Pseudorapidity dependence of multiplicity and transverse momentum fluctuations at the SPS energies

Daria Prokhorova for the NA61/SHINE Collaboration
Laboratory of Ultra-High Energy Physics, St. Petersburg State University

The XXIVth International Baldin Seminar on High Energy Physics Problems, JINR, Dubna, Russia
September 19, 2018

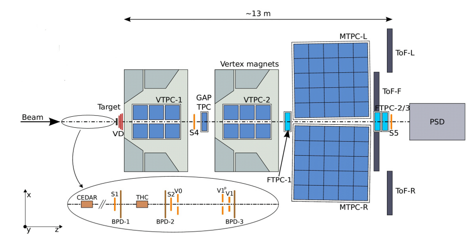
Outline

1. NA61/SHINE experiment at CERN SPS
2. Strong Interactions programme of NA61/SHINE
3. Probes of the critical behaviour
4. Results on energy and system scan
5. Analysis extension: choice of phase space
6. inelastic $\mathrm{p+p}$ and $0-8\%\ ^{7}\mathrm{Be}+^{9}\mathrm{Be}$ results
7. Summary and outlook

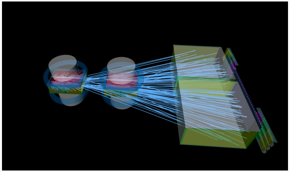
NA61/SHINE experiment at CERN SPS

NA61/SHINE detector

- NA61/SHINE (**S**PS **H**eavy **I**on and **N**eutrino **E**xperiment) is a particle physics fixed-target experiment at CERN SPS
- Performs momenta (13A - 150/158A GeV/c) and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) scan
- Large acceptance hadron spectrometer - full coverage in the forward hemisphere (down to $p_T = 0$ GeV/c)
- Centrality selection in A+A by measuring of forward energy with Projectile Spectator Detector (PSD)



Schematic picture of the NA61/SHINE experiment
NA61 JINST 9: 06005

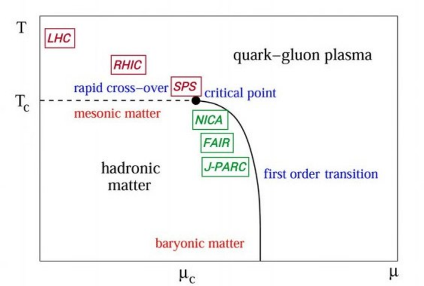


Event browser
http://shine3d.web.cern.ch/shine3d/

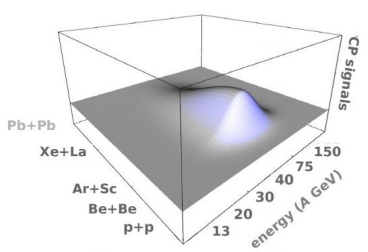
Strong Interactions programme of NA61/SHINE

- study the properties of the onset of deconfinement
- search for the critical point (CP) of strongly interacting matter

Gazdzicki et al. Acta Phys.Polon.B47:1201



Sketch of the phase diagram of strongly interacting matter



Sketch of the expected «critical hill», where the characteristic fluctuation signals of the CP are maximal

What is the CP signal amplitude?
What if it is shadowed by trivial fluctuations?

Probes of the critical behaviour

Intensive and Strongly intensive quantities

Let A and B be any extensive event quantities. Then one can define **intensive quantity** as the scaled variance (still depends on volume fluctuations):

$$\omega[\mathrm{A}] = \frac{\langle \mathrm{A}^2 \rangle - \langle \mathrm{A} \rangle^2}{\langle \mathrm{A} \rangle} \tag{1}$$

and two families of **strongly intensive quantities** (independent of volume and event-by-event volume fluctuations in statistical model of the ideal Boltzmann gas in the grand canonical ensemble):

$$\Delta[\mathrm{A},\mathrm{B}] = \frac{1}{\mathrm{C}_\Delta} \left[\langle \mathrm{B} \rangle \omega[\mathrm{A}] - \langle \mathrm{A} \rangle \omega[\mathrm{B}] \right] \tag{2}$$

$$\Sigma[\mathrm{A},\mathrm{B}] = \frac{1}{\mathrm{C}_\Sigma} \left[\langle \mathrm{B} \rangle \omega[\mathrm{A}] + \langle \mathrm{A} \rangle \omega[\mathrm{B}] - 2 \cdot \left(\langle \mathrm{A} \cdot \mathrm{B} \rangle - \langle \mathrm{A} \rangle \langle \mathrm{B} \rangle \right) \right] \tag{3}$$

