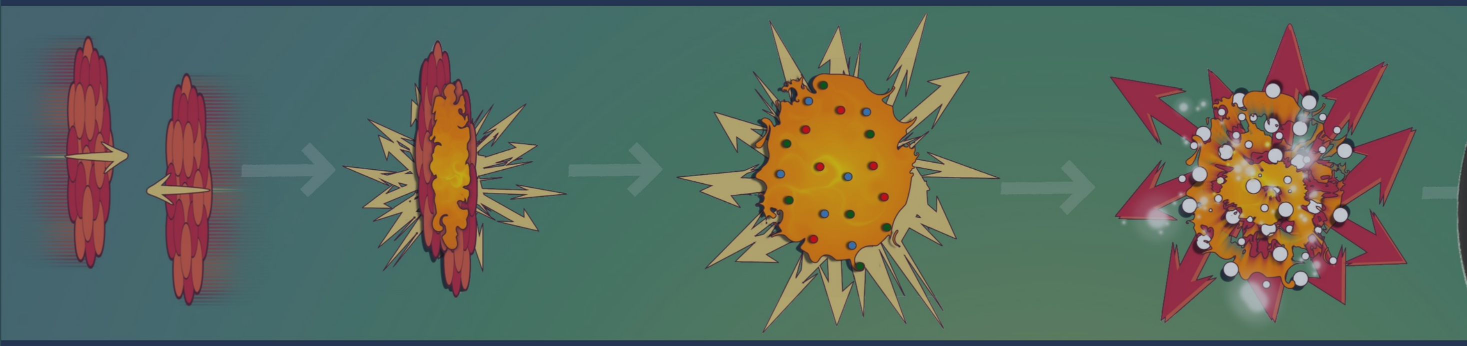
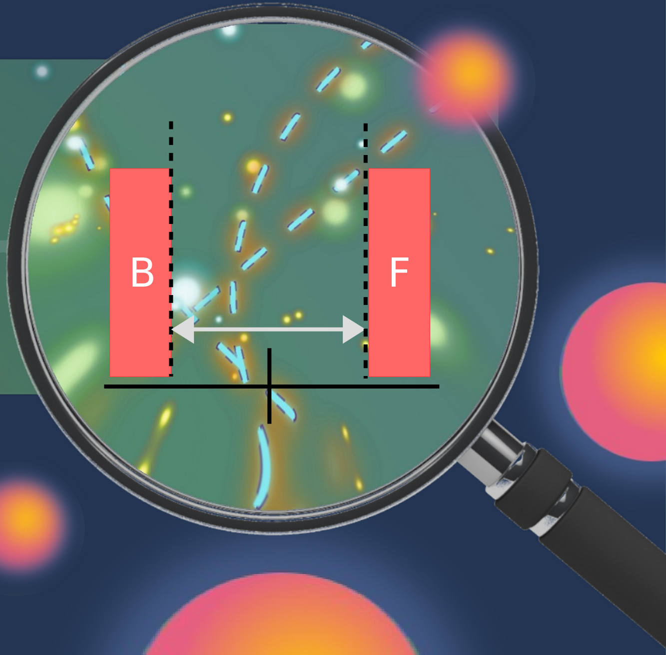
The forward-backward multiplicty correlations with the observable Σ at LHC energies



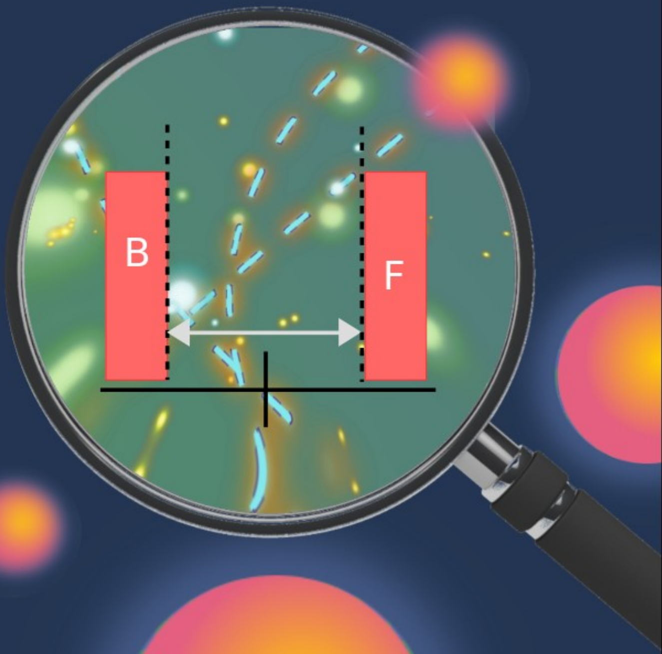


Iwona Sputowska

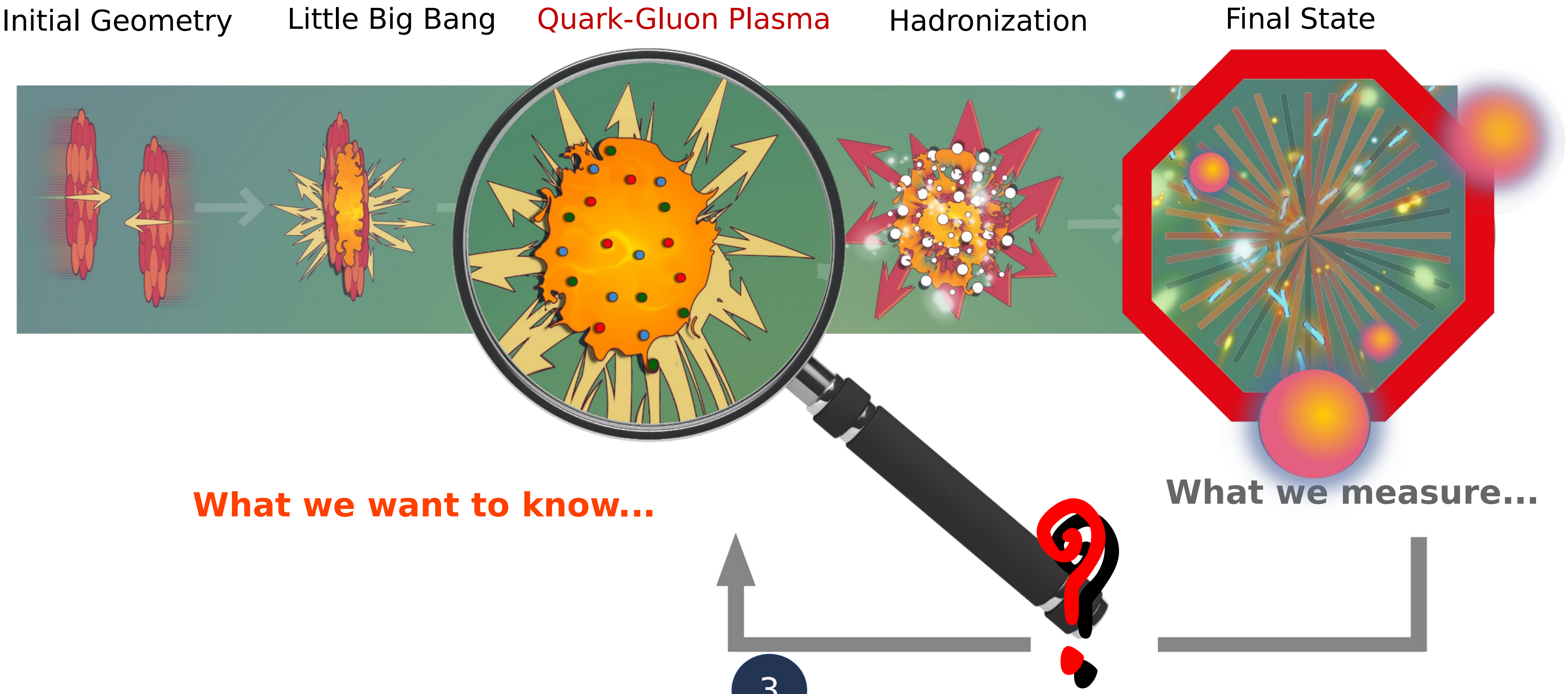
NZ23

Outline:

1. **Motivation: why forward–backward correlations?**
   → What we want to learn and why standard tools struggle.
2. **The observable Σ: definition and key properties**
   → Why Σ is useful?
3. **Experimental results from ALICE**
   → Pb–Pb, Xe–Xe, pp: main system-dependent trends.
4. **Interpretation within simple source-based models**
   → What we can learn from WNM/WQM.
5. **Multi-source superposition approach**
   → A general statistical framework to organise contributions to Σ.
6. **Broader implications and summary**
   → What Σ tells us and what remains open.

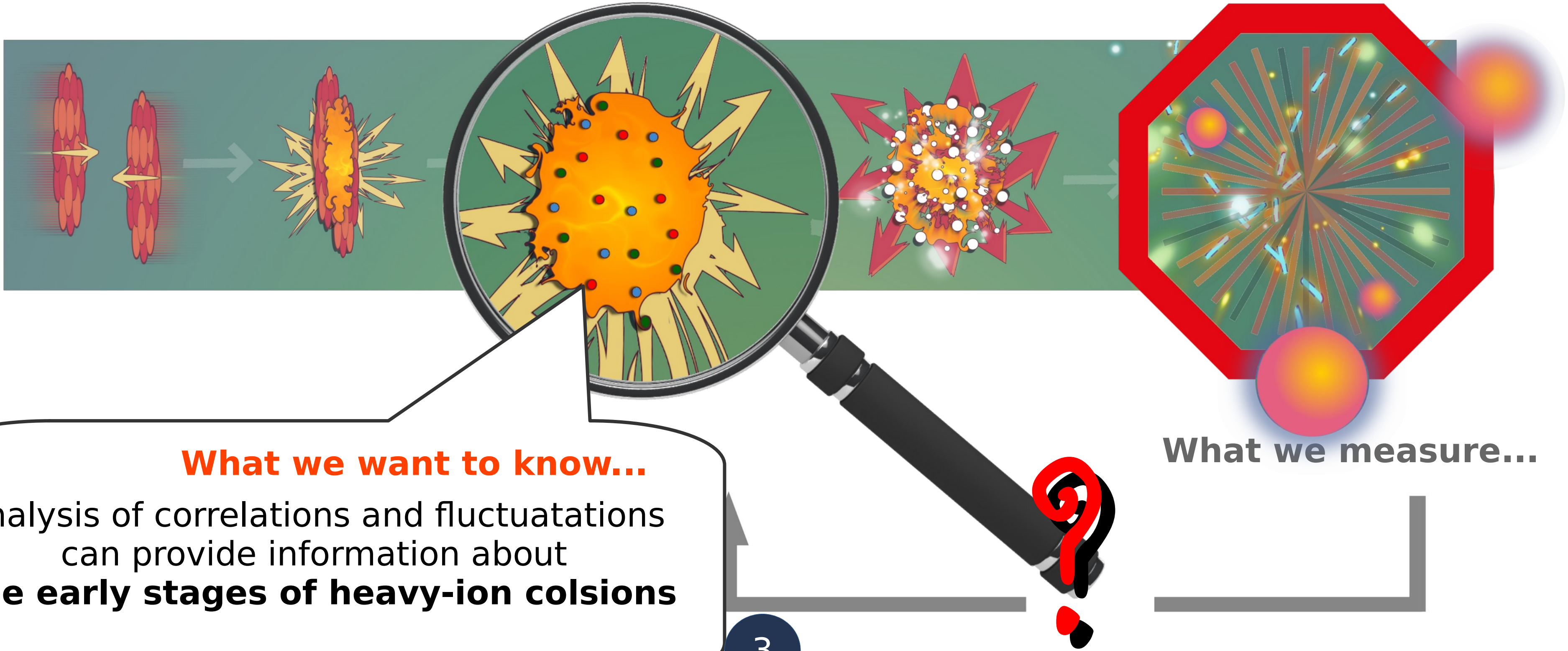


Motivation: Why do we study correlations and fluctuations?



Motivation: Why do we study correlations and fluctuations?

Initial Geometry | Little Big Bang | Quark-Gluon Plasma | Hadronization | Final State

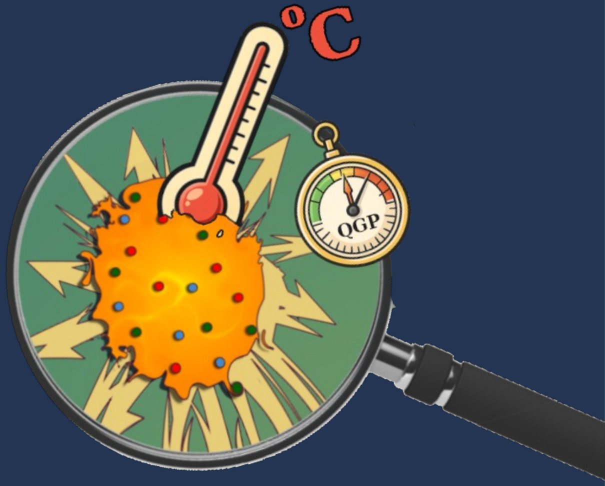


What we measure...

What we want to know...

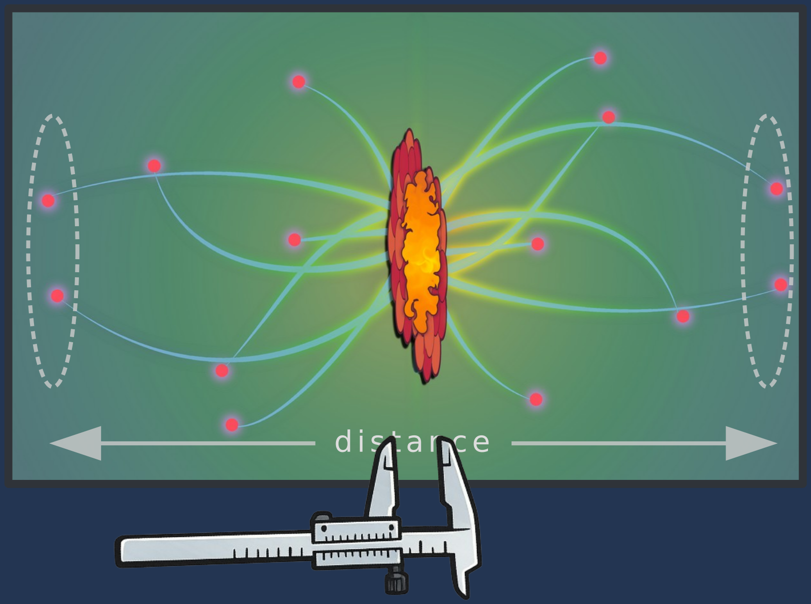
Analysis of correlations and fluctuatations can provide information about **the early stages of heavy-ion colsions**

Motivation: Why do we study correlations and fluctuations?



1. Thermodynamic insight:

→ Related to QCD susceptibilities via fluctuations of conserved charges.



