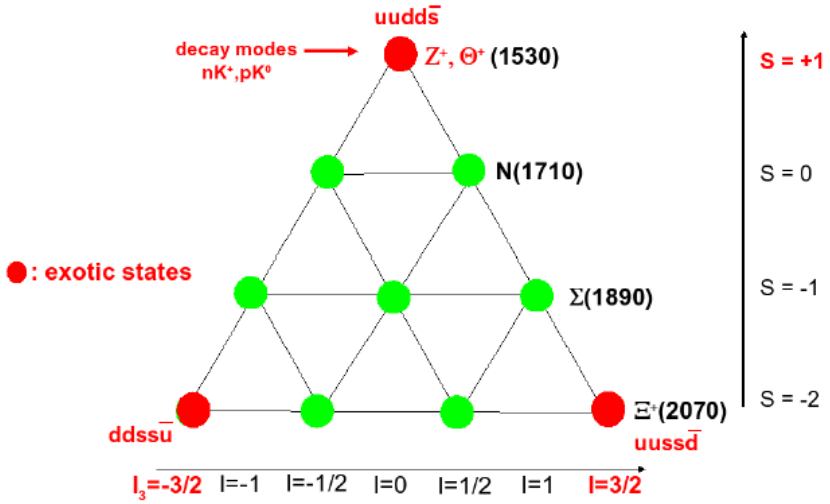
NA49 indication for $\Xi^{--}(1860)$ pentaquark

(NA49, PRL 92, 042003, 2004)



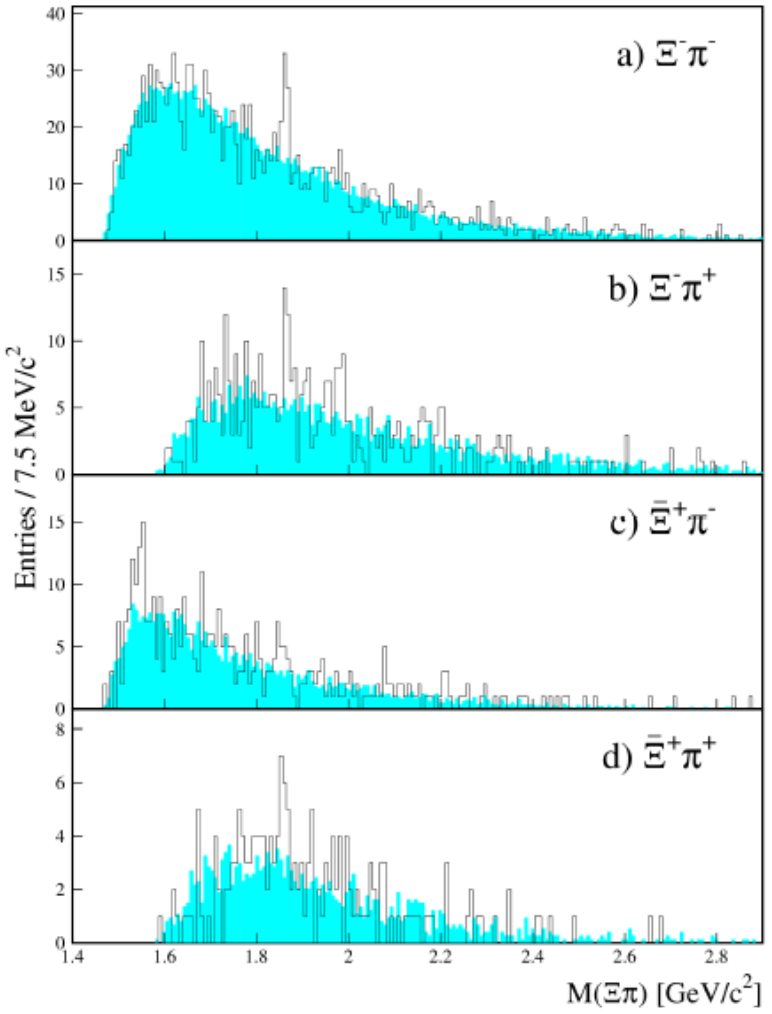
Anti-decuplet of baryons ($J^P=1/2^+$) predicted in chiral soliton model

