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

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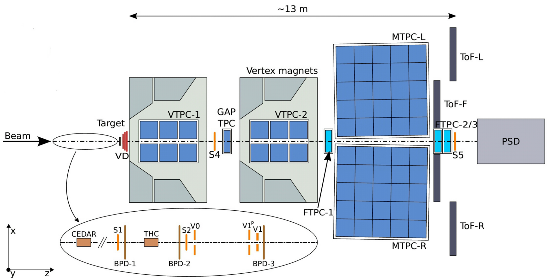
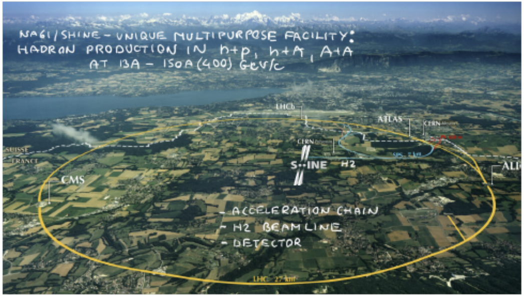
NA61/SHINE experiment at the SPS CERN

NA61/SHINE (**S**PS **H**eavy **I**on and **N**eutrino **E**xperiment) is a particle physics fixed-target experiment at the Super Proton Synchrotron (SPS) at the European Organization for Nuclear Research (CERN)



Schematic picture of the NA61/SHINE experiment



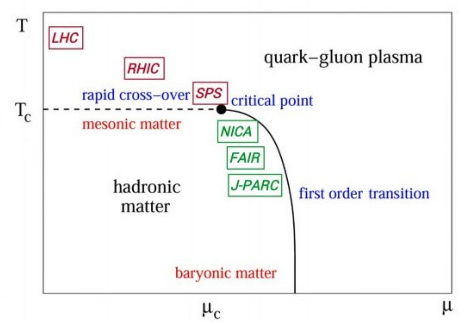
Location

Strong interaction programme at the NA61/SHINE

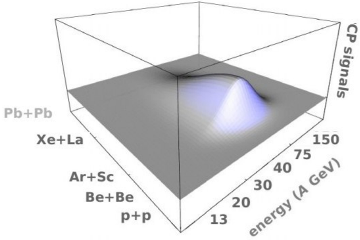
- study the properties of the onset of deconfinement

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

- search for the critical point (CP) of strongly interacting matter



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

Study p+p collisions is a baseline for comparison with heavier systems

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

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):

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

and two families of strongly intensive quantities (don't depend on volume and event-by-event volume fluctuations in statistical model of the ideal Boltzmann gas in the grand canonical ensemble):

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

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

$\omega[A] = 1$ for the Poisson distribution of A, $\Sigma[A,B] = \Delta[A,B] = 1$ for independent particle model;
$\omega[A] = 0$, $\Sigma[A,B] = \Delta[A,B] = 0$ in the absence of A and B fluctuations.

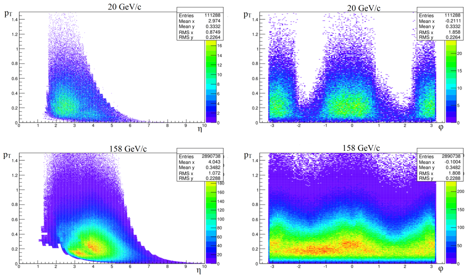
Gazdzicki et al. PRC 88:024907

Analysis details

- 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}[GeV/c]	20	31	40	80	158
$\sqrt{s_{NN}}$[GeV]	6.27	7.62	8.73	12.32	17.27

- The results are corrected only for off-target interactions (simulation-based corrections for other biases are in progress)
- NA61/SHINE acceptance: fixed-target experiment $\rightarrow$ acceptance depends on collision energy