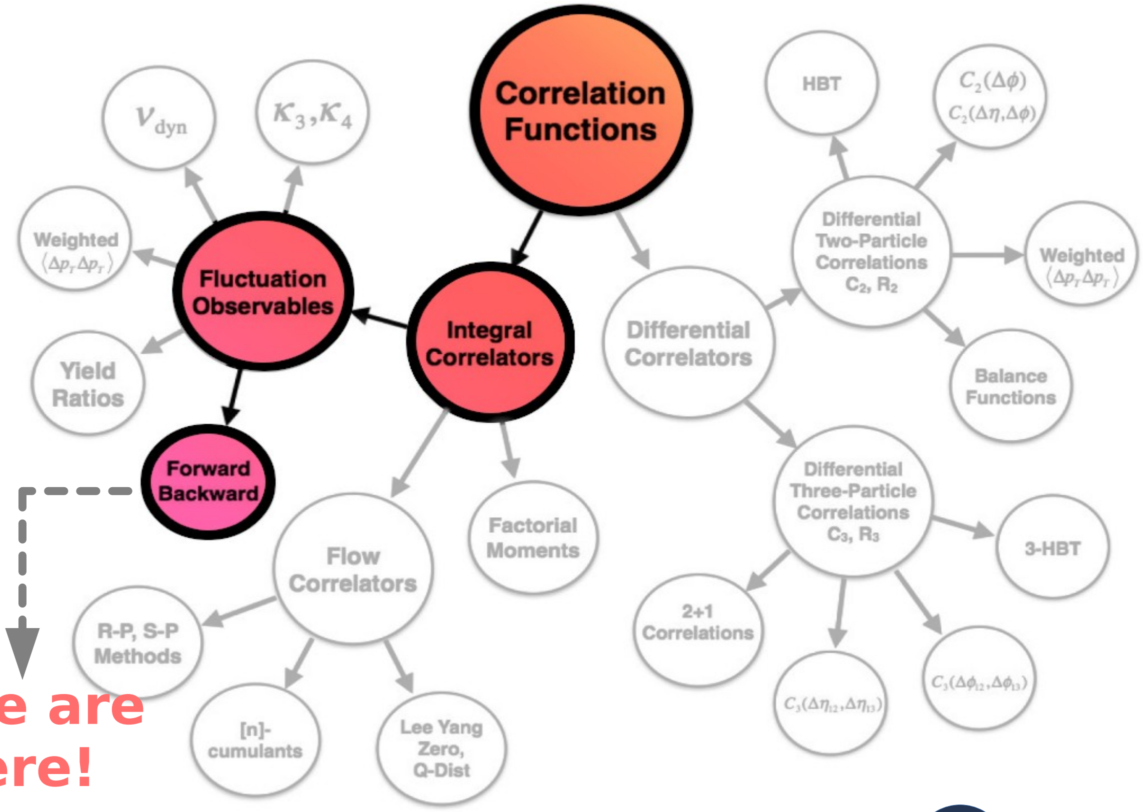
2. Early-stage sensitivity:

→ Long-range correlations must originate before longitudinal expansion.

3. Particle production dynamics:

→ Correlation patterns reveal source structure and help test models.

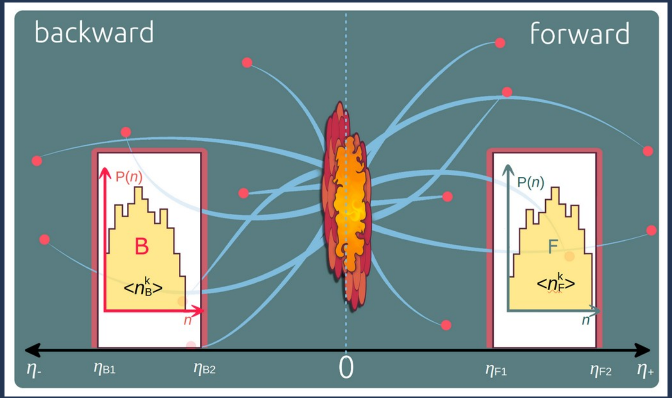
The Analysis: How do we study correlations and fluctuations?



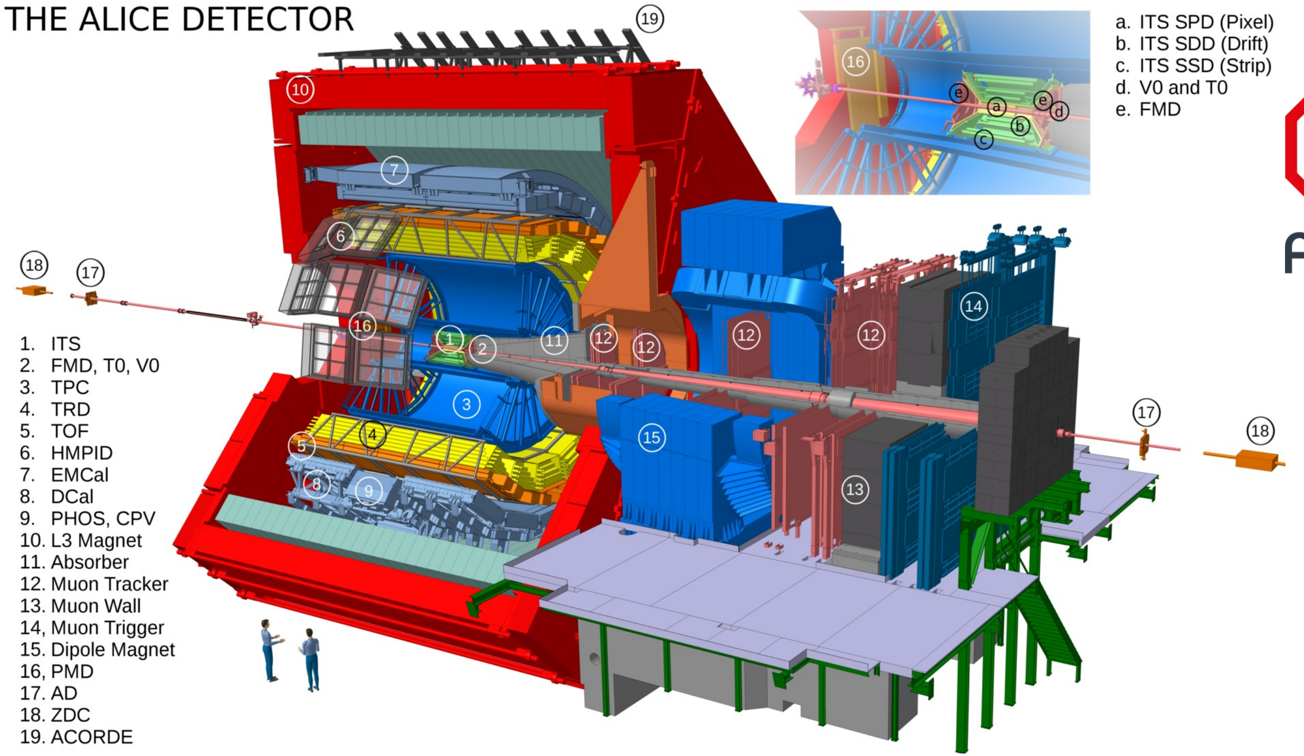
We are here!

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

The forward-backward (FB) correlation:



The Analysis: How do we study correlations and fluctuations?



ALICE

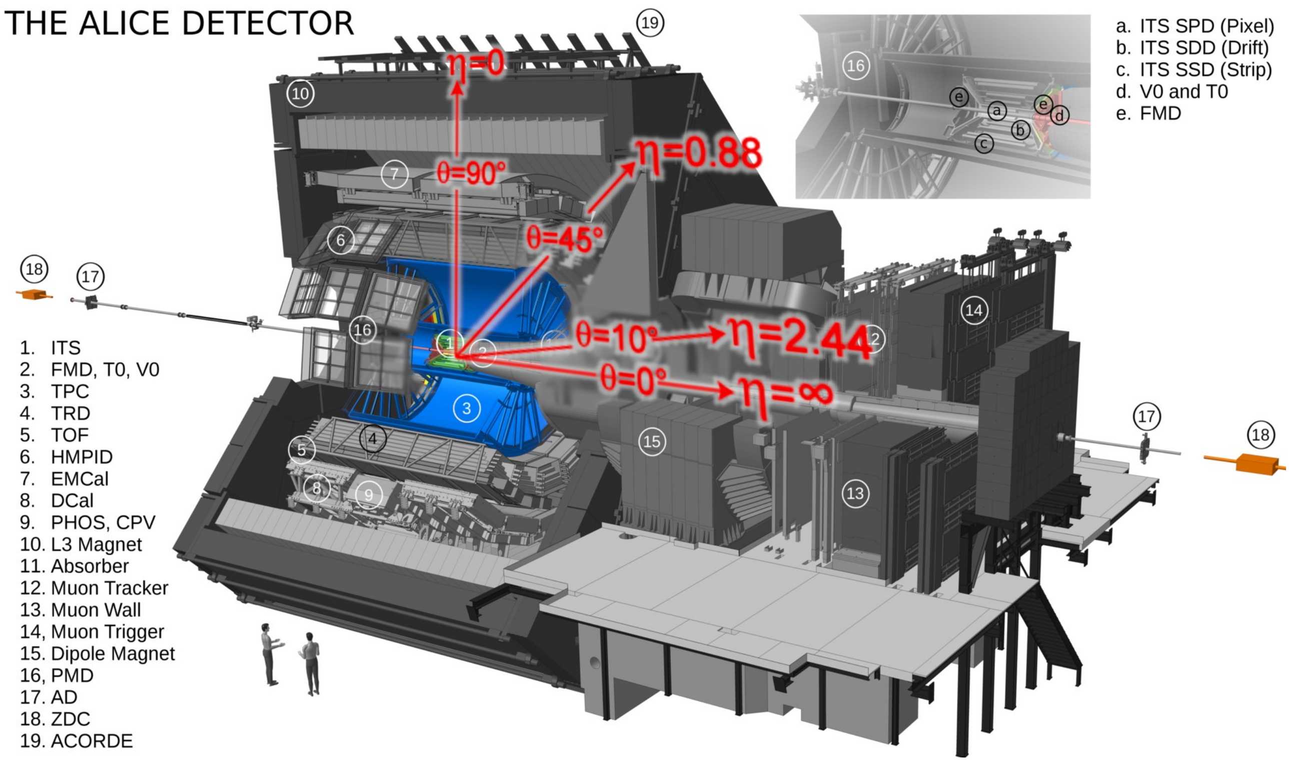
A Large Ion Collider Experiment

Experimental data:

→ Pb–Pb @ $\sqrt{s_{NN}}$= 2.76 and 5.02 TeV
→ Xe–Xe @ $\sqrt{s_{NN}}$ = 5.44 TeV

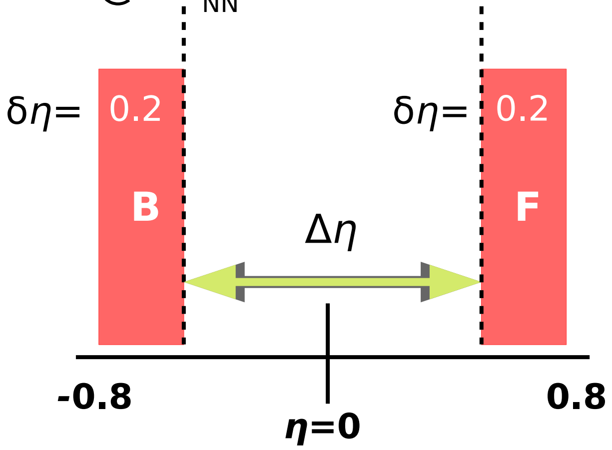
Compared to → pp @ $\sqrt{s}$ =0.9, 2.76, 5.02, 7 and 13 TeV

The Analysis: How do we study correlations and fluctuations?



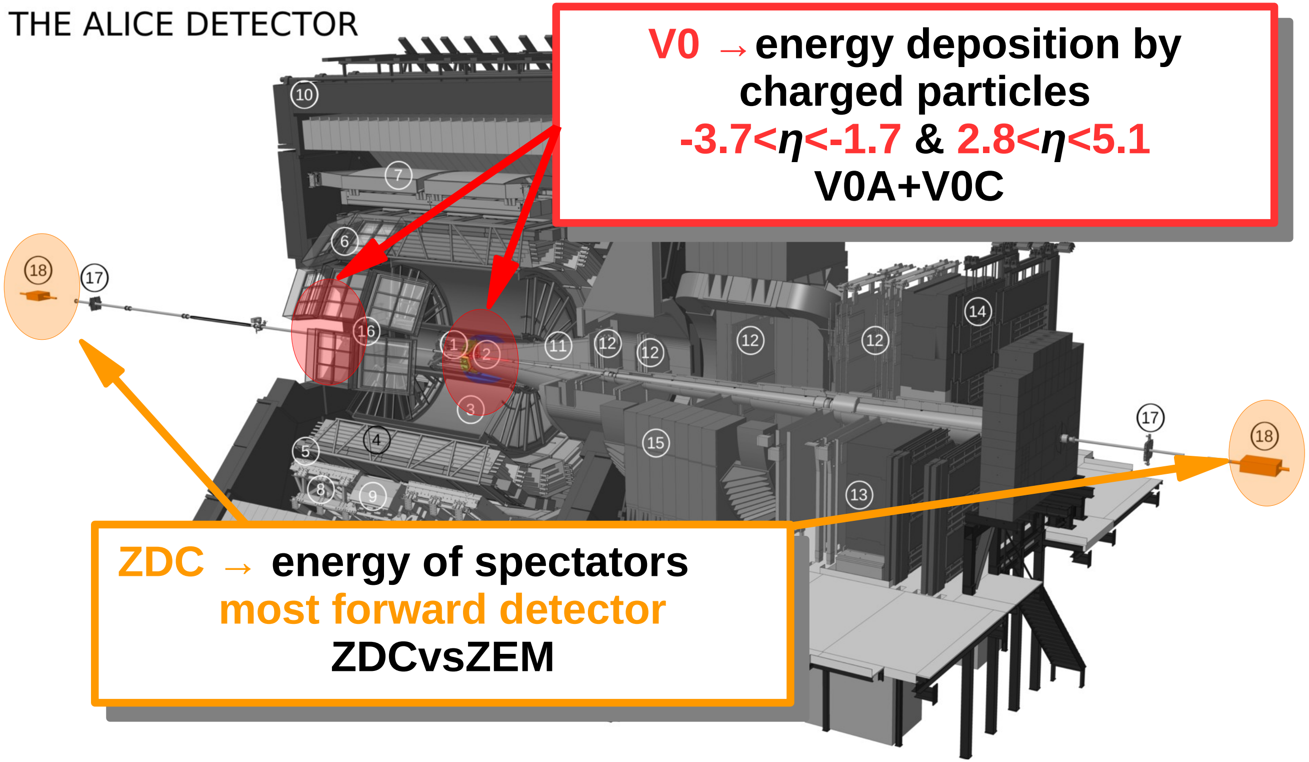
Experimental data:

→ Pb–Pb @ $\sqrt{s_{NN}}$= 2.76 and 5.02 TeV
→ Xe–Xe @ $\sqrt{s_{NN}}$ = 5.44 TeV



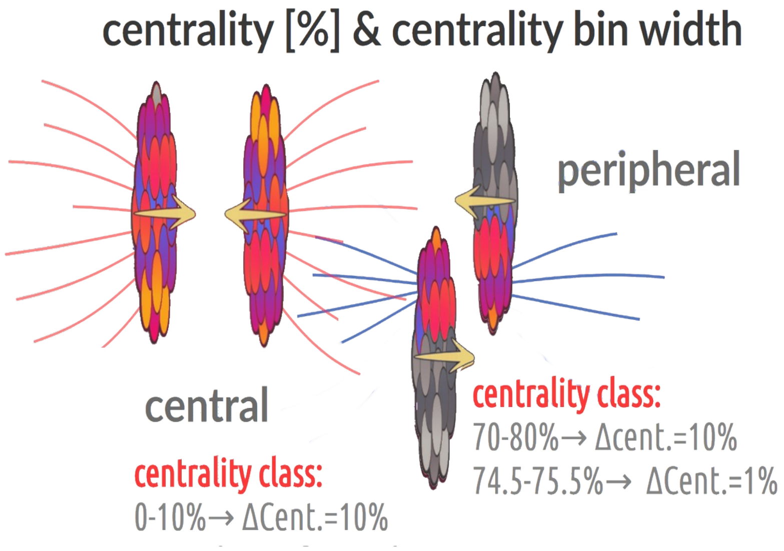
- $0<\varphi<2\pi$,
- $0.2< p_T<5$ GeV/c

The Analysis: How do we study correlations and fluctuations?



