Results from NA61/SHINE ion program

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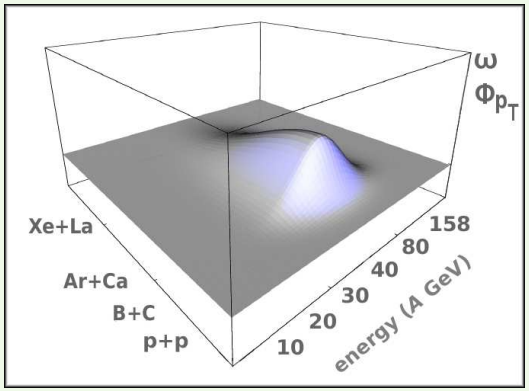
The NA61/SHINE heavy-ion program

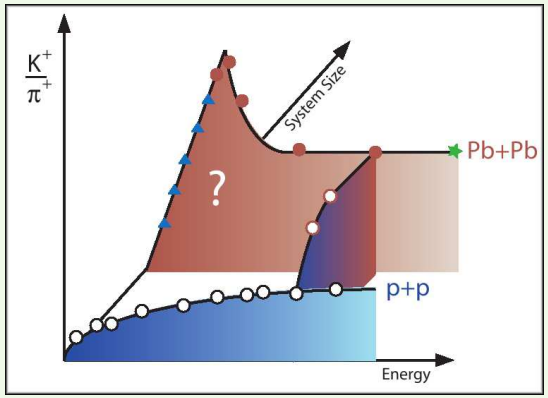
Search for the Critical Point

Search for a maximum of CP signatures: fluctuations of N, average p_T, etc., intermittency, when system freezes out close to CP



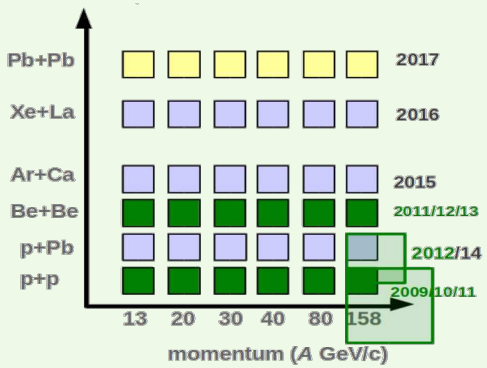
Study of the Onset of Deconfinement

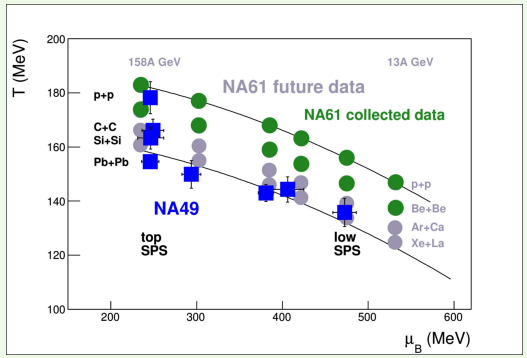
Search for the onset of the horn/kink/step in collisions of light nuclei; additional analysis of fluctuations and correlations



2D phase-space scan

NA61/SHINE is performing 2D phase diagram (T, μ_B) scan - colliding various nuclei at various energies.



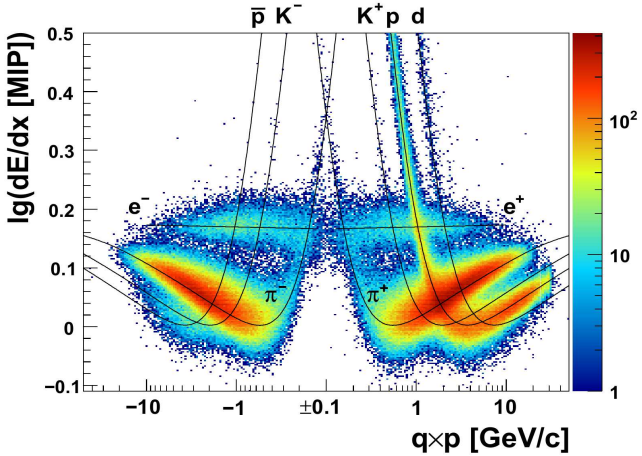


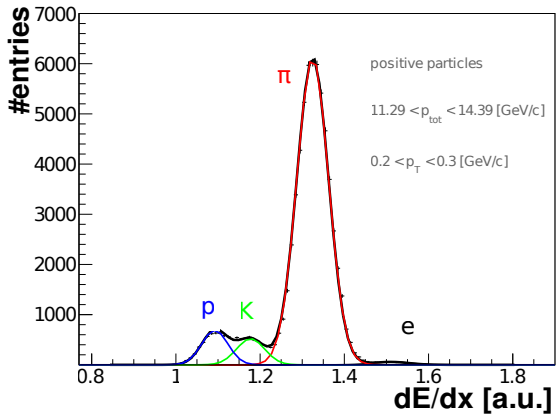
Spectra and yields in p+p collisions

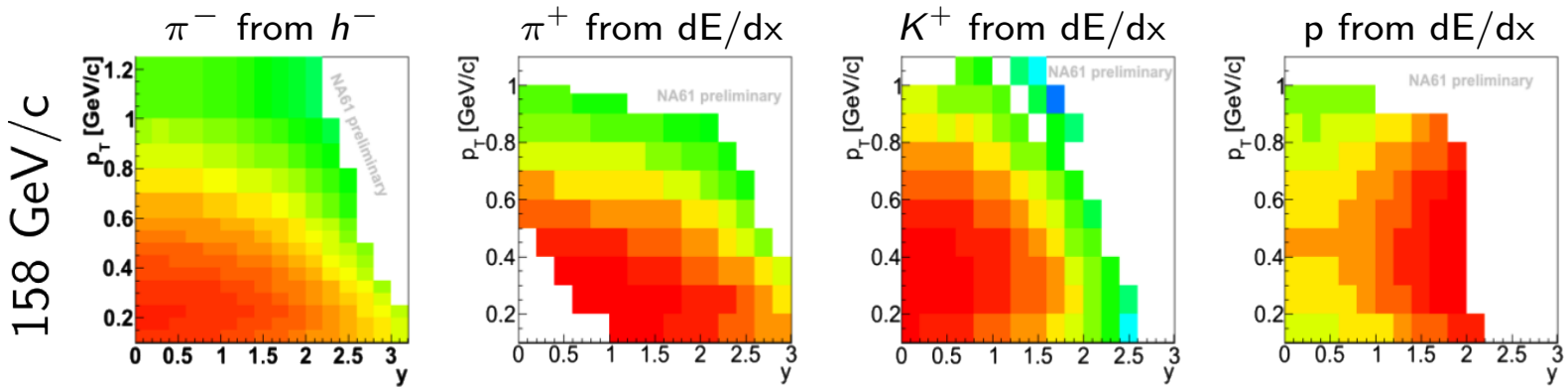
Spectra and yields in p+p collisions

- h^- **analysis method** – majority of negatively charged particles are π^- mesons. Contribution of other particles is subtracted using VENUS and EPOS models.
- **dE/dx analysis** uses information on energy loss in the TPC gas to identify particles (Bethe-Bloch relativistic rise region used)

The results are corrected for particles from weak decays (feed-down) and the detector effects using simulations. Out of target interactions are subtracted using events recorded with empty liquid hydrogen target.

