# Charge balancing in heavy-ion collisions

Piotr Bożek and Wojciech Broniowski

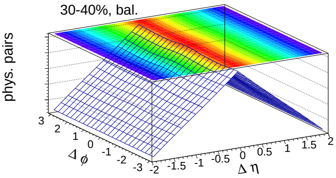
IFJ PAN & UJK

IX Polish Workshop on Relativistic Heavy-Ion Collisions, UJ, 24-25.11.2012

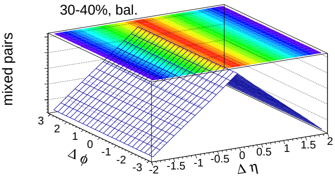
[based on PRL **109** (2012) 062301 and arXiv:1211.0845]

# Correlations

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



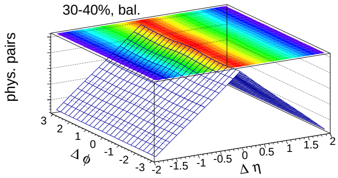

$/$



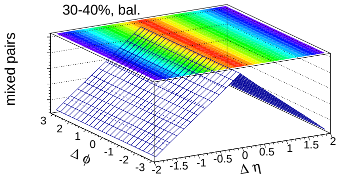

$\rightarrow$

# Correlations

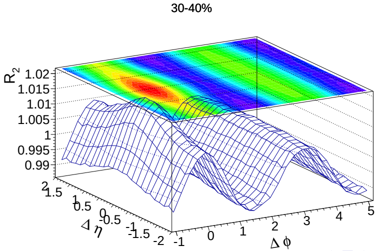
$$R_2(\Delta\eta,\Delta\phi) = \frac{N^{\rm pairs}_{\rm phys}(\Delta\eta,\Delta\phi)}{N^{\rm pairs}_{\rm mixed}(\Delta\eta)}$$




/



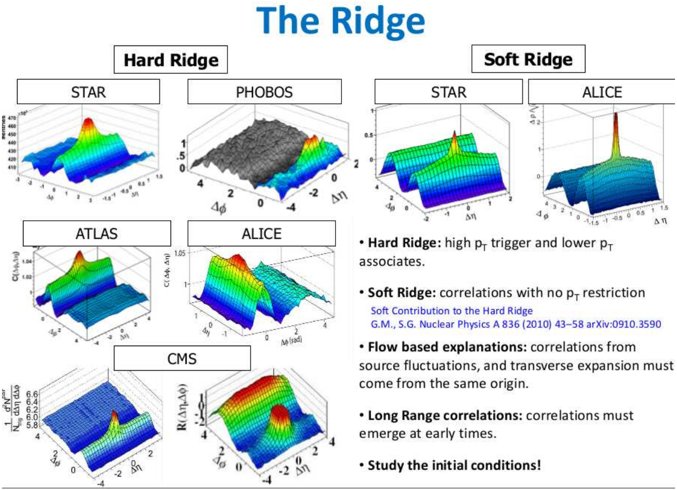

→



# Sources of correlations

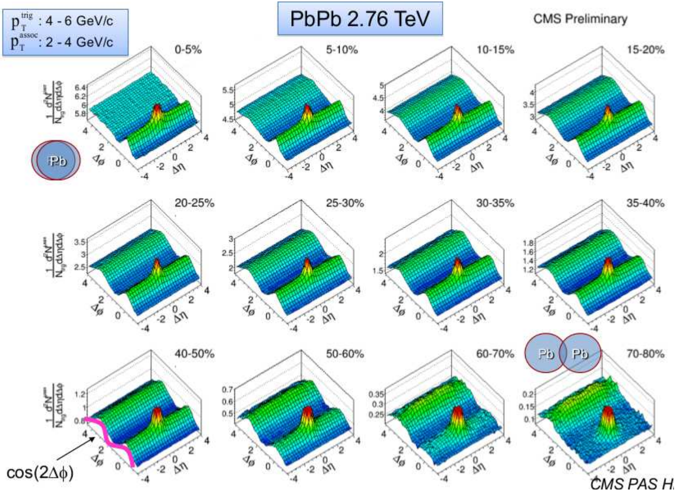
- jets $\rightarrow$ central peak (same jet), away-side ridge (back-to-back jets)
- collective harmonic flow $\rightarrow$ near- and away-side ridges
- charge balancing $\rightarrow$ central peak, shape of the near-side ridge
- resonance decays $\rightarrow$ away-side ridge
- Bose-Einstein $\rightarrow$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

