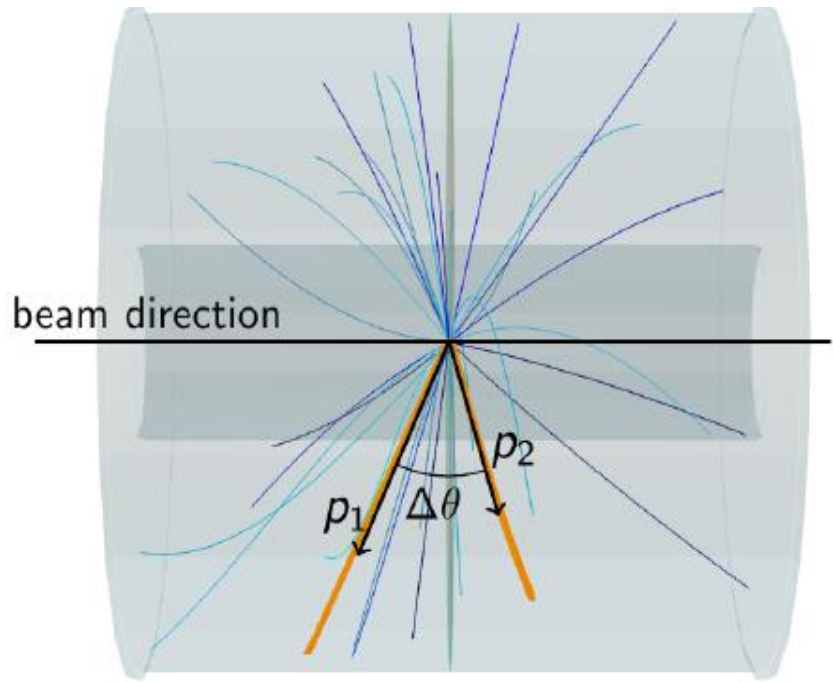


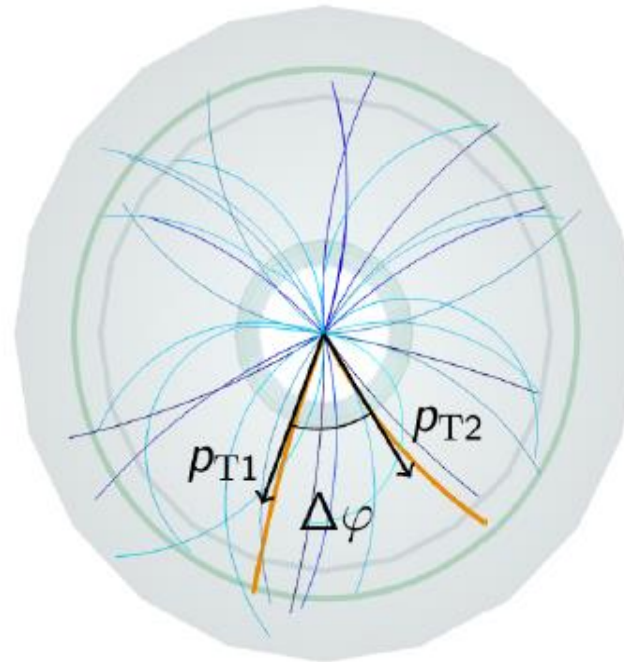
Korelacje kątowe $\Delta\eta\Delta\varphi$

Anna Kawęcka



p - particle momentum;
 θ - polar angle;
 η - pseudorapidity:

$$\eta = -\ln \left| \text{tg} \frac{\theta}{2} \right|$$



p_T - transverse momentum;
 φ - azimuthal angle;

Badamy wzajemne zachowanie się cząstek wyprodukowanych w zderzeniu w zakresie różnic pseudopospieszności $\Delta\eta$ i kątów azymulatnych $\Delta\varphi$.

Per trigger yields – parujemy ze sobą cząstki trygerujące i stowarzyszone, z czego cząstka trygerująca ma wyższy pęd

Definicija:

$$C(\Delta\eta, \Delta\varphi) = \frac{N_{pairs}^{mixed} S(\Delta\eta, \Delta\varphi)}{N_{pairs}^{signal} B(\Delta\eta, \Delta\varphi)}$$

↑ **signal**
↑ **tto**

Definition

Yield of associated particles per trigger particle measured as a function of the azimuthal angle difference $\Delta\varphi$ and pseudorapidity difference $\Delta\eta$ expressed as:

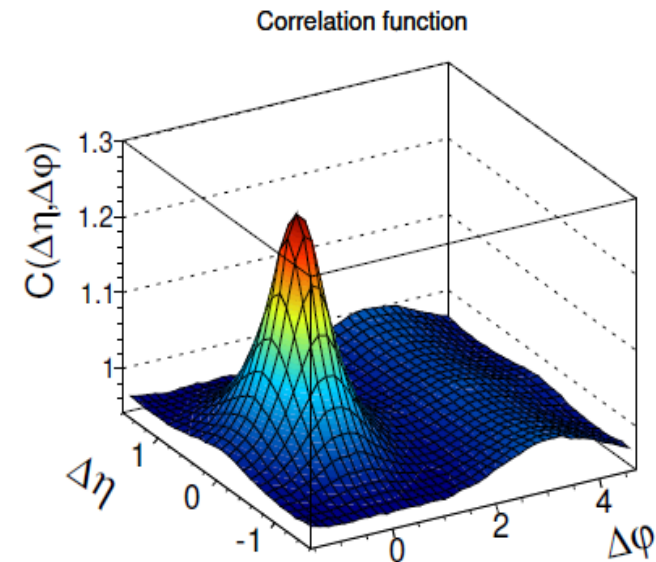
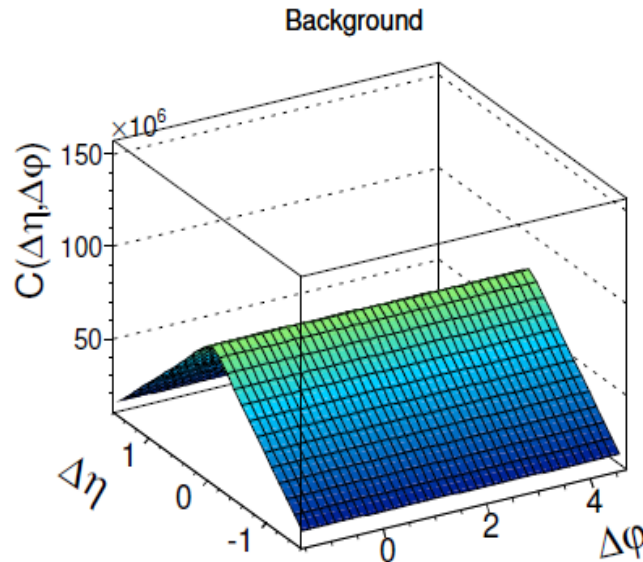
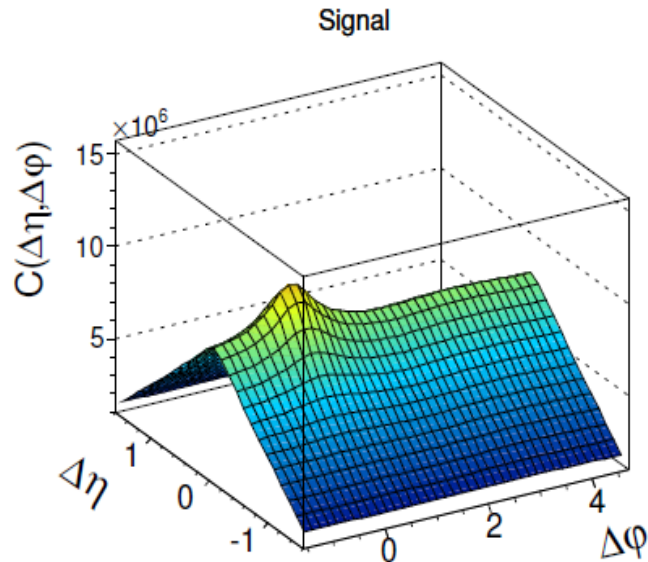
$$\frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\Delta\eta d\Delta\varphi} = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}, \quad (1)$$

where:

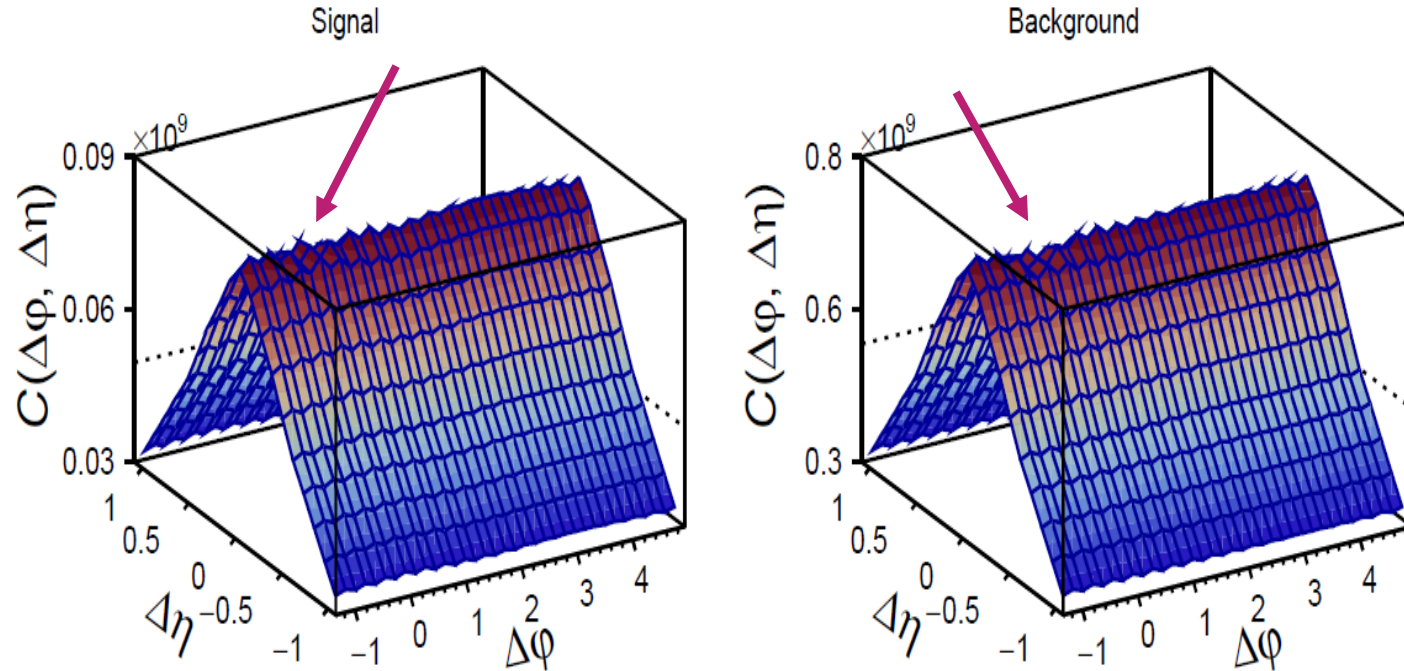
$$S(\Delta\eta, \Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2 N_{same}}{d\Delta\eta d\Delta\varphi}, \quad B(\Delta\eta, \Delta\varphi) = \frac{1}{\alpha N_{trig}} \frac{d^2 N_{mixed}}{d\Delta\eta d\Delta\varphi}$$

α - normalization factor

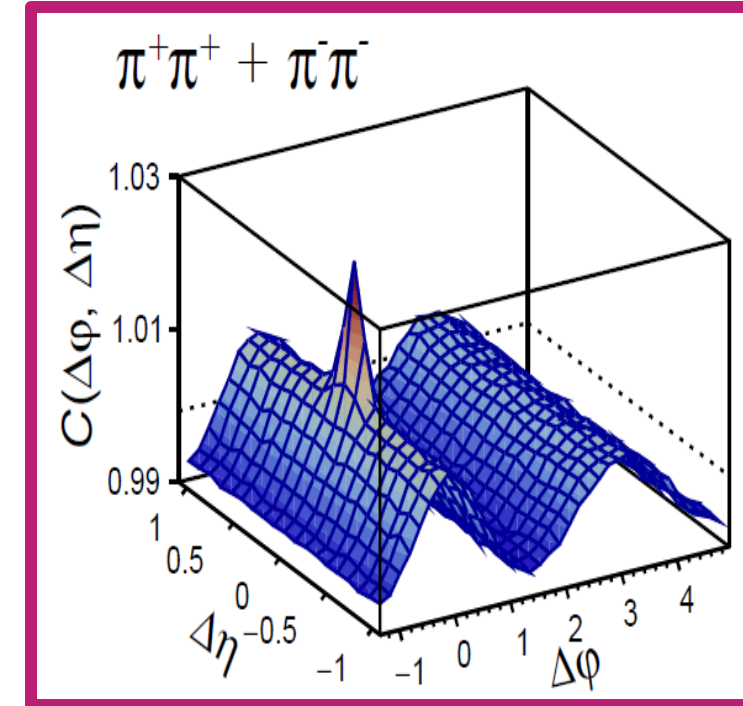
N_{trig} - total number of trigger particles in the event class and p_T interval



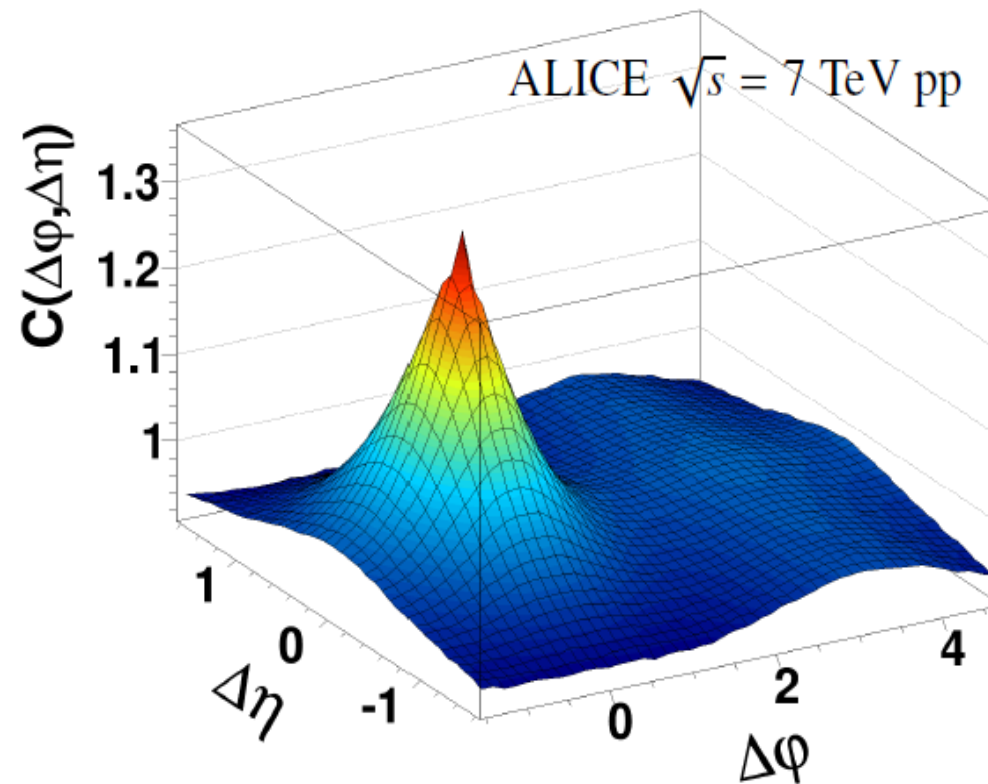
- Kształt namiotu (splot 2 rozkładów jednostajnych)
- Sygnał i tło podobne do siebie

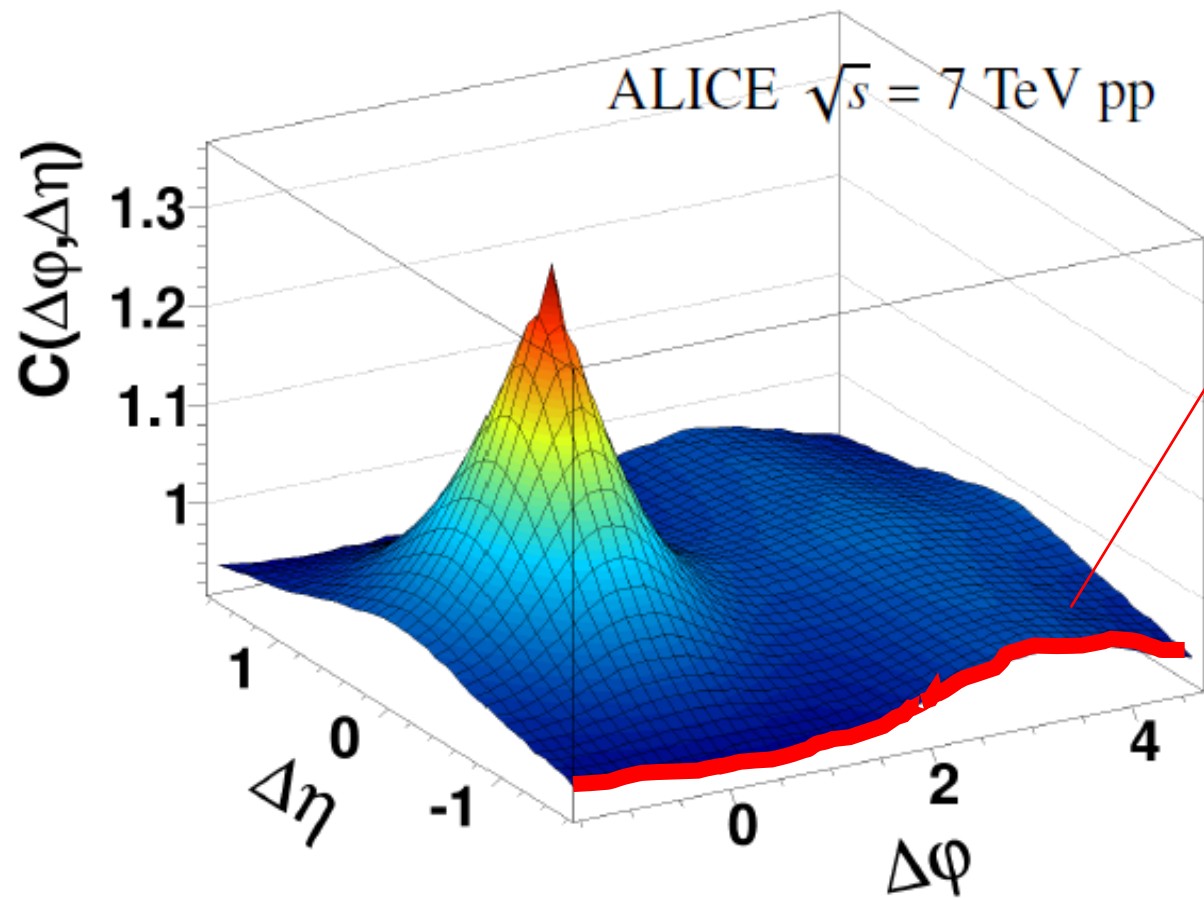


... jednak po podzieleniu widać różnicę!

