Event plane and flow in heavy ion collisions

- Where it all began: BEVALAC
- 2nd generation: KaoS
- 3rd generation: NA49
- RHIC?

Streamer Chamber at the BEVALAC

PHYSICAL REVIEW C VOLUME 27, NUMBER 3 MARCH 1983

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than 3½ printed pages and must be accompanied by an abstract and a keyword abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

Charged-particle exclusive analysis of central Ar + KCl and Ar + Pb reactions at 1.8 and 0.8 GeV/nucleon

H. Ströbele, R. Brockmann, J. W. Harris, F. Riess,* A. Sandoval, R. Stock, and K. L. Wolf†
Gesellschaft für Schwerionenforschung, Darmstadt, West Germany

H. G. Pugh and L. S. Schroeder
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

R. E. Renfordt and K. Tittel
Institut für Hochenergiephysik, Universität Heidelberg, West Germany

M. Maier
Fachbereich Physik, Universität Marburg, West Germany
(Received 26 October 1982)

An event by event analysis is carried out for all charged particles observed in central collisions of ^{40}Ar + KCl and ^{40}Ar + Pb at 1.808 and 0.772 GeV/nucleon, respectively. Total transverse energy is used for impact parameter selection within the central trigger condition. The central Ar + KCl reaction exhibits a forward-backward oriented momentum flux. The flux distribution of the most central Ar + Pb events is approximately isotropic in the fireball center of mass.

Streamer Chamber at the BEVALAC

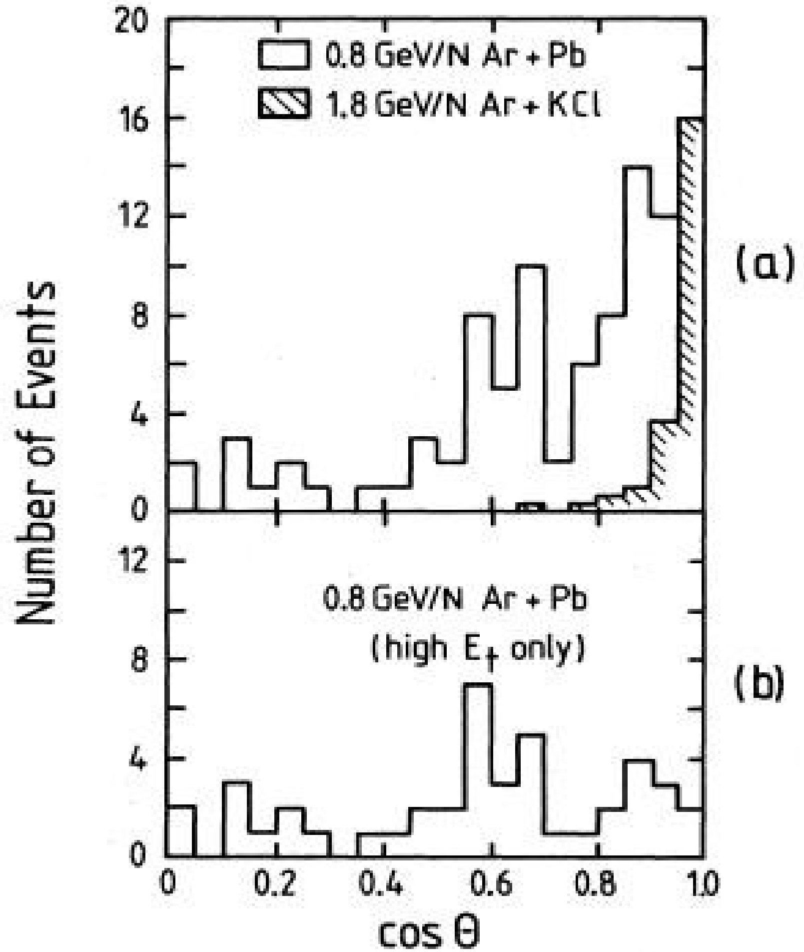


FIG. 2. Distributions of cosθ, with θ being the angle of the main axis of the momentum tensor with respect to the beam direction (a) for Ar + KCl and Ar + Pb, where the Ar + KCl histogram (hatched) is normalized to the last bin of Ar + Pb, and (b) for Ar + Pb events with E_t greater than the mean E_t ($\langle E_t \rangle = 5$ GeV).

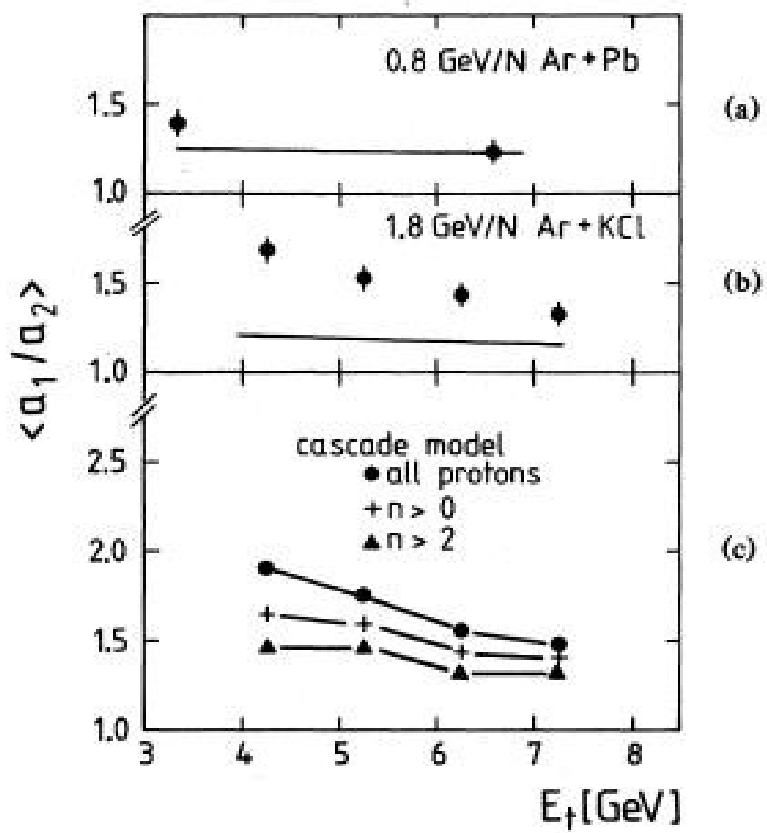


FIG. 3. (a) Aspect ratio (main axis and second largest axis) as a function of E_t for Ar + Pb. The solid line represents the aspect ratio expected for isotropic events with similar multiplicities. (b) The same for Ar + KCl. (c) The same for cascade generated Ar + KCl events: (●) all charged particles; (+) only particles which interacted at least once; (▲) only particles which interacted at least three times.

Plastic Ball at the BEVALAC

VOLUME 52, NUMBER 18 PHYSICAL REVIEW LETTERS 30 APRIL 1984

Collective Flow Observed in Relativistic Nuclear Collisions

H. A. Gustafsson, H. H. Gutbrod, B. Kolb, H. Löhner,[a] B. Ludewigt, A. M. Poskanzer, T. Renner, H. Riedesel,[b] H. G. Ritter, A. Warwick,[c] F. Weik,[d] and H. Wieman

Gesellschaft fur Schwerionenforschung, Darmstadt, West Germany, and Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 21 February 1984)

The reactions Ca + Ca and Nb + Nb at 400 MeV/nucleon have been studied at the Bevalac using the "Plastic Ball" spectrometer. A global analysis of the events shows two nontrivial collective flow effects: the bounceoff of the projectile fragments, and the side-splash of the intermediate-rapidity fragments for the higher-multiplicity Nb + Nb events. Neither effect is seen in a knockon cascade calculation. A simulation with an event-generating statistical model has been done in order to extract the magnitudes of the effects.

Plastic Ball at the BEVALAC

- The „sphericity tensor“:

$$F_{ij} = \sum_{\nu} p_i(\nu) p_j(\nu) w(\nu)$$

  Its main axis has polar and azimuthal angles.
- The finding for its polar angle: →
- Azimuth = 0 defines the event plane.

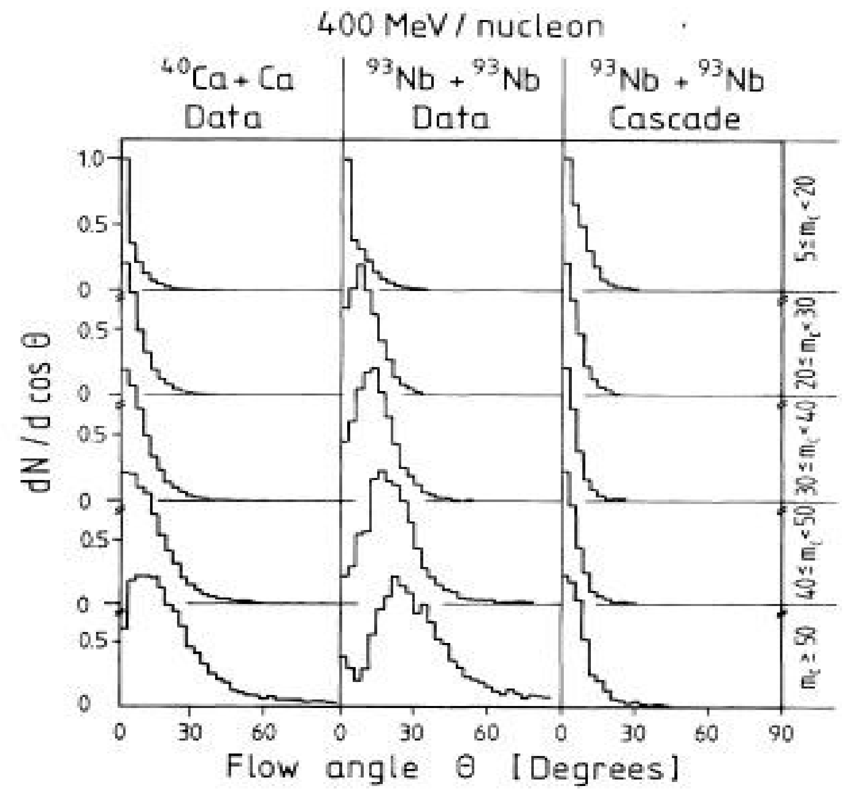
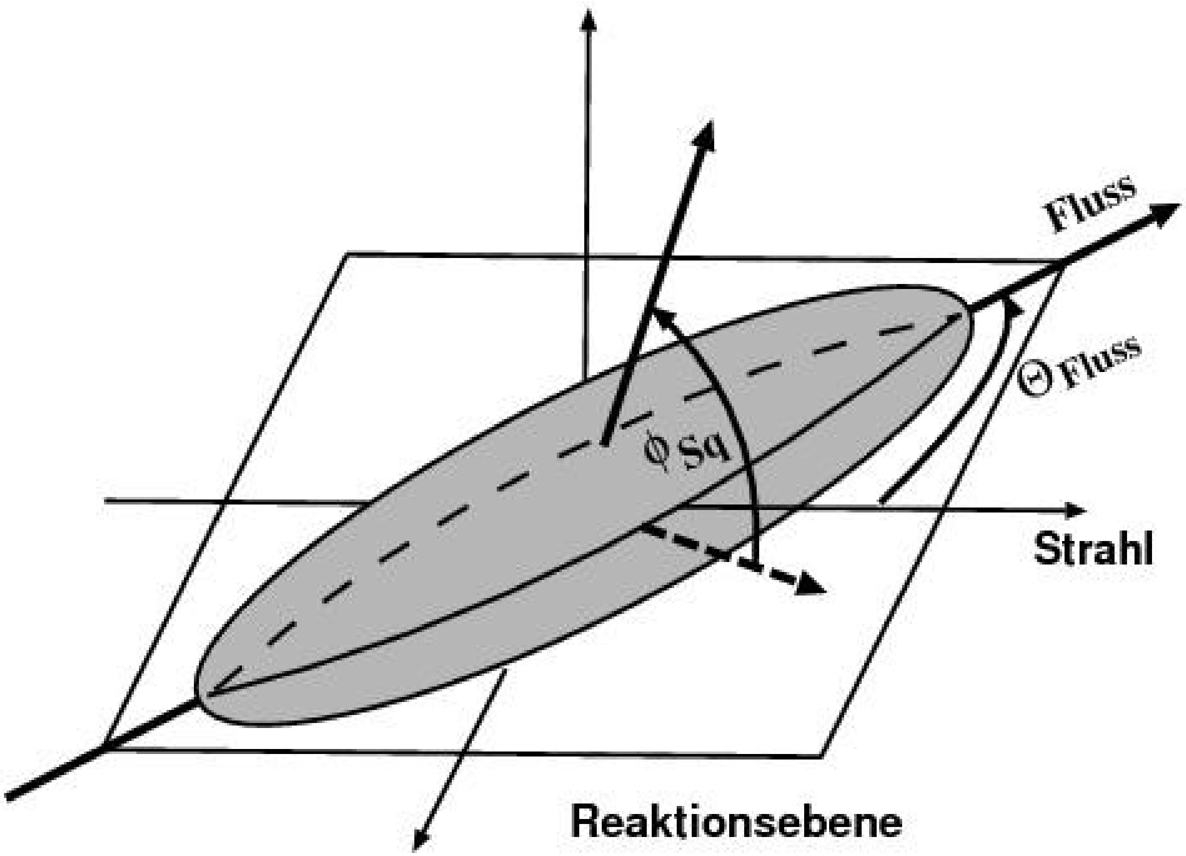


FIG. 1. Frequency distributions of the flow angle θ for two sets of data and a cascade calculation for different multiplicity bins. For the case of Ca the multiplicities are half the indicated values.

Plastic Ball at the BEVALAC

- The „sphericity tensor“:

$$F_{ij} = \sum_{\nu} p_i(\nu) p_j(\nu) w(\nu)$$



Streamer Chamber at the BEVALAC

VOLUME 53, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 1984

Stopping Power and Collective Flow of Nuclear Matter in the Reaction Ar + Pb at 0.8 GeV/u

R. E. Renfordt and D. Schall
Institute für Hochenergiephysik der Universität, D-6900 Heidelberg, Federal Republic of Germany

and

R. Bock, R. Brockmann, J. W. Harris, A. Sandoval, R. Stock, and H. Ströbele
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Federal Republic of Germany

and

D. Bangert and W. Rauch
Fachbereich Physik der Universität, D-3500 Marburg, Federal Republic of Germany

and

G. Odyniec, H. G. Pugh, and L. S. Schroeder
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 29 May 1984)

Charged-particle exclusive data for Ar + Pb collisions at 0.772 GeV/u are analyzed in terms of collective variables for the event shapes in momentum space. Semicentral collisions lead to sidewards flow whereas nearly head-on collisions have spherical shapes in the c.m. frame, resulting from complete stopping of projectile motion. The hydrodynamical model predictions agree qualitatively with the data whereas the standard cascade model disagrees, lacking in stopping power and collective flow.

