Correlations and Fluctuations in QCD
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Correlations and Fluctuations in Nucleus–Nucleus Collisions from NA49 at the CERN SPS

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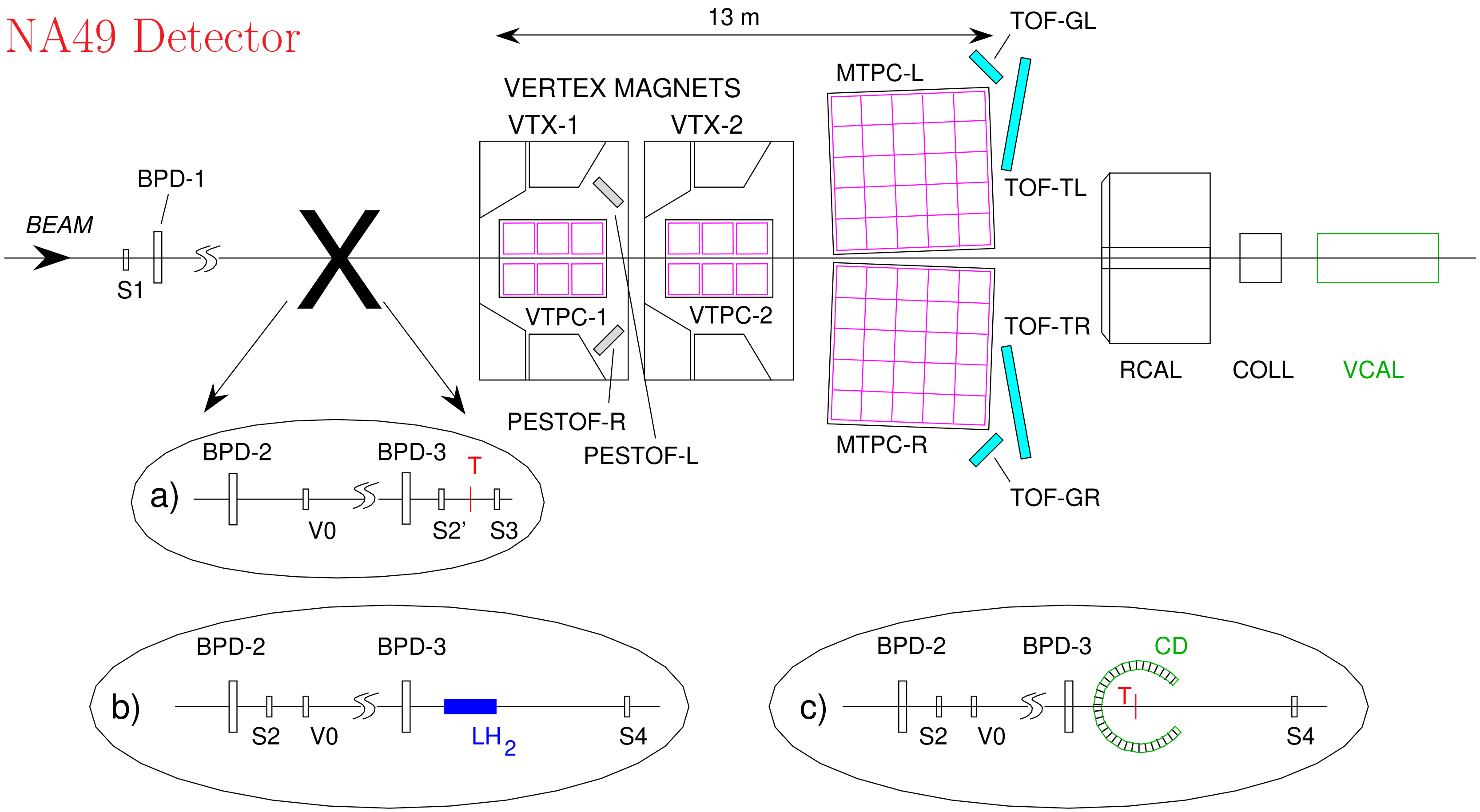
  - transverse momentum: Φ_{p_T}
  - charge: $\tilde{D}$, Φ_q and $\Delta\Phi_q$
- two particle correlations
  - Bose–Einstein correlations ($\pi\pi$, KK)
  - unlike particles ($\pi^+\pi^-$, π^+p)
- anisotropic flow

any evidence for a transient deconfined (QGP) phase ??

The NA49 Detector



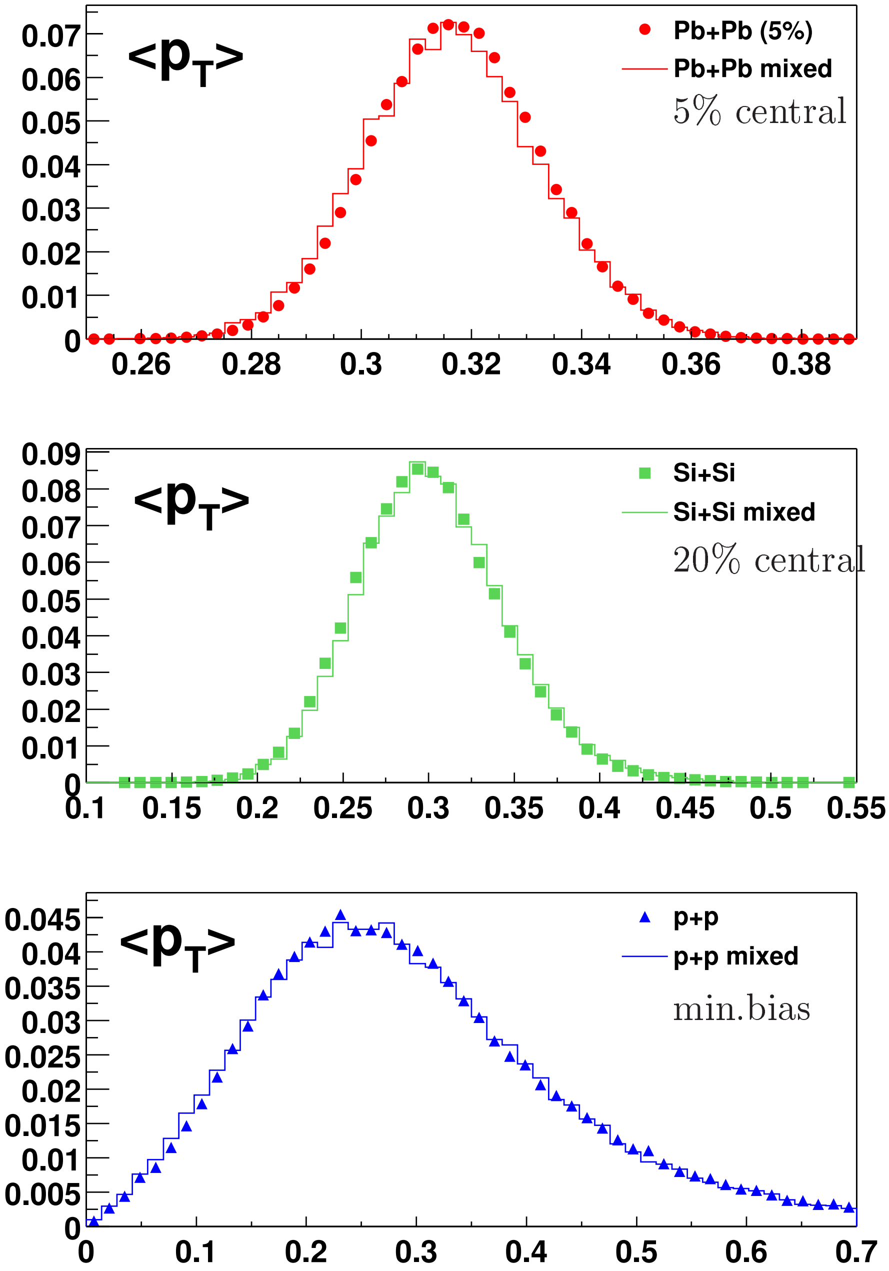
- large acceptance hadron spectrometer
- tracking (TPCs), particle identification (dE/dx,TOF)
- centrality selection (VCAL, CD - slow proton detecor)

energy	centrality	$\langle N_{part} \rangle$
40 A·GeV	7.2%	349±5
80 A·GeV	7.2%	349±5
158 A·GeV	5.0%	362±5

Fluctuations of $\langle p_T \rangle$ at 158 A·GeV

- distinct event classes ?
- reduced fluctuations as signature of equilibration (disputed)
- increased fluctuations in vicinity of critical point, DCC

forward rapidity $4.0 < y < 5.5$ (NA49 preliminary)



- width scales like $N_{ch}^{-0.5}$
- close to purely statistical fluctuations (mixed events)

