Laying the groundwork at the AGS: Recent results from E895

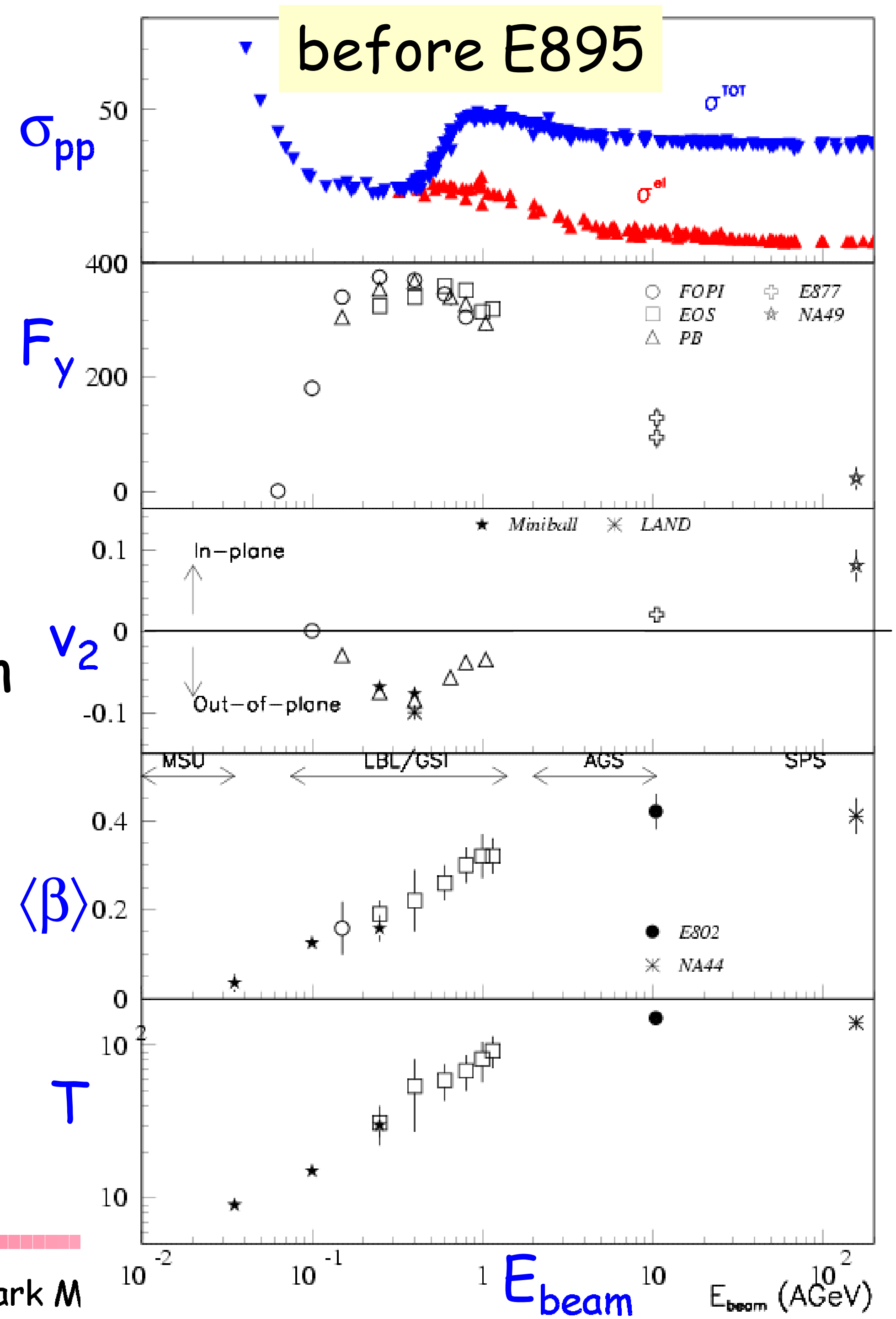
Mike Lisa, for the E895 Collaboration

N.N. Ajitanand, J. Alexander, D. Best, P. Brady, T. Case, B. Caskey, D. Cebra, J. Chance, P. Chung, B. Cole, K. Crowe, A. Das, J. Draper, S. Gushue, M. Gilkes, M. Heffner, H. Hiejima, A. Hirsch, E. Hjort, L. Huo, M. Justice, M. Kaplan, J. Klay, D. Keane, J. Kintner, D. Krofcheck, R. Lacey, J. Lauret, E. LeBras, M. Lisa, H. Liu, Y. Liu, B. McGrath, Z. Milosevich, D. Olson, S. Panitkin, C. Pinkenburg, N. Porile, G. Rai, H.