Directed & Elliptic Flow & Delta++ Production in 158 A GeV Pb + Pb Collisions

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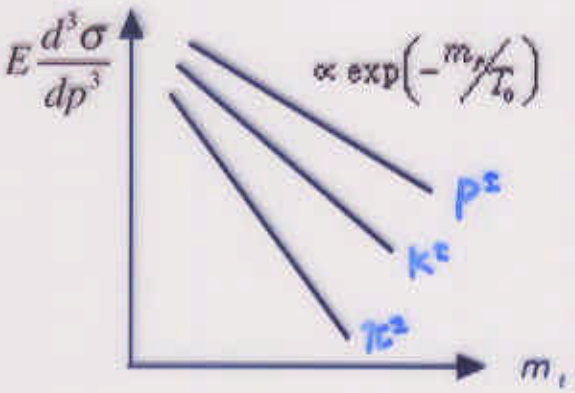
- Hadron Production in AA
- WA98 Experiment
- Delta Production
- Flow Analysis
- Directed Flow at target rapidity
- Azimuthal distribution at mid-rapidity
- Summary

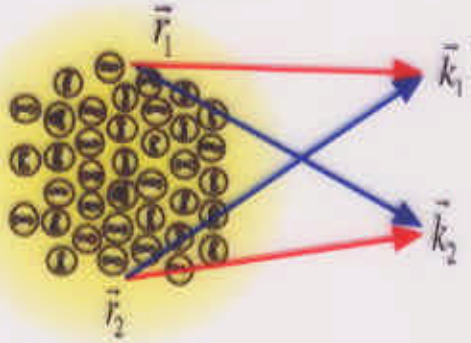
Hadron Production in AA

Distinct Features



$$P = 1 + \cos(\vec{q} \cdot \vec{r})$$

$$\begin{cases} \vec{q} = \vec{k}_1 - \vec{k}_2 \\ \vec{r} = \vec{r}_1 - \vec{r}_2 \end{cases}$$



$T \sim T_0 + m\langle\beta\rangle^2$

$R \sim R_0 \, (T_0/m_T\langle\beta\rangle^2)^{1/2}$

- **1) Single Particle Spectra**

  Exponential in mt as is in pp-pA

  Slope parameters proportional to the mass in AA, while same in pp-pA

- **2) HBT Correlations**

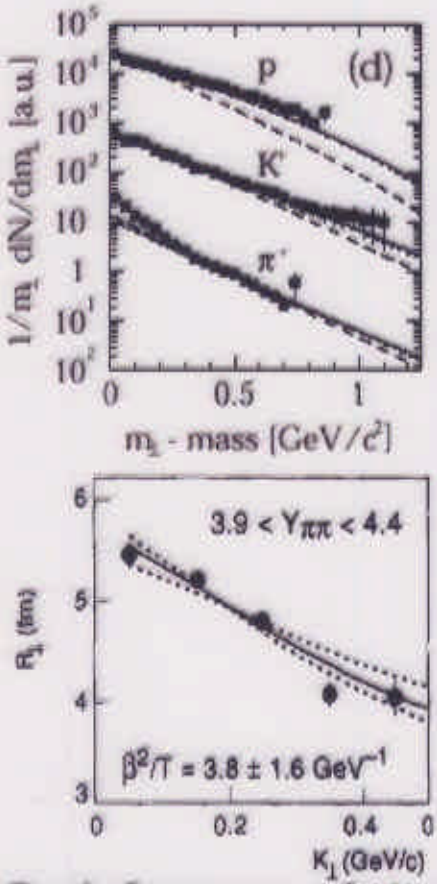
  Measurements support creation of large pion gas

  Depend on relative momentum (k_1-k_2)

  Clear dependence on the pair momentum (k_1+k_2) observed

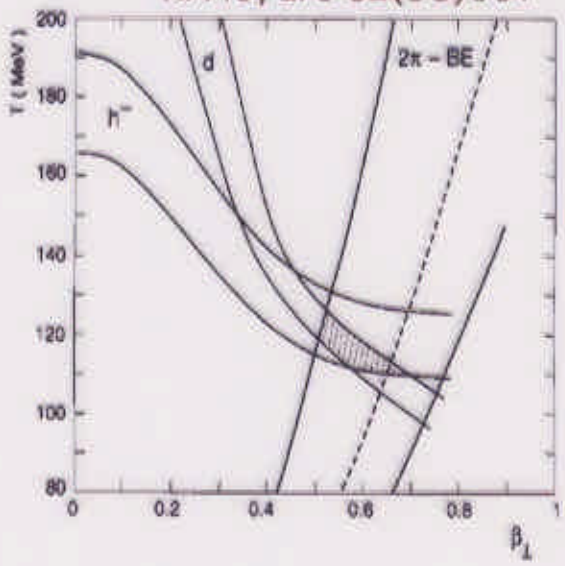
- **Success of Expanding Fireball Model**

Success of Expanding Fireball Model



SPS

NA49, EPJ C2(98)661



- **Both features of single particle & HBT corr. explained by Expanding Fire Ball Model!**

  Blue Shift ; not necessarily high temp but rapid flow.

  One set of (β , T) explains all

- **Next Issues;**

  Low mt region in pion claimed as contribution from delta's.