Streamer Chamber at the BEVALAC

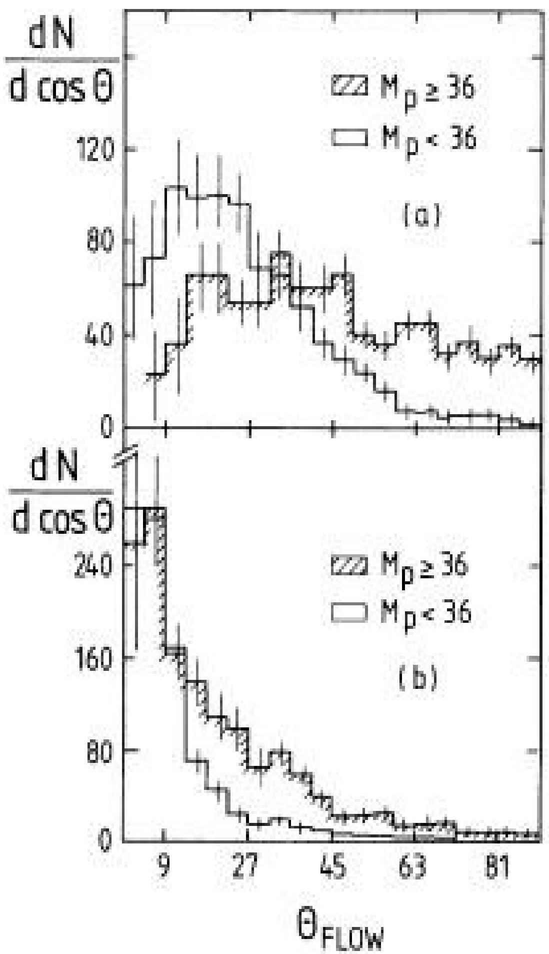


FIG. 2. (a) Distributions of the angle of maximum momentum flow in the c.m. frame for Ar+Pb events with participant proton multiplicities smaller and larger than $\langle M_p \rangle$. (b) Same for the corresponding samples of cascade model generated events.

3 are projected perpendicular to the reaction plane, no sidewards deflection appears and the results are

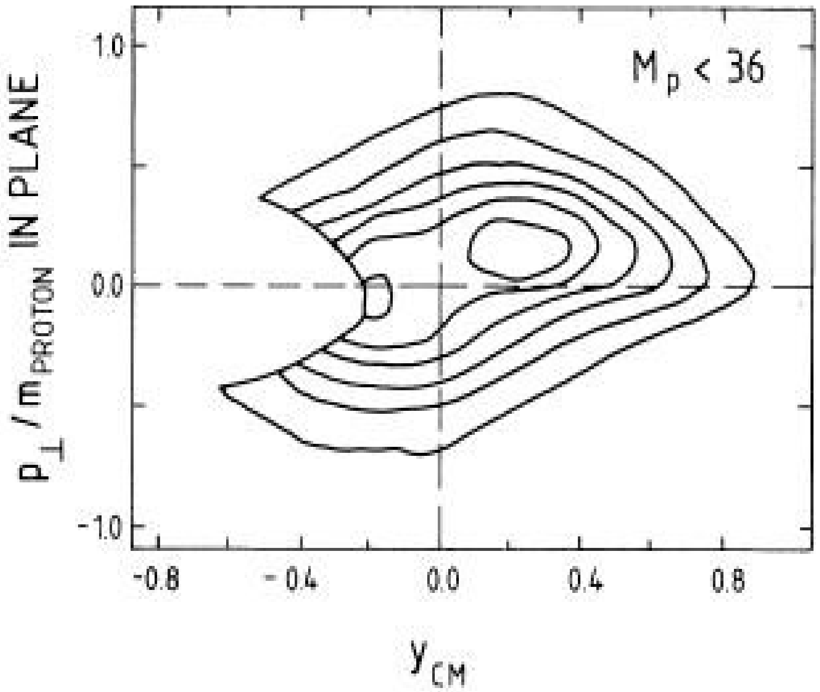


FIG. 3. Projection onto the reaction plane of the invariant proton cross section, shown by contour lines, for intermediate impact parameter Ar+Pb events which have been rotated into a common reaction plane orientation. The cutout at target rapidity reflects the target absorption losses.

Event plane from the transverse momentum method

Volume 157B, number 2,3 PHYSICS LETTERS 11 July 1985

TRANSVERSE MOMENTUM ANALYSIS OF COLLECTIVE MOTION IN RELATIVISTIC NUCLEAR COLLISIONS ☆

P. DANIELEWICZ [1] and G. ODYNIEC

Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

Received 15 March 1985

A novel transverse-momentum technique is used to analyse charged-particle exclusive data for collective motion in the Ar + KCl reaction at 1.8 GeV/nucleon. Previous analysis of this reaction, employing the standard sphericity tensor, revealed no significant effect. In the present analysis, collective effects are observed, and they are substantially stronger than in the Cugnon cascade model, but weaker than in the hydrodynamical model.

Event plane from the transverse momentum method

Volume 157B, number 2,3 PHYSIC

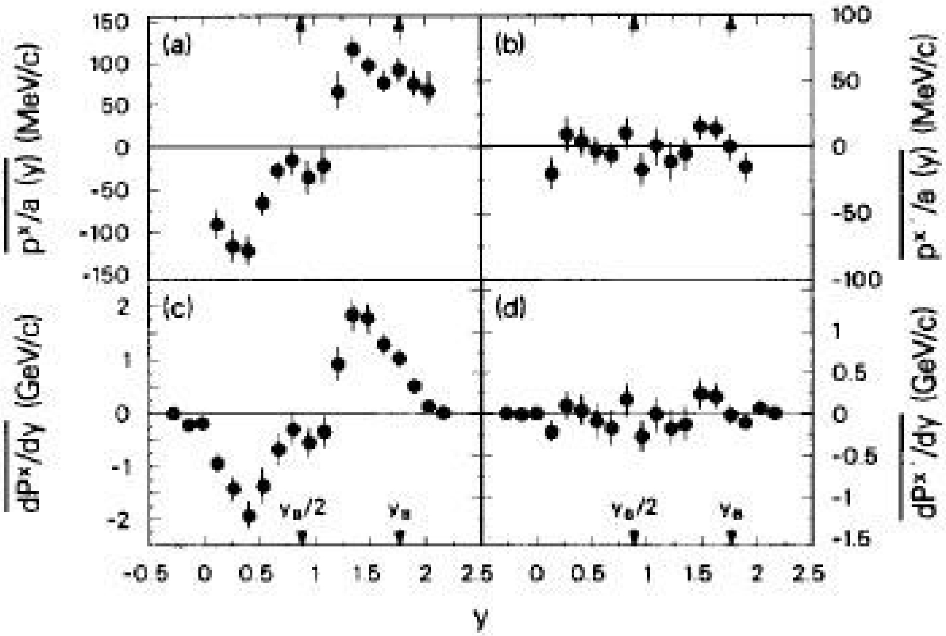


Fig. 3. (a), (b) Average momentum per nucleon in the estimated reaction plane $\overline{p^{x'}/a}(y)$, upon removal of finite-multiplicity distortions, for data and Monte Carlo events, respectively. (c), (d) Differential, per unit rapidity, transverse momentum deposition in the estimated reaction plane in terms of nuclear charges $\overline{dP^{x'}/dy}$, for data and Monte Carlo events, respectively. Left-hand scales in (a) and (c) yield respective estimated average momenta per nucleon $\overline{p^x/a}(y)$, and deposition $\overline{dP^x/dy}$, in the true reaction plane.

$$p_\nu^{x'} = p_\nu^\perp \cdot Q_\nu / Q_\nu$$

$$Q_\nu = \sum_{\mu \neq \nu} \omega_\mu p_\mu^\perp .$$

The Kaonspectrometer (KaoS)
(differences to HADES)

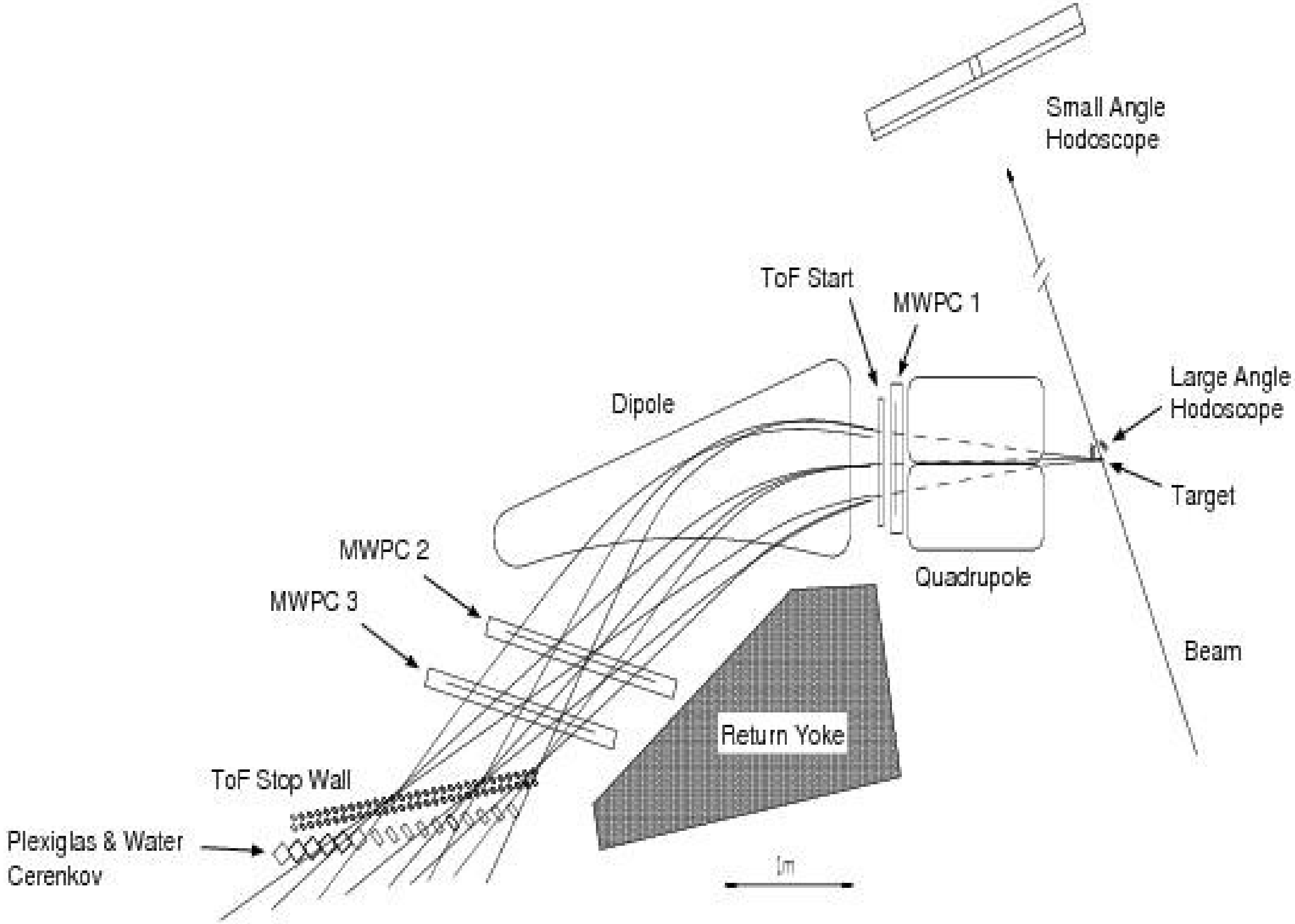
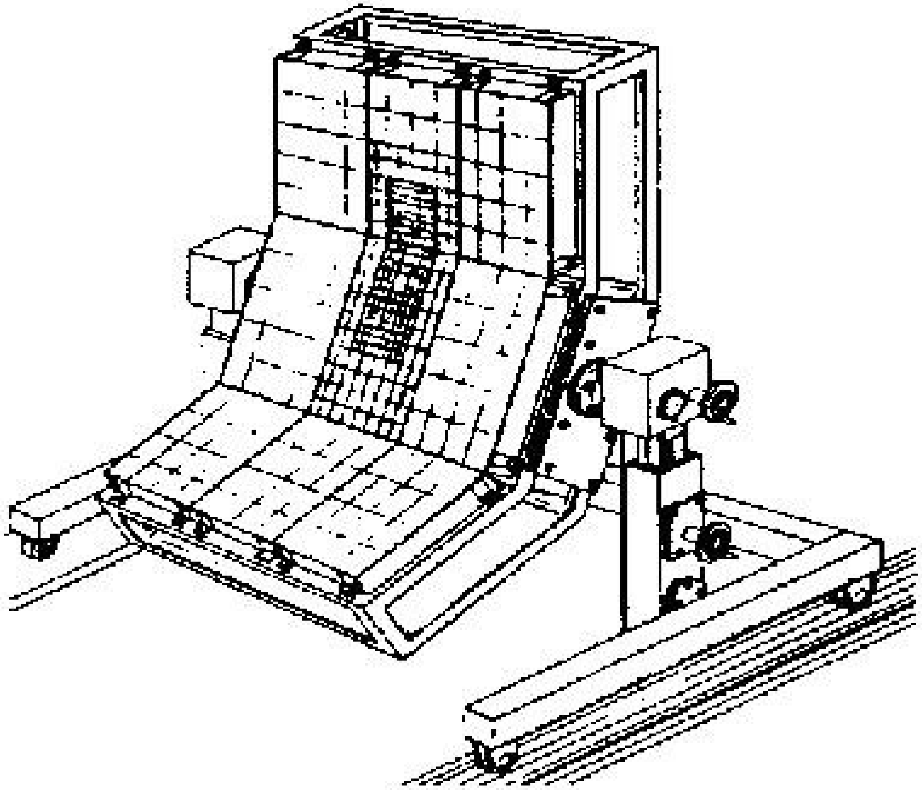
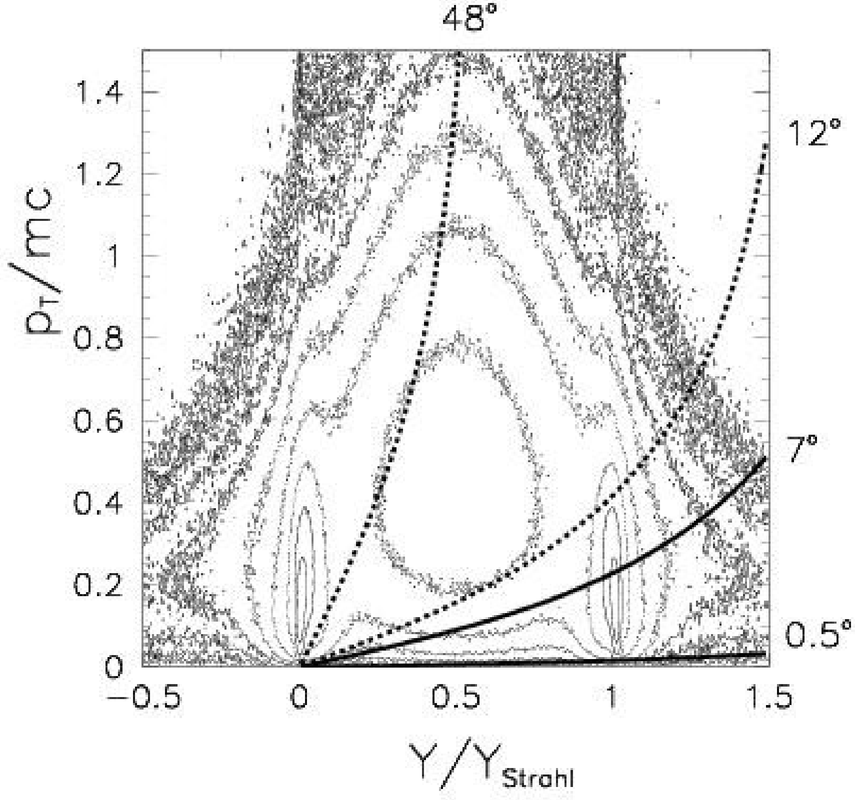


