Korelacje w zderzeniach ciężkich jonów

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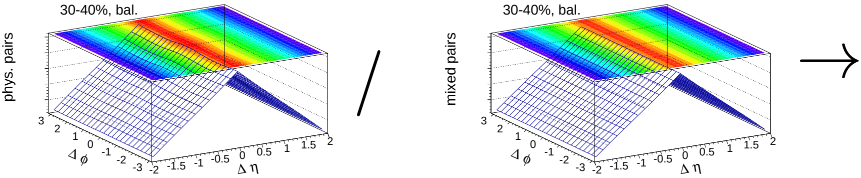
IFJ PAN & UJK

Seminarium, Instytut Fizyki UJ, 13 XI 2012

[**P. Bożek** & WB, PRL **109** (2012) 062301 oraz arXiv:1211.0845]

Definition

$$R_2(\Delta\eta, \Delta\phi) = \frac{N^{\text{pairs}}_{\text{phys}}(\Delta\eta,\Delta\phi)}{N^{\text{pairs}}_{\text{mixed}}(\Delta\eta)}$$



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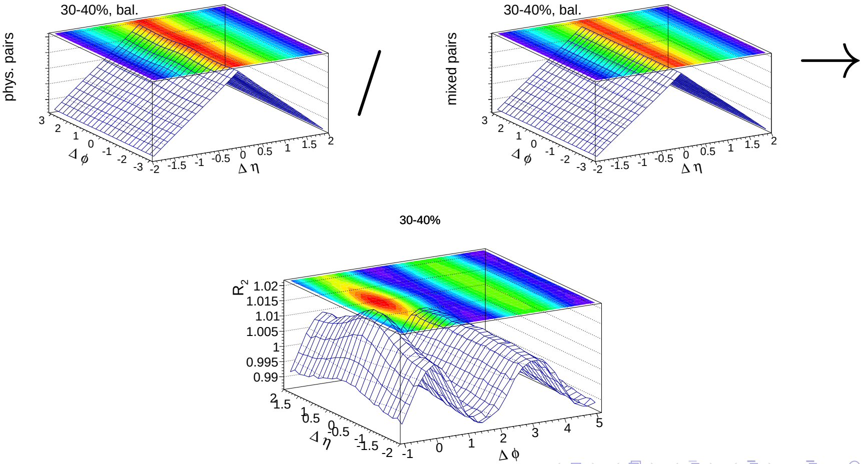
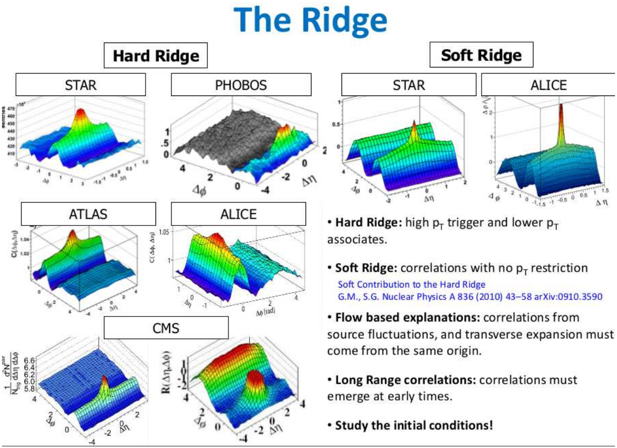


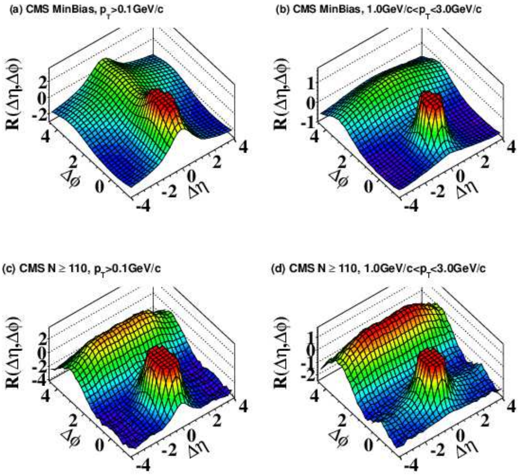
Sources of correlations

- jets $\rightarrow$ central peak (same jet), away-side ridge (back-to-back jets)
- collective harmonic flow $\rightarrow$ near- and away-side ridges
- charge balancing $\rightarrow$ central peak, shape of the near-side ridge
- resonance decays $\rightarrow$ away-side ridge
- Bose-Einstein $\rightarrow$ central peak
- Coulomb, final-state, ...

Ridges


The Ridge
Hard Ridge
Soft Ridge
STAR
PHOBOS
STAR
ALICE
ATLAS
ALICE
CMS
• Hard Ridge: high p_T trigger and lower p_T associates.
• Soft Ridge: correlations with no p_T restriction
Soft Contribution to the Hard Ridge
G.M., S.G. Nuclear Physics A 836 (2010) 43–58 arXiv:0910.3590
• Flow based explanations: correlations from source fluctuations, and transverse expansion must come from the same origin.
• Long Range correlations: correlations must emerge at early times.
• Study the initial conditions!

