Recent results from NA61/SHINE

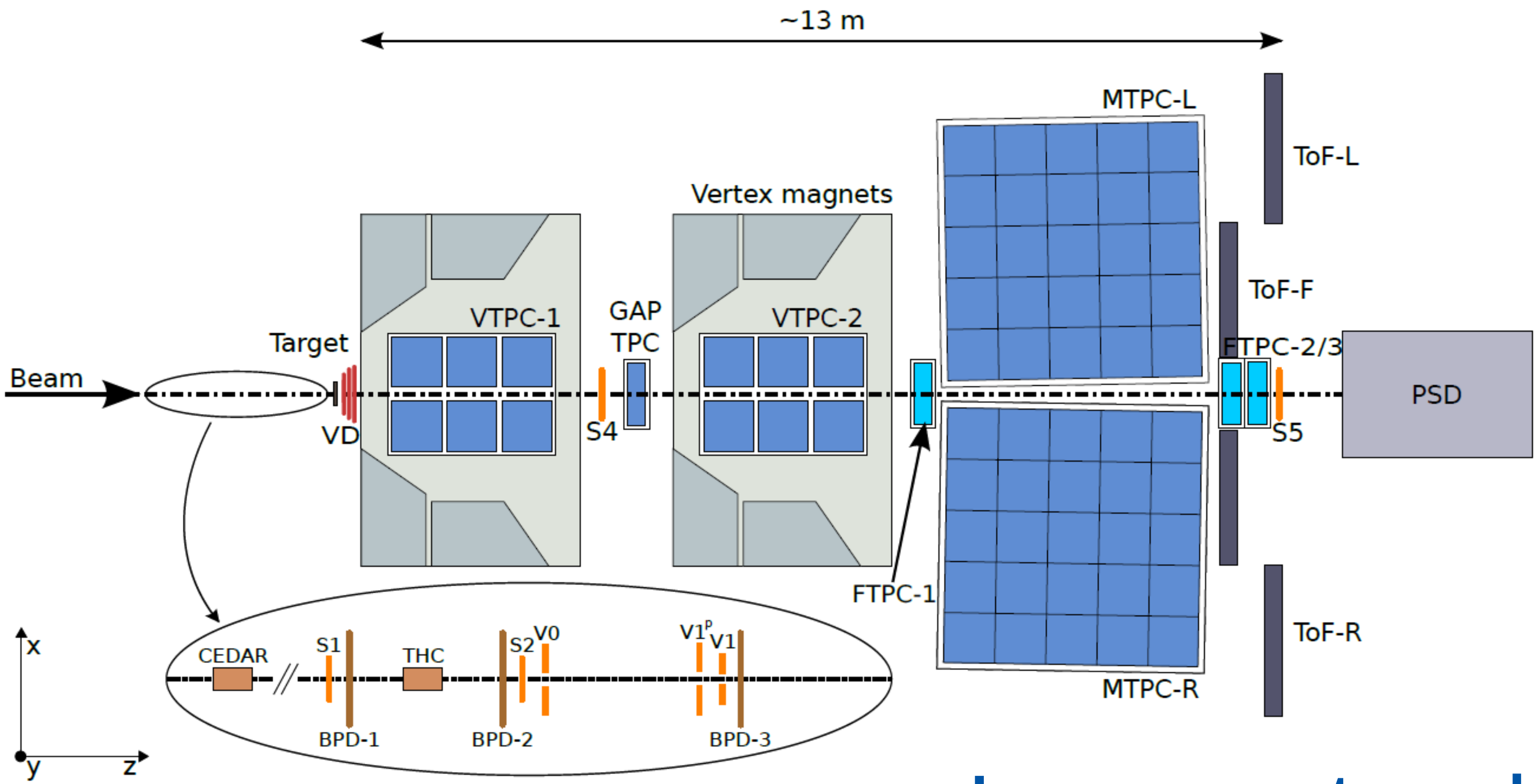
Szymon Puławski
for NA61/SHINE

Outline

- **Introduction**
- **Study of the onset of deconfinement**
  - NEW **Particle production properties** See P. Podlaski Tuesday
  - NEW **Flow**
- NEW **Onset of fireball**
- NEW **Search for critical point**
- NEW **Strangeness production in p+p at 158 GeV/c:**
  - NEW **$K^*(892)^0$** See A. Tefelska Thursday 4.10PM
  - NEW **Ξ production**
  - NEW **Search for pentaquark**
- **NA61/SHINE beyond 2020** See D. Tefelski Thursday, Poster A. Merzlaya
- **Summary**

NA61/SHINE

Fixed target experiment located at the CERN SPS accelerator



Beams:

- ions (Be, Ar, Xe, Pb)

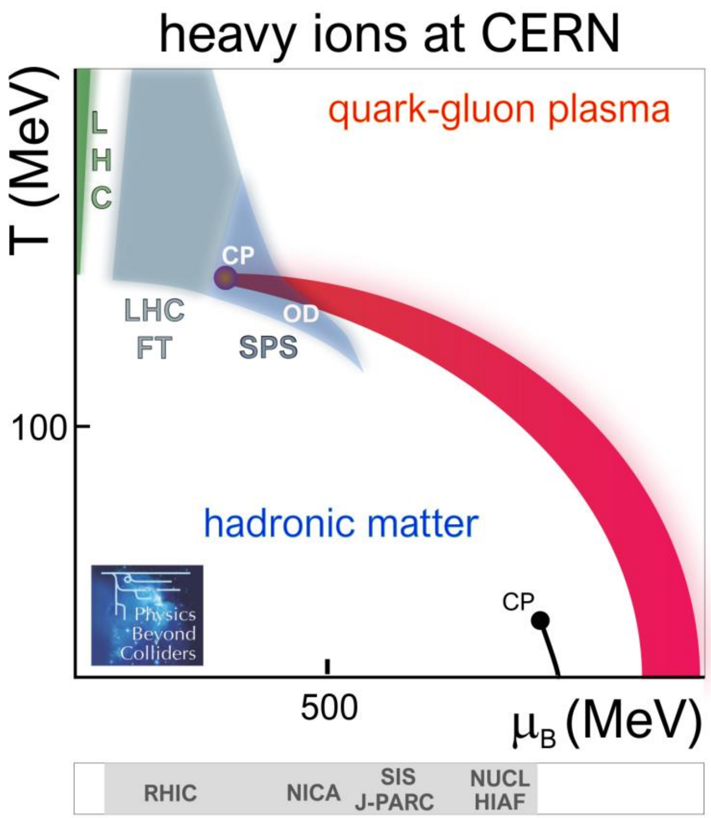
  p_{beam}=13*A*–150*A* GeV/*c*
- hadrons (π, K, p)

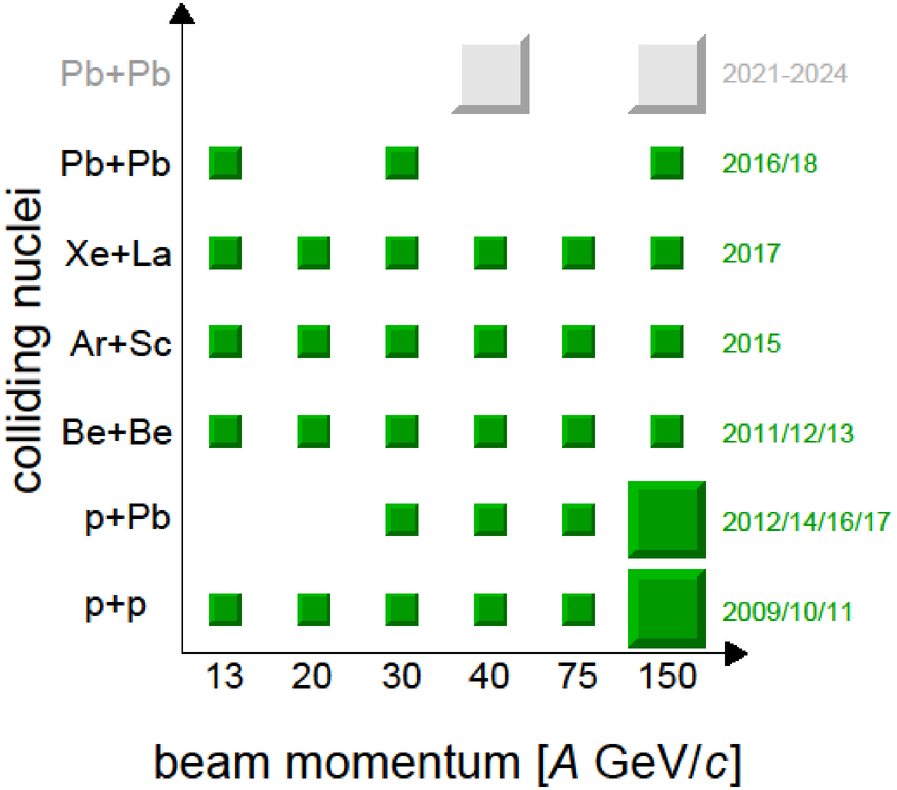
  p_{beam}=13–400 GeV/*c*
- $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

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

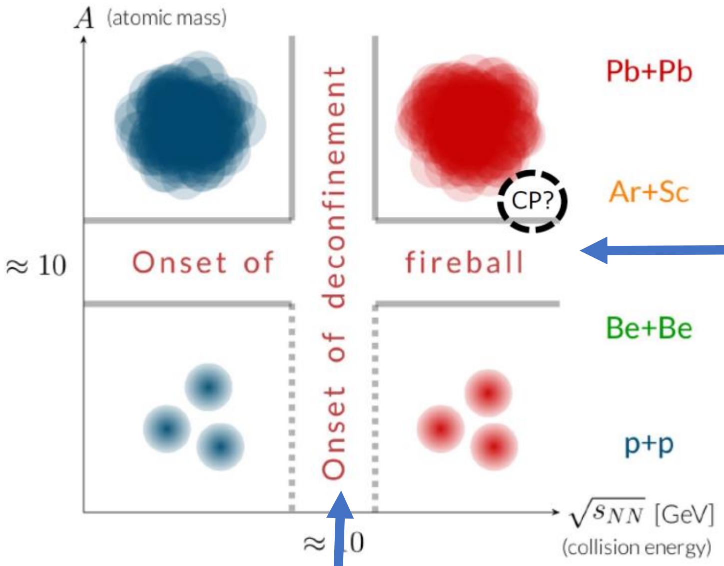
NA61/SHINE 2-dimensional scan

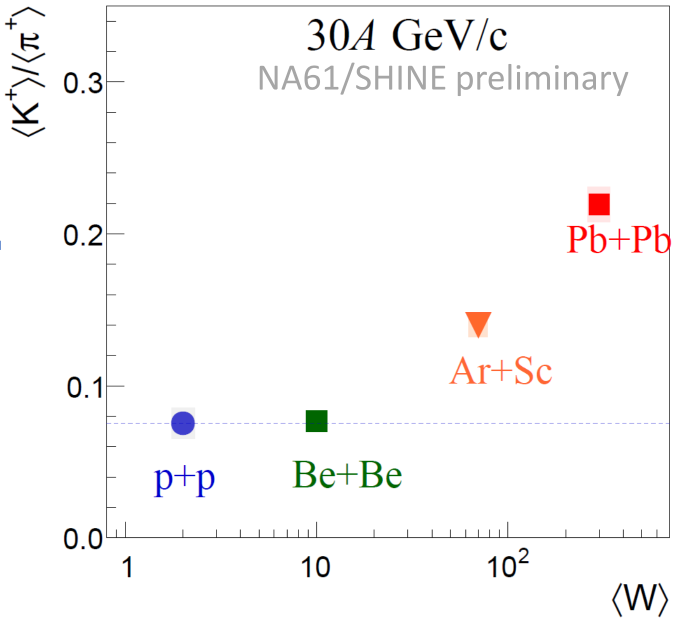
NA61/SHINE performed the 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter

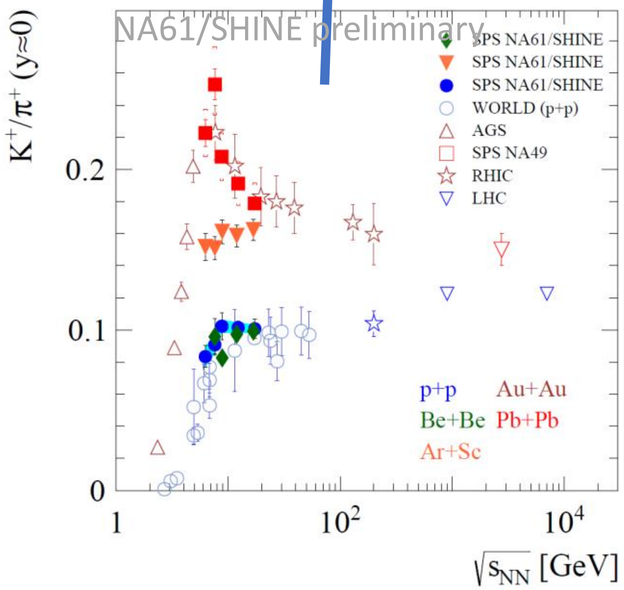




Uniqueness of heavy ion results from NA61/SHINE







NA61/SHINE recorded unique data for:

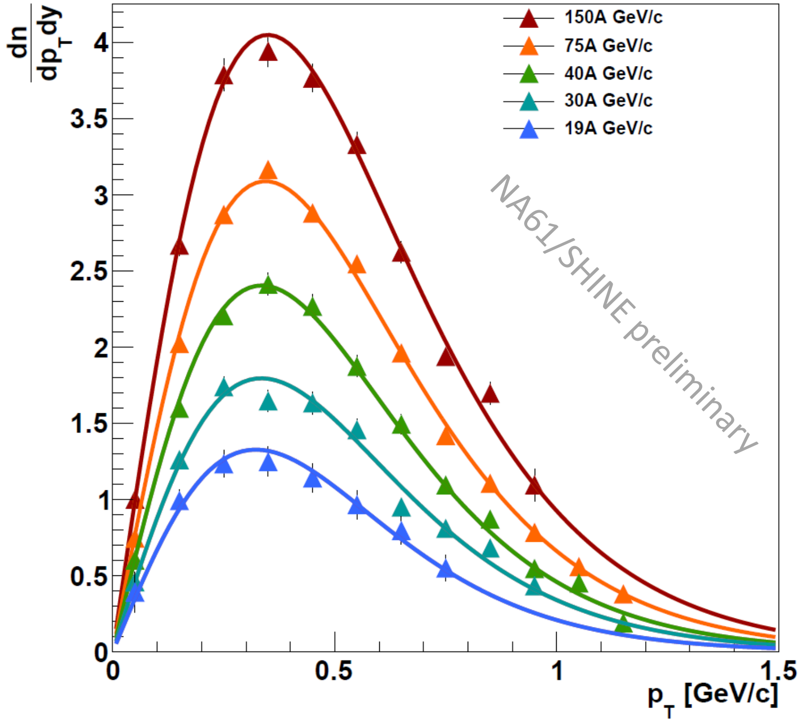
- Onset of deconfinement
- Onset of fireball
- Critical point?