Abbildung 3.1: *Die Aufsicht auf das Kaonenspektrometer mit dem Detektorsystem: Start–(D) und Stoppdetektor (F) zur Messung der Flugzeit, drei Vieldrahtkammern (MWPC–L,M,N) zur Spurrekonstruktion, Cherenkov–Detektor (C) und zwei Hodoskope (T und H) zur Charakterisierung der Stoßgeometrie*

The Kaonspectrometer (KaoS)





Au+Au 1 GeV/u   FRESCO

The Kaonspectrometer (KaoS)
first observation of pion sqeeze (Brill thesis)

Phys. Rev. Lett. 71 (1993) 336

Au + Au 1 GeV/u

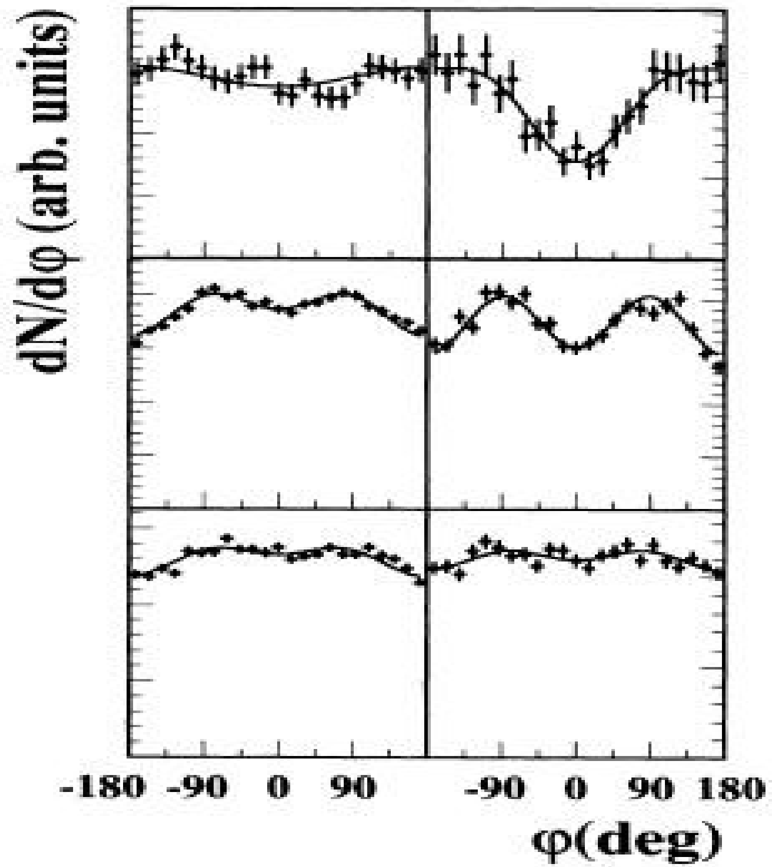


FIG. 2. Azimuthal distributions of the vector **Q** for peripheral, semicentral, and central collisions (from top to bottom). The ordinate is linear starting at zero. Shown on the left are π^+ in the range $160 < p_T < 260$ MeV/c, on the right, π^+ in the range $260 < p_T < 600$ MeV/c. The solid lines are fits with $\cos(\varphi)$ and $\cos(2\varphi)$ terms. $\varphi = 0°$ represents an in-plane emission of pions parallel to the **Q** vector, $\varphi = \pm 180°$ an in-plane emission antiparallel to the **Q** vector. $\varphi = \pm 90°$ corresponds to an emission of pions perpendicular to the reaction plane.

The Kaonspectrometer (KaoS)
Event plane resolution in Bi+Bi (Brill thesis)

Z. Phys. A 355 (1996) 61

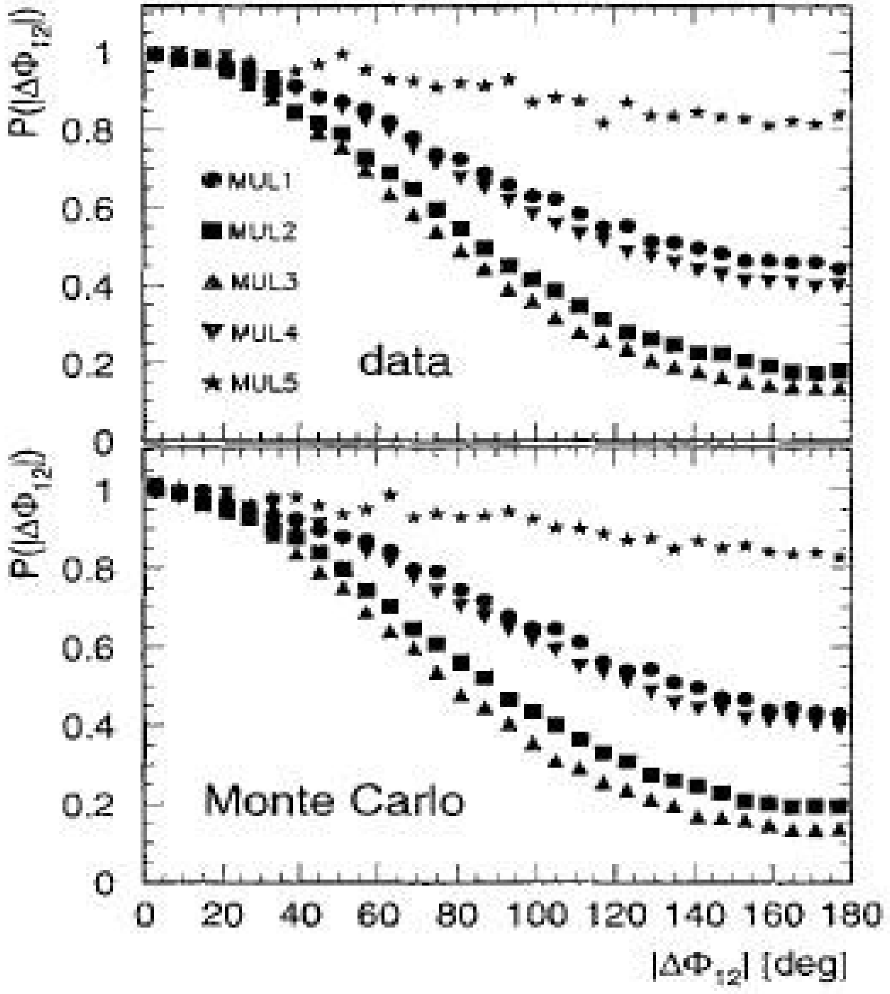


Fig. 3. Probability distribution $P(\Delta\Phi_{12})$ for the angular difference $\Delta\Phi_{12}$ between Q_1 and Q_2 as measured at a beam energy of $E_{Lab}/A = 1000$ MeV (*upper*) and simulated (*lower*). The distributions are shown for different multiplicity ranges

The Kaonspectrometer (KaoS)

Event plane resolution in Bi+Bi (Brill thesis)

Table 4. Uncertainties of the azimuthal difference between the reaction plane calculated from the subevents and between the estimated and the true reaction plane, respectively, as extracted from the simulation (see text). The statistical errors are negligible

	$E_{Lab}/A = 400$ MeV		
	$< \Delta\Phi_{12}^2 >^{1/2}$	$< \Delta\Phi^2 >^{1/2}$	$< cos(2\Delta\Phi) >$
MUL1	98.2°	74.3°	0.13
MUL2	86.4°	51.9°	0.35
MUL3	82.1°	47.4°	0.41
MUL4	93.5°	67.4°	0.18
MUL5	100.5°	86.5°	0.03
	$E_{Lab}/A = 700$ MeV		
	$< \Delta\Phi_{12}^2 >^{1/2}$	$< \Delta\Phi^2 >^{1/2}$	$< cos(2\Delta\Phi) >$
MUL1	91.7°	59.5°	0.27
MUL2	76.7°	40.2°	0.49
MUL3	75.0°	39.7°	0.51
MUL4	91.7°	61.0°	0.25
MUL5	101.2°	85.8°	0.04
	$E_{Lab}/A = 1000$ MeV		
	$< \Delta\Phi_{12}^2 >^{1/2}$	$< \Delta\Phi^2 >^{1/2}$	$< cos(2\Delta\Phi) >$
MUL1	91.2°	54.9°	0.30
MUL2	77.5°	40.0°	0.50
MUL3	73.1°	36.4°	0.55
MUL4	89.0°	55.9°	0.31
MUL5	101.1°	80.5°	0.08

The Kaonspectrometer (KaoS)
Bi+Bi (Brill thesis), results on p, d, t

Z. Phys. A 355 (1996) 61

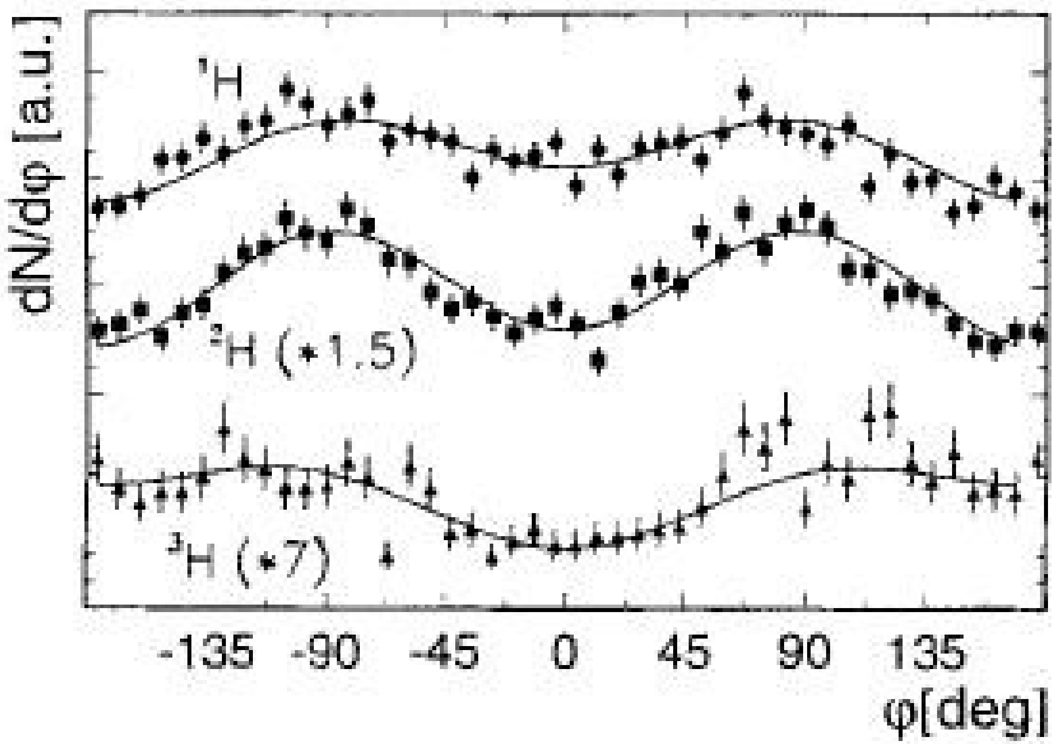


Fig. 4. Typical dN/dφ-distributions for H-isotopes measured at E_{Lab}/A = 400 MeV for semi-central collisions (MUL2,MUL3). The ordinate is linear starting at zero. The particles analysed stem from a momentum range of $400 < p_T/A < 500$ MeV/c. The solid lines are fits with cos(φ) and cos(2φ) terms

The Kaonspectrometer (KaoS)

