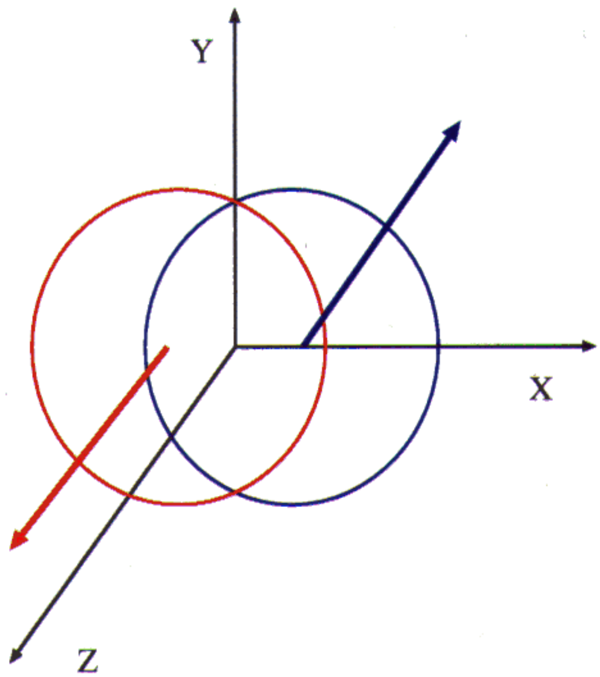
Anisotropic transverse flow; where it stands, where it is moving.

Sergei VOLOSHIN *LBNL/MEPI*

SUBJECT: Anisotropic transverse flow

Or: Anisotropies and asymmetries in nuclear collisions

Or: Particle production in non-central collisions wrt the reaction plane



Non-central collision ⇒ event anisotropy in transverse (X, Y) plane. (Yields as well as geometry of the effective source depend on $(\phi - \Psi_r)$).

$$\frac{Ed^3n}{d^3p} \Rightarrow \frac{d^3n}{p_t dp_t dy d(\phi - \Psi_r)}$$

Ψ_r – the reaction plane

$$\frac{E_1 E_2 d^6n}{d^3p_1 d^3p_2} \Rightarrow$$

HBT: R_{side}, R_{out}, R_{long}, τ - now functions of $(\phi - \Psi_r)$

FLOW: Distribution wrt the reaction plane

$$\frac{d^3N}{d^3p'} = \frac{d^3N}{dy\, p_t dp_t\, d(\phi - \Psi_r)}$$

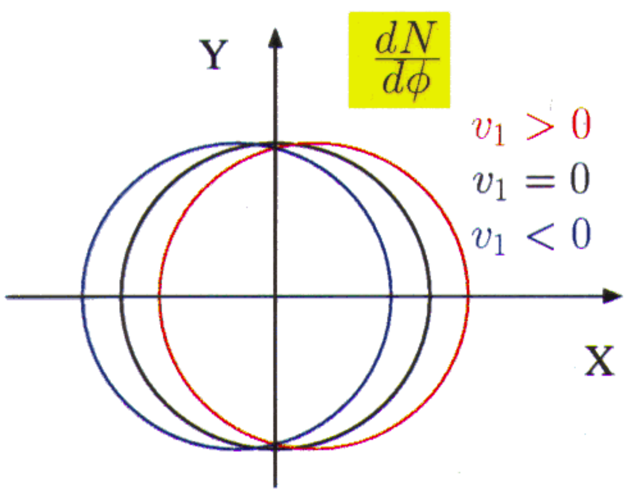
TECHNIQUE: Fourier expansion of azimuthal distribution:

S.V. and Y.Zhang, hep-ph/940782; Z.Phys **C70**, *665 (1996)*
E877 publications;
J.-Y. Ollitrault, Proceedings of QM'95 and QM'97; nucl-ex/9711003
A. M. Poskanzer, S. V., Phys. Rev. C58, 1671 (1998)

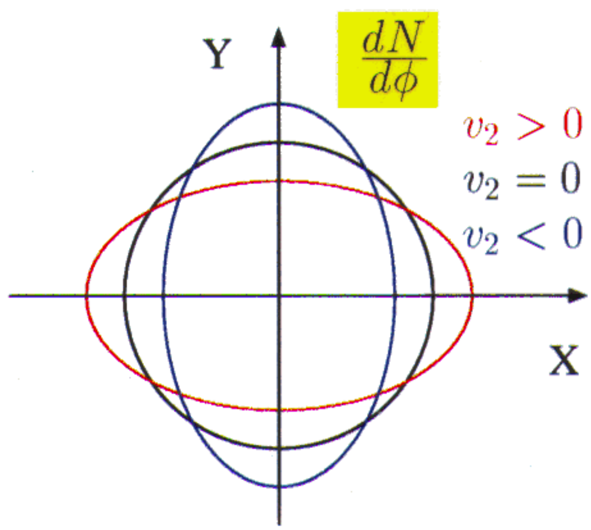
$$\frac{d^3N}{dy\, p_t dp_t\, d\phi'} = \frac{d^2N}{dy\, p_t dp_t} \frac{1}{2\pi}(1 + 2v_1 \cos(\phi') + 2v_2 \cos(2\phi') + \ldots)$$

$$\phi' = \phi - \Psi_r$$

$$v_n = \langle \cos(n(\phi - \Psi_r)) \rangle$$



Directed flow



Elliptic flow

METHOD

Definitions:
"Event" – all (detected) particles in some (pseudo)rapidity window.
"Subevent" – some part of the "event".

Flow vectors

$$\mathbf{Q}_\mathbf{n}^{(\mathbf{a})} = (X_n^{(a)}, Y_n^{(a)}) = (\sum_{(a)} w_i \cos(n\phi_i), \sum_{(a)} w_i \sin(n\phi_i))$$

Correlation between flow vectors

$$\langle \mathbf{Q}_\mathbf{n}^{(\mathbf{a})} \mathbf{Q}_\mathbf{n}^{(\mathbf{b})} \rangle = \langle X_n^{(a)} X_n^{(b)} + Y_n^{(a)} Y_n^{(b)} \rangle = \langle v_n^{(a)} N^{(a)} \rangle \langle v_n^{(b)} N^{(b)} \rangle$$

$v_n \equiv \langle \cos(n(\phi - \Psi_r)) \rangle$

– EbE analysis –

Reaction plane resolution

$\langle \cos(\Psi_1 - \Psi_r) \rangle$

Ψ_r – true reaction plane,
Ψ_1 – reconstructed reaction plane

FLOW SUMMARY

1. Flow (anisotropy) "survives" (at the level of a few percent on average) up to very high energies (currently up to the SPS, and, in most models, at RHIC). v_2 is positive!

2. There exist no model describing data in details (the "best" descriptions is, probably, by RQMD). "Theory" is (still) "behind" of the "experiment". Hydro type models predict far stronger flow than observed.

3. The physics is very interesting, measurable, and important.

What have been measured ($E_{beam} > 10\ GeV/nucleon$)

- AGS: E877, E802
  Directed and elliptic flow of N_{ch}, E_t, $\pi^\pm$, $K^\pm$, p, $\bar{p}$, d, t, ^3He, ^4He..
  Identified particles: $v_{1,2}(p_t)$.
  pp and $\pi\pi$ correlations wrt RP.

- SPS: NA49, NA45, WA98
  Directed and elliptic flow of N_{ch} and E_t, pions, protons, fragments.
  $v_{1,2}(y, p_t)$ of pions and protons.

