Recent Results from the NA61/SHINE Experiment

Andrzej Wilczek
for the NA61 Collaboration

Institute of Physics, University of Silesia, Katowice

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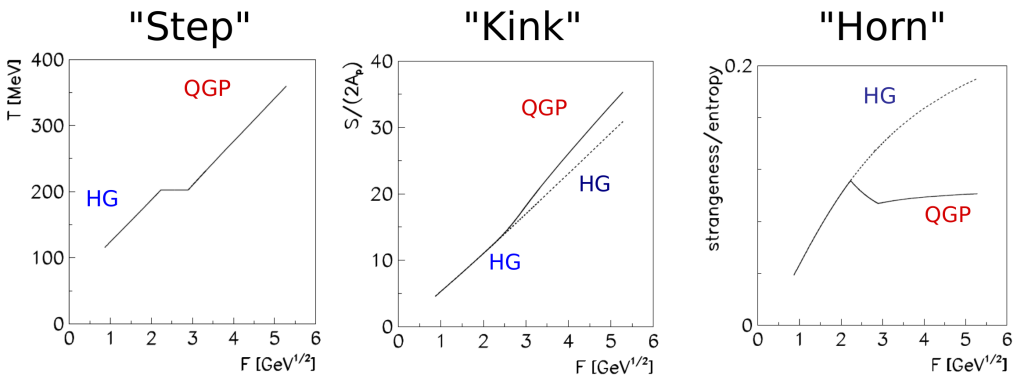
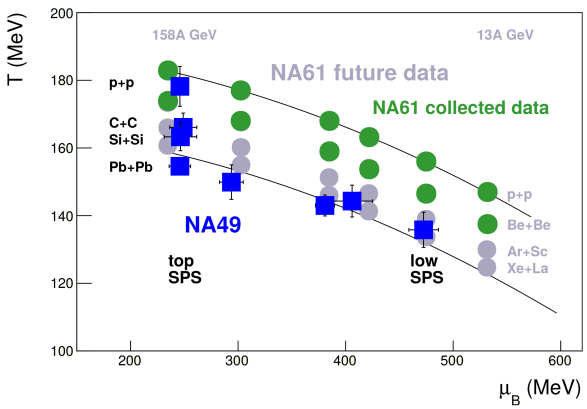
NA61/SHINE and its strong interaction program

- NA61/SHINE is a large acceptance spectrometer for fixed target experiments on primary (ions) and secondary (ions, hadrons) beams
- Presented are results on inelastic p+p and ^{7}Be+^{9}Be interactions
- The strong interaction program of NA61/SHINE aims at:
  - Studying properties of the onset of deconfinement:

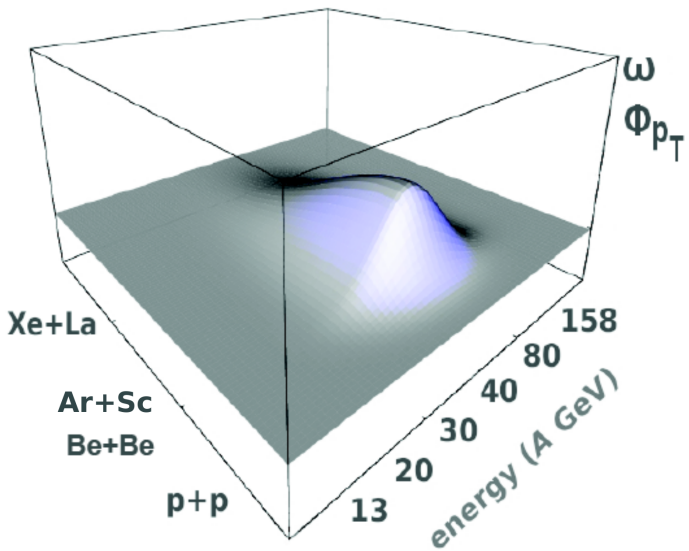


$$F \approx \sqrt[4]{s_{NN}}$$

Gaździcki, Gorenstein, Acta Phys. Polon. B30 (1999)

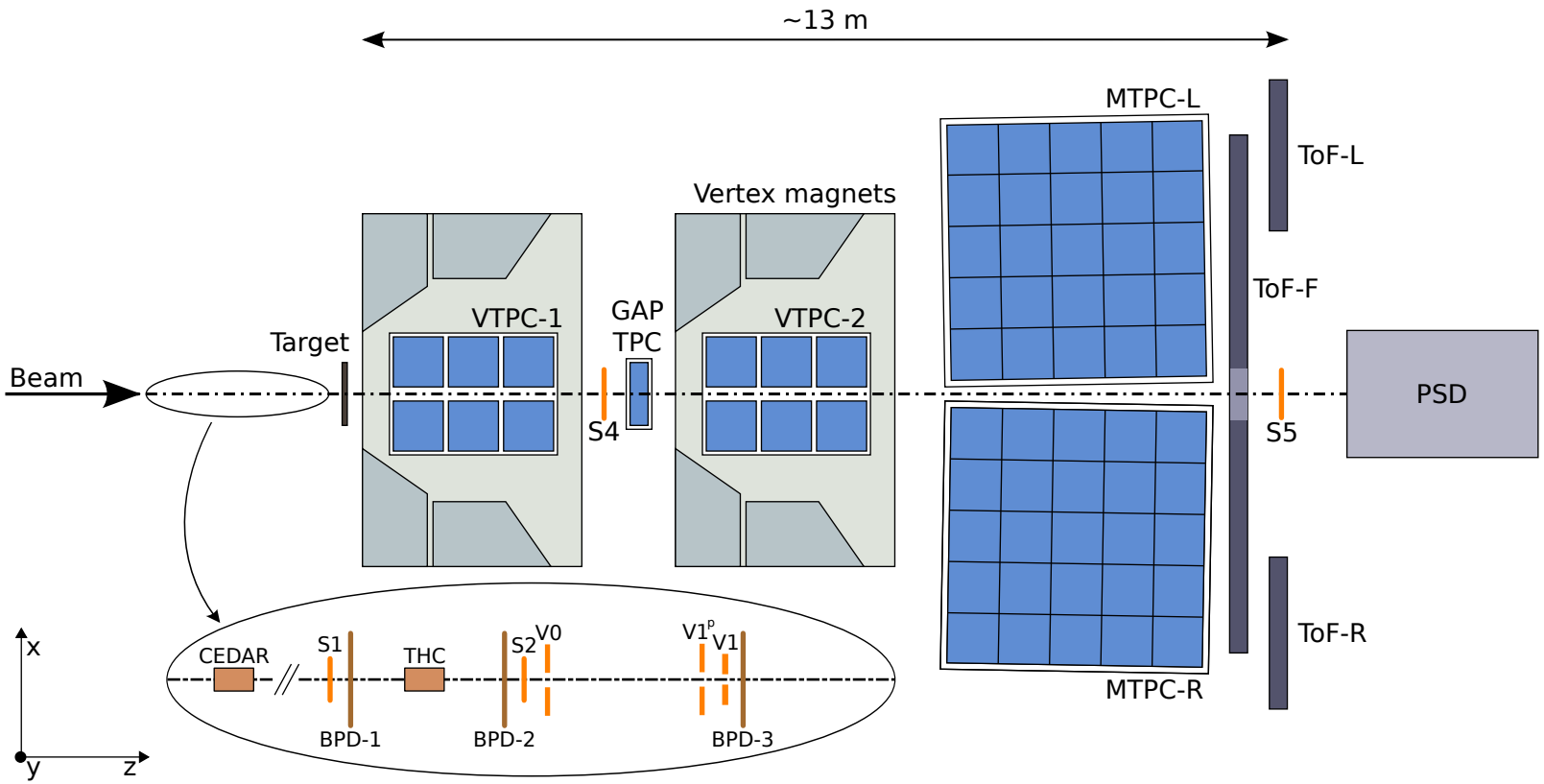


- Searching for the critical point of strongly interacting matter:



