



Uniwersytet  
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# PION SPECTRA IN AR+SC INTERACTIONS



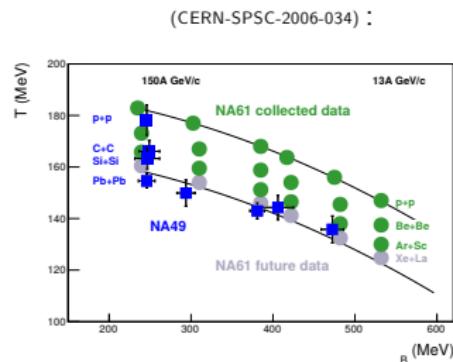
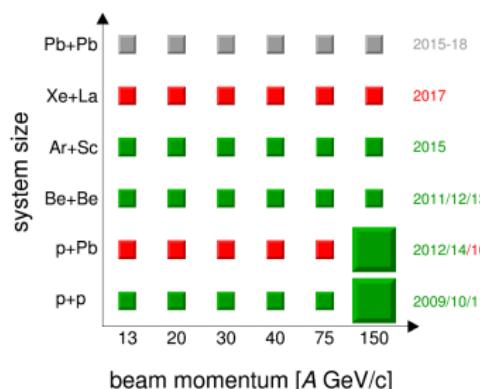
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Faculty of Physics and Astronomy  
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May 28, 2016

- ▶ The search for the **critical point** of the phase transition
- ▶ The study of the **onset of deconfinement**.

Two-dimensional scan in collision energy and the system size probes the QCD phase diagram:



This presentation focuses on the preliminary results on **Ar+Sc** collisions.

$^{40}\text{Ar} + ^{45}\text{Sc}$  energy scan:

13A, 19A, 30A, 40A, 75A, 150A GeV/c:

- ▶ Preliminary results on  $\pi^-$  produced in strong and electromagnetic processes at the primary interactions.  
Selected 0%-5% most central events.
  - Double differential spectra in **transverse momentum** ( $p_T = \sqrt{p_x^2 + p_y^2}$ ) and **rapidity** ( $y$ ).
  - Rapidity spectra.
  - **Asymmetry** of the rapidity distribution.
  - **Width** of the rapidity distribution.
  - Spectra of **transverse mass**  $m_T = \sqrt{m_{\pi^-}^2 + p_T^2}$ .
- ▶ **System size dependence** of  $\pi^-$  spectra –
  - a comparison with other systems (p+p, Be+Be, Pb+Pb).



## PRESENTED Ar+Sc DATA

- **Ar+Sc 5% most central collisions from NA61/SHINE**  
at:  $19A$ ,  $30A$ ,  $40A$ ,  $75A$  and  $150A$  GeV/c

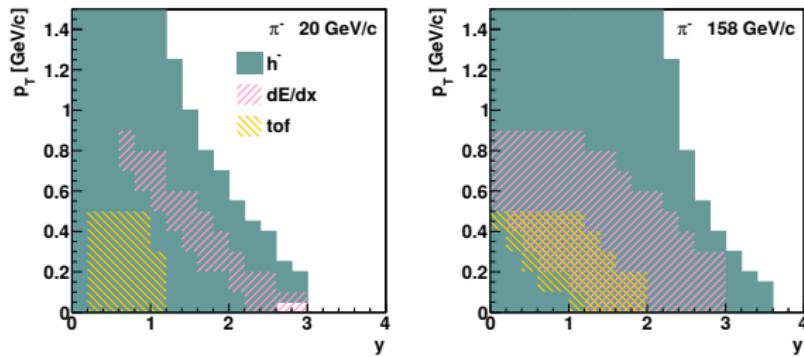
## OTHER SYSTEMS

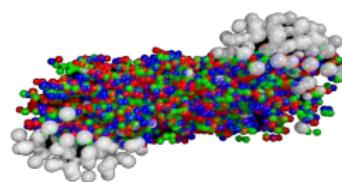
- **p+p inelastic collisions from NA61/SHINE**  
at:  $20$ ,  $31$ ,  $40$ ,  $80$  and  $158$  GeV/c  
[Eur.Phys.J. C74 (2014) 2794]
- **Be+Be 5% most central collisions from NA61/SHINE**  
at:  $19A$ ,  $30A$ ,  $40A$ ,  $75A$  and  $150A$  GeV/c  
Preliminary results: [PoS CP0D2014 (2015) 053]
- **Pb+Pb 5%-7% most central collisions from NA49**  
at:  $20A$ ,  $31A$ ,  $40A$ ,  $80A$  and  $158A$  GeV/c  
[Phys.Rev.C (2002) 66:054902; Phys.Rev.C (2008) 77:024903]

Using spectra of negatively charged hadrons for pion analysis

- ▶  $\approx 90\%$  of produced negatively charged hadrons are  $\pi^-$ .
- ▶ A small contribution of other particles ( $K^-$ ,  $\bar{p}$ , and decays from  $\Lambda$  and  $K_S^0$ ) is subtracted based on EPOS model.
- ▶ The  $dE/dx$  and tof identification methods cover much narrower region of the phase-space.