Reaction Plane Resolution

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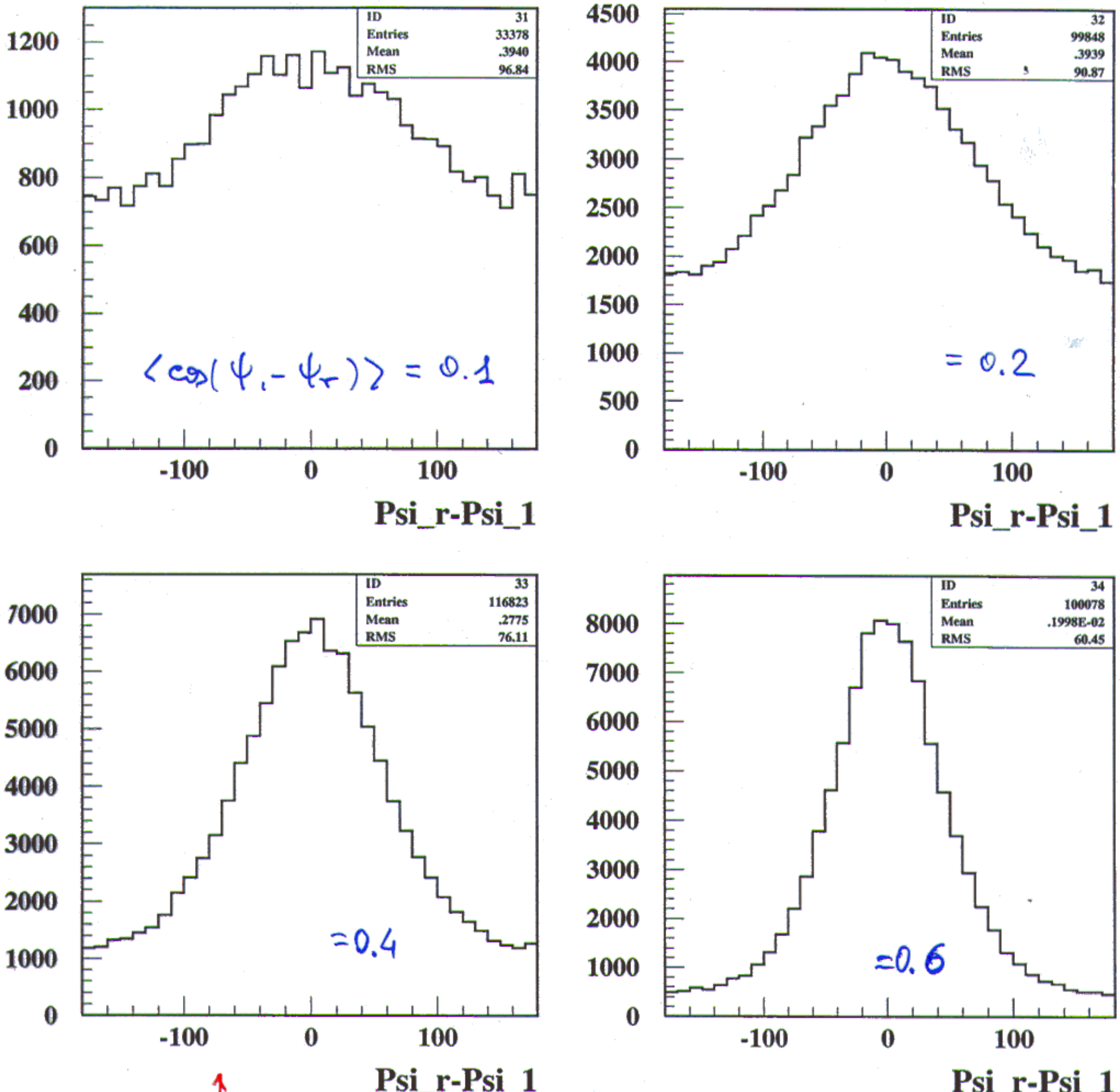


↑ SPS, RHIC

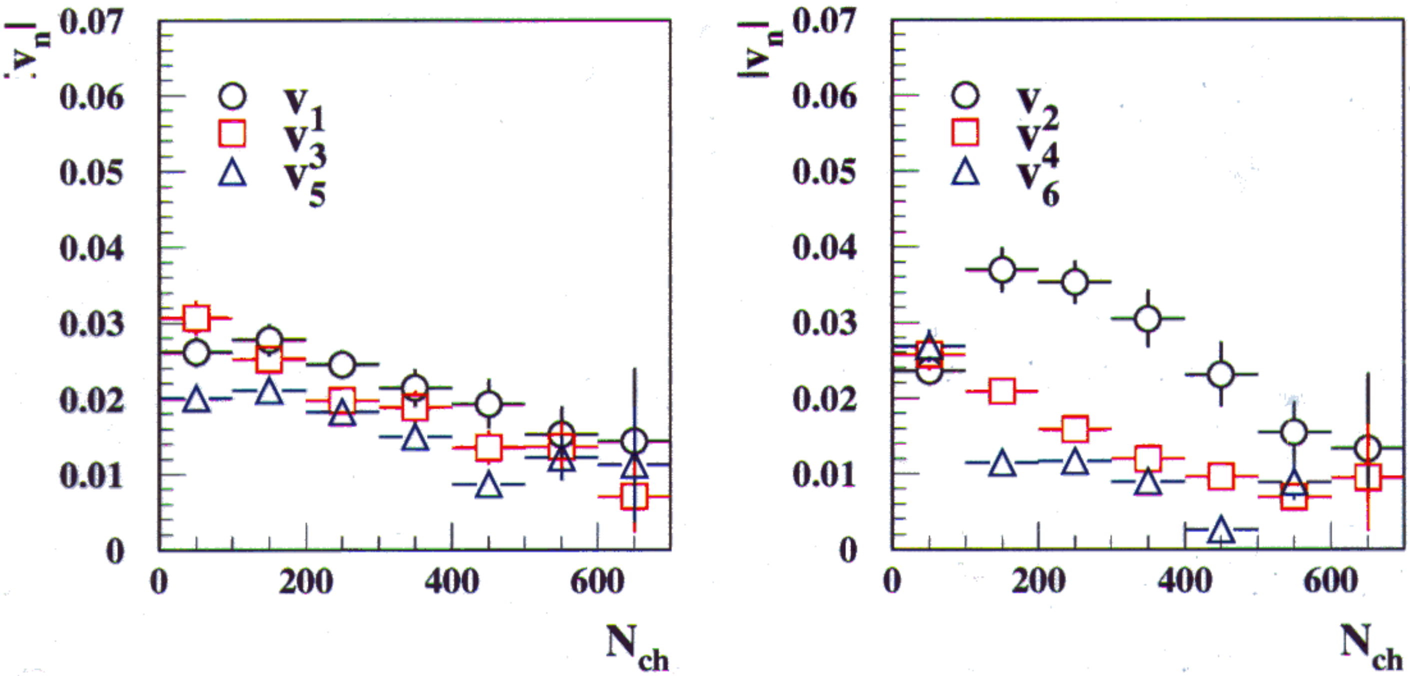
↑ AGS

$$\langle\cos(\psi_1-\psi_r)\rangle \simeq \sqrt{\frac{\pi}{4}}\cdot v_1\cdot\sqrt{N}$$

GOALS and APPROACHES

1. Physics: "Flow" and ...
   - QGP (phase transitions)
     – flow vs centrality and/or beam energy
   - DCC
     – "charged" flow vs "neutral" flow, higher harmonics
   - Fireball evolution (expansion)
     – Radial vs anisotropic flow – $v_n(p_t)$
     – In plane expansion – HBT + non-identical 2-particle correlations
   - (Mini) jet physics
     – High p_t particle production and (y and ϕ) 2-particle correlations
   - J/Ψ production/suppression
2. Difficulties and open questions
   - Conservation laws and flow analysis
   - Coulomb and flow
   - Higher harmonics
3. What is studied experimentally
   - v_n as a function p_t, rapidity, and centrality ($n = 1 \ldots 6$)
   - 2-particle spectra wrt RP.
     - HBT
     - non-identical particle correlations
     - long range (rapidity and azimuthal angle, high p_t) 2-particle correlations
   - Flow (event-by-event) fluctuations