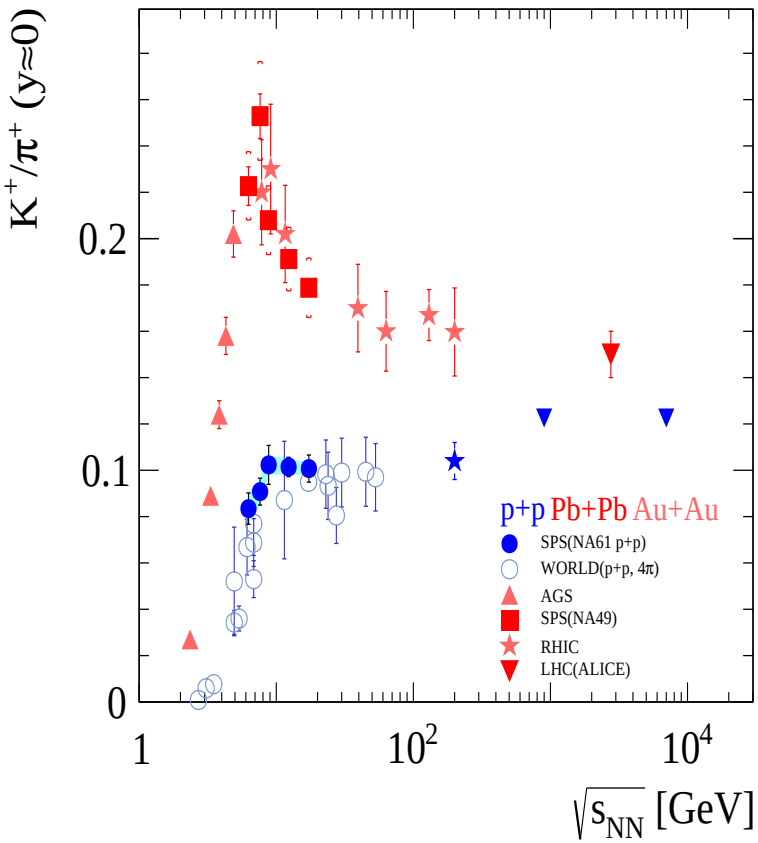
NA61/SHINE Detector

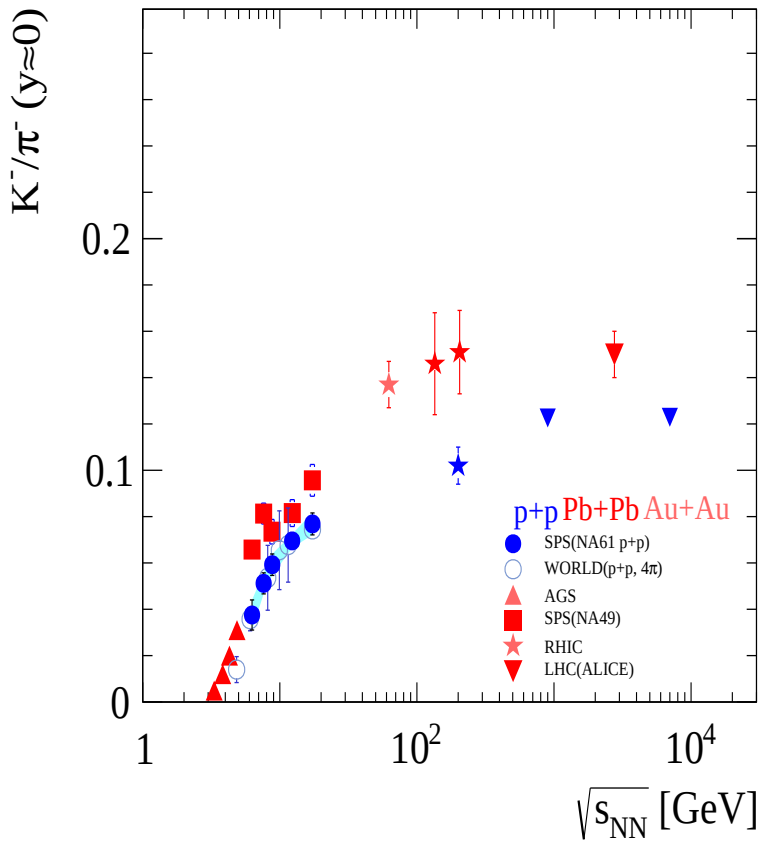
- Unique, multi-purpose facility to study hadron production in hadron-proton, hadron-nucleus, and nucleus-nucleus collisions at the CERN SPS
- p, Be, Ar, Xe, Pb beam in momentum range 13-158 GeV/c per nucleon, and π beam up to 350 GeV/c are used



N Abgrall et al 2014 JINST 9 P06005

K/π ratio - horn

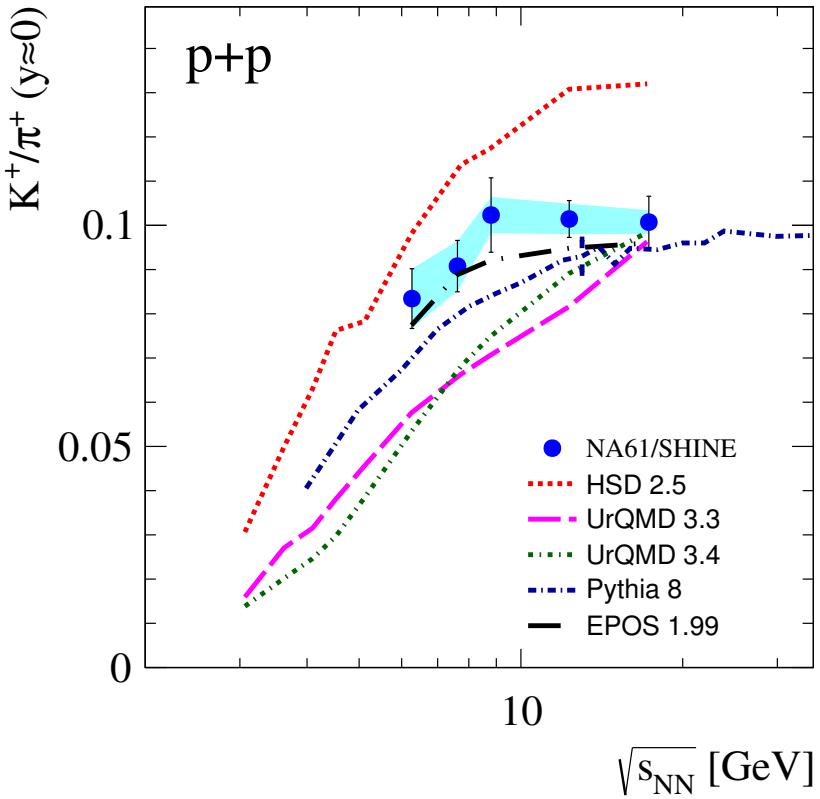


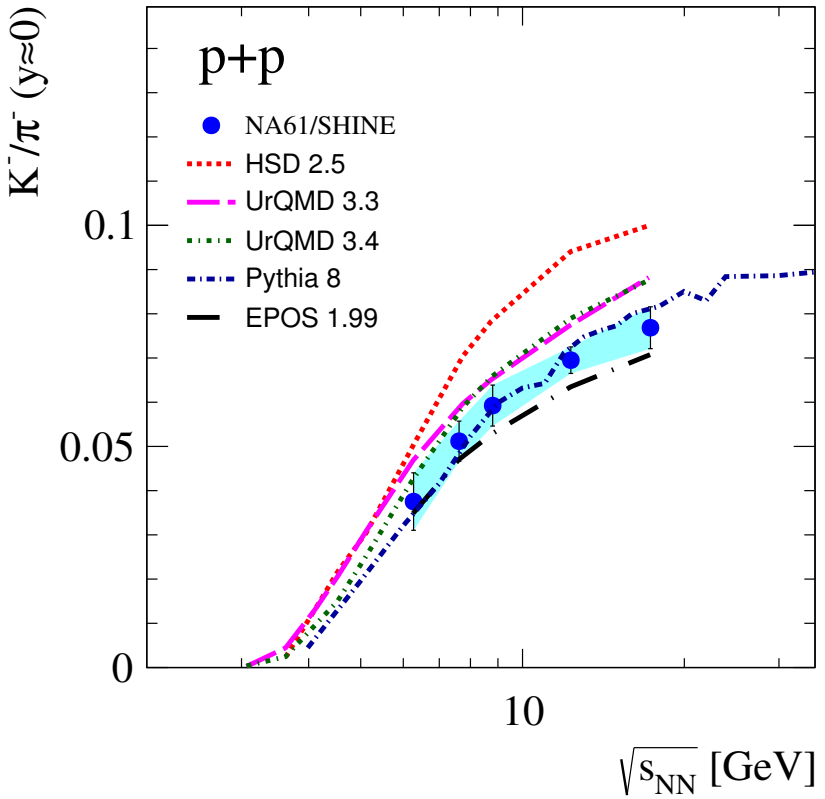


- The energy dependence of K^+/π^+ ratio in p+p changes at the energy where the horn structure is visible in Pb+Pb