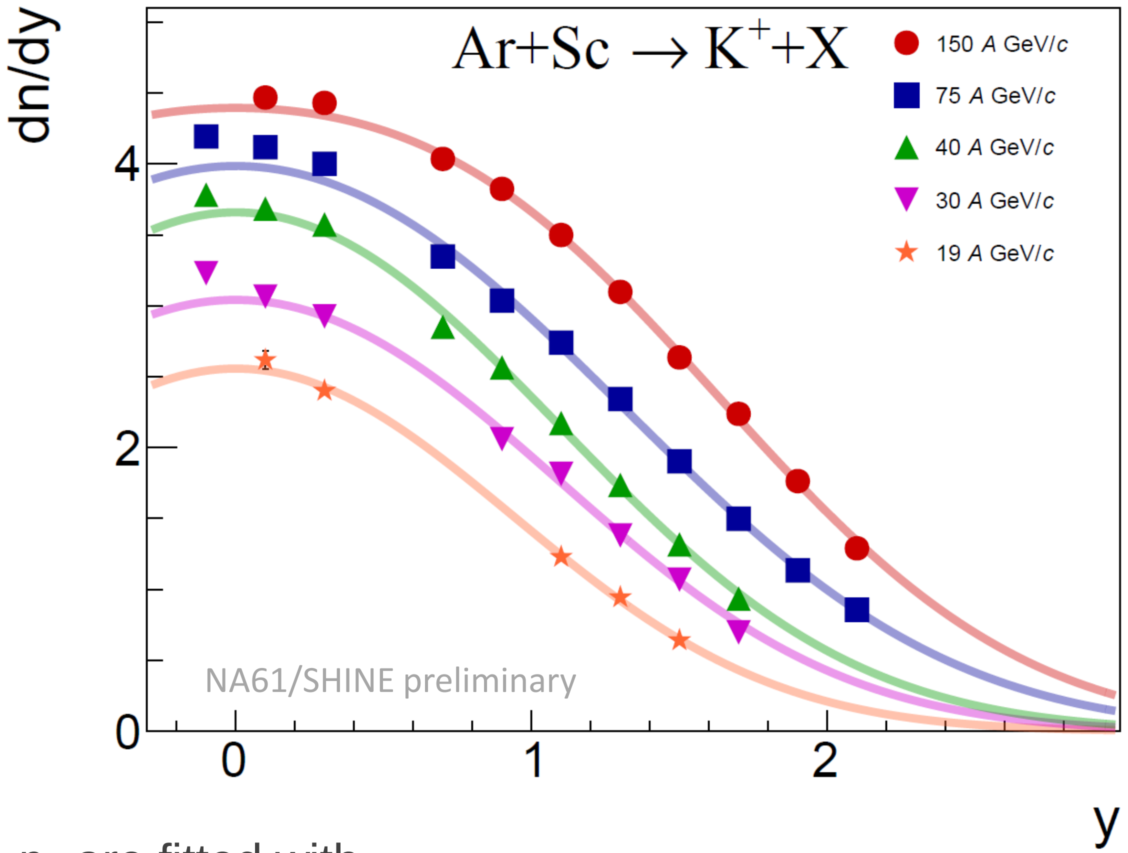
Study of the onset of deconfinement:
Particle production properties

See P. Podlaski Tuesday

NEW

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





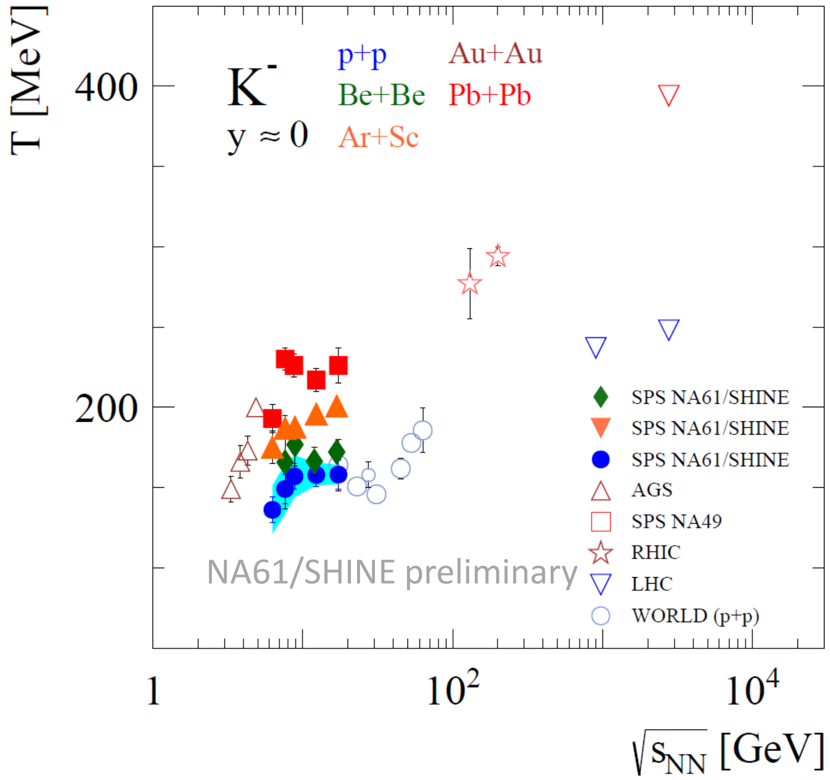
$K^{\pm}$ spectra in p_T are fitted with

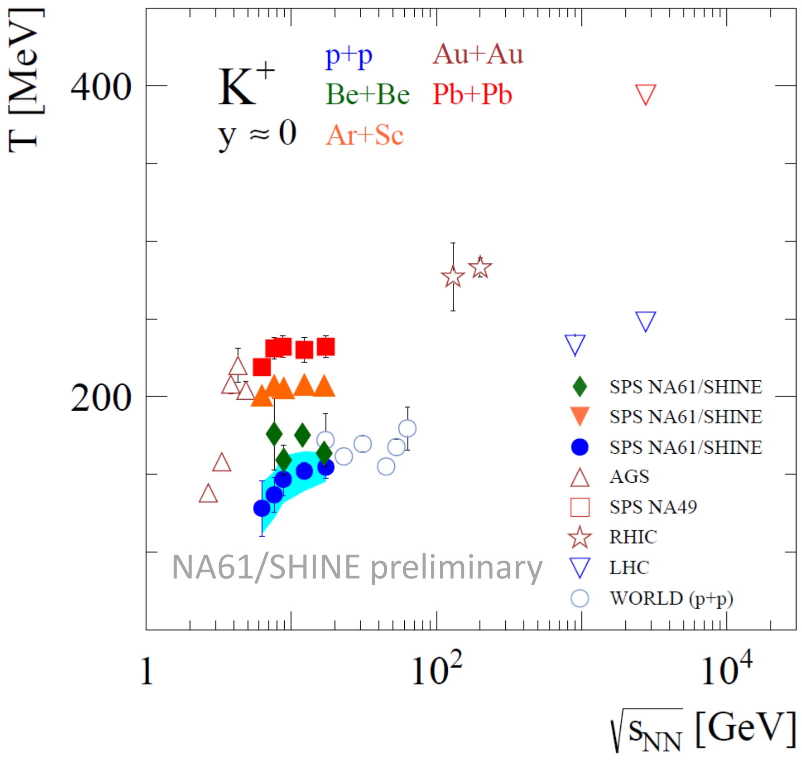
$$\frac{d^2 n}{dp_T dy} = \frac{S\ p_T}{T^2 + T\ m_K}\ exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$$

Onset of deconfinement: step

See P. Podlaski Tuesday

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

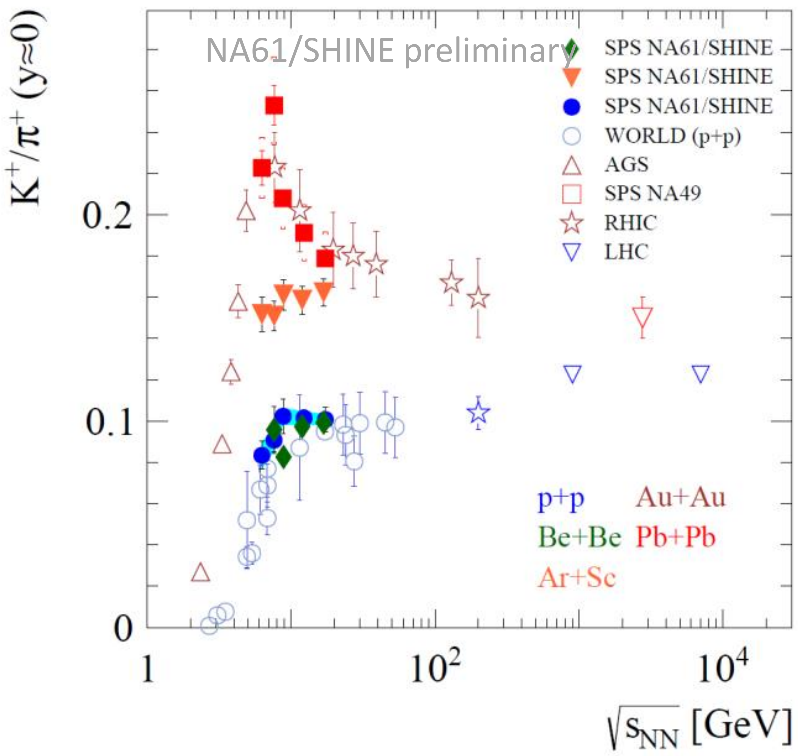
Ar+Sc results between p+p/Be+Be and Pb+Pb

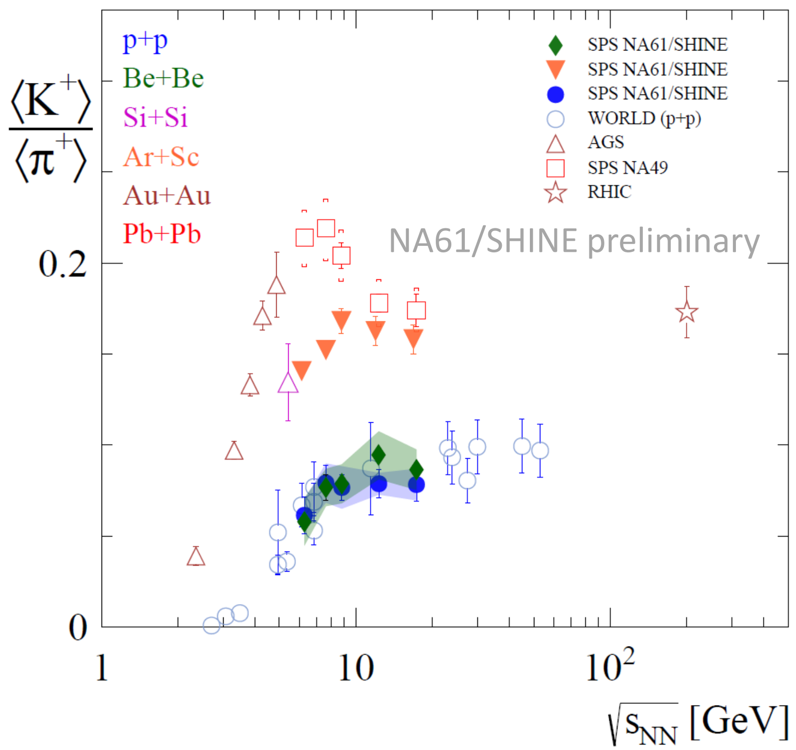
Onset of deconfinement: horn

See P. Podlaski
Tuesday

NEW

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.