Bi+Bi (Brill thesis), results on pions

Z. Phys. A 357 (1997) 207

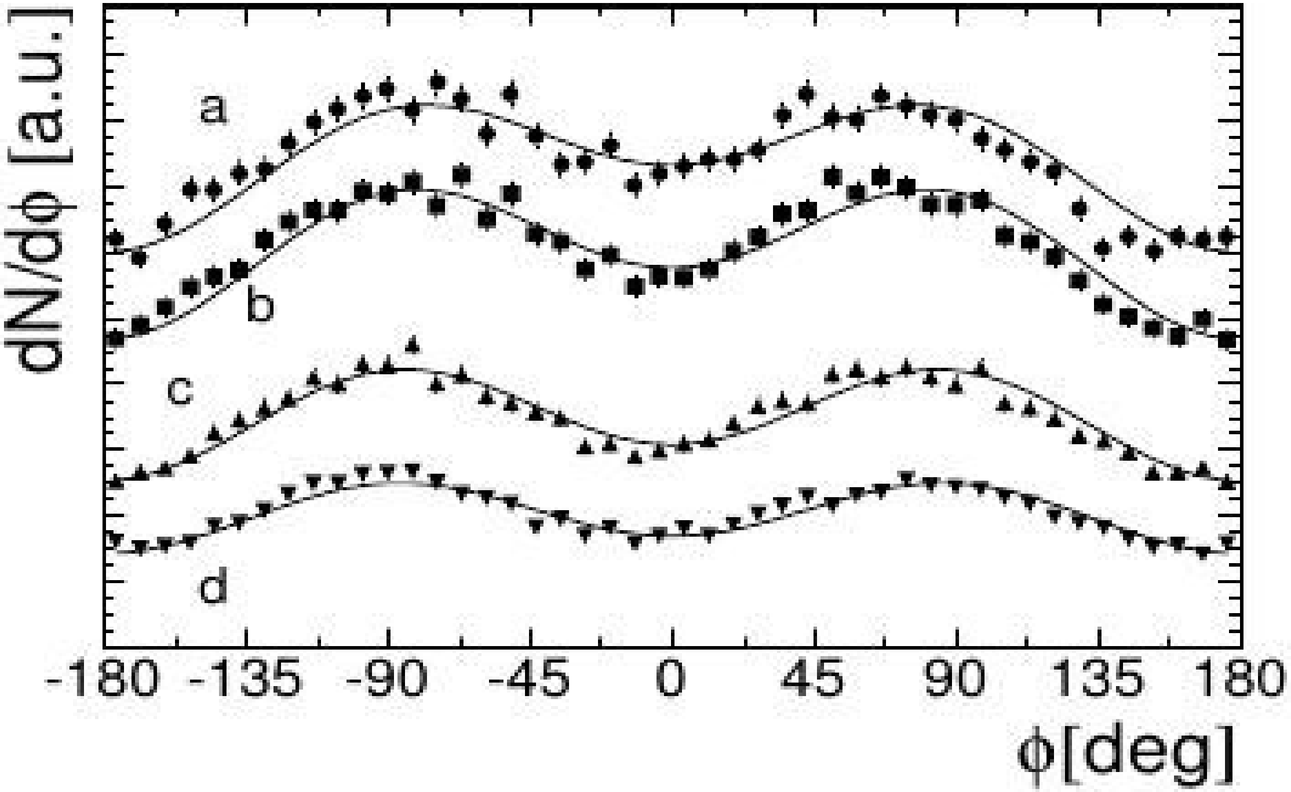


Fig. 2. Azimuthal distribution of π^+ measured at E_{Lab}= 700 AMeV for semi-central collisions (MUL2,MUL3). The curves correspond to different bins in transverse momentum: (*a*) 240–300 MeV/c, (*b*) 300–360 MeV/c, (*c*) 360–420 MeV/c, (*d*) 420 -480 MeV/c. The ordinate is linear starting at zero

The Kaonspectrometer (KaoS)
Au+Au (Shin thesis), results on K^+

Phys. Rev. Lett. 81 (1998) 1576

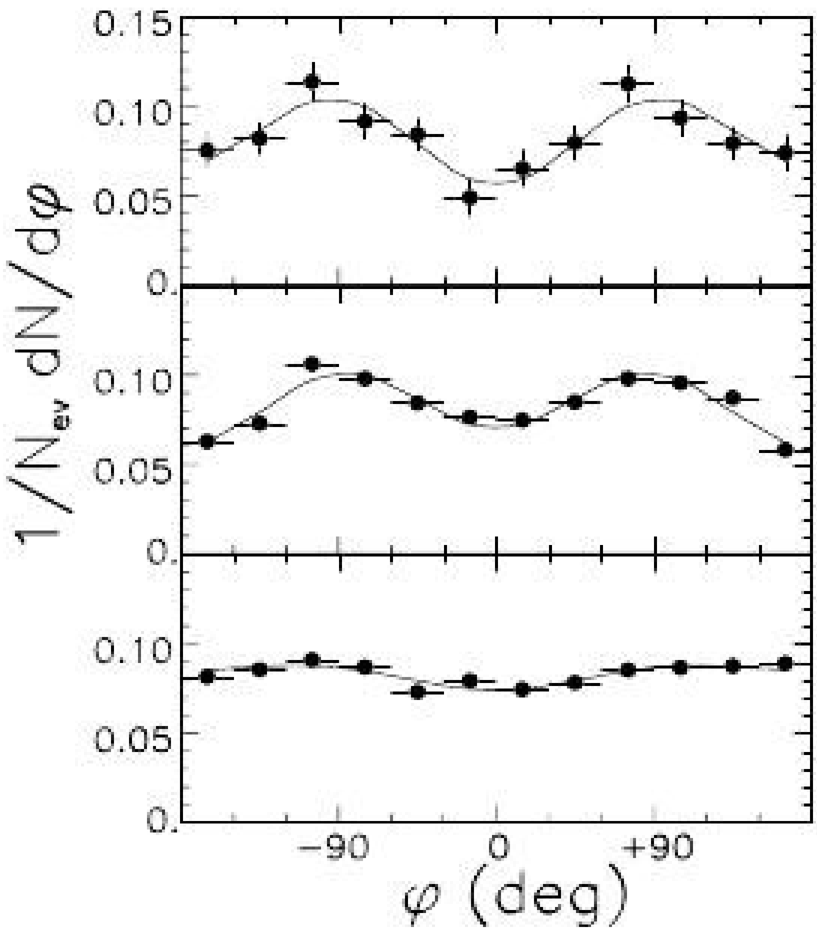


FIG. 1. K^+ azimuthal angular distribution for peripheral ($b \geq$ 10 fm), semicentral ($b = 5-10$ fm), and central ($b \leq 5$ fm) Au + Au collisions at 1A GeV (from top to bottom). The data cover normalized rapidities in the interval $0.2 \leq y/y_{proj} < 0.8$ and transverse momenta in the interval $0.2 \leq p_t < 0.8$ GeV/c. The lines represent fits to the data (see text).

The Kaonspectrometer (KaoS)
Pion camera (thesis Wagner)

VOLUME 85, NUMBER 1 PHYSICAL REVIEW LETTERS 3 JULY 2000

Emission Pattern of High-Energy Pions: A New Probe for the Early Phase of Heavy-Ion Collisions

A. Wagner,* C. Müntz,† H. Oeschler, and C. Sturm
Technische Universität Darmstadt, D-64289 Darmstadt, Germany

R. Barth, M. Cieślak, M. Dębowski,* E. Grosse,* P. Koczoń, F. Laue,‡ M. Mang, D. Miśkowiec, E. Schwab, and P. Senger
Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany

P. Beckerle, D. Brill, Y. Shin, and H. Ströbele
Johann Wolfgang Goethe Universität, D-60054 Frankfurt, Germany

W. Waluś
Uniwersytet Jagielloński, PL-30-059 Kraków, Poland

B. Kohlmeyer, F. Pühlhofer, J. Speer, and I. K. Yoo
Phillips-Universität Marburg, D-35037 Marburg/Lahn, Germany
(Received 5 November 1999)

The emission pattern of charged pions has been measured in Au + Au collisions at 1 GeV/nucleon incident energy. In peripheral collisions and at target rapidities, high-energy pions are emitted preferentially towards the target spectator matter. In contrast, low-energy pions are emitted predominantly in the opposite direction. The corresponding azimuthal anisotropy is explained by the interaction of pions with projectile and target spectator matter. This interaction with the spectator matter causes an effective shadowing which varies with time during the reaction. Our observations show that high-energy pions stem from the early stage of the collision whereas low-energy pions freeze out later.

The Kaonspectrometer (KaoS)
Pion camera (thesis Wagner)

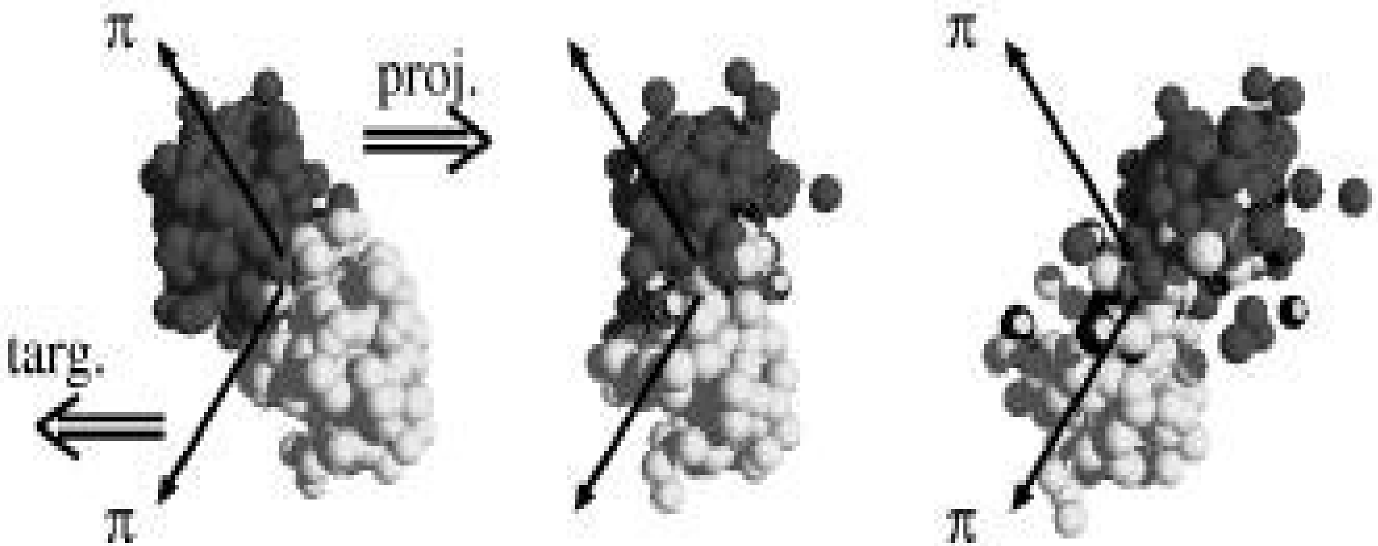
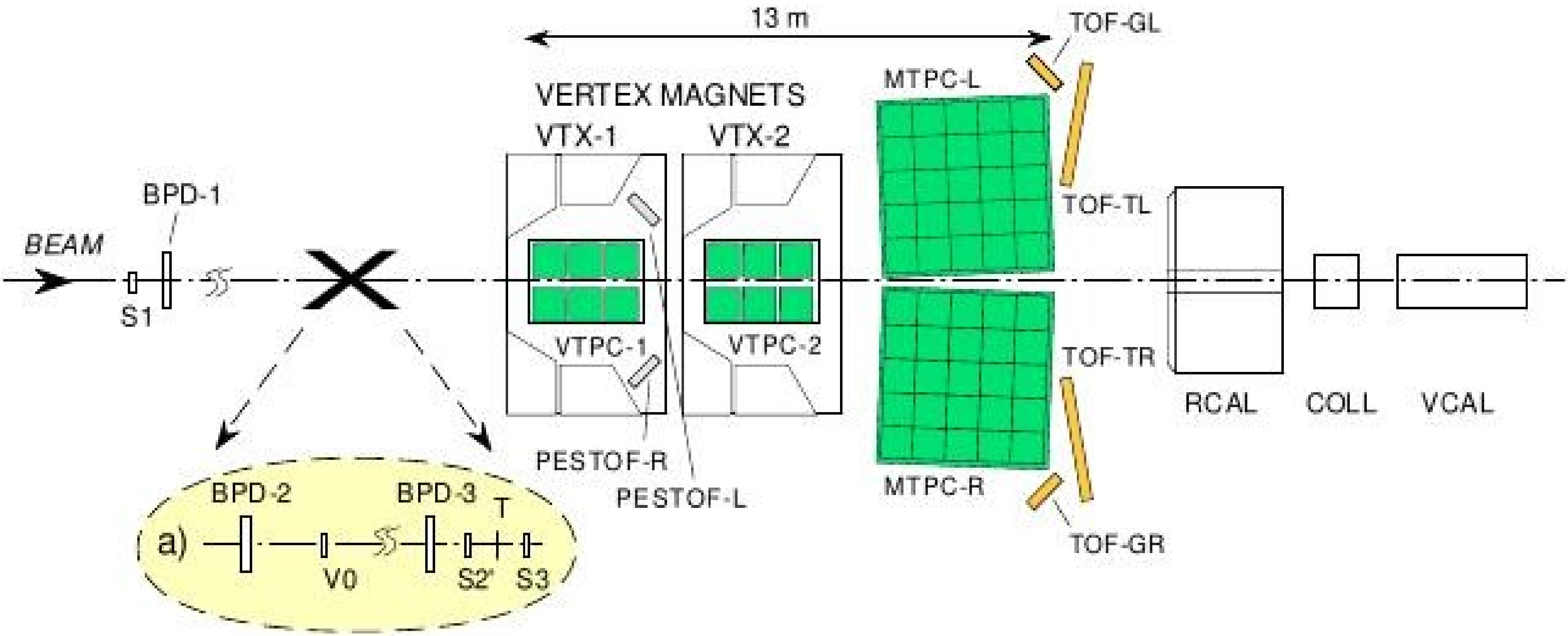


FIG. 1. Sketch of an Au + Au collision at 1 GeV/nucleon with an impact parameter of 7 fm as calculated by a transport code [13]. The snapshots are taken at 6.5 fm/c (left), 12.5 fm/c (middle), and 18.5 fm/c (right) after time zero (see text for definition of time zero). The arrows indicate the direction of the spectrometer at target rapidity.

