Latest results from the NA61/SHINE beam energy scan with p+p and Be+Be collisions

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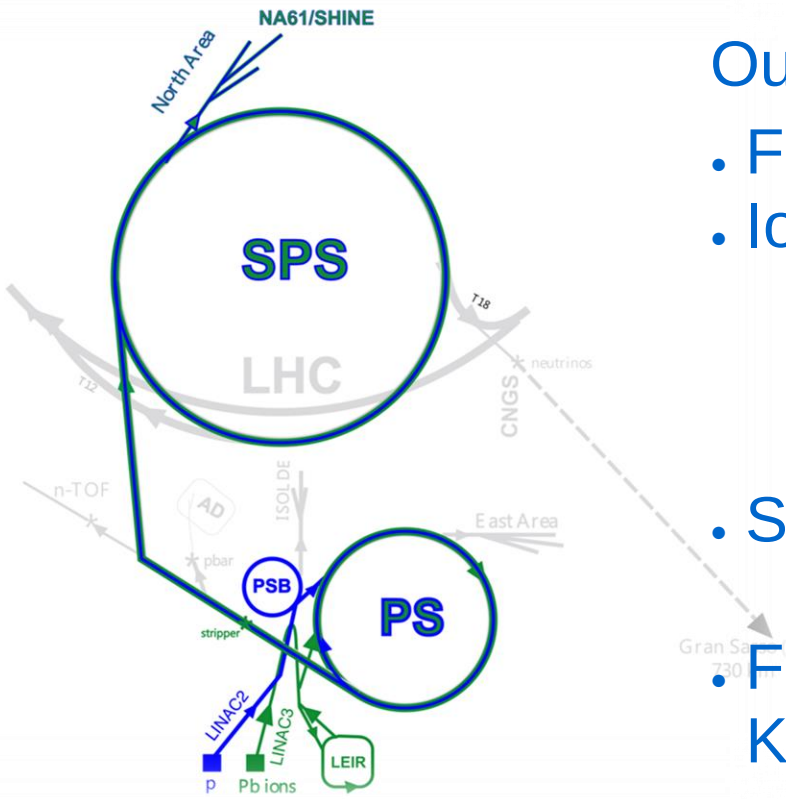
Wartsaw University of Technology



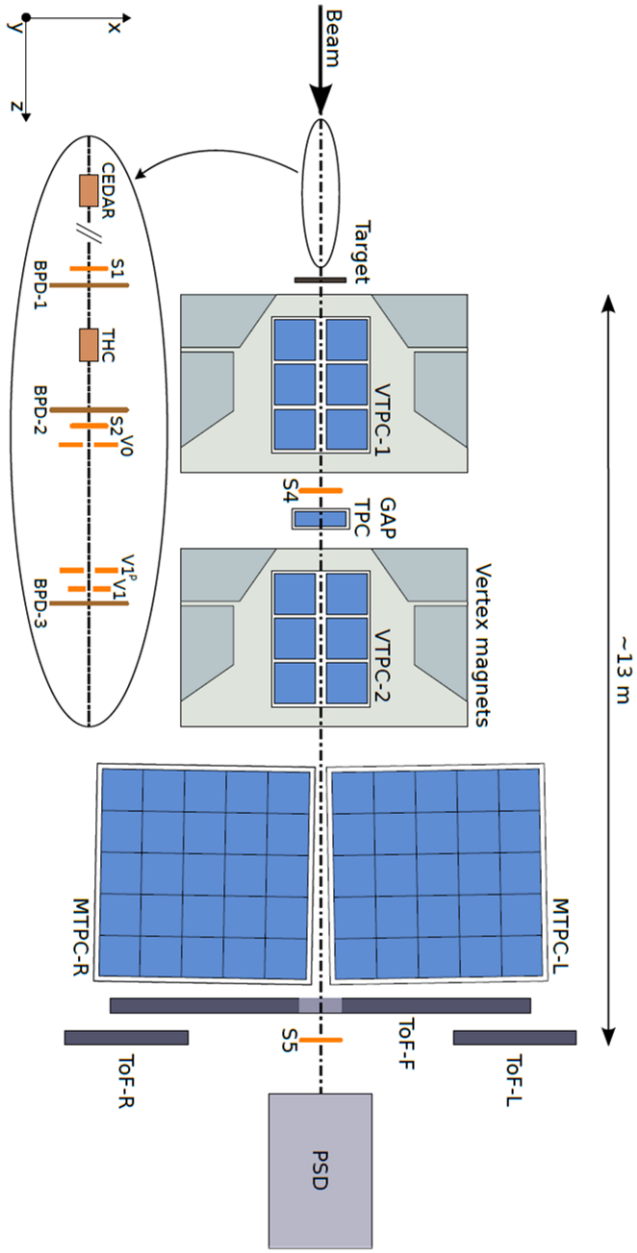
Outline

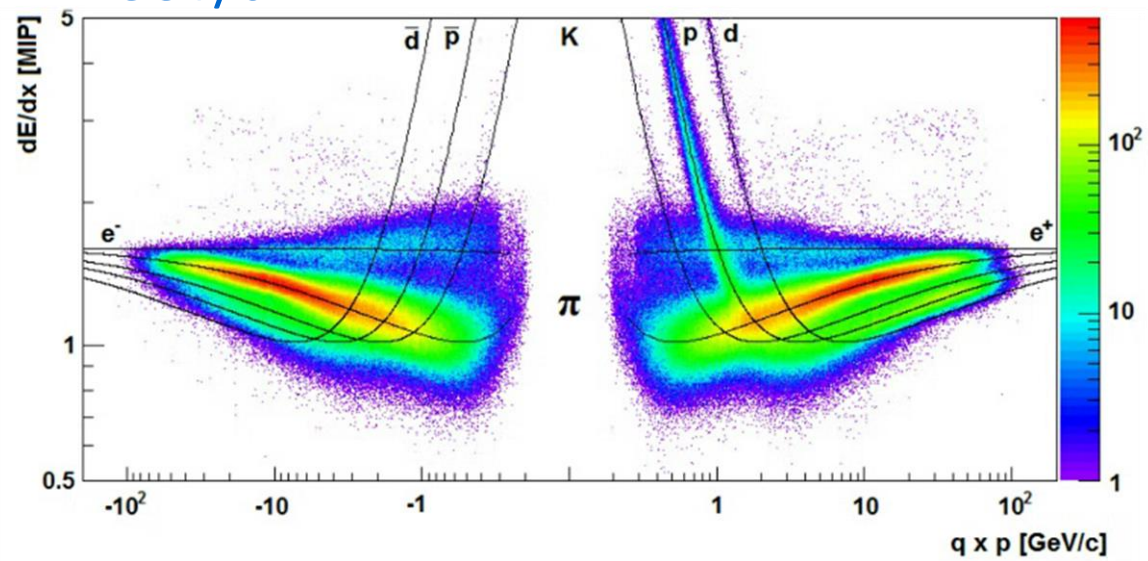
- Facility
- Ion program:
  - ✓ Study of the onset of deconfinement
  - ✓ Search of the critical point of strongly interacting matter
- Summary

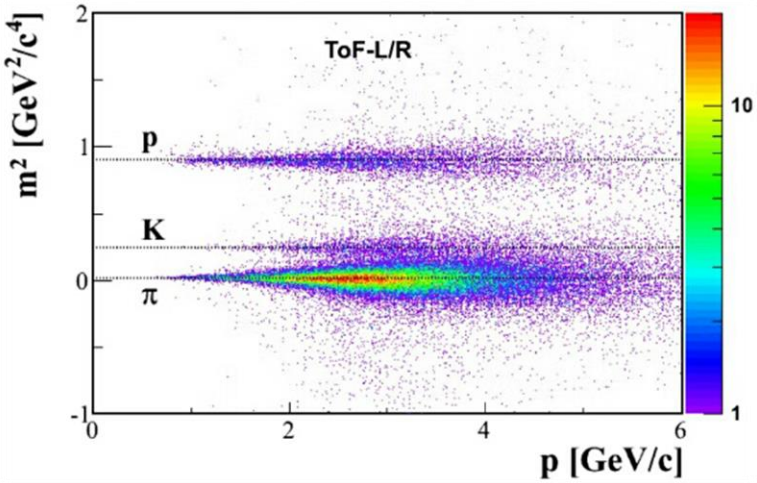
- For neutrino program see Alexander Korzenev's talk (12:15 Thu)

Facility

It is a unique multi-purpose detector which allows to measure hadron production in: h+p, h+A, A+A at beam momentum 13A-150A(400) GeV/c







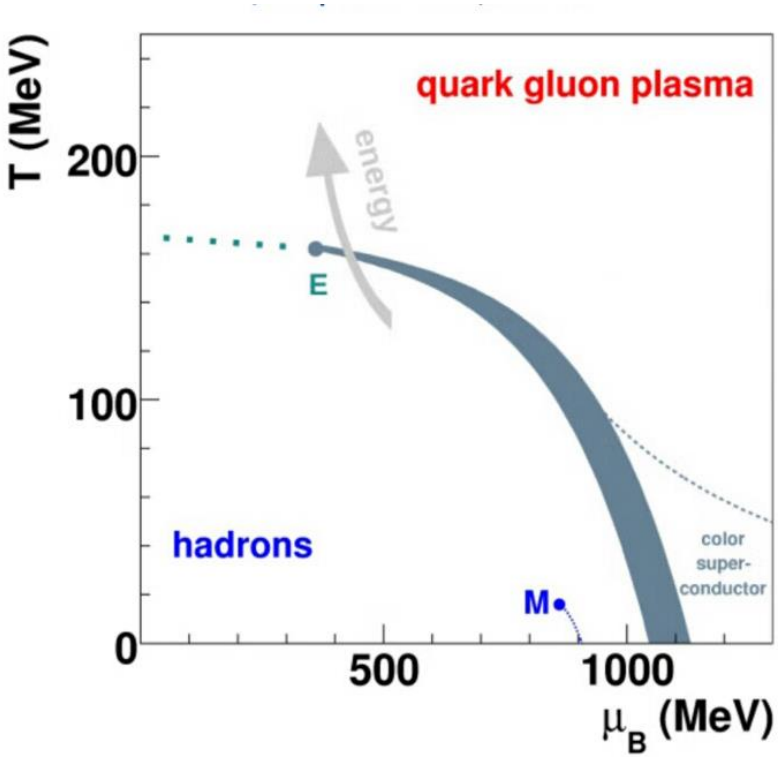
$$\sigma(p)/p^2 \approx 10^{-4}(GeV/c)^{-1}$$