-G. Ritter, J. Romero, R. Scharenberg, L. Schroeder, B. Srivastava, N. Stone, J. Symons, S. Wang, R. Wells, J. Whitfield, T. Wienold, R. Witt, L. Wood, X. Yang, Y. Zhang, W. Zhang

Auckland - BNL - CMU - Columbia - UC Davis - Harbin - KSU - LBL - St. Mary's College - OSU - Purdue - Stony Brook

Reminder: why AGS is (still) interesting

- sets baseline systematics
  "your systematics deviate from what?"
- the "other" extreme condition
  - maximum baryon density
  - probe medium & bulk effects
- transition region for bulk properties



This talk

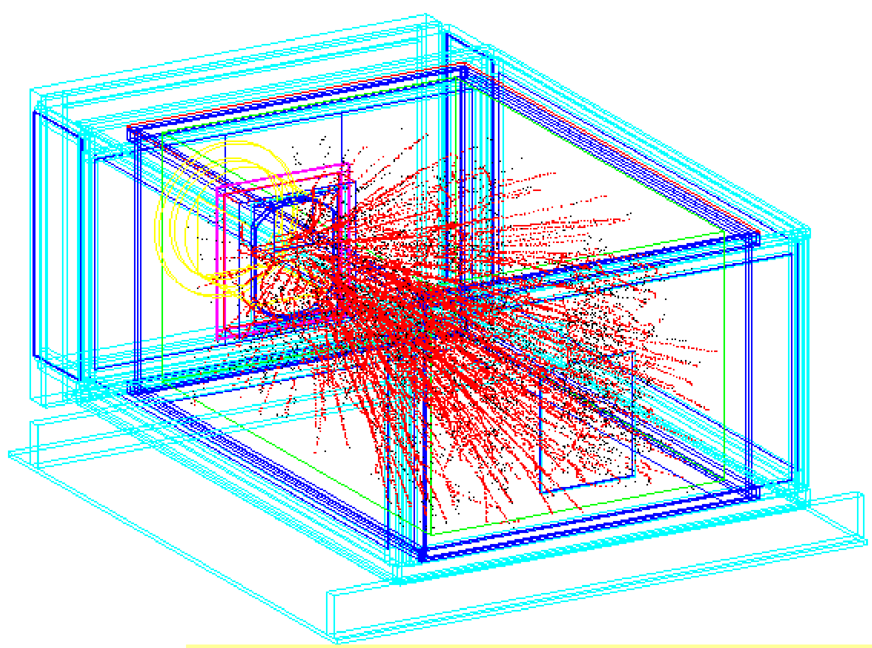
Not a "final wrap-up" of E895, which is still alive. Since QM99:

