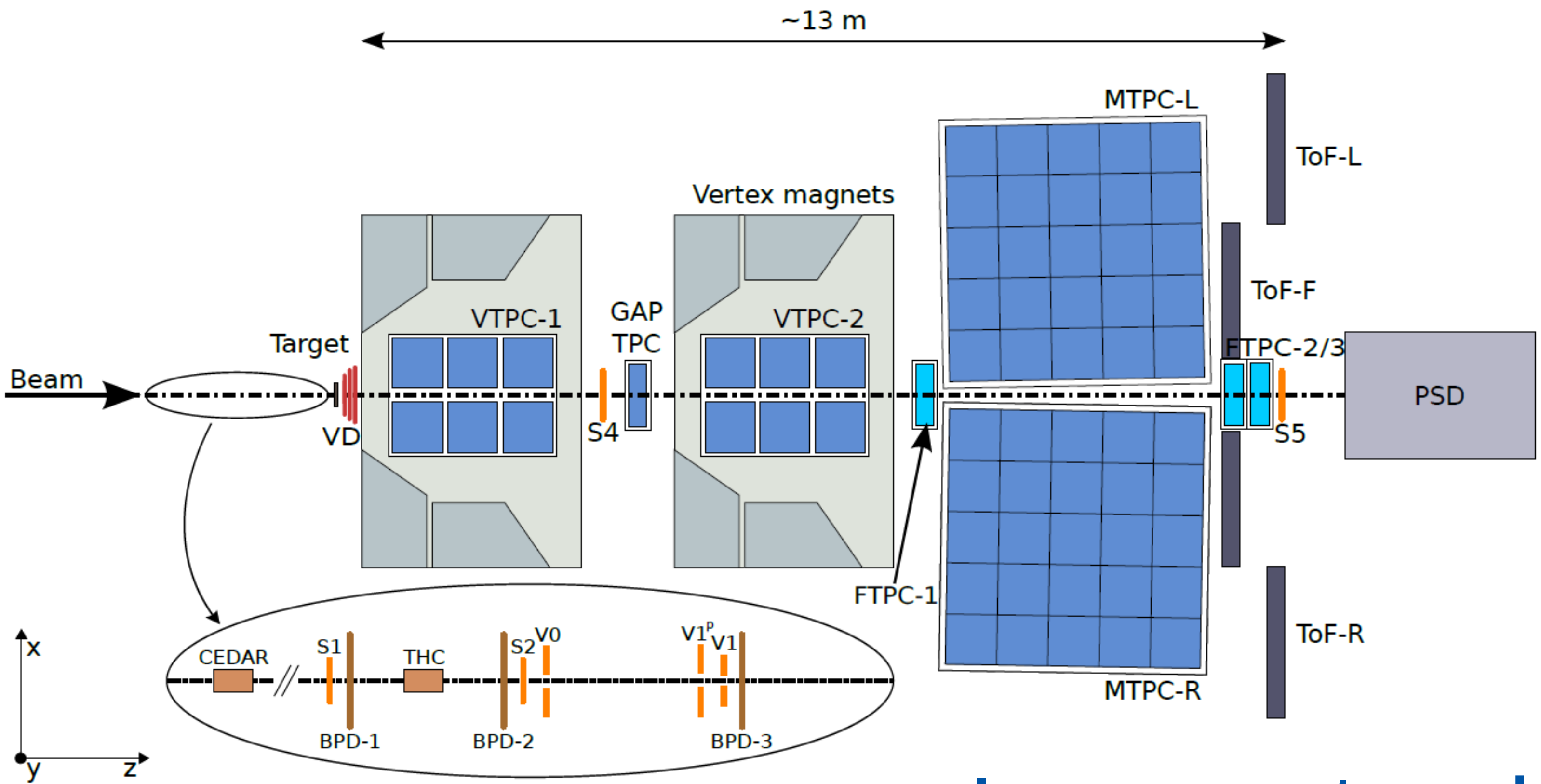
Particle production properties at SPS energy range - recent results from NA61/SHINE experiment

Szymon Puławski
for NA61/SHINE

Fixed target experiment located at the CERN SPS accelerator



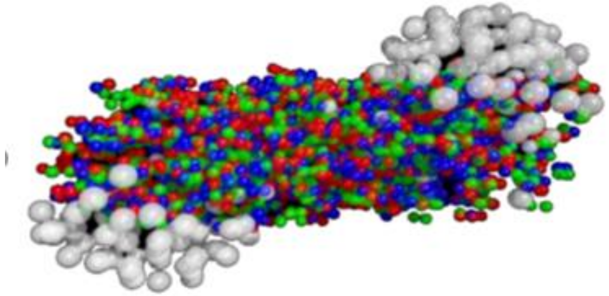
Beams:

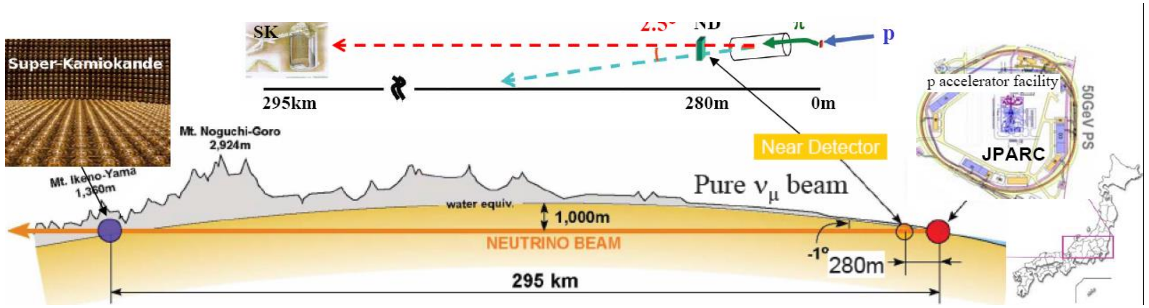
- ions (Be, Ar, Xe, Pb)
  p_{beam}=13*A*–150*A* GeV/*c*
- hadrons (π, K, p)
  p_{beam}=13–400 GeV/*c*
- $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

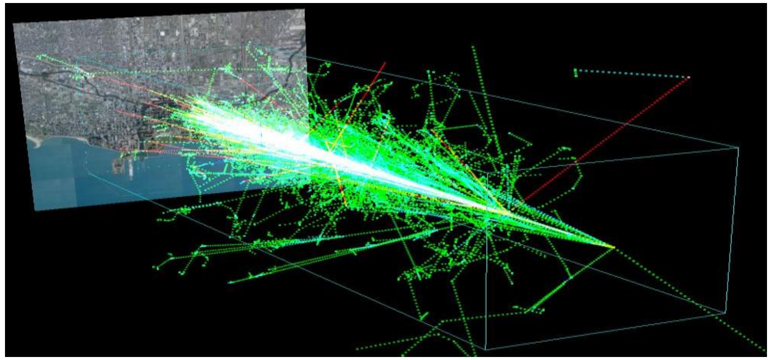
Large acceptance hadron spectrometer –
coverage of the full forward hemisphere, down to $p_T = 0$

NA61/SHINE - Research programme

- Strong interactions physics
  - search for the critical point of strongly interacting matter
  - study of the properties of the onset of deconfinement
  - heavy quarks: direct measurement of open charm at SPS energies
- Neutrino and cosmic ray physics:
  - hadron measurements for the J-PARC neutrino programme
  - hadron measurements for the Fermilab neutrino programme
  - measurements for cosmic-ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
  - measurements of nuclear fragmentation cross sections of intermediate mass nuclei needed to understand the propagation of cosmic rays in our Galaxy







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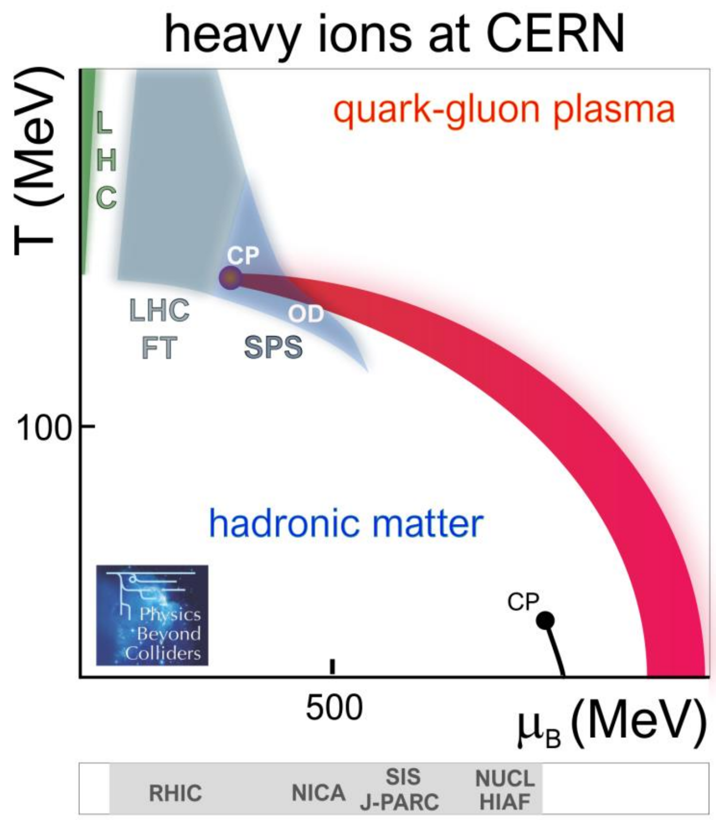
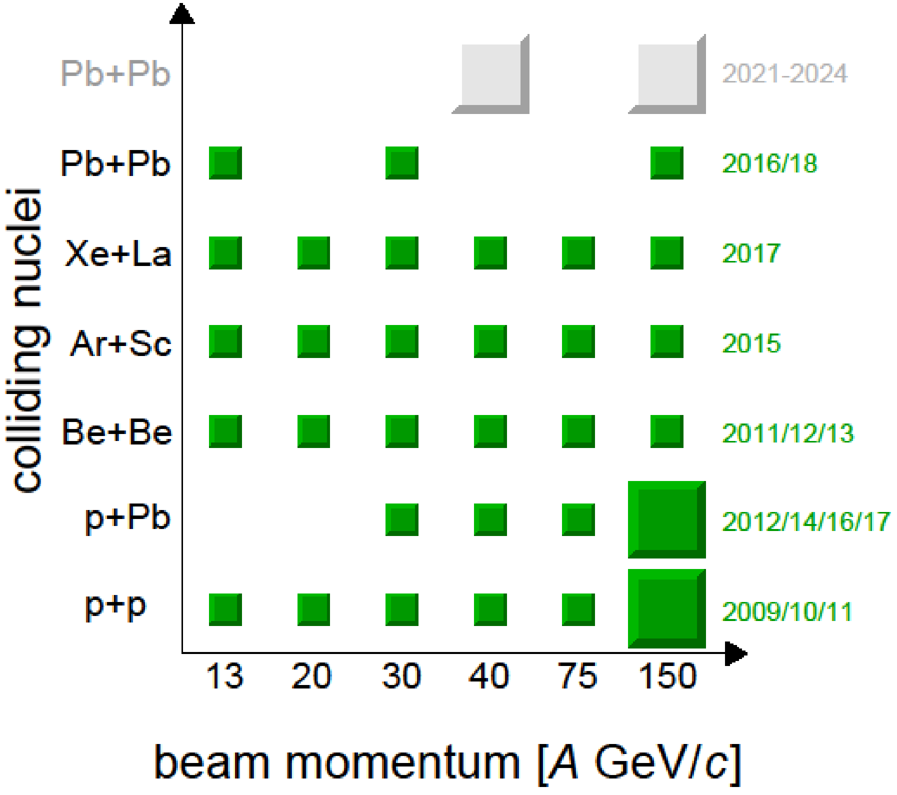
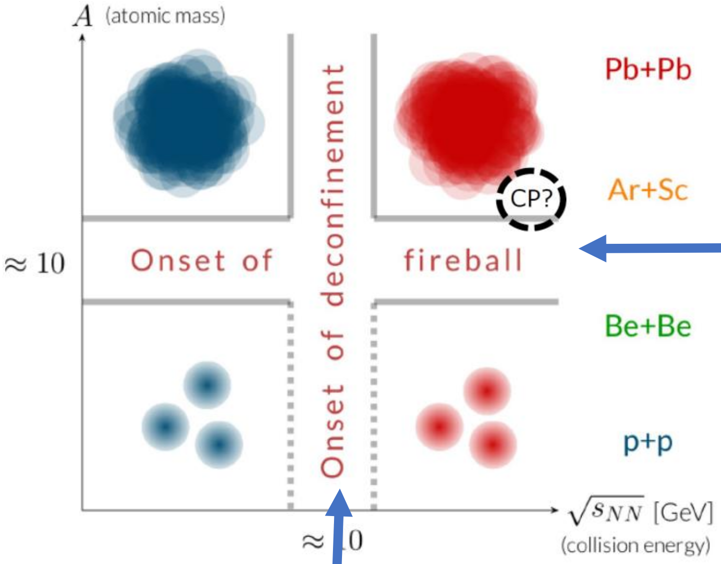
NA61/SHINE 2-dimensional scan

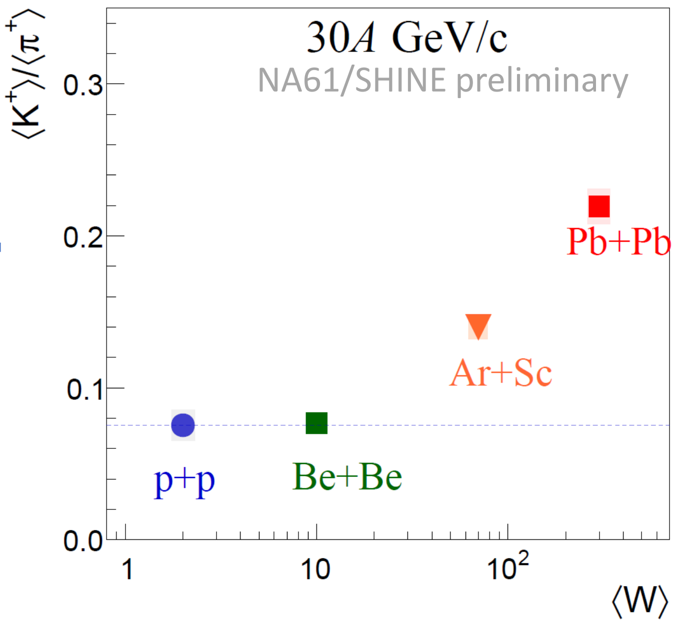
NA61/SHINE performed the 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter

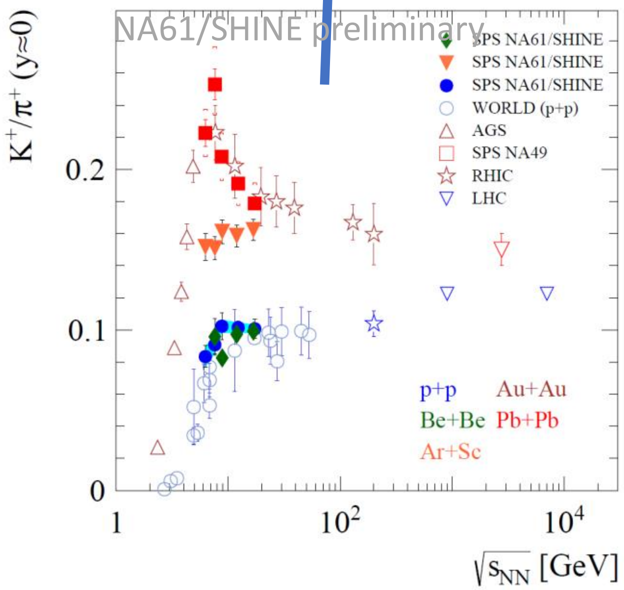




Uniqueness of heavy ion results from NA61/SHINE







NA61/SHINE recorded unique data for:

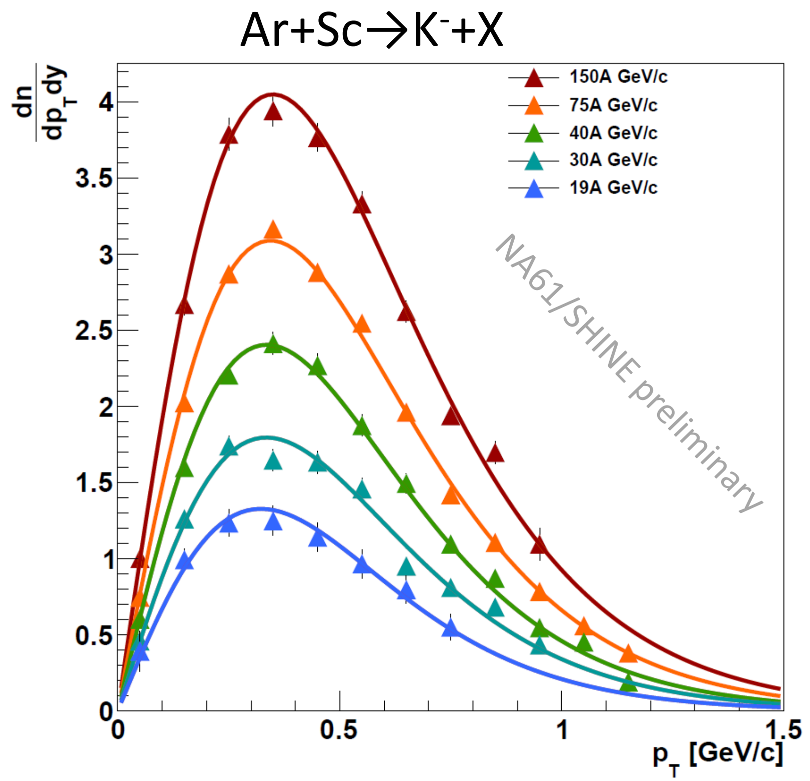
- Onset of deconfinement
- Onset of fireball
- Critical point?

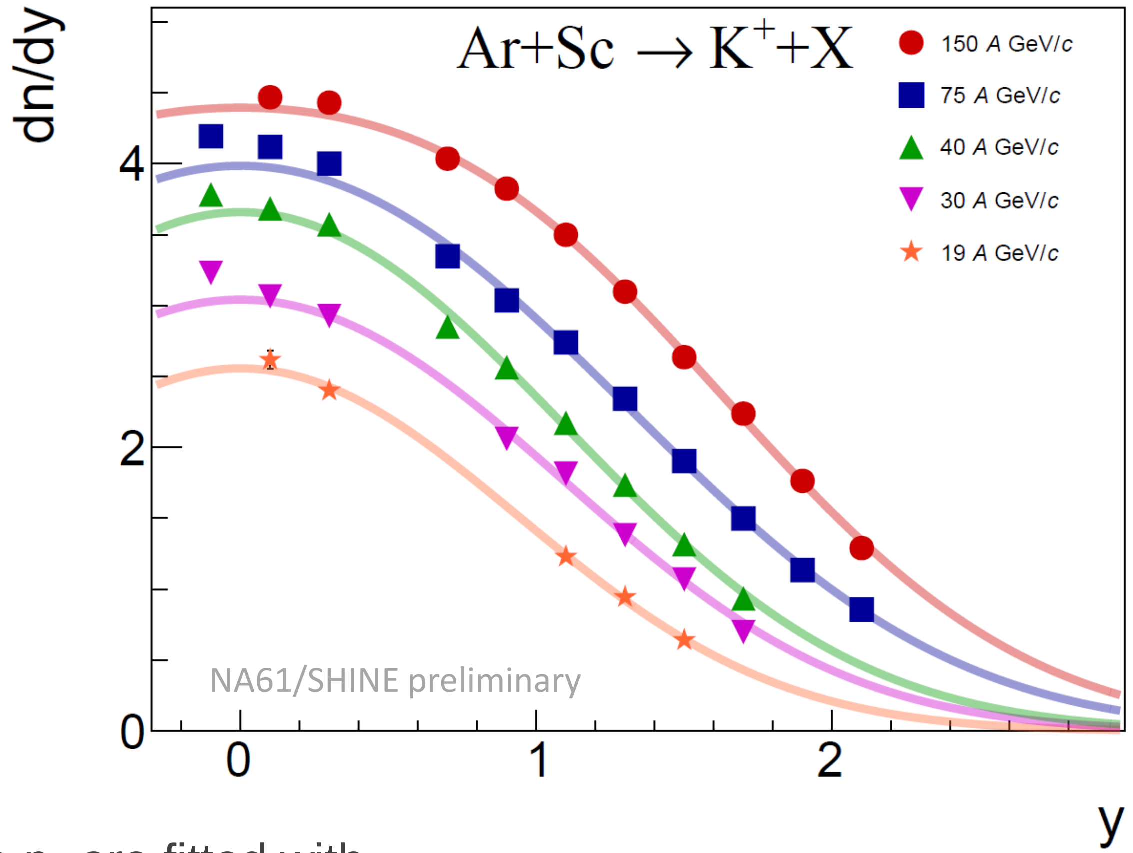
See D. Prokhorova talk

Study of the onset of deconfinement:
Particle production properties

Onset of deconfinement: step and horn

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



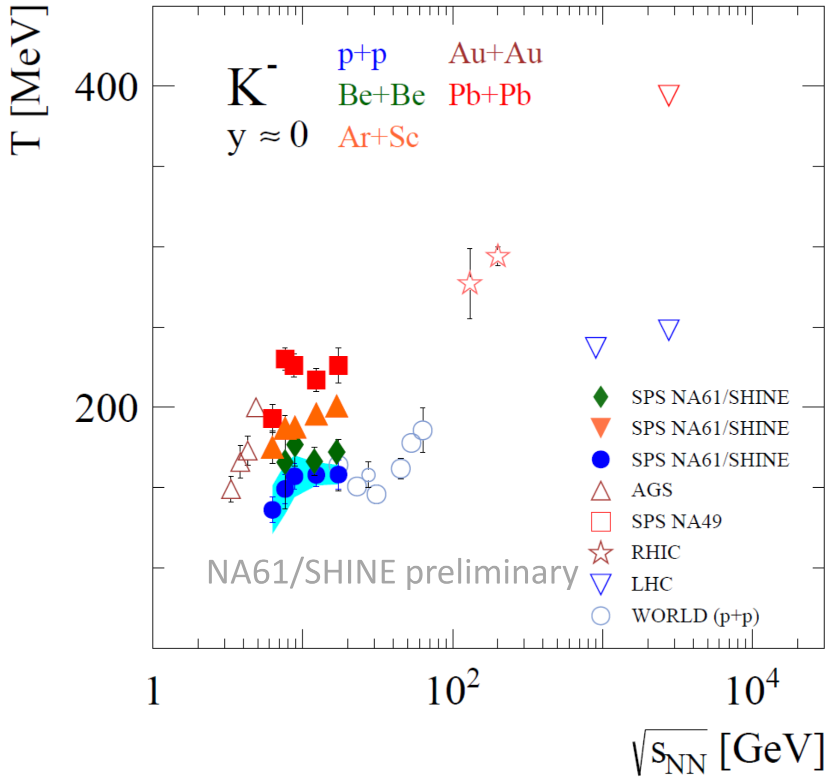


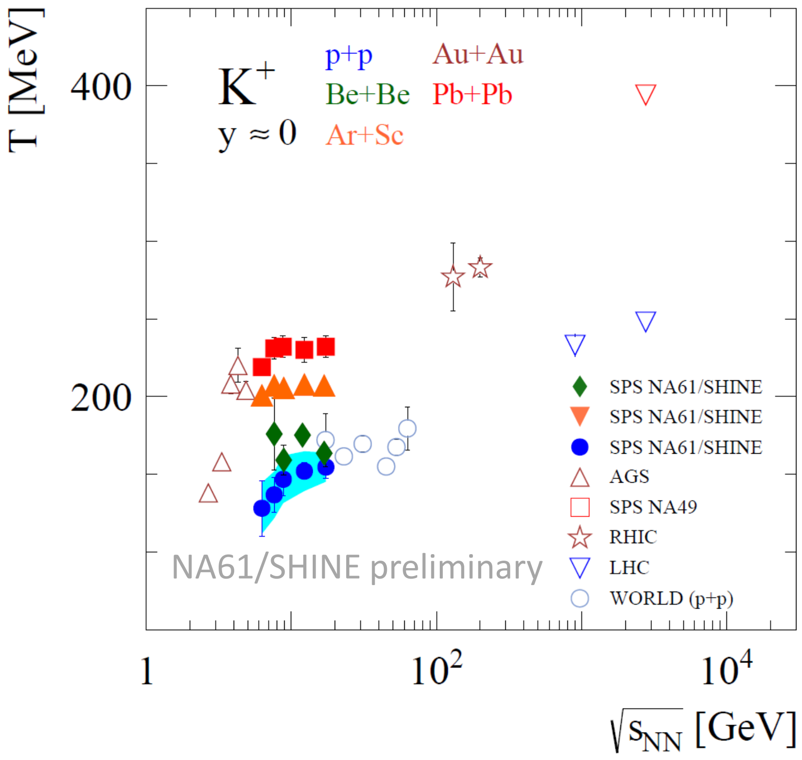
$K^{\pm}$ spectra in p_T are fitted with

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

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).





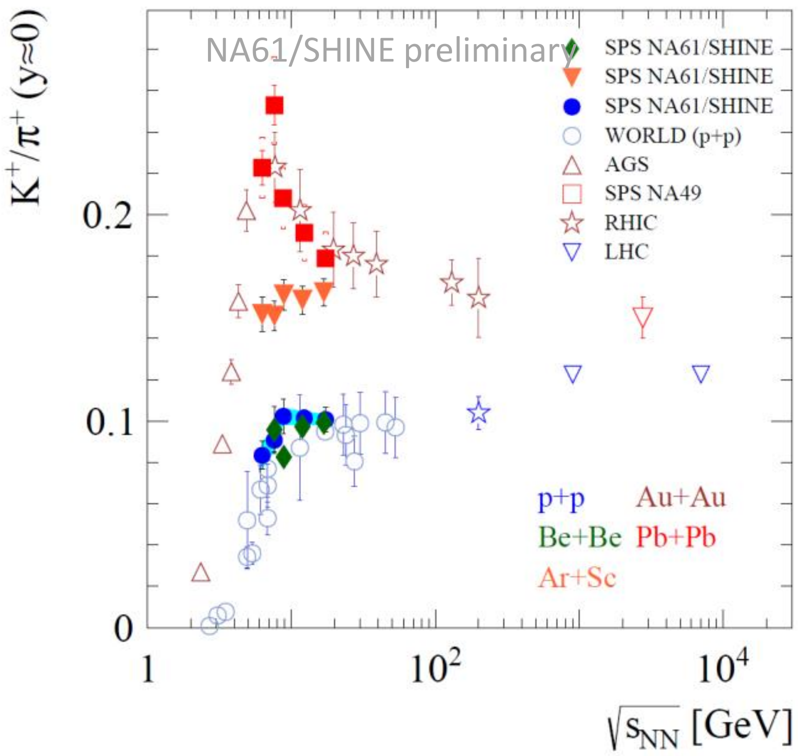
Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions

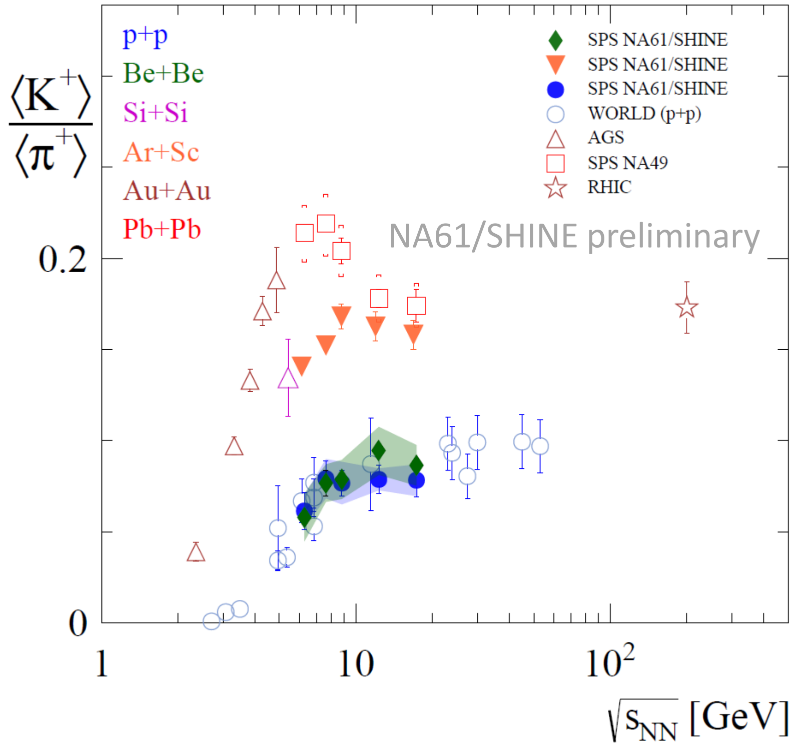
Magnitude of T in Be+Be slightly higher than in p+p

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.



