Forward-backward correlations in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ and 5.02 TeV with ALICE

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What are the sources of long-range correlations?

Long-range correlations (LRC) – can be explored with correlations between particles separated by pseudorapidity gap. Typically: $|\Delta \eta| > 1.0 \implies$ suppress contribution from resonances and (mini) jets.

- LRC can be created predominantly at early stages of the collision
  - geometry, interactions between strings
- can be modified by medium and final state interactions
  - hydrodynamic expansion
  - energy loss in medium
  - conservation laws

Pb-Pb, p-Pb and pp collisions are under investigation at the LHC.
ALICE experiment

**Inner Tracking System (ITS)**
tracking + triggering

**Time Projection Chamber (TPC)**
tracking

**V0 detector**
Two forward scintillator arrays
(-3.7<η<-1.7, 2.8<η<5.1)
centrality: particles at forward rapidity

**Zero-Degree Calorimeters**
centrality: spectators

- **Number of min. bias Pb-Pb events:** \(\approx 11 \times 10^6 \) @ 2.76 TeV, \(\approx 50 \times 10^6 \) @ 5.02 TeV
- **Tracks:** -0.8<η<0.8, 0.2<p_\text{T}<2.0 GeV/c
- **Centrality estimators:** V0, ZDC
**Event-by-event calculation:** choose some \( F \) and \( B \) quantities from separated \( \eta \) windows and assess correlation strength:

\[
\text{Forward-Backward correlations:}
\]

\[
\begin{align*}
\text{Correlation coefficient: } b_{\text{corr}} &= \frac{\langle FB \rangle - \langle F \rangle \langle B \rangle}{\langle F^2 \rangle - \langle F \rangle^2}
\end{align*}
\]
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\end{align*}
\]

\( \eta \)-gap

- \( n_B - n_F \) – between multiplicities in \( F \) and \( B \)
- \( \overline{\rho}_{tB} - \overline{\rho}_{tF} \) – between event-mean transverse momenta in \( F \) and \( B \)
- \( \overline{\rho}_{tB} - n_F \) – between event-mean transverse momentum in \( B \) and multiplicity in \( F \)

*a “classical” measurement, done in many experiments*

**Forward-Backward correlations: the observables**

*Event-by-event calculation:* choose some $F$ and $B$ quantities from separated $\eta$ windows and assess correlation strength:

$$b_{\text{corr}} = \frac{\langle FB \rangle - \langle F \rangle \langle B \rangle}{\langle F^2 \rangle - \langle F \rangle^2}$$

- $n_B - n_F$ — between multiplicities in $F$ and $B$
- $\rho_{tB} - \rho_{tF}$ — between event-mean transverse momenta in $F$ and $B$
- $\rho_{tB} - n_F$ — between event-mean transverse momentum in $B$ and multiplicity in $F$

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Igor Altsybeev, Forward-backward correlations, ICPPA, 3.10.2017
**FB multiplicity correlations in Pb-Pb:**
centrality dependence

- Predictions for Pb-Pb from CGC, DPM, ...

Centrality classes by V0 detector:
(-3.7<\(\eta\)<-1.7 and 2.8<\(\eta\)<5.1)

\[
b_{\text{corr}} = \frac{\langle n_B n_F \rangle - \langle n_B \rangle \langle n_F \rangle}{\langle n_F^2 \rangle - \langle n_F \rangle^2}
\]

\(0.2<p_t<2.0\text{ GeV/c}\)
\(\eta_{\text{gap}}=0.8,\ \delta\eta=0.4\)

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FB multiplicity correlations in Pb-Pb: centrality dependence

- Predictions for Pb-Pb from CGC, DPM, ...

**Centralitiy classes by V0 detector:**

(-3.7<\(\eta\)<-1.7 and 2.8<\(\eta\)<5.1)

\[
\begin{align*}
\frac{b_{\text{corr}}}{n_{\text{corr}}} & = \frac{\langle n_B n_F \rangle - \langle n_B \rangle \langle n_F \rangle}{\langle n^2_F \rangle - \langle n_F \rangle^2} \\
& = \frac{\langle n_B n_F \rangle - \langle n_B \rangle \langle n_F \rangle}{\langle n^2_F \rangle - \langle n_F \rangle^2}
\end{align*}
\]

- Strong dependence on centrality class width (volume fluctuations)

Notes:

- \(b_{\text{corr}}\) is non-vanishing in peripheral collisions
- \(b_{\text{corr}}\) depends on the width of the centrality class
- \(b_{\text{corr}}\) depends on the width of the \(\eta\) windows

Growth of Long Range Forward-Backward Multiplicity Correlations with Centrality in Au+Au Collisions at \(\sqrt{s_{\text{NN}}} = 200\) GeV

CGC model predicts the growth of LRC with collision centrality [21]. Both DPM and CGC argue that the long range correlations are produced by multiple parton-parton interactions.