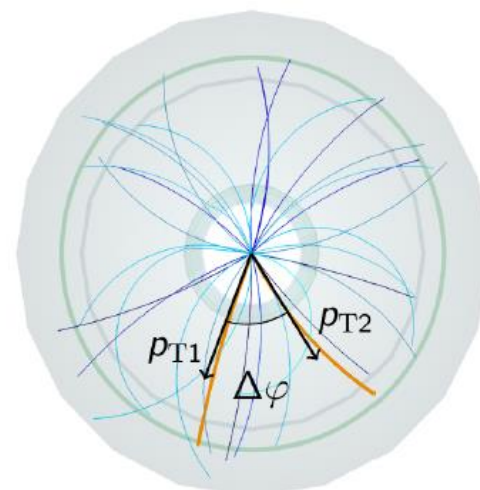
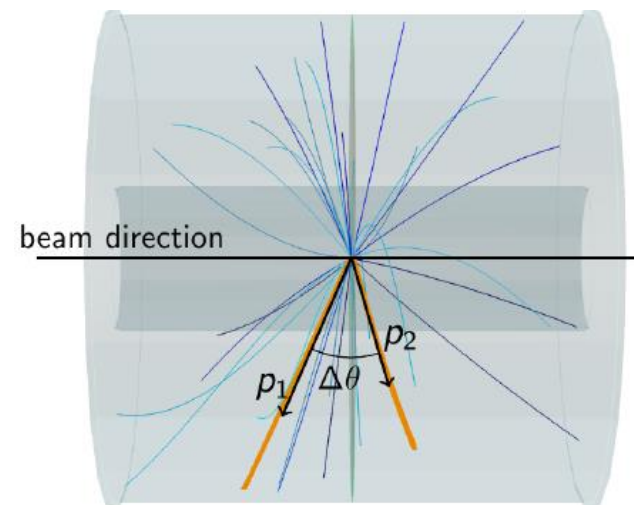


Efekty fizyczne w funkcji $\Delta\eta\Delta\phi$



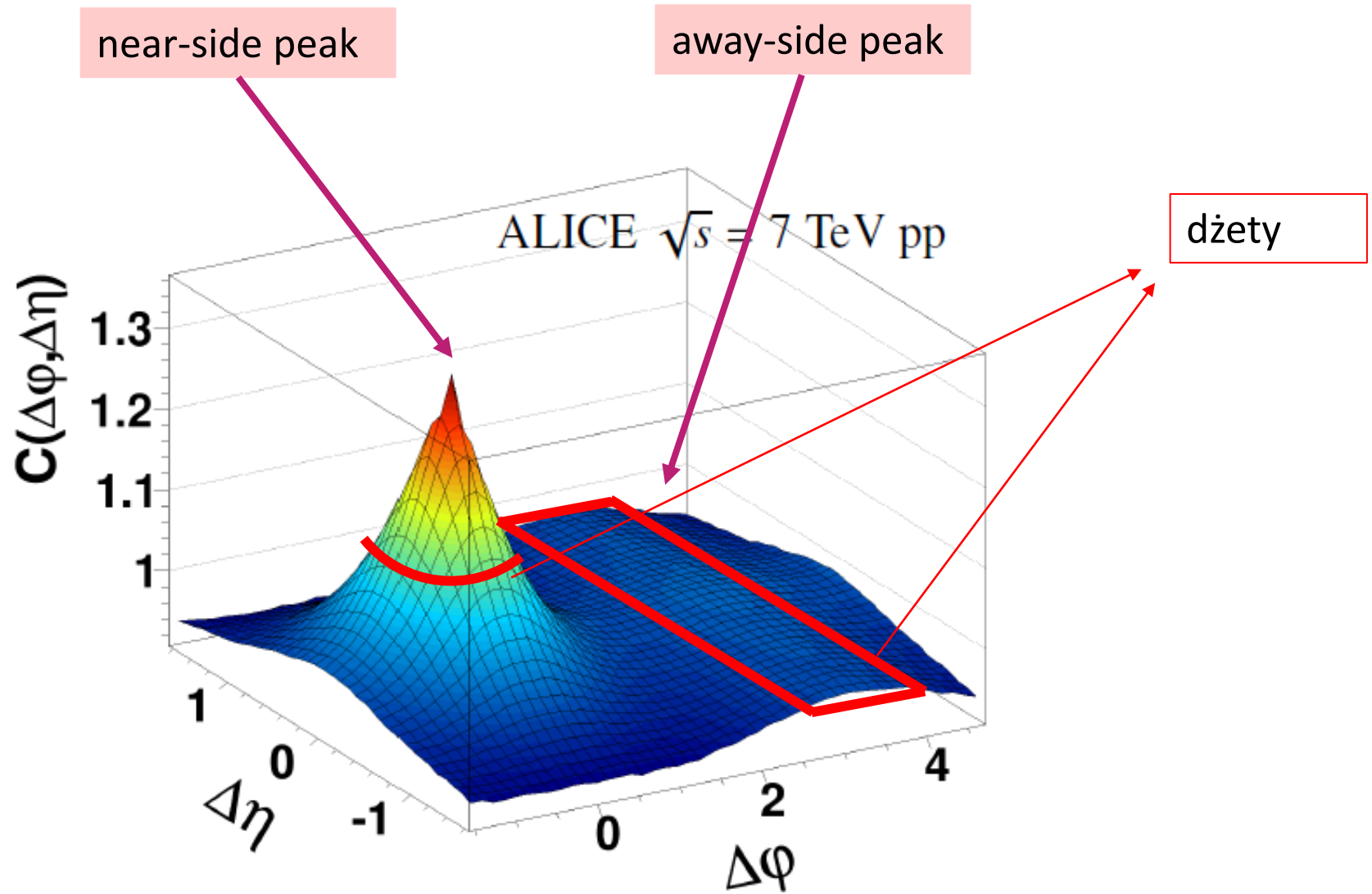


zasada zachowania pędu

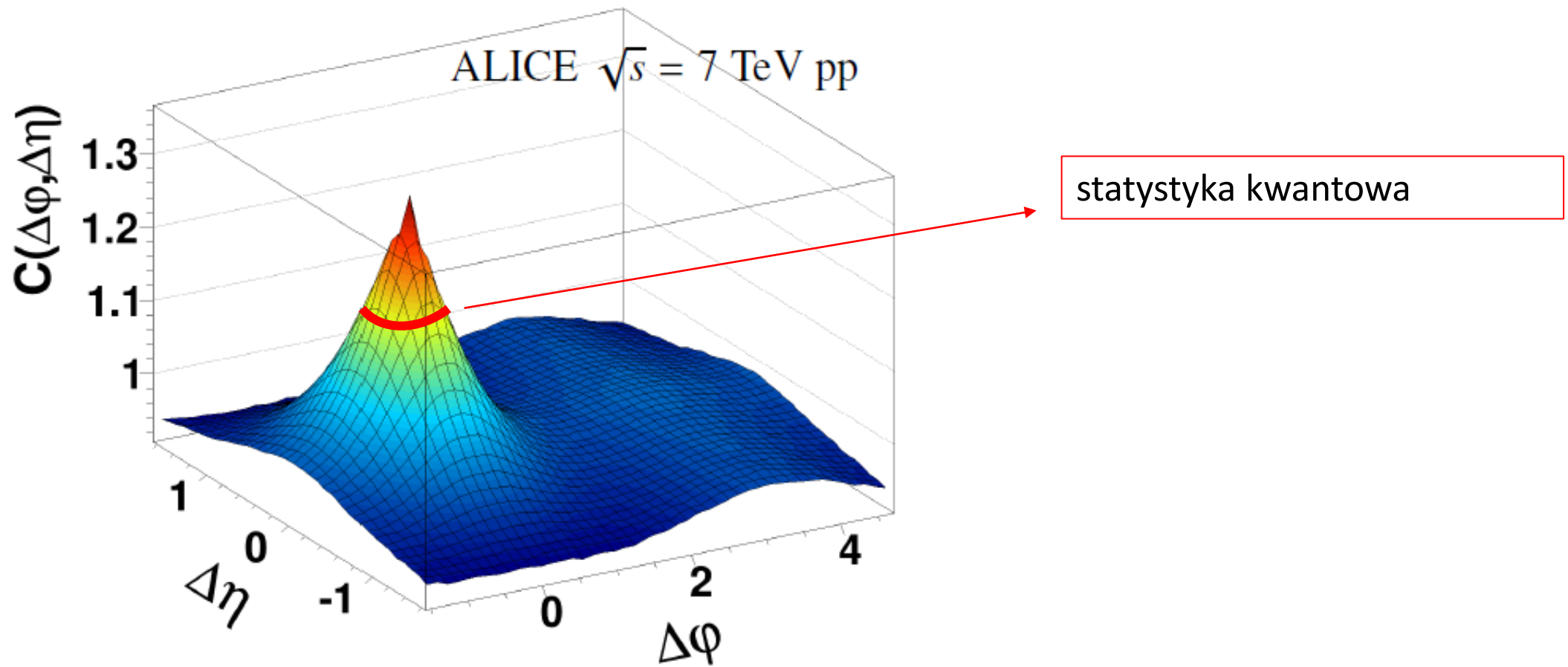


A. Zaborowska, *Pair angular correlations for pions, kaons and protons in proton-proton collisions in ALICE*

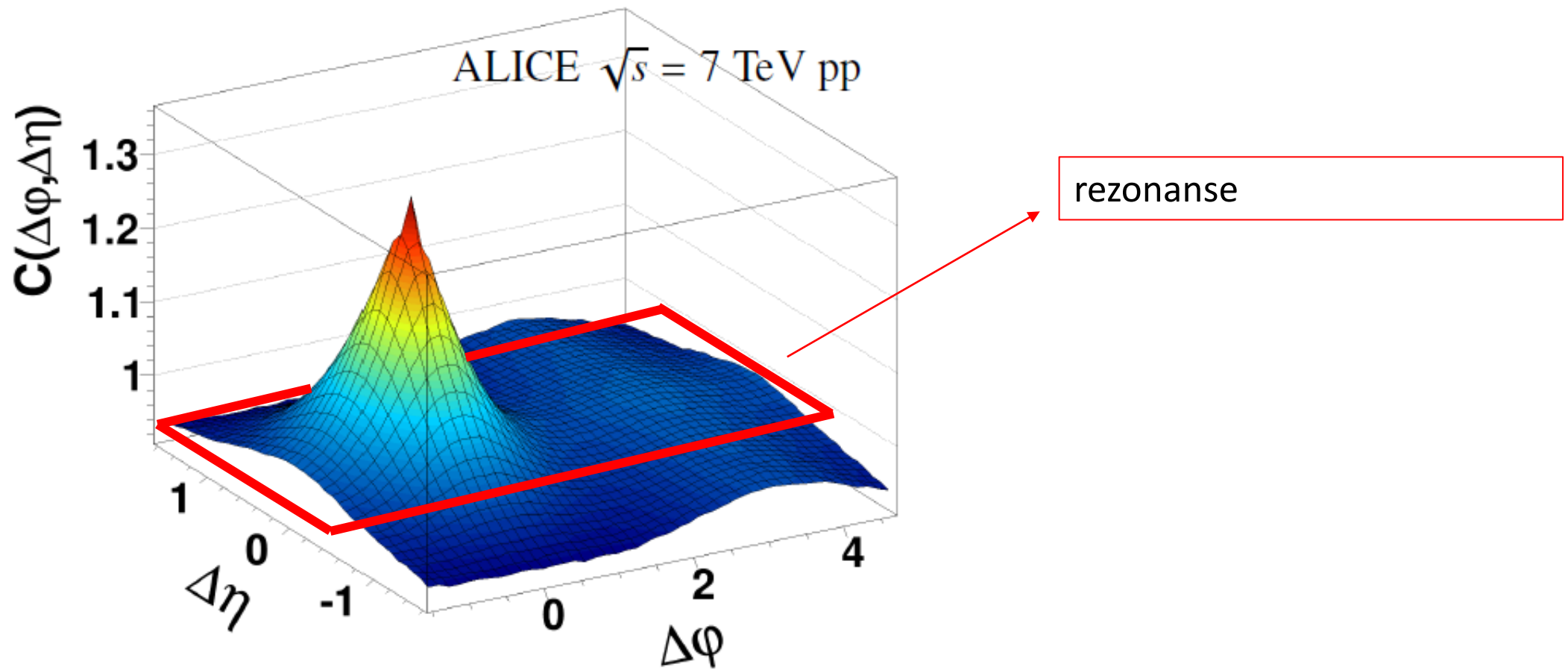
M. A. Janik, *Two-particle correlations as a function of relative azimuthal angle and pseudorapidity in proton-proton collisions registered by the ALICE experiment*



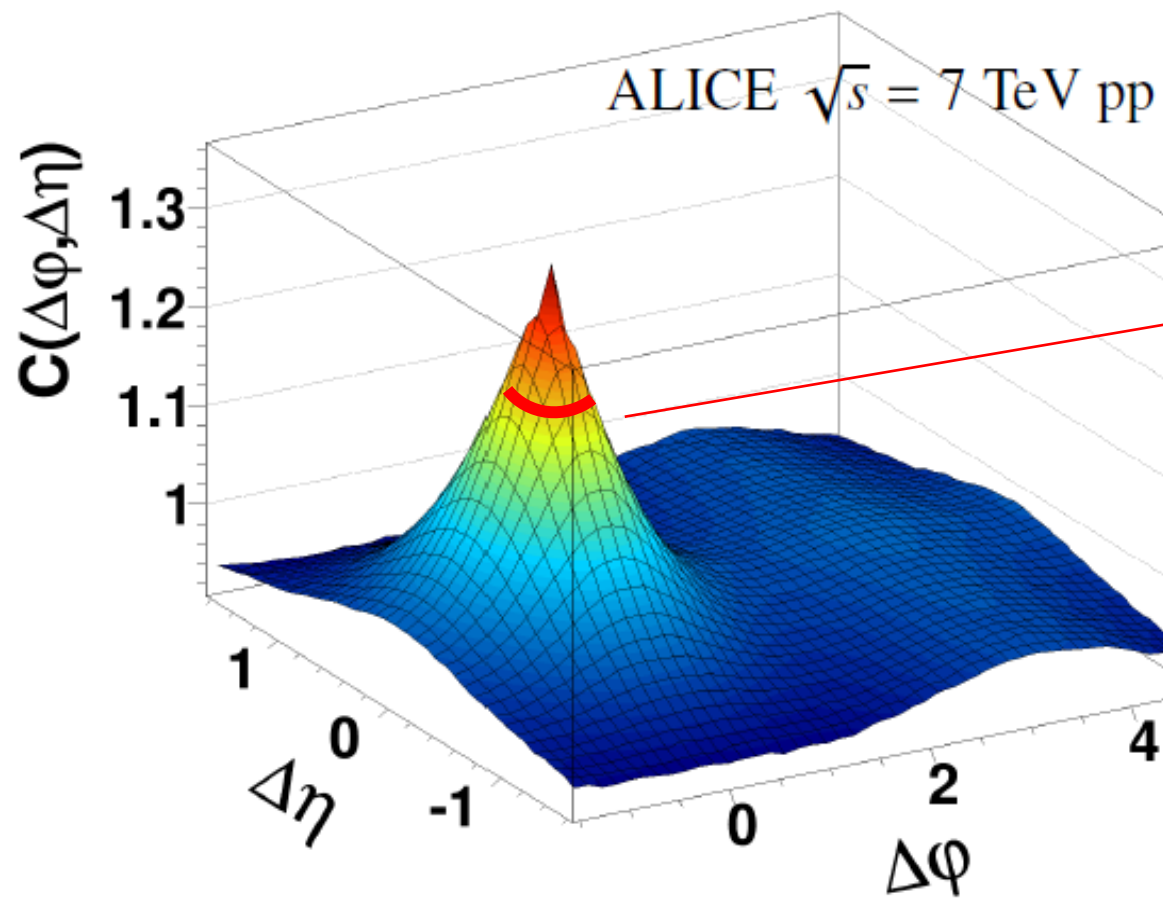
M. A. Janik, *Two-particle correlations as a function of relative azimuthal angle and pseudorapidity in proton-proton collisions registered by the ALICE experiment*



M. A. Janik, *Two-particle correlations as a function of relative azimuthal angle and pseudorapidity in proton-proton collisions registered by the ALICE experiment*



M. A. Janik, *Two-particle correlations as a function of relative azimuthal angle and pseudorapidity in proton-proton collisions registered by the ALICE experiment*