V0 → energy deposition by charged particles
$-3.7<\eta<-1.7$ & $2.8<\eta<5.1$
V0A+V0C

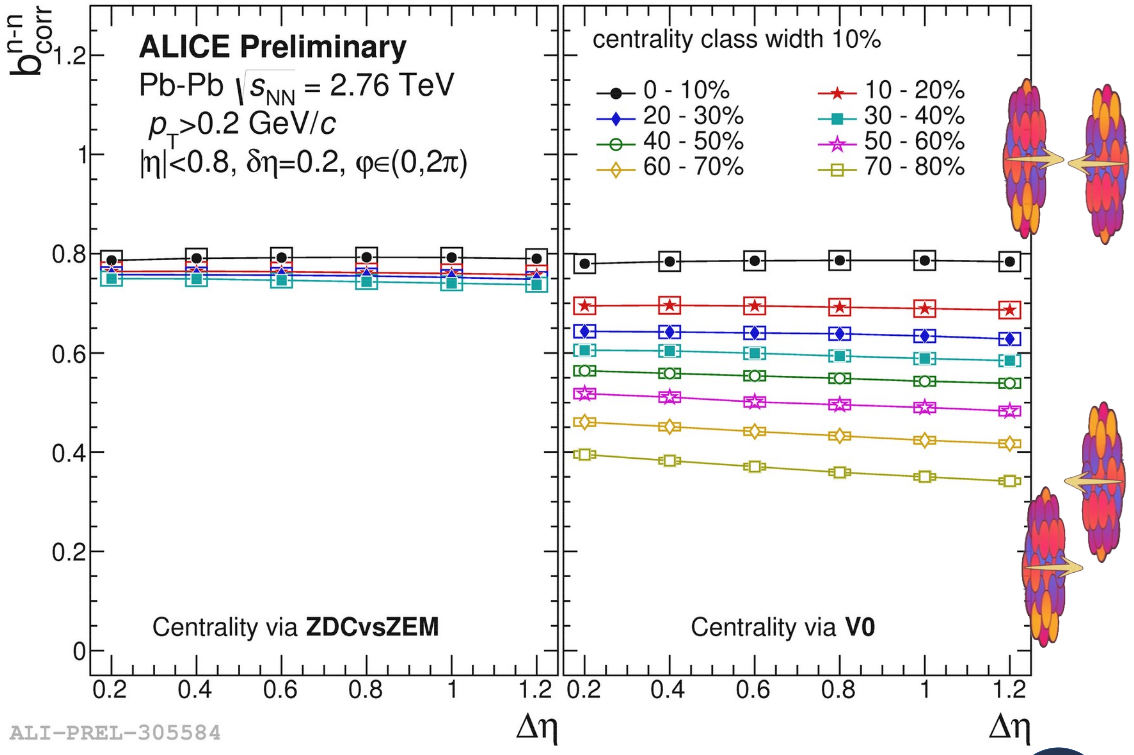
ZDC → energy of spectators
most forward detector
ZDCvsZEM



Results: Forward-backward correlations with b_{corr}

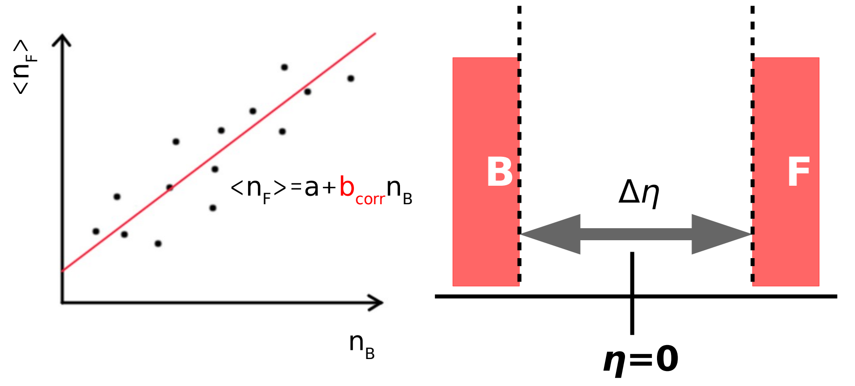
Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0



Correlation coefficient:

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

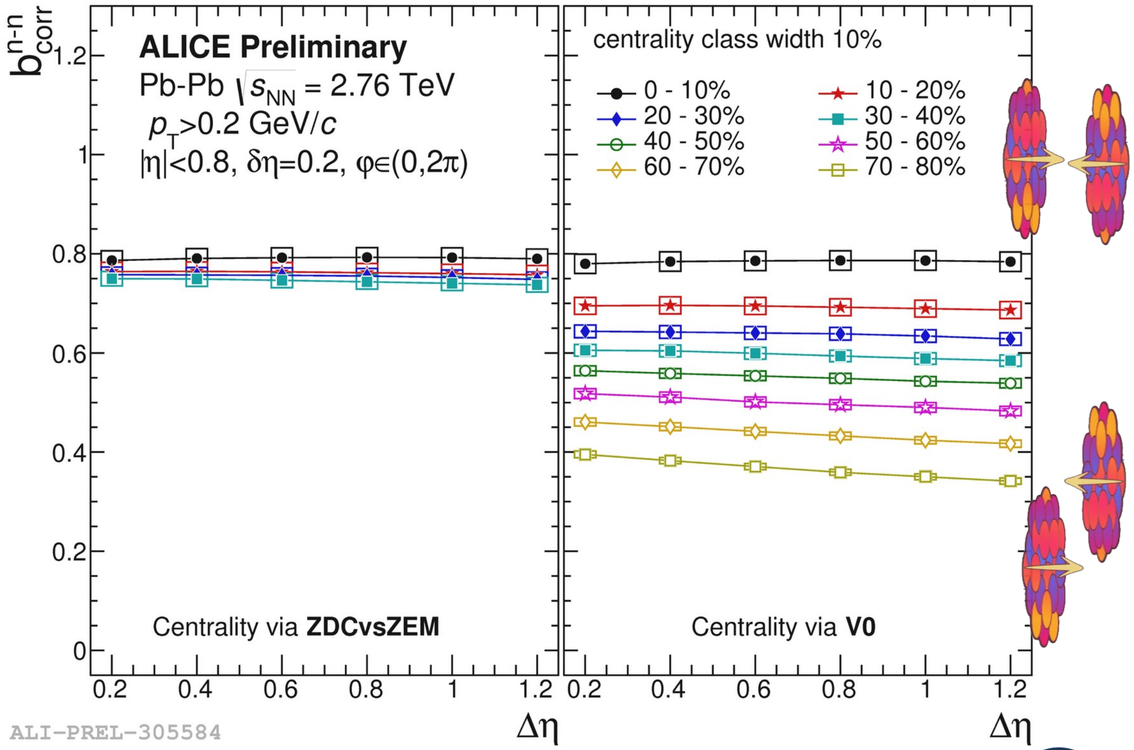


- is largely influenced by **geometrical (volume) fluctuations.**
- is dependent on **centrality estimator**;

Results: Forward-backward correlations with b_{corr}

Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0



Correlation coefficient:

Schoolchildren

Heavy-ion collisions

b_{corr}(**weight**, **IQ**) ≈ **0.62**

b_{corr}(**nF**, **nB**) ≈ **0.8**

age fluctuation

Large correlations

event geometrical fluctuation

strict age selection

Spurious effect of external variable leads to absurd conclusions!

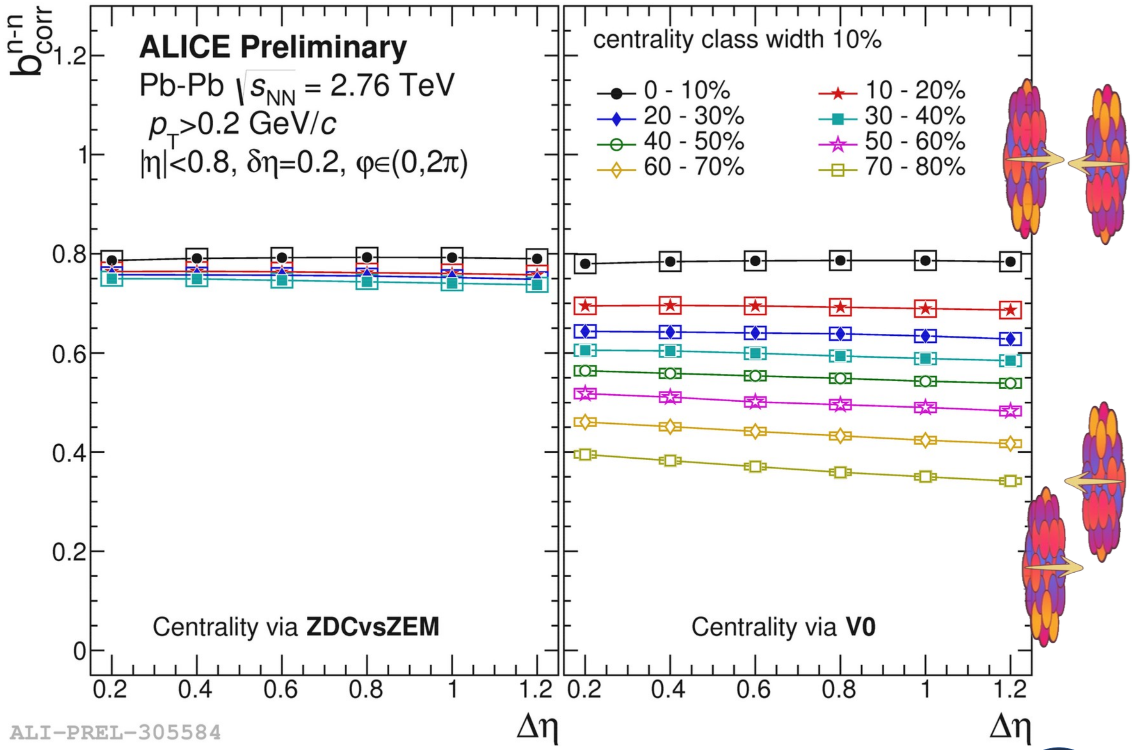
narrow centrality classes

b_{corr}(**weight**, **IQ**) ≈ **0**

Results: Forward-backward correlations with b_{corr}

Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0



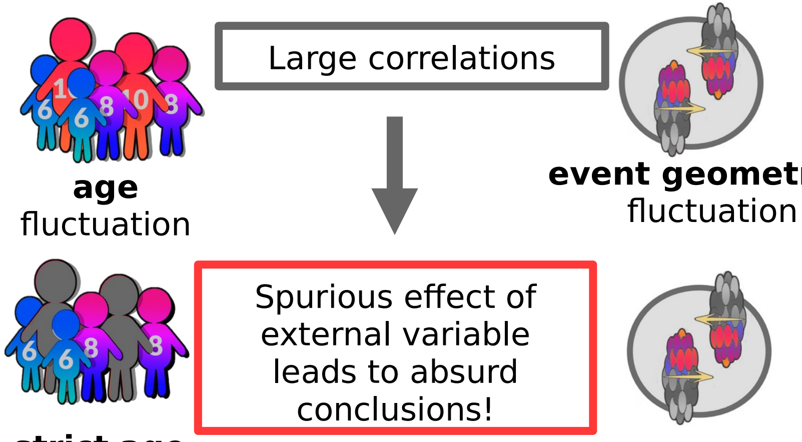
Correlation coefficient:

Schoolchildren

b_{corr}(**weight**, **IQ**) ≈ **0.62**

Heavy-ion collisions

b_{corr}(**nF**, **nB**) ≈ **0.8**



age fluctuation

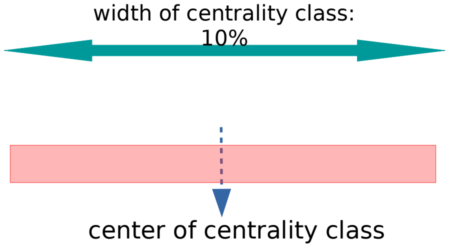
Large correlations

event geometrical fluctuation

Spurious effect of external variable leads to absurd conclusions!

strict age selection

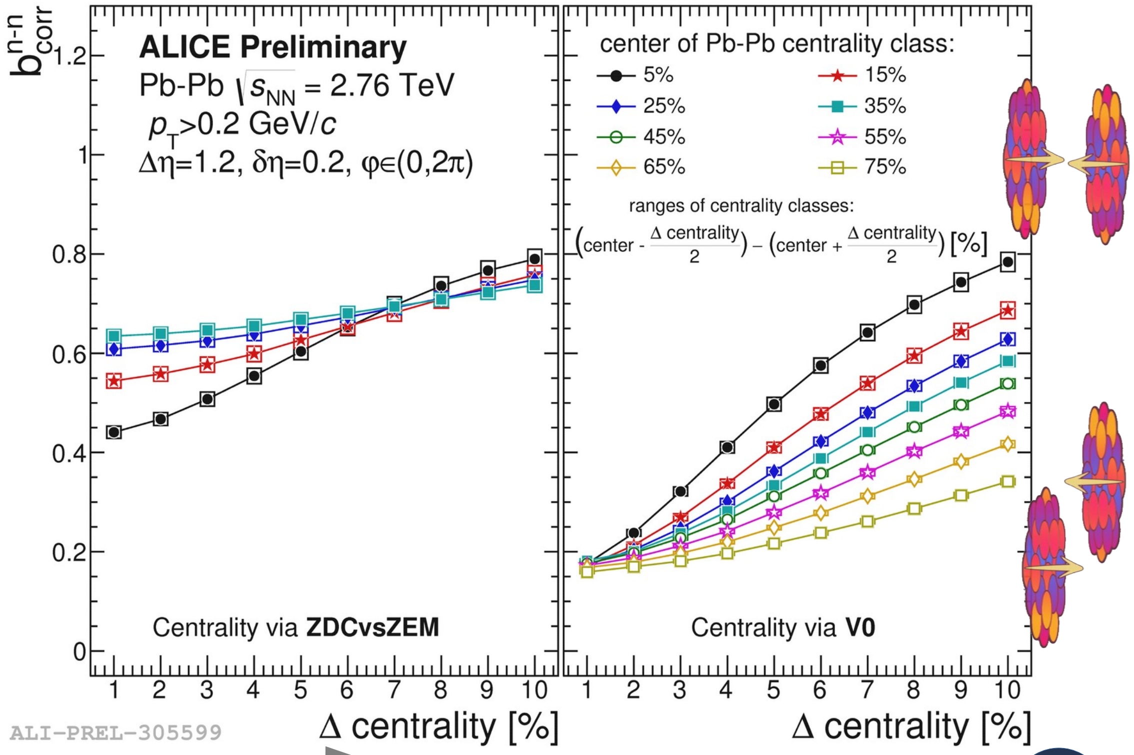
narrow centrality classes



Results: Forward-backward correlations with $\mathbf{b_{corr}}$

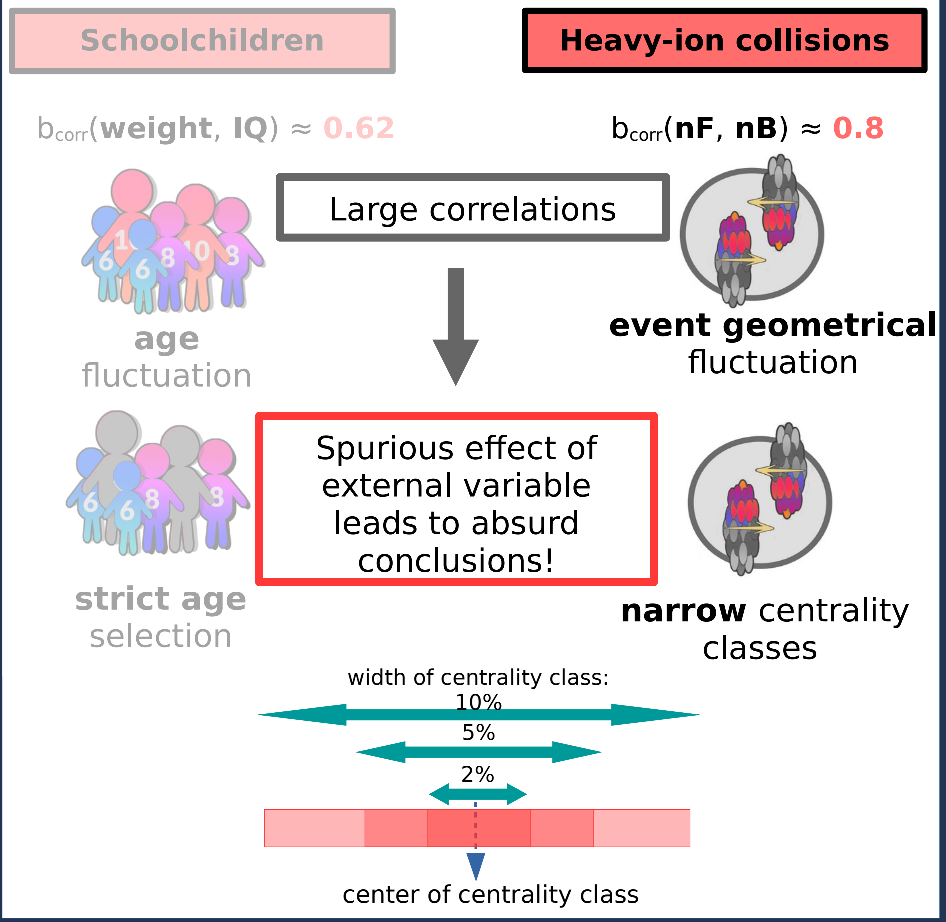
Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0