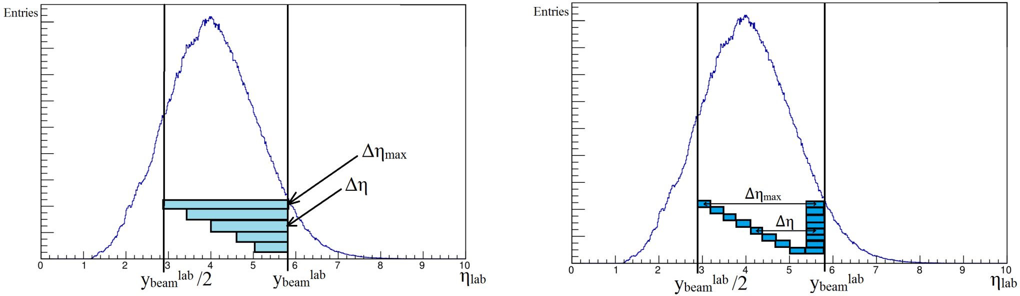


20 GeV/c

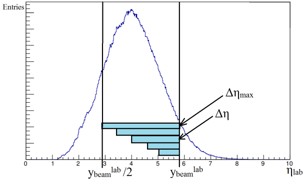
158 GeV/c

Pseudorapidity dependence study

- **One Window Analysis**: $\omega[N]$, $\Delta[P_T, N]$ and $\Sigma[P_T, N]$ in one window with changing window width
- **Two Windows Analysis**: $\Sigma[N_F, N_B]$ in two separated windows with changing distance between windows



Definitions for One Window Analysis



Let us consider A as event multiplicity of charged hadrons N and B as total event transverse momentum 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:

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

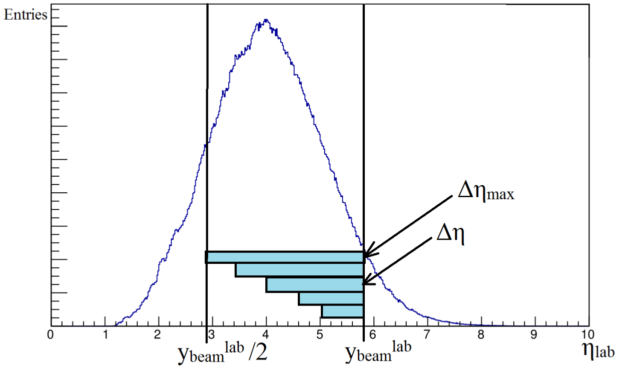
$$\Sigma[P_T, N] = \frac{1}{C_\Sigma} \left[\langle N \rangle \omega[P_T] + \langle P_T \rangle \omega[N] - 2 \cdot \left(\langle P_T \cdot N \rangle - \langle P_T \rangle \langle N \rangle \right) \right] \tag{5}$$

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

Gazdzicki et al. PRC 88:024907

Pseudorapidity intervals definition for One Window Analysis

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

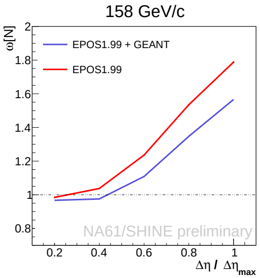


$$y_{beam}^{lab} = \frac{1}{2}\frac{\sqrt{m_p^2 + p_{beam}^2} + p_{beam}}{\sqrt{m_p^2 + p_{beam}^2} - p_{beam}}$$

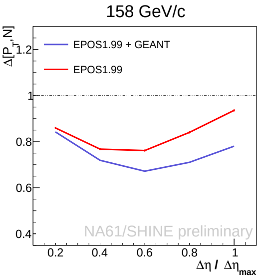
- 5 pseudorapidity intervals of different width are considered
- η is considered in the range of $(y_{beam}^{lab}/2,\, y_{beam}^{lab})$ to exclude the influence of bad acceptance coverage at small η^{lab} and to reduce elastic processes effects at $\eta^{lab} > y_{beam}^{lab}$
- studied quantities are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

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

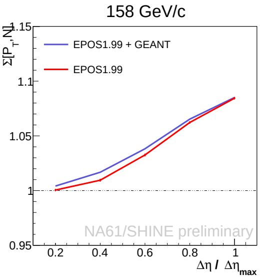
Comparison between EPOS1.99 and EPOS1.99 + GEANT for future simulation-based corrections