Diakonov, Petrov, Polyakov, ZP A359, 305, 1997

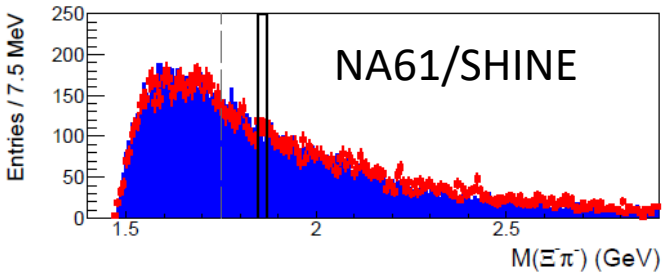


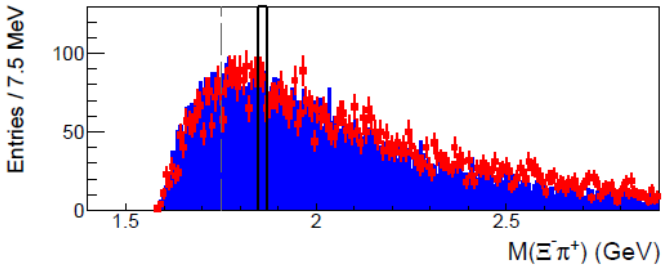
NA49

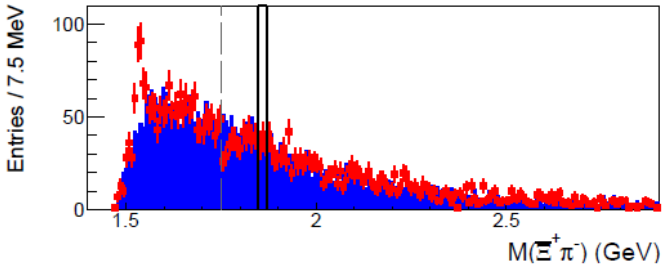
p+p at 158 GeV/c

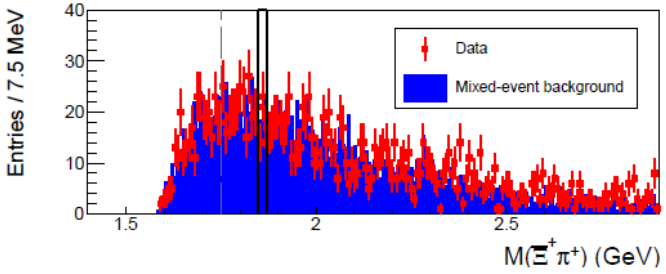


$\Xi^{--}(1860)$ pentaquarks search in NA61/SHINE







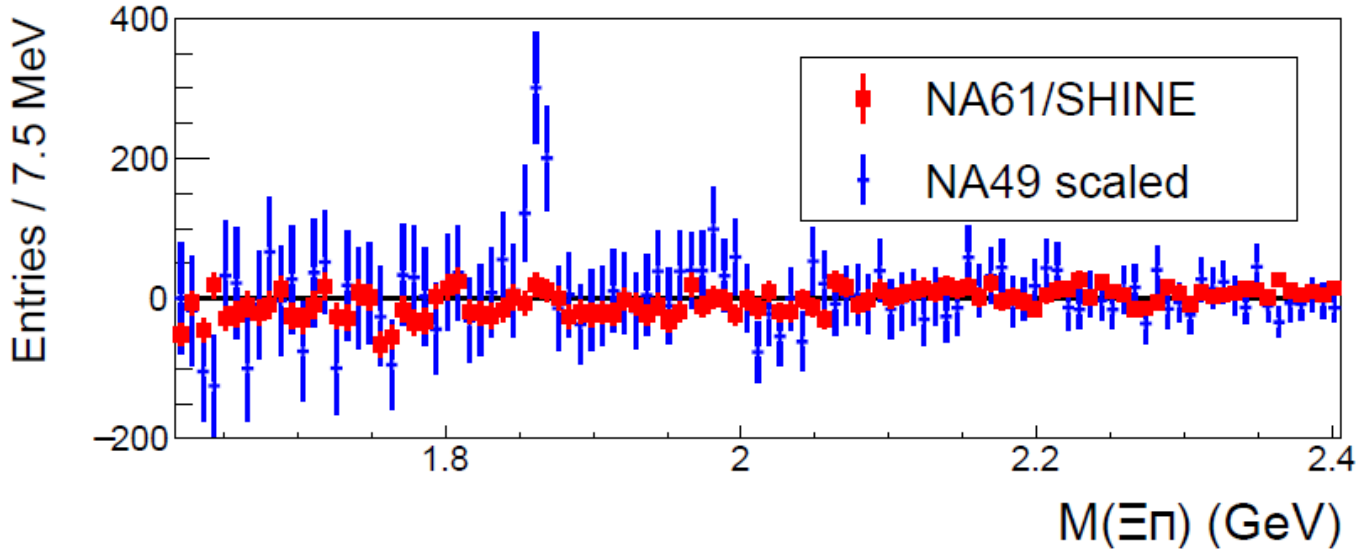


NA49: NA49, PRL 92, 042003, 2004

- 6M events
- resonance with mass of 1.862+/-0.002 GeV/c^2
- width below the detector resolution.
- the significance was estimated to be 4.0 sigma.