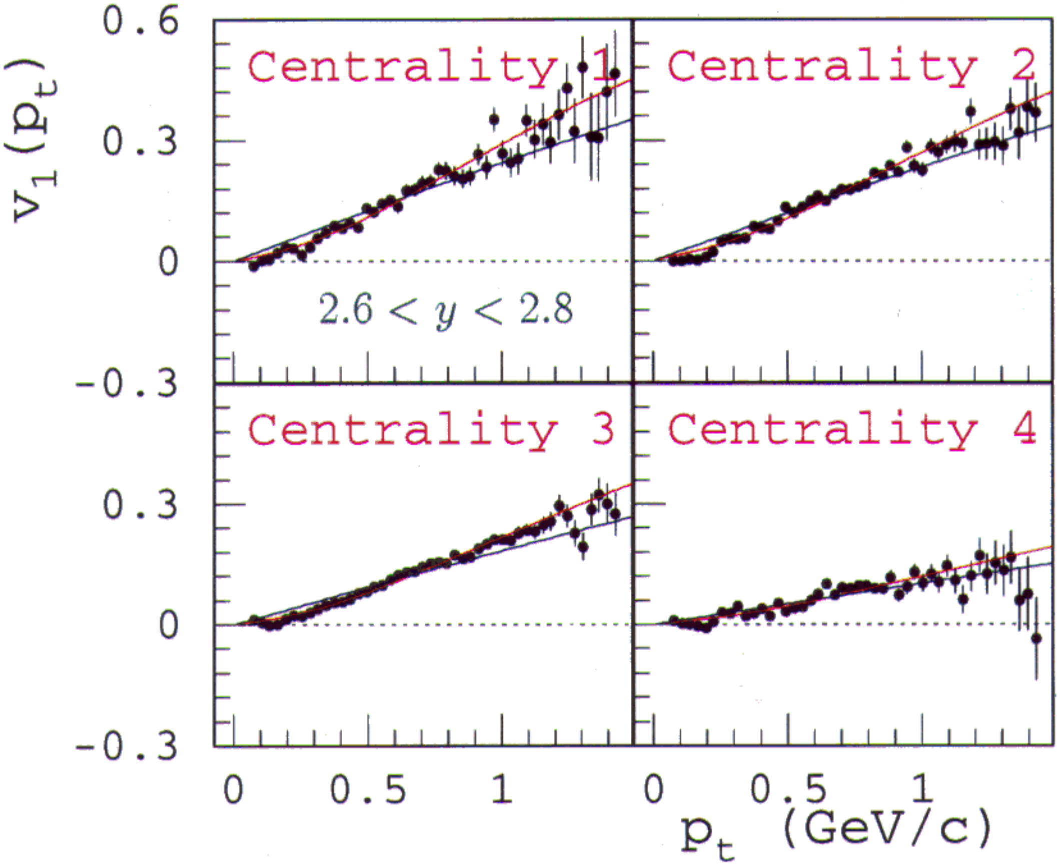
NA45 (CERES), preliminary



$2 < \eta < 2.5 \cup 3.2 < \eta < 3.4$ $2 < \eta < 3.4$

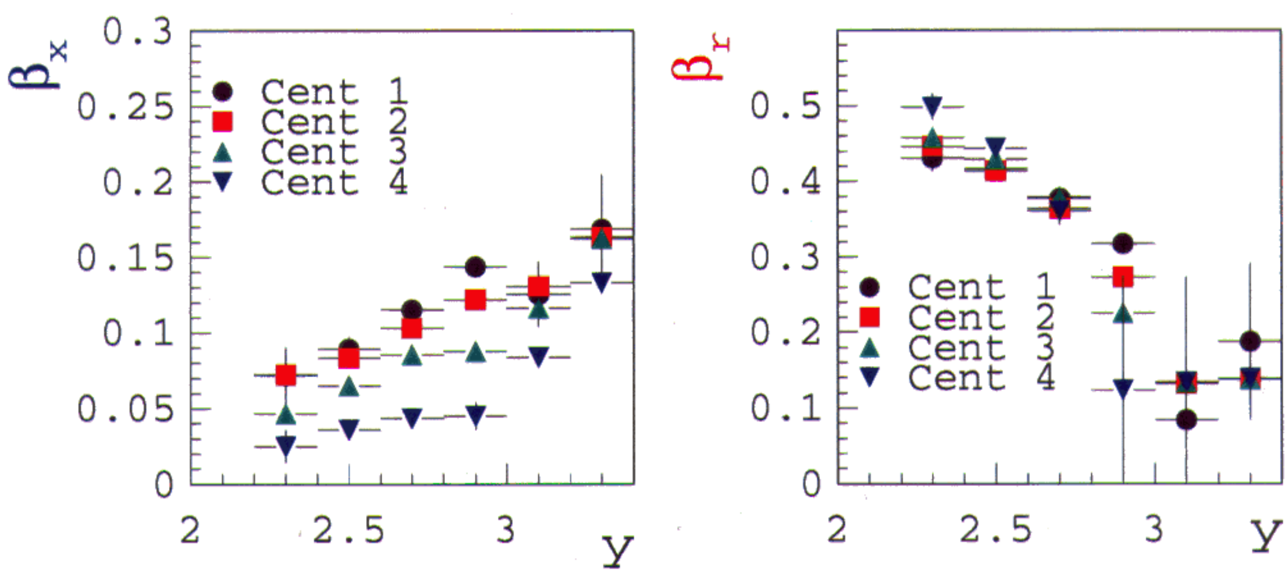
DIRECTED ⊕ RADIAL FLOW: FIT TO DATA

S.V. for the E877, QM '97



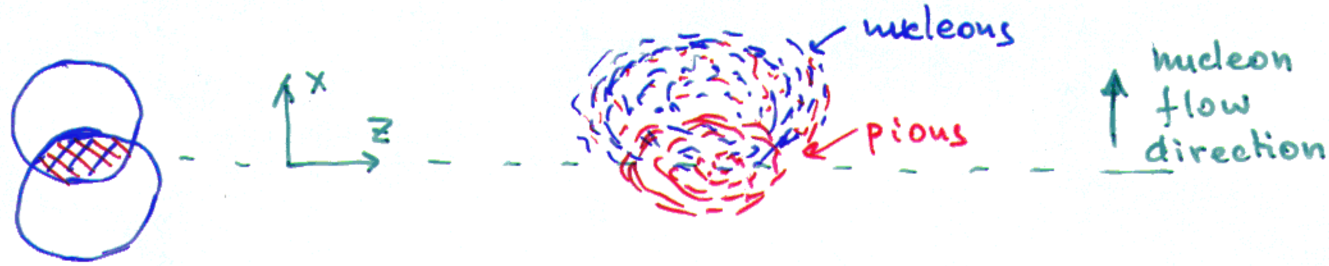
Fits: Blue: Moving Thermal Source

Red: ⊕ radial expansion (T=110 MeV, $y - y^* = 0.5$)



Particle effective source from different directions

1. Pion source (forward rapidities)



$t \simeq 0$ $\qquad$ $t \simeq t_{freeze\text{-}out}$

⟹ From $+x$ direction pion source looks dim and wide

From $-x$ —— " —— bright and narrow

2. Midrapidy region

$t \approx 0$ $\qquad$ $t \simeq t_{freeze\text{-}out}$

⟹ After in-plane expansion source is (?) wider in „x" direction than in „y" direction

RQMD v2.3

$\pi^{\pm}$

$4 < b < 10$

$1.5 < y < 3.5$ $\quad (p_x + p_y) > |p_x - p_y|$

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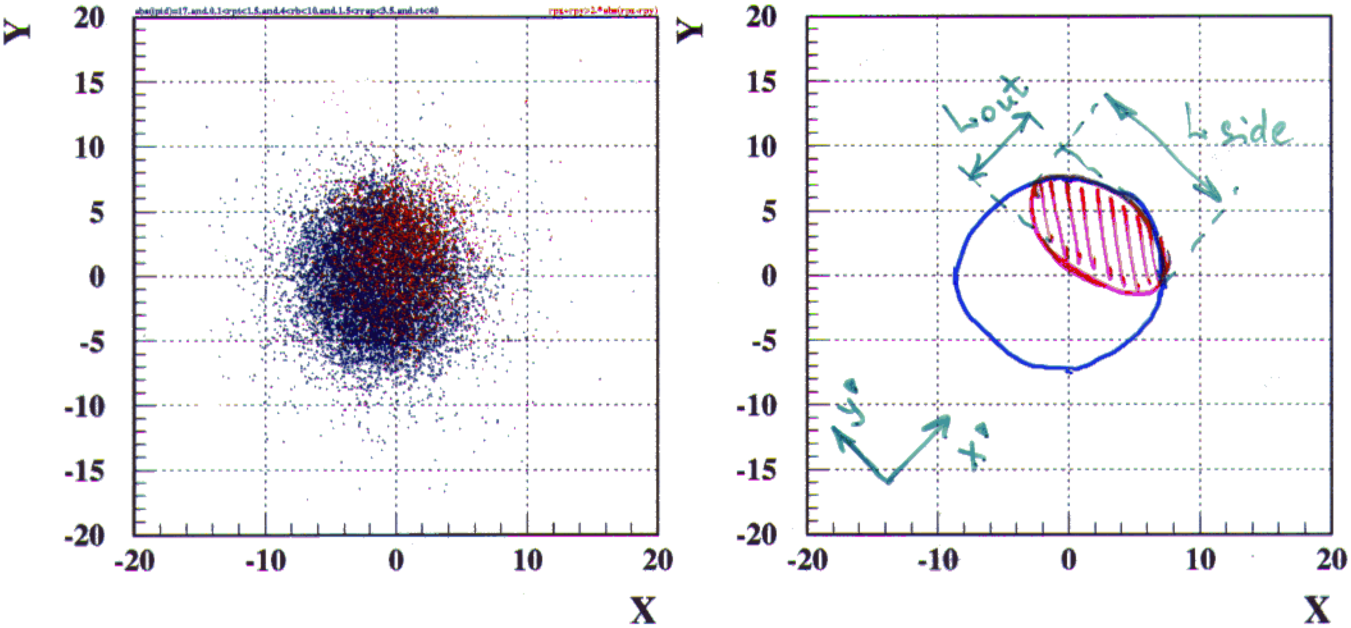