Baseline: quantities with trivial properties in the reference models.
Normalizations:

$\omega[\mathrm{A}] = 1$ for the Poisson distribution of A,

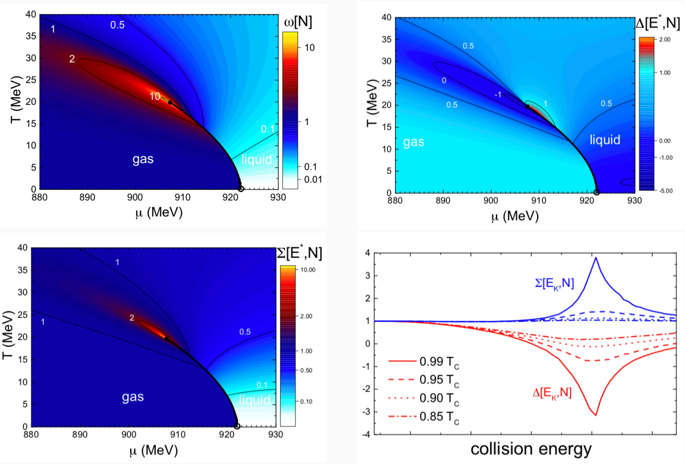
$\Sigma[\mathrm{A},\mathrm{B}] = \Delta[\mathrm{A},\mathrm{B}] = 1$ for independent particle model,

$\omega[\mathrm{A}] = 0$, $\Sigma[\mathrm{A},\mathrm{B}] = 0$, $\Delta[\mathrm{A},\mathrm{B}] = 0$ in the absence of A and B fluctuations.

Gazdzicki et al. PRC 88:024907

Expected model sensitivity to the Critical Point

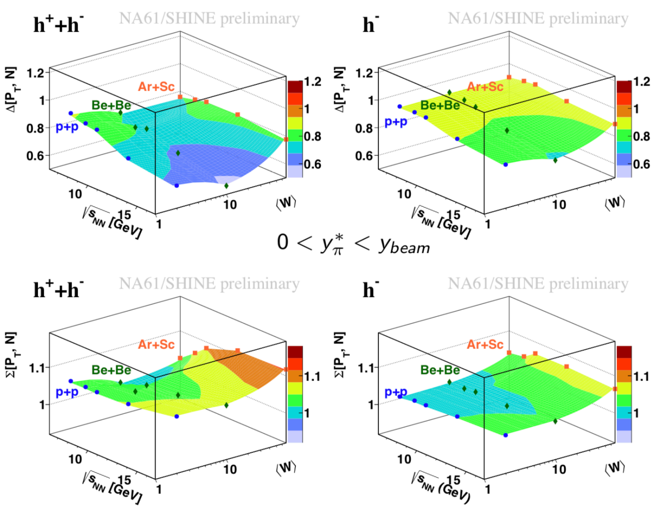
Nucleon system with van der Waals EOS in GCE formulation in the vicinity of the Critical Point (E^* - excitation energy)



Vovchenko, Gorenstein, Stoecker, PRL 118: 182301, Vovchenko, et al., JPA 48: 305001

Results on energy and system scan

Inelastic $p + p$ vs $0 - 5\%$ $^{7}Be +^{9} Be$ vs $0 - 5\%$ $^{40}Ar +^{45} Sc$



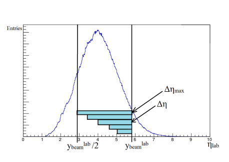
Andronov, Acta Phys. Pol. B Proc. Suppl. 10 449