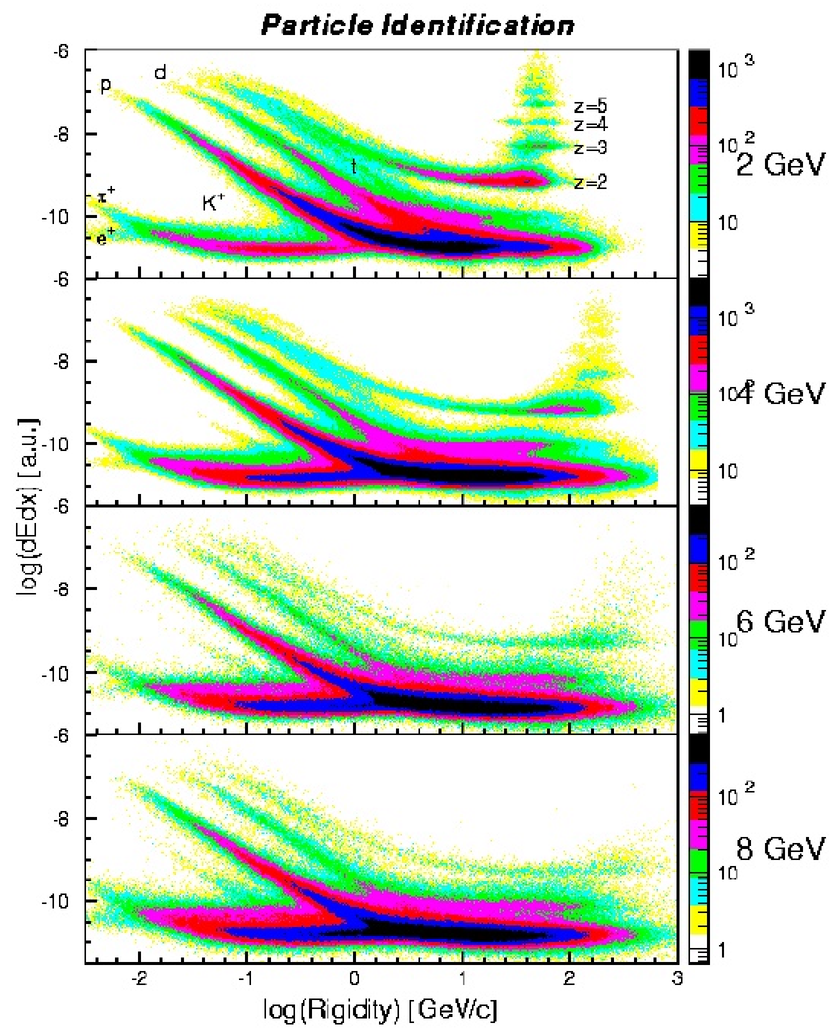
- PRL **83** 1295 (1999) — Transition from out-of-plane to in-plane elliptic flow
- PRL **84** 2798 (2000) — Bombarding energy dependence of π^- HBT at the AGS
- PRL **84** 5488 (2000) — Sideward flow in Au+Au collisions at 2-8 AGeV
- PRL **85** 940 (2000) — Anti-flow of K^0 mesons in 6 AGeV Au+Au collisions
- PLB **496** 1 (2000) — Azimuthal dependence of pion interferometry
- PRL accepted (2000) — Λ flow in 2-6AGeV Au+Au collisions

- Published E895 flow
- Beyond proton flow - collective flow of strange particles
- Geometrical dependence of flow
- HBT Beyond "R_π = 5 fm"
  - geometric aspects of collective flow
  - 6D phasespace density
  - Λ-p correlations
- Summary