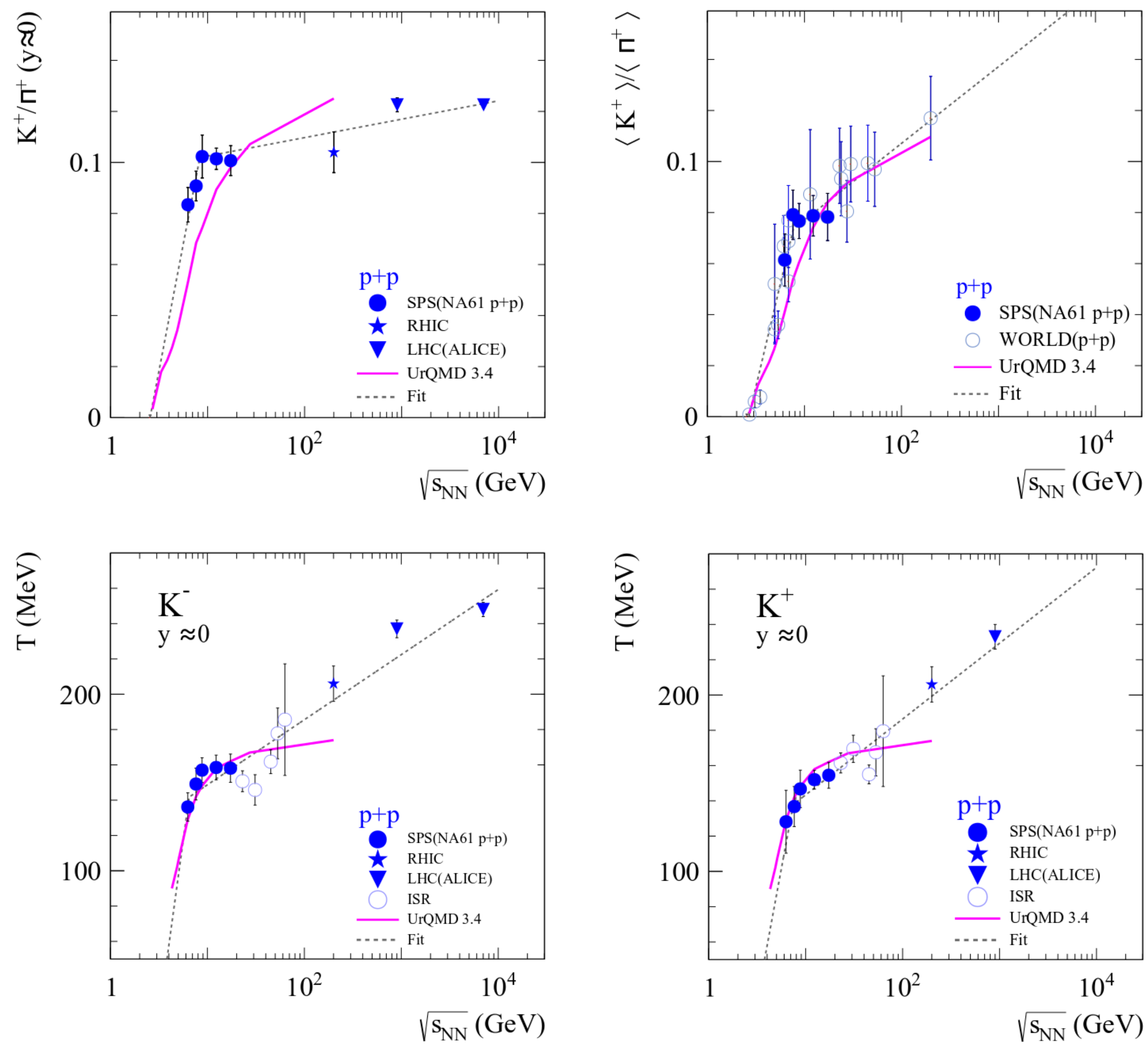


Plateau like structure visible in p+p

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

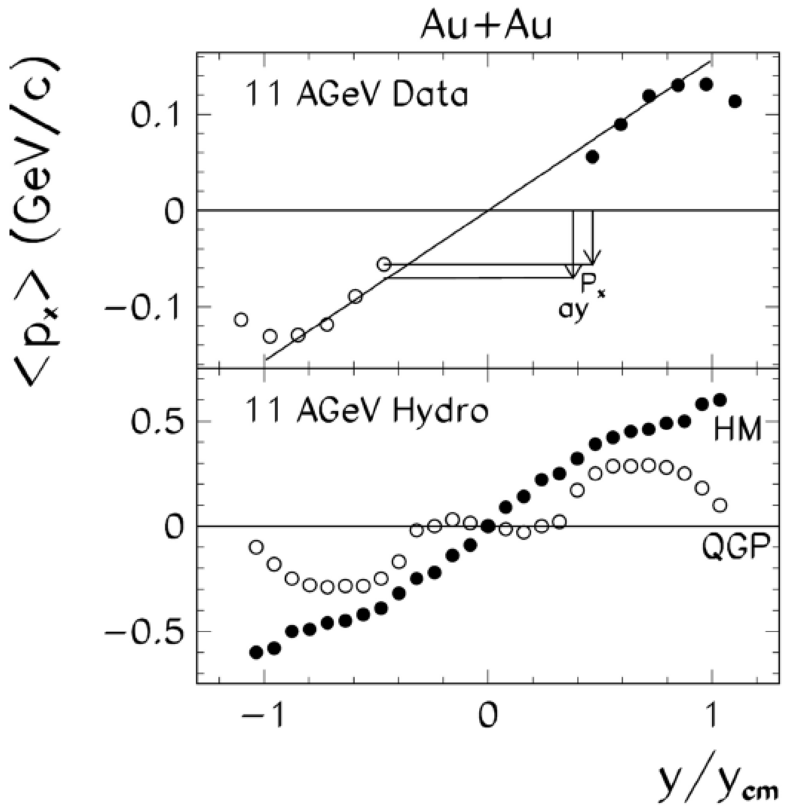
Resonance-string model (UrQMD) fails to reproduce data

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”

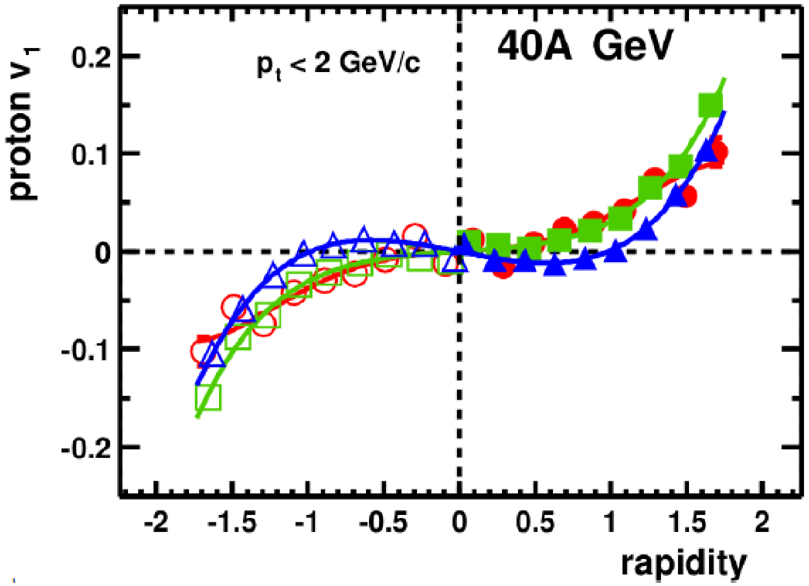
Predictions of hydrodynamical model:



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

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

Central mid-central peripheral

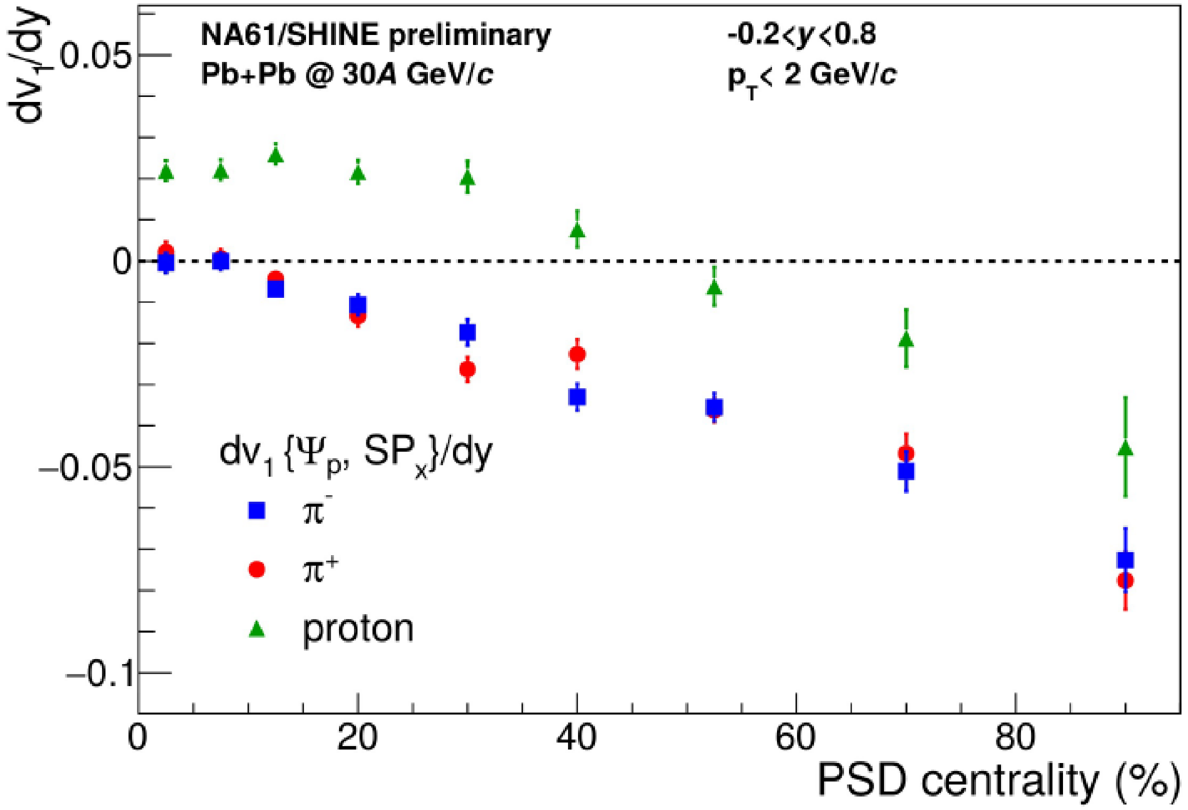


Centrality dependence of dv_1/dy in Pb+Pb at $\sqrt{s_{NN}} = 7.6$ GeV

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

NEW



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

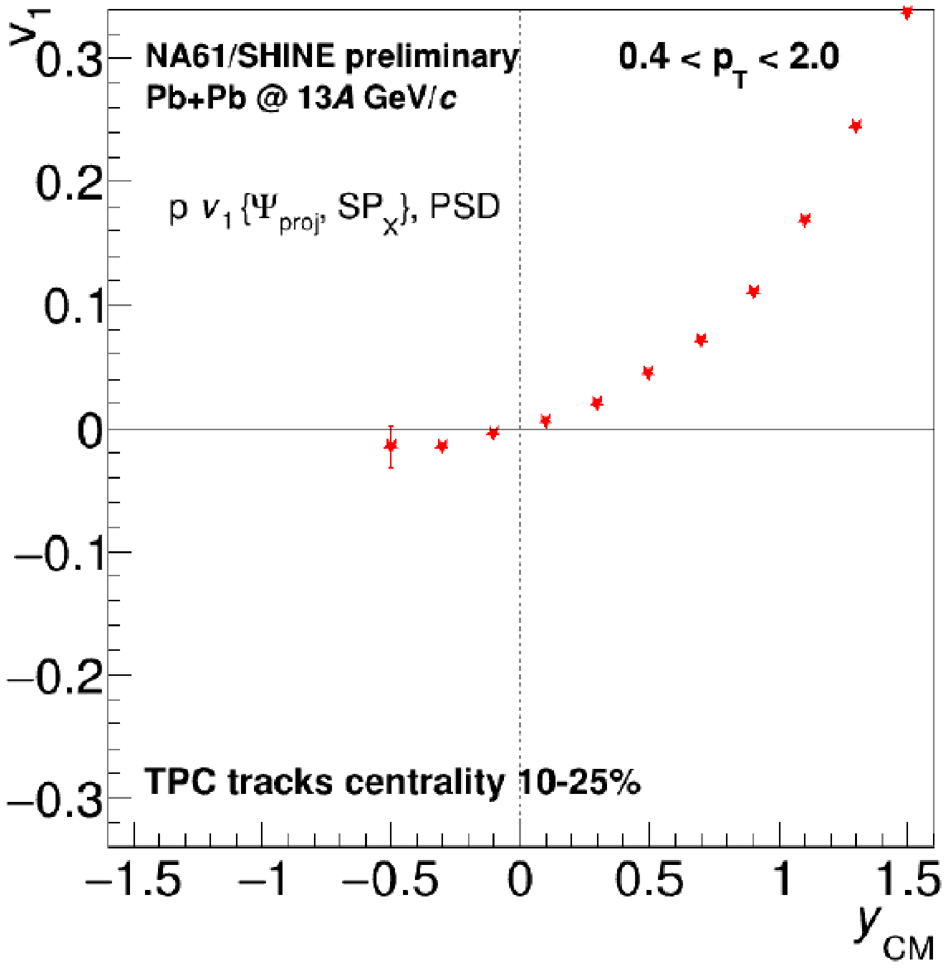
- slope of pion v_1 is negative for all centralities