CERN-SPSC-2014-031; SPSC-SR-145

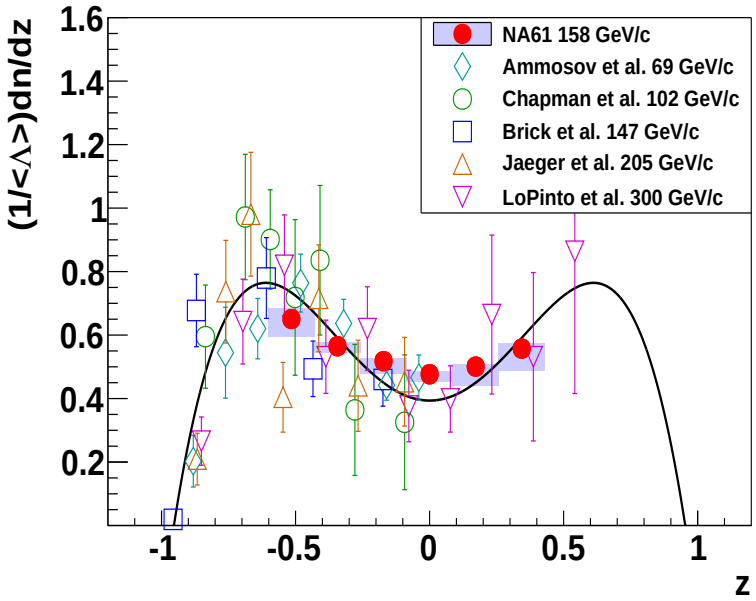
Model comparison

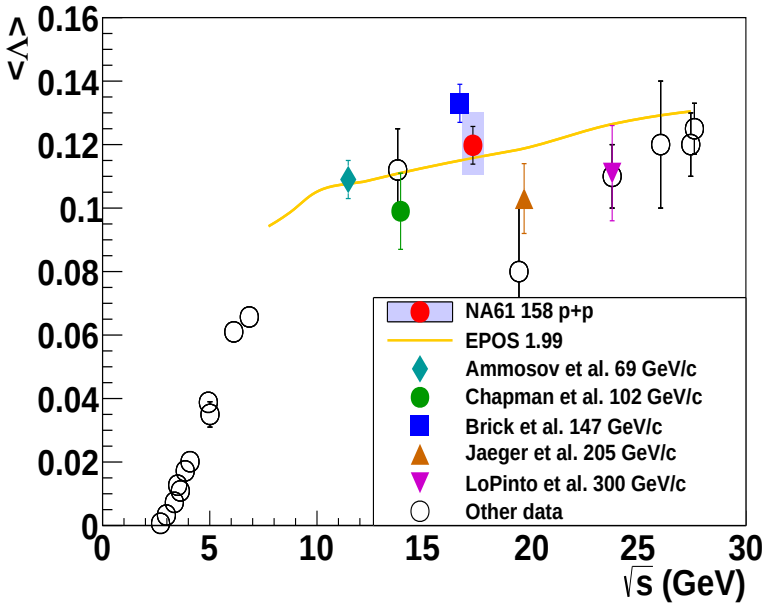




- Monte-Carlo models provide a poor description of the data

Λ rapidity spectrum & multiplicity

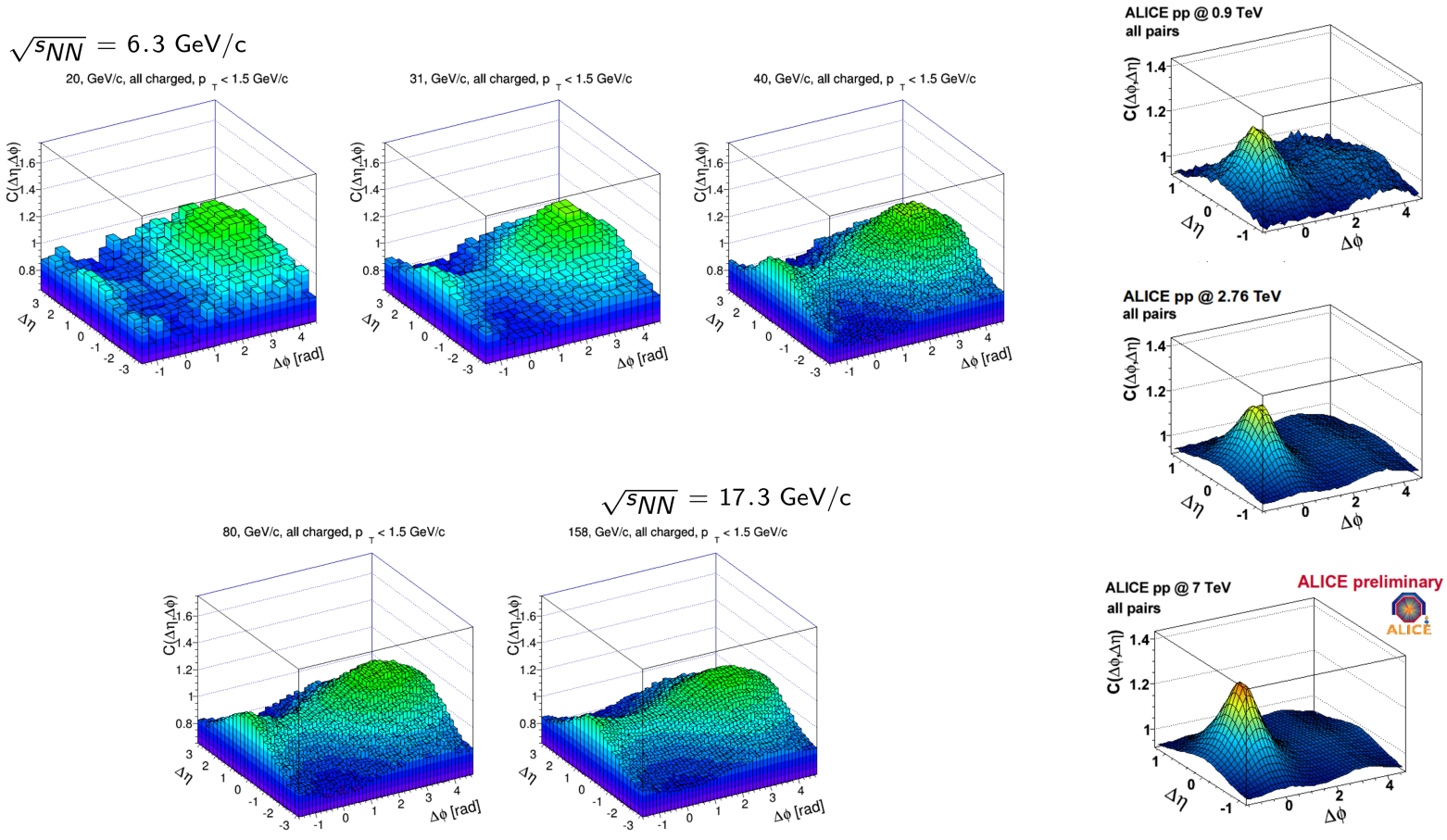




$$z = y/y_{beam}$$

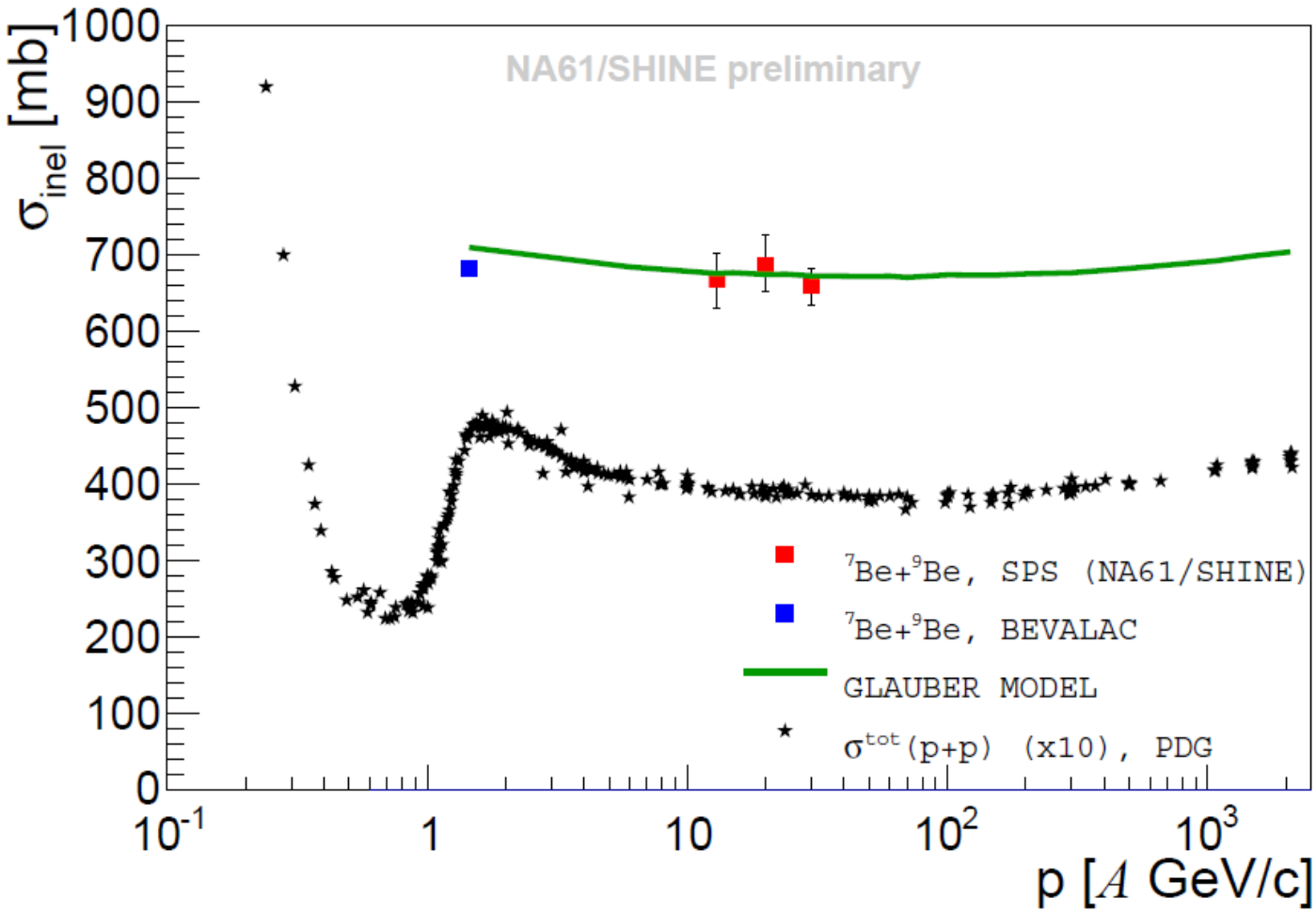
- NA61/SHINE results consistent with world data
- Other NA61/SHINE energies – work in progress

Two-particle correlations in $\Delta\eta,\Delta\phi$ in p+p



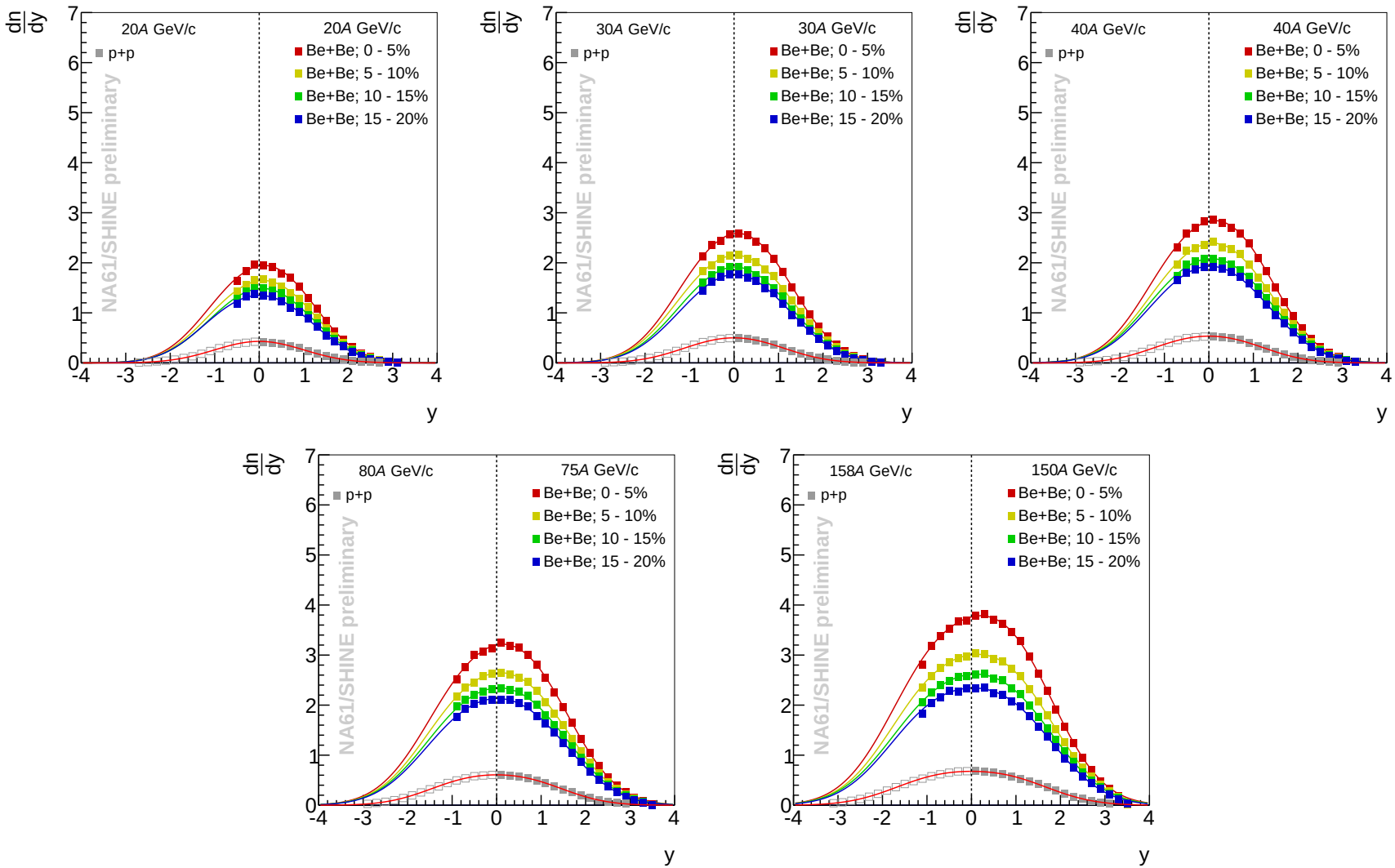
- NA61/SHINE: maximum at $(\Delta\eta, \Delta\phi)$=(0,π) probably due to resonance decays and momentum conservation
- In comparison with ALICE, the NA61/SHINE results show stronger enhancement in $\Delta\phi \approx \pi$ and no 'jet peak'