increase of volume fluctuations

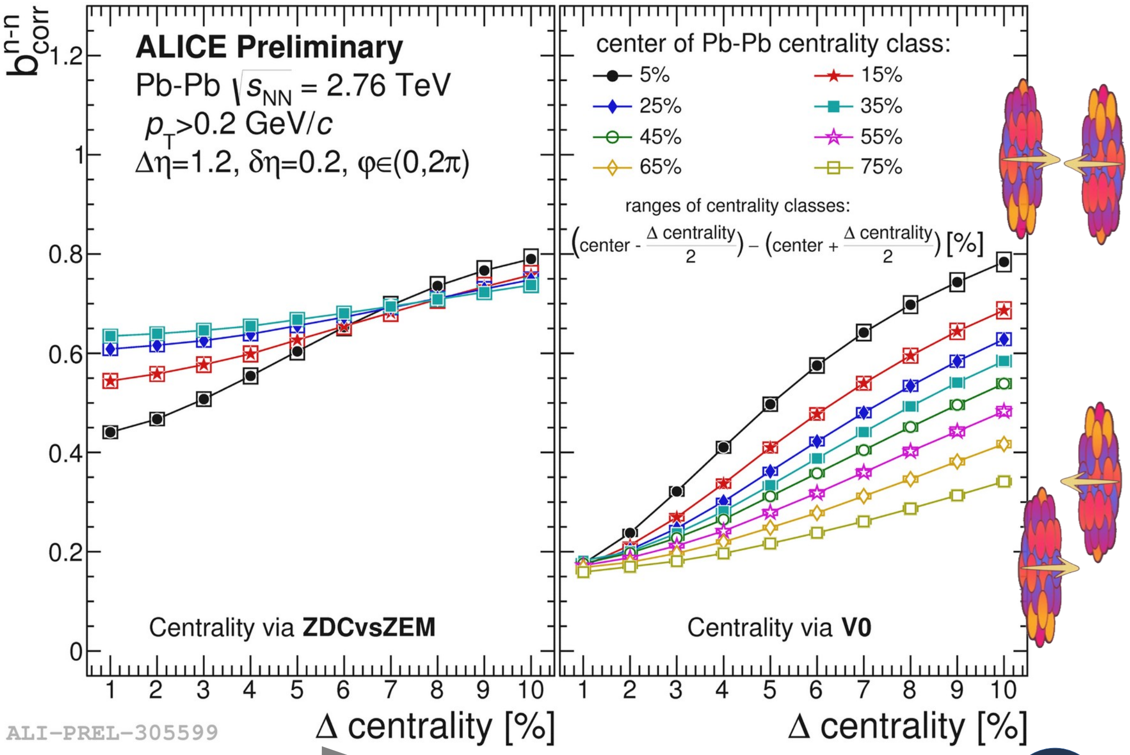
Correlation coefficient:



Results: Forward-backward correlations with b_{corr}

Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0



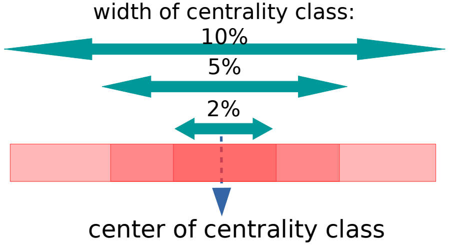
increase of volume fluctuations

Correlation coefficient:

- **Large values of b_{corr}** but large centrality bin width → **large geometrical** (N_{part}) **fluctuations** within centrality class.
- Dependence on centrality estimator.
- Theoretical predictions: $b = 1 - \left[1 + \frac{\bar{n}}{4}\left(\frac{2}{k} + \frac{\langle w^2\rangle - \langle w\rangle^2}{\langle w\rangle}\right)\right]^{-1}$

A. Bzdak, Phys. Rev. C 80 (2009) 024906

Scaled variance of number of participants ω_{part}

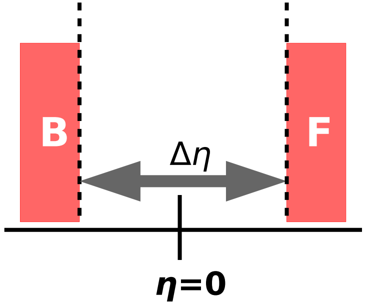


Results: FB correlations with strongly intensive quantity Σ

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

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

STRONGLY INTENSIVE QUANTITY Σ

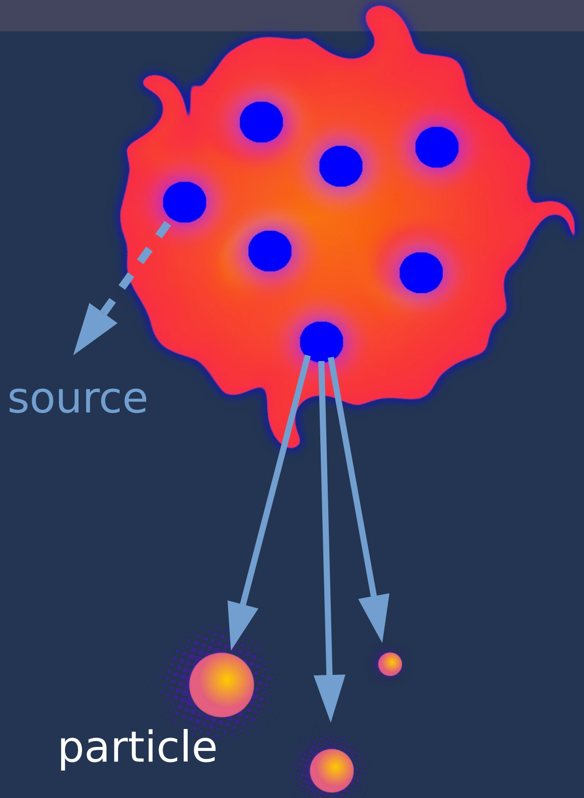


where ω is scaled variance: ω=Var(n)/<n>

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

Independent source model:

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

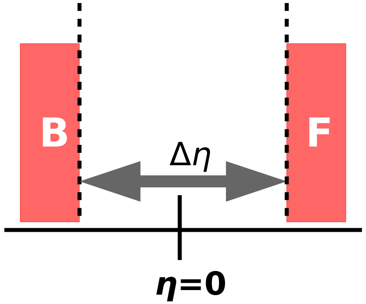


Results: FB correlations with strongly intensive quantity Σ

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

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

STRONGLY INTENSIVE QUANTITY Σ



where ω is scaled variance: ω=Var(n)/<n>

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

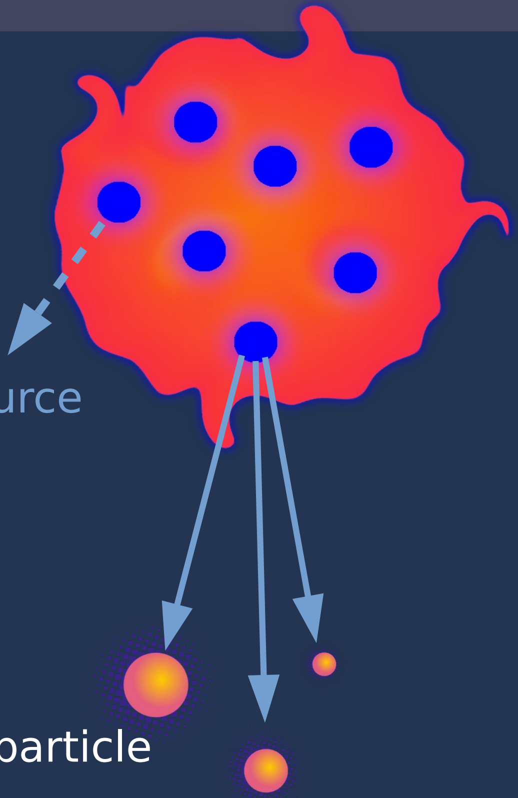
- For a symmetric collision $\boldsymbol{\omega_B = \omega_F}$ and $\boldsymbol{\langle n_F\rangle = \langle n_B\rangle}$

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

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

Independent source model:

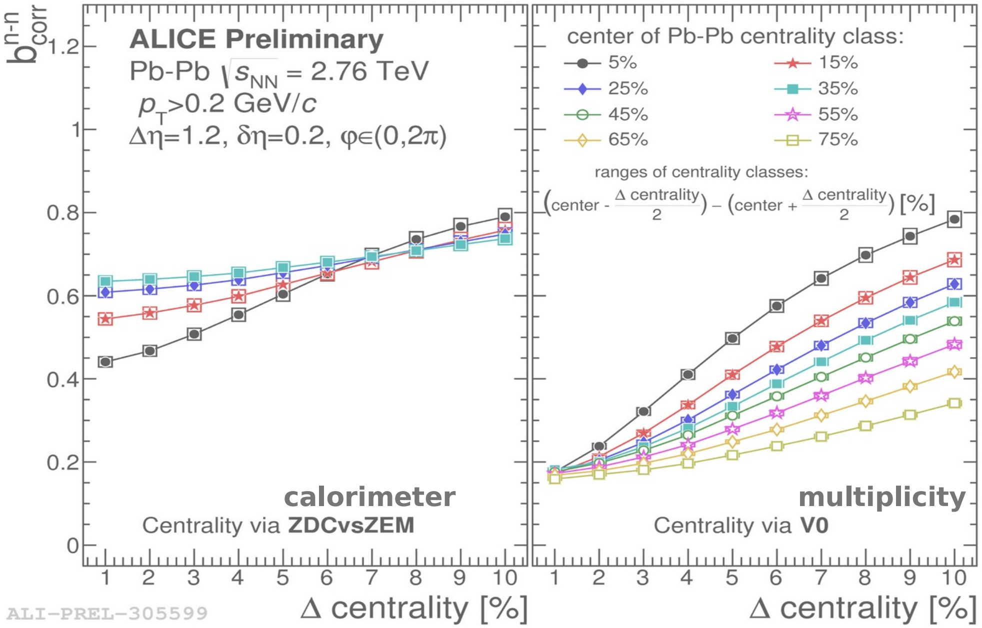
Σ → give direct information about characteristics of **single source distribution!**

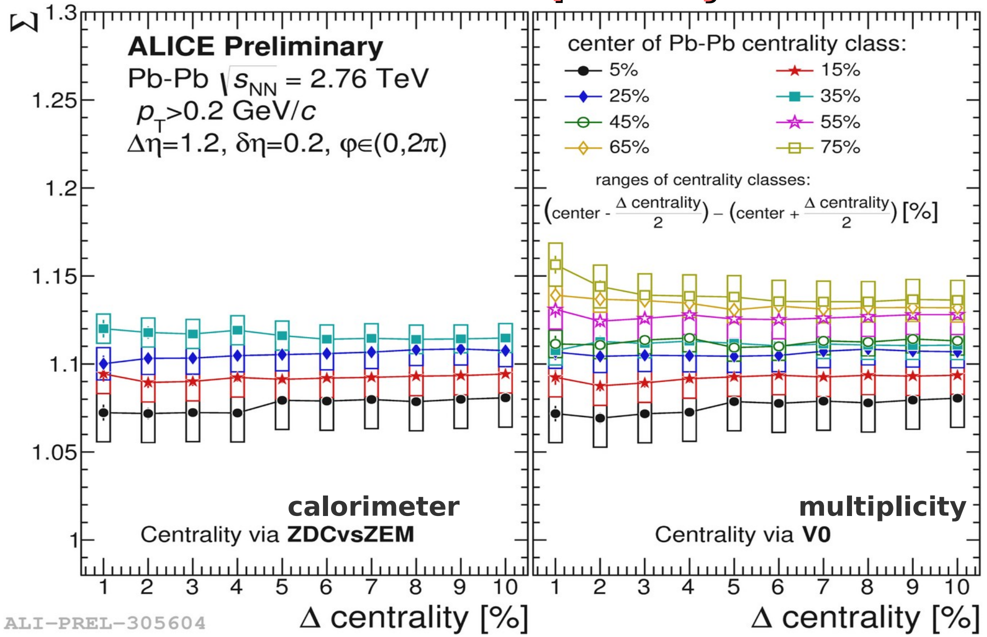


Results: Σ as a function of centrality bin width

The FB **correlation coefficient** $\boldsymbol{b_{corr}}$

The Σ quantity

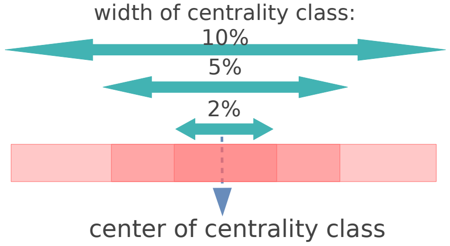




increase of volume fluctuations

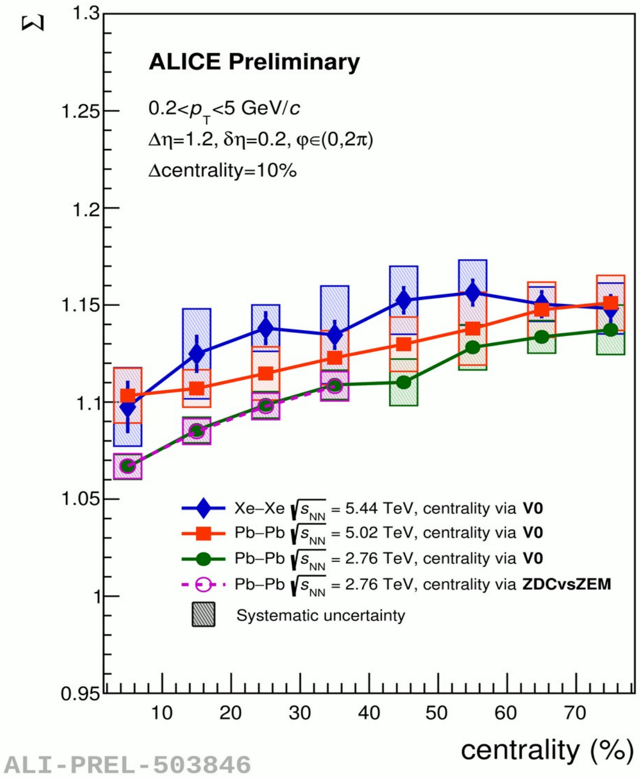
- **Σ does not** depend on centrality bin width (volume fluctuations).
- **Σ does not** depend on centrality estimator!

exhibits the properties of a strongly intensive quantity!

