Event-by-event hydrodynamics and correlations in relativistic heavy-ion collisions

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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? 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]

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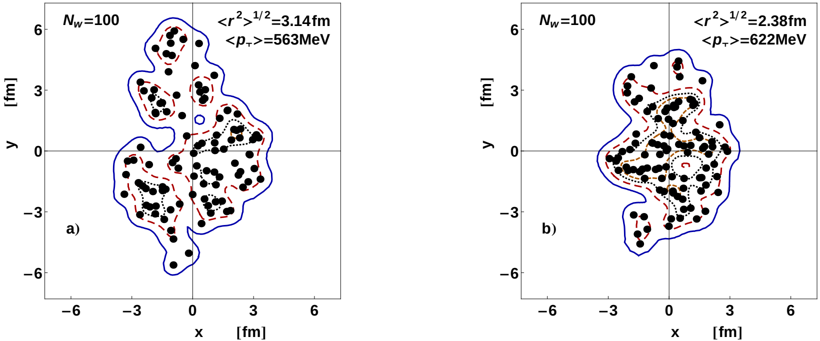
Local charge conservation (balancing) very important for 2-particle correlations → explanation of the data

Initial fluctuations

transverse-plane view



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

Hydrodynamics

3+1D viscous event-by-event hydrodynamics, tuned to reproduce the one-body **RHIC** data [Bożek 2012]
$\tau_{\rm init} = 0.6$ fm/c, $\eta/s = 0.08$ (**shear**), $\zeta/s = 0.04$ (**bulk**),
$T_f = 140$ MeV

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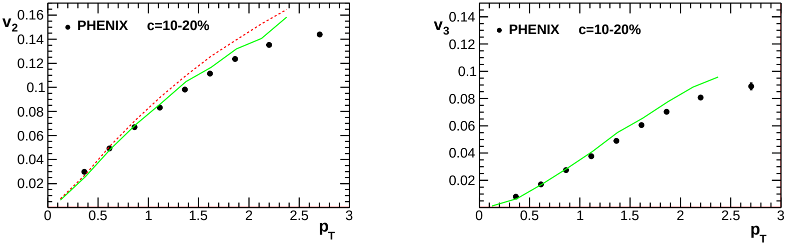
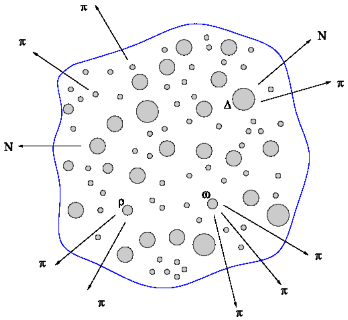
sample results:



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

Final fluctuations

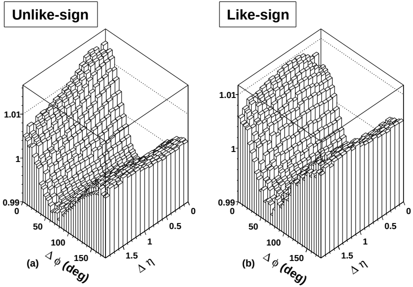


Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR)

Definition and results

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

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



STAR data, 2007

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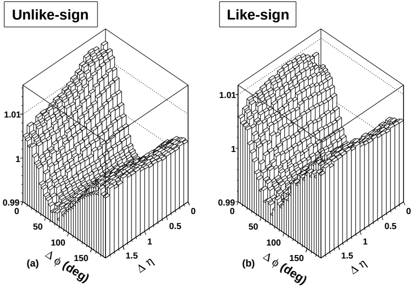
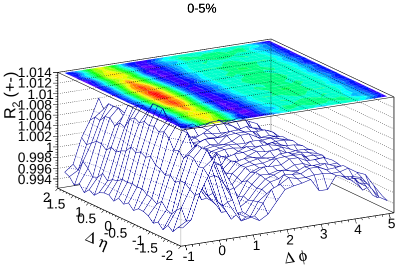
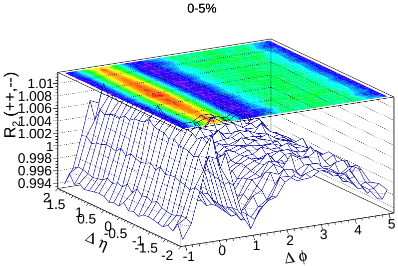


STAR data, 2007

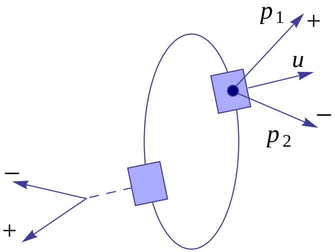
No balancing





Charge balancing (from resonance decays and "direct")

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



direct balancing: pair emitted from the neutral hydro medium from the same space-time point
resonances also contribute