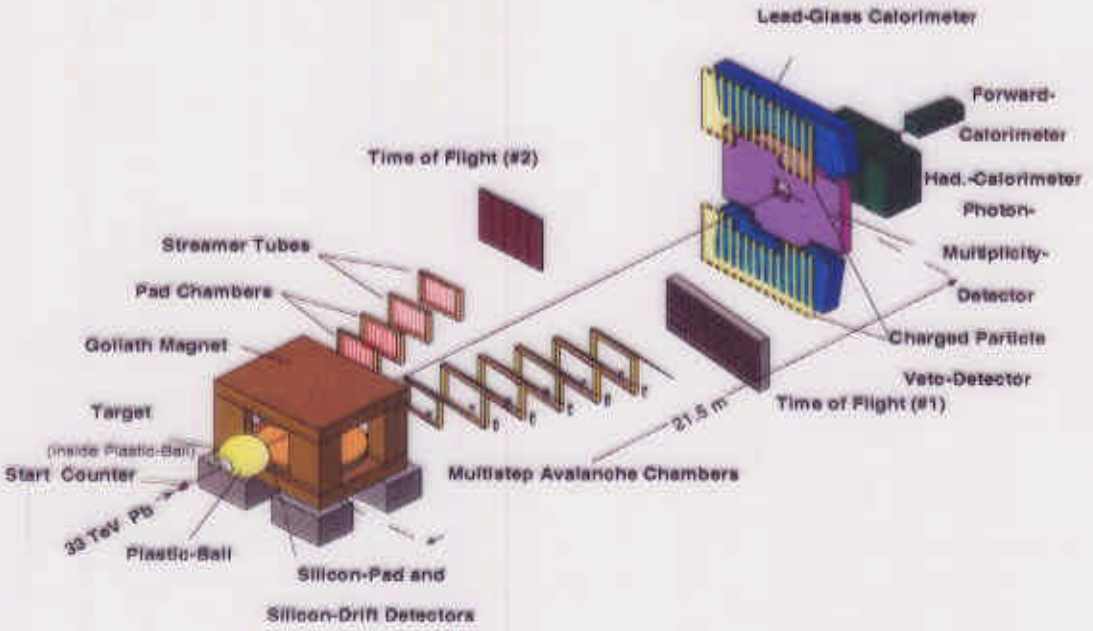
  ➡Direct measurement of Delta++

  Importance of radial flow has been well demonstrated

  ➡Other mode of collective flow

WA98 Experiment

From photons to charged hadrons



20 Institutes

- University of Geneve,
- GSI Darmstadt,
- INS Warsaw,
- IOP Bhubaneswar,
- University of Jammu,
- JINR Dubna,
- KVI Groningen,
- University of Lund,
- MIT Cambridge,
- University of Muenster,
- NPI Rez,
- ORNL Oak Ridge,
- University of Panjab,
- University of Rajasthan,
- RRC (Kurchatov) Moscow,
- SUBATECH Nantes,
- University of Tenessee Knoxville,
- University of Tsukuba,
- University of Utrecht, and
- VECC Calcutta

- **Selected topics;**

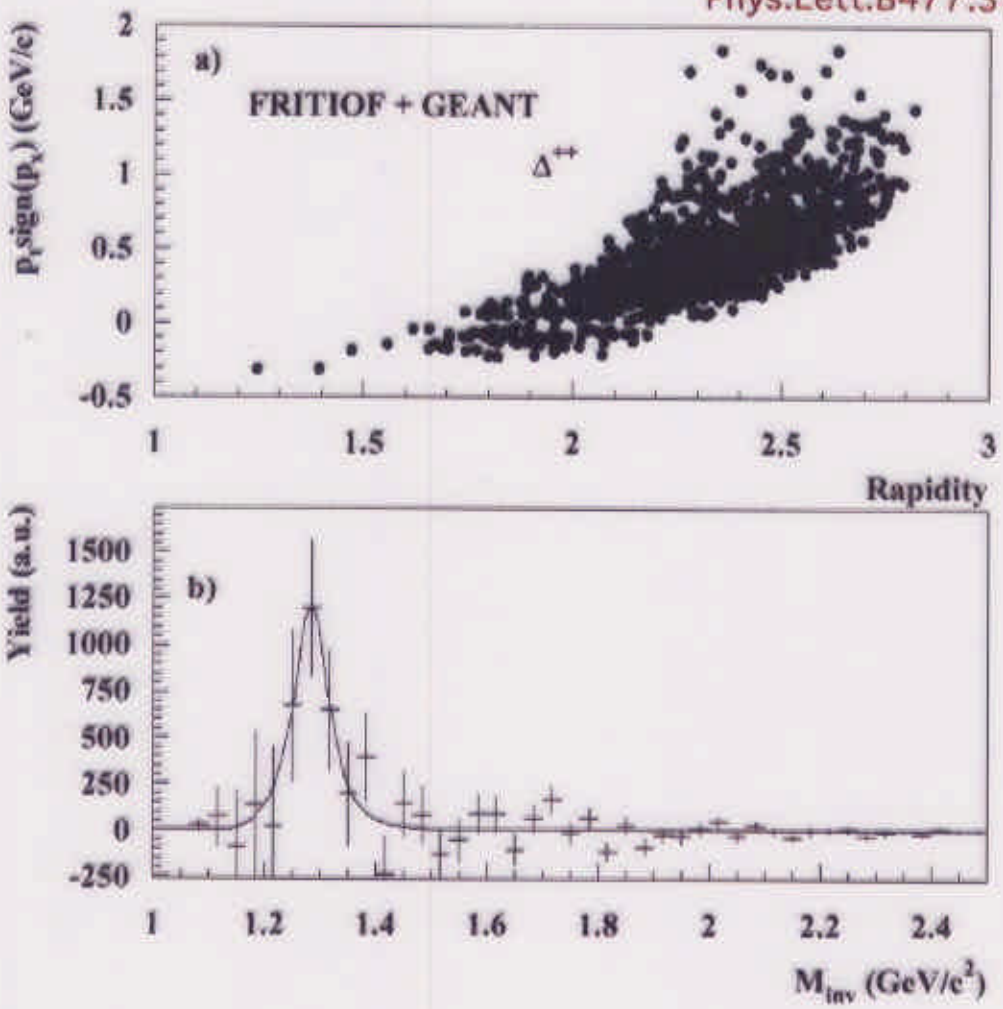
  Delta Production

  Directed and Elliptic Flow Analysis

Delta Production

$\Delta^{++} \rightarrow p + \pi^+$

Phys.Lett.B477:37,2000



- Proton and pion simultaneously detected with magnetic spectrometer

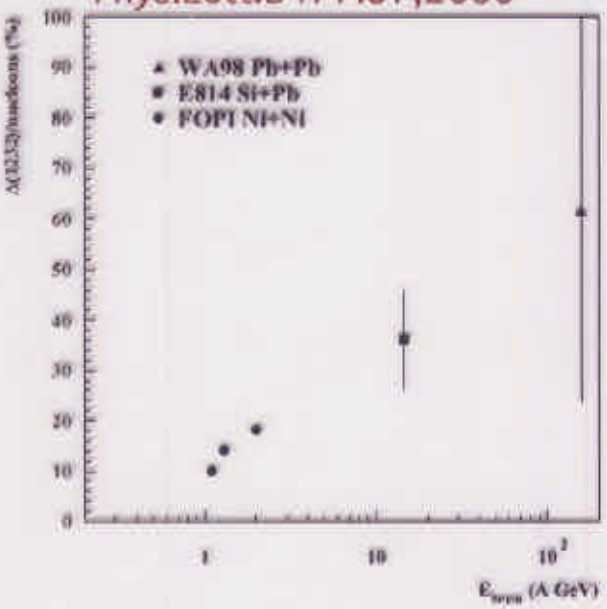
  Evaluate combinatorial background with mixed events