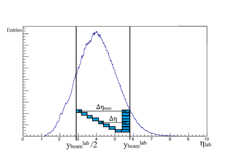
Data shows that $\Delta[P_T, N] < 1$, $\Sigma[P_T, N] \geqslant 1$

No prominent structures which could be related to the critical point

Analysis extension: choice of phase space

Intensive and strongly intensive quantities are proposed to be studied in different pseudorapidity intervals:



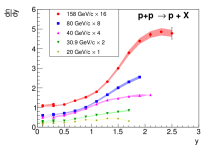


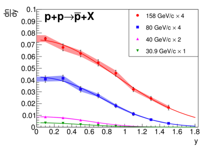
- the lower edge: low acceptance coverage at backward hemisphere
- the upper bound: to suppress possible elastic effect

D. Prokhorova, KnE Energ. Phys. 3 (2018) 217–225

- one window analysis corresponds to changing rapidity-averaged baryo-chemical potential at the freeze-out stage (Becattini F, Manninen J and Gazdzicki M PRC 73 044905)
- two windows analysis of $\Sigma[N_F, N_B]$ is supposed to be sensitive to the initial conditions of particle production and short- and long-range multiplicity correlations (E. Andronov, V. Vechernin, 1808.09770)

the ratio of p and $\overline{p}$ in inelastic $p+p$ at the SPS energies changes significantly with rapidity:

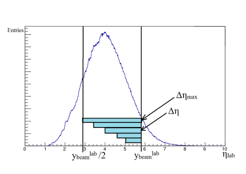




NA61, EPJC 77 10: 671

Definitions for One Window Analysis

Let us consider A as event multiplicity of charged hadrons N and B as total event transverse momentum $\mathrm{P_T}$. If $\langle\cdots\rangle$ means the average value over all events, $\overline{\cdots}$ means the inclusive average value (over all particles and all events), then one can define:



$$\omega[\mathrm{N}] = \frac{\langle \mathrm{N}^2\rangle - \langle \mathrm{N}\rangle^2}{\langle \mathrm{N}\rangle}, \quad \omega[\mathrm{P_T}] = \frac{\langle \mathrm{P_T^2}\rangle - \langle \mathrm{P_T}\rangle^2}{\langle \mathrm{P_T}\rangle}, \quad \omega(\mathrm{p_T}) = \frac{\overline{\mathrm{p_T^2}} - \overline{\mathrm{p_T}}^2}{\overline{\mathrm{p_T}}} \tag{4}$$

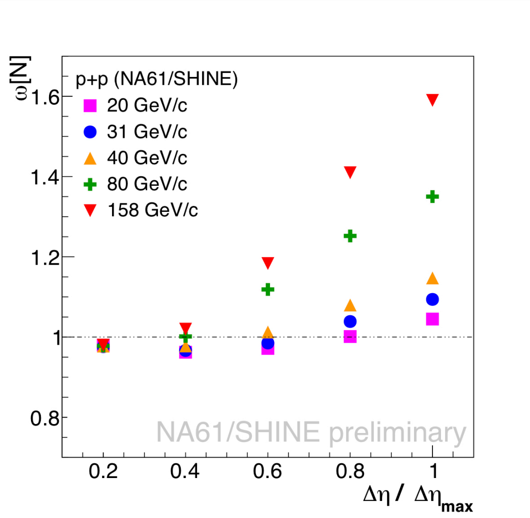
$$\Sigma[\mathrm{P_T},\mathrm{N}] = \frac{1}{\mathrm{C}_\Sigma}\left[\langle \mathrm{N}\rangle\omega[\mathrm{P_T}] + \langle \mathrm{P_T}\rangle\omega[\mathrm{N}] - 2\cdot(\langle \mathrm{P_T}\cdot \mathrm{N}\rangle - \langle \mathrm{P_T}\rangle\langle \mathrm{N}\rangle)\right] \tag{5}$$

$$\Delta[\mathrm{P_T},\mathrm{N}] = \frac{1}{\mathrm{C}_\Delta}\left[\langle \mathrm{N}\rangle\omega[\mathrm{P_T}] - \langle \mathrm{P_T}\rangle\omega[\mathrm{N}]\right], \qquad \mathrm{C}_\Sigma = \mathrm{C}_\Delta = \langle \mathrm{N}\rangle\omega(\mathrm{p_T}) \tag{6}$$

