Hydrodynamic picture of ultra-relativistic heavy-ion collisions

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UW, 14 I 2013

Reseach with Piotr Bożek, Wojciech Florkowski, Adam Kisiel, Mikołaj Chojnacki, Maciej Rybczyński

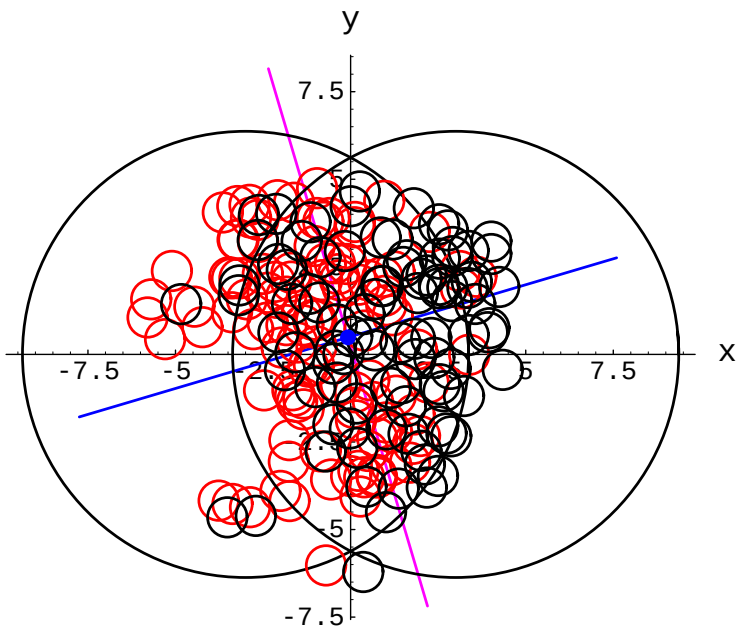
Approach

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

- **Initial phase** - Glauber model (or Color Glass, KLN)
- **Hydrodynamics**
- **Statistical hadronization** at freeze-out

GLISSANDO

GLauber Initial State Simulations AND mOre...
[WB, Bożek, Rybczyński]



wounded nucleons + binary collisions

Hydrodynamics (Bożek)

EM tensor of the perfect fluid

$$T_0^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - pg^{\mu\nu}$$

+ stress corrections from shear π and bulk Π viscosities (Israel-Stewart)

$$T^{\mu\nu} = T_0^{\mu\nu} + \pi^{\mu\nu} + \Pi\Delta^{\mu\nu}$$

$$\partial_\mu T^{\mu\nu} = 0$$

The viscous corrections are solutions of

$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^\gamma\partial_\gamma\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{4}{3}\pi^{\mu\nu}\partial_\alpha u^\alpha$$

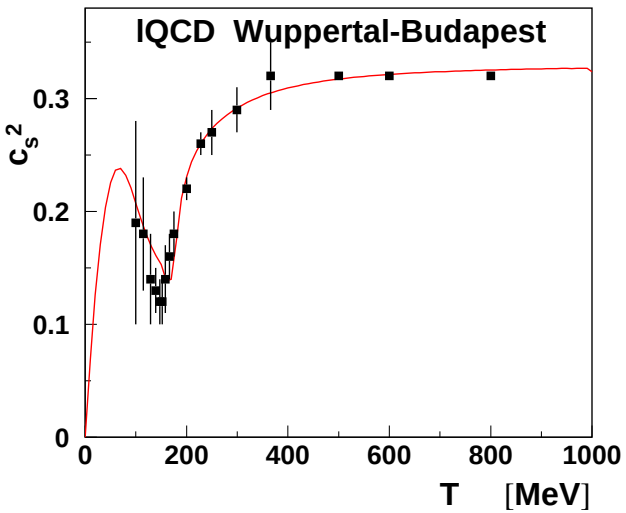
$$u^\gamma\partial_\gamma\Pi = \frac{-\zeta\partial_\gamma u^\gamma - \Pi}{\tau_\Pi} - \frac{4}{3}\Pi\partial_\alpha u^\alpha$$

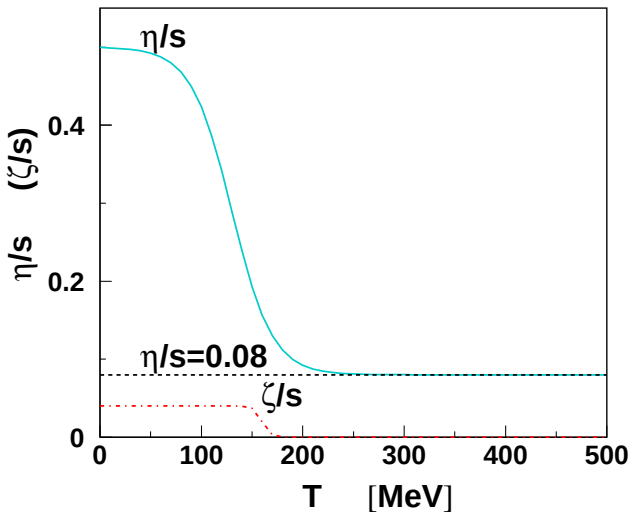
$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu,\ \nabla^\mu = \Delta^{\mu\nu}\partial_\nu$$

$$\sigma_{\mu\nu} = \frac{1}{2}\left(\nabla_\mu u_\nu + \nabla_\mu u_\nu - \frac{2}{3}\Delta_{\mu\nu}\partial_\alpha u^\alpha\right)$$

The relaxation time is taken as $\tau_\pi = \tau_\Pi = \frac{3\eta}{Ts}$

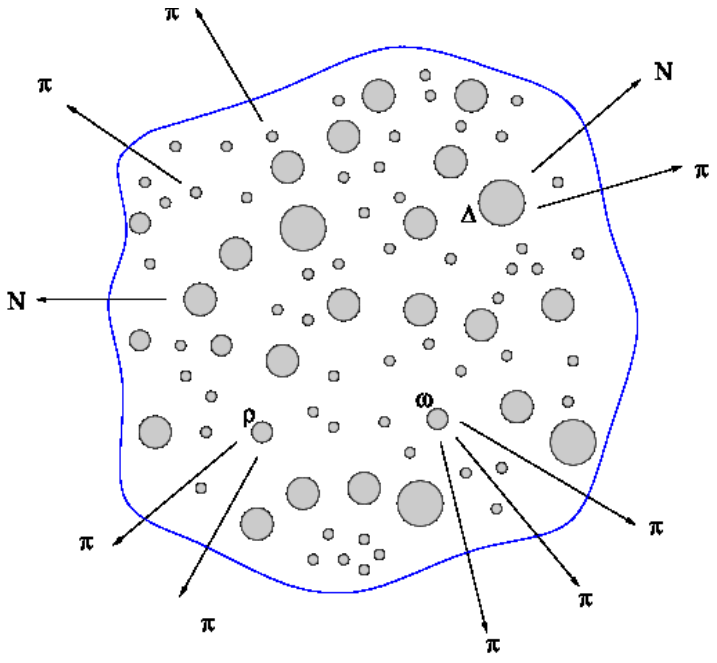
Sound velocity and viscosity





3+1 D viscous $\rightarrow$ thousand of hours of CPU!

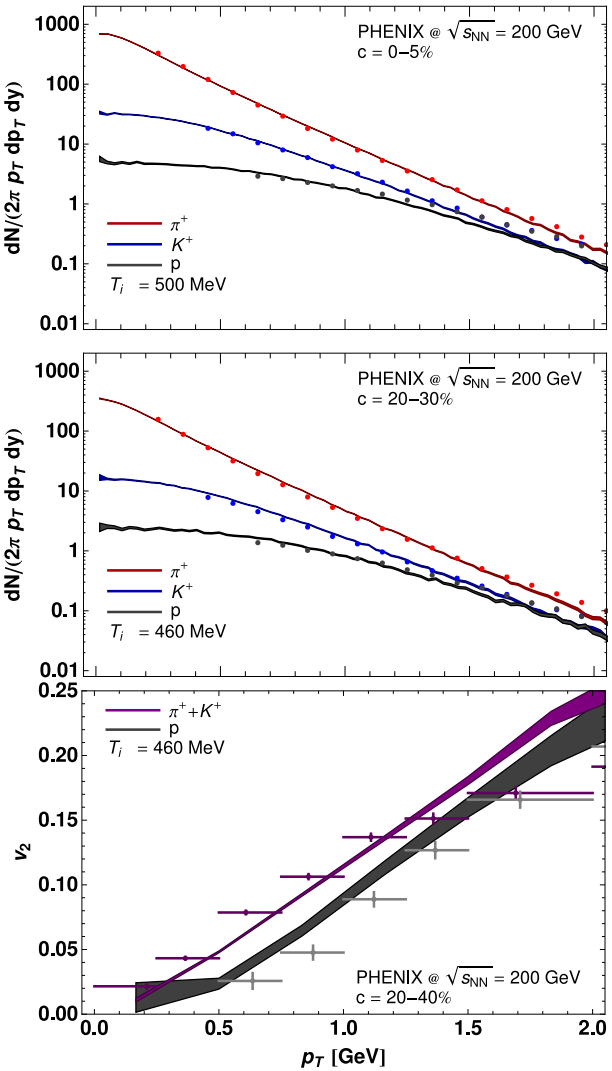
Statistical hadronization

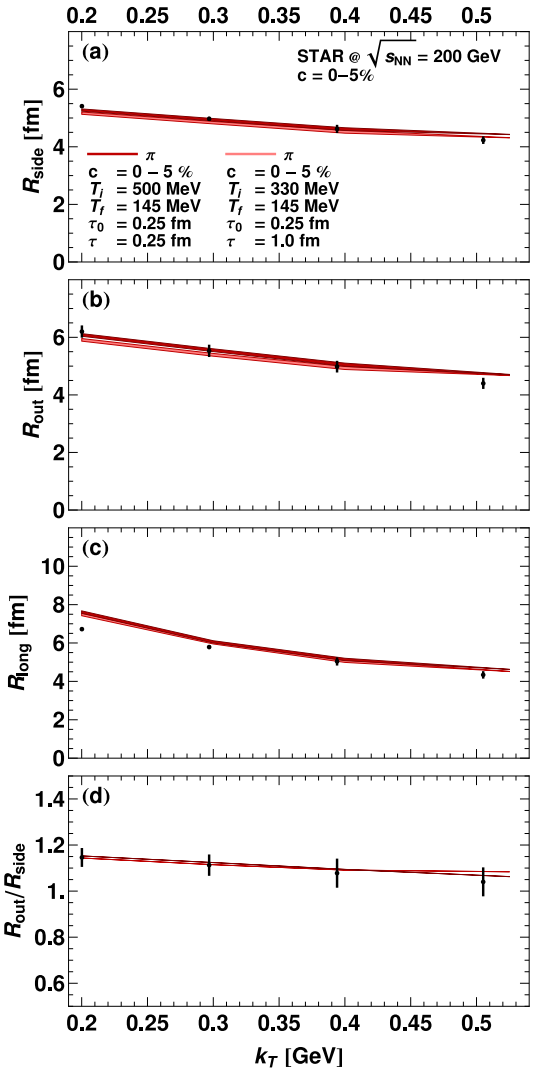


Statistical hadronization at freeze-out via Frye-Cooper formula + resonance decays (THERMINATOR), transverse-momentum conservation approximately imposed, charge conservation imposed

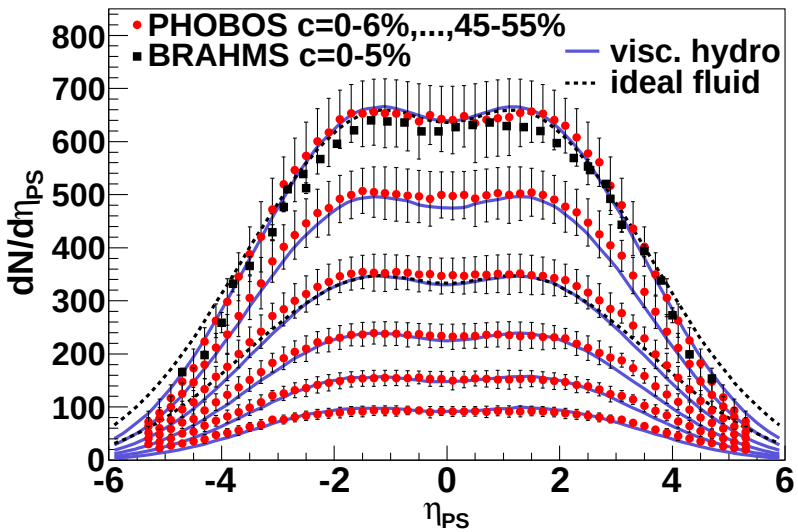
$$\frac{Ed^3N_i}{d^3p} = \int d\Sigma_\mu(x)p^\mu \, f_i[p \cdot u(x)]$$

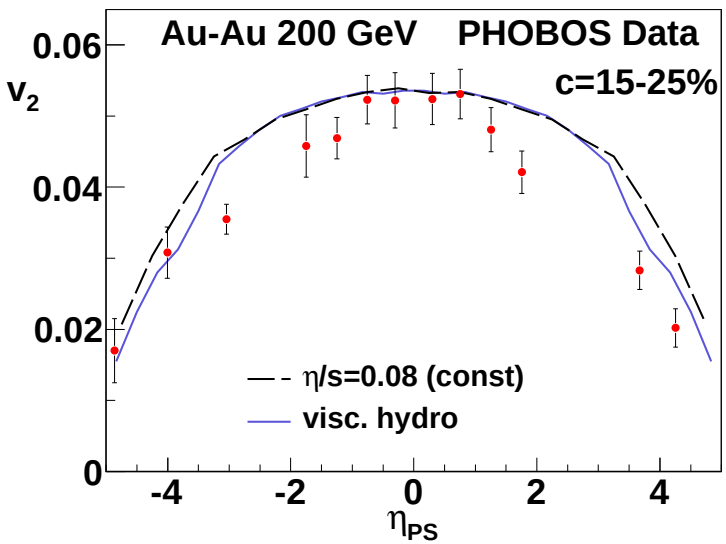
How hydro works?