# Ridges found everywhere!

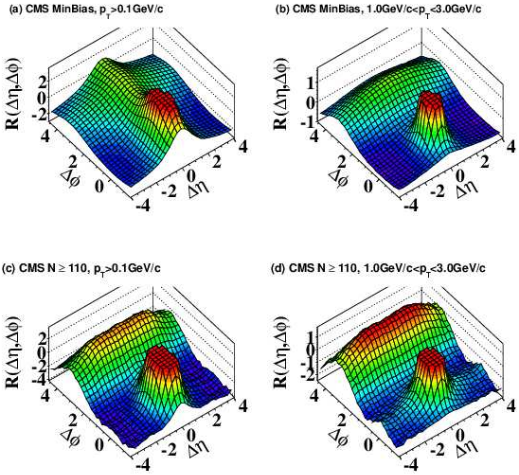



[from G. Moschelli]

# 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-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

IOP A website from the Institute of Physics — Sign in | Forgotten your password? | Sign up | Contact us

physicsworld.com

Search — Filter by topic: Please select... — Filter

Home | News | Blog | Multimedia | In depth | Jobs | Events | Buyer's guide

## 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 –

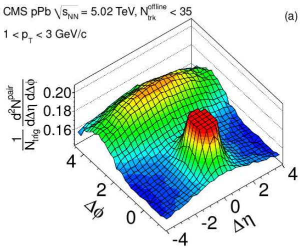
News archive: 2012, 2011, 2010 (December 2010, November 2010, October 2010, September 2010, August 2010, July 2010, June 2010, May 2010, April 2010, March 2010, February 2010, January 2010), 2009, 2008, 2007, 2006, 2005, 2004, 2003, 2002, 2001, 2000, 1999, 1998, 1997

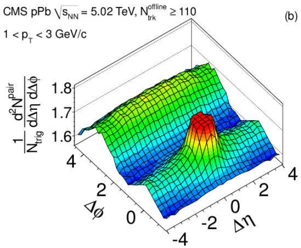
Share this: E-mail to a friend, StumbleUpon, Twitter, Facebook, Connotea, CiteUlike, SHARE

Related stories: RHIC nets strange antimatter; Life at the high-energy frontier; A strange quark plasma (in depth); Of gluons, atoms and strings (in depth)

Related links: arXiv: 1009.4122; CMS; CERN; RHIC

# p-Pb




(released last month - see Piotr Bożek's talk)

# Flow

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

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

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

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

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

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

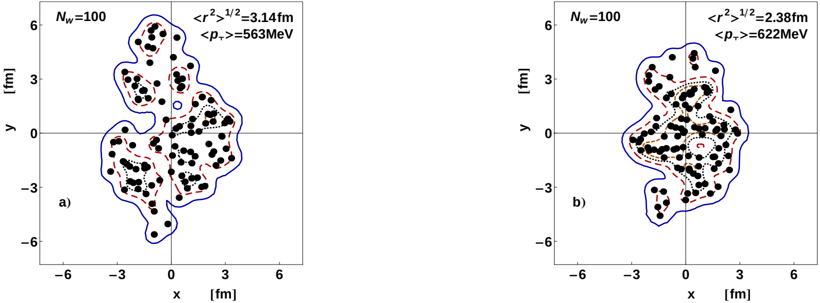
# Fluctuations

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

**For A-A collisions the local charge conservation (balancing)** very important for 2-particle correlations $\rightarrow$ 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 $\rightarrow$ **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.)

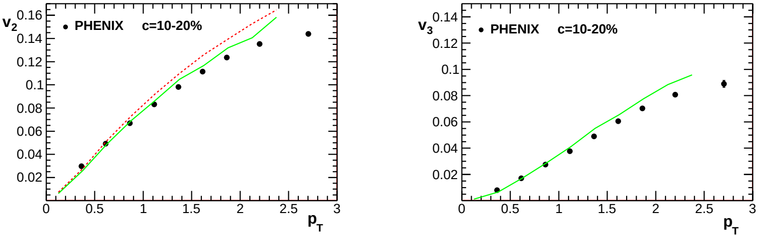
# Hydrodynamics [Bożek]

3+1D viscous event-by-event hydrodynamics, tuned to reproduce the one-body **RHIC** data [Bożek 2012]

standard set of parameters:

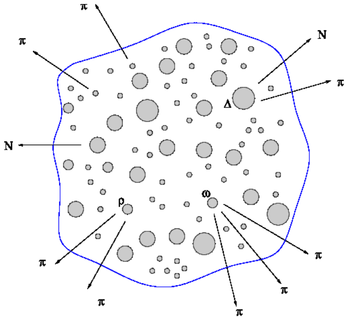
$\tau_{\rm init} = 0.6$ fm/c, $\eta/s = 0.08$ (**shear**), $\zeta/s = 0.04$ (**bulk**), $T_f = 150$ MeV

sample results → it works for one-body observables




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

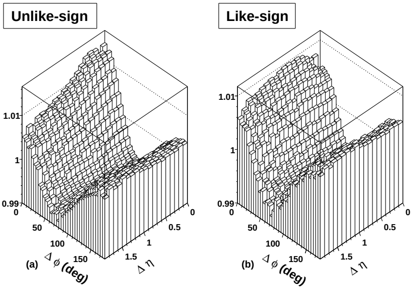
# Final fluctuations




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

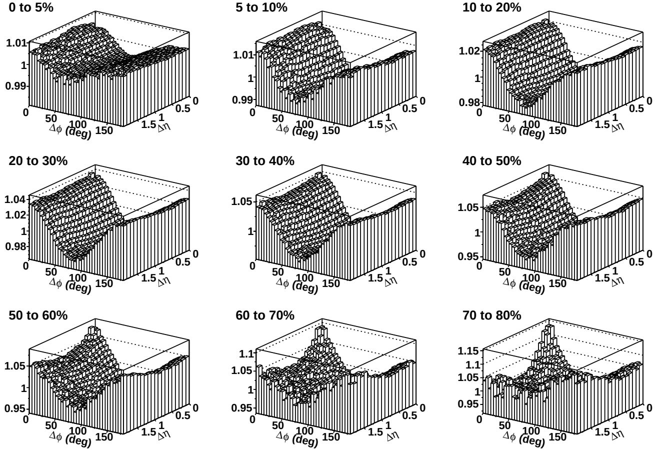
# Star data, 2007

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



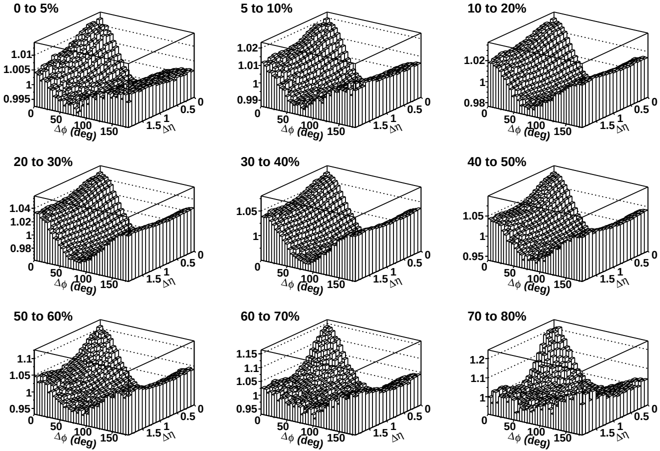
# STAR data, 2008

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



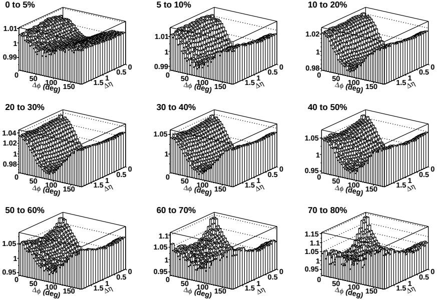
# STAR data, 2008

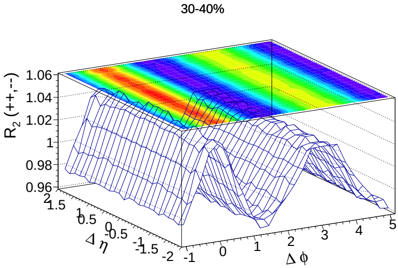
unlike sign ($0.8 < p_T < 4$ GeV - “unbiased”)



# STAR vs. model

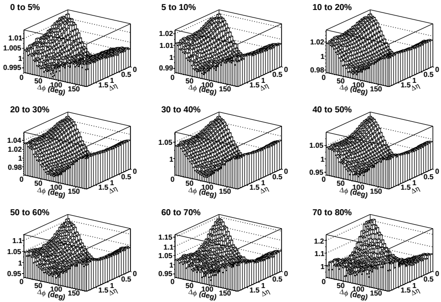
(like sign, $0.8 < p_T < 4$ GeV, model unbalanced)