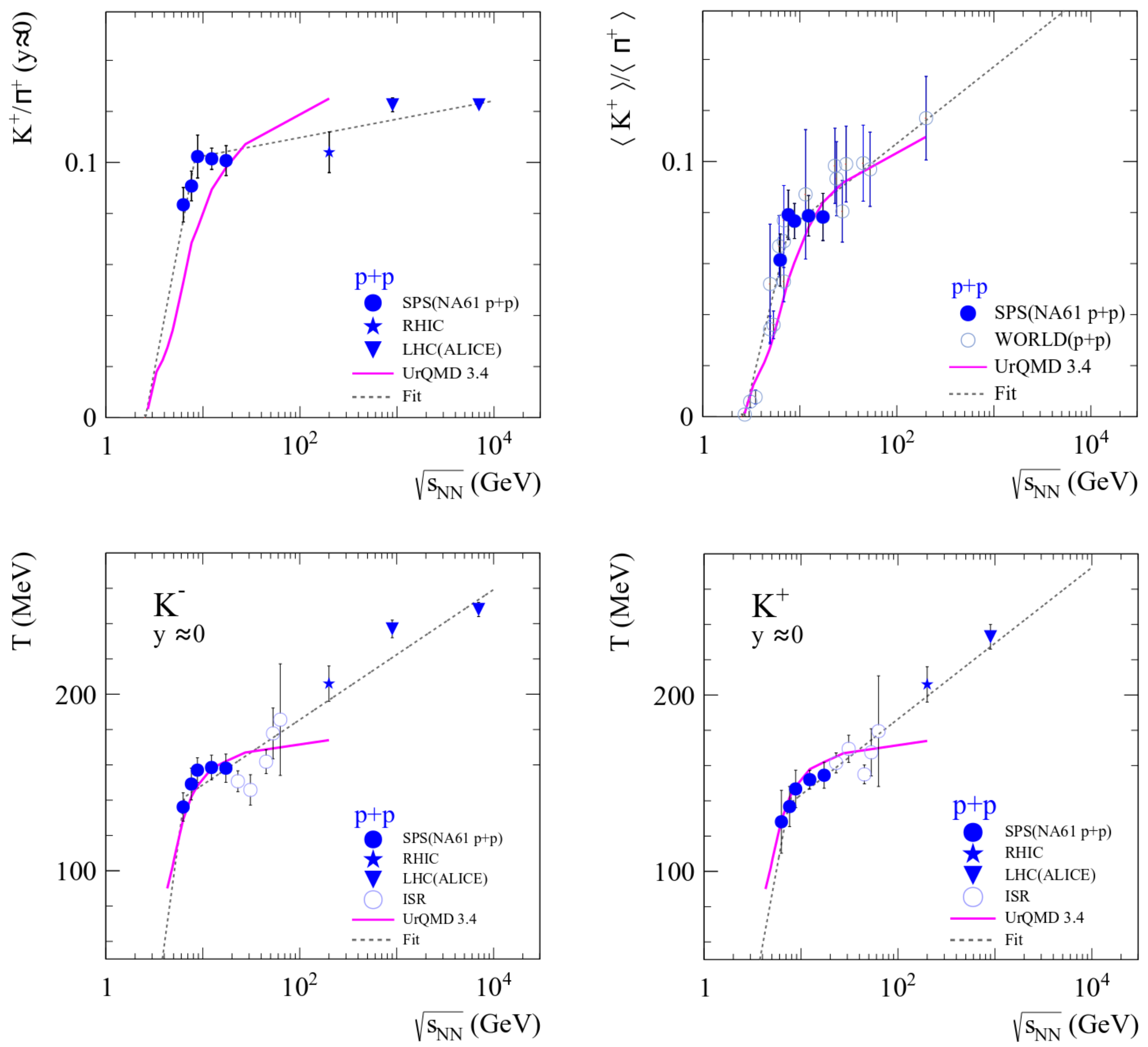


Plateau like structure visible in p+p

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



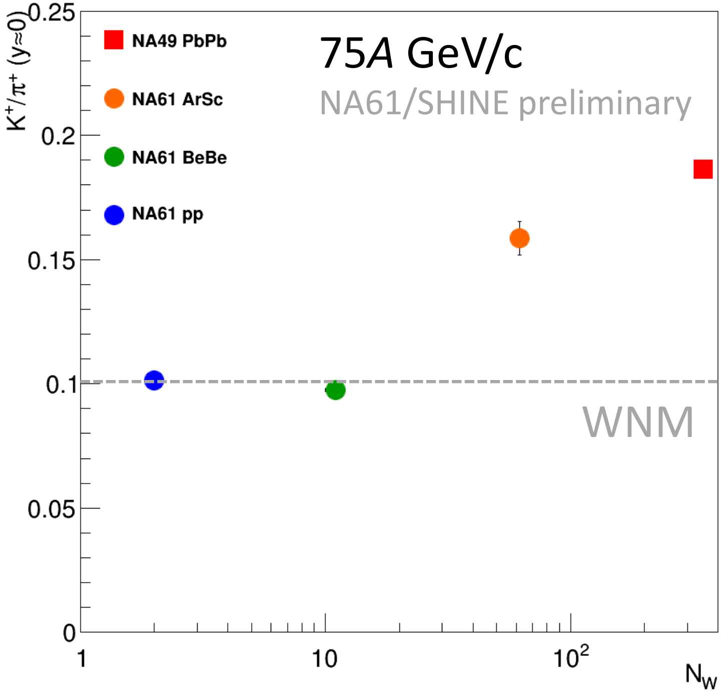
Rates of increase of K^+/π^+ and T change sharply in p+p collisions at SPS energies

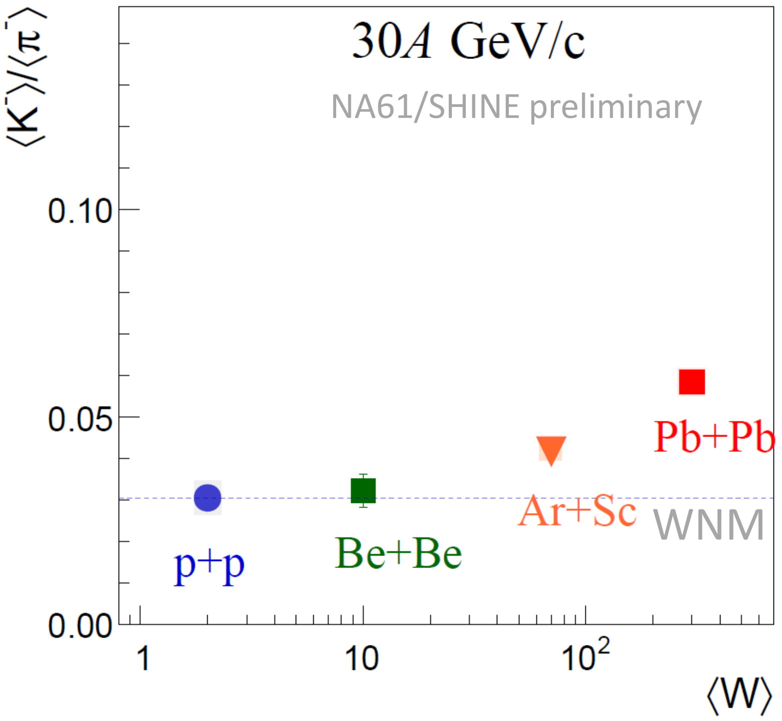
The fitted break energy is ≈7 GeV - close to the energy of the onset of deconfinement ≈8 GeV

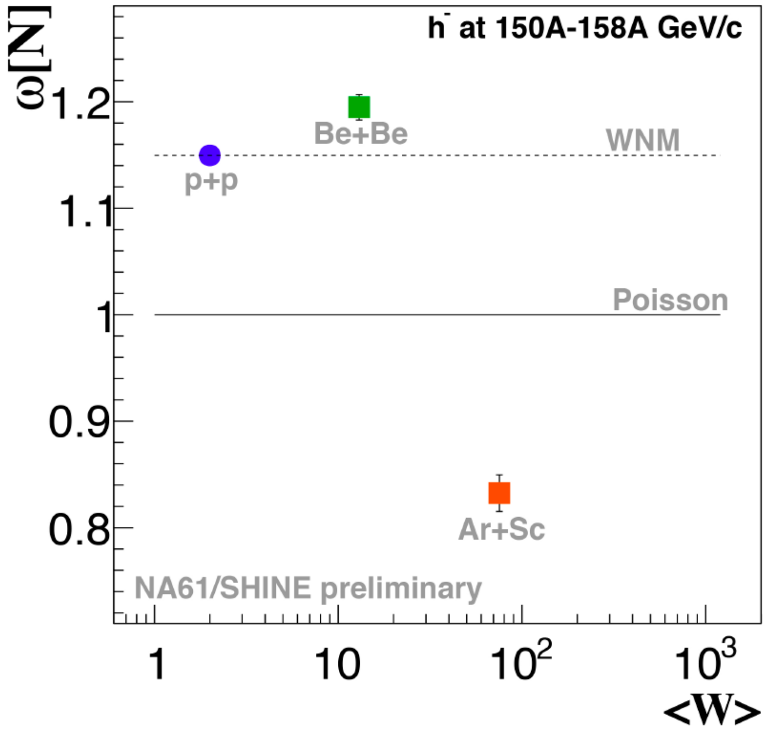
Resonance-string model (UrQMD) fails to reproduce data

Study of the onset of fireball

Onset of fireball: system size dependence







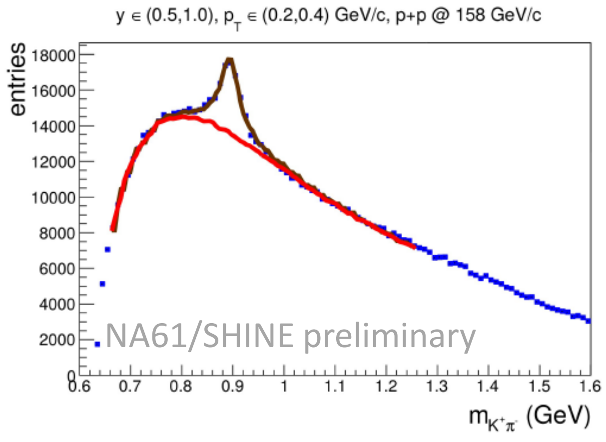
Change between

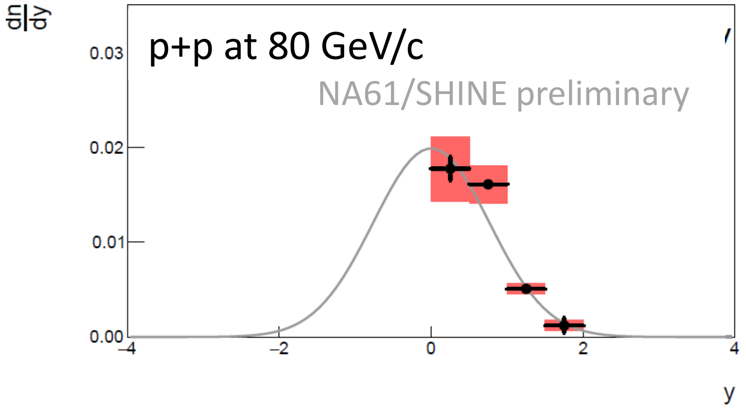
p+p ≈ Be+Be and Ar+Sc, Pb+Pb results

- 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%

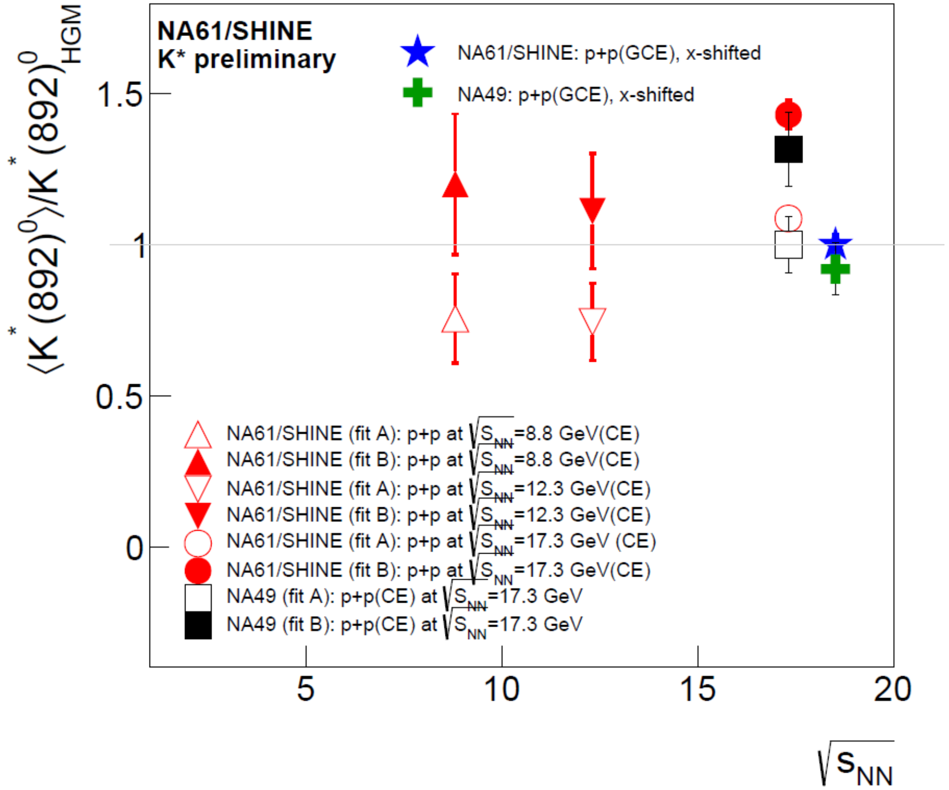
Strangeness production in p+p at 158 GeV/*c*: $K^*(892)^0$

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





<K*(892)>=0.03812 ± 0.00538 ± 0.00372



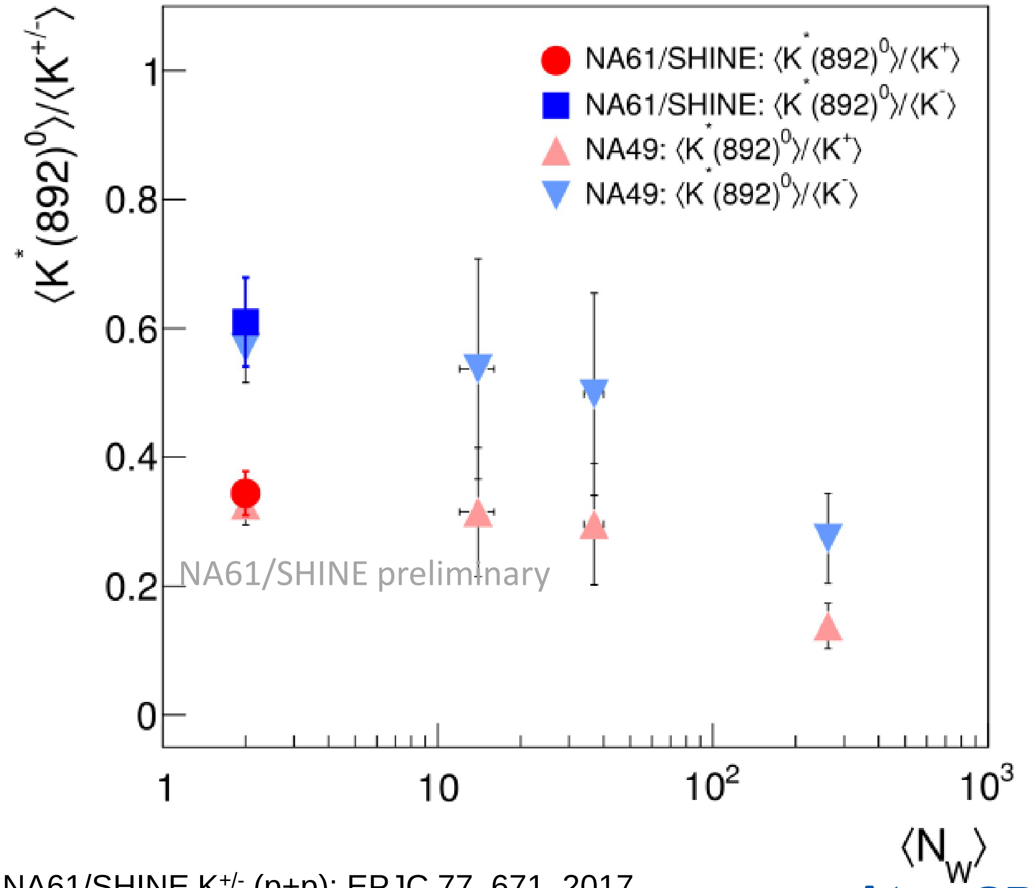
K*(892)⁰ p+p collisions can be described by HRG