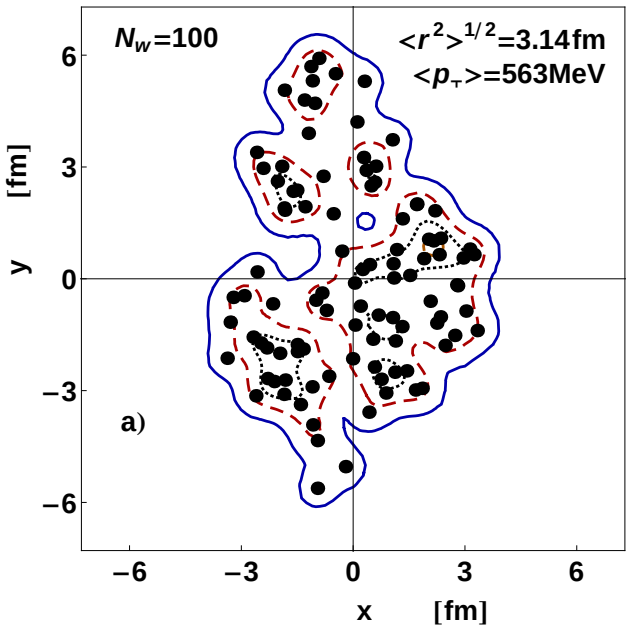


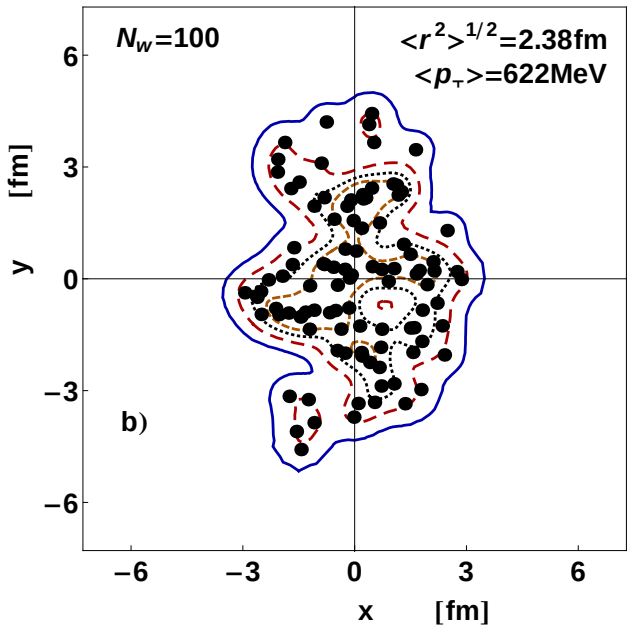
3+1 D viscous hydro





Initial fluctuations in the Glauber approach



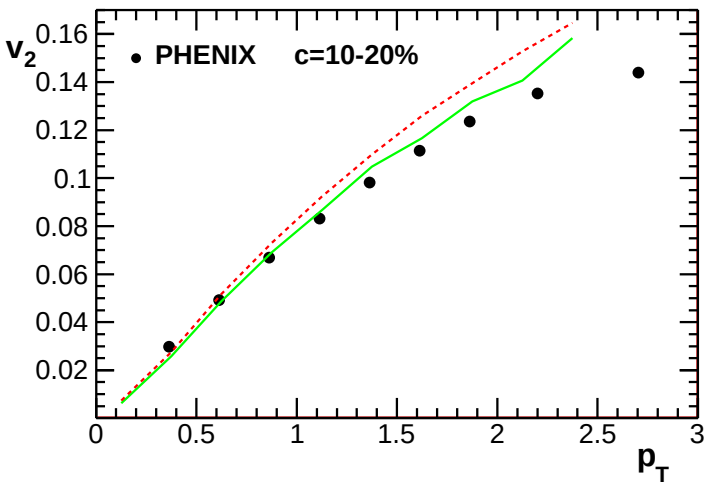


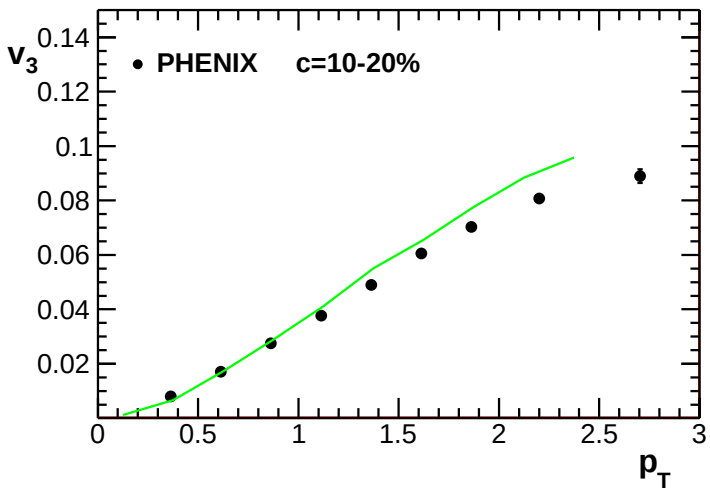
Two typical configuration of wounded nucleons in the transverse plane generated with GLISSANDO, isentropes at $s = 0.05$, 0.2, and 0.4 GeV^{-3}

Odd harmonic flow from fluctuations

$$\frac{d^2N}{d_T^p} = \frac{d^2N}{2\pi p_T dp_T}\left(1 + \sum_{i=1}^{\infty} v_i(p_T)\cos[i(\phi - \Psi_i)]\right)$$

triangular flow

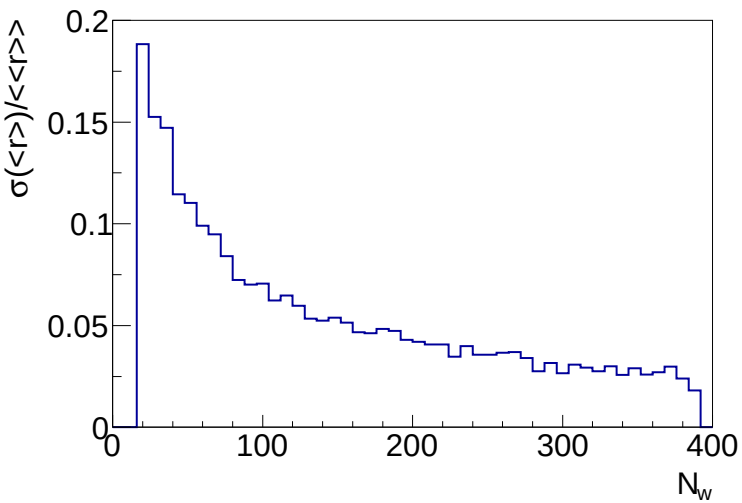


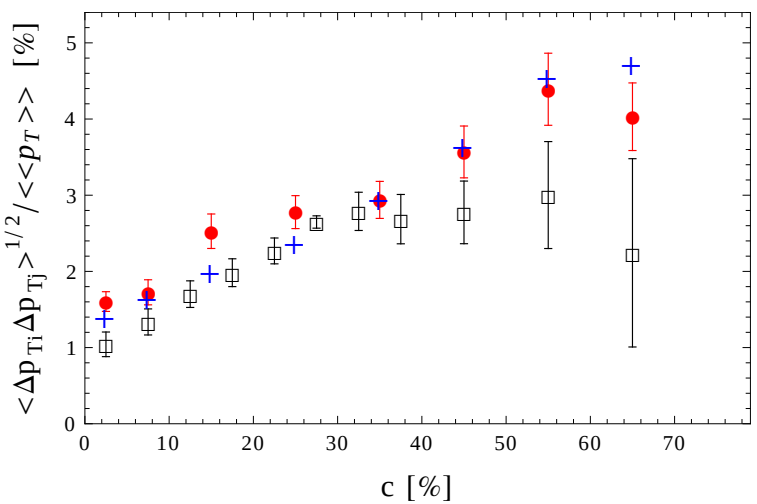


solid: e-by-e, dashed: averaged initial condition

Transverse-momentum fluctuations

smaller initial size in the event → stronger hydro push → larger radial flow velocity → larger average transverse momentum in the event, and vice versa

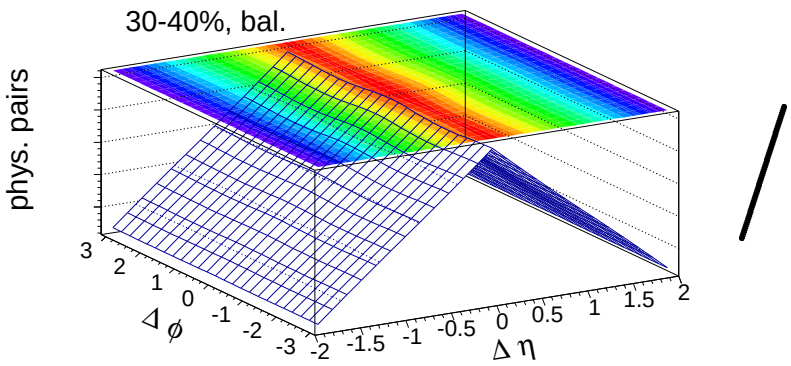


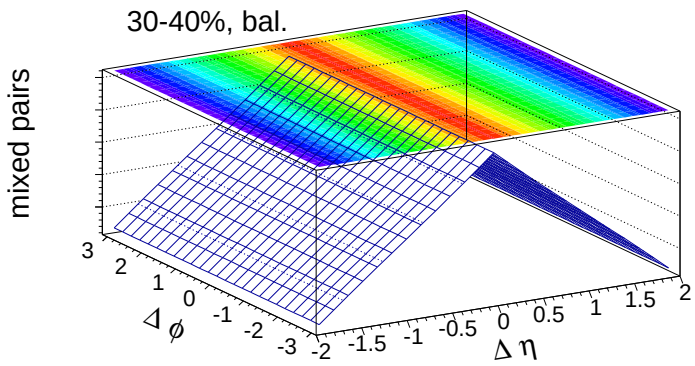


red dots - model, squares - PHENIX

2D two-particle correlations

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





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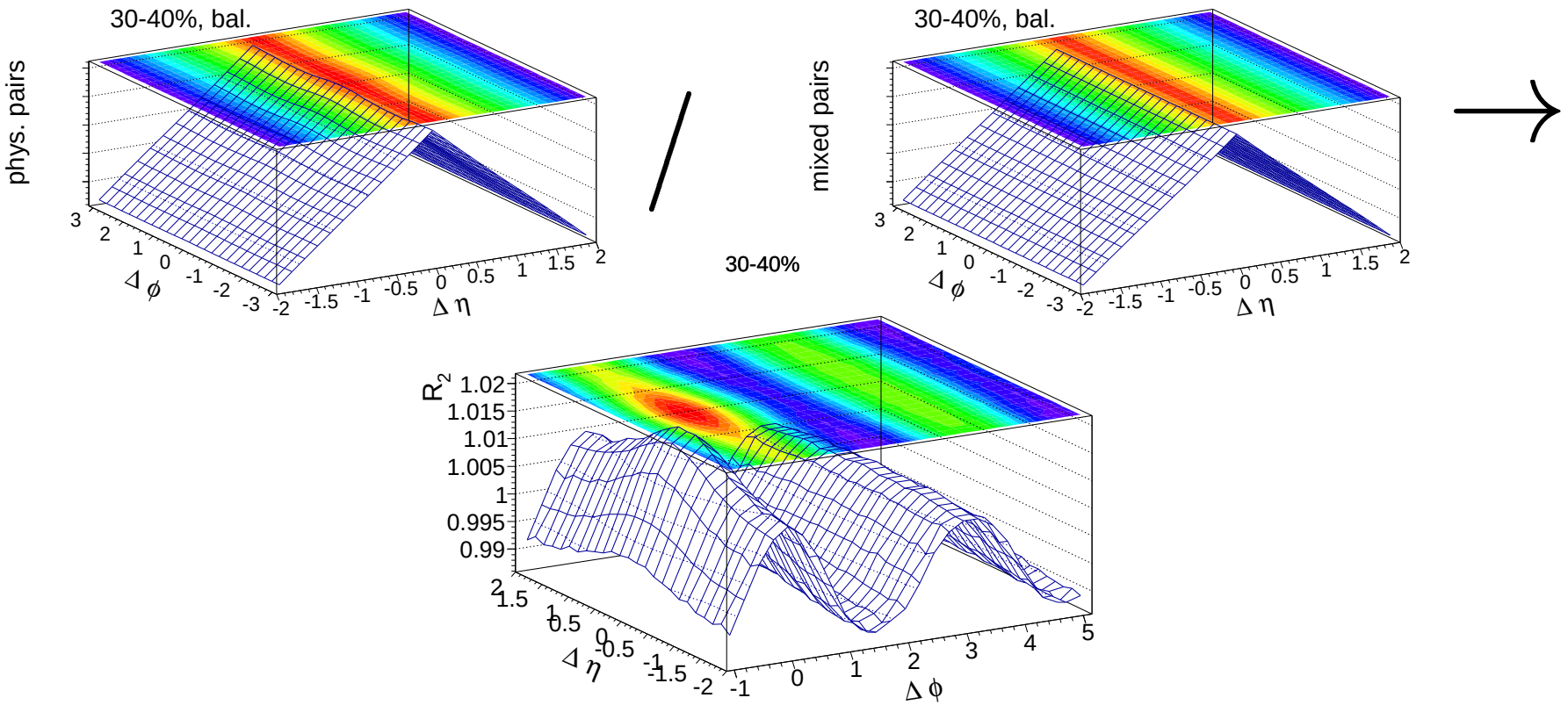


Sources of correlations

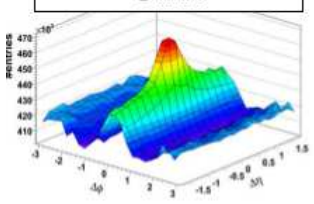
- jets $\rightarrow$ central peak (same jet), away-side ridge (back-to-back jets)
- collective harmonic flow $\rightarrow$ near- and away-side ridges
- charge balancing $\rightarrow$ central peak, shape of the near-side ridge
- resonance decays $\rightarrow$ away-side ridge
- Bose-Einstein $\rightarrow$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