- First measurement at SPS heavy ion
- Results

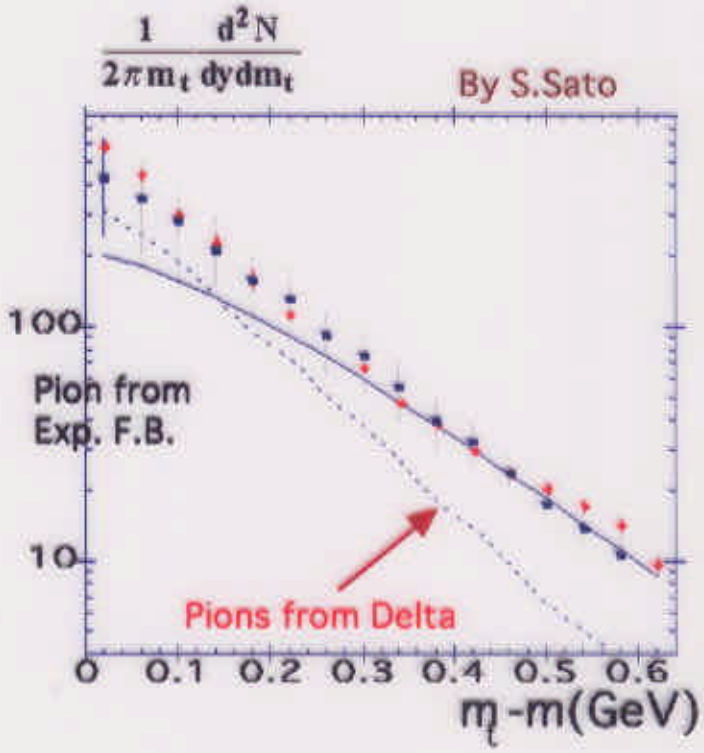
Results

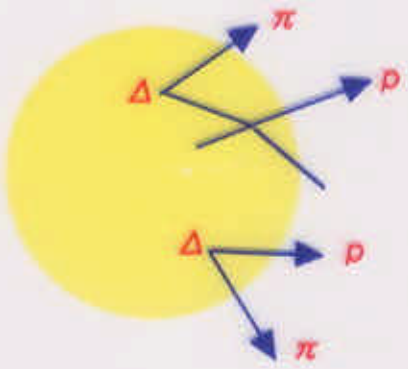
Large error bars due to combinatorial backgrounds

