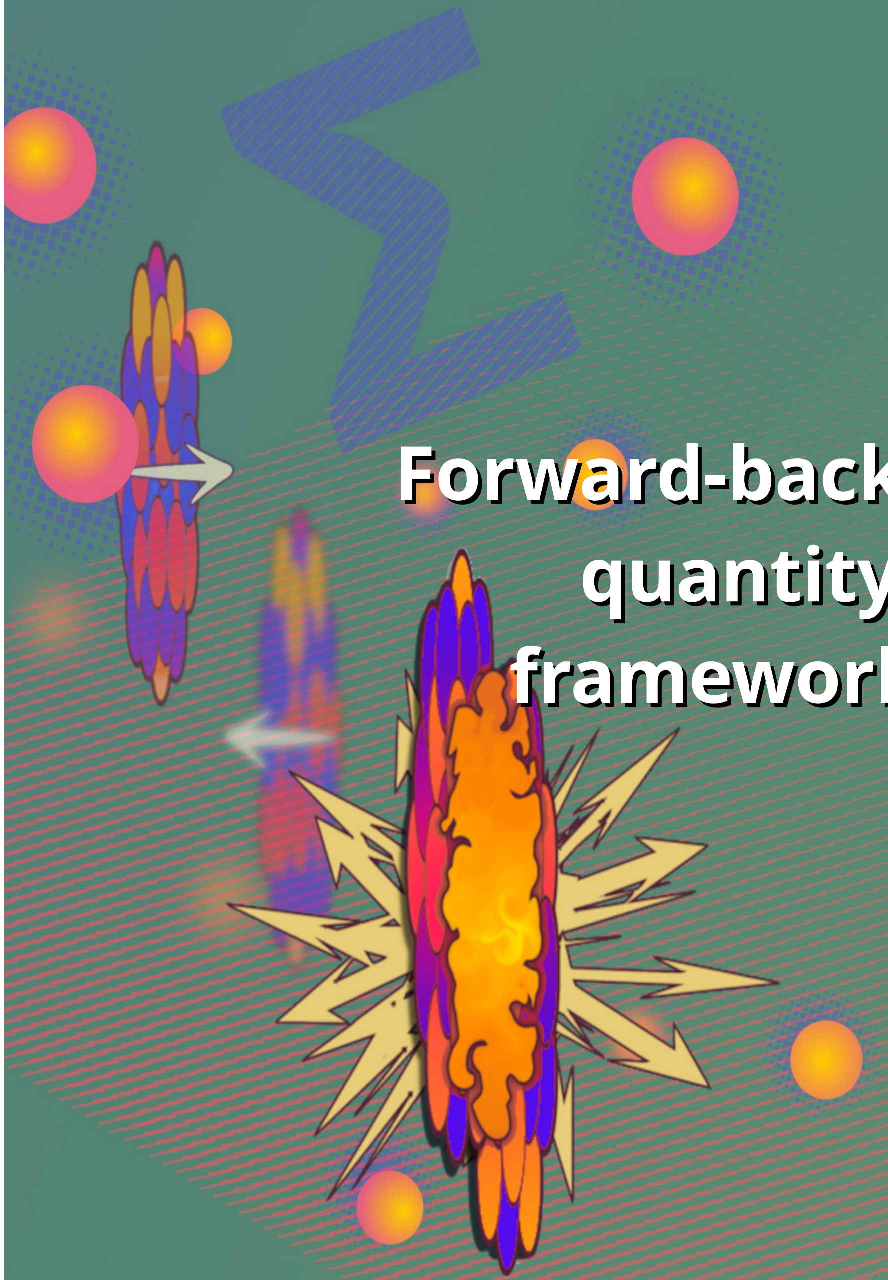
X[th] November 2023

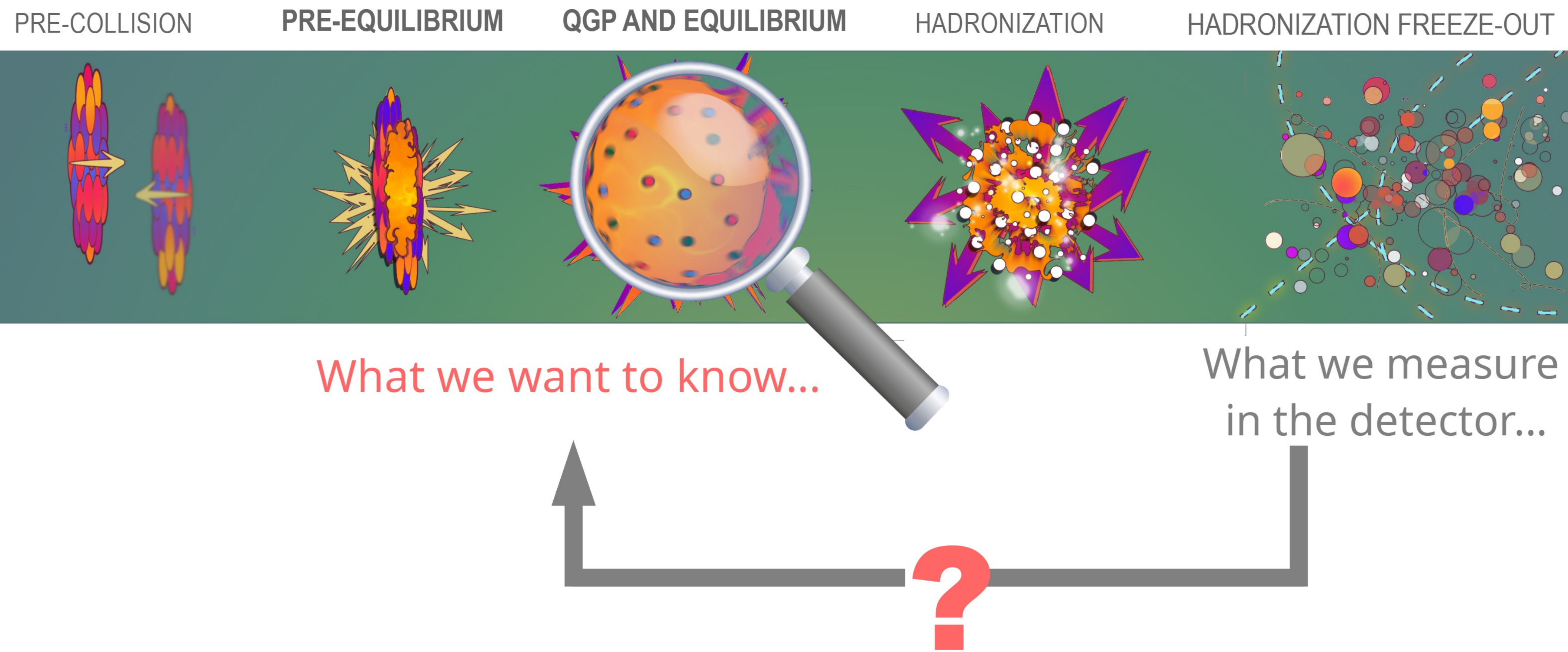
Forward-backward correlations with the Σ quantity in the wounded-constituent framework at energies available at the CERN Large Hadron Collider