$v_{side} = 0$

$v_{out} = p_t / E$

$v_{long} = p_z / E$

out ≡ x'

side ≡ y'

long ≡ z

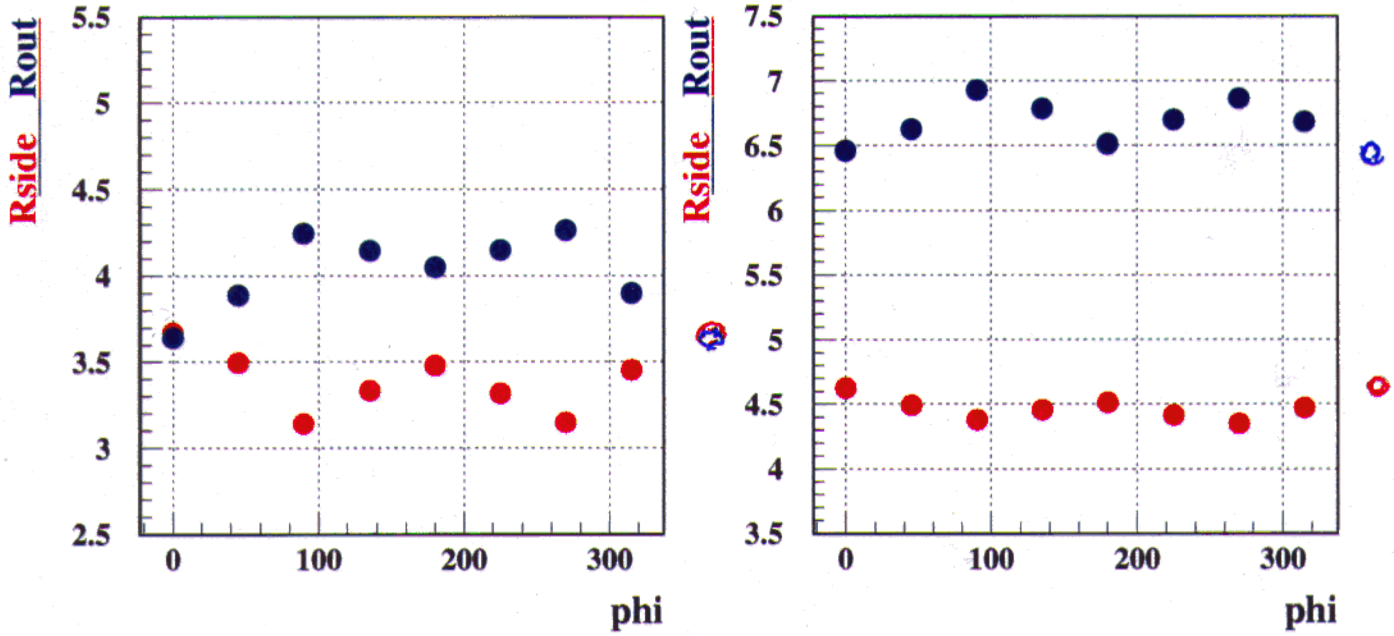
$$L^2_{side} = \langle (y' - \langle y' \rangle)^2 \rangle = R^2_{side}$$

$$L^2_{out} = \langle (x' - \langle x' \rangle)^2 \rangle \neq R^2_{out}$$

$$R^2_{out} = \langle [(x' - v_{out} t) - \langle x' - v_{out} t \rangle]^2 \rangle$$

$$R^2_{long} = \langle [(z - v_z t) - \langle z - v_z t \rangle]^2 \rangle$$

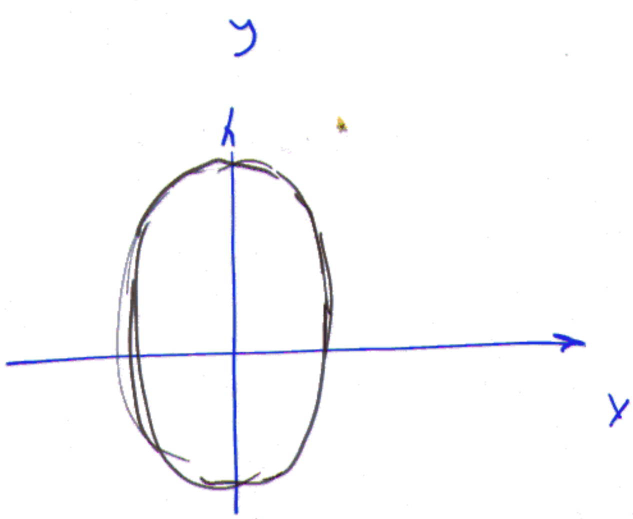
RQMD v2.3 , Pb+Pb , 158 GeV/nucleon

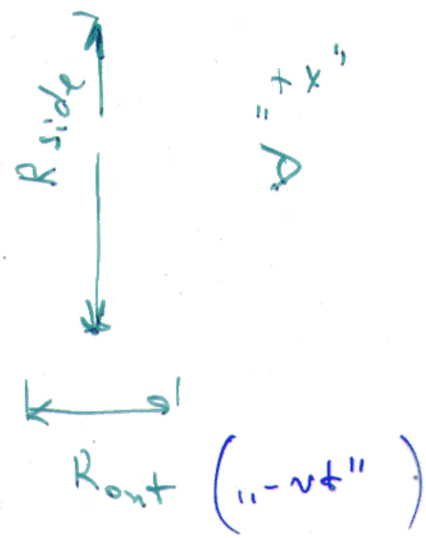


$-4 < y < -2$ $-2 < y < 0$

Centrality: $4 < b < 8$

$0.3 < P_t < 0.45$





Does  change to  with P_t? E_{beam}?

Literature: [illegible] and W. Cleland: PRC, [illegible]

PRC, 54 (1996) 3212

U. Wiedemann : PRC, 57 (1998) 266

H. Heiselberg : nucl-th/9809077

Urs: Minimal parametrization (6 parameters)

$$R^2_{side}, \; R^2_{out}, \; R^2_{long}, \; R^2_{ol},$$

(cosine term; side; first harmonic; out)

$$\alpha_1 \approx R^{c\,2}_{s,1} \approx \frac{1}{3} R^{c\,2}_{o,1} \approx - R^{s\,2}_{os,1}$$

$$\alpha_2 \simeq R^{c\,2}_{o,2} \approx - R^{c\,2}_{s,2} \approx - R^{s\,2}_{os,2}$$

Henning: $r_1 \equiv 0$

$$R_s^2 = g_s R^2 [1 + \delta \cos(2\varphi)]$$

$$R_o^2 = g_o R^2 [1 - \delta \cos(2\varphi)] + \beta_o^2 \delta\tau^2$$

$$R_{os} = g_{os} R^2 \delta \sin(2\phi)$$

Moderately opaque source: $g_o/g_s \simeq 0.5$

($p_t = 0$ discontinuity!)

