Fluctuations and correlations from the energy scan in p+p and Be+Be interactions at the SPS energies

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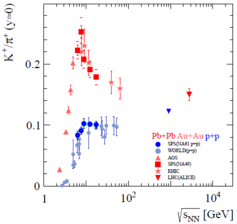
Fluctuations and correlations are universal tool to:

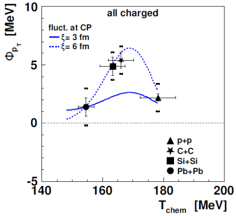
- study the onset of deconfinement
- search for the critical point of strongly interacting matter
- study resonance abundances, influence of conservation laws and other properties of strongly interacting matter

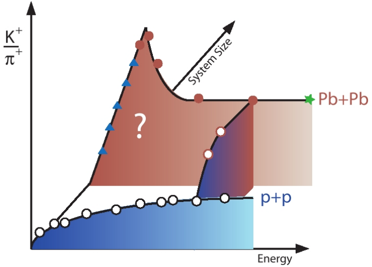
http://www.nova-pen.pl

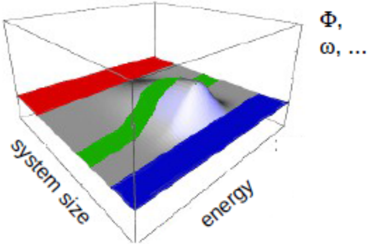
The most interesting region of the phase diagram is accessible at the SPS:

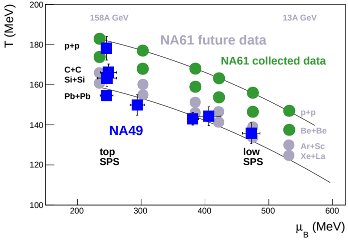
- the onset of deconfinement at $\sqrt{s_{NN}} = 7.6$ GeV
- indications of the critical point located at $\sqrt{s_{NN}} = 17.3$ GeV







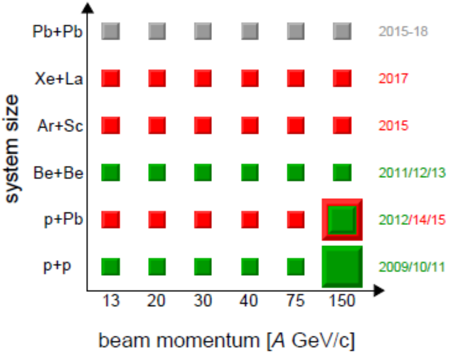




Estimated (NA49) and expected (NA61) chemical freeze-out points PRC 73, 044905

The NA61/SHINE experiment performs comprehensive scan with light and intermediate mass nuclei in energy range 13A-158A GeV

Data taking schedule for the ion program and its proposed extension (in gray)



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.:

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

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

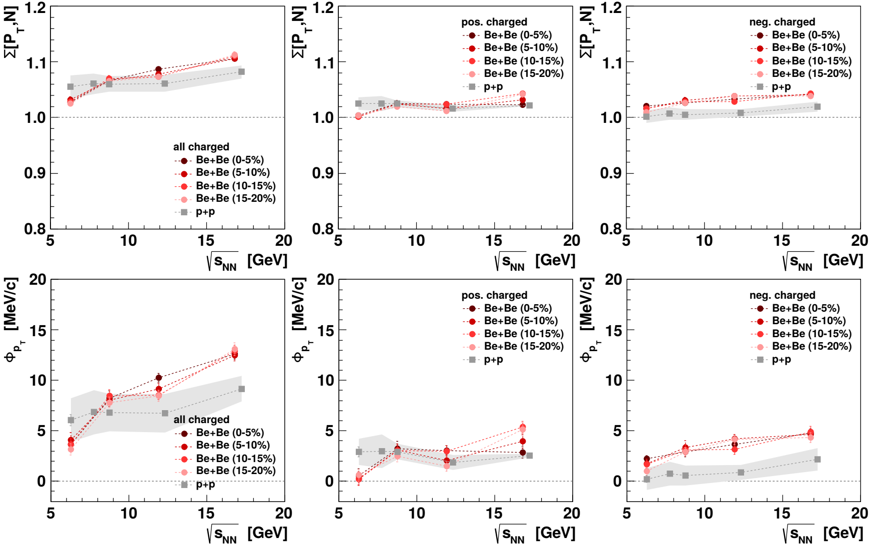
- independent of N_W and fluctuations of N_W
- normalization chosen such that $\Delta[A, B] = \Sigma[A, B] = 1$ for independent particle model and both quantities are dimensionless
- $\Delta[A, B] = \Sigma[A, B] = 0$ in the absence of fluctuations