Ridges

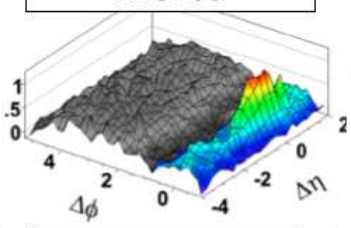
The Ridge

Hard Ridge

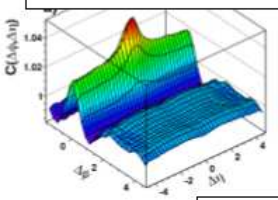
STAR



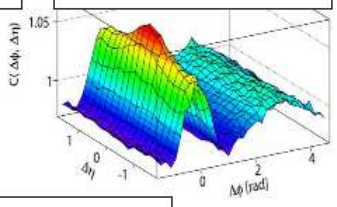
PHOBOS



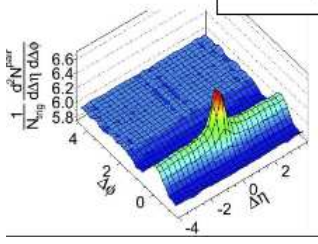
ATLAS

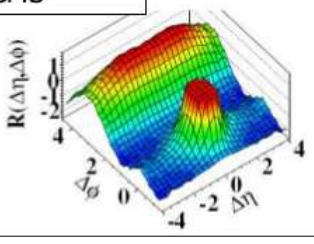


ALICE



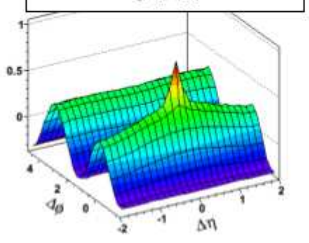
CMS





Soft Ridge

STAR



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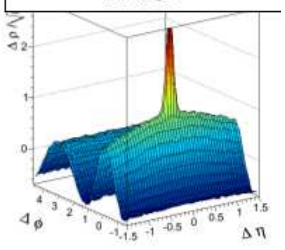
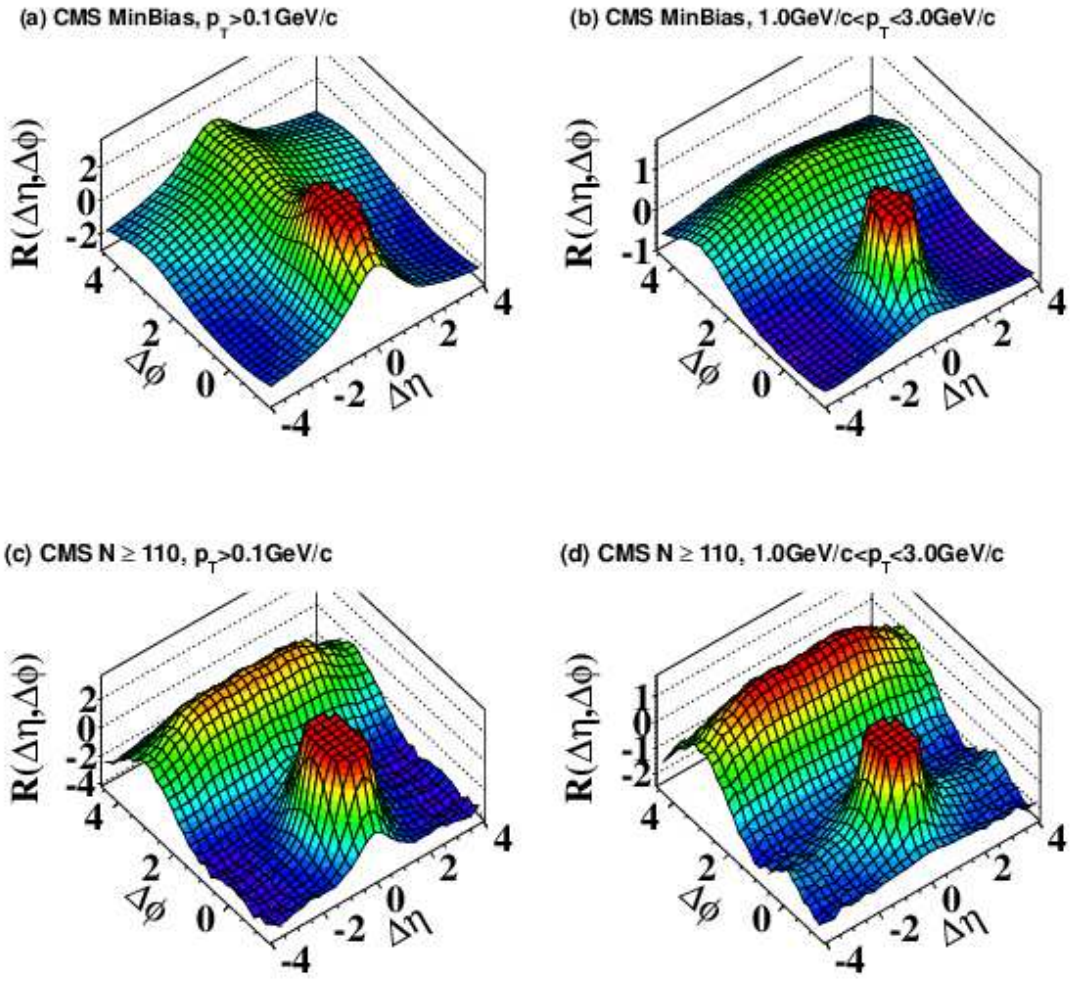


- **Hard Ridge:** high p_T trigger and lower p_T associates.
- **Soft Ridge:** correlations with no p_T restriction

  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, pp

News archive
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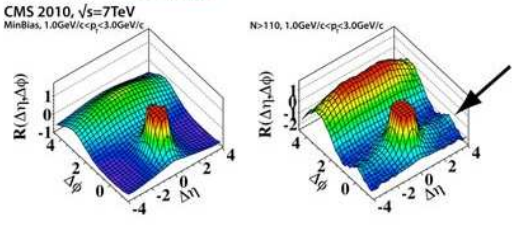
- 1999
- 1998
- 1997

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.

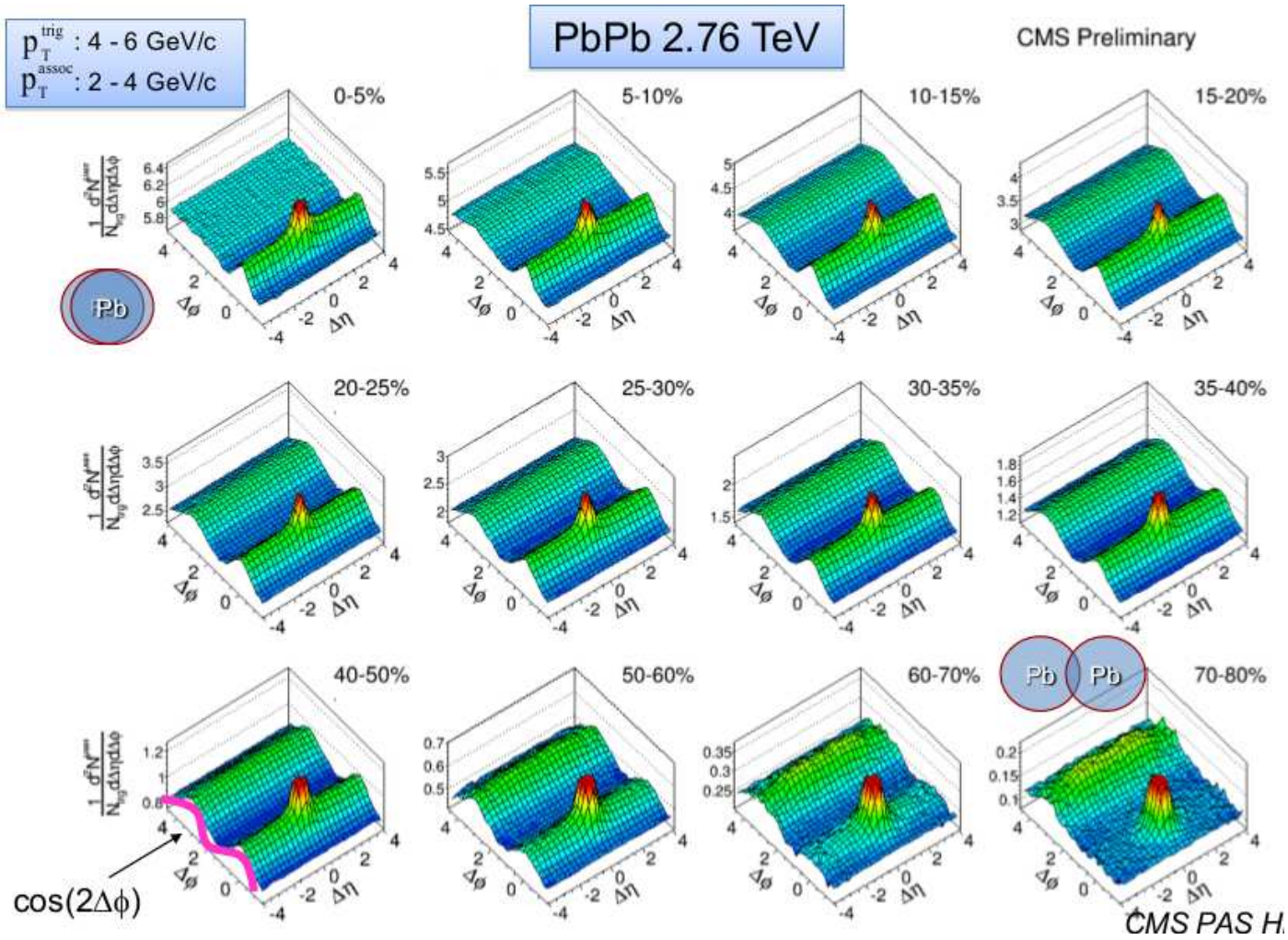
Hundreds of particles

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.

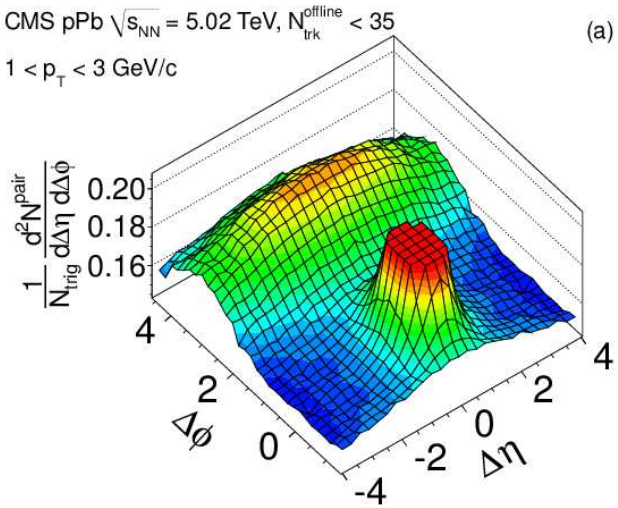
Researchers using the Compact Muon Solenoid (CMS) experiment at the LHC had expected that a plot of the correlations would show a peak where the angles are zero, which would mean that the particles are leaving the collision point in a jet pointing in a specific direction. Instead, the peak seems to be 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.

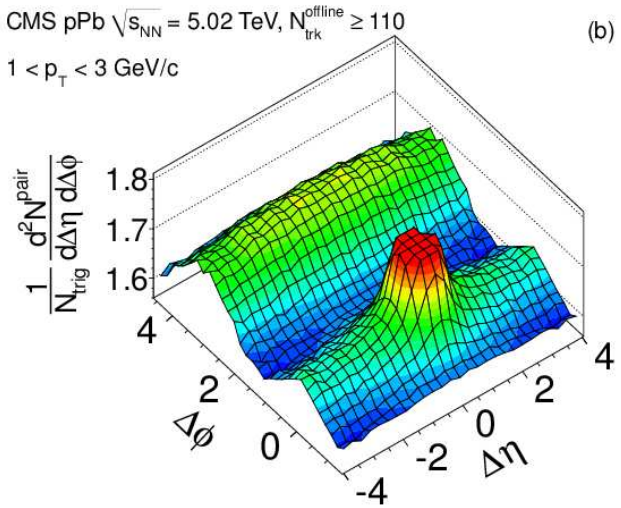
One possible interpretation of the ridge is that the collision creates a dense fluid of many quarks and gluons – a quark–gluon plasma –

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
$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi}$
$\Delta\phi$
$\Delta\eta$
cos(2Δϕ)
CMS PAS H

p-Pb





(released October 2012)

Near-side ridge indicates collectivity

Flow

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

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

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

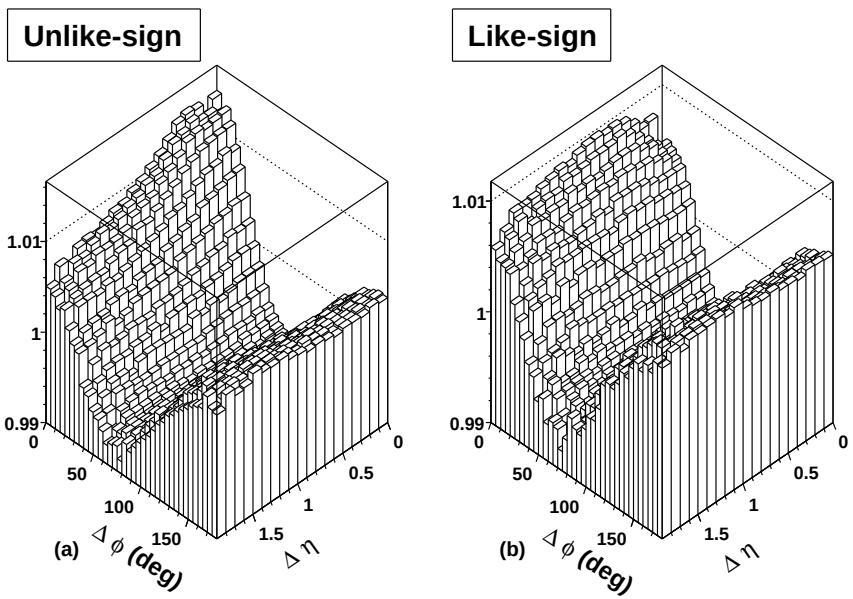
$$R_2 = \frac{\langle\int d\eta_1 d\eta_2 n(\eta_1)n(\eta_2)\left[1+2\sum_n v_n(\eta_1)v_n(\eta_2)\cos(n\Delta\phi)\right]\delta_{\Delta\eta-\eta_2+\eta_1}+\rho_c\rangle_{\rm events}}{\langle\int d\eta_1 d\eta_2 n(\eta_1)n(\eta_2)\delta_{\Delta\eta-\eta_2+\eta_1}\rangle_{\rm events}} =$$