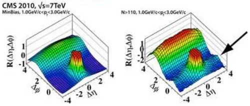
p-p


(a) CMS MinBias, p_T>0.1GeV/c
(b) CMS MinBias, 1.0GeV/c<p_T<3.0GeV/c
(c) CMS N ≥ 110, p_T>0.1GeV/c
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c
R(Δη,Δφ)
Δφ
Δη

Physics World

Curious correlations seen by CMS

Sep 23, 2010 · 16 comments



Does a mysterious ridge point to a quark–gluon plasma?

A subtle and unexpected signal in data from the Large Hadron Collider (LHC) in Geneva could mean that the proton accelerator is capable of creating a "hot soup" of interacting particles called a quark–gluon plasma.

The result comes as a surprise because physicists had believed that colliding protons at the LHC should not create such a plasma – hints of which have already been spotted by the RHIC accelerator in the US, which smashes heavy ions such as gold together.

Hundreds of particles

When two protons collide at 7 TeV at the LHC, hundreds of particles can sometimes be produced and detected. In order to understand the underlying physics, physicists look for correlations between the angles at which pairs of particles fly away from the point of impact.

Researchers using the Compact Muon Solenoid (CMS) experiment at the LHC had expected that a plot of the correlations would show a peak where the angles are zero, which would mean that the particles are leaving the collision point in a jet pointing in a specific direction. Instead, the peak seems to be riding on top of a ridge-like structure. This suggests that some particles are heading off in completely different directions – and correlations between pairs of these wayward particles are set by some sort of interaction between the particles when they were created in the collision.

One possible interpretation of the ridge is that the collision creates a dense fluid of many quarks and gluons – a quark–gluon plasma –

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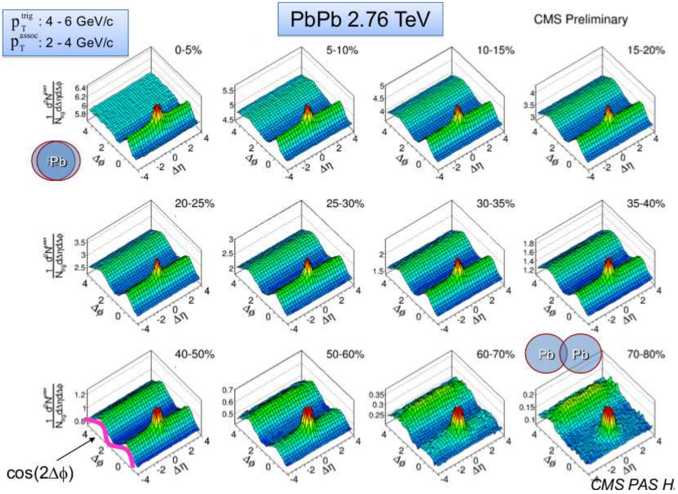
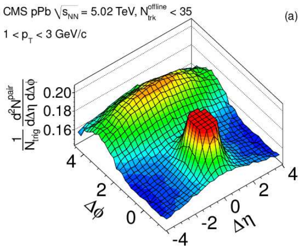
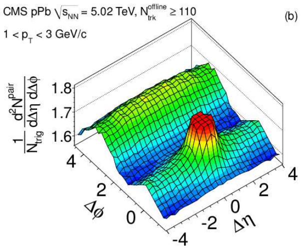
Pb-Pb


p_T^{trig} : 4 - 6 GeV/c
p_T^{assoc} : 2 - 4 GeV/c
PbPb 2.76 TeV
CMS Preliminary
0-5%
5-10%
10-15%
15-20%
20-25%
25-30%
30-35%
35-40%
40-50%
50-60%
60-70%
70-80%
Pb
Pb
Pb
$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi}$
Δφ
Δη
cos(2Δφ)
CMS PAS H

p-Pb





(released last month)

Flow

$$\rho_2^{\rm phys}(\Delta\phi,\Delta\eta)=\frac{1}{2\pi}\int d\phi_1 d\phi_2 d\eta_1 d\eta_2 \rho_1(\phi_1,\eta_1)\rho_1(\phi_2,\eta_2)\delta_{\Delta\phi-\phi_2+\phi_1}\delta_{\Delta\eta-\eta_2-\eta_1}+\rho_c(\Delta\phi,\Delta\eta)$$

$$\rho_2^{\rm mixed}(\Delta\eta)=\frac{1}{(2\pi)^2}\int d\Psi d\phi_1 d\phi_2 d\eta_1 d\eta_2 \rho_1(\phi_1,\eta_1)\rho_1(\phi_2-\Psi,\eta_2)\delta_{\Delta\phi-\phi_2+\phi_1}\delta_{\Delta\eta-\eta_2-\eta_1}$$

$$\rho_1(\phi,\eta)=n(\eta)[1+2\sum_n v_n(\eta)\cos(n\phi-\Psi_n)$$

$$R_2=\frac{\langle\int d\eta_1 d\eta_2 n(\eta_1)n(\eta_2)\left[1+2\sum_n v_n(\eta_1)v_n(\eta_2)\cos(n\Delta\phi)\right]\delta_{\Delta\eta-\eta_2+\eta_1}+\rho_c\rangle_{\rm events}}{\langle\int d\eta_1 d\eta_2 n(\eta_1)n(\eta_2)\delta_{\Delta\eta-\eta_2+\eta_1}\rangle_{\rm events}}=$$

$$=1+2\sum_n v_n^2(\Delta\eta)\cos(n\Delta\phi)\quad\text{(includes nonflow)}$$

spectra and flow coefficients as functions of η yield $v_n^2(\Delta\eta)$ only if $\rho_c=0$
e-by-e $\rightarrow$ presence of odd harmonics also for symmetric collisions