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

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

Proton directed flow vs rapidity

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

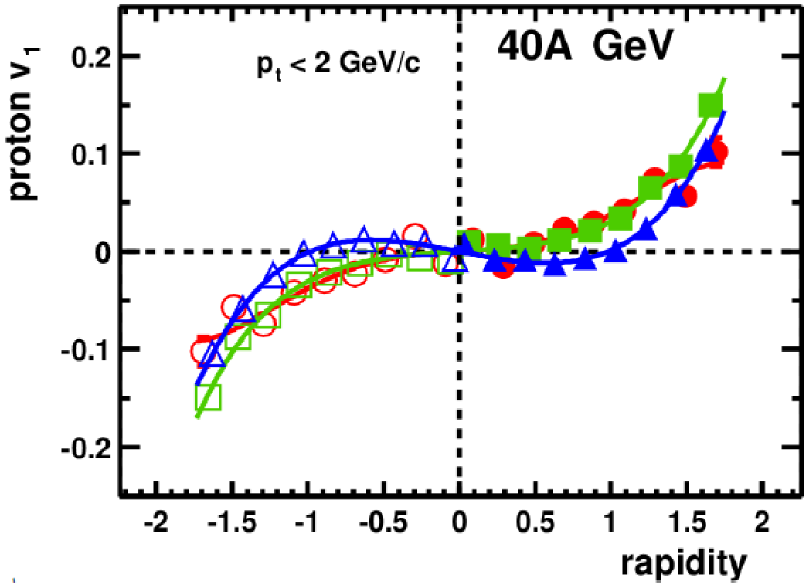


No evidence for the collapse of proton directed flow in Pb+Pb at 13*A* GeV/c

NEW

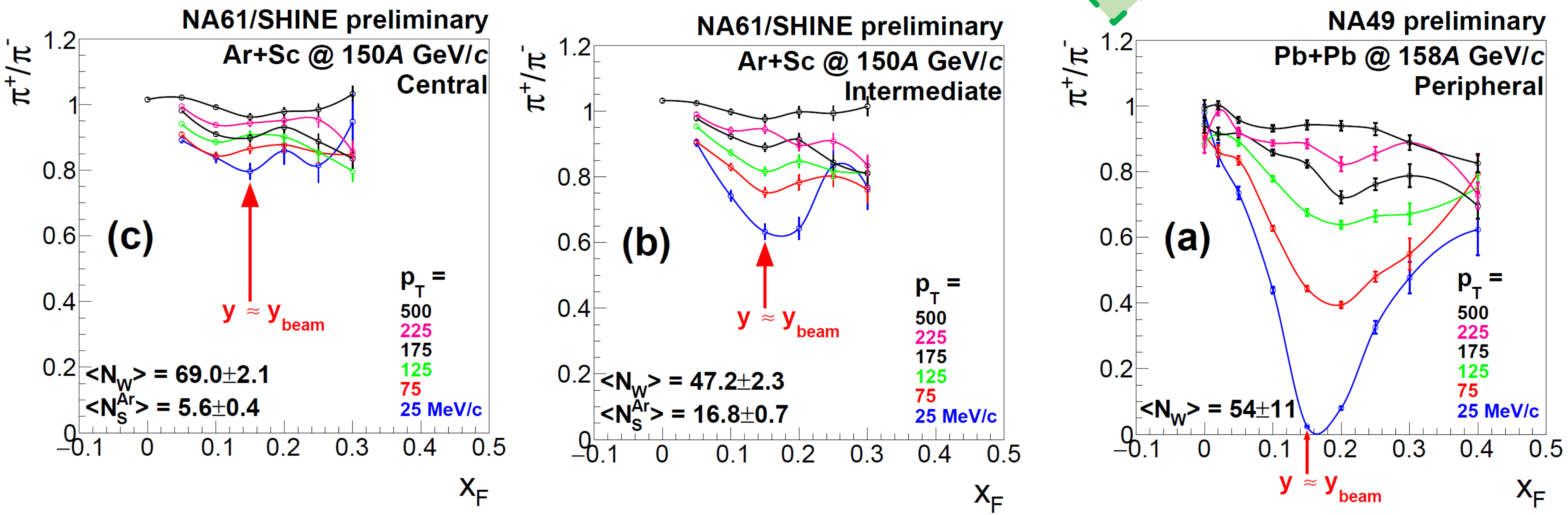
Directed flow measured by NA49 at middle SPS energy ("anti-flow" of protons at mid-rapidity):

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

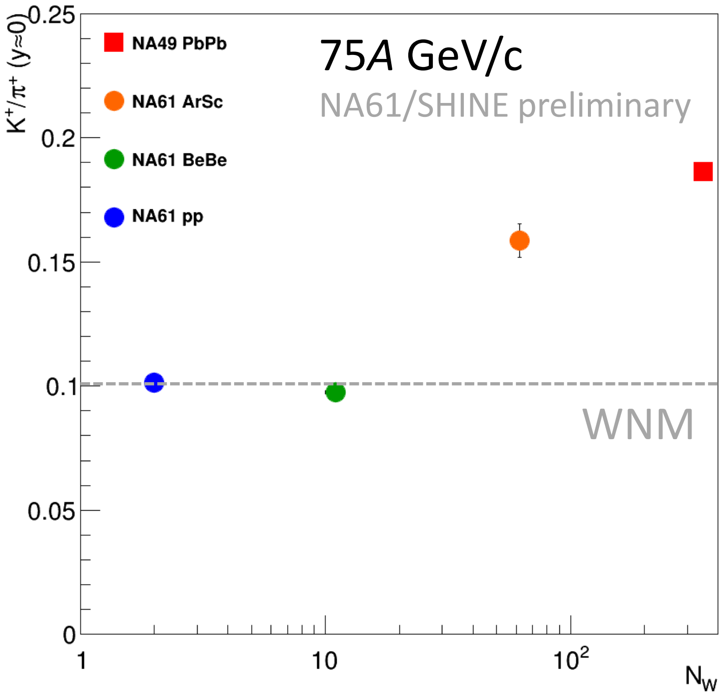
First observation of spectator induced EM effects in small systems at SPS

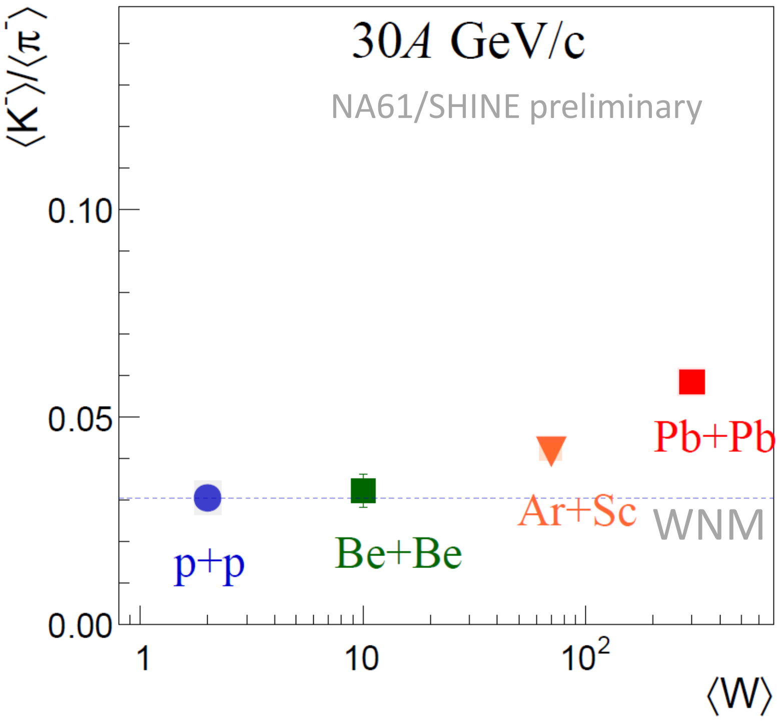
Similar effect seen in intermediate centrality Ar+Sc (NA61/SHINE) and peripheral Pb+Pb (NA49)

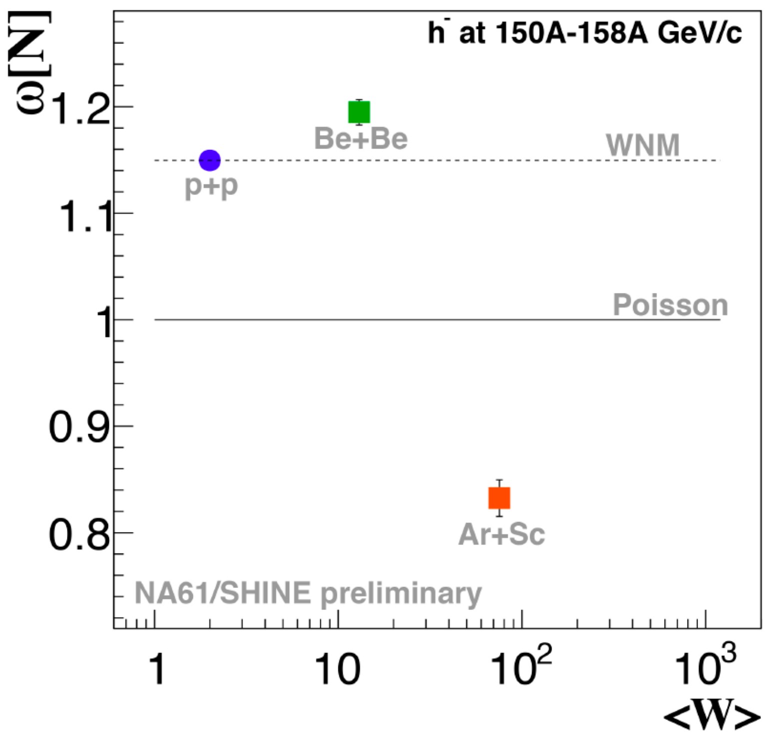
Study of the onset of fireball

Onset of fireball: system size dependence

See P. Podlaski
Tuesday







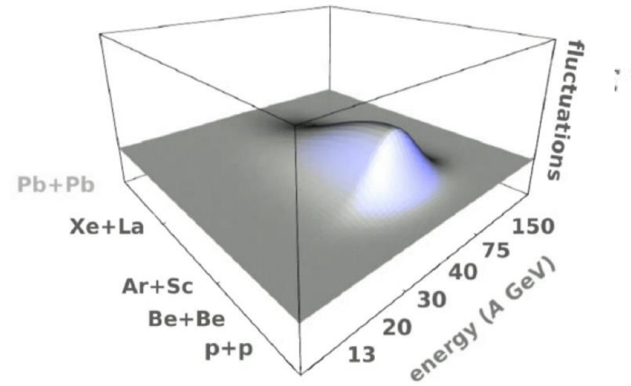
Change between

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%

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

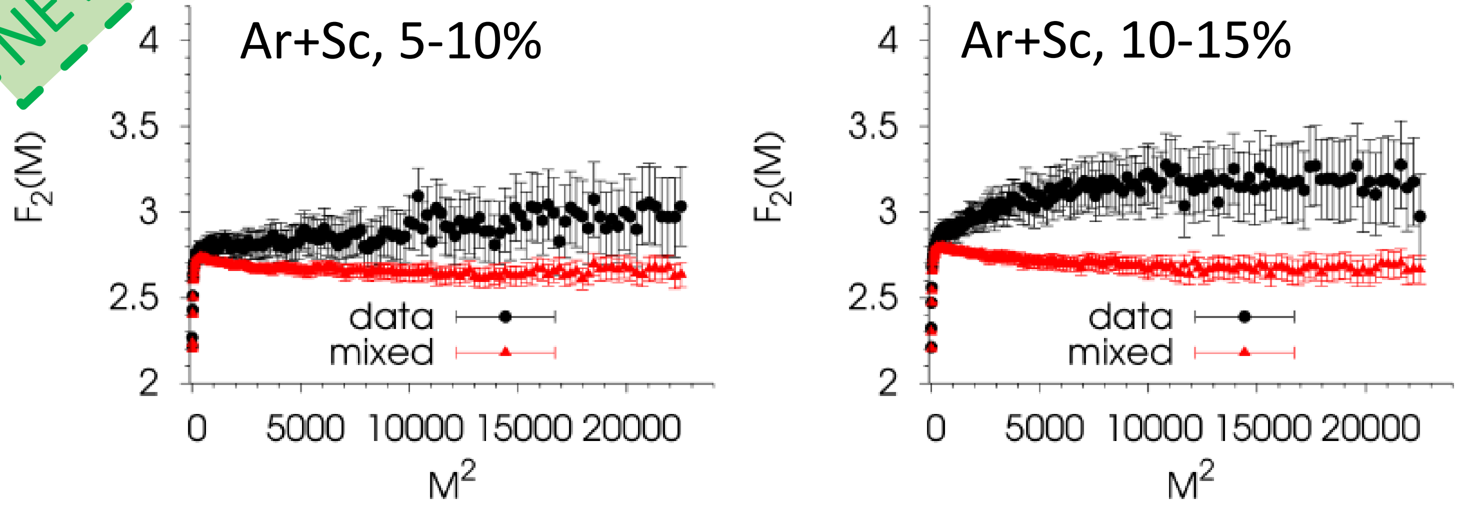
at critical point power law dependence is expected

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

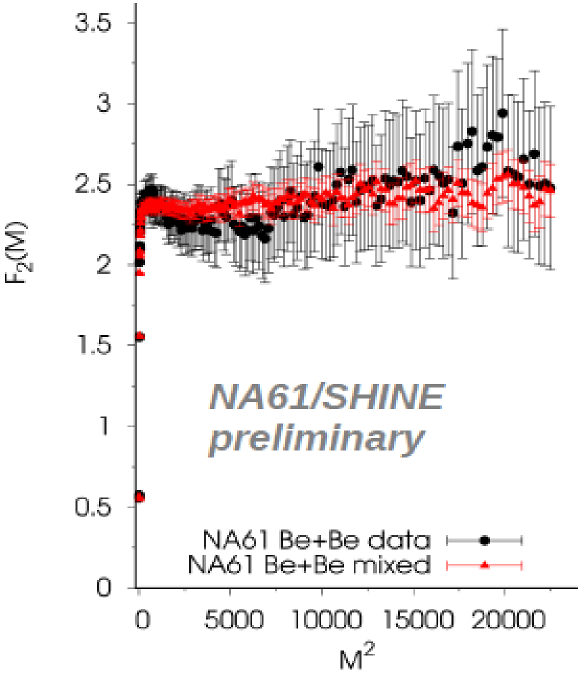
Critical point: Proton intermittency in Ar+Sc and Be+Be at 150*A* GeV/*c*