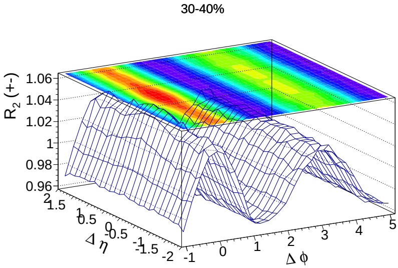


# STAR vs. model

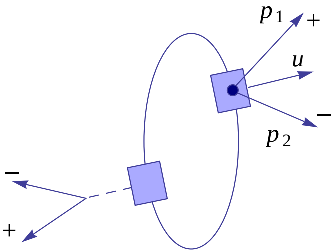
(unlike sign, $0.8 < p_T < 4$ GeV, model unbalanced)



# Charge balancing (from resonance decays and “direct”)

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

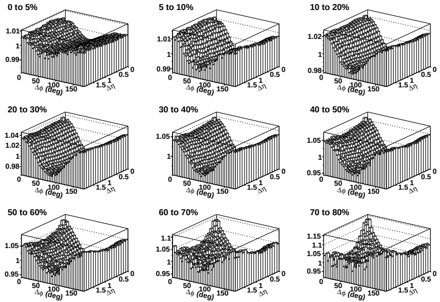


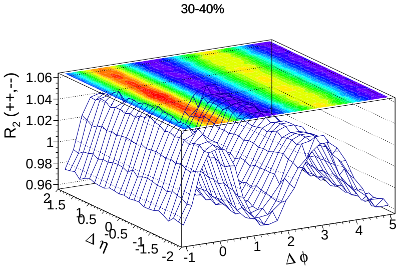

**direct balancing**: particle-antiparticle pair emitted from the neutral hydrodynamic medium at freeze-out from the same space-time point, e.g., $\pi^+\pi^-$, $K^+K^-$, $p\bar{p}$, . . . , $\Delta^0\bar{\Delta}^0$ . . .
resonances also contribute
special kind of clusters

many ways to modify/improve

# STAR vs. model

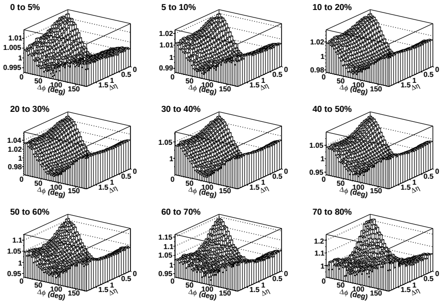
(like sign, $0.8 < p_T < 4$ GeV, balanced)

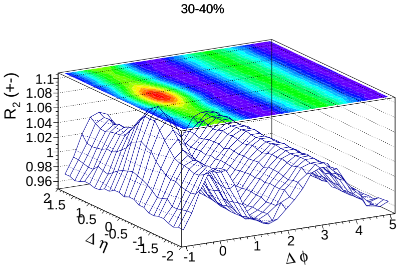


# STAR vs. model

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

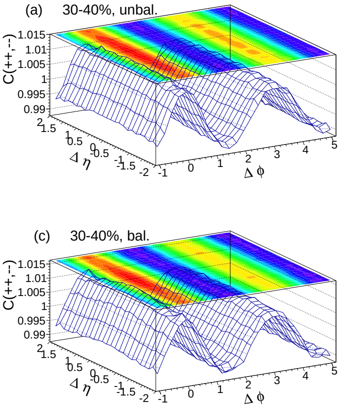



(correct “offsets” - compare to Takahashi et at. 2009, Sharma et al. 2011)

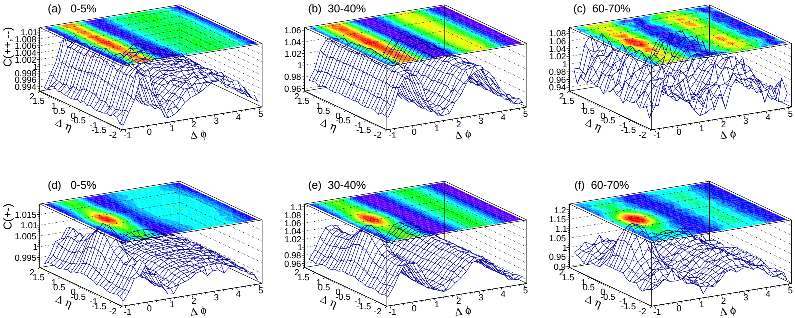
# Role of balancing

$(0.2 < p_T < 2$ GeV, $C = R_2)$



# 3 centralities

$(0.8 < p_T < 4$ GeV)