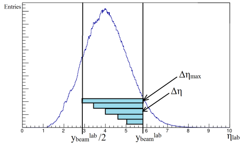
$\omega[N]$



$\Delta[P_T, N]$



$\Sigma[P_T, N]$

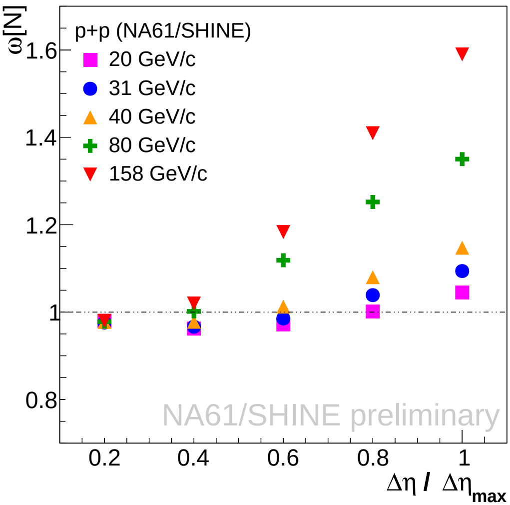


Example of the difference between pure and reconstructed Monte Carlo simulations due to experimental biases for beam momentum 158 GeV/c.

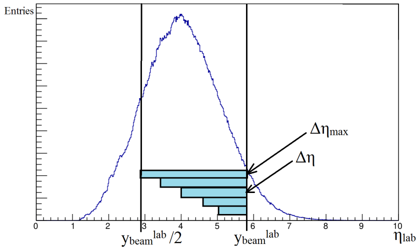
Simulation-based corrections are in progress. Could be significant due to trigger biases for p+p collisions

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

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

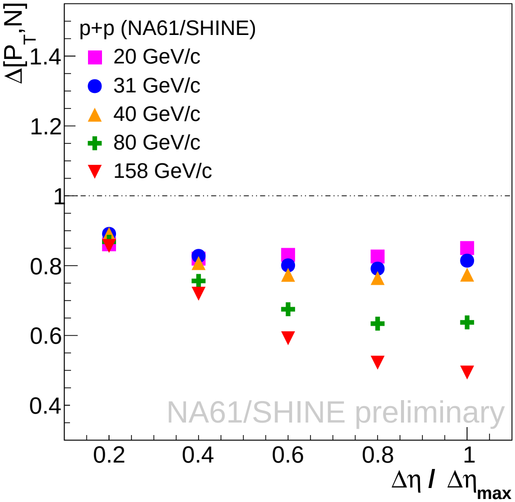


The value of $\omega[N]$ grows rapidly with pseudorapidity interval width. It is more pronounced for higher collision energy. $\omega[N]$ is almost equal to 1 for small window width for all energies

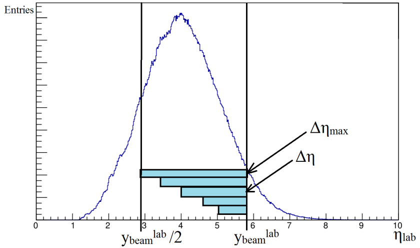


Sketch of η_{lab} uncorrected spectrum of charged hadrons with suggested windows

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

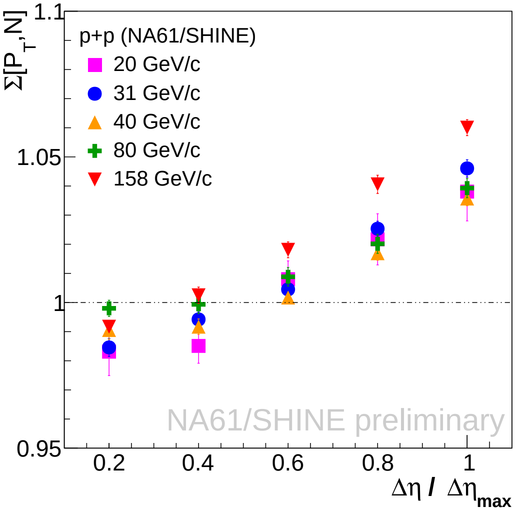


$\Delta[P_T, N]$ decreases monotonically with the increase of pseudorapidity window width. For smaller collision energies $\Delta[P_T, N]$ moreover starts to tend to the 1 with the interval width