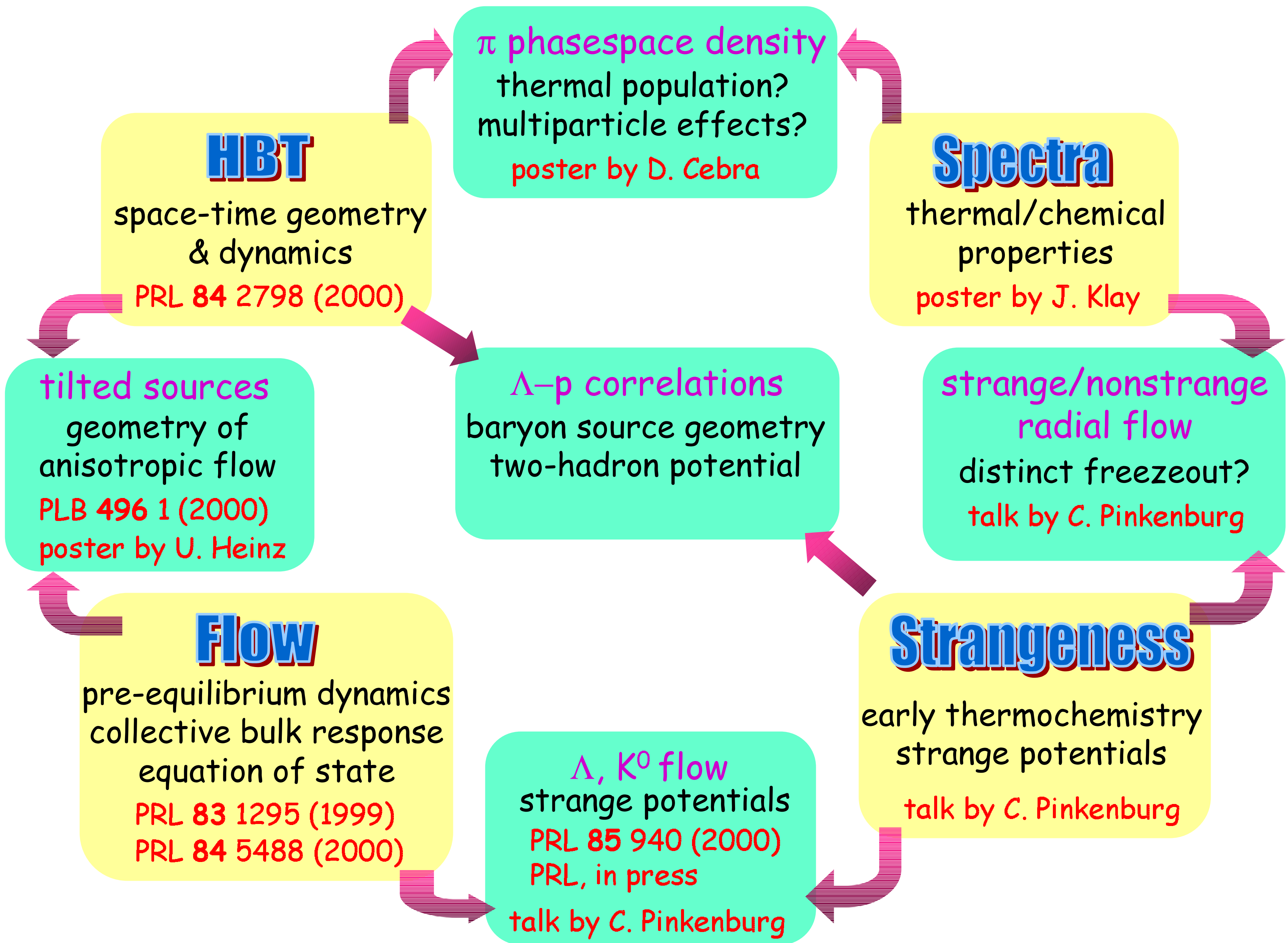
Measurement with the EOS TPC

- Up to ~350 particles/event measured over large phase space
- Good reaction plane resolution
- $\delta p/p \approx 3\%$ (dominated by MCS)