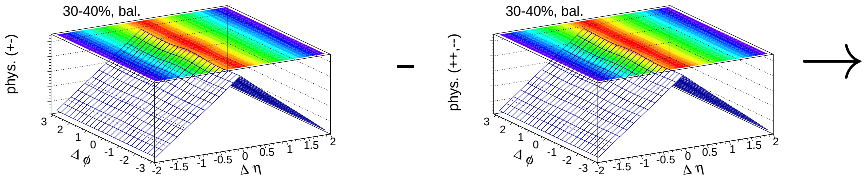

Balancing effect relatively strongest for central and peripheral collisions, as in the experiment

# 2D balance functions

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

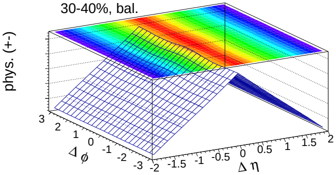
# 2D balance functions

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

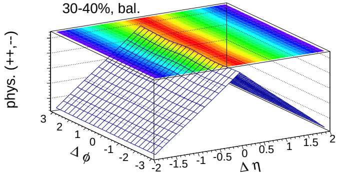


# 2D balance functions

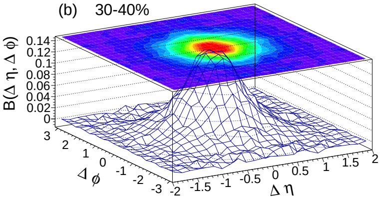
$$B(\Delta\eta, \Delta\phi) = \frac{\langle\ N_{+-} - N_{++}\rangle}{\langle N_{+}\rangle} + \frac{\langle N_{-+} - N_{--}\rangle}{\langle N_{-}\rangle}$$




−

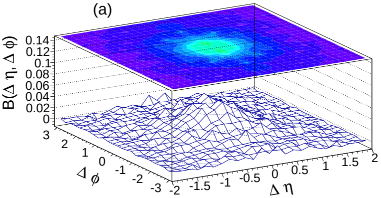



→



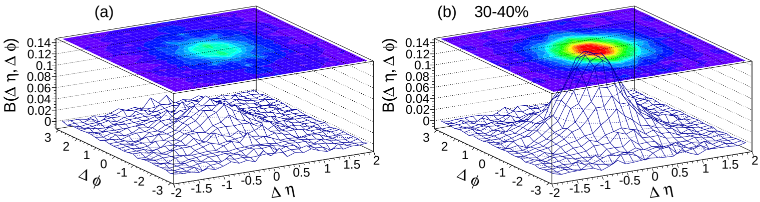
# 2D balance functions

Crucial role of charge balancing



# 2D balance functions

Crucial role of charge balancing

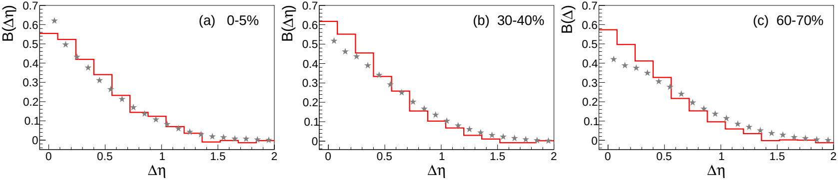



small (resonance decays only) big (direct balancing)

balancing + flow → collimation
important non-flow effect, a way to look at the data
(flow effects in correlations ≡ obtainable by folding the single-particle distributions containing flow)

# Balance functions in relative pseudrapidity $\Delta\eta$

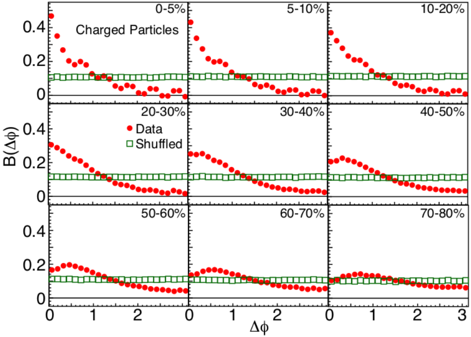
Marginal distribution of the above 2D function: the charge balance function in $\Delta\eta$




comparison to the STAR data

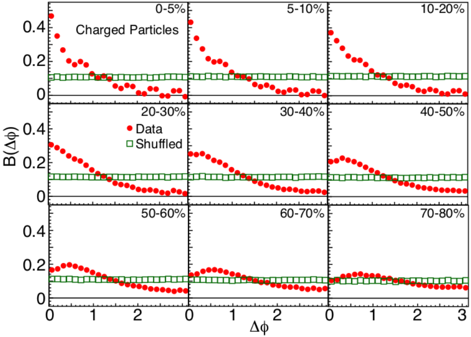
# Balance functions in relative azimuth $\Delta\phi$