NEW

NA61/SHINE preliminary



Be+Be, 0-12%



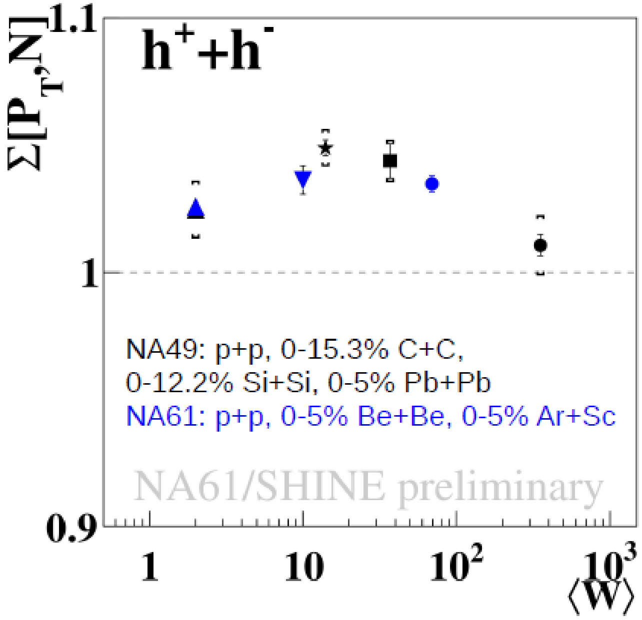
M^2 – numbers of bins in (p_x, p_y) space

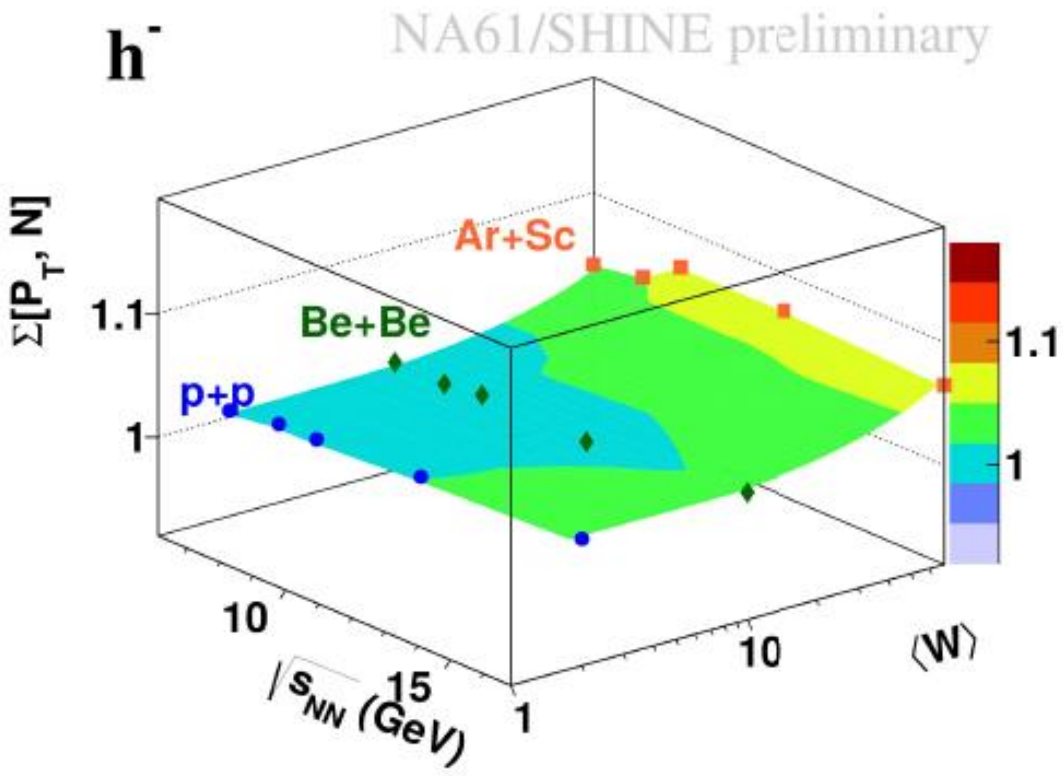
$F_2(M^2)$ moment are higher in data than in mixed events in Ar+Sc collisions - detailed investigation of significance of this result is in progress

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

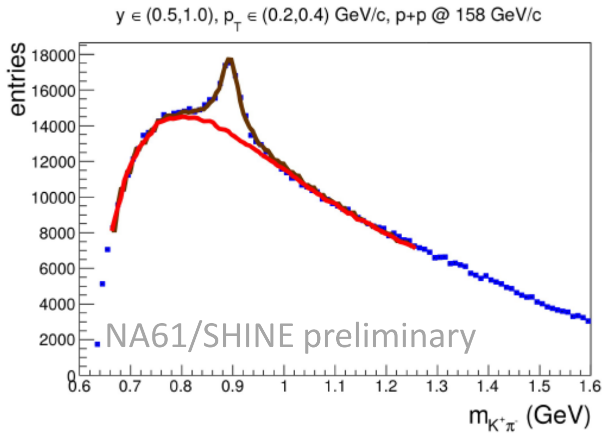
NA49: PR C92, 044905, 2015

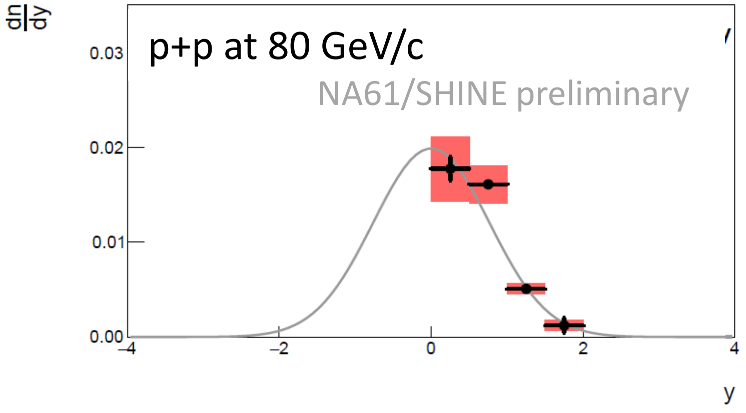
Strangeness production in p+p at 158 GeV/*c*: $K^*(892)^0$

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

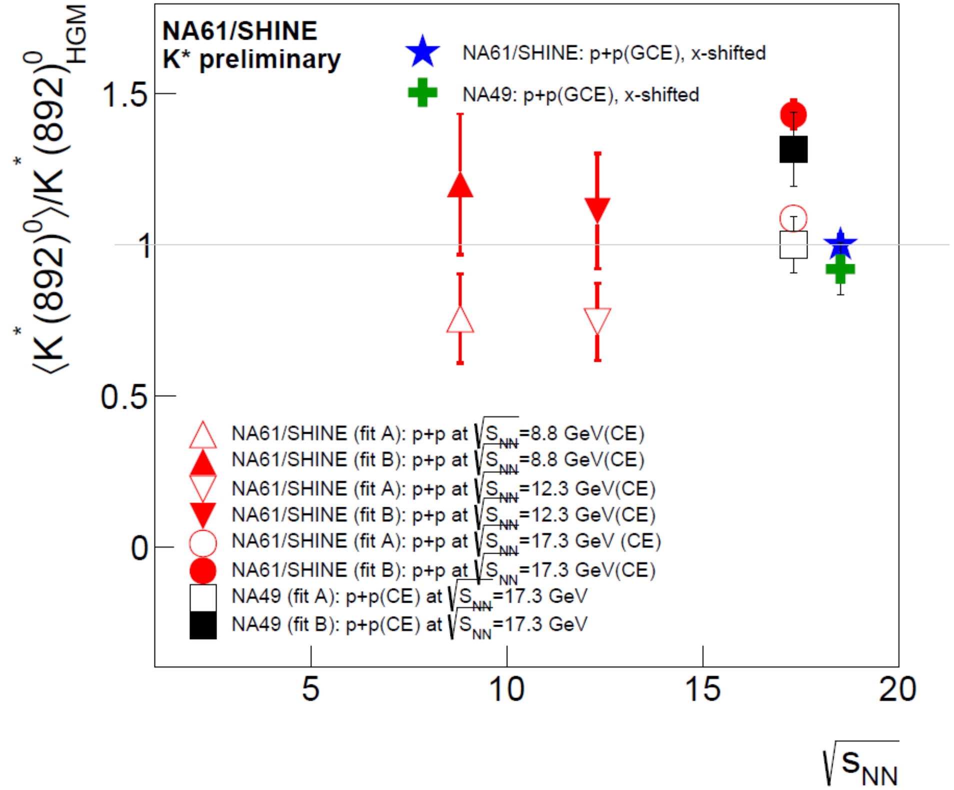
See A. Tefelska Thursday

NEW





$<K^*(892)> = 0.03812 \pm 0.00538 \pm 0.00372$



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

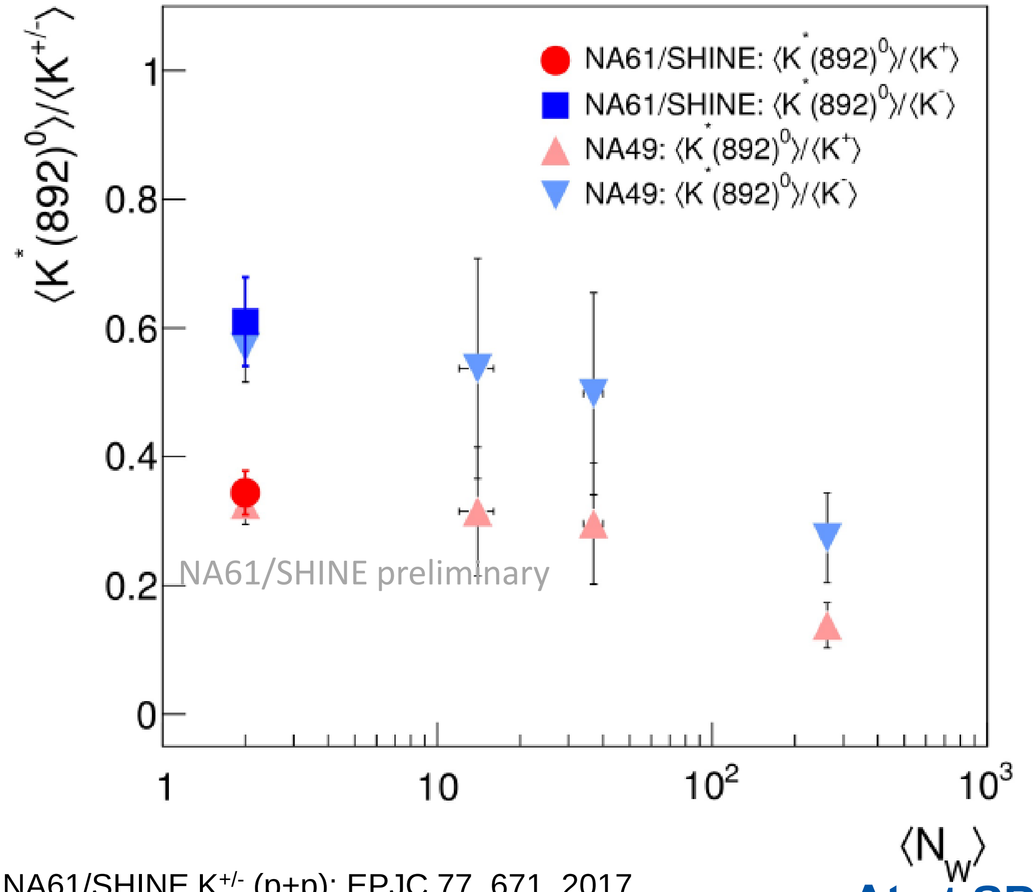
HRG by F.Becattini et al. (PR C73, 044905, 2006)

- 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*

See A. Tefelska Thursday



NEW

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

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

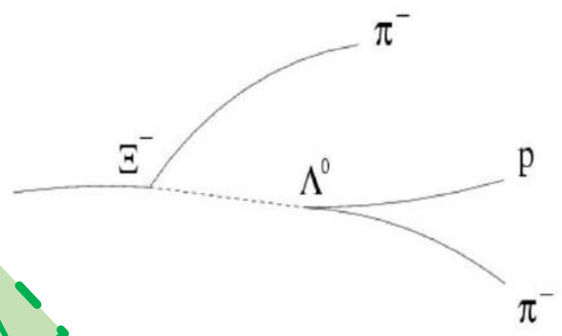
Δt at SPS > Δt at RHIC (2±1 fm/*c*, STAR, PR C71, 064902, 2005) suggesting that:

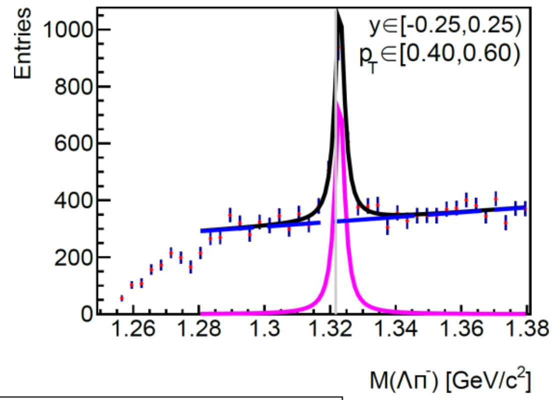
- regeneration effects play significant role for higher energies
- regeneration may happen also at SPS → obtained **Δt is the lower limit of time between freeze-outs**