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

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

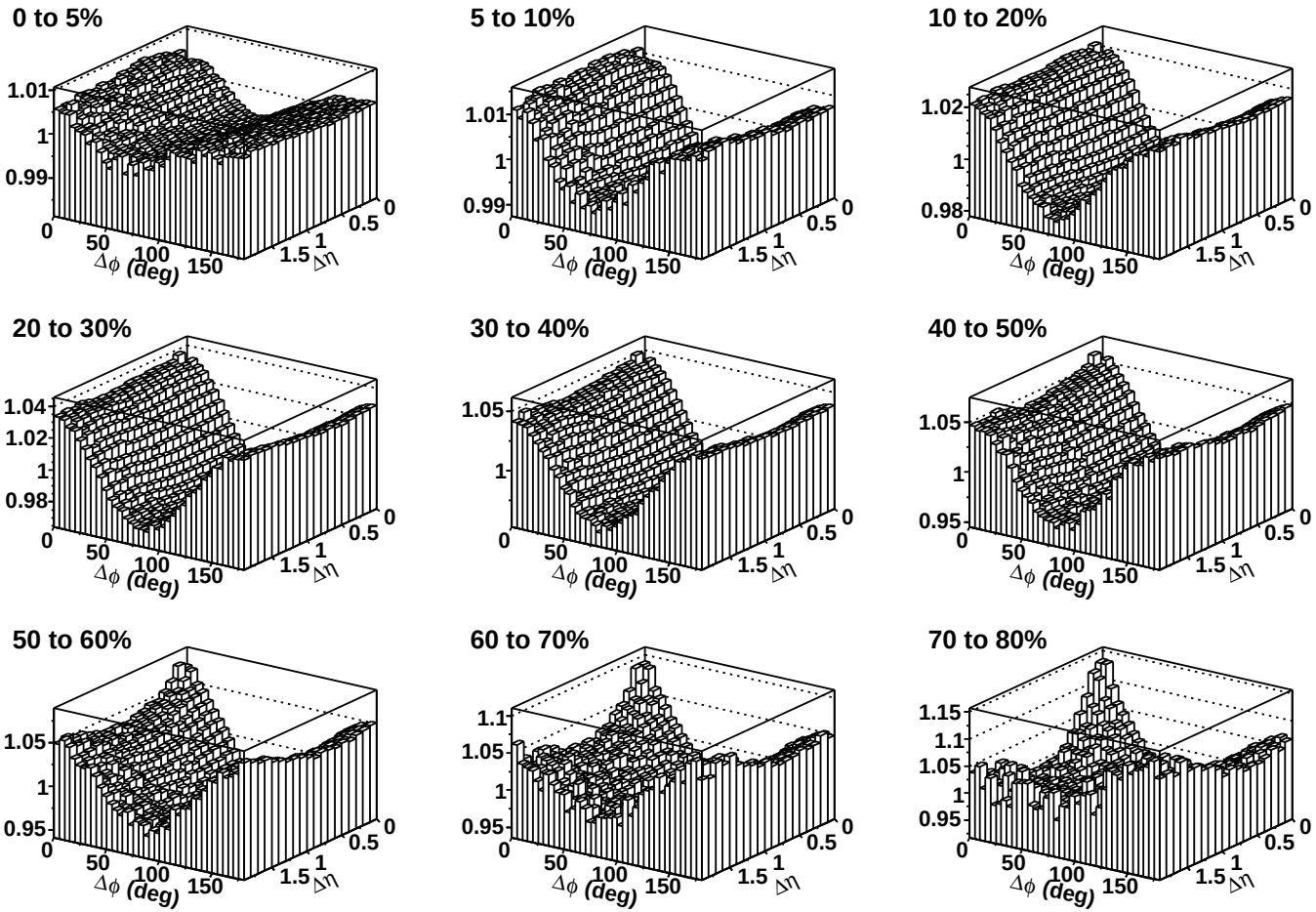
Star data, 2007

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



STAR data, 2008

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



STAR data, 2008

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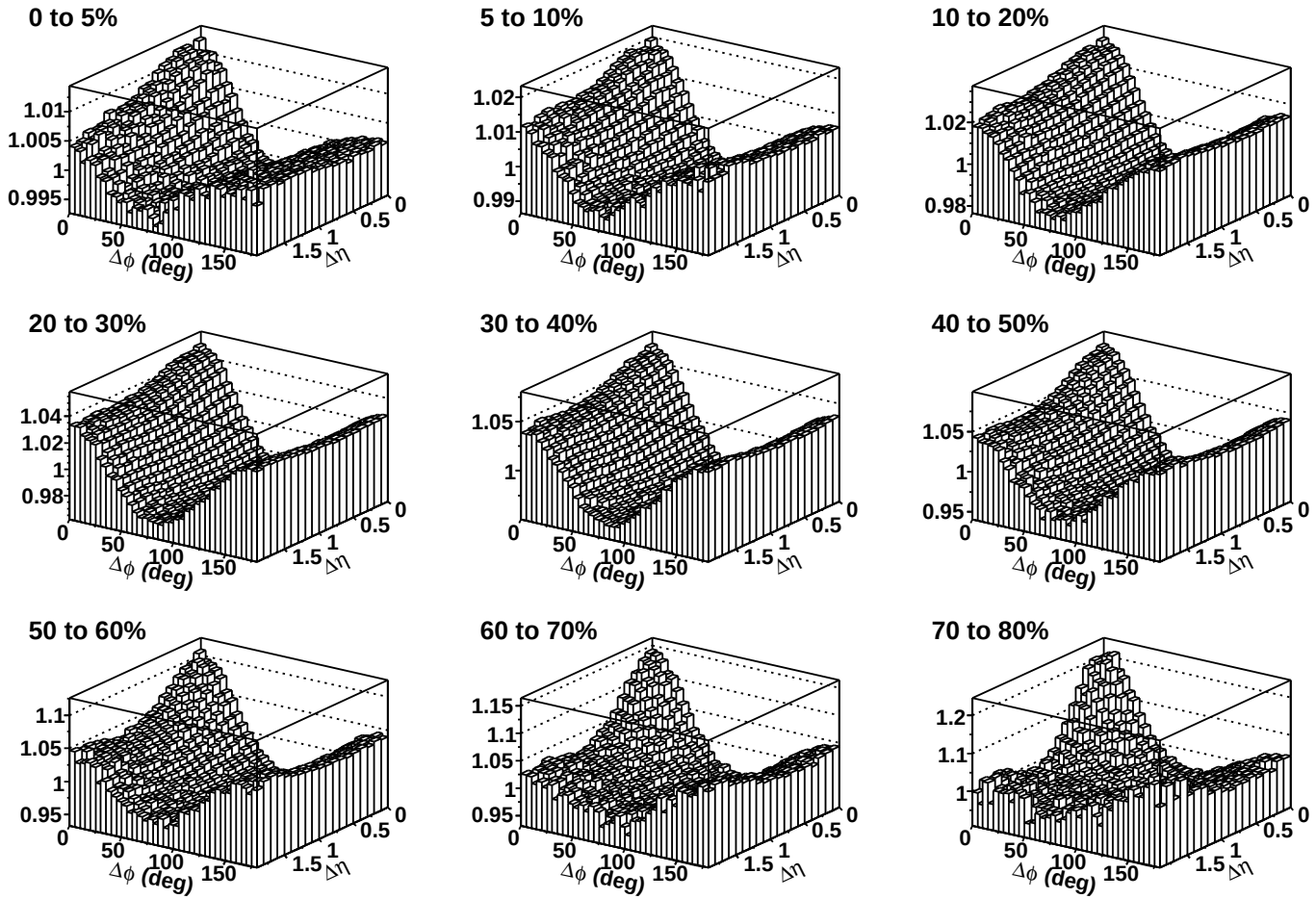
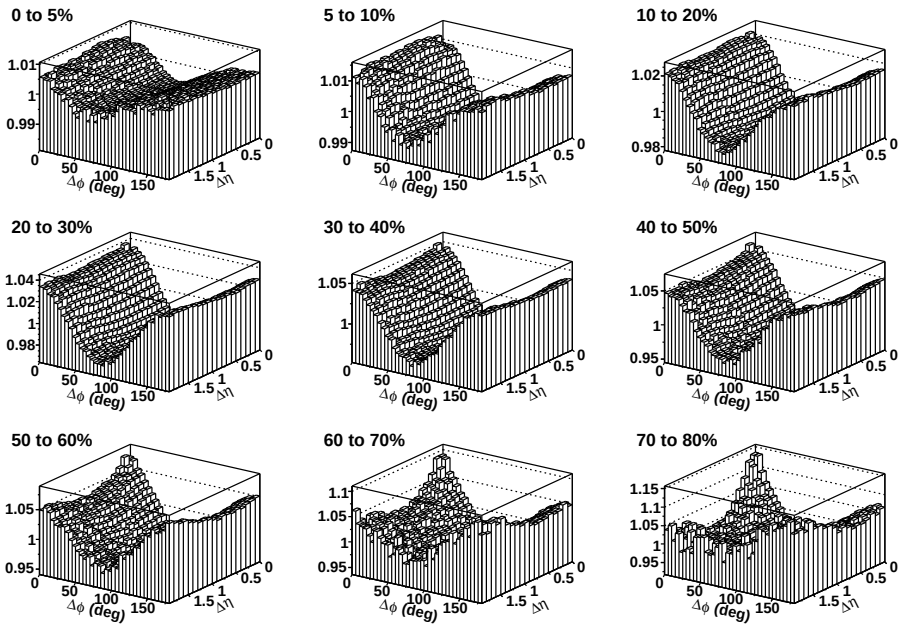
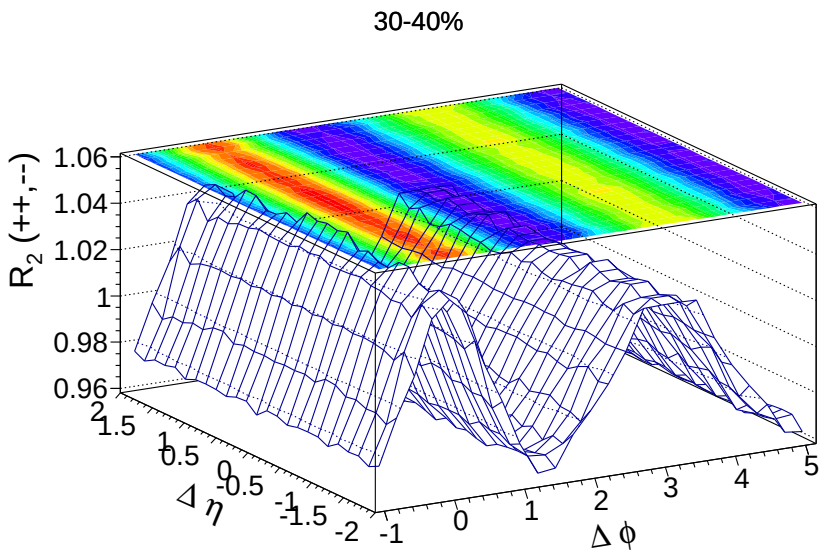


STAR vs. model

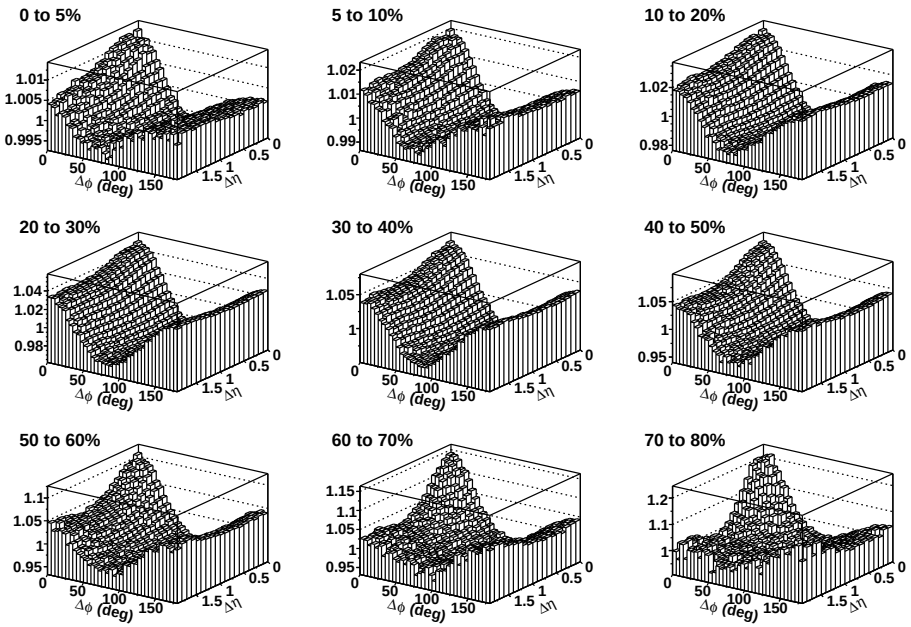
(like sign, $0.8 < p_T < 4$ GeV, model unbalanced)

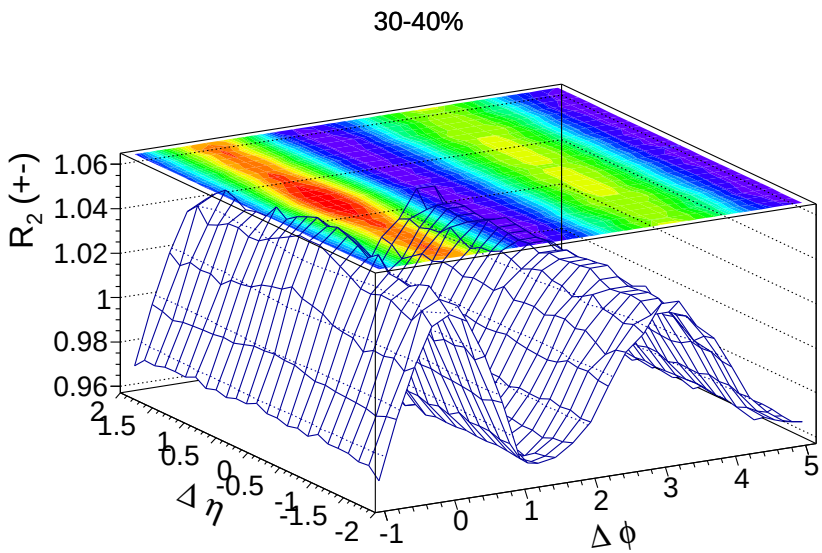




STAR vs. model

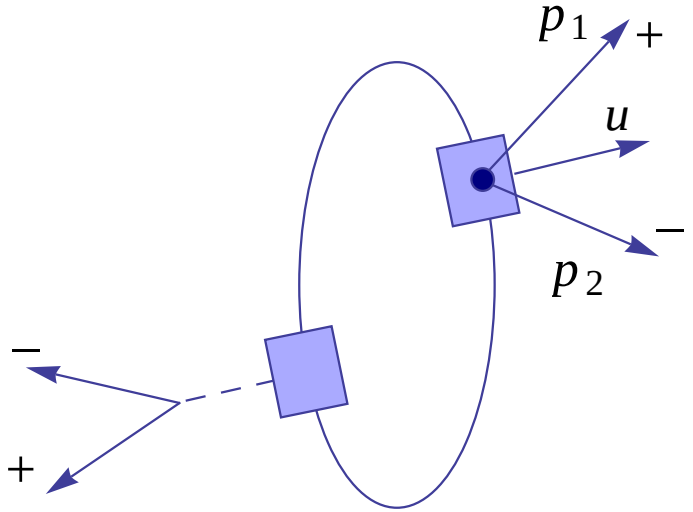
(unlike sign, $0.8 < p_T < 4$ GeV, model unbalanced)