IWONA SPUTOWSKA

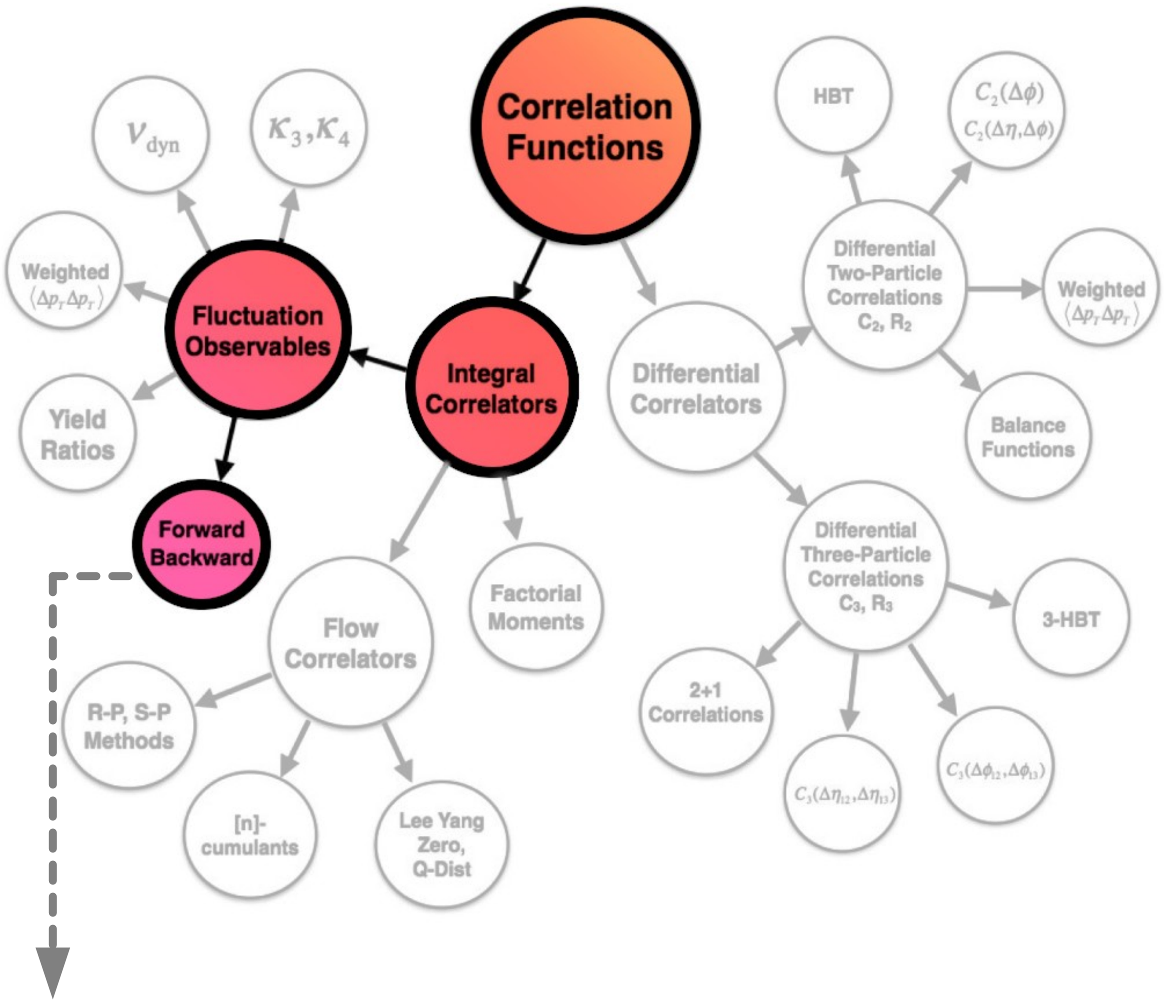
Institute of Nuclear Physics
Polish Academy of Sciences

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.**

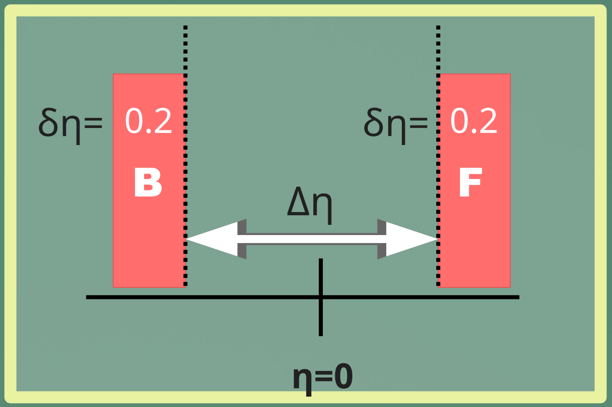
Introduction: Why and how do we study correlations and fluctuations?



We are here!

Picture from: Claude A. Pruneau, Data Analysis Techniques for Physical Scientists, 2017, Cambridge University Press.

The forward-backward (FB) correlation:



A popular technique:

The FB **correlation coefficient** b_{corr} is:

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

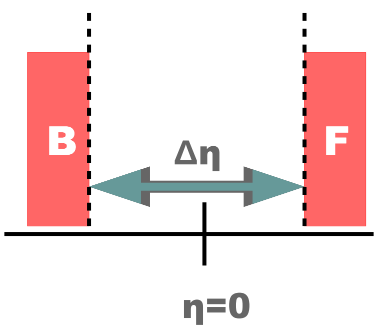
- largely influenced by **geometrical (volume) fluctuations.**
- dependent on **centrality estimator.**

Introduction: FB correlations with strongly intensive quantity Σ

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

Gaździcki, Gorenstein, Phys.Rev. C84 (2011) 014904

STRONGLY INTENSIVE QUANTITY Σ:



$$\Sigma = \frac{\langle n_F \rangle \omega_B + \langle n_B \rangle \omega_F - 2\mathrm{Cov}(n_F, n_B)}{\langle n_F \rangle + \langle n_B \rangle},$$

where ω is scaled variance: $\omega = \mathrm{Var}(n)/\langle n \rangle$

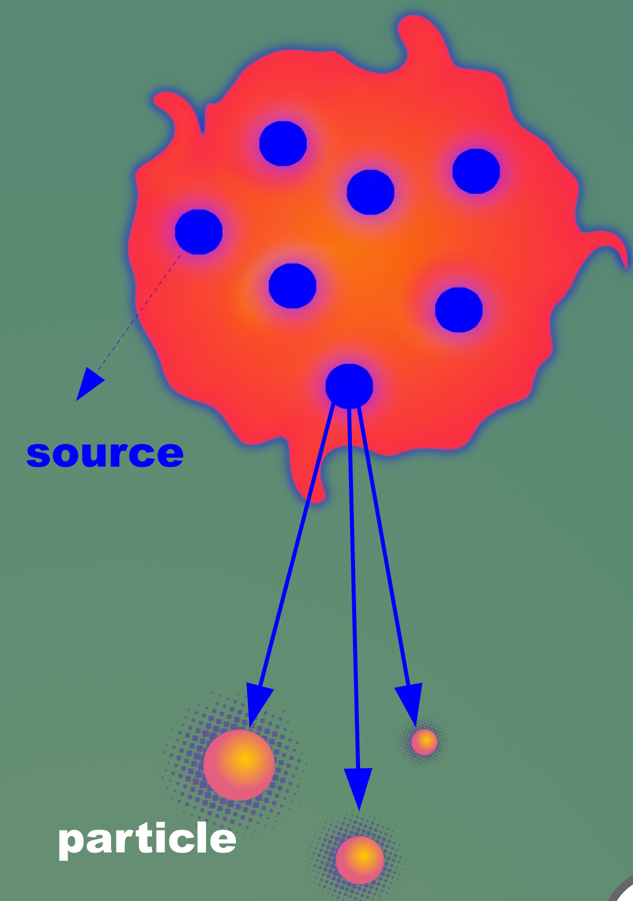
- For a symmetric collision $\omega_B = \omega_F$ and $\langle n_F \rangle = \langle n_B \rangle$,