Fluctuations

Our approach ("Standard Model of heavy-ion collisions"):
initial $\rightarrow$ hydro $\rightarrow$ statistical hadronization

- **Initial phase** - "geometric fluctuations" from the distribution of nuclei
- **Hydrodynamics** - deterministic
- **Statistical hadronization** - fluctuations from a finite number of hadrons

Fluctuations

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initial $\to$ hydro $\to$ statistical hadronization

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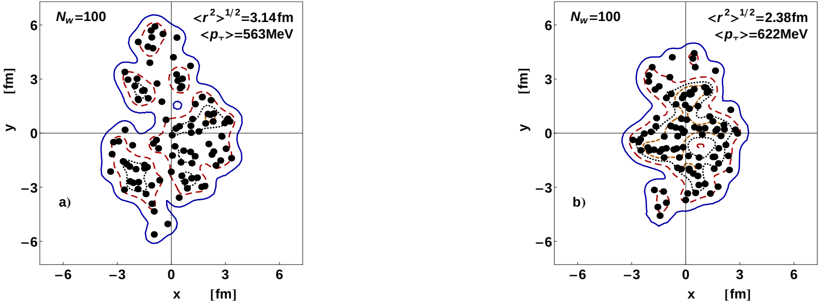
- **Hydrodynamics** - deterministic
- **Statistical hadronization** - fluctuations from a finite number of hadrons

1) Central p-Pb collisions are hydro-like – near-side ridge appears naturally for the first time
2) for A-A collisions the local charge conservation (balancing) very important for 2-particle correlations $\to$ explanation of bulk of the data for $\Delta\eta <\sim 1$, $\Delta\phi <\sim 1$ – explanation of the "puzzling nature" of the near-side ridge $\to$ **late charge separation**

Initial fluctuations in the Glauber approach



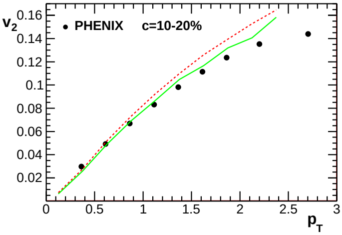
Two typical configuration of wounded nucleons in the transverse plane generated with GLISSANDO, isentropes at $s = 0.05$, 0.2, and 0.4 GeV^{-3}

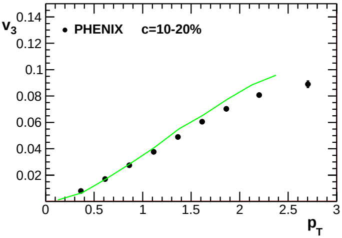
(taken as is, no need to talk about hotspots, tubes, etc.)

Hydrodynamics [Bożek]

3+1D viscous event-by-event hydrodynamics, tuned to reproduce the one-body **RHIC** data [Bożek 2012]
standard set of parameters:
$\tau_{\rm init} = 0.6$ fm/c, $\eta/s = 0.08$ (**shear**), $\zeta/s = 0.04$ (**bulk**), $T_f = 150$ MeV

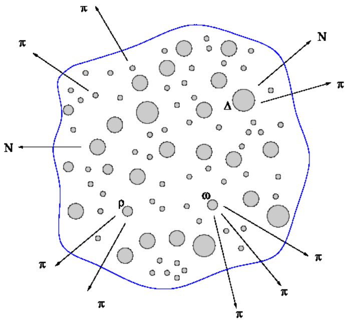
sample results → it works for one-body observables





solid: e-by-e, dashed: averaged initial condition

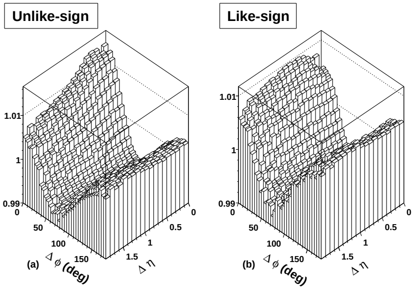
Final fluctuations



Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR), transverse-momentum conservation approximately imposed

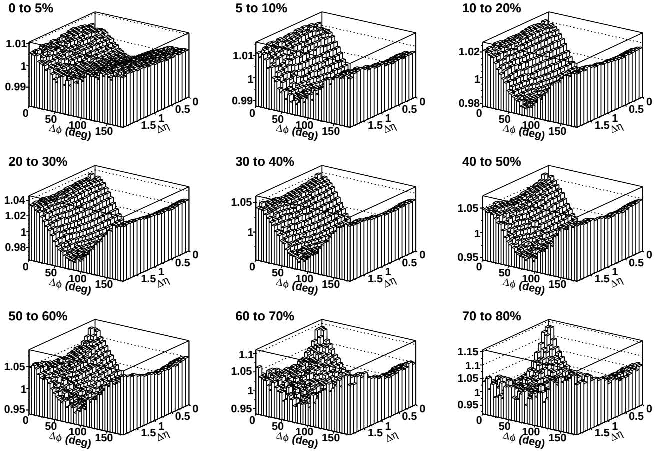
Star data, 2007

($0.8 < p_T < 4$ GeV - "unbiased", HBT peak removed)