Charge balancing (from resonance decays and "direct")

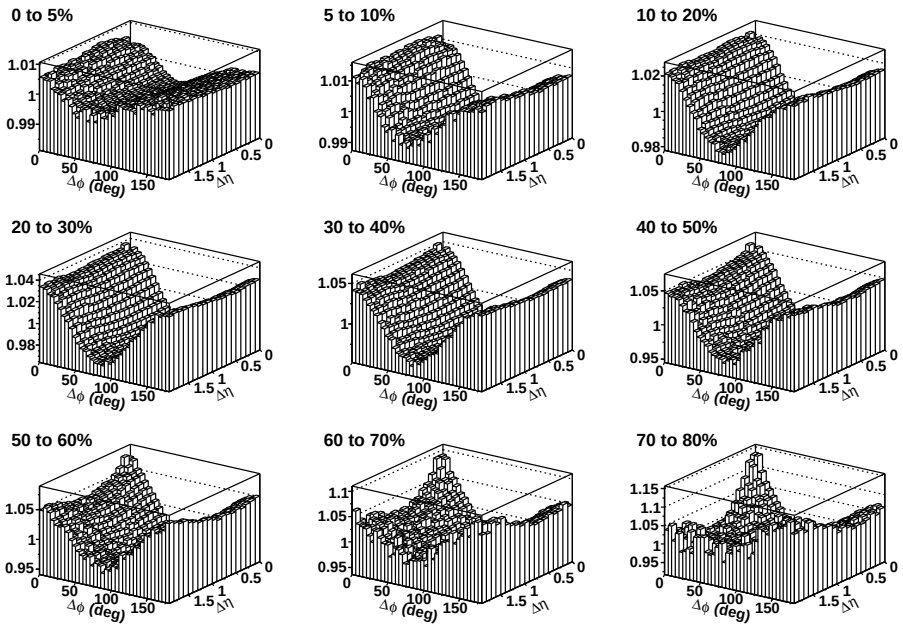
transverse-plane view of the expanding system at freeze-out

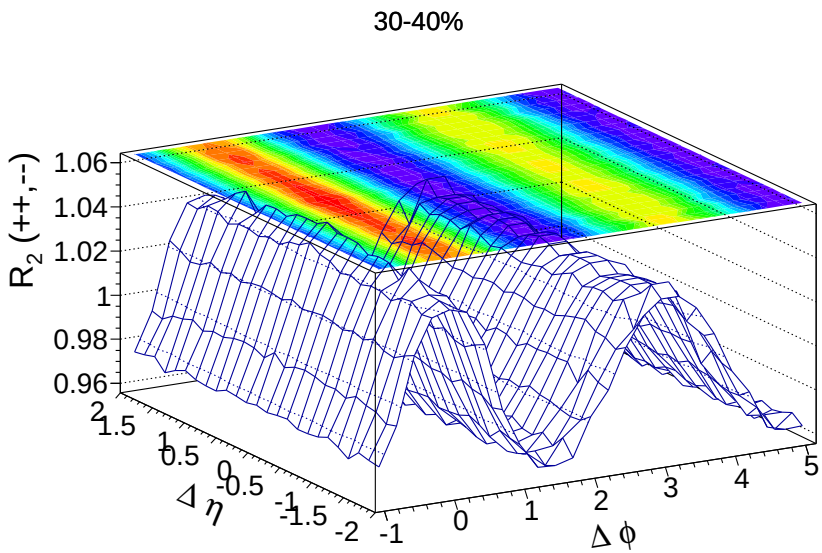


direct balancing: particle-antiparticle pair emitted from the neutral hydrodynamic medium at freeze-out from the same space-time point, e.g., $\pi^+\pi^-$, K^+K^-, $p\bar{p}$, ..., $\Delta^0\bar{\Delta}^0$ ...
resonances also contribute

STAR vs. model

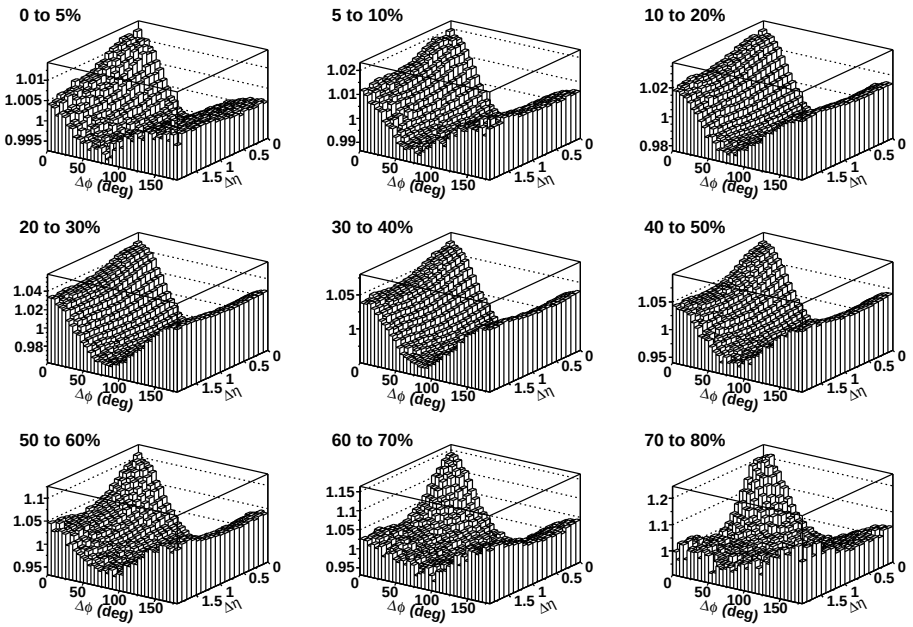
(like sign, $0.8 < p_T < 4$ GeV, balanced)

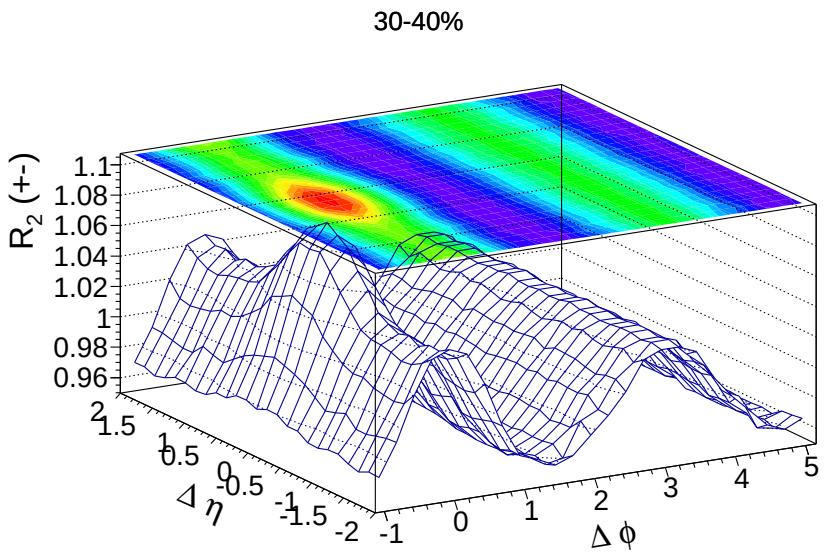




STAR vs. model

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

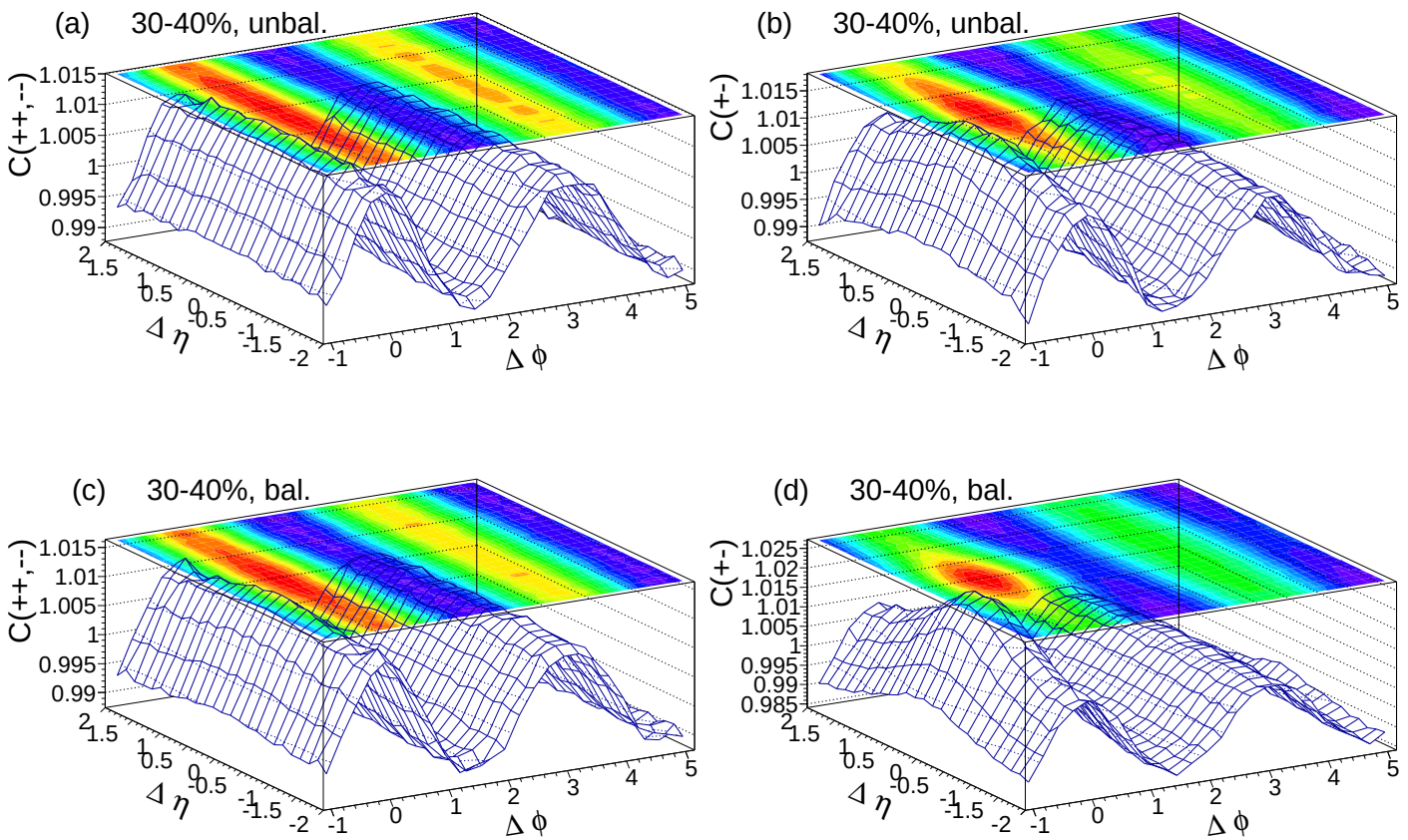




(correct "offsets" - compare to Takahashi et at. 2009, Sharma et al. 2011)

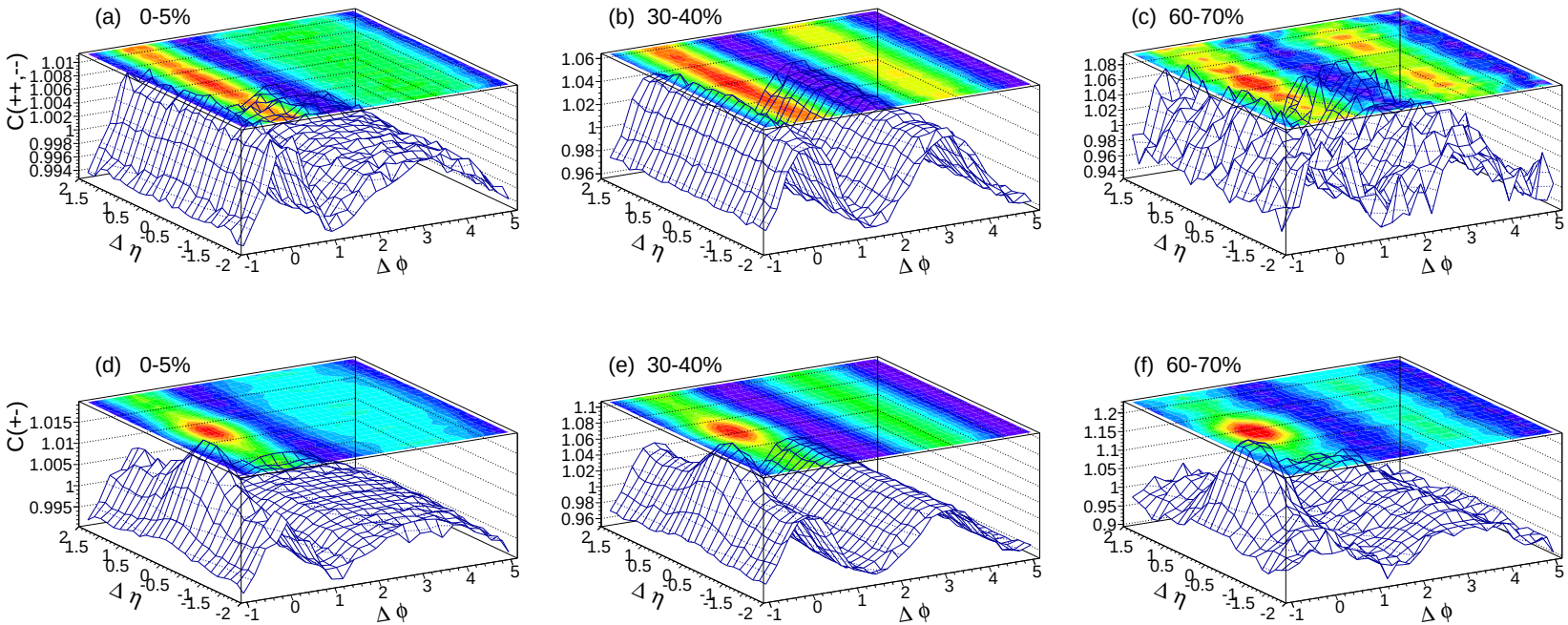
Role of balancing

$(0.2 < p_T < 2$ 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

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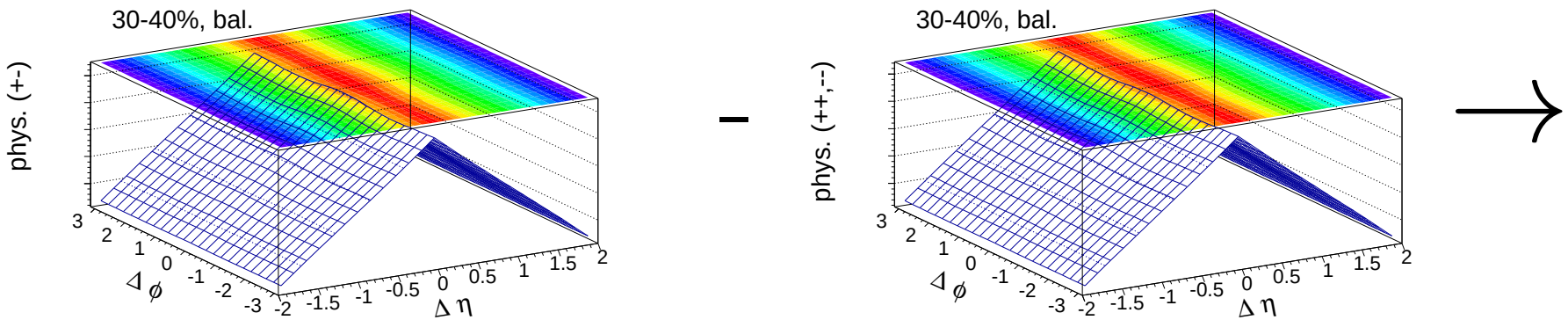