Centrality classes by V0 detector:

\((-3.7<\eta<-1.7 \text{ and } 2.8<\eta<5.1)\)

\[\text{Pb-Pb } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \]

\[\text{centrality by V0M} \]

\[\text{0.2}<p_T<2.0 \text{ GeV/c} \]

\[\eta_{\text{gap}} = 0.8, \delta\eta = 0.4 \]

Igor Altsybeev, Forward-backward correlations, ICPPA, 3.10.2017
FB multiplicity correlations in Pb-Pb: centrality dependence

- Strong dependence on centrality class width (volume fluctuations)
- Dramatic dependence on centrality estimator (acceptance and resolution)

Details of centrality selection are crucial for FB multiplicity correlation studies in A-A.

- STAR claims “growth with centrality” – this should be taken with care.
  
  *Some conclusions made in STAR FB paper should be rethought*

\[ \text{Details of centrality selection are crucial for FB multiplicity correlation studies in A-A.} \]

\[ \text{Strong dependence on centrality class width (volume fluctuations)} \]

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FB correlations between intensive observables: take event-mean transverse momentum

\[ B \equiv \overline{p_{TB}} = \frac{\sum_{i=1}^{n_B} p_T^{(i)}}{n_B} \]

\[ F \equiv \overline{p_{TF}} = \frac{\sum_{j=1}^{n_F} p_T^{(j)}}{n_F} \]

Correlation coefficient:

\[ b_{\text{corr}}^{p_T-p_T} = \frac{\langle p_F p_B \rangle - \langle p_F \rangle \langle p_B \rangle}{\langle p_F^2 \rangle - \langle p_F \rangle^2} \]
FB correlations between intensive observables: take event-mean transverse momentum

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B \equiv \bar{p}_{TB} = \frac{\sum_{i=1}^{n_B} p_{T}^{(i)}}{n_B}, \quad F \equiv \bar{p}_{TF} = \frac{\sum_{j=1}^{n_F} p_{T}^{(j)}}{n_F}
\]

Correlation coefficient:

\[
b_{corr}^{p_T} = \frac{\langle p_{F} p_{B} \rangle - \langle p_{F} \rangle \langle p_{B} \rangle}{\langle p_{F}^2 \rangle - \langle p_{F} \rangle^2}
\]

\[\rightarrow \text{Traditional } b_{corr} \text{ is related to slope of the linear fit.}\]
FB correlations between intensive observables: take event-mean transverse momentum

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\[ F \equiv \bar{p}_{TF} = \frac{\sum_{j=1}^{n_F} p_T^{(j)}}{n_F} \]

Correlation coefficient:

\[ b_{corr}^{p_T} = \frac{\langle p_F \cdot p_B \rangle - \langle p_F \rangle \cdot \langle p_B \rangle}{\langle p_F^2 \rangle - \langle p_F \rangle^2} \]

Correlation functions:

ALICE Preliminary Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)
\( \eta_{gap} = 0.8, \delta\eta = 0.4 \)

\( 0.2 < p_T < 2.0 \text{ GeV/c} \)

\( 0-5\% \), \( 30-35\% \), \( 50-55\% \), \( 70-75\% \)

\( \text{linear in 5\% classes} \)

\( 0-80\% \)

\( \text{non-linear in 0-80\% class} \)

\( \implies \text{Traditional } b_{corr} \text{ is related to slope of the linear fit.} \)

\( \implies \text{Always important to look at correlation functions themselves.} \)
The reason is that the FB multiplicity correlation is a correlation between extensive observables, whereas the FB mean-$p_T$ correlation is a correlation between intensive observables, which are not influenced by trivial "volume" fluctuations.

- **Mean-$p_T$** is an **intensive** observable
  → **robust against volume fluctuations**
**FB mean-**$p_T$** correlations vs centrality**

- Mean-$p_T$ is an **intensive** observable
  - $\rightarrow$ **robust against volume fluctuations**
FB mean-$p_T$ correlations vs centrality

- **Mean-$p_T$** is an *intensive* observable
  - robust against volume fluctuations
  - and thus the centrality determination methods

### Centrality classes by V0, ZDC and CL1 estimators:

- **ALICE Preliminary Pb-Pb $s_{NN} = 2.76$ TeV**
  - $0.2 < p_T < 2.0$ GeV/c
  - $\eta_{gap} = 0.8$, $\delta\eta = 0.4$

