Charge balancing in 2-dimensional correlations

Wojciech Broniowski and Piotr Bożek

Institute of Nuclear Physics PAN, Cracow, &
Jan Kochanowski U., Kielce

VIII Workshop on Particle Correlations and Femtoscopy
Frankfurt am Main, Germany, Sept. 10-14, 2012

[based on PRL **109** (2012) 062301]

Initial fluctuations

Correlations carry rich info on the physics of the heavy-ion collision
Our approach: initial → hydro → statistical hadronization

- **Initial phase** - "geometric fluctuations" from the distribution of nuclei [Miller & Snellings 2003, PHOBOS 2006, Andrade et al. 2006]
- **Hydrodynamics** - here deterministic
- **Statistical hadronization** - fluctuations from a finite number of hadrons

flow/non-flow? HBT, resonances, Coulomb, final-state, jets

[Takahashi et al. 2009, Alver et al. 2010, Staig & Shuryak 2010, Moscy & Sorensen 2010, Luzum 2011, Schenke et al. 2011, Qiu et al. 2012, Kapusta, Mueller & Stephanov 2012 . . . Trainor]

Initial fluctuations

Correlations carry rich info on the physics of the heavy-ion collision
Our approach: initial → hydro → statistical hadronization

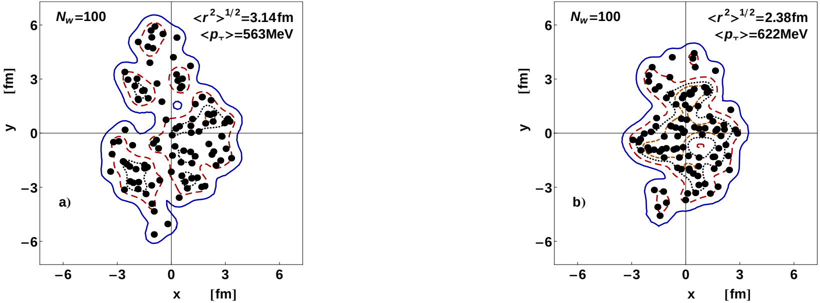
- **Initial phase** - "geometric fluctuations" from the distribution of nuclei [Miller & Snellings 2003, PHOBOS 2006, Andrade et al. 2006]
- **Hydrodynamics** - here deterministic
- **Statistical hadronization** - fluctuations from a finite number of hadrons

flow/non-flow? HBT, resonances, Coulomb, final-state, jets

[Takahashi et al. 2009, Alver et al. 2010, Staig & Shuryak 2010, Moscy & Sorensen 2010, Luzum 2011, Schenke et al. 2011, Qiu et al. 2012, Kapusta, Mueller & Stephanov 2012 . . . Trainor]

Local charge conservation (balancing) very important for 2-particle correlations → explanation of bulk of the data for $\Delta\eta <\sim 1$, $\Delta\phi <\sim 1$

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

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**), $T_f = 140$ MeV

$\eta/s = 0.16$ $T_f = 150$ MeV

Hydrodynamics

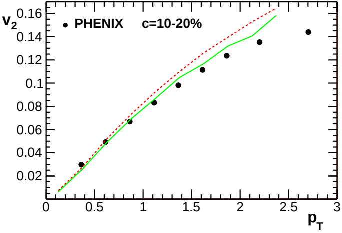
3+1D viscous event-by-event hydrodynamics, tuned to reproduce the one-body **RHIC** data [Bożek 2012]

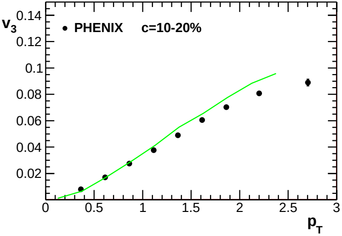
standard set of parameters:

$\tau_{\rm init} = 0.6$ fm/c, $\eta/s = 0.08$ (**shear**), $\zeta/s = 0.04$ (**bulk**), $T_f = 140$ MeV