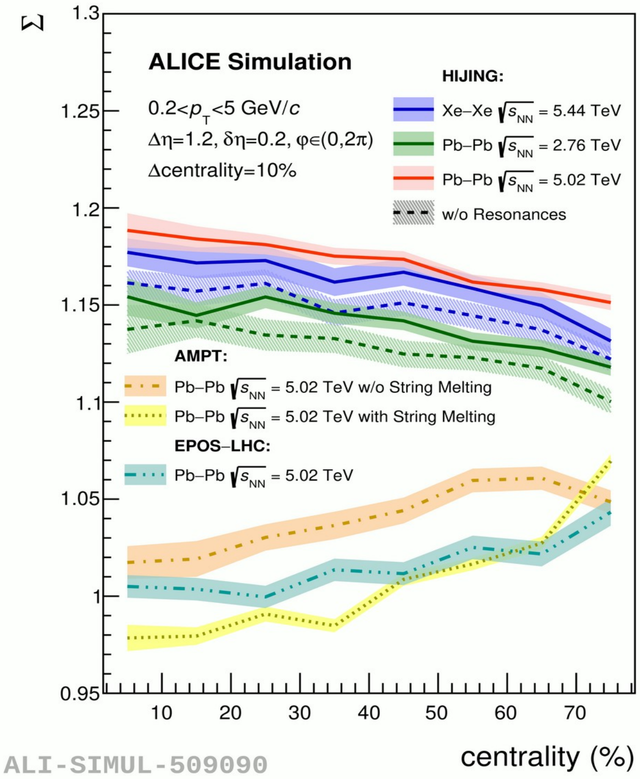


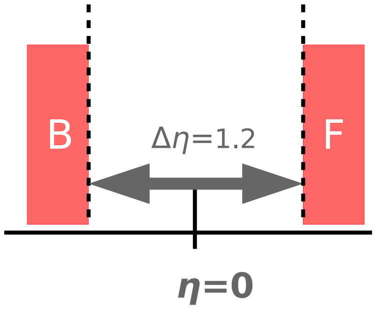
Results: Σ as a function of centrality

Experimental data



MC simulations



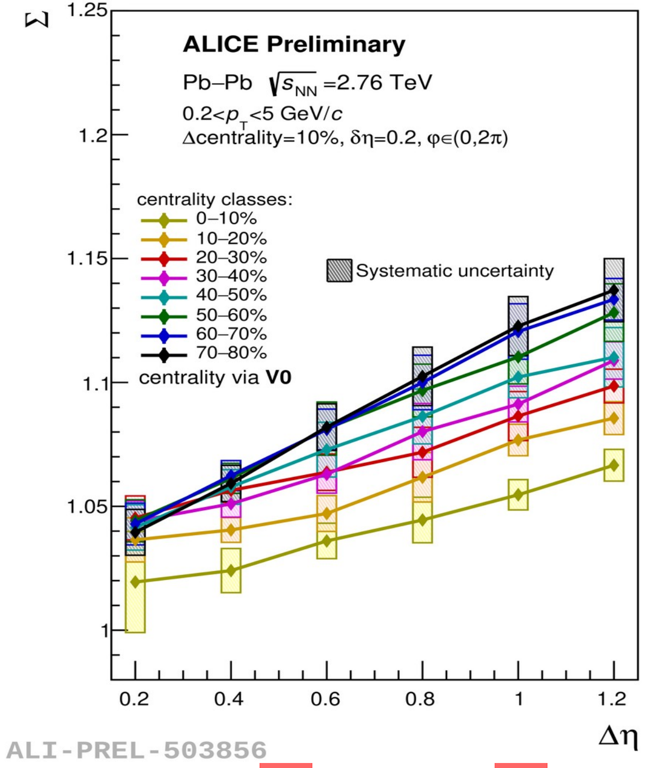


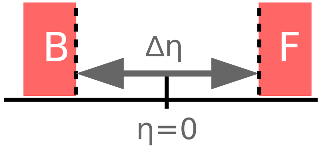
- In experimental data, Σ **increases** with **energy** and with **decreasing centrality**, opposite to the MC HIJING behavior.
- MC AMPT and MC EPOS reproduce the centrality trend of Σ **qualitatively** but **not quantitatively.**
- MC AMPT results indicate that Σ is sensitive to the particle-production mechanism.

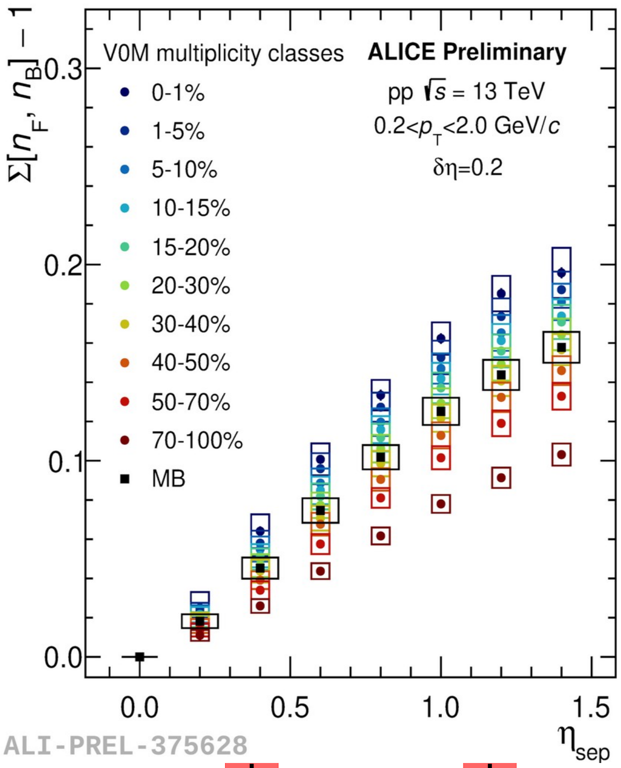
note!

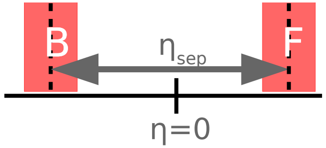
V0 ≈ ZDCvsZEM
→ no dependence on centrality estimator!

Results: Σ as a function $\Delta\eta$









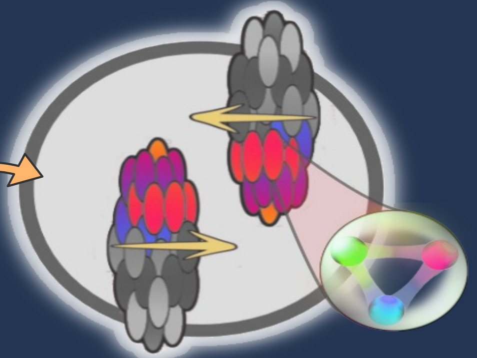
- **increase** with $\Delta\eta$;
- **Pb–Pb: decrease** of Σ with increasing centrality class;
- **pp:** Σ **grows** with the increase of forward event multiplicity; **contrary to Pb–Pb.**

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

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

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

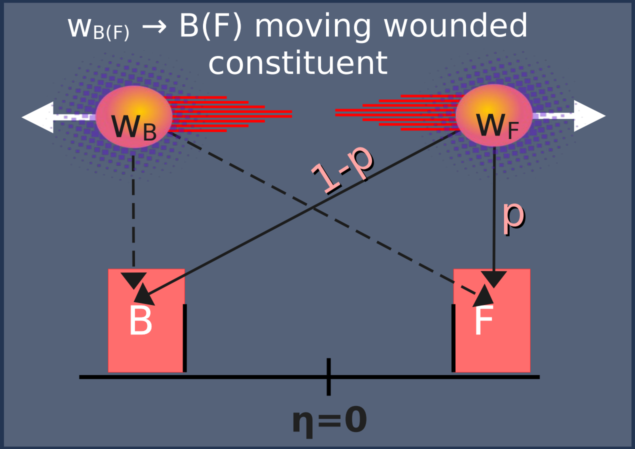
AA collision → a **superposition**
of constituent-constituent interactions



wounded nucleon model (WNM)[1]

wounded quark model (WQM)[2]

Two-component scenario[3]:



[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] A. Bzdak, Phys. Rev. C 80, 024906

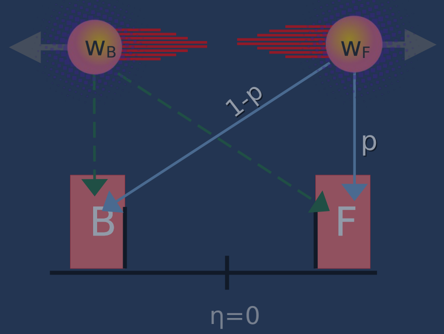
Σ in WNM and WQM for a symmetric AA collision:

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

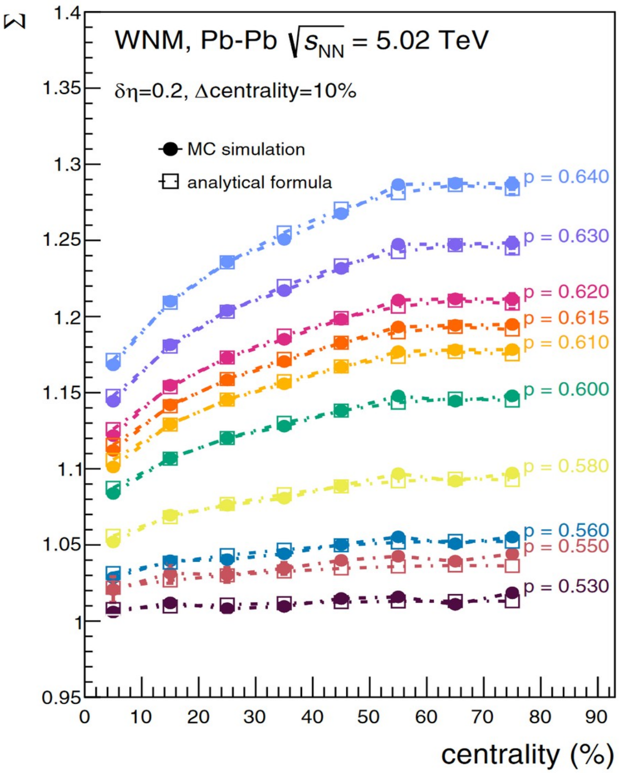
p ≠0.5 breaks ISM assumption

intrinsic dependence on the number of $\boldsymbol{w_F}$ and $\boldsymbol{w_B}$

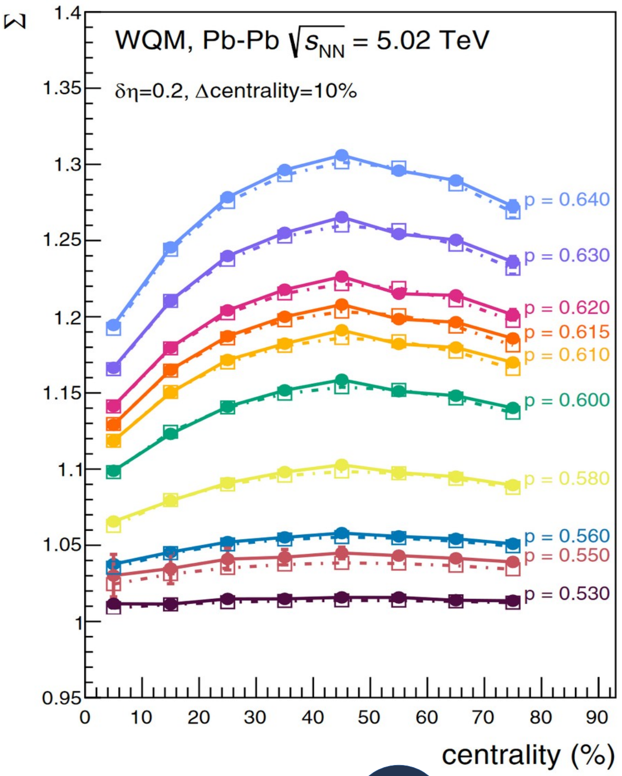
FB correlations with the Σ quantity in **the wounded-constituent framework:**



WNM



WQM



symmetric AA collision:

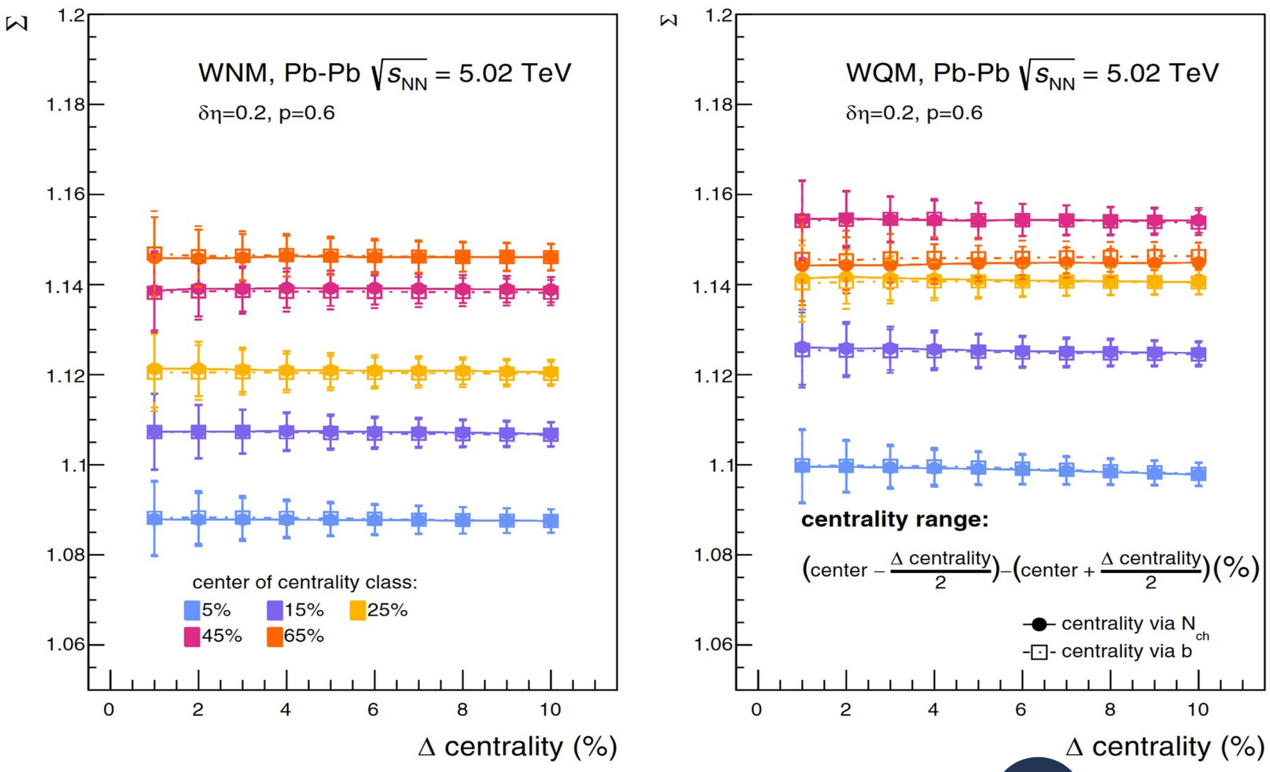
$$\Sigma = 1 + \frac{\bar{n}}{2}(2p-1)^2\left[\frac{\langle (w_B - w_F)^2\rangle}{2\langle w_F\rangle} + \frac{2}{k}\right]$$

- **p = 0.5 → Σ=1** and **Σ is SIQ**;
- **p ≠0.5 → Σ>1** and shows intrinsic dependence on the number of w_F and w_B

no longer a strongly intensive quantity!

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

WNM   WQM



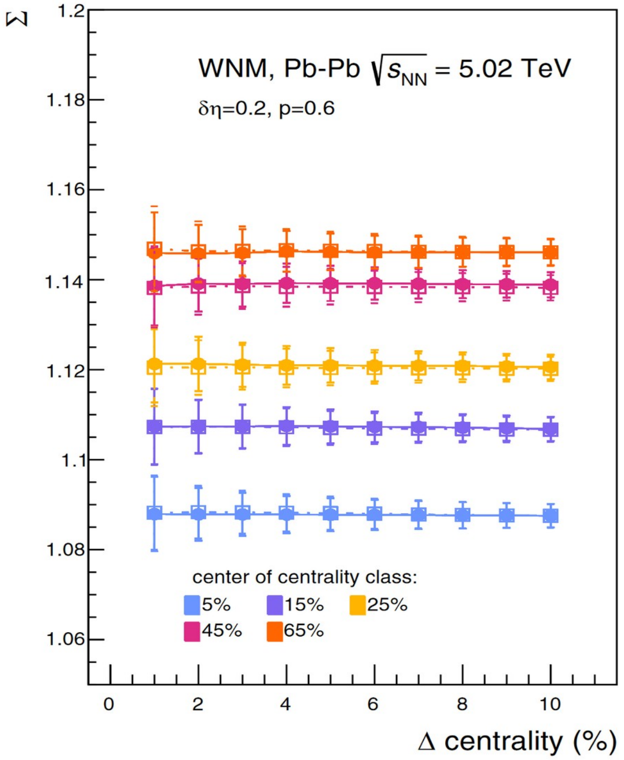
Σ no longer a strongly intensive quantity!

symmetric AA collision:

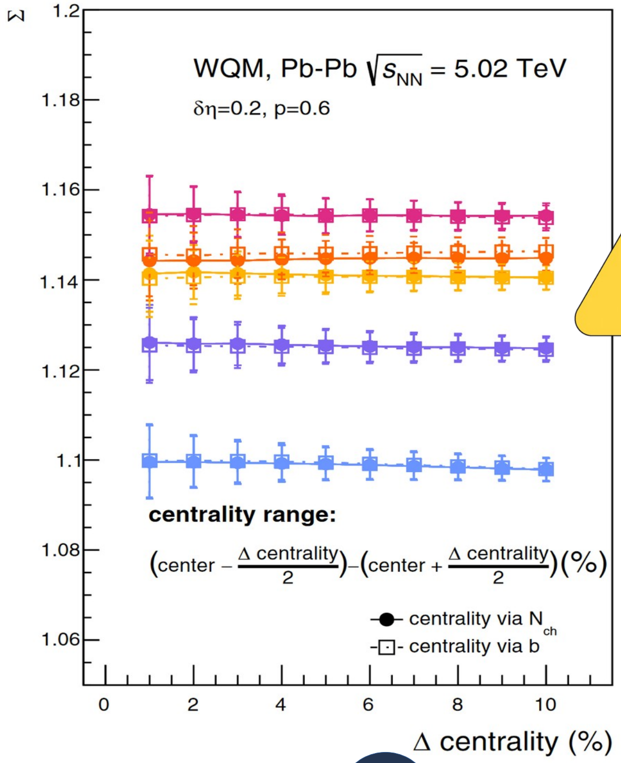
$$\Sigma = 1 + \frac{\bar{n}}{2}(2p-1)^2\left[\frac{\langle (w_B - w_F)^2\rangle}{2\langle w_F\rangle} + \frac{2}{k}\right]$$

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

WNM



WQM



Σ no longer a strongly intensive quantity!