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

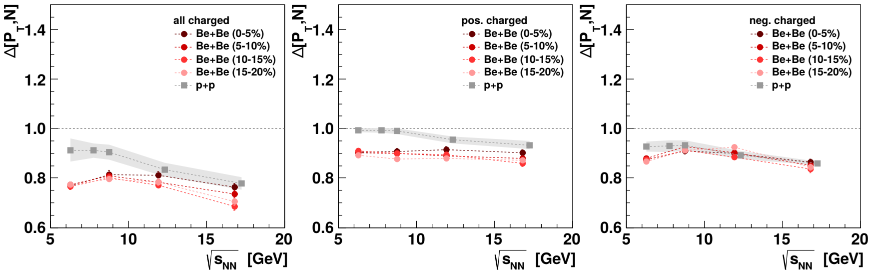
$$P_T = \sum_{i=1}^{N} p_{T_i} \quad \Phi_{p_T} = \sqrt{\bar{p_T} \omega[p_T]} \left[\sqrt{\Sigma[P_T, N]} - 1 \right] \qquad \Phi_{ij} = \frac{\sqrt{<N_i><N_j>}}{<N_i + N_j>} \cdot [\sqrt{\Sigma[i,j]} - 1]$$

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

T. Czopowicz, CPOD(2014)



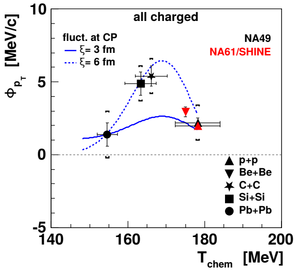
Energy dependence of $\Delta[P_T, N]$



- 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)

Comparison with Pb+Pb interactions

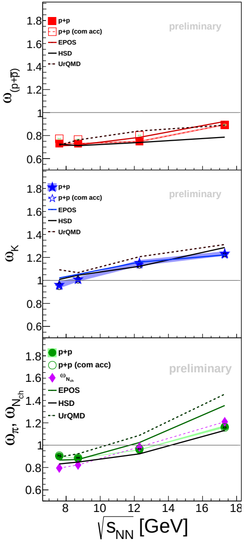
In order to compare the Φ_{p_T} results, NA49 cuts have been applied to NA61/SHINE data.



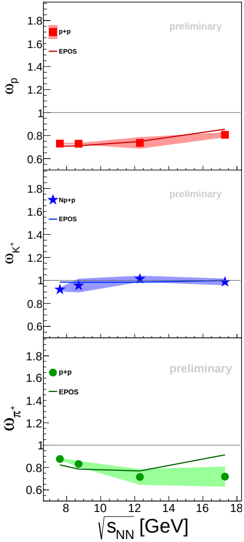
New results of the NA61/SHINE experiment are in agreement with dependence observed by the NA49 experiment.

Fluctuations of identified particles

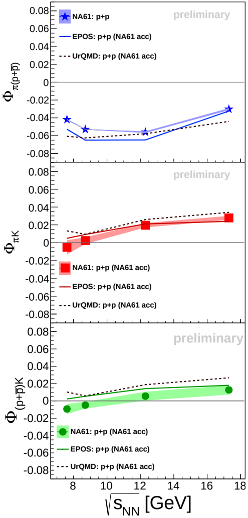
M. Mackowiak-Pawlowska, CPOD(2013)



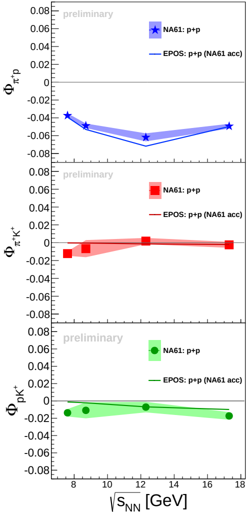
- identity method (PRC84,024902) used for identification
- $\omega_{p+\bar{p}} \approx \omega_p < 1$ probably due to baryon number conservation
- $\omega_K > 1$ and $\omega_{K^+} \approx 1$ probably due to strangeness conservation
- increase of ω_π reflects increase of $\omega_{N_{ch}}$ in full phase-space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