$\eta/s = 0.16$ $T_f = 150$ MeV

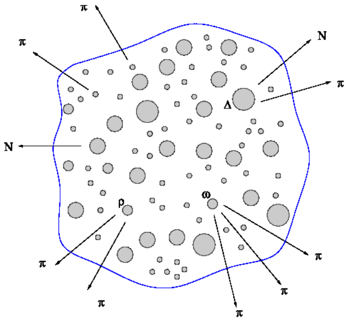
sample results (see Piotr Bożek's talk) → it works





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

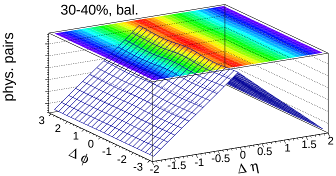
Final fluctuations



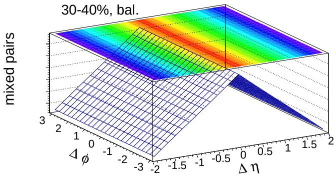
Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR)

Definition

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



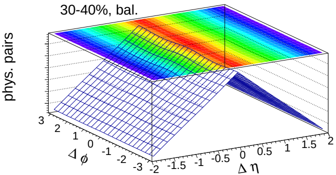
/



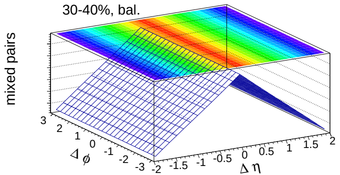
$\rightarrow$

Definition

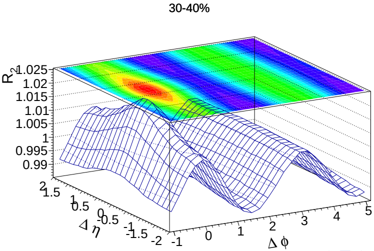
$$R_2(\Delta\eta, \Delta\phi) = \frac{N^{\text{pairs}}_{\text{phys}}(\Delta\eta, \Delta\phi)}{N^{\text{pairs}}_{\text{mixed}}(\Delta\eta)}$$