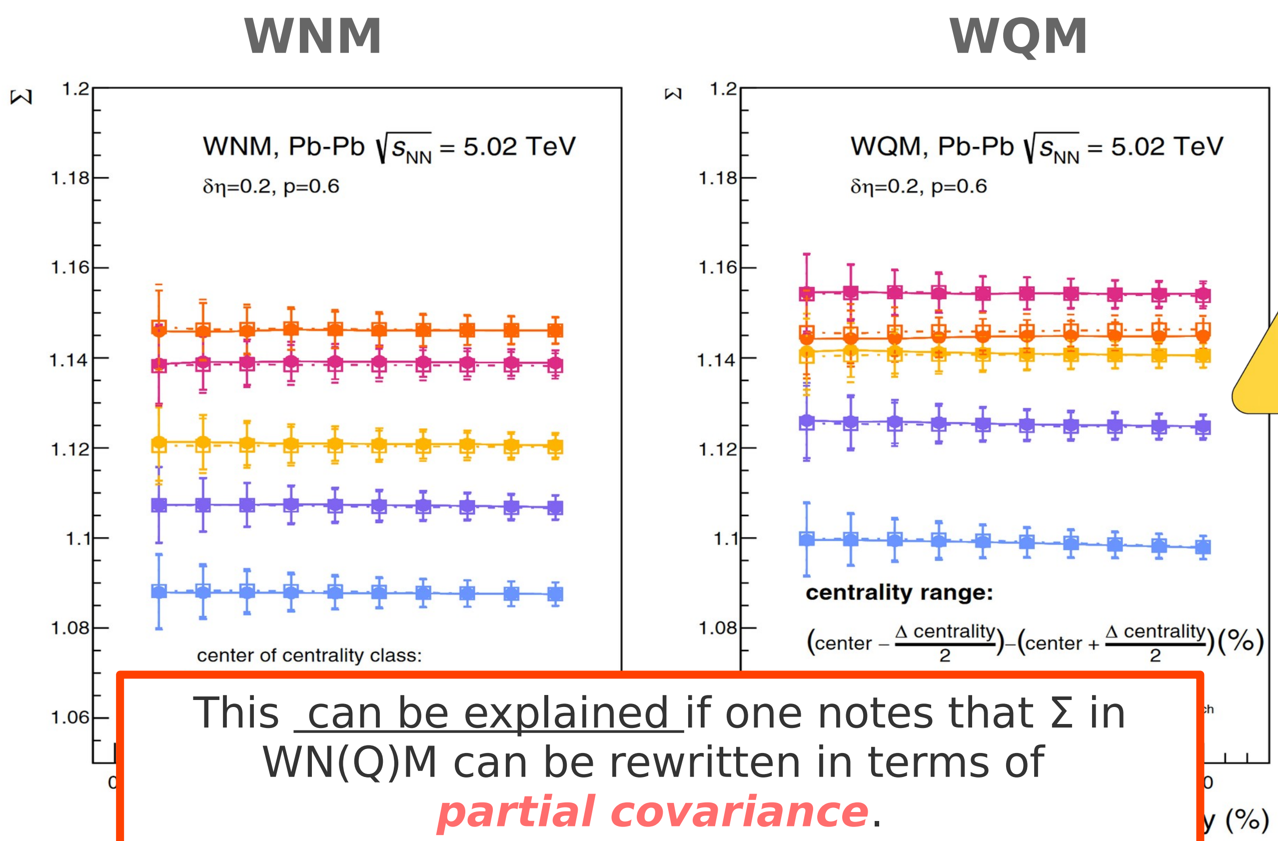
symmetric AA collision:

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

- resemblance to the behavior reported by ALICE (slide 11)
- **Σ does not** depend on centrality bin width (volume fluctuations).
- **Σ does not** depend on centrality estimator!

"SIQ-like" properties!

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



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

I. Sputowska, Phys.Rev.C 108 (2023) 1, 014903

Σ no longer a strongly intensive quantity!

symmetric AA collision:

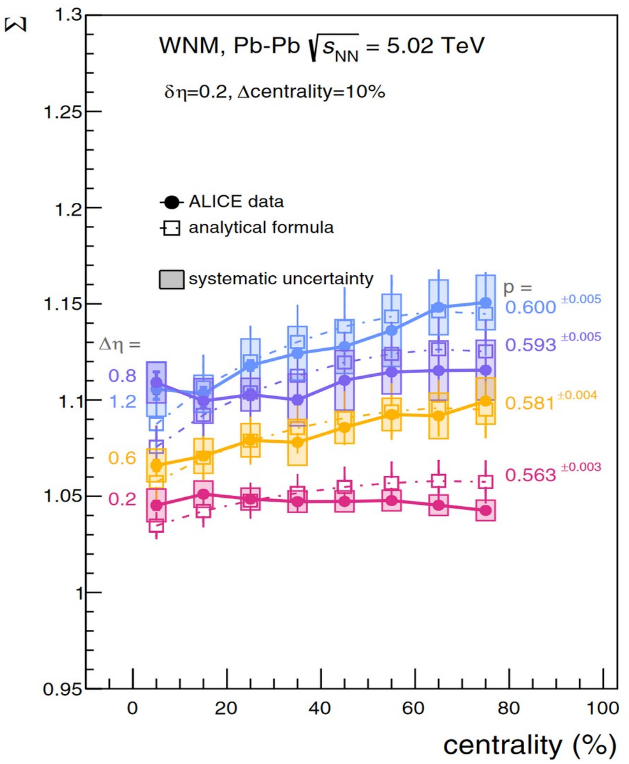
$$\Sigma = 1 + \frac{\bar{n}}{2}(2p-1)^2 \left[\frac{\langle (w_B - w_F)^2 \rangle}{2\langle w_F \rangle} + \frac{2}{k} \right]$$

- resemblance to the behavior reported by ALICE (slide 11)
- **Σ does not** depend on centrality bin width (volume fluctuations).
- **Σ does not** depend on centrality estimator!

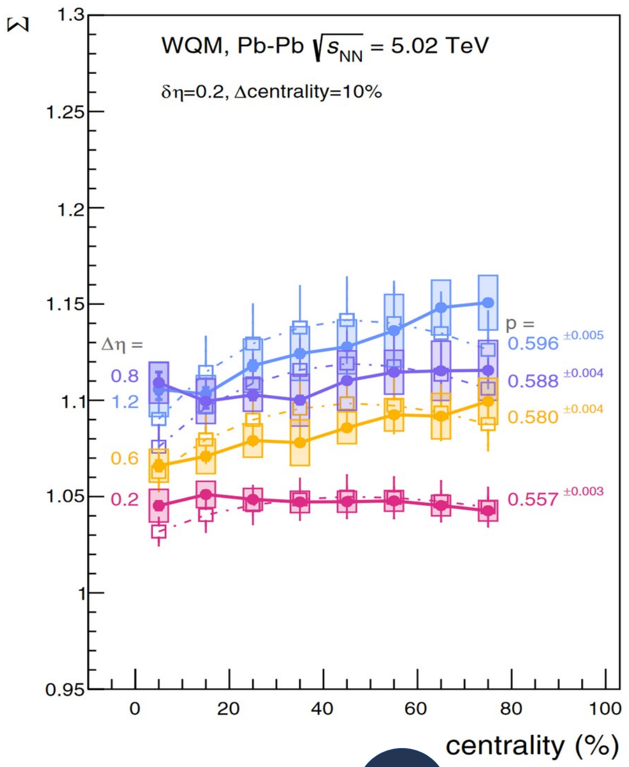
"SIQ-like" properties!

WN(Q)M: Σ quantity as a function of centrality

WNM



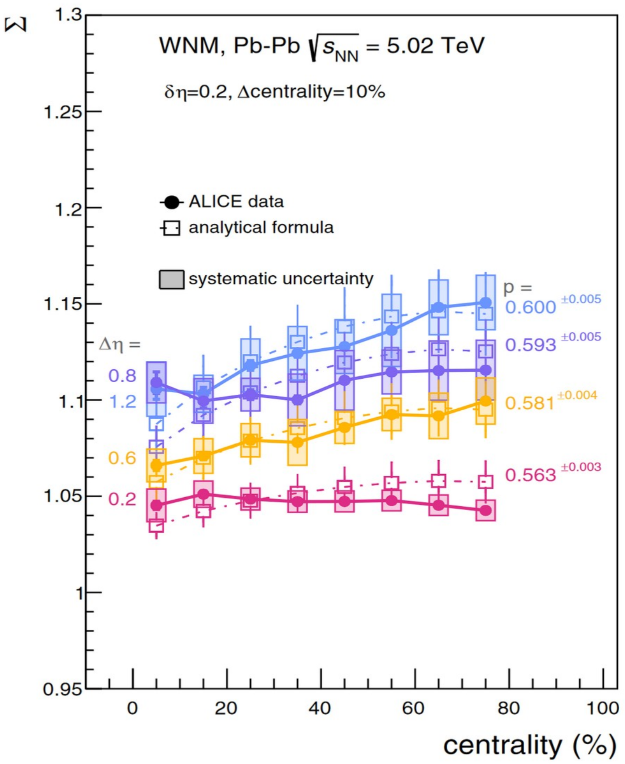
WQM



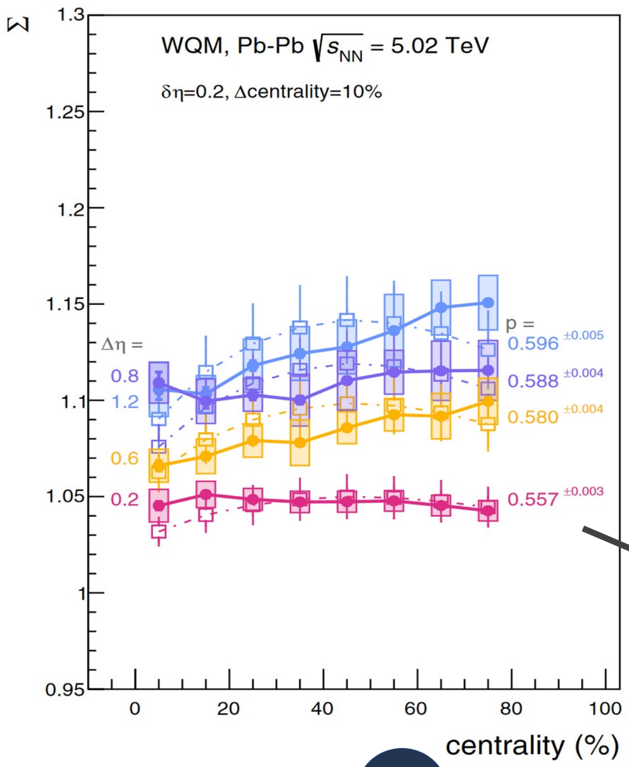
- WNM and WQM→ accurately depict the trend of Σ with centrality observed in the experimental data[4] (also for Pb-Pb at $\sqrt{s_{NN}}$=2.76 and Xe-Xe at $\sqrt{s_{NN}}$=5.44 TeV[5]).
- Values of Σ in the WNM and WQM are sensitive to the probability value *p*.

WN(Q)M: Σ quantity as a function of centrality

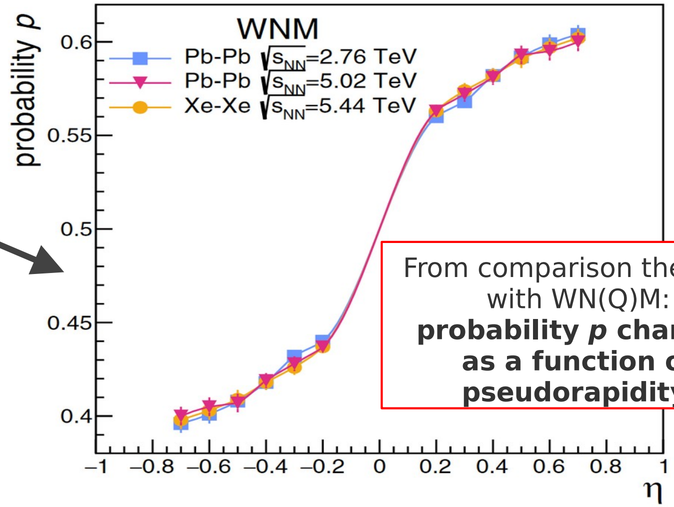
WNM



WQM

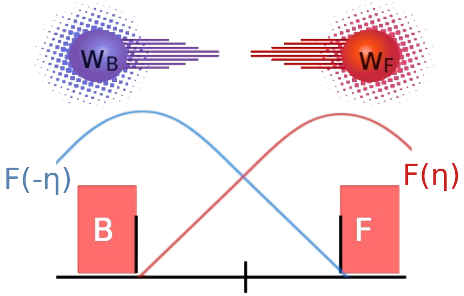


- WNM and WQM→ accurately depict the trend of Σ with centrality observed in the experimental data[4] (also for Pb-Pb at $\sqrt{s_{NN}}$=2.76 and Xe-Xe at $\sqrt{s_{NN}}$=5.44 TeV[5]).
- Values of Σ in the WNM and WQM are sensitive to the probability value *p*.



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

Wounded constituent fragmentation functions F(η) in symmetric Pb-Pb collisions



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

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

F(*η*) DETERMINATION:

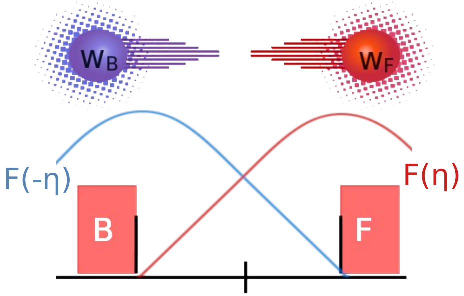
"STANDARD" METHOD

→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 **<wF> ≠ <wB>**.

Wounded constituent fragmentation functions F(η) in symmetric Pb-Pb collisions



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

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

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 **<wF> ≠ <wB>**.

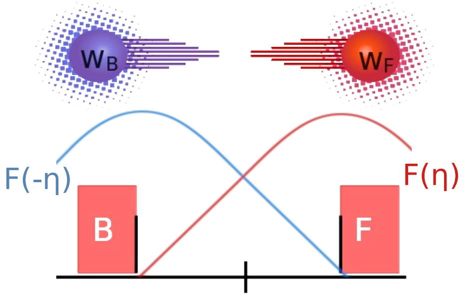
NEW APPROACH:

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

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

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

Wounded constituent fragmentation functions F(η) in symmetric Pb-Pb collisions



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

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

F(*η*) DETERMINATION:

"STANDARD" METHOD

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

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

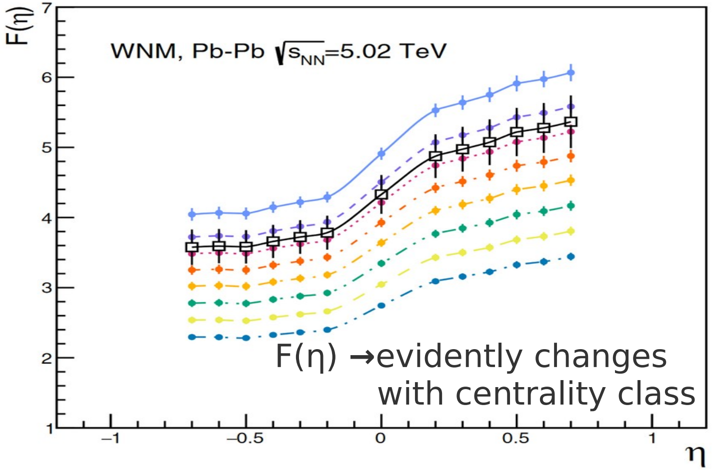
only for asymmetric collisions **<wF> ≠ <wB>**.