$$\Sigma \approx \omega(1 - b_{corr}).$$

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

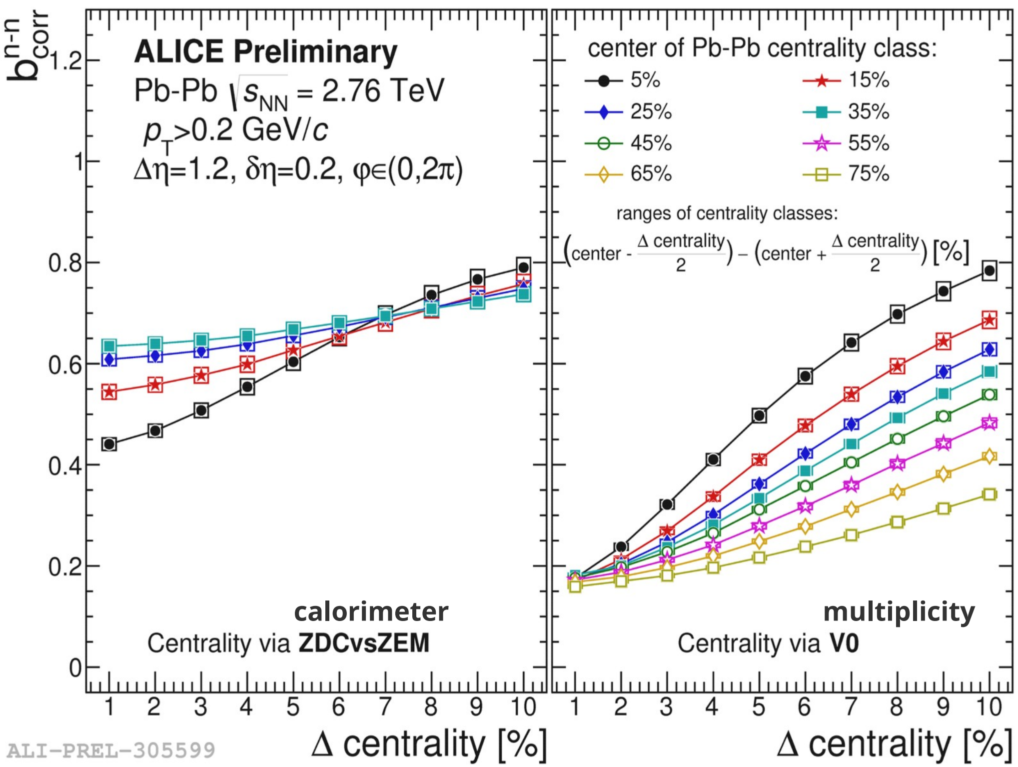
Independent source model:

Σ → gives direct information about characteristics of **single source distribution!**