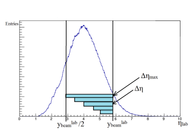
Gazdzicki et al. PRC 88:024907

INELASTIC $\mathrm{p} + \mathrm{p}$ AND $0 - 8\%$ $^7\mathrm{Be} +^9\mathrm{Be}$ RESULTS

Energy dependence of $\omega[N]$ for $h^+ + h^-$ in inelastic $p+p$



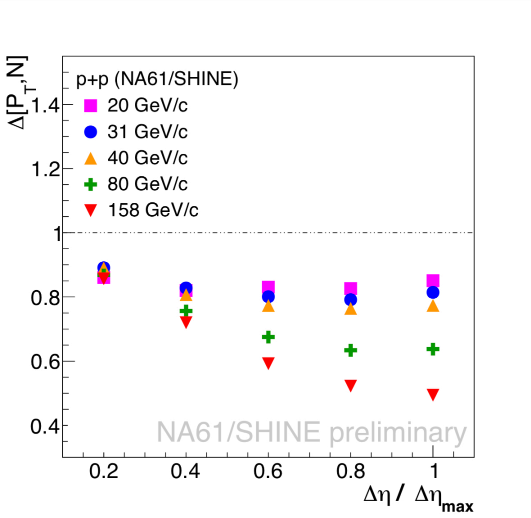
D. Prokhorova, KnE Energ. Phys. 3 (2018) 217–225



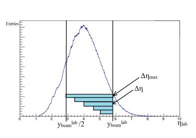
Sketch of η_{lab} uncorrected spectrum of charged hadrons with suggested windows

The value of $\omega[N]$ grows rapidly with pseudorapidity interval width, being more pronounced for higher collision energy

Energy dependence of $\Delta[P_T, N]$ for $h^+ + h^-$ in inelastic $p + p$



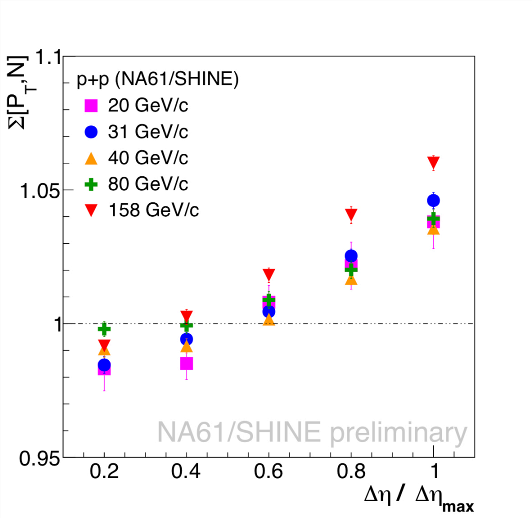
D. Prokhorova, KnE Energ. Phys. 3 (2018) 217–225



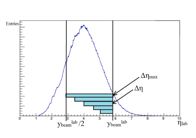
Sketch of η_{lab} uncorrected spectrum of charged hadrons with suggested windows

The value of $\Delta[P_T, N]$ decreases monotonically with the increase of pseudorapidity window width

Energy dependence of $\Sigma[\mathrm{P_T}, \mathrm{N}]$ for $\mathrm{h}^+ + \mathrm{h}^-$ in inelastic $\mathrm{p} + \mathrm{p}$