2D balance functions

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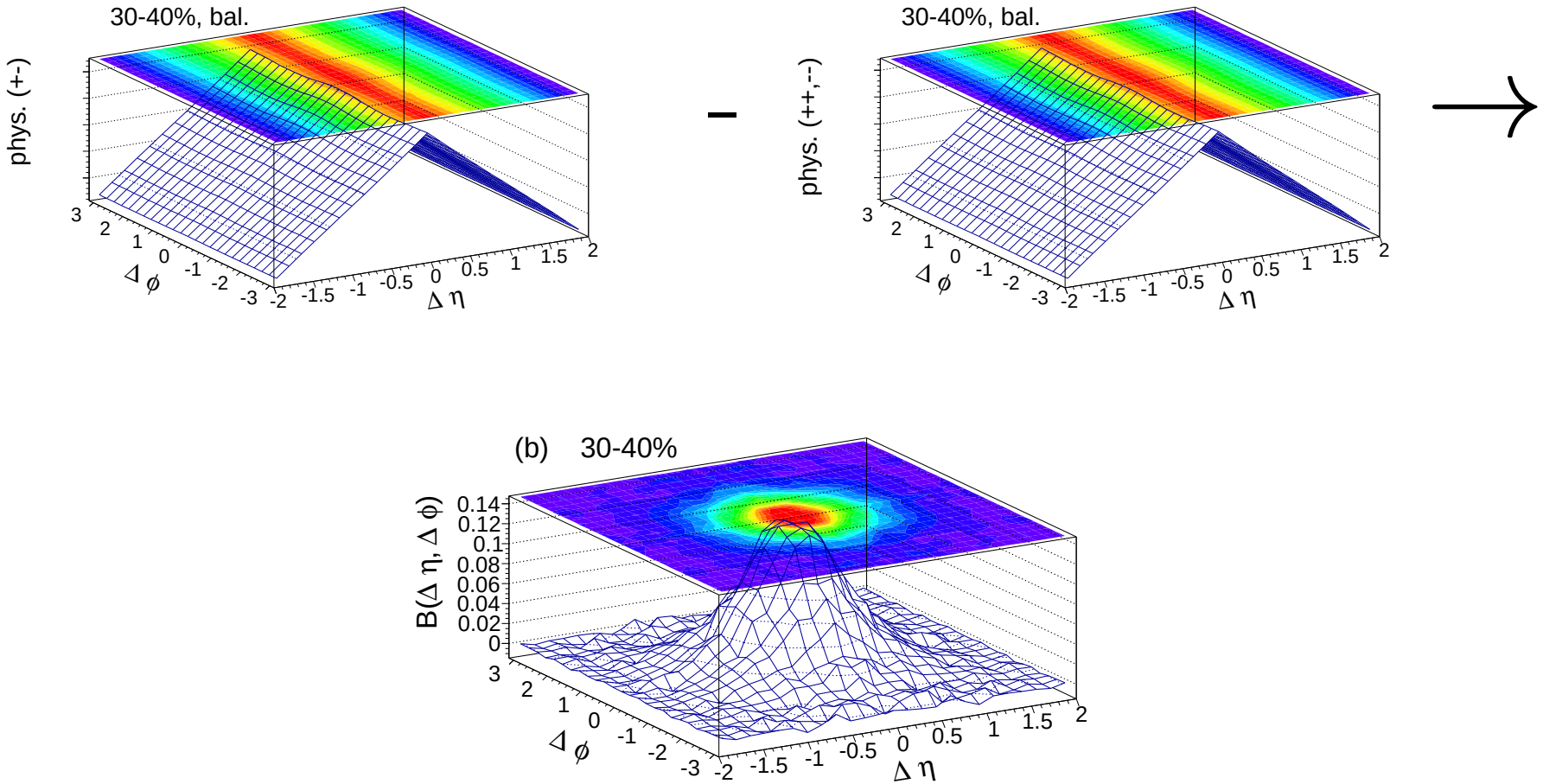
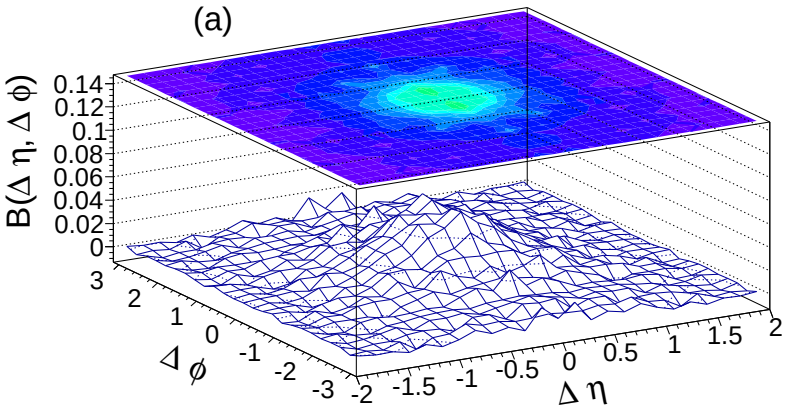


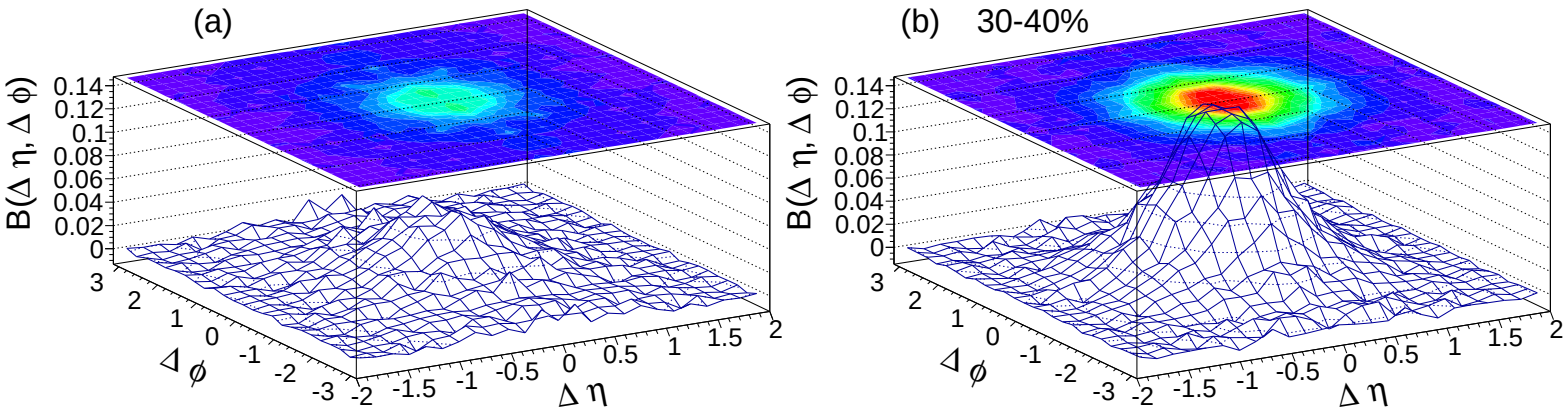
2D balance functions

Crucial role of charge balancing



2D balance functions

Crucial role of charge balancing



small (resonance decays only)

big (direct balancing)

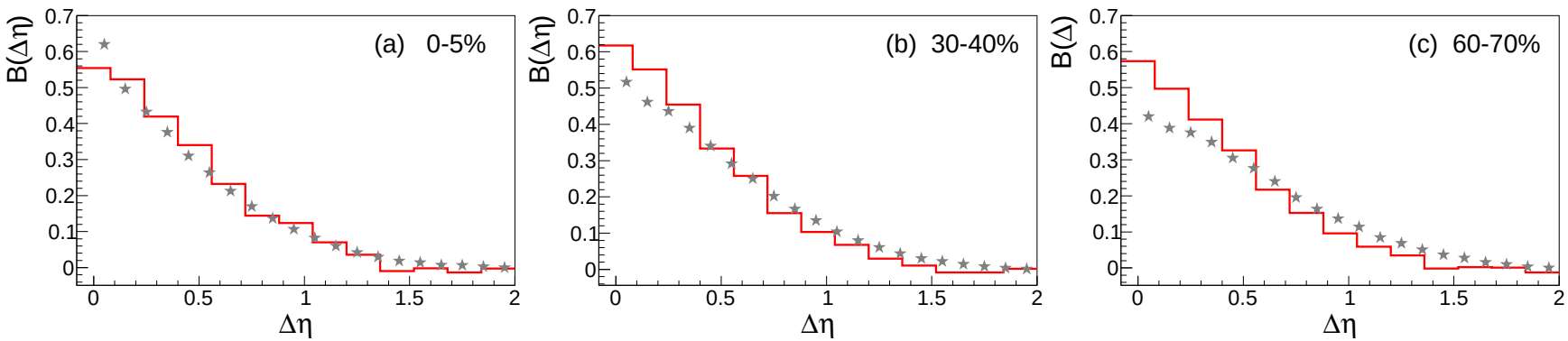
balancing + flow $\rightarrow$ collimation

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 $\Delta\eta$

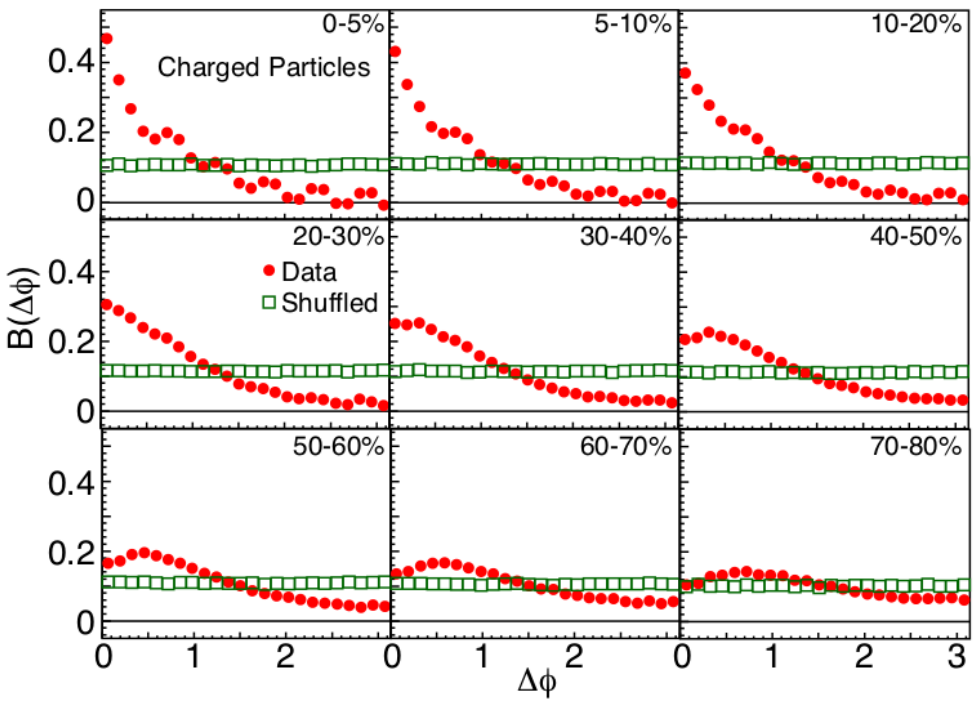
Marginal distribution of the above 2D function: the charge balance function in $\Delta\eta$



comparison to the STAR data

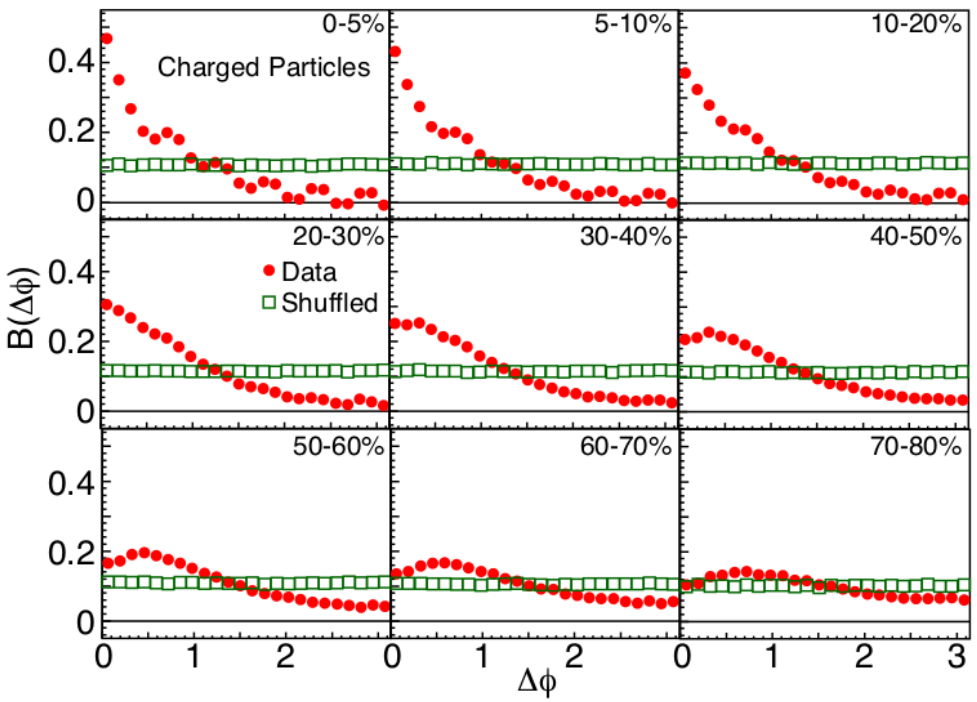
Balance functions in relative azimuth $\Delta\phi$