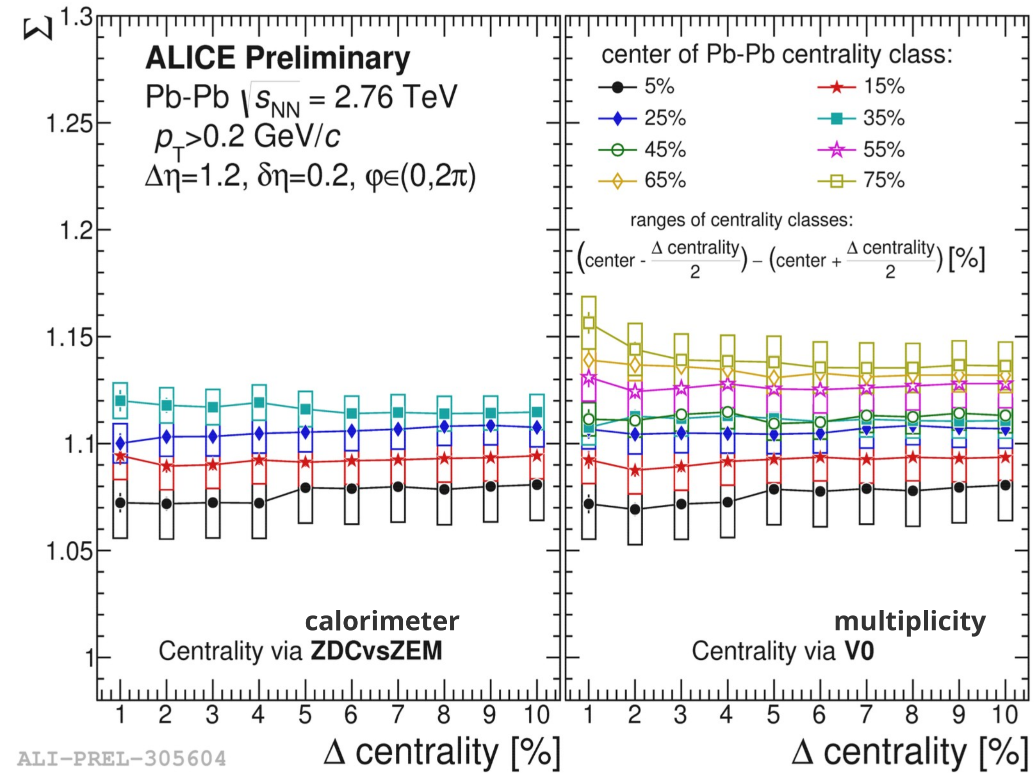


ALICE: Σ as a function of centrality bin width

The FB **correlation coefficient** b_{corr}



The Σ quantity

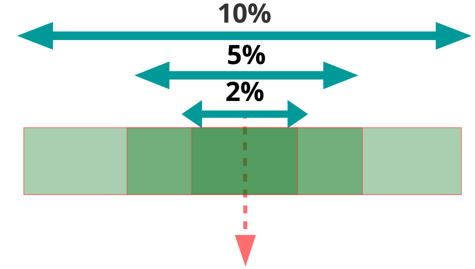


increase of volume fluctuations

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

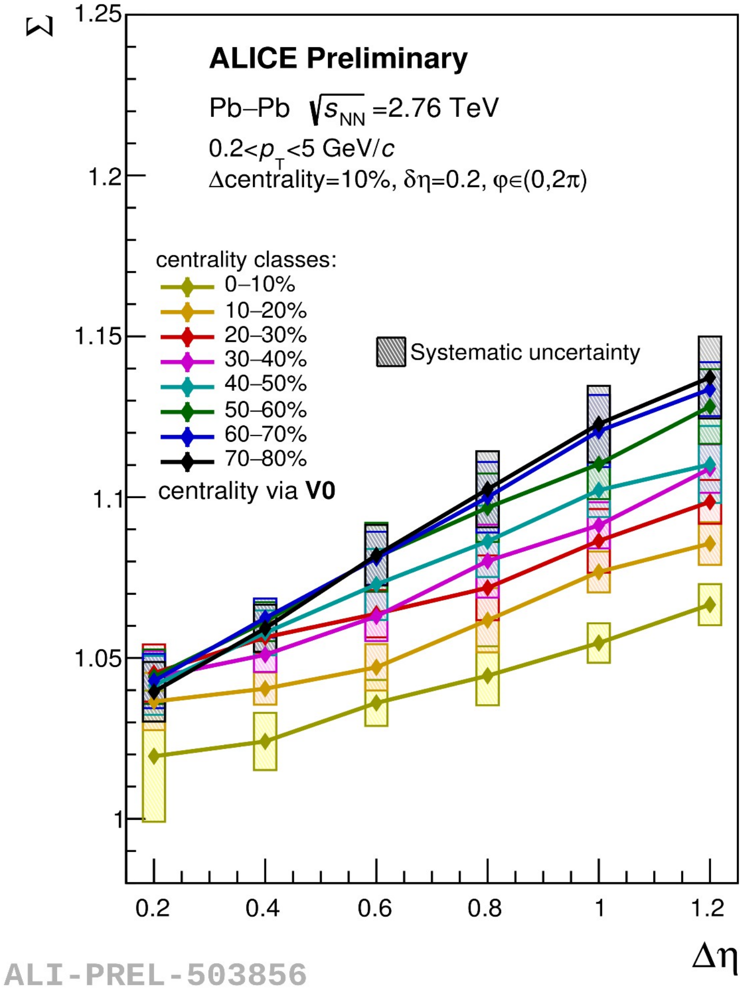
exhibits the properties of a strongly intensive quantity!

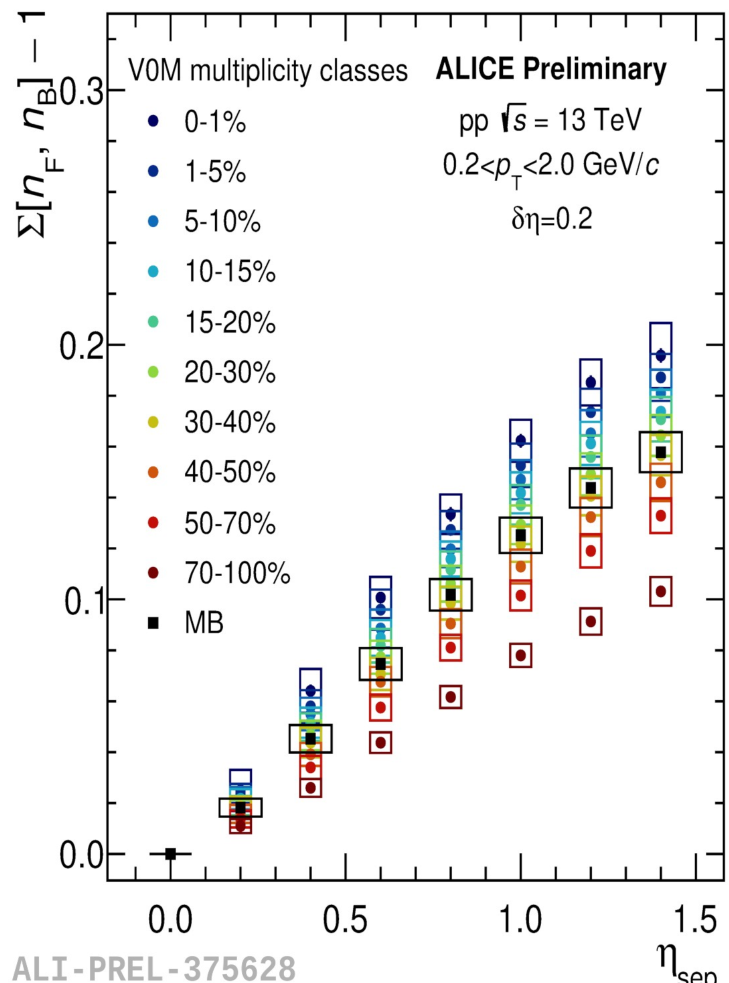
width of centrality class (**Δ centrality**):



center of centrality class

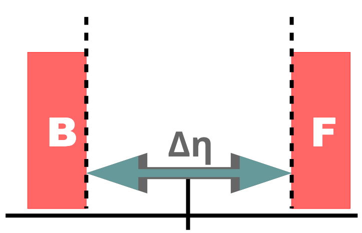
ALICE: Σ as a function of Δη



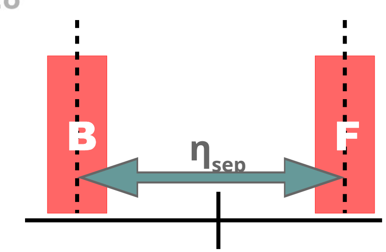


- **increase** with Δη;
- **Pb–Pb: decrease** of Σ with increasing centrality class;
- **pp:** Σ **grows** with the increase of forward event multiplicity; **contrary to Pb–Pb.**

Different ordering of Σ with centrality for Pb–Pb and pp.