RQMD

$6 < b < 12$

$p_t / m_t < 0.8$, $|y| < 1.5$

$p_x > 2 |p_y|$

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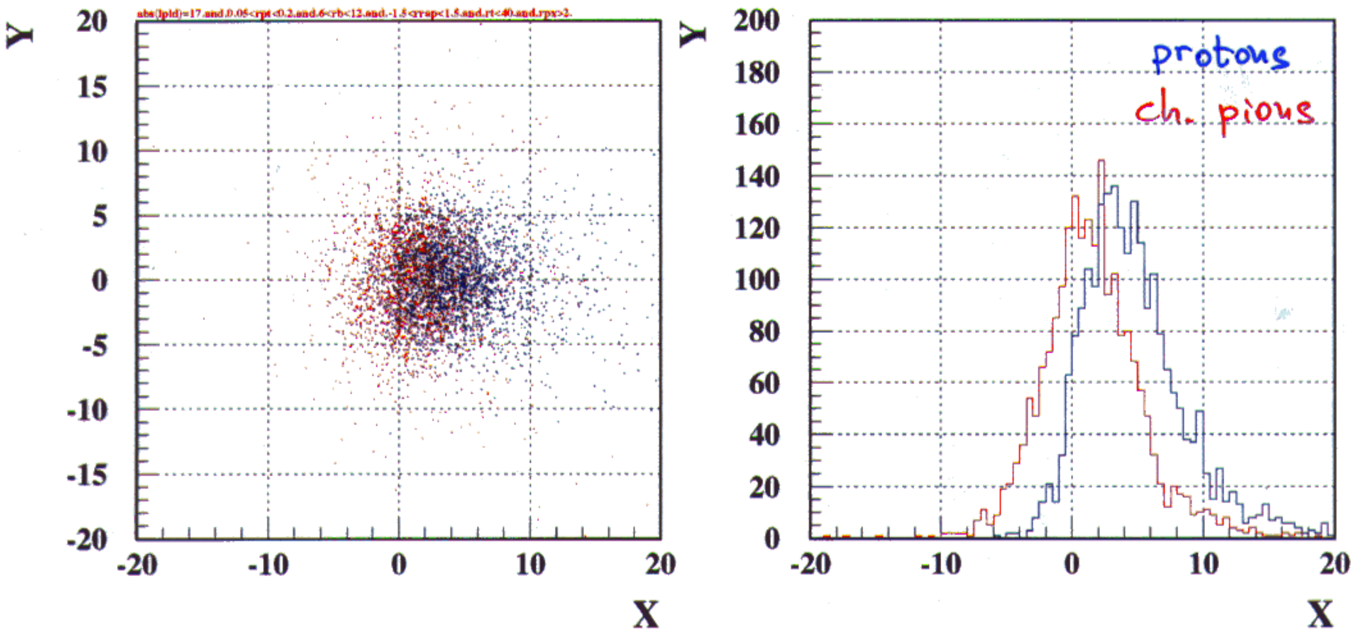
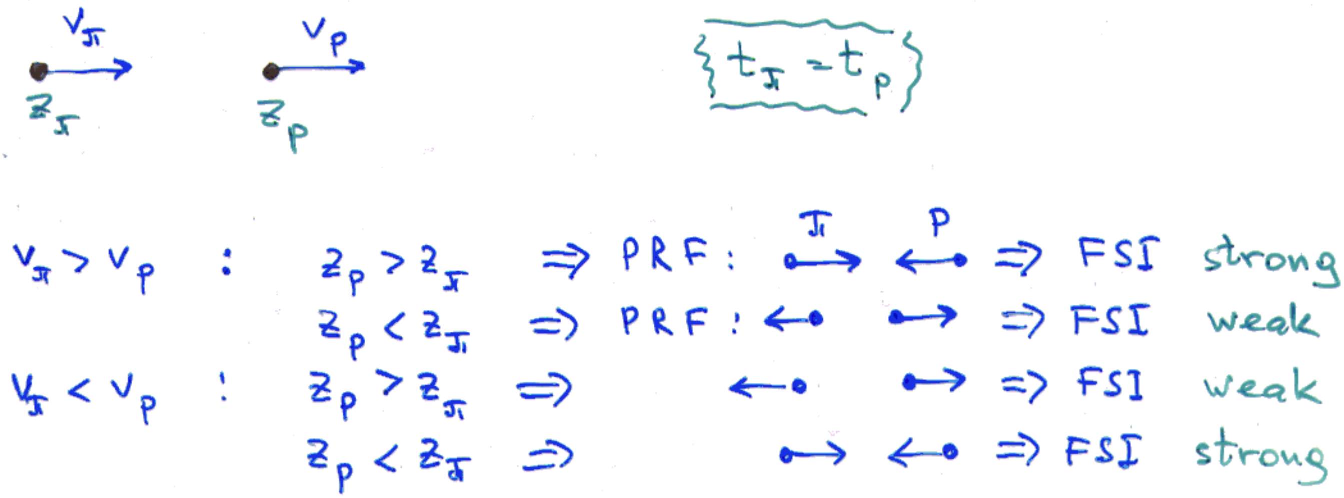


Relative space-time asymmetries in pion and nucleon production in non-central nucleus-nucleus collisions at high energies

S. Voloshin, R. Lednicky, S. Panitkin, Nu Xu. PRL, **79** (1997) 4766



$$\frac{R_i^{(+)}}{R_i^{(-)}} \approx \frac{1 + 2\langle \mathbf{r}^* \rangle \langle \mathbf{k}^*/k^* \rangle^{(+)}/a}{1 + 2\langle \mathbf{r}^* \rangle \langle \mathbf{k}^*/k^* \rangle^{(-)}/a} \approx 1 + 2\langle \mathbf{r}^* \rangle_i / a$$

$$\mathbf{k}^* = \mathbf{p}_\pi = -\mathbf{p}_p; \; \mathbf{r}^* = \mathbf{r}_\pi - \mathbf{r}_p$$ * – PRF

$R_i^{(+)}$ and $R_i^{(-)}$ correspond to $k_i^* > 0$ and $k_i^* < 0$

a – Bohr radius ($a_{\pi^\pm p} \approx \pm 222$ fm)

Coulomb only: $R = A_c(\eta)\langle |F(-i\eta, 1, i\rho)|^2 \rangle$

$$\eta = 1/(k^* a), \; \rho = k^* r^* + \mathbf{k}^* \mathbf{r}^*$$

$$A_c(\eta) = 2\pi\eta / [\exp(2\pi\eta) - 1]$$

$$F(\alpha, 1, z) = 1 + \alpha z + \alpha(\alpha + 1)(z/2!)^2 + \cdots$$

$$k\langle r \rangle << 1, \langle r \rangle << a \Rightarrow F \approx 1 + \rho\eta = 1 + (k^* r^* + \mathbf{k}^* \mathbf{r}^*)/(k^* a)$$

$$k^* \ll \langle p_t \rangle, \; \langle \mathbf{r}^* \rangle \langle \mathbf{k}^*/k^* \rangle^{(\pm)} = \pm \langle \mathbf{r}^* \rangle_i / 2$$

RQMD v2.3 , PbPb , 158 GeV/nucleon

$6 < b < 12$ – centrality

$\cos\varphi > 0.7$ – orientation wrt RP

$0.6 < P_t/m_t < 0.8$

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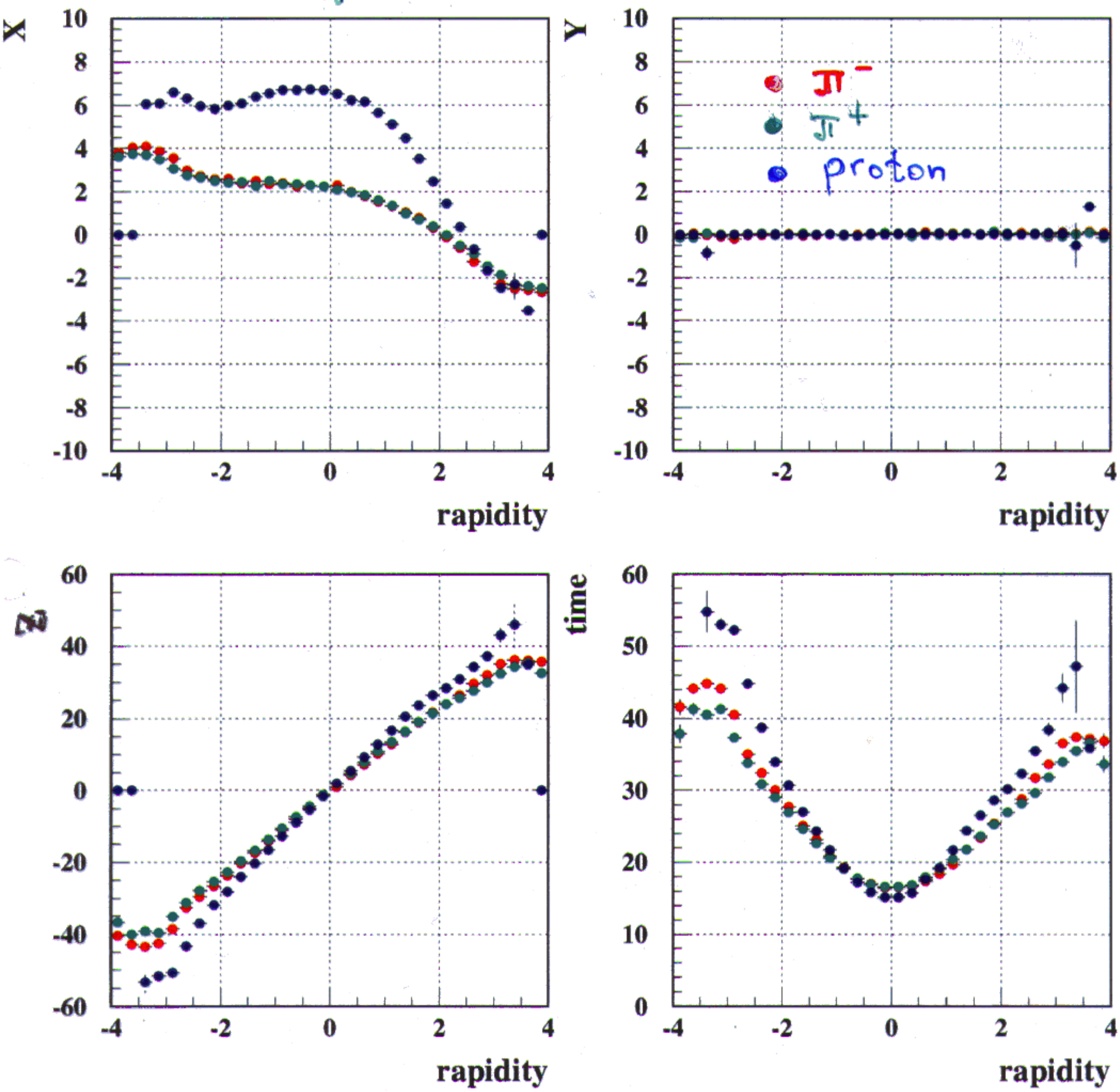


