Forward-backward correlations and multiplicity fluctuations in Pb-Pb collisions form ALICE at the LHC

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Outline

First attempt to obtain information on forward-backward correlation coefficient, **partial correlation** coefficient and **strongly intensive quantity** **Σ**

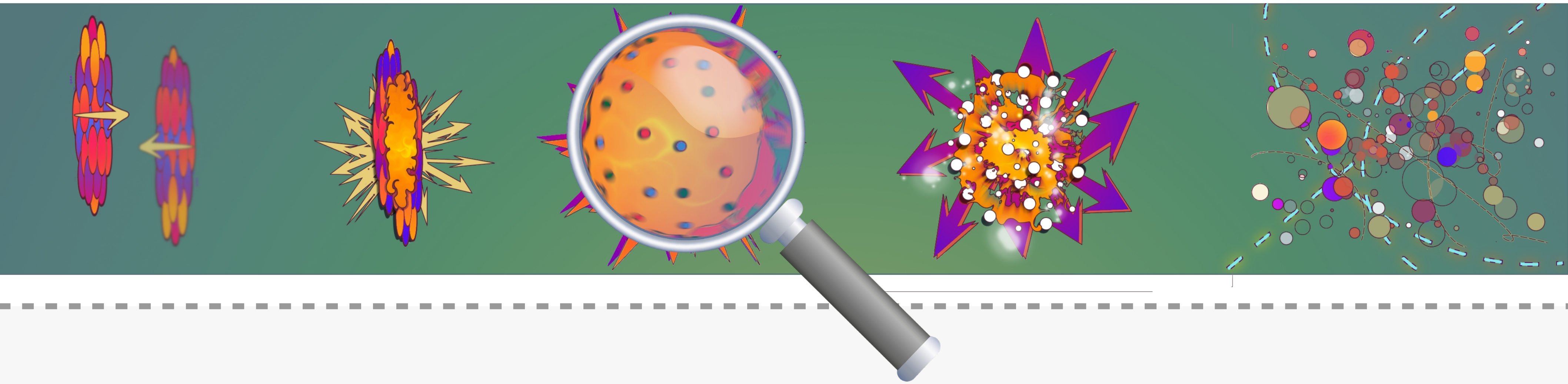
…in various colliding systems and energies.

Plan:

1. Introduction;
2. Motivation;
3. Analysis;
4. Results;
5. Summary.

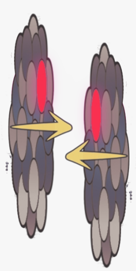
Introduction: Relativistic Heavy-Ion Collisions

PRE-COLLISION STAGE | PRE-EQUILIBRIUM STAGE | QGP AND EQUILIBRIUM STAGE | HADRONIZATION STAGE | HADRONIZATION FREEZE-OUT STAGE



ENERGY OF THE COLLISION
IN THE C.M.S.

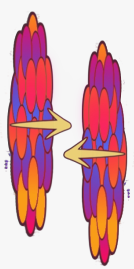
PER NUCLEON PAIR



Pb-Pb

$\sqrt{s_{NN}} = 2.76$ TeV

PER NUCLEUS



Pb-Pb

$\sqrt{s} = \underline{574}$ TeV $= 574 \cdot 10^6$ MeV

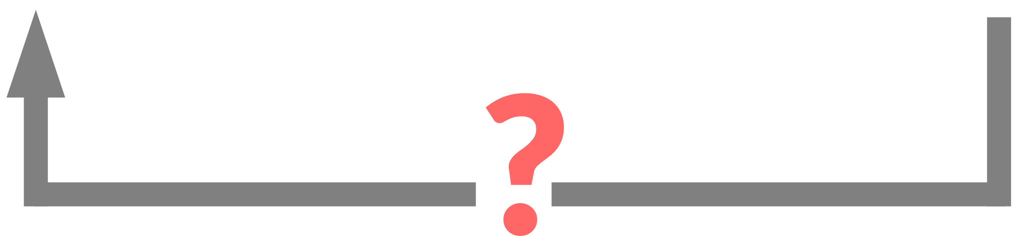
Energy transfer in HIC >> Energy of any binding state of nucleons

Motivation: Why do we study correlations and fluctuations?

PRE-COLLISION STAGE | PRE-EQUILIBRIUM STAGE | QGP AND EQUILIBRIUM STAGE | HADRONIZATION STAGE | HADRONIZATION FREEZE-OUT STAGE

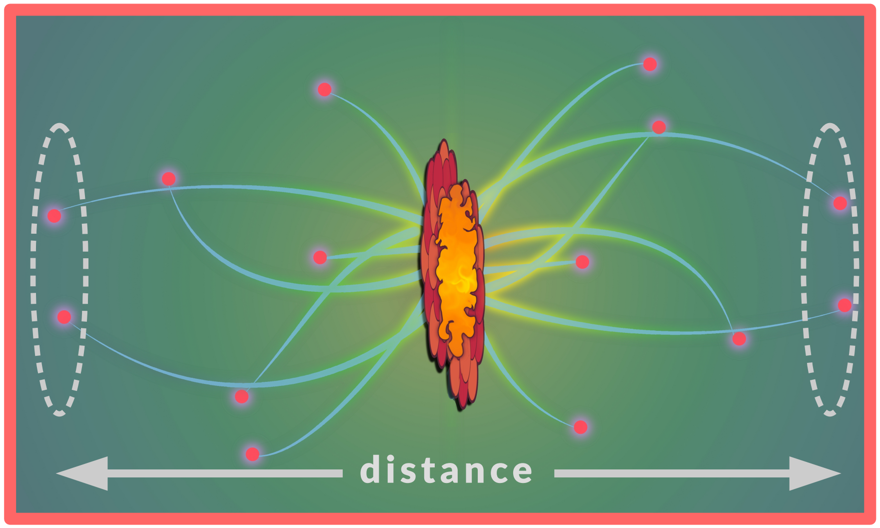
What we want to know...

What we measure in the detector...



Analysis of correlations and fluctuations can provide information about **early stages of heavy-ion collisions.**

Motivation: Why do we study correlations and fluctuations?

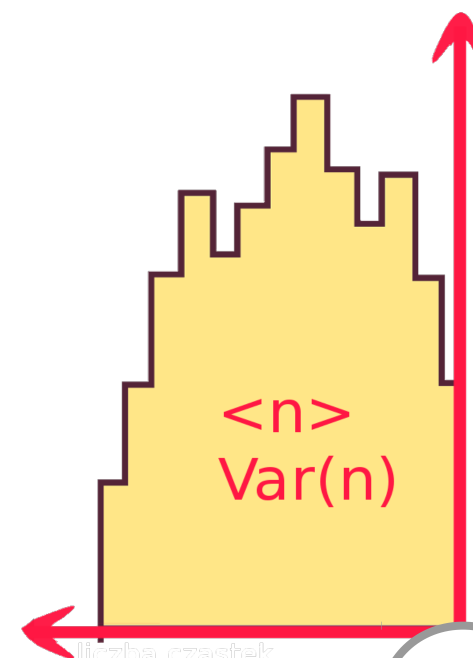


1. Study of **Long-Range Correlations** (LRC):

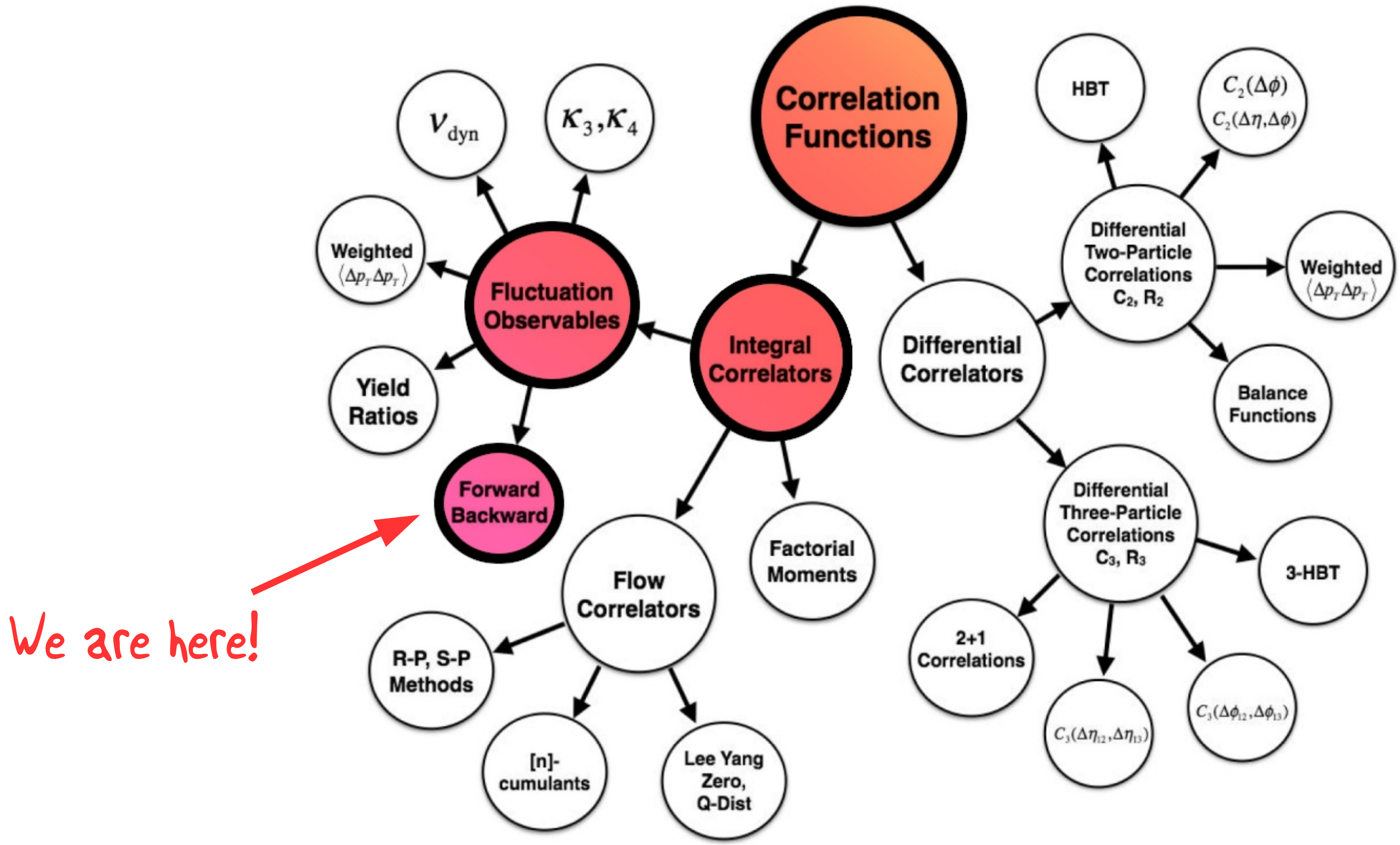
   - LRC carry **information** on the **early dynamics** of the nuclear collision.

2. Analysis of **fluctuations** in the number of particles produced in nucleus-nucleus collisions:

   - A good way to check dynamical models of particle production.
   - Gives a chance to study observables sensitive to the early dynamics of the collision, independent of trivial fluctuations of the volume of the system.



The Analysis: How do we study correlations and fluctuations?

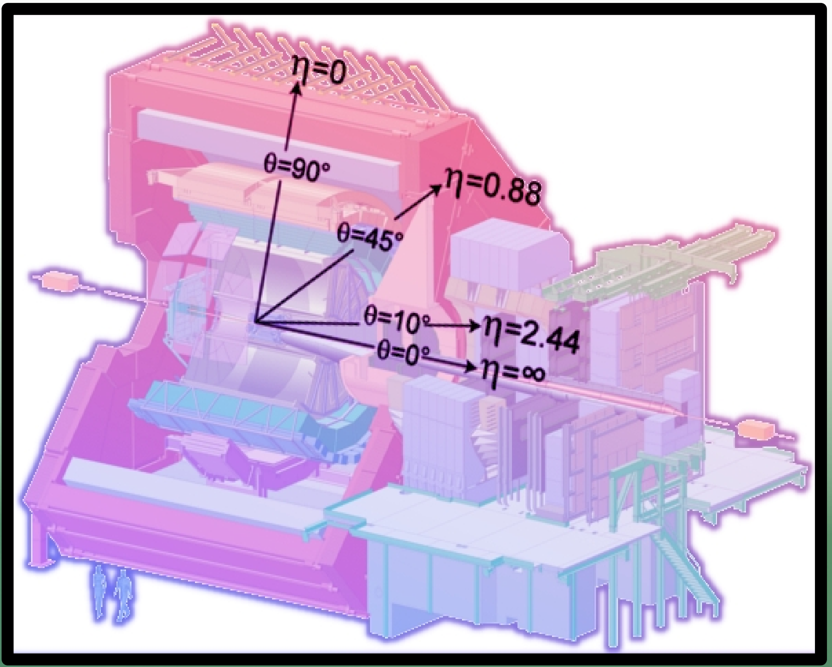


Picture from: Claude A. Pruneau, Data Analysis Techniques for Physical Scientists, 2017, Cambridge University Press.