STAR data, 2008

like sign ($0.8 < p_T < 4$ GeV - “unbiased”)



STAR data, 2008

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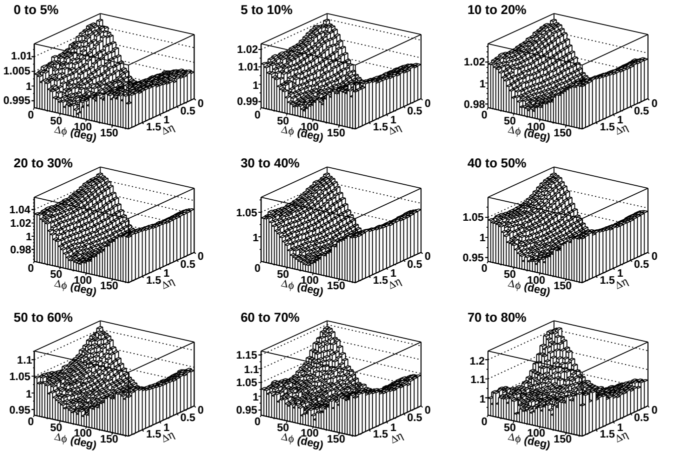
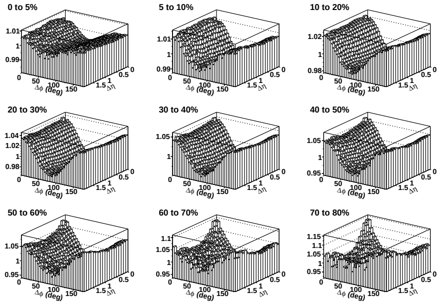
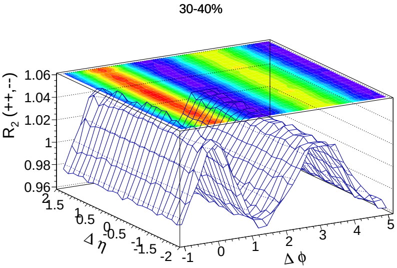


STAR vs. model

(like sign, $0.8 < p_T < 4$ GeV, model unbalanced)





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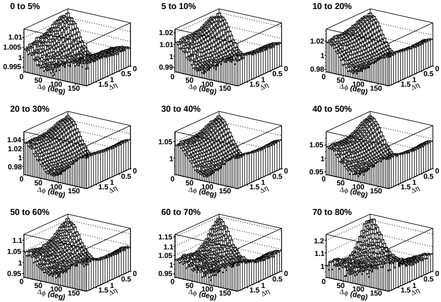
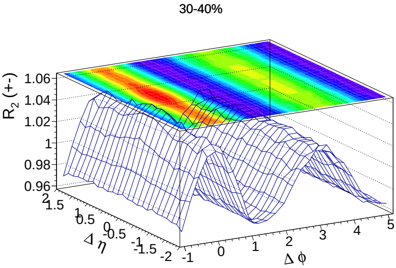
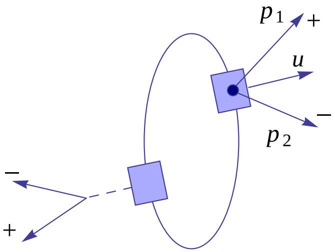




Charge balancing (from resonance decays and “direct”)

transverse-plane view of the expanding system at freeze-out

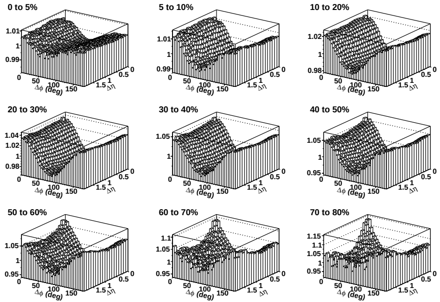


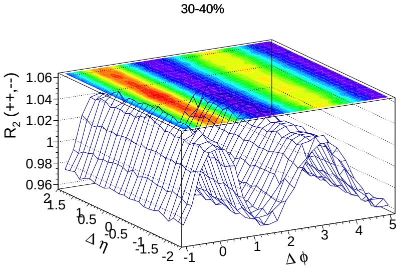
direct balancing: particle-antiparticle pair emitted from the neutral hydrodynamic medium at freeze-out from the same space-time point, e.g., $\pi^+\pi^-$, K^+K^-, $p\bar{p}$, ..., $\Delta^0\bar{\Delta}^0$ ...
resonances also contribute
special kind of clusters

many ways to modify/improve

STAR vs. model

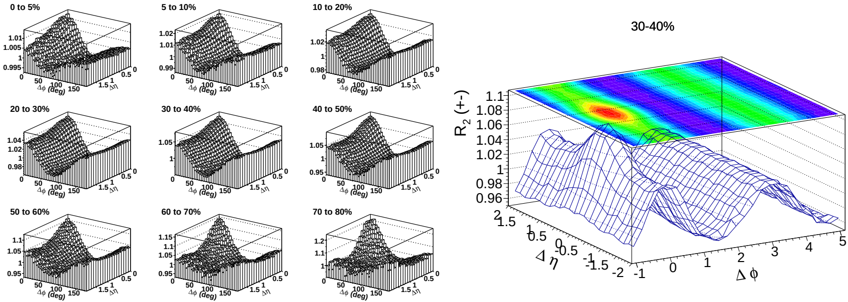
(like sign, $0.8 < p_T < 4$ GeV, balanced)