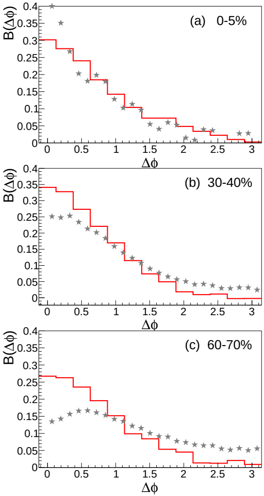
[STAR 2010]



# Balance functions in relative azimuth $\Delta\phi$

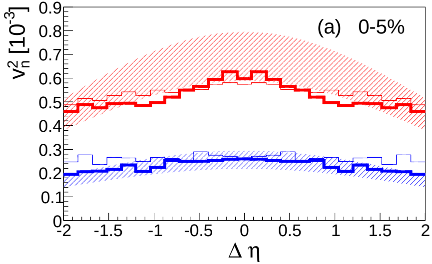
[STAR 2010]



# $v_n^2(\Delta\eta)$

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

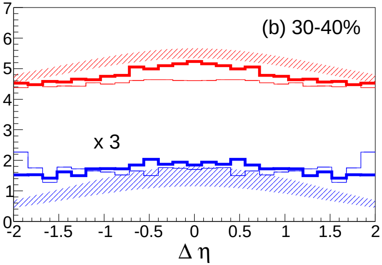



comparison to extracted STAR data (HBT removed), $v_2^2$, $v_3^2$
fat: with balancing, thin: no balancing - completely **flat**

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

# $v_n^2(\Delta\eta)$

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

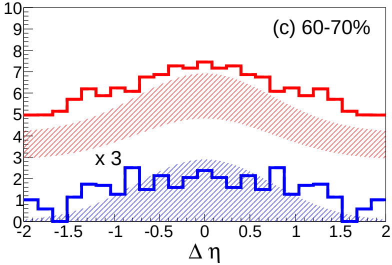



comparison to extracted STAR data (HBT removed), $v_2^2$, $v_3^2$
fat: with balancing, thin: no balancing - completely **flat**

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

# $v_n^2(\Delta\eta)$

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

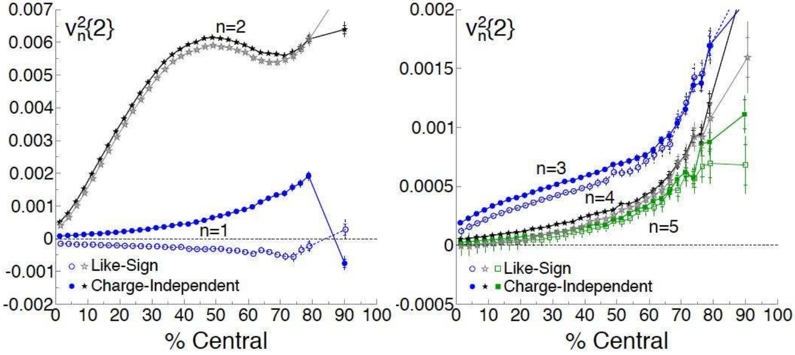



comparison to extracted STAR data (HBT removed), $v_2^2$, $v_3^2$
fat: with balancing, thin: no balancing - completely **flat**

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

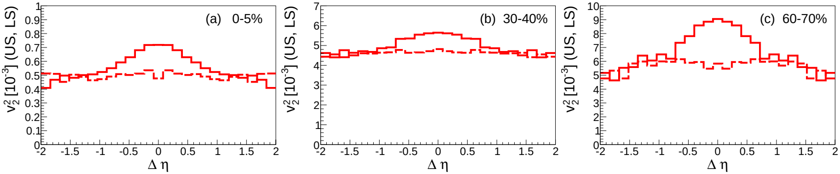
# STAR 2011

Paul Sorensen at QM2011



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

$(0.15 < p_T < 2$ GeV)




solid: unlike, dashed: like

# 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**