Inelastic ^{7}Be+^{9}Be cross section



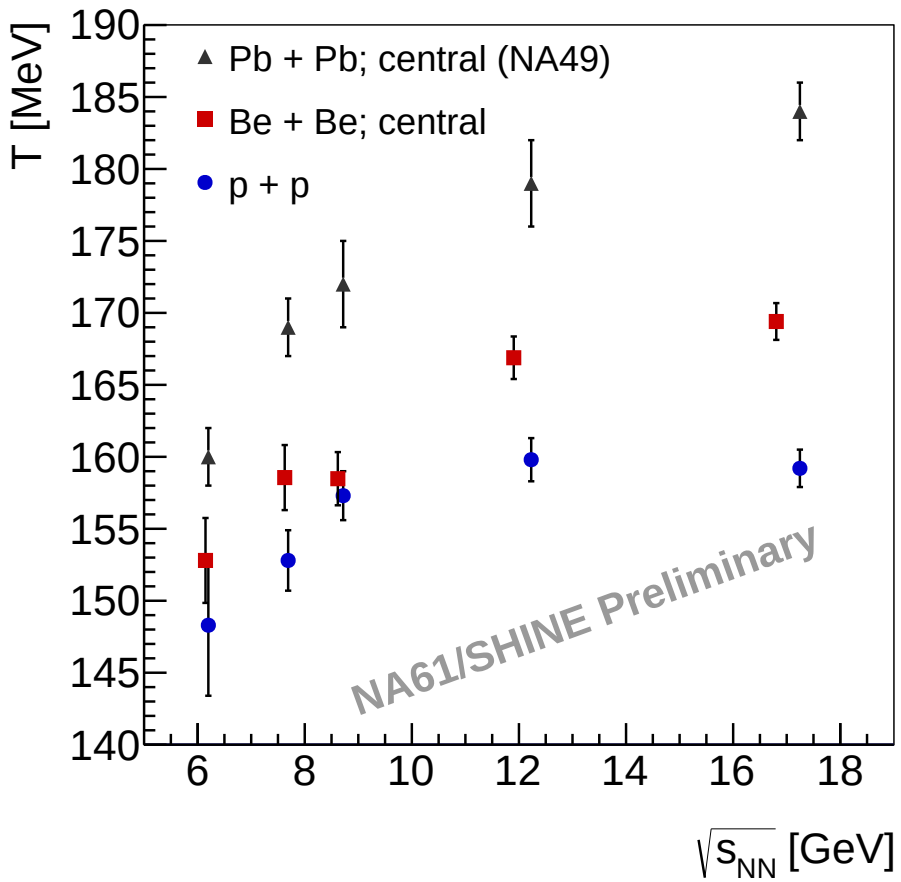
- NA61 measurements together with 1A GeV/c Bevalac data established energy dependence of inelastic cross section

Rapidity spectra

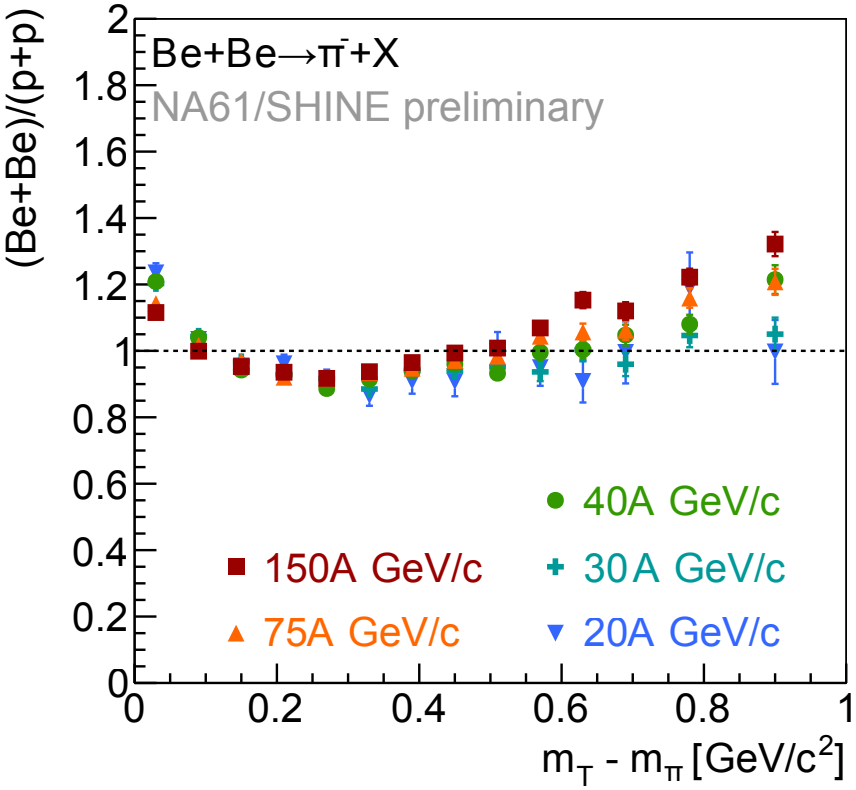


Inverse slope parameter, system size and energy dependence

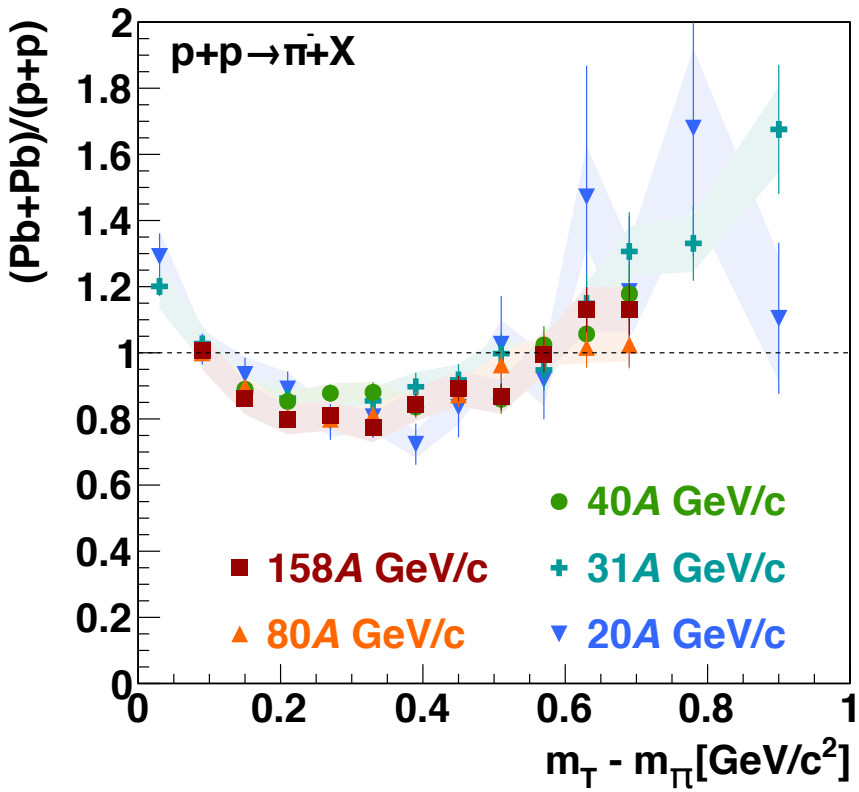
- Pb+Pb: high inverse slope parameter due to radial flow
- ^{7}Be+^{9}Be points are between p+p and Pb+Pb - a possible evidence of transverse collective flow in Be+Be
- Note: T parameter in A+A collisions is sensitive to the fit range and size of rapidity bin