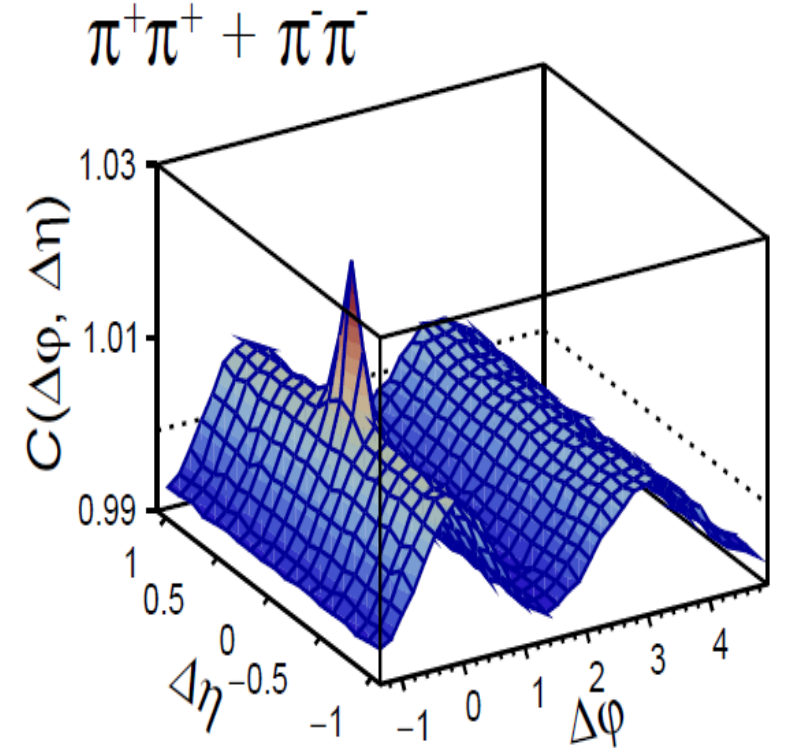
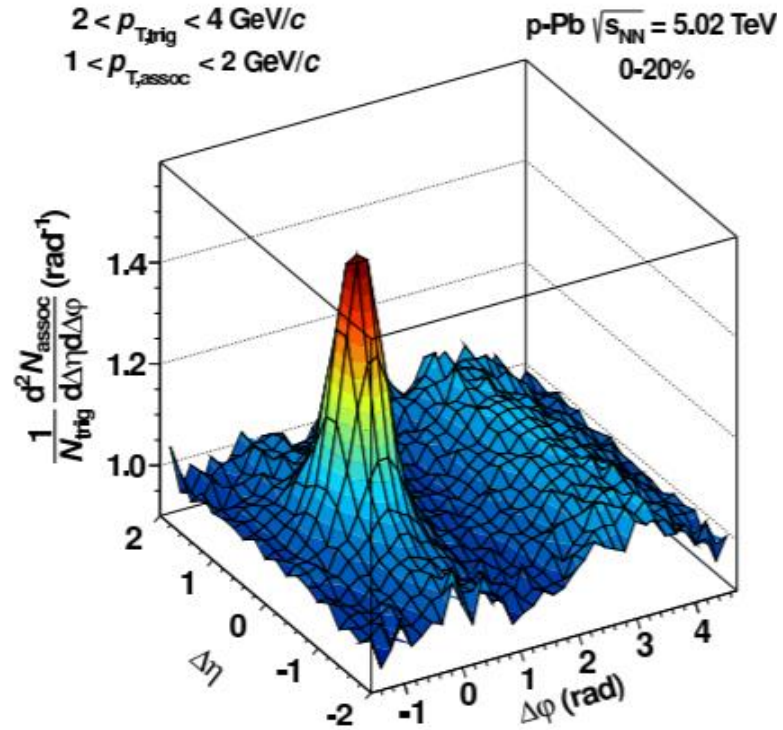
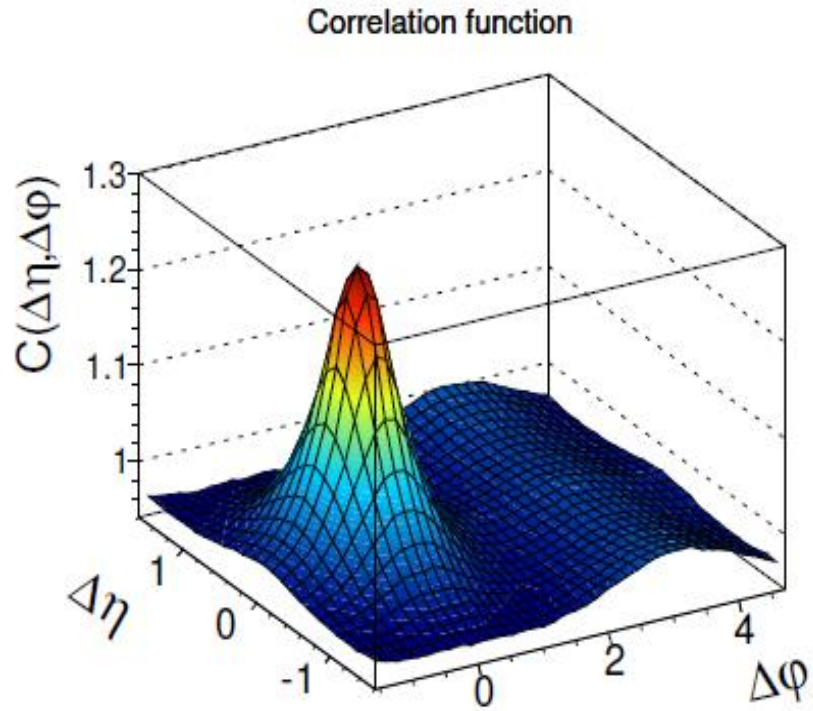


konwersja gamma + Coulomb

small systems

pp vs p-Pb vs ciężkie jony

Xe-Xe



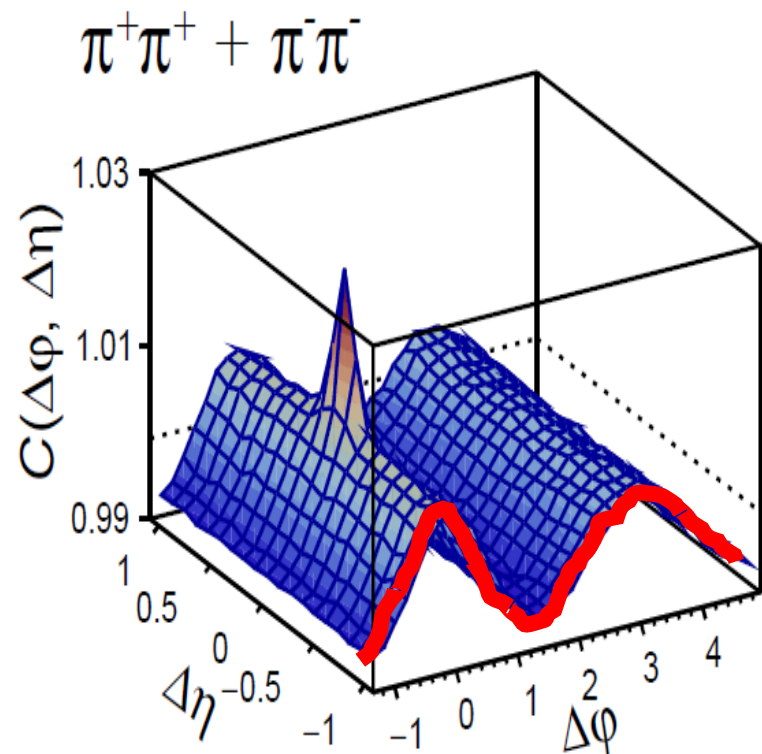
M. A. Janik, *Two-particle correlations as a function of relative azimuthal angle and pseudorapidity in proton-proton collisions registered by the ALICE experiment*

ALICE Collaboration, *Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$,*

A. Kawałcka, *Two-particle angular correlations of π mesons in Xe-Xe collisions in the ALICE experiment.*

[arXiv:1212.2001](https://arxiv.org/abs/1212.2001)

Xe-Xe,
5.44 TeV



ciężkie jony



główna różnica w
porównaniu do small
systems: **elliptic flow**

Badania

- Rezonansów
- Zachowań kolektywnych
- Zasad zachowania
- Dżetów i minidżetów
- ...

Rezonanse

zmierzone funkcje

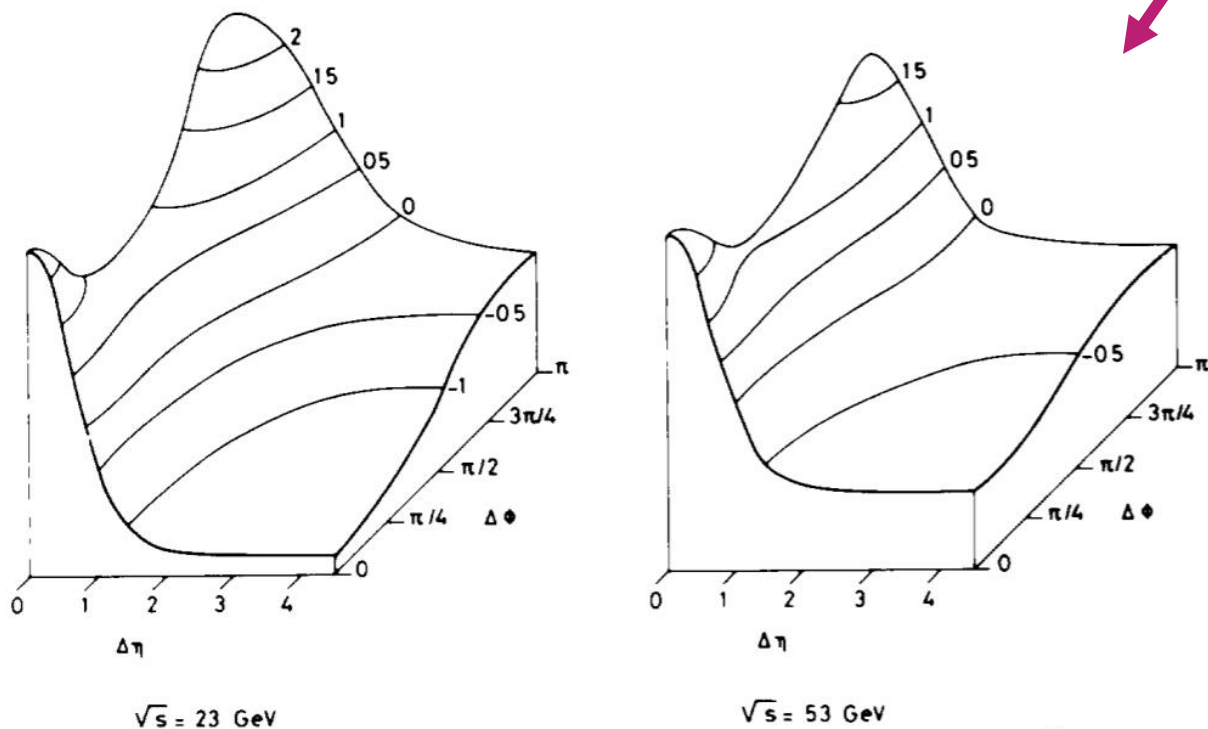


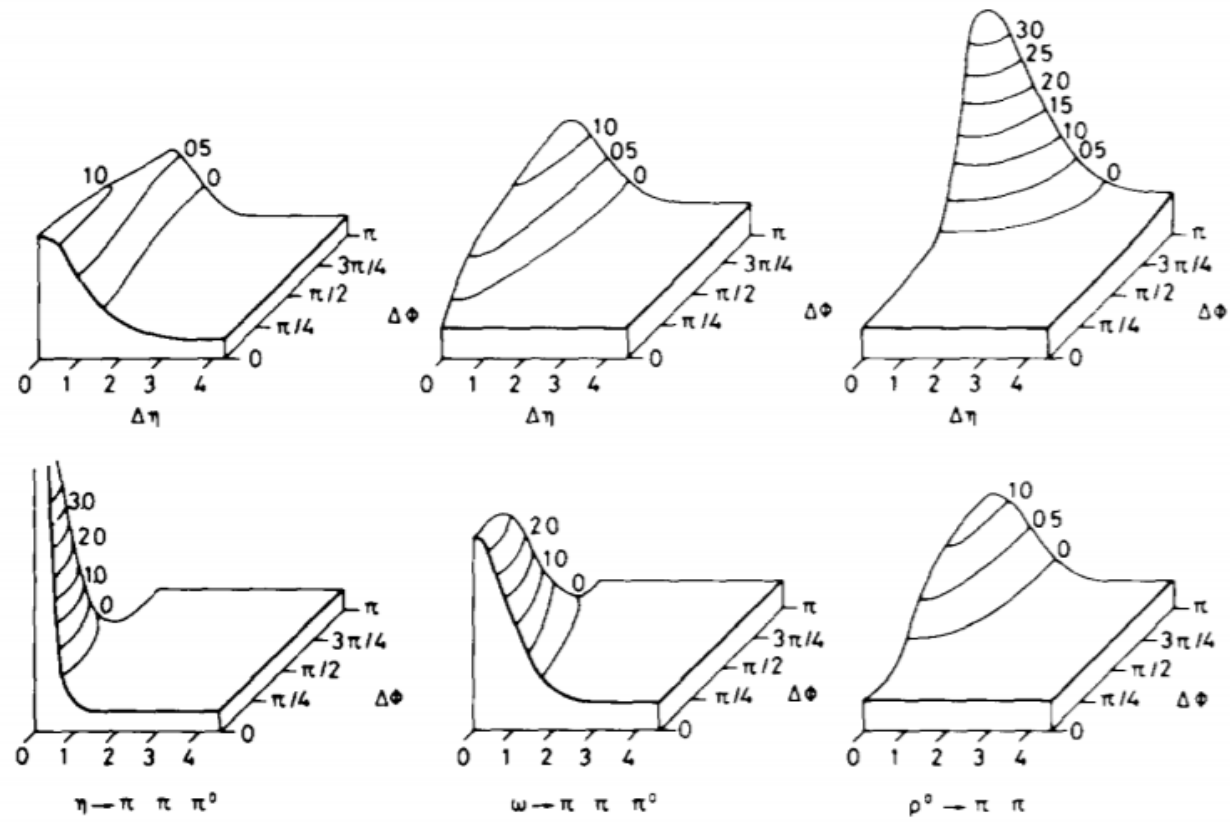
Fig 5 The measured angular correlation functions, $C^{II}(\Delta\eta, \Delta\phi)$, in units of 10^{-3} . For clarity, smooth curves have been drawn through the data which have typical error bars of $\pm 0.4 \times 10^{-3}$.

Eksperyment **ISR** (1975 r)

- zderzenia pp
- region central rapidity → żeby stłumić produkty dyfrakcyjne
- duże multiplicity (żeby badać zdarzenia o podobnej charakterystyce → multiplicity ma wpływ na kształt f korelacyjnej)

R. Eggert et al., *Angular correlations between the charged particles produced in pp collisions at ISR energies.*, Nucl.Phys., vol. B86, 1975

obliczone funkcje – wkład od rezonansów
 η, ω, ρ^0



Eksperyment **ISR** (1975 r)

- zderzenia pp
- region central rapidity → żeby stłumić produkty dyfrakcyjne
- duże multiplicity (żeby badać zdarzenia o podobnej charakterystyce → multiplicity ma wpływ na kształt f korelacyjnej)

Fig 6 Calculated angular correlation functions, $C^{II}(\Delta\eta, \Delta\phi)$, for $\rho^0 \rightarrow \pi^+\pi^-$, η and $\omega \rightarrow \pi^+\pi^-\pi^0$ decays. Invariant cross sections for meson production have the form $\exp(-\frac{1}{4}y^2) \times \exp(-Bp_T)$, where y and p_T are the rapidity and transverse momentum of the decaying meson B has the value 6 GeV^{-1} in the case of the top curves. For the bottom curves, B was adjusted to yield an invariant cross section of the form $\exp(-6p_T)$ for the decay pions. Density functions are normalized in the square $|\eta| < 2.5$ as for the $\sqrt{s} = 53 \text{ GeV}$ data. Lines of constant $C^{II}(\Delta\eta, \Delta\phi)$ are labelled in units of 10^{-3} .