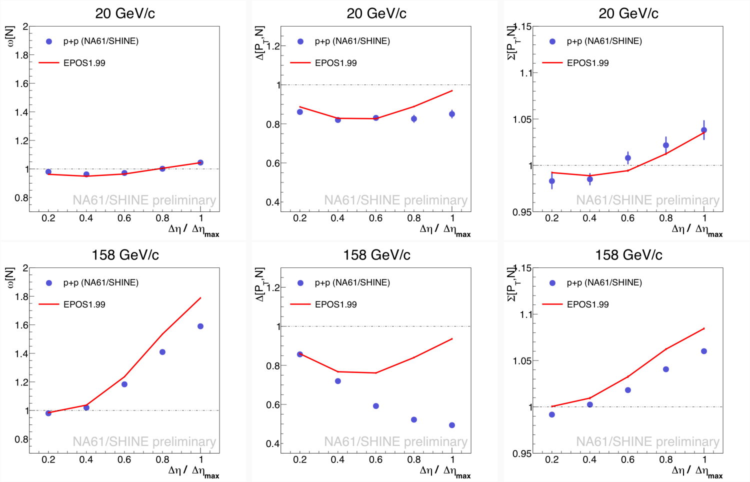
D. Prokhorova, KnE Energ. Phys. 3 (2018) 217–225

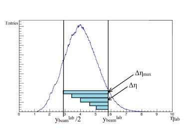


Sketch of η_{lab} uncorrected spectrum of charged hadrons with suggested windows

The value of $\Sigma[\mathrm{P_T}, \mathrm{N}]$ grows monotonically with the pseudorapidity window width similarly for all collision energies

Comparison between experimental data and EPOS1.99 in inelastic $p + p$



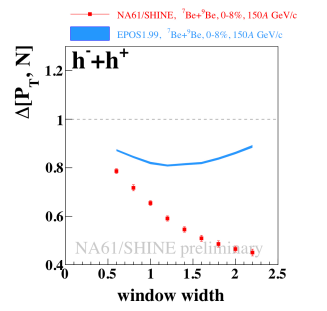


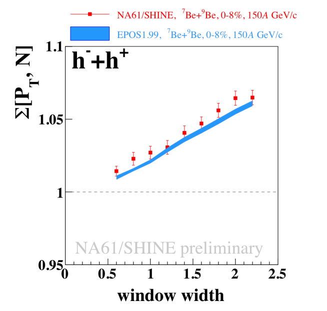
D. Prokhorova, KnE Energ. Phys. 3 (2018) 217–225

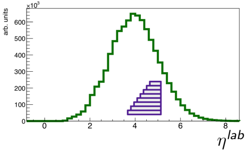
The significant disagreement between experimental data and the EPOS1.99 for $\Delta[P_T, N]$

Comparison between experimental data and EPOS1.99 for $0-8\%\ ^7\mathrm{Be}+^9\mathrm{Be}$

Andronov, KnE Energy and Physics 3 1:226



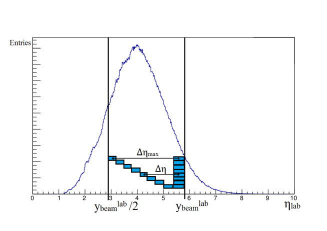




Again the significant disagreement between data and EPOS1.99 is observed for $\Delta[\mathrm{P_T}, \mathrm{N}]$ measure with the width of pseudorapidity window, however the $\Sigma[\mathrm{P_T}, \mathrm{N}]$ description is in agreement

Definitions for Two Windows Analysis

Let us consider extensive event quantities as
$\mathrm{N_F}$ - **multiplicity in Forward window,**
$\mathrm{N_B}$ - **multiplicity in Backward window**
Then one can define:



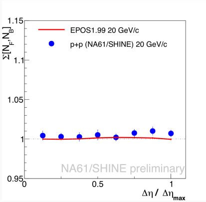
$$\Sigma[\mathrm{N_F},\mathrm{N_B}] = \frac{1}{\mathrm{C_\Sigma}}\left[\langle \mathrm{N_B}\rangle\omega[\mathrm{N_F}] + \langle \mathrm{N_F}\rangle\omega[\mathrm{N_B}] - 2\cdot(\langle \mathrm{N_F}\cdot \mathrm{N_B}\rangle - \langle \mathrm{N_F}\rangle\langle \mathrm{N_B}\rangle)\right] \tag{7}$$

$$\omega[\mathrm{N_F}] = \frac{\langle \mathrm{N_F^2}\rangle - \langle \mathrm{N_F}\rangle^2}{\langle \mathrm{N_F}\rangle}, \qquad \omega[\mathrm{N_B}] = \frac{\langle \mathrm{N_B^2}\rangle - \langle \mathrm{N_B}\rangle^2}{\langle \mathrm{N_B}\rangle} \tag{8}$$

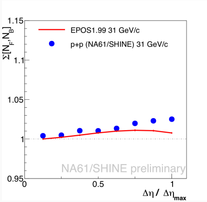
$$\mathrm{C_\Sigma} = \langle \mathrm{N_B}\rangle + \langle \mathrm{N_F}\rangle \tag{9}$$

Andronov, TMPh 185 1:1383

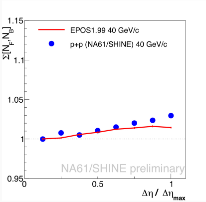
$\Sigma[N_F, N_B]$ in Separated windows for $h^+ + h^-$ in inelastic $p+p$



20 GeV/c



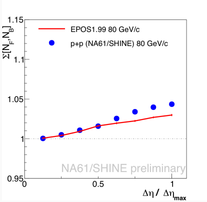
31 GeV/c



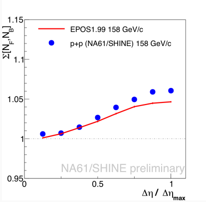
40 GeV/c

$\Sigma[N_F, N_B]$ increases with the distance between F and B pseudorapidity intervals

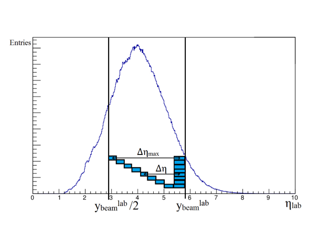
D. Prokhorova, KnE Energ. Phys. 3 (2018) 217–225



80 GeV/c



158 GeV/c



The behaviour corresponds to the prediction by the model of independent quark gluon strings (E. Andronov, V. Vechernin, 1808.09770). EPOS1.99 describes data better for closer windows.

Summary and outlook

Summary and outlook

The main results of pseudorapidity dependence of fluctuations:

- Studied fluctuation measures significantly depend on width and location of pseudorapidity intervals
- Results for $\omega[\mathrm{N}]$ and $\Delta[\mathrm{P_T}, \mathrm{N}]$ depend on the collision energy, on the other hand $\Sigma[\mathrm{P_T}, \mathrm{N}]$ has the same tendency for all considered beam momenta
- The increase of $\Sigma[\mathrm{N_F}, \mathrm{N_B}]$ value with distance between forward and backward pseudorapidity intervals is more pronounced for higher energy
- EPOS1.99 well describes data for $\omega[\mathrm{N}]$, $\Sigma[\mathrm{P_T}, \mathrm{N}]$, $\Sigma[\mathrm{N_F}, \mathrm{N_B}]$
- A **significant discrepancy between data and EPOS1.99 is observed for** $\Delta[\mathrm{P_T}, \mathrm{N}]$ for $\mathrm{p}+\mathrm{p}$ at all collision energies and $0-8$% $^{7}\mathrm{Be}+^{9}\mathrm{Be}$ at $150\mathrm{A}$ GeV/c, which is more pronounced for large width of a pseudorapidity interval

Summary and outlook

- NA61/SHINE conducts search for the critical point of strongly interacting matter by means of analysis of fluctuations, namely, multiplicity and $[\mathrm{P_T}, \mathrm{N}]$ fluctuations
- Results on system size vs. energy dependence of N and $[\mathrm{P_T}, \mathrm{N}]$ fluctuations for particles produced in strong processes within the NA61/SHINE acceptance show **no indication of the critical point so far**
- The detailed analysis of the accumulated experimental data is being continued by the NA61/SHINE