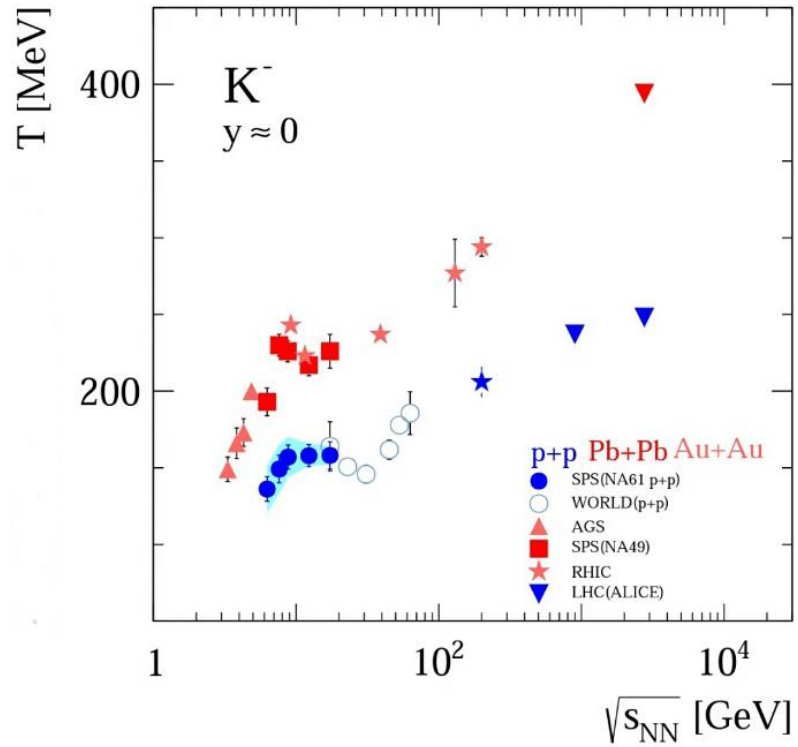
$$\sigma(dE/dx) \approx 4\%$$

$$\sigma(ToF) \approx 100\,ps$$

JINST 9 (2014) P06005

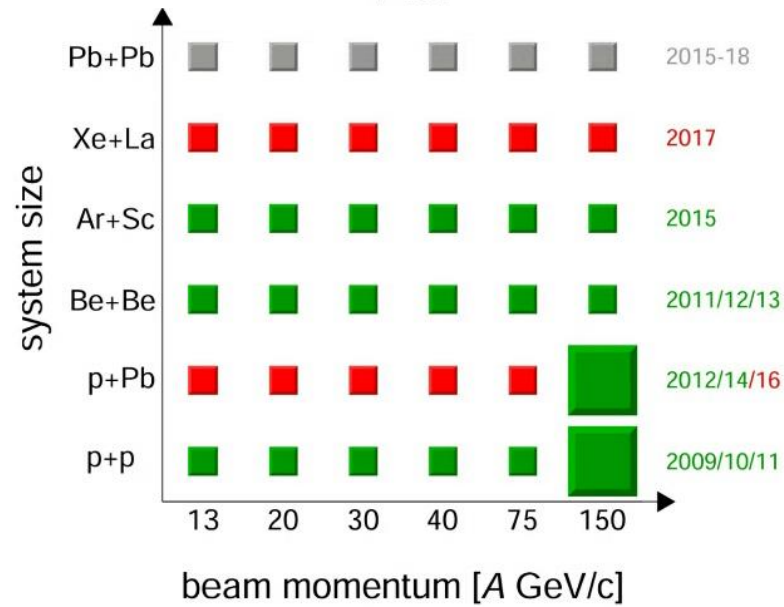
Strongly interacting matter



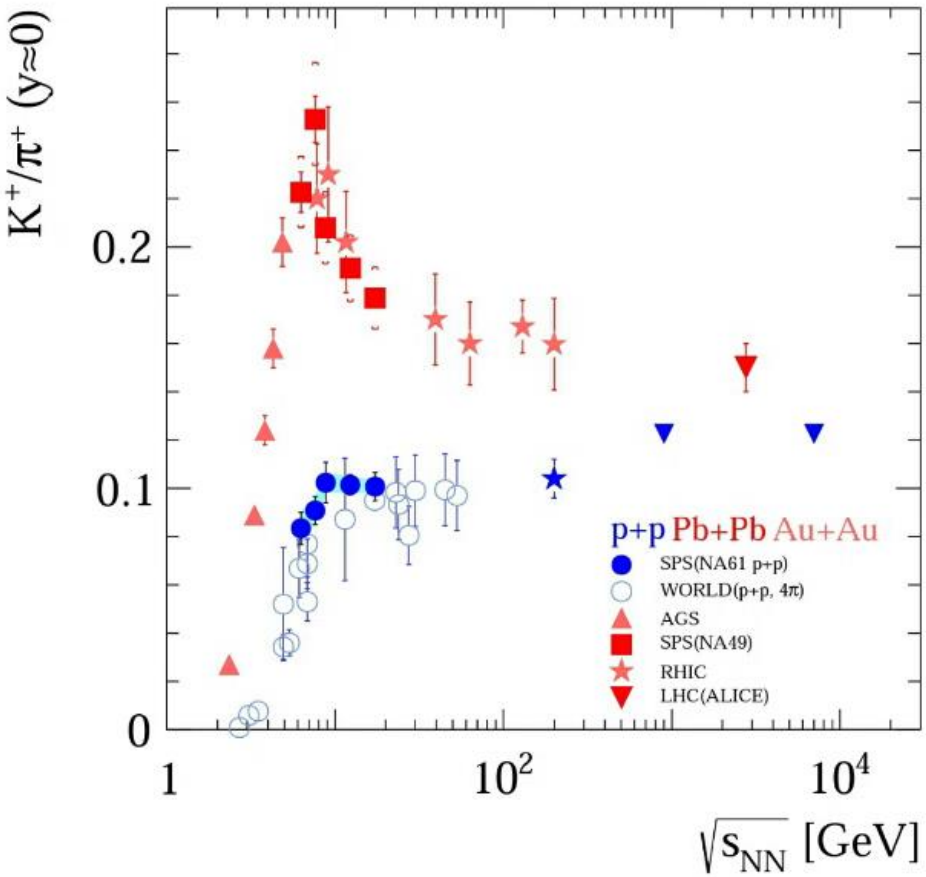


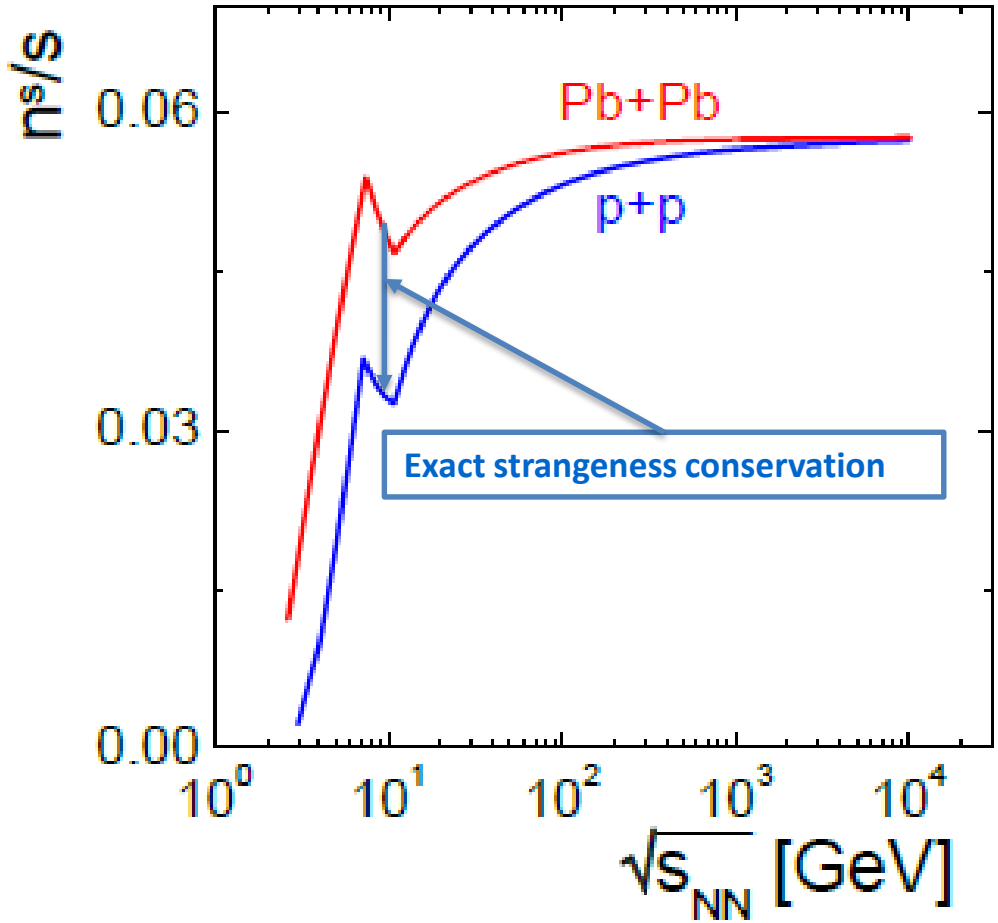
The NA49 observation of rapid changes in collision energy dependence of hadron production in heavy ion collisions in comparison to p+p interactions led to:

NA61/SHINE energy – system size scan



Evidence of rapid changes in p+p

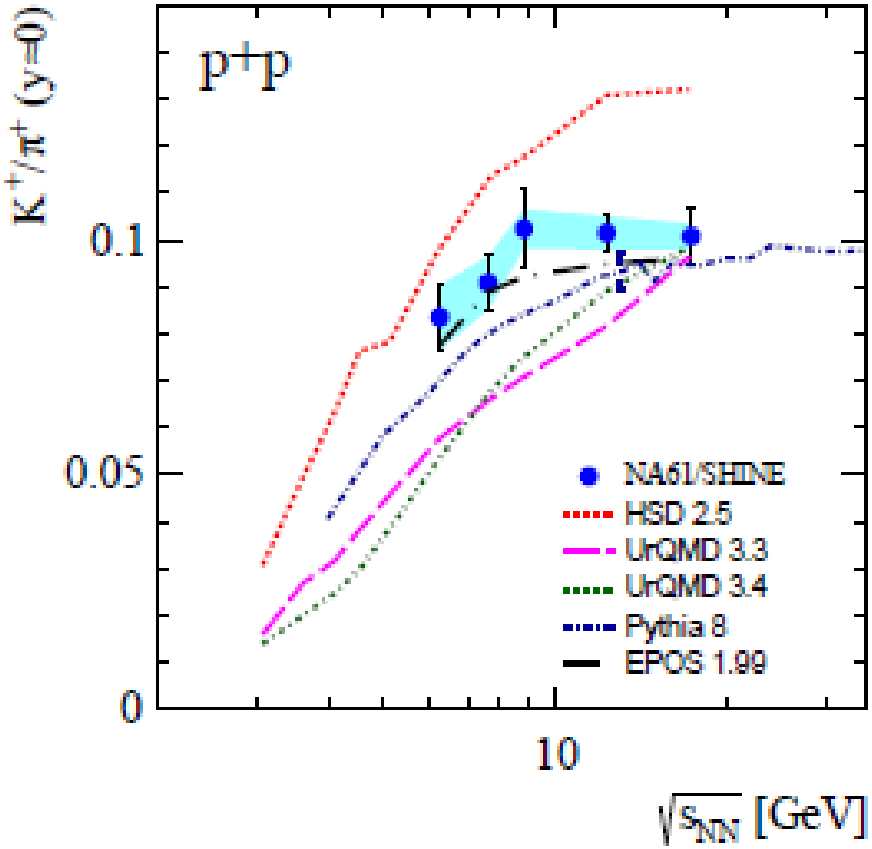


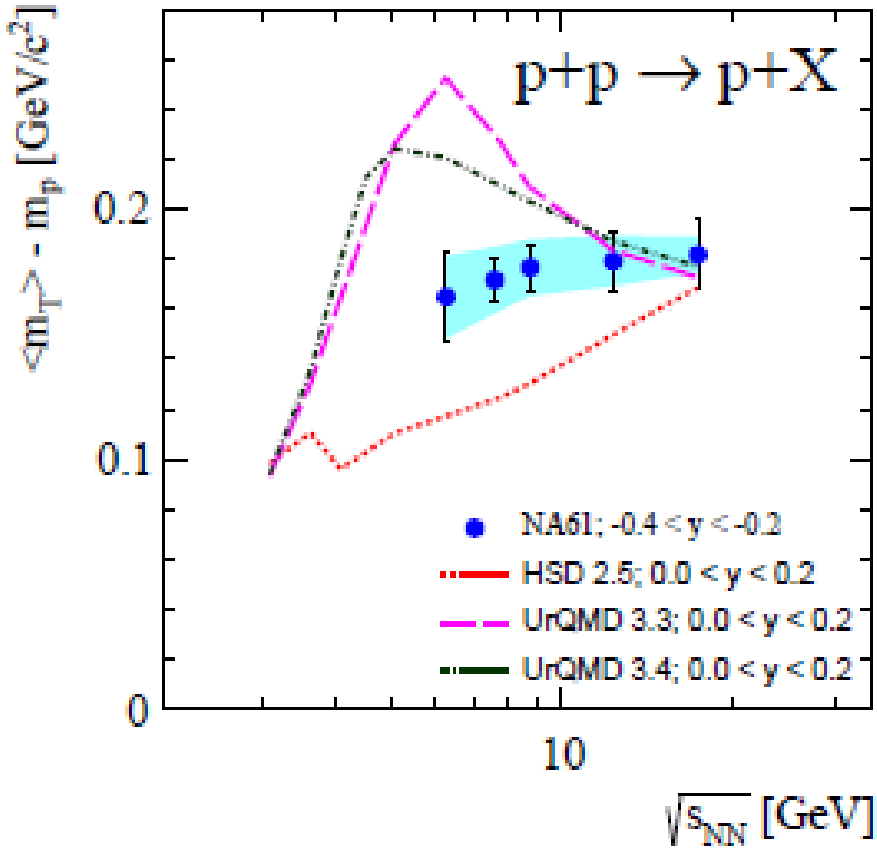


The NA61/SHINE data suggest that even in inelastic p+p interactions the energy dependence of the K+/π+ and the inverse slope parameter of K^- m_T spectra exhibits rapid changes in the SPS energy range but it is reduced in comparison to Pb+Pb.

In p+p interactions an exact strangeness conservation should be taken into account as number of strangeness carriers < 1

Challenge for string-resonance models



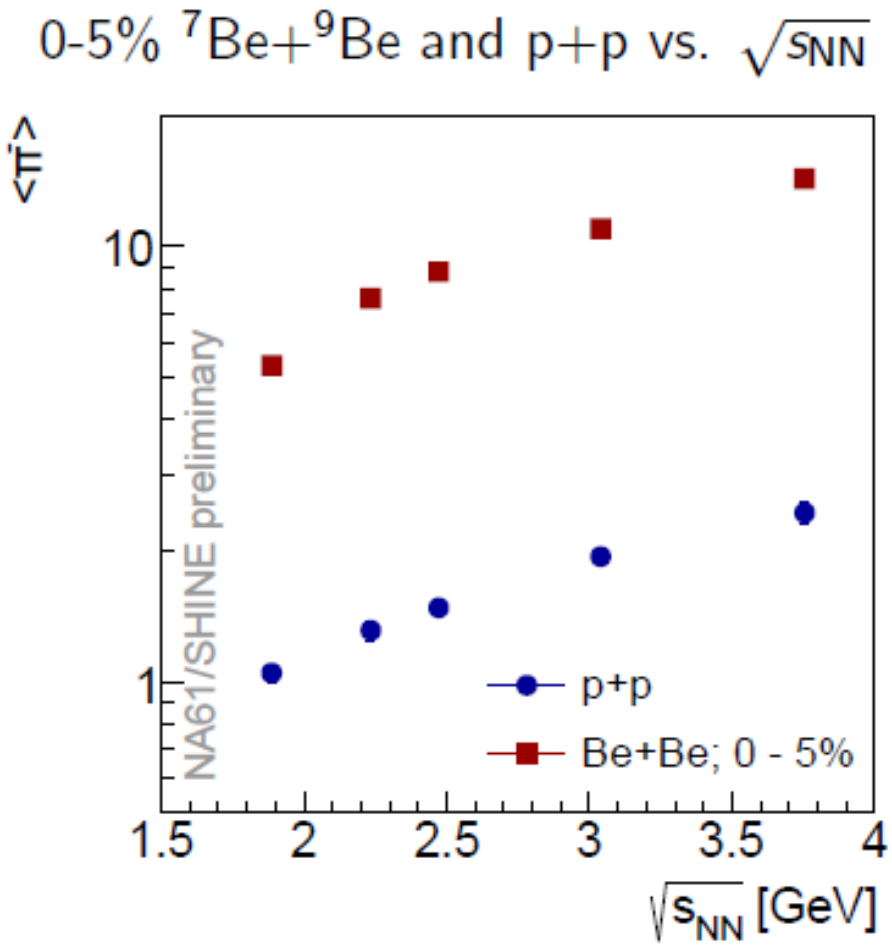


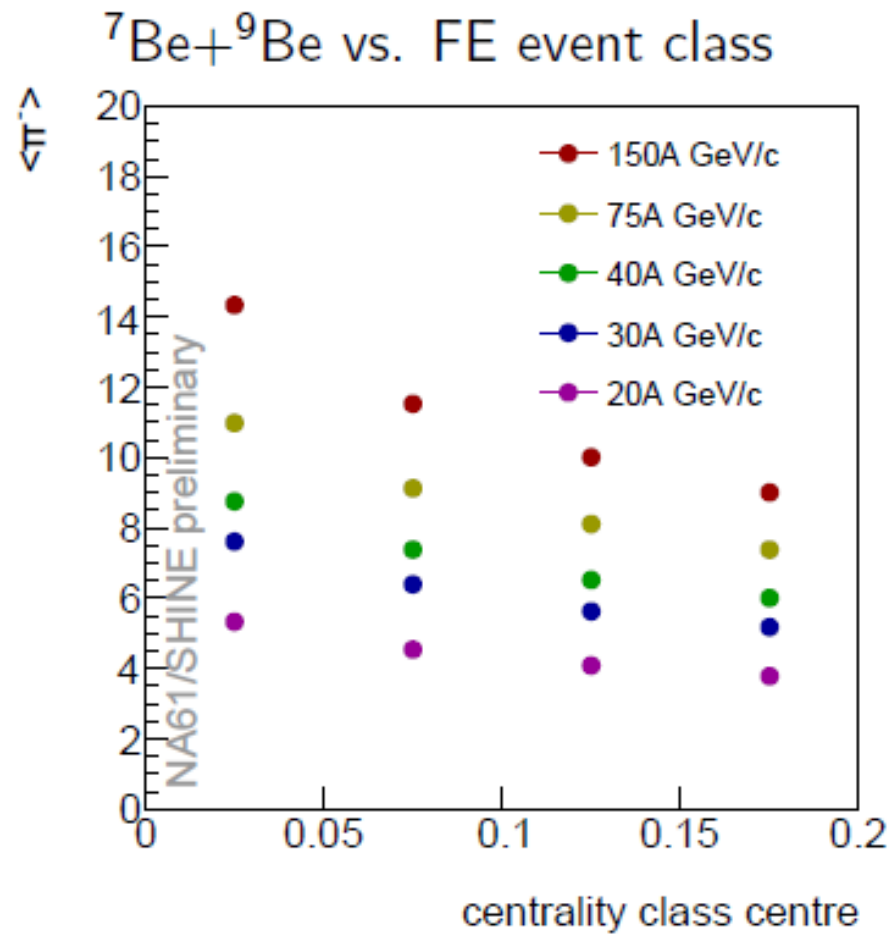
arXiv:1502.07916

High precision NA61/SHINE data allows to impose rigorous constraints for Monte-Carlo models.

In general string hadronic models do not describe the p+p data quantitatively.