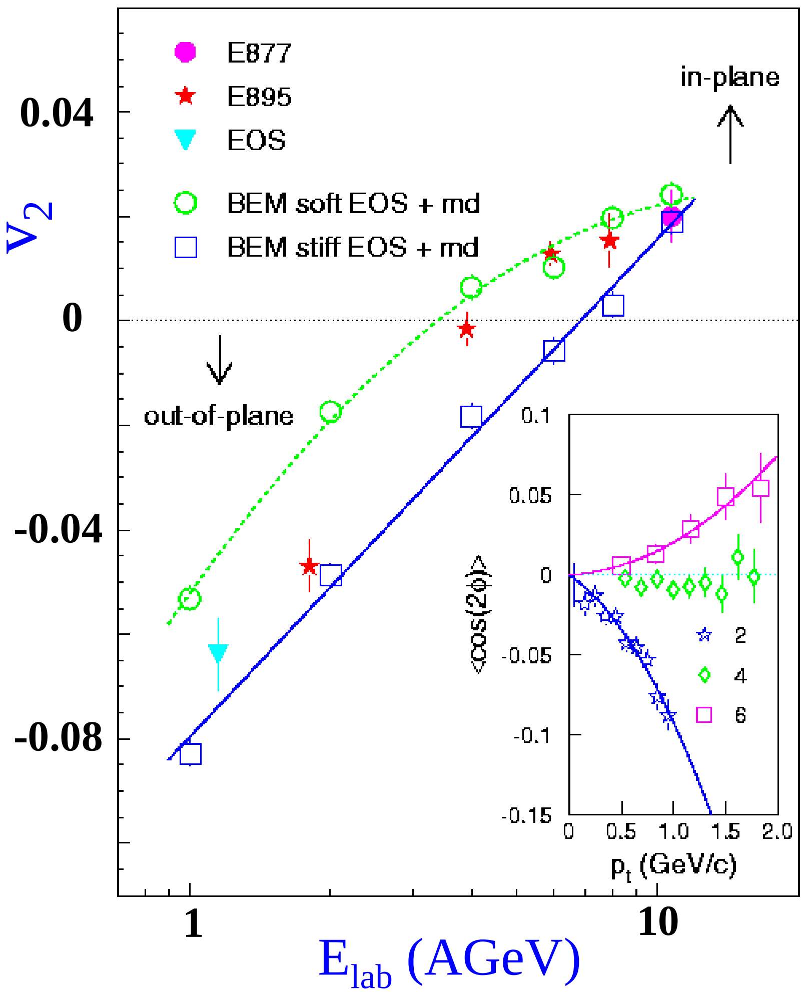
"Grandfather of STAR TPC"

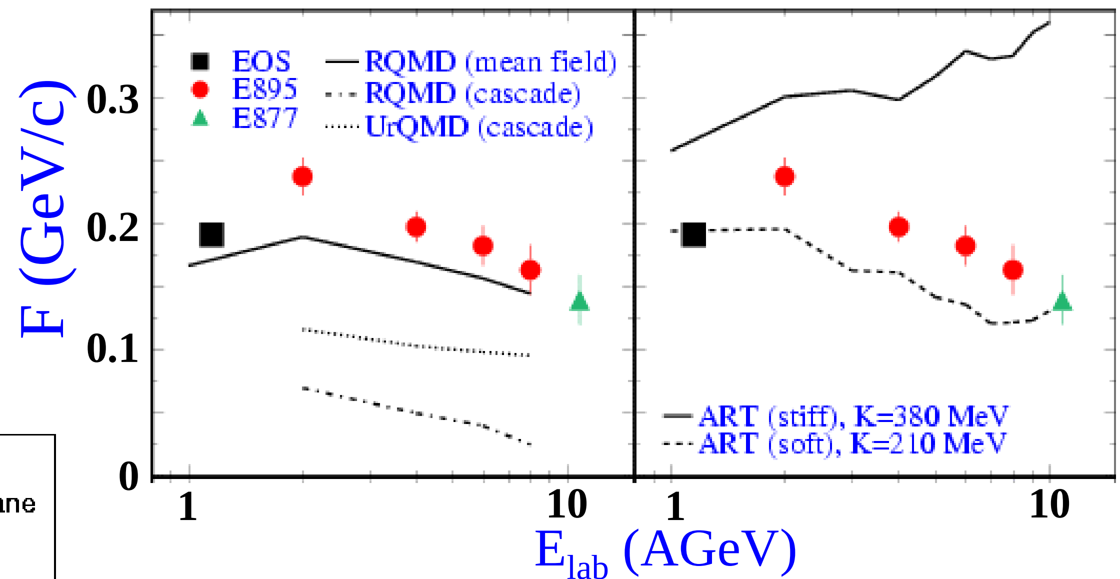

π phasespace density
thermal population?
multiparticle effects?
poster by D. Cebra
HBT
space-time geometry
& dynamics
PRL 84 2798 (2000)
Spectra
thermal/chemical
properties
poster by J. Klay
tilted sources
geometry of
anisotropic flow
PLB 496 1 (2000)
poster by U. Heinz
Λ–p correlations
baryon source geometry
two-hadron potential
strange/nonstrange
radial flow
distinct freezeout?
talk by C. Pinkenburg
Flow
pre-equilibrium dynamics
collective bulk response
equation of state
PRL 83 1295 (1999)
PRL 84 5488 (2000)
Λ, K0 flow
strange potentials
PRL 85 940 (2000)
PRL, in press
talk by C. Pinkenburg
Strangeness
early thermochemistry
strange potentials
talk by C. Pinkenburg