Stay tuned and have a **SHINY** day !

daria.prokhorova@cern.ch

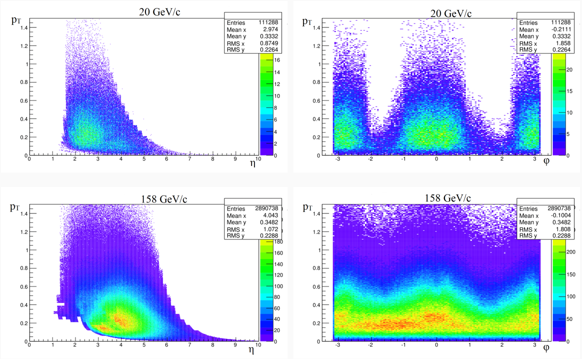
THANK YOU!

This work is supported by the Russian Science Foundation, grant 17-72-20045

Back-up

Analysis details of inelastic $\mathrm{p+p}$

- The final results refer to **charged hadrons** with $p_T < 1.5$ GeV/c produced in the analysis acceptance (https://edms.cern.ch/document/1549298/1) of the NA61/SHINE experiment in 2009 in inelastic p+p collisions at p_{beam}^{lab} = 20, 31, 40, 80 and 158 GeV/c (at $\sqrt{s_{NN}}$ = 6.27, 7.62, 8.73, 12.32 and 17.27 GeV)
- The results are **corrected only for off-target interactions** (simulation-based corrections for other biases are in progress)
- NA61/SHINE acceptance: fixed-target experiment → **acceptance depends on collision energy**



20 GeV/c

158 GeV/c

To make a correction for off-target interactions one should calculate:

$$\langle \mathrm{X} \rangle = \frac{1}{\mathrm{N}_{\mathrm{ev}}^{\mathrm{I}} - \epsilon \cdot \mathrm{N}_{\mathrm{ev}}^{\mathrm{R}}} \cdot \left(\sum_{\mathrm{i}=1}^{\mathrm{N}_{\mathrm{ev}}^{\mathrm{I}}} \mathrm{X}_{\mathrm{i}}^{\mathrm{I}} - \epsilon \cdot \sum_{\mathrm{j}=1}^{\mathrm{N}_{\mathrm{ev}}^{\mathrm{R}}} \mathrm{X}_{\mathrm{j}}^{\mathrm{R}} \right), \tag{10}$$

where $\mathrm{N}_{\mathrm{ev}}^{\mathrm{I}}$ is a number of events with target inserted, $\mathrm{N}_{\mathrm{ev}}^{\mathrm{R}}$ - with target removed, ϵ is a normalization factor:

$$\epsilon = \left. \frac{\mathrm{N}_{\mathrm{ev}}^{\mathrm{I}}}{\mathrm{N}_{\mathrm{ev}}^{\mathrm{R}}} \right|_{\mathrm{z} > -450\mathrm{cm}} \tag{11}$$

z - is the z position of the fitted primary vertex

p+p: Event Cuts

- T2 trigger = $\mathrm{S1} \wedge \mathrm{S2} \wedge \overline{\mathrm{V0}} \wedge \overline{\mathrm{V1}} \wedge \overline{\mathrm{V1^p}} \wedge \mathrm{CEDAR} \wedge \overline{\mathrm{THC}}$
- no off-time beam particle was detected within $\pm 1.5\ \mu\mathrm{s}$ around the trigger particle
- the beam particle trajectory was measured in BPD-3 and at least one of BPD-1 or BPD-2 detectors
- there was at least one track reconstructed in the TPCs and fitted to the interaction vertex
- Good Fit Quality
- z position of the vertex should be between (-620.3, -540.3) cm
- events with a single, well measured positively charged track with absolute momentum close to the beam momentum were rejected: $(\mathrm{p_{beam}} - 1)$ GeV/c