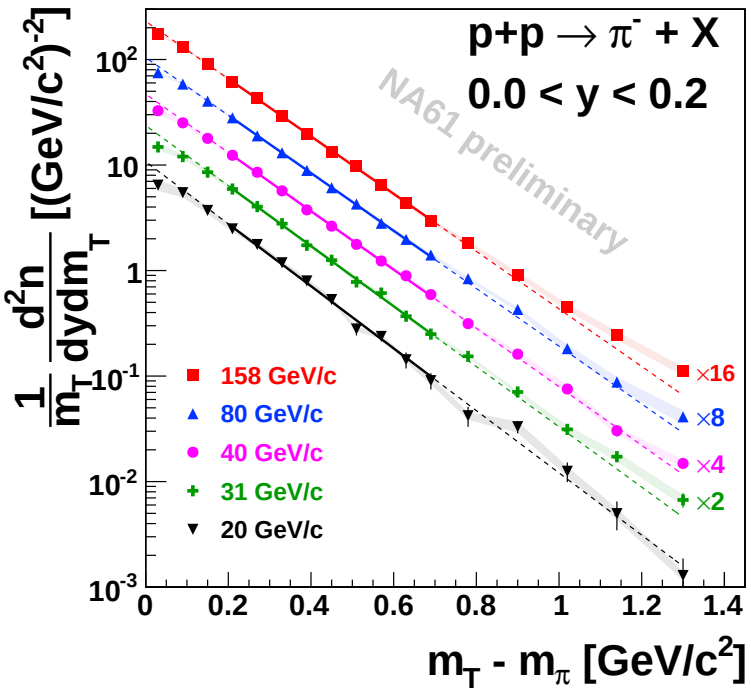


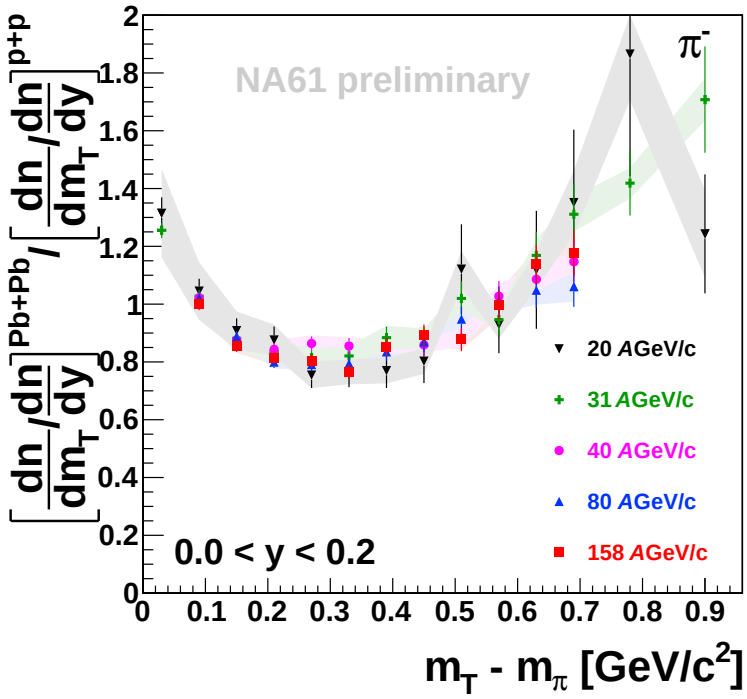




Spectra and yields in p+p collisions

π^- transverse mass spectra



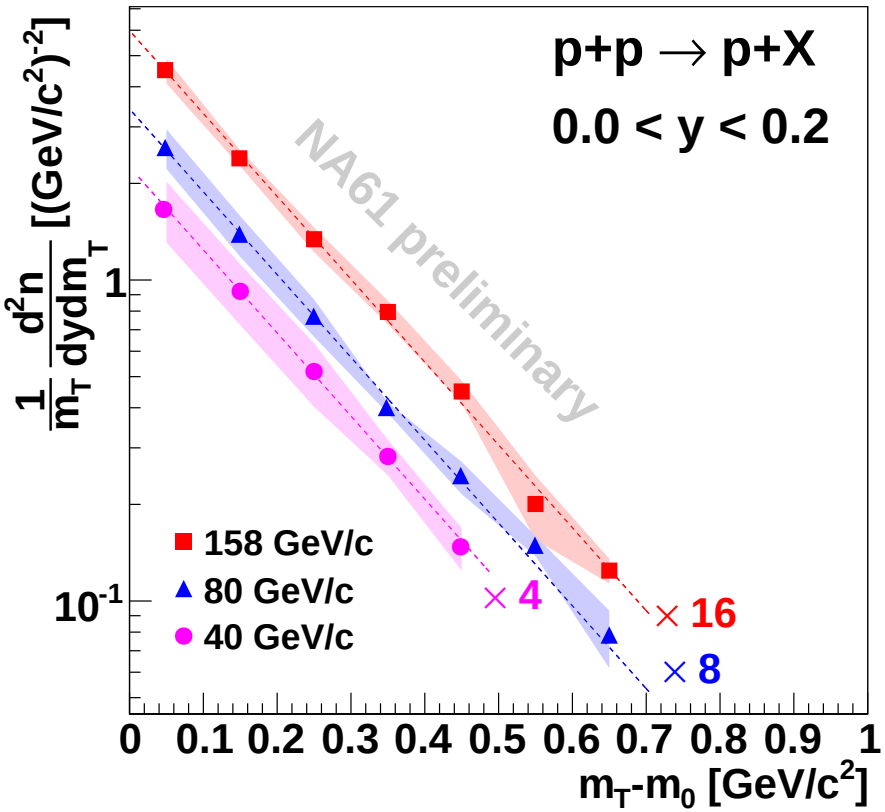


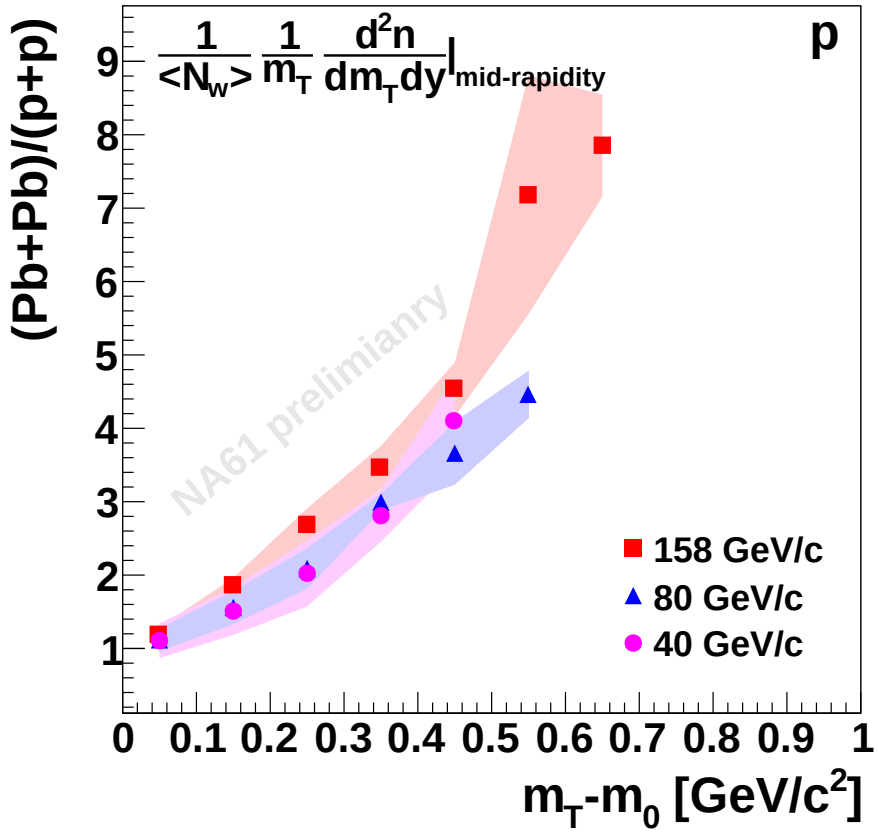
Shape differs significantly between p+p and central (7%) Pb+Pb collisions due to transverse collective flow in Pb+Pb. No change with collision energy.