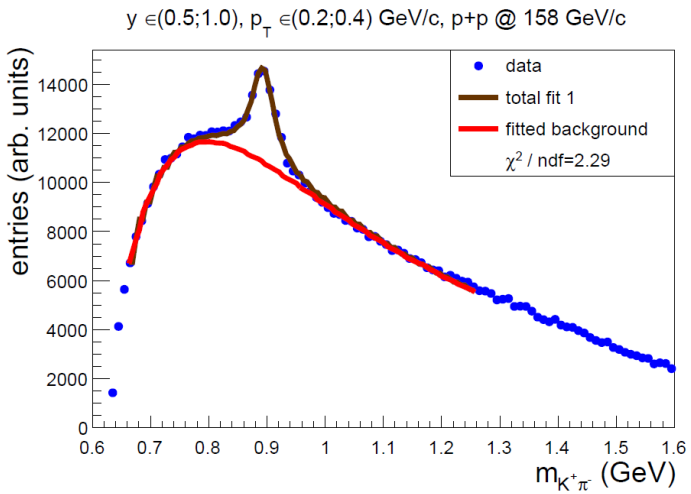
NA61/SHINE:

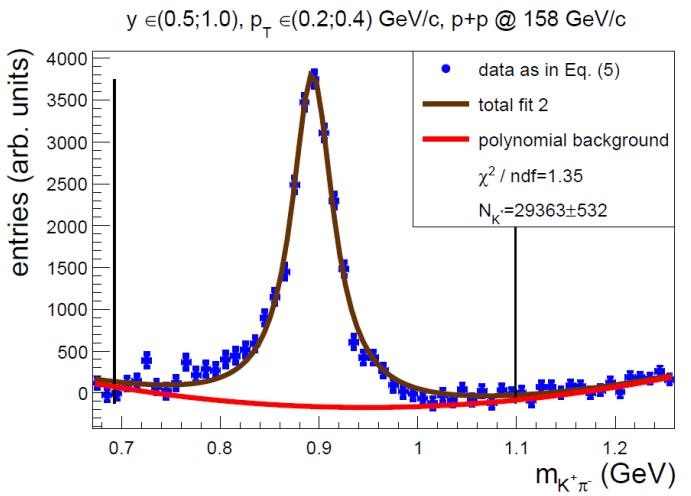
- 26M events
- Same analysis as NA49
- **No $\Xi^{--}(1860)$ pentaquark signal**
- Ξ(1530) well visible