/

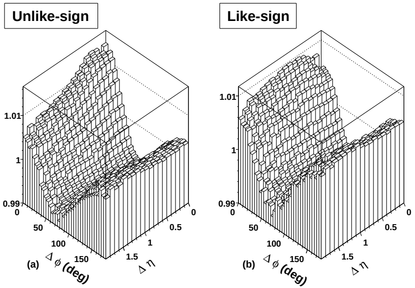


→



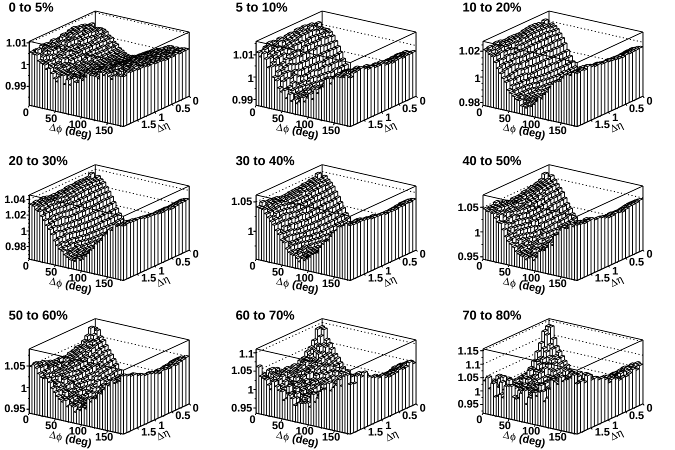
Star data, 2007

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



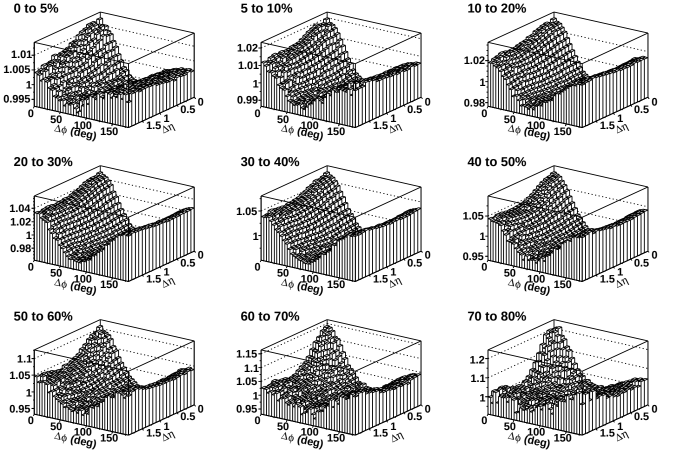
STAR data, 2008

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



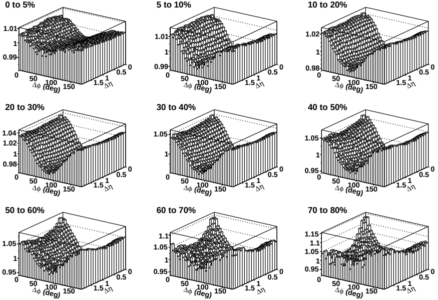
STAR data, 2008

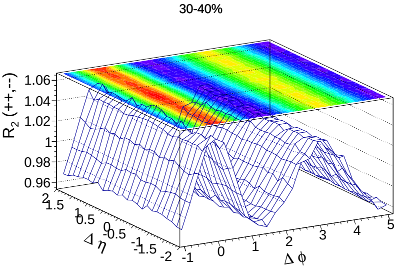
unlike sign ($0.8 < p_T < 4$ GeV - "unbiased")



STAR vs. model

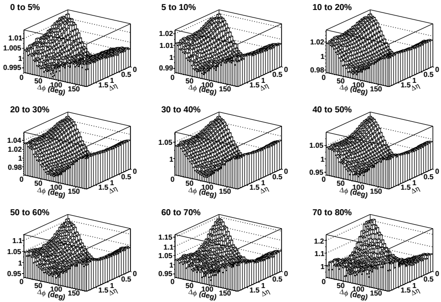
(like sign, $0.8 < p_T < 4$ GeV, model unbalanced)

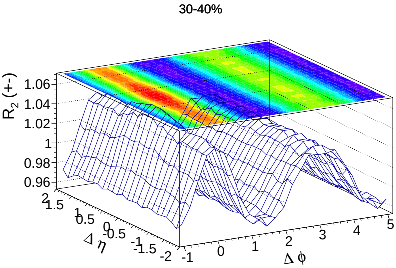




STAR vs. model

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

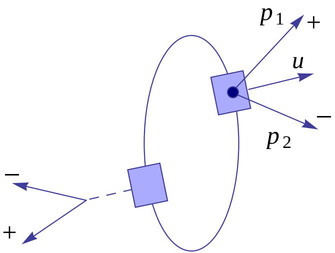




Charge balancing (from resonance decays and "direct")

[Jeon & Pratt 2002, Bass et al. 2010, Bożek et al. 2005]

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^-, $p\bar{p}$, . . . , $\Delta^0\bar{\Delta}^0$ . . .