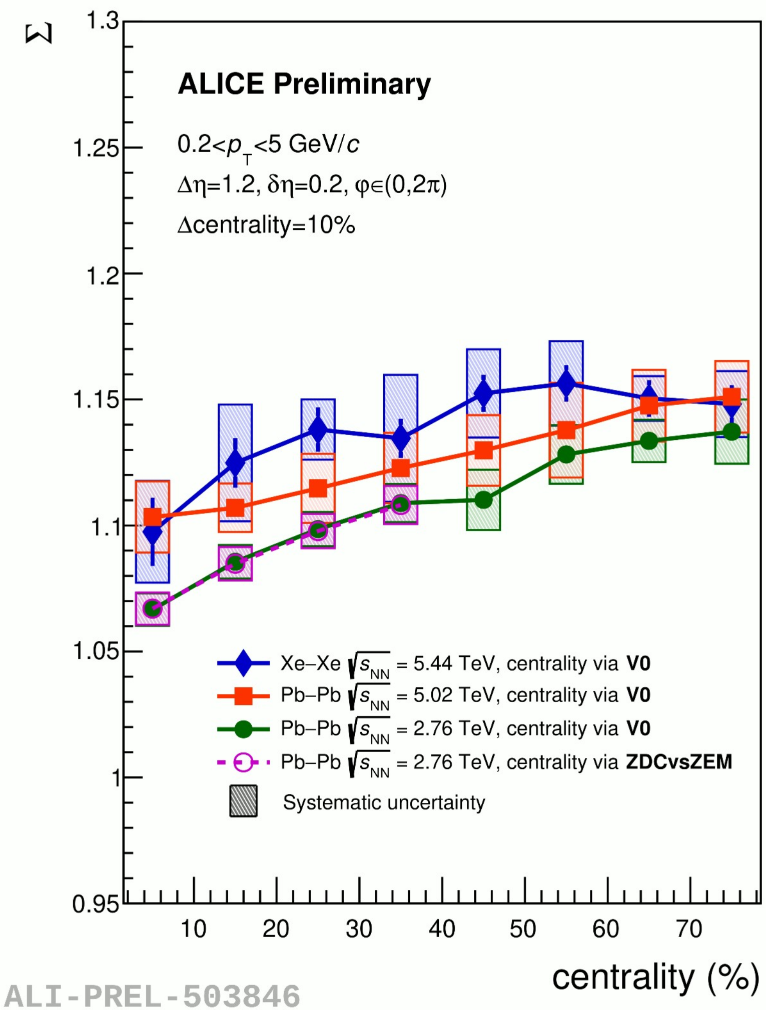


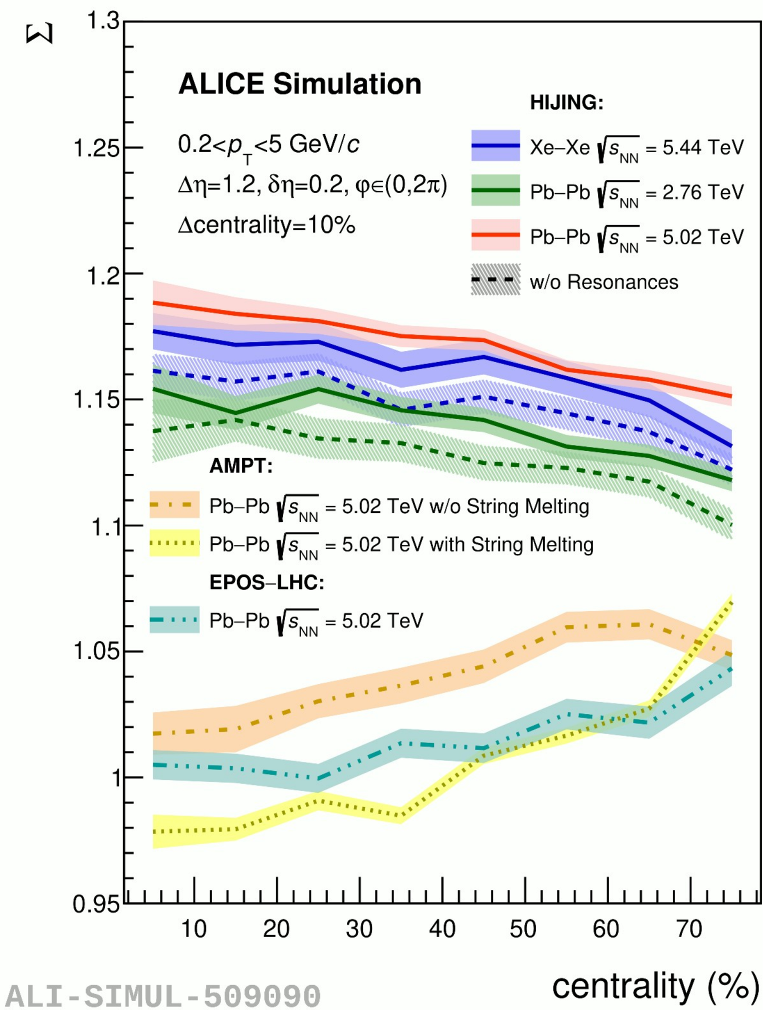
η_{sep} = Δη +0.2

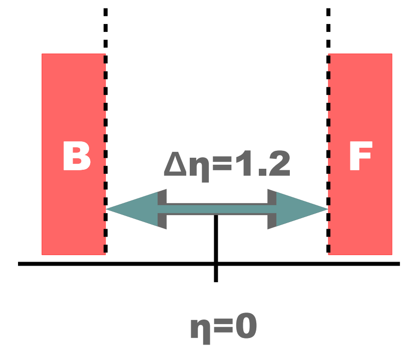


$\Sigma \approx \omega(1-b_{corr})$

ALICE: Σ as a function of centrality







note!

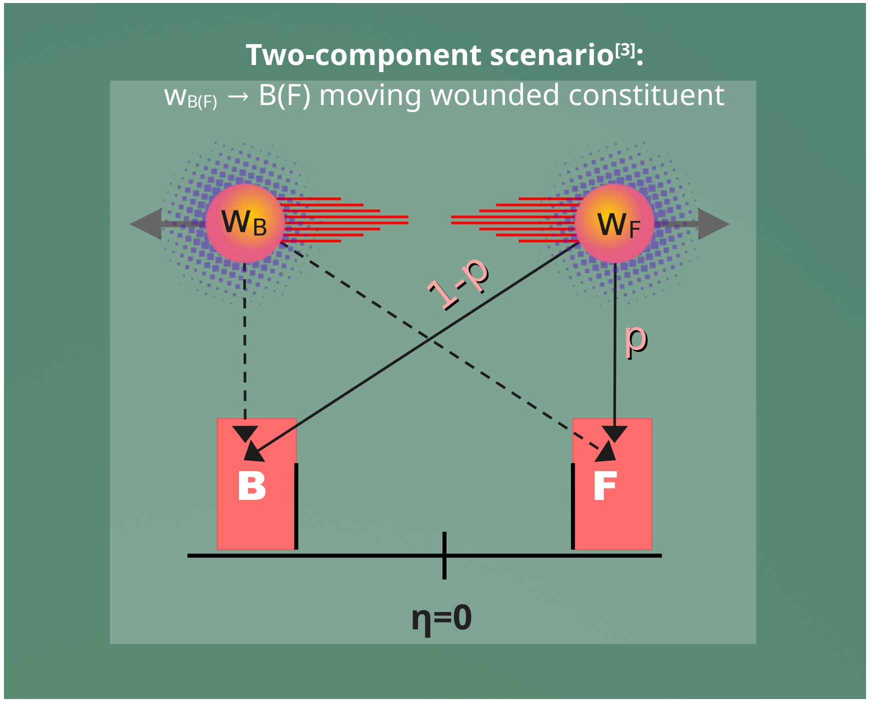
V0 ≈ ZDCvsZEM

→ no dependence

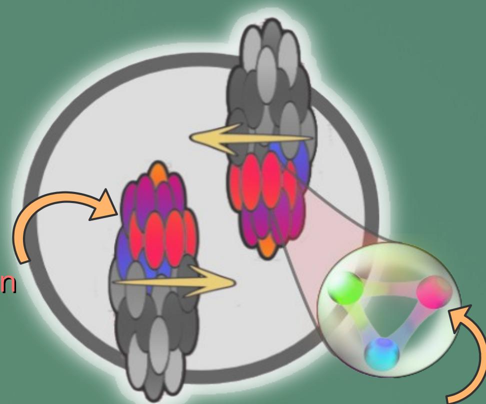
on centrality estimator!

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

FB correlations with the Σ quantity in **the wounded-constituent framework:**



AA collision → a **superposition** of constituent-constituent interactions



wounded nucleon model (WNM)[1]

wounded quark model (WQM)[2]

Σ in WNM and WQM for a symmetric AA collision:

$$C = 2p - 1$$

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

- **p = 0.5** ⟺ C=0: **Σ=1** and **Σ is SIQ**;
- **p ≠0.5** ⟺ C≠0: **Σ>1** and shows intrinsic dependence on the number of $\boldsymbol{w_F}$ and $\boldsymbol{w_B}$ → **no longer** a strongly intensive quantity!