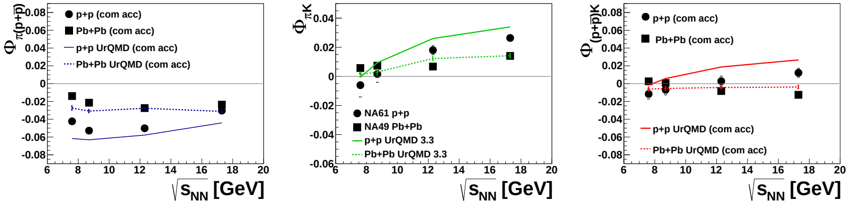
Fluctuations of identified particles



- $\Phi_{\pi(p+\bar{p})}$ and $\Phi_{\pi^+ p}$ 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

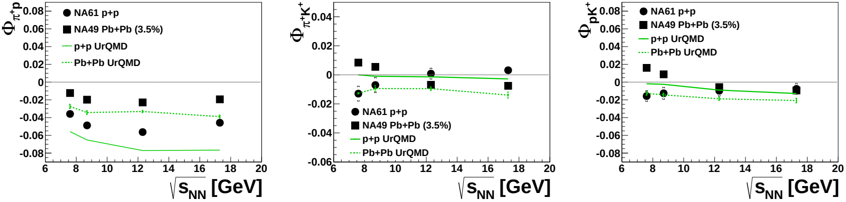


Comparison with Pb+Pb interactions - all charged



- 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

Comparison with Pb+Pb interactions - positively charged



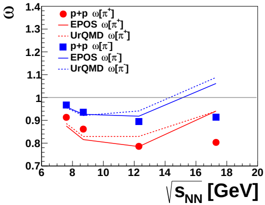
- similar tendency of Φ_{π^+p} in p+p and Pb+Pb
- in p+p interactions $\Phi_{\pi^+K^+}$ weakly increases with energy whereas in Pb+Pb interactions it decreases with energy
- UrQMD model does not describe $\Phi_{\pi^+K^+}$ and Φ_{pK^+} in Pb+Pb at low SPS energies

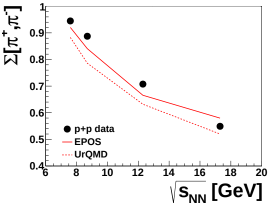
Fluctuations of π^+ and π^-

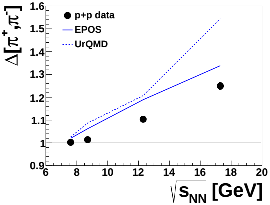
may be sensitive to:

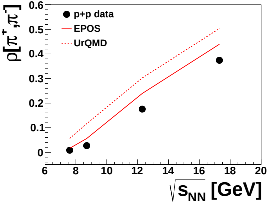
- the main feature of thermodynamics near the critical point is the presence of long-wavelength fluctuations of the magnitude of the σ-field [PRD60:114028,PRL81:4816]. Such σ-quanta cannot decay at freeze-out. **If it occurs near the critical point their large population survives** until the time after freeze-out when their rising mass exceeds the 2π threshold. The **contribution of σ decay is similar to the contribution of other resonances** but it is only present near the critical point[PRC63:064903].
- **e-by-e fluctuations of π^+ and π^-** are believed to be **sensitive to the abundances of resonances at the chemical freeze-out**. Moreover, the resonance abundances can be found by measuring the fluctuations and correlations of the numbers of stable hadrons [arXiv:1409.3023].