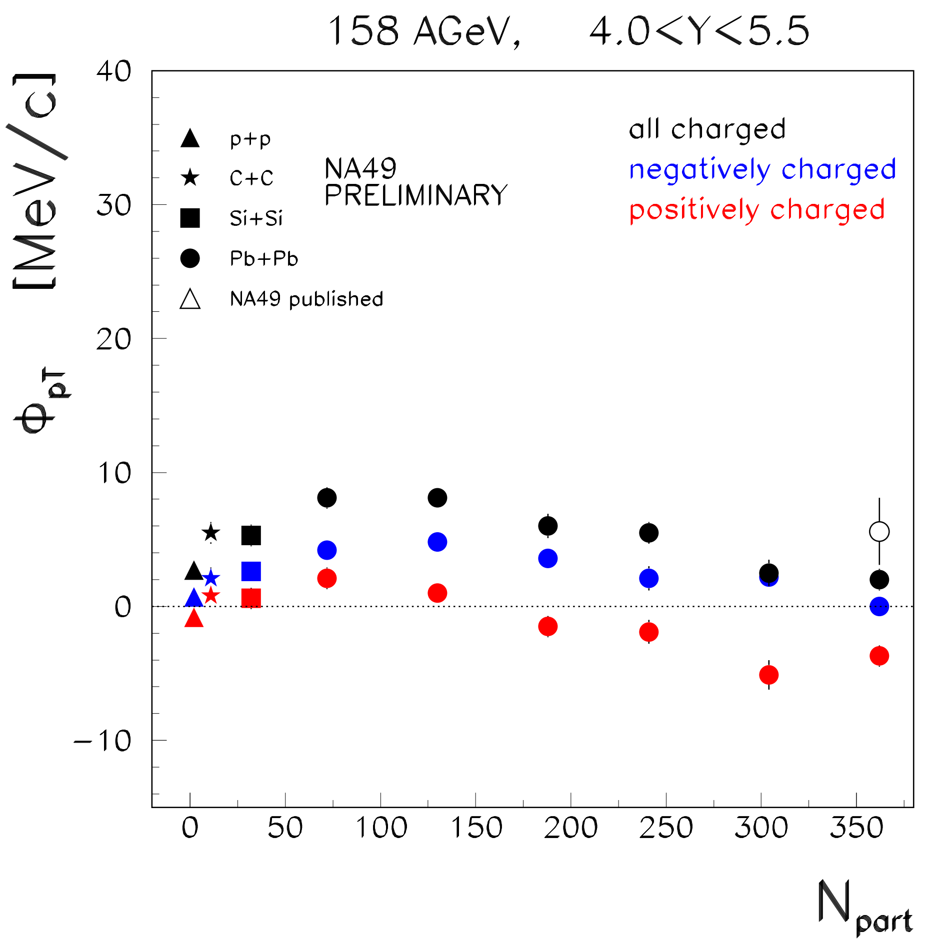
quantitative measure of $\langle p_T \rangle$ fluctuations

$$\Phi_{p_T} = \sqrt{\frac{\langle Z^2 \rangle}{\langle N_{ch} \rangle}} - \sqrt{\bar{z^2}} \qquad \text{(Gazdzicki,Mrowczynski)}$$

$$Z = \sum_{i=1}^{N_{ch}^{event}} p_{T,i} - \overline{p_T}\ ,\ z_i = p_{T,i} - \overline{p_T}\ ,\ \overline{p_T} \text{ inclusive average}$$

- independent of number of superimposed particle sources
- vanishes for independent particle emission

(we have to restrict to forward rapidity at present)



- fluctuations small (in forward region)
- probably many effect contribute
  resonances, elliptic flow, correlations (BE, FD, Coulomb) ...

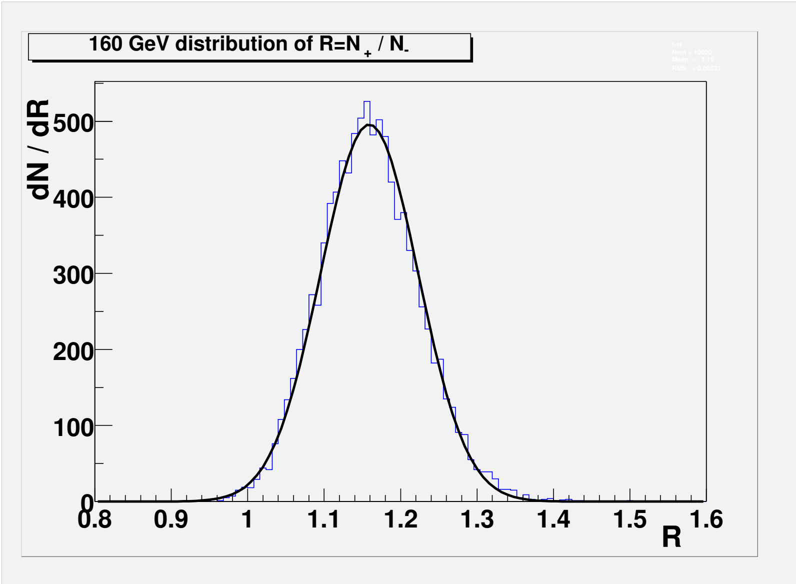
event-by-event charge fluctuations

smaller charge quanta in the deconfined phase could result in reduction of charge fluctuations

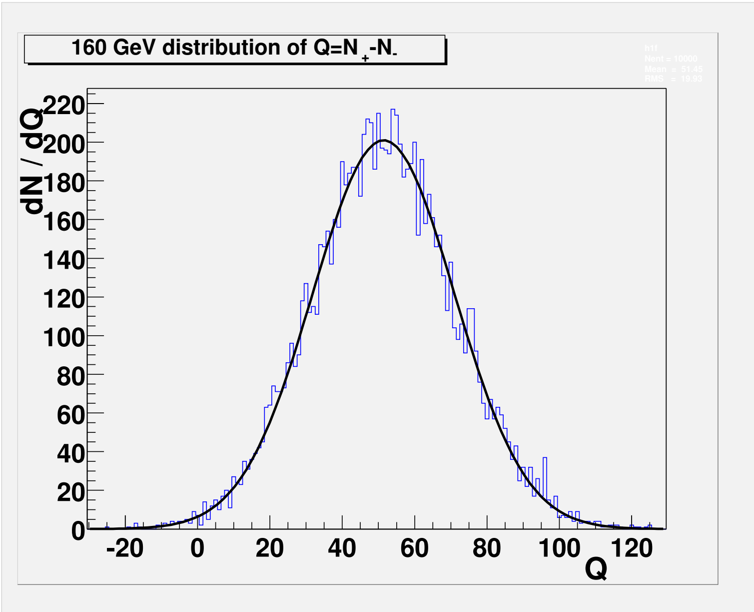
NA49 data:

energy	centrality	$\langle N_{ch} \rangle_{total}$	Y_{mean}	events
40 A·GeV	7.2 %	$\approx$ 850	2.9	800 K
80 A·GeV	7.2 %	$\approx$1170	3.2	300 K
158 A·GeV	10 %	$\approx$1500	3.6	800 K

example of event-to-event fluctuation of $\mathrm{R} = \mathrm{N}_+/\mathrm{N}_-$



example of event-to-event fluctuation of $\mathrm{Q} = \mathrm{N}_+ - \mathrm{N}_-$

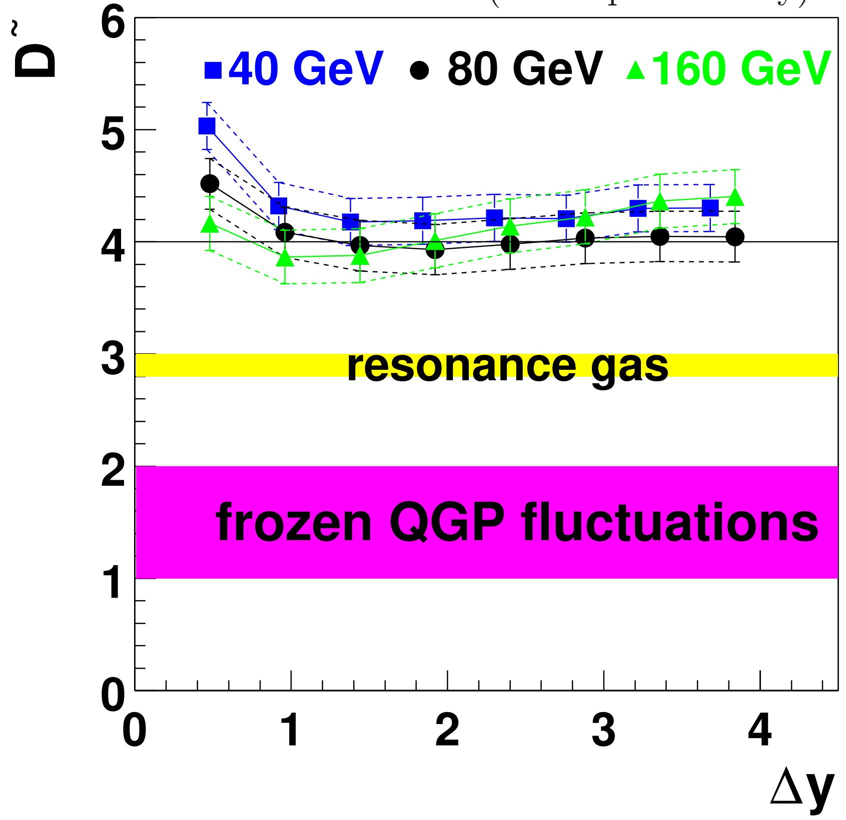


Fluctuations of the Charge Ratio R = N_+/N_-

- proposal of S.Jeon and V.Koch PRL 85(2000) 2076 :
  define fluctuations of $R = N_+/N_-$ (multiplicity scaled)
  $$D = (\langle R^2\rangle - \langle R\rangle^2) \cdot \langle N_{ch}\rangle$$
- corrections for residual charge : $C_\mu = \langle N_+\rangle^2/\langle N_-\rangle^2$
  global charge conservation : $C_y = 1 - \langle N_{ch}\rangle/\langle N_{ch}\rangle_{total}$

$$\tilde{D} = \frac{\langle \delta R^2\rangle \cdot \langle N_{ch}\rangle}{C_\mu \cdot C_y}$$

(NA49 preliminary)



- no significant change in the SPS energy range
- close to independent particle emission + global charge conservation ($\tilde{D} = 4$)
- predicted reduction due to resonances ??
- can small QGP fluctuations survive hadronisation ?