Comparison of π transverse mass spectra



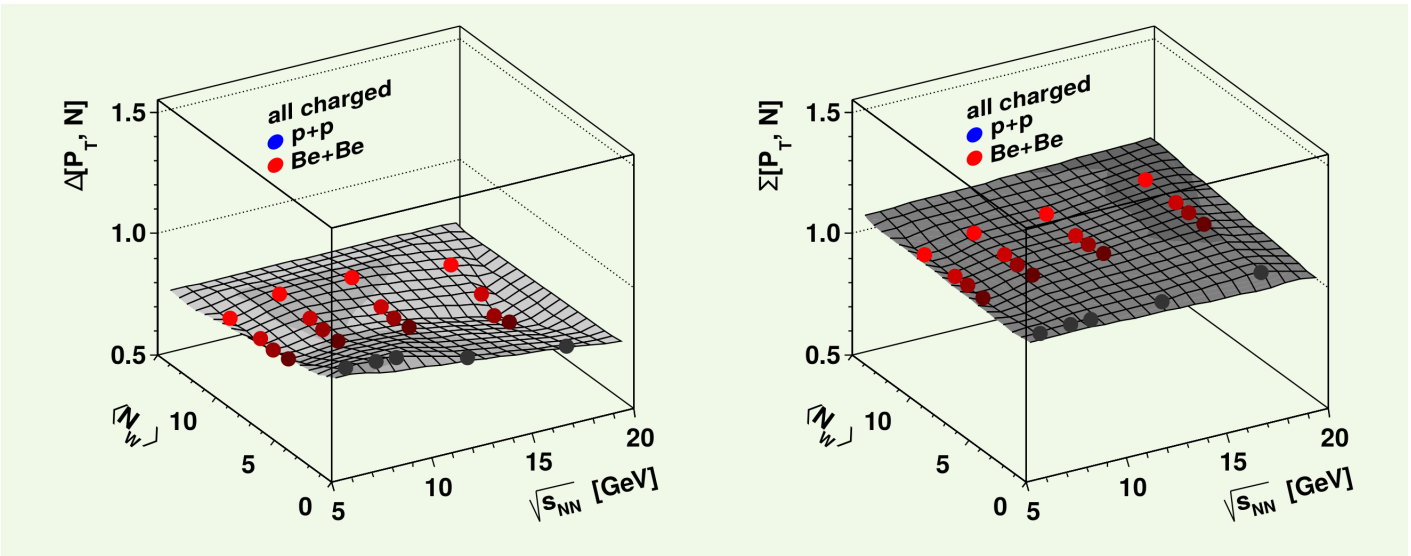
- Ratio of normalised m_T spectra at different energies
- ^{7}Be+^{9}Be data for 15% of the most central interactions
- Pb+Pb data for 5 or 7.5% of the most central interactions



- For $m_T - m_{\pi^-} < 0.3$ the ratio decreases with increasing energy
- For $m_T - m_{\pi^-} > 0.3$ the ratio increases
- The shape indicates a presence of radial collective flow

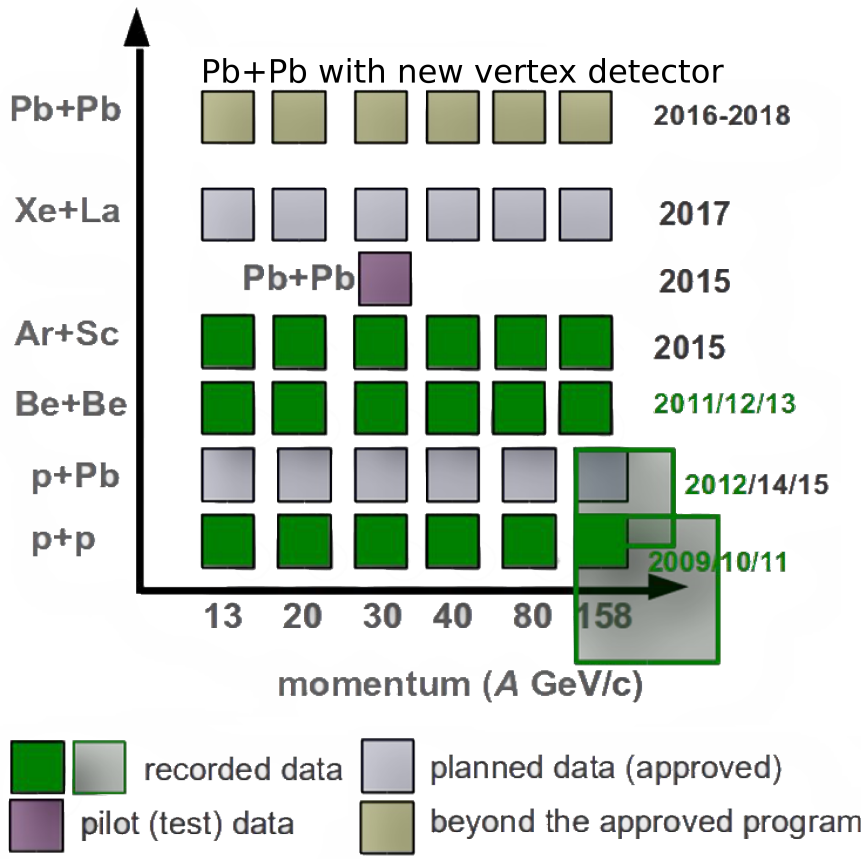
Transverse momentum multiplicity fluctuations in p+p and ^{7}Be+^{9}Be

- Δ and Σ fluctuation measures
  - Δ and Σ are observables characterising fluctuations of system properties
  - They are strongly intensive in GCE
  - $\Delta = 1$ and $\Sigma = 1$ for independed particle emission
  - Critical point of strongly interacting matter: extremum of fluctuations
- First results
  - No sign of any anomaly that can be attributed to the critial point (neither in p+p nor ^{7}Be+^{9}Be)
  - The analysis will be continued for Ar+Sc - data taken this year



Summary and outlook

- NA61/SHINE measures collisions of hadrons and ions in the SPS energy range
- High precision double-differential pion spectra were measured in p+p and ^{7}Be+^{9}Be collisions at 5 different energies
- Rapid changes in particle production are observed in p+p collisions at mid-SPS energy
- Collective effects are observed in ^{7}Be+^{9}Be reaction
- No sign of any anomaly that can be attributed to critical point in p+p and ^{7}Be+^{9}Be interactions
- The analysis of Ar+Sc data is in progress



BACKUP

Full physical program

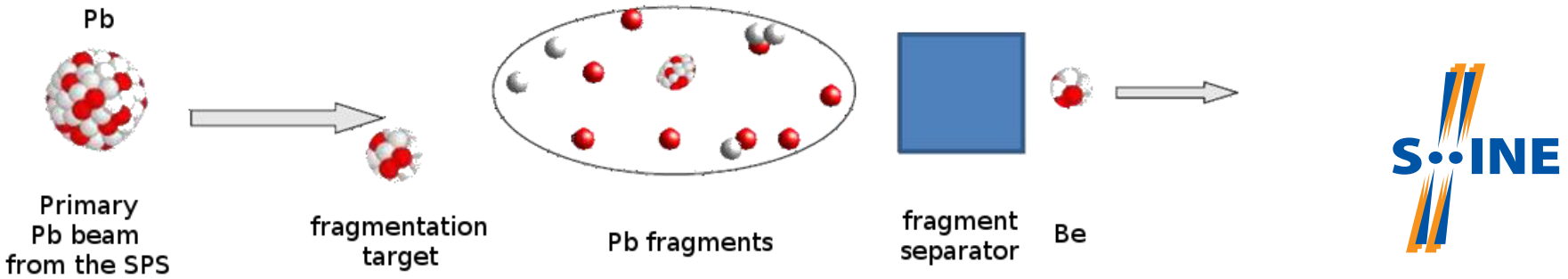
What is it?

- A TPC-based large acceptance (50%) spectrometer in fixed-target configuration
- High momentum resolution $\sigma(p)/p^2 \approx 10^{-4}(GeV/c)^{-1}$ (at full $\int B\, dl = 9T \cdot m$)
- Very well particle identification $\sigma(dE/dx)/ < dE/dx > \approx 0.04$
- TOF resolution for TOF-L/R $\sigma(t) \approx 60\ ps$ TOF-F: $\sigma(t) \approx 120\ ps$
- The second largest non-LHC experiment at CERN
- proton, Be, Ar, Xe, Pb beam momentum range 13-158 GeV/c, π beams up to 350 GeV/c.

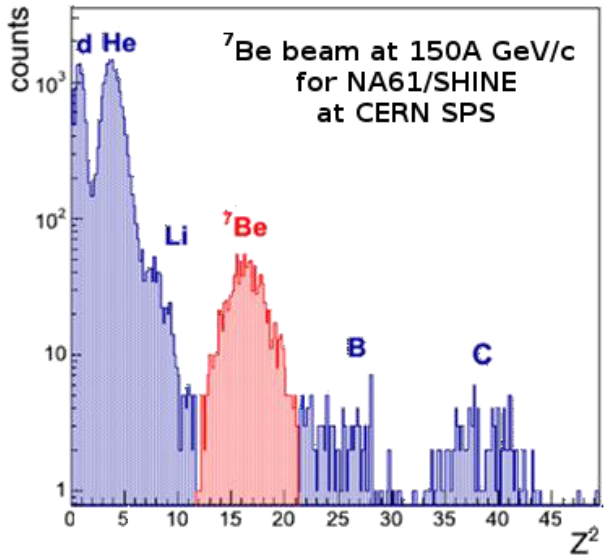
Physics program

- Strong interactions program:
  - Search for the critical point of strongly interacting matter
  - Research on the properties of the onset of deconfinement
  - Studies on high p_T (energy dependence of nuclear modification factor)
- Measurement of hadroproduction for neutrino experiments
  - Reference measurements of p+C interactions for the T2K experiment - initial neutrino flux calculations
- Measurement of hadroproduction for cosmic-ray experiments
  - Reference measurements of p+p, p+C, π+C and K+C interactions for improving air shower simulations (Pierre-Auger and KASCADE experiments)

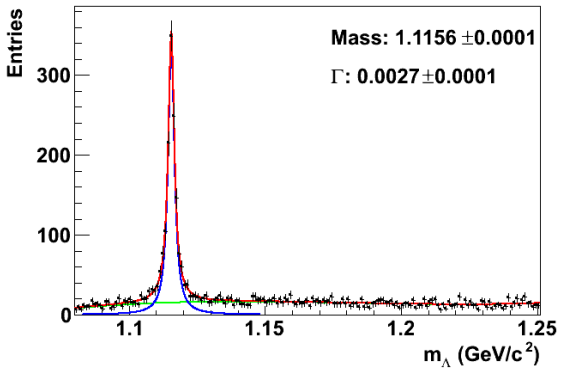
Be secondary beam



- Target length optimised such to maximise the production of ^{7}Be
- Double magnetic spectrometer used to separate fragments due to selected magnetic rigidity
- Cu plate can be used as a degrader to damp the content of multiply charged fragments
- ^{7}Be is triggered on using a very low threshold (0.88A GeV/c) Cherenkov detector with quartz plate as a radiator