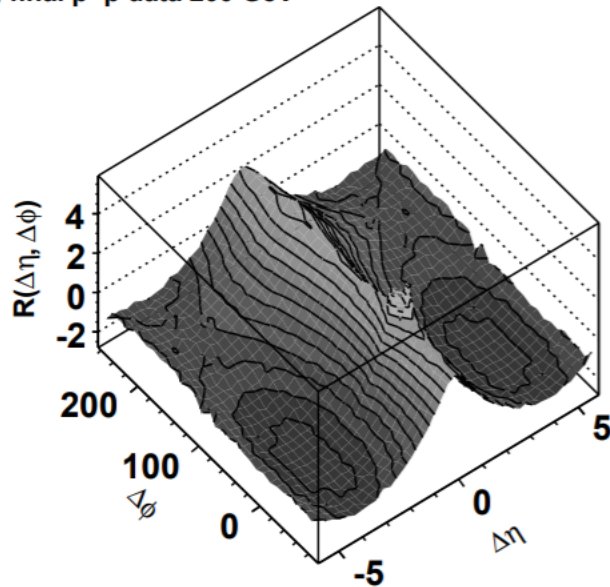
R. Eggert et al., *Angular correlations between the charged particles produced in pp collisions at ISR energies.*, Nucl.Phys., vol. B86, 1975

ISR – wnioski dot. rezonansów

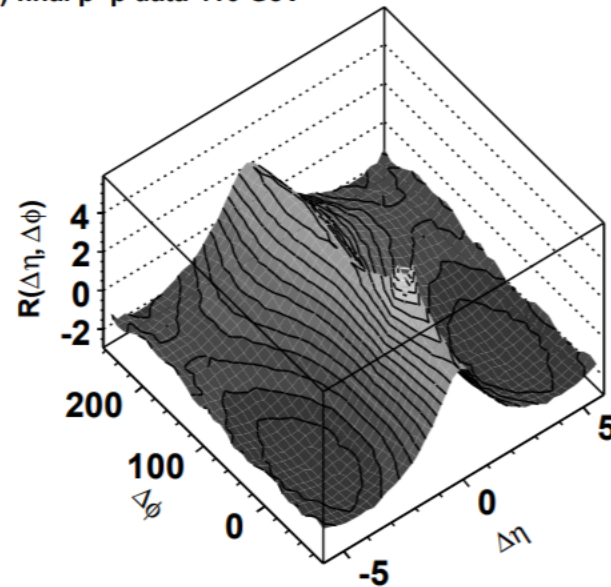
- Rezonanse kontrybuują do kształtu funkcji korelacyjnej $\Delta\eta\Delta\varphi$
- Rozpady dwuciałowe \rightarrow struktura dla $\Delta\varphi = \pi$
- Rozpady trzyciałowe \rightarrow struktura dla near-side peak i/lub longitudinal ridge
- Mała zależność kształtu funkcji od y , duża zależność od p_T

Rezonanse cd

a) final p+p data 200 GeV



b) final p+p data 410 GeV



Eksperyment PHOBOS (2007 r)

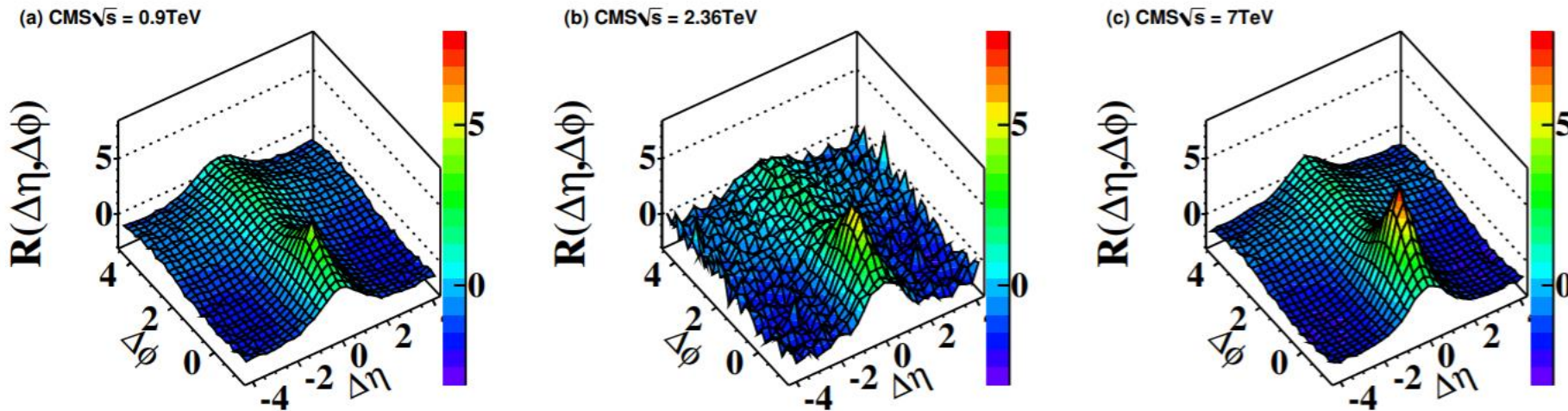
Wyniki zgodne z przewidywaniami
ISR –

„The qualitative features of the observed correlation structure are consistent with an independent cluster approach according to a simulation study from the ISR experiment using a low-mass resonance (ρ, ω, η) gas model”.

B. Alver et al., (PHOBOS Collaboration), *Cluster properties from two-particle angular correlations in p+p collisions at $\sqrt{s} = 200$ GeV and 410 GeV*, Phys.Rev., vol. C75, p. 054913, 2007.

[arXiv:0704.0966](https://arxiv.org/abs/0704.0966)

Rezonanse cd



Eksperyment **CMS** (2010 r)

Potwierdzenie wyników ISR i PHOBOS *ale* podobne są tylko cechy jakościowe – ilościowo korelacja jest silniejsza → jest jeszcze jakieś dodatkowe źródło korelacji.

V. Khachatryan et al., (CMS Collaboration), *Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC*, JHEP, vol. 1009, p. 091, 2010

Model PYTHIA odtwarza kształt longitudinal ridge, ale ma aż tak silnej korelacji.

Zachowania kolektywne – korelacje długozasięgowe

- Zderzenia ciężkich jonów – widoczny charakterystyczny kształt cosinusa
- Zderzenia centralne – duży wkład od elliptic flow, peryferyczne – podobne do zdarzeń small systems
- Współczynniki $v_n \rightarrow$ z rozkładu sygnału na szereg Fouriera

$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left[1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right] \quad v_n = \sqrt{V_{n\Delta}}$$

Zależność od centralności zderzenia

zderzenia peryferyczne

zderzenia centralne

STAR, Au-Au,
200 i 62 GeV

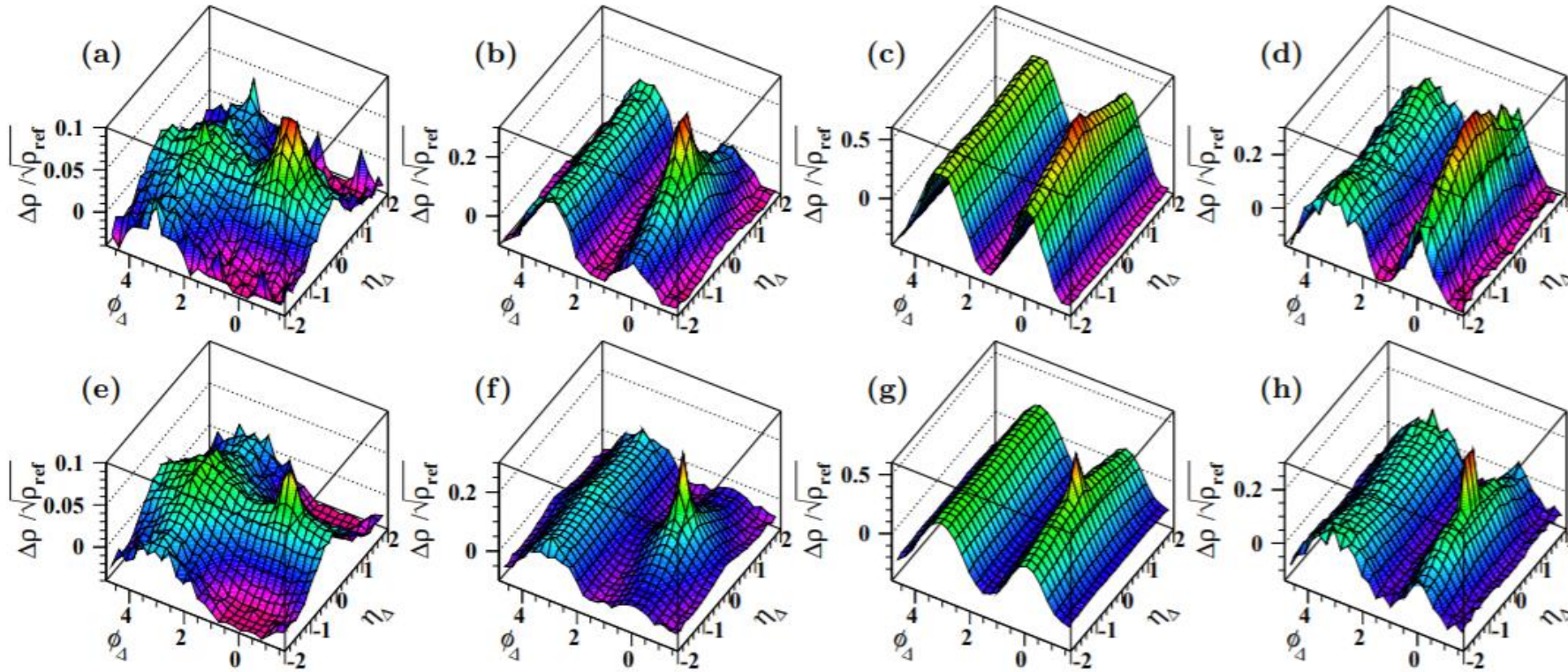


FIG. 1: (Color online) Perspective views of two-dimensional charge-independent angular correlations $\Delta\rho/\sqrt{\rho_{\text{ref}}}$ on $(\eta_{\Delta}, \phi_{\Delta})$ for Au-Au collisions at $\sqrt{s_{\text{NN}}} = 200$ and 62 GeV (upper and lower rows respectively). Centrality increases left-to-right from most-peripheral to most-central. Corrected total cross-section fractions are (left to right) 84-93%, 55-64%, 18-28% and 0-5% for the 200 GeV data and 84-95%, 56-65%, 18-28% and 0-5% for the 62 GeV data (see Tables III and IV).

Wyznaczenie v_2 i składowych wyższych rzędów metodą korelacji dwucząstkowych, ALICE

przykłady funkcji korelacyjnych dla różnych p_T i różnych centralności

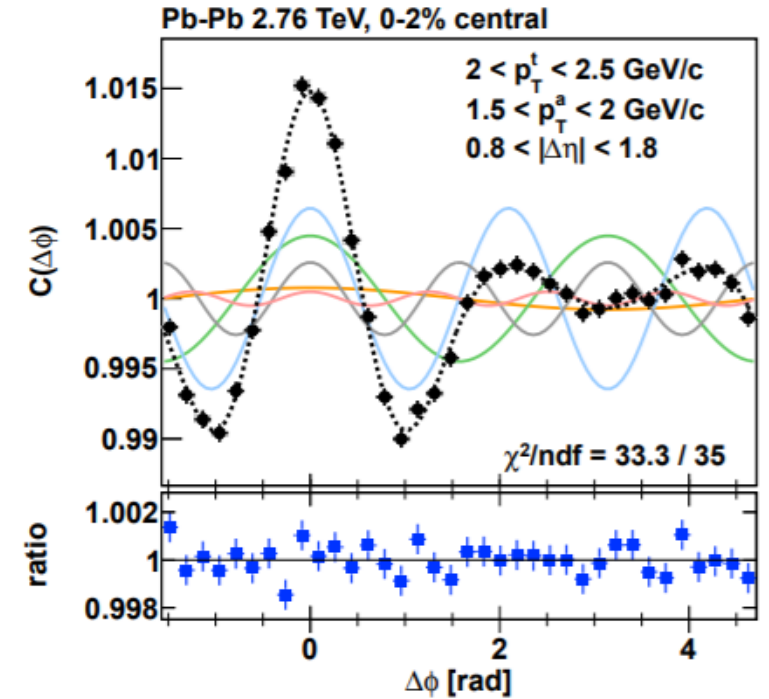
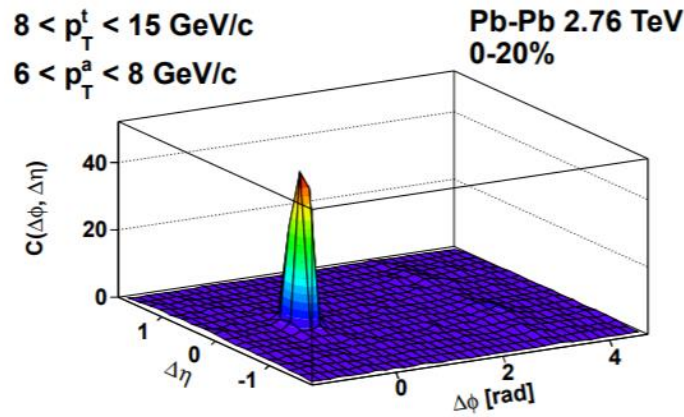
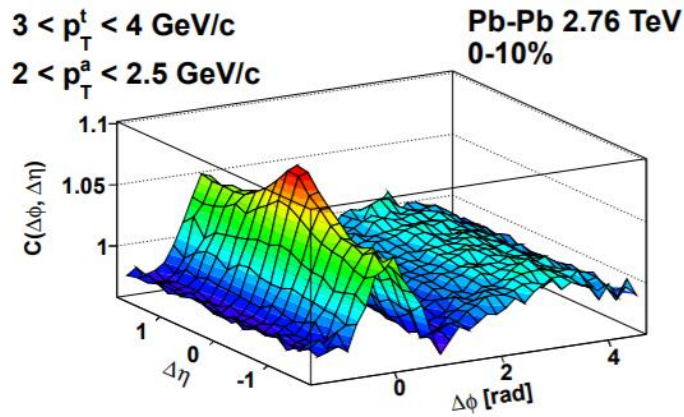


Fig. 1: Examples of two-particle correlation functions $C(\Delta\phi, \Delta\eta)$ for central Pb–Pb collisions at low to intermediate transverse momentum (left) and at higher p_T (right). Note the large difference in vertical scale between panels.

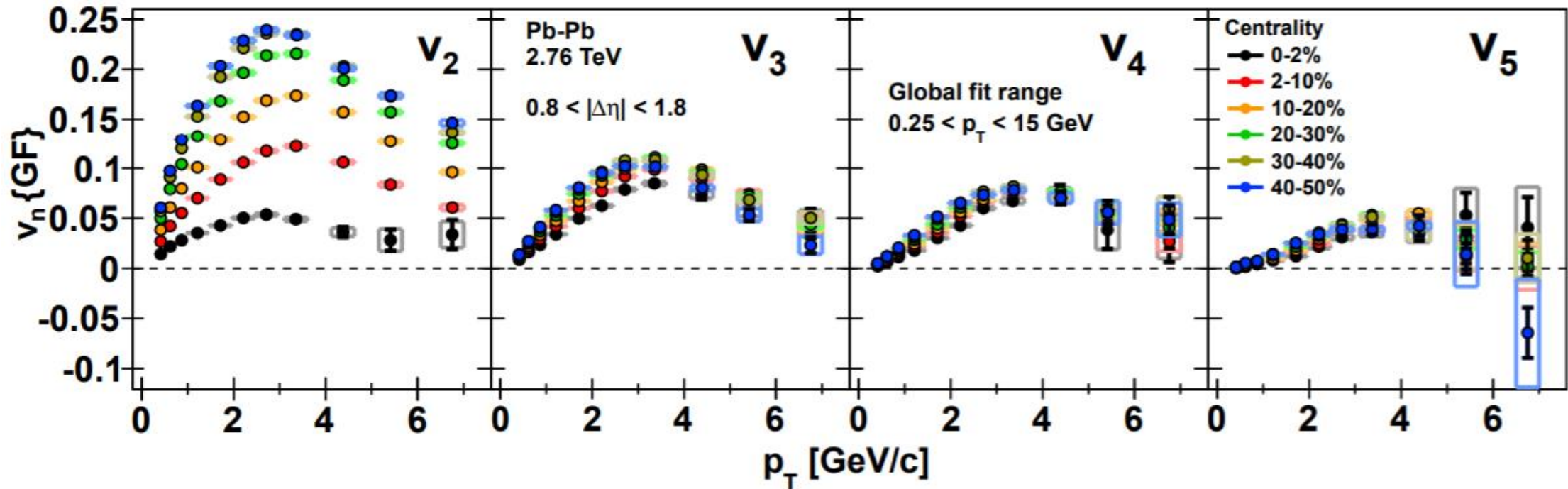
ALICE Collaboration, *Harmonic decomposition of two-particle angular correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*

10.06.2020

arXiv:1109.2501

Rozkład funkcji na szereg Fouriera – kolorowe linie - kolejne rzędy, linia przerywana to suma, punkty to dane doświadczalne

Wyznaczenie v_2 i składowych wyższych rzędów metodą korelacji dwucząstkowych, ALICE



ALICE Collaboration, *Harmonic decomposition of two-particle angular correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*

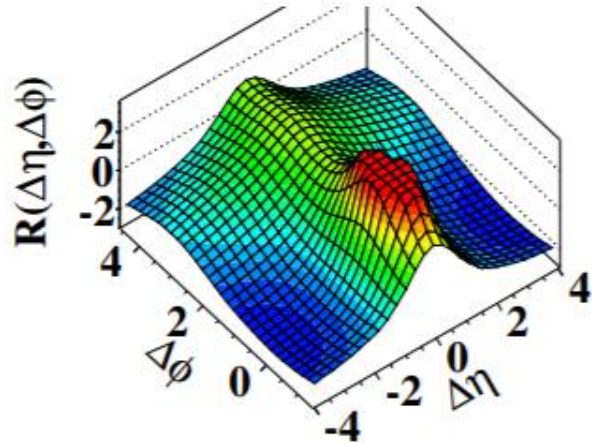
10.06.2020

[arXiv:1109.2501](https://arxiv.org/abs/1109.2501)

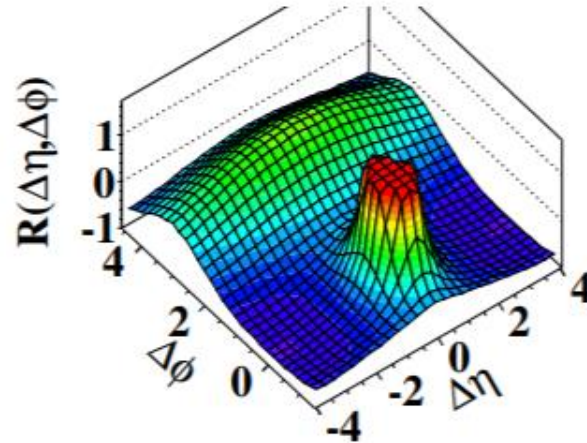
22

Efekty kolektywne w zderzeniach p-p?