(Pb+Pb results on central (7%; 5%) collisions measured by NA49: PR C66, 054902 (2002); PR C77, 024903 (2008))

Spectra and yields in p+p collisions

proton transverse mass spectra





Shape differs significantly between p+p and central (7%) Pb+Pb collisions due to transverse collective flow in Pb+Pb. In first approximation differences don't change with collision energy.

Pb+Pb results on central (7%; 5%) collisions measured by NA49: PR C73, 044910 (2006)

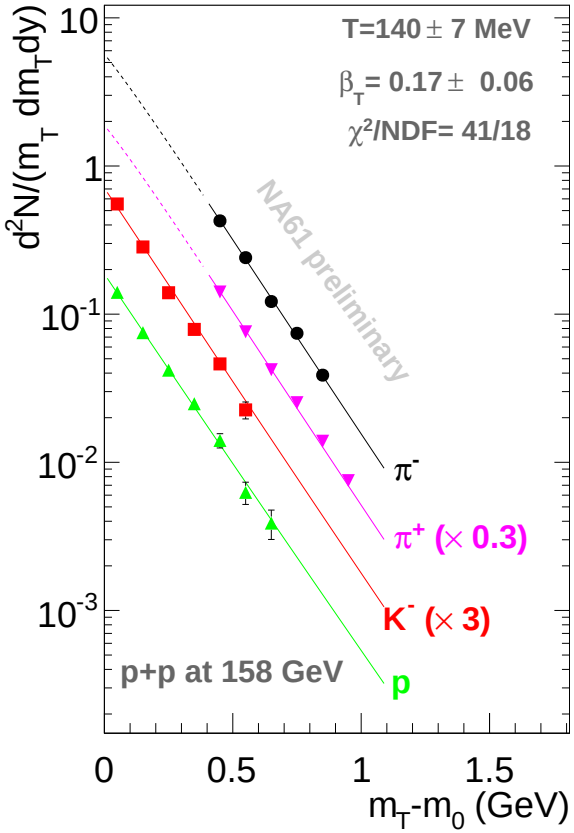
(y intervals: -0.32 < y < 0.80 for 40A GeV/c, -0.37 < y < 0.30 for 80A GeV/c, -0.50 < y < -0.1 for 158A GeV/c)

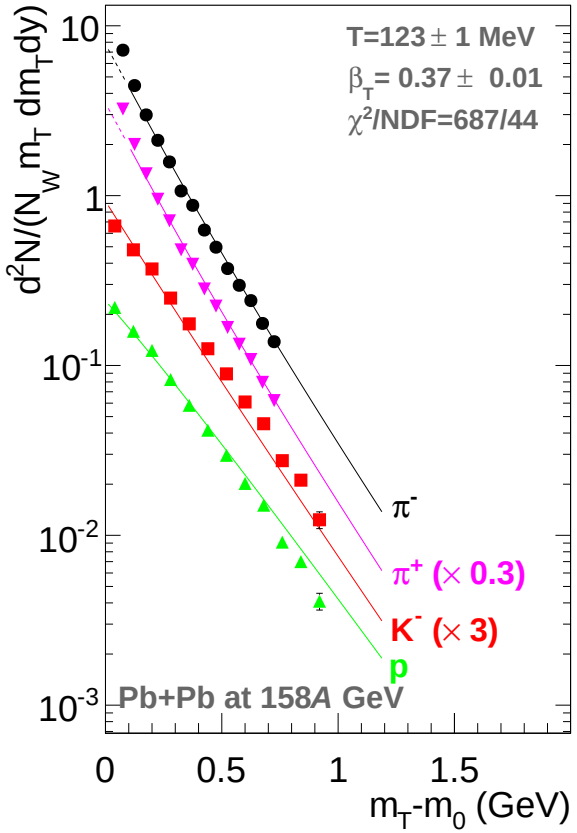
Spectra and yields in p+p collisions

m_T spectra in p+p collisions at 158 GeV/c fitted with Blast Wave Model

$$\frac{dN_i}{m_T dm_T dy} = A_i m_T K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right)$$

Schnedermann, Sollfrank, Heinz, PR C48, 2462 (1993)



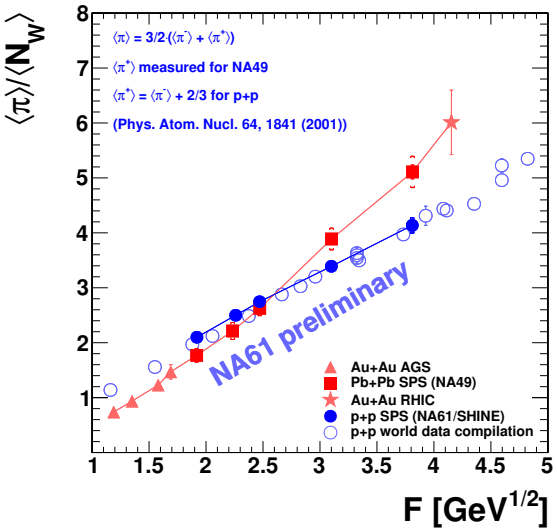


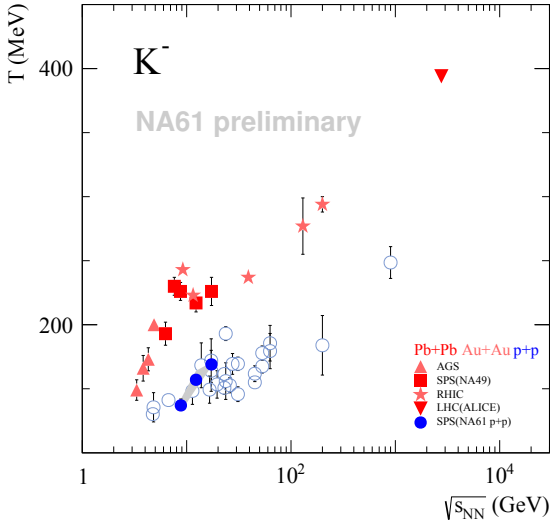
Transverse mass spectra are approximately exponential in p+p interactions. In central Pb+Pb collisions the exponential dependence is modified by the transverse flow.

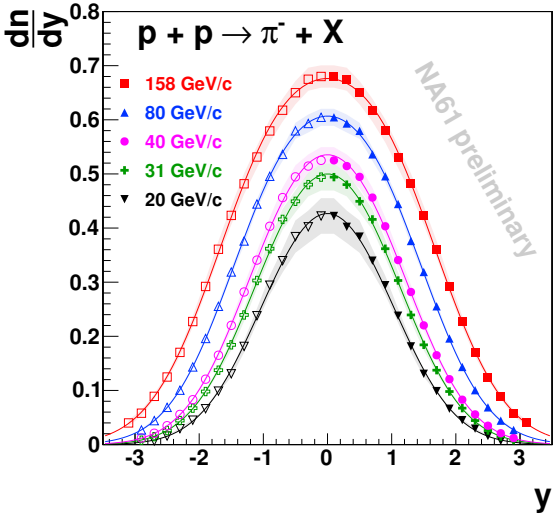
Kink, step, dale

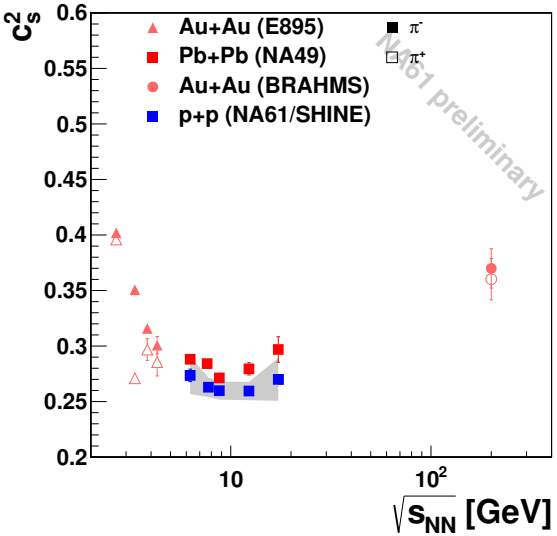
Kink, step, dale

studying the properties of the onset of deconfinement









π^- multiplicity at the SPS energies increases faster in central Pb+Pb than in p+p collisions (**kink**). The two dependencies cross at about 40A GeV.