The Analysis: How do we study correlations and fluctuations?

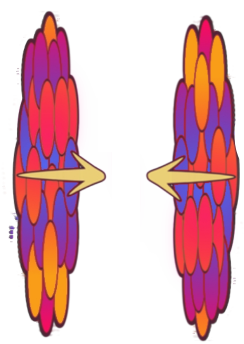
Analysis of correlations and fluctuations as a function of :

pseudorapidity η



$\eta = -\ln[\tan(\theta/2)]$

centrality [%] & centrality bin width



central

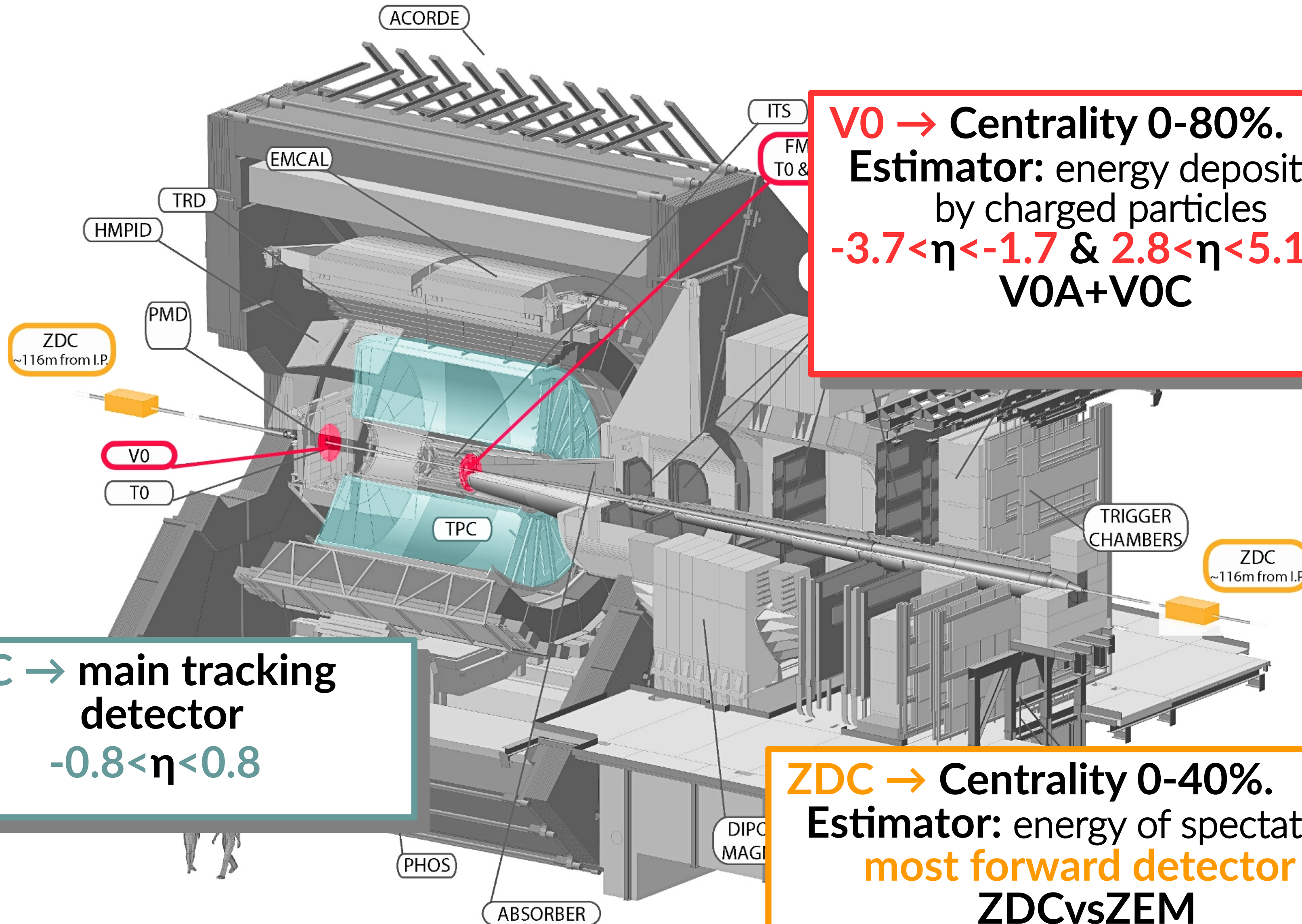
centrality class:
0-10%→ ΔCent.=10%
4.5-5.5%→ ΔCent.=1%

peripheral

centrality class:
70-80%→ ΔCent.=10%
74.5-75.5%→ ΔCent.=1%

Examples of estimators: $N_{charged}$, N_{part}

The Analysis: ALICE experiment



V0 → Centrality 0-80%.
Estimator: energy deposition by charged particles
$-3.7<\eta<-1.7$ & $2.8<\eta<5.1$
V0A+V0C

TPC → main tracking detector
$-0.8<\eta<0.8$

ZDC → Centrality 0-40%.
Estimator: energy of spectators
most forward detector
ZDCvsZEM

The Analysis: Data Sample

Experimental data:

→ Pb-Pb @ $\sqrt{s_{NN}}$= 2.76 TeV (approved)
→ Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV (ongoing)
→ Xe-Xe @ $\sqrt{s_{NN}}$ = 5.44 TeV (ongoing)

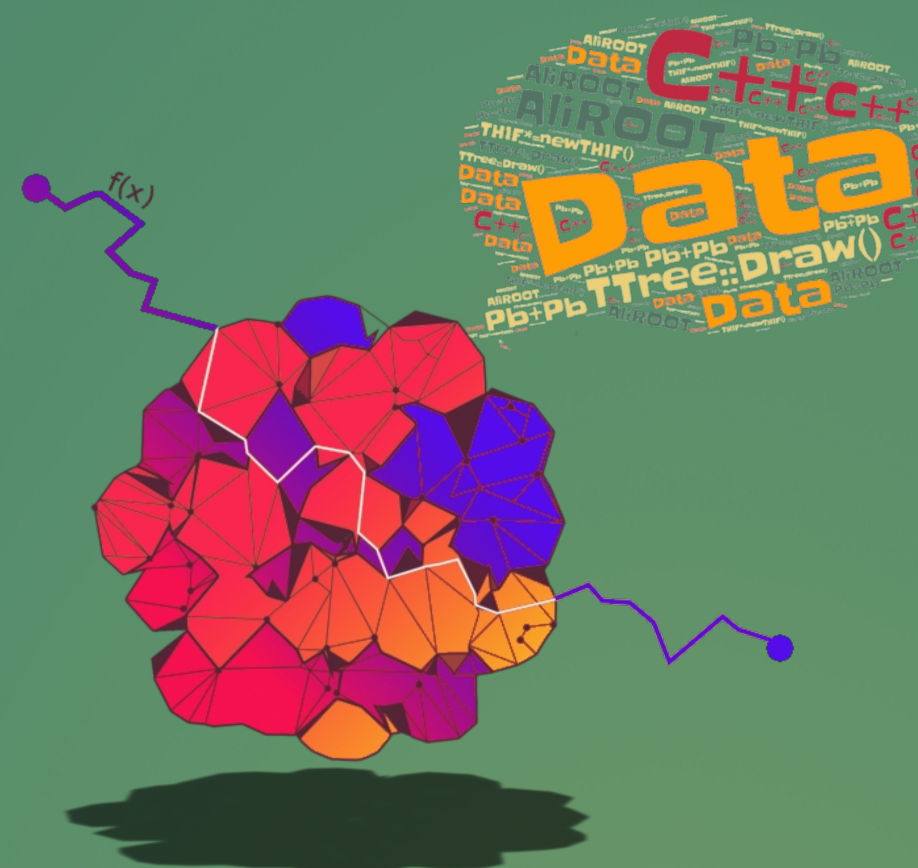
Tracks: $-0.8<\eta<0.8$, $p_T>0.2$ GeV/c
$0.2 < p_T < 5$ GeV/c

Centrality estimators: V0 ($N_{charged}$),
ZDC (N_{part})

MC simulations:

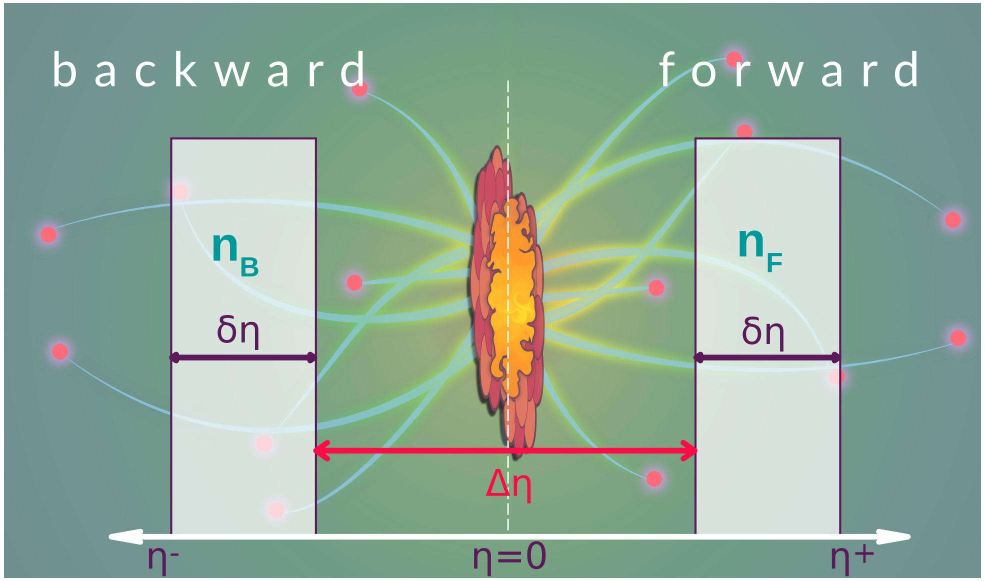
MC HIJING

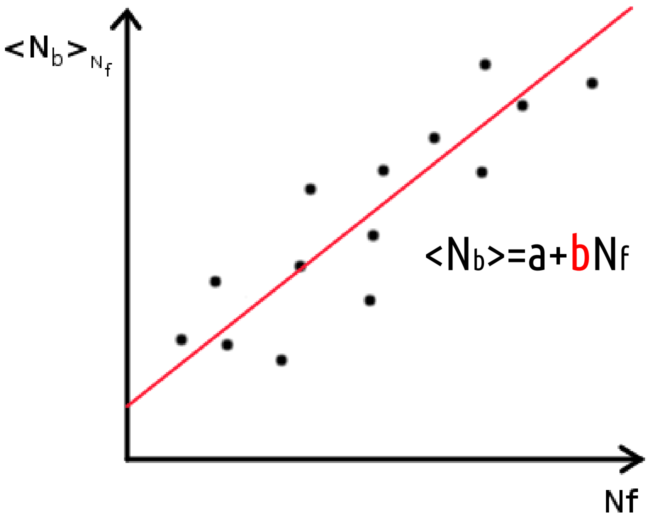
- Pb-Pb @ $\sqrt{s_{NN}}$=2.76 TeV
  Tracks: $-0.8<\eta<0.8$, $p_T>0.2$ GeV/c
  Centrality:
  → estimated by impact parameter
  → estimated by V0