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

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

- 3.8 ± 1.1 fm/*c* for $K^*(892)^0/K^+$
- 3.3 ± 1.2 fm/*c* for $K^*(892)^0/K^-$

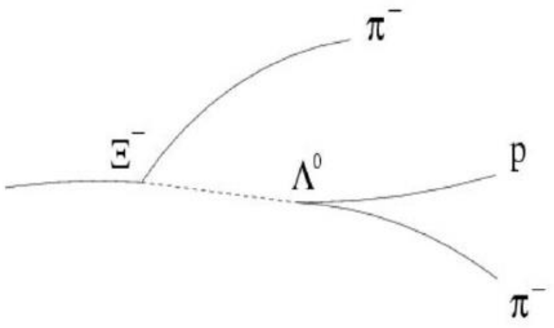
NA61/SHINE $K^{+/-}$ (p+p): EPJC 77, 671, 2017
NA49 K^*: PR C84, 064909, 2011
NA49 $K^{+/-}$ (p+p): EPJC 68, 1, 2010
NA49 $K^{+/-}$ (C+C, Si+Si): PRL 94, 052301, 2005
NA49 $K^{+/-}$ (Pb+Pb): PR C66, 054902, 2002→ rescaled from 5% to 23.5% most central

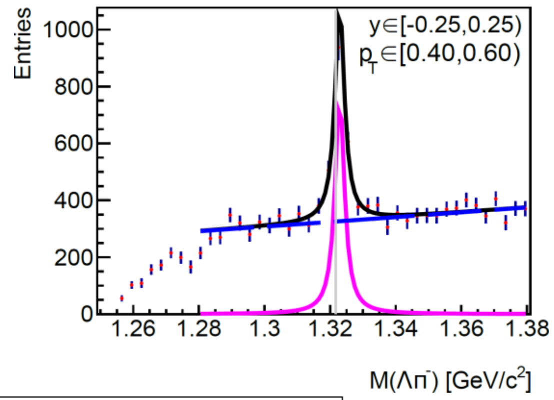
Δt at SPS > Δt at RHIC (2±1 fm/*c*, STAR, PR C71, 064902, 2005) suggesting that:

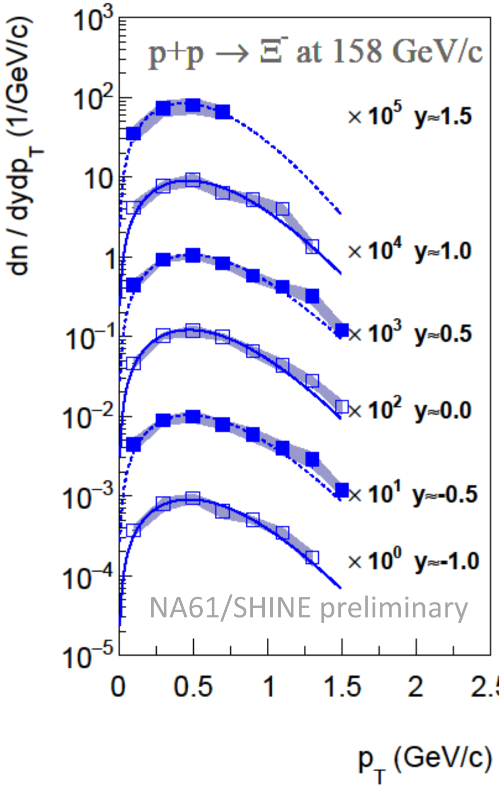
- regeneration effects play significant role for higher energies
- regeneration may happen also at SPS → obtained **Δt is the lower limit of time between freeze-outs**

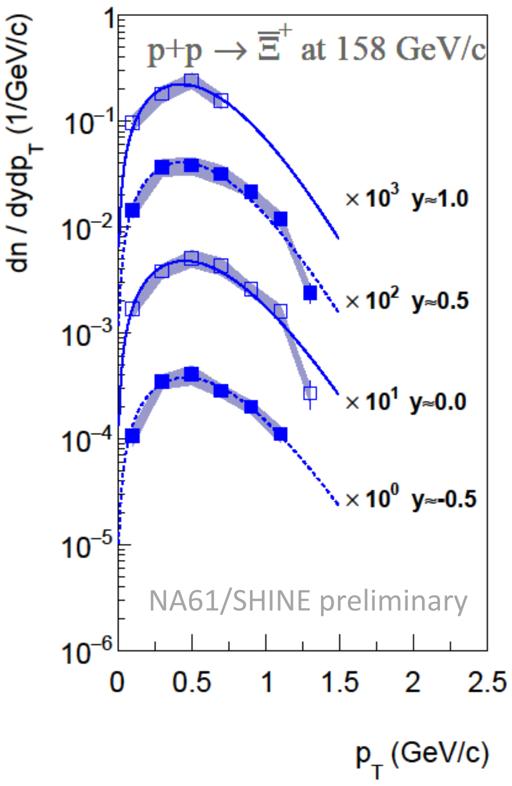
Strangeness production in p+p at 158 GeV/*c*:
Ξ production

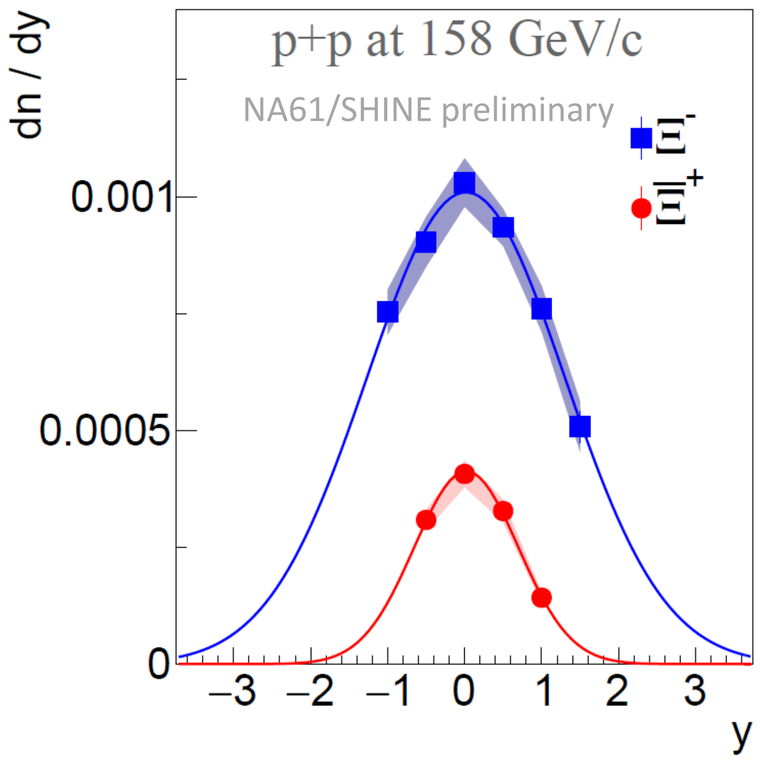
Ξ production in inelastic p+p collisions at 158 GeV/c





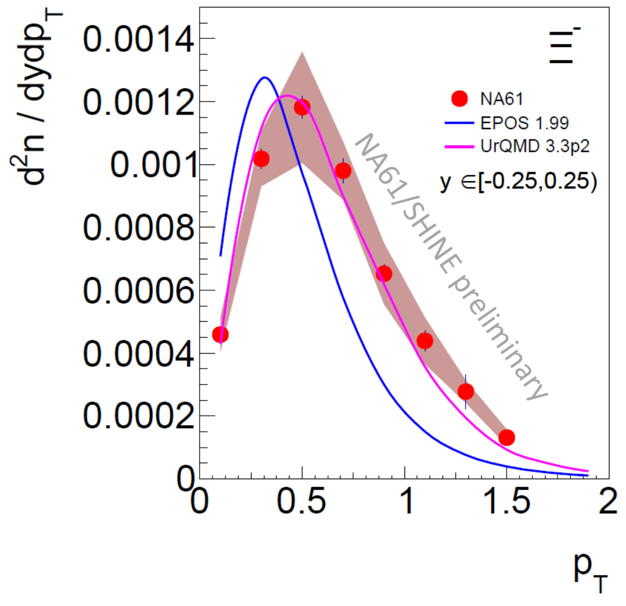


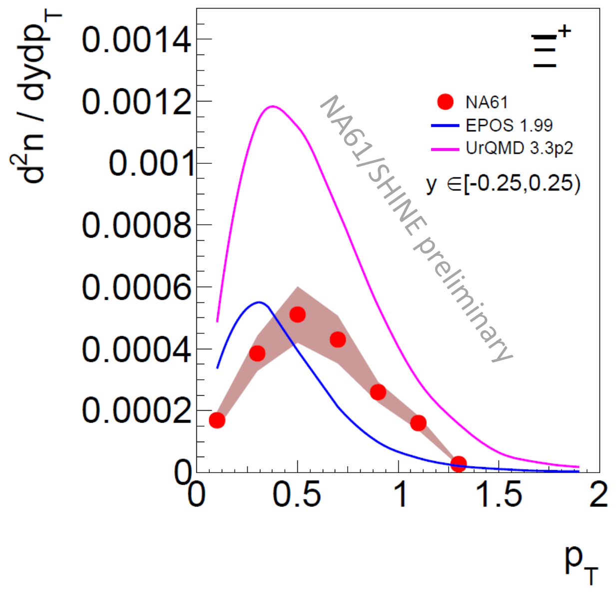


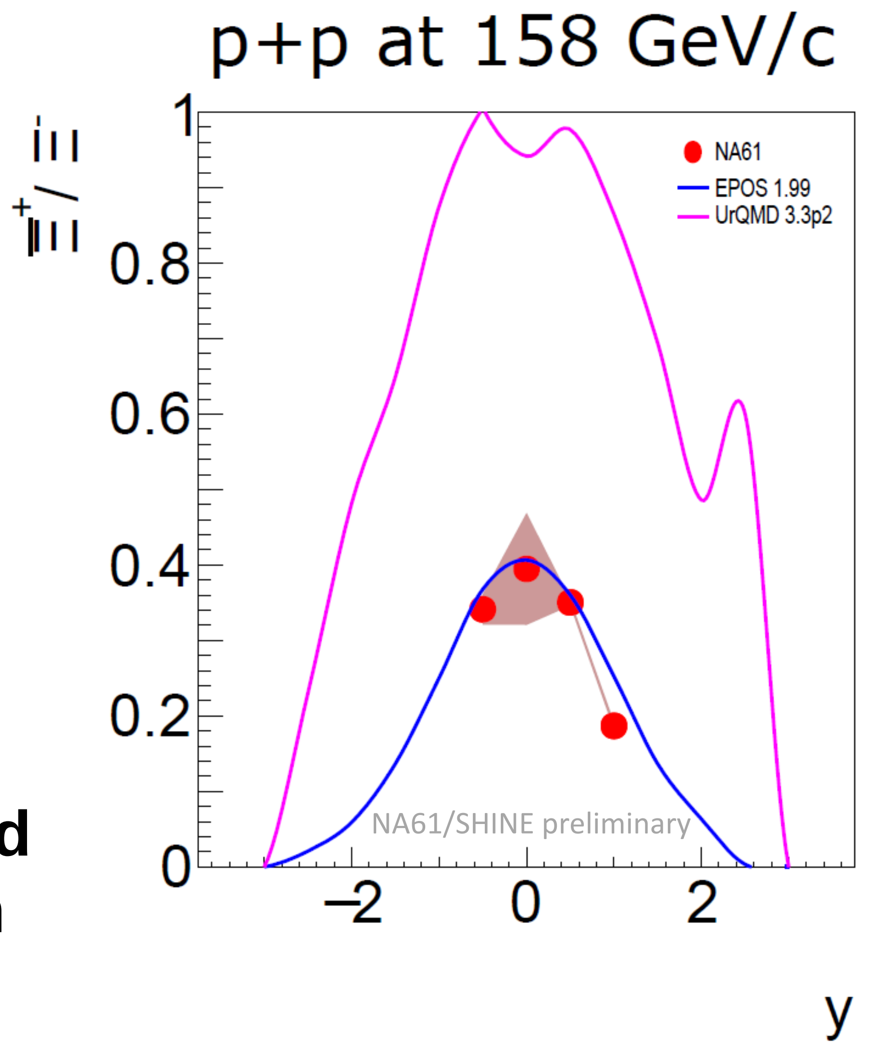


$$\langle \bar{\Xi}^+ \rangle = 0.00079 \pm 0.00002 \pm 0.00010$$
$$\langle \Xi^- \rangle = 0.0033 \pm 0.0001 \pm 0.0006$$

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







UrQMD fails to describe $\overline{\Xi}^+/\Xi^-$ ratio – known problem of string models

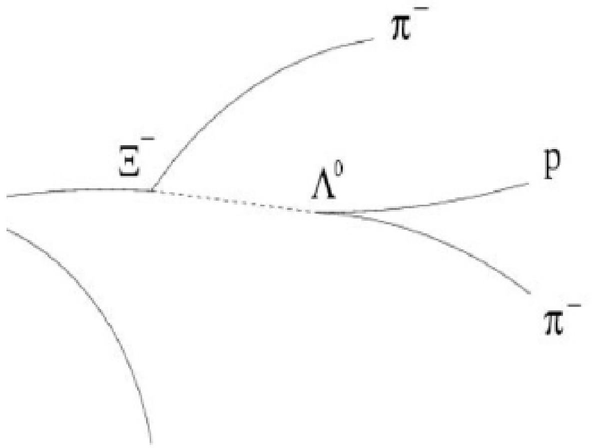
EPOS describes rapidity distributions of $\overline{\Xi}^+, \Xi^-$ and their ratio, but not shape of transverse momentum spectrum.