STAR vs. model

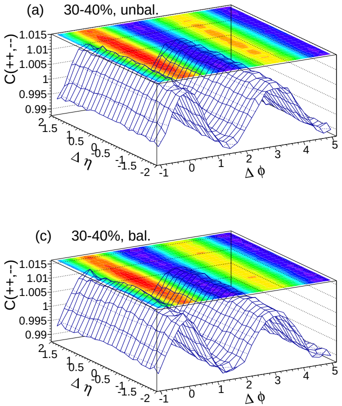
(unlike sign, $0.8 < p_T < 4$ GeV, balanced)



(correct "offsets" - compare to Takahashi et at. 2009, Sharma et al. 2011)

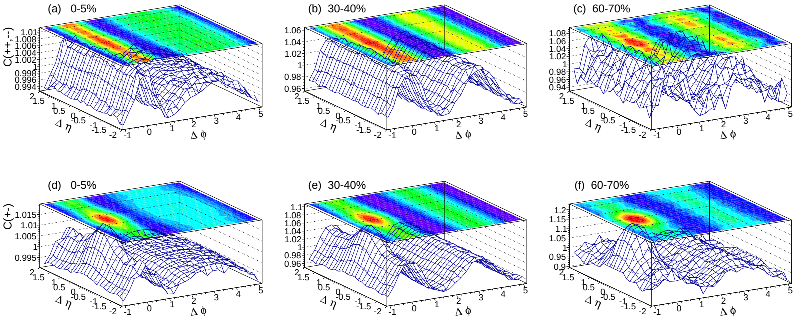
Role of balancing

$$(0.2 < p_T < 2 \text{ GeV}, \; C = R_2)$$



3 centralities

$(0.8 < p_T < 4$ GeV)



Balancing effect relatively strongest for central and peripheral collisions, as in the experiment

2D balance functions

$$B(\Delta\eta, \Delta\phi) = \frac{\langle\ N_{+-} - N_{++}\rangle}{\langle N_{+}\rangle} + \frac{\langle N_{-+} - N_{--}\rangle}{\langle N_{-}\rangle}$$

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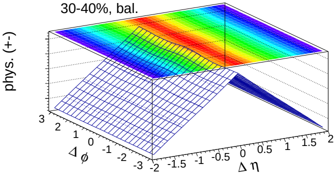

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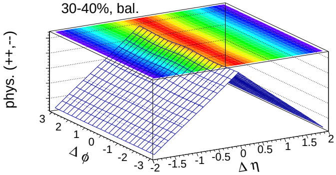
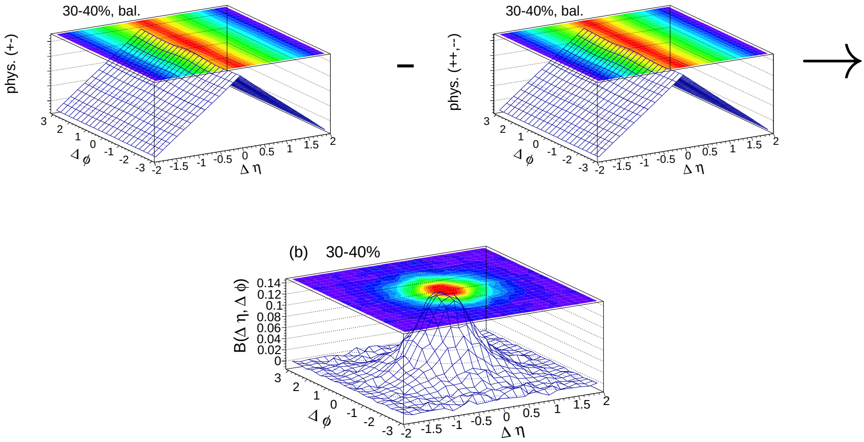


$\rightarrow$

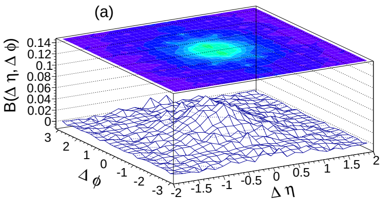
2D balance functions

$$B(\Delta\eta, \Delta\phi) = \frac{\langle N_{+-} - N_{++}\rangle}{\langle N_+\rangle} + \frac{\langle N_{-+} - N_{--}\rangle}{\langle N_-\rangle}$$



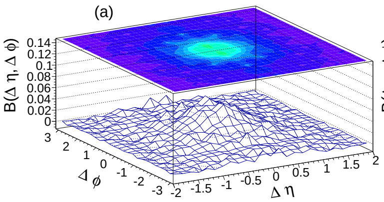
2D balance functions

Crucial role of charge balancing



2D balance functions

Crucial role of charge balancing



small (resonance decays only) big (direct balancing)