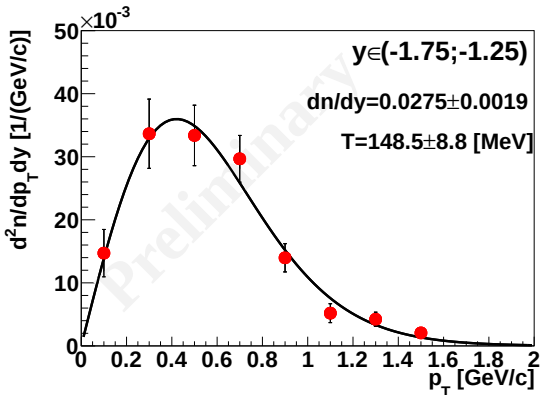


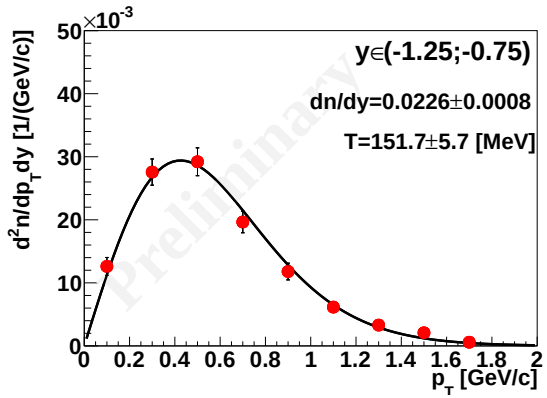
Lambda p_T spectra

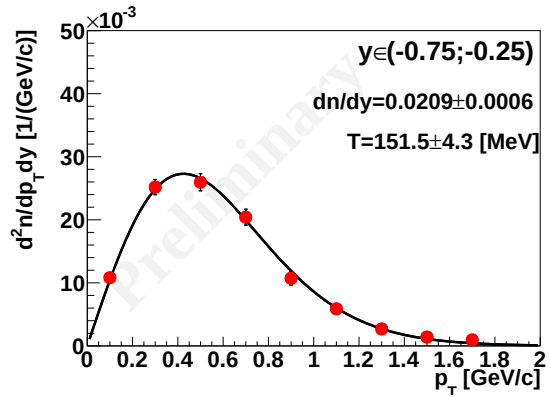


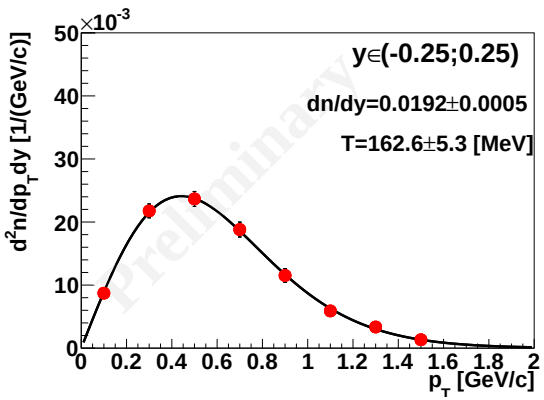
- y-pT spectra calculated
- fitted function:

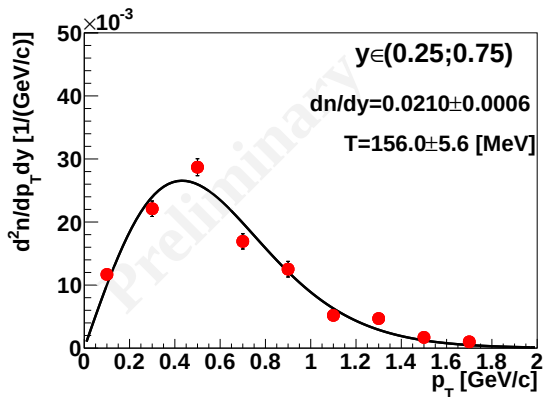
$$\left.\frac{n2n}{dp_T dy}(p_T)\right|_y = A p_T e^{-\frac{\sqrt{p_T^2+m_\Lambda^2}}{T}}$$

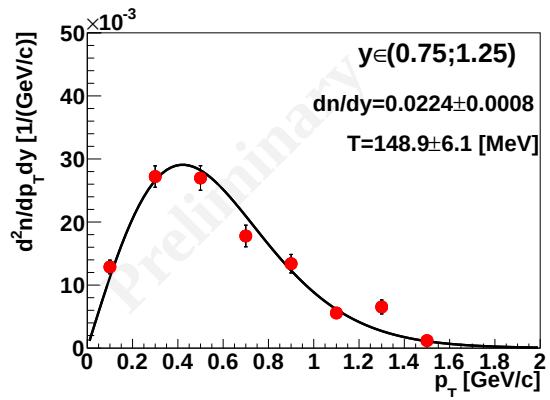








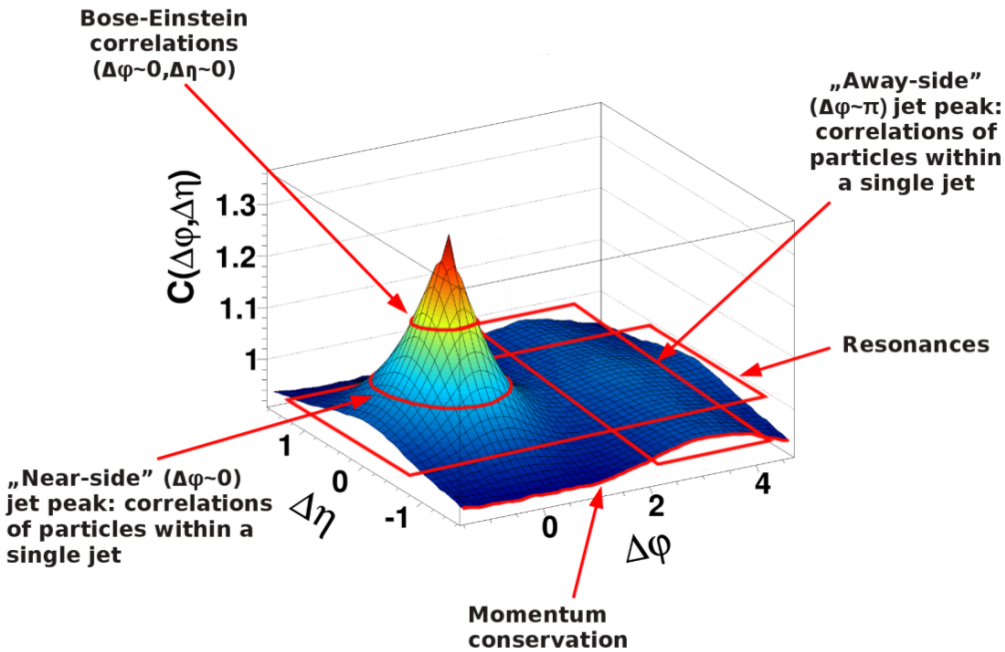




Two-particle correlations - motivation

Two-particle correlations in $\Delta\eta$, $\Delta\phi$.

- Studied extensively at RHIC and LHC.
- This method allows to disentangle different sources of correlations:
  - jets,
  - flow,
  - resonance decays,
  - quantum statistics effects,
  - conservation laws.



The motivation

To study the sources of correlations in the (fixed target) NA61 experiment.

Two-particle correlations - definitions

Correlations are calculated by finding the difference in pseudo-rapidity and azimuthal angle between two particles in the same event.

$\Delta\eta = |\eta_1 - \eta_2|$ η transformed from LAB to CMS assuming pion mass
$\Delta\phi = |\phi_1 - \phi_2|$
The azimuthal angle is folded (to improve statistics):
if $\Delta\phi > \pi$ then $\Delta\phi = 2\pi - \Delta\phi$.

Correlation function

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

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

Correlation function ratio is calculated and normalized in restricted $\Delta\eta$ region:
$0 < \Delta\eta < 3$.
Event and track cuts were chosen to select only inelastic interactions with particles produced in strong and EM processes within the NA61/SHINE acceptance. The results are corrected on detector effects: tracking inefficiencies, trigger bias (see next slides).

Strongly intensive quantities

Δ, Σ, and Φ definitions

$$\Delta[P_T, N] = \frac{1}{C_\Delta}\left[\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N]\right]$$

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

$$\Phi_{pT} = \sqrt{\langle p_T\rangle\omega[p_T]\left[\Sigma[P_T, N] - 1\right]}$$

where

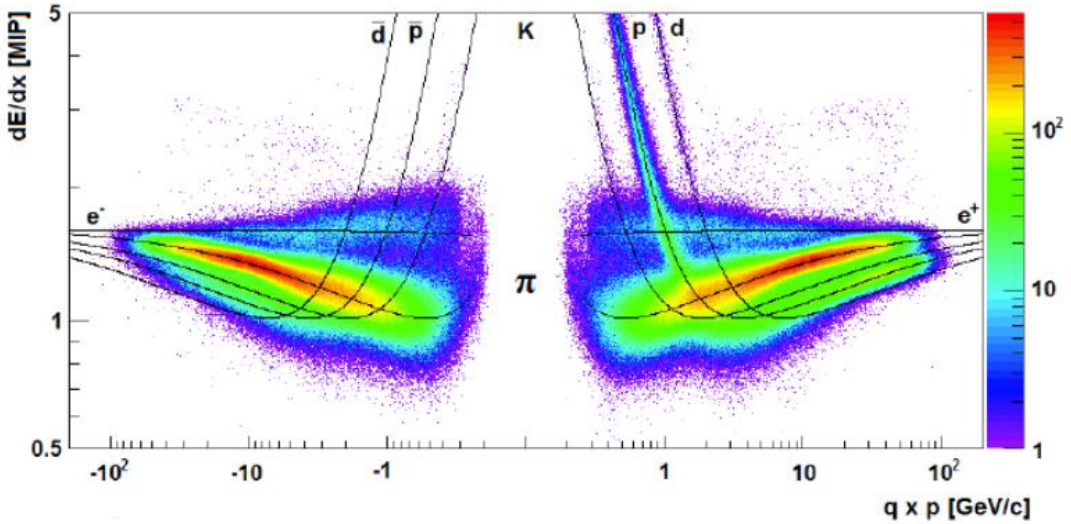
$$P_T = \sum_{i=1}^{N} p_{T_i}$$

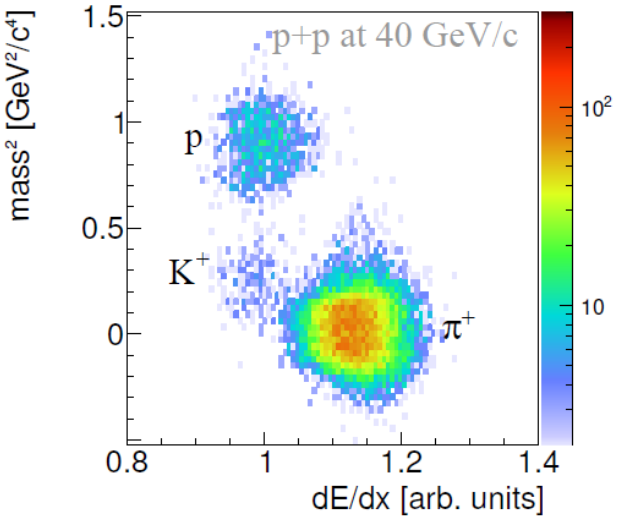
M.Gorenstein, M.Gazdzicki, Phys. Rev. C 84 (2011) 014904
M.Gorenstein, M.Gazdzicki, M.Mackowiak-Pawlowska, Phys. Rev. C 88 (2013) 2, 024907