Fluctuations of π^+ and π^-







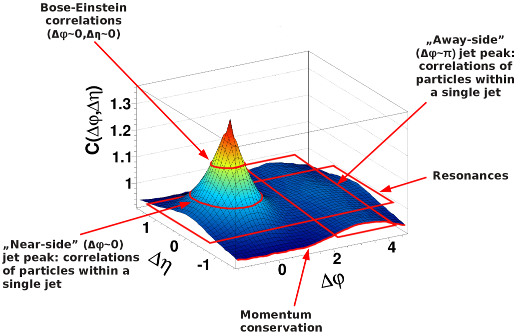


- UrQMD model predictions are comparable with the data
- No indications of the CP

In order to pinpoint the sources of correlations we can use **two particle correlations in $\Delta\eta\Delta\phi$.**

They allow to disentangle different sources of correlations like:

- jets
- flow
- resonance decays
- quantum statistics
- conservation laws



Correlations are obtained by finding the difference in pseudo-rapidity $\Delta\eta = |\eta_1 - \eta_2|$ and azimuthal angle $\Delta\phi = |\phi_1 - \phi_2|$ between two particles in the same event. Next they are normalized using mixed events.

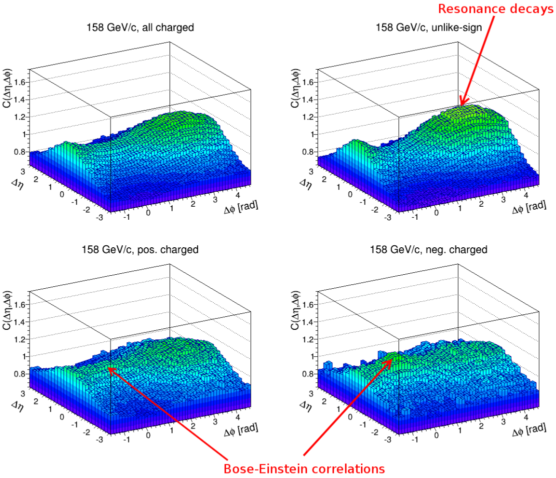
$$C(\Delta\eta, \Delta\phi) = \frac{N^{pairs}_{mixed}}{N^{pairs}_{data}} \frac{S(\Delta\eta,\Delta\phi)}{M(\Delta\eta,\Delta\phi)},$$

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

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

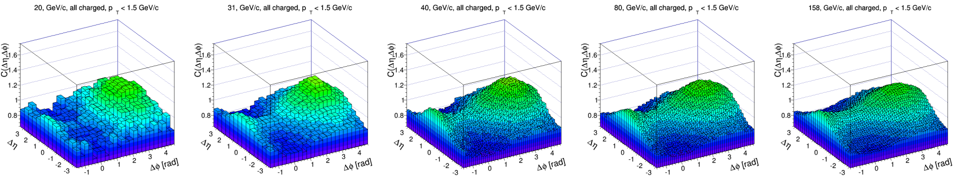
Structures visible at 158 GeV/c

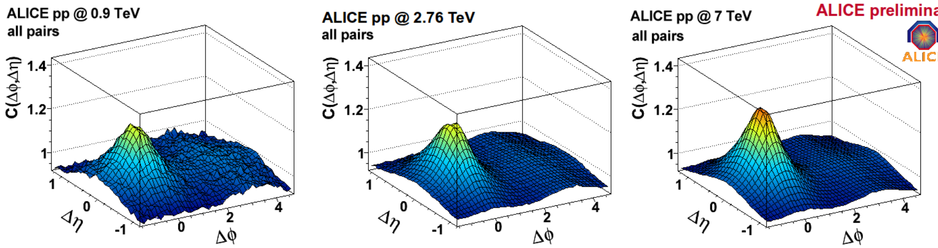
B. Maksiak, CPOD(2014)



- 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)

Energy dependence from 6.3 GeV up to 7 TeV

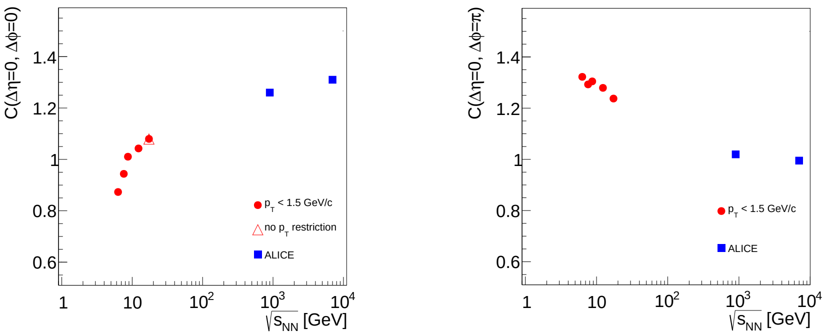




M.Janik, PoS(WPCF2011) 026

Resonance decay hill is more visible **at lower energies** whereas **jets dominate at higher energies**.