Forward-Backward Correlations

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



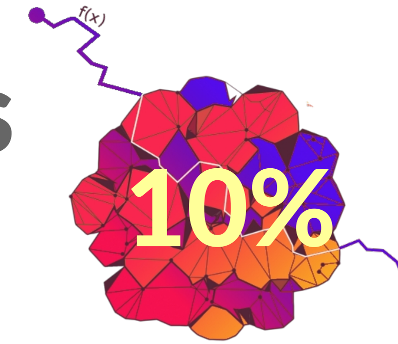


SRC
Δη<1

LRC
Δη>1

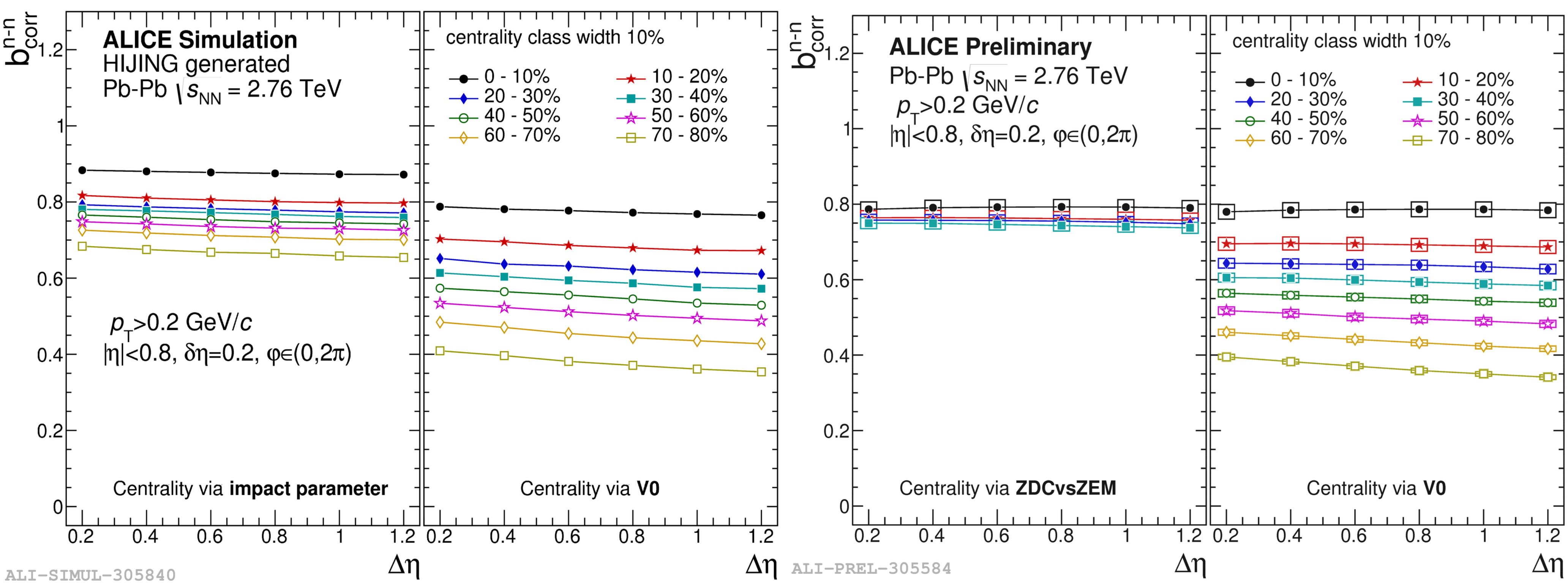
Challenge → "depends on everything":
- Dynamics (SRC+LRC) ;
- "trivial" system size (~N_{part}) ;
- "trivial" system volume fluctuations
(→ dependence on centrality bin width).

Forward-Backward Correlations



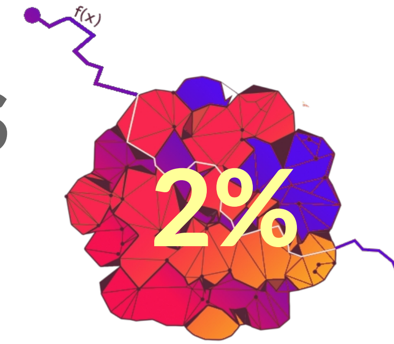
MC simulations

Experimental data



- **Large values of b_{corr}** but large centrality bin width → **large volume (N_{part}) fluctuations** within a single bin of selected centrality.

Forward-Backward Correlations



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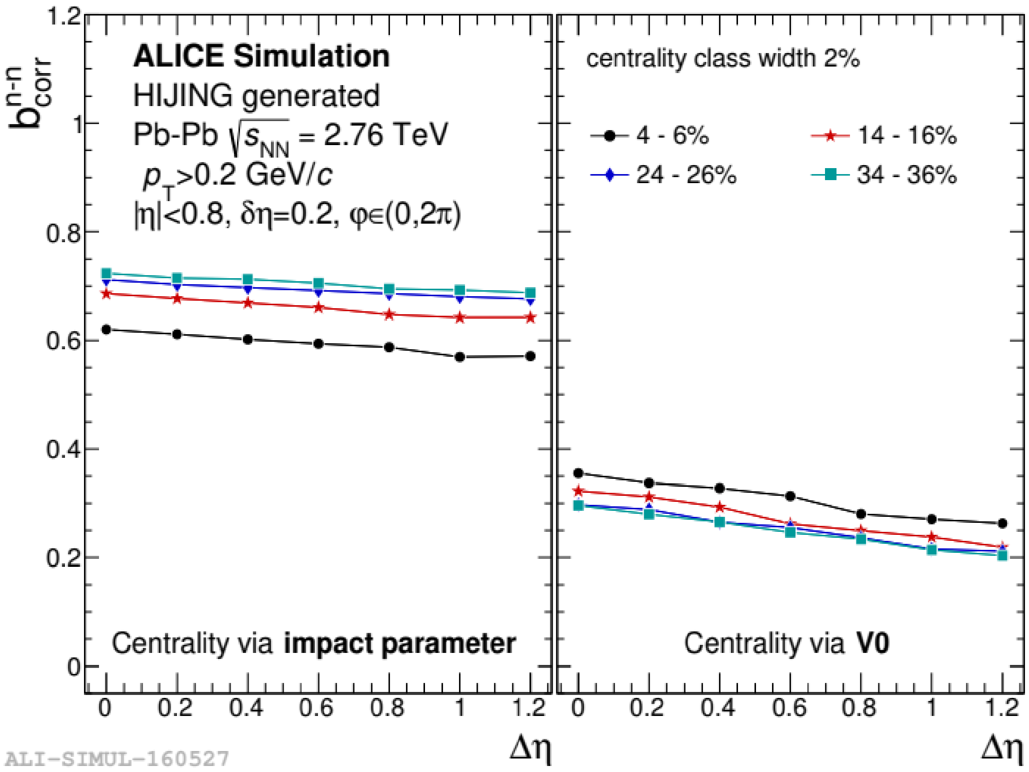
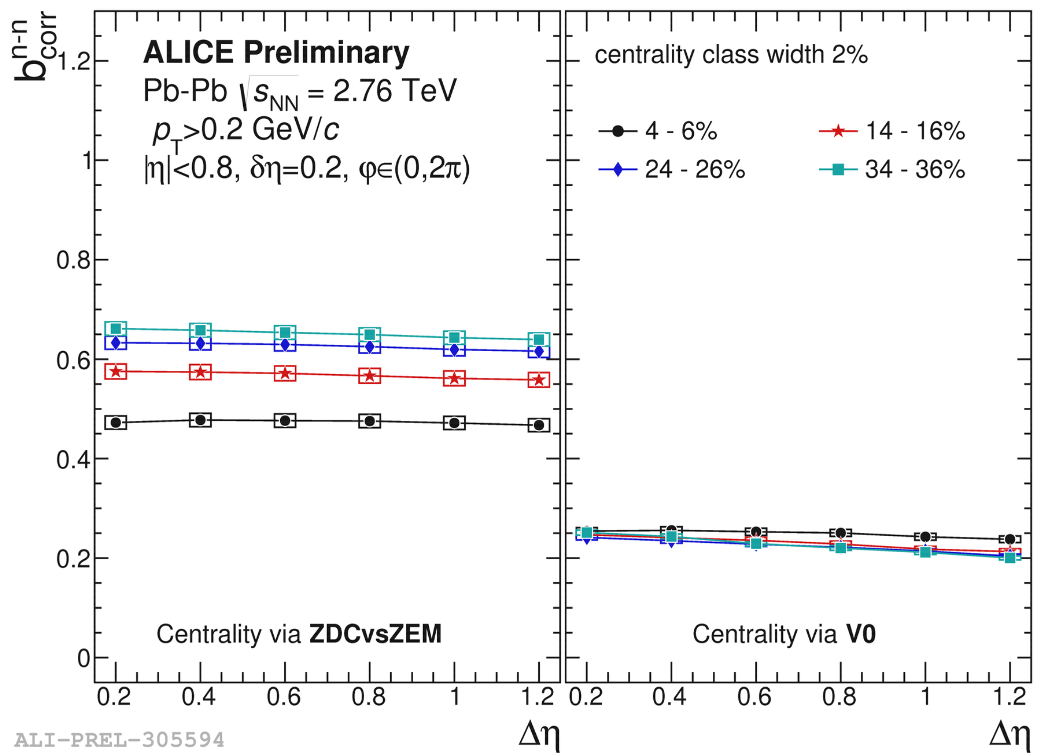




centrality bin width: 10% → 2%:

- dependence on centrality estimator;
- drop of the value of b_{corr} (because of reduced fluctuations of N_{part}).

Forward-Backward Correlations

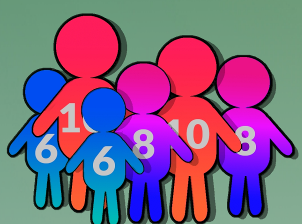
Understanding the effect of geometrical fluctuations on b_{corr}:

Schoolchildren

W. Krzanowski, Principles of Multivariate Analysis, Oxford U. Press, 2000

b_{corr}(**weight, IQ**) ≈ 0.62

Large values of correlations

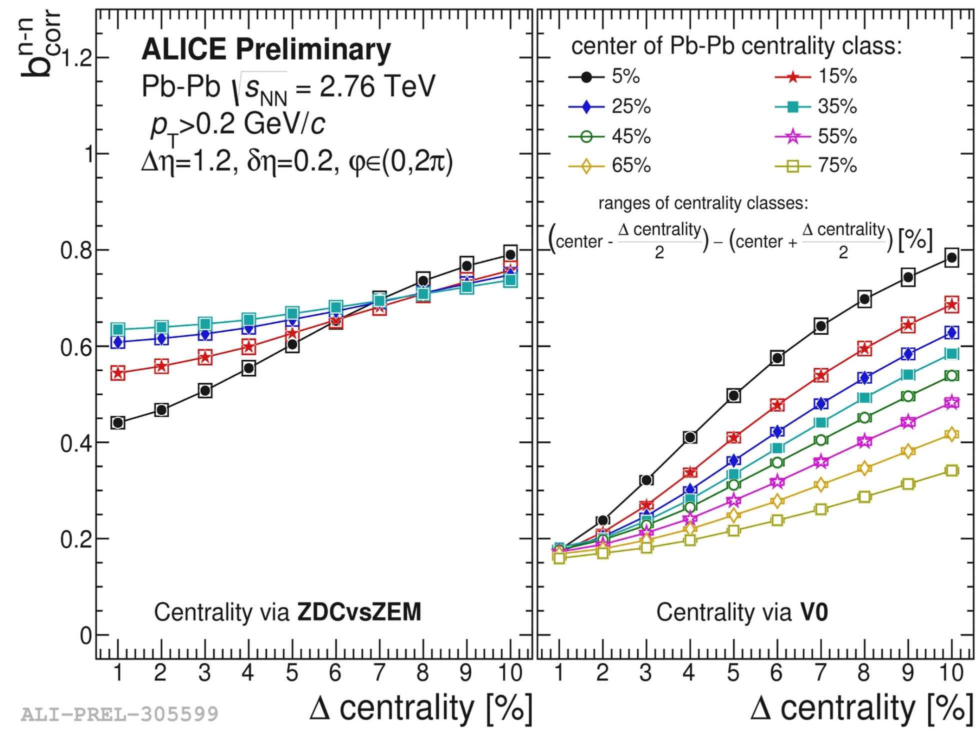


age fluctuations

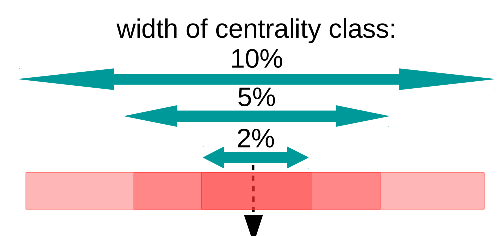
Spurious effect of **external variable** leads to absurd conclusions!

Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0



increase of volume fluctuations



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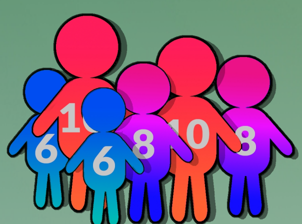

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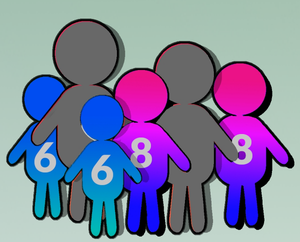
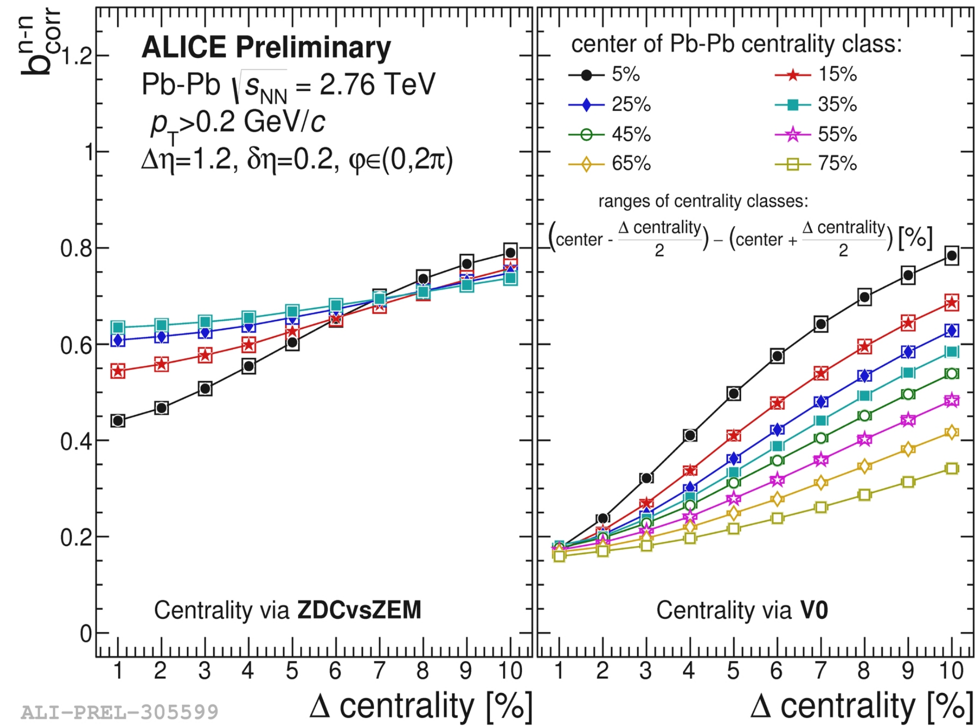
reduce fluctuation



strict age selection

Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0



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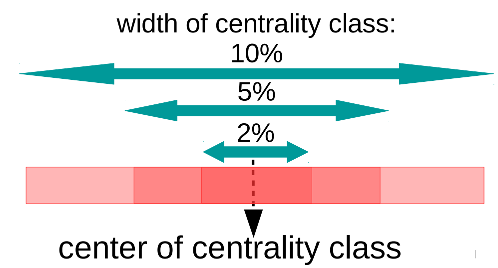

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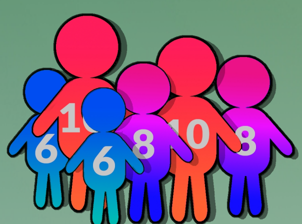
Heavy-ion collisions

sample of most central Pb-Pb events

$b_{corr}(n_B, n_F) \approx 0.8$

Large values of correlations



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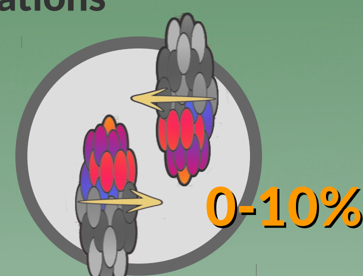
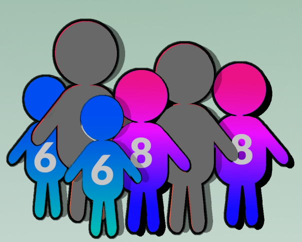


event geometrical fluctuations

Spurious effect of **external variable** leads to absurd conclusions!

reduce fluctuation



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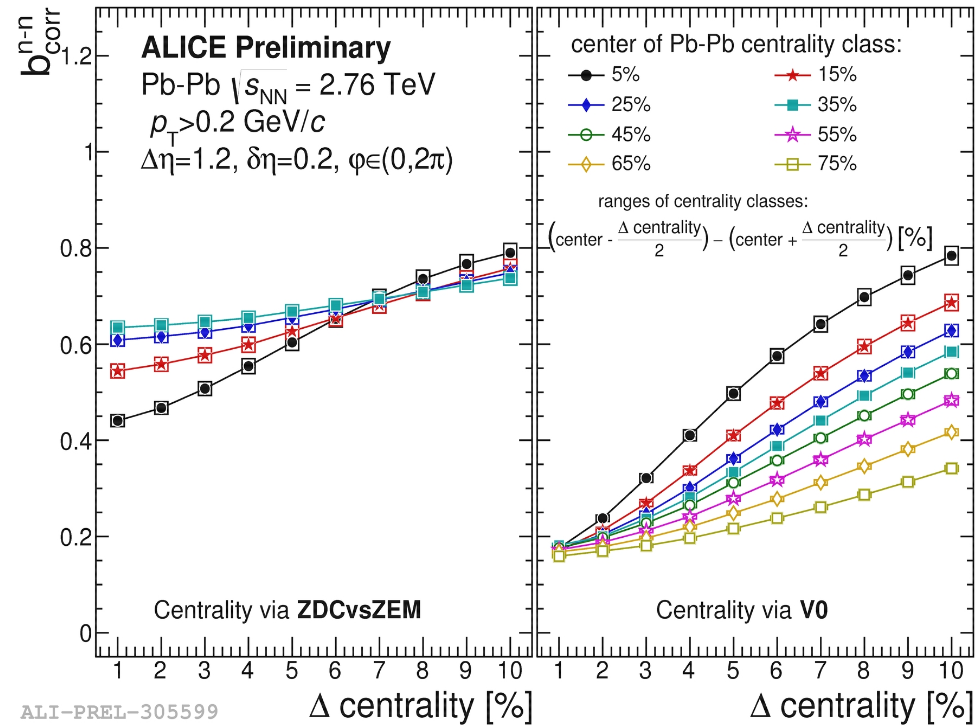

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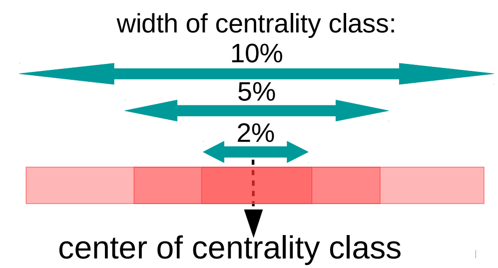

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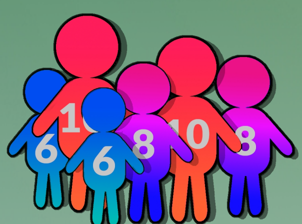

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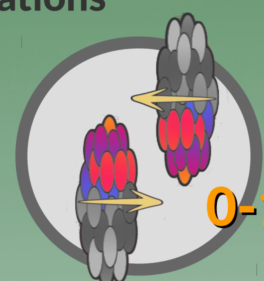

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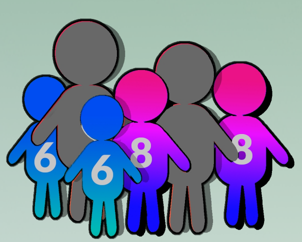
reduce fluctuation



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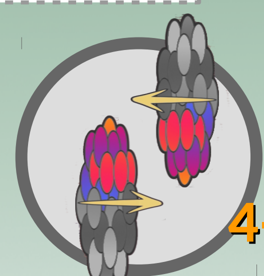
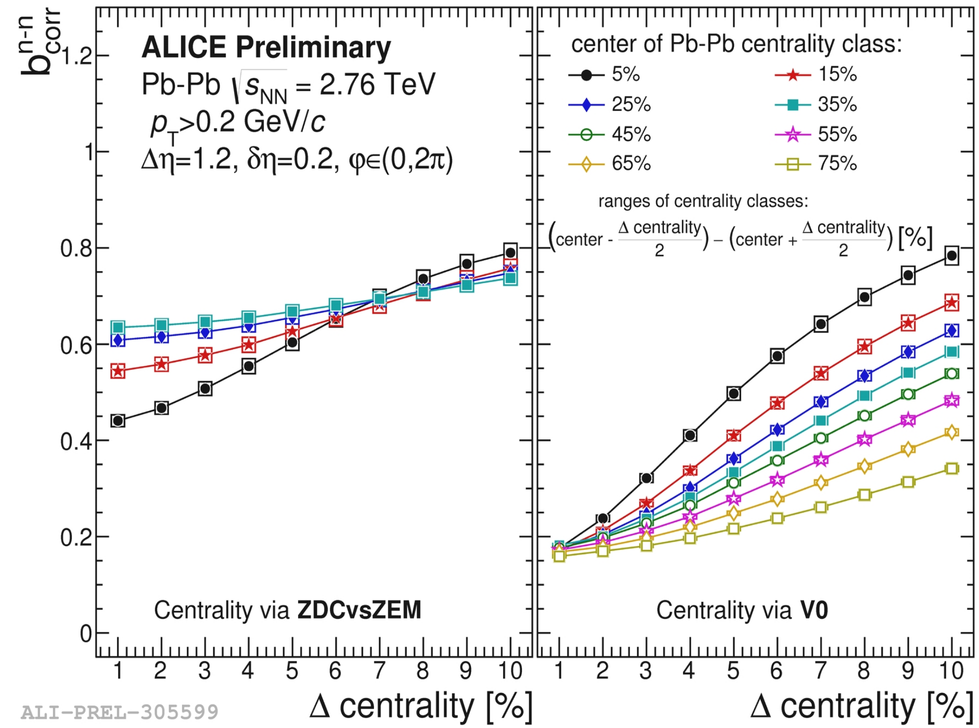


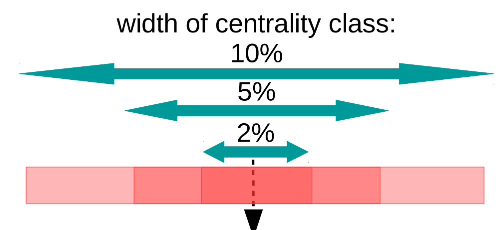
narrow centrality classes

Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0



increase of volume fluctuations



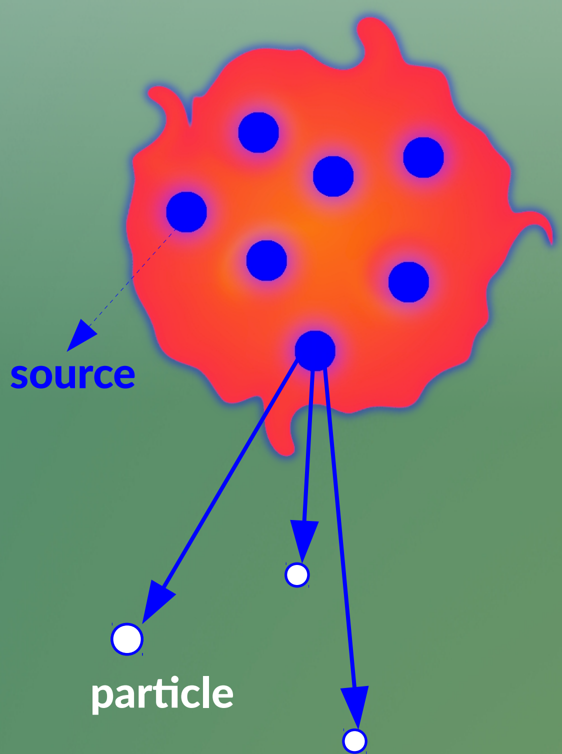
Strongly intensive quantities

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

Intensive quantities do not depend on system volume.