Example of coverage for p+p interactions:





- ▶ The PSD is located most downstream on the beam line and measures the projectile spectator energy  $E_F$  of the non-interacting nucleons of the beam nucleus.
- ▶ The energy measured by the PSD is used to select events classes corresponding to the collision centrality.

*For details please see Andrey Seryakov's presentation.*

## MODEL CORRECTIONS

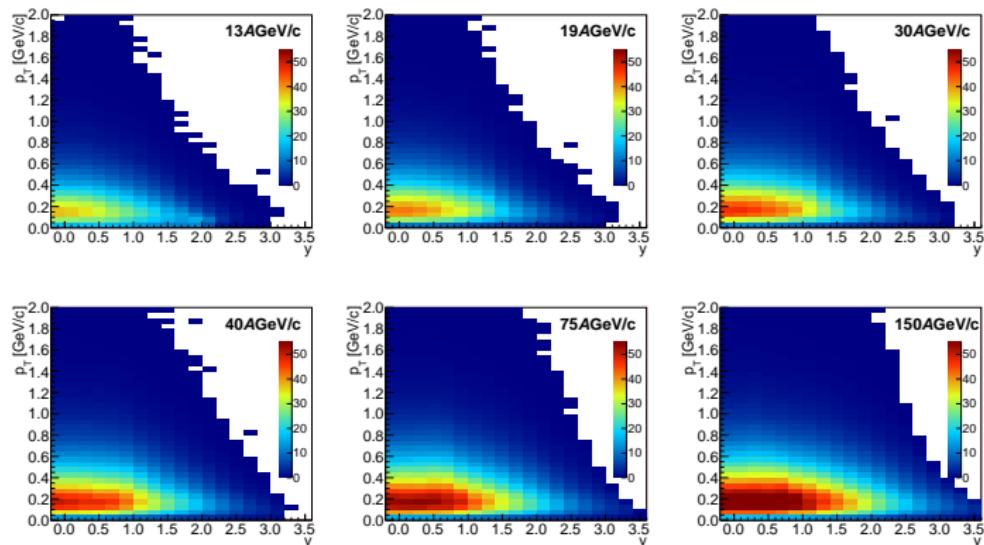
- ▶ Monte Carlo used for corrections: EPOS1.99 model (version CRMC 1.5.3), GEANT3.2.
- ▶ The centrality classes selected by the number of forward spectators.

## ERRORS

- ▶ All data points are drawn with statistical errors only. There are two sources:
  - Data uncertainties.
  - MC corrections uncertainties (insignificant).
- ▶ Based on a previous analysis for other systems (i.e. Be+Be, p+p) in NA61/SHINE, we estimate systematic errors on a level of 5%-10%.

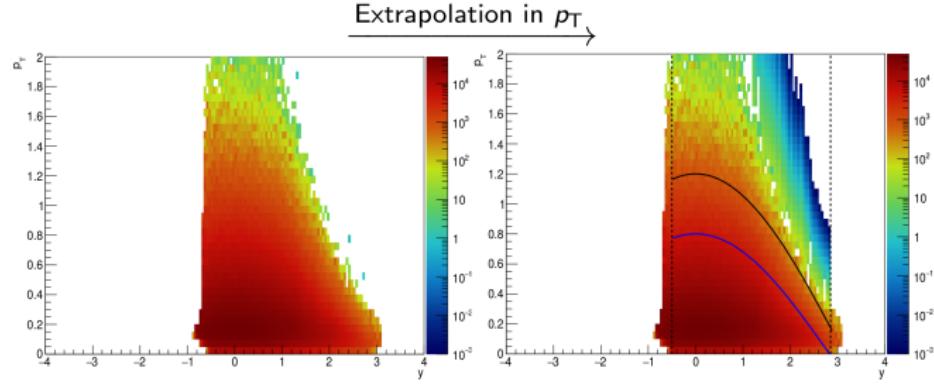
## Preliminary double differential spectra:

$$\frac{dn^2}{dy \ dp_T}$$



Measurements cover almost full acceptance in the forward rapidity.