NA49 (Pb+Pb at 158 GeV/u)



- No position sensitive detector for projectile fragments
- Magnetic field breaks azimuthal symmetry

NA49 (thesis Wetzler)

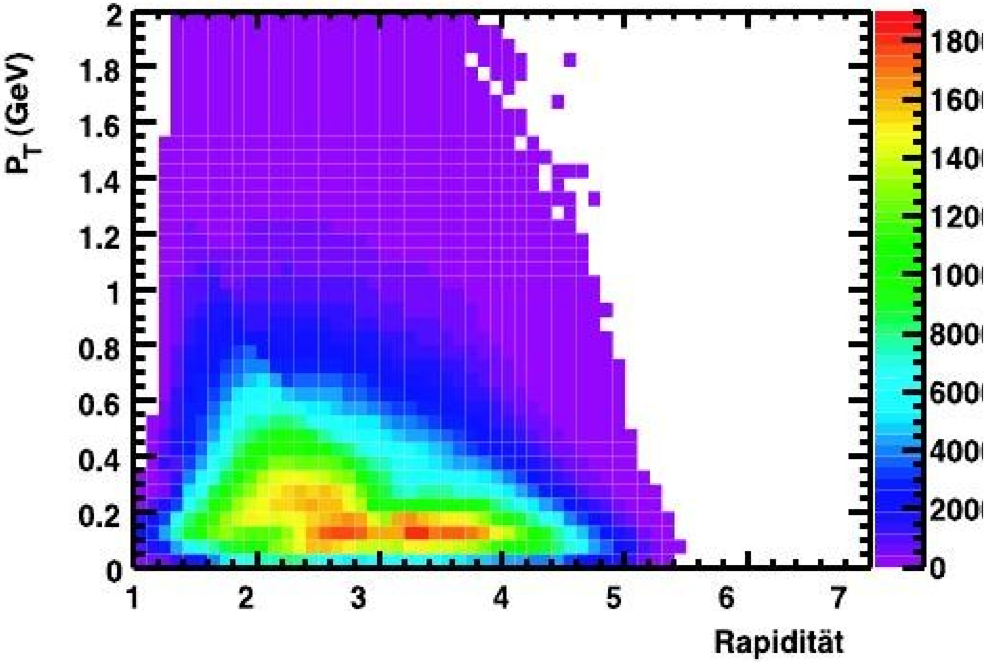
- Selection of appropriate regions of phase space for the determination of the event planes of v_1 and v_{2}.

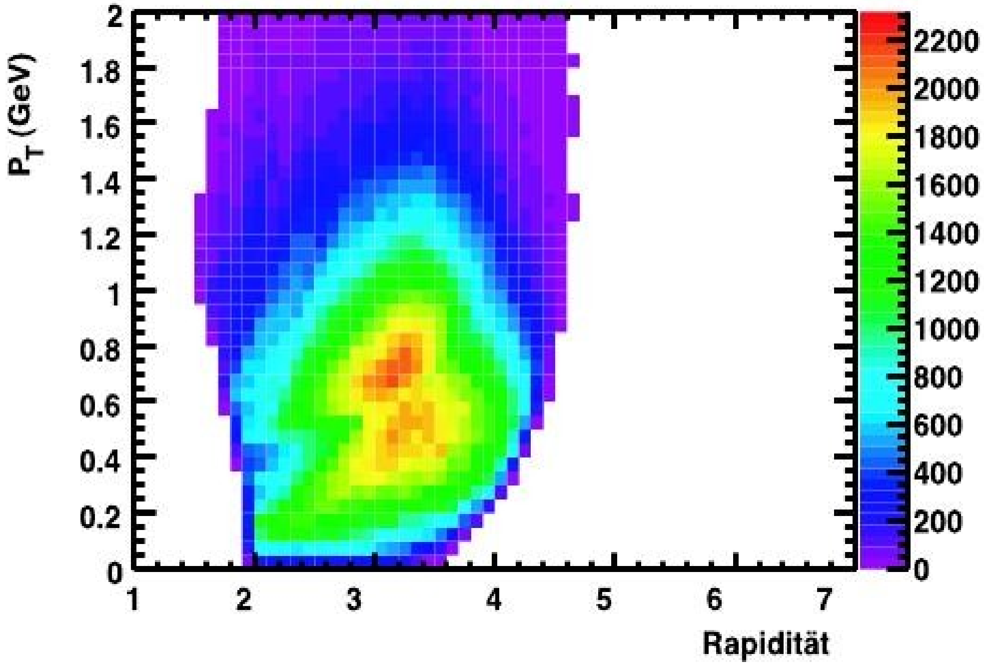
	v_1	v_2
y	[3.0;4.48]	[1.8;3.5]
$p_T(GeV/c)$	[0.05;1.0]	[0.05;1.0]

Tabelle 5.4: Schnitte in y und p_T im Phasenraum auf den Bereich der Spuren zur Bestimmung der Ereignisebene

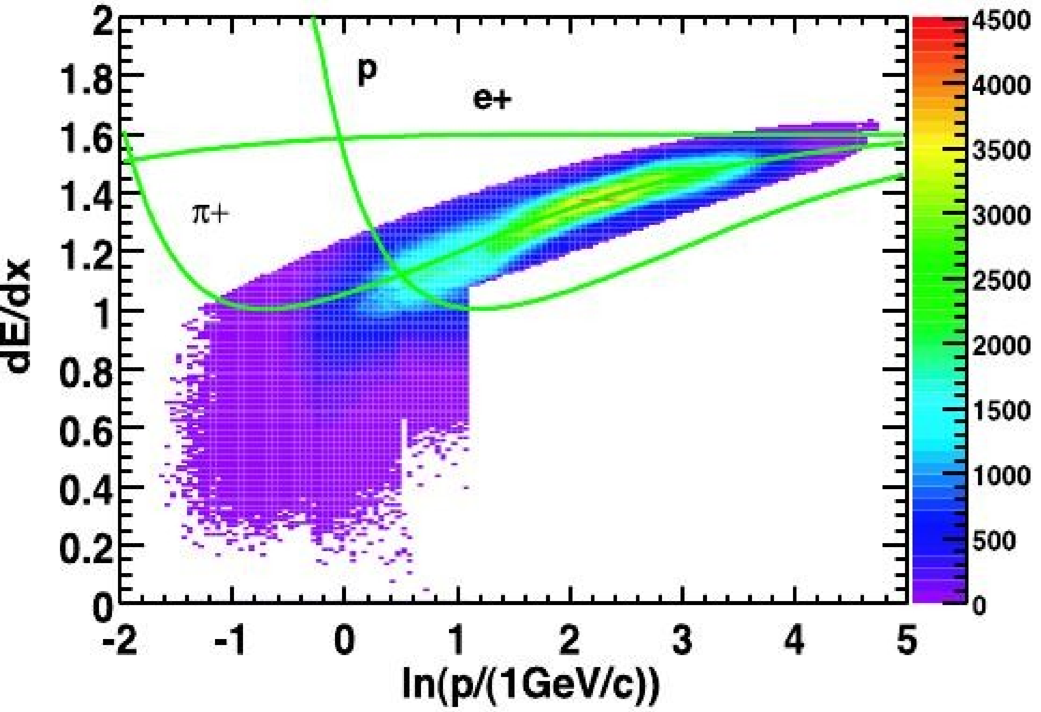
$0 < Y_{lab} < 6$

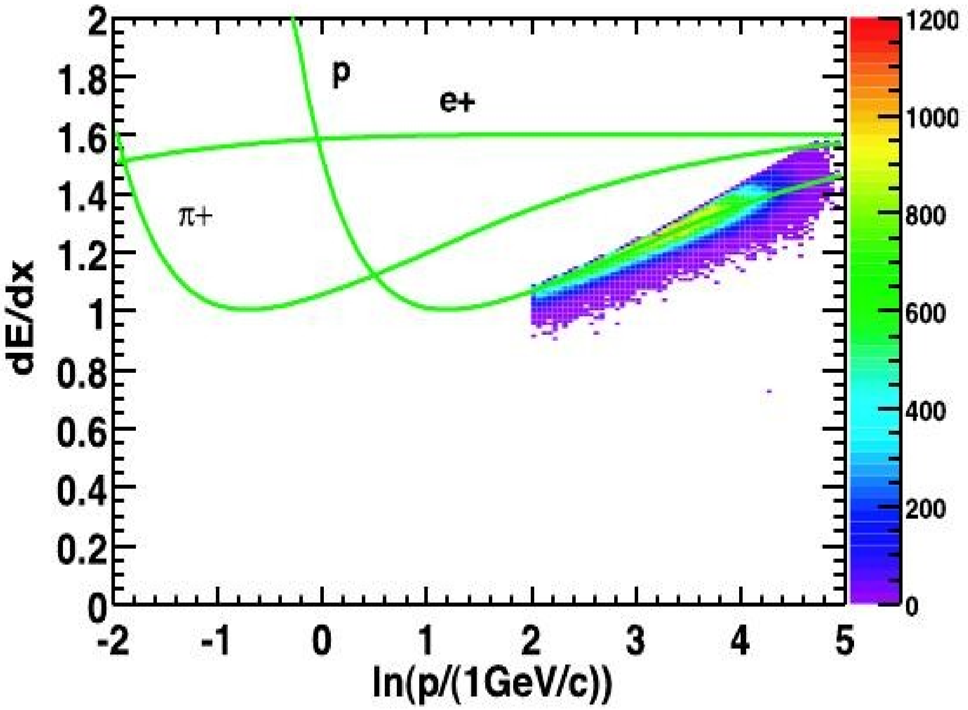
NA49 (“acceptance“ p and π)



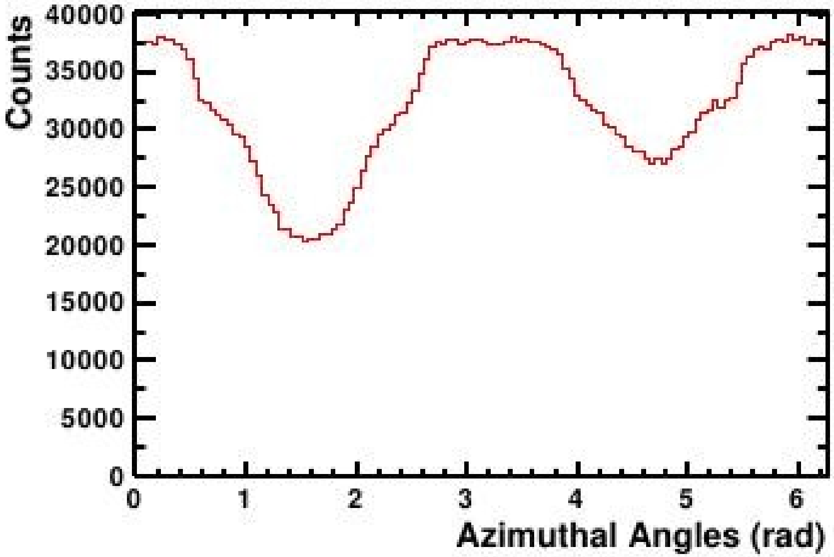


NA49 (identification)

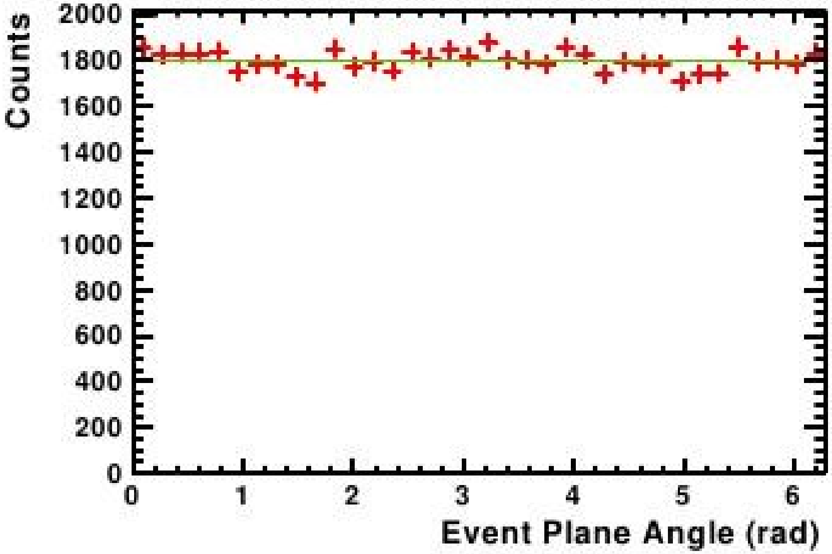




NA49 (azimuthal losses)



inclusive



after (recentering) correction

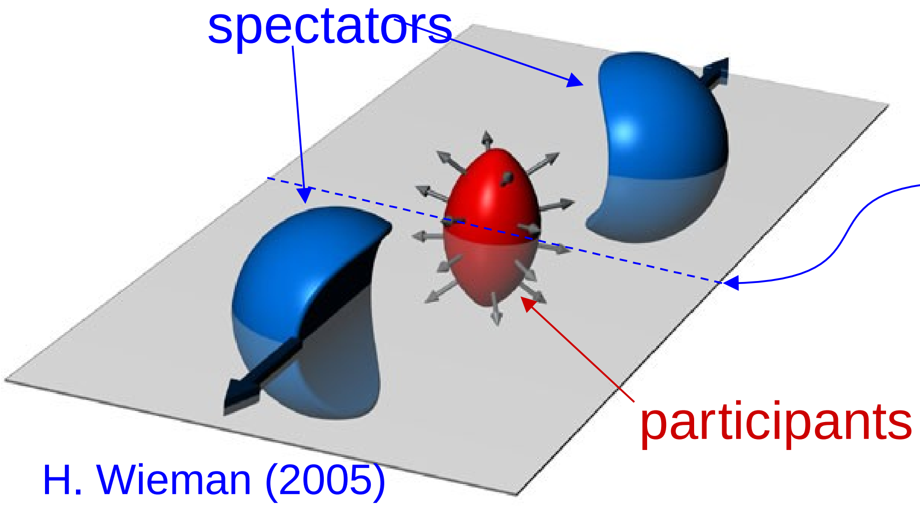
Reminder (definitions)