Scaled variance: $\omega_{B(F)} = \frac{Var(n_{B(F)})}{\langle n_{B(F)} \rangle}$

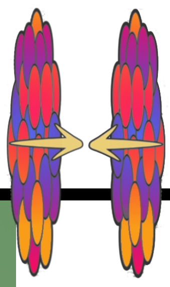
Independent source model:



Strongly Intensive quantities do not depend on system volume nor system volume fluctuations (i.e. Var(N_s),ω_s) → Σ

$$\Sigma = \frac{1}{\langle n_B \rangle + \langle n_F \rangle} [\langle n_F \rangle \omega_B + \langle n_B \rangle \omega_F - 2\, Cov(n_F, n_B)]$$

For a symmetric collision, like Pb-Pb:



$\omega_B = \omega_F$ and $\langle n_F \rangle = \langle n_B \rangle$

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

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

Strongly intensive quantities

→ Σ **does not depend** on centrality estimator;

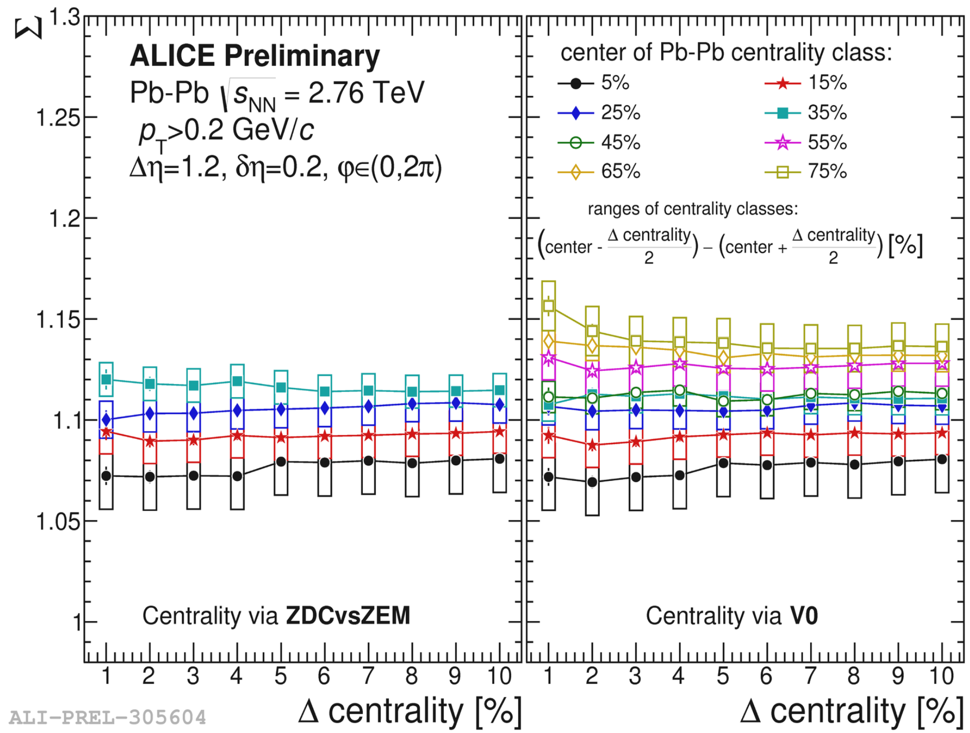
+

→ Σ **does not depend** on centrality bin width;

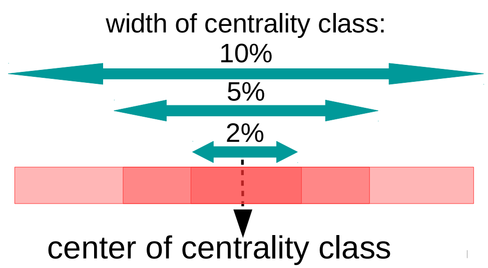
Σ indeed shows the properties of a strongly intensive quantity

Centrality estimator: spectators in ZDC

Centrality estimator: charged particles in V0

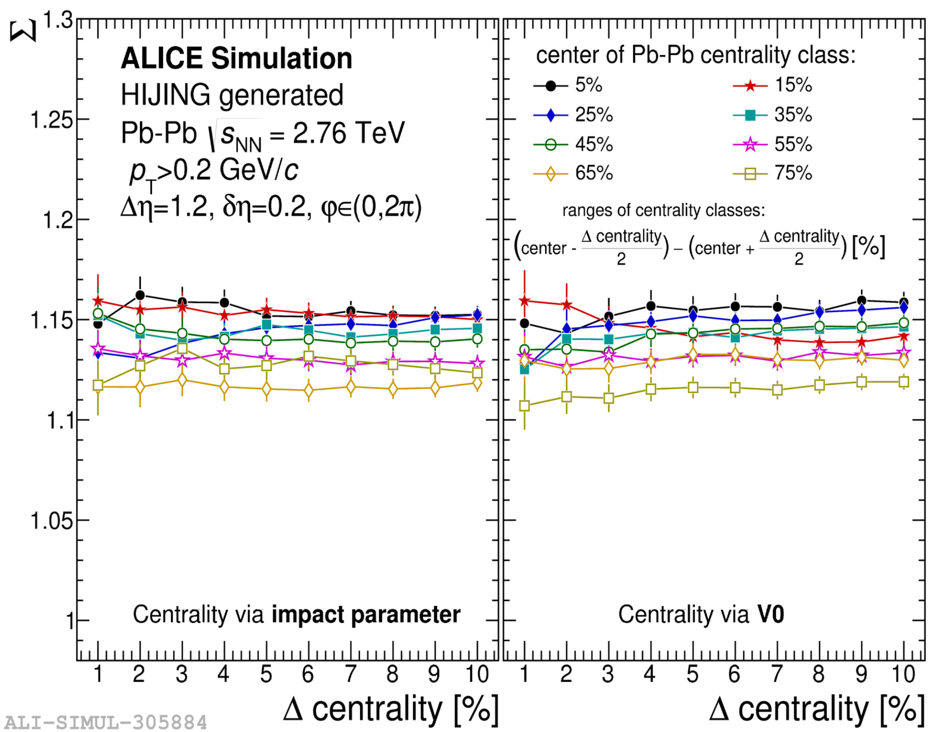


increase of volume fluctuations



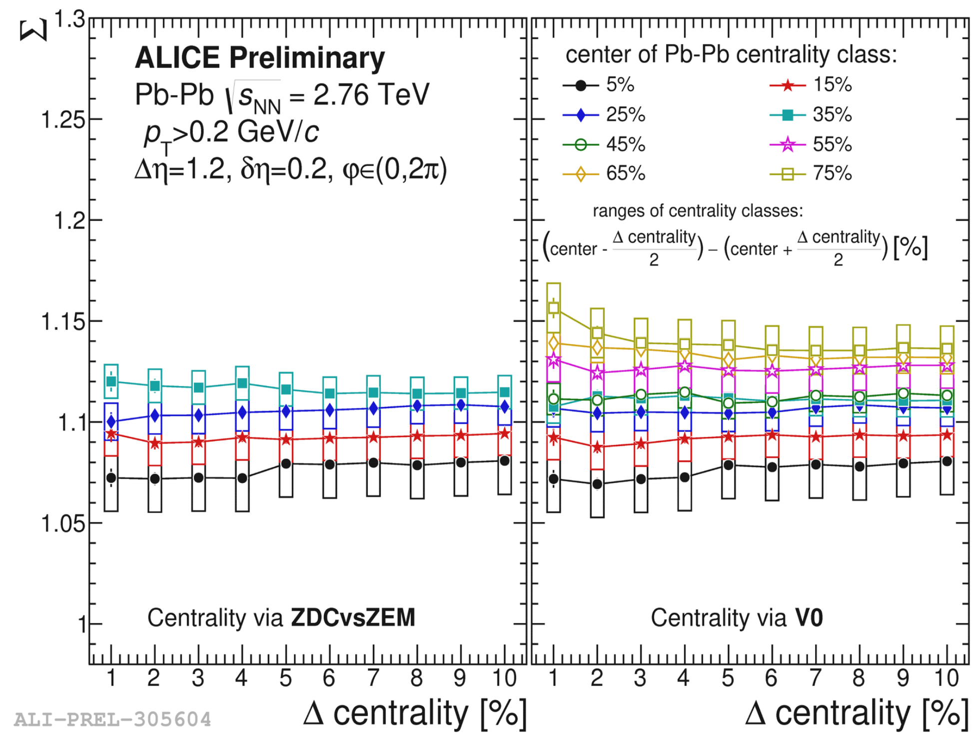
Strongly intensive quantities

MC simulations



increase of volume fluctuations

Experimental data



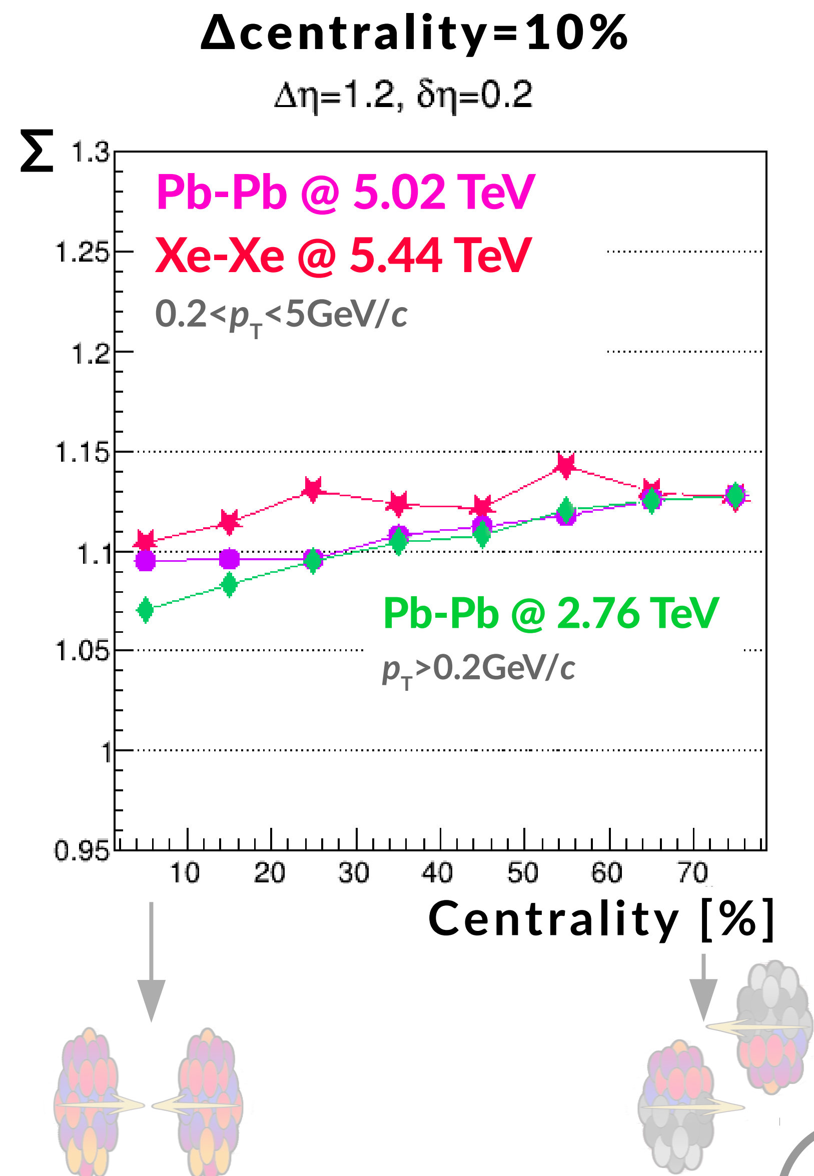
increase of volume fluctuations

- Σ provides direct information about particle production from single averaged source;
- Different ordering of the values of Σ with centrality→ possible hint about the early dynamics?

Strongly intensive quantities

→ **Pb-Pb @5.02TeV** show **reasonable** ordering of Σ with centrality.

→ **Xe-Xe @ 5.44TeV show** dependence on centrality in agreement with **Pb-Pb @ 2.76 TeV**.



Next step: Analysis of strongly intensive quantities for identified particles.

Forward-Backward Partial Correlations

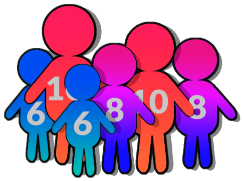
A. Olszewski, W. Broniowski, Phys.Rev.C 96 (2017) 5, 054903

The **partial correlation** measures the degree of association between two random variables **X,Y** with the effect control random variable Z **removed**.

$$b_{corr}^{part}(X, Y \cdot Z) = \frac{Cov(X, Y \cdot Z)}{\sqrt{Var(X \cdot Z) Var(Y \cdot Z)}}$$

Schoolchildren

W. Krzanowski, Principles of Multivariate Analysis, Oxford U. Press, 2000



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

Z =**age**

b_{corr}^{part}(weight, IQ• **age**) ≈ 0.02!

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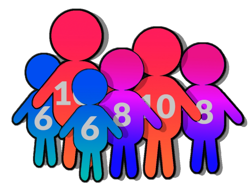

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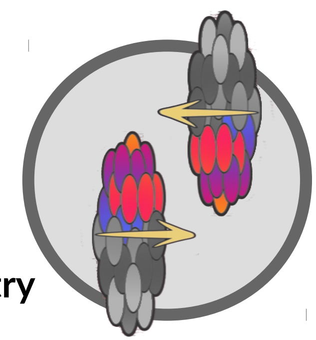
Heavy-ion collisions



$b_{corr}(n_B, n_F) \approx 0.8$

Z =event geometry

$b^{part}_{corr}(n_B, n_F$ • event geometry$) \approx$?