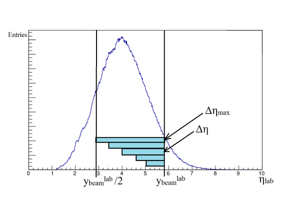
p+p: Track Cuts

- track existence
- the track should be measured in a high tracking efficiency (90%) TPC acceptance (https://edms.cern.ch/document/1549298/1)
- the sum of the number of reconstructed points in VTPC-1 and VTPC-2 should be greater than 15 or the number of reconstructed points in the GAP-TPC should be greater than 5
- the total number of reconstructed points on the track should be greater than 30
- $|\mathrm{B_x}| < 4$ cm, $|\mathrm{B_y}| < 2$ cm
- $\mathrm{p_T} < 1.5$ GeV/c
- electrons and positrons are rejected

Pseudorapidity intervals definition for One Window Analysis

$$y_{beam}^{lab} = \frac{1}{2}\frac{\sqrt{m_p^2 + p_{beam}^2} + p_{beam}}{\sqrt{m_p^2 + p_{beam}^2} - p_{beam}}$$

Sketch of η_{lab} uncorrected spectrum of charged hadrons with suggested windows

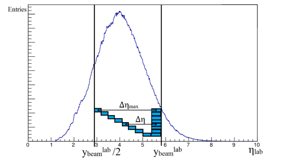


- 5 pseudorapidity intervals of different width are considered
- η is considered in the range of $(y_{beam}^{lab}/2, y_{beam}^{lab})$ to exclude the influence of bad acceptance coverage at small η^{lab} and to reduce elastic processes effects at $\eta^{lab} > y_{beam}^{lab}$
- studied quantities are plotted as functions of $\Delta\eta/\Delta\eta_{max}$

Pseudorapidity width dependence study corresponds to observation of different baryo-chemical potentials $\rightarrow$ additional way to extend the phase diagram scan

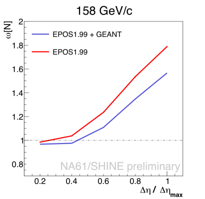
Pseudorapidity intervals definition for Two Windows Analysis

Sketch of η_{lab} uncorrected spectrum of charged hadrons with suggested windows

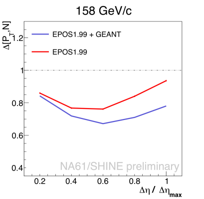


- 8 pairs of separated pseudorapidity intervals of equal width are considered
- η is considered in the range of $(\mathrm{y}^{\mathrm{lab}}_{\mathrm{beam}}/2, \mathrm{y}^{\mathrm{lab}}_{\mathrm{beam}})$ to exclude the influence of bad acceptance coverage at small η^{lab} and to reduce elastic processes effects at $\eta^{\mathrm{lab}} > \mathrm{y}^{\mathrm{lab}}_{\mathrm{beam}}$
- studied quantities are plotted as functions of $\Delta\eta/\Delta\eta_{\mathrm{max}}$

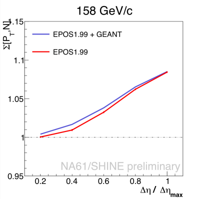
This analysis was done in terms of strongly intensive quantity $\Sigma[\mathrm{N_F}, \mathrm{N_B}]$ which was supposed to be sensitive to the initial conditions of particle production such as string fragmentation, string fusion and conservation laws (E. Andronov, V. Vechernin, 1808.097705) and was used in the **analysis of short- and long-range multiplicity correlations**.



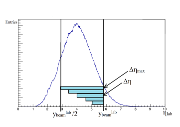
$\omega[\mathrm{N}]$



$\Delta[\mathrm{P_T}, \mathrm{N}]$



$\Sigma[\mathrm{P_T}, \mathrm{N}]$



Example of the difference between pure and reconstructed Monte Carlo simulations due to experimental biases for beam momentum 158 GeV/c. **Simulation-based corrections are in progress.** Could be significant due to trigger biases for p+p collisions

EPOS1.99 - Werner, et al., PRC 74:044902