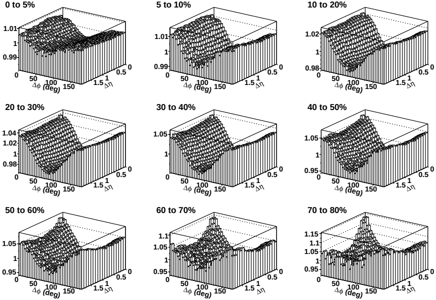
resonances also contribute

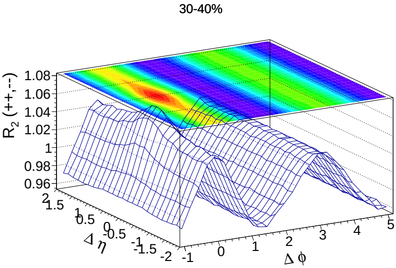
special kind of clusters

many ways to modify/improve

STAR vs. model

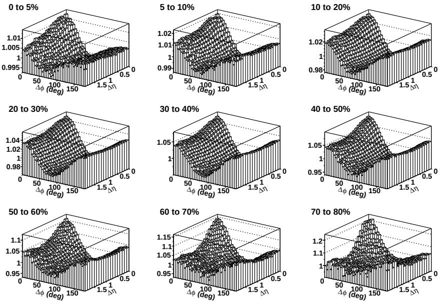
(like sign, $0.8 < p_T < 4$ GeV, balanced)

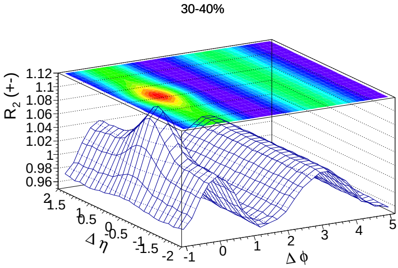




STAR vs. model

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

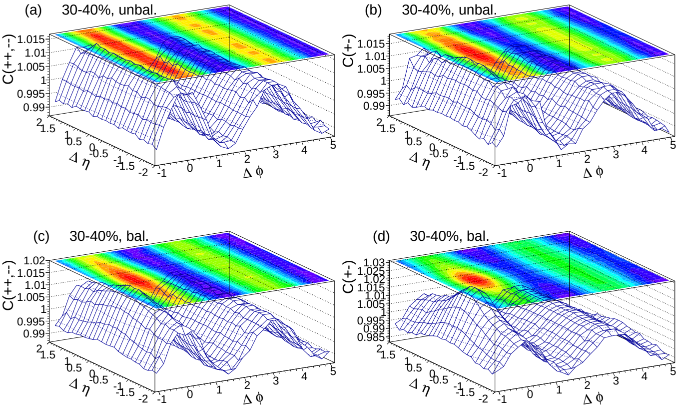




(correct "offsets" - compare to Takahashi et at. 2009, Sharma et al. 2011)