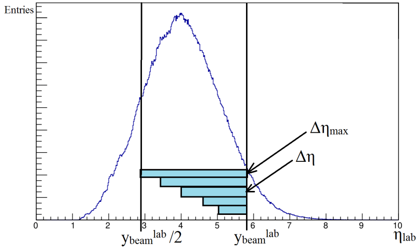


Sketch of η_{lab} uncorrected spectrum of charged hadrons with suggested windows

Energy dependence of $\Sigma[P_T, N]$ for $h^+ + h^-$

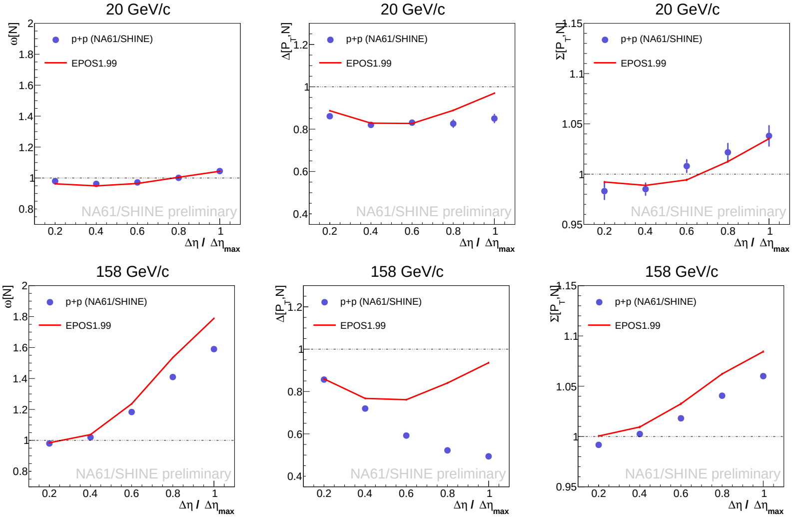


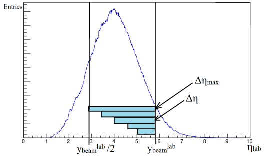
The value of $\Sigma[P_T, N]$ grows monotonically with the pseudorapidity window width. Plots for all collision energies are close to each other. For small pseudorapidity windows $\Sigma[P_T, N]$ approaches the value of 1



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

Comparison between experimental data and EPOS1.99

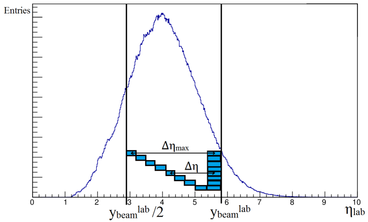




This crucial disagreement between experimental data and the EPOS1.99 results for pseudorapidity dependence of $\Delta[P_T, N]$ was also observed in $^7Be+^9Be$ (Andronov, ICPPA-2017)

Definitions for Two Windows Analysis

Let us consider extensive event quantities as N_F - **multiplicity in Forward window,** N_B - **multiplicity in Backward window**. Then one can define:



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

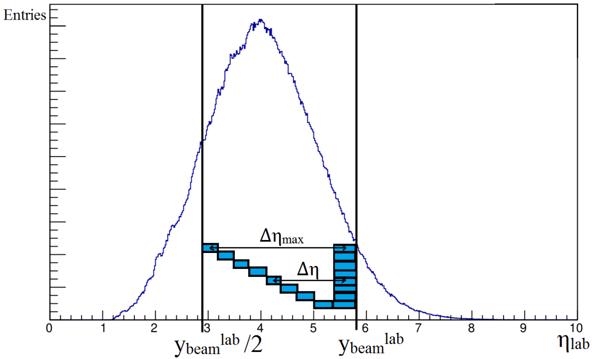
$$\omega[N_F] = \frac{\langle N_F^2\rangle - \langle N_F\rangle^2}{\langle N_F\rangle}, \qquad \omega[N_B] = \frac{\langle N_B^2\rangle - \langle N_B\rangle^2}{\langle N_B\rangle} \quad (8)$$

$$C_\Sigma = \langle N_B\rangle + \langle N_F\rangle \quad (9)$$

Andronov, TMPh 185 1:1383

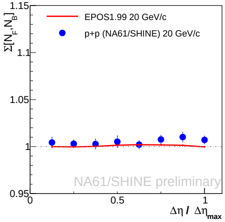
Pseudorapidity intervals definition for Two Windows Analysis

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

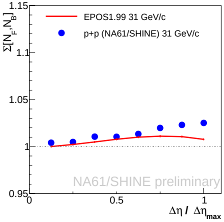


- 8 pairs of separated pseudorapidity intervals of equal width are considered
- η is considered in the range of $(y_{beam}^{lab}/2,\ y_{beam}^{lab})$ to exclude the influence of bad acceptance coverage at small η^{lab} and to reduce elastic processes effects at $\eta^{lab} > y_{beam}^{lab}$
- studied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