Phys.Lett.B477:37,2000



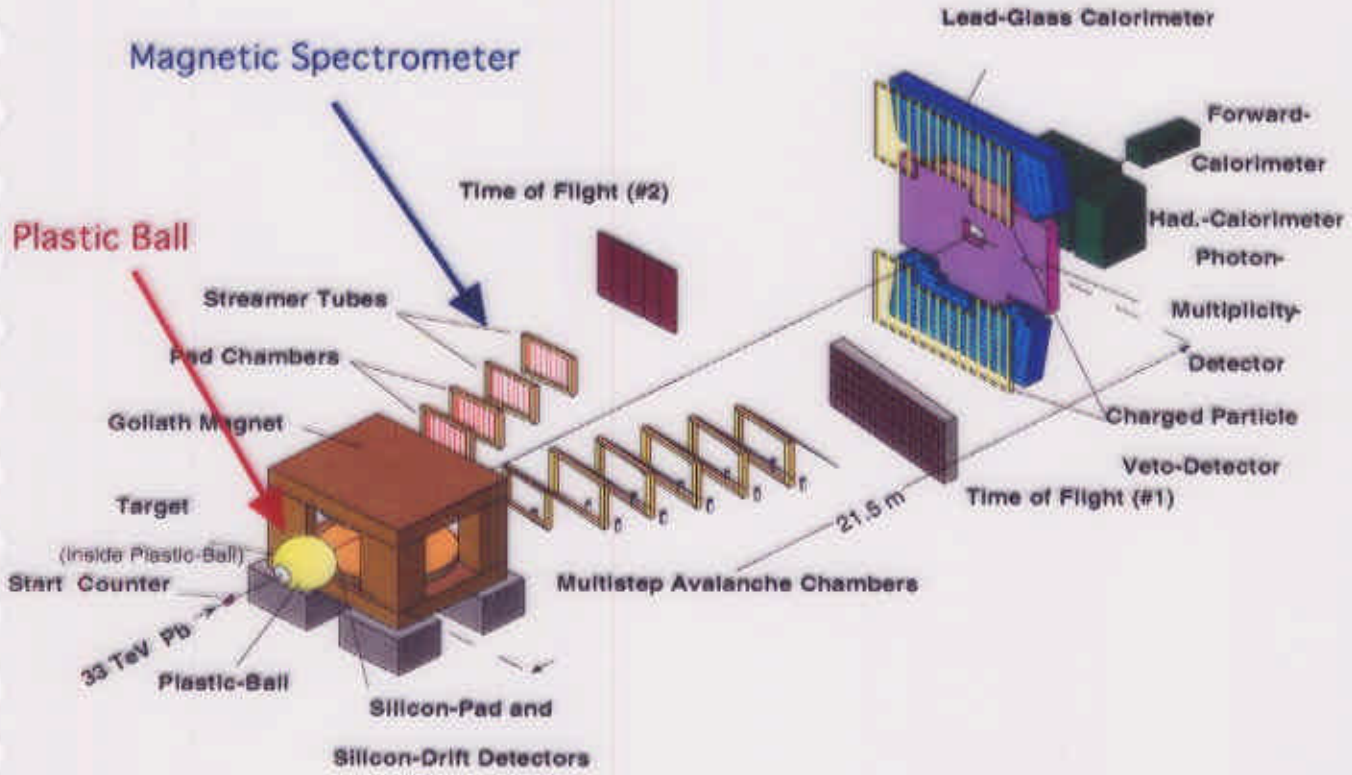
By S.Sato

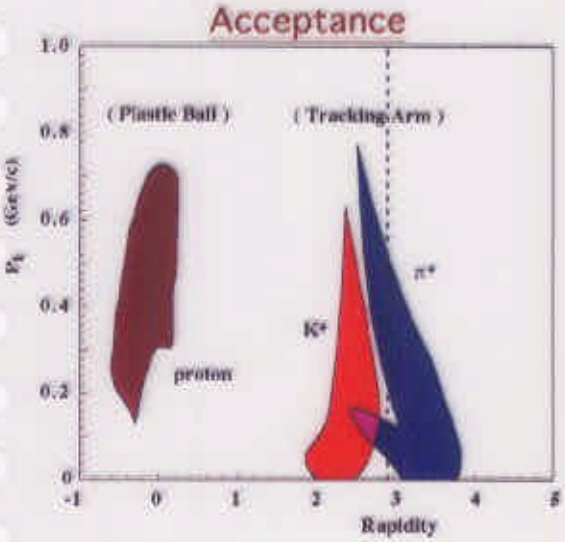




- **Comparison with lower energies**
  - Consistent with gradual increase
- **Effect on low pt pions**
  - Evaluate pions from observed delta production with the help of intra nuclear cascade model
  - Delta as major contribution to low pt enhancement

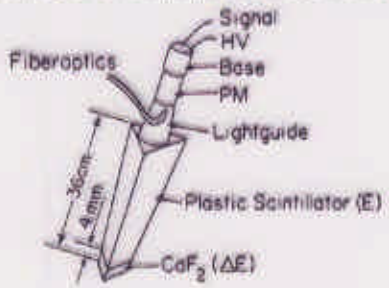
Flow Analysis





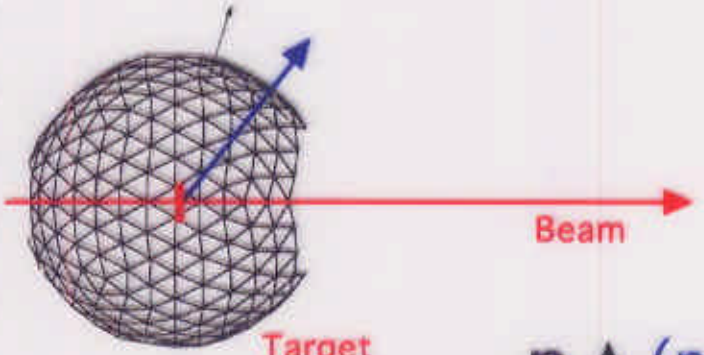
- **Features of WA98 Flow Analysis**
  - Azimuthal Correlation among particles w PID
    - Plastic Ball Detector; ΔE-E & delayed signal for π+
    - Spectrometer ; Time-of-Flight
- **Analysis of Plastic Ball**
- **Protons & Pions at target rapidity**

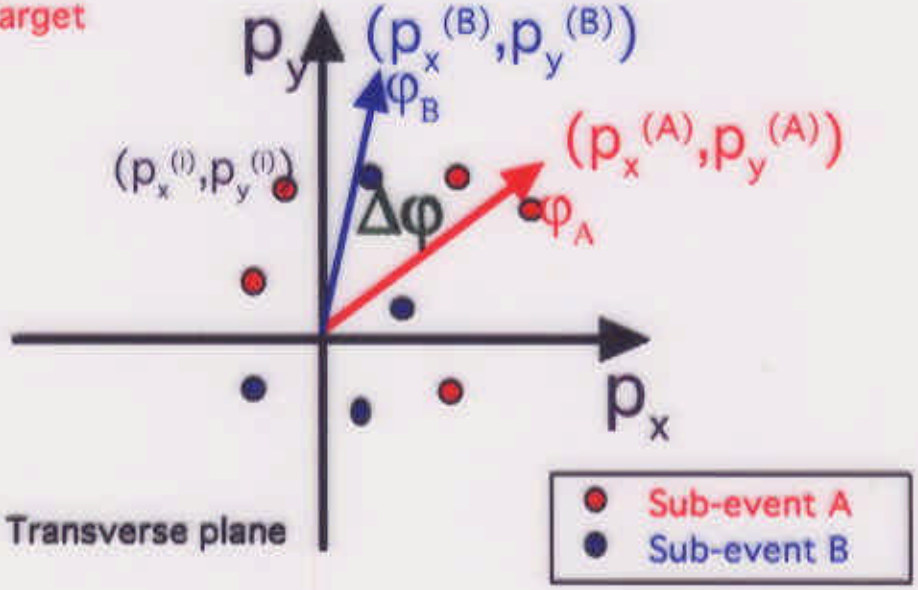
Analysis of Plastic Ball



Full azimuthal Coverage
at target rapidity ($-1.7 < \eta < 0.5$)

$$\Phi_0 = \tan^{-1}\left(\frac{\sum_{i=1}^{N} p_{T_i}\sin(\phi_i)}{\sum_{i=1}^{N} p_{T_i}\cos(\phi_i)}\right)$$