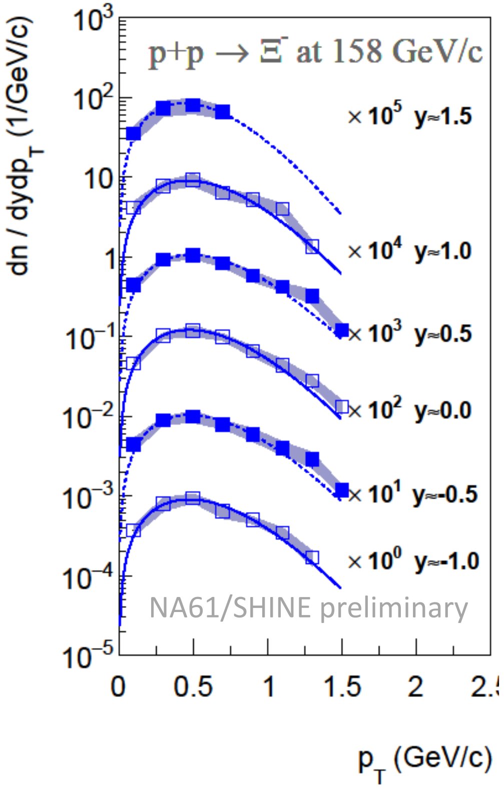
Strangeness production in p+p at 158 GeV/*c*:
Ξ production

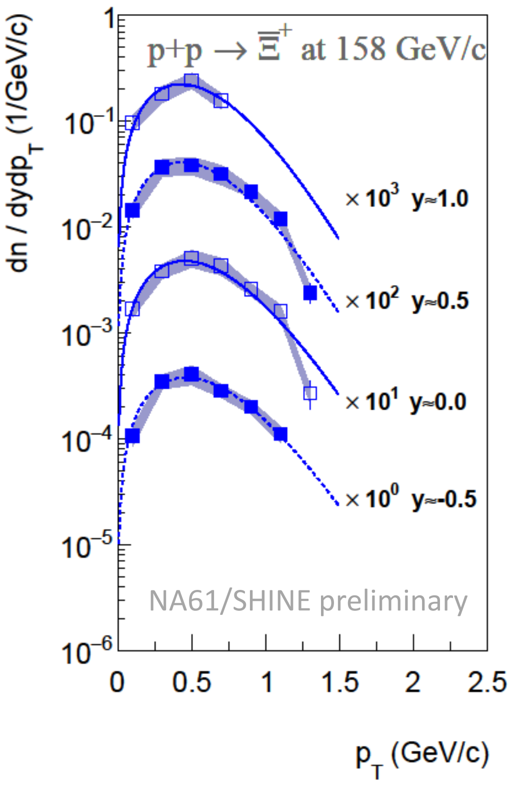
Ξ production in inelastic p+p collisions at 158 GeV/*c*

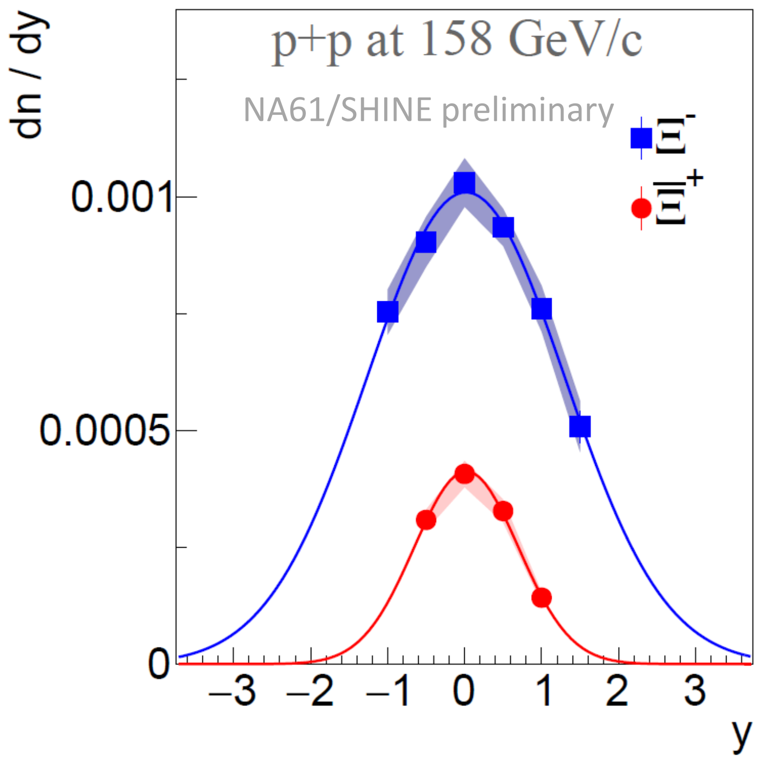
NEW





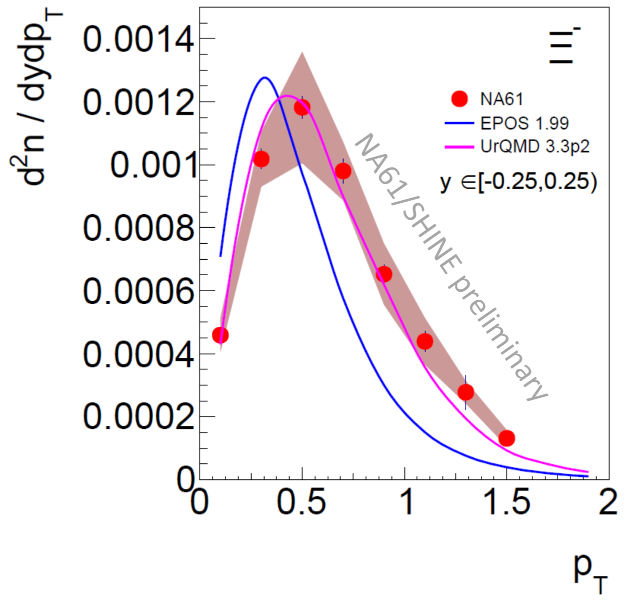


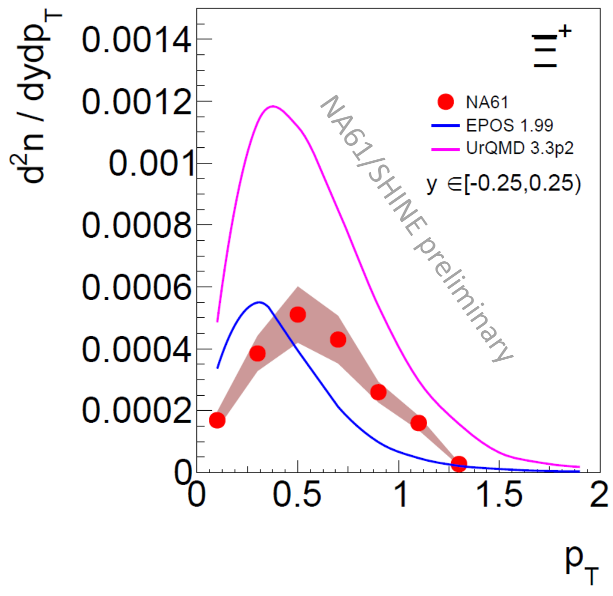


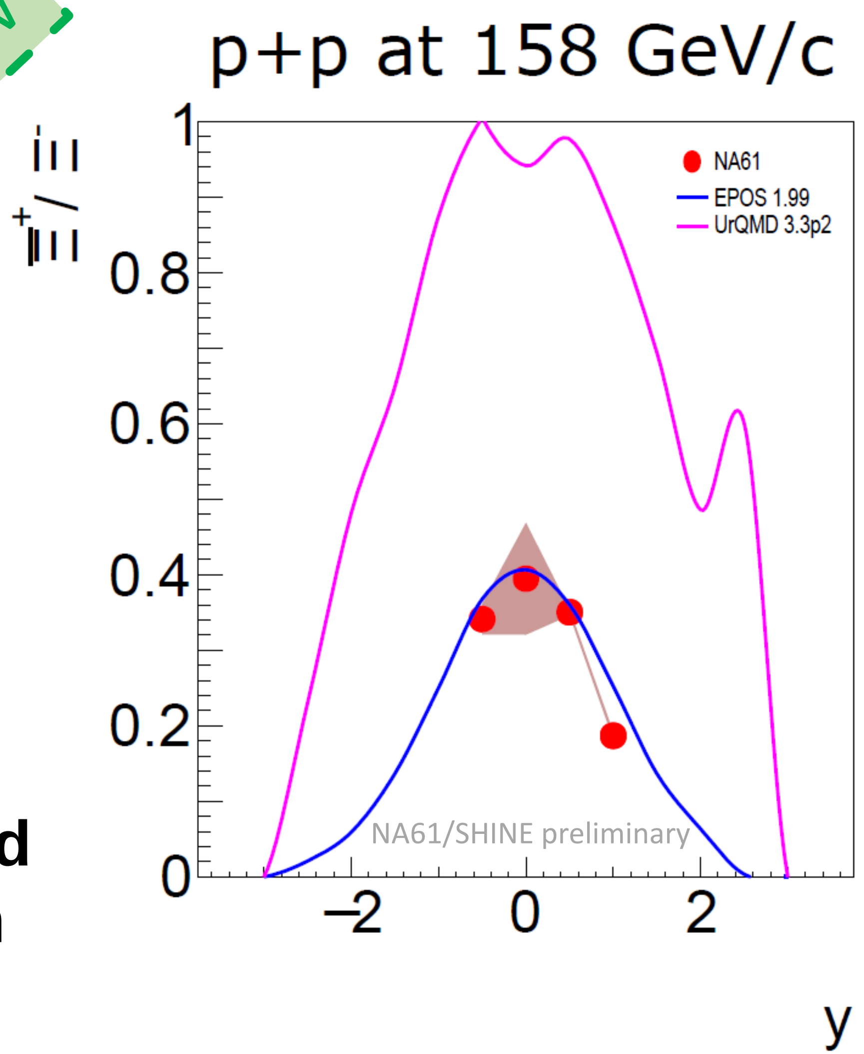


$$\langle \bar{\Xi}^+ \rangle = 0.00079 \pm 0.00002 \pm 0.00010$$
$$\langle \Xi^- \rangle = 0.0033 \pm 0.0001 \pm 0.0006$$

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







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

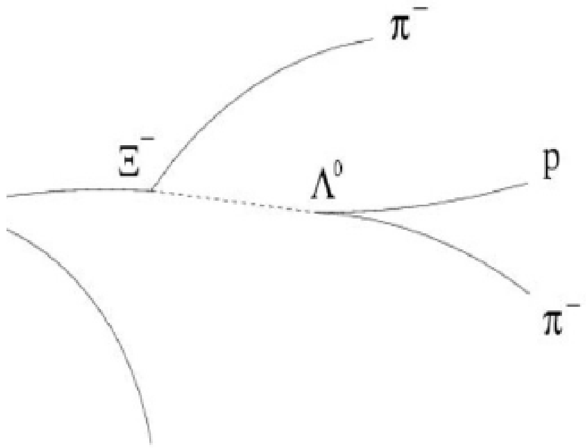
EPOS describes rapidity distributions of $\overline{\Xi}^+$, Ξ^- and their ratio, but not shape of transverse momentum spectrum.

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

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

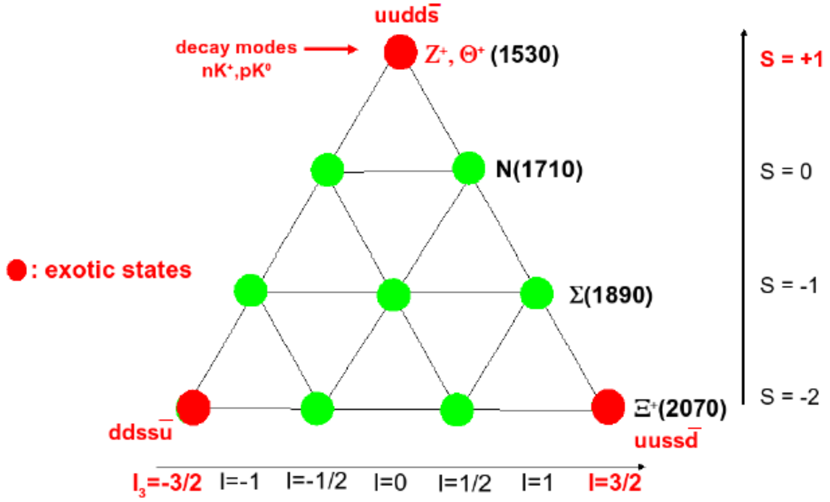
NA49 indication for Ξ^{--}(1860) pentaquark

(NA49, PRL 92, 042003, 2004)