Energy dependence of $C(0,0)$ and $C(0,\pi)$



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

Summary

- **results on fluctuations and correlations in p+p and Be+Be at 20-158 *A*GeV beam momentum were shown**
- **fluctuations in p+p and Be+Be** interactions are similar and dominated by **conservation laws and resonance decays**
- **no indications of CP** are observed
- **fluctuations in p+p and Pb+Pb interactions are similar**
- **Ar+Sc interactions are coming soon(!)**

Thank you.

Data

Beam momentum [GeV/c]	$\sqrt{s_{NN}}$ [GeV]	p+p	Be+Be
20	6.3	1.3M	1.2M
31	7.6	3.2M	-
40	8.7	5.2M	0.9M
80	12.3	4.4M	1.2M
158	17.3	3.5M	0.9M

Event selection

Event selection criteria:

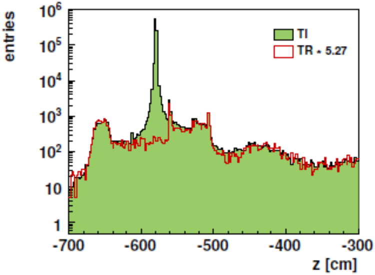
- well defined p+p/Be+Be interaction
- no off-time particles
- centrality selected by forward energy measurements (Be+Be)

Track selection

- sufficient number of points in TPCs
- track trajectory points to the interaction point
- no e^+/e^-
- $p_T < 1.5$ GeV/c

p+p, C+C, Si+Si and Pb+Pb interactions, used for comparison, were measured by the NA49 experiment.

Non-target interactions
In order to correct the data for non-target interactions, NA61/SHINE acquires data of both target-inserted and target-removed collisions. Then, in the analysis procedure, non-target interactions are subtracted.
Example of z position distribution of the fitted vertex for Be+Be at 150 GeV/c:



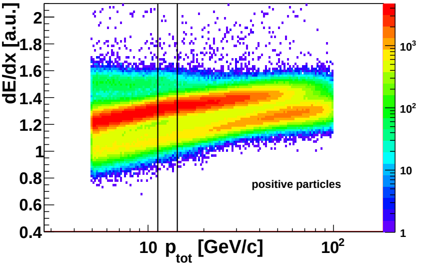
Detector effects
Corrections for detector effects are estimated to be small but still under investigation.

Chemical fluctuation analysis

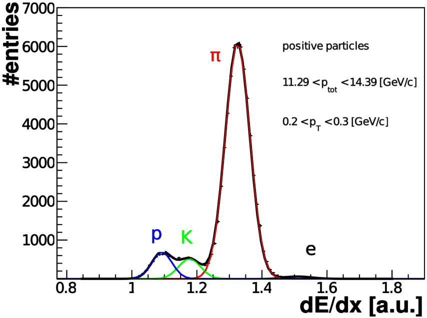
- presented results were obtained from **p+p data collected in 2009 by NA61/SHINE** at $\sqrt{s_{NN}} = 7.6 - 17.3$ GeV
  - p+p at 17.3 GeV - 4.0M events
  - p+p at 12.3 GeV - 5.0M events
  - p+p at 8.7 GeV - 5.8M events
  - p+p at 7.6 GeV - 3.5M events
- event and track cuts were chosen to select only **inelastic interactions** with particles produced in **strong and EM processes within the NA61/SHINE acceptance**.
- analysis focuses on **fluctuations of** $\pi = \pi^+ + \pi^-$**,** $K = K^+ + K^-$ **and** $p + \overline{p}$ **as well as positively charged hadrons (**p**,** K^+**,** π^+**)** by getting **first and second (pure and mixed) moments** of identified particle multiplicity distributions
- second moments of identified particle multiplicity distributions are **corrected for the misidentification** effect using the **identity method** [1].
- Presented results of NA61/SHINE include statistical errors and first estimate of systematic uncertainties (work to finalize systematic uncertainties is in progress e.g. feed down and detector effects).