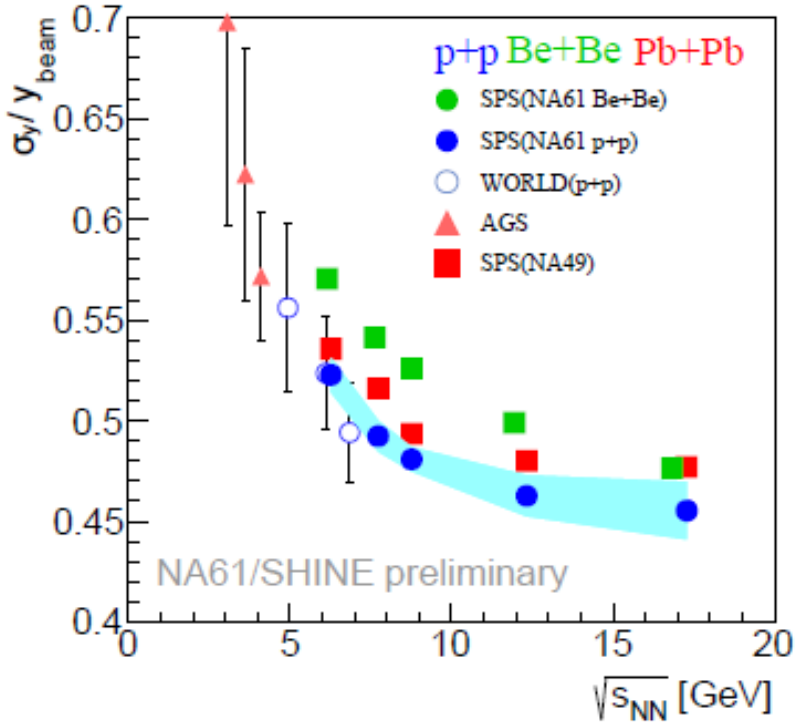
^{7}Be+^{9}Be results





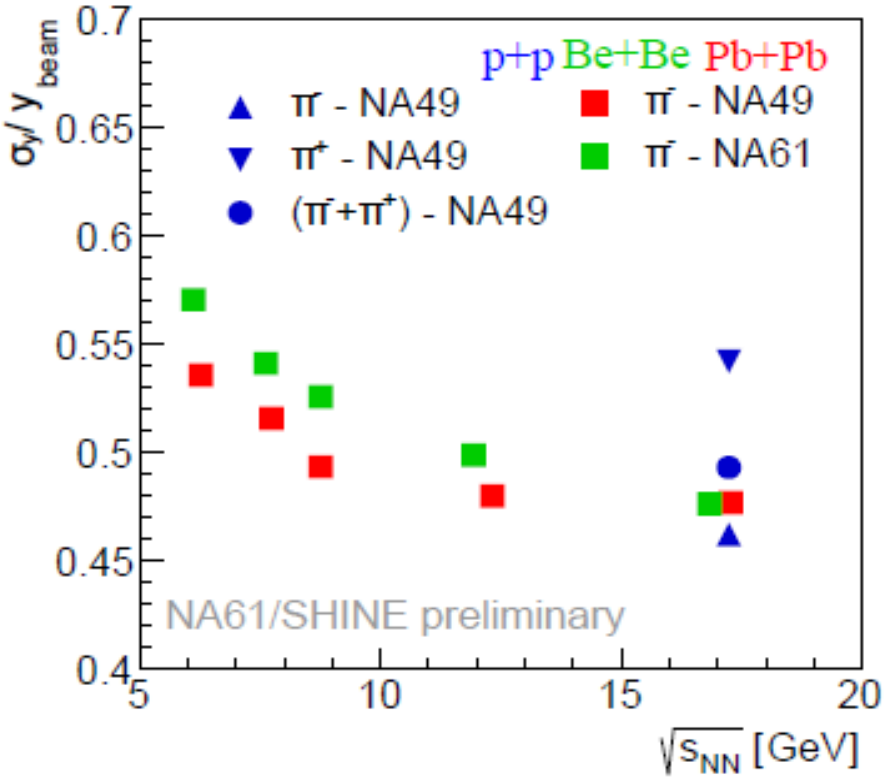
To compare results in system size scan a precise centrality determination is needed. **Particle Spectator Detector (PSD)** allows for a precise centrality selection by Forward Energy (FE) event selection.

Width of the rapidity distribution

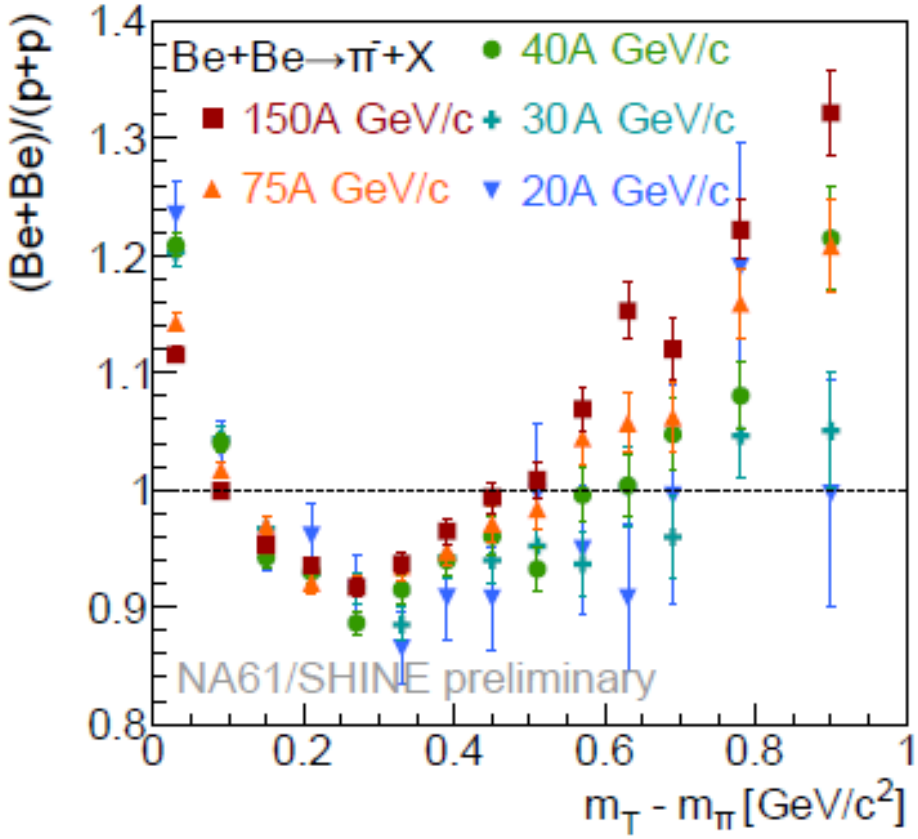


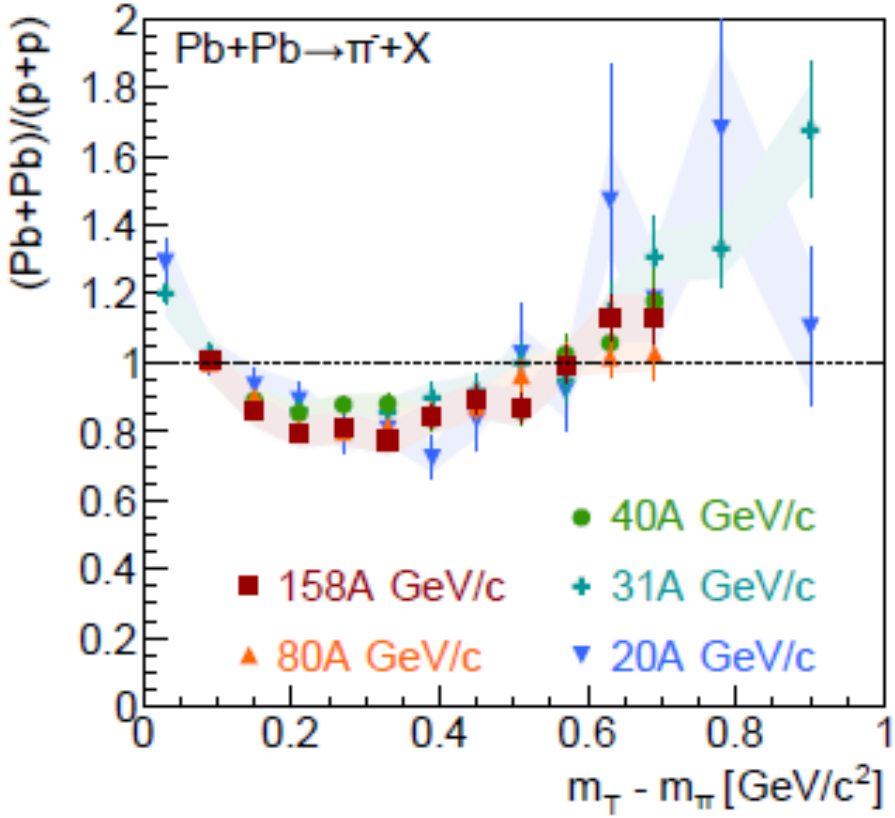
- σ_y calculated from fit of two symmetrically displaced Gaussians
- σ_y related to speed of sound c_s^2 („dale")
- Smooth, monotonic behaviour with energy
- Non-monotonic behaviour with system size

The isospin asymmetry affects width of the π- rapidity distribution in p+p and Pb+Pb but Be+Be is almost isospin symmetric



Comparison of transverse mass spectra



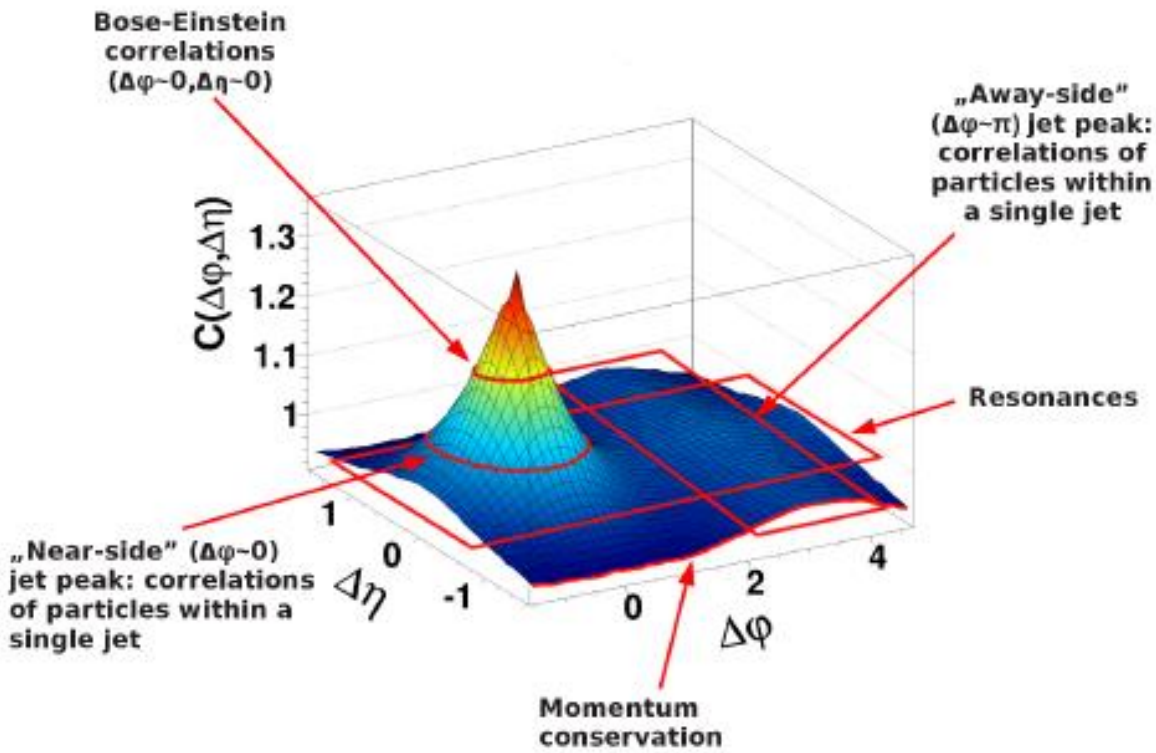


Ratio of normalized m_T spectra allow to compare shape of the spectra

The beam momentum dependence of the ratio observed in ^{7}Be+^{9}Be is not visible in Pb+Pb interactions. The shape of the ratio indicates the presence of radial collective flow in ^{7}Be+^{9}Be

^{7}Be+^{9}Be data for 0-15% FE event class
Pb+Pb data for 5% or 7.5% most central collisions

Two-particle correlations



Two-particle correlations in Δη, ΔΦ

- Studied extensively in RHIC and LHC
- Allow to disentangle different sources of correlations:
  - ✓Jets
  - ✓Flow
  - ✓Resonance decays
  - ✓Quantum statistics
  - ✓Conservation laws

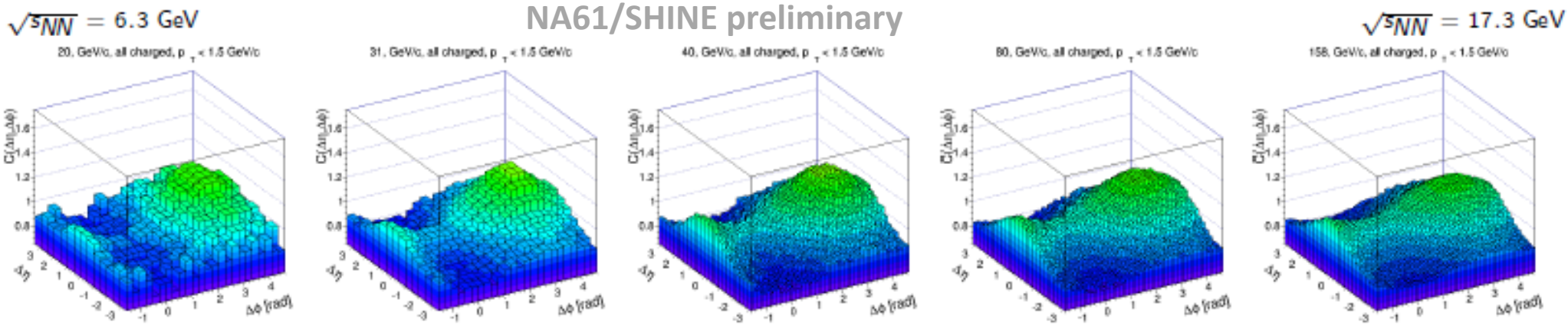
Correlations are calculated by finding the difference in pseudo-rapidity and azimuthal angle between two particles in the same event. Next they are normalized using mixed events.

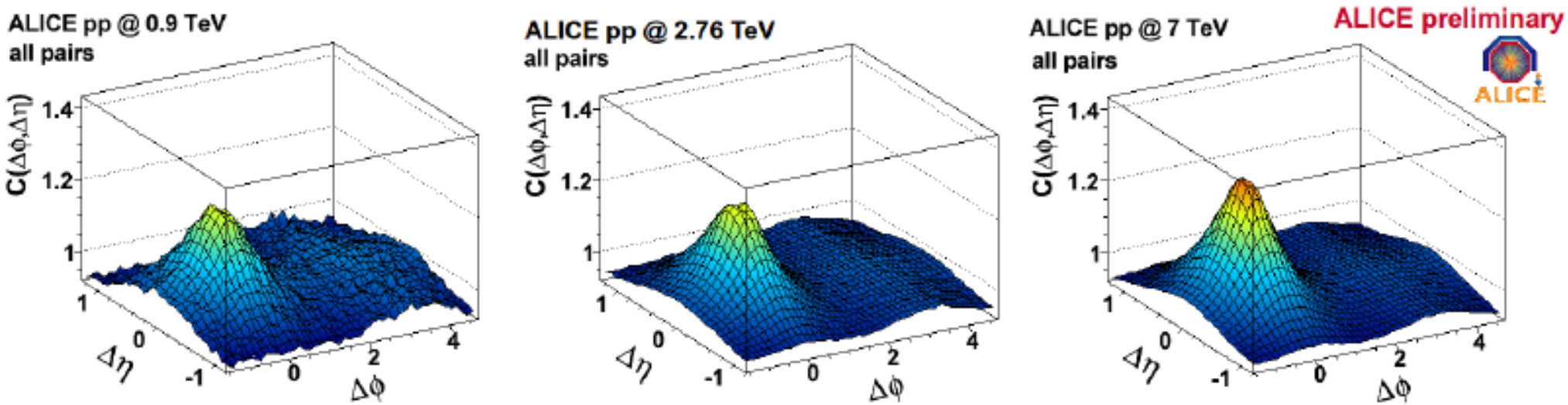
$$C(\Delta\eta,\Delta\phi) = \frac{N^{pairs}_{mixed}}{N^{pairs}_{data}} \frac{S(\Delta\eta,\Delta\phi)}{M(\Delta\eta,\Delta\phi)},$$

$$S(\Delta\eta,\Delta\phi) = \frac{d^2N^{signal}}{d\Delta\eta d\Delta\phi}$$

$$M(\Delta\eta,\Delta\phi) = \frac{d^2N^{mixed}}{d\Delta\eta d\Delta\phi}$$

NA61/SHINE vs ALICE (energy dependence)