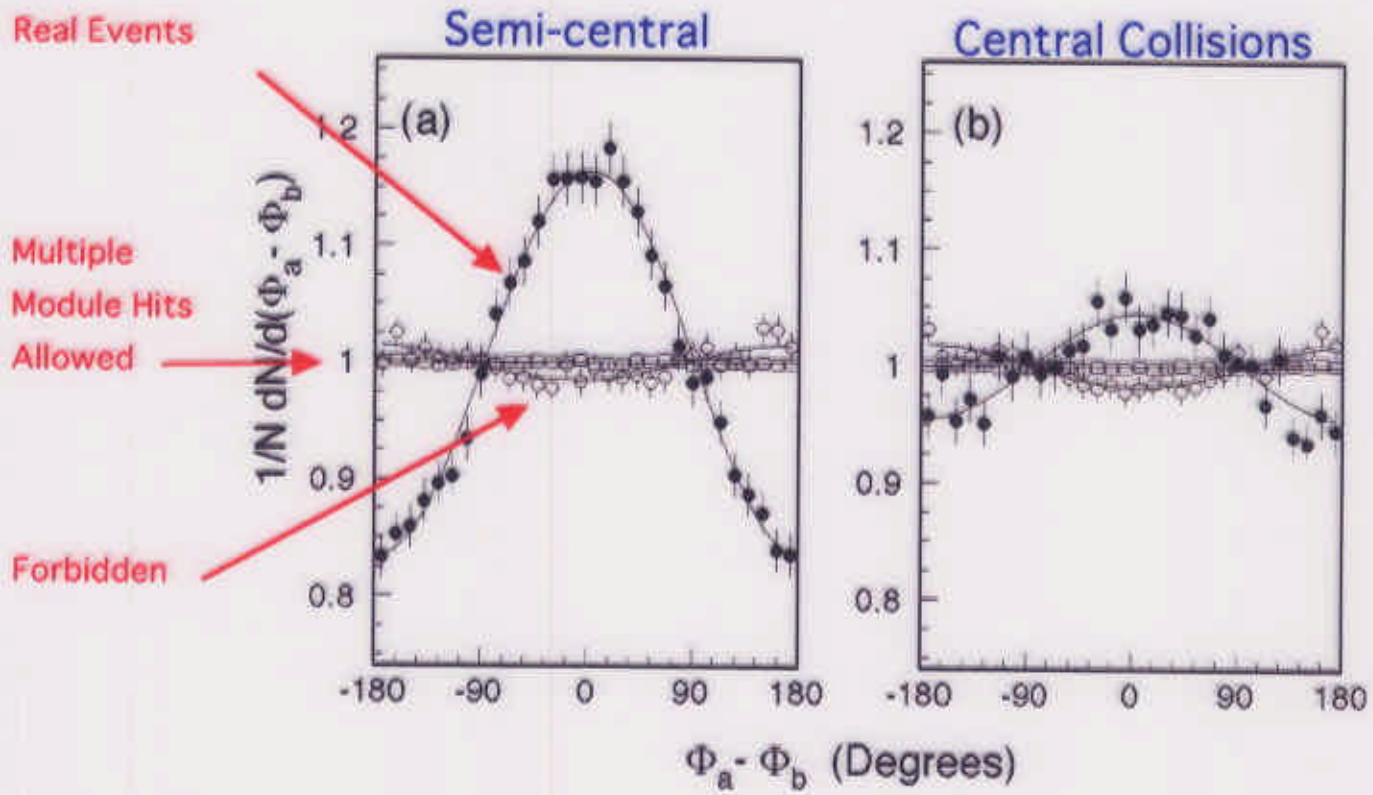
- In each event, fragments (p,d,t) are randomly categorized into two groups.

  Obtain the flow angle in each sub-event and look for the correlation

- Sub-event Analysis for Real & Mixed

Sub-event Analysis for Real & Mixed

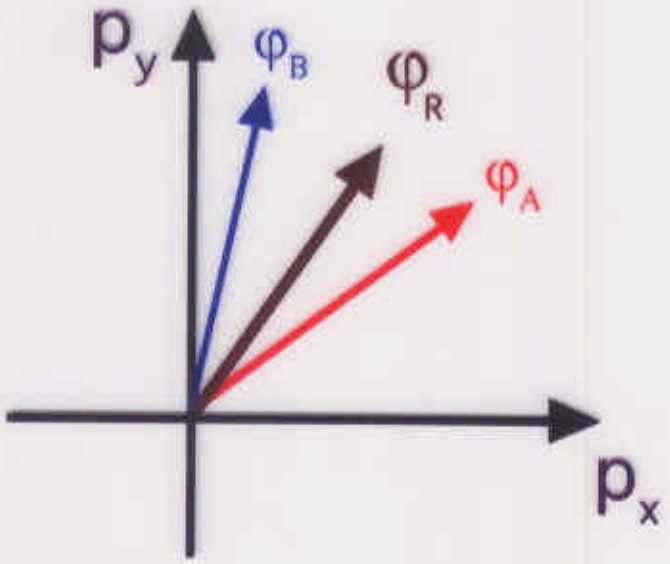
Reference of azimuthal angle



- In Real events, clear azimuthal asymmetry observed.
- Two type of mixed events;
  - Multiple module hits allowed
    - ➡Flat
  - Multiple module hits forbidden
    - ➡Weak anti-correlation due to excluded-module effect
- ➡Fragments (p,d,t) have preferred direction for their emission at target rapidity.
  - Resolution of reference determination also studied
    - Resolution of the Reaction Plane

→ Define Φ_0 as opposite to the total transverse momentum vector at P.B.

Resolution of the Reaction Plane



φ_R	Real Reaction Plane
φ_A	From sub-event A
φ_B	From sub-event B
φ_{A+B}	From whole event (A+B)

- The flow angle fluctuates around the real value due to the statistics

$$\cos(\phi_a - \phi_b) = \cos[(\phi_a - \phi_R) - (\phi_R - \phi_b)]$$
$$= \cos(\phi_a - \phi_R)\cos(\phi_R - \phi_b) - \sin(\phi_a - \phi_R)\sin(\phi_R - \phi_b)$$

Since $\overline{\sin(\phi_a - \phi_R)\sin(\phi_R - \phi_b)} = 0$

$$\overline{\cos(\phi_a - \phi_b)} = \overline{\cos(\phi_a - \phi_R)\cos(\phi_R - \phi_b)}$$
$$= \left(\overline{\cos(\phi_a - \phi_R)}\right)^2$$

$$\overline{\cos(\phi_a - \phi_R)} = \sqrt{\overline{\cos(\phi_a - \phi_b)}}$$

$$\overline{\cos(\phi_{A+B} - \phi_R)} = \sqrt{2} \cdot \sqrt{\overline{\cos(\phi_a - \phi_b)}}$$