Strangeness production in p+p at 158 GeV/*c*: Search for *Ξ*⁻⁻(1860) pentaquark

Ξ^{--}(1860) pentaquark search in NA61/SHINE - motivation

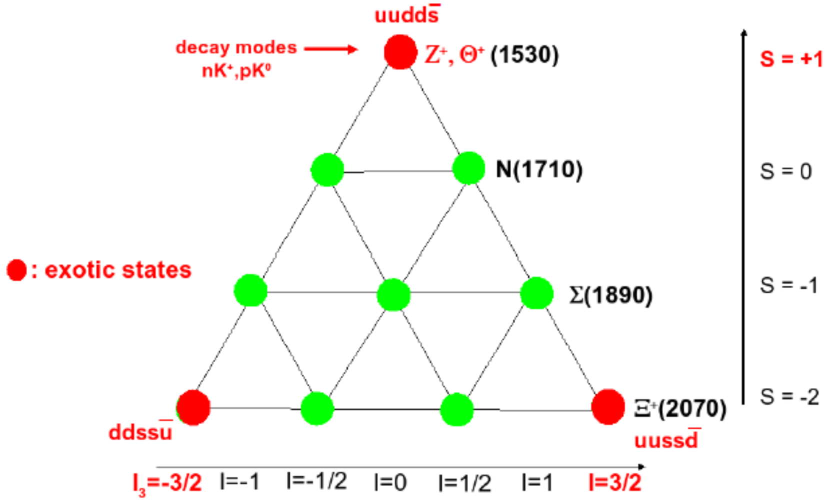
NA49 indication for Ξ^{--}(1860) pentaquark

(NA49, PRL 92, 042003, 2004)



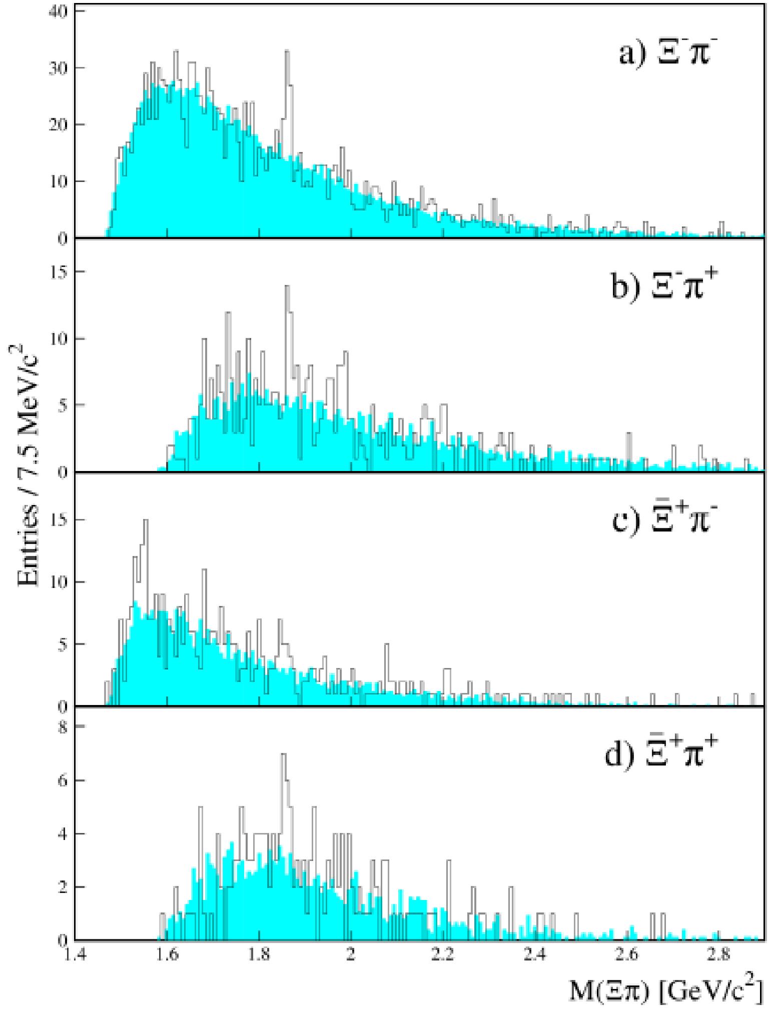
Anti-decuplet of baryons ($J^P=1/2^+$) predicted in chiral soliton model

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

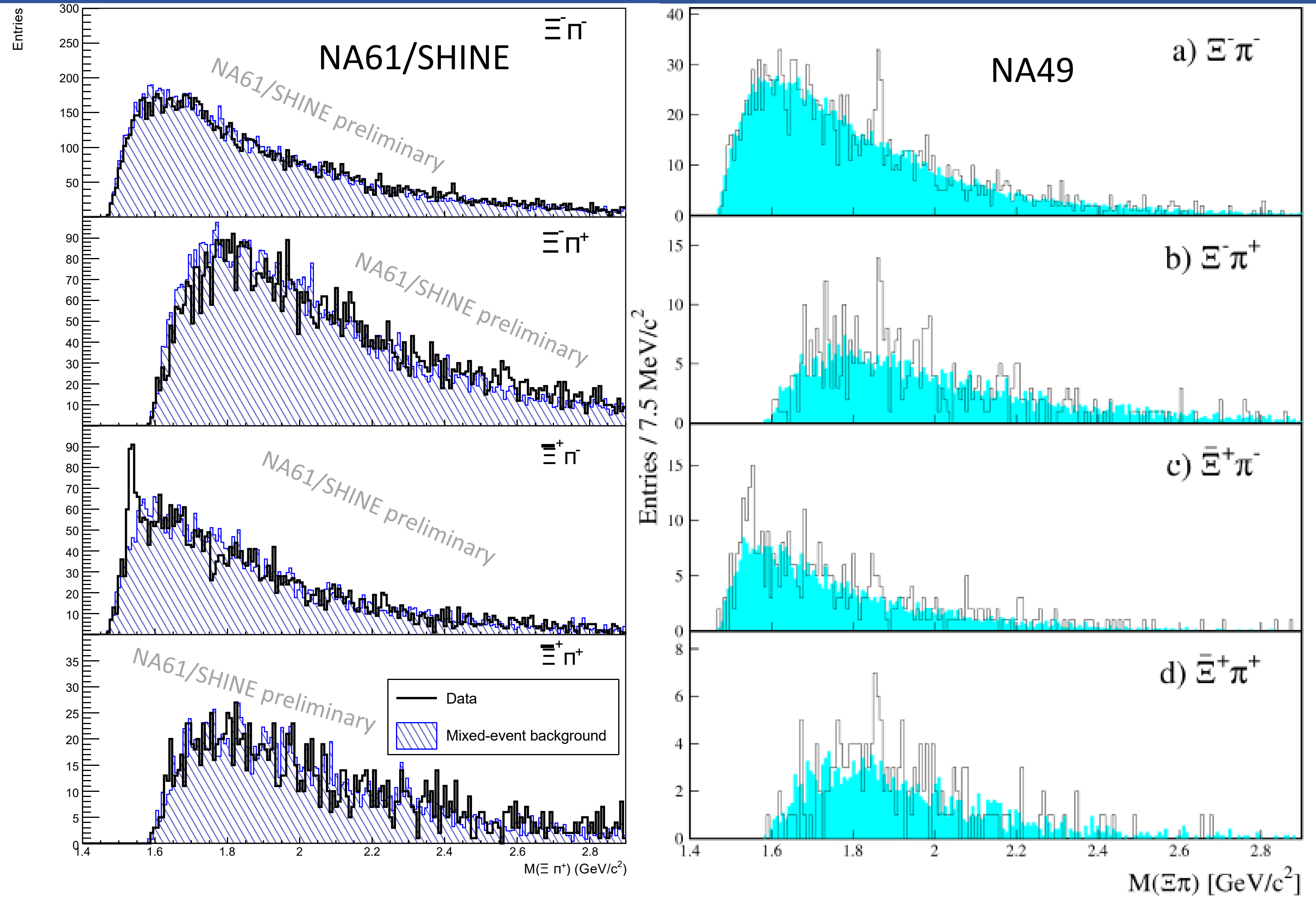


NA49

p+p at 158 GeV/c



Ξ^{--}(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:

- 33M events
- Same analysis as NA49
- **No Ξ^{--}(1860) pentaquark signal**
- Ξ(1530) well visable

NA61/SHINE beyond 2020

NA61/SHINE program for 2021-2024

NA61 physics program beyond 2021

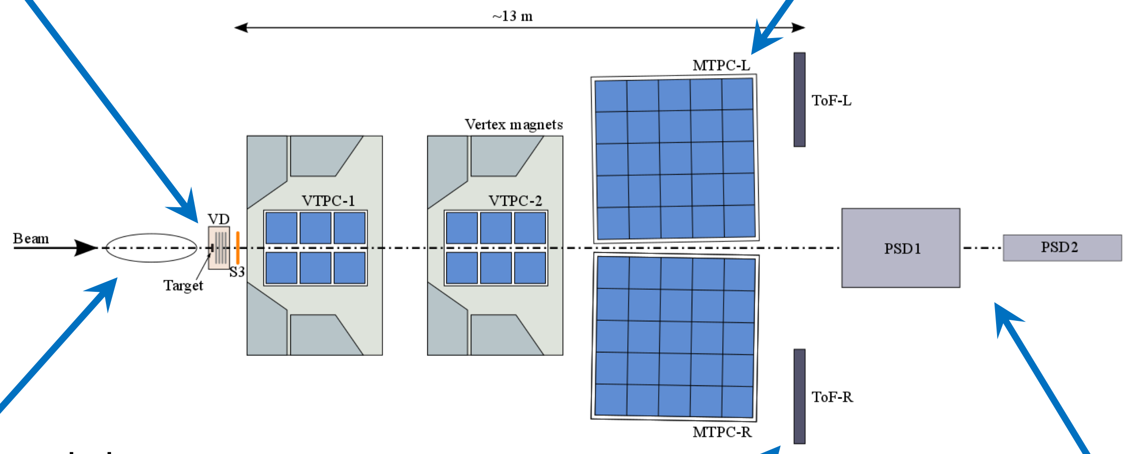
Strong interaction program	Cosmic ray program	Neutrino program
Open charm in heavy ion collisions See P. Staszel talk	Fragmentation cross sections needed for interpretation of CR data	Neutrino experiments expressed interest in thin-target and long-target measurements

Detector upgrade during LS2

See D. Tefelski talk

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)
- No Ξ^{--}(1860) pentaquark signal in p+p at 158 GeV/c
- Plans to extend NA61/SHINE program in 2021-2024

BACKUP

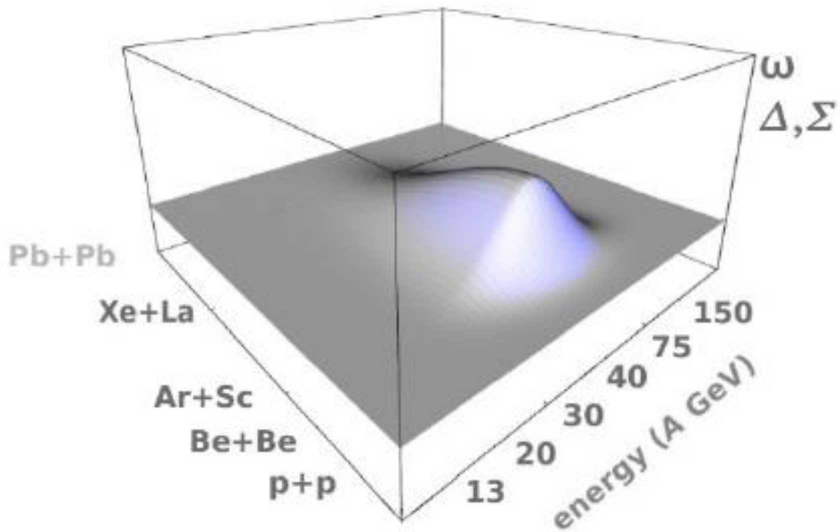
Critical point: Strongly intensive measures Δ and Σ

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

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

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

Expected: non-monotonic behavior of CP signatures



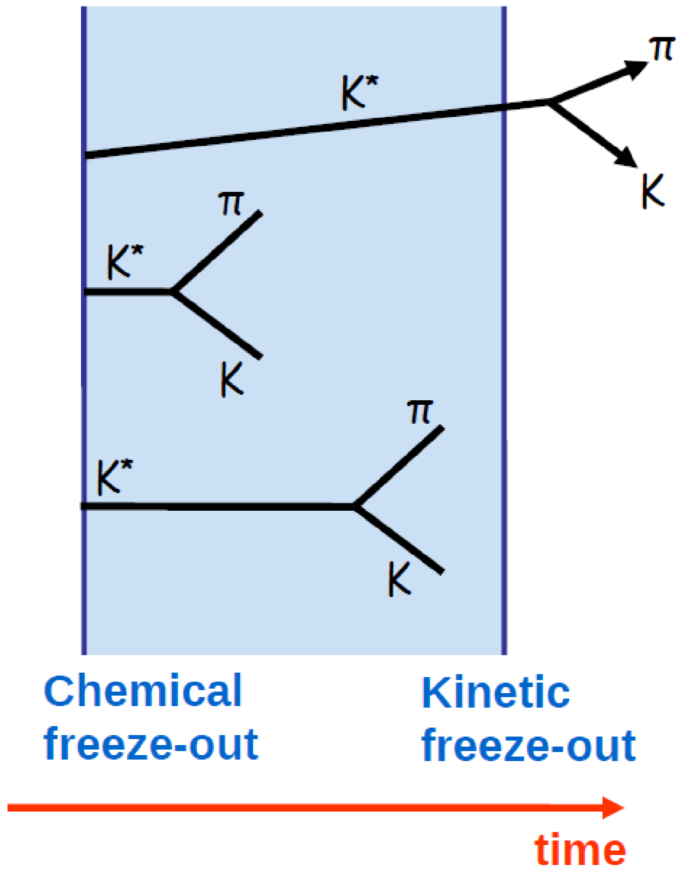
$\Delta = \Sigma = 0$ for no fluctuations

$\Delta = \Sigma = 1$ 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

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):

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

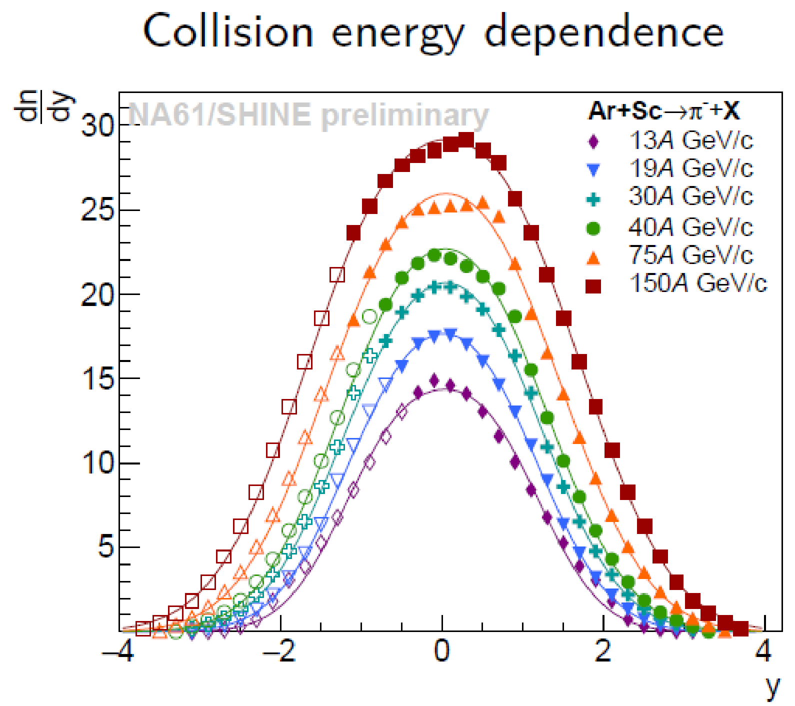
use Pb+Pb or Au+Au ratio — use p+p ratio

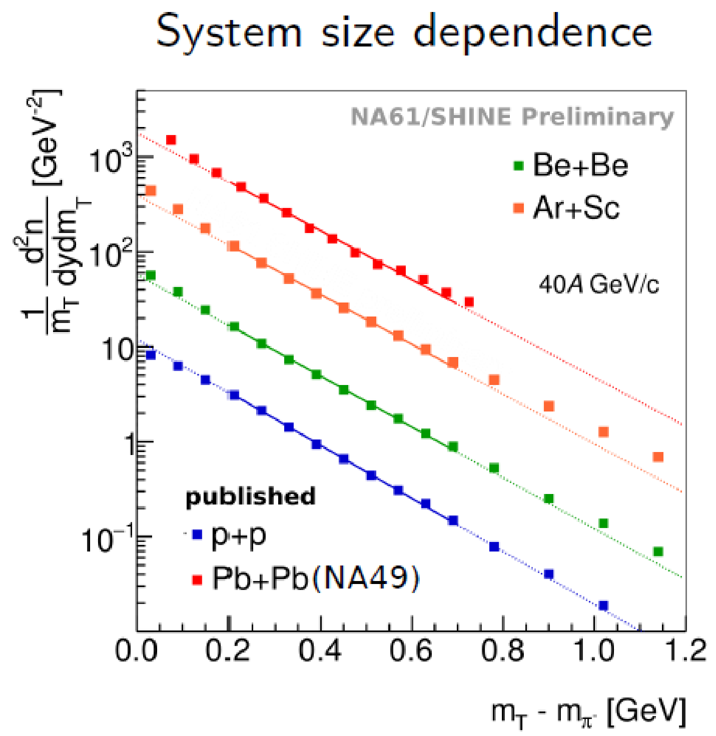
Δt – time between kinetic and chemical freeze-outs