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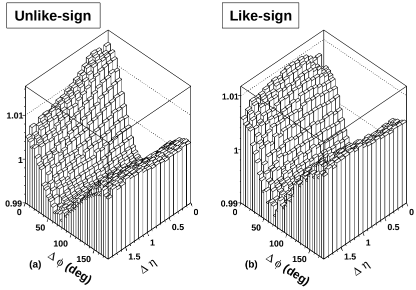
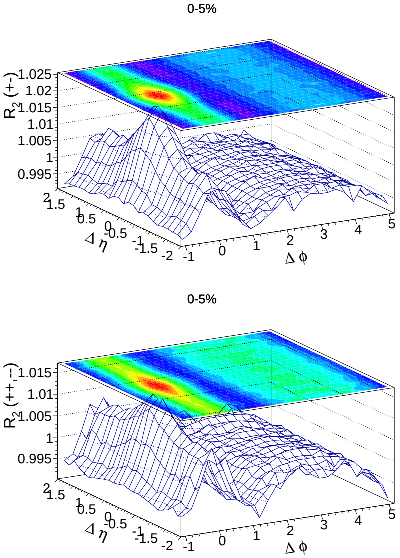
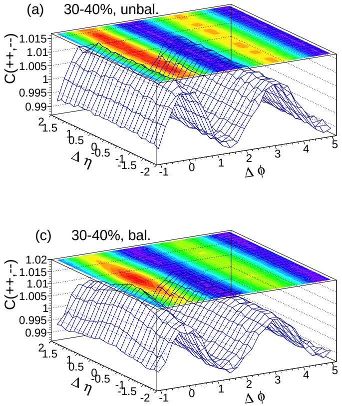


STAR data

With balancing!

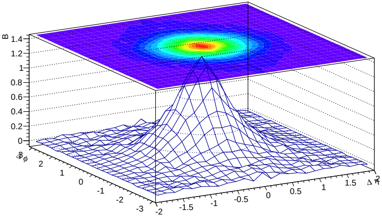


Summary



2D balance functions

$$B(\Delta\eta, \Delta\phi) = \frac{\langle\ N_{+-} - N_{++}\rangle}{\langle N_{+}\rangle} + \frac{\langle N_{-+} - N_{--}\rangle}{\langle N_{-}\rangle}$$
$$c = 0 - 5\%$$



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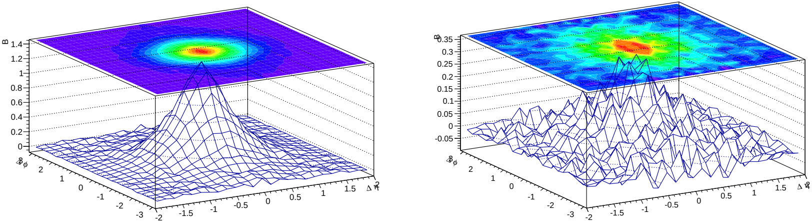


big (direct balancing) small (resonance decays only)

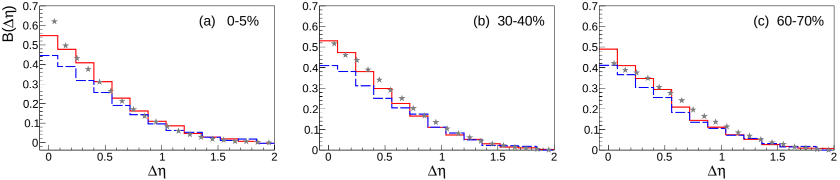
balancing $\rightarrow$ collimation

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

Balance functions in relative rapidity

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

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

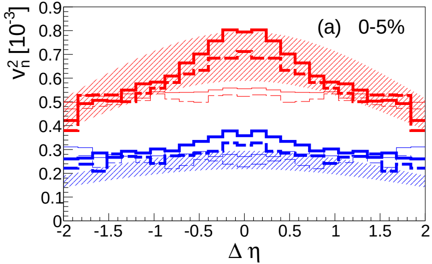


comparison to the STAR data

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

$v_n^2(\Delta\eta)$

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



comparison to the STAR data, v_2^2, v_3^2
fat: with balancing, thin: no balancing - completely **flat**
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balancing → explanation of the fall-off of the same-side ridge in $\Delta\eta$

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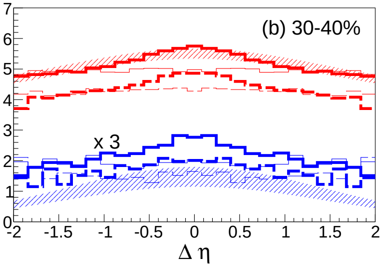

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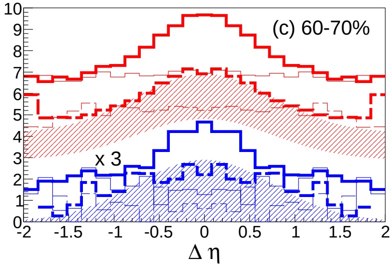

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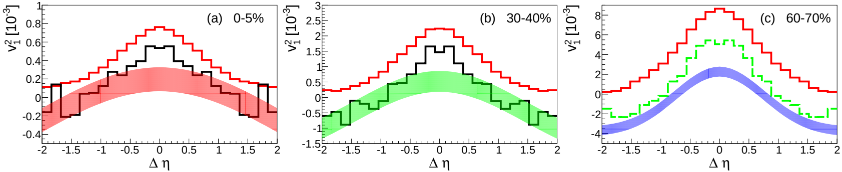
balancing $\rightarrow$ explanation of the fall-off of the same-side ridge in $\Delta\eta$