Method proposed by A.M. Poskanzer & S.A. Voloshin, (PRC58,1671(1998)) →

$$\langle \cos(\Phi_0 - \Phi_R) \rangle = 0.360 \pm 0.018$$
$$\langle \cos(2(\Phi_0 - \Phi_R)) \rangle = 0.084 \pm 0.005$$

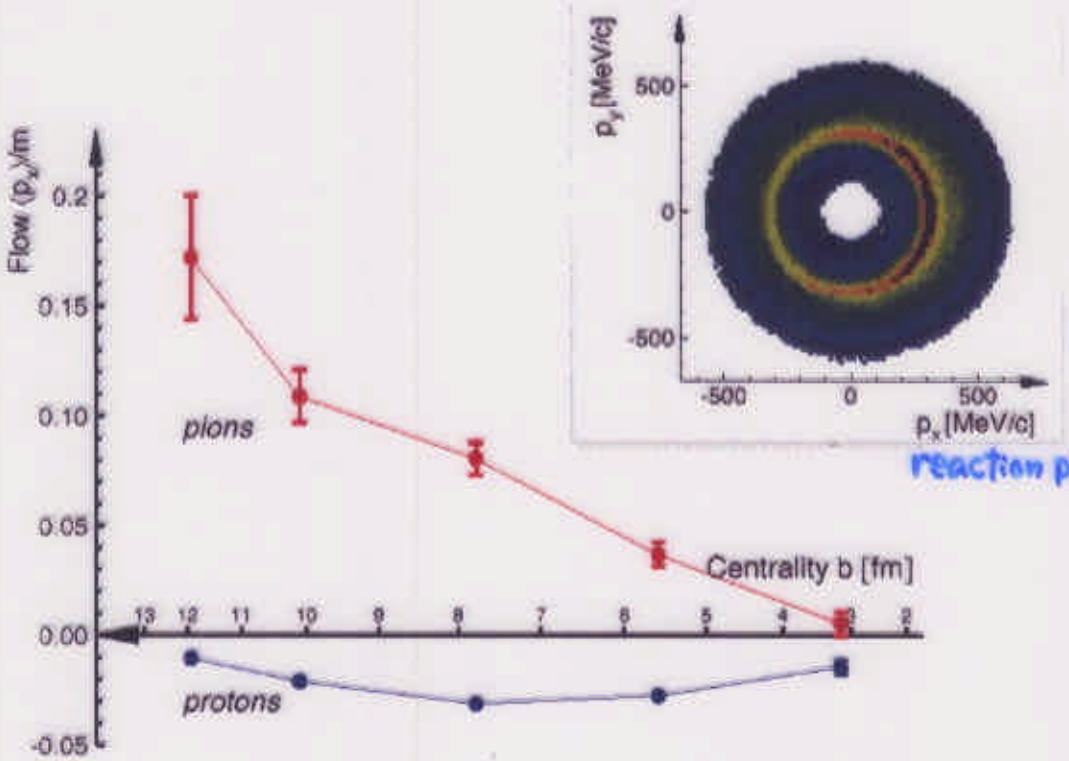
at semi-central col.

From observed ; $\frac{1}{N}\frac{dN}{d(\phi - \Phi_0)} = 1 + 2v_1' \cos(\phi - \Phi_0) + 2v_2' \cos(2(\phi - \Phi_0))$

$$v_n = \frac{v_n'}{\langle \cos(n(\Phi_0 - \Phi_R)) \rangle} \qquad \langle p_x' \rangle = \langle p_x \rangle \cdot \langle \cos(\Psi_0 - \Psi_R) \rangle$$

Protons & Pions at target rapidity

Rotate the event by Φ_0 to obtain (px, py)



reaction plane coord.

- Round pt distribution, but the center of pt is shifted

  Large v1, Small v2

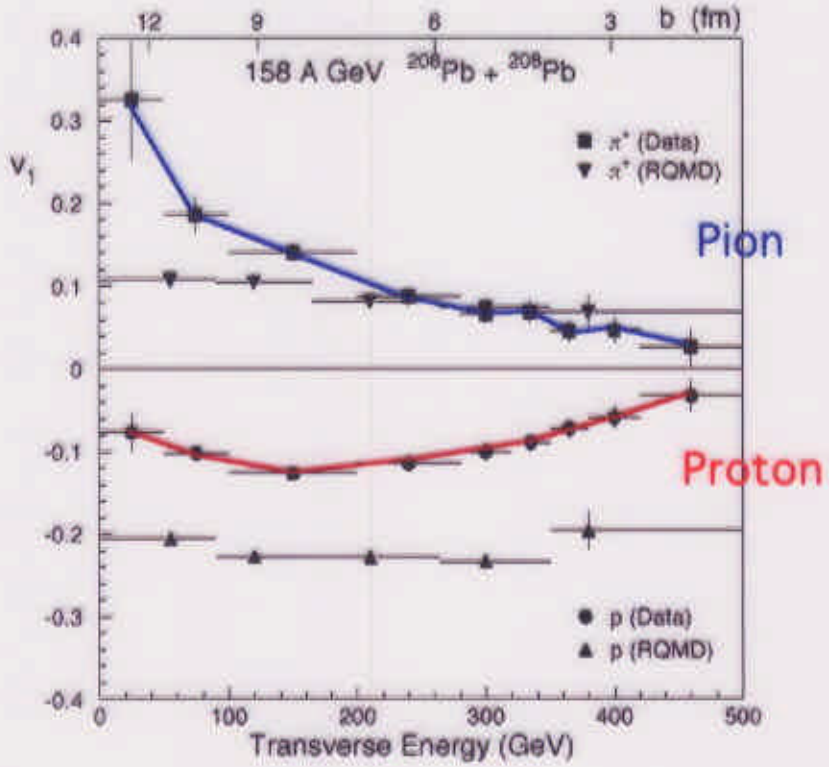
  protons and pions are anti-correlated at target rapidity

- Study Fourier expansion of azimuthal distributions

$$F(\phi) = F_0\left\{1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right\}$$