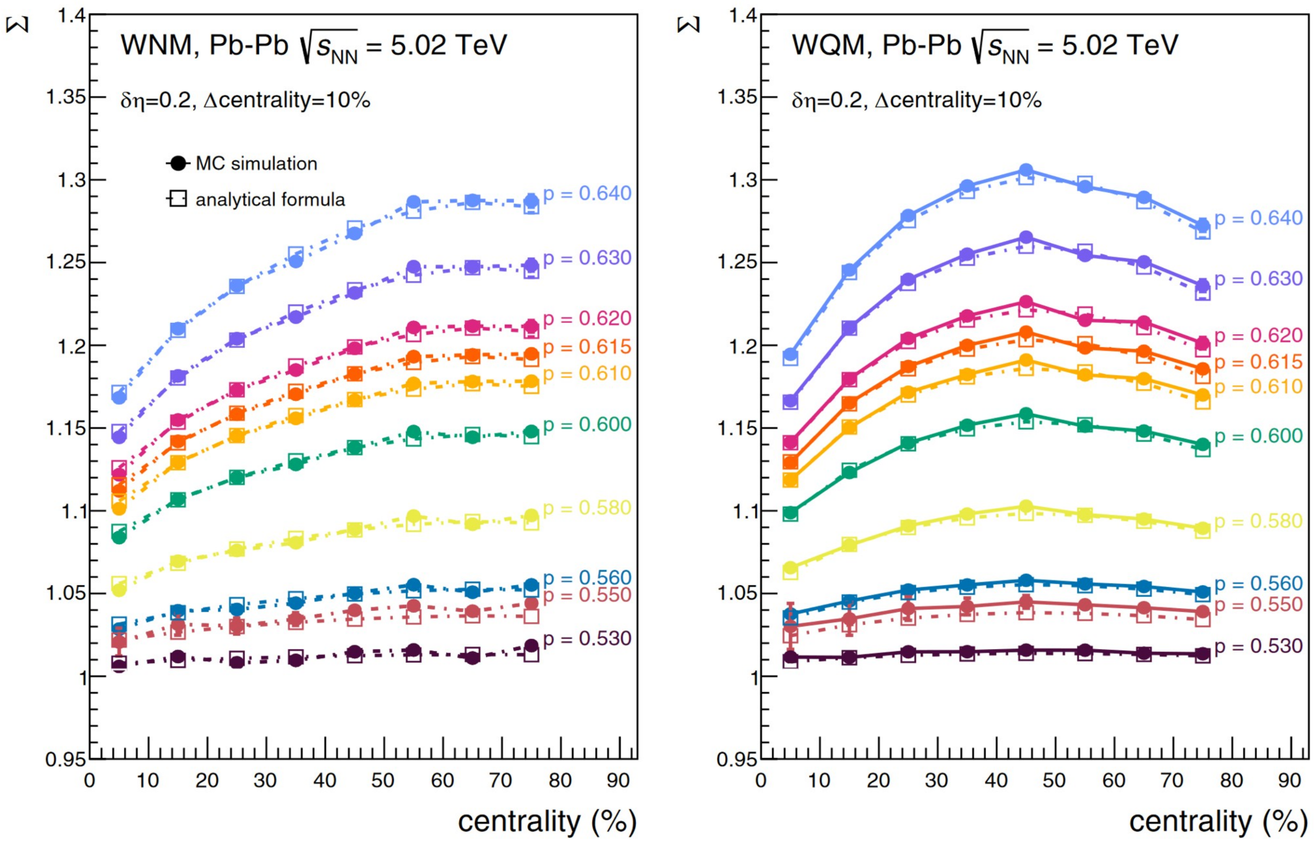
wounded constituent:

→ undergoes at least one inelastic collision,
→ emits particles regardless of the number collisions it went through.

[1] A. Białas, M. Bleszyński and W. Czyż, Nucl. Phys. B 111, 461 (1976)
[2] A. Białas, W. Czyż and W. Furmański, Acta Phys. Polon. B 8, 585 (1977)
[3] Adam Bzdak, Phys. Rev. C 80, 024906

FB correlations with the Σ quantity in **the wounded-constituent framework:**

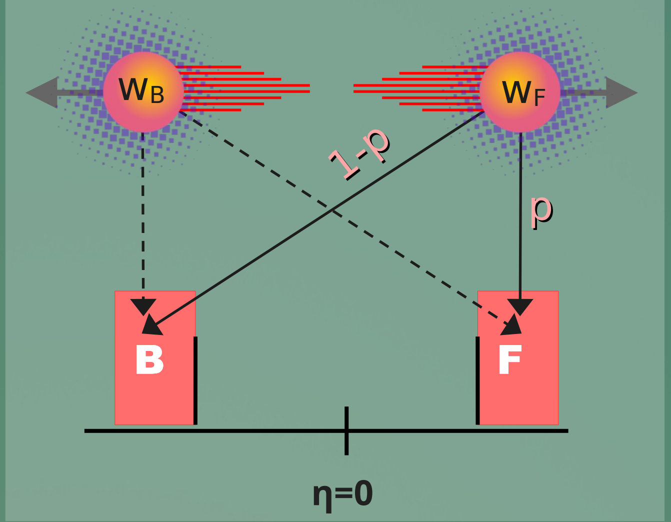
Σ in WNM and WQM for a symmetric AA collision:



- **p = 0.5** ⟺ C=0: **Σ=1** and **Σ is SIQ**;
- **p ≠0.5** ⟺ C≠0: **Σ>1** and shows intrinsic dependence on the number of w_F and w_B → **no longer** a strongly intensive quantity!

Two-component scenario[1-3]:

$w_{B(F)}$ → B(F) moving wounded constituent

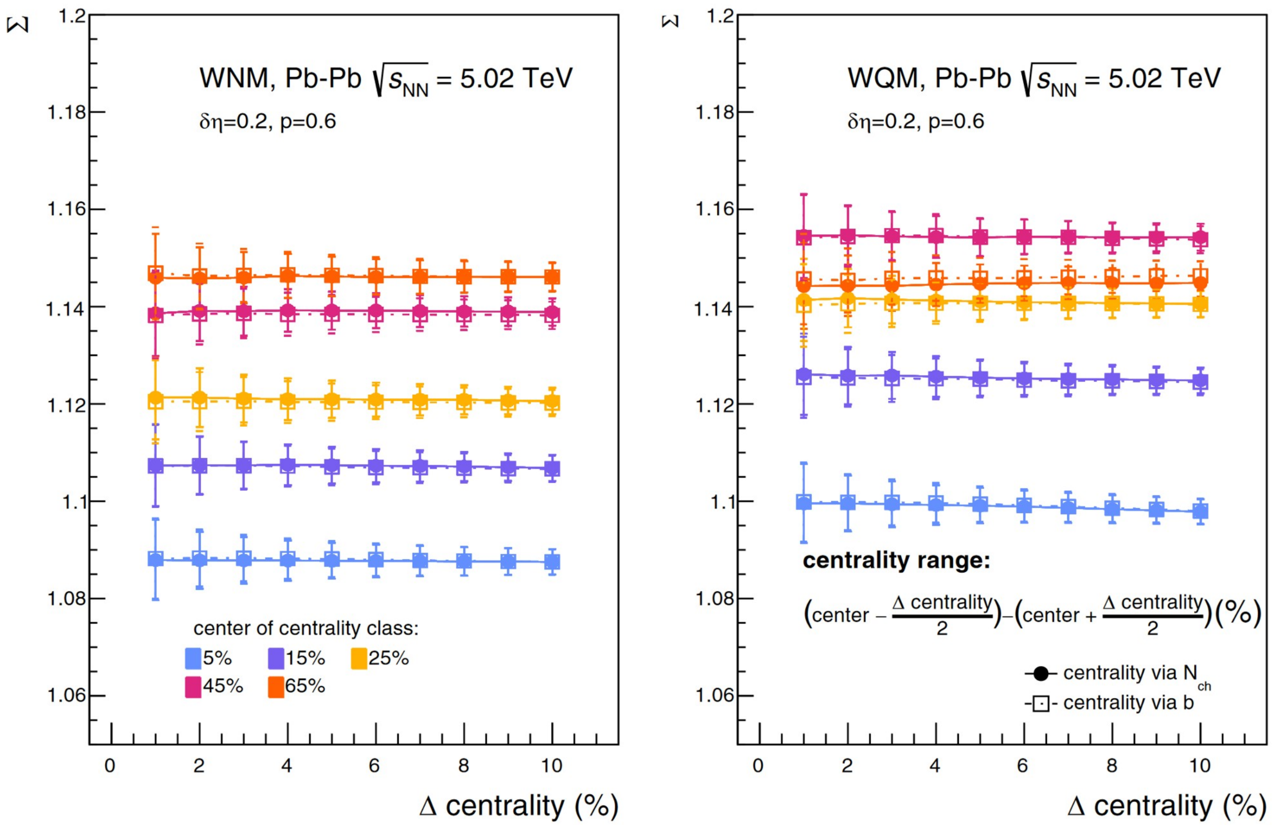


$$\Sigma = 1 + \frac{\bar{n}}{2}C^2\left[\frac{\langle (w_B - w_F)^2\rangle}{2\langle w_F\rangle} + \frac{2}{k}\right]$$

$$C = 2p - 1$$

[1] A. Białas, M. Bleszyński and W. Czyż, Nucl. Phys. B 111, 461 (1976)
[2] A. Białas, W. Czyż and W. Furmański, Acta Phys. Polon. B 8, 585 (1977)
[3] Adam Bzdak, Phys. Rev. C 80, 024906

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



Σ in WNM and WQM:

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

- p≠0 → C≠0: intrinsic dependence on the number of w_F and w_B → no longer a strongly intensive quantity!

, but ...

- 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!

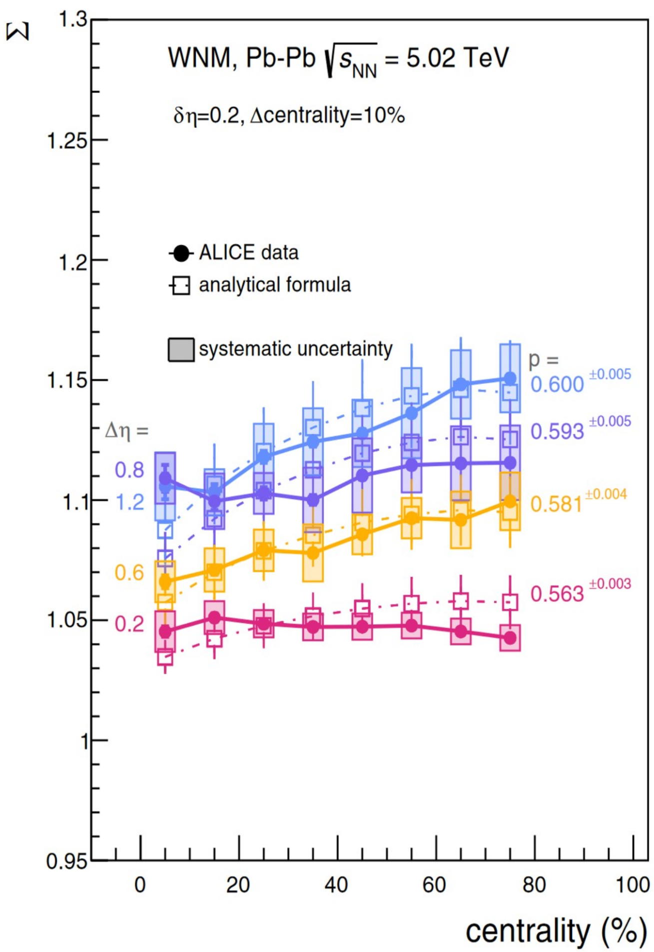
"strongly-intensive-quantity-like" properties!

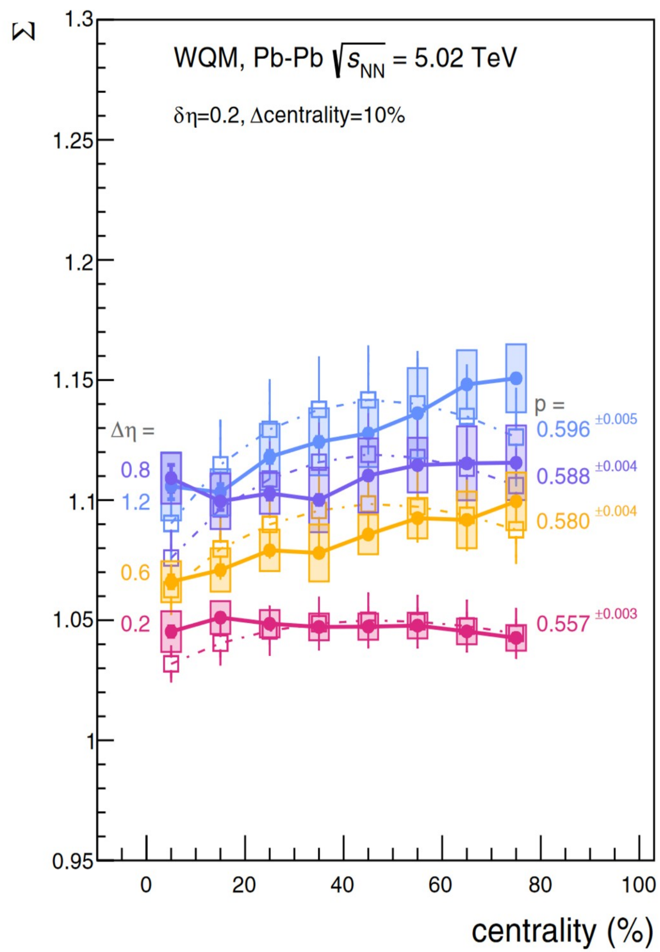
This can be explained theoretically if one notes that Σ in WN(Q)M can be rewritten in terms of ***partial covariance***.