NEW APPROACH:

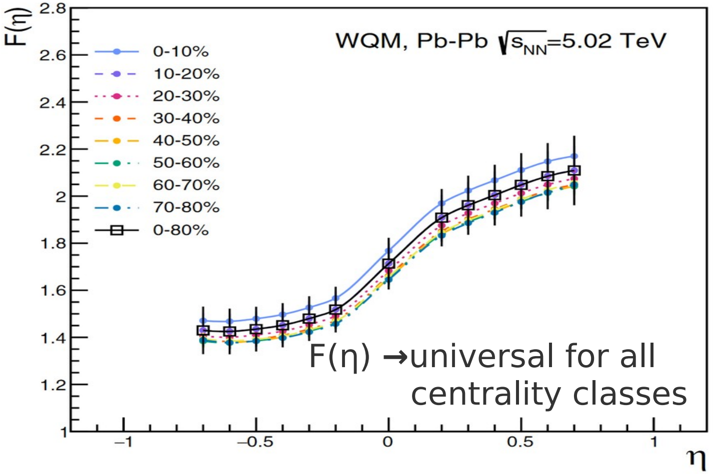
→ based on the **relation between *p* and *Σ*** in WN(Q)M

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

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



F(η) →evidently changes with centrality class



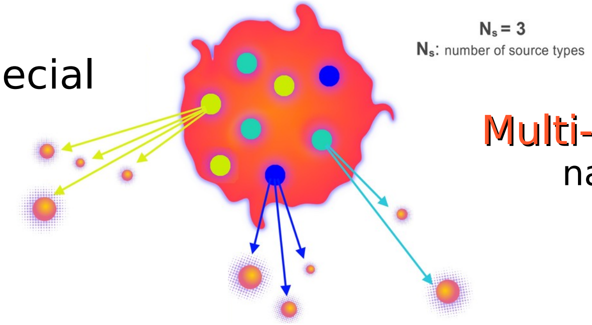
F(η) →universal for all centrality classes

Σ within a multi-source superposition approach

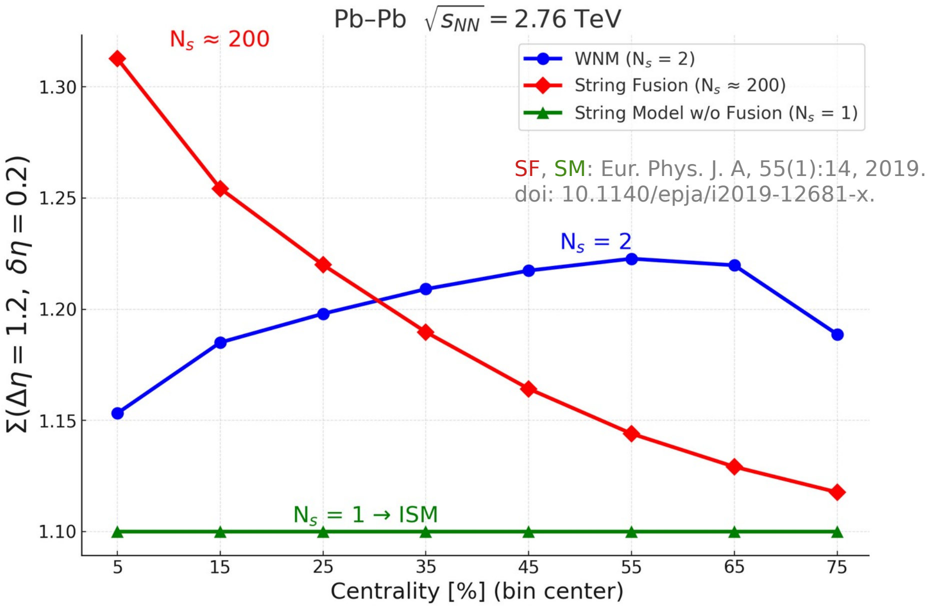
- Several standard superposition models → a special cases of the multi-source statistical apprach.
- Not a dynamical model → a transparent **diagnostic/statistical tool** for organising contributions to Σ.
- Within a multi-source setup, Σ decomposes into three generic contributions:

$$\Sigma = \sum_{i=1}^{N_S} \xi_i^{(I)} E_i + \sum_{i=1}^{N_S}\left(\xi_i^{(II)} + \sum_{j\neq i}\xi_{ij}^{(III)}\right)\mathrm{Var}(s_i) - \sum_{1\le i<j\le N_S}\xi_{ij}^{(III)}\,\mathrm{Var}(s_i - s_j)$$

intrinsic emission fluctuations | fluctuations of the number of sources | relative fluctuations of source types



Multi-source superposition → natural extension of ISM



Summary

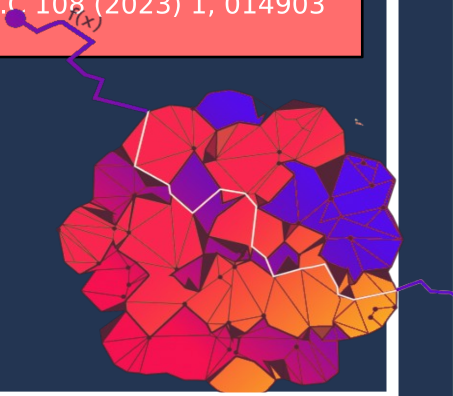
- Σ **is robust** in Pb–Pb/Xe–Xe collisions → independent of centrality selection & volume fluctuations → **closer to genuine dynamics.**
- Σ increases with Δη, system energy and centrality dependence (AA ↑ pp ↓).
- HIJING, AMPT, EPOS **fail to describe** Σ consistently across AA; simple source-based models capture the trends.
- In WNM/WQM Σ **is not SIQ**, but retains **SIQ-like properties** in symmetric AA via partial covariance.
- Σ is sensitive to emission probability p → **new method** of extraction of the wounded-source fragmentation function.
- Multi-source superposition → clean statistical language to compare production scenarios.
- Σ connects to cumulants, charge fluctuations & partial covariance → a tool beyond classical FB correlations.

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).

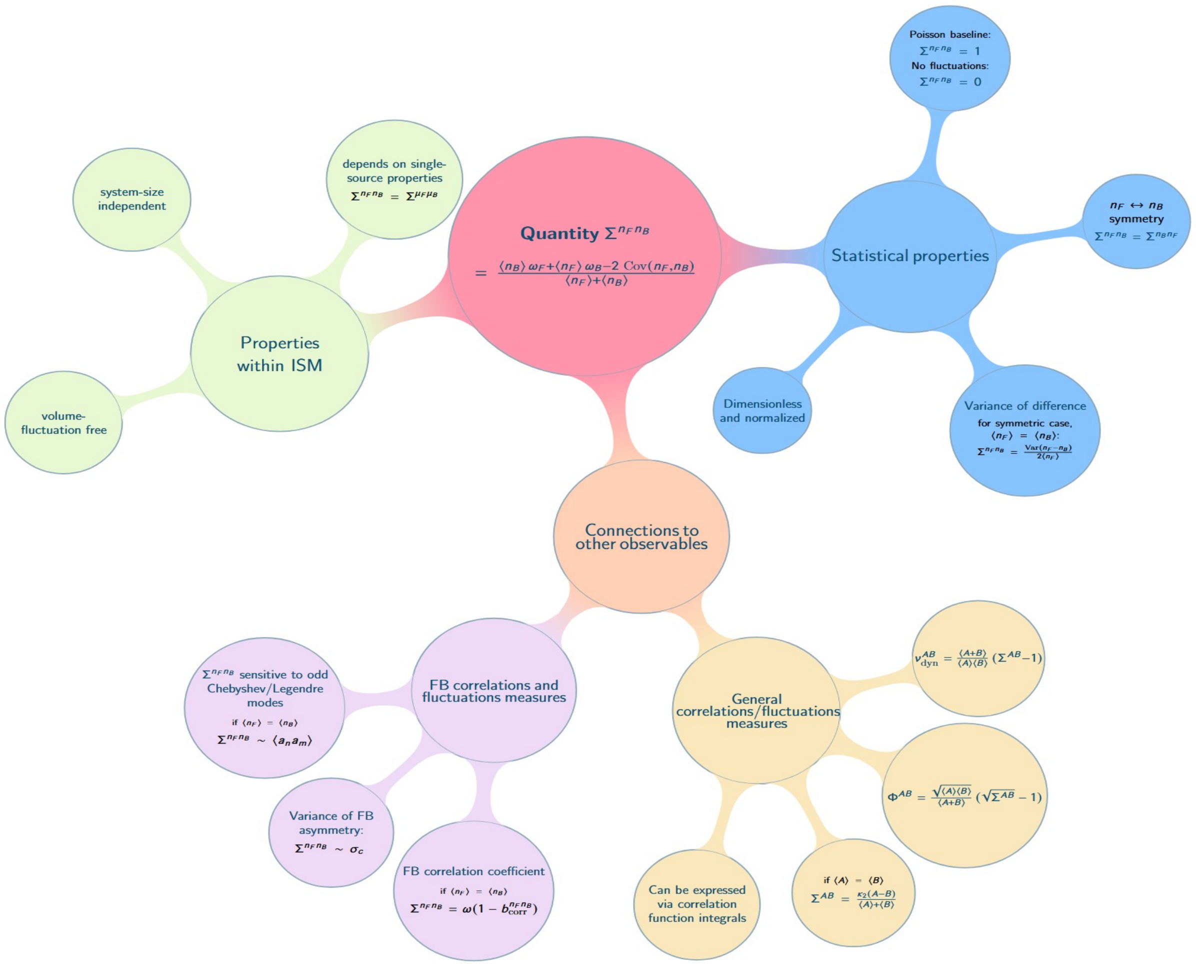
Strongly Intensive Quantities
M. I. Gorenstein and M. Gazdzicki,
Phys. Rev. C 84, 014904 (2011),
arXiv:1101.4865 [nucl-th].

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



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

Backup

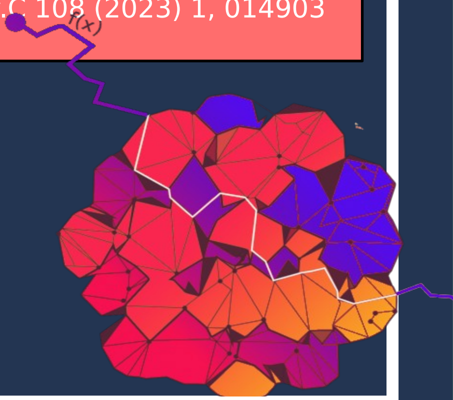


Σ dependence on centrality selection and volume fluctuations
I. Sputowska (ALICE), MDPI Proc. 10, 14 (2019)

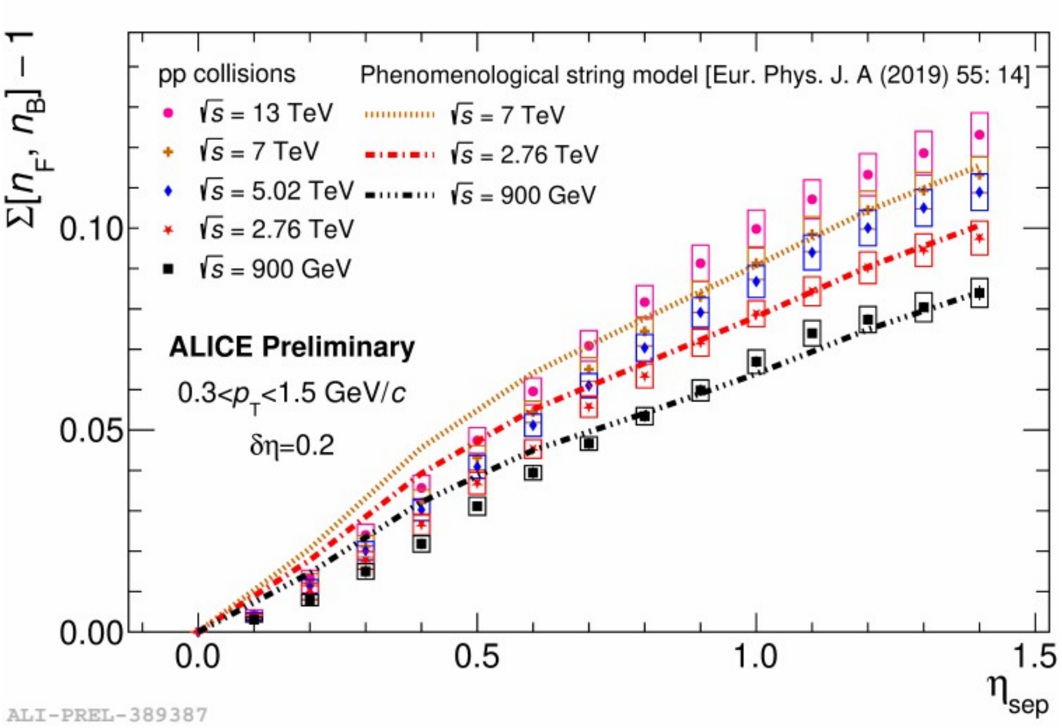
Σ in AA and pp collisions
I. Sputowska (ALICE), EPJ Web Conf. 274, 05003 (2022).

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



Backup

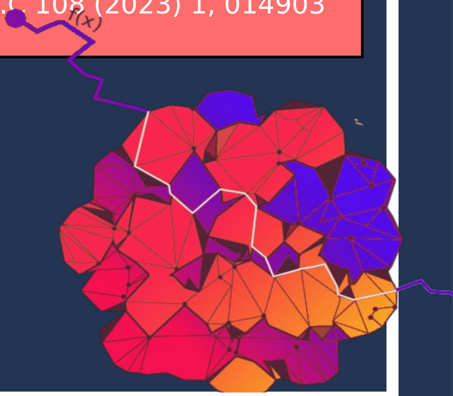


Σ dependence on centrality selection and volume fluctuations
I. Sputowska (ALICE), MDPI Proc. 10, 14 (2019)

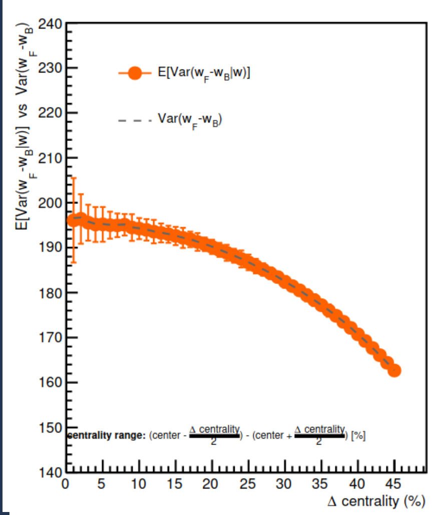
Σ in AA and pp collisions
I. Sputowska (ALICE), EPJ Web Conf. 274, 05003 (2022).

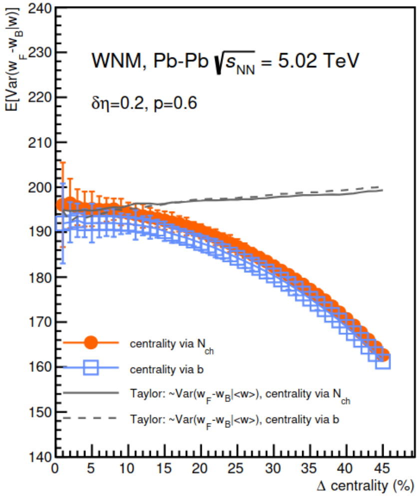
Strongly Intensive Quantities
M. I. Gorenstein and M. Gazdzicki, Phys. Rev. C 84, 014904 (2011), arXiv:1101.4865 [nucl-th].