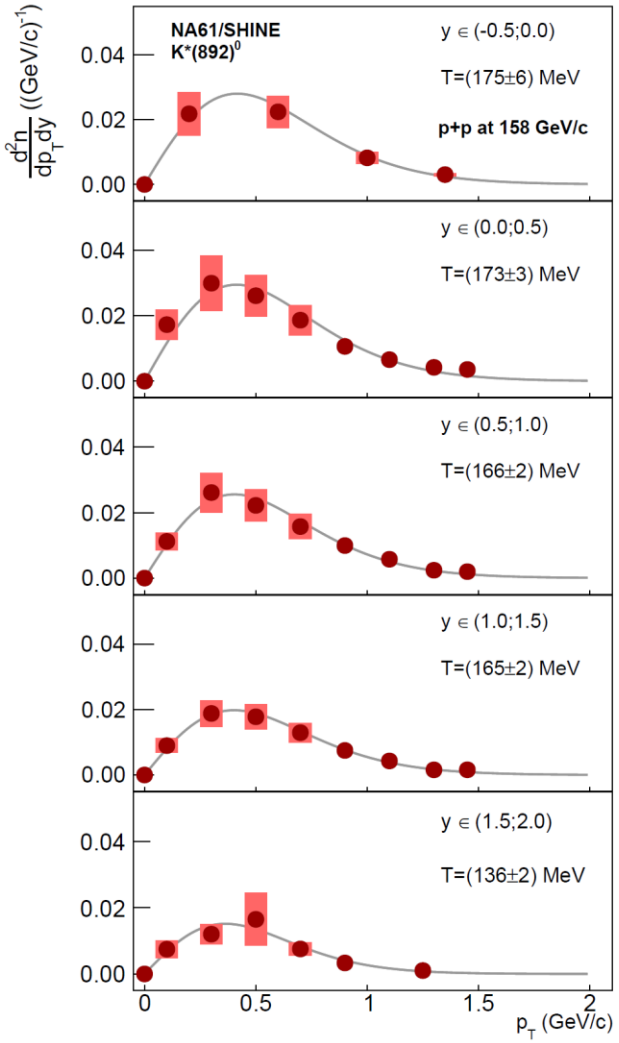


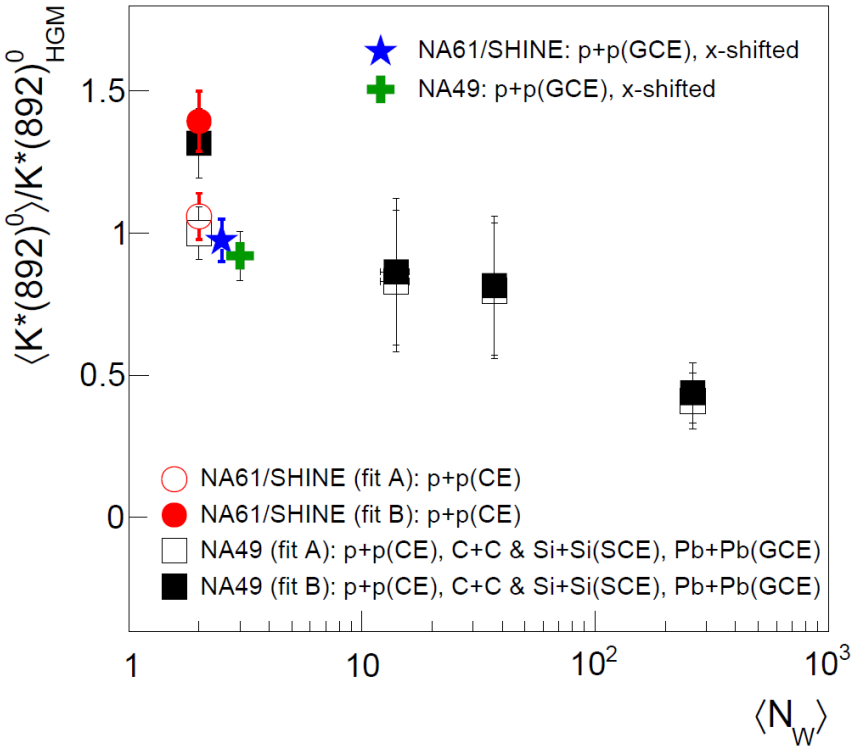
Strangeness production in p+p at 158 GeV/*c*.
$K^*(892)^0$

$K^*(892)^0$ production in inelastic p+p collisions







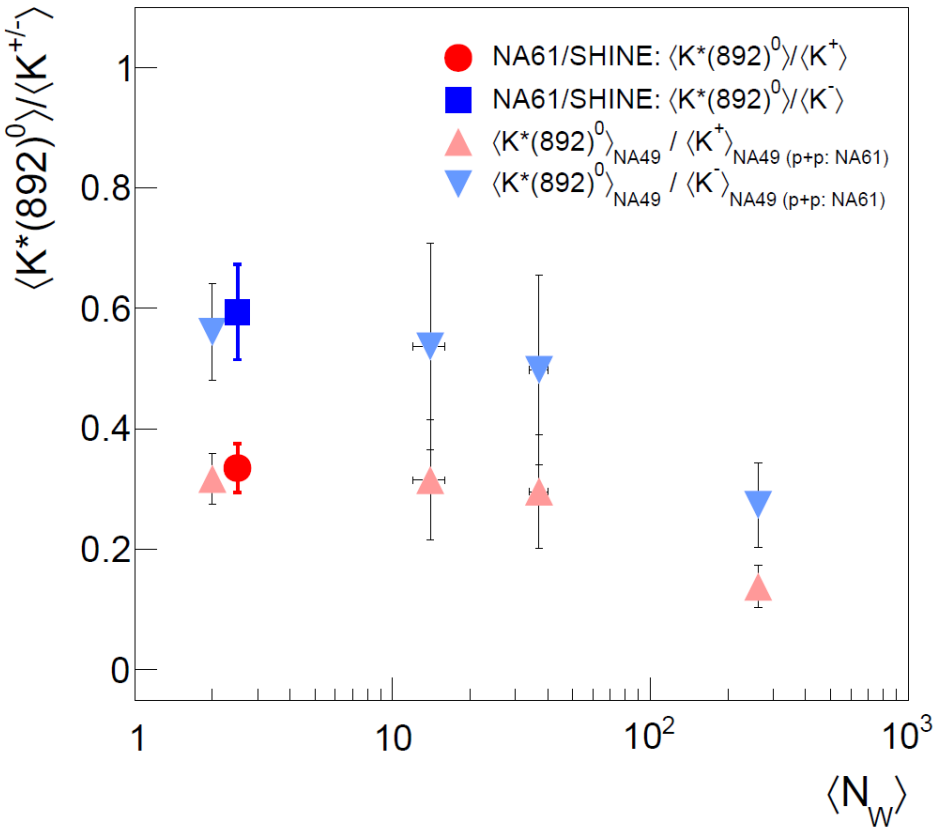


HRG by F.Becattini et al. (PR C73, 044905, 2006)
- Fit B; uses "standard" γs ; for p+p Ξ and Ω baryons excluded from fit
- Fit A: γs replaced $\langle s\bar{s}\rangle$; for p+p ϕ meson excluded from fit

HRG by V.Begun et al. (arXiv:1805.01901)
p+p: GCE with meson ϕ included

$K^*(892)^0$ p+p collisions can be described by HRG

System size dependence of $K^*(892)^0$ to $K^\pm$ ratio at 158A GeV/c



$$\frac{K^*}{K}(\text{kinetic}) = \frac{K^*}{K}(\text{chemical}) \cdot e^{\frac{-\Delta t}{\tau}}$$

use Pb+Pb or Au+Au ratio — use p+p ratio

Time between chemical and kinetic freeze-outs (Δt):

- 5.3 fm/c for $K^*(892)^0/K^+$
- 4.6 fm/c for $K^*(892)^0/K^-$

NA61/SHINE $K^{+/-}$ (p+p): EPJC 77, 671, 2017
NA49 K^*: PR C84, 064909, 2011
NA49 $K^{+/-}$ (p+p): EPJC 68, 1, 2010
NA49 $K^{+/-}$ (C+C, Si+Si): PRL 94, 052301, 2005
NA49 $K^{+/-}$ (Pb+Pb): PR C66, 054902, 2002→ rescaled from 5% to 23.5% most central