(a) CMS MinBias, $p_T > 0.1 \text{ GeV}/c$



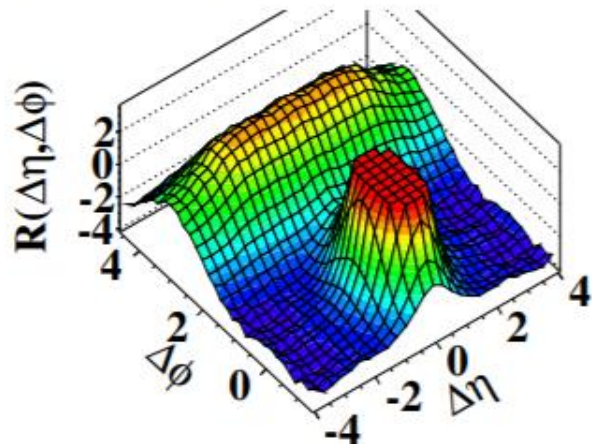
(b) CMS MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



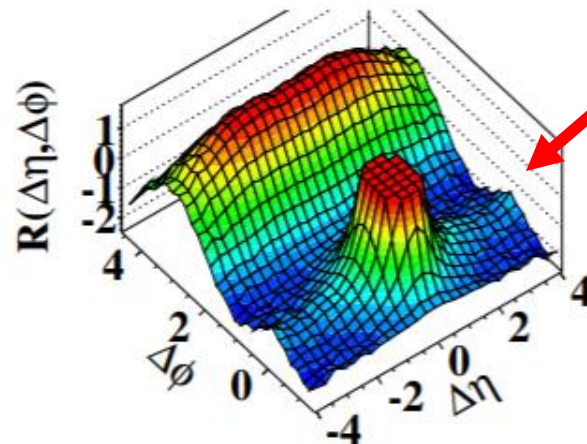
CMS, 2010

Zachowanie kolektywne w systemie pp?

(c) CMS $N \geq 110$, $p_T > 0.1 \text{ GeV}/c$



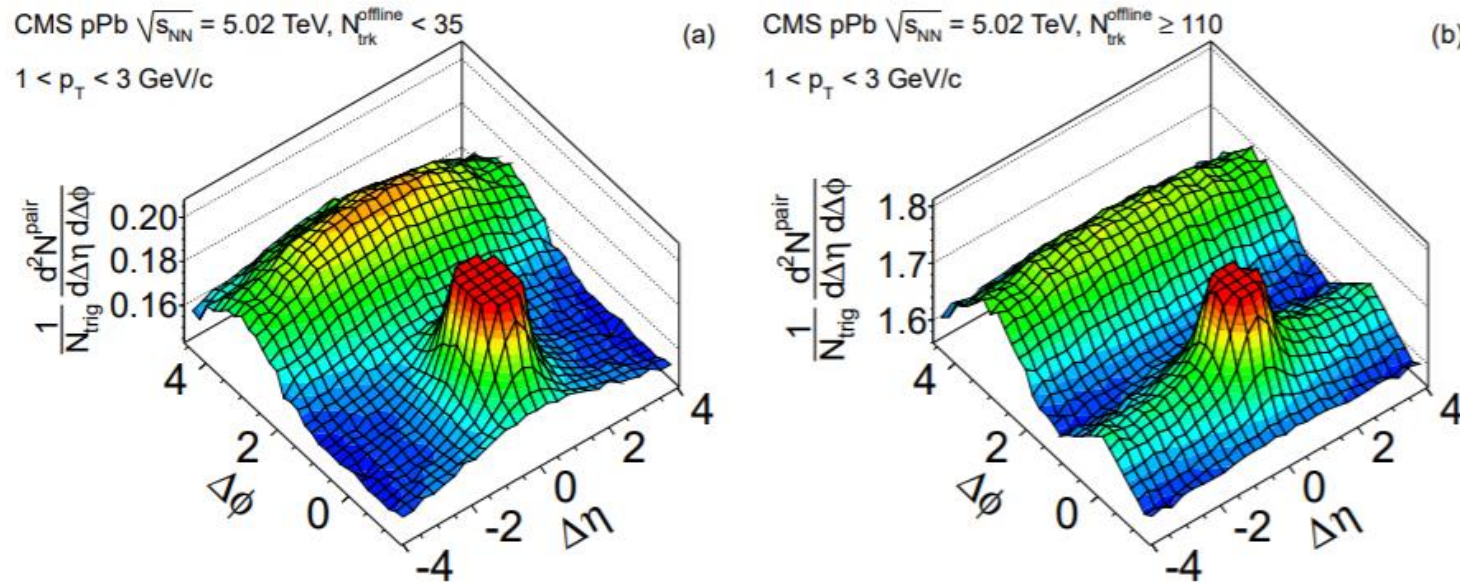
(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



The CMS Collaboration, *Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC*

[arXiv:1009.4122](https://arxiv.org/abs/1009.4122)

Podobne wyniki dla systemu p-Pb



CMS, 2013

These observations are qualitatively similar to those in pp collisions when selecting the same observed particle multiplicity, while the overall strength of the correlations is significantly larger in pPb collisions.

Figure 1: 2-D two-particle correlation functions for 5.02 TeV pPb collisions for pairs of charged particles with $1 < p_T < 3$ GeV/c. Results are shown (a) for low-multiplicity events ($N_{\text{trk}}^{\text{offline}} < 35$) and (b) for a high-multiplicity selection ($N_{\text{trk}}^{\text{offline}} \geq 110$). The sharp near-side peaks from jet correlations have been truncated to better illustrate the structure outside that region.

The CMS Collaboration, *Observation of long-range, near-side angular correlations in pPb collisions at the LHC*

[arXiv:1210.5482](https://arxiv.org/abs/1210.5482)

Podobne wyniki – ATLAS i inne eksperymenty na LHC

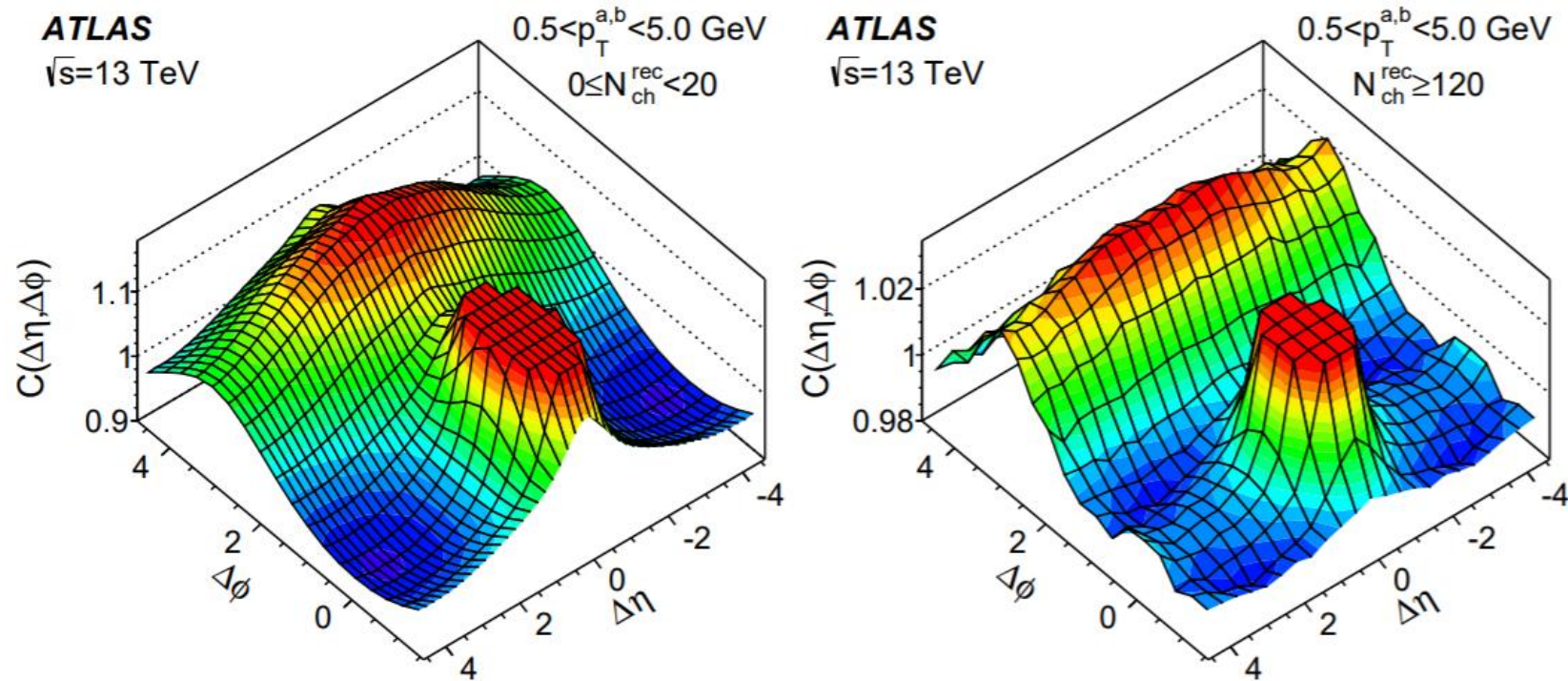
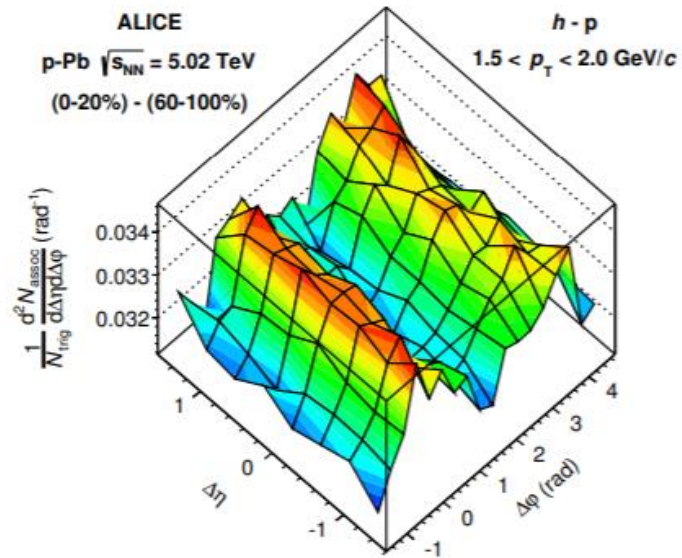
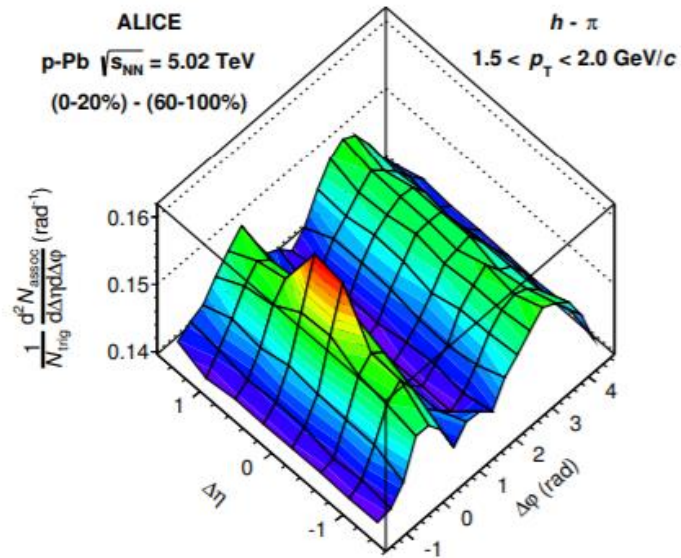


Figure 2: Two-particle correlation functions, $C(\Delta\eta, \Delta\phi)$, in 13 TeV pp collisions in N_{ch}^{rec} intervals 0–20 (left) and ≥ 120 (right) for charged particles having $0.5 < p_T^{a,b} < 5$ GeV. The distributions have been truncated to suppress the peak at $\Delta\eta = \Delta\phi = 0$ and are shown over $|\eta| < 4.6$ to avoid statistical fluctuations at larger $|\Delta\eta|$.

ATLAS Collaboration, *Observation of long-range elliptic azimuthal anisotropies in $\sqrt{s} = 13$ and 2.76 TeV pp collisions with the ATLAS detector*

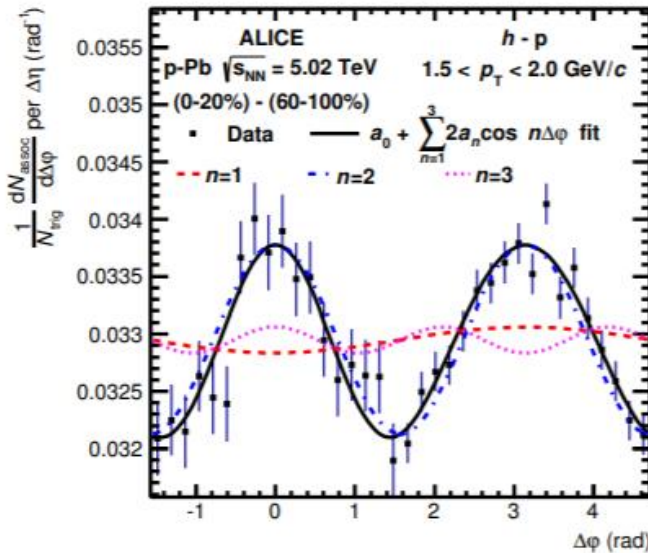
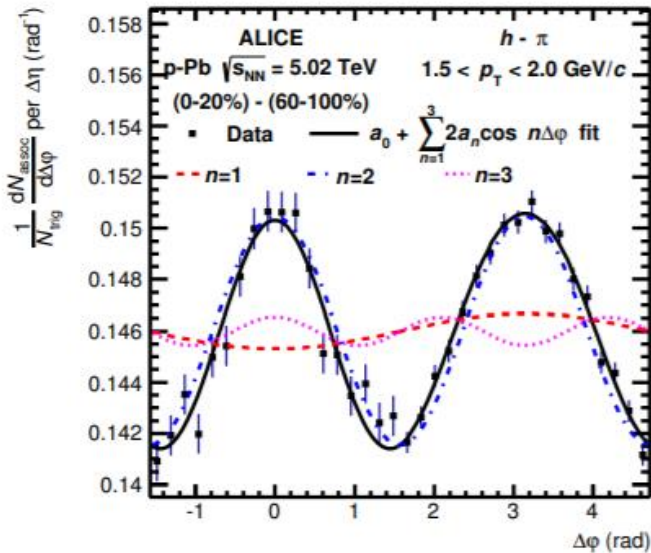
[arXiv:1509.04776](https://arxiv.org/abs/1509.04776)

Zderzenia p-Pb – niezidentyfikowana cząstka trygująca + zidentyfikowana stowarzyszona, ALICE



Odjęto zderzenia o niskiej krotności od zderzeń o wysokiej krotności

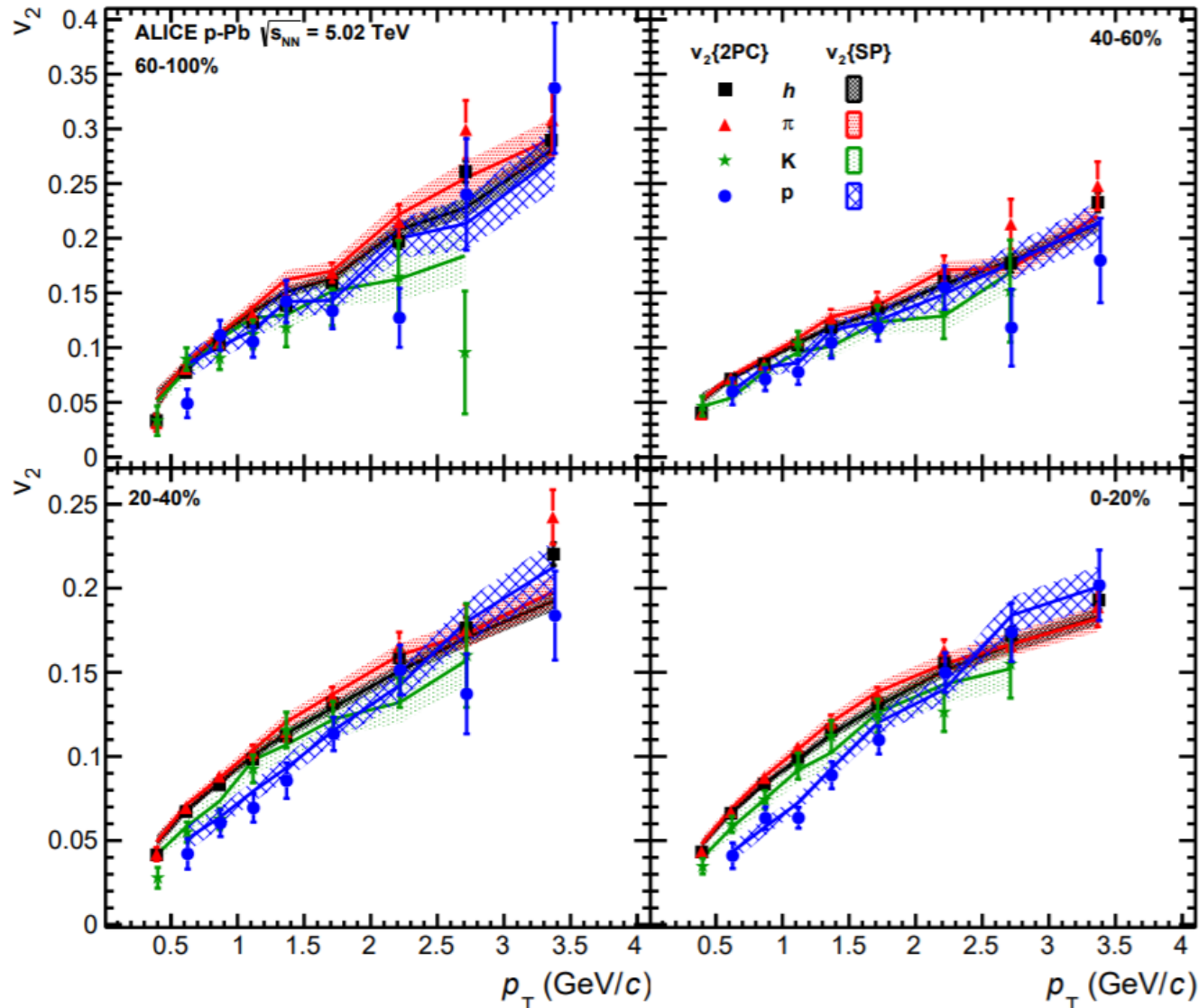
Obliczono v_2 dla pionów, kaonów i protonów → zbliżone wartości



arXiv:1307.3237

ALICE Collaboration, *Long-range angular correlations of π , K and p in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*