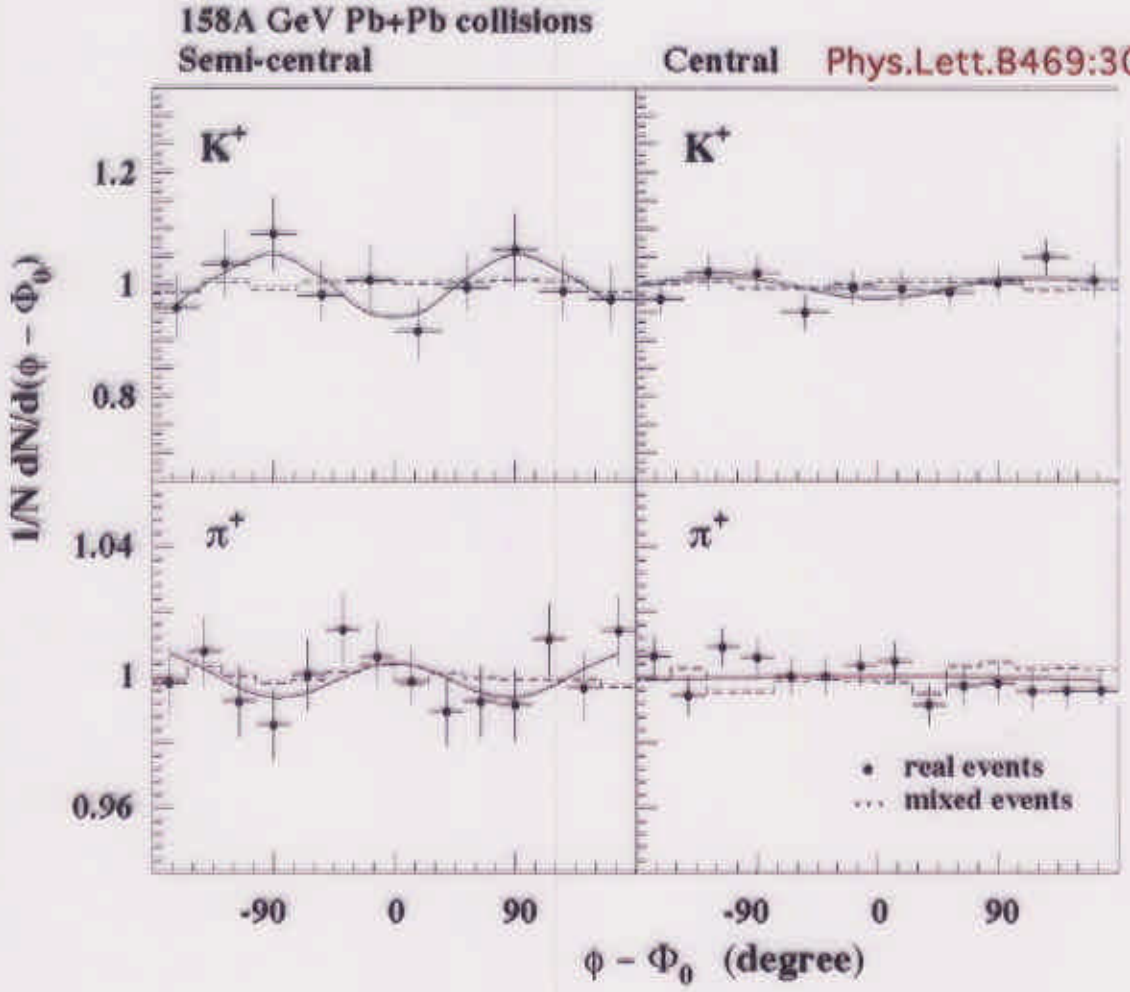
Directed Flow — Elliptic Flow

Directed Flow at target rapidity



- Centrality determined by transverse energy in MIRAC
- Protons show their peak in mid-central collisions (b~8fm), while pions in most peripheral.
  - Protons ; consistent with directed flow
  - Pions ; absorption by the spectator (Larger absorption in more peripherals)
- Qualitative agreement with RQMD
  - RQMD 2.3 (cascade) overpredicts protons by a factor of >2, while at AGS underestimates!?

Azimuthal distribution at mid-rapidity



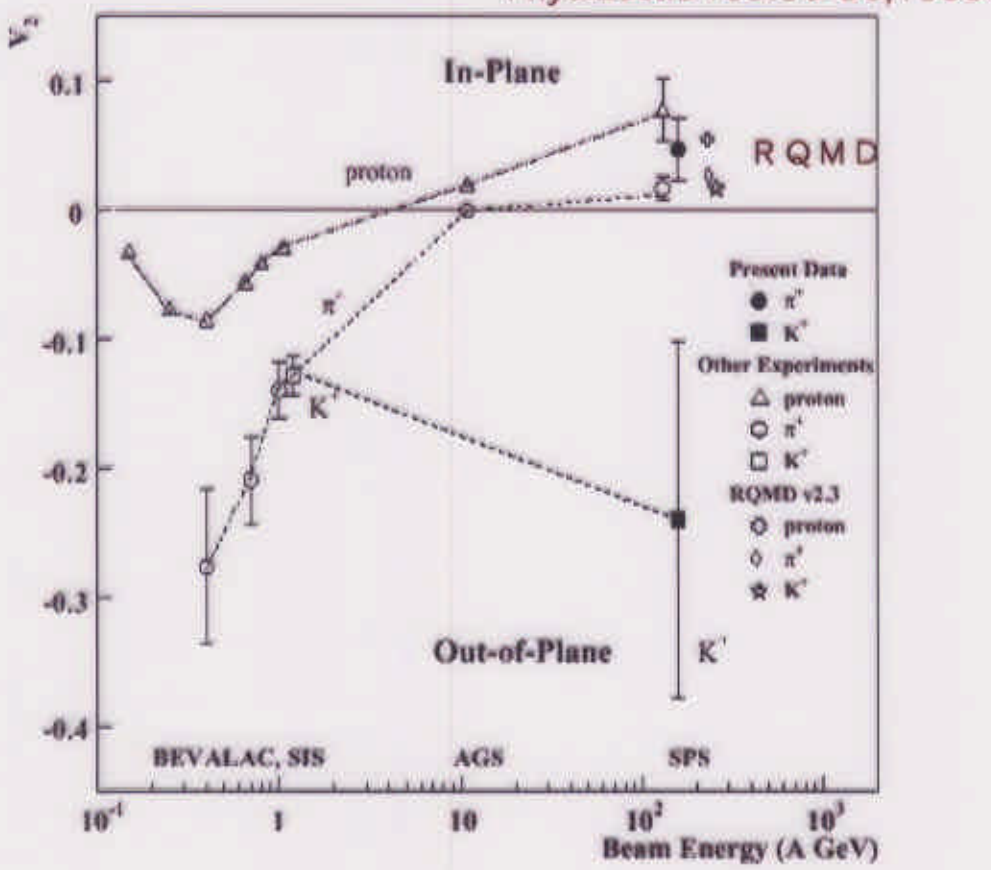
	y	v1	v2
K+	2.2 - 2.8	- 0.004 +/- 0.031	- 0.24 +/- 0.14
π+	2.4 - 3.4	- 0.010 +/- 0.006	0.047 +/- 0.024