Δt at SPS > Δt at RHIC (3.5±1 fm/c, STAR, PR C71, 064902, 2005) suggesting that:

- regeneration effects play significant role for higher energies
- regeneration may happen also at SPS → obtained **Δt is the lower limit of time between freeze-outs**

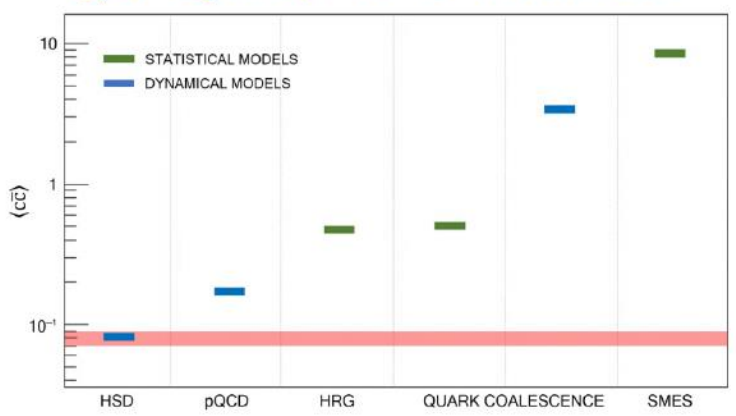
NA61/SHINE beyond 2020

NA61/SHINE program for 2021-2024

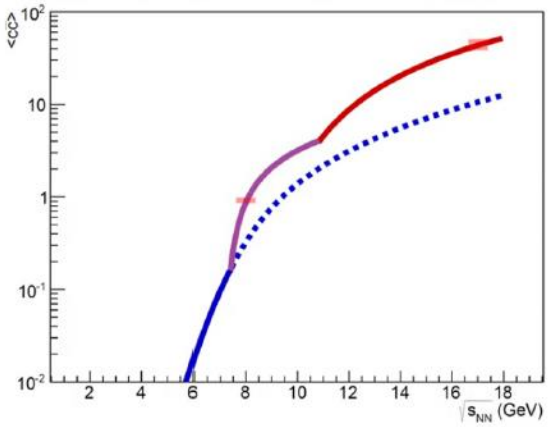
- **What is the mechanism of open charm production?**
- **How does the onset of deconfinement impact open charm production?**
- **How does the formation of quark gluon plasma impact J/ψ production?**

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**.

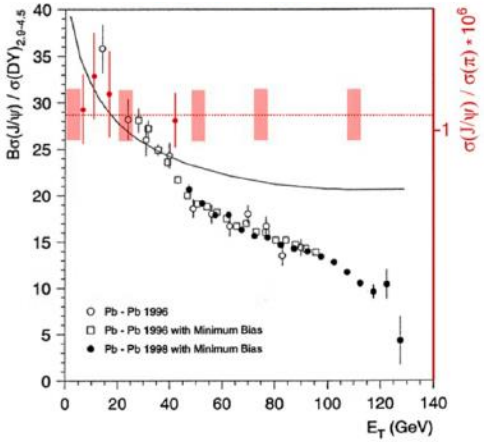
$\langle c\bar{c}\rangle$ and models



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



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

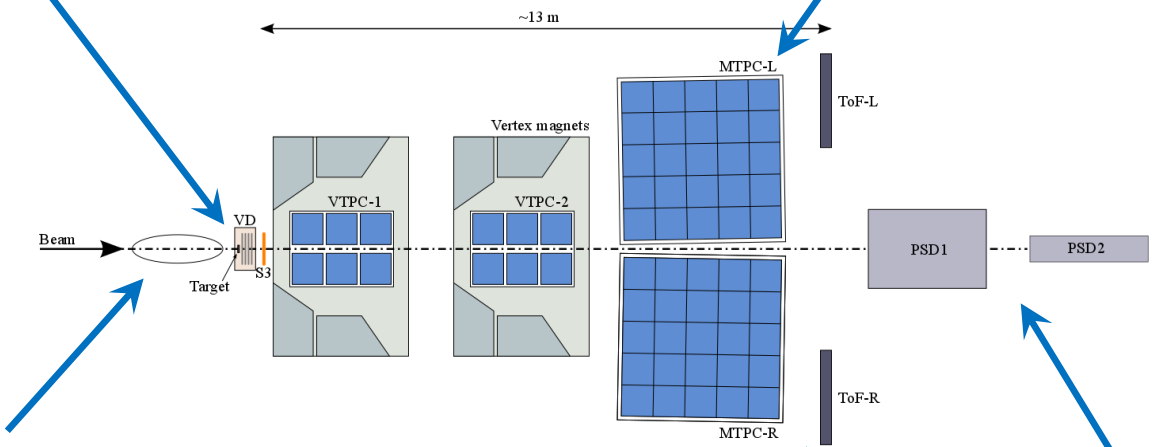


Foreseen NA61/SHINE resolution is sufficient to answer addressed questions

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

Summary

- Many interesting physics topics in NA61/SHINE:
  - Onset of deconfinement
  - Onset of fireball
  - Search of rare particles
  - …
- Extension of NA61/SHINE program with measurements of open charm production in 2021-2024