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

π^- spectra from 2D-scan

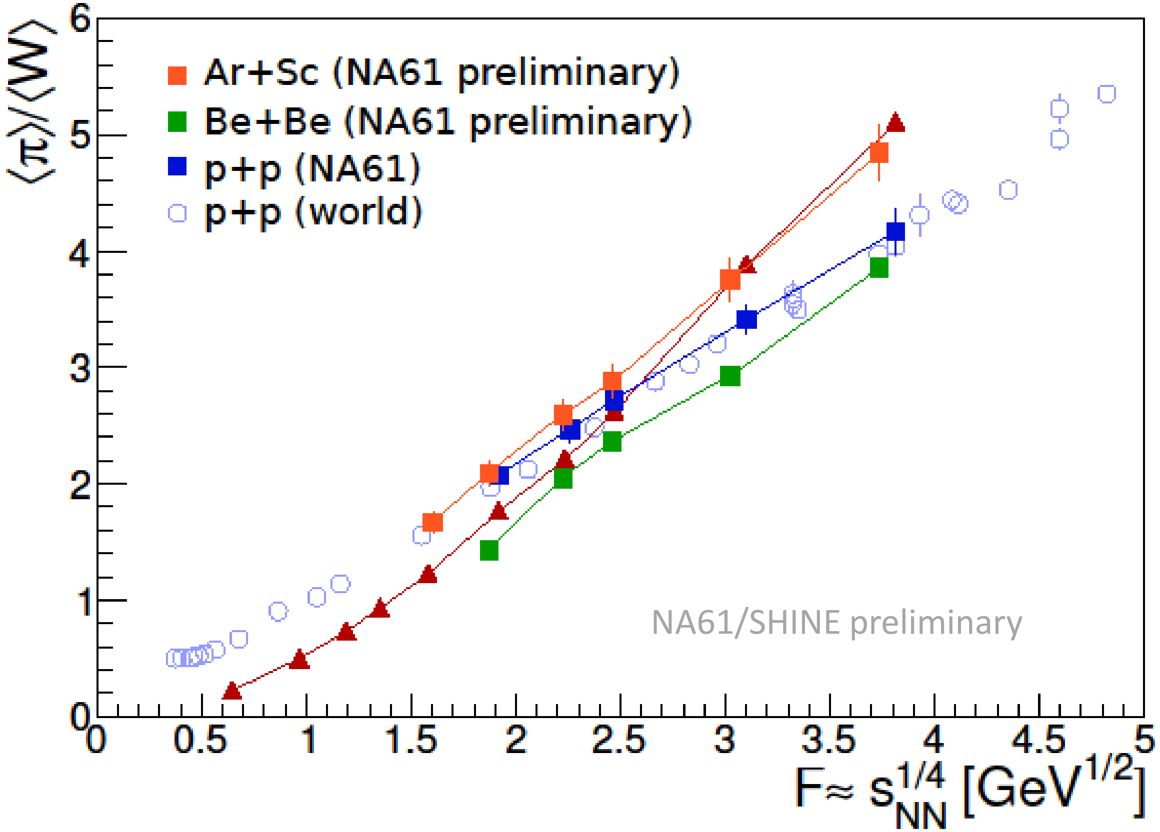
π^- spectra measured in large acceptance: p_T down to 0, in full forward hemisphere





- 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

Onset of deconfinement: kink

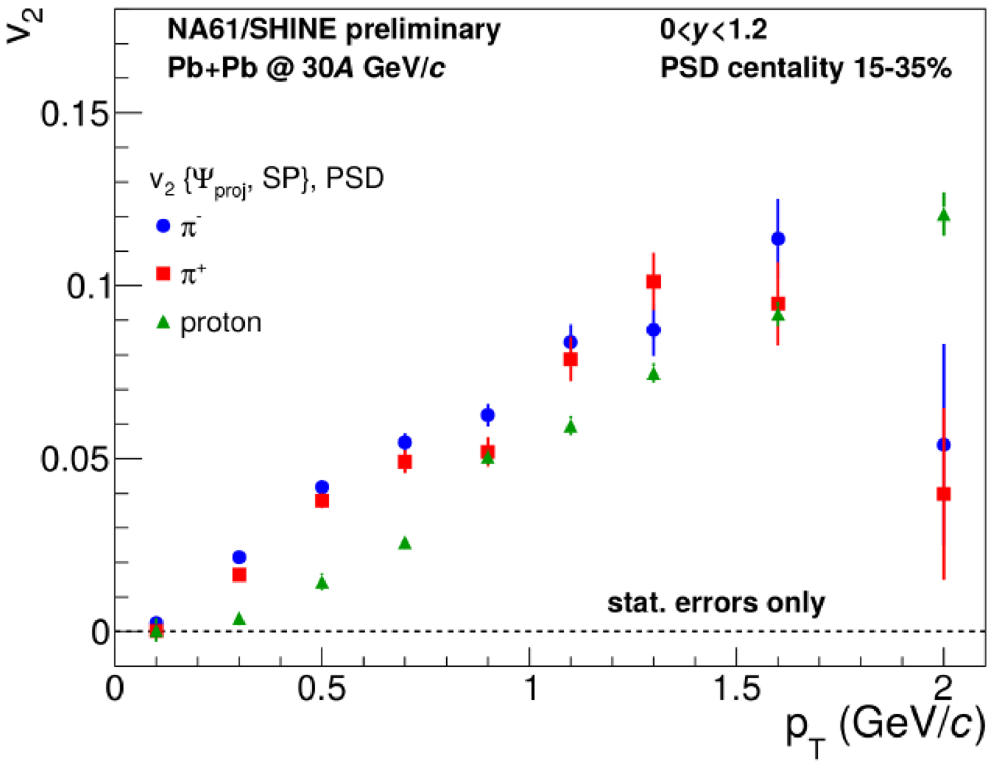


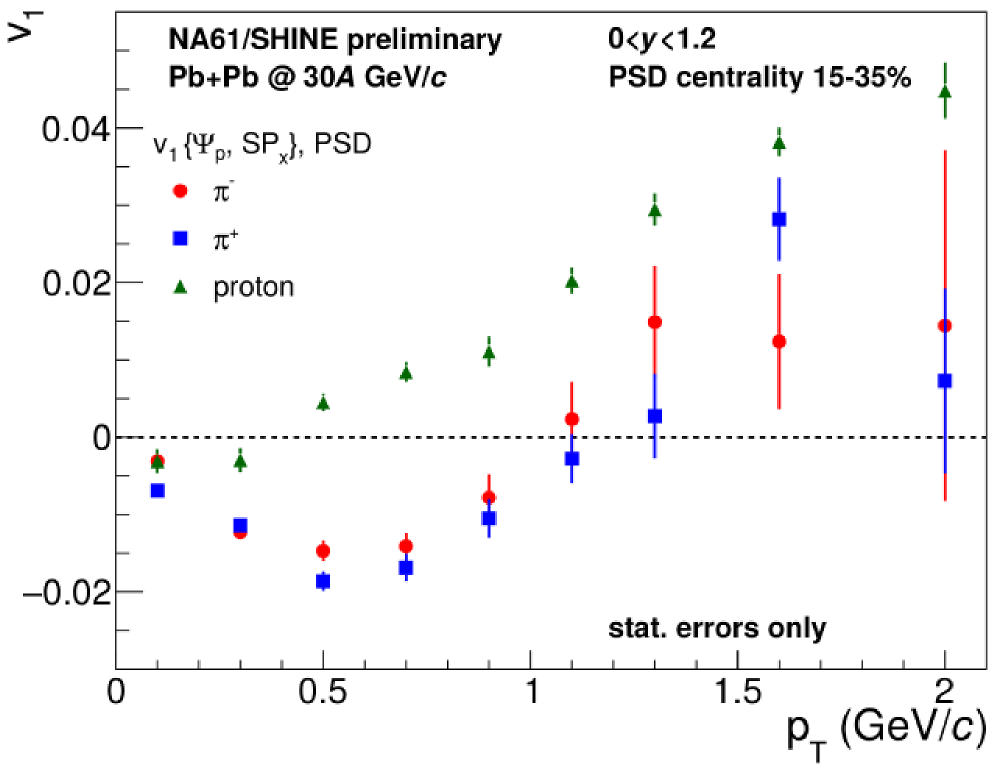
<π> – mean multiplicity in full acceptance
<W> – mean number of wounded nucleons

The increase of <π>/<W> with collision energy is stronger for heavier than for lighter systems at high SPS energies

Statistical model with phase transition (SMES - Acta Phys. Pol. B30 (1999) 2705) predicts a steepening of the rate of increase – **KINK** – of <π>/<W> in QGP due to the larger number of degrees of freedom in comparison to HRG.

Particle type dependence of elliptic and directed flow





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.

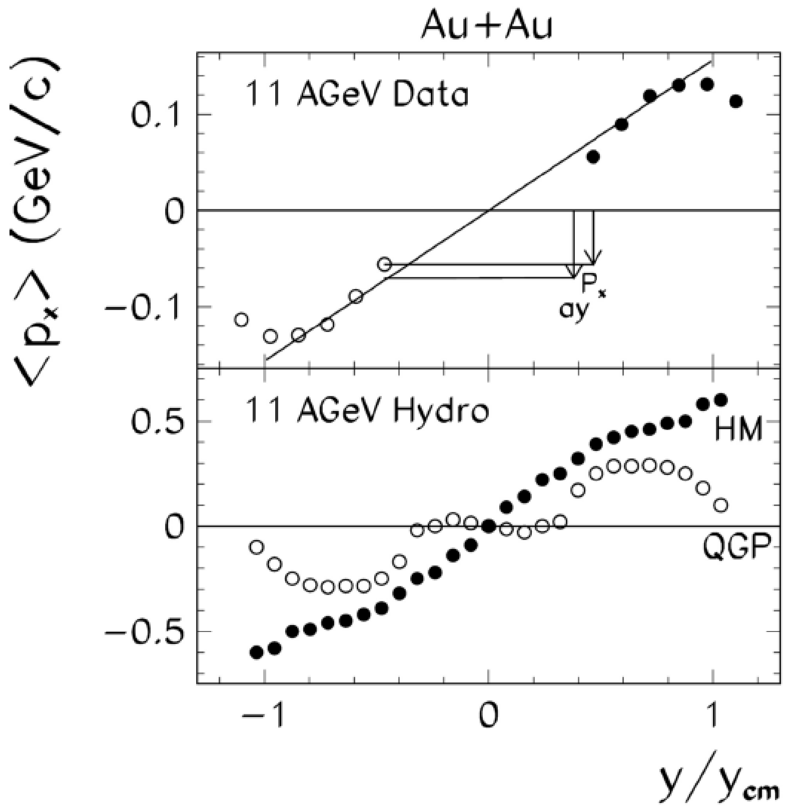
A. Rybicki and A. Szczurek, Phys. Rev. C87, 054909 (2013)

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”

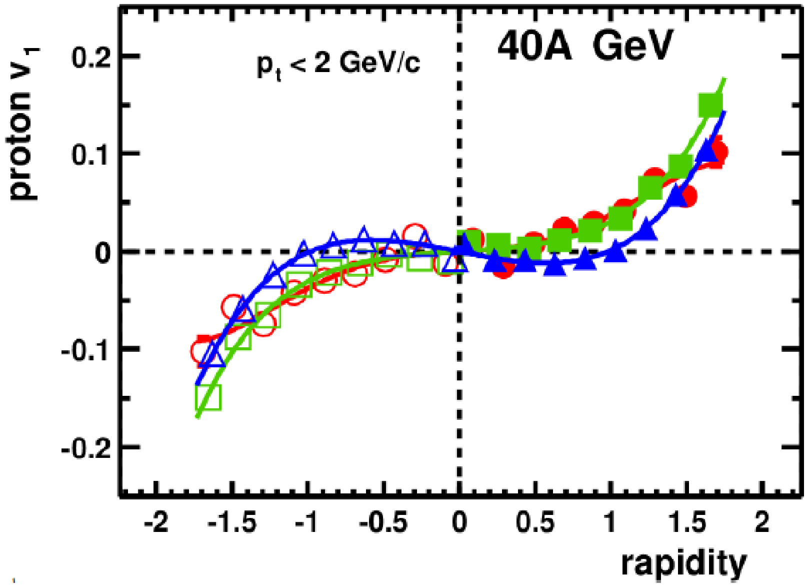
Predictions of hydrodynamical model:



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

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

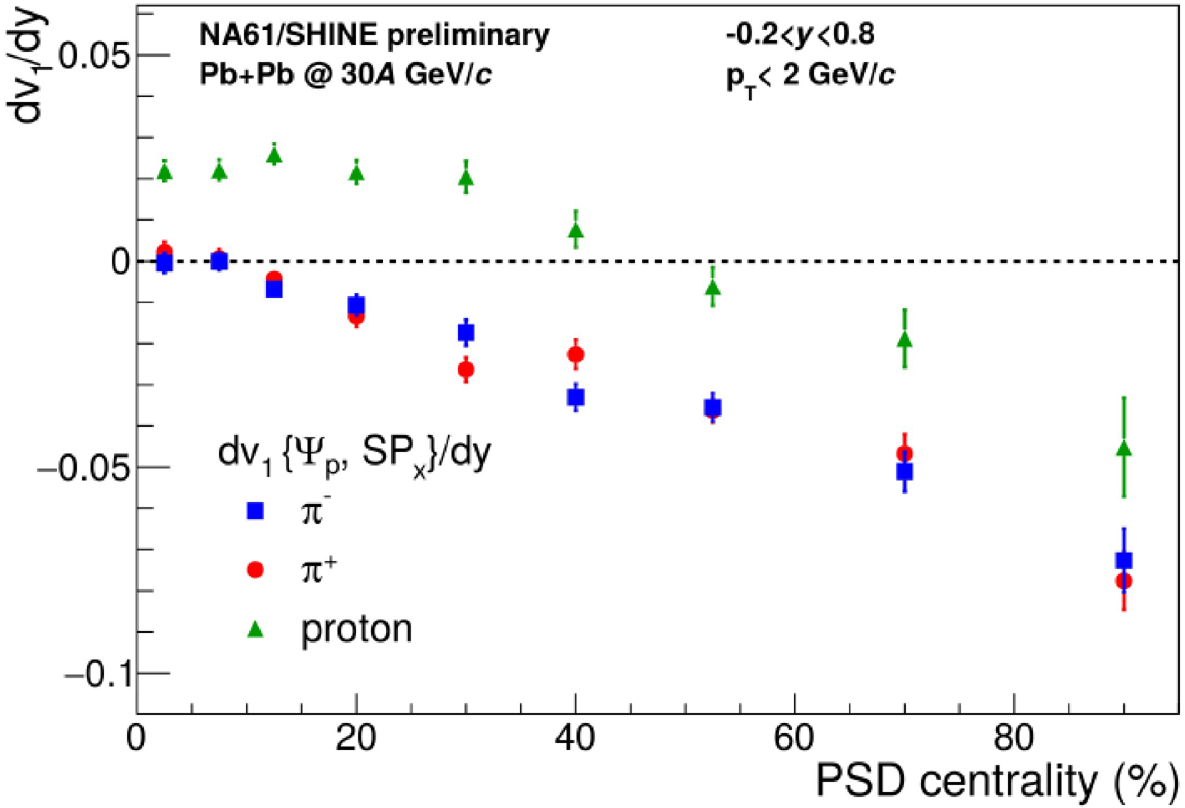
Central mid-central peripheral



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)