RQMD, Au+Au, 11.5 GeV/n

$2.8 < y_{lab} < 3.2$; $p_x > (<)0$; $|p_y/p_x| < 0.5$

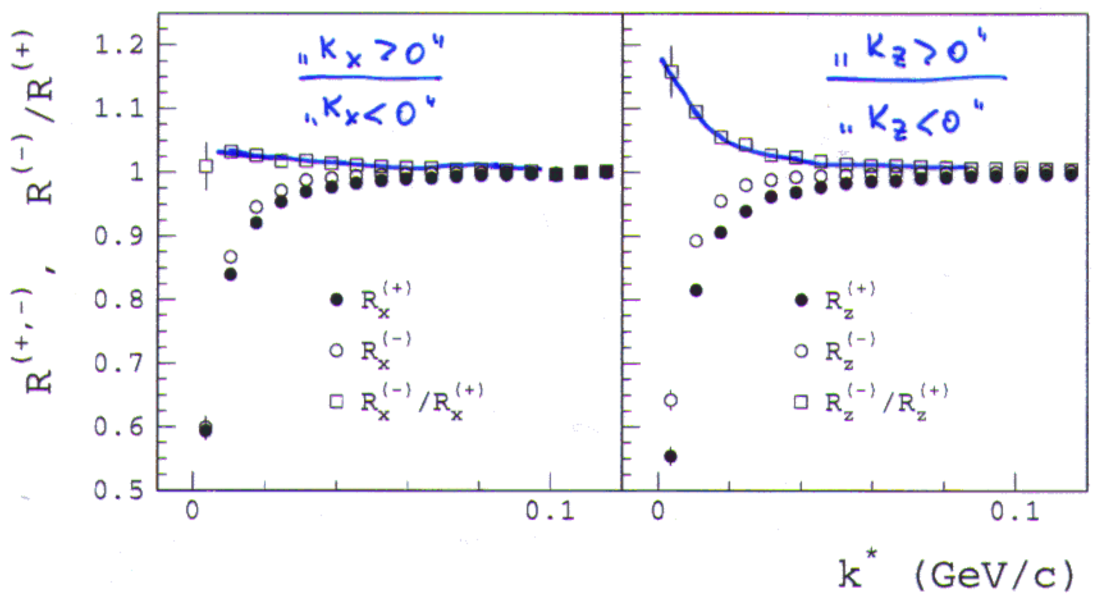
($V_z \approx 0.89$ and $V_x \approx 0.17$)

	$\langle x_\pi - x_p \rangle$	$\langle y_\pi - y_p \rangle$	$\langle z_\pi - z_p \rangle$	$\langle t_\pi - t_p \rangle$
$\Psi_r = 0$	-4.7	0.1	-8.3	-3.7
$\Psi_r = \pi$	1.5	0.1	-7.1	-2.8

CMS

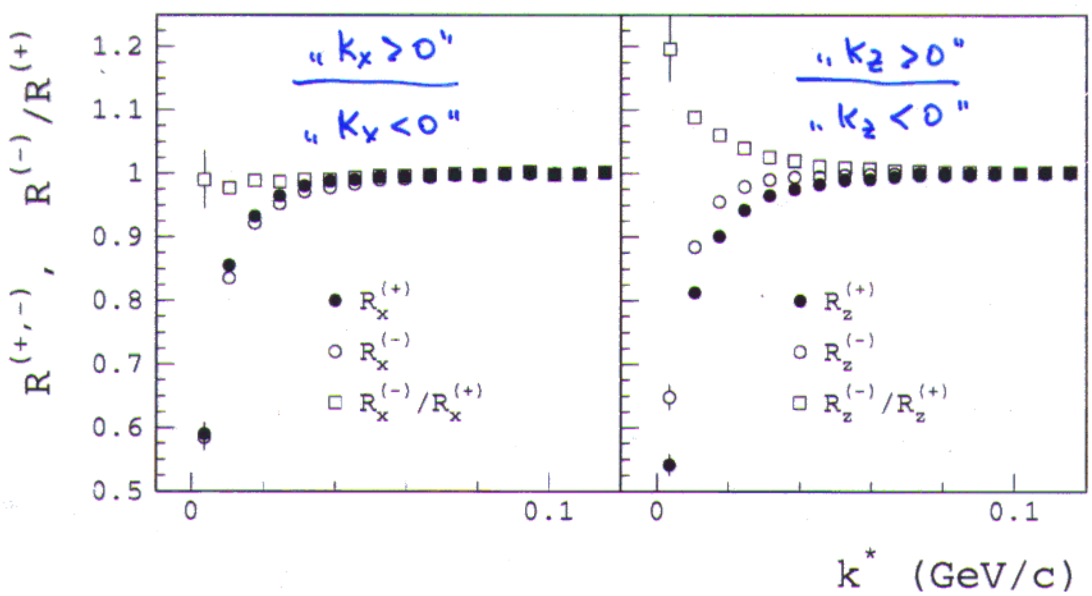
	$\langle x^*_\pi - x^*_p \rangle$	$\langle y^*_\pi - y^*_p \rangle$	$\langle z^*_\pi - z^*_p \rangle$	$\langle t^*_\pi - t^*_p \rangle$
$\Psi_r = 0$	-5.8	0.1	-12.3	10.3
$\Psi_r = \pi$	0.9	0.2	-10.5	8.3

PRF



$\Psi_r = 0$

„$\pi \uparrow \uparrow p$"



$\Psi_r = \pi$

$\pi \uparrow \downarrow p$

D. Miśkowiec (E877 Collaboration), talk at CRIS '98

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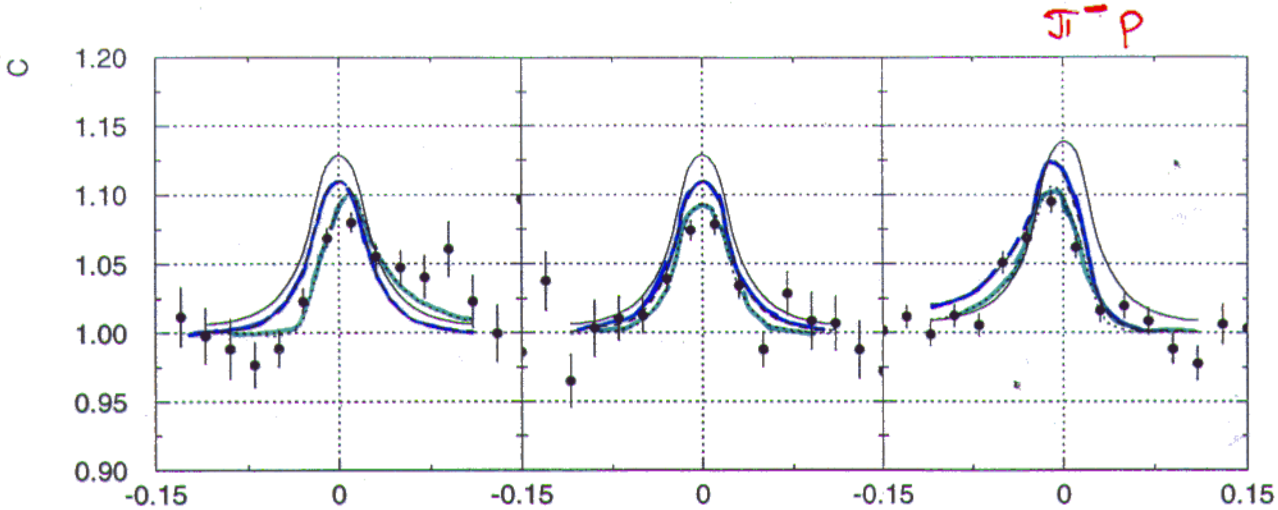


Figure 6: Projections of three-dimensional $\pi^- p$ correlation functions. The solid, dashed, and dotted lines represent calculations with ($\Delta x = 0$ fm, $\Delta z = 0$ fm), ($\Delta x = 0$ fm, $\Delta z = 10$ fm), and ($\Delta x = -10$ fm, $\Delta z = 10$ fm), respectively. $\Delta \mathbf{r}$ is defined as the difference between the positions of the sources of protons and pions: $\Delta \mathbf{r} = \langle \mathbf{r}^{\mathrm{proton}} \rangle - \langle \mathbf{r}^{\mathrm{pion}} \rangle$.