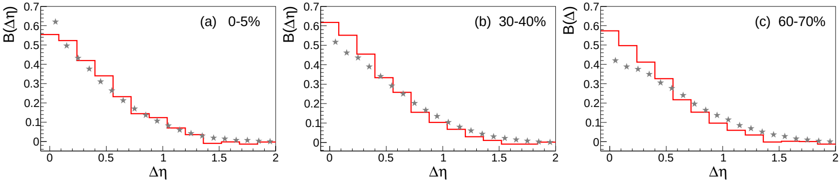
balancing + flow $\rightarrow$ collimation

important non-flow effect, a way to look at the data

(flow effects in correlations $\equiv$ obtainable by folding the single-particle distributions containing flow)

Balance functions in relative pseudrapidity $\Delta\eta$

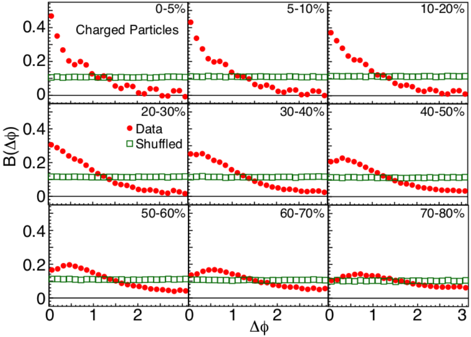
Marginal distribution of the above 2D function: the charge balance function in $\Delta\eta$



comparison to the STAR data

Balance functions in relative azimuth $\Delta\phi$

[STAR 2010]



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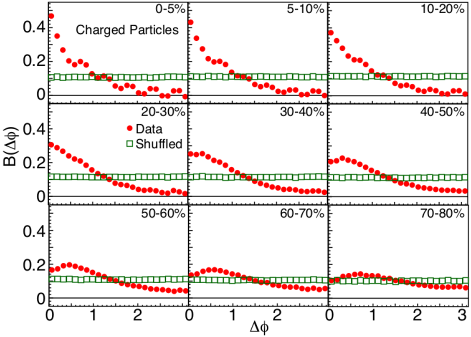
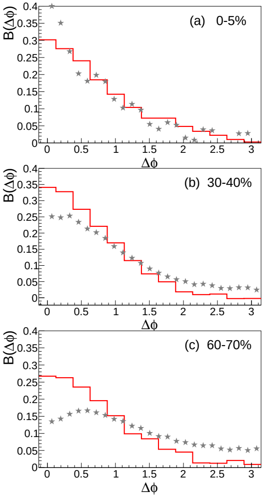
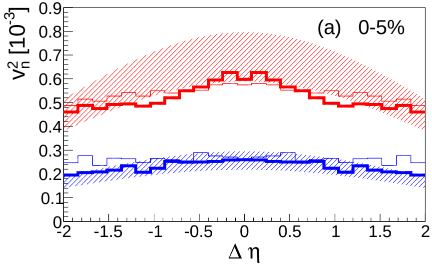




$v_n^2(\Delta\eta)$

$$v_n^2(\Delta\eta) = \int d\Delta\phi/(2\pi)\ \cos(n\Delta\phi) R_2(\Delta\eta, \Delta\phi)$$



comparison to extracted STAR data (HBT removed), v_2^2, v_3^2
fat: with balancing, thin: no balancing - completely **flat**

balancing → explanation of the fall-off of the same-side ridge in $\Delta\eta$

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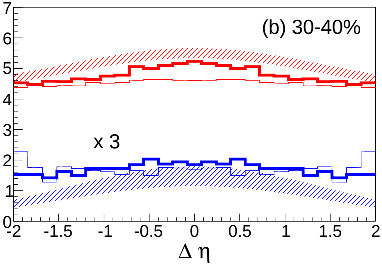

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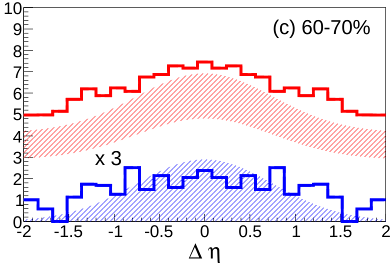
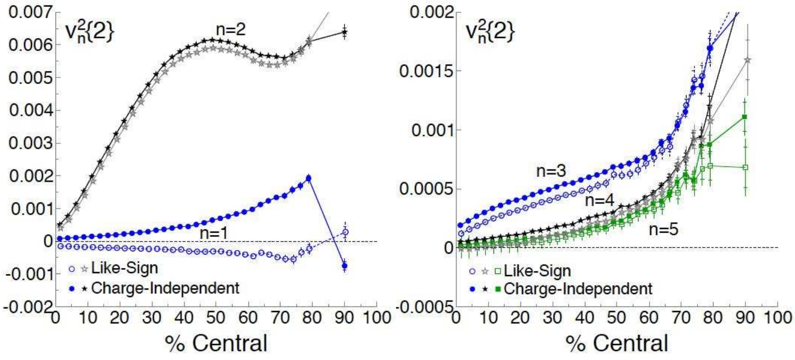