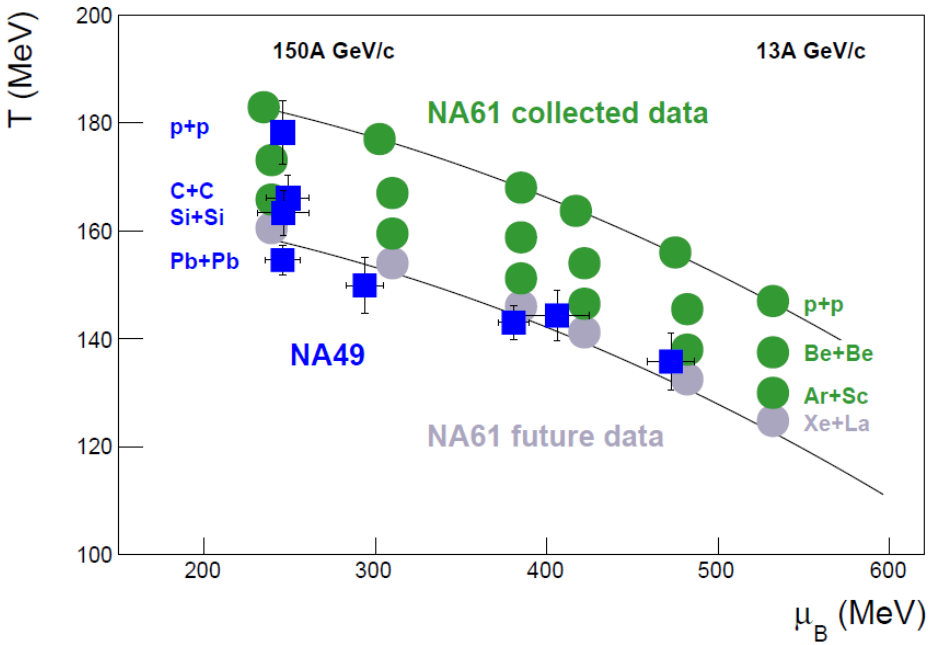


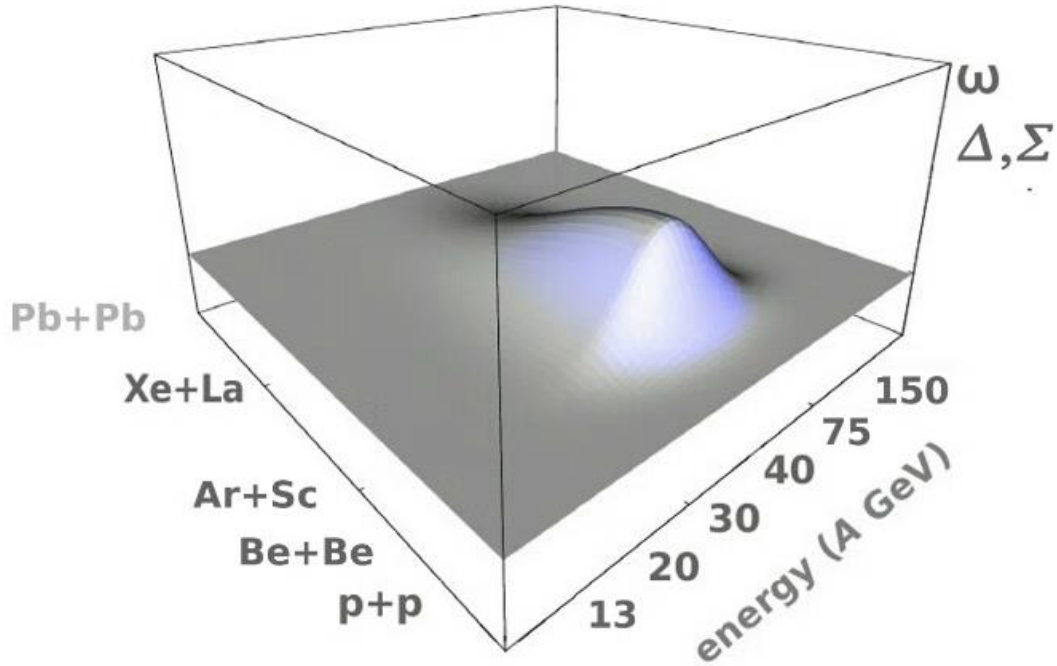


M.Janik, PoS(WPCF2011) 026

Resonance decay hill is more visible at lower energies. Jets dominate at higher energies.

Search for the critical point





Fluctuations are the main tool to search for the critical point of strongly interacting matter. But in order to compare results from different systems specific quantities are required.

Fluctuations may give also information on conservation laws, resonance decays, onset of deconfinement and many other (e.g. Phys.Rept.351,161-194; J.Phys.G:Nucl.Part.Phys.42,075101)

Strongly Intensive Quantities

Special combination of extensive quantities (depending on volume in GCE) can be a strongly intensive measure

$$\Delta[A,B] = \frac{1}{C_\Delta}[\langle B\rangle\omega_A - \langle A\rangle\omega_B]$$

$$\Sigma[A,B] = \frac{1}{C_\Sigma}[\langle B\rangle\omega_A + \langle A\rangle\omega_B - 2(\langle AB\rangle - \langle A\rangle\langle B\rangle)]$$

They are:

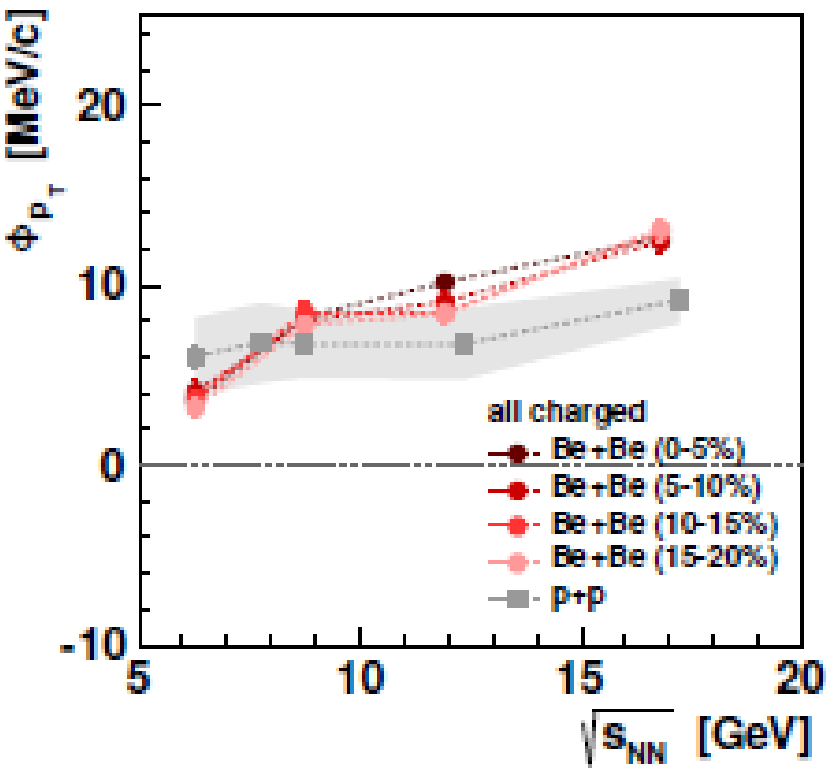
- dimensionless
- independent of volume and volume fluctuations
- normalization chosen such that Δ[A,B]=Σ[A,B]=1 for independent particle model
- Δ[A,B]=Σ[A,B]=0 in the absence of fluctuations

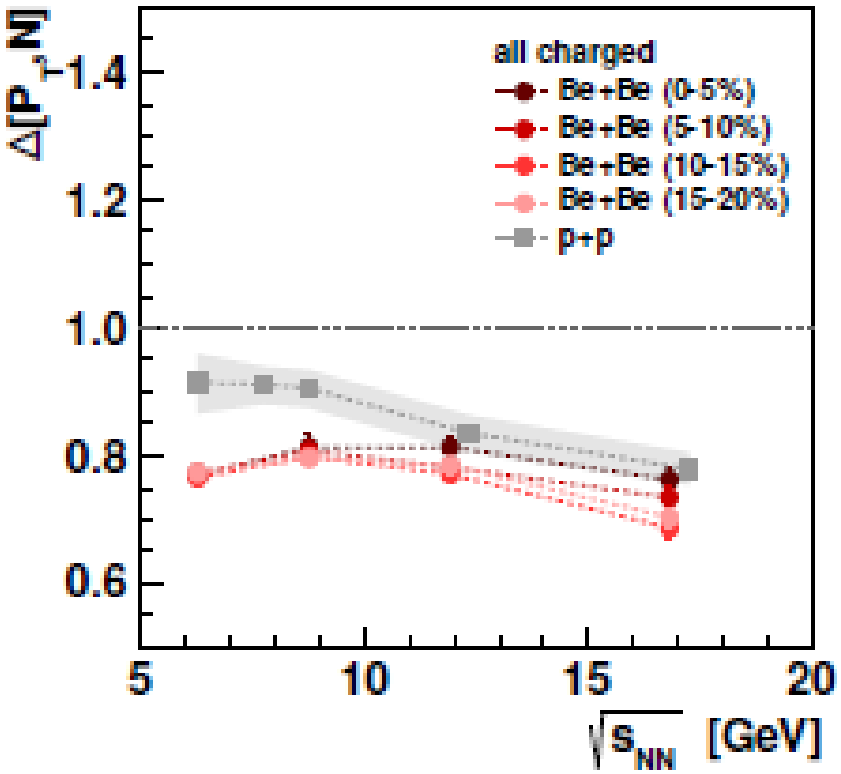
For comparison with the NA49 experiment the Φ quantity is used:

$$P_T = \sum_{i=0}^{N} p_{Ti} \qquad \Phi_{p_T} = \sqrt{\overline{p_T}\omega[p_T]}\left(\sqrt{\Sigma[P_T,N]} - 1\right)$$

$$\Phi_{ij} = \frac{\sqrt{\langle N_i\rangle\langle N_j\rangle}}{\langle N_i + N_j\rangle}\left(\sqrt{\Sigma[i,j]} - 1\right)$$

Energy dependence of P_T and N fluctuations

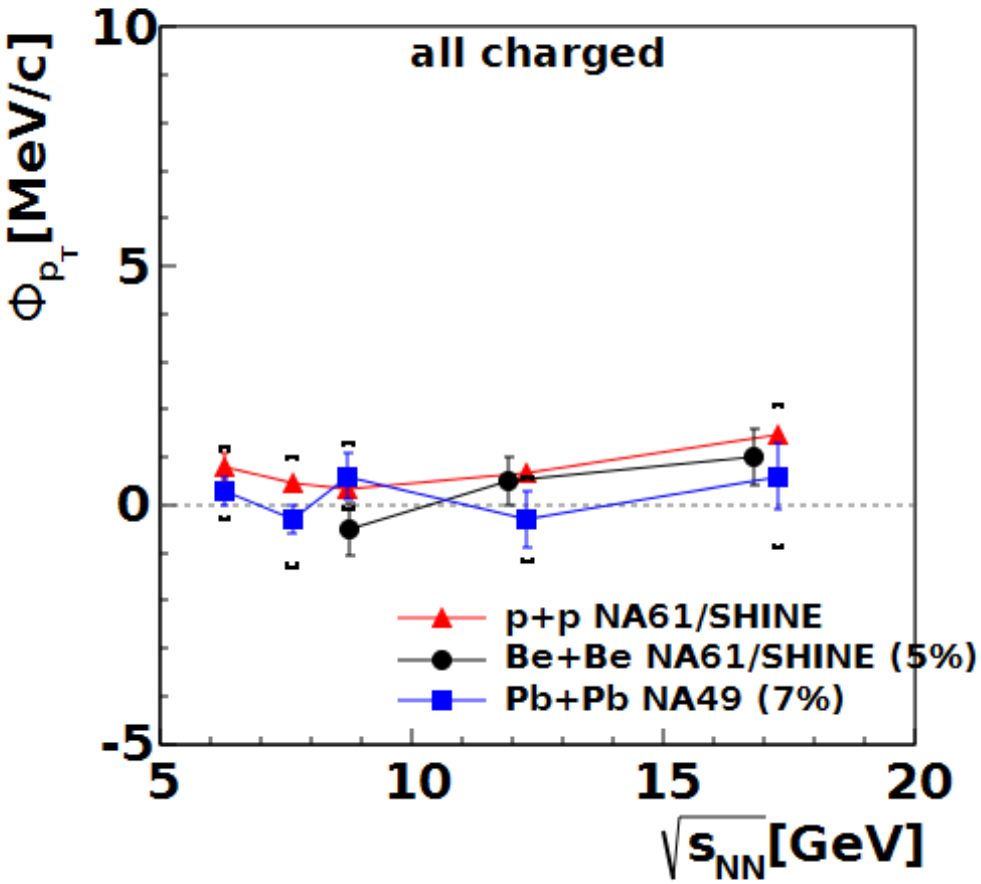


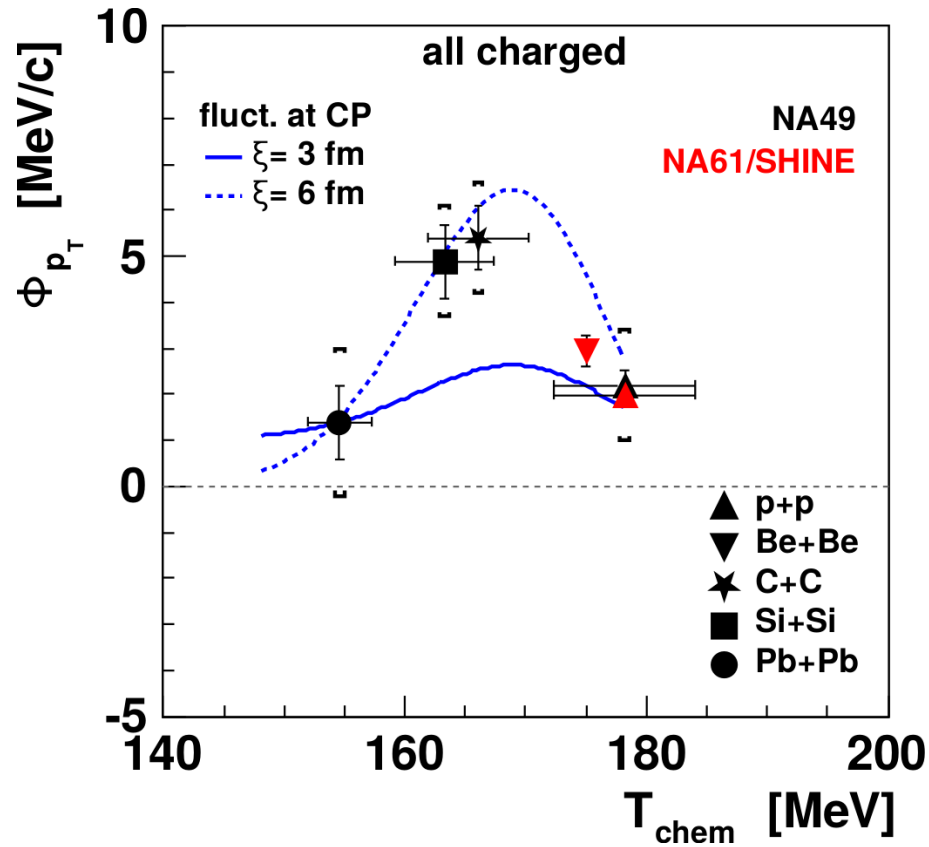


- Be+Be results close to p+p
- no structures which could be connected to the CP/OD in p+p and Be+Be
- no centrality dependence in Be+Be
- Bose-Einstein statistics and PT/N-N correlations probably introduce difference between Δ and Σ (PRC 89, 034903)

Comparison with NA49

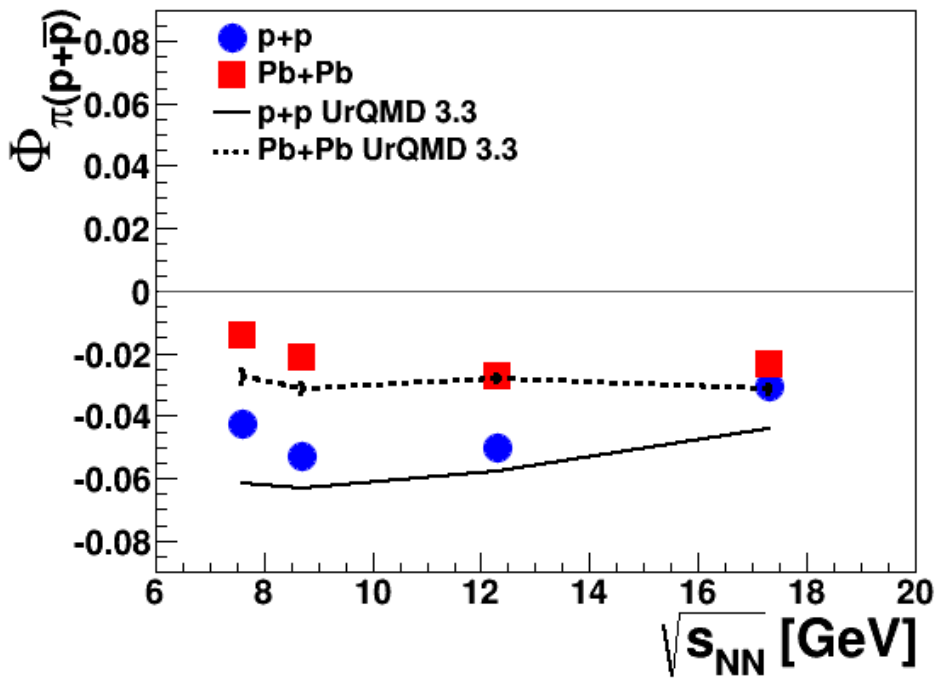
Fluctuations can not be corrected for the detector acceptance thus results from different reactions has to be compared in the same phase-space region.