- ▶ In order to increase the accuracy, the data is extrapolated beyond the detector acceptance.
- ▶ Exponential dependence in  $p_T$  is assumed.
- ▶ The extrapolation functions are fitted in the region between the blue and the black curve.
- ▶ The function integral from acceptance edge to  $p_T = 3.0$  is added to the rapidity bin.

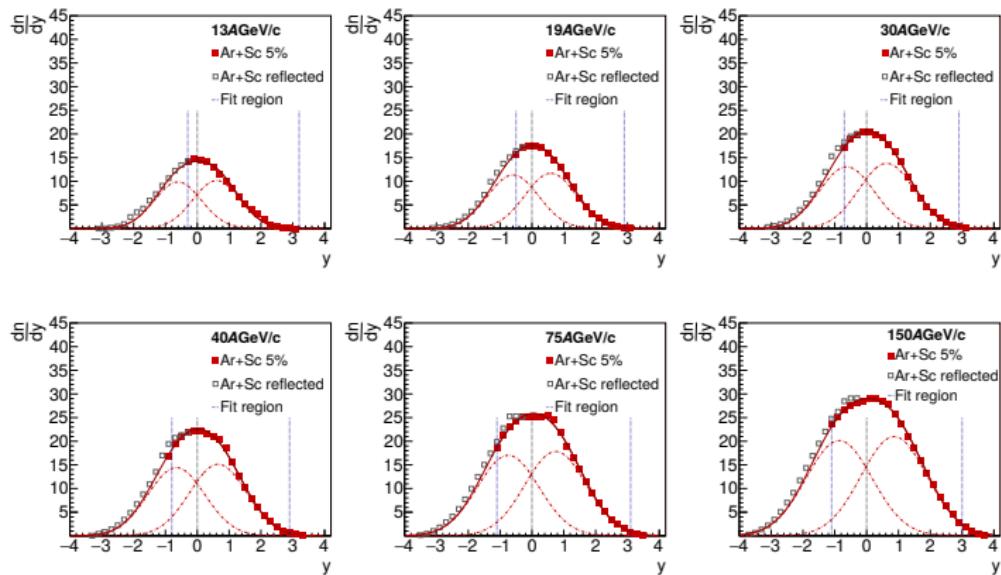


# $\pi^-$ RAPIDITY SPECTRA

## PRELIMINARY RESULTS

NA61/SHINE  
PHYSICS  
OUTLINE  
ANALYSIS METHOD  
ERRORS  
 $\pi^-$  SPECTRA

SYSTEM SIZE  
DEPENDENCE  
SUMMARY



Spectra indicate an asymmetry with respect to c.o.m. rapidity.

Preliminary results



Two symmetricaly placed gaussians, with different amplitudes, are used to construct the fitting function:

$$f_1 = \frac{A_0 A_{rel}}{\sigma_0 \sqrt{2\pi}} \exp\left(-\frac{(y - y_0)^2}{2\sigma_0^2}\right), \quad f_2 = \frac{A_0}{\sigma_0 \sqrt{2\pi}} \exp\left(-\frac{(y + y_0)^2}{2\sigma_0^2}\right)$$