BACKUP

Critical point: Strongly intensive measures Δ and Σ

$$\Delta[P_T,N]=\frac{1}{\omega[p_T]\langle N\rangle}\left[\langle N\rangle\omega[P_T]-\langle P_T\rangle\omega[N]\right] \qquad P_T=\sum_{i=1}^{N}p_{Ti}$$

$$\Sigma[P_T,N]=\frac{1}{\omega[p_T]\langle N\rangle}\left[\langle N\rangle\omega[P_T]+\langle P_T\rangle\omega[N]-2\left(\langle P_T N\rangle-\langle P_T\rangle\langle N\rangle\right)\right]$$

$$\omega[P_T]=\frac{\langle P_T^2\rangle-\langle P_T\rangle^2}{\langle P_T\rangle} \qquad \omega[p_T]=\frac{\overline{p_T^2}-\overline{p_T}^2}{\overline{p_T}} \qquad \omega[N]=\frac{\langle N^2\rangle-\langle N\rangle^2}{\langle N\rangle}$$

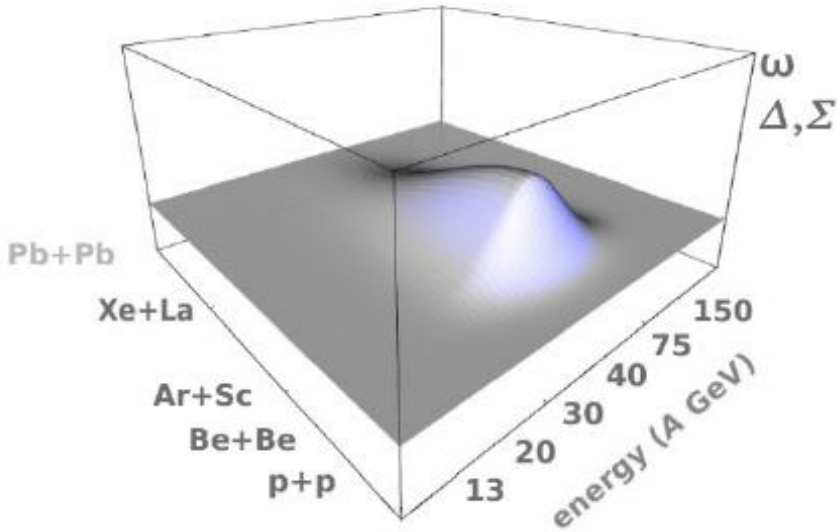
$\Delta = \Sigma = 0$ for no fluctuations

$\Delta = \Sigma = 1$ for Independent Particle Model

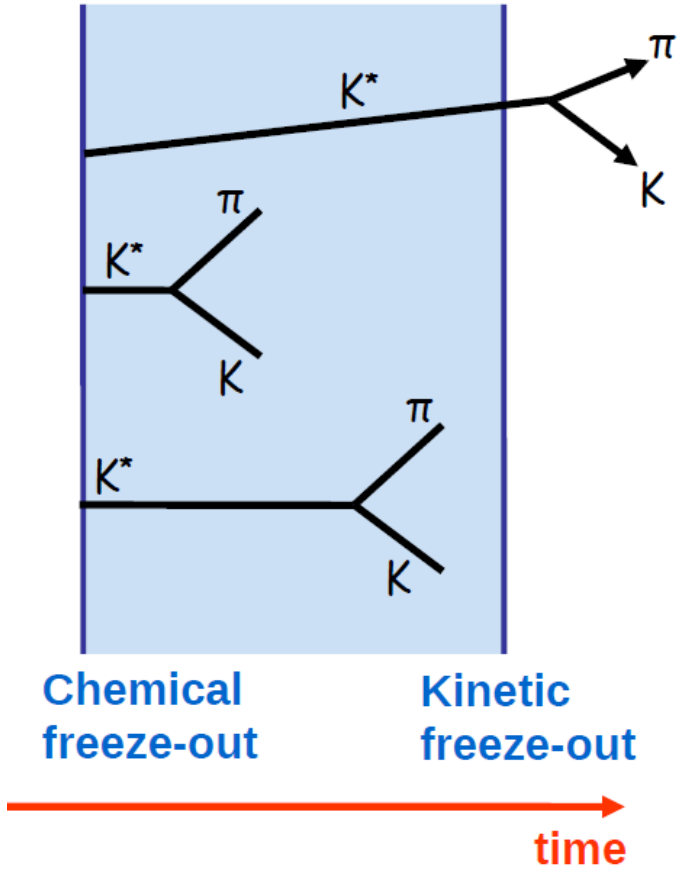
- $\Delta[P_T, N]$ uses only first two moments: $\langle N\rangle$, $\langle P_T\rangle$, $\langle P_T^2\rangle$, $\langle N^2\rangle$
- $\Sigma[P_T, N]$ uses also correlation term: $\langle P_T N\rangle$-$\langle P_T\rangle\langle N\rangle$

thus Δ and Σ can be sensitive to several physics effects in different ways

Expected: non-monotonic behavior of CP signatures



Motivation of K* measurement



The picture assumes that conditions at chemical freeze-out of p+p and Pb+Pb are the same