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

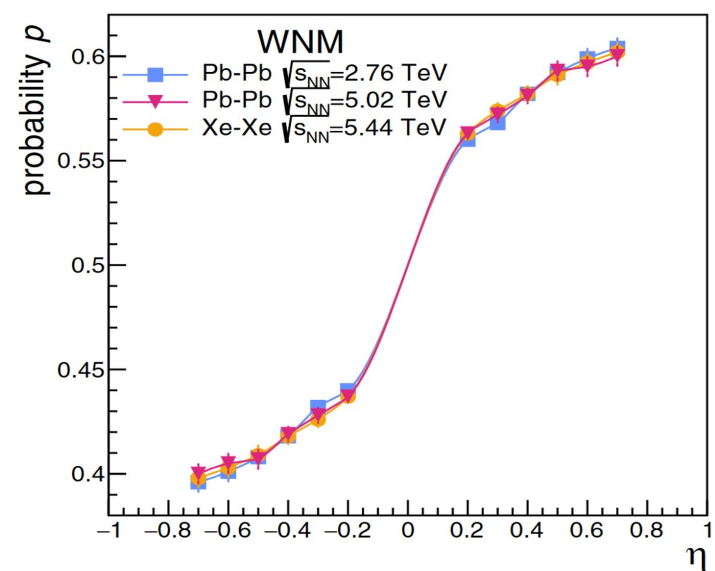
$w = w_F + w_B$

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(η)**:

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

F(η) DETERMINATION :

"STANDARD" METHOD

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

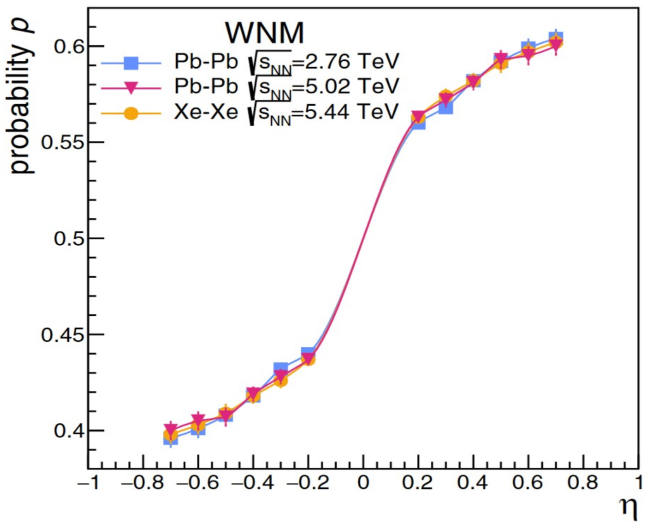
→ It is based on the **relation between *p* and Σ** in WN(Q)M.

→ It provides a unique opportunity to determine **the F(η) in a symmetric nucleus-nucleus collision**.

Eq.(☼) **+**

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

based of measurement of Σ



$$F(\eta) \approx \frac{p}{\langle w_F\rangle + \langle w_B\rangle}\left[N(-\eta) + N(\eta)\right].$$

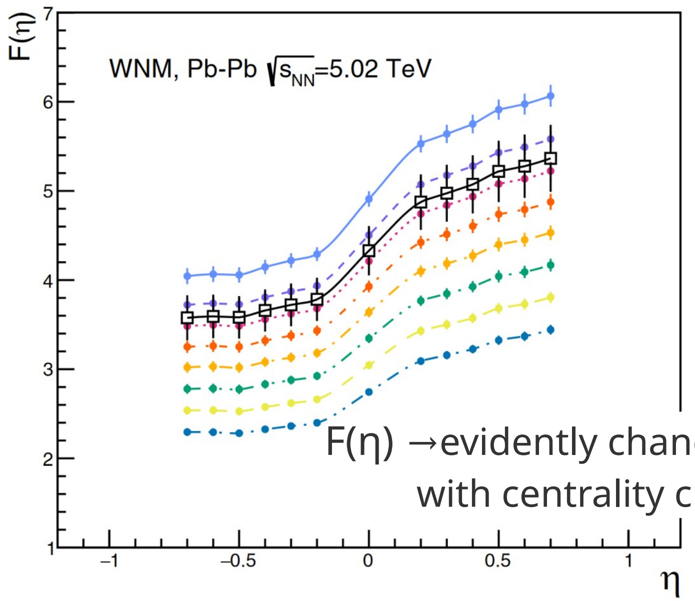
p: based of measurement of Σ

$\langle w_F\rangle + \langle w_B\rangle$: from MC sim.

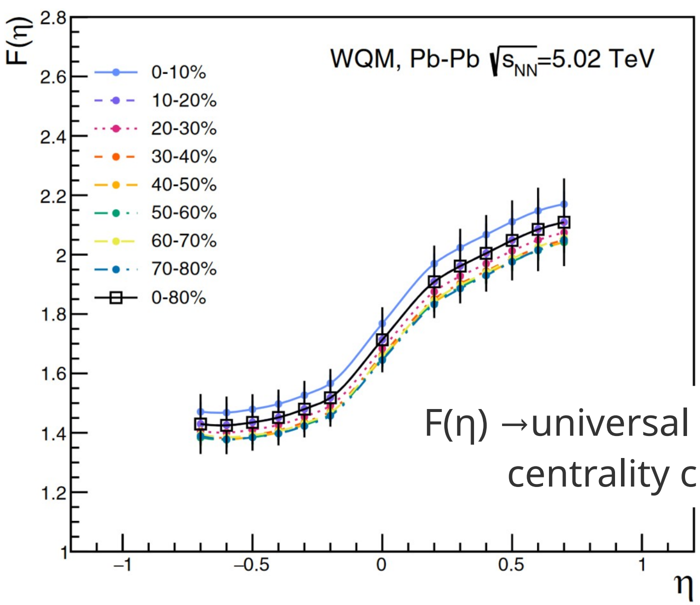
$N(-\eta) + N(\eta)$: Pb-Pb ALICE data[6]

[6] ALICE Collab. Phys. Lett. B 772, 567 (2017).

Wounded constituent fragmentation functions in symmetric Pb–Pb collisions



F(η) →evidently changes with centrality class



F(η) →universal for all centrality classes

The particle production for each wounded nucleon/quark → described by **universal fragmentation function F(η)**:

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

F(η) DETERMINATION :

NEW APPROACH:

- It is based on the **relation between *p* and Σ** in WN(Q)M.
- It provides a unique opportunity to determine the F(η) **in a symmetric nucleus-nucleus collision**.

based of measurement of Σ

$$F(\eta) \approx \frac{p}{\langle w_F \rangle + \langle w_B \rangle}[N(-\eta) + N(\eta)].$$

from MC sim.

Pb-Pb ALICE data[6]

[6] ALICE Collab. Phys. Lett. B 772, 567 (2017).

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 propability p of a 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!

This work was supported by the National Science Centre, Poland (grant No. 2021/43/D/ST2/02195).

Σ dependence on centrality selection and volume fluctuations
I. Sputowska (ALICE), MDPI Proc. 10, 14 (2019)

Σ in AA and pp collisions
I. Sputowska (ALICE), EPJ Web Conf. 274, 05003 (2022).

Strongly Intensive Quantities
M. I. Gorenstein and M. Gazdzicki, Phys. Rev. C 84, 014904 (2011), arXiv:1101.4865 [nucl-th].

Σ in WNM and WQM
I. Sputowska, Phys.Rev.C 108 (2023) 1, 014903