comparison to extracted STAR data (HBT removed), v_2^2, v_3^2
fat: with balancing, thin: no balancing - completely **flat**

balancing → explanation of the fall-off of the same-side ridge in $\Delta\eta$

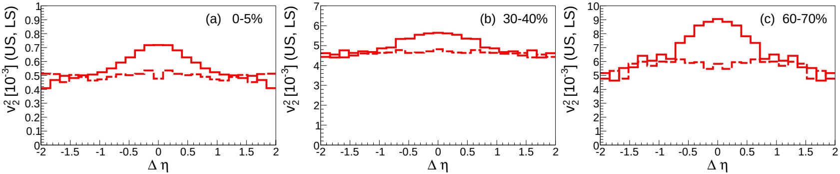
STAR 2011

Paul Sorensen at QM2011



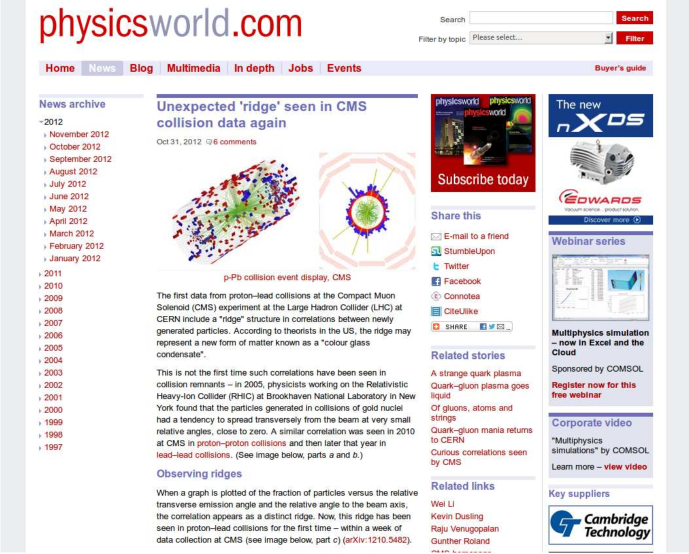
Charge-dependence of $v_n^2(\Delta\eta)$

$(0.15 < p_T < 2$ GeV)



solid: unlike, dashed: like

Physics World again



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Unexpected 'ridge' seen in CMS collision data again

Oct 31, 2012 6 comments

p-Pb collision event display, CMS

The first data from proton–lead collisions at the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN include a "ridge" structure in correlations between newly generated particles. According to theorists in the US, the ridge may represent a new form of matter known as a "colour glass condensate".

This is not the first time such correlations have been seen in collision remnants – in 2005, physicists working on the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in New York found that the particles generated in collisions of gold nuclei had a tendency to spread transversely from the beam at very small relative angles, close to zero. A similar correlation was seen in 2010 at CMS in proton–proton collisions and then later that year in lead–lead collisions. (See image below, parts *a* and *b*.)

Observing ridges

When a graph is plotted of the fraction of particles versus the relative transverse emission angle and the relative angle to the beam axis, the correlation appears as a distinct ridge. Now, this ridge has been seen in proton–lead collisions for the first time – within a week of data collection at CMS (see image below, part *c*) (arXiv:1210.5482).

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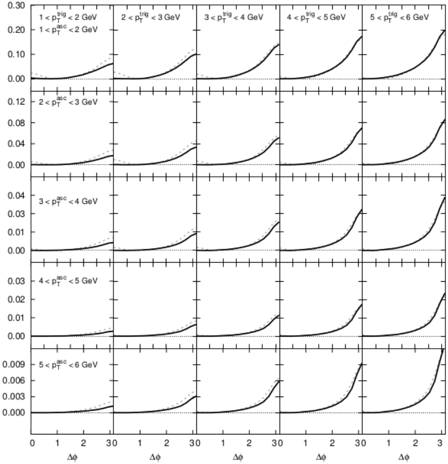
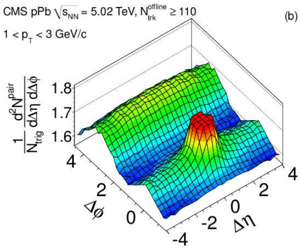
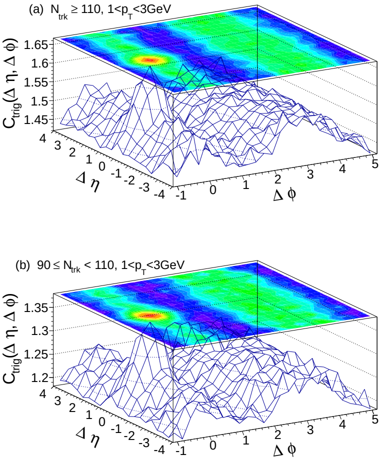


solid - pPb, dashed - pp

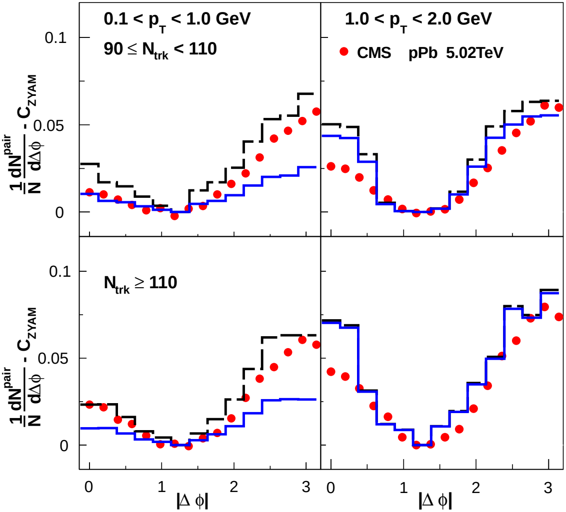
No near-side ridge!