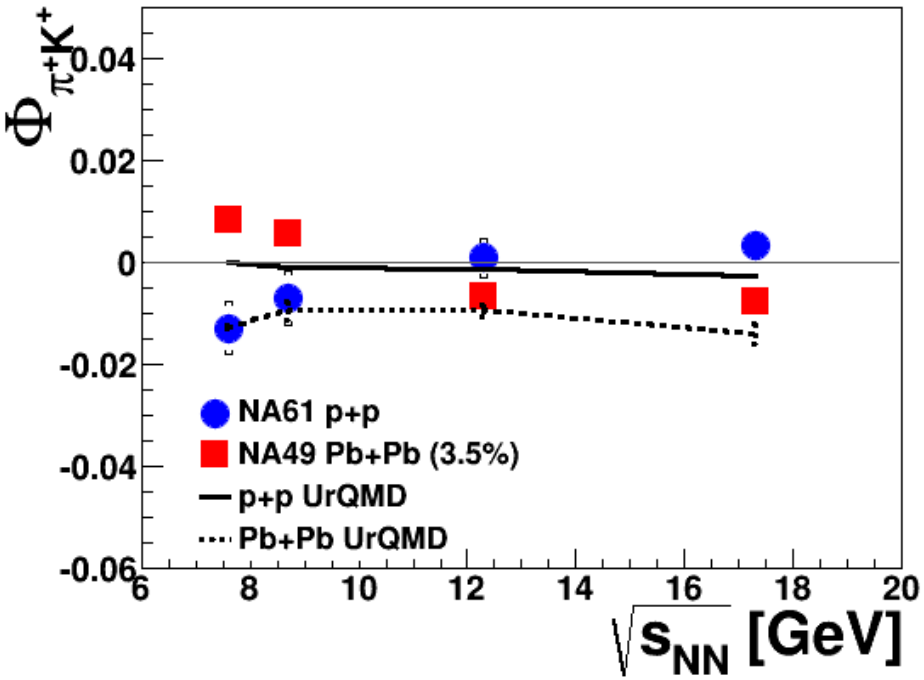




New results of the NA61/SHINE are in agreement with dependence observed by the NA49 experiment.

Identified particle fluctuations





- p+p interactions close to Pb+Pb
- no structures which could be connected with CP
- different energy dependence of $\Phi_{\pi+K+}$ in p+p and Pb+Pb (possibly connected to OD)
- $\Phi_{\pi(p+\bar{p})}$ dominated by resonance decays and conservation laws

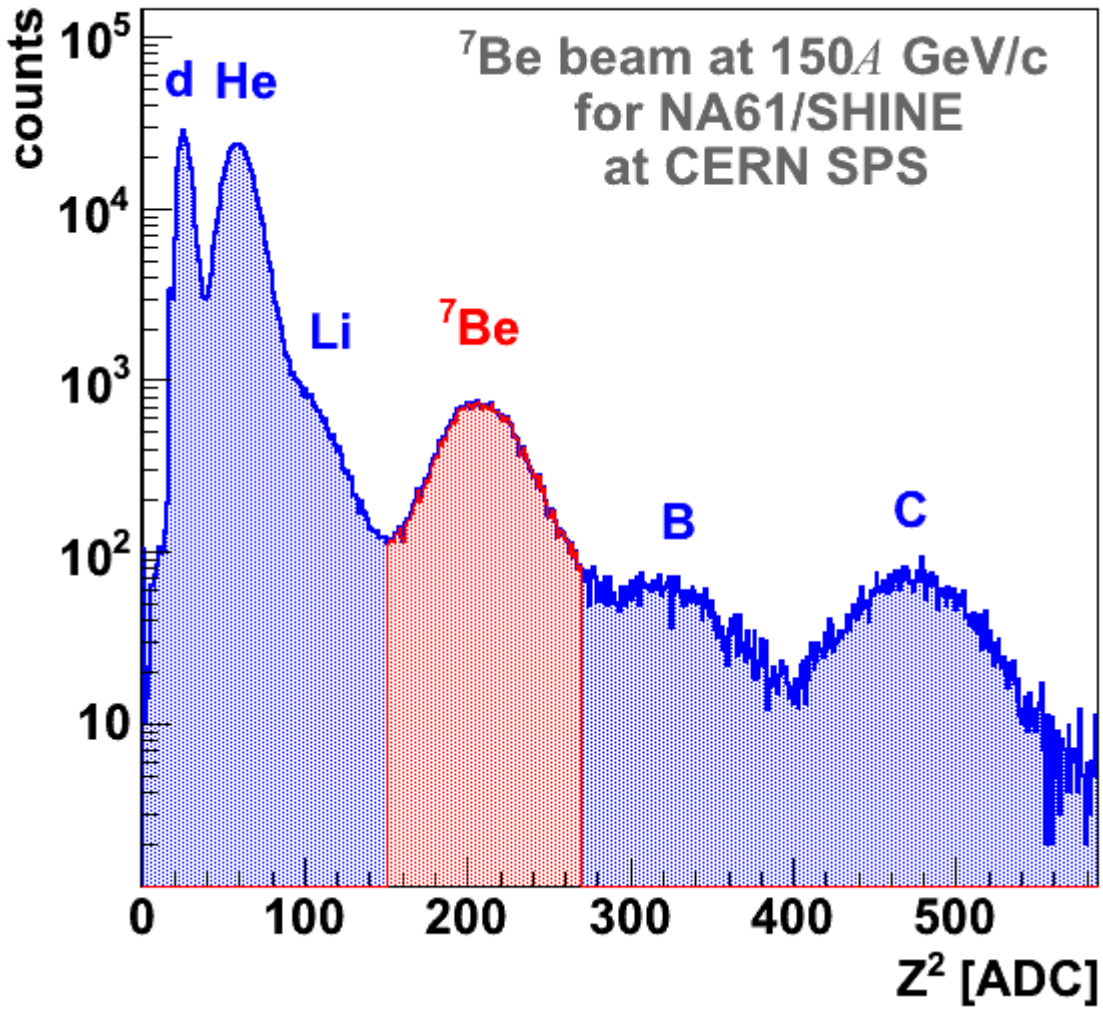
Summary

- data taking for system size – energy scan is well advanced
- observation of rapid changes in p+p interactions at SPS
- string-hadronic model do not describe p+p spectra
- no CP signal in p+p and Be+Be interactions; waiting for Ar+Sc
- fluctuations in p+p and Be+Be interactions are similar and dominated by conservation laws and resonance decays
- fluctuations in p+p and Pb+Pb interactions are similar

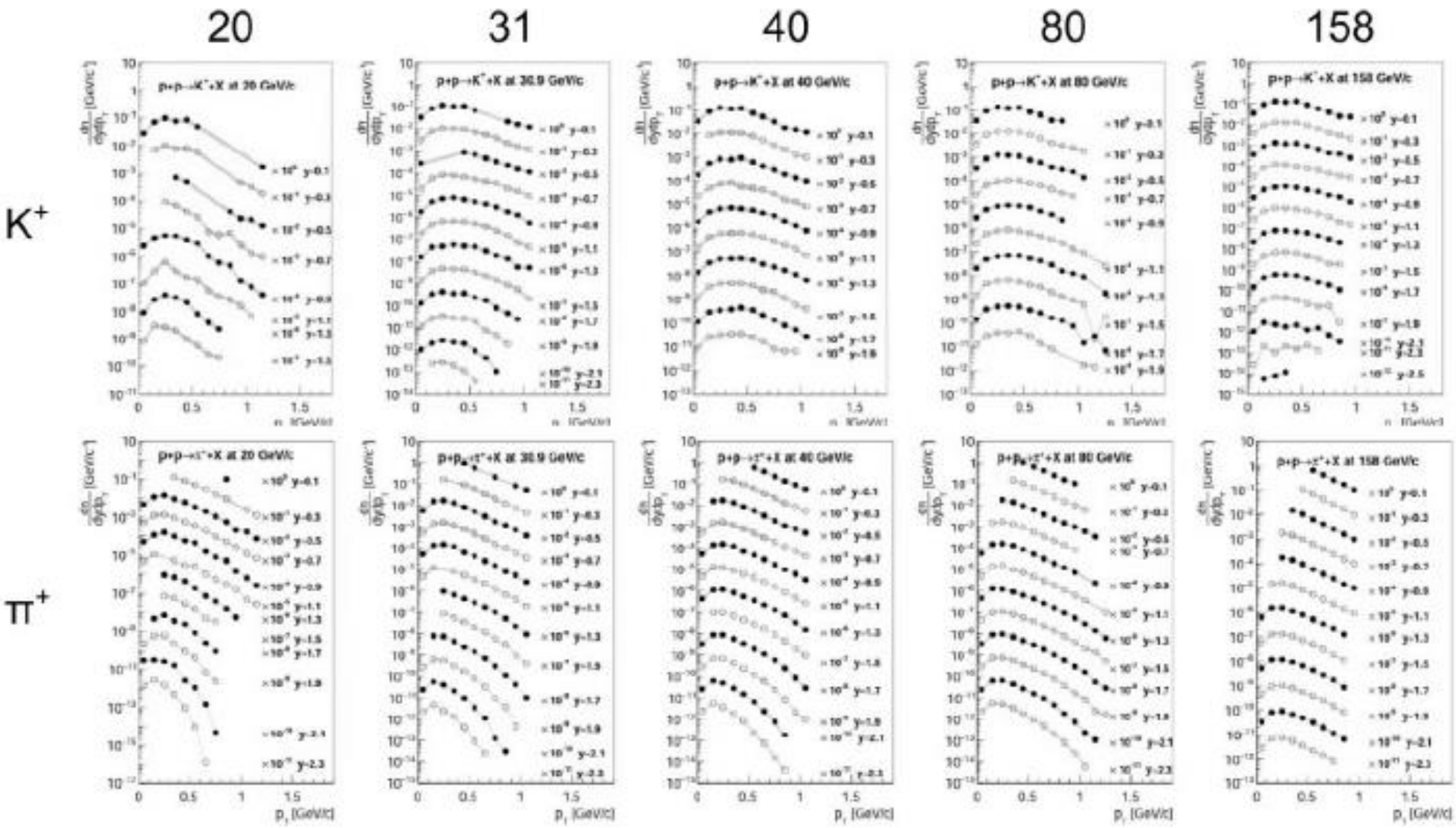
Thank you

Beams for NA61/SHINE

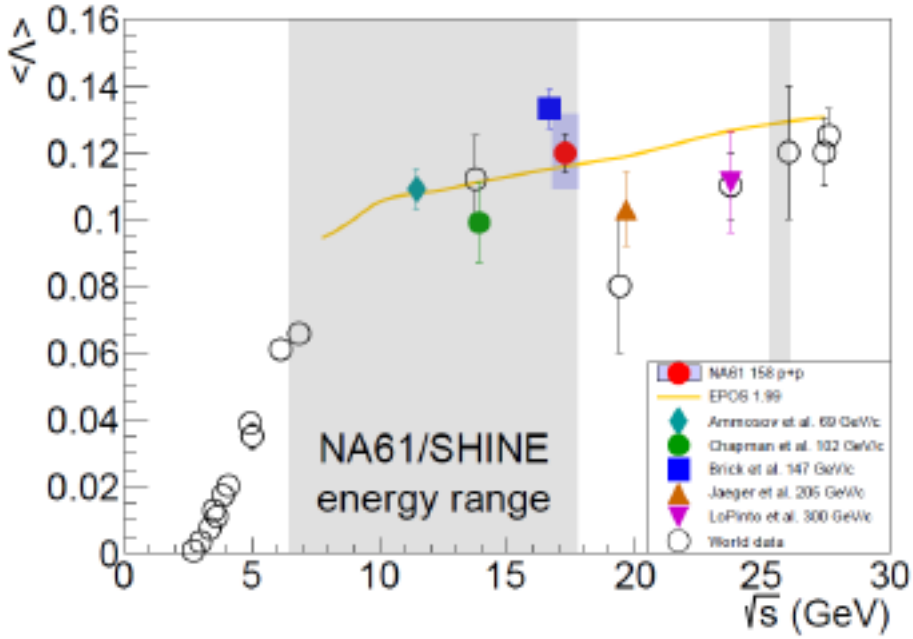
- Primary ions (13A-158A GeV): argon, xenon, lead
- Secondary ions:
  - Hadrons 13-350 GeV
  - Ions 13A-150A GeV