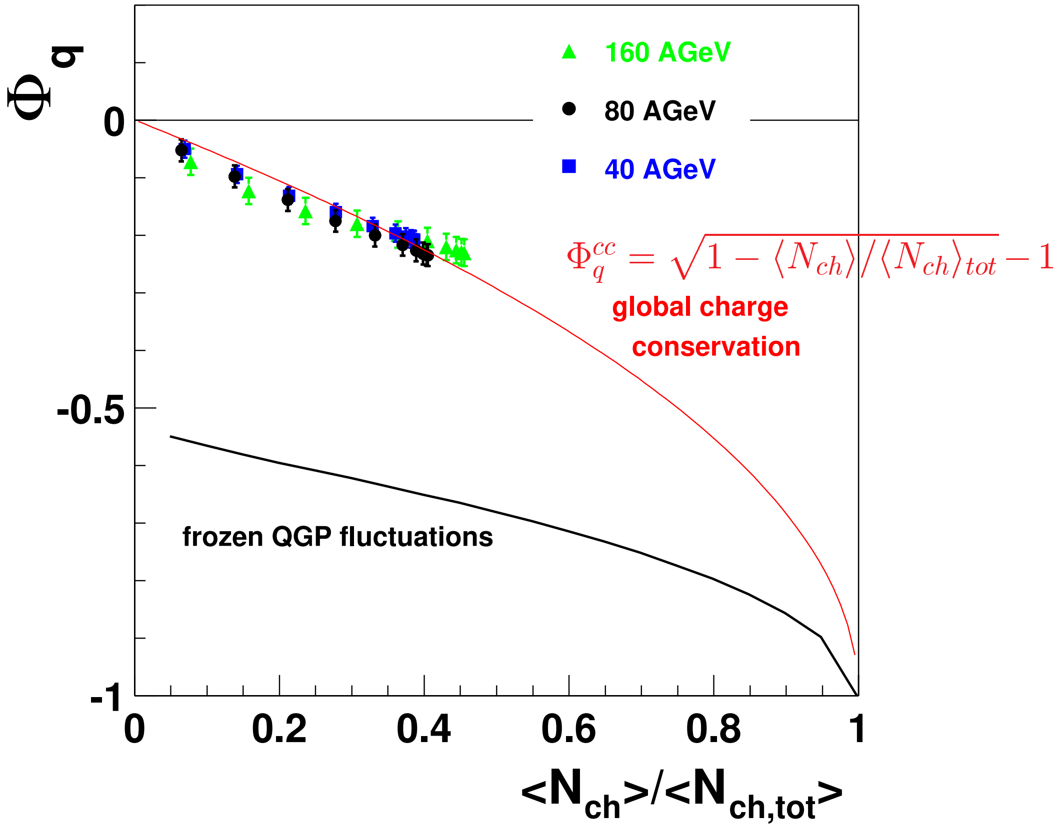
Fluctuations of the Net Charge Q = $N_+ - N_-$

$$\Phi_q = \sqrt{\frac{\langle Z^2\rangle}{\langle N_{ch}\rangle}} - \sqrt{1 - \frac{\langle Q\rangle^2}{\langle N_{ch}\rangle^2}} \qquad \text{(Gazdzicki,Mrowczynski)}$$

$$Z = \sum_{i=1}^{N_{ch}^{event}} Q_i - \overline{Q}\ ,\ \overline{Q}\ \text{inclusive mean charge}$$

- independent of number of superimposed particle sources
- vanishes for independent particle emission
- local charge conservation $\rightarrow \Phi_q \approx$ -1

(NA49 preliminary)



- no significant energy dependence
- approximate independent pion emission
  + global charge conservation

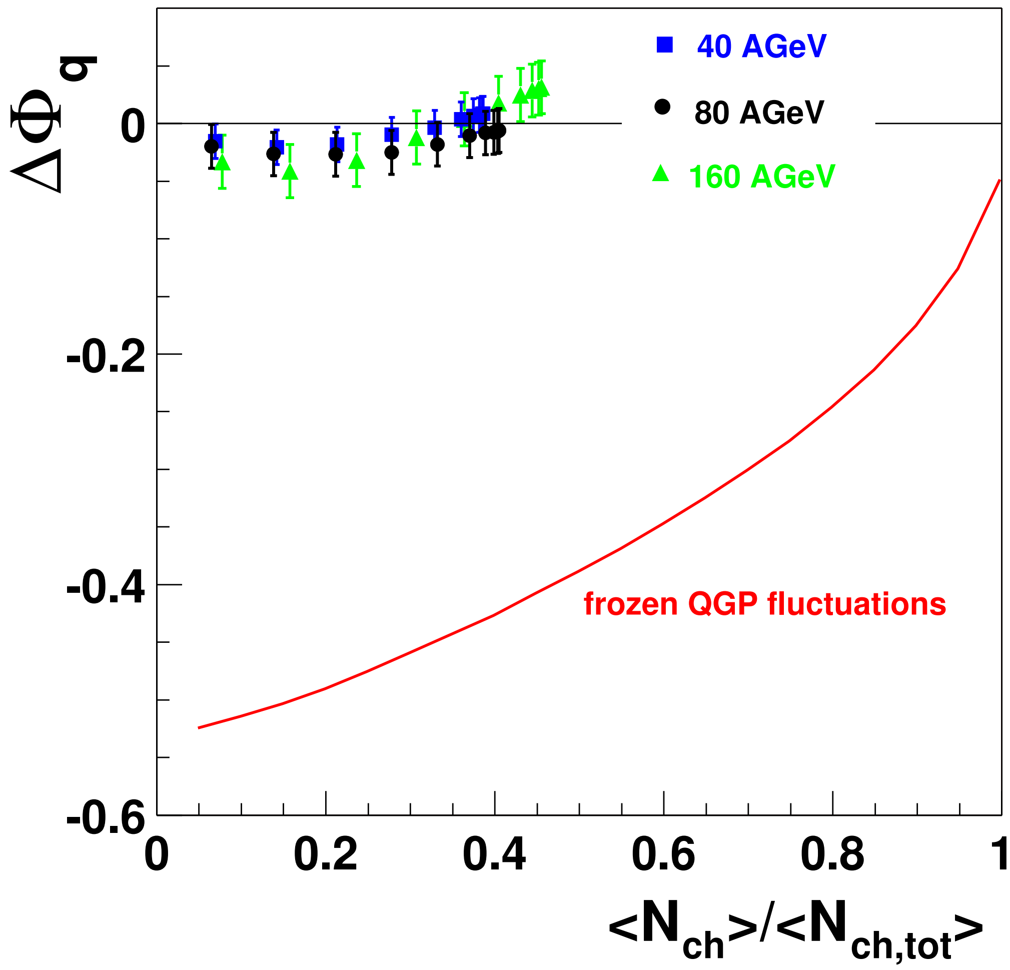
fluctuations in central PbPb collisions are close to values expected for independent particle emission and global charge conservation

$\Downarrow$

subtract contribution of global charge conservation
to show deviations more clearly

$$\begin{aligned}\Delta\Phi_q &= \Phi_q - \Phi_q^{cc} \\ &= \Phi_q - (\sqrt{1 - \langle N_{ch}\rangle / \langle N_{ch}\rangle_{tot}} - 1)\end{aligned}$$

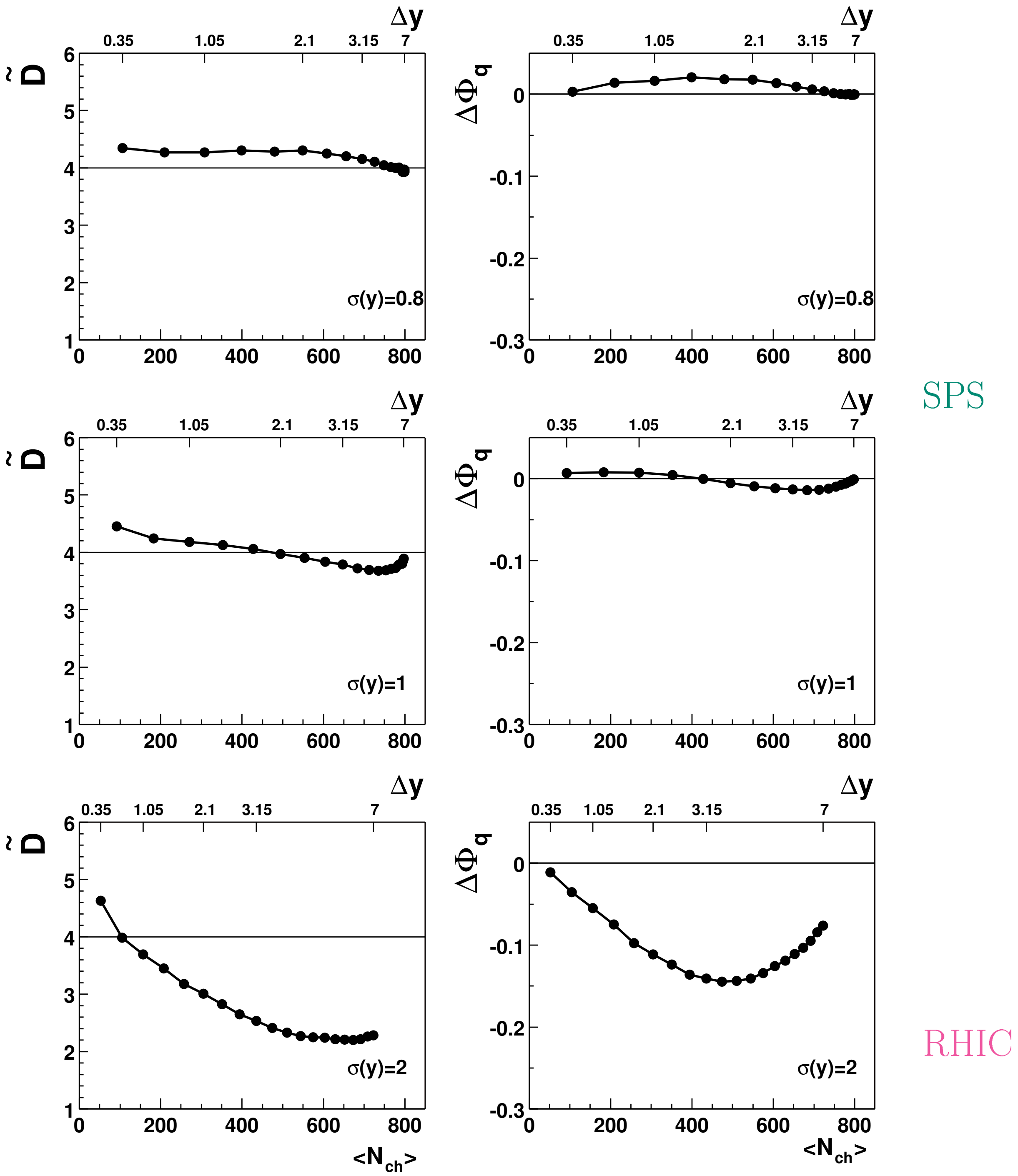
(NA49 preliminary)