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$b^{part}_{corr}(n_B, n_F$ • Z= event geometry$)$ ≈ ?

event geometry
- i.e. **centrality via V0**
- and/or
- **centrality via ZDCvsZEM**

Schoolchildren

W. Krzanowski, Principles of Multivariate Analysis, Oxford U. Press, 2000

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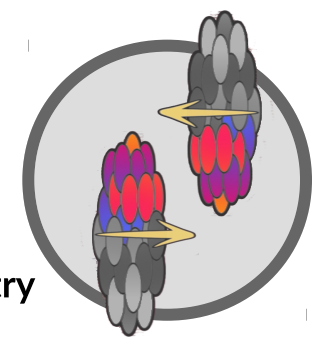
Heavy-ion collisions



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$b^{part}_{corr}(n_B, n_F$ • event geometry$)$ ≈ ?

Forward-Backward Partial Correlations

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The **partial correlation** measures the degree of association between two random variables **X,Y** with the effect control random variable **Z removed**.

$$b_{corr}^{part}(X, Y \cdot Z) = \frac{Cov(X, Y \cdot Z)}{\sqrt{Var(X \cdot Z) Var(Y \cdot Z)}}$$

$b_{corr}^{part}(n_B, n_F \bullet Z = \text{event geometry}) \approx ?$

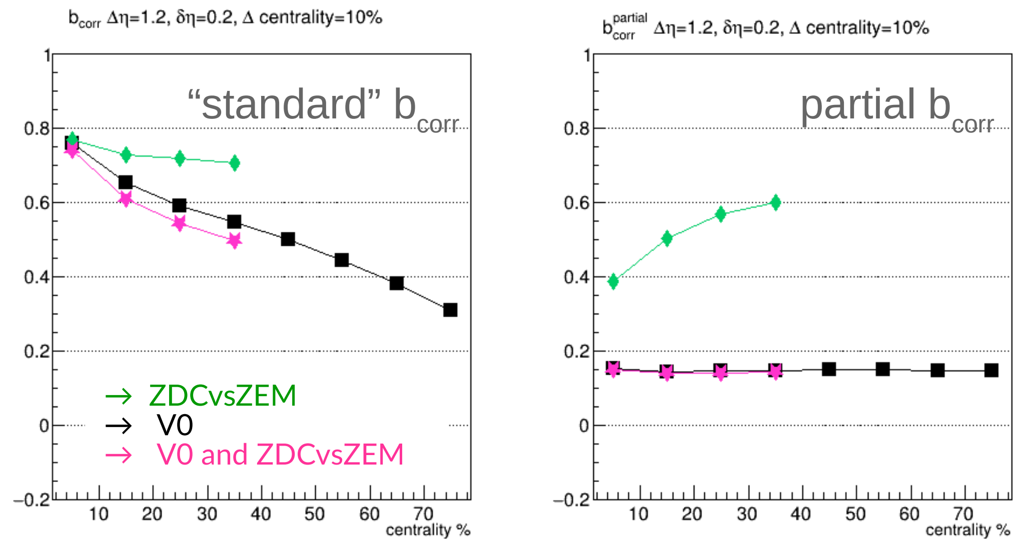
event geometry

i.e. **centrality via V0**

and/or

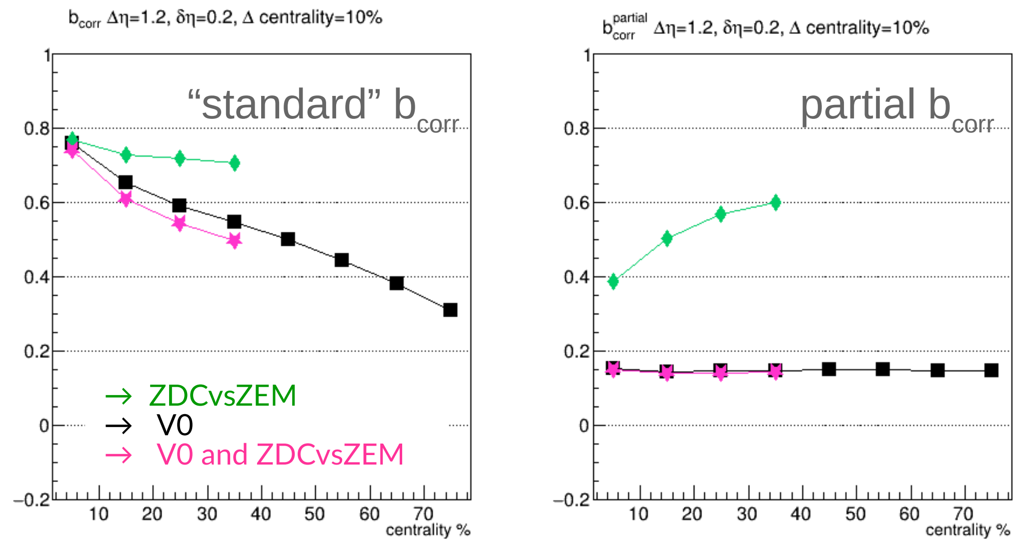
centrality via ZDCvsZEM

Δcentrality=10%



Forward-Backward Partial Correlations

Δcentrality=10%



- For wide centrality classes $b_{corr} > b_{corr}^{partial}$.
- The $b_{corr}^{partial}$ depend on the way centrality was selected (!).

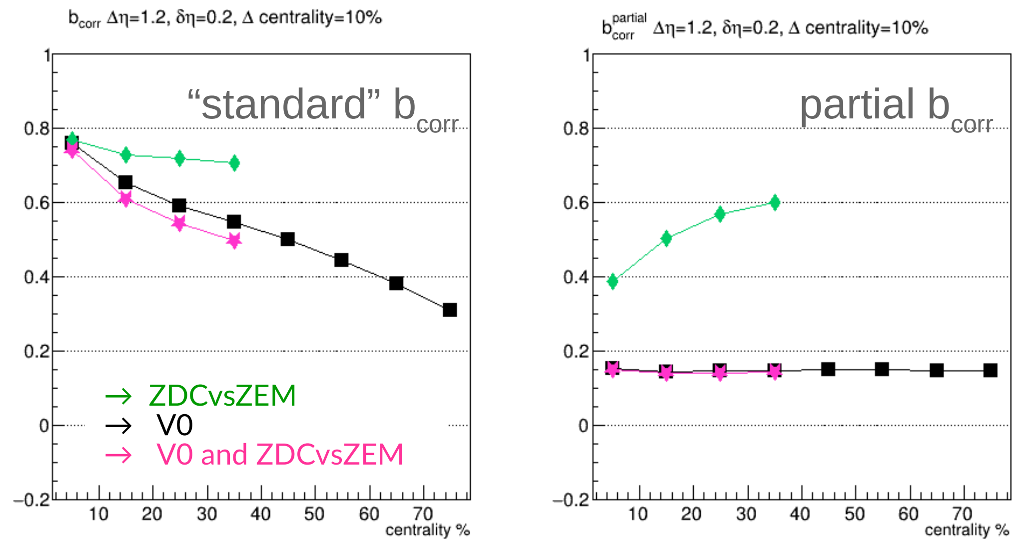
Next step: partial correlation between sources $b_{corr}^{part}(S_B, S_F \bullet S_c) \rightarrow$ *A. Olszewski, W. Broniowski, Phys.Rev.C 96 (2017) 5, 054903*

Forward-Backward Partial Correlations

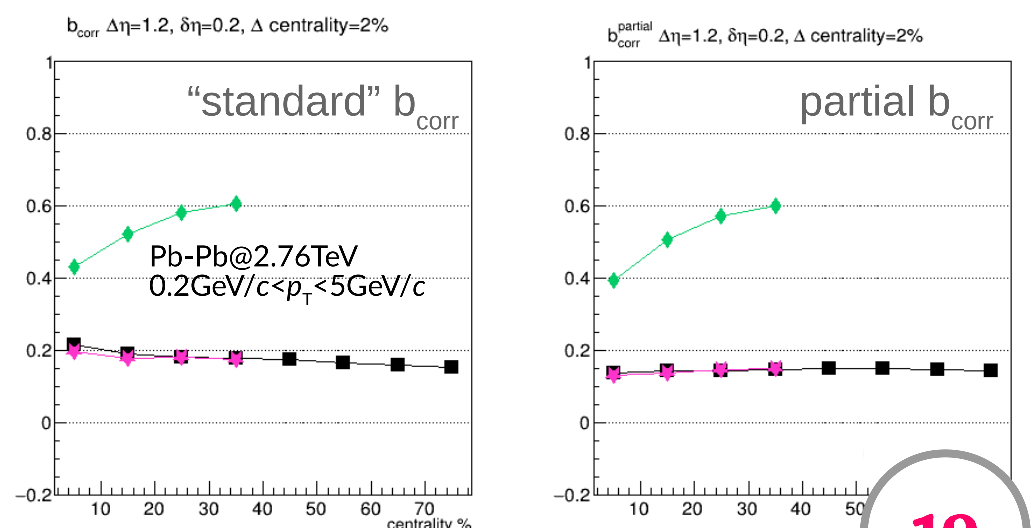
- For wide centrality classes $b_{corr} > b_{corr}^{partial}$.
- The $b_{corr}^{partial}$ depend on the way centrality was selected (!).

- The $b_{corr}^{partial}$ **independent** on centrality bin width.

Δcentrality=10%



Δcentrality=2%



Next step: partial correlation between sources $b_{corr}^{part}(S_B, S_F \bullet S_c) \rightarrow$ *A. Olszewski, W. Broniowski, Phys.Rev.C 96 (2017) 5, 054903*

Forward-Backward Partial Correlations

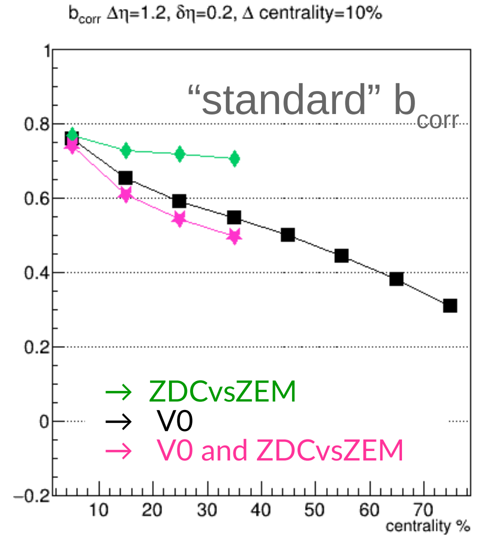
- For wide centrality classes $b_{corr} > b_{corr}^{partial}$.
- The $b_{corr}^{partial}$ depend on the way centrality was selected (!).

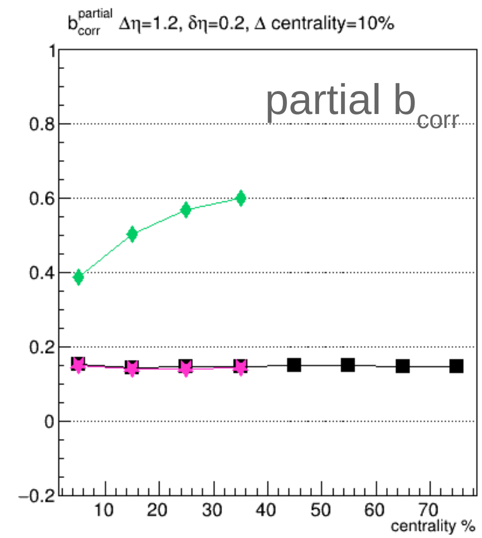
- The $b_{corr}^{partial}$ **independent** on centrality bin width.

- "Standard" $b_{corr} \approx b_{corr}^{partial}$ → **for very narrow** centrality bin width.
- No problems with low multiplicity samples.