Inverse slope parameters T of m_T spectra at the SPS energies show different behavior in central Pb+Pb (**step**) than in p+p (smooth increase)

Yad. Fiz.16, 395 (1972):

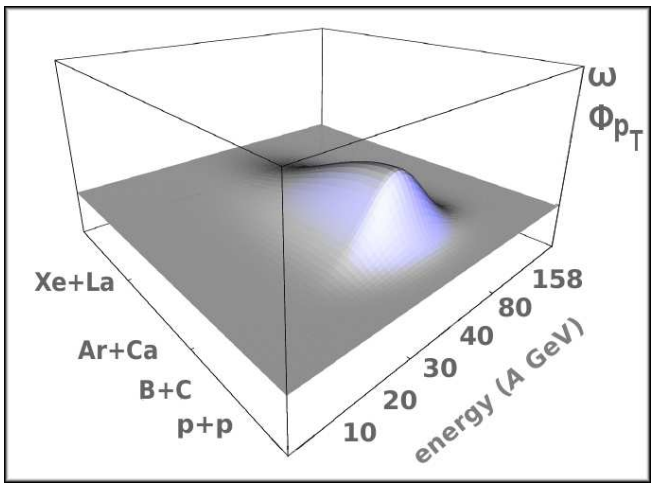
$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4} ln\left(\sqrt{s_{NN}/2m_p}\right)$$

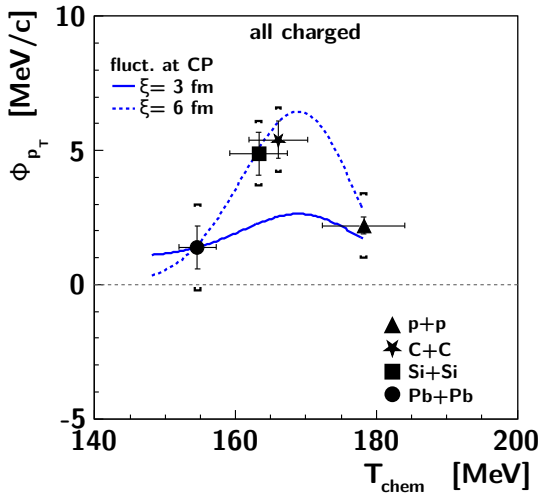
The dale appears to be present also in p+p reactions

Transverse momentum fluctuations

Transverse momentum fluctuations

NA61/SHINE aims to measure fluctuations of charged particles
produced in various nucleus' inelastic collisions at various energies

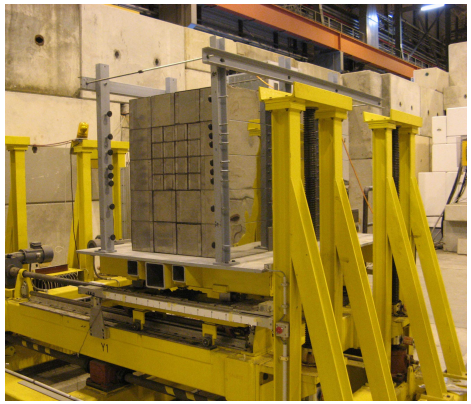




As predicted, the NA49 experiment observed indications of enhanced fluctuations in medium-sized systems at the top SPS energy. Systematic and precise measurements of fluctuations in p+p, Be+Be, Ar+Ca and Xe+La as function of collision energy by NA61 may lead to the discovery of the critical point...

Transverse momentum fluctuations

Many popular fluctuation measures are sensitive to the fluctuations of the system size (centrality). Experimentally one limits these fluctuations employing forward calorimeters (in NA61 Projectile Spectator Detector) which measure the number of spectators. The impact of the remaining system size fluctuations can be removed by use of properly defined fluctuation measures.



$$\Delta^{NX} = \frac{1}{C_\Delta}\Big[\langle X\rangle\omega[N] - \langle N\rangle\omega[X]\Big]$$

$$\Sigma^{NX} = \frac{1}{C_\Sigma}\Big[\langle X\rangle\omega[N] + \langle N\rangle\omega[X] - 2\Big(\langle NX\rangle - \langle N\rangle\langle X\rangle\Big)\Big]$$

$$\Phi_{p_T} = \sqrt{\frac{\langle X^2\rangle}{\langle N\rangle} - \frac{2\langle X\rangle\langle NX\rangle}{\langle N\rangle^2} + \frac{\langle X\rangle^2\langle N^2\rangle}{\langle N\rangle^2}} - \sqrt{\frac{\langle X_2\rangle}{\langle N\rangle} - \frac{\langle X\rangle^2}{\langle N\rangle^2}}$$

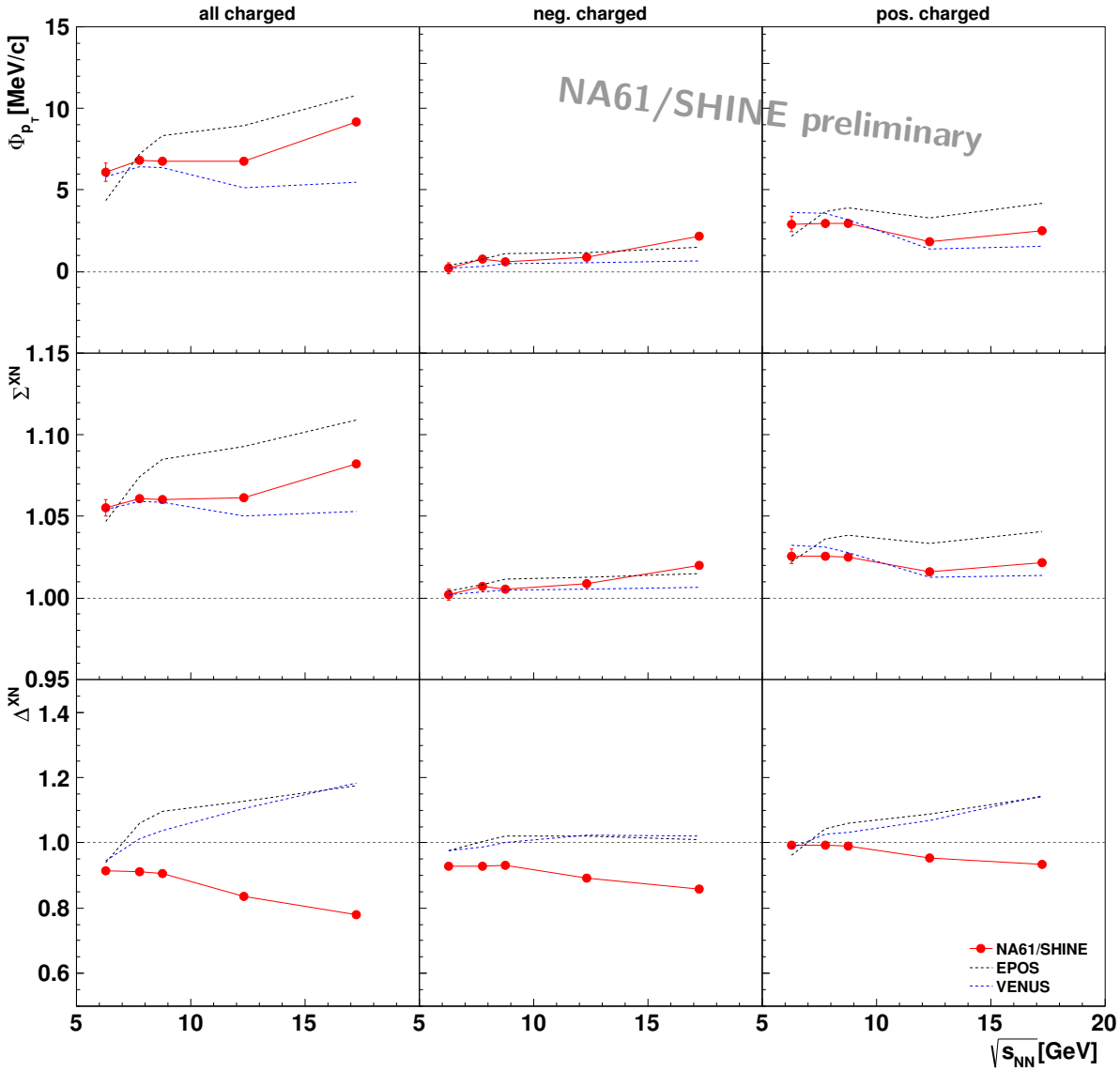
$$C_\Sigma = C_\Delta = \frac{1}{\langle N\rangle\omega[p_T]} \qquad \omega[p_T] = \frac{Var(p_T)}{\bar{p_T}}$$