marginal signal of reduced fluctuations ?

toy model: resonance gas $\rho \rightarrow \pi^+\pi^-$ (J.Zaranek,hep-ph/0111228)

- fixed mass M_ρ = 770 MeV, multiplicity N_ρ = 400
- $dN/dm_T^2 dy \;\propto\; \exp((y{-}y_0)^2/2\sigma^2) \cdot \exp(-\,m_T\,/\,T)$ with T = 170 MeV
- fluctuations only due to decay kinematics



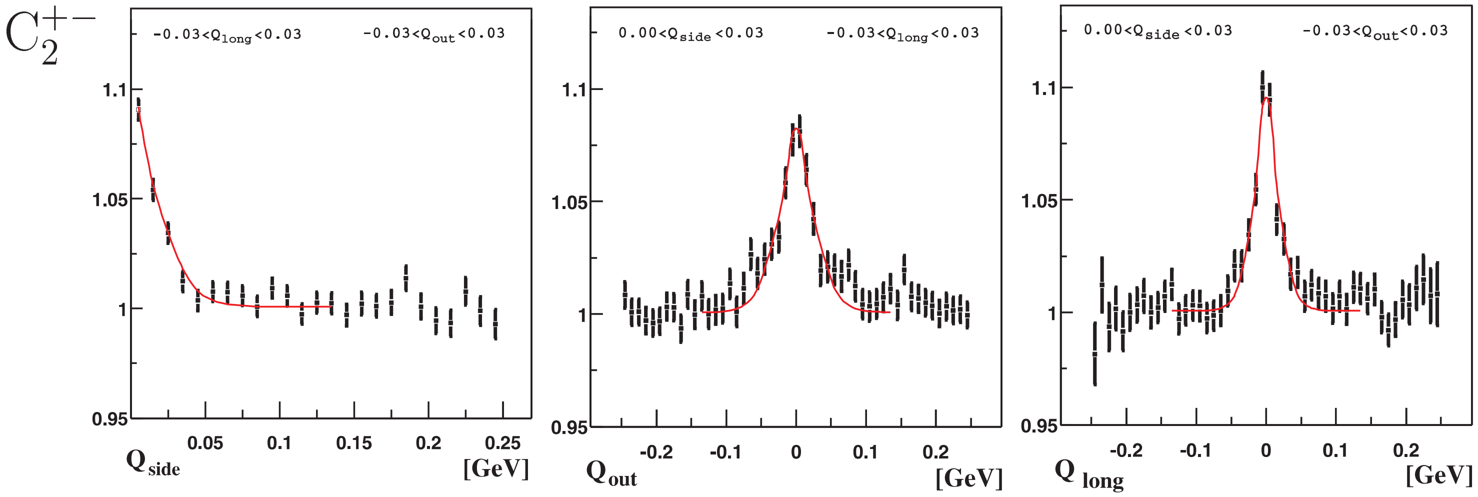
reduction of fluctuations only shows up when:
ΔY(decay) (≈ 1) < ΔY(acceptance) and ΔY(resonance distribution)

Correlations of Pion Pairs

provide information on the size and internal dynamics
of the fireball at freezeout

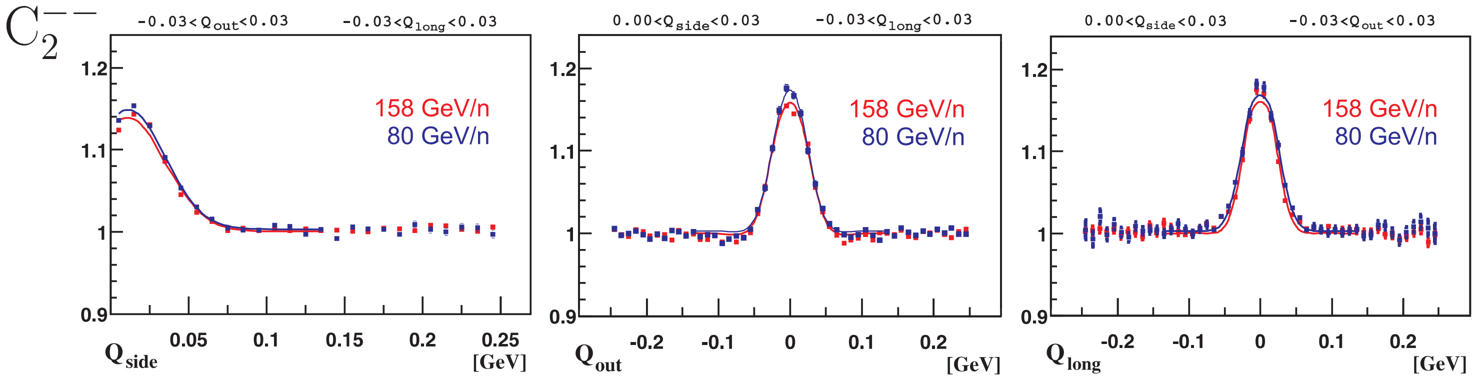
cartesian decomposition of $Q = p_1 - p_2$ into longitudinal(beam), side(transverse) and out(pair momentum) components

$\pi^+\pi^-$ Coulomb correlation (40 A·GeV, 0.1$\leq K_T \leq$0.2 GeV/c)



finite source size Coulomb wave calculation fits
$\pi^+\pi^-$ correlation (Sinyukov et al.,Phys.Lett.B432(1998),248)

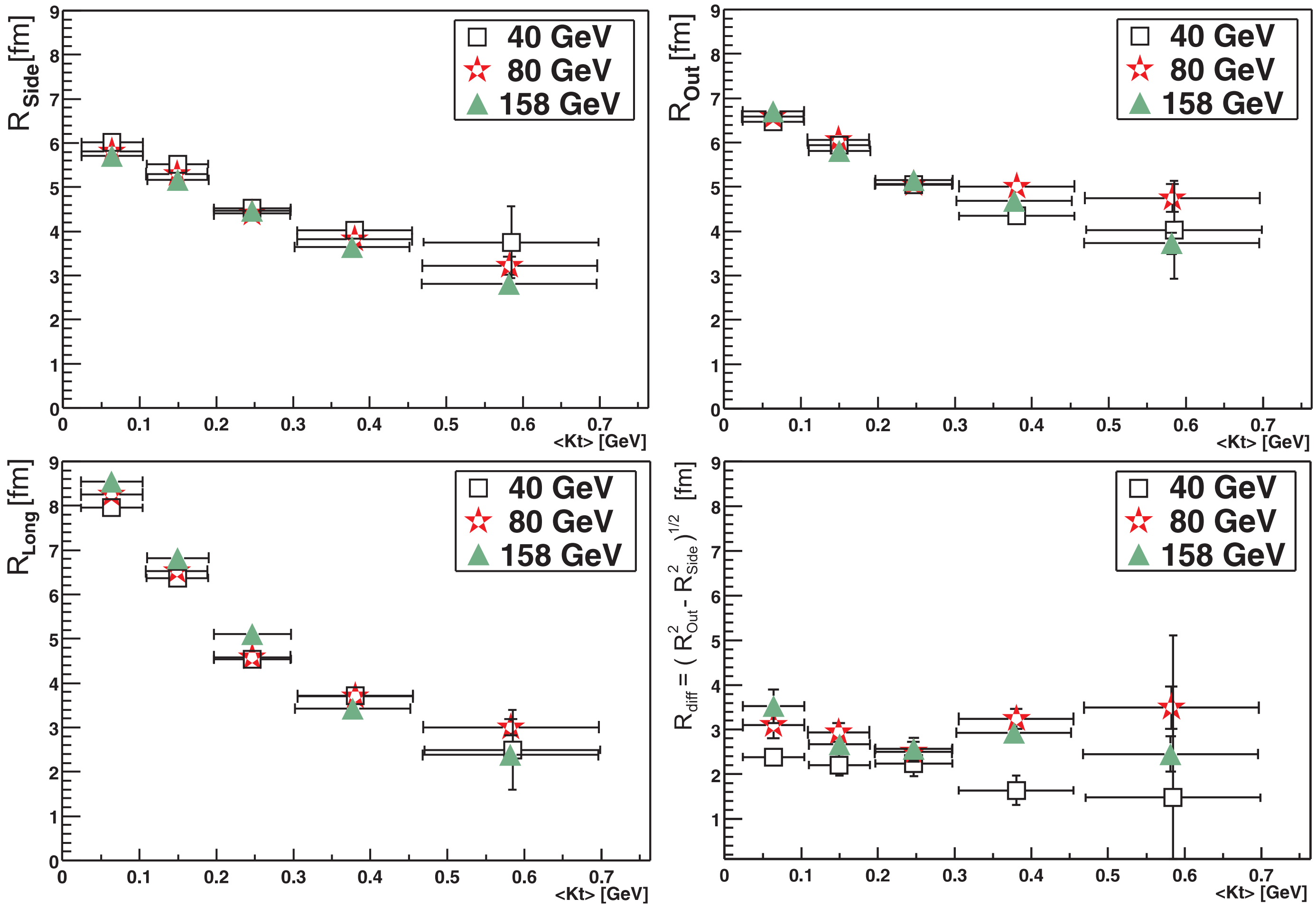
$\pi^-\pi^-$ BE+Coulomb correlation ($y_{cm} \leq y \leq y_{cm}$+0.5 , 0.1$\leq K_T \leq$0.2 GeV/c)