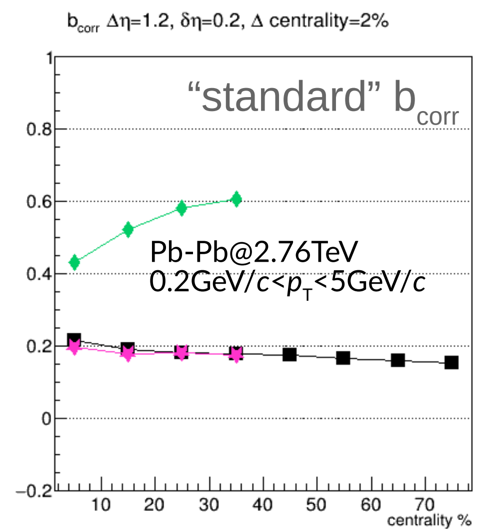
Next step: partial correlation between sources $b_{corr}^{part}(S_B, S_F \bullet S_c) \rightarrow$ *A. Olszewski, W. Broniowski, Phys.Rev.C 96 (2017) 5, 054903*

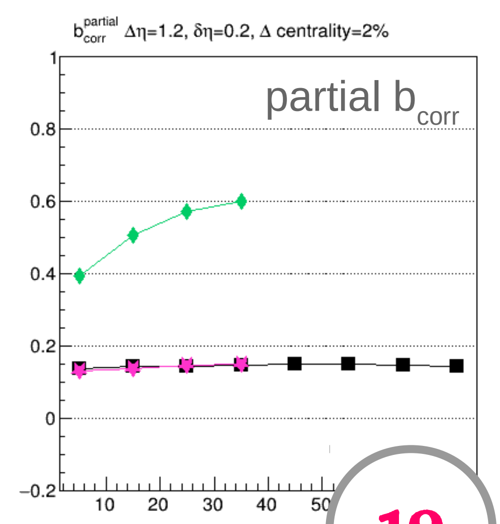
Δcentrality=10%





Δcentrality=2%





Summary

We obtained new data on forward-backward correlations; this was a first attempt at measurement of strongly intensive quantities and forward-backward partial correlations at the LHC:

1. The b_{corr} coefficient:

   → shows large dependence on centrality bin width and estimator!

   → provides information on early dynamics **which is mixed** with trivial geometrical fluctuations.

2. The Σ observable :

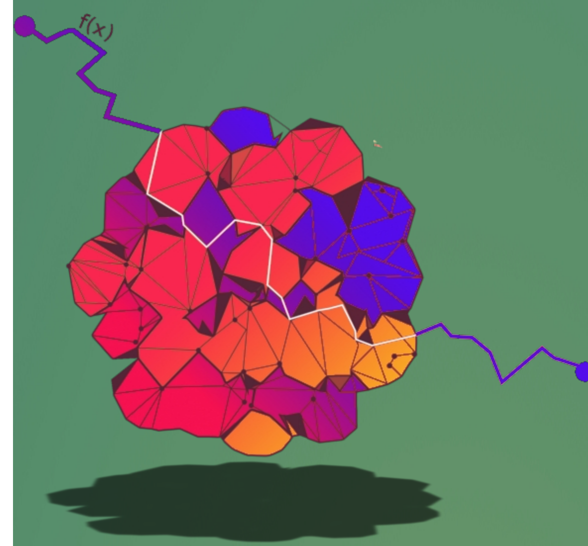
   → shows a deviation from unity;

   → **exhibits properties of strongly intensive quantity;**

   → independent source model? → info about average source → direct probe for phenomenological models.

3. Partial correlations:

   → methodology indeed eliminates spurious correlations induced by (trivial) external variables like system volume, leaving out only the "true" dynamics.



THANK YOU!

Backup

Strongly Intensive quantities:

1. M. I. Gorenstein, M. Gazdzicki, **Phys.Rev. C84 (2011) 01490**, https://arxiv.org/abs/1101.4865

Partial correlation in heavy-ion collisions:

2. A. Olszewski and W. Broniowski, *“Partial Correlation Analysis Method in Ultrarelativistic Heavy-Ion Collisions”*, **Physical Review C 96.5 (2017)**, https://arxiv.org/pdf/1706.02862.pdf

Influence of geometry fluctuation on correlation measurement:

3. A. Bzdak, **Physical Review C 80.2 (2009)**, https://arxiv.org/pdf/0902.2639.pdf
4. Konchakovski, V. P. et al. *“Forward-Backward Correlations in Nucleus-Nucleus Collisions: Baseline Contributions from Geometrical Fluctuations”*, **Physical Review C 79.3 (2009)**, https://arxiv.org/pdf/0812.3967.pdf
5. I.Sputowska, *“Forward-Backward Correlations and Multiplicity Fluctuations in Pb–Pb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV from ALICE at the LHC”*, **Proceedings 2019, 10, 14**, https://doi.org/10.3390/proceedings2019010014

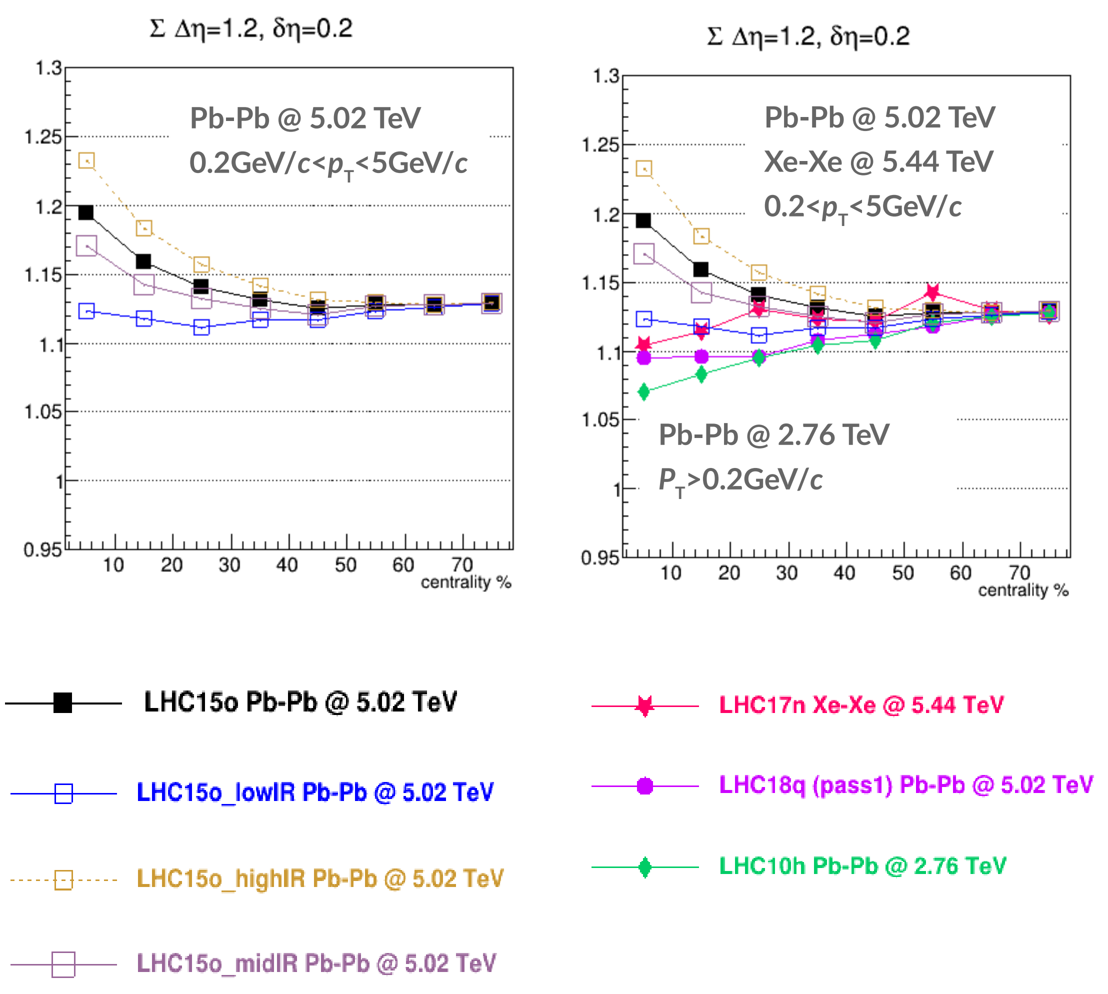
Strongly intensive quantities

→ 2015 data (LHC15o) **depend on IR**.

→ **Pb-Pb LHC18q** show **reasonable** ordering of Σ with centrality.

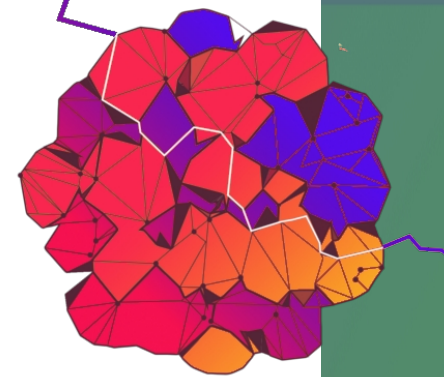
→ **Xe-Xe @ 5.44TeV show** dependence on centrality in agreement with **Pb-Pb @ 2.76 TeV**.

Σ, Δcentrality=10%



Next step: Analysis of strongly intensive quantities for identify particle species.

Backup



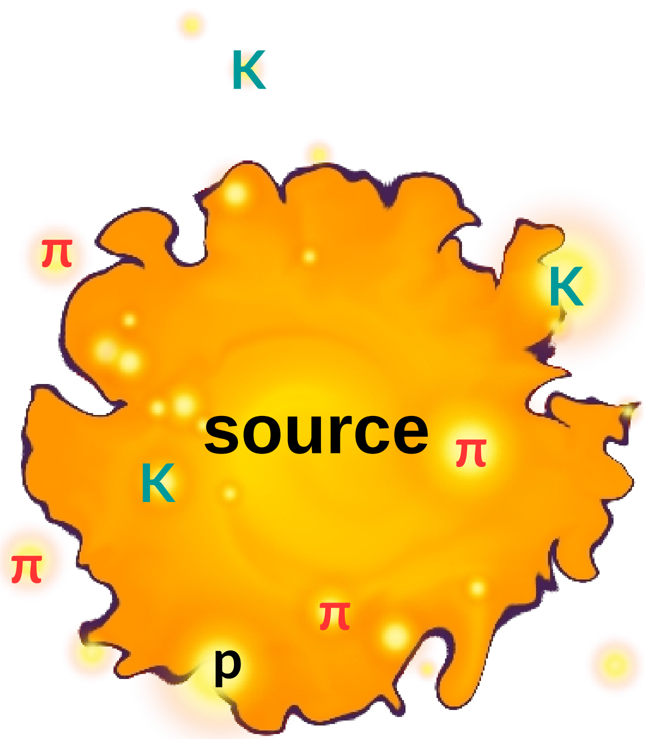
https://indico.cern.ch/event/786203/

Strongly intensive quantity Σ

→ Strongly Intensive quantities do not depend on system volume and system volume fluctuations (i.e. Var(N_s),ω_s);

$$\Sigma=\frac{1}{\langle n_B\rangle+\langle n_F\rangle}\left[\langle n_F\rangle\omega_B+\langle n_B\rangle\omega_F-2\,\mathrm{Cov}(n_F,n_B)\right]=\frac{1}{\langle n_b\rangle+\langle n_f\rangle}\left[\langle n_f\rangle\omega_b+\langle n_b\rangle\omega_f-2\,\mathrm{Cov}(n_f,n_b)\right]$$

If understood as „components of ∑", these would be all characteristics of the single (average!) source distribution



= <initial sources, resonances , etc.>

Different particle species have different contribution form resonances → **protons, for instance (**no resonance x → pp**)**

Systematic uncertainties

TPC only tracks & hybrid tracks

There are 6 main sources of systematic uncertainties taken into account in this analysis:

(a) time/run dependence → <0.5%

→ averaged deflection of measured quantity in a run-by-run analysis from the value obtained from the total data sample;

(b) the multiplicity distribution tail cut and the presence of the tail under the multiplicity distribution → <0.8%

→averaged influence of varying the cut on tail in multiplicity distribution on measured observables.

(c) chosen data correction method & MC closure → <1.2%

(d) chosen track cuts (TPC only vs hybrid tracks)→ <2.3%

(e) material budget → insignificant;

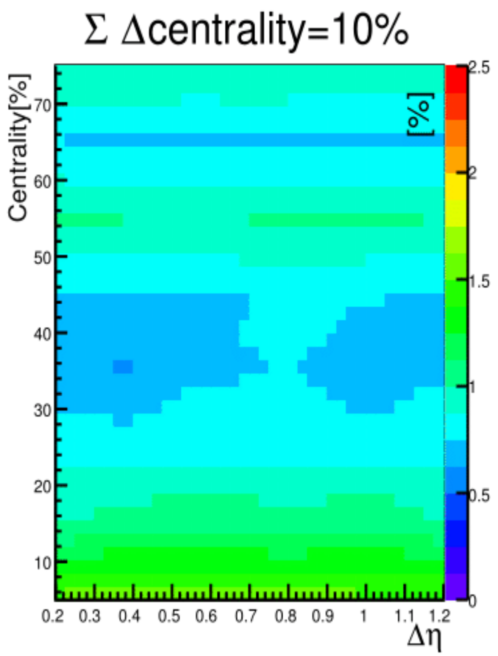
(f) fluctuations of correction factors<1.2%

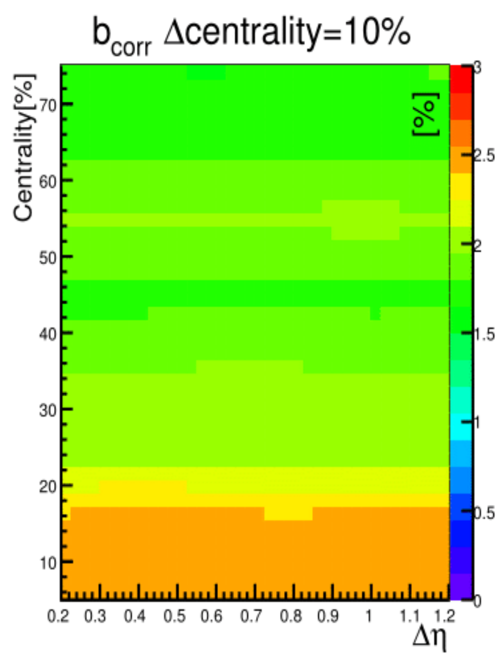
Given systematic uncertainties were averaged over centrality bin widths (Δcent$\geq$ 5%) for given centrality class and over eta gap in range $0.2 \leq \Delta \leq 1.2$.