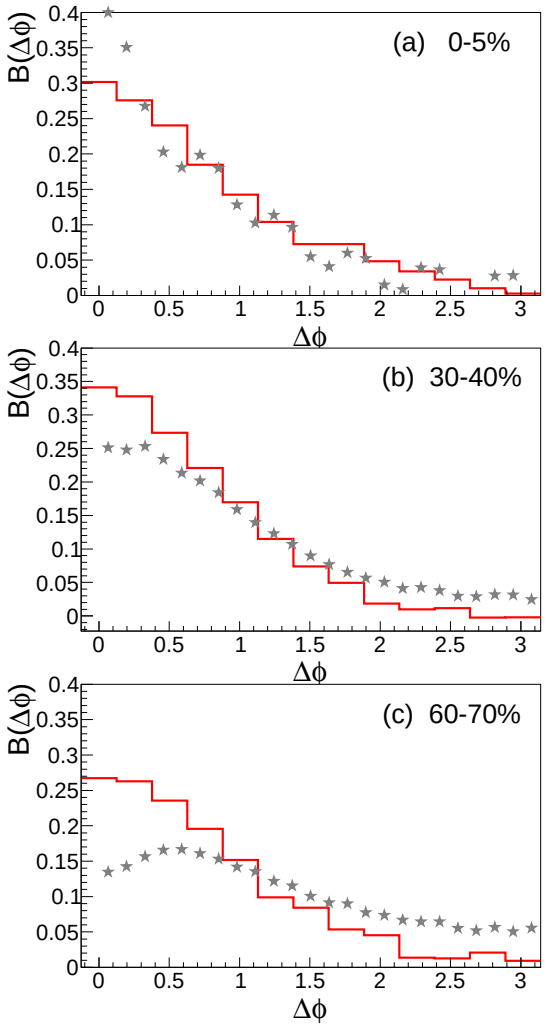
[STAR 2010]



Balance functions in relative azimuth $\Delta\phi$

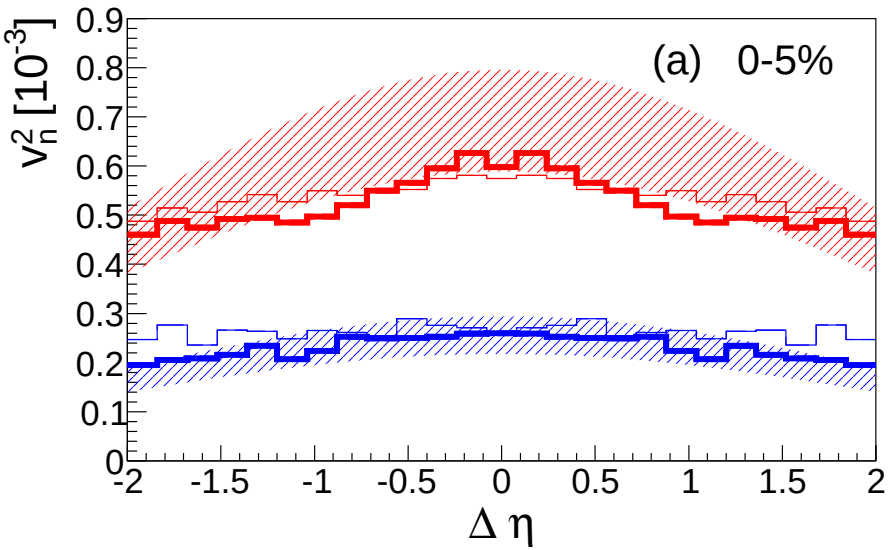
[STAR 2010]





$v_n^2(\Delta\eta)$

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

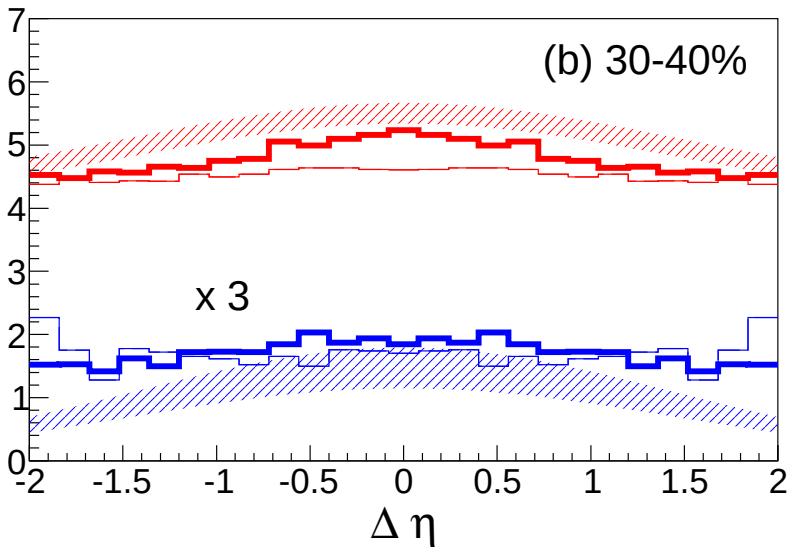


comparison to extracted STAR data (HBT removed), v_2^2, v_3^2
fat: with balancing, thin: no balancing - completely **flat**

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

$v_n^2(\Delta\eta)$

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



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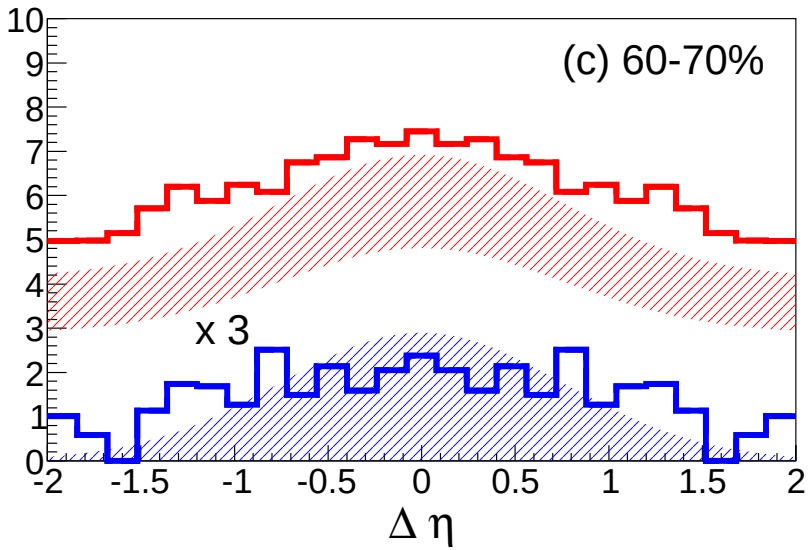
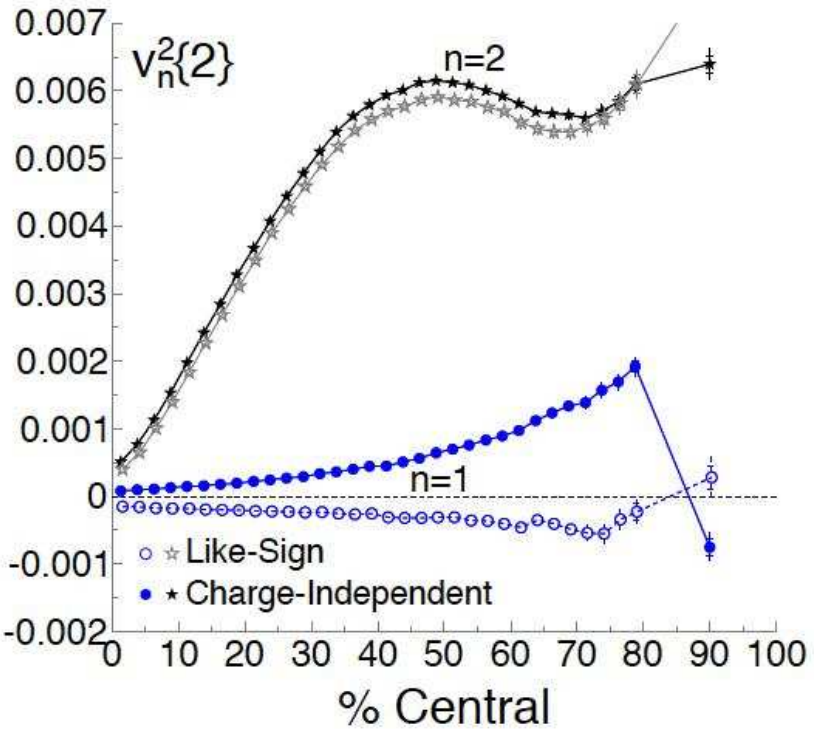


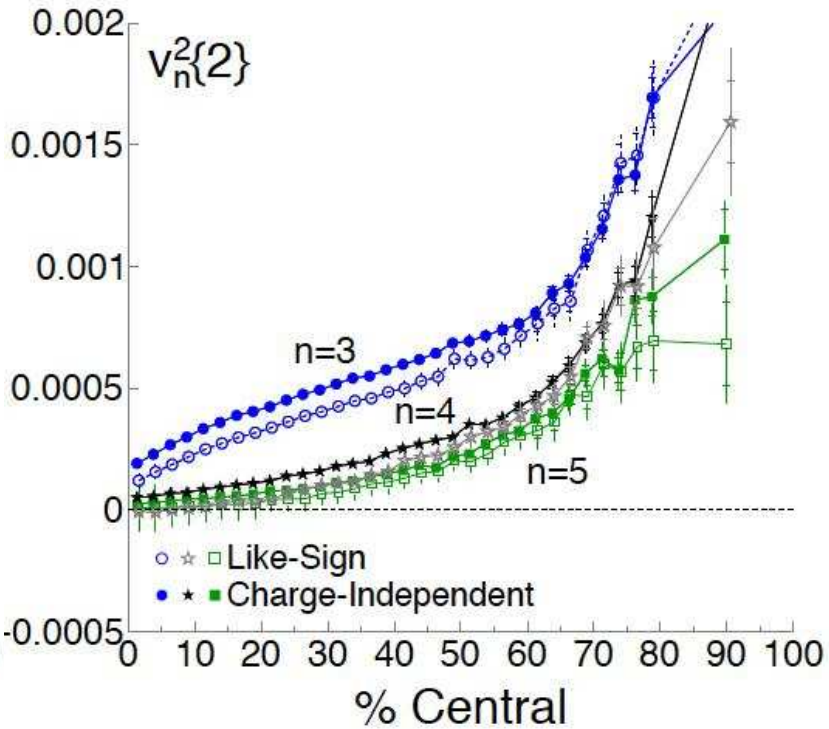
comparison to extracted STAR data (HBT removed), v_2^2, v_3^2
fat: with balancing, thin: no balancing - completely **flat**

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

STAR 2011

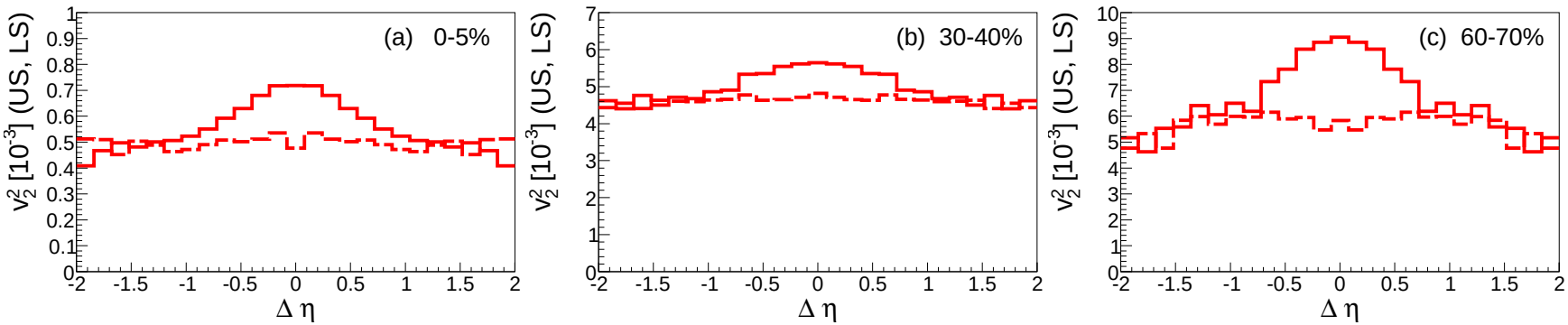
Paul Sorensen at QM2011





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

$(0.15 < p_T < 2$ GeV)



solid: unlike, dashed: like

Physics World again, p-Pb

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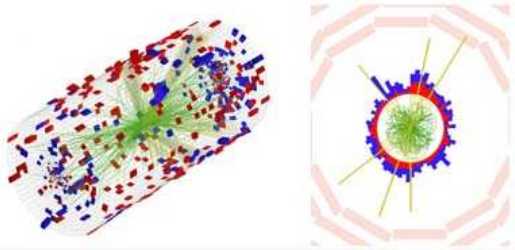
Unexpected 'ridge' seen in CMS collision data again

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).