$$C_2 = C_{coul} \cdot \{1 + \lambda \cdot exp(-R^2_{side}Q^2_{side} - R^2_{out}Q^2_{out} - R^2_{long}Q^2_{long} -2R_{out,long}Q_{out}Q_{long})\}$$

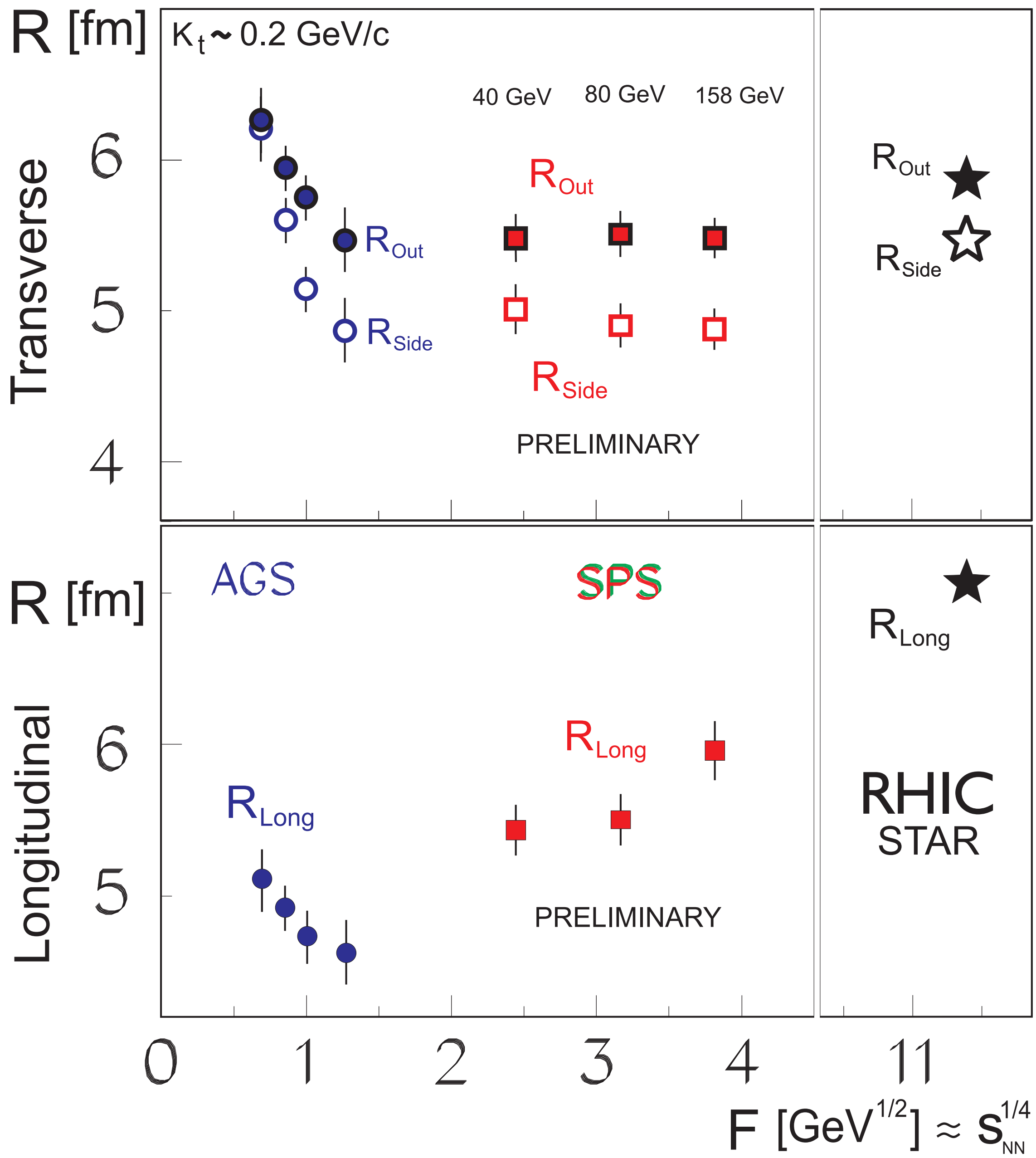
fitted radius parameters at midrapidity:

(NA49 preliminary)



- similar values at 40, 80, 158 A·GeV
  (syst.err.$\approx$ 0.5 fm)
- decrease with K_T manifests strong collective flow longitudinal (R_{long}) and radial (R_{side}, R_{out})
- $R_{diff} \approx \Delta\tau \frac{T}{\sqrt{2}M_T}$ small
  $\rightarrow$ no evidence for long-lived mixed phase

energy systematics of radius parameters:



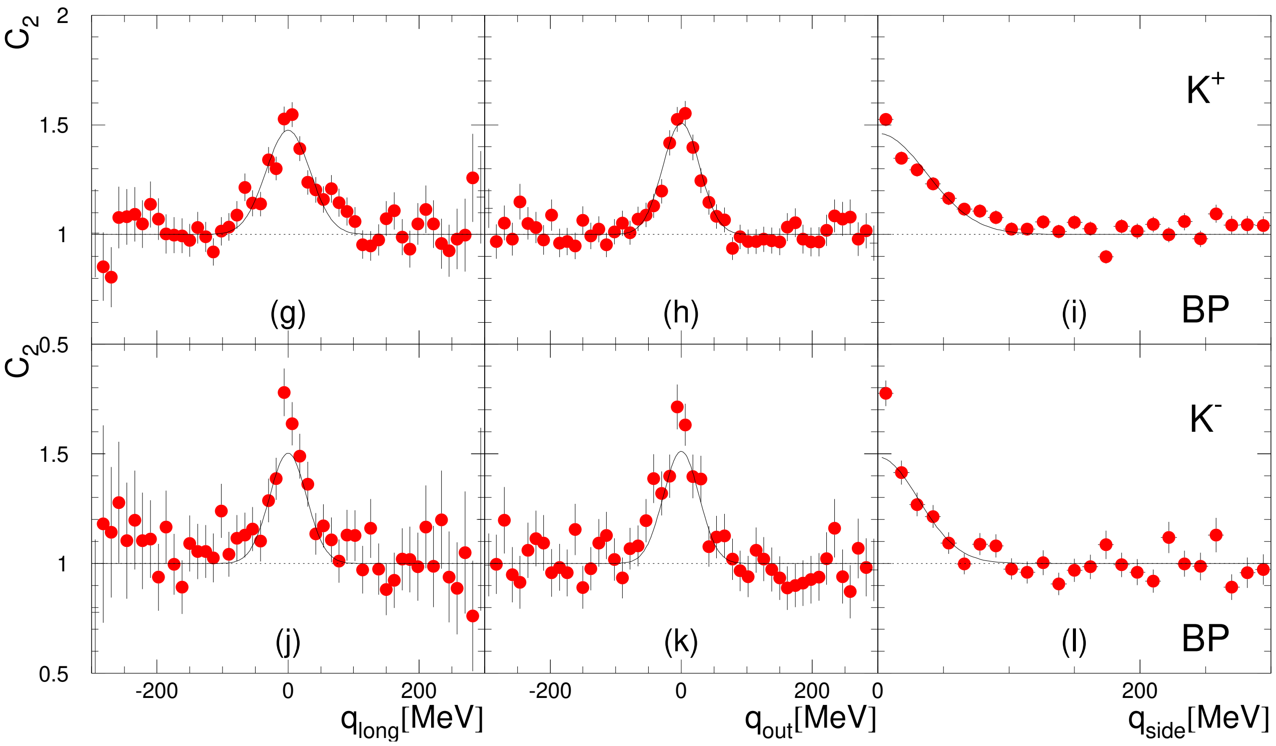
- decrease at AGS due to buildup of expansion flow ?
- litte change of transverse radii SPS $\rightarrow$ RHIC
- $R_{long} \approx \tau\sqrt{\frac{T}{M_T}}$ (τ lifetime of fireball)