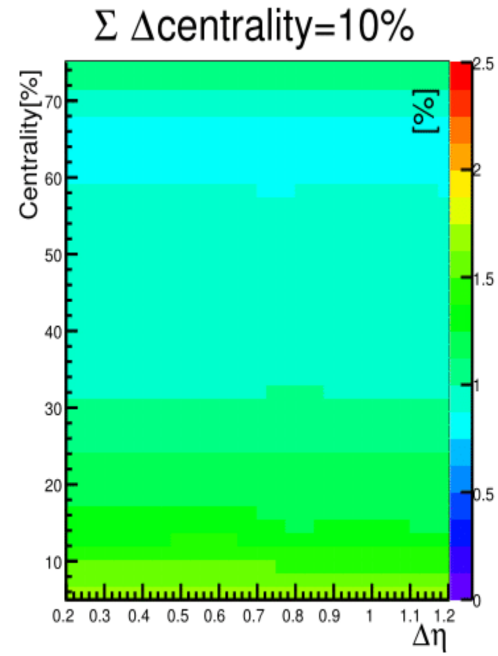
Total systematic error: partial systematic errors added in square.

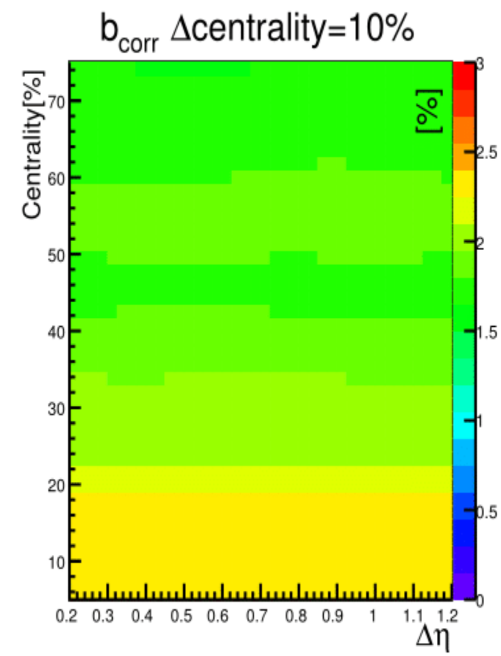
Systematic uncertainties

Total systematics map:



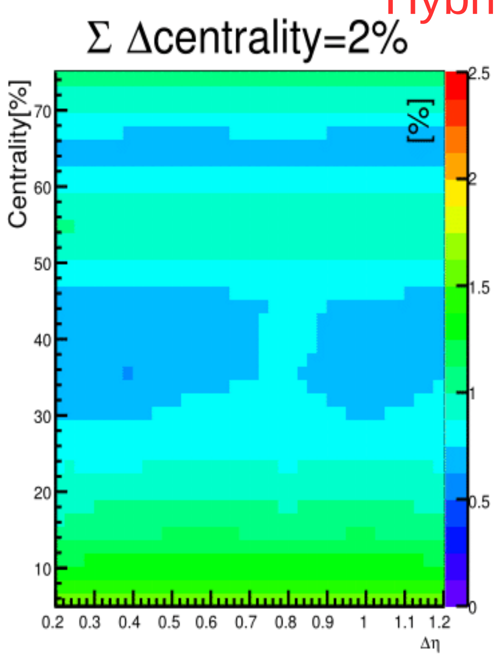


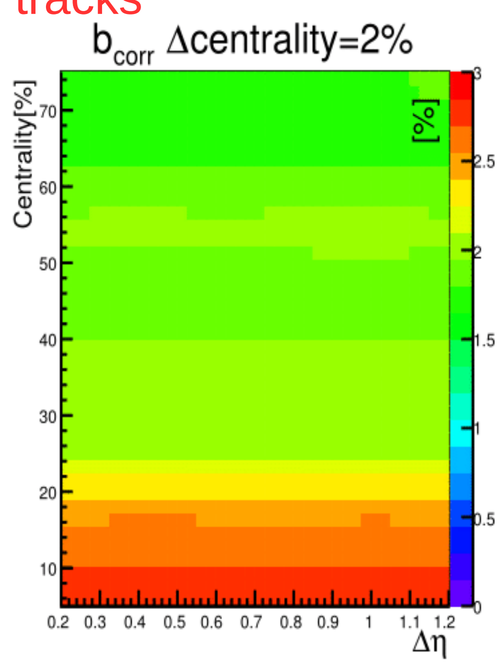


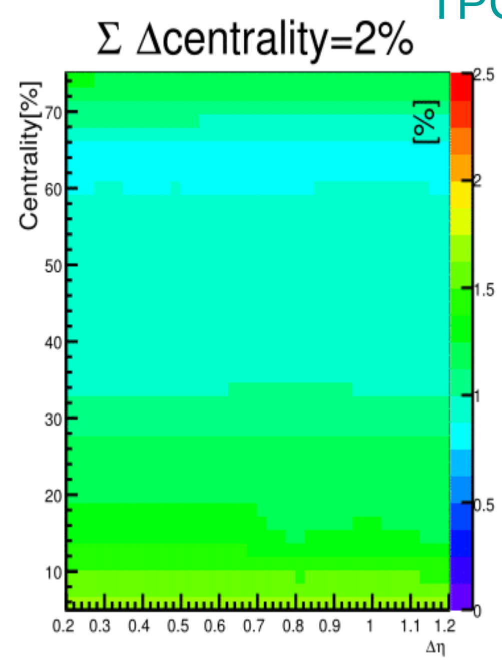


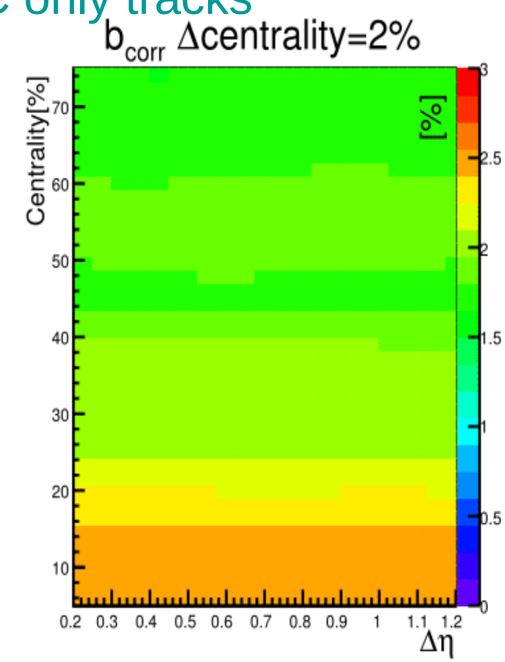
Hybrid tracks

TPC only tracks

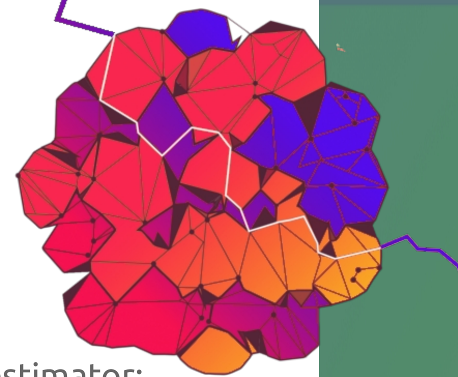






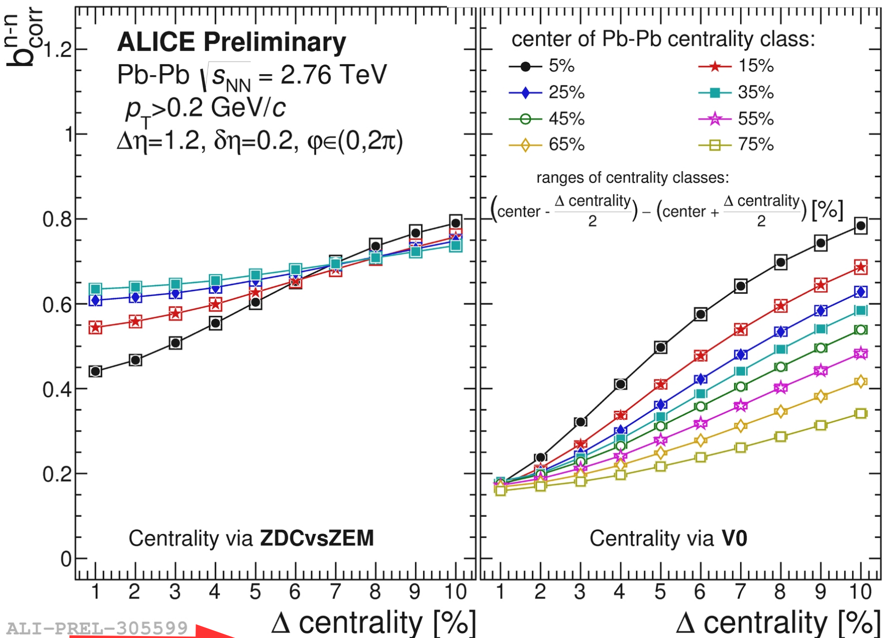


Backup



Centrality estimator: spectators in ZDC

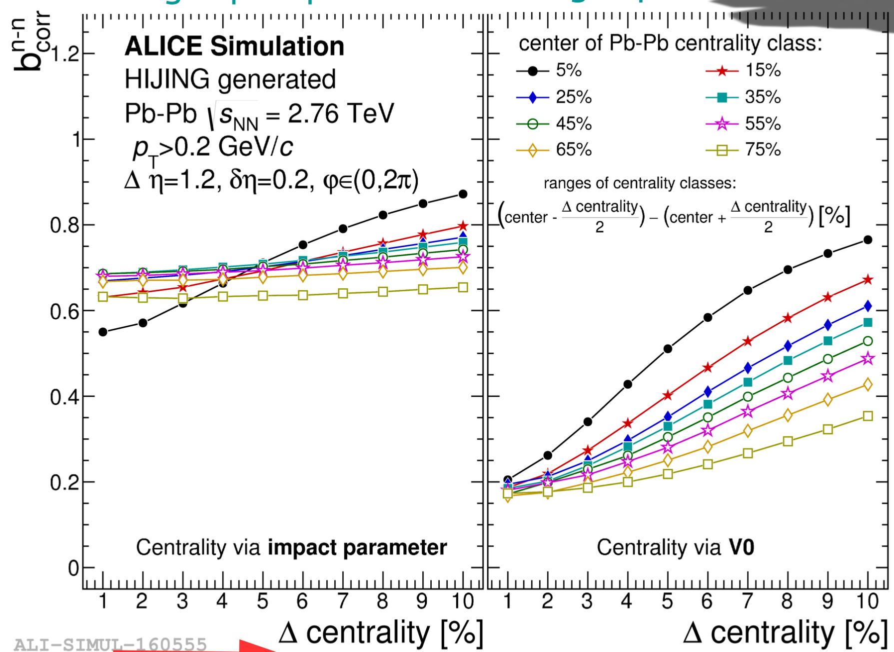
Centrality estimator: charged particles in V0



geometrical fluctuations

Centrality determined using impact parameter

Centrality estimator: charged particles in V0



geometrical fluctuations

- **Large values of b_{corr}** but large centrality bin width **→ large geometrical (N_{part}) fluctuations** within a single bin of selected centrality.
- Theoretical predictions:

$$b = 1 - \left[1 + \frac{\bar{n}}{4}\left(\frac{2}{k} + \frac{\langle w^2\rangle - \langle w\rangle^2}{\langle w\rangle}\right)\right]^{-1}$$

Scaled variance of number of participants ω_{part}

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