$$X = \sum_{i=1}^{N} p_{T_i} \qquad X_2 = \sum_{i=1}^{N} p_{T_i}^2$$

- $\Delta^{NX} = \Sigma^{NX} = 0$ in the absence of fluctuations
- $\Delta^{NX} = \Sigma^{NX} = 1$ for independent particle sources

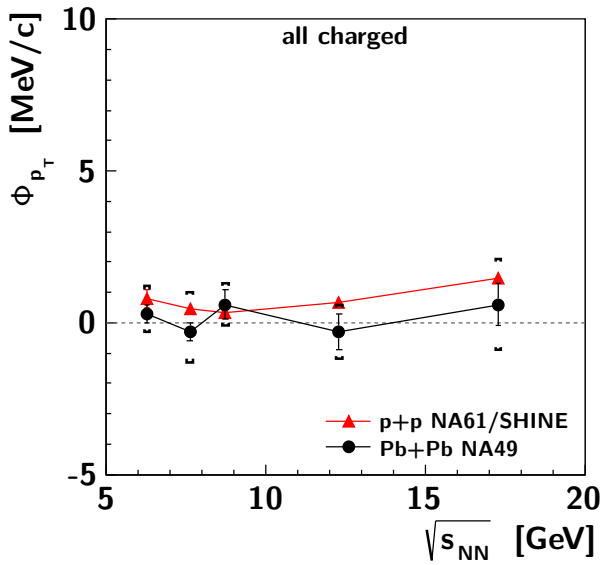
(Phys. Rev. C 84, 014904 (2011), arXiv:1303.0871)

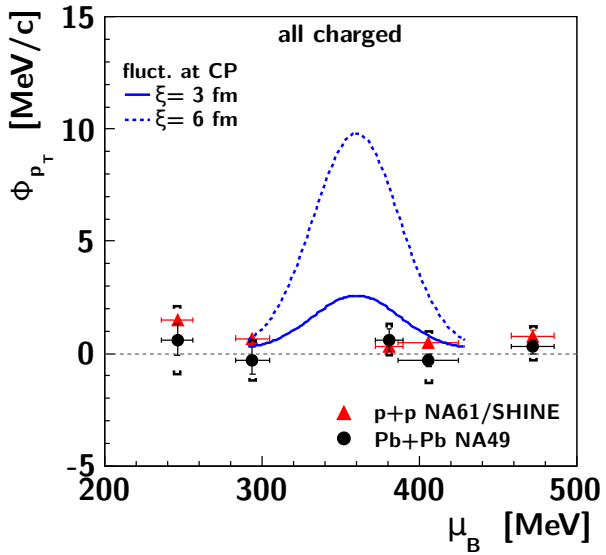
Transverse momentum fluctuations in p+p



Transverse momentum fluctuations

comparison with NA49 Pb+Pb





After limiting to the NA49 acceptance (forward rapidity only, common azimuthal acceptance for all energies), Φ_{p_T} value has decreased and became equal (within errors) to NA49 Pb+Pb results.

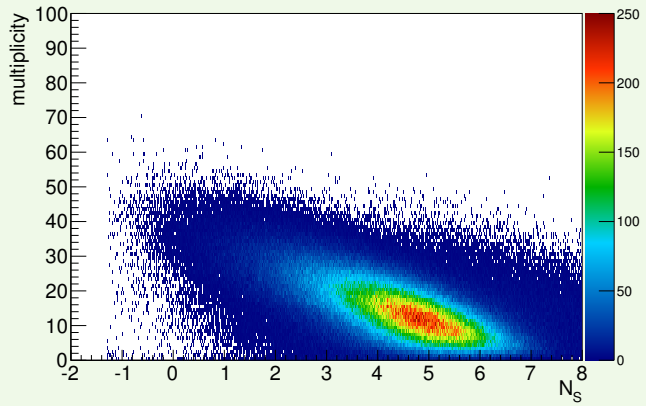
No indications of CP in NA49 Pb+Pb and in NA61 p+p. We are waiting for results from Be+Be, Ar+Ca and Xe+La...

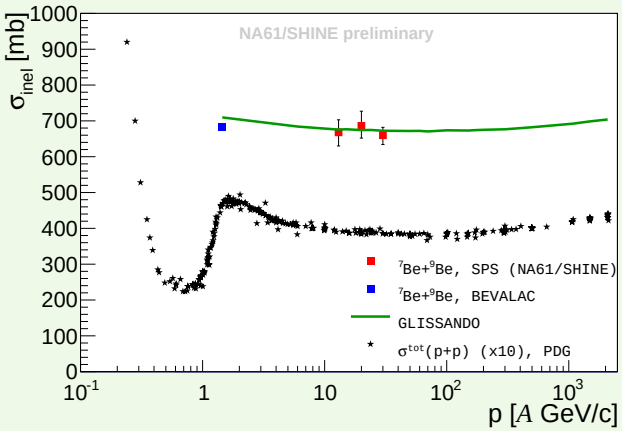
Beyond spectra and p_T fluctuations in p+p

Beyond spectra and p_T fluctuations in p+p

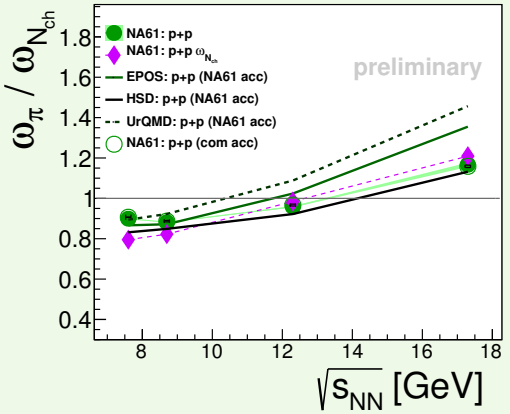
Be+Be results

First Be+Be data will be released soon...

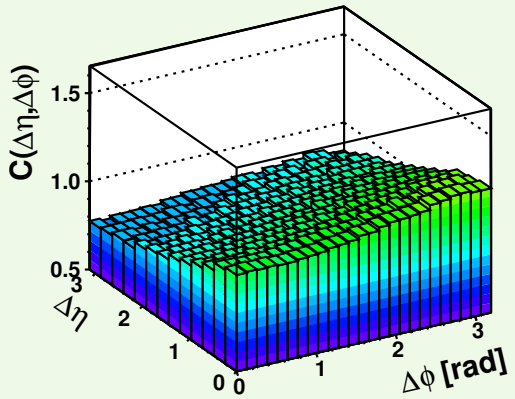




Chemical (particle type) fluctuations



Two-particle correlations



Summary

The NA61/SHINE ion program started with measurements of p+p and Be+Be interactions. Soon Ar+CA and Xe+La collisions will be measured. The data are taken at 13A, 20A, 30A, 40A, 80A, 158A GeV/c.