  seems to increase with $\sqrt{s}$

KK correlations

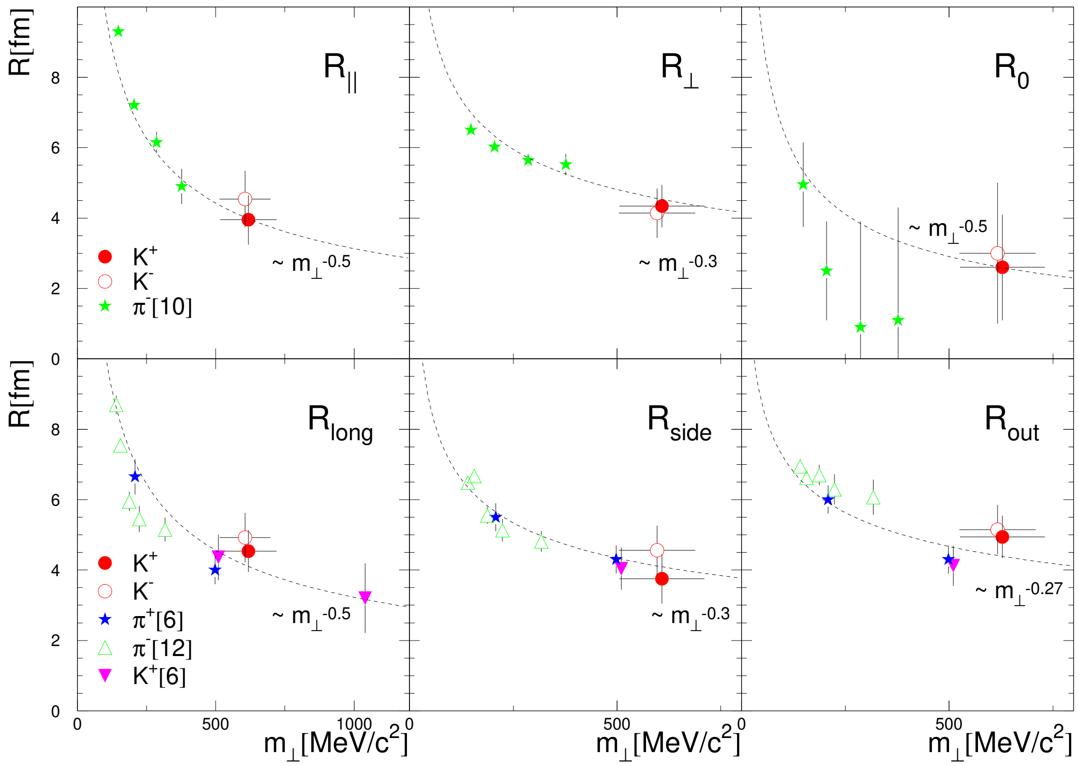
- TOF + dE/dx identification with 93% purity
- small acceptance near midrapidity
- results from 1.7 M central (5%) Pb+Pb collisions at 158 A·GeV

midrapidity, $\langle m_\perp \rangle = 0.61$ GeV (NA49 preliminary)

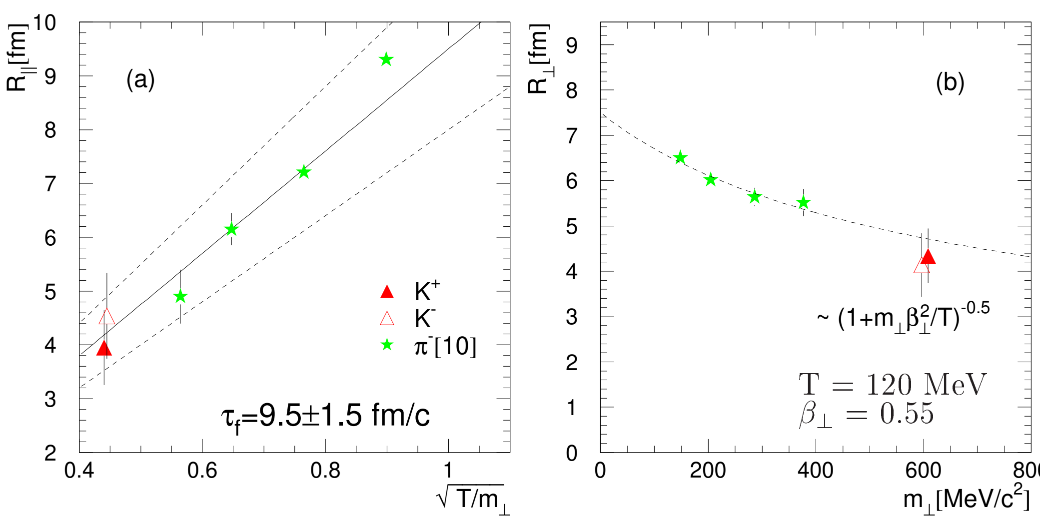


systematics of radially expanding fireball ($m_\perp$ scaling)

- KK results extend $m_\perp$ range of $\pi\pi$ data



- consistent with fit of expanding fireball model



NA49 unlike particle correlations: $\pi^+\pi^-$, $\pi^\pm p$

- dominated by Coulomb FSI
  - validity of Coulomb FSI correction in QS correlation analysis
- femtometry using unlike particles
  - sensitive to gaussian size as well as tails (fitted scale factor applied to RQMD)
- study of relative space–time asymmetries of particle emission
  - sensitive to collective flow
  - further tests of reaction models (sequence of emission/freezeout)
- $\pi^+\pi^-$ correlations also sensitive to strong interaction ($\pi\pi$ scattering length f_0)
- microscopic production model required for numerical calculation of theoretical correlation function

acceptance region of MTPC, i.e. $p \geq 3.5$ GeV/c

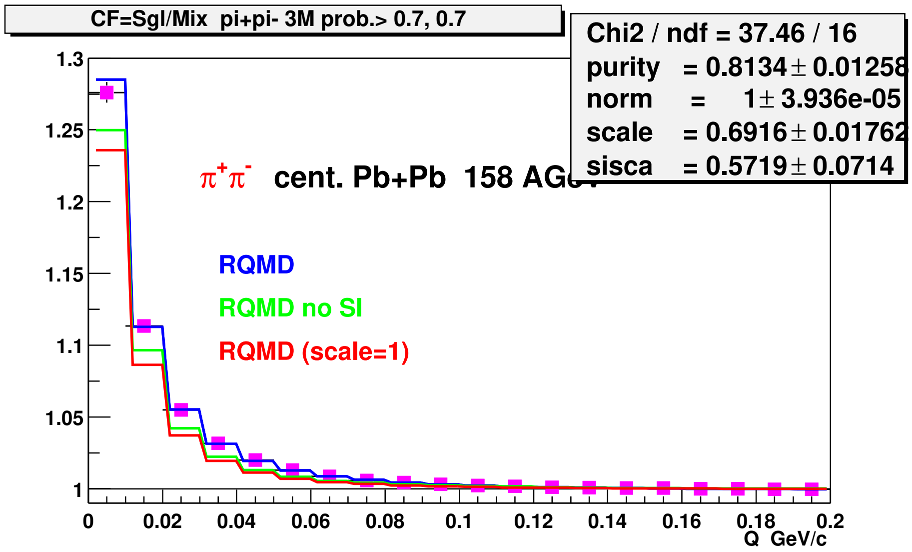
π, proton purification via probability cuts

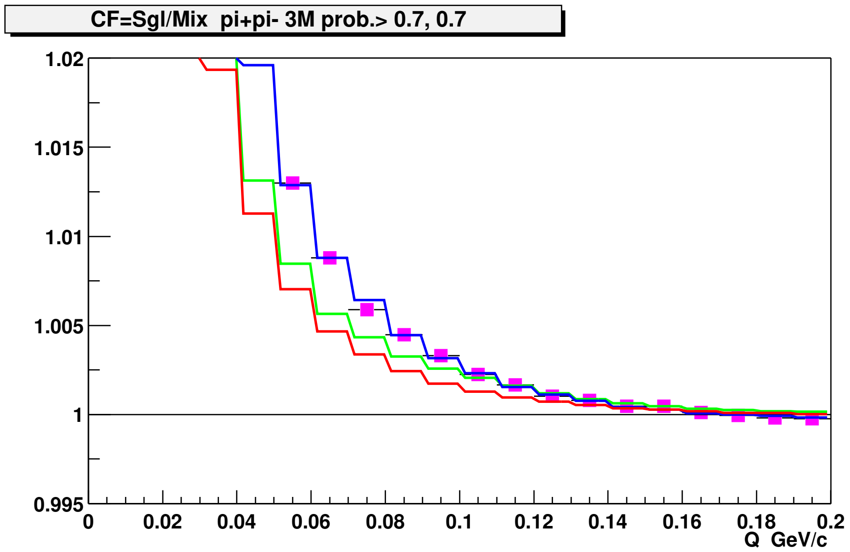
C_2 = signal/mixed pairs, normalised to equal numbers

geometrical size, strong interaction scale ($\pi^+\pi^-$)

- distribution of $r^* = |\vec{x_1} - \vec{x_2}|$ taken from RQMD
- RQMD prediction smeared with measuring resolution
- fit also strong interaction scale (sisca) :