Transverse momentum conservation

transverse-momentum conservation lowers
$v_1^2(\Delta\eta) \equiv \langle \cos(\phi_1 - \phi_2) \rangle$



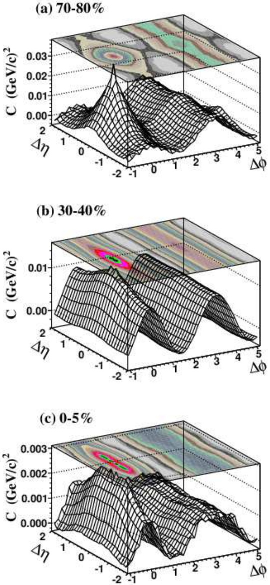
comparison to the STAR data

(our statistics too small for the “parity-violation” observable
$\langle \cos(\phi_1 + \phi_2 - 2\phi_3) \rangle$)

Definition

Similar to R_2, but weighting with p_T:

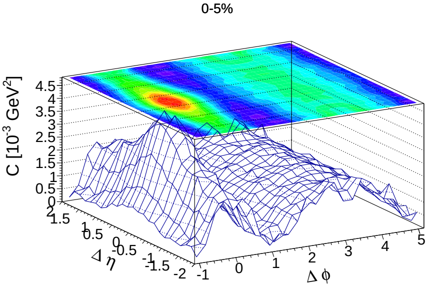
$$C(\Delta\eta, \Delta\phi) = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{i \neq j=1}^{n_2} p_{Ti} p_{Tj} \right\rangle - \left\langle \sum_{i=1}^{n_1} p_{Ti} \right\rangle \left\langle \sum_{j=1}^{n_2} p_{Tj} \right\rangle}{\left\langle \sum_{i=1}^{n_1} 1_i \right\rangle \left\langle \sum_{j=1}^{n_2}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

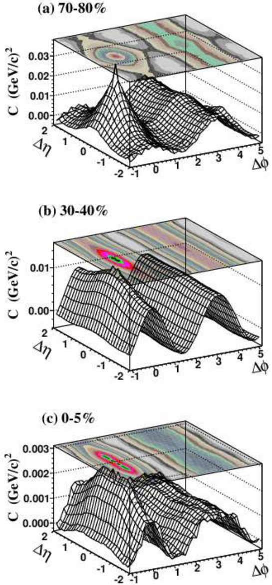


$(0.2 < p_T < 2$ GeV)

$\leftarrow$ STAR

With charge balancing and p_T conservation





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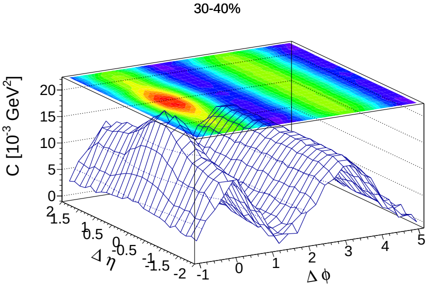

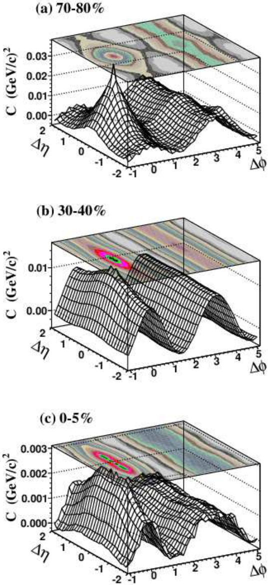

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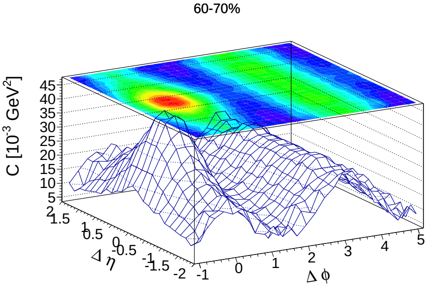

Conclusions

- E-by-e hydro with charge balancing in semi-quantitative agreement with the (soft) data for 2-particle 2D correlations, dependence on the relative charge of the pair appears in a natural way
- **Charge balancing** explains the shape of the same-side ridge - major **non-flow** effect
- Dependence of the flow coefficients on $\Delta\eta$ reproduced
- Transverse-momentum conservation important for v_1^2
- Differential transverse-momentum conservation also reproduced
- (not covered) Transverse-momentum fluctuations follow from initial size fluctuations [Bożek & Broniowski 2012]
- (not covered) Torque effect - FB reaction plane correlations [Moreira et al. 2011]

Soft effects dependent on the initial fluctuations in the transverse plane are properly reproduced with 3+1D viscous e-by-e hydro with the Glauber initial conditions and statistical hadronization including charge balancing