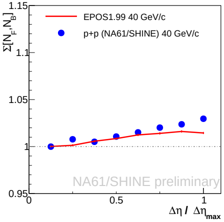
$\Sigma[N_F, N_B]$ in Separated windows for $h^+ + h^-$



20 GeV/c

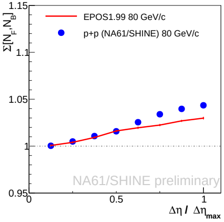


31 GeV/c

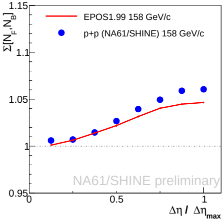


40 GeV/c

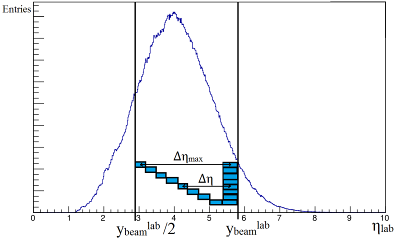
$\Sigma[N_F, N_B]$ increases with the distance between F and B pseudorapidity intervals as it is predicted by the model of independent quark gluon strings (Vechernin, WPCF-2017). EPOS1.99 describes data better for closer windows



80 GeV/c



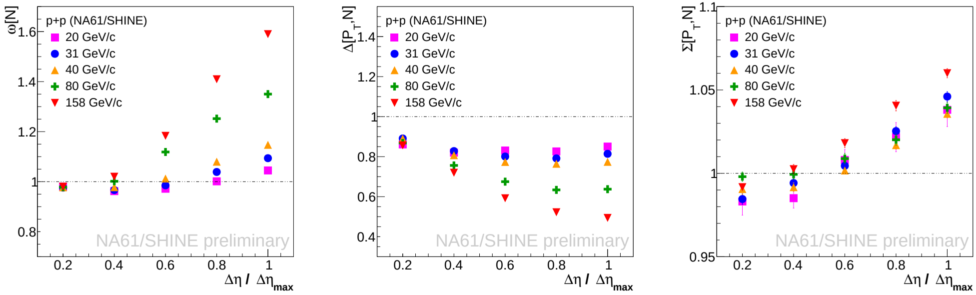
158 GeV/c



Conclusions

New results on pseudorapidity dependence of fluctuation measures in inelastic p+p collisions were presented

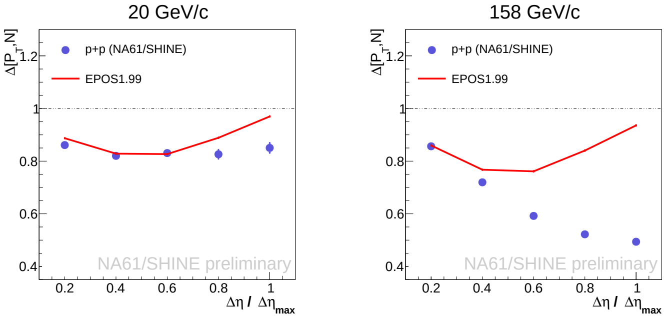
- Studied fluctuation measures significantly depend on width and location of pseudorapidity intervals
- Results for $\omega[N]$ and $\Delta[P_T, N]$ depend on the collision energy, on the other hand $\Sigma[P_T, N]$ has the same tendency for all considered beam momenta



$\omega[N]$ $\Delta[P_T, N]$ $\Sigma[P_T, N]$

Conclusions

- EPOS1.99 does not describe data for $\Delta[P_T, N]$



- The increase of $\Sigma[N_F, N_B]$ value with distance between forward and backward pseudorapidity intervals is more pronounced for higher energy

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THANK YOU!

Back-up

p+p: Off-Target corrections

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

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

where N_{ev}^{I} is a number of events with target inserted, N_{ev}^{I} - with target removed, ϵ is a normalization factor:

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

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 $\pm 1.5\ \mu s$ 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: $(p_{beam} - 1)$ 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
- $|B_x| < 4$ cm, $|B_y| < 2$ cm
- $p_T < 1.5$ GeV/c
- electrons and positrons are rejected