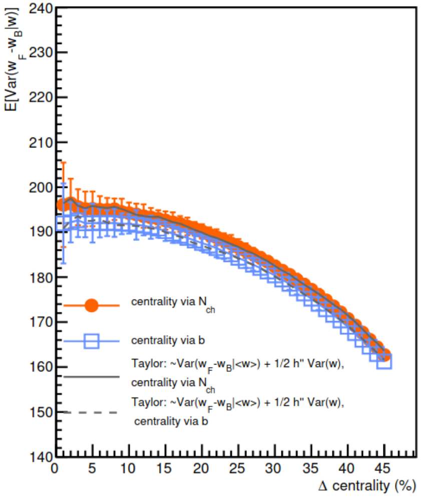
Σ in WNM and WQM
I. Sputowska, Phys.Rev.C 108 (2023) 1, 014903



Backup





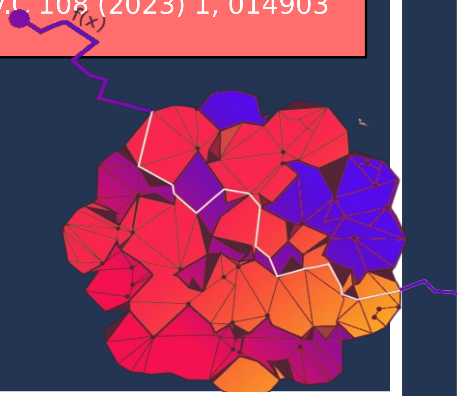


Σ dependence on centrality selection and volume fluctuations
I. Sputowska (ALICE), MDPI Proc. 10, 14 (2019)

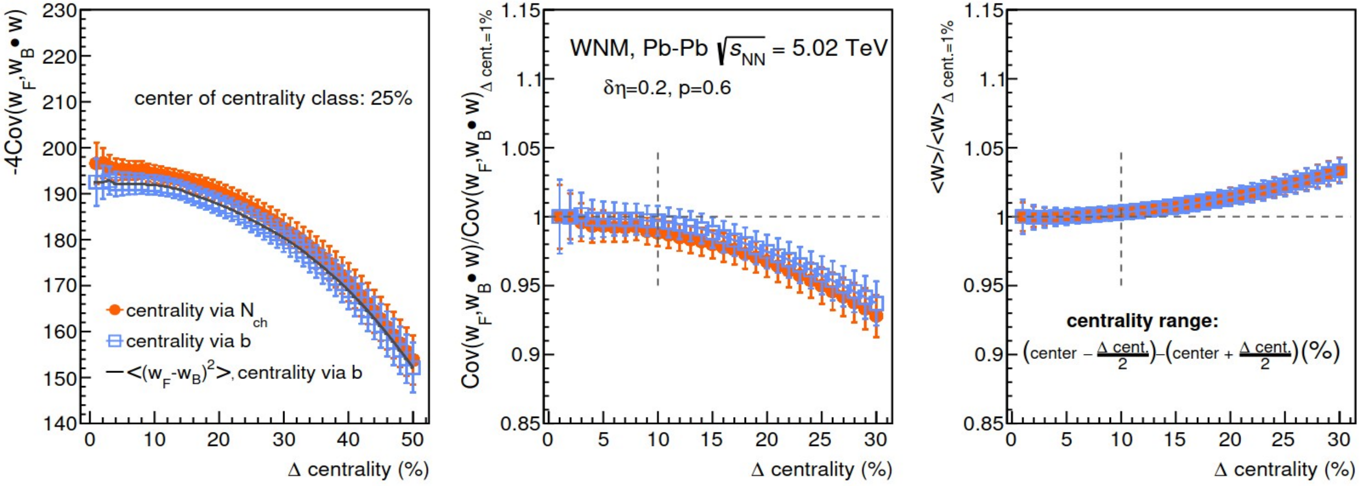
Σ in AA and pp collisions
I. Sputowska (ALICE), EPJ Web Conf. 274, 05003 (2022).

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



Backup



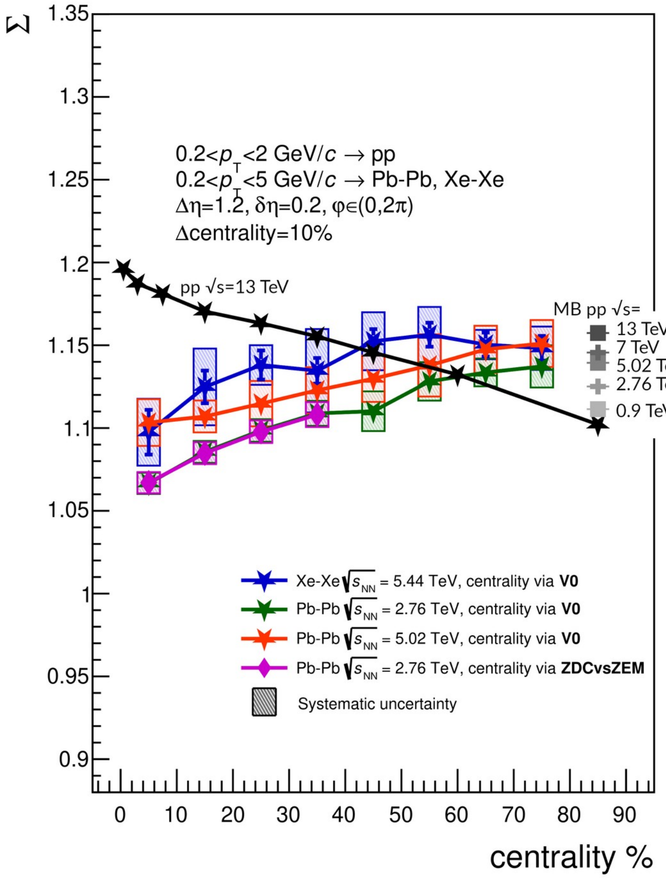
Σ dependence on centrality selection and volume fluctuations
I. Sputowska (ALICE), MDPI Proc. 10, 14 (2019)

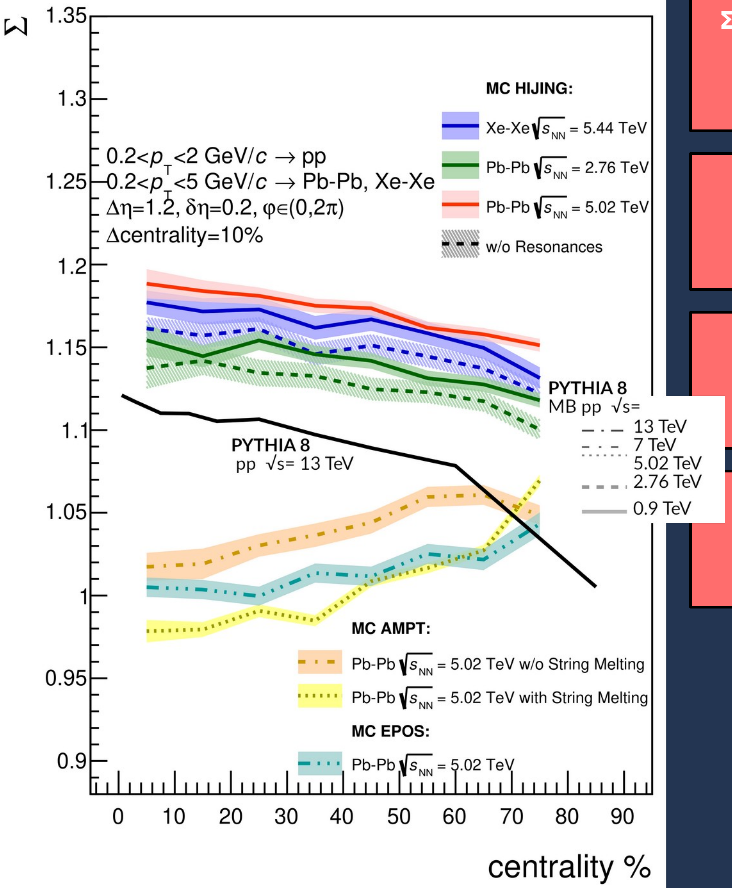
Σ in AA and pp collisions
I. Sputowska (ALICE), EPJ Web Conf. 274, 05003 (2022).

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

Backup



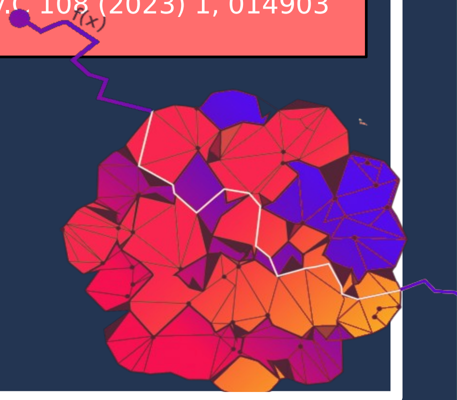


Σ dependence on centrality selection and volume fluctuations
I. Sputowska (ALICE), MDPI Proc. 10, 14 (2019)

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



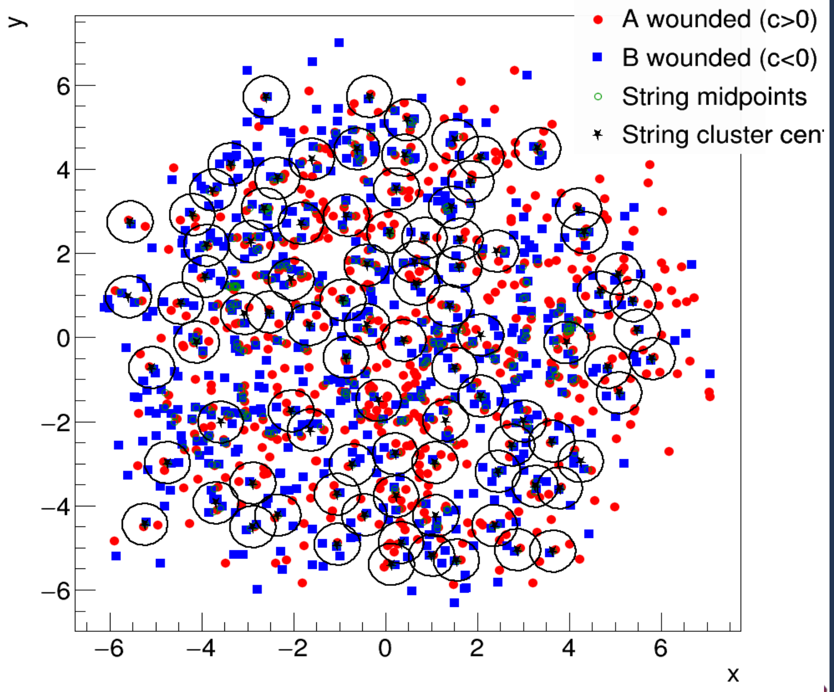
Quantity	Formula	
$\langle \mu_F^{(i)} \rangle$	$\mu_0^{(i)} \delta\eta \quad \rightarrow$	where $\mu_0^{(i)}$ is a distribution density of particles from string type i
$\langle \mu_B^{(i)} \rangle$	$\mu_0^{(i)} \delta\eta \quad \rightarrow$	$\delta\eta$ is the width of pseudorapidity interval
$\mathrm{Var}(\mu_F^{(i)})$	$\langle \mu_F^{(i)} \rangle \left(1 + \langle \mu_F^{(i)} \rangle \Lambda^{(i)}(0)\right)$	
$\mathrm{Var}(\mu_B^{(i)})$	$\langle \mu_B^{(i)} \rangle \left(1 + \langle \mu_B^{(i)} \rangle \Lambda^{(i)}(0)\right)$	
$\mathrm{Cov}(\mu_F^{(i)}, \mu_B^{(i)})$	$\langle \mu_F^{(i)} \rangle^2 \, \Lambda^{(i)}(\Delta\eta)$	

For symmetric collisions, the final expression for Σ takes the form:

$$\Sigma = \sum_{i=1}^{N_S} \xi_i^{(I)} \underbrace{\left(1 + \mu_0^{(i)} \delta\eta \left[\Lambda^{(i)}(0) - \Lambda^{(i)}(\Delta\eta)\right]\right)}_{\Sigma^{\mu_F^{(i)} \mu_B^{(i)}}} . \qquad \text{(E.2)}$$

which coincides with the formula for Σ derived in Ref. [110].

Most central event (max RDS)



Quantity	Formula	Quantity	Formula
$\langle \mu_F^{(1)} \rangle$	$p\langle \mu_0 \rangle$	$\langle \mu_B^{(1)} \rangle$	$(1-p)\langle \mu_0 \rangle$
$\langle \mu_F^{(2)} \rangle$	$(1-p)\langle \mu_0 \rangle$	$\langle \mu_B^{(2)} \rangle$	$p\langle \mu_0 \rangle$
$\mathrm{Var}(\mu_F^{(1)})$	$p(1-p)\langle \mu_0 \rangle + p^2\,\mathrm{Var}(\mu_0)$	$\mathrm{Var}(\mu_B^{(1)})$	$p(1-p)\langle \mu_0 \rangle + (1-p)^2\,\mathrm{Var}(\mu_0)$
$\mathrm{Var}(\mu_F^{(2)})$	$p(1-p)\langle \mu_0 \rangle + (1-p)^2\,\mathrm{Var}(\mu_0)$	$\mathrm{Var}(\mu_B^{(2)})$	$p(1-p)\langle \mu_0 \rangle + p^2\,\mathrm{Var}(\mu_0)$
$\mathrm{Cov}(\mu_F^F, \mu_B^F)$	$p(1-p)\,(\mathrm{Var}(\mu_0) - \langle \mu_0 \rangle)$	$\mathrm{Cov}(\mu_F^B, \mu_B^B)$	$p(1-p)\,(\mathrm{Var}(\mu_0) - \langle \mu_0 \rangle)$

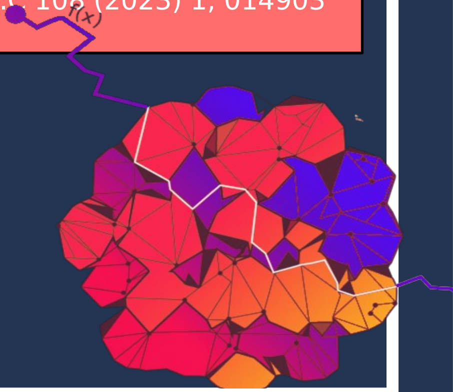
$$\Sigma = 1 + (2p-1)^2 \cdot \frac{\bar{n}}{k} + \frac{(2p-1)^2\,\bar{n}}{4\langle s_1 \rangle} \cdot \mathrm{Var}(s_1 - s_2) = 1 + (2p-1)^2 \cdot \frac{\bar{n}}{2} \cdot \left(\frac{2}{k} + \frac{\mathrm{Var}(s_1 - s_2)}{2\langle s_1 \rangle} \right). \quad \text{(E.6)}$$

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



Quantity	Formula	Quantity	Formula
$\langle \mu_F^{(1)} \rangle$	$p\langle \mu_0 \rangle$	$\langle \mu_B^{(1)} \rangle$	$(1-p)\langle \mu_0 \rangle$
$\langle \mu_F^{(2)} \rangle$	$(1-p)\langle \mu_0 \rangle$	$\langle \mu_B^{(2)} \rangle$	$p\langle \mu_0 \rangle$
$\mathrm{Var}(\mu_F^{(1)})$	$p(1-p)\langle \mu_0 \rangle + p^2\,\mathrm{Var}(\mu_0)$	$\mathrm{Var}(\mu_B^{(1)})$	$p(1-p)\langle \mu_0 \rangle + (1-p)^2\,\mathrm{Var}(\mu_0)$
$\mathrm{Var}(\mu_F^{(2)})$	$p(1-p)\langle \mu_0 \rangle + (1-p)^2\,\mathrm{Var}(\mu_0)$	$\mathrm{Var}(\mu_B^{(2)})$	$p(1-p)\langle \mu_0 \rangle + p^2\,\mathrm{Var}(\mu_0)$
$\mathrm{Cov}(\mu_F^F, \mu_B^F)$	$p(1-p)\,(\mathrm{Var}(\mu_0) - \langle \mu_0 \rangle)$	$\mathrm{Cov}(\mu_F^B, \mu_B^B)$	$p(1-p)\,(\mathrm{Var}(\mu_0) - \langle \mu_0 \rangle)$

$$\Sigma = 1+(2p-1)^2\cdot\frac{\bar{n}}{k}+\frac{(2p-1)^2\,\bar{n}}{4\langle s_1\rangle}\cdot\mathrm{Var}(s_1-s_2) = 1+(2p-1)^2\cdot\frac{\bar{n}}{2}\cdot\left(\frac{2}{k}+\frac{\mathrm{Var}(s_1-s_2)}{2\langle s_1\rangle}\right). \quad \text{(E.6)}$$

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