Zderzenia p-Pb – niezidentyfikowana cząstka trygująca + zidentyfikowana stowarzyszona, ALICE



Obliczono v_2 dla pionów, kaonów i protonów → zbliżone wartości, ale widać *mass ordering*

arXiv:1307.3237

ALICE Collaboration, *Long-range angular correlations of π , K and p in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*

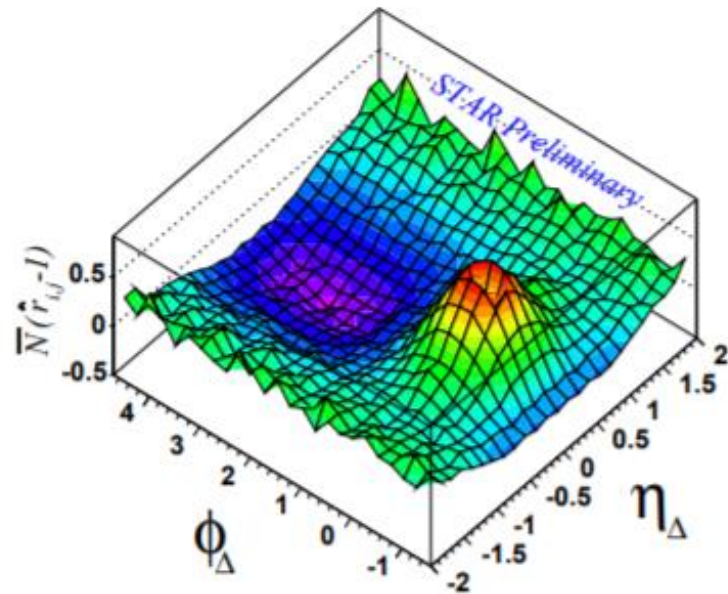
Dzety i minidzety

- Dzety – wkład głównie dla dużych p_T dla near-side i away-side peak
- Dobrze widoczne dla zderzeń elementarnych
- Zderzenia ciężkich jonów – tłumienie dżetów

STAR – analiza wkładu od procesów twardych i miękkich

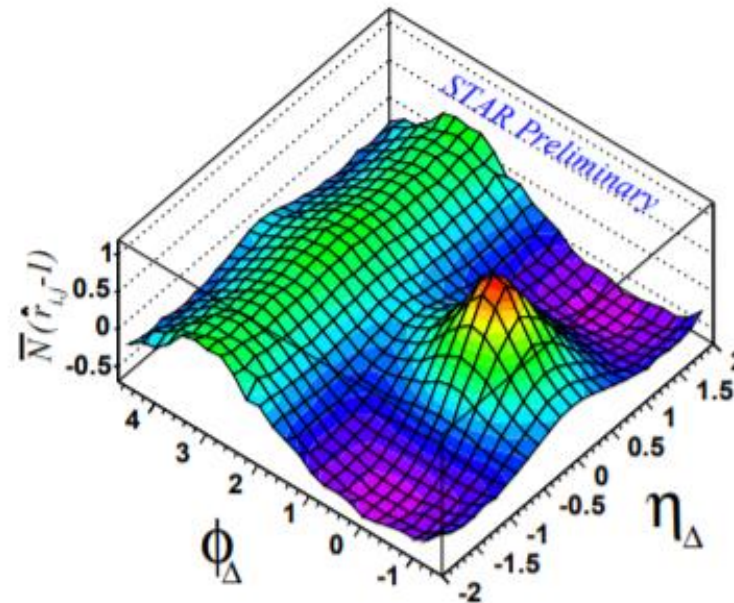
Zderzenia p-p, 200 GeV

$0.15 < p_t < 0.5 \text{ GeV}/c$



longitudinal string fragmentation

$0.5 < p_t < 6 \text{ GeV}/c$



minijets (z głęboko nieelastycznego rozpraszania)

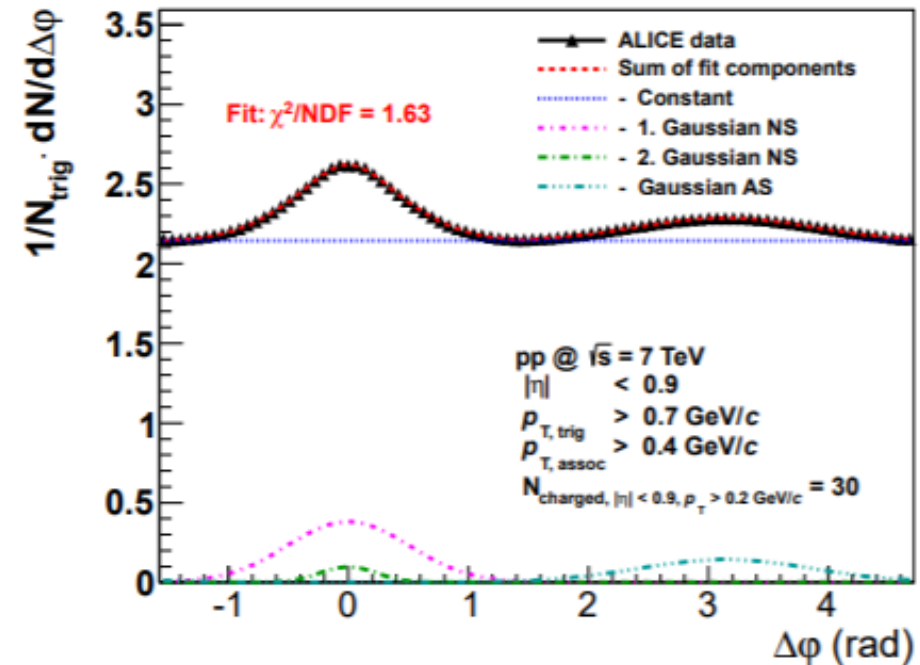
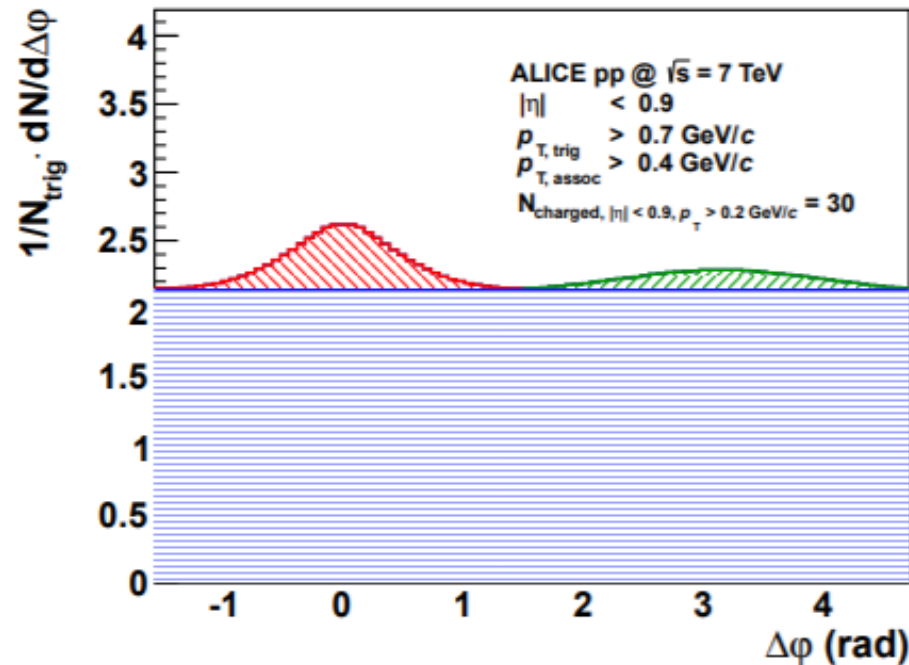
Za pomocą cutu na $y_T = \ln\left\{\frac{m_T + p_T}{m_\pi}\right\} = 2$ (odpowiada to p_T około 0.5 GeV/c) „odcięto” procesy miękkie od twardych

R. J. Porter and T. A. Trainor, *Soft and hard components of two-particle distributions on (y, η, ϕ) from p-p collisions at $\sqrt{s} = 200 \text{ GeV}$*

[hep-ph/0406330](https://arxiv.org/abs/hep-ph/0406330)

ALICE – badanie zależności „jet-like structure” od multiplicity

Zderzenia p-p



ALICE Collaboration, *Multiplicity dependence of two-particle azimuthal correlations in pp collisions at the LHC*

arXiv: 1307.1249

ALICE – badanie zależności „jet-like structure” od multiplicity

badano też energie 2.76 i 0.9 TeV

Do funkcji dofitowano 3 Gaussy i z ich parametrów:

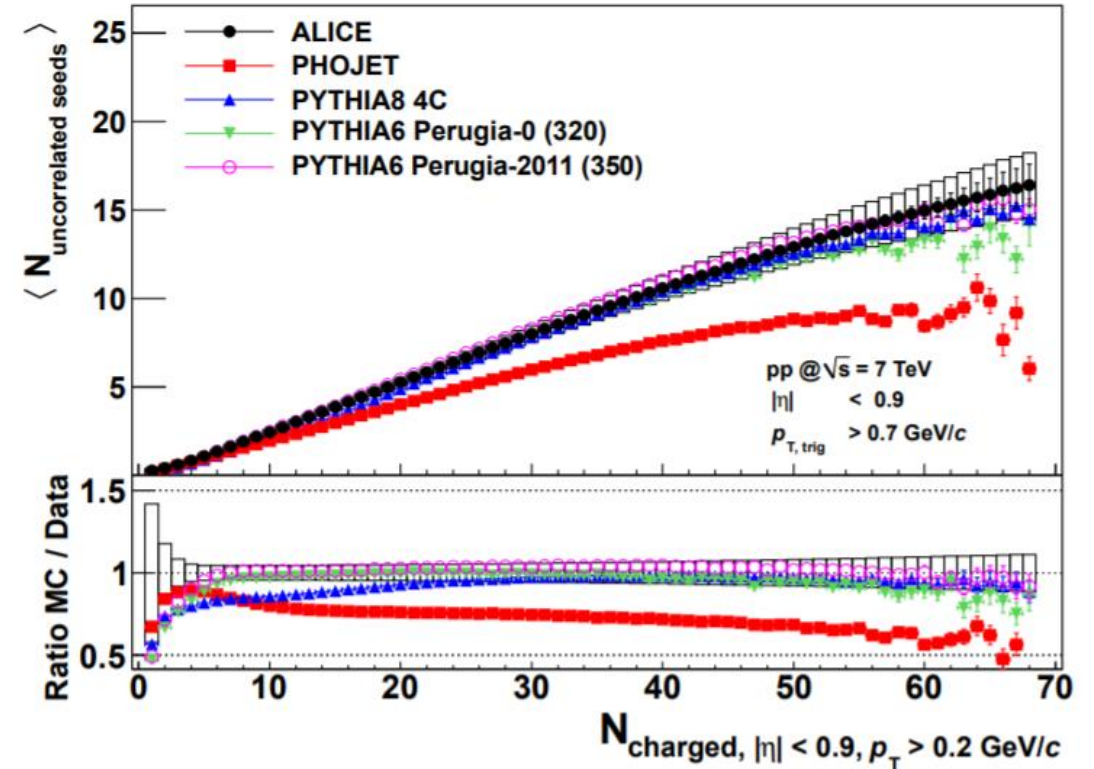
$$\langle N_{\text{assoc, near-side}} \rangle = \frac{\sqrt{2\pi}}{N_{\text{trigger}}} (A_1 \cdot \sigma_1 + A_2 \cdot \sigma_2)$$

$$\langle N_{\text{assoc, away-side}} \rangle = \frac{\sqrt{2\pi}}{N_{\text{trigger}}} (A_3 \cdot \sigma_3)$$

$$\langle N_{\text{trigger}} \rangle = \frac{N_{\text{trigger}}}{N_{\text{events}}}$$

$$\langle N_{\text{uncorrelated seeds}} \rangle = \frac{\langle N_{\text{trigger}} \rangle}{\langle 1 + N_{\text{assoc, near+away, } p_T > p_{T, \text{trig}}} \rangle}$$

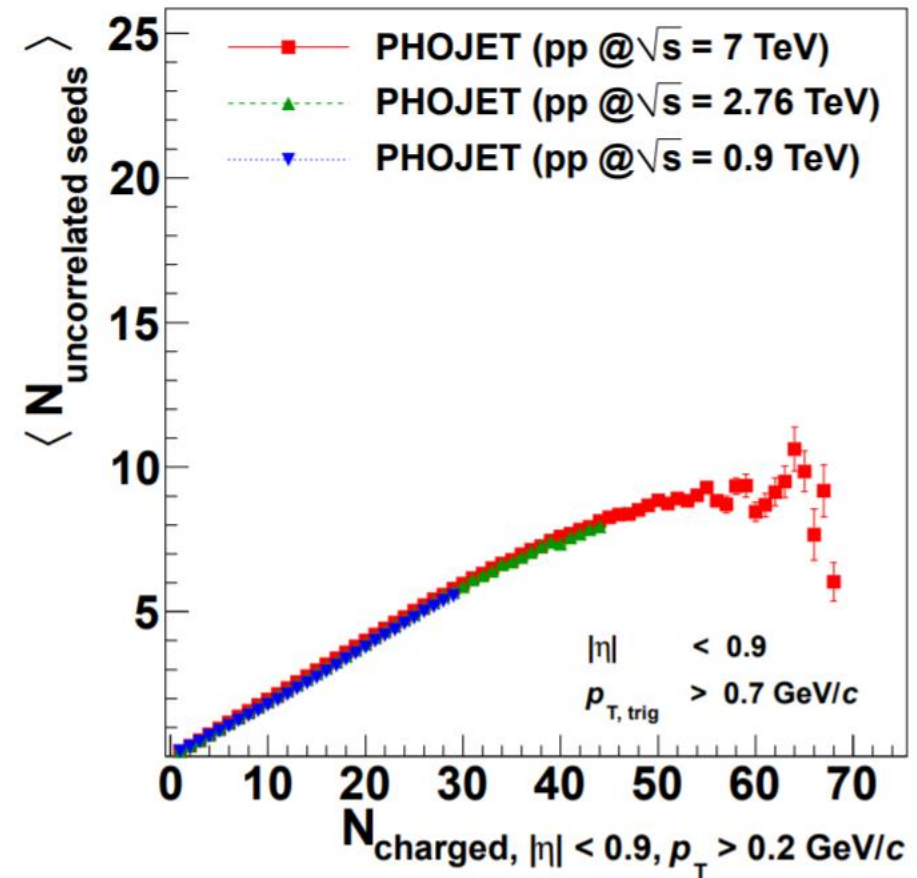
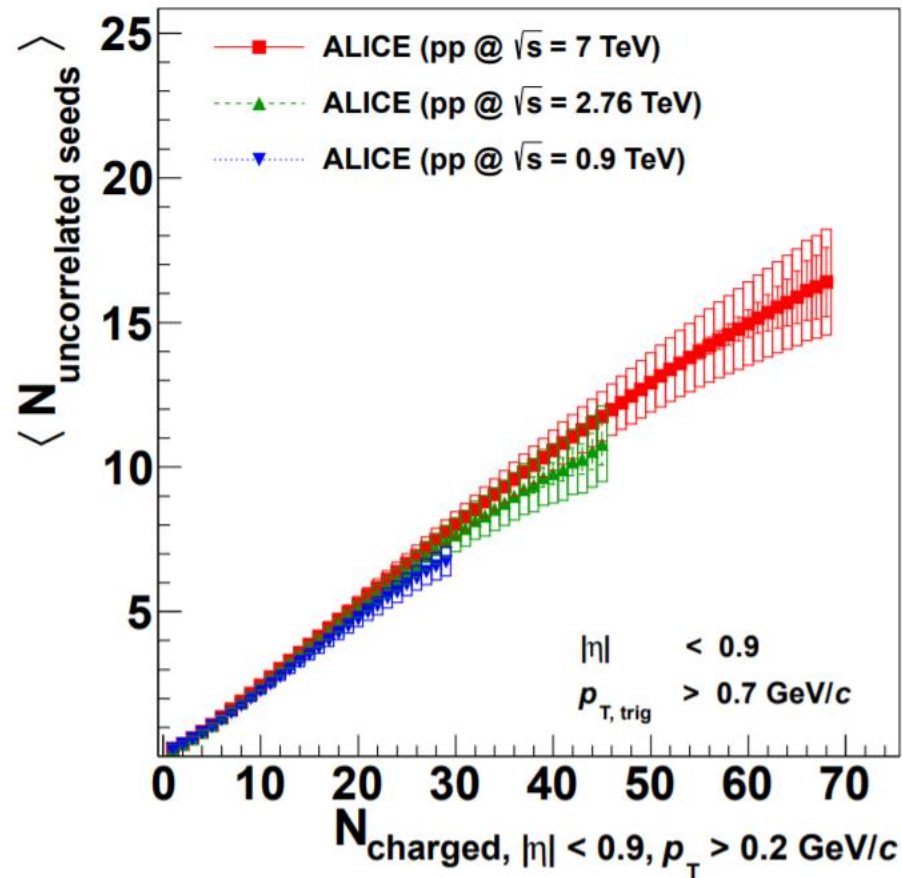
$$\langle N_{\text{assoc, near+away, } p_T > p_{T, \text{trig}}} \rangle = \langle N_{\text{assoc, near-side}} \rangle + \langle N_{\text{assoc, away-side}} \rangle$$



