Forward-backward correlations with the $\Sigma$ quantity in the wounded-constituent framework at energies available at the CERN Large Hadron Collider

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Introduction: Why and how do we study correlations and fluctuations?

Analysis of correlations and fluctuations can provide information about the early stages of heavy-ion collisions.
**Introduction:** Why and how do we study correlations and fluctuations?

The forward-backward (FB) correlation coefficient $b_{\text{corr}}$ is:

$$b_{\text{corr}} = \frac{\text{Cov}(n_F, n_B)}{\sqrt{\text{Var}(n_F)\text{Var}(n_B)}}$$

- largely influenced by geometrical (volume) fluctuations.
- dependent on centrality estimator.

\[ \Sigma = \frac{\langle n_F \rangle \omega_B + \langle n_B \rangle \omega_F - 2 \text{Cov}(n_F, n_B)}{\langle n_F \rangle + \langle n_B \rangle}, \]

where \( \omega \) is scaled variance: \( \omega = \text{Var}(n)/\langle n \rangle \).

For a symmetric collision \( \omega_B = \omega_F \) and \( \langle n_F \rangle = \langle n_B \rangle \),

\[ \Sigma \approx \omega(1-b_{\text{corr}}). \]

For Poisson distribution: \( \omega = 1 \) & \( b_{\text{corr}} = 0 \rightarrow \Sigma = 1 \)

**Introduction:** FB correlations with strongly intensive quantity \( \Sigma \)

- **Strongly intensive quantities** do not depend on system volume nor system volume fluctuations.


**Strongly intensive quantity \( \Sigma \):**

**Independent source model:**

\( \Sigma \rightarrow \) gives direct information about characteristics of single source distribution!
**ALICE: Σ as a function of centrality bin width**

The FB correlation coefficient $b_{\text{corr}}$

**The Σ quantity**

ALICE Preliminary
Pb-Pb \( \frac{S_{NN}}{S_{NN}} = 2.76 \text{ TeV} \)
\( p_T > 0.2 \text{ GeV/c} \)
\( \Delta \eta = 1.2, \ \delta \eta = 0.2, \ \varphi \in (0,2\pi) \)

The quantity $\Sigma$ exhibits the properties of a strongly intensive quantity!

- $\Sigma$ does **not** depend on centrality bin width (volume fluctuations).
- $\Sigma$ does **not** depend on centrality estimator!

increase of volume fluctuations

width of centrality class (Δ centrality): 10%, 5%, 2%

center of centrality class
**ALICE: \( \Sigma \) as a function of centrality**

- Values of \( \Sigma \) **increase with energy** and **increase with decreasing centrality** in experimental data, contrary behavior noted for MC HIJING results.
- MC AMPT and MC EPOS reproduce dependence on centrality **qualitatively** but **not quantitatively**.
- From results for MC AMPT it is evident that \( \Sigma \) is sensitive to the **mechanism** of particle production.

**Note:** \( V_0 \approx ZDCvsZEM \) → no dependence on centrality estimator!
FB correlations with the $\Sigma$ quantity in the wounded-constituent framework:

\[ \Sigma\text{ in WNM and WQM for a symmetric AA collision:} \]

\[ C = 2p - 1 \quad \rightarrow \quad \Sigma = 1 + \frac{n}{2}C^2 \left[ \langle (w_B - w_F)^2 \rangle + \frac{2}{k} \right] \]

- $p = 0.5 \implies C=0$: $\Sigma=1$ and $\Sigma$ is SIQ;
- $p \neq 0.5 \implies C\neq0$: $\Sigma>1$ and shows intrinsic dependence on the number of $w_F$ and $w_B \rightarrow$ no longer a strongly intensive quantity!

WN(Q)M: Σ quantity as a function of centrality bin width and centrality selection method

This can be explained theoretically if one notes that Σ in WN(Q)M can be rewritten in terms of partial covariance:

\[ Σ = 1 + \frac{n}{2} C^2 \left[ \frac{-2 \text{Cov}(w_F, w_B \bullet w)}{\langle w_F \rangle} + \frac{2}{k} \right] \]

where \( w = w_F + w_B \) and \( \text{Cov}(w_F, w_B \bullet w) \) is the partial covariance of \( w_F \) and \( w_B \) given \( w \).

Σ in WNM and WQM:

\[ Σ = 1 + \frac{n}{2} C^2 \left[ \frac{(w_B - w_F)^2}{2\langle w_F \rangle} + \frac{2}{k} \right] \]

- p≠0 → C≠0: intrinsic dependence on the number of \( w_F \) and \( w_B \) → no longer a strongly intensive quantity!
- resemblance to the behavior reported by ALICE (slide 5)
- Σ does not depend on centrality bin width (volume fluctuations).
- Σ does not depend on centrality estimator!

"strongly-intensive-quantity-like" properties!
WN(Q)M: Σ quantity as a function of centrality

- WNM and WQM accurately depict the trend of Σ with centrality observed in the experimental data\(^4\) (also for Pb-Pb at $\sqrt{s_{NN}}=2.76$ and Xe-Xe at $\sqrt{s_{NN}}=5.44$ TeV\(^5\)).

- Values of Σ in the WNM and WQM are sensitive to the probability value $p$.

- From comparison the data with WN(Q)M: probability $p$ changes as a function of pseudorapidity.

- These probability values provide a new way to estimate the wounded nucleon (quark) fragmentation function in symmetric AA collisions!

\(^4\) I. Sputowska (ALICE), EPJ Web Conf. 274, 05003 (2022)
\(^5\) I. Sputowska, Phys.Rev.C 108 (2023) 1, 014903
Wounded constituent fragmentation functions in symmetric Pb—Pb collisions

The particle production for each wounded nucleon/quark → described by universal fragmentation function $F(\eta)$:

$$N(\eta) = \langle w_F \rangle F(\eta) + \langle w_B \rangle F(-\eta)$$

"STANDARD" METHOD

→ based on measurement of $N(\eta) = dN_{ch}/d\eta$ distribution:

$$F(\eta) = \frac{1}{2} \left( \frac{N(\eta) + N(-\eta)}{\langle w_F \rangle + \langle w_B \rangle} + \frac{N(\eta) - N(-\eta)}{\langle w_F \rangle - \langle w_B \rangle} \right)$$

only for asymmetric collisions $\langle w_F \rangle \neq \langle w_B \rangle$.

NEW APPROACH:

- It is based on the relation between $p$ and $\Sigma$ in WN(Q)M.
- It provides a unique opportunity to determine the $F(\eta)$ in a symmetric nucleus-nucleus collision.

$$p = \frac{\int_{F(B)}^{} F(\eta) \, d\eta}{\int_{F(B)}^{} F(\eta) \, d\eta + \int_{B}^{} F(\eta) \, d\eta}$$

based of measurement of $\Sigma$ from MC sim.
Summary

In this study I investigated the properties of Σ quantity at LHC energies using the wounded nucleon and wounded quark models:

(1) Two-component scenario of forward- and backward-moving constituents → **collapses the strongly intensive properties** of Σ!

(2) Even though in the WNM and WQM Σ is no longer a strongly intensive quantity, it **retains some of its properties** in symmetric AA collisions → due to its relation to partial covariance.

(3) Σ results determined in WNM and WQM are in **good agreement with the ALICE data**. The models outperform more complex ones such as HIJING, AMPT, or EPOS, which struggle to describe Σ properly.

(4) Σ is sensitive to probability p of particle emission in η interval by a wounded source. This relation allows the **direct determination of the fragmentation function** of a wounded nucleon or quark in a symmetric nucleus-nucleus collision, which has not been possible so far!

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