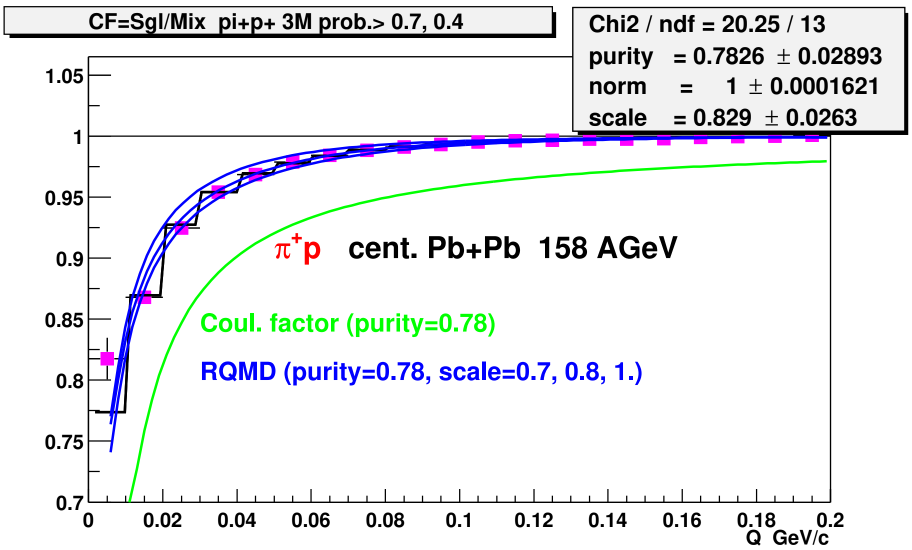
$$C_2(k^*) = \text{norm} \cdot [\ (\ 1.\ \text{- purity}\ ) + \text{purity} \cdot \text{RQMD}(r^* \to \text{scale} \cdot r^*,\ f_0 \to \text{sisca} \cdot f_0)\ ]$$

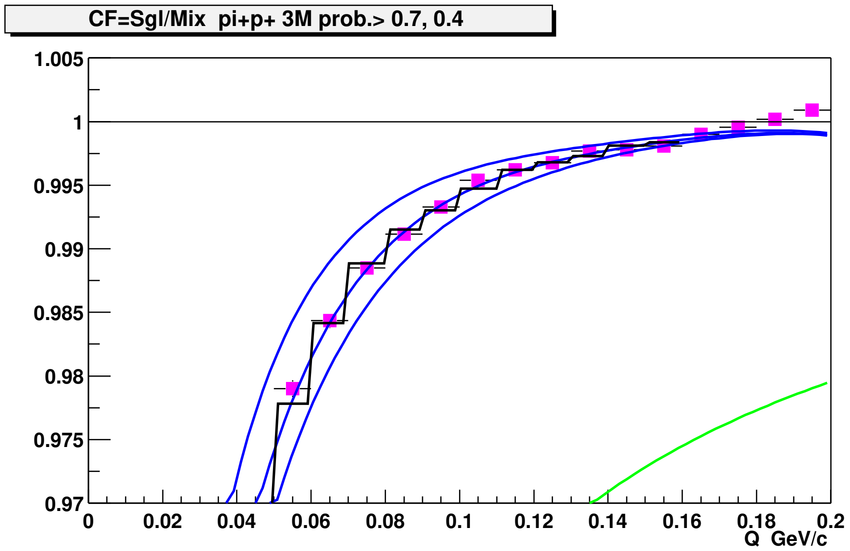




- scaling down of RQMD predicted $\langle r^* \rangle$ by 30% required
- SI scale of 0.6 consistent with new BNL results from K decays
- strong correlation between size and SI scale parameters
- fitted purity (identification, weak decays) consistent with expectation

π^+p





- Gamov factor (scaled for purity) much too large
- good fit with RQMD $\langle r^* \rangle$ scaled down by 20 %
- fitted purity consistent with expectation
- SI contribution (suppresses CF by 0.02) smaller than for $\pi^+\pi^-$

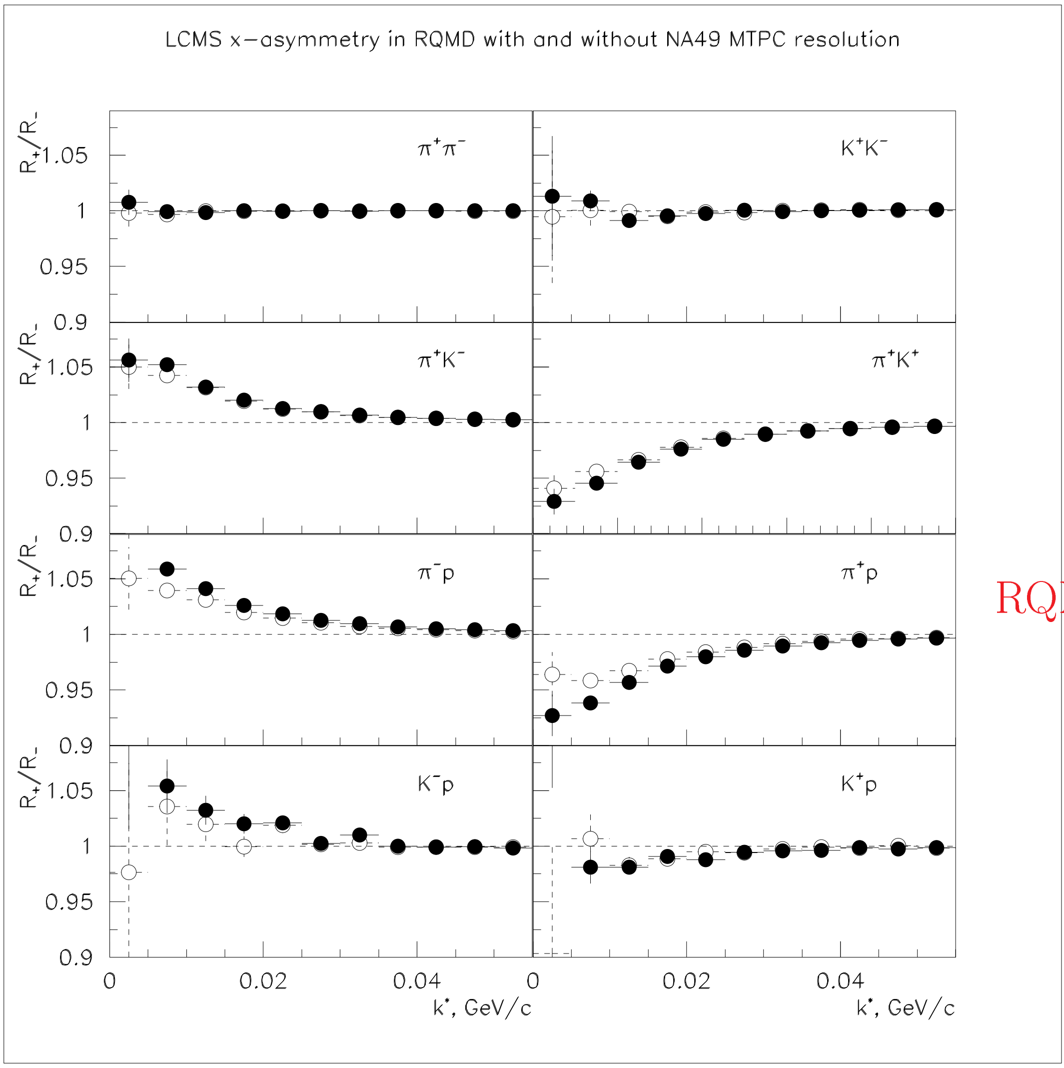
correlation asymmetries R_+/R_-

compare the correlation function C_2 for pairs with +/- projection of the relative velocity vector onto the chosen direction $\vec{x}$

evaluation in LCMS system (Coulomb interaction dominates):

$$\frac{R_{+\vec{x}}}{R_{-\vec{x}}} \sim 1 + \frac{\langle \Delta x^* \rangle}{a} \longrightarrow 1 + 2\frac{\langle \gamma_\perp (\Delta x - v_\perp \Delta t) \rangle}{a}$$