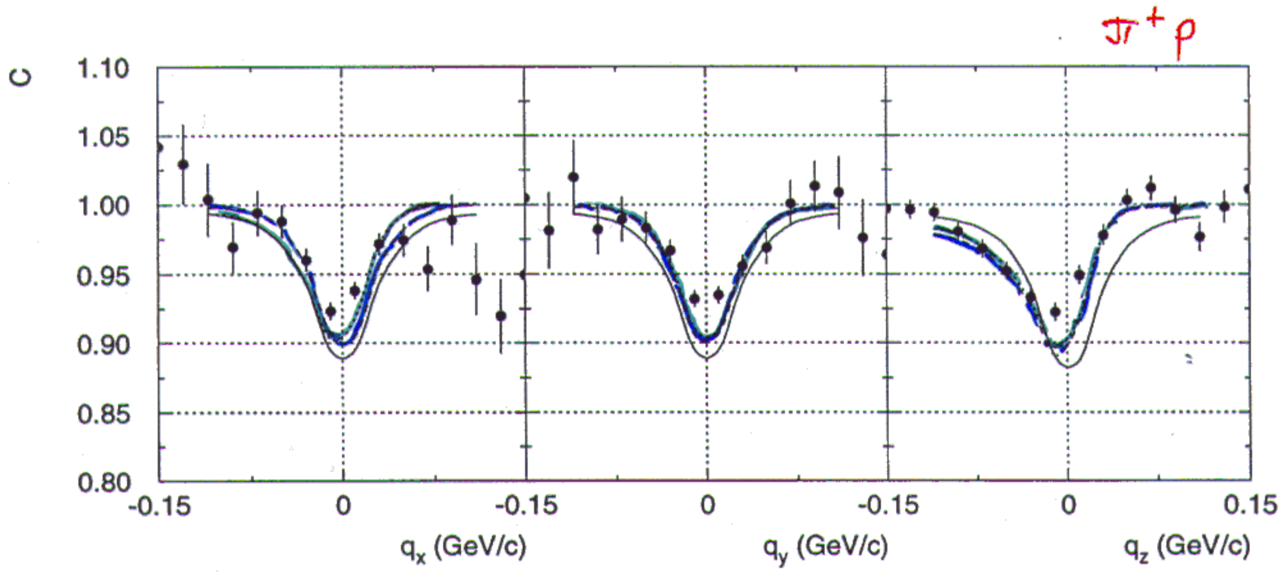


Figure 7: Projections of three-dimensional $\pi^+ p$ correlation functions. The solid, dashed, and dotted lines represent calculations with ($\Delta x = 0$ fm, $\Delta z = 0$ fm), ($\Delta x = 0$ fm, $\Delta z = 10$ fm), and ($\Delta x = 5$ fm, $\Delta z = 10$ fm), respectively.

The discrepancy can be removed by assuming a finite displacement between the sources of pions and protons. Calculations using different values of the displacement are compared to the data in Figures 6 and 7. A reasonable agreement was achieved with a 10 fm separation in z and -10 fm or +5 fm, depending on the charge of the pions, in x.

Long range correlations

Soft particle correlations — (anisotropic) flow, $\sigma_{\langle p_t \rangle}$, ...

High p_t particle correlations – (mini) jet production, parton propagation through dense matter, ...

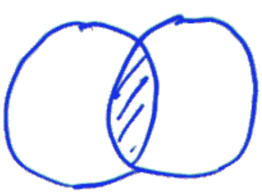
$$\overline{R_2}(\Delta\varphi, y_1, y_2) \equiv \frac{d^6 n}{d^3 n\, d^3 n}$$

is sensitive to

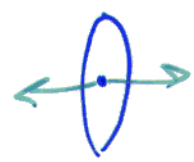
1) jet production
2) jet quenching
3) initial p_t broadening ...
4) Role of corona effect ?

One can study R_2 as a function of

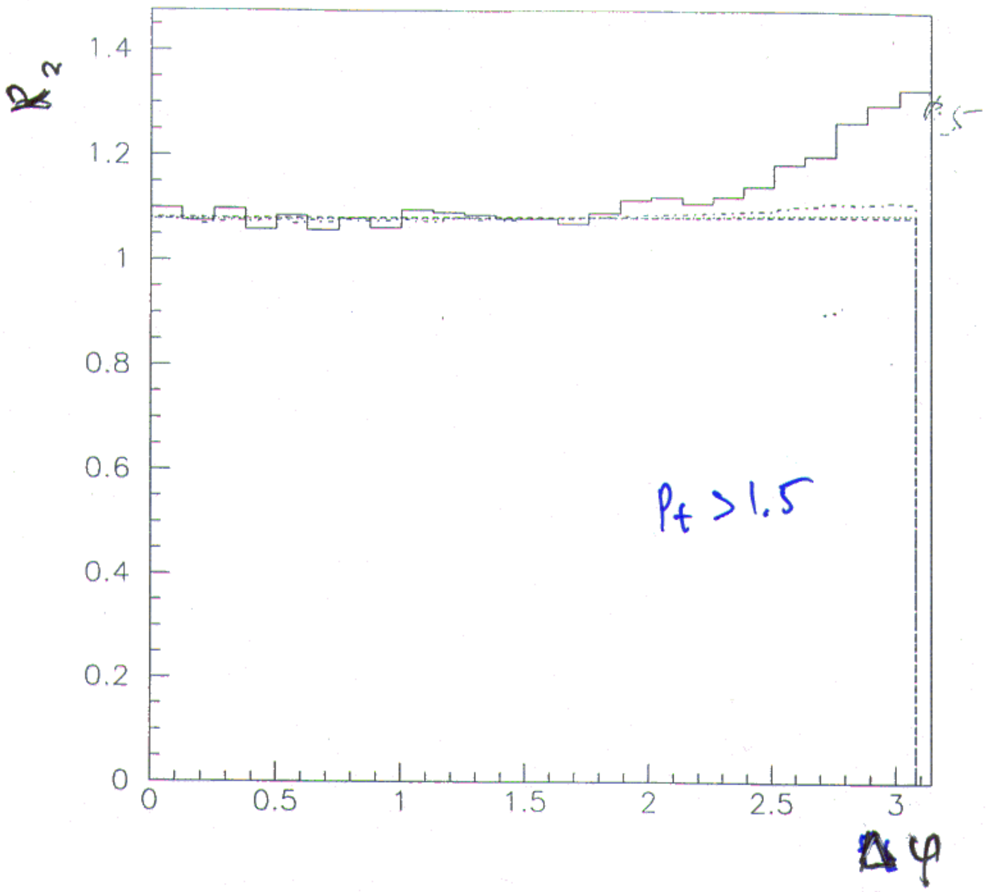
1) centrality
2) orientation of tag particle emission wrt RP

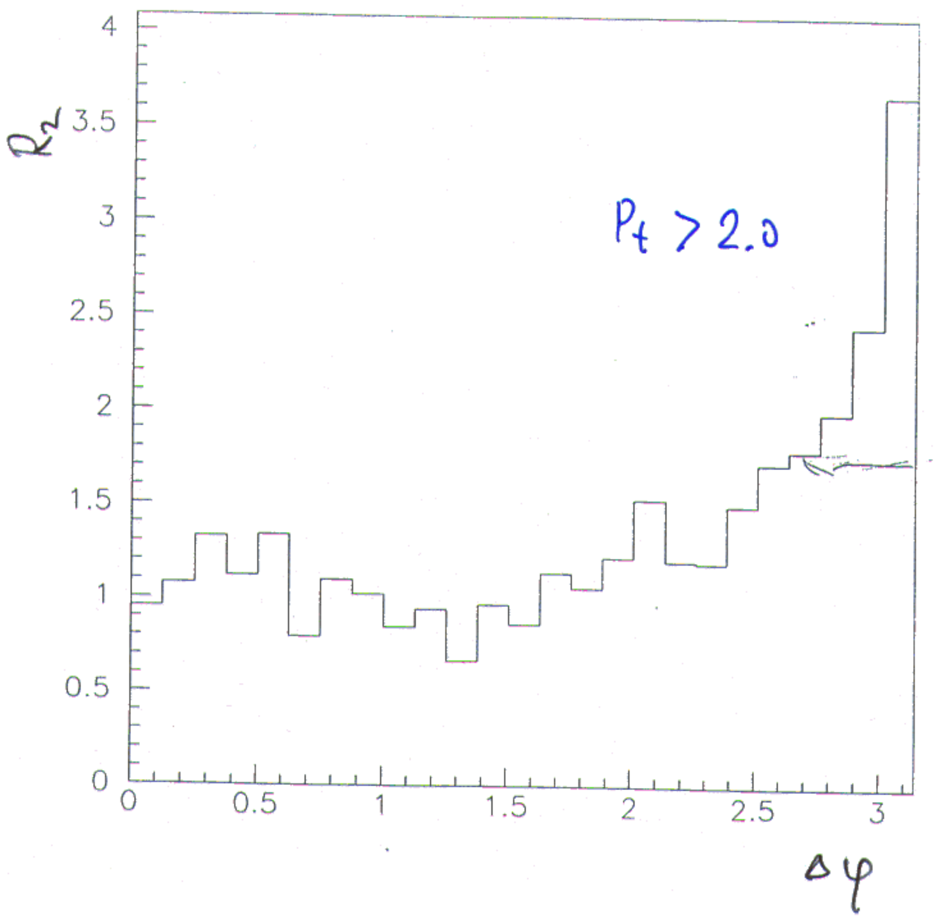


a) 

b) 