Results of single particle spectra of identified hadrons in inelastic p+p interactions:

1. spectra of π^-, π^+, K^- and p are realized, more particles soon,
2. the Pb+Pb *kink* is absent in p+p interactions,
3. the Pb+Pb *dale* seems to be present also in p+p interactions.

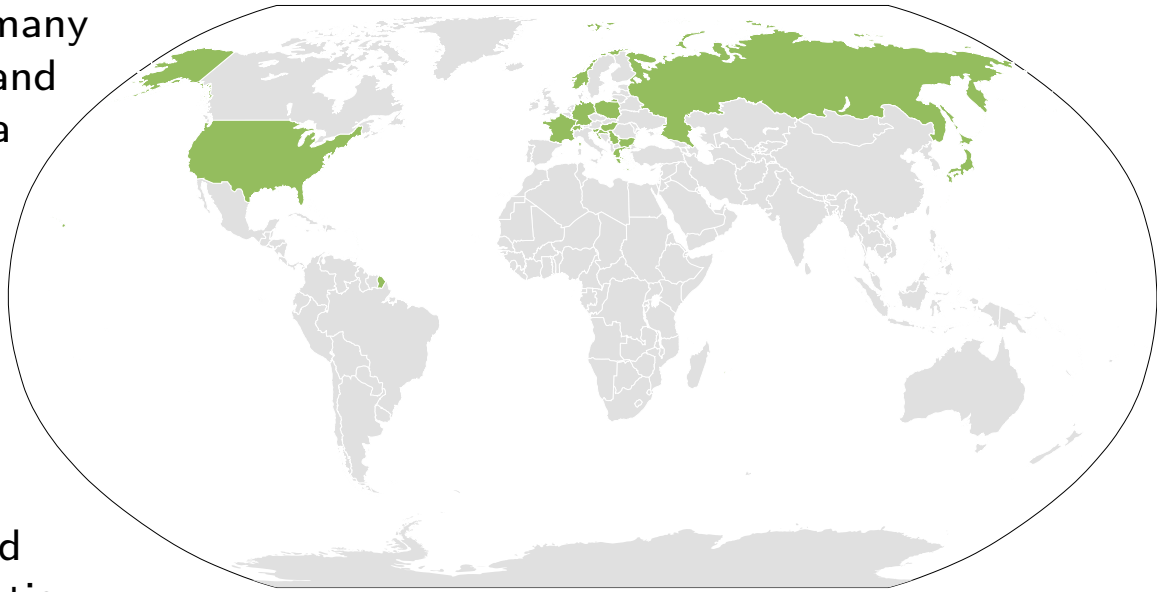
Results on fluctuations in p+p interactions:

1. p_T and chemical fluctuations similar in p+p interactions and central Pb+Pb collisions, (important to perform the comparison using strongly intensive quantities and within the same acceptance),
2. no indication for enhanced fluctuations due to the critical point in p+p interactions and central Pb+Pb collisions,
3. the results in p+p interactions approximately agree with predictions of EPOS and VENUS.

First results from Be+Be interactions:

1. energy dependence of inelastic cross section agrees with the predictions of GLISSANDO (*GLauber Initial-State Simulation AND mOre...*)
2. spectra and fluctuations soon ...

Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Hungary
St. Petersburg State University, St. Petersburg, Russia
Karlsruhe Institute of Technology, Karlsruhe, Germany
Faculty of Physics, University of Sofia, Sofia, Bulgaria
LPNHE, University of Paris VI and VII, Paris, France
Institute for Nuclear Research, Moscow, Russia
Jan Kochanowski University in Kielce, Poland
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
University of Belgrade, Belgrade, Serbia
Jagiellonian University, Cracow, Poland
University of Bern, Bern, Switzerland
ETH, Zurich, Switzerland
University of California, Irvine, USA
University of Athens, Athens, Greece
University of Bergen, Bergen, Norway
University of Silesia, Katowice, Poland
University of Wroclaw, Wroclaw, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
Fachhochschule Frankfurt, Frankfurt, Germany
Warsaw University of Technology, Warsaw, Poland
Joint Institute for Nuclear Research, Dubna, Russia
National Center for Nuclear Research, Warsaw, Poland
Faculty of Physics, University of Warsaw, Warsaw, Poland
Laboratory of Astroparticle Physics, University Nova Gorica, Nova Gorica, Slovenia



Thank You!

Chemical (particle type) and multiplicity fluctuations

Chemical (particle type) and multiplicity fluctuations

$$\omega_i = \frac{\langle N_i^2 \rangle - \langle N_i \rangle^2}{\langle N_i \rangle}$$

$$\Phi_{ij} = \frac{\langle N_i \rangle \langle N_j \rangle}{\langle N_i + N_j \rangle} \cdot \left[\sqrt{\Sigma^{ij}} - 1 \right]$$

$$\Sigma^{ij} = \left[\langle N_i \rangle \cdot \omega_j + \langle N_j \rangle \cdot \omega_i - 2 \left(\langle N_{ij} \rangle - \langle N_i \rangle \langle N_j \rangle \right) \right] / \langle N_i + N_j \rangle$$

For Poissonian mult. dist. $\omega = 1$
Intensive measure: in WNM ω independent of N_W but dependent on fluctuations of N_W

For independent particle emission $\Phi = 0$
Strongly intensive measure: in WNM Φ independent of N_W and fluctuations of N_W

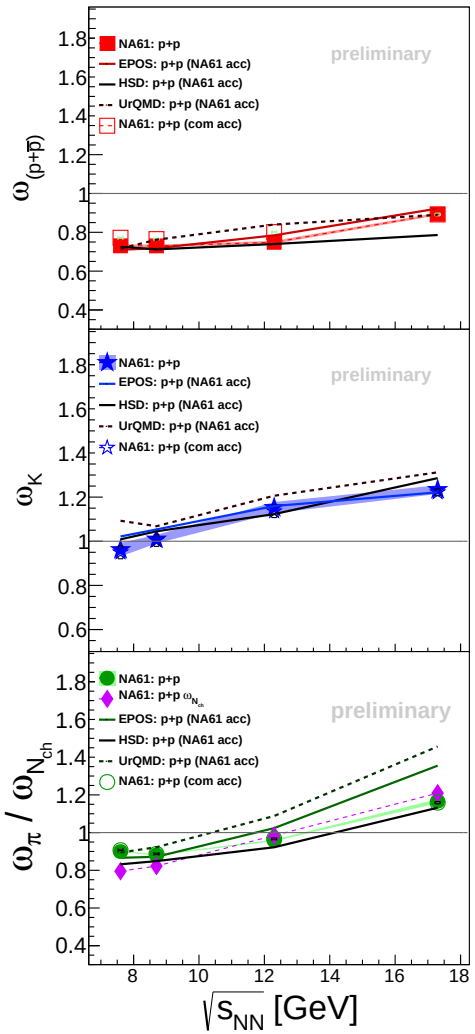
In experiment chemical fluctuations of identified particles multiplicities may be distorted by incomplete particle identification.

Results on chemical fluctuations in NA49 and NA61 presented here are **corrected for misidentification using the unfolding procedure of the identity method**:
Gaździcki, Grebieszkow, Maćkowiak, Mrówczyński, PR C83, 054907 (2011);
Gorenstein, PR C84, 024902 (2011);
Rustamov, Gorenstein, PR C86, 044906 (2012).