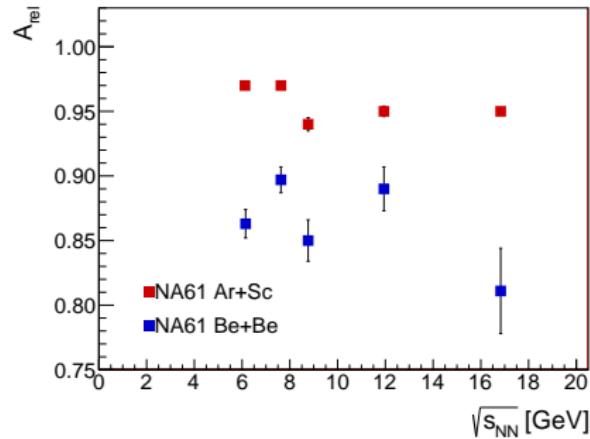
$$f_{fit} = f_1 + f_2$$

Energy	$A_0$	$A_{rel}$	$\sigma_0$	$y_0$	$\sigma$
13. A GeV/c	$18.61 \pm 0.019$	$0.97 \pm 0.0002$	$0.60 \pm 0.0014$	$0.72 \pm 0.0010$	$0.94 \pm 0.043$
19. A GeV/c	$23.59 \pm 0.017$	$0.97 \pm 0.0036$	$0.59 \pm 0.0018$	$0.80 \pm 0.0016$	$0.99 \pm 0.049$
30. A GeV/c	$29.78 \pm 0.049$	$0.94 \pm 0.0051$	$0.62 \pm 0.0026$	$0.86 \pm 0.0018$	$1.06 \pm 0.053$
40. A GeV/c	$33.88 \pm 0.045$	$0.95 \pm 0.0040$	$0.65 \pm 0.0021$	$0.89 \pm 0.0016$	$1.10 \pm 0.048$
75. A GeV/c	$43.09 \pm 0.034$	$0.95 \pm 0.0021$	$0.74 \pm 0.0013$	$0.96 \pm 0.0012$	$1.21 \pm 0.038$
150. A GeV/c	$54.39 \pm 0.040$	$0.96 \pm 0.0019$	$0.86 \pm 0.0011$	$1.03 \pm 0.0013$	$1.34 \pm 0.036$

Where  $\sigma = \sqrt{\sigma_0^2 + y_0^2}$ .

DISTRIBUTION ASYMMETRY  
PRELIMINARY RESULTS

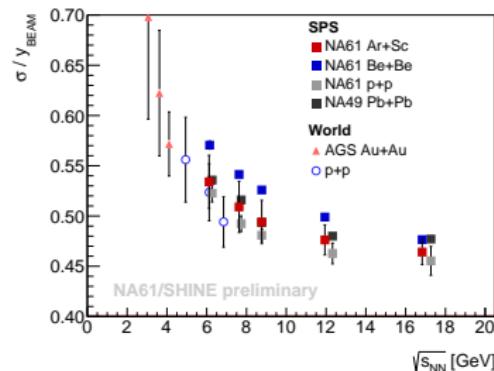
NA61/SHINE  
PHYSICS  
OUTLINE  
ANALYSIS METHOD  
ERRORS  
 $\pi^-$  SPECTRA  
SYSTEM SIZE  
DEPENDENCE  
SUMMARY



Two opposite effects influence the asymmetry of the spectra:

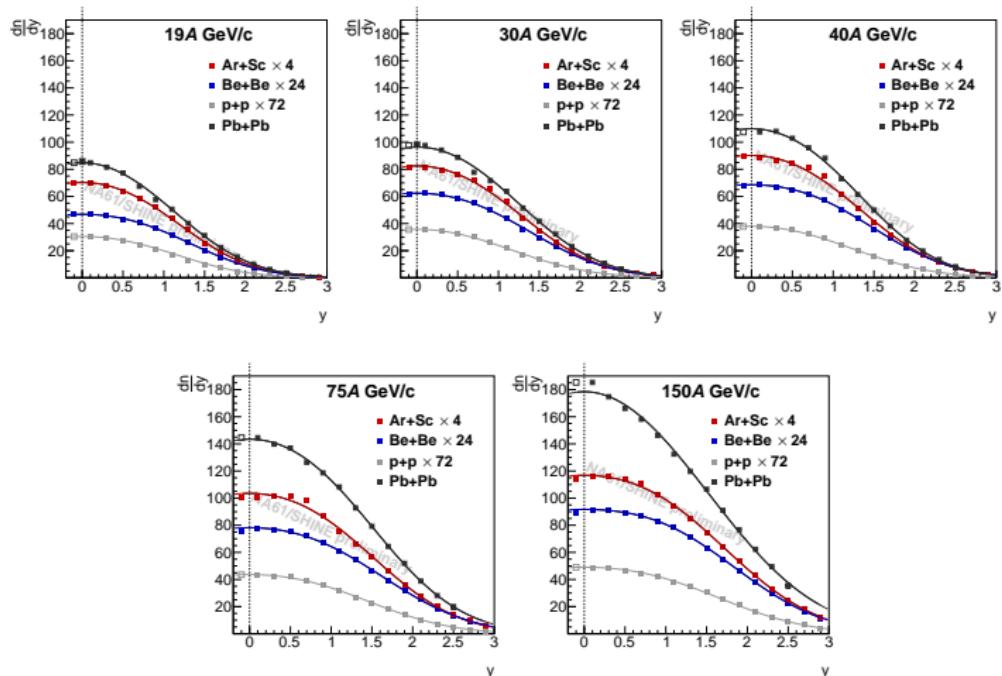
- ▶ Asymmetric system –  $^{40}\text{Ar}$  projectile on  $^{45}\text{Sc}$  target (small effect,  $> 1$ ).
- ▶ Centrality selection based on projectile spectators (large effect,  $< 1$ ).