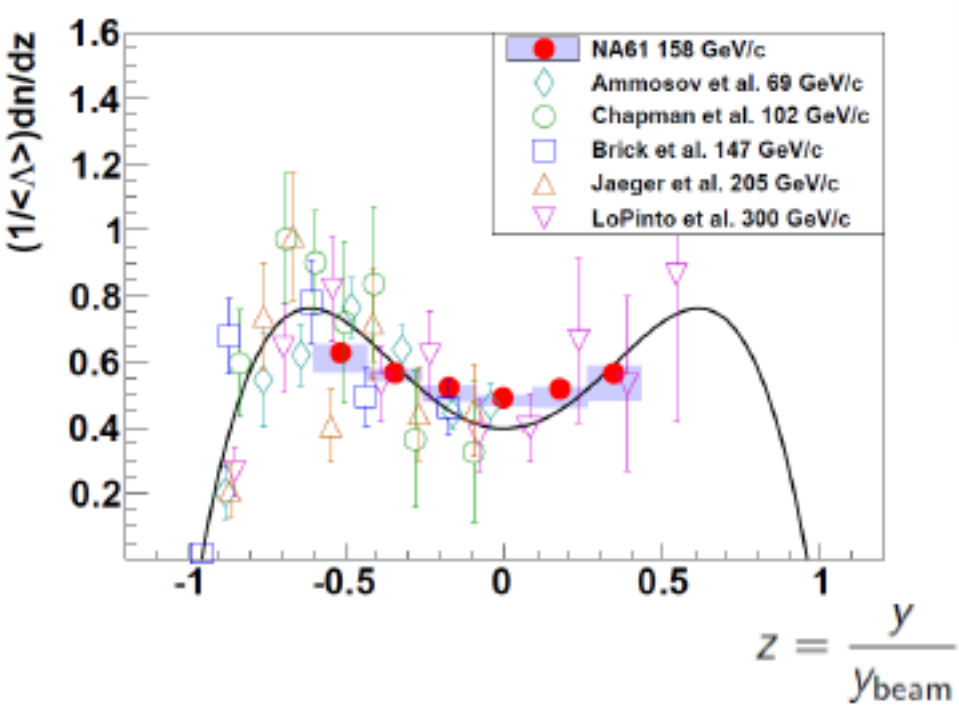


Single particle spectra in p+p interactions



Lambda spectra



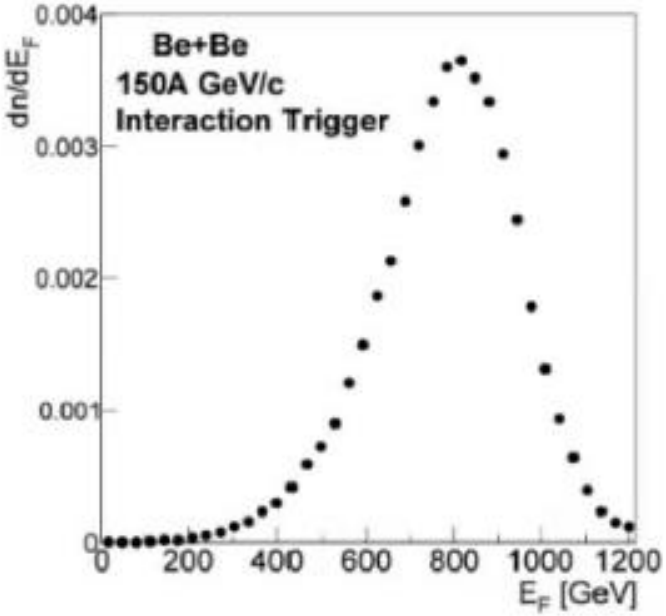


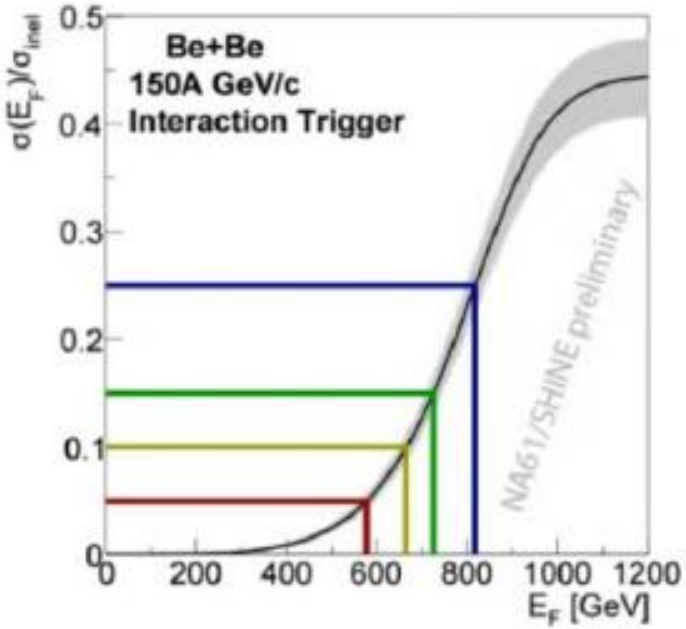
NA61/SHINE results are in agreement with the world data

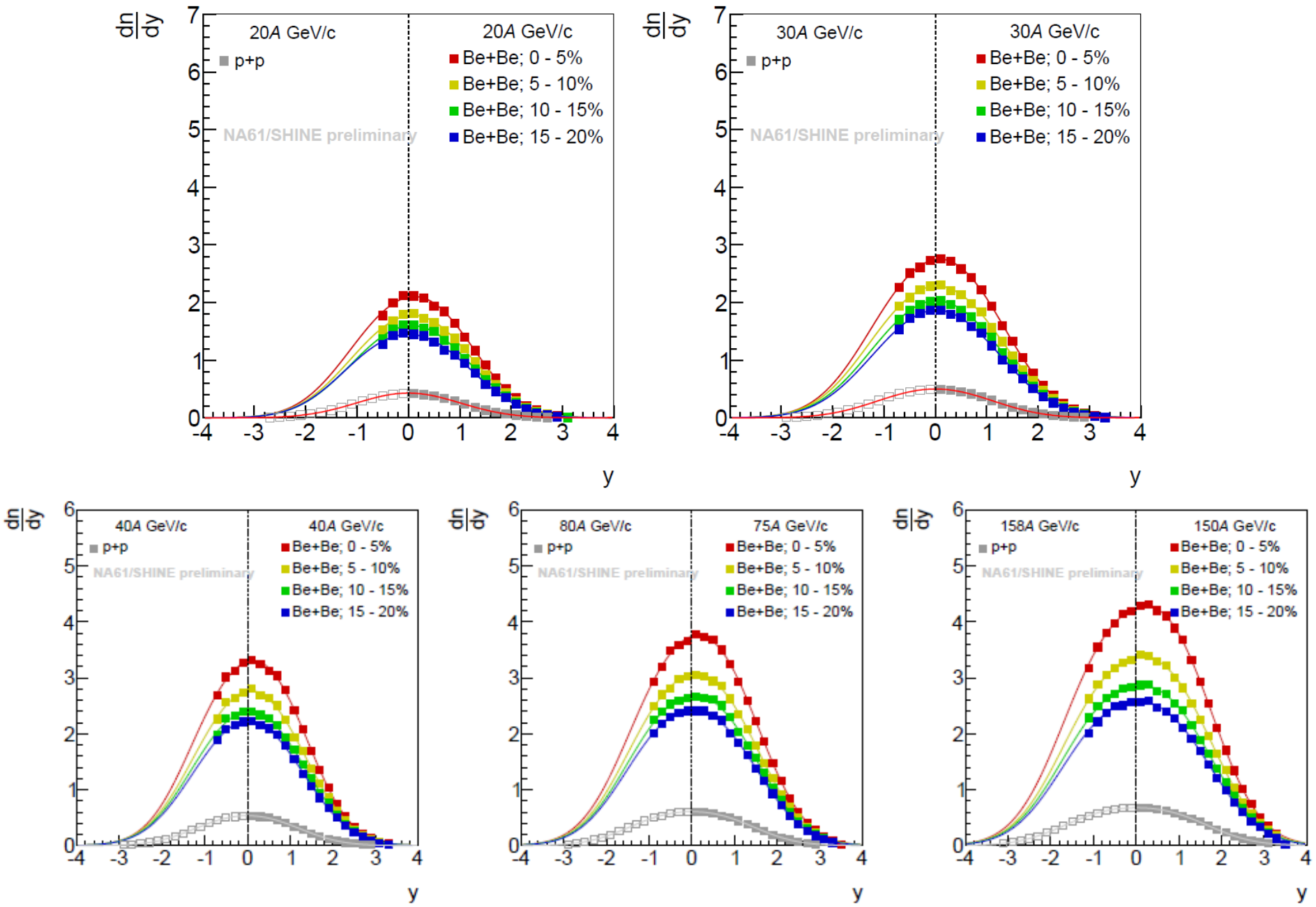
Centrality selection

- PSD (Projectile Spectator Detector) is located on the beam axis and measures the forward energy Ef related to the non-interacting nucleons of the beam nucleus
- Cuts on Ef allows to select different centrality classes (we select four centralities)

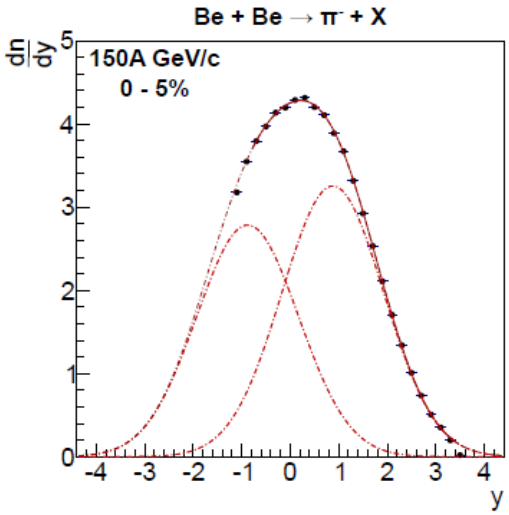
0 - 5% 5 - 10% 10 - 15% 15 - 25%

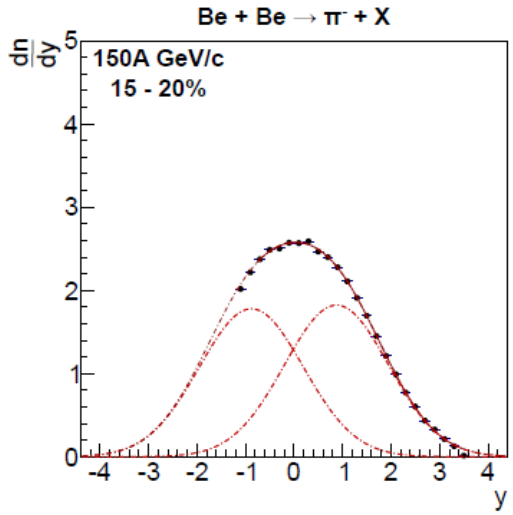


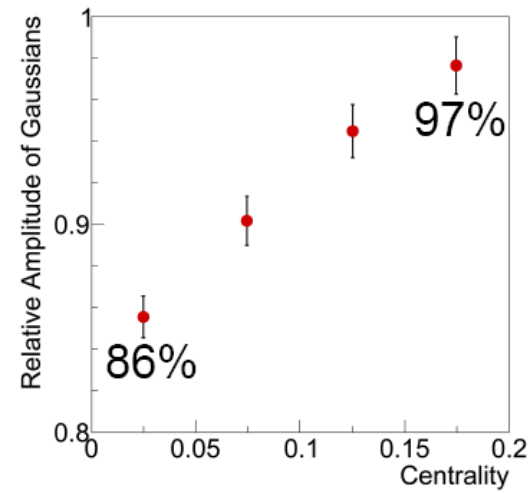



dn/dy
20A GeV/c
20A GeV/c
p+p
Be+Be; 0 - 5%
Be+Be; 5 - 10%
Be+Be; 10 - 15%
Be+Be; 15 - 20%
NA61/SHINE preliminary
y
30A GeV/c
30A GeV/c
40A GeV/c
40A GeV/c
80A GeV/c
75A GeV/c
158A GeV/c
150A GeV/c

Assymetry in π^- distribution in $^7Be+^9Be$

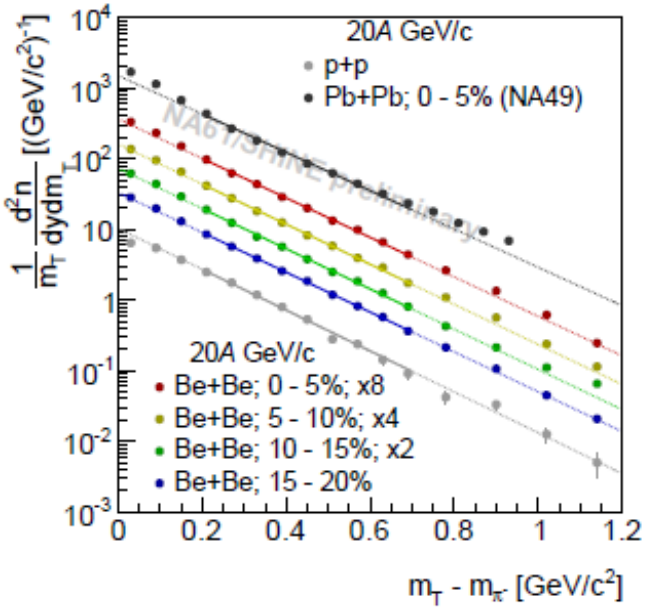


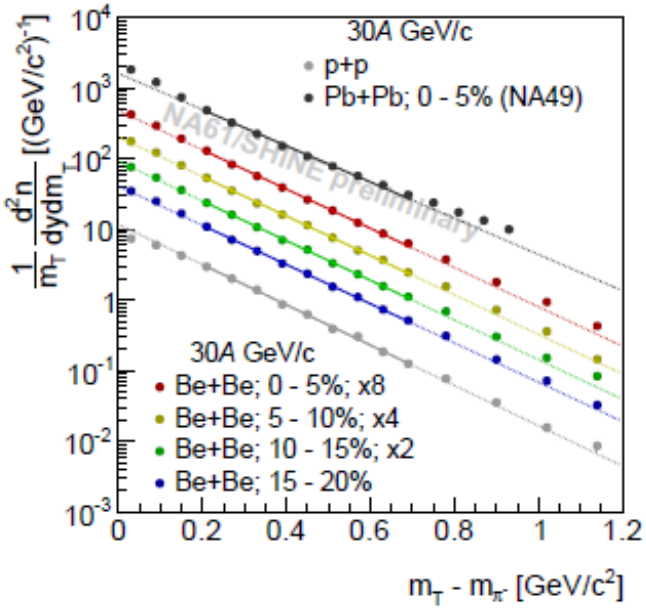


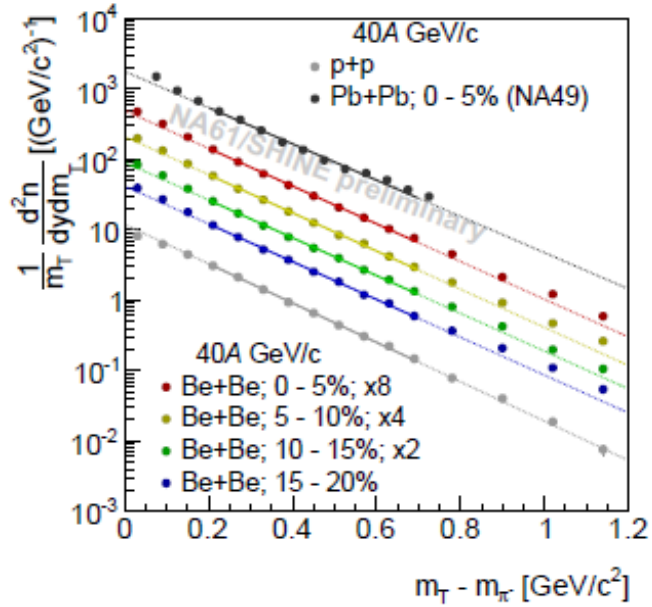


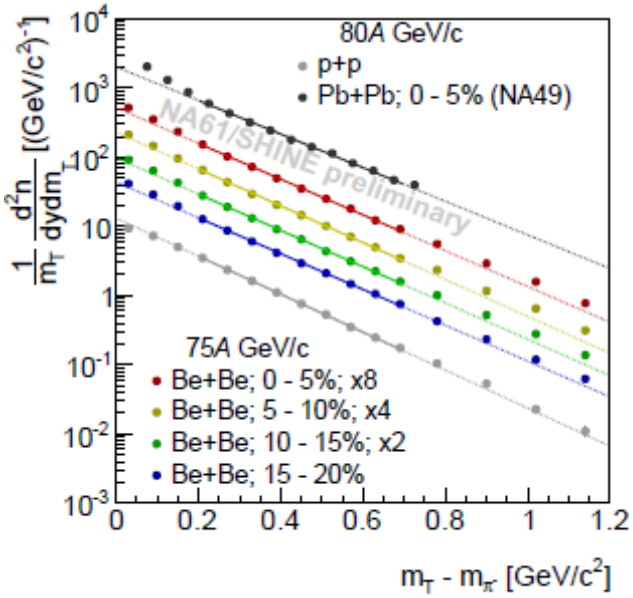
- Fitted: double Gaussian function symetrically from mid-rapidity (both Gaussians have the same width, but they differ in amplitude)
- Asymmetry decreases from 0.86(0-5%) to 0.97(15-20%)
- Two opposite effects influance asymmetry of the spectra: asymetric system (small effect) and centrality selection based on projectile spectators (large effect)

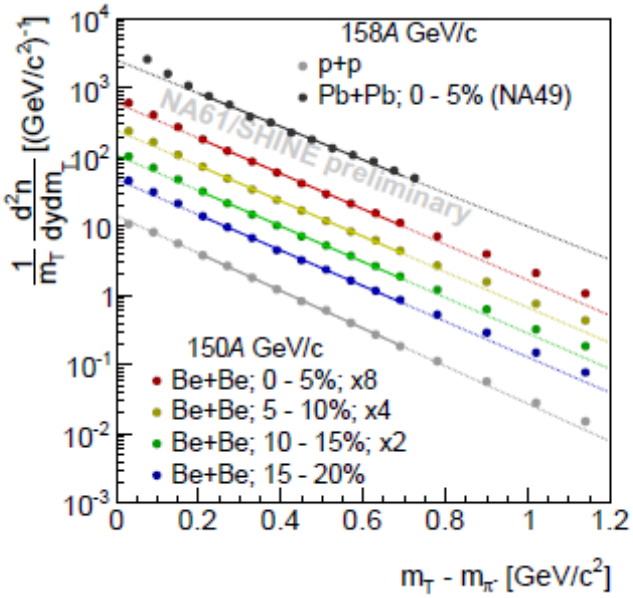
Transverse mass spectra of π-











$0.2 < m_T < 0.7$ GeV/c²

$$\frac{d^2n}{dydm_T} = Am_T exp\left(\frac{-m_T}{T}\right)$$

Fluctuations quantities

Two families of quantities which in wounded nucleon model or GCE are:

Intensive

A ratio of two extensive quantities ($\sim N_W$) is an intensive measure e.g.:

$$\omega[A] = \frac{\langle A^2\rangle - \langle A\rangle^2}{\langle A\rangle},$$

where A stands for an event quantity.