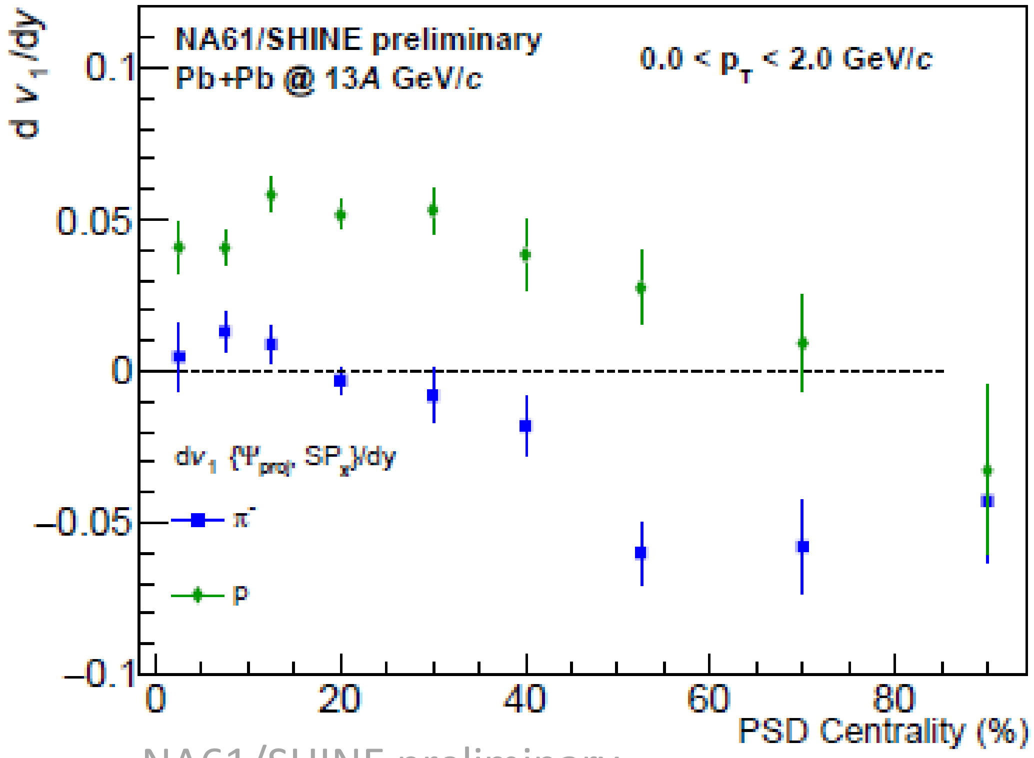
- slope of pion v_1 is negative for all centralities

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

More NA61/SHINE flow results: Klochkov, Selyuzhenkov (QM2018 talk)

Anisotropic flow v_1

The energy dependence of v_1 slope at midrapidity is sensitive to the change in EOS, phase transition, and details of the fireball 3D space-momentum evolution



NA61/SHINE preliminary

dv_1/dy, for p and π^- starts with positive values for central collisions and decreases for more peripheral collisions, turning negative rather fast in case of π^-

E. Kashirin, O. Golosov, V. Klochkov, and I. Selyuzhenkov, "Anisotropic flow measurements from the NA61/SHINE and NA49 beam momentum scan programs at CERN SPS," 2019. XIV International Workshop Particle Correlations and Femtoscopy (WPCF2019), Dubna, Russia.

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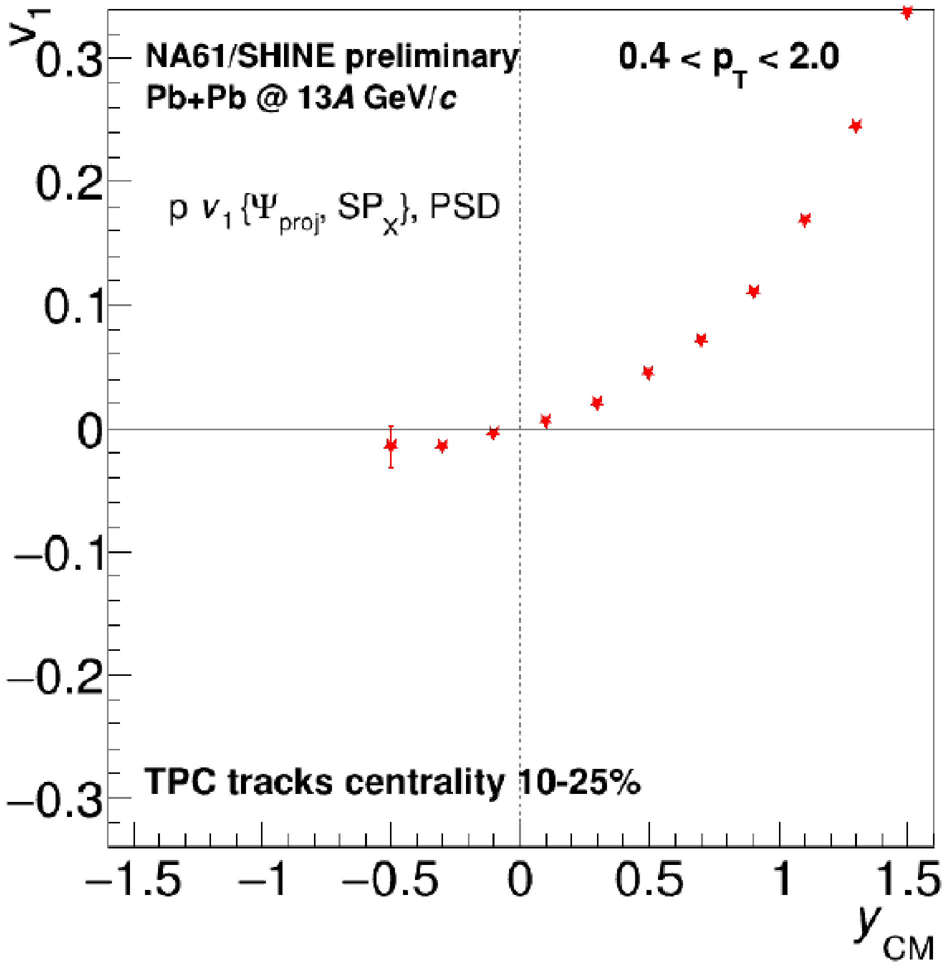
Proton directed flow vs rapidity

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

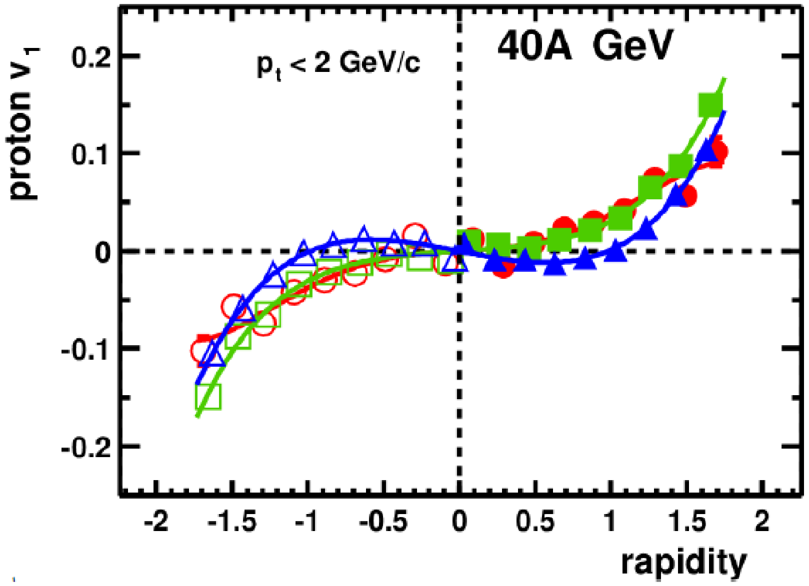


No evidence for the collapse of proton directed flow in Pb+Pb at 13*A* GeV/c

NEW

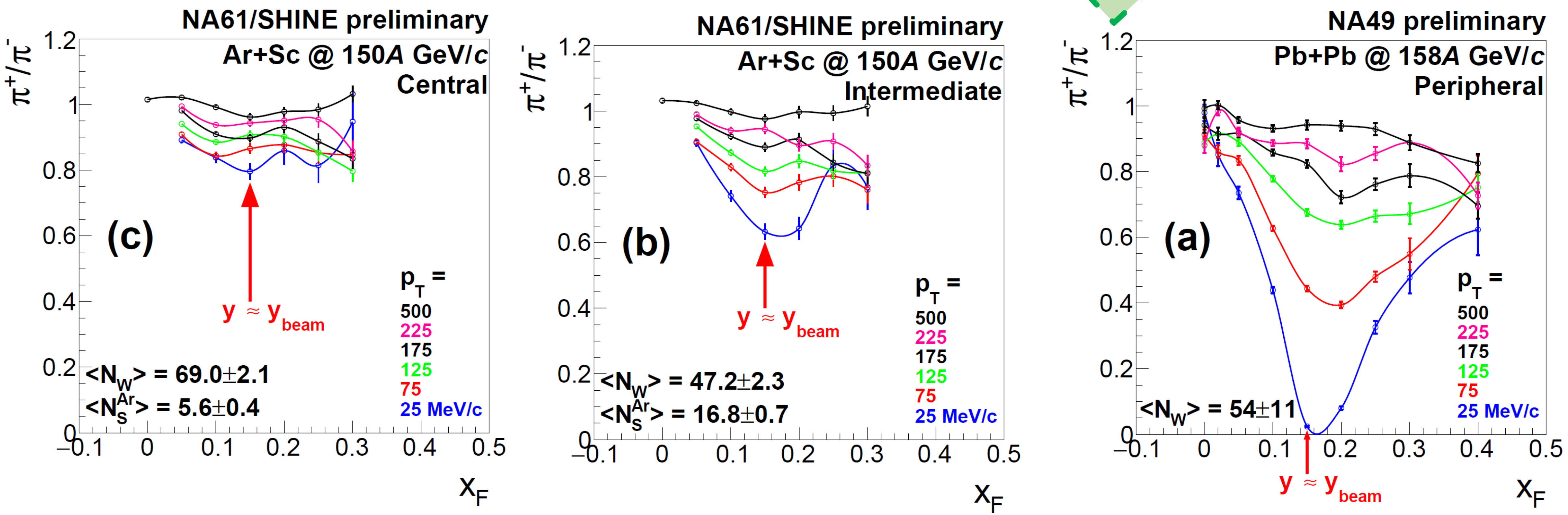
Directed flow measured by NA49 at middle SPS energy ("anti-flow" of protons at mid-rapidity):

Central mid-central peripheral



Spectator-induced electromagnetic effects

NEW



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

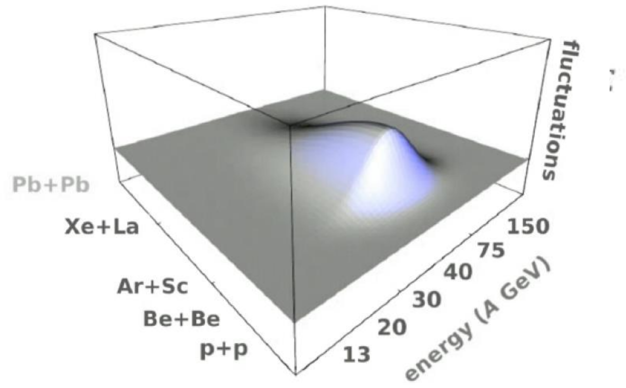
First observation of spectator induced EM effects in small systems at SPS

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

brings new information on the space time evolution of the system, see also NICA White Paper, A.R. et al, Eur.Phys.J. A52 (2016), 221

Search for critical point

Expected: non-monotonic behavior of CP signatures



Critical point: Proton intermittency as signal of CP

Second order phase transition → scale invariance → characteristic dependence of fluctuations on size δ of subdivision intervals of momentum space Δ

$M = \Delta/\delta$ – numer of intervals

$$F_2(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m (n_m - 1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^2}$$

where:

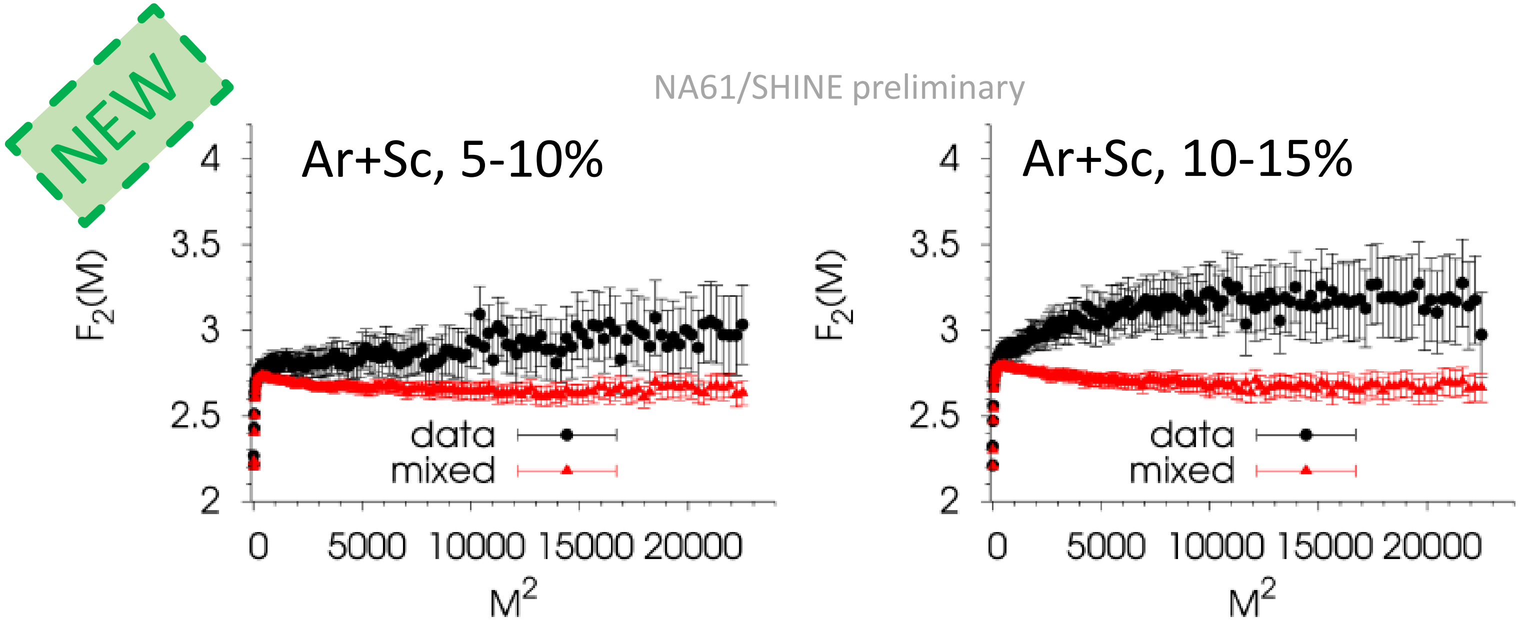
n_m – particle number in bin i,

<…> - averaging over events

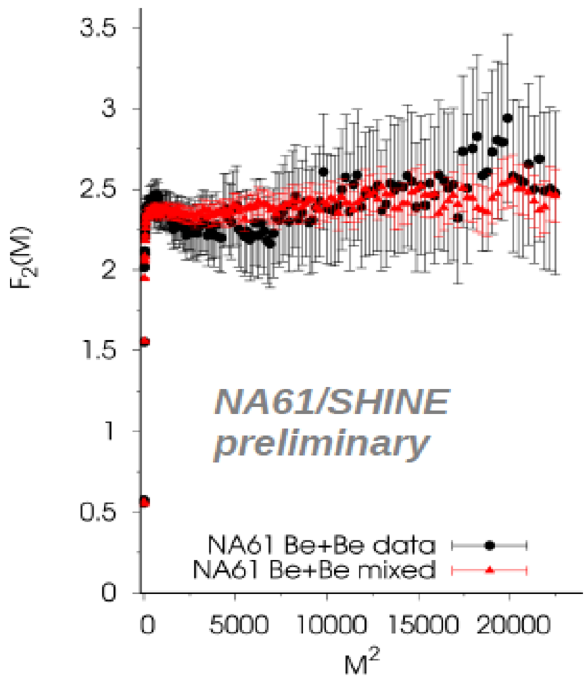
at critical point power law dependence is expected