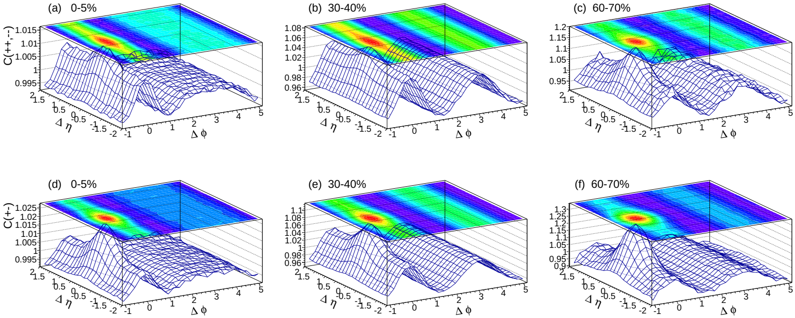
Role of balancing

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

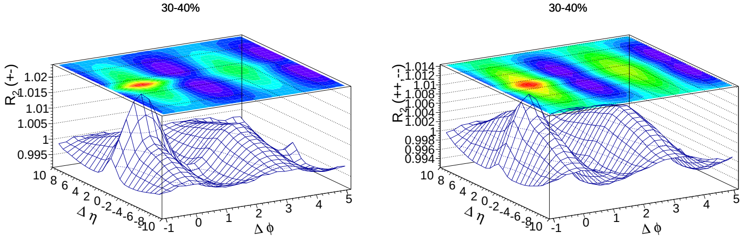


3 centralities

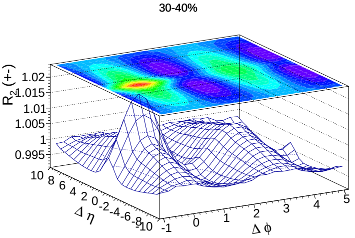
$(0.8 < p_T < 4$ GeV$)$

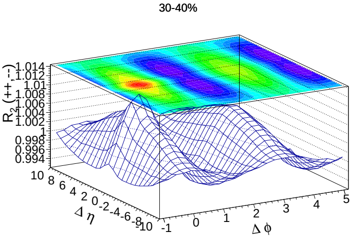


Large η coverage



Large η coverage





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

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

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

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

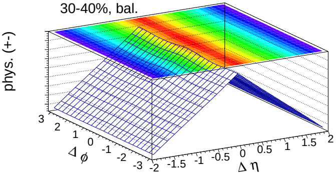
$$= 1 + 2\sum v_n^2(\Delta\eta)\cos(n\Delta\eta) \quad \text{(includes nonflow)}$$

2D balance functions

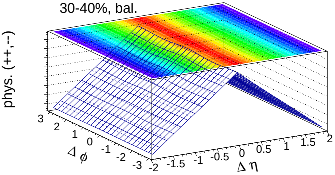
$$B(\Delta\eta, \Delta\phi) = \frac{\langle\ N_{+-} - N_{++}\rangle}{\langle N_+\rangle} + \frac{\langle N_{-+} - N_{--}\rangle}{\langle N_-\rangle}$$

2D balance functions

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



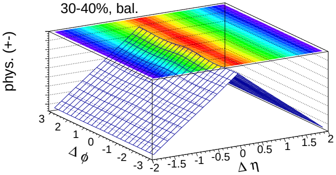
–



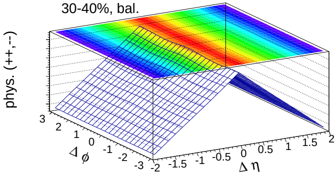
$\longrightarrow$

2D balance functions

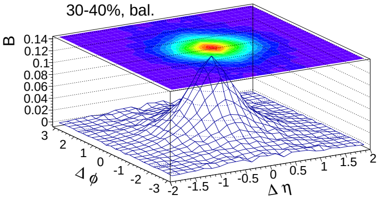
$$B(\Delta\eta,\Delta\phi) = \frac{\langle N_{+-} - N_{++}\rangle}{\langle N_+\rangle} + \frac{\langle N_{-+} - N_{--}\rangle}{\langle N_-\rangle}$$



−

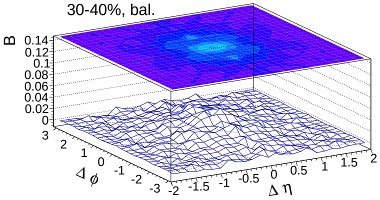


→



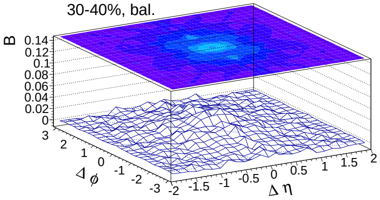
2D balance functions

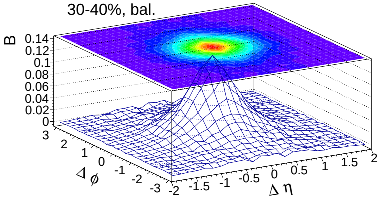
Crucial role of charge balancing



2D balance functions

Crucial role of charge balancing



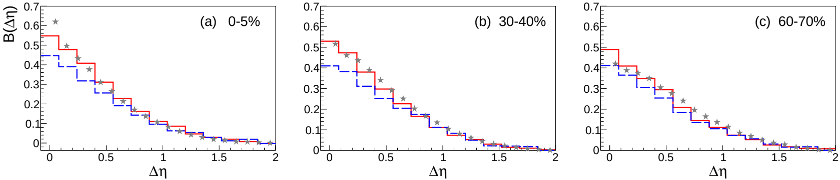


small (resonance decays only) big (direct balancing)