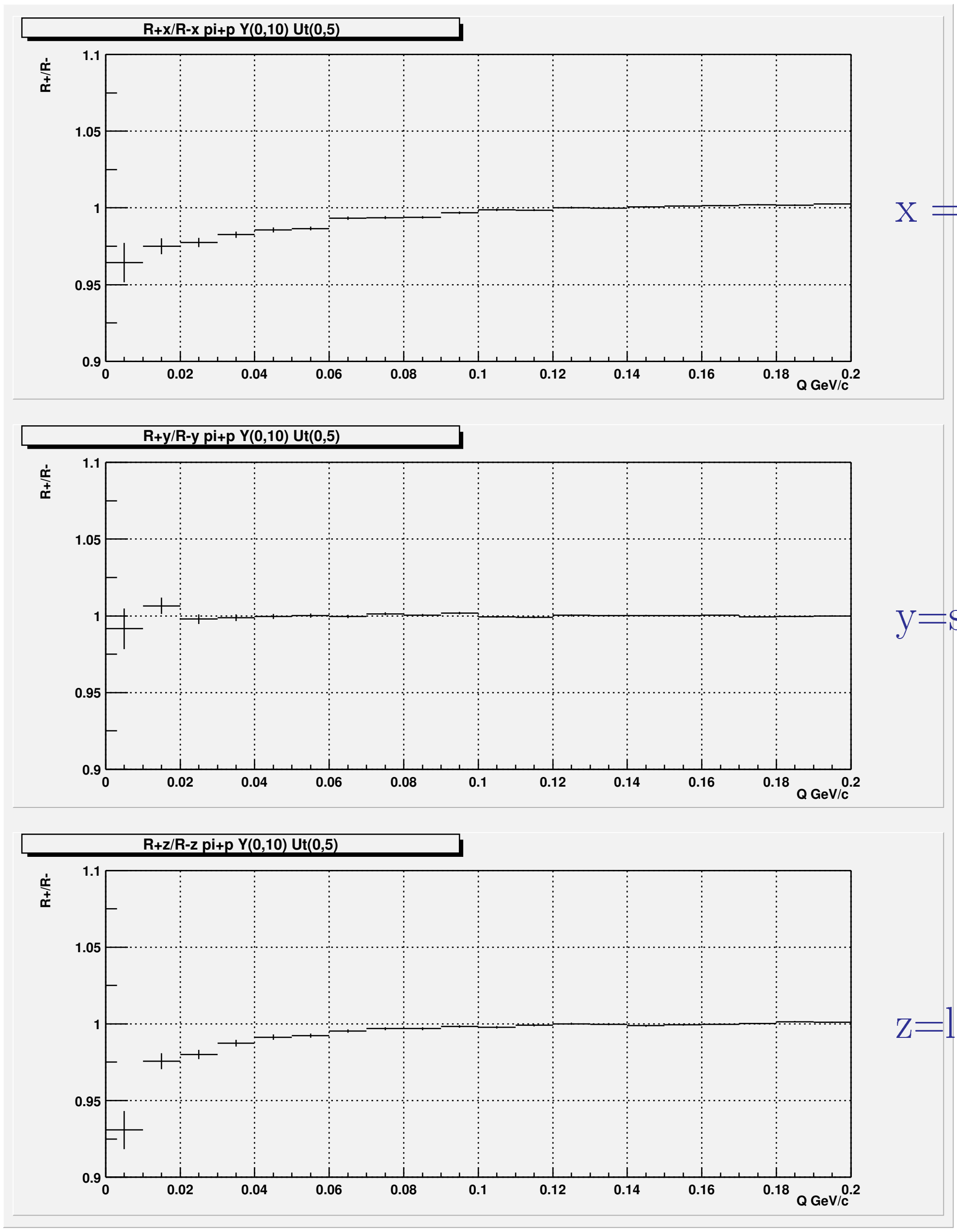
$a = -388(\pm 223) fm$, Bohr radius of $\pi^+\pi^-(\pi^\pm p)$



RQMD 2.3

- no asymmetry for $\pi^+\pi^-$
- significant asymmetry for $\pi^\pm$p, reflection symmetry
- effect of measuring resolution (open circles) requires correction ($k^* = Q_{inv}/2$)

space–time asymmetry R_{+i}/R_{-i} for π^+p



x = out

y=side

z=long

- similar negative X and Z asymmetries up to 5 % in accordance with RQMD prediction (purity, resolution and acceptance taken into account) $\rightarrow$ direct evidence of strong transverse flow
- Y asymmetry absent as required by symmetry

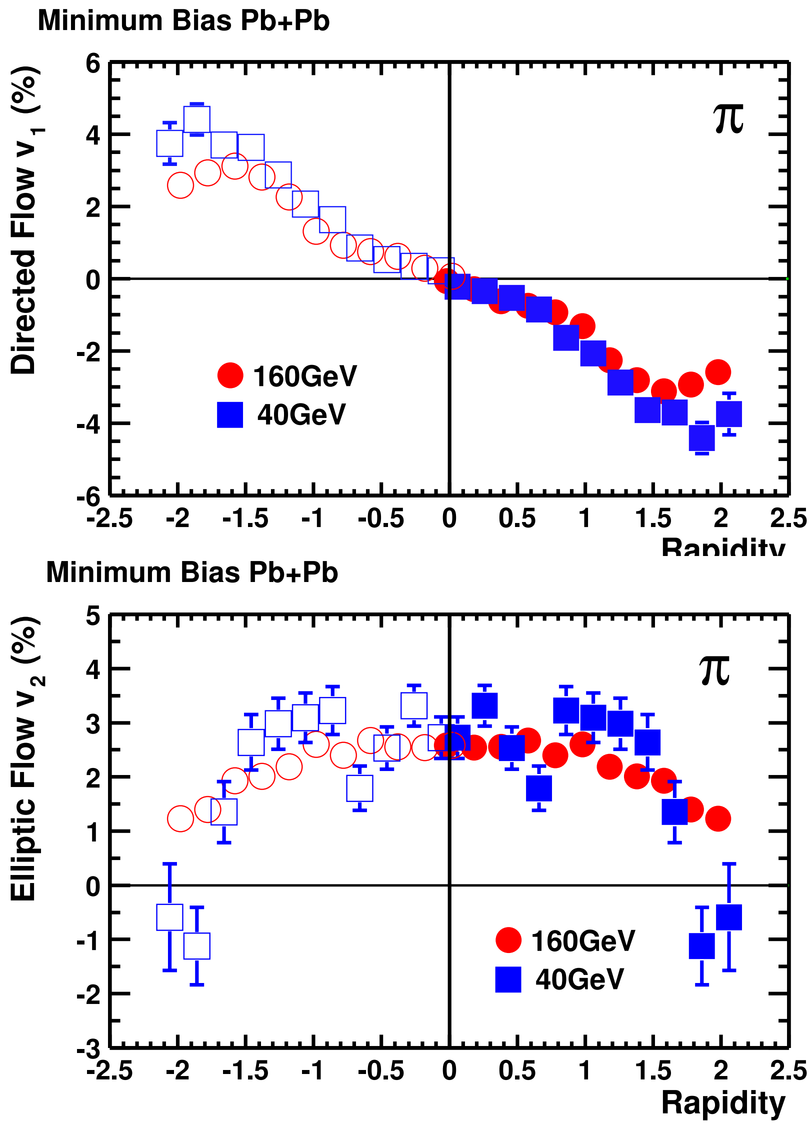
Anisotropic Flow in non-central Collisions

sensitive to pressure in the early stage of the reaction, self quenching

$$v_n = \langle cos(n(\Phi_i - \Psi_n)) \rangle = \sqrt{2} \langle sin(n \cdot \Phi_i) \cdot sin(n \cdot \Psi_n) \rangle$$

Φ_i particle azimuthal angle, Ψ_n angle of reaction plane

corrections for: reaction plane resolution (Poskanzer,Voloshin)
momentum conservation



- v_1 decreases slightly 40 $\rightarrow$ 158 A·GeV
- v_2 shows no clear trend

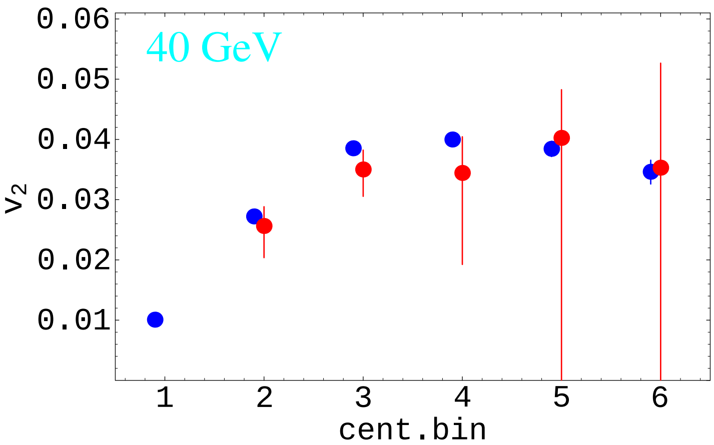
(factor 2 statistics available at 40 A·GeV)

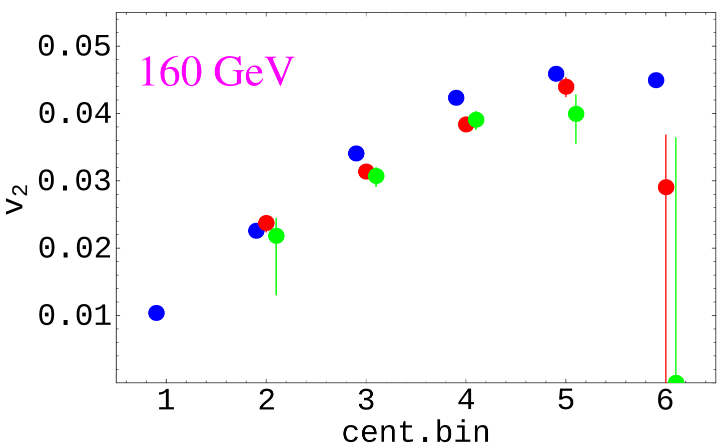
Flow Analysis based on multi–particle Cumulants

(N.Borghini,P.M.Dinh,J.Y.Ollitrault, PRC64(2001),054901)

- reaction plane not required, uses azimuthal correlations
- reduces influence of non–flow correlations by use of higher order cumulants
- acceptance correction using single particle distributions
- needs better statistics than conventional method

PbPb collisions in NA49: preliminary analysis by P.M.Dinh





the plots show:

$v_2\{2\}$ equivalent to standard method

$v_2\{4\}$ derived from 4^{th} order cumulant

$v_2\{6\}$ derived from 6^{th} order cumulant

$\Rightarrow$ non–flow contribution not large

Conclusion

- strong collective behaviour is observed in central Pb+Pb collisions at the SPS
  - k_T–depencence of BE–correlations
  - asymmetry in π^+p correlations
  - directed and elliptic flow
- the non–monotonic energy dependence of the K^+/π^+ (strangeness to entropy) ratio as well as the steepening of the pion to participant nucleon ratio (increase of entropy production) may suggest the onset of deconfinement in the lower SPS energy range
- however, event-to-event fluctuations of $\langle p_T \rangle$ and of the charge ratio do not show unusual features