$$\boldsymbol{F_2(M) = F_2(\Delta) M^{\varphi_2}}$$

Critical point: Proton intermittency in Ar+Sc and Be+Be at 150*A* GeV/*c*



Be+Be, 0-12%



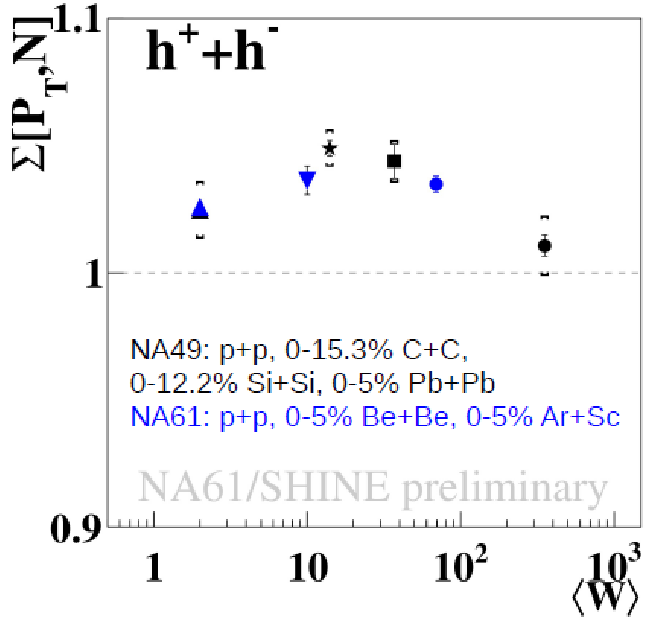
M^2 – numbers of bins in (p_x, p_y) space

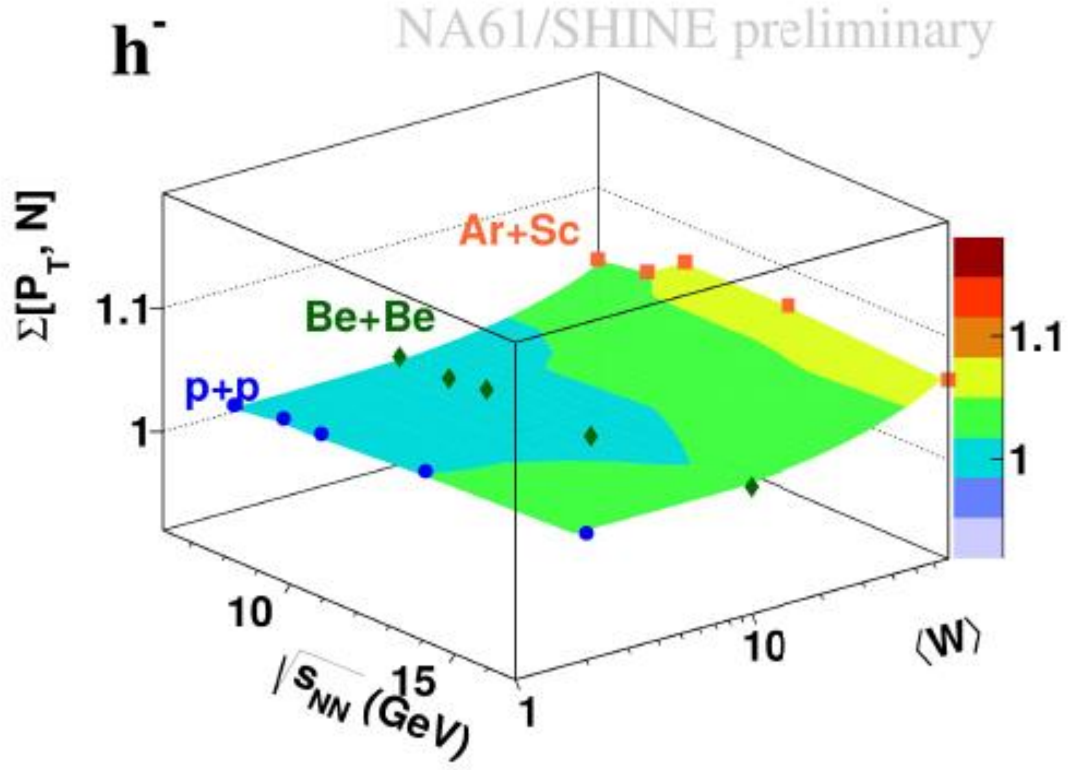
$F_2(M^2)$ moment are higher in data than in mixed events in Ar+Sc collisions - detailed investigation of significance of this result is in progress

No signal visible in Be+Be.

Critical point: Strongly intensive measures $\Sigma[P_T,N]$

Comparison to NA49 *A+A* at 158*A* GeV/*c*
within NA49 two different acceptances





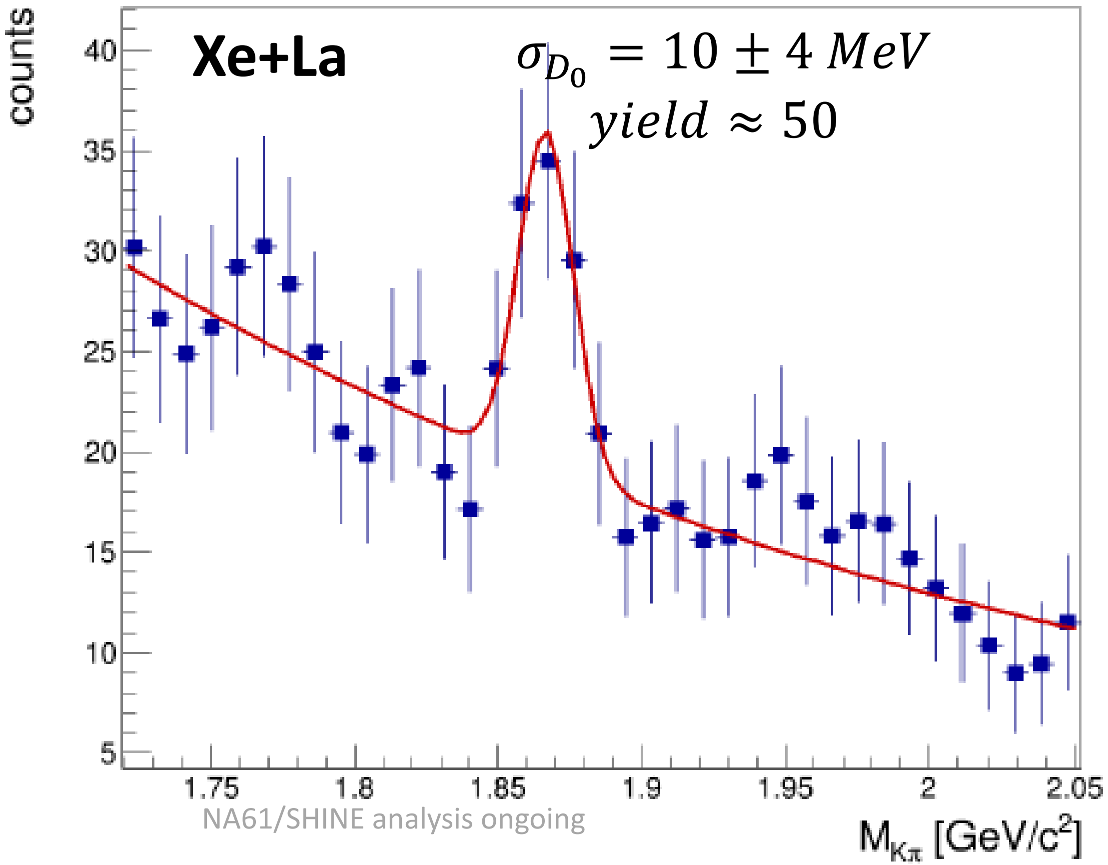
System size dependence of $\Sigma[P_T,N]$ at 150/158A GeV/c: NA49 and NA61/SHINE points show consistent trends

So far there are no prominent structures which could be related to critical point

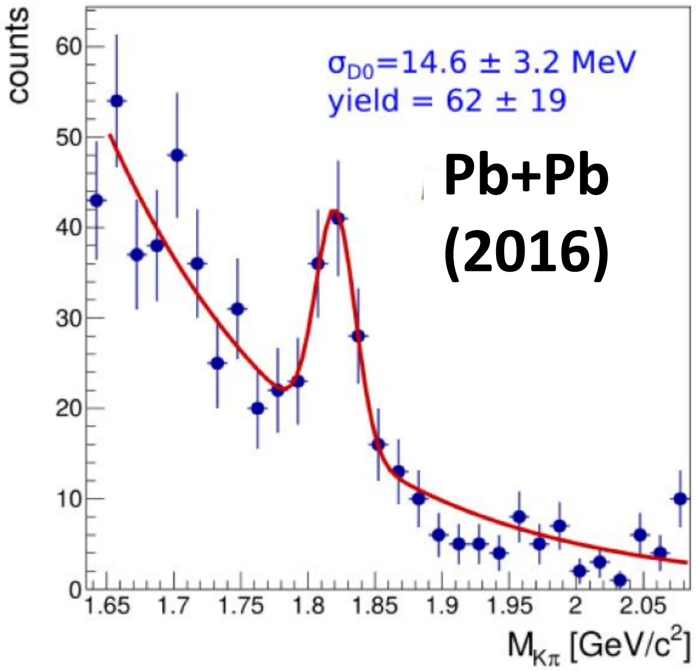
Eur.Phys.J. C77 (2017) no.2, 59,
CERN-SPSC-2018-029

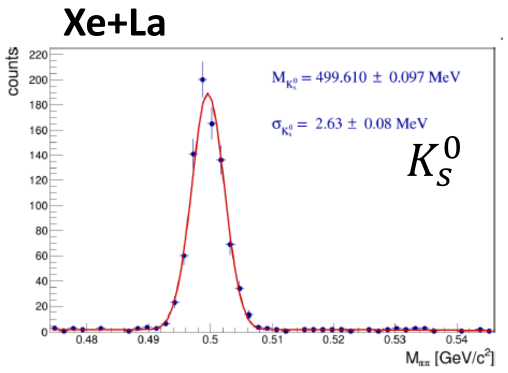
NA49: PR C92, 044905, 2015

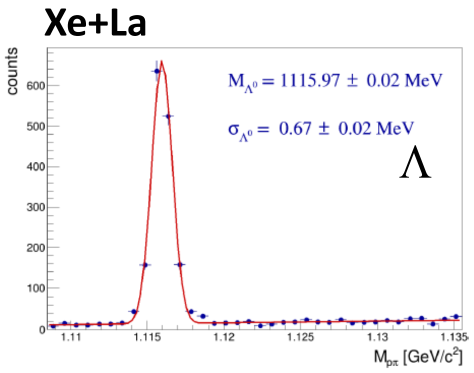
Open charm signal in Xe+La at 150A GeV/c



NA61/SHINE analysis ongoing





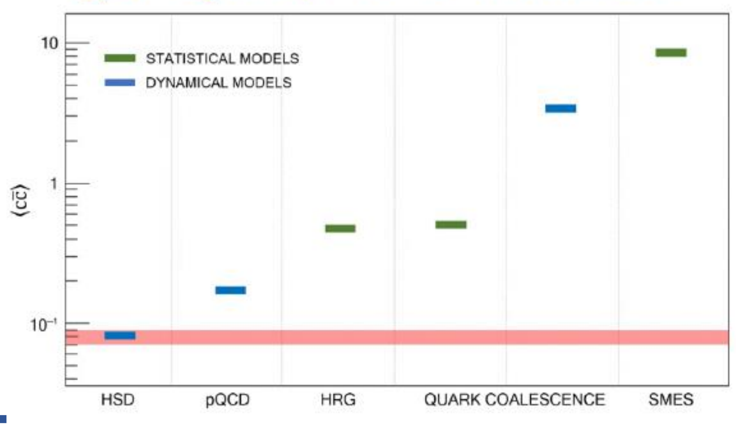


See P. Staszel talk

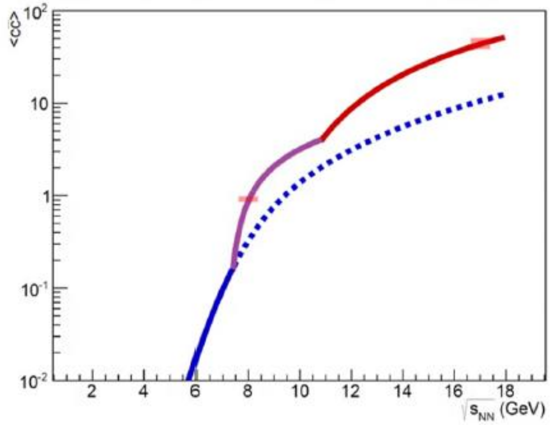
- **What is the mechanism of open charm production?**
- **How does the onset of deconfinement impact open charm production?**
- **How does the formation of quark gluon plasma impact J/ψ production?**

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**.

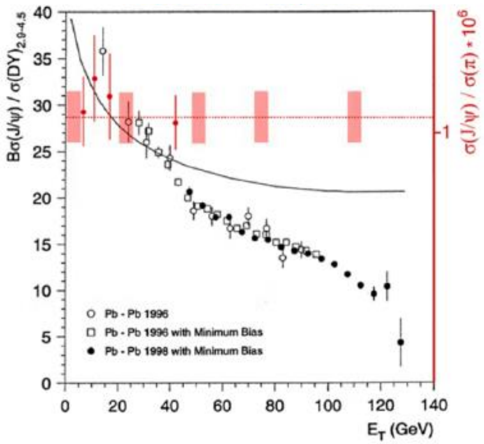
$\langle c\bar{c}\rangle$ and models



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