HIJING (X. Wang)



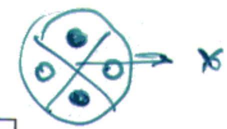


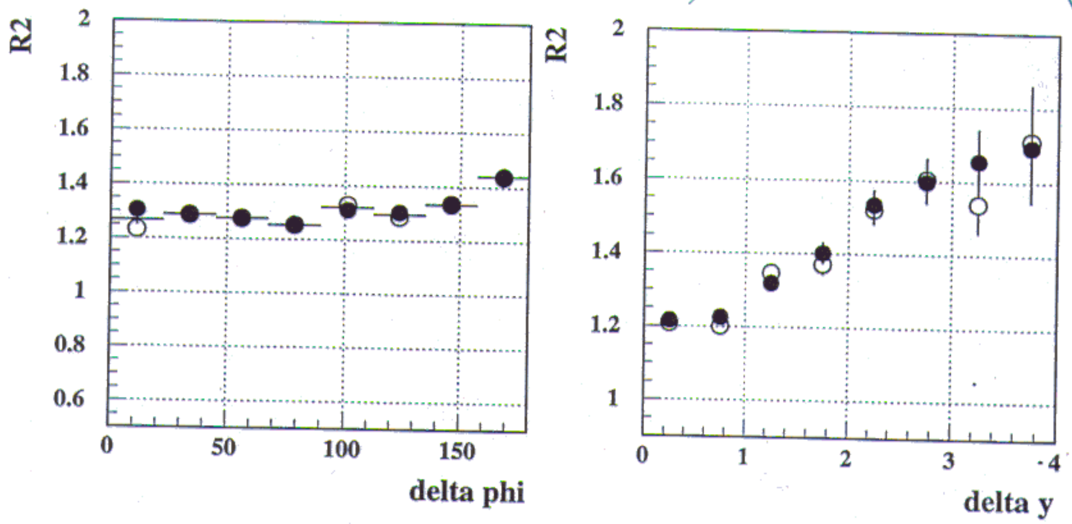
PbPb , SPS ; 4<b<10

$\pi^{\pm}$, $p_t > 1.5$ GeV

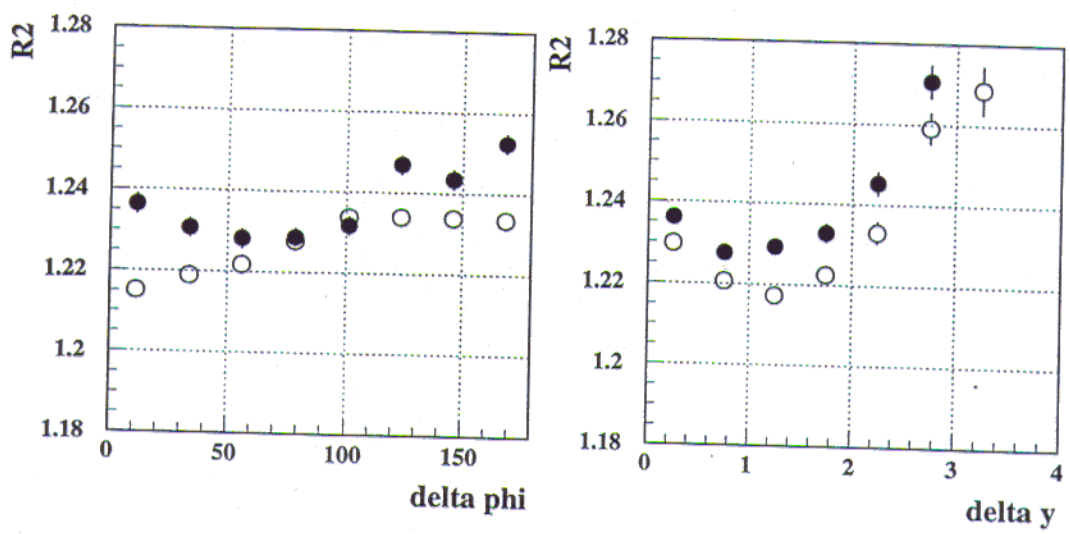
HIJING

(no jet quenching => the same)

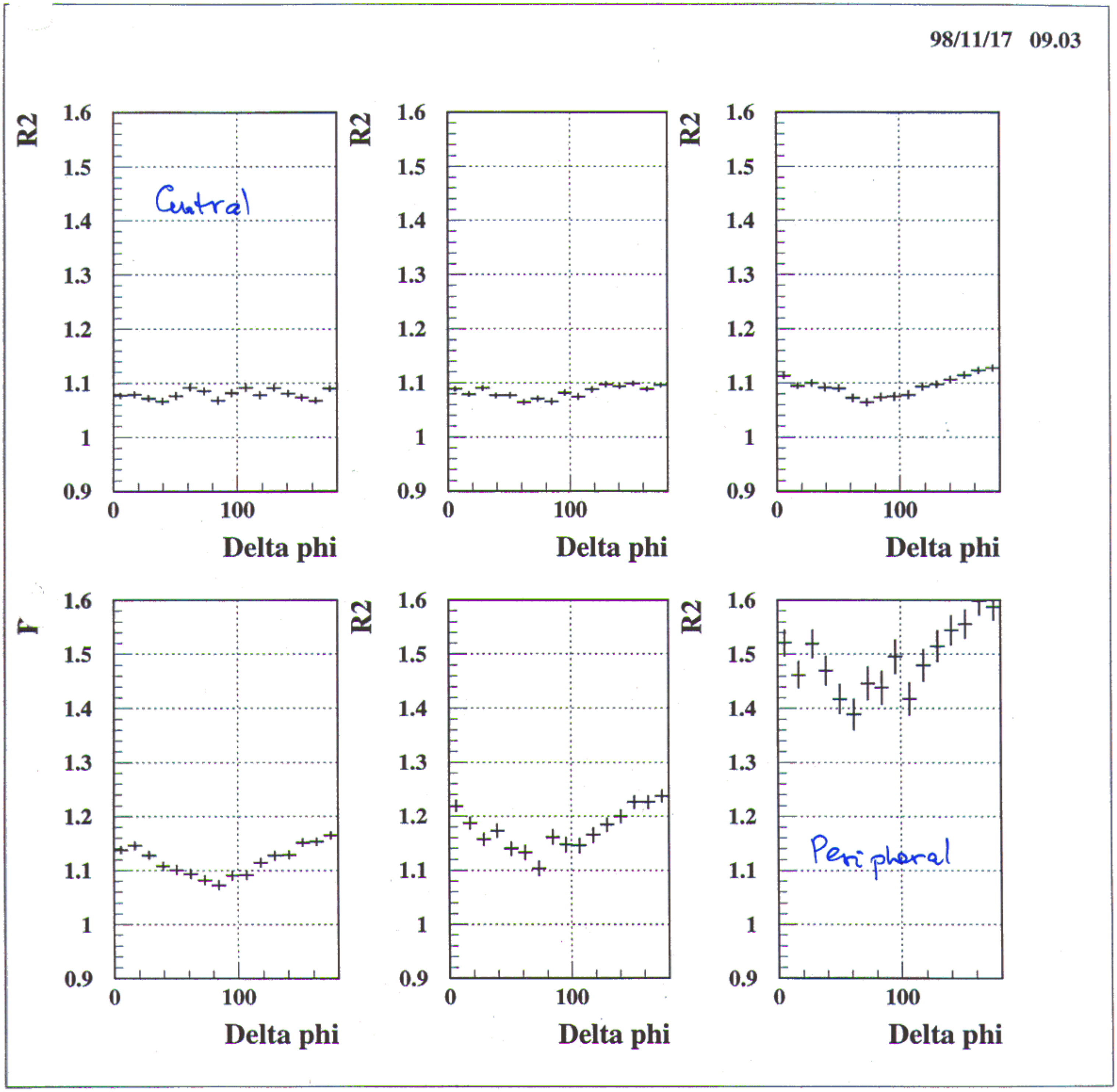




RQMD



NA49, very preliminary
$P_t > 1.5$ test $p_t\phi$



NA49, Very preliminary

test pt∅