Characteristics

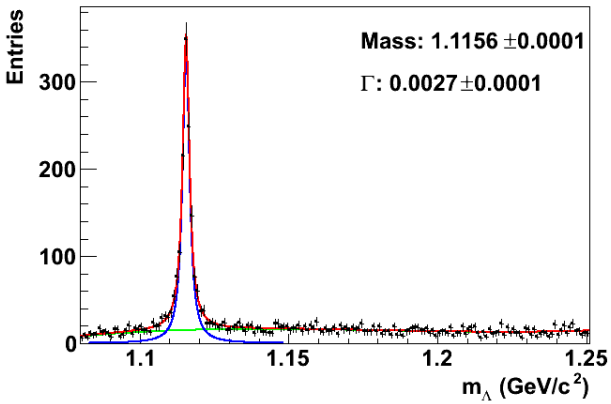
- Strongly intensive quantities are special combinations of intensive quantities
- They are not only independent of N_W (volume in GCE), but also of its fluctuations
- The measures are equal to 1 for the independent particle emission
- The normalisation factors ensure the quantities are dimensionless

Particle identification and corrections

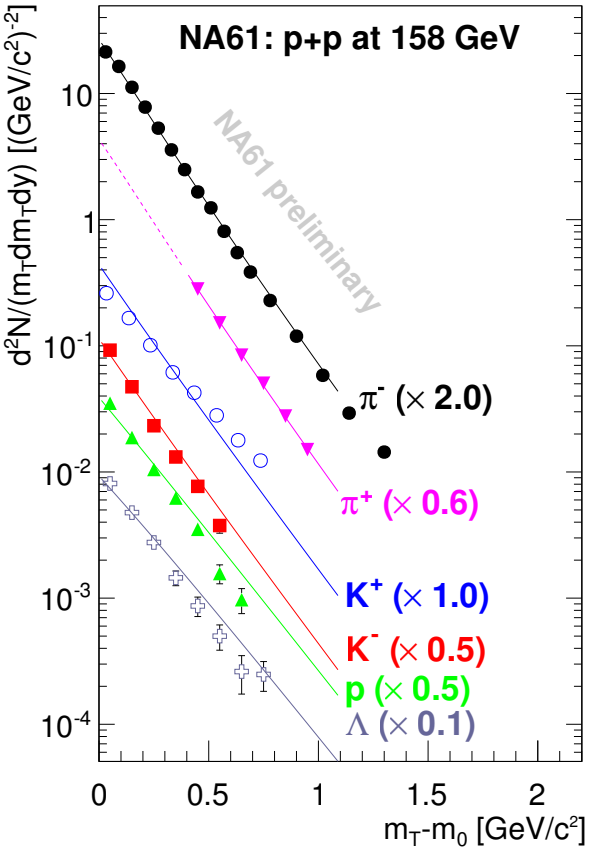


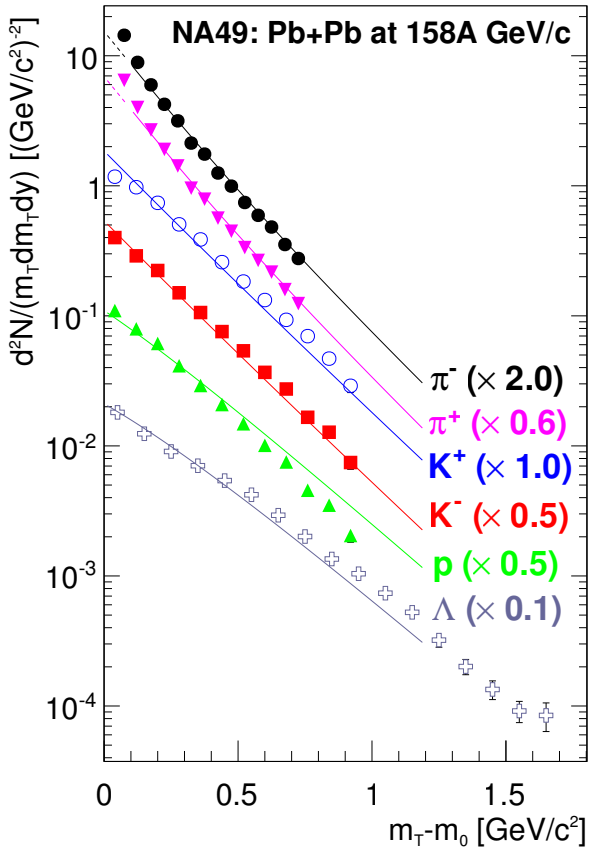


- h^- analysis, dE/dx, tof-dE/dx and V^0 identification is used
- The results are corrected for particles from week decays (feed-down) and detector effects



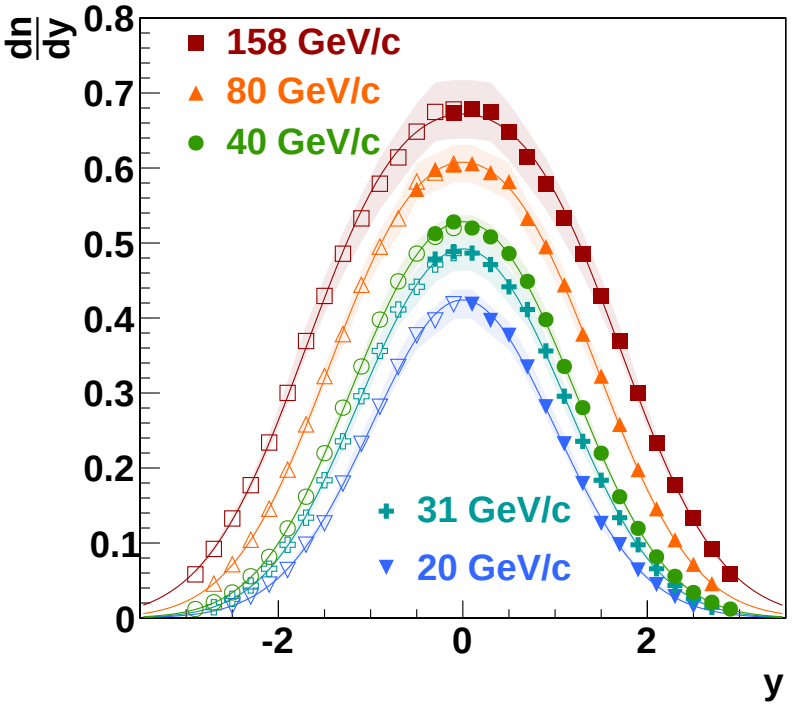
p+p interactions: transverse mass spectra at mid-rapidity

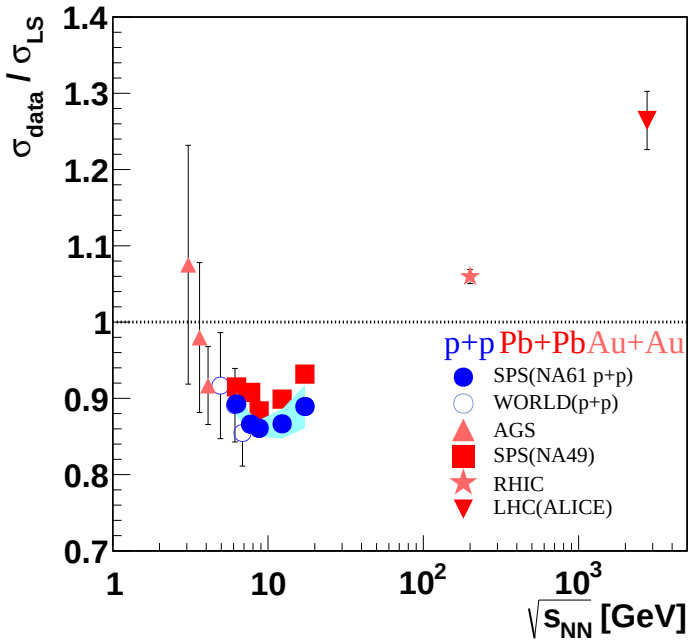




- m_T spectra are approximately exponential in p+p interactions
- In central Pb+Pb collisions the exponential dependence is modified by transverse flow