K* lifetime (≈ 4 fm/*c*) comparable with time between freeze-outs →

Some **resonances may decay inside fireball**; momenta of their decay products can be modified due to elastic scatterings → problems with experimental reconstruction of resonance via invariant mass →

Suppression of observed K* yield

Assuming no regeneration processes (Fig.) time between freeze-outs can be determined from (STAR, PR C71, 064902, 2005):

$$\frac{K^*}{K}(\text{kinetic}) = \frac{K^*}{K}(\text{chemical}) \cdot e^{\frac{-\Delta t}{\tau}}$$

use Pb+Pb or Au+Au ratio — use p+p ratio

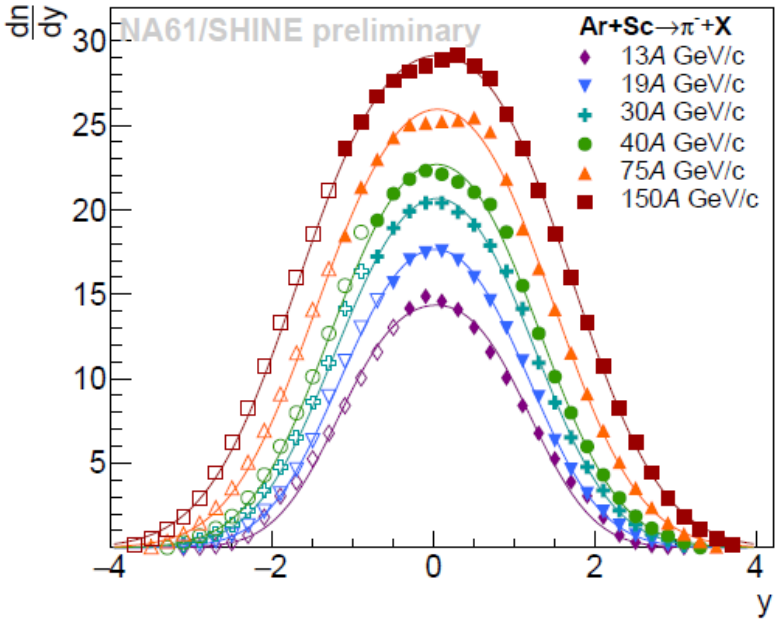
Δt – time between kinetic and chemical freeze-outs

τ – $K^*(892)^0$ lifetime = 4.17 fm/*c*; PDG, PR D98, 030001, 2018

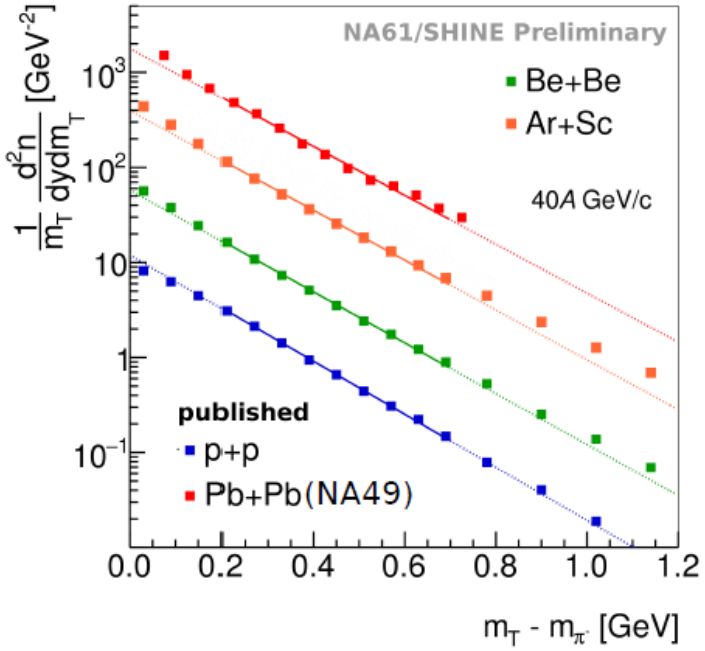
π^- spectra from 2D-scan

π^- spectra measured in large acceptance: p_T down to 0, in full forward hemisphere