Preliminary results



- ▶ The width  $\sigma$  shows monotonic behavior with increasing energy.
- ▶ Non-monotonic behavior is observed in dependence on the system size: 
$$\frac{\sigma_y(p+p)}{y_{beam}} < \frac{\sigma_y(Ar+Sc)}{y_{beam}} \approx \frac{\sigma_y(Pb+Pb)}{y_{beam}} < \frac{\sigma_y(Be+Be)}{y_{beam}}$$
- ▶ Shown p+p collisions are uncorrected for isospin effects.

NA61/SHINE p+p results published in Eur.Phys.J. C74 (2014) 2794



*Lines to guide the eye*

Preliminary results

# $\pi^-$ RAPIDITY SPECTRA

## RATIO TO $p + p$ COLLISIONS

NA61/SHINE  
PHYSICS

OUTLINE

ANALYSIS METHOD

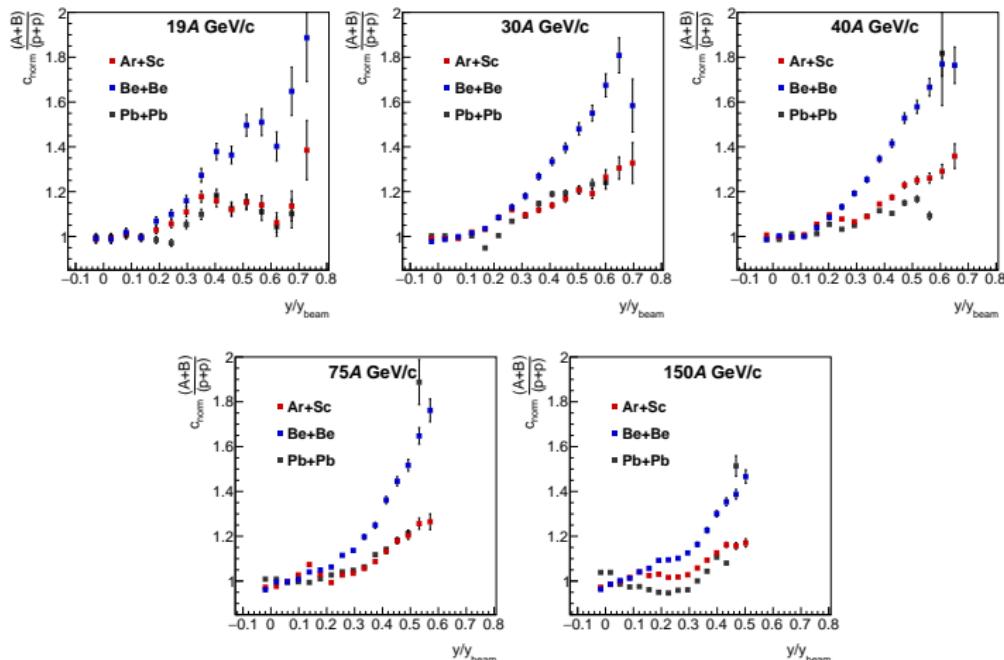
ERRORS

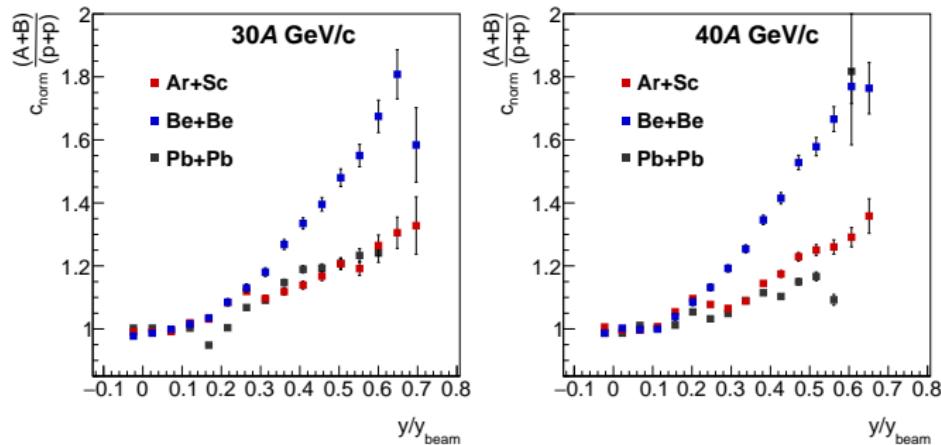
 $\pi^-$  SPECTRASYSTEM SIZE  
DEPENDENCE

SUMMARY

Normalized  $\frac{dn}{dy}$  spectra divided by the normalized  $\frac{dn}{dy}$  data on  $p+p$  inelastic interactions.