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 $\Delta\eta$

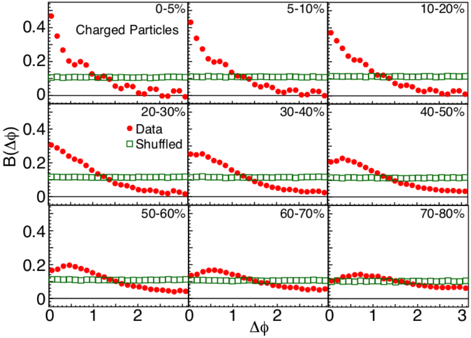


comparison to the STAR data (HBT not removed)

solid: $T_f = 140$ MeV, dashed: $T_f = 150$ MeV

Balance functions in relative azimuth $\Delta\phi$

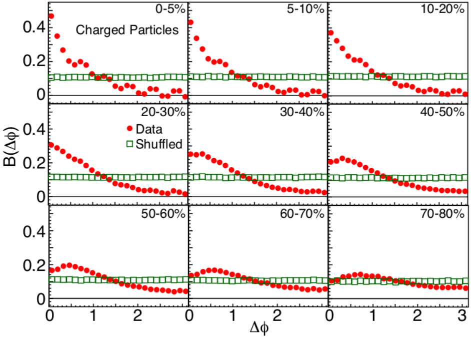
[STAR 2010]



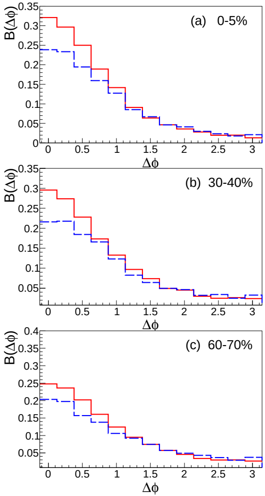
(HBT not removed)

Balance functions in relative azimuth $\Delta\phi$

[STAR 2010]

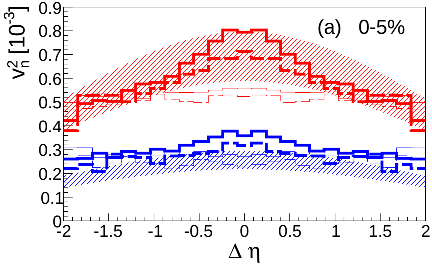


(HBT not removed)



$v_n^2(\Delta\eta)$

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

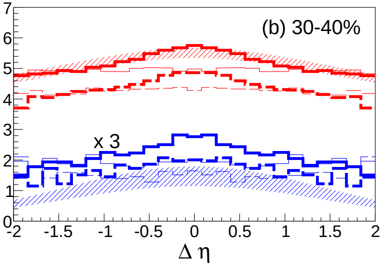


comparison to extracted STAR data (HBT removed), v_2^2, v_3^2
fat: with balancing, thin: no balancing - completely **flat**
solid: $T_f = 140$ MeV, dashed: $T_f = 150$ MeV

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

$v_n^2(\Delta\eta)$

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

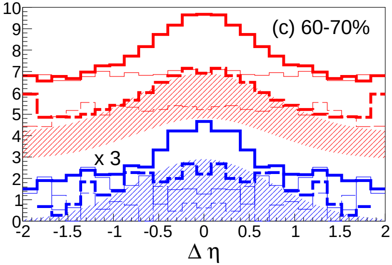


comparison to extracted STAR data (HBT removed), v_2^2, v_3^2
fat: with balancing, thin: no balancing - completely **flat**
solid: $T_f = 140$ MeV, dashed: $T_f = 150$ MeV