Ridge

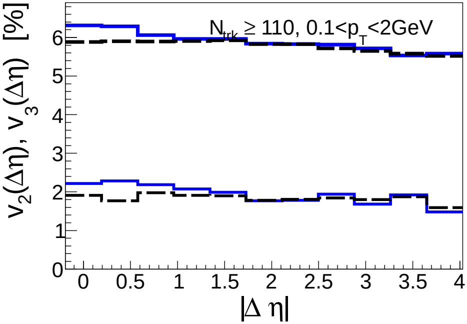

CMS pPb √s_NN = 5.02 TeV, N_trk^offline ≥ 110
(b)
1 < p_T < 3 GeV/c
1/N_trig d²N^pair/dΔη dΔφ
Δφ
Δη


(a) N_trk ≥ 110, 1<p_T<3GeV
C_trig(Δ η, Δ φ)
Δ η
Δ φ
(b) 90 ≤ N_trk < 110, 1<p_T<3GeV
C_trig(Δ η, Δ φ)
Δ η
Δ φ

Projection $2 \leq |\Delta\eta \leq 4$

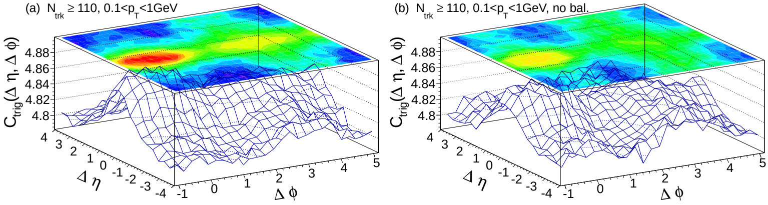


Flow in p-Pb



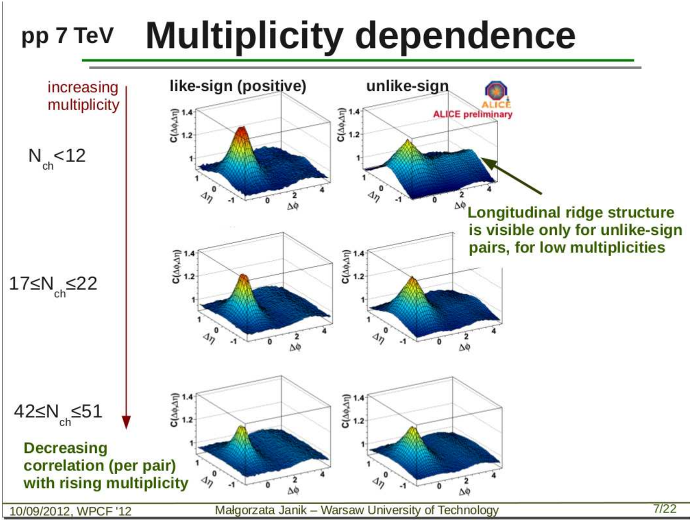
possible to measure directly in the experiment

“Longitudinal” ($\Delta\eta \sim 0$) ridge

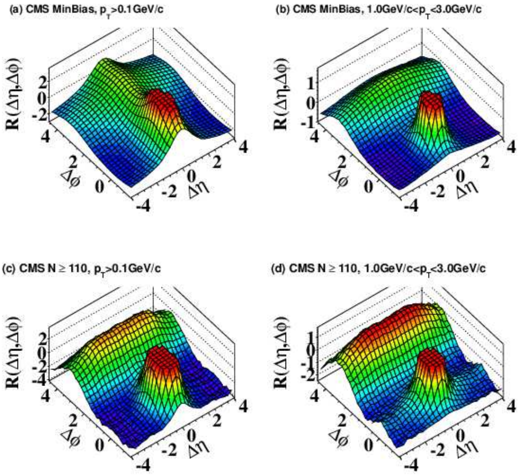


back-to-back emission for soft particles

p-p in ALICE, Małgorzata Janik @ WPCF 2012



Longitudinal ridge in p-p from CMS



Conclusions

- E-by-e hydro in semi-quantitative agreement with the (soft) data for 2-particle 2D correlations from RHIC and LHC for A-A and p-A collisions
- **Charge balancing** combined with flow explains the shape of the same-side ridge for $\Delta\eta <\sim 1$ and $\Delta\phi$ - major **non-flow** effect
- The fall-off of the flow coefficients $v_n^2(\Delta\eta)$ reproduced
- Charge balancing increases $v_n^2\{2\}$ by a few % and splits the like-sign and unlike-sign combinations

  $\rightarrow$ **late charge separation**

- Explanation of the same-side ridge in p-Pb

  $\rightarrow$ **collective behavior in high-multiplicity small systems**

- Longitudinal ridge