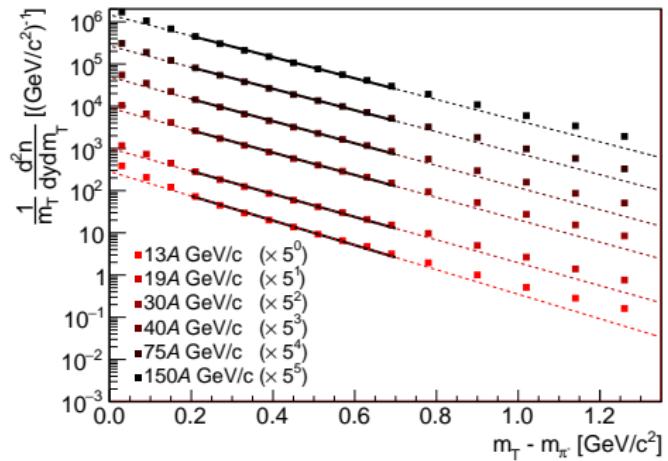
"Normalized" – divided by integral in  $y \in (0.0, 0.5)$ .





- ▶ The spectrum shape for **Ar+Sc** interactions is resembling very closely **Pb+Pb** spectrum.
- ▶ **Ar+Sc** spectra differ significantly from the ones for **Be+Be**.

Preliminary results



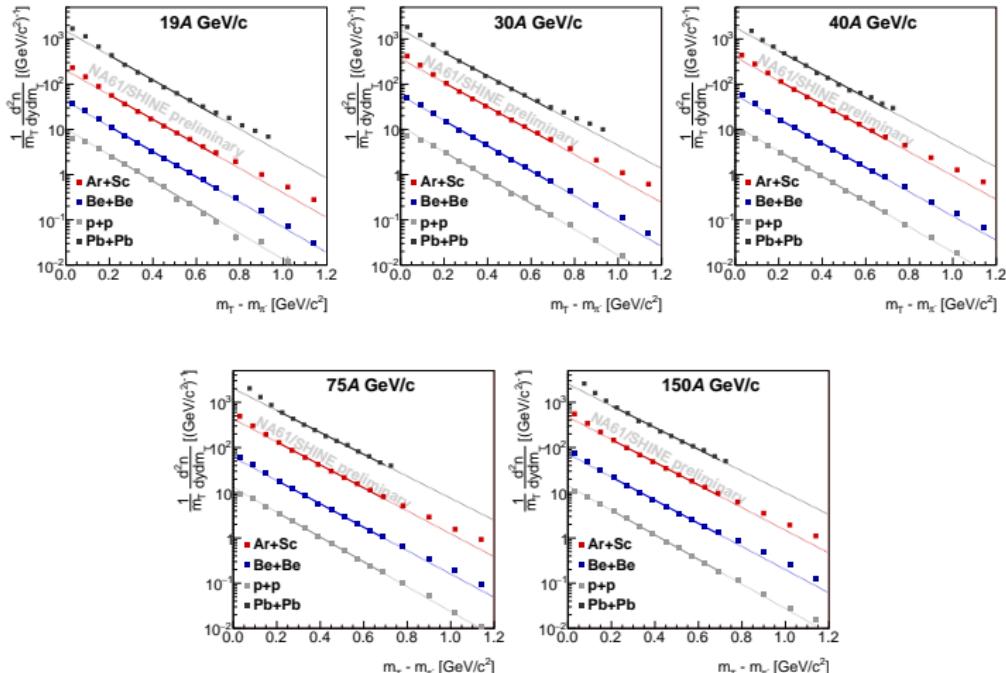
- ▶ The  $m_T$  spectra are scaled by an arbitrary constant for a better clarity of the plot.
- ▶ Indications of the radial flow in high  $m_T$ .