Related stories

- A strange quark plasma
- Quark–gluon plasma goes liquid
- Of gluons, atoms and strings
- Quark–gluon mania returns to CERN
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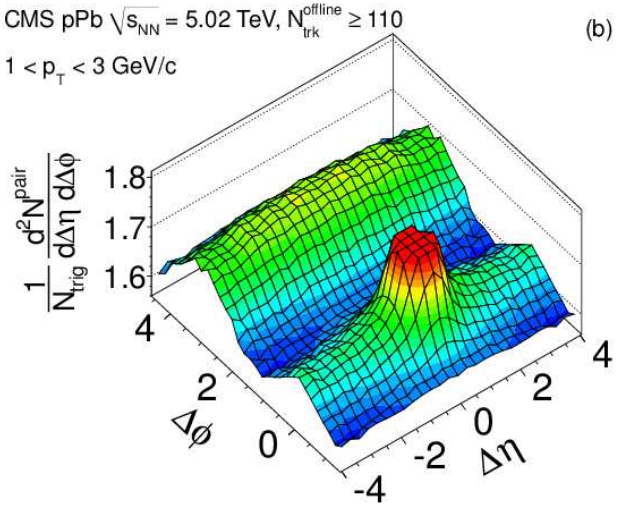
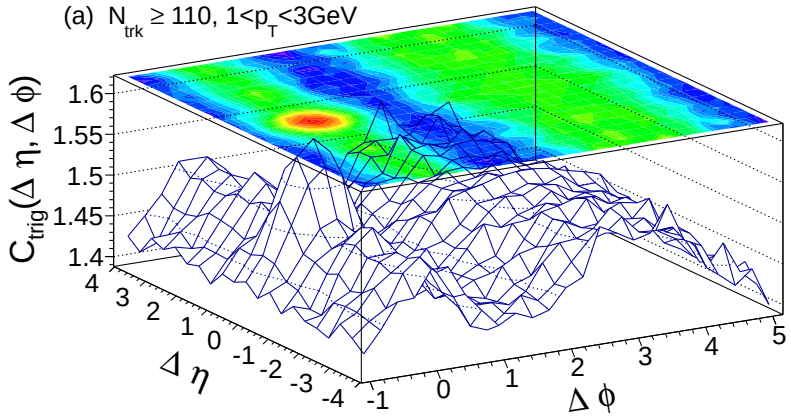
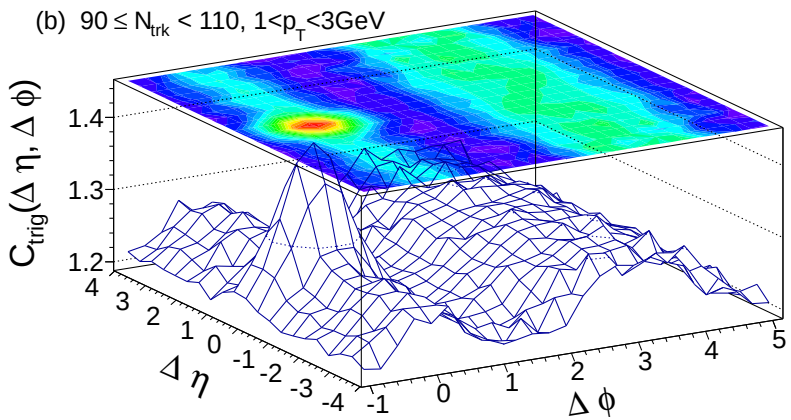
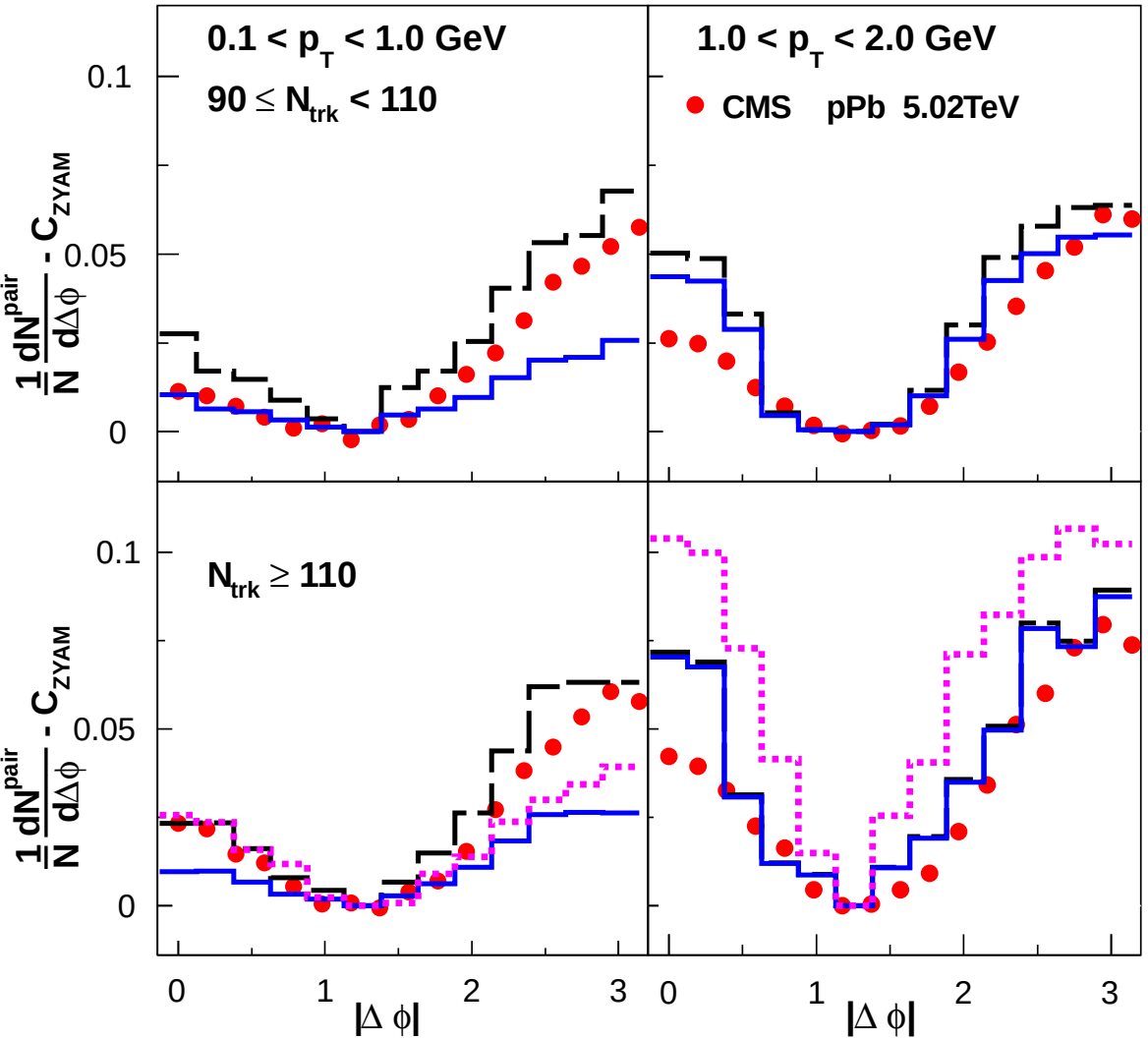
Ridge


CMS pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $N_{trk}^{offline} \geq 110$
(b)
$1 < p_T < 3$ GeV/c
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
1.8
1.7
1.6
4
2
0
-2
-4
$\Delta\phi$
$\Delta\eta$

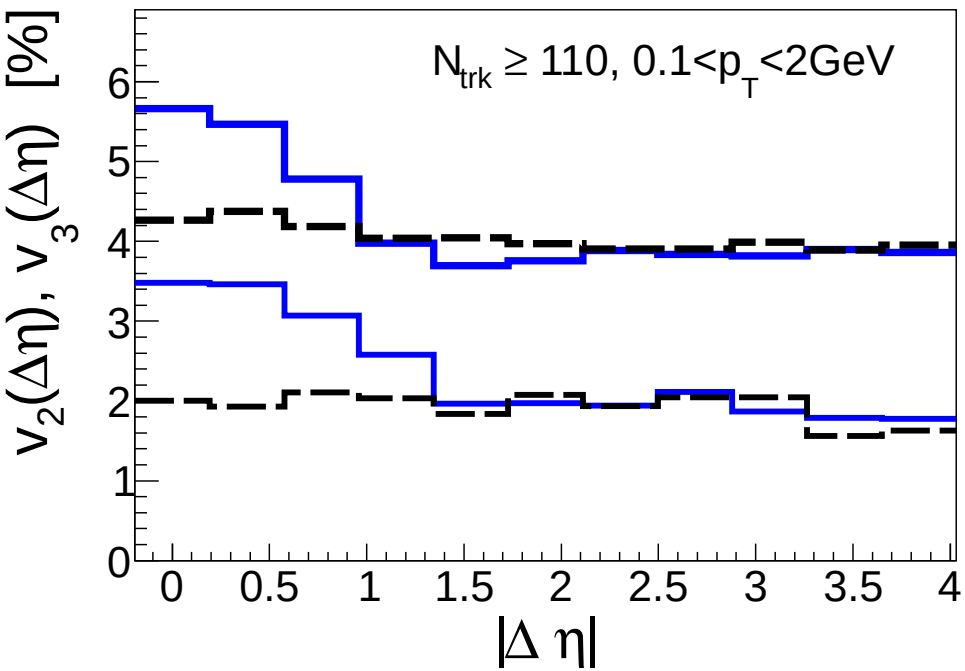

(a) $N_{trk} \geq 110$, $1<p_T<3$GeV
$C_{trig}(\Delta\eta, \Delta\phi)$
1.6
1.55
1.5
1.45
1.4
$\Delta\eta$
$\Delta\phi$


(b) $90 \leq N_{trk} < 110$, $1<p_T<3$GeV
$C_{trig}(\Delta\eta, \Delta\phi)$
1.4
1.3
1.2
$\Delta\eta$
$\Delta\phi$

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



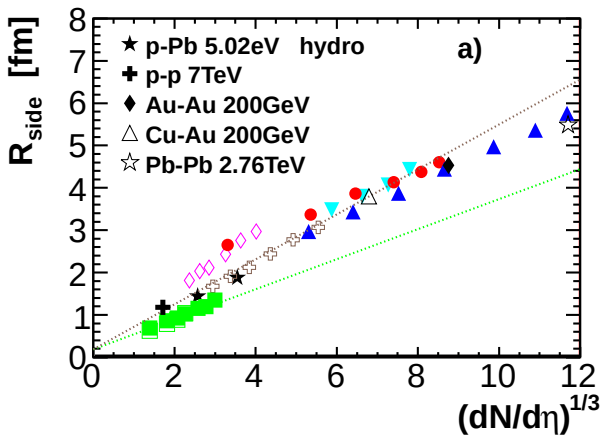
Flow in p-Pb

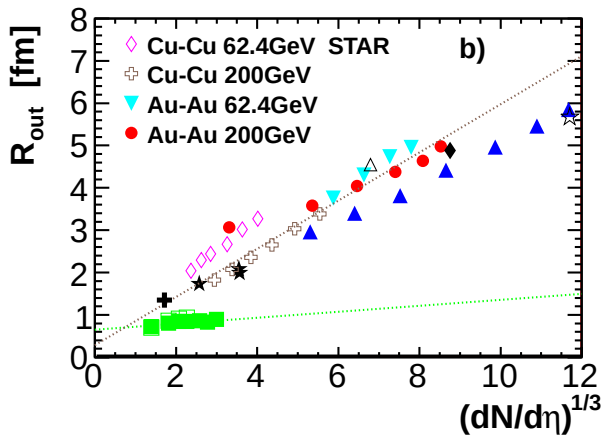


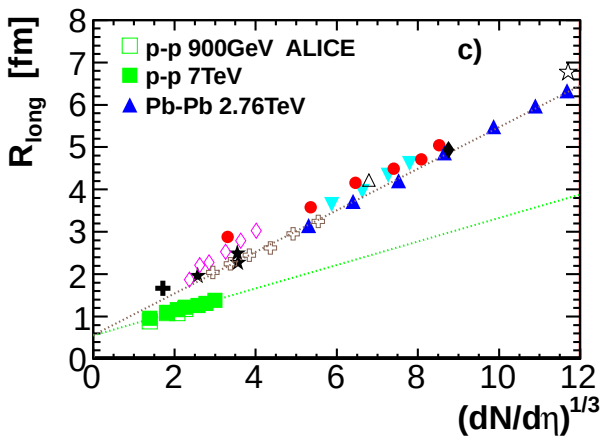
possible to measure directly in the experiment

HBT in p-Pb

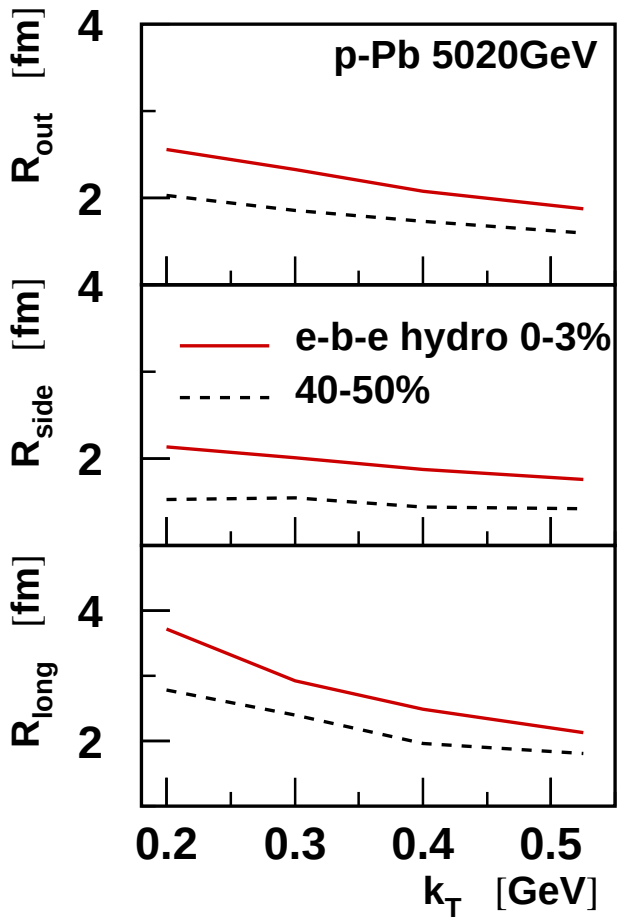
$$C(q,k) = \frac{\sum_{i\neq j} \delta_{q-p_i+p_j}\delta_{2k-p_i-p_j}\left|\Psi(k^*,r^*)\right|^2}{\sum_{i\neq j} \delta_{q-p_i+p_j}\delta_{2k-p_i-p_j}}$$







k_T dependence



Conclusions

- Standard model of HIC works! (spectra, flow, interferometry radii)
- New development: description of e-by-e fluctuations
- 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**, at freeze-out
- Explanation of the same-side ridge in p-Pb
- Prediction: HBT radii for p-Pb as in peripheral A-A collisions

  $\rightarrow$ **collective behavior in high-multiplicity p-Pb systems**