Fluctuations cannot be corrected for the limited acceptance → results are presented in NA61 acceptance (https://edms.cern.ch/document/1237791/1)

Chemical (particle type) and multiplicity fluctuations

Scaled variance of the multiplicity distributions in p+p interactions



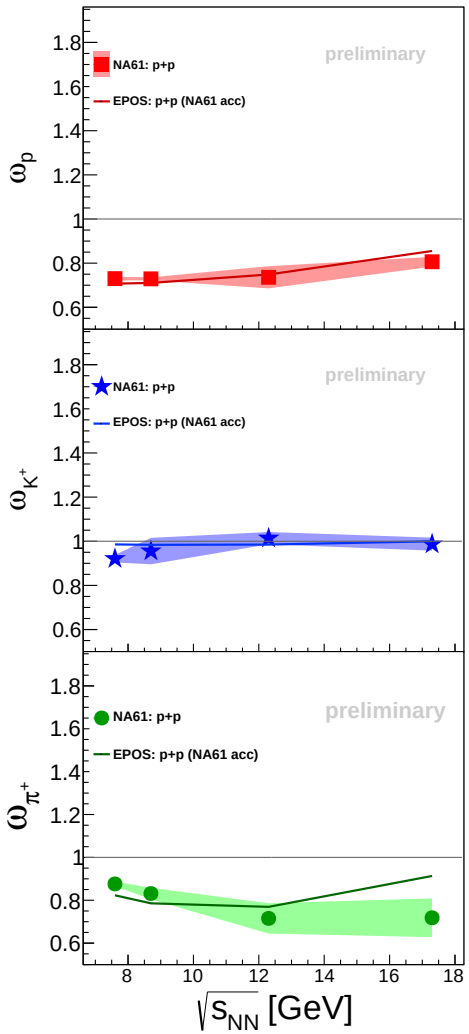
$\omega_{p+\bar{p}}$ **and** $\omega_p < 1$ probably due to **baryon number conservation**. ω_p and $\omega_{p+\bar{p}}$ similar (small fraction of antiprotons).

$\omega_K > 1$ probably due to **strangeness conservation**. ω_{K^+} close to 1 and $< \omega_K$, which suggests that strangeness conservation contributes to ω_K.

Increase of ω_π **with energy** reflecting increase of $\omega_{N_{ch}}$ measured in full phase-space (see PR 351, 161 (2001)). $\omega_{\pi^+} < \omega_\pi$ **possibly due to charge conservation.**

ω_π **and** $\omega_{N_{ch}}$ **similar at higher energies** (at lowest energies the fraction of protons is significant).

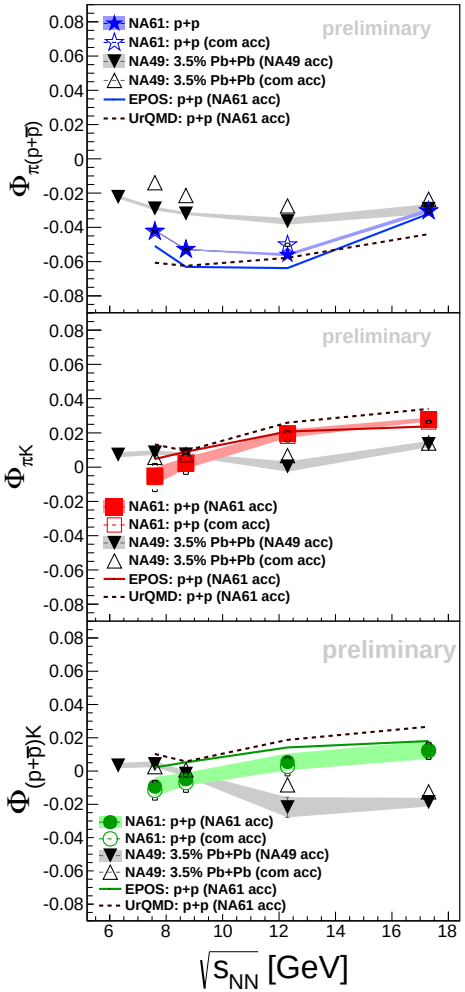
All models predictions are similar to experimental results.



ADDITIONAL SLIDES

Chemical (particle type) and multiplicity fluctuations

Φ measure of chemical fluctuations: comparison of p+p with central Pb+Pb (NA49) collisions

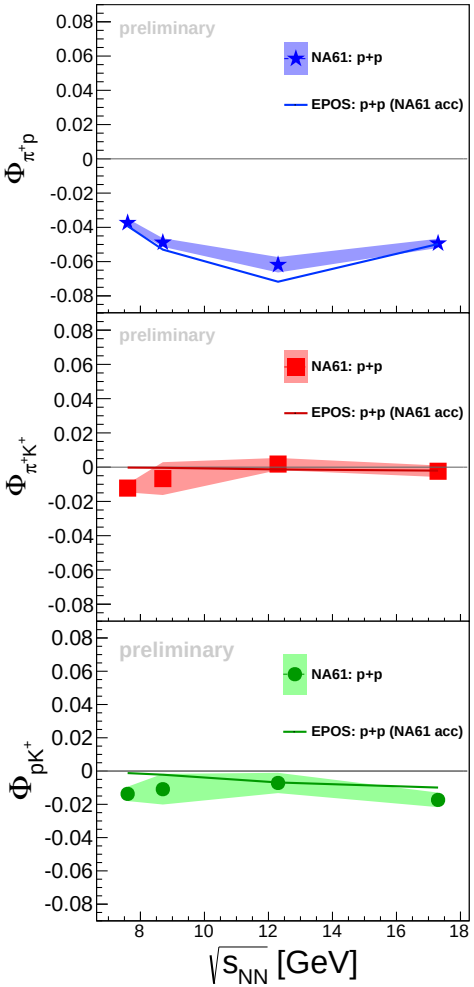


$\Phi_{\pi(p+\bar{p})}$ **and** $\Phi_{\pi^+ p} < 0$ most probably due to **charge conservation and resonance decays** (PR C70, 064903 (2004)). Similar tendency for NA61 p+p and NA49 Pb+Pb.

In p+p $\Phi_{\pi K} > 0$ probably due to **strangeness conservation** ($\Phi_{\pi^+ K^+}$ close to 0 supports this interpretation). For p+p $\Phi_{\pi K}$ slightly increases with energy; such effect not visible for NA49 Pb+Pb.

Very weak increase of $\Phi_{(p+\bar{p})K}$ **with energy in p+p** data, whereas for Pb+Pb $\Phi_{(p+\bar{p})K}$ decreases with energy (high momentum part removed from NA49 Pb+Pb data). **For both systems** $\Phi_{(p+\bar{p})K}$ **crosses zero at middle SPS energies**. No energy dependence of Φ_{pK^+}.

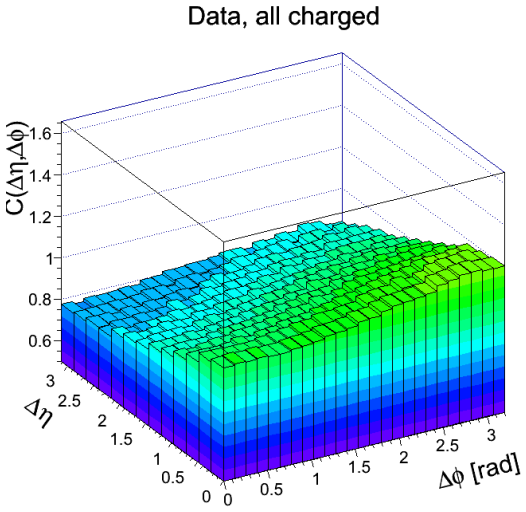
All models predictions are similar to measurements in p+p.