Preliminary results

# $m_T$ SPECTRA – SYSTEM SIZE DEPENDENCE

MIDRAPIDITY: ( $y \in (-0.2; 0.2)$ )

NA61/SHINE  
PHYSICS  
OUTLINE  
ANALYSIS METHOD  
ERRORS  
 $\pi^-$  — SPECTRA  
 SYSTEM SIZE  
DEPENDENCE  
 SUMMARY



Preliminary results

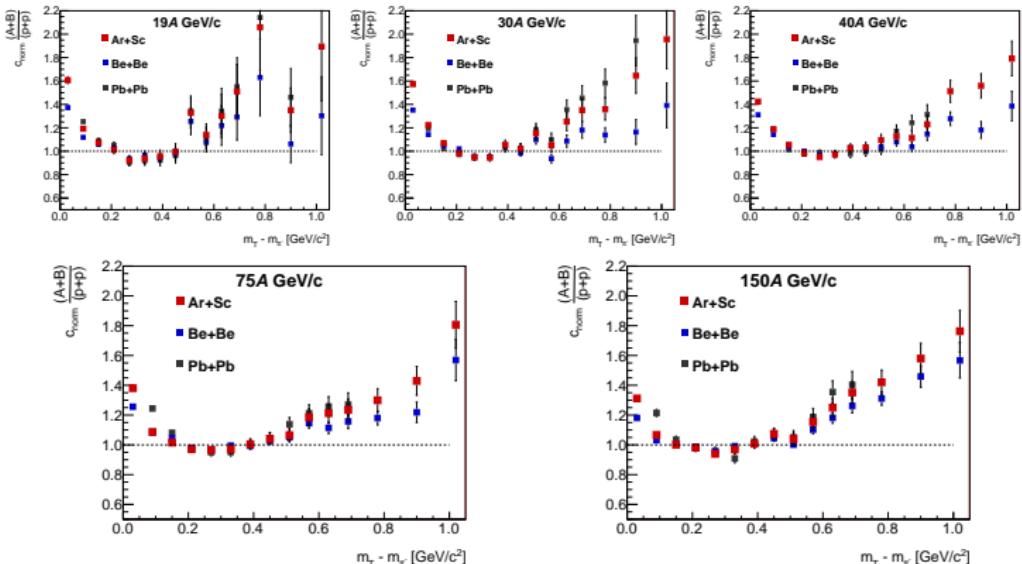
# $m_T$ SPECTRA – RATIO TO $p + p$ COLLISIONS

MIDRAPIDITY: ( $y \in (-0.2; 0.2)$ )

NA61/SHINE  
PHYSICS  
OUTLINE  
ANALYSIS METHOD  
ERRORS  
 $\pi^-$  SPECTRA  
SYSTEM SIZE  
DEPENDENCE  
SUMMARY

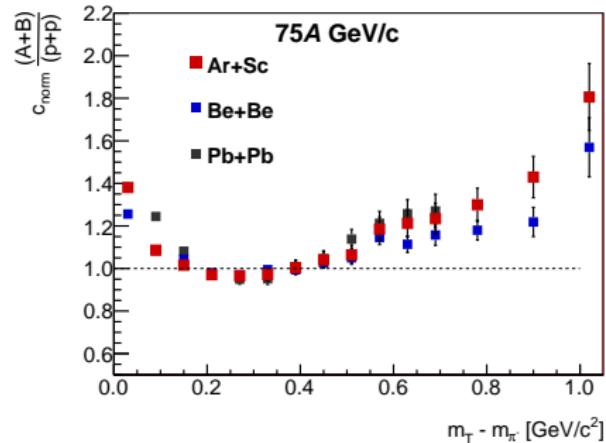
Normalized ion spectra divided by the normalized  $p+p$  data.

"Normalized" – divided by integral in  $(m_T - m_{\pi^-}) \in (0.2, 0.7)$ .



Various systems for each collision momentum.