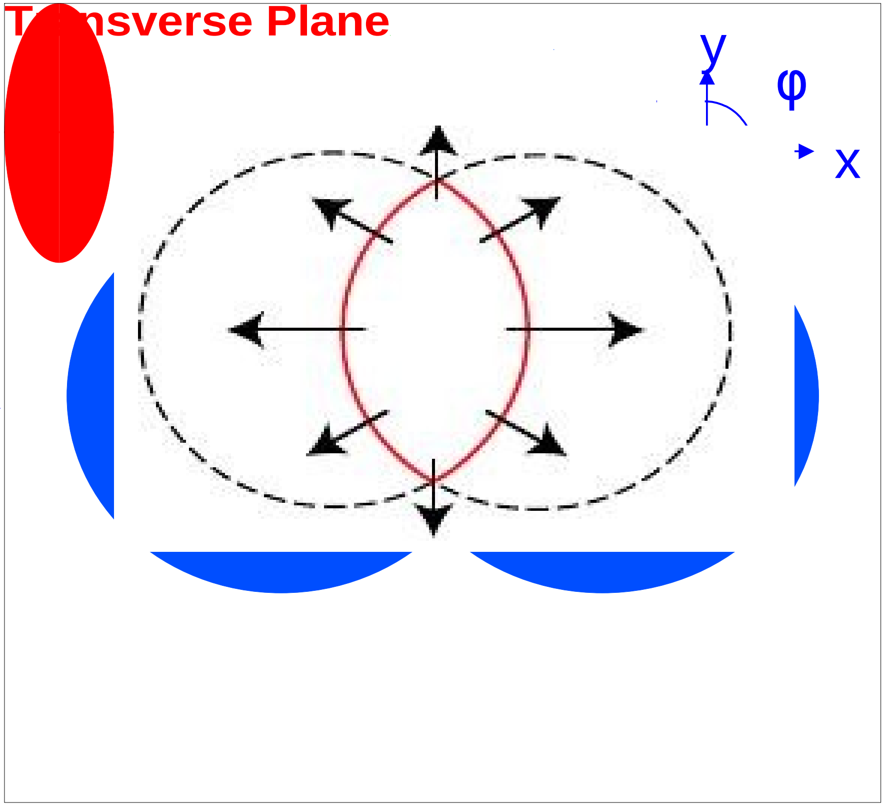
- Reaction plane

  (given by impact paramete, $\vec{p}_{beam} \times \vec{b}$)

- Event plane (measured for individual events)
  - Directed flow: v
    - Event plane ~ reaction plane
  - Elliptic flow: v_2
    - in-plane
    - out-of-plane (squeeze)
  - Radial flow (isotropic)

Hadronic Probe of Early Time





azimuthal angle around the beam axis

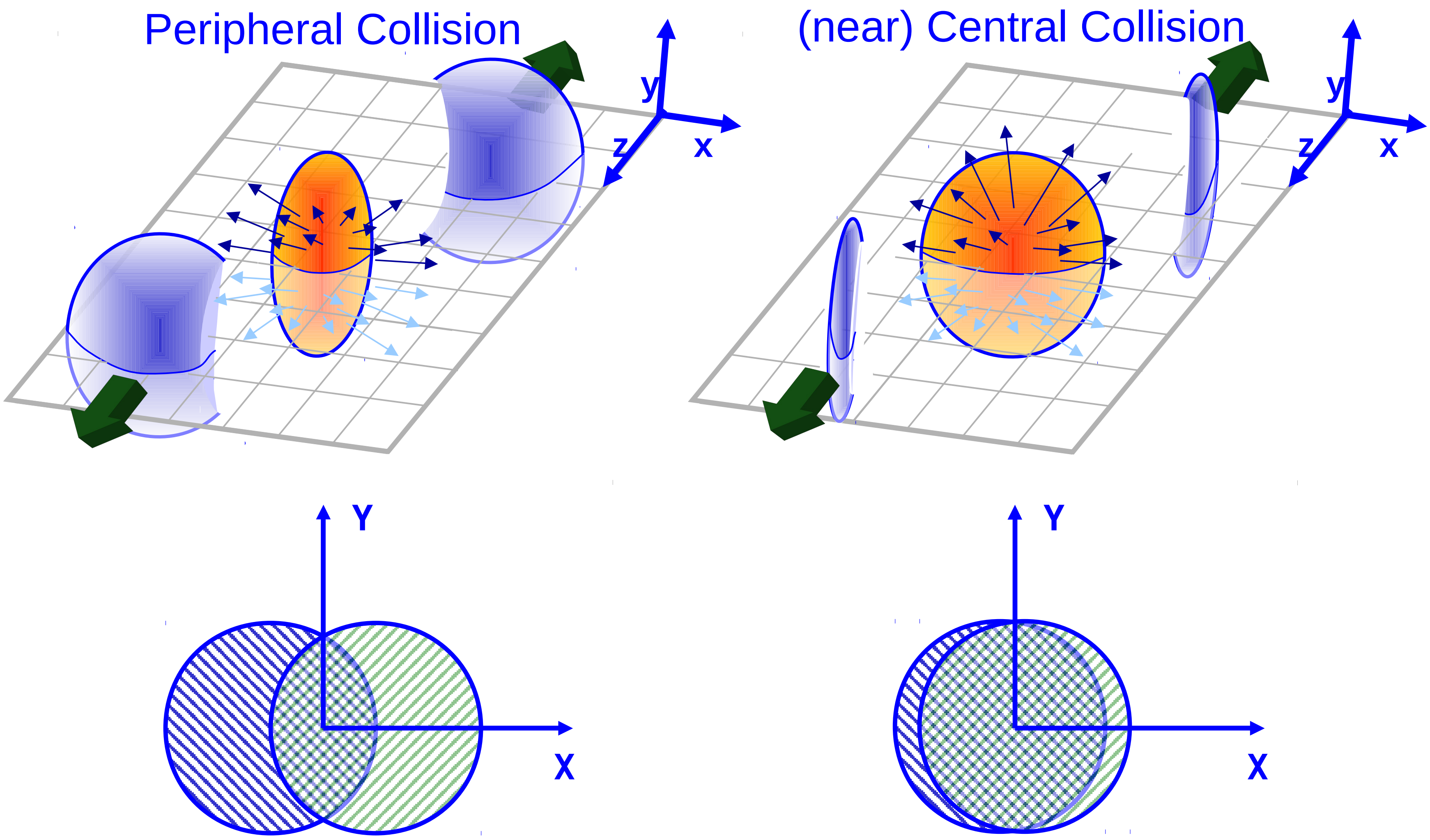
QuickTime and a decompressor are needed to see this picture.

A

QuickTime and a decompressor are needed to see this picture.

density gradient -> pressure
for anisotropic expansion

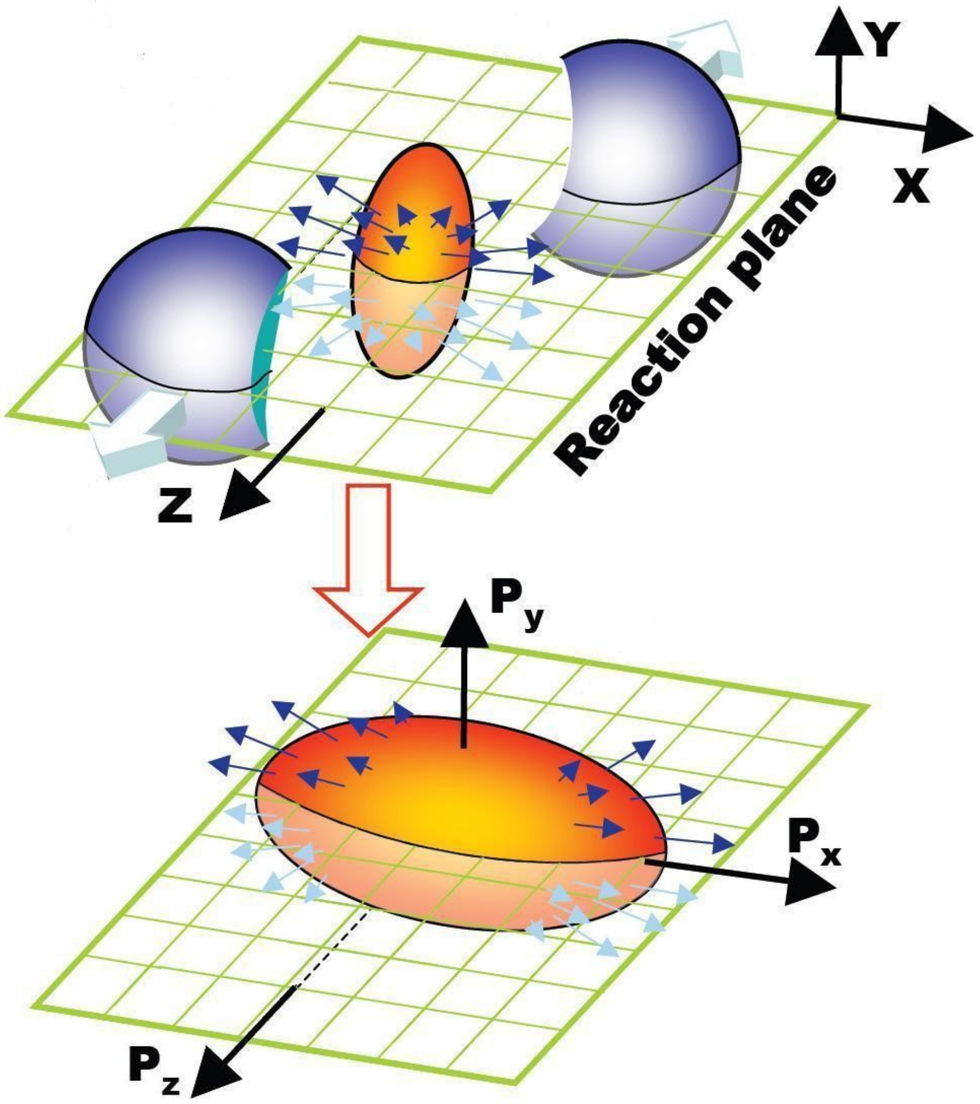
Centrality Dependence



Centrality measured by the multiplicity of charged particles

Masashi Kaneta

Expansion In Plane



Hiroshi Masui (2008)

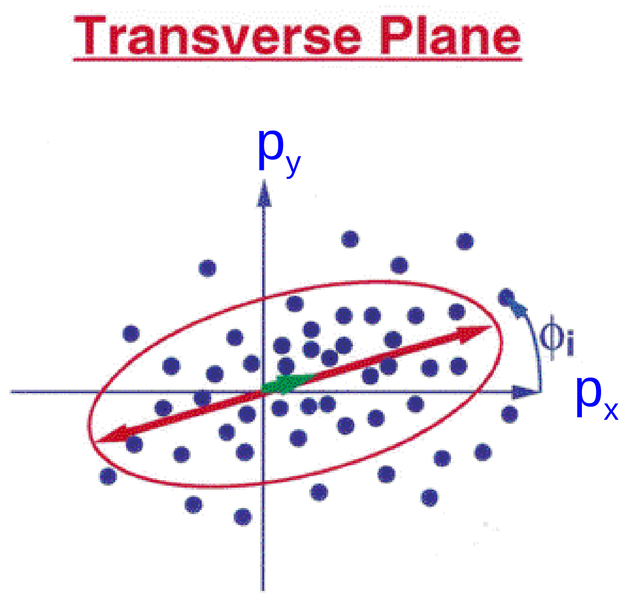
spatial anisotropy ε_2

↓ ↓

momentum anisotropy v_2

Flow Vector

Sum of vectors of all the particles



$$\Psi_{plane} = \tan^{-1}\frac{\sum \sin(\phi_i)}{\sum \cos(\phi_i)}$$

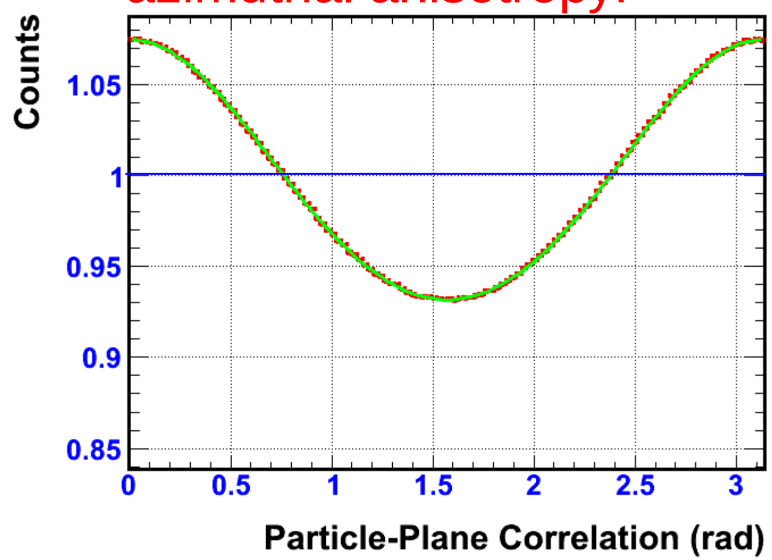
$$2\,\Psi_{ellipse} = \tan^{-1}\frac{\sum \sin(2\phi_i)}{\sum \cos(2\phi_i)}$$

For each harmonic n:

$$\mathbf{Q} = \sum_{\nu=1}^{N} \omega_\nu \, \mathbf{p}_{t;\,\nu}$$

Q is a 2D vector
for odd harmonics $w_i(-y) = -w_i(y)$

azimuthal anisotropy:



S. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996)

Fourier Harmonics

$$1 + 2v_1 \cos(\phi - \Psi_{RP}) + 2v_2 \cos[2(\phi - \Psi_{RP})] + \cdots$$

directed flow (v_1) — elliptic flow (v_2) — reaction plane (Ψ_{RP})

$$v_n = \langle \cos[n(\phi_i - \Psi_{RP})] \rangle$$

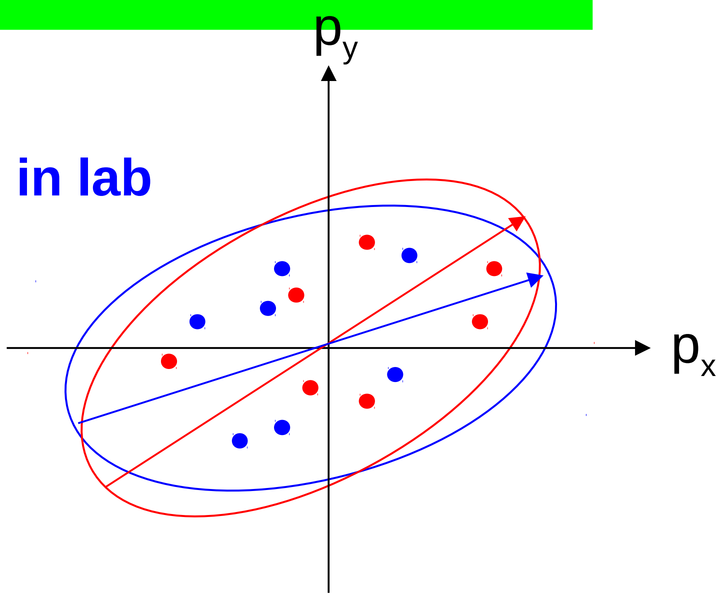
- angle of Q-vector, ψ_n, is experimental event plane angle
- ψ_{RP} is real reaction plane angle
- event plane resolution tells how well the event plane angle approximates the reaction plane angle:

$$res \equiv \langle \cos(n(\Psi_n - \Psi_{RP})) \rangle$$

S. Voloshin and Y. Zhang, hep-ph/940782; Z. Phys. C **70**, 665 (1996)
See also, J.-Y. Ollitrault, arXiv nucl-ex/9711003 (1997)
and J.-Y. Ollitrault, Nucl. Phys. **A590**, 561c (1995)