[1] PRC83:054907,PRC84:024902,PRC86:044906

Particle identification for chemical fluctuation analysis is based on dE/dx measurements in relativistic rise region.



Inclusive dE/dx spectra is sliced in p_{tot}, p_T bins.



sum of Gaussian functions is fitted in each phase-space bin.

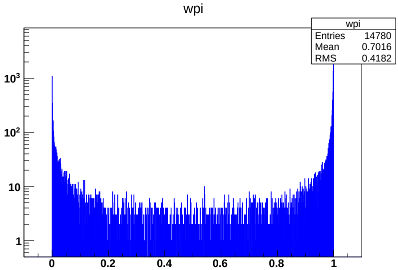
Identity method - single particle identity

The identity method allows to obtain second and third moments (pure and mixed) of identified particle multiplicity distribution corrected for misidentification effect.

A particle identity is calculated as:

$$w_i = \frac{\rho_i(dE/dx)}{\rho(dE/dx)},$$

where ρ_i - function fitted to i^{th} particle type and ρ - function fitted to total dE/dx distribution in a given phase-space bin



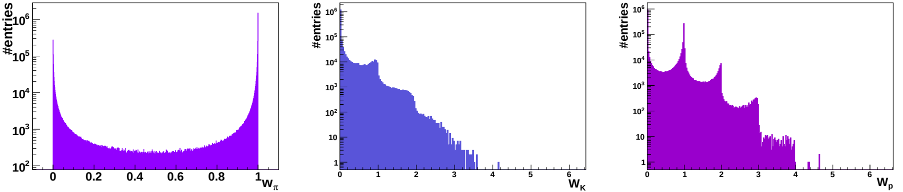
example of w_π distribution for p+p at 12.3 GeV

Identity method - event identity measure

Event quantity W_i defined as:

$$W_i = \Sigma w_j ,$$

where summation runs over all particles in an event



example of event variable W_π, W_K, $W_{p+\bar{p}}$ for p+p at 12.3 GeV

Once, detector response (ρ_i) and W distributions are known the identity method is used to obtain moments of identified particle multiplicity distributions.

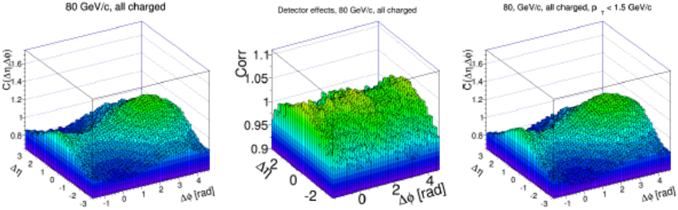
Correction for detector effects

Corrections for detector effects were calculated using EPOS model as the ratio of generated tracks and the reconstructed tracks.

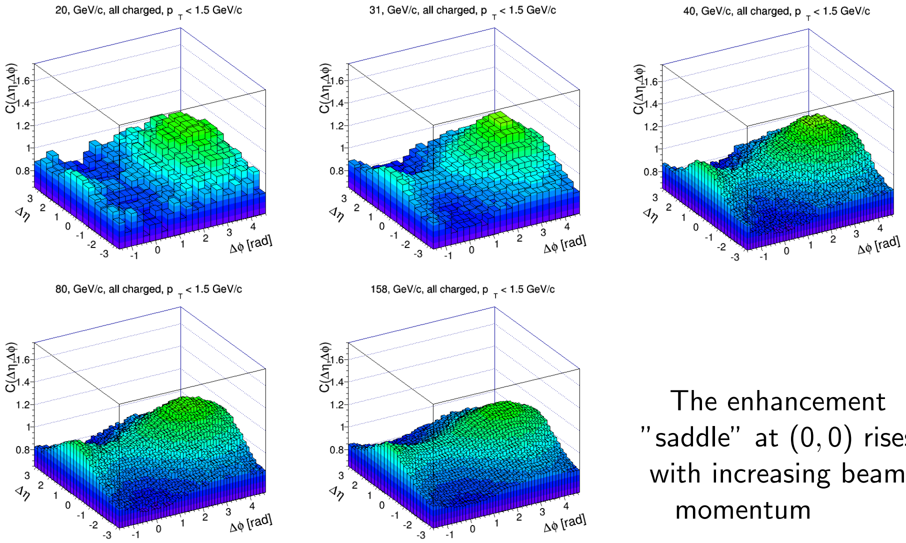
$$Corr(\Delta\eta, \Delta\phi) = \frac{MC_{pure}(\Delta\eta,\Delta\phi)}{MC_{rec}(\Delta\eta,\Delta\phi)}$$