Rapidity spectra - dale





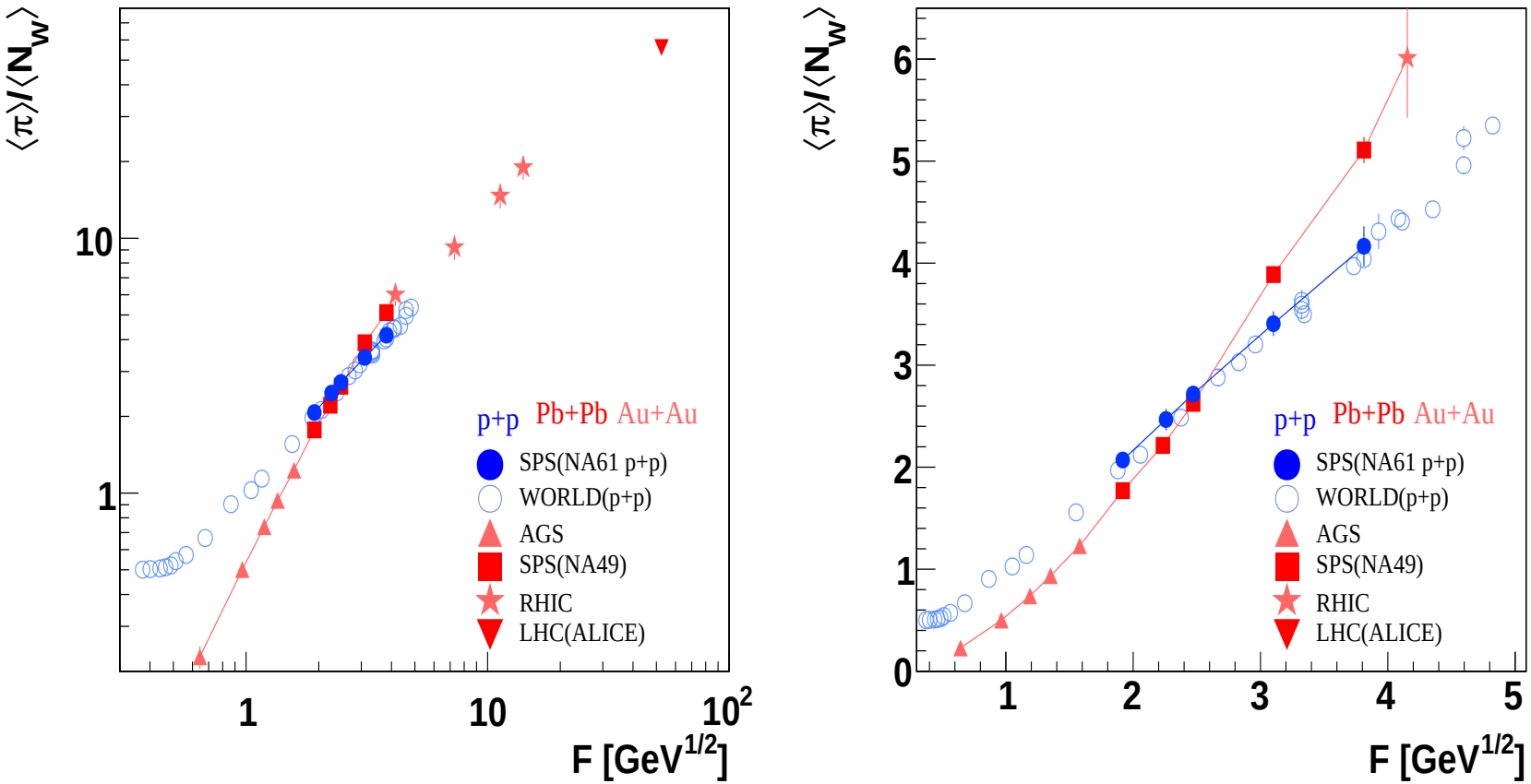
- A sum of two identical Gaus functions symmetricaly displaced from y=0 is fitted to dn/dy
- $\sigma_{data}/\sigma_{LS}$ has minimum at $\sqrt{s_{NN}} \approx 10\ GeV$
- The energy dependence is similar in Pb+Pb and p+p

- Results not corrected for isospin effects

σ_{LS}: Landau, Izv. Akad. Nauk Ser. Fiz. 17, 51 (1953). Shuryak, Yad. Fiz. 16, 395 (1972)

E895: PRC68:054905,2003, PHENIX: PRC69:034909,2004; ALICE: Phys. Lett. B 726 (2013) 610-622, NA61 p+p EPJ C74 (2014) 2794

Pion multiplicity - kink

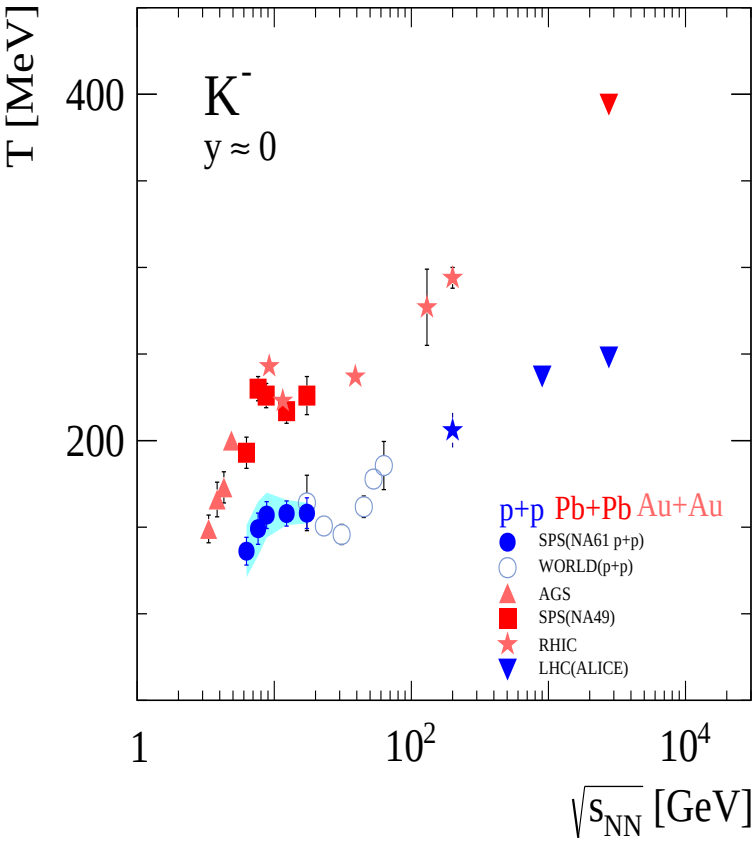


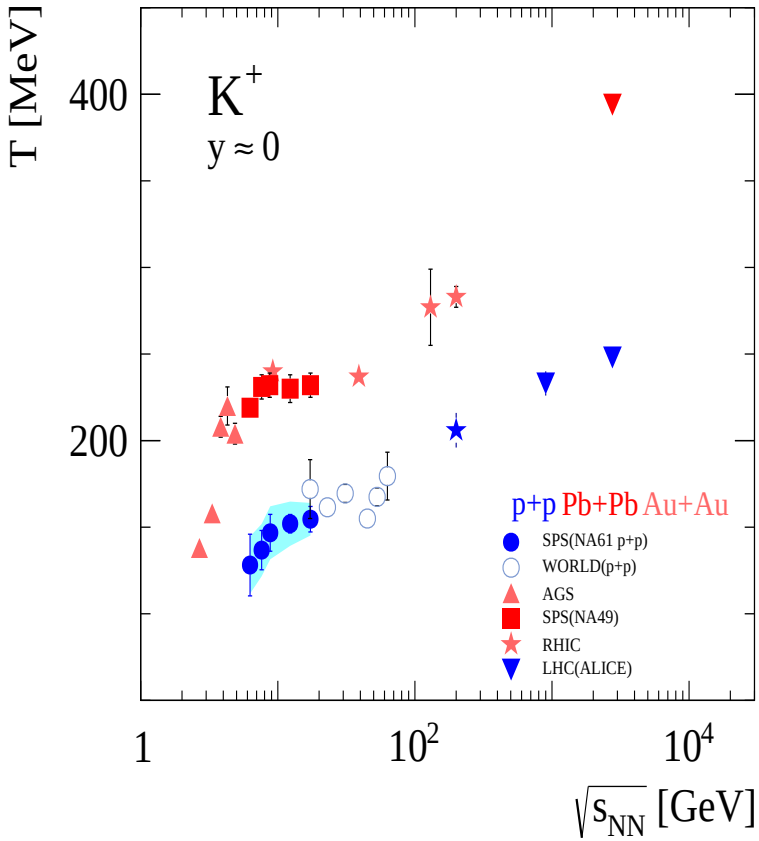
$$F \approx s_{NN}^{1/4}$$

- Mean π multiplicity per wounded nucleon at the SPS energies increases faster in central Pb+Pb than in p+p
- The crossing is visible at about 40A GeV/c

NA61/SHINE p+p: EPJC74:2794,2014 ALICE: Phys. Lett. B 726 (2013), PRL 109, 252301 (2012)

Inverse slope parameter T - step





- Dependence of the inverse slope parameter on energy exhibits similar structure in p+p interactions as in central Pb+Pb

CERN-SPSC-2014-031; SPSC-SR-145

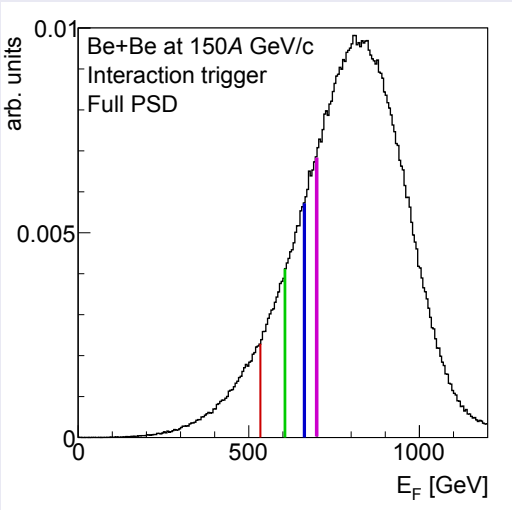
Centrality selection

Method

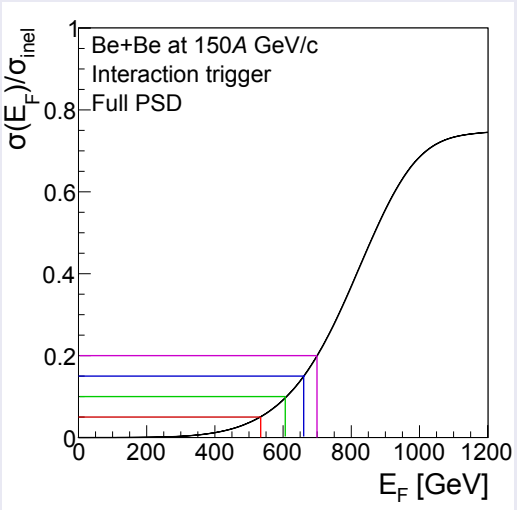
- The Projectile Spectator Detector (PSD) is a modular zero-degree calorimeter
- Forward energy (E_F) measured by PSD (mostly spectator energy) is used to group events in four centrality classes:
  0-5%, 5-10%, 10-15%, 15-20%

PSD calorimeter

Deposition in the calorimeter



Centrality classes



Transverse mass spectra