$\Delta\eta - \Delta\phi$ correlations

$\Delta\eta - \Delta\phi$ correlations

p+p at 158 GeV/c (all pairs)

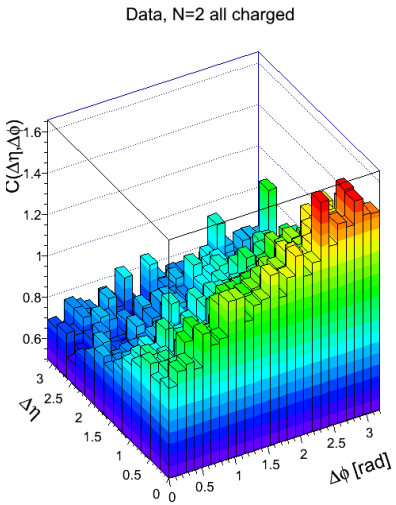


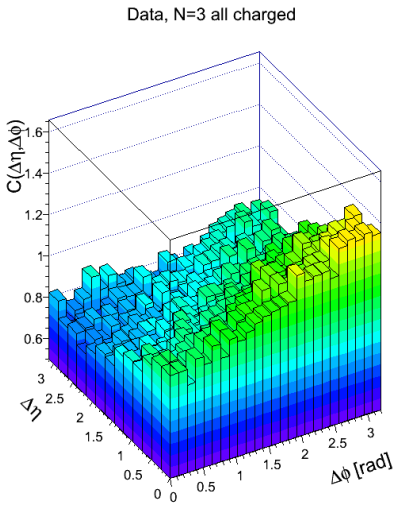
$$\Delta\eta = |\eta_1 - \eta_2| \qquad \Delta\phi = |\phi_1 - \phi_2|$$

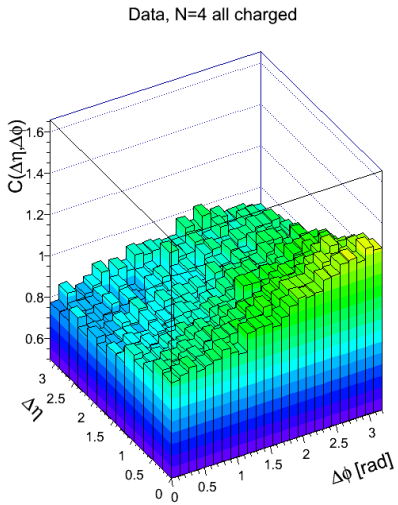
$$C(\Delta\eta, \Delta\phi) = \frac{N^{pairs}_{mixed}}{N^{pairs}_{data}} \frac{S(\Delta\eta,\Delta\phi)}{M(\Delta\eta,\Delta\phi)}$$

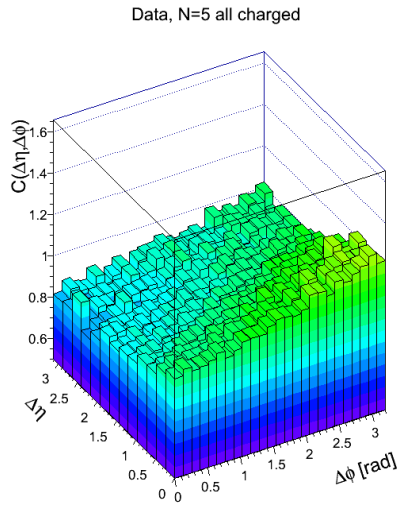
$$S(\Delta\eta, \Delta\phi) = \frac{d^2 N^{signal}}{d\Delta\eta d\Delta\phi} \qquad M(\Delta\eta, \Delta\phi) = \frac{d^2 N^{mixed}}{d\Delta\eta d\Delta\phi}$$

- Maximum at $(\Delta\eta, \Delta\phi) = (0, \pi)$, better visible in narrow mult. bins. Resonance decays and momentum conservation.
- Coulomb and quantum effects contribute to a weak enhancement at (0,0).





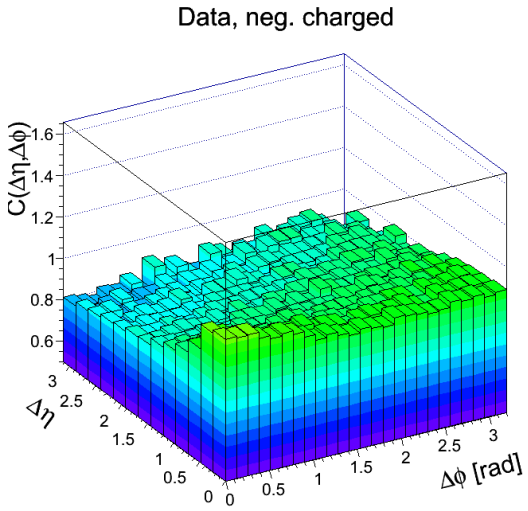




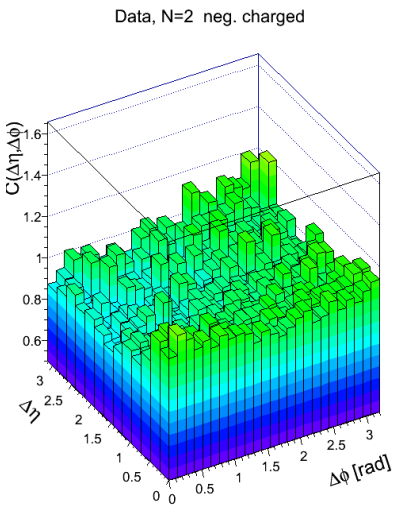
By dividing two-particle correlations analysis into multiplicity bins one can study contributions of certain phenomena to the inclusive correlations (e.g. resonance decays). (See also ZPC 64, 301 (1994)).

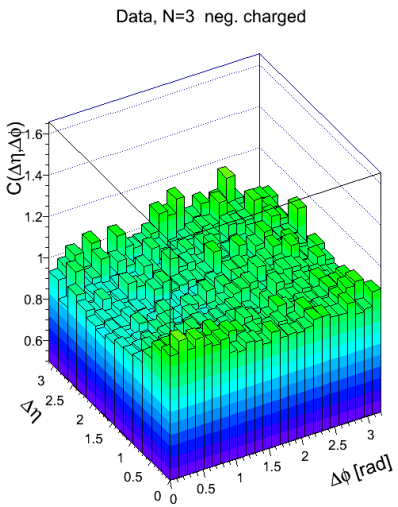
$\Delta\eta - \Delta\phi$ correlations

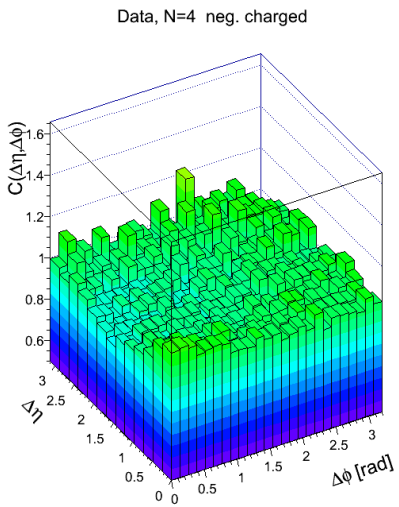
p+p at 158 GeV/c (pairs of negatively charged particles)

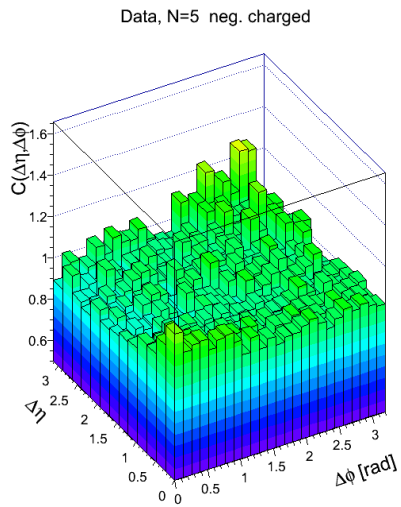


- Practically no resonances which decay into two negatively charged particles.
- Very low momentum conservation hill visible at $(0, \pi)$ on averaged distribution and on multiplicity bins distributions.
- Quite difficult to observe, because it is masked by:
  - Quantum statistics hill at (0,0).
  - Hill at $(3, \pi)$ for multiplicity selected correlations. Probably global momentum conservation.









The same analysis is currently performed on NA49 Pb+Pb data.