Standard Event Plane Method

- **Define 2 independent groups of particles**
- **Flatten event plane azimuthal distributions in lab**
  - **to remove acceptance correlations**
- **Correlate subevent planes:**



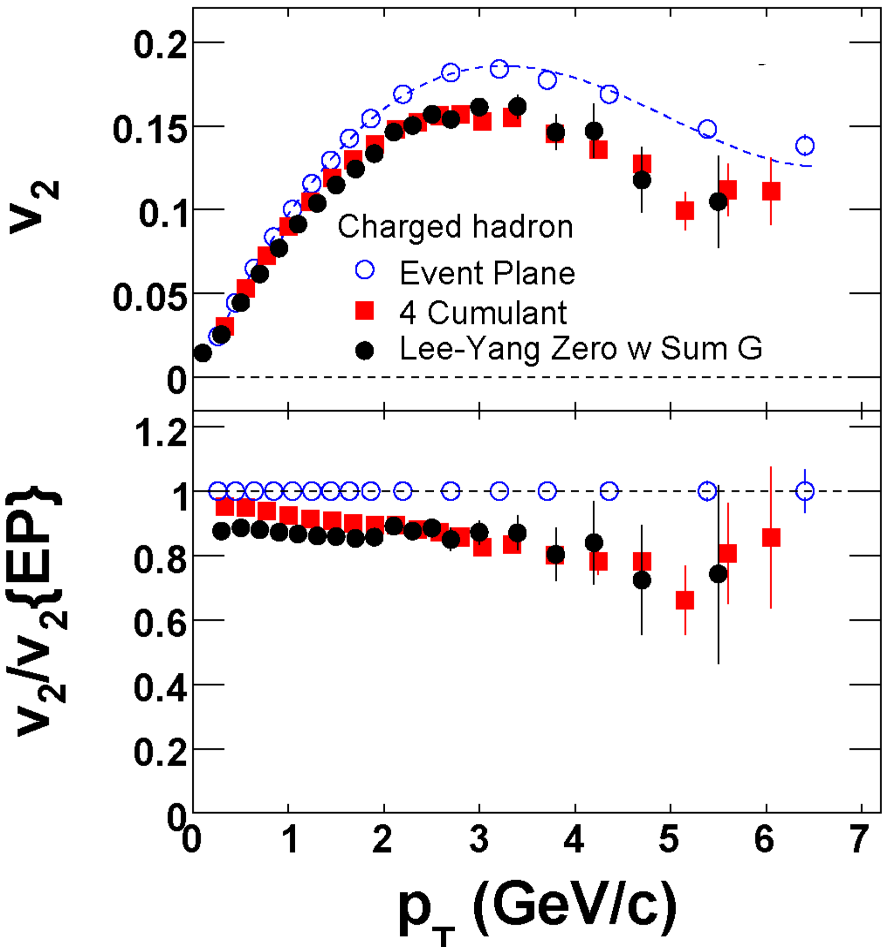
- **Subevent plane resolution is the square root of this correlation**
- **Event plane resolution (res) is √2 times subevent plane resolution**
- **Correlate particles with the event plane to get v_n^{obs}**
- **Correct for the event plane resolution** $v_n(\eta, p_t) = v_n^{obs}/res$

- **Average differential $v_n(\eta,p_t)$ over η, p_t, or both (with yield weighting)**

A.M. Poskanzer and S.A. Voloshin, PRC **58**, 1671 (1998)

Non-Flow Effects

Non-flow effects are correlations not associated with the reaction plane.
(They include resonance decays, 2-particle small angle correlations, and jets of particles.)



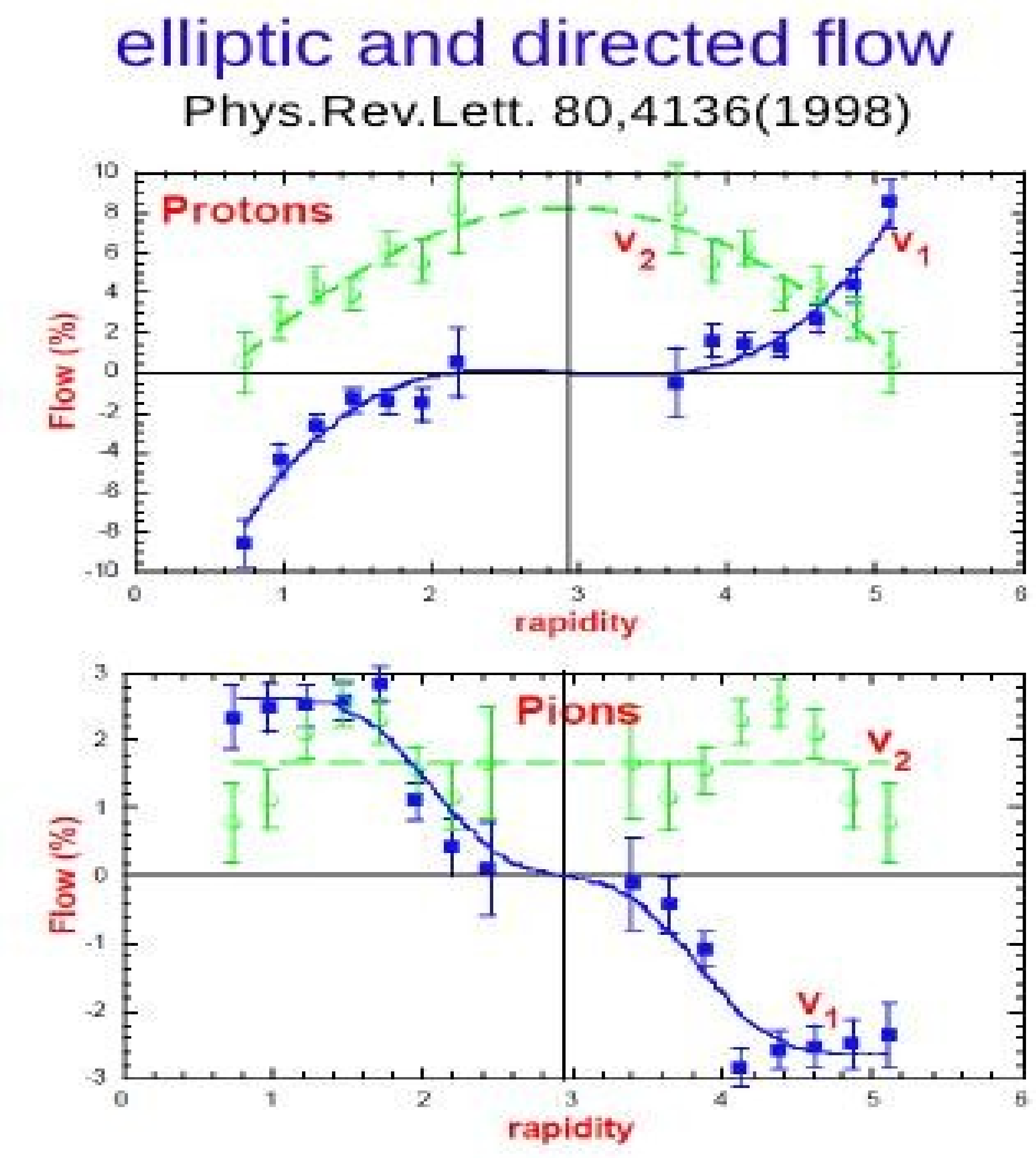
Momentum conservation!

Non-flow effects are caused by few-particle correlations

Multi-particle methods remove non-flow.

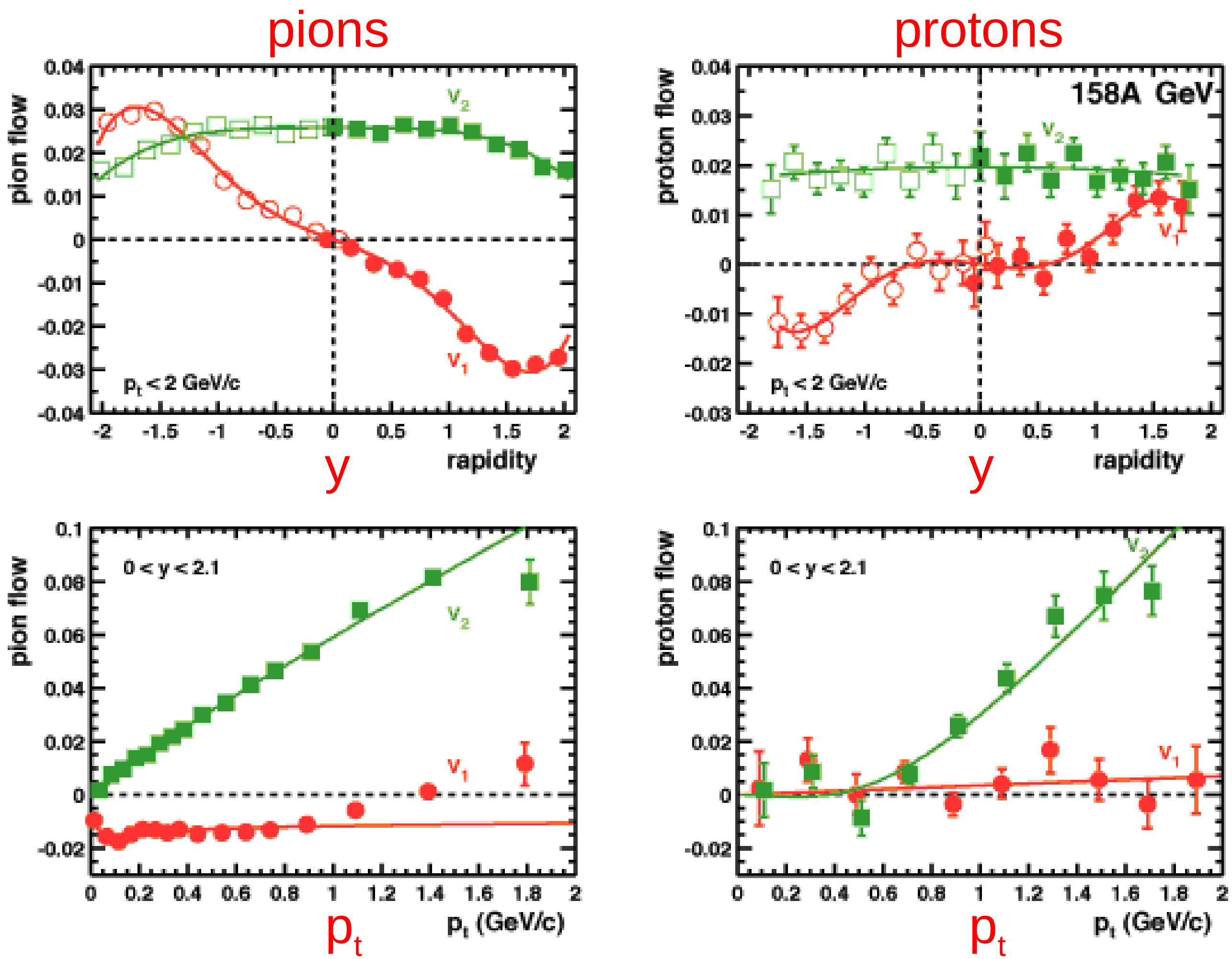
STAR, B.I. Abelev et al., arXiv:0801.3466; PRC, submitted (2008)

Directed and Elliptic Flow at the SPS (NA49)