- independent of N_W
- depends on fluctuations of N_W
- $\omega = 1$ for Poisson distribution

In WNM $\omega_i = \frac{Var(a)}{\langle a\rangle} + \langle a\rangle \frac{Var(N_W)}{\langle N_W\rangle}$, where a - particles produced from single wounded nucleon

Strongly intensive

Special combination of extensive quantities can be a strongly intensive measure e.g.:

$$\Delta[A, B] = \frac{1}{C_\Delta}\left[\langle B\rangle\omega_A - \langle A\rangle\omega_B\right]$$

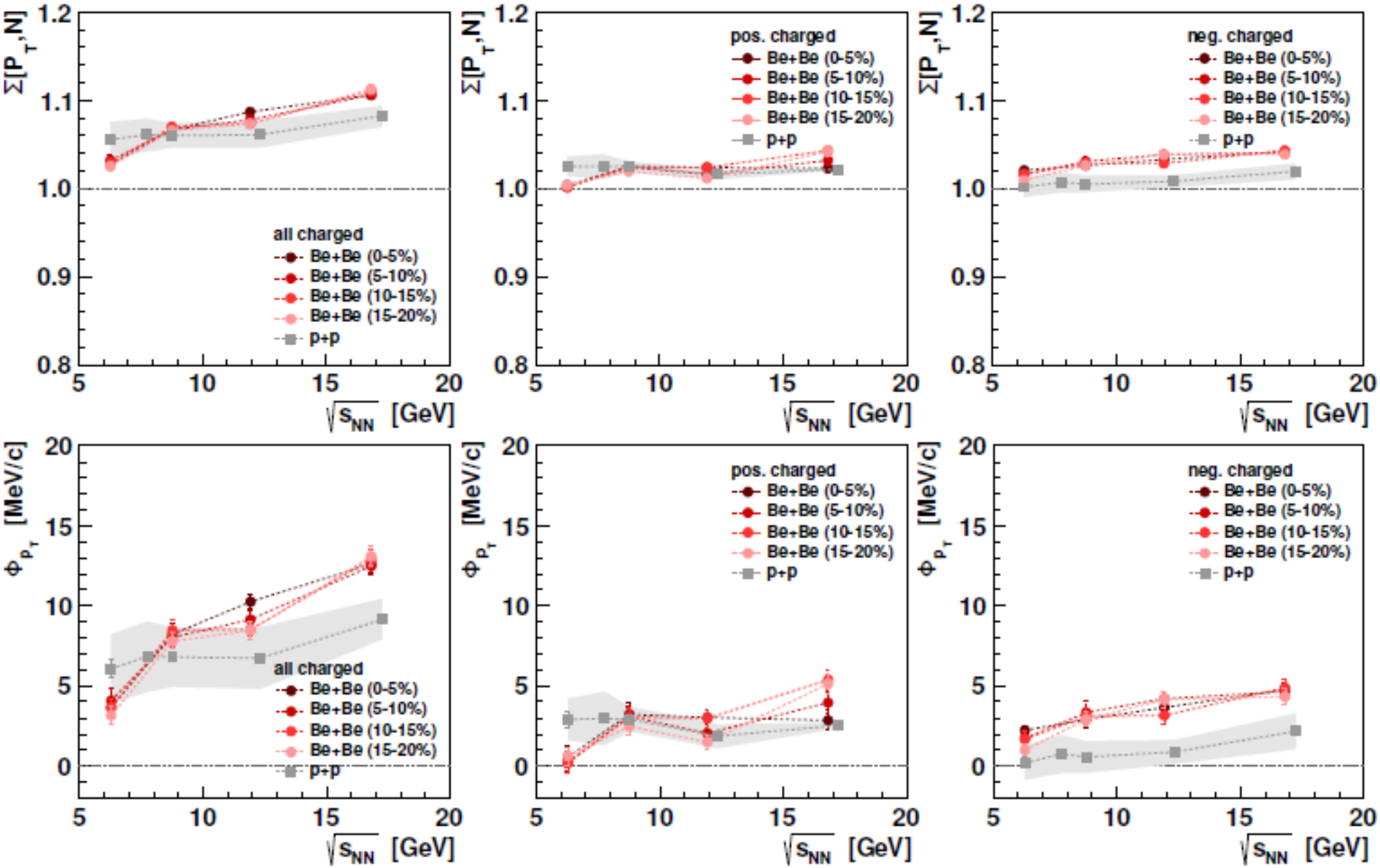
$$\Sigma[A, B] = \frac{1}{C_\Sigma}\left[\langle B\rangle\omega_A + \langle A\rangle\omega_B - 2\left(\langle AB\rangle - \langle A\rangle\langle B\rangle\right)\right]$$

- independent of N_W and fluctuations of N_W
- normalization chosen such that $\Delta[A, B] = \Sigma[A, B] = 1$ for independent particle model and both quantities are dimensionless
- $\Delta[A, B] = \Sigma[A, B] = 0$ in the absence of fluctuations

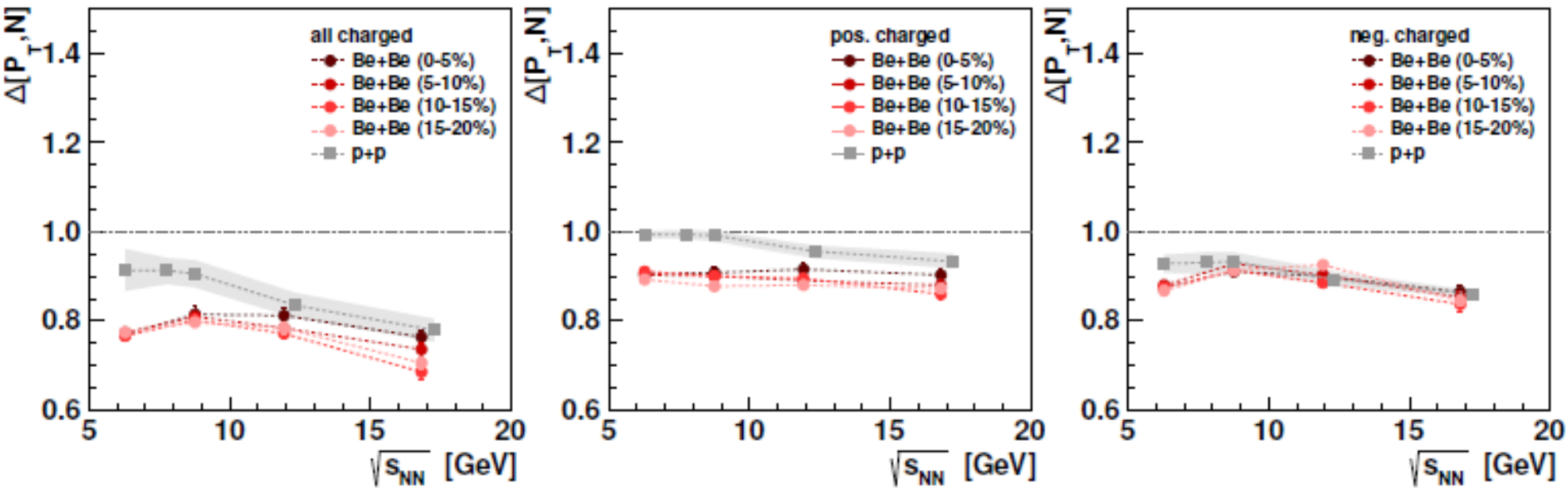
For comparison with the NA49 experiment the Φ quantity is used:

$$P_T = \sum_{i=1}^{N} p_{T_i} \quad \Phi_{p_T} = \sqrt{\bar{p_T}\omega[p_T]}\left[\sqrt{\Sigma[P_T, N]} - 1\right] \qquad \Phi_{ij} = \frac{\sqrt{<N_i><N_j>}}{<N_i+N_j>} \cdot \left[\sqrt{\Sigma[i, j]} - 1\right]$$

Energy dependence of $\Sigma[P_T,N]$ and Φ_{P_T}

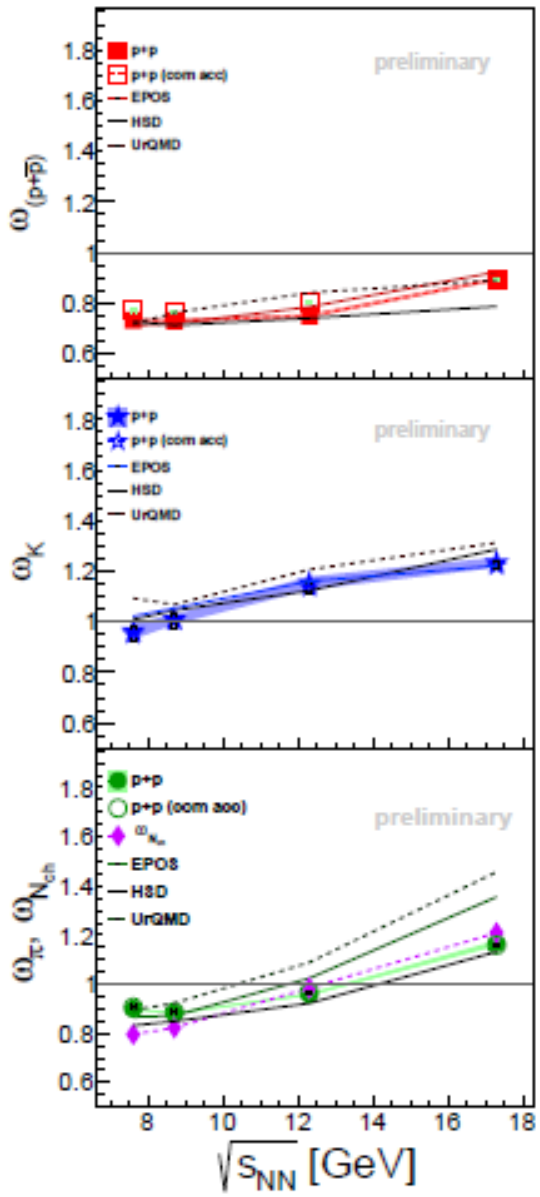


Energy dependence of $\Delta[P_T,N]$

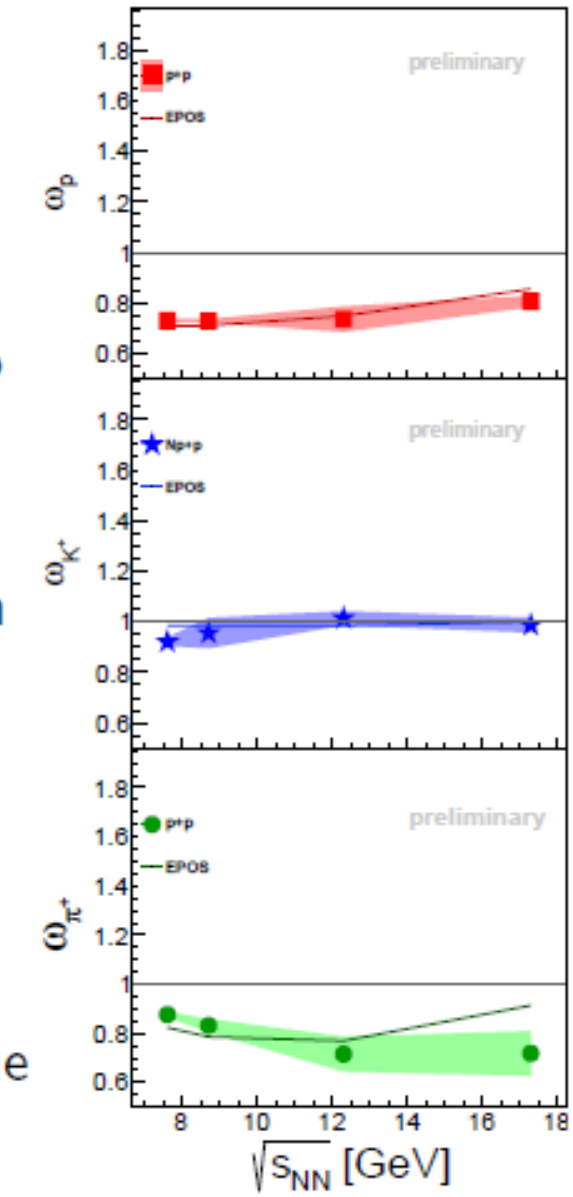


- Be+Be results close to p+p
- no structures which could be connected to the CP/OD in p+p and Be+Be
- no centrality dependence in Be+Be
- Bose-Einstein statistics and $P_T/N - N$ correlations probably introduce difference between Δ and Σ (PRC 89, 034903)

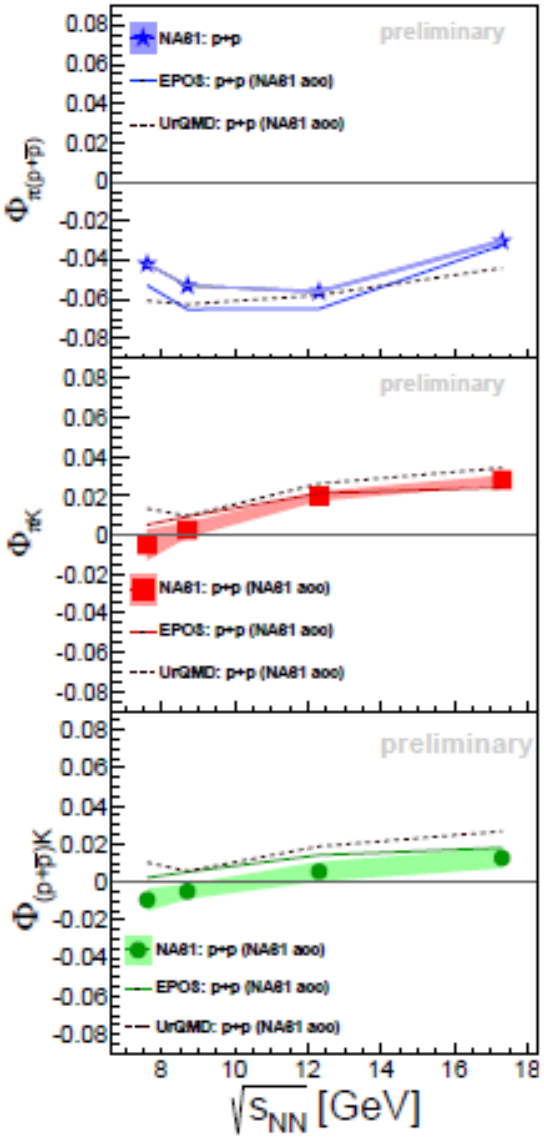
Energy dependence of identified particle fluctuations