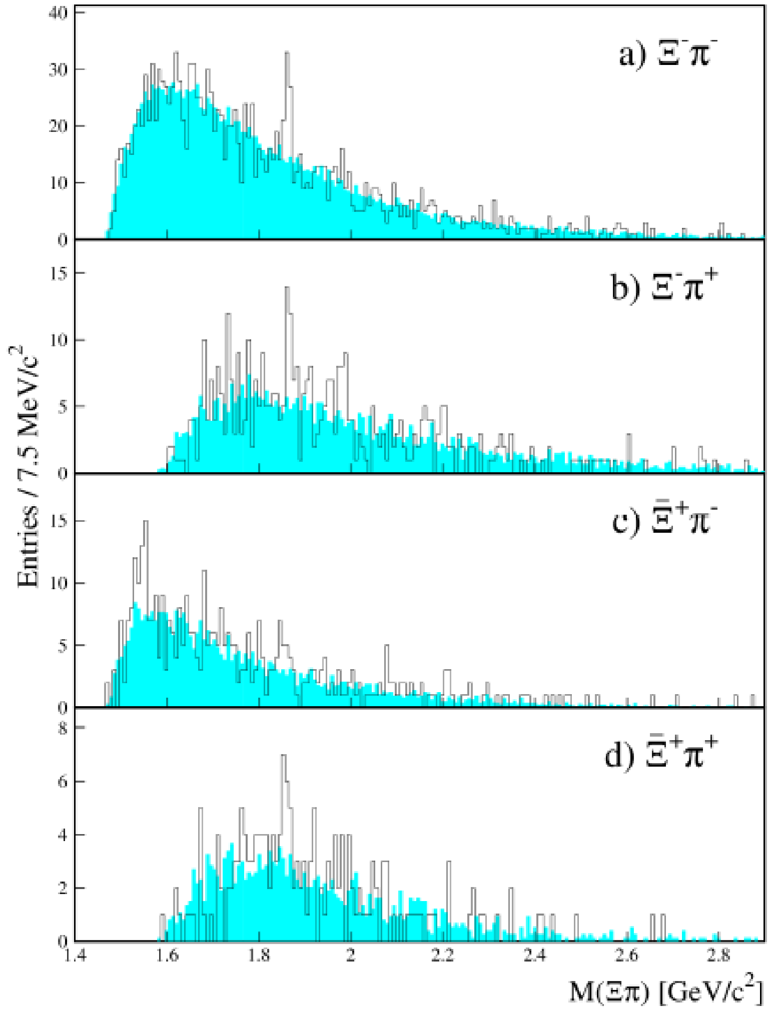


Anti-decuplet of baryons ($J^P=1/2^+$)
predicted in chiral soliton model

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

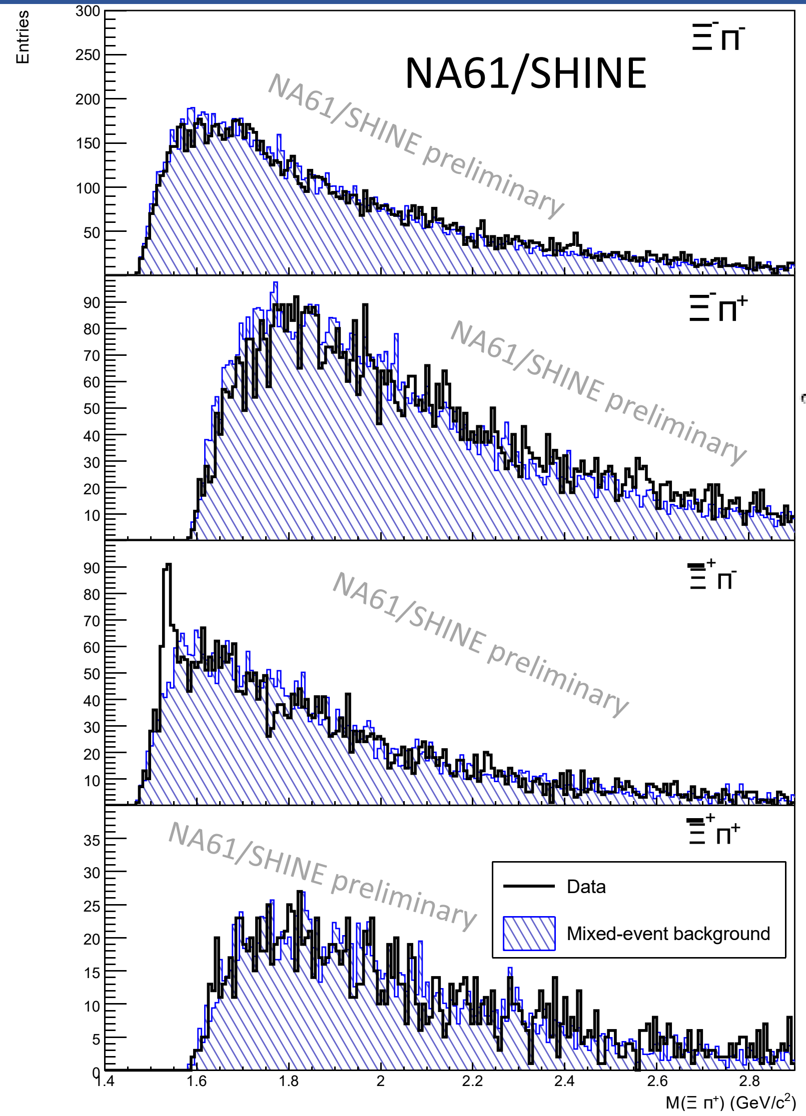


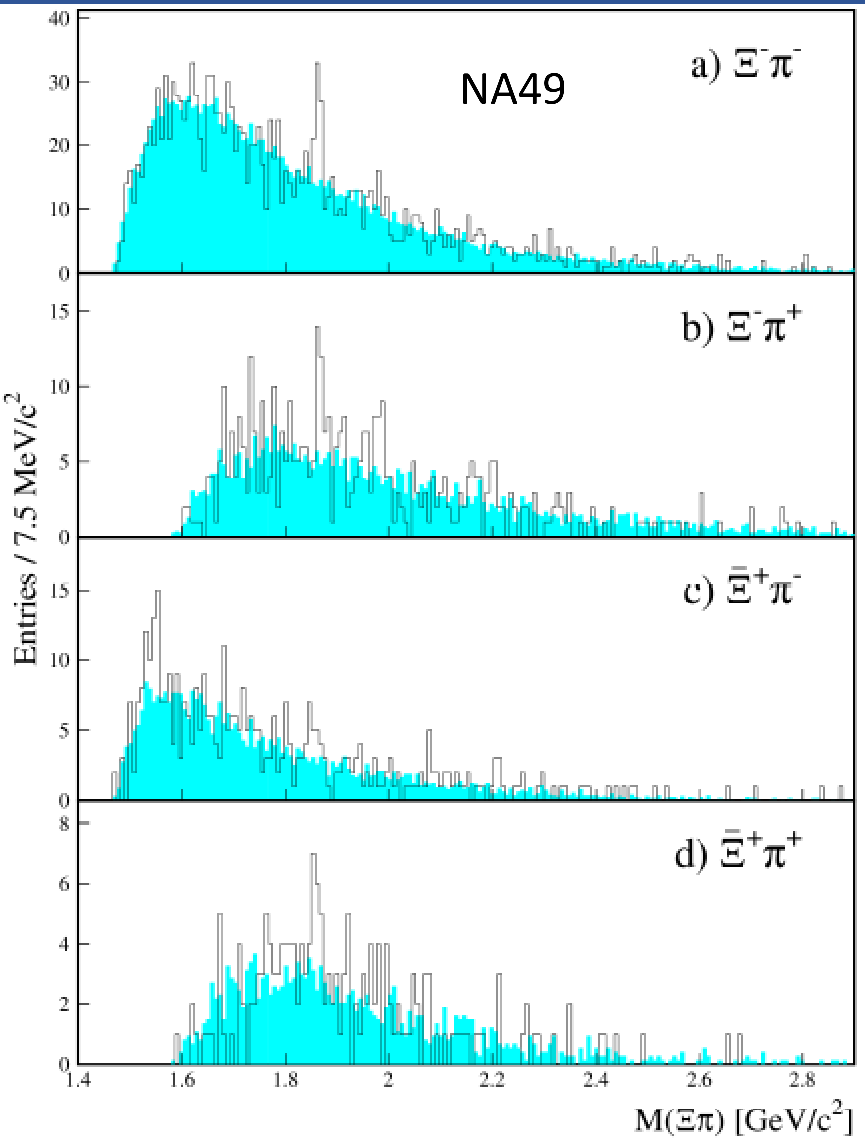
NA49
p+p at 158 GeV/c



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

NEW





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

See D. Tefelski
Thursday

Poster A. Merzlaya

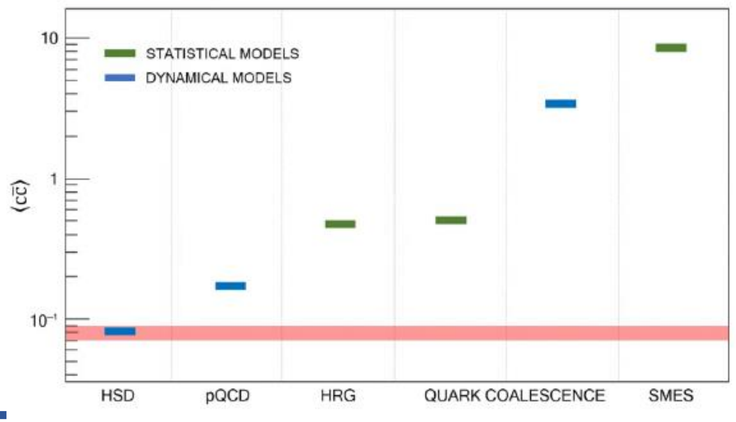
- **What is the mechanism of open charm production?**

- **How does the onset of deconfinement impact open charm production?**

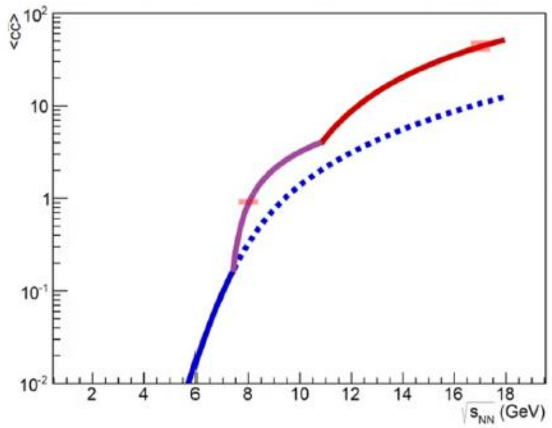
- **How does the formation of quark gluon plasma impact J/ψ production?**

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**.

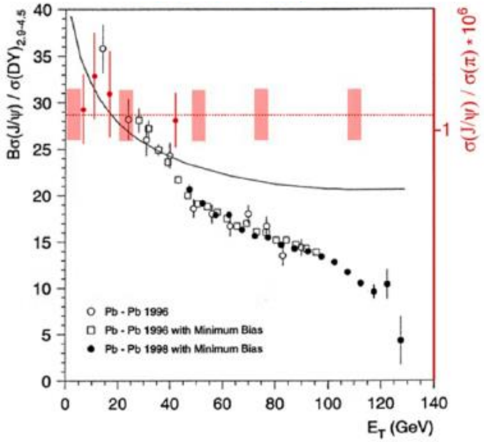
$\langle c\bar{c}\rangle$ and models



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



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



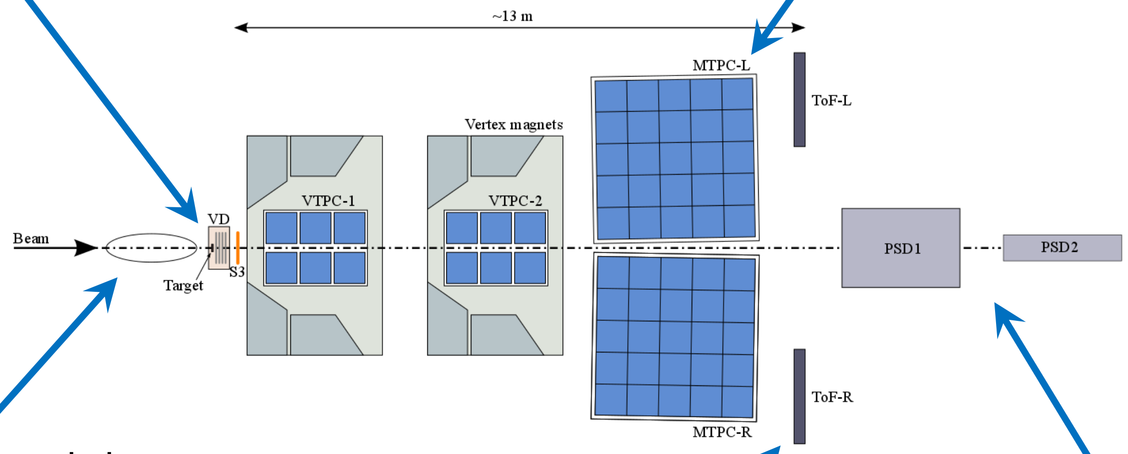
Foreseen NA61/SHINE resolution is sufficient to answer addressed questions

Detector upgrade during LS2

See D. Tefelski
Thursday

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 convincing indication of CP, proton intermittency signal in Ar+Sc is under scrutiny
- No Ξ^{--}(1860) pentaquark signal in p+p at 158 GeV/c
- Plans to extend NA61/SHINE program with measurements of open charm production in 2021-2024

BACKUP

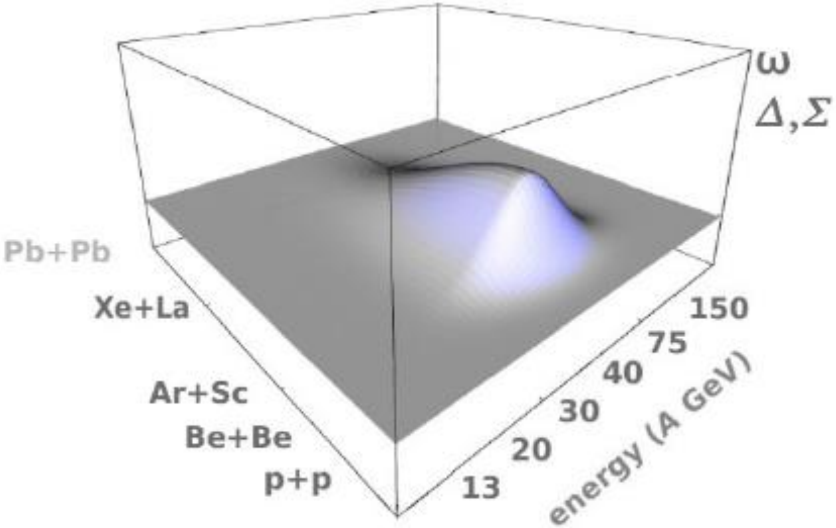
Critical point: Strongly intensive measures Δ and Σ