- π+; maxima at 0 and ±180 deg
  - Enhanced emission in R.P.
  - In-plane elliptic emission
- K+; maxima at ± 90 degrees
  - Enhanced emission out of the R.P.
  - Out-of-plane elliptic emission
- Beam energy dependence

Beam energy dependence

v2 values observed at around mid-rapidity

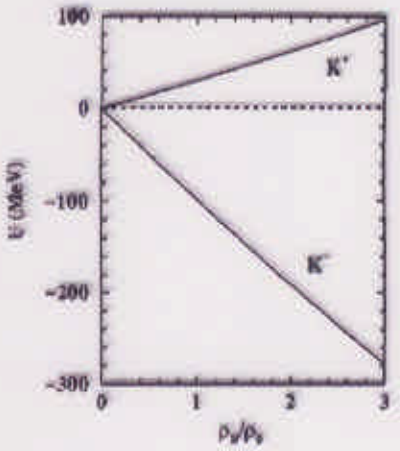
Phys.Lett.B469:30-36,1999



- For proton & pions, transition from out-of-plane to in-plane emission
  - Our pi+ agrees with NA49 data within errors.
- Agreement with RQMD except for K+
- K+ ; Out of Plane, similar to SIS
  - Note for the erro; 1.7 σ separation from zero; 95% C.L.
  - K+ at SPS exhibit out-of-plane similar to 1 A GeV Au+Au.
- Toy Model

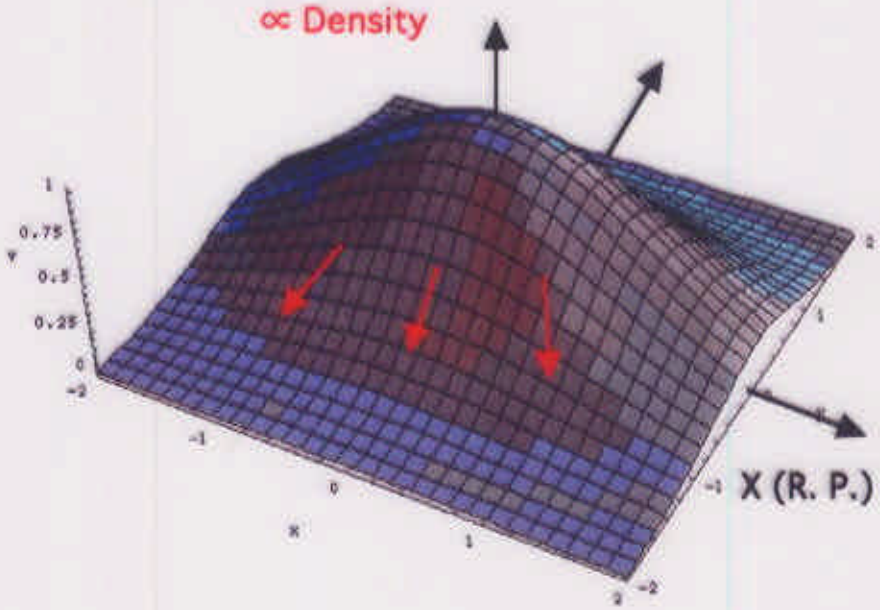
Toy Model

Effect of repulsive K+ N potential proportional to density !?

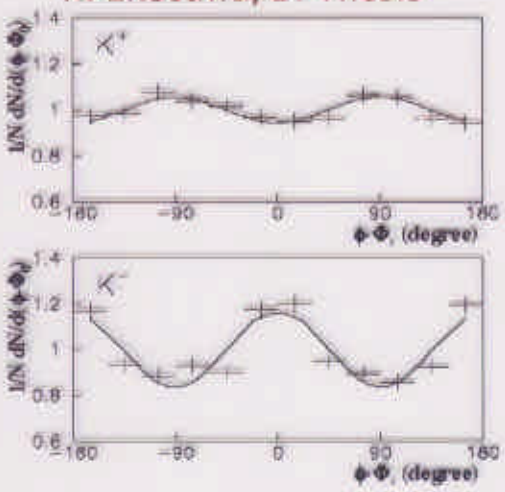


K+n Potential

∝ Density



K. Enosawa, D. Thesis



- **Assumptions**
  - Elliptic nucleon distribution at freeze out (RQMD)
  - K-n potential proportional to density
  - Propagate K+ through potential
- **Right tendency obtained**
  - ➡ K+ emission in out-of-plane
  - ➡ K- emission in plane

Summary

- Δ^{++}

  $\Delta^{++} \rightarrow p + \pi^{+}$ measured as a first time at SPS heavy ion

- **Directed flow at target rapidity region measured for protons, pions.**

  The effect is largest for impact parameter ~8 fm which is considerably more peripheral than observed at AGS.

  RQMD cascade overestimates by a factor of 2 at SPS, while at AGS underestimated.

- **Elliptic flow near mid-rapidity observed for pi+ and K+.**

  First observation of K+ flow at SPS.

  K+ preferentially emitted perpendicular to the reaction plane, while pions and protons are emitted in the reaction plane.

  RQMD reproduces ellipticity of proton and pions, but failed for K+.

  Additional ingredient such as in-medium potential may be needed for K+.