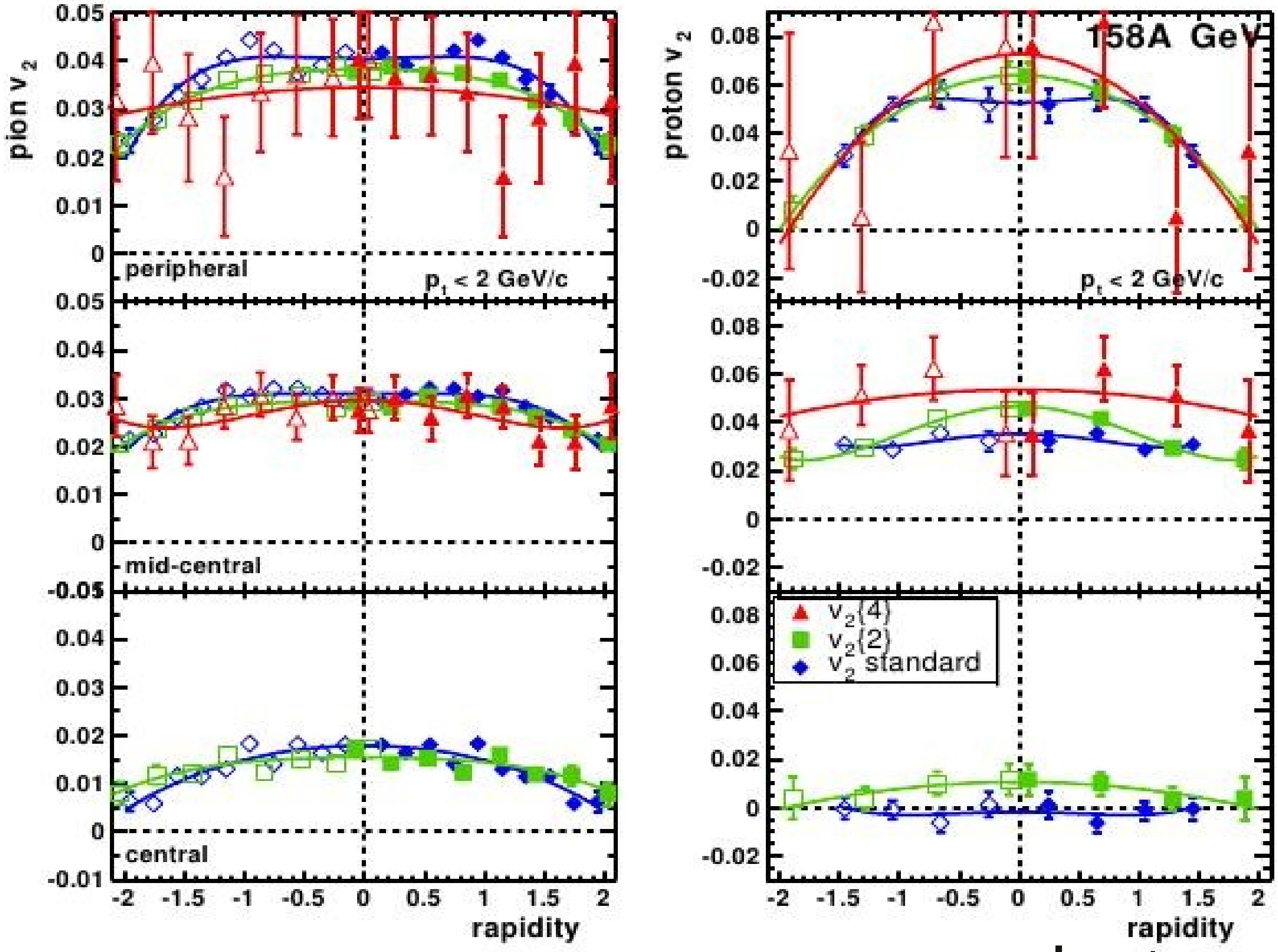
Directed and Elliptic Flow at the SPS (NA49)

y = relativistic velocity along beam direction
p_t = transverse momentum



NA49, C. Alt et al., PRC **68**, 034903 (2003)

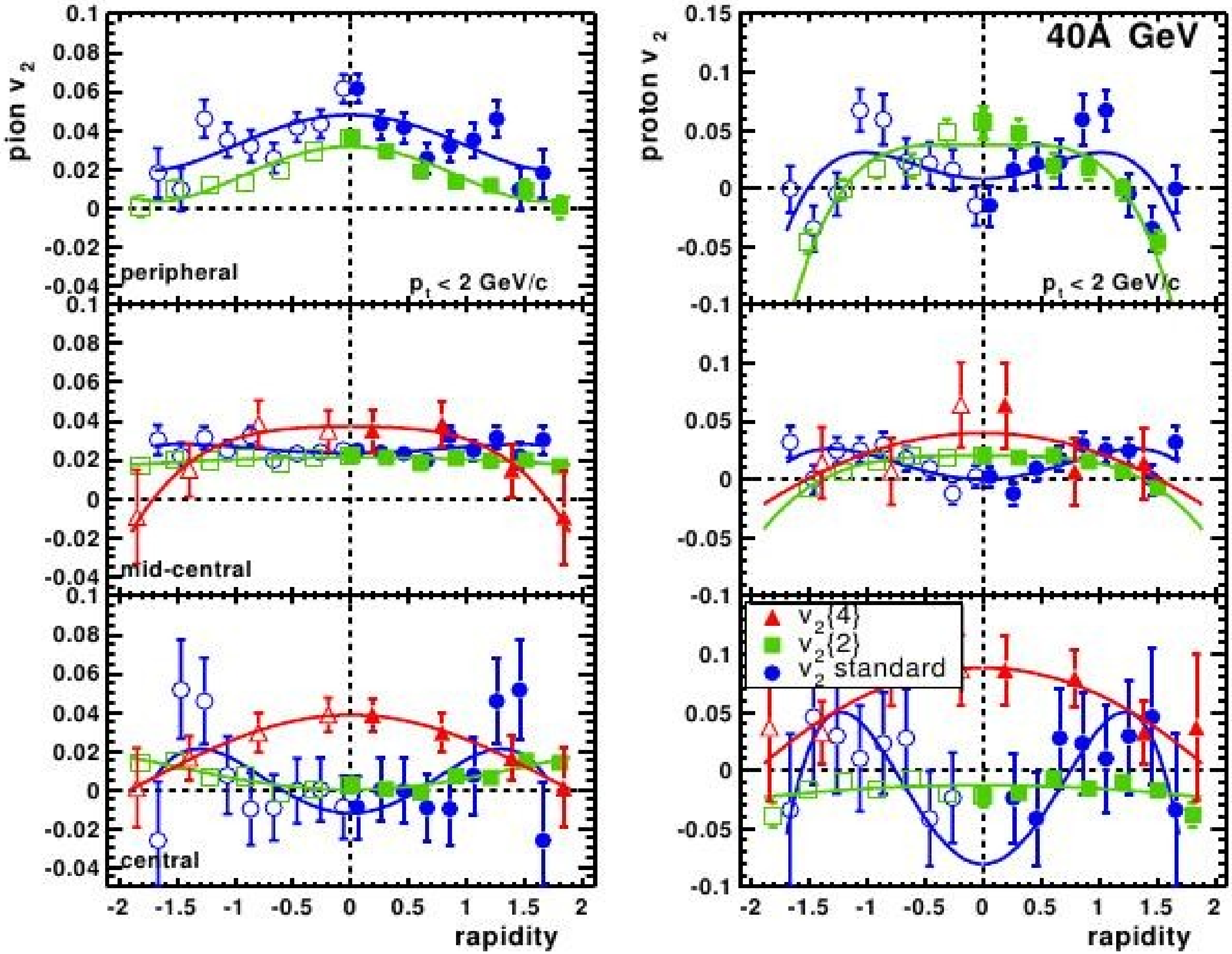
Directed and Elliptic Flow at the SPS (NA49)



NA49, C. Alt et al., PRC **68**, 034903 (2003)

cumulants

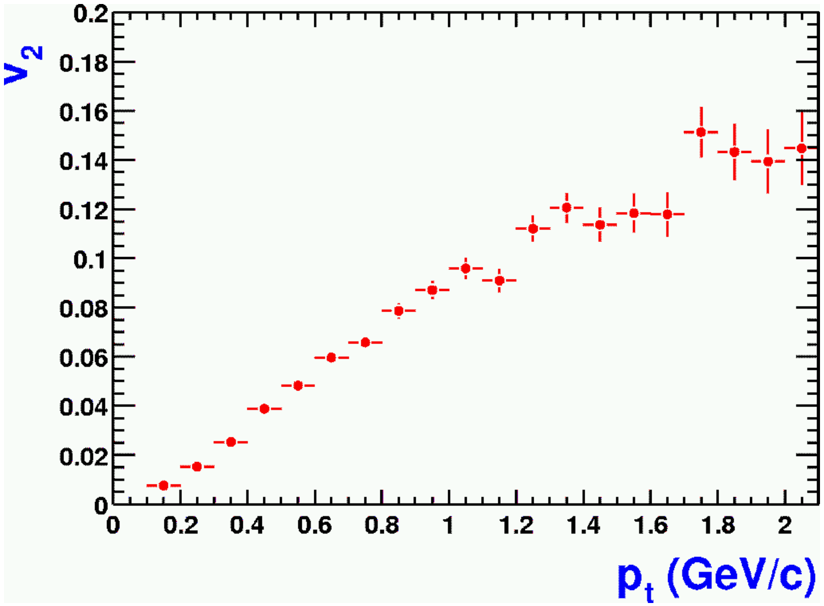
Directed and Elliptic Flow at the SPS (NA49)



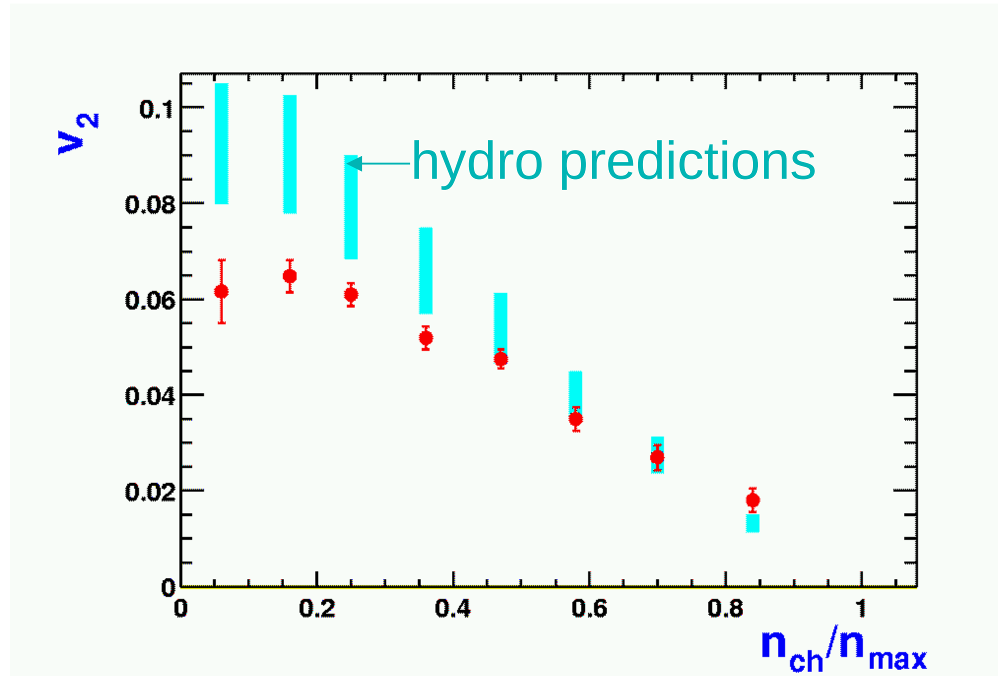
NA49, C. Alt et al., PRC **68**, 034903 (2003)

cumulants

Discovery of Elliptic Flow at RHIC



First paper from STAR
22 k events



peripheral ⟶ central

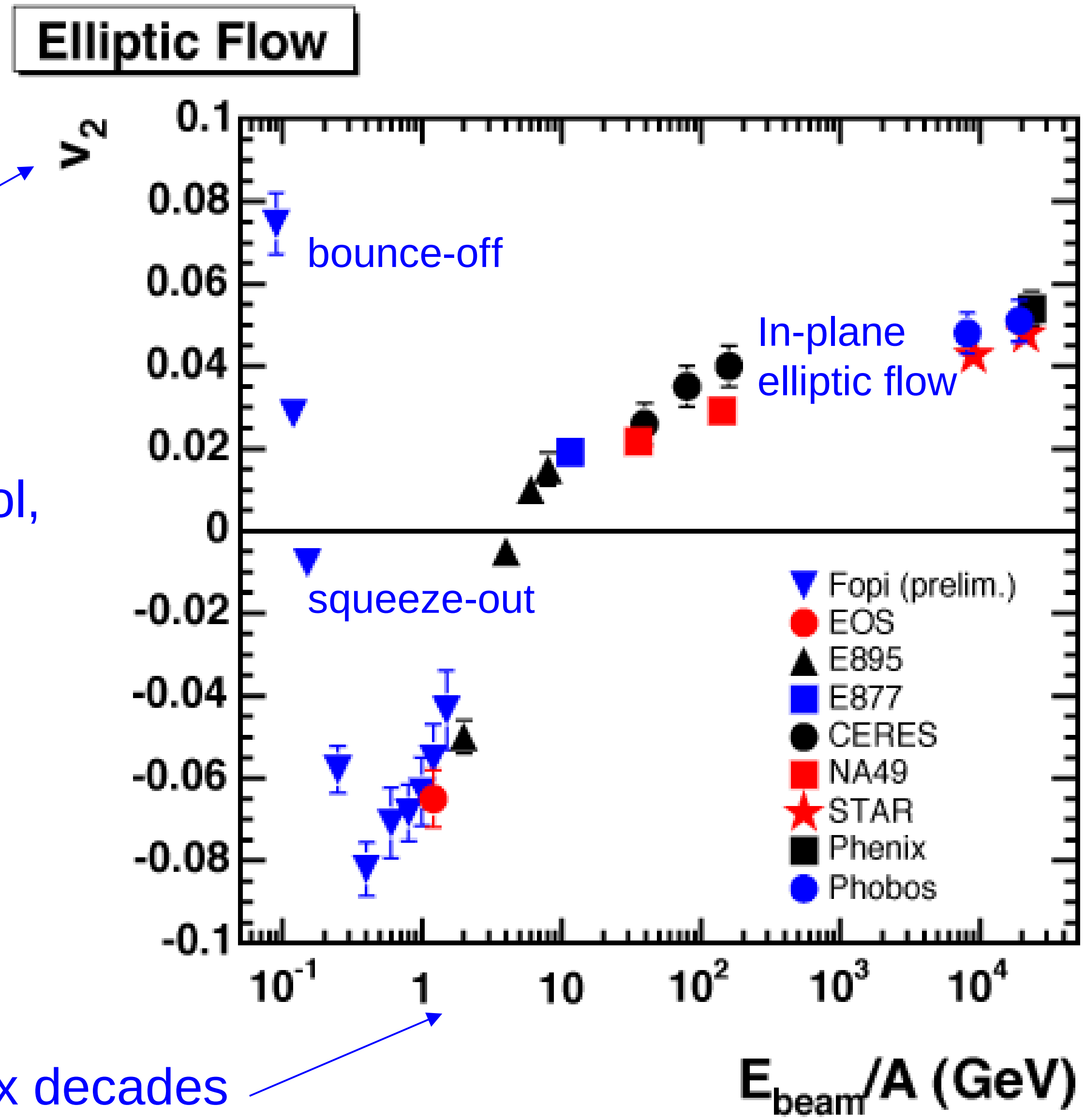
Significant that data approach hydro
for central collisions
Was not true at lower beam energies

STAR, K.H. Ackermann et al., PRL **86**, 402 (2001)

Elliptic Flow vs. Beam Energy

25% most central
mid-rapidity

all v_2 {EP}



powerful, widely-used tool,
to study EOS of
nuclear matter

six decades

A. Wetzler (2005)