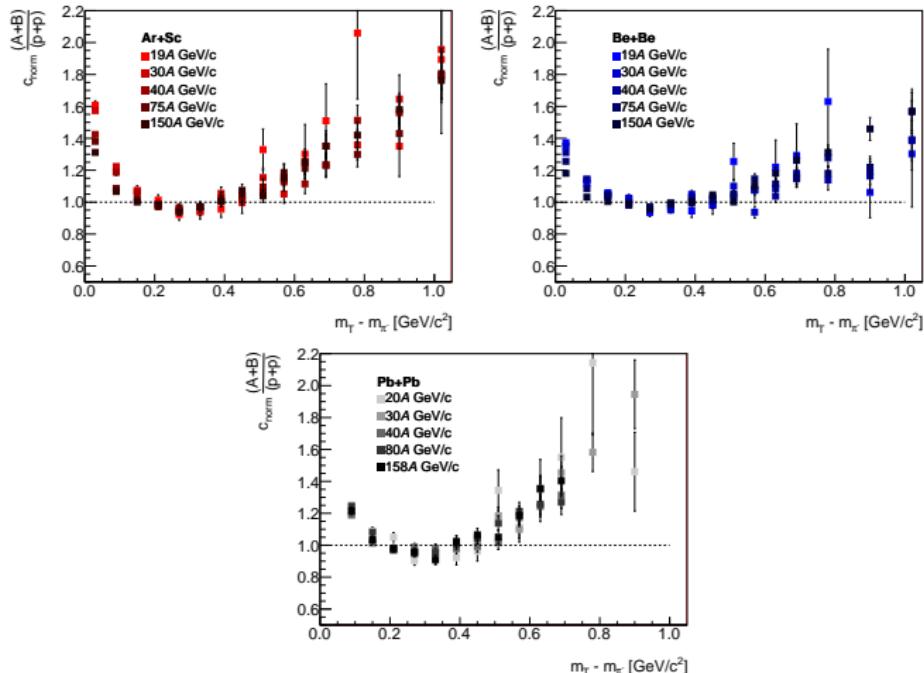
Preliminary results



- ▶ The shape of the  $m_T$  spectra for all ions' interactions is similar.
- ▶ The deviation from the  $p+p$  data in high  $m_T$  is higher for heavier ions.

Preliminary results

## Various collision momenta for each system.



Preliminary results



The new preliminary results on negative pion production properties in **Ar+Sc** at six beam momenta (13A-150A GeV/c) were presented.

- ▶ Rapidity spectrum is almost symmetric for **Ar+Sc** interaction (**Be+Be** data shows far higher asymmetry).
- ▶ The rapidity distribution width decreases monotonically with collision energy and falls close to the values for **Pb+Pb**
- ▶ The rapidity spectrum shape resembles the one of **Pb+Pb** interactions.
- ▶ The  $m_T$  distribution for all compared ion systems is qualitatively similar. This suggests the presence of the radial flow.

More analysis on this subject will follow in a near future.

NA61/SHINE  
PHYSICS

OUTLINE

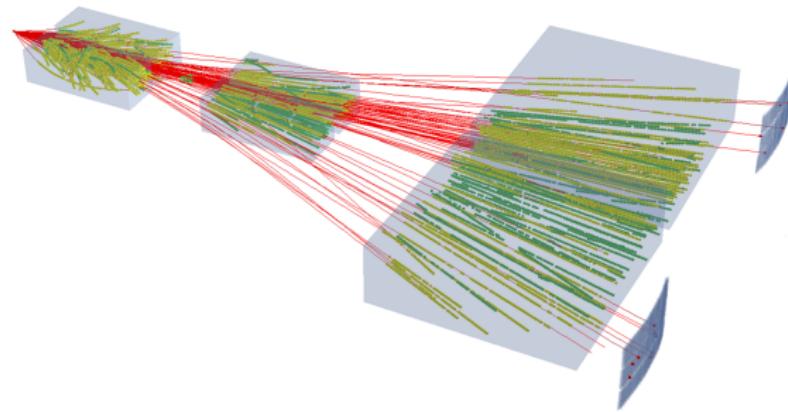
ANALYSIS METHOD

ERRORS

 $\pi^-$  SPECTRASYSTEM SIZE  
DEPENDENCE

SUMMARY

# Thank you for your attention!



*Event of Ar+Sc collision  
as recorded by NA61/SHINE*



## BACKUP SLIDES



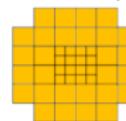
- ▶ Checked on **p+p** data:
  - The EPOS model reproduced the  $K^-/\pi^-$  ratio very well.
  - The EPOS model reproduced the  $\Lambda$  production well.
  - "h<sup>-</sup>" reproduced very well the results from  $dE/dx$  and  $dE/dx$ -tof analysis.
- ▶ ... and on **Be+Be** data
  - Preliminary results on  $dE/dx$  and  $dE/dx$ -tof analysis showed good agreement.

Due to the:

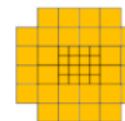
- ▶ Ratio of *Fermi motion* to the beam rapidity,
- ▶ Differences in magnetic field and
- ▶ PSD position for various energies,

different set of modules is chosen to calculate the  $E_F$ :

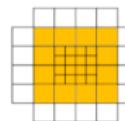
13 AGeV/c



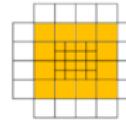
19 AGeV/c



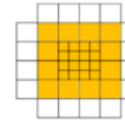
30 AGeV/c



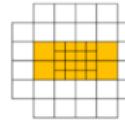
40 AGeV/c



75 AGeV/c



150 AGeV/c



The module sets are chosen on the basis of correlations between energy and multiplicity for each module.

The comparison of the slope  $T$  of the fitted exponents.  
(The errors are fit uncertainties)