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

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

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

Expected: non-monotonic behavior of CP signatures



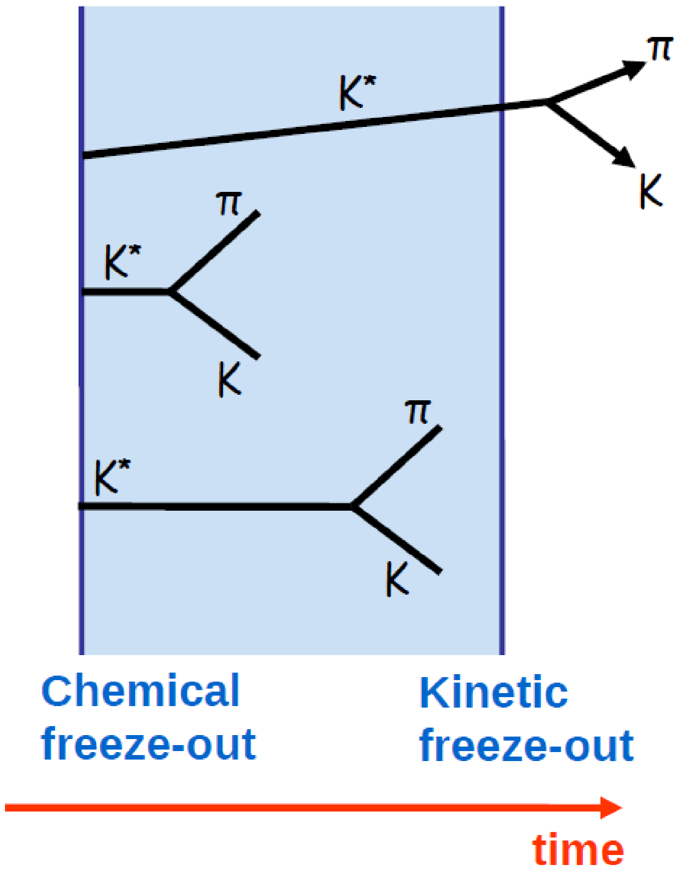
$\Delta = \Sigma = 0$ for no fluctuations

$\Delta = \Sigma = 1$ 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):

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

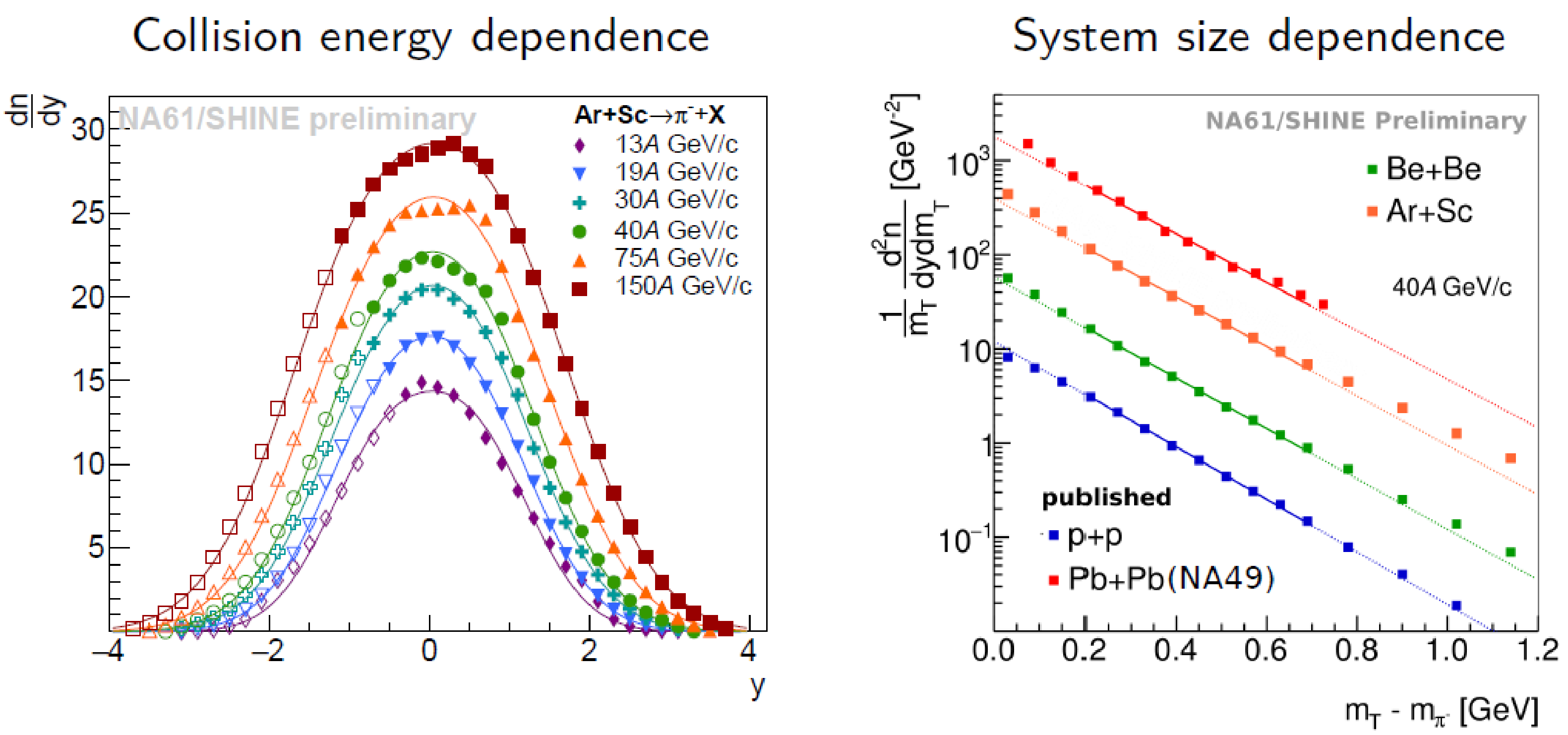
use Pb+Pb or Au+Au ratio   use p+p ratio

Δt – time between kinetic and chemical freeze-outs

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

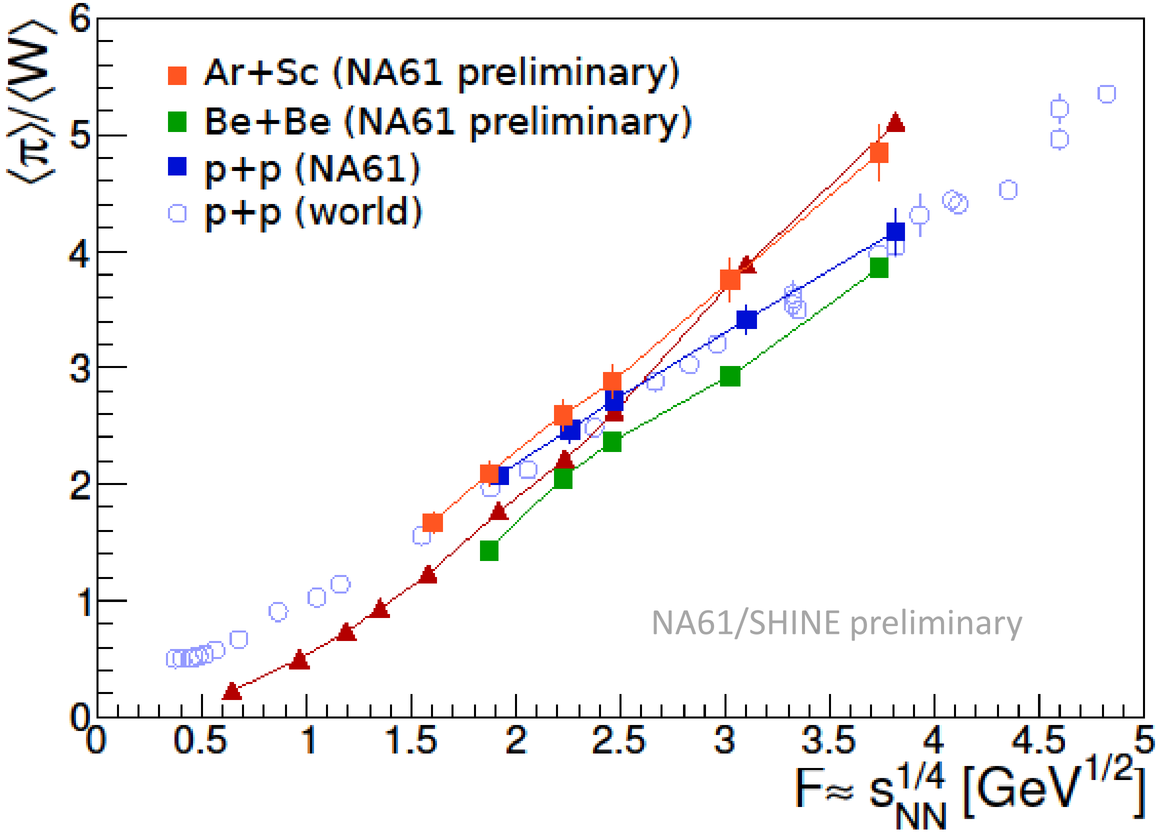
π⁻ spectra from 2D-scan

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

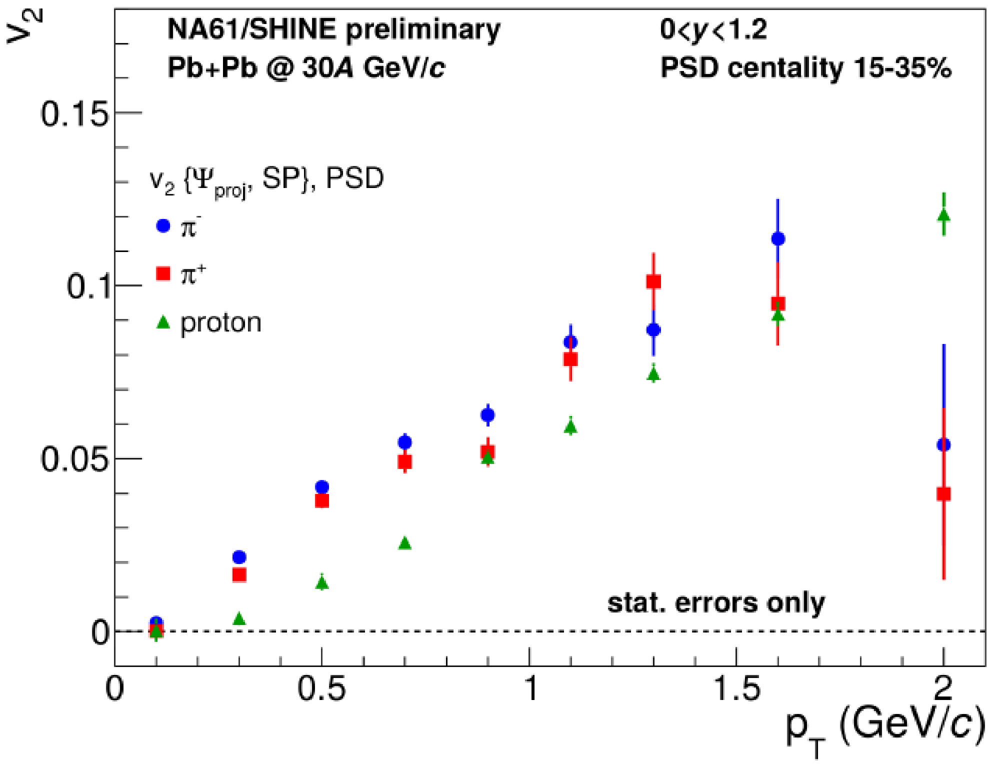


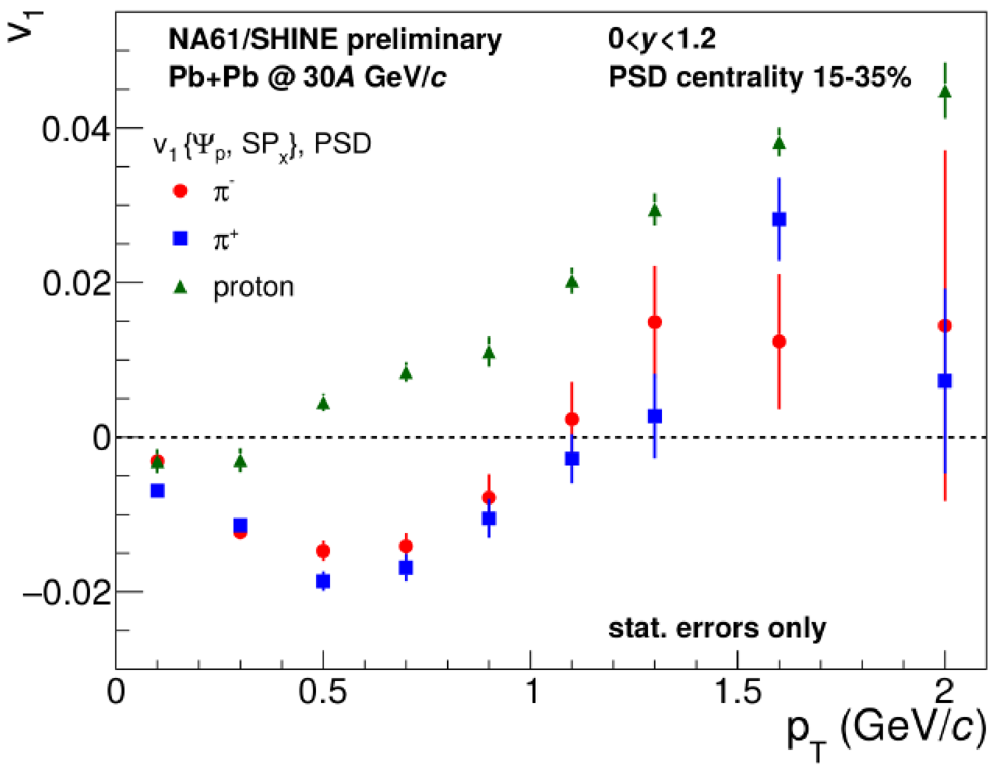
<π> – mean multiplicity in full acceptance
<W> – mean number of wounded nucleons

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





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)