ALICE Collaboration, *Multiplicity dependence of two-particle azimuthal correlations in pp collisions at the LHC*

arXiv: 1307.1249

ALICE – badanie zależności „jet-like structure” od multiplicity

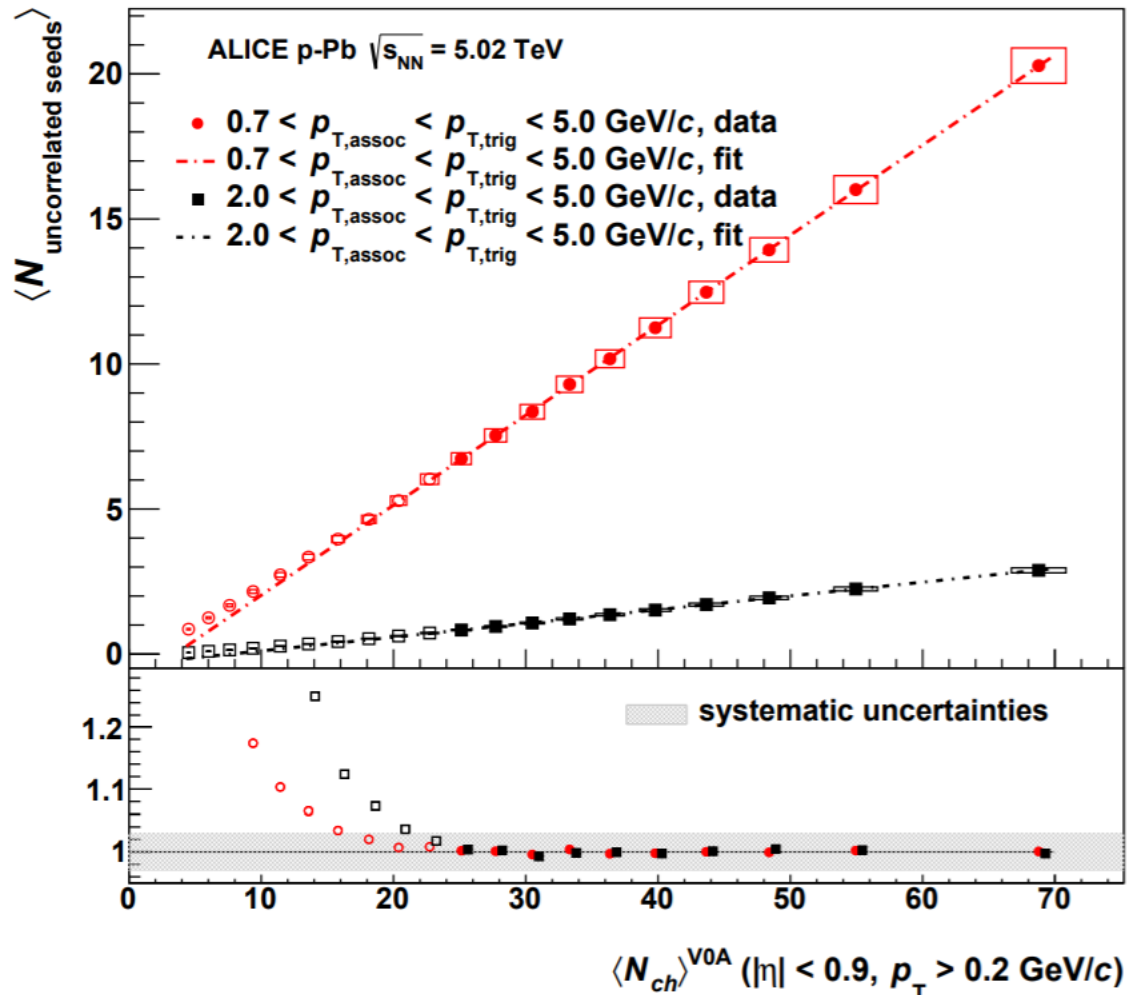


ALICE Collaboration, *Multiplicity dependence of two-particle azimuthal correlations in pp collisions at the LHC*

[arXiv:1307.1249](https://arxiv.org/abs/1307.1249)

ALICE – badanie zależności „jet-like structure” od multiplicity

Zderzenia p-Pb, 5.02 TeV



Wyniki zgodne z wynikami dla pp.

Wnioski:

- ridge w zderzeniach o dużej krotności nie pochodzi od minijetów, tylko od innych źródeł.

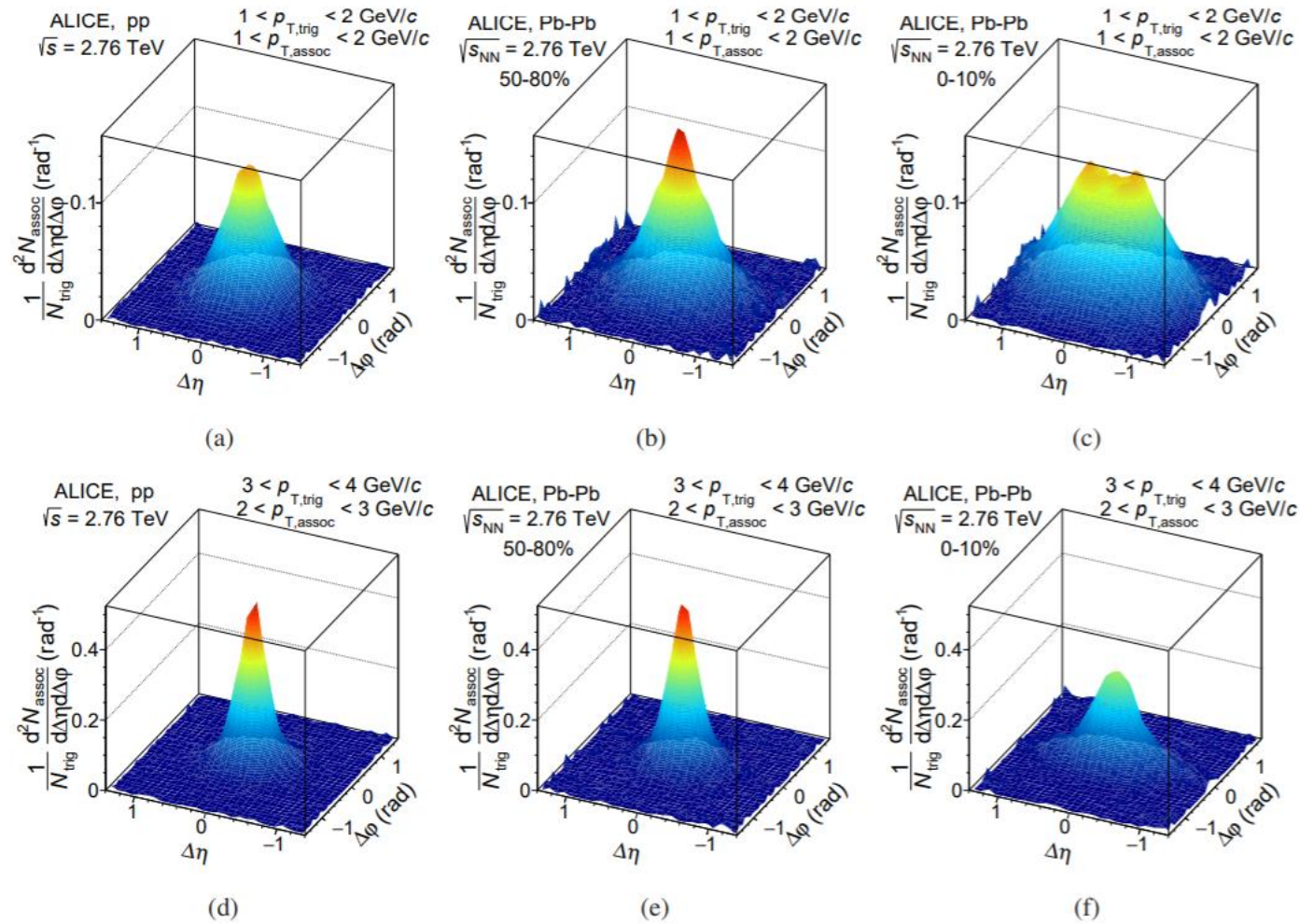
These findings are consistent with a picture where independent parton-parton scatterings with subsequent incoherent fragmentation produce the measured minijet associated yields, while the ridge yields, which vary with multiplicity, are the result of other sources.

ALICE Collaboration, *Multiplicity dependence of jet-like two-particle correlation structures in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*

arXiv:1406.5463

ALICE – badanie dżetów w zależności od p_T

Zderzenia Pb-Pb i p-p,
2.76 TeV

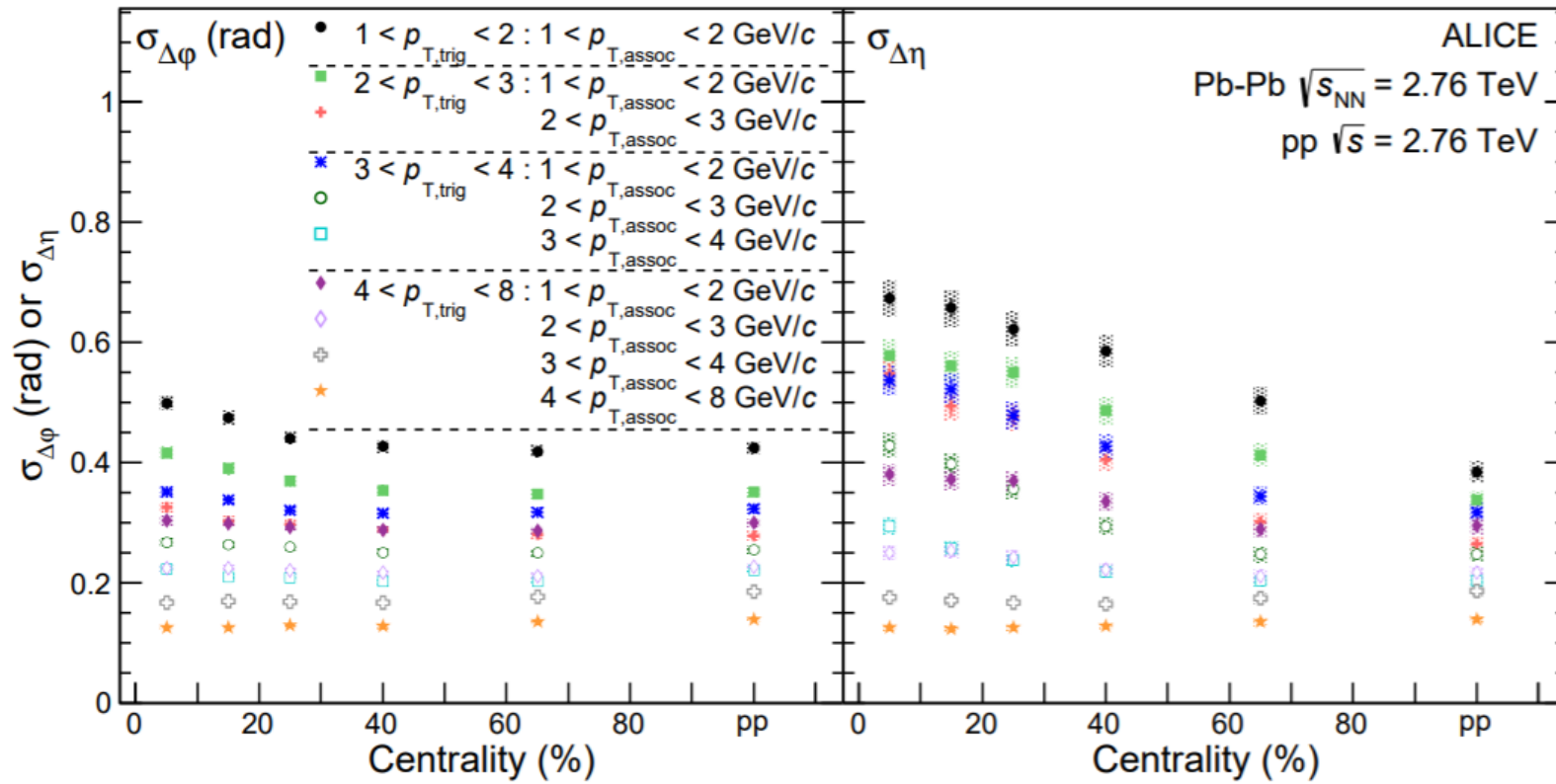


ALICE Collaboration, *Evolution of the longitudinal and azimuthal structure of the near-side jet peak in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$*

arXiv:1609.06667

ALICE – badanie dżetów w zależności od p_T

Zderzenia Pb-Pb i p-p,
2.76 TeV



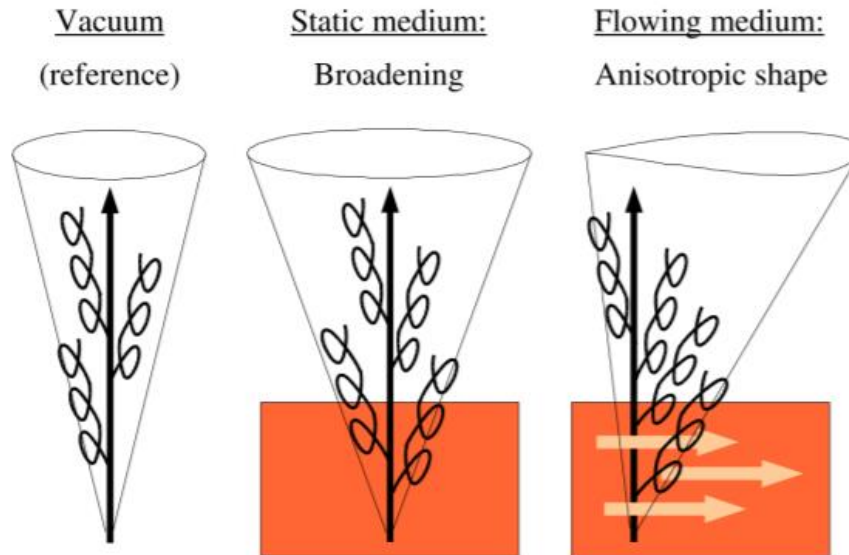
Wnioski:

- near-side peak pokazuje charakterystyczną zależność od p_T (szerokość maleje ze wzrostem p_T),
- Zależność od centralności

ALICE Collaboration, *Evolution of the longitudinal and azimuthal structure of the near-side jet peak in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*

arXiv:1609.06667

- Larger width in $\Delta\eta$ than in $\Delta\varphi$
 - Interaction with longitudinal flowing medium
Romatschke, Phys. Rev. C75 (2007) 014901
Armesto, Salgado, Wiedemann, Phys. Rev. C72 (2005) 064910
Armesto, Salgado, Wiedemann, PRL 93,242301 (2004)