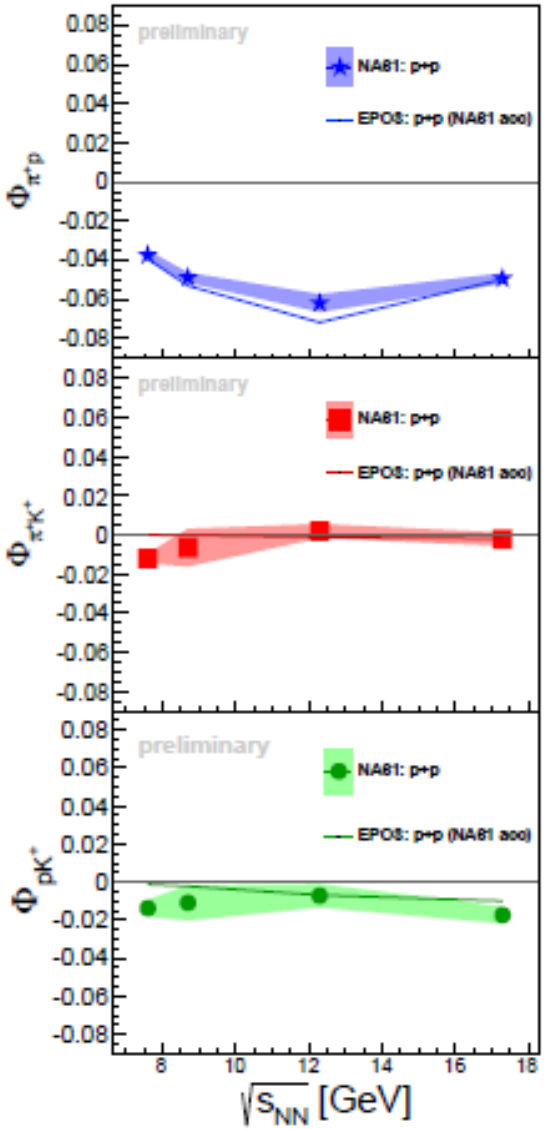
- identity method (PRC84,024902) used for identification
- $\omega_{p+\bar{p}} \approx \omega_p < 1$ probably due to baryon number conservation
- $\omega_K > 1$ and $\omega_{K^+} \approx 1$ probably due to strangeness conservation
- increase of ω_π reflects increase of $\omega_{N_{ch}}$ in full phase-space
- $\omega_{\pi^+} < \omega_\pi$ probably due to charge conservations
- popular HIC models describe the data

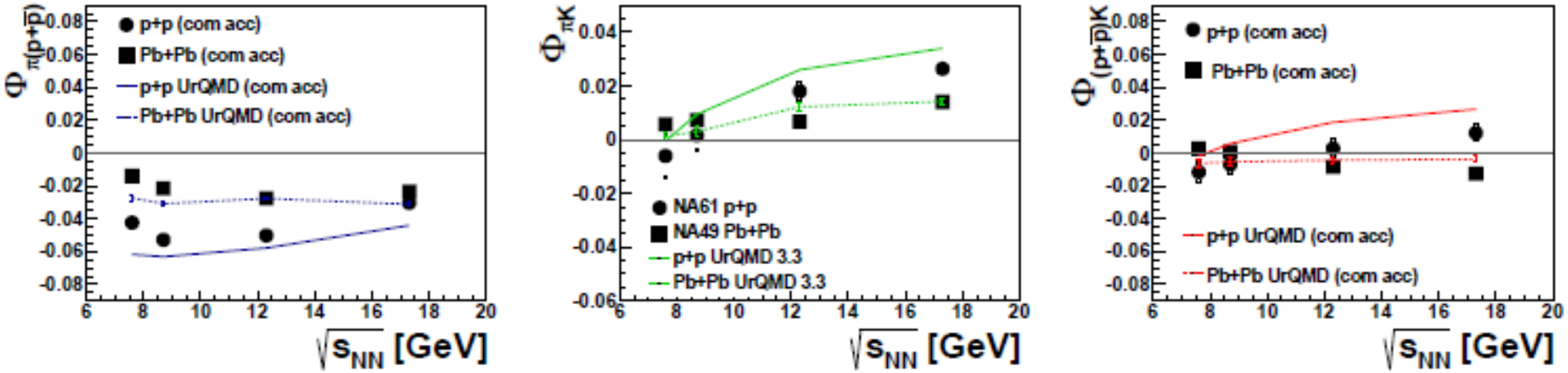


Energy dependence of identified particle fluctuations

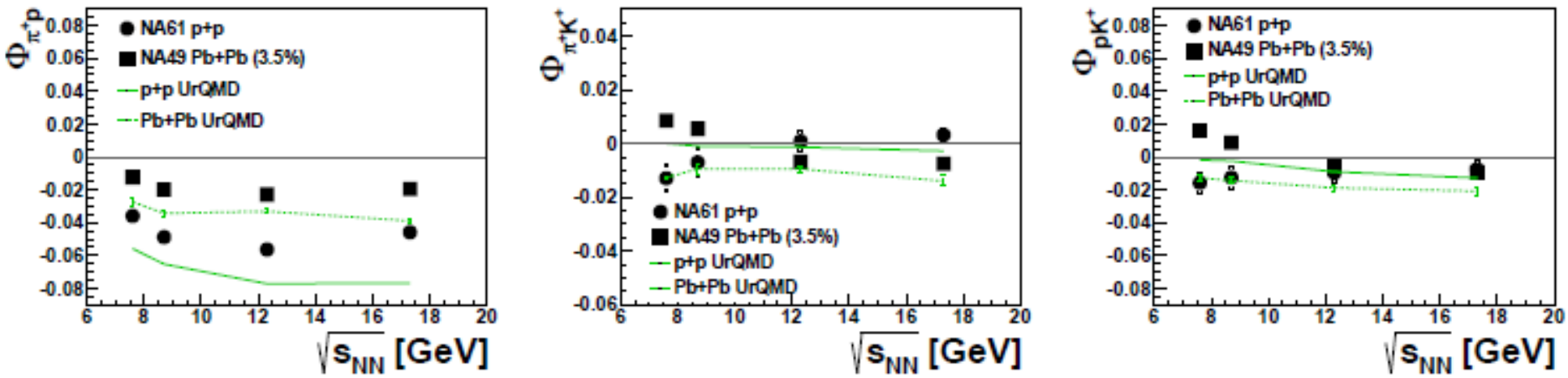


- $\Phi_{\pi(p+\bar{p})}$ and Φ_{π^+p} below 0 probably due to conservation laws and resonance decays
- $\Phi_{\pi K} > 0$ probably due to strangeness conservation. $\Phi_{\pi^+K^+} \approx 0$ supports this interpretation.
- $\Phi_{(p+\bar{p})K}$ shows very weak energy dependence and crosses 0 at middle SPS energies
- EPOS and UrQMD model predictions qualitatively describe the data





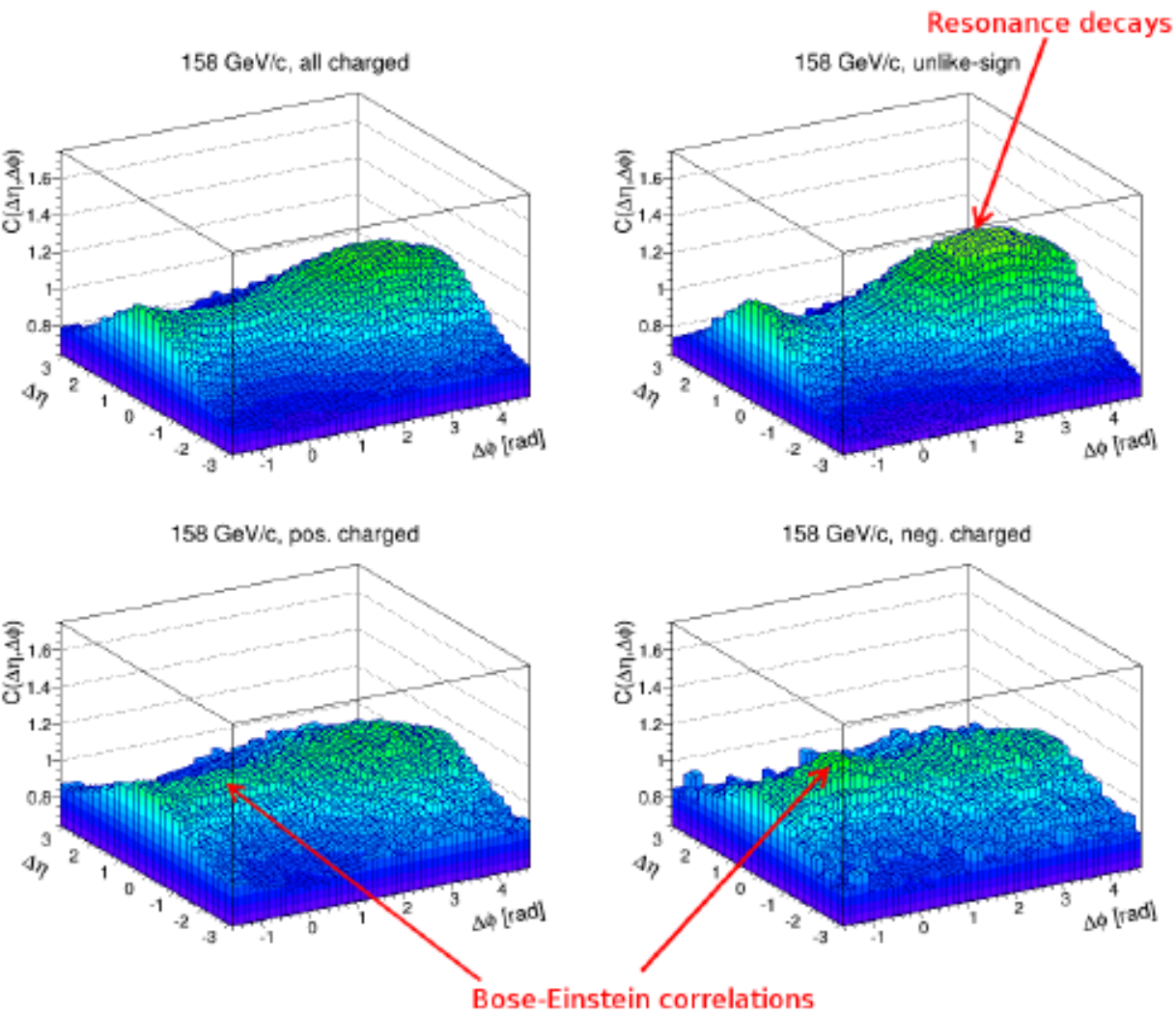
- fluctuations in p+p and Pb+Pb interactions are comparable
- $\Phi_{\pi K}$ in p+p interactions increases with energy whereas in Pb+Pb interaction it is not
- in p+p interactions $\Phi_{(p+\bar{p})K}$ weakly increases with energy whereas in Pb+Pb interactions it decreases with energy. In both reactions it crosses 0 at the same energy
- UrQMD model describes energy dependence in p+p and Pb+Pb interactions except $\Phi_{(p+\bar{p})K}$ in Pb+Pb



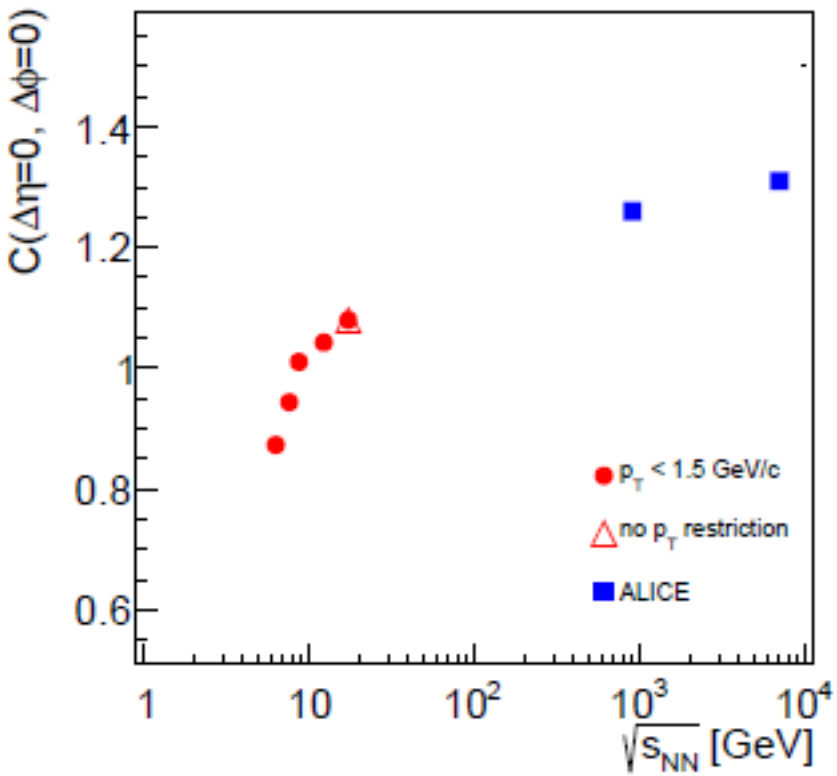
- similar tendency of Φ_{π^+p} in p+p and Pb+Pb
- in p+p interactions $\Phi_{\pi^+K^+}$ weakly increases with energy whereas in Pb+Pb interactions it decreases with energy
- UrQMD model does not describe $\Phi_{\pi^+K^+}$ and Φ_{pK^+} in Pb+Pb at low SPS energies

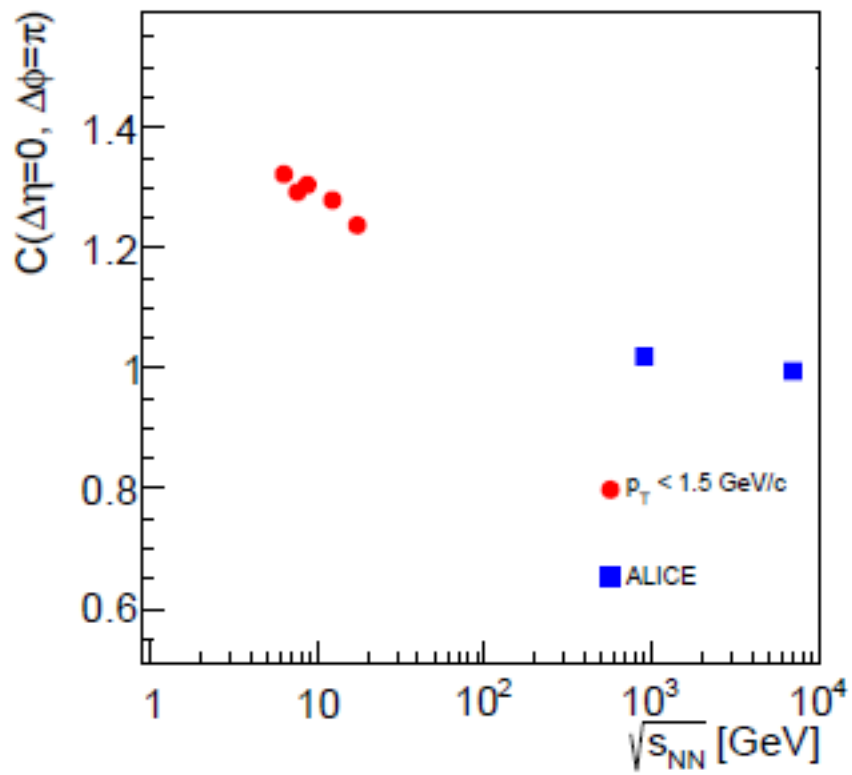
Charged pion fluctuations

B. Maksiak, CPOD(2014)



- Maximum at $(0, \pi)$ - probably due to resonance decays and momentum conservation
  - strong in unlike-sign pairs
  - visible in positively charged pairs (Δ^{++} decay)
  - non-visible in negatively charged pairs
- Enhancement at $(0, 0)$ - probably due to Coulomb or quantum statistics (not strong in unlike-sign pairs, visible in same charge pairs)





$C(0,0)$ rises whereas $C(0,\pi)$ decreases with energy dependence.