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

$v_n^2(\Delta\eta)$

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

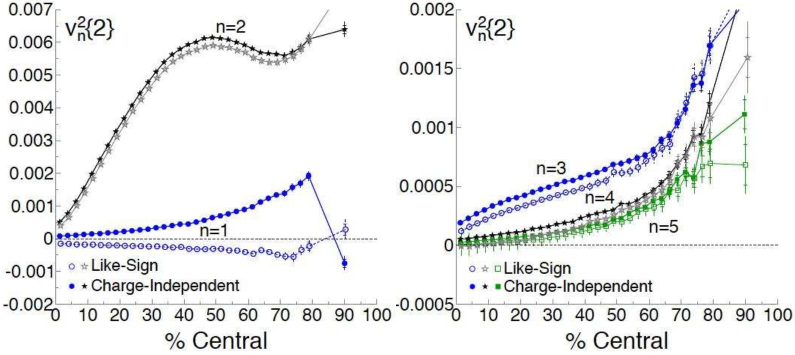


comparison to extracted STAR data (HBT removed), v_2^2, v_3^2
fat: with balancing, thin: no balancing - completely **flat**
solid: $T_f = 140$ MeV, dashed: $T_f = 150$ MeV

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

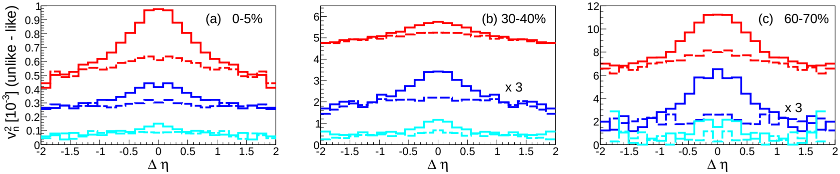
STAR 2011

Paul Sorensen at QM2011



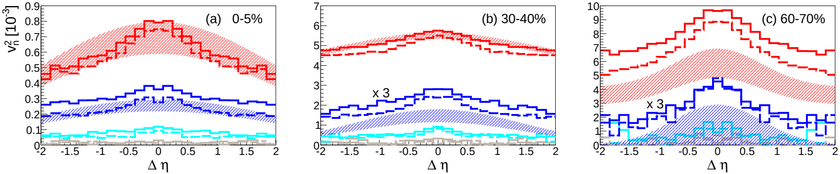
Charge-dependence of $v_n^2(\Delta\eta)$

$(0.15 < p_T < 2$ GeV)



solid: unlike, dashed: like

Dependence on viscosity



solid: $\eta/s = 0.08$, dashed: $\eta/s = 0.16$

$v_n^2\{2\}$

$(0.15 < p_T < 2$ GeV$)$

$c = 0 - 5\%$

$v_n^2\{2\}$ $[10^{-3}]$	no balancing			with balancing		
	CI	$(++,--)$	$(+-)$	CI	$(++,--)$	$(+-)$
2	0.54(1)	0.53(1)	0.55(1)	0.66(1)	0.58(1)	0.74(1)
3	0.27(1)	0.26(1)	0.27(1)	0.32(1)	0.28(1)	0.34(1)
4	0.074(3)	0.071(4)	0.077(4)	0.081(3)	0.075(4)	0.088(4)

$c = 30 - 40\%$

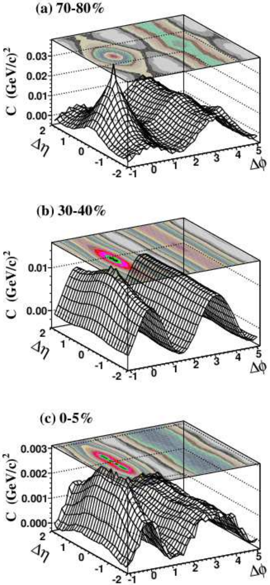
$v_n^2\{2\}$ $[10^{-3}]$	no balancing			with balancing		
	CI	$(++,--)$	$(+-)$	CI	$(++,--)$	$(+-)$
2	4.76(3)	4.75(3)	4.78(3)	5.14(2)	4.98(2)	5.39(2)
3	0.63(2)	0.64(2)	0.62(2)	0.78(1)	0.69(1)	0.88(1)
4	0.16(1)	0.16(2)	0.16(2)	0.19(1)	0.15(1)	0.23(1)

balancing $\rightarrow$ splitting, overall increase by a few %

Definition

Similar to R_2, but weighting with p_T:

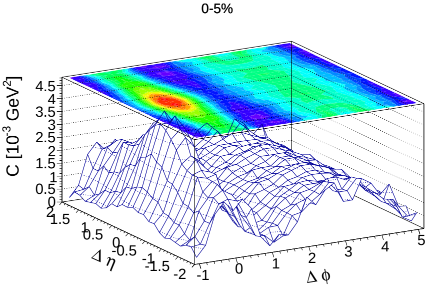
$$C(\Delta\eta, \Delta\phi) = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{i \neq j=1}^{n_2} p_{Ti} p_{Tj} \right\rangle - \left\langle \sum_{i=1}^{n_1} p_{Ti} \right\rangle \left\langle \sum_{j=1}^{n_2} p_{Tj} \right\rangle}{\left\langle \sum_{i=1}^{n_1} 1_i \right\rangle \left\langle \sum_{j=1}^{n_2} 1_j \right\rangle}$$

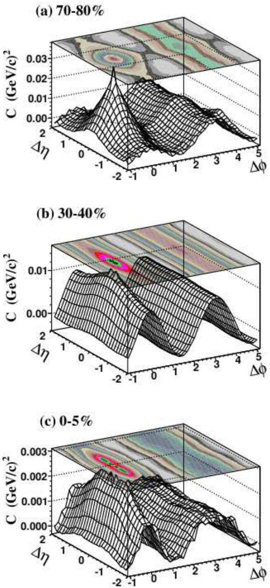


$(0.2 < p_T < 2$ GeV)

$\leftarrow$ STAR

With charge balancing and p_T conservation

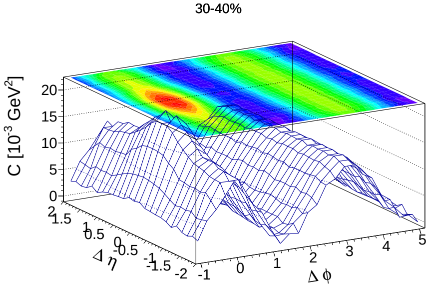


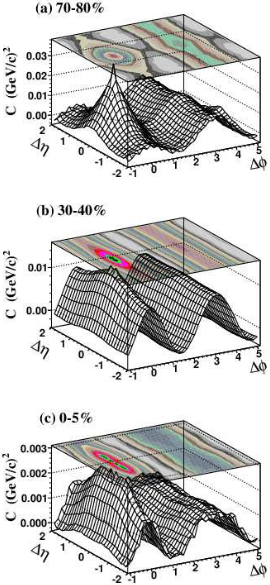


$(0.2 < p_T < 2$ GeV)

$\leftarrow$ STAR

With charge balancing and p_T conservation

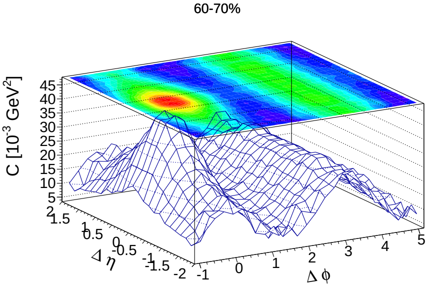




$(0.2 < p_T < 2$ GeV)

$\leftarrow$ STAR

With charge balancing and p_T conservation



Conclusions

- E-by-e hydro with charge balancing in semi-quantitative agreement with the (soft) data for 2-particle 2D correlations from RHIC, dependence on the relative charge of the pair appears in a natural way
- **Charge balancing** combined with flow is necessary to explain the shape of the same-side ridge for $\Delta\eta <\sim 1$ and $\Delta\phi$ - major **non-flow** effect
- Dependence of the flow coefficients on $\Delta\eta$ reproduced
- Charge balancing increases $v_n^2\{2\}$ by a few % and splits the like-sign and unlike-sign combinations
- Differential transverse-momentum conservation also reproduced
- v_1 and CME - see Piotr Bożek's talk