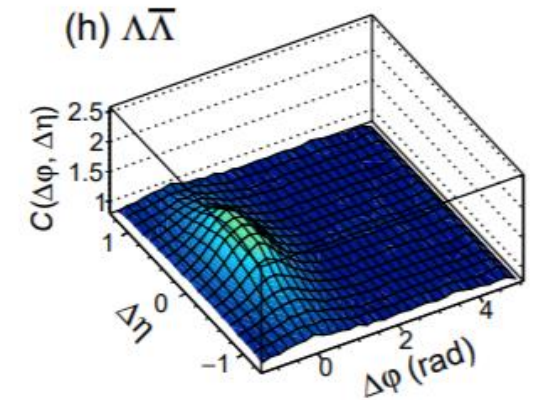
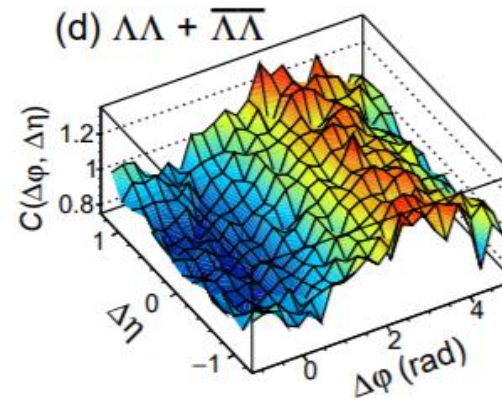
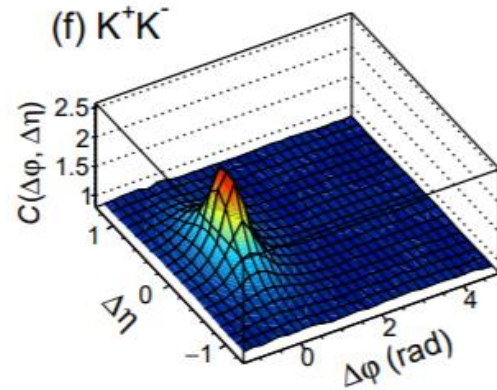
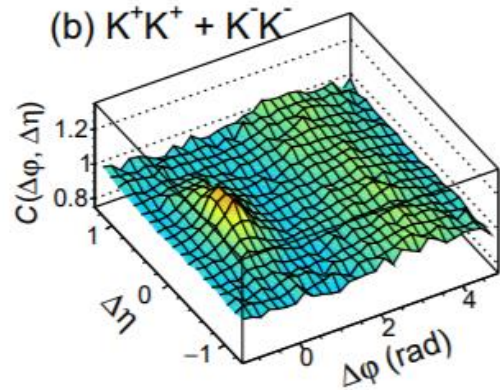
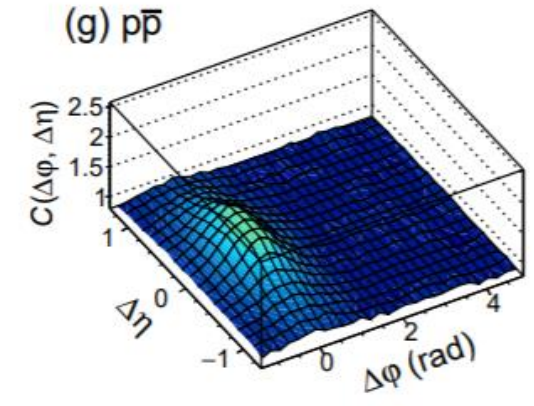
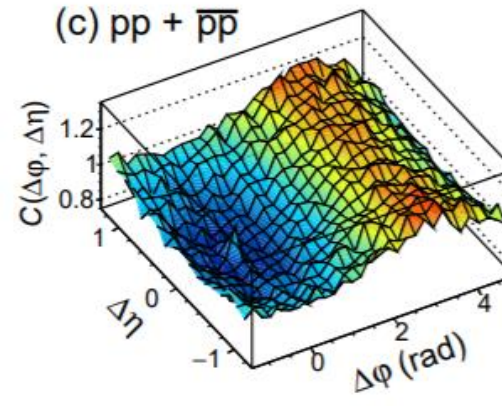
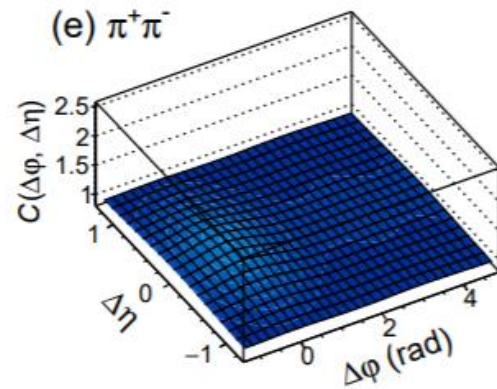
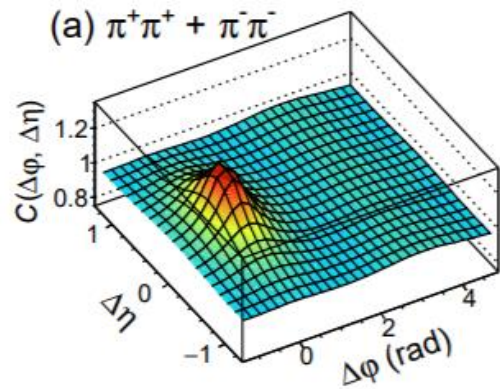
- Interaction with turbulent color fields
Majumder, Muller, Bass, Phys. Rev. Lett. 99 (2007) 042301
- Double hump-shape in the energy distribution of the jet
Armesto, Salgado, Wiedemann – PRL 93,242301 (2004)

Zderzenia Pb-Pb i p-p,
2.76 TeV

Przyczyny?

Korelacje cząstek zidentyfikowanych

ALICE pp $\sqrt{s} = 7$ TeV

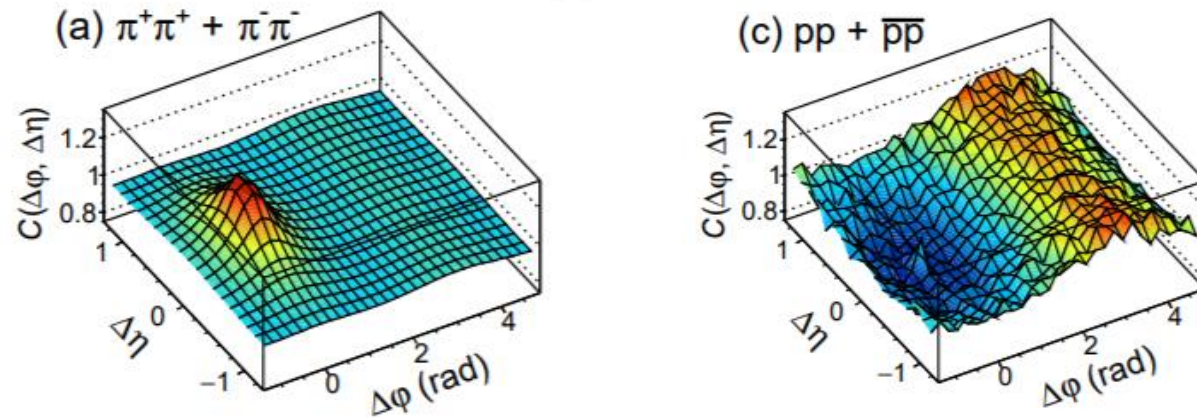


Korelacje cząstek zidentyfikowanych

mezon-mezon

vs

barion-barion



ALICE Collaboration, *Insight into particle production mechanisms via angular correlations of identified particles in pp collisions at $\sqrt{s} = 7$ TeV*

particles	momentum	charge	strangeness	baryon number
pions	✓	✓		
kaons	✓	✓	✓	
protons	✓	✓		✓

A. Zaborowska, *Pair angular correlations for pions, kaons and protons in proton-proton collisions in ALICE*

Oprócz pionów, kaonów i protonów możemy badać inne, bardziej *egzotyczne* cząstki

np. Ξ czy Ω

Particle	Composed quarks	Charge	Spin
Proton	uud	+	1/2
Lambda	uds	0	1/2
Xi	dss	-	1/2
Omega	sss	-	3/2

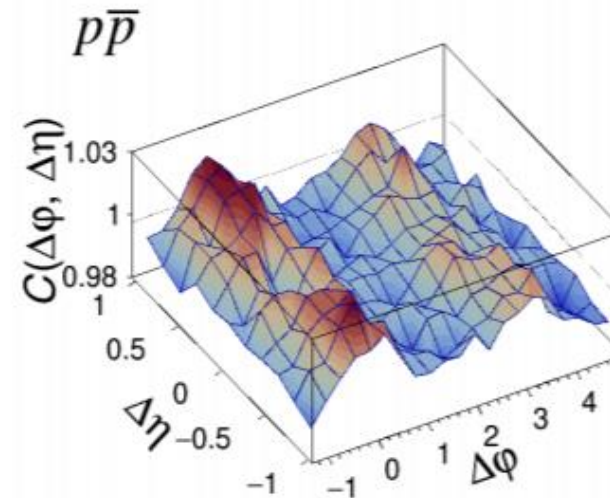
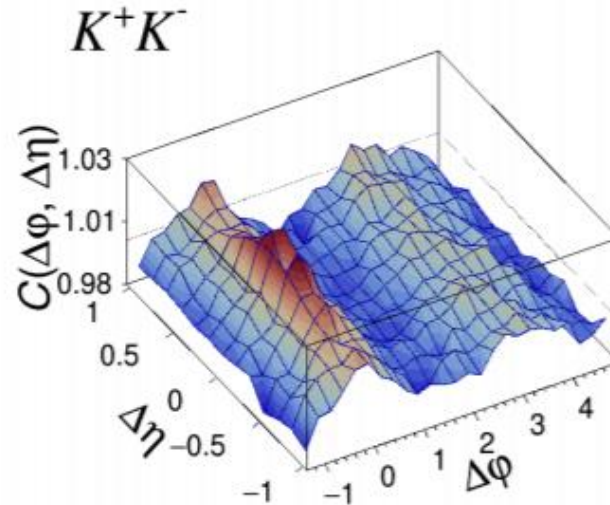
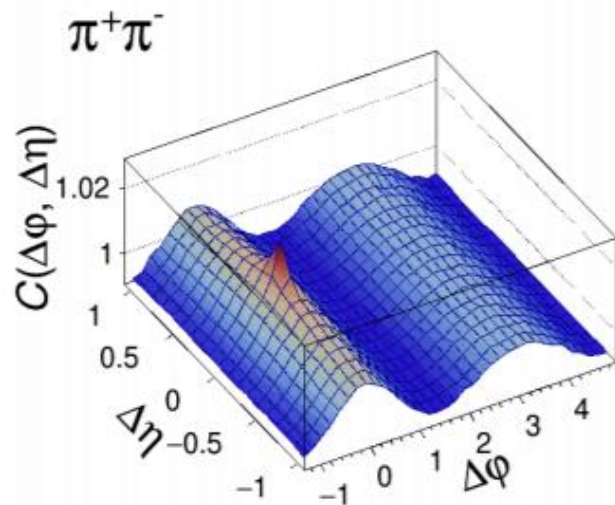
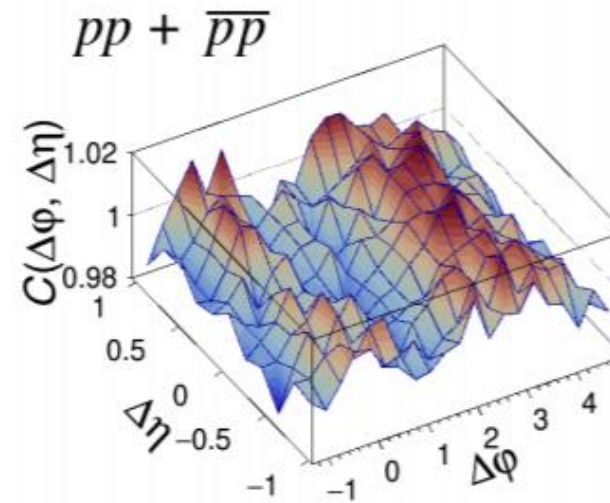
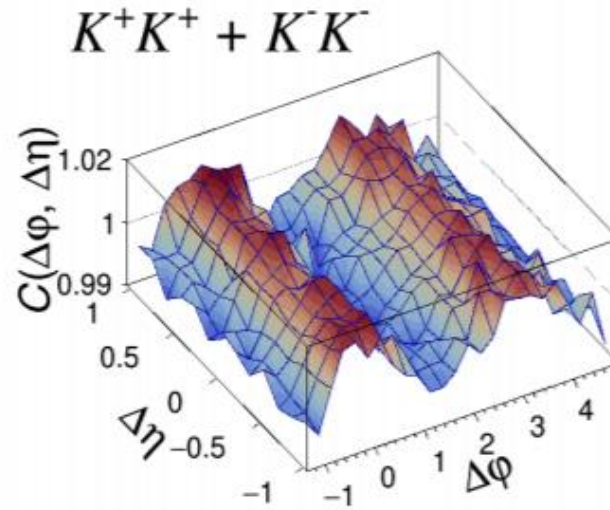
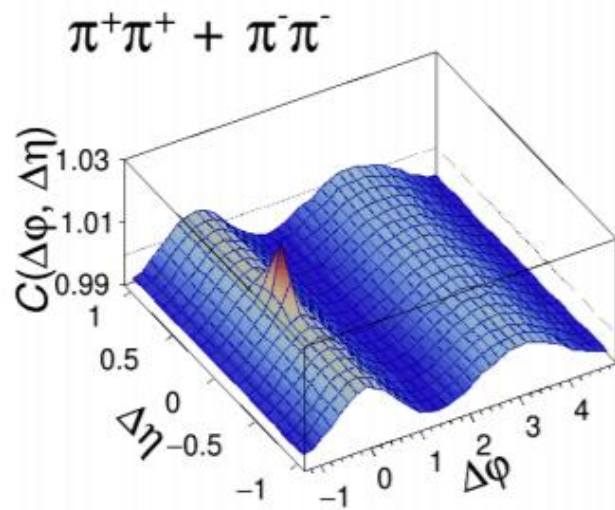
Table 1.1: Properties of analyzed baryons.

E. Łobejko, Ł. Graczykowski, M. Janik, G. Kornakov, *$\Delta\eta\Delta\phi$ angular correlations of baryons (pp , $p\Lambda$, $\Lambda\Lambda$, $p\Xi$, and $p\Omega$) in high multiplicity pp collisions at $\sqrt{s}=13$ TeV*, Analysis Note

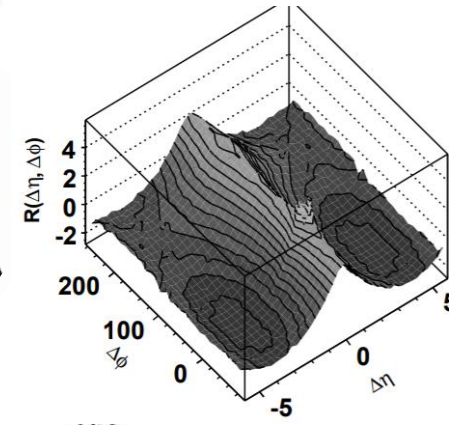
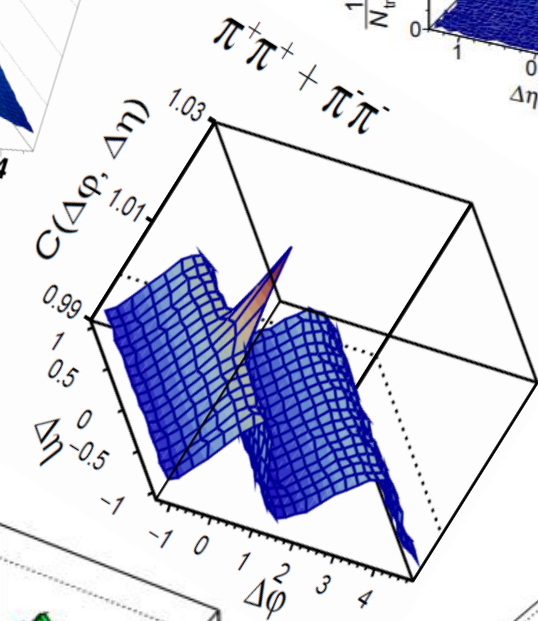
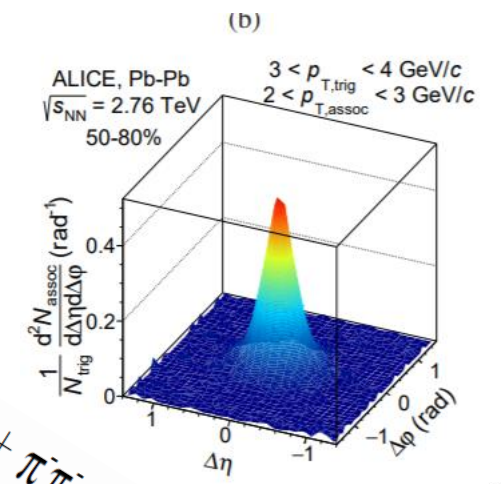
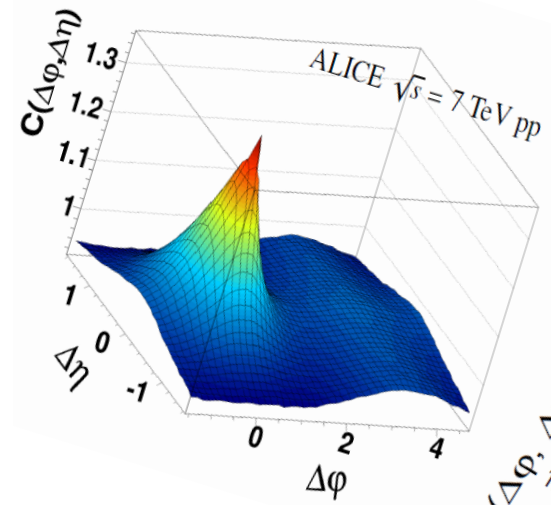
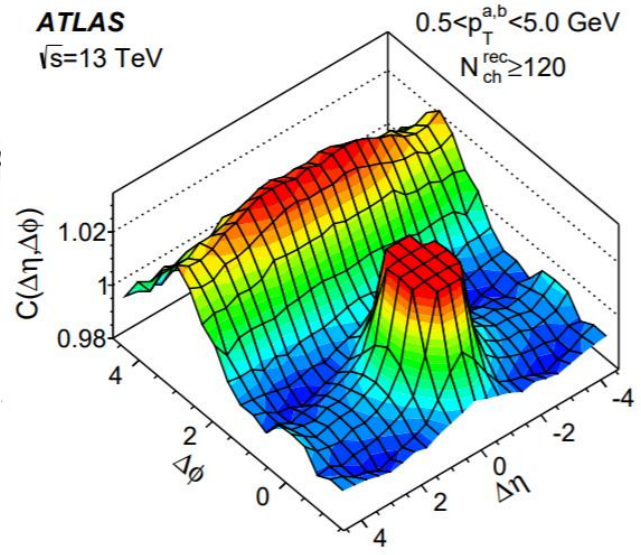
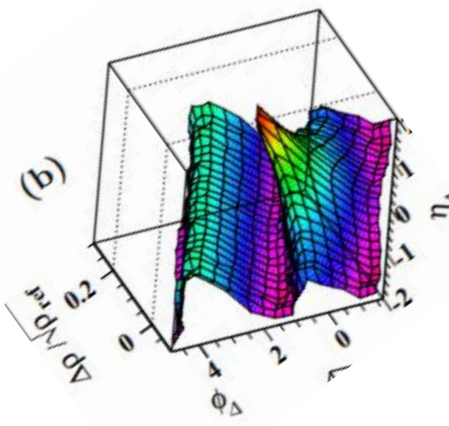
Korelacje kątowe

- Dobre narzędzie do obserwowania szerokiej gamy efektów fizycznych
- Punkt startowy do dalszych analiz
- Chcemy, żeby modele teoretyczne odtwarzały efekty widoczne w funkcjach $\Delta\eta\Delta\varphi$

Bonus – funkcje korelacyjne dla zidentyfikowanych cząstek, zderzenia Xe-Xe



Jeżeli ktoś zastanawiał się, jak wyglądają funkcje korelacyjne w całym zakresie centralności dla zderzeń ciężkich jonów przy energii 5.44 TeV...



Dziękuję za uwagę