For both data and simulation NA61 detector acceptance was applied.
Data correction is done by multiplying each bin in uncorrected data distribution with the corresponding bin in corrections distribution of detector effects.

$$C(\Delta\eta, \Delta\phi) = C^{raw}(\Delta\eta, \Delta\phi) \cdot Corr(\Delta\eta, \Delta\phi)$$

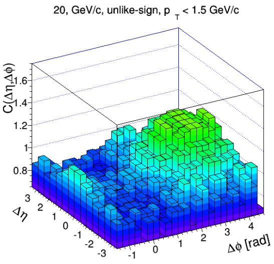


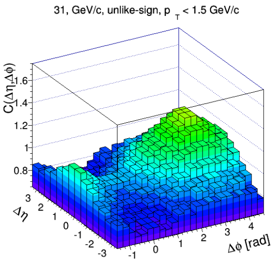
Energy dependence of two particle correlations - all charged

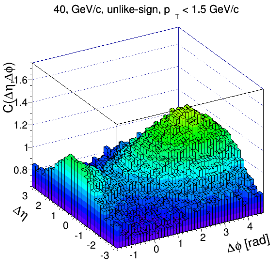


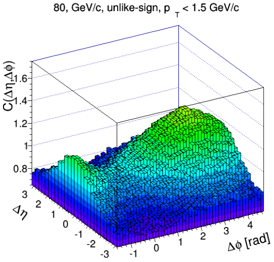
The enhancement "saddle" at $(0, 0)$ rises with increasing beam momentum

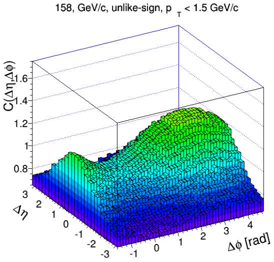
Energy dependence of two particle correlations - unlike sign





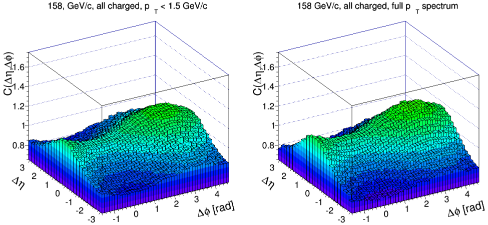




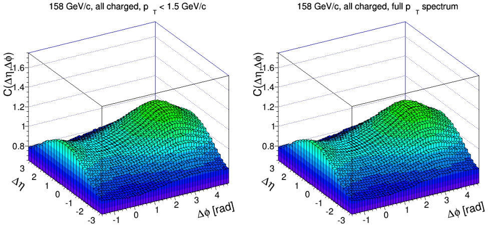


The enhancement at $(0, 0)$ rises with increasing beam momentum

DATA



EPOS



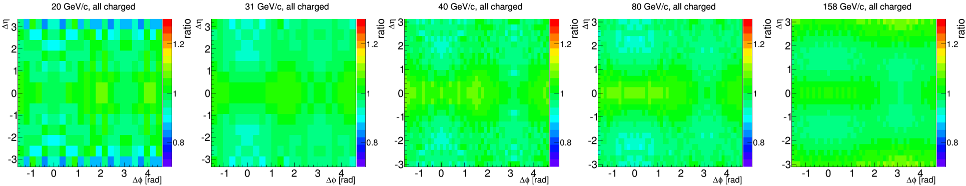
- EPOS in qualitative agreement with the data
- no influence of p_T cut
- no jets at top SPS energy

$C(\Delta\eta, \Delta\phi)_{data} / C(\Delta\eta, \Delta\phi)_{EPOS}$

All charged

6.3 GeV

17.3 GeV



Unlike-sign