- Mean-$p_T$ is intensive observable
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**Compare with FB multiplicity correlations**

- **by V0**
  - centrality by VOM
    - 10%, 2%
    - 5%, 1%
    - 0.5%

- **by ZDC**
  - centrality by ZDC vs ZEM
    - 10%, 2%
    - 5%, 1%
    - 0.5%

Igor Altsybeev, Forward-backward correlations, ICPPA, 3.10.2017
**FB mean-$p_T$ correlations for several $\eta$-gaps**

- at all $\eta$ gaps, **same shape of the centrality dependence**
- **higher values at $\eta$ gap=0** due to short-range contributions

![Graph showing mean-$p_T$ correlations for different $\eta$-gaps](image_url)
FB mean-$p_T$ correlations at 2.76 and 5.02 TeV

- Similar behavior with centrality at both energies
- Higher $b_{corr}$ values at 5.02 TeV (by 10-20%)
FB mean-$p_T$ correlations: interpretations

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What can cause mean-$p_T$ FB correlations?

- Size fluctuations $\leftrightarrow p_T$ fluctuations
- Pressure gradients in the fireball reflect the fluctuations of the density in the fireball.

Correlation strength:
- rises from peripheral to mid-central
- drops towards central collisions.


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**FB mean-$$p_T$$ correlations: interpretations**

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What can cause mean-$$p_T$$ FB correlations?

**Size fluctuations ↔ $$p_T$$ fluctuations**

- pressure gradients in the fireball reflect the fluctuations of the density in the fireball.

**String fusion model**

strings overlap → modification of string tension → increased $$p_T$$ of particles from the fused strings

MC realization: arXiv:1308.6618

**What is important for models to capture:**

**pattern of mean-$$p_T$$ correlations vs centrality.**

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**FB mean-$p_T$ correlations:** what can we learn from comparison with models?

- **HIJING:** weak correlations, no dependence on centrality
- **AMPT:** generally reproduces the shapes, not the magnitude in detail
  - Rescattering off $\rightarrow$ rise of $b_{\text{corr}}$
  - String melting off $\rightarrow$ large “jump” of $b_{\text{corr}}$

**GOOD on AMPT:**

- Monika: 
  - Shadowing, quenching?

[Fig. 2](http://indico.cern.ch/event/539093/contributions/2568083/agachments/1474554/2283289/Kofarago.pdf)

Igor Altsybeev, Forward-backward correlations, ICPEPA, 3.10.2017
**FB mean-$p_T$ correlations:**

what can we learn from comparison with models?

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**HIJING:** weak correlations, no dependence on centrality

**AMPT:** generally reproduces the shapes, not the magnitude in detail

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**THERMINATOR:** freeze-out hypersurface, Cooper-Frye + decays

$\rightarrow$ no mean-$p_T$ correlations due to absence of e-by-e fluctuations

**String fusion** $\rightarrow$ qualitatively describes behaviour with centrality

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**Mean-$p_T$ correlations** provide higher sensitivity to the properties of the initial state and evolution of the medium created in A-A collisions.

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**Comparison to other MC generators:**

(diff. $\eta$-windows, no $p_T$ cuts)
Forward-backward multiplicity correlations:

✧ Correlation strength heavily depends on centrality selection (type of estimator, class width)  ➔ any physical conclusions should be made very carefully.

Forward-backward mean-$p_T$ correlations:

✧ Measured for the first time in ALICE in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ and 5.02 TeV.
✧ Evolution with centrality: described by some models qualitatively, but not quantitatively.
✧ Robust against volume fluctuations and thus the centrality determination methods  ➔ higher sensitivity to the properties of the initial state and medium evolution.
Summary

Forward-backward **multiplicity** correlations:

- Correlation strength heavily depends on centrality selection (type of estimator, class width)
- any physical conclusions should be made very carefully.

Forward-backward **mean-\(p_T\)** correlations:

- Measured for the first time in ALICE in Pb-Pb collisions at \(\sqrt{s_{NN}}=2.76\) and 5.02 TeV.
- Evolution with centrality: described by some models qualitatively, but not quantitatively.
- Robust against volume fluctuations and thus the centrality determination methods
  - higher sensitivity to the properties of the initial state and medium evolution.

Thank you for your attention!
Backup
FB mean-$p_T$ correlations for several $\eta$-gaps

- at all $\eta$ gaps, same shape of the centrality dependence
- higher values at $\eta$ gap=0 due to SR contributions

As a function of $\eta$ gap:

- Peripheral events: steeper rise for smaller $\eta$ gaps
FB mean-$p_T$ correlations vs $N_{ch}$ density: compare with AMPT