Collision energy dependence

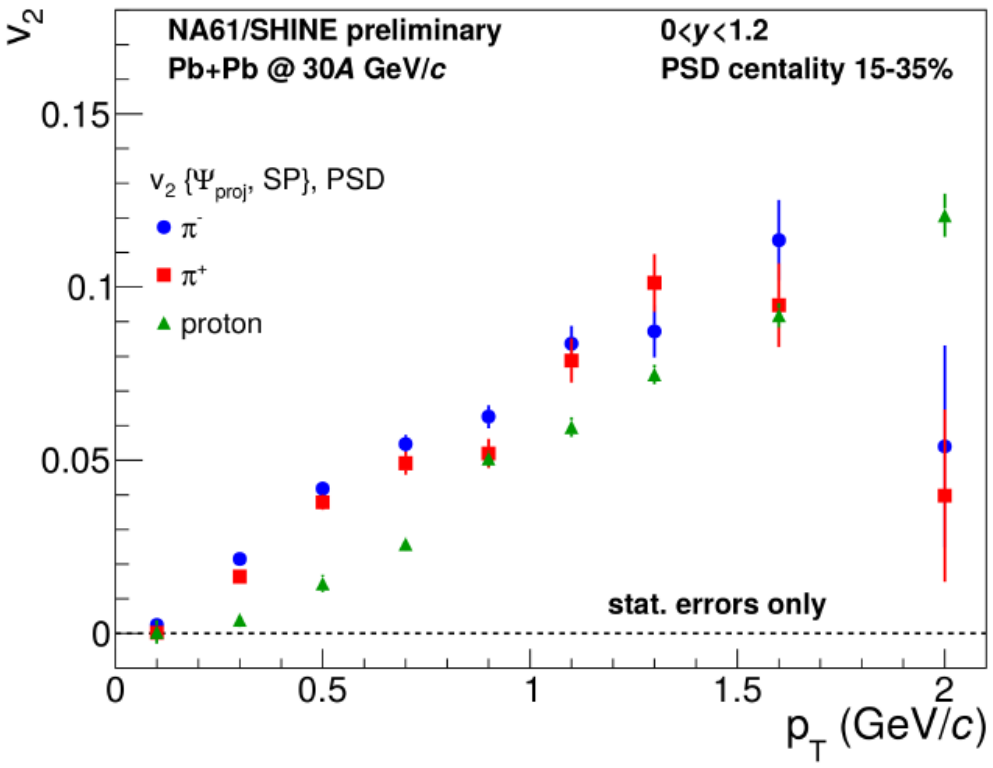


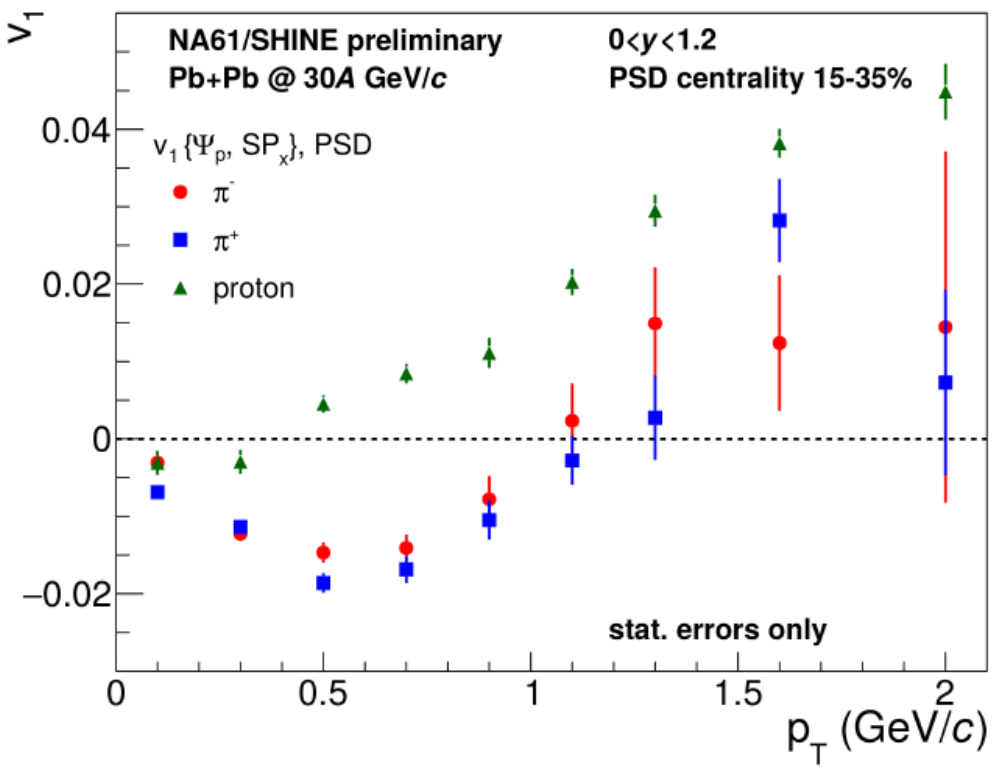
System size dependence



- Rapidity spectra ≈ gaussian, independently of collision energy and system size
- Large acceptance allows to obtain 4π multiplicity **(Eur.Phys.J. C74 (2014) no.3, 2794)**
- m_T spectra in p+p are exponential, in larger systems (central collisions) deviate from the exponential shape

Particle type dependence of elliptic and directed flow





NEW

Clear mass hierarchy of v_2 - radial flow

Difference between v_2 for π^+ and π^- is small

Significant mass dependence of v_1

Difference between v_1 for π^+ and π^- is sensitive to electromagnetic effects.

A. Rybicki and A. Szczurek, Phys. Rev. C87, 054909 (2013)