Reminder from QM99: Proton Flow

sideward flow $F \equiv \frac{d\langle p_x \rangle}{dy_n}$

elliptic flow $v_2 = \langle \cos 2\phi \rangle$



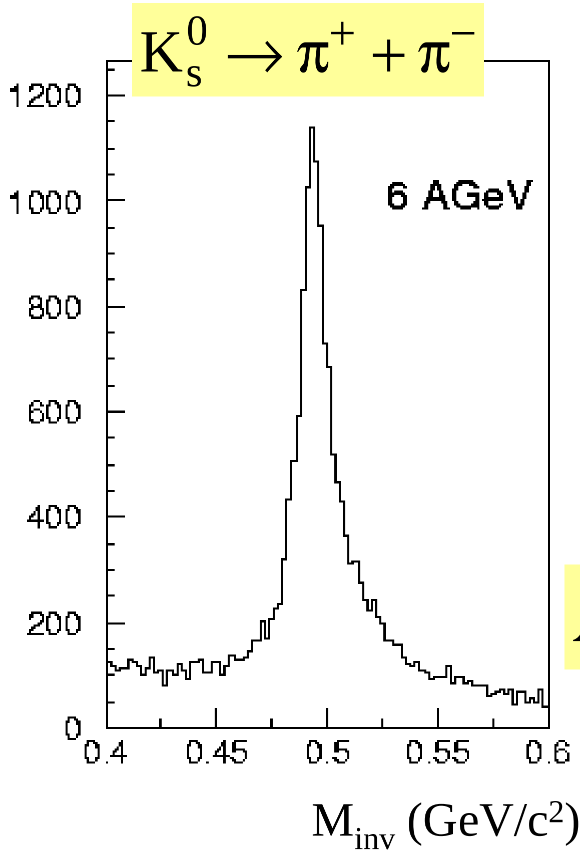


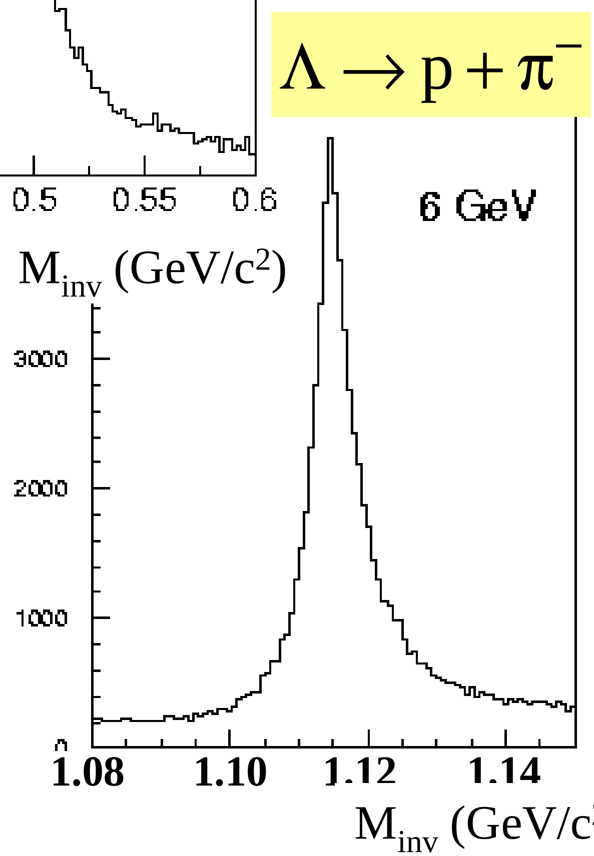
- Transition region for flow mapped
- F drops as resonances dominate
- Strong sensitivity to medium contributions to pressure
- No single parameterization reproduces flow details
- No sudden drops in pressure (flow) signaling phase transition

PRL **83** 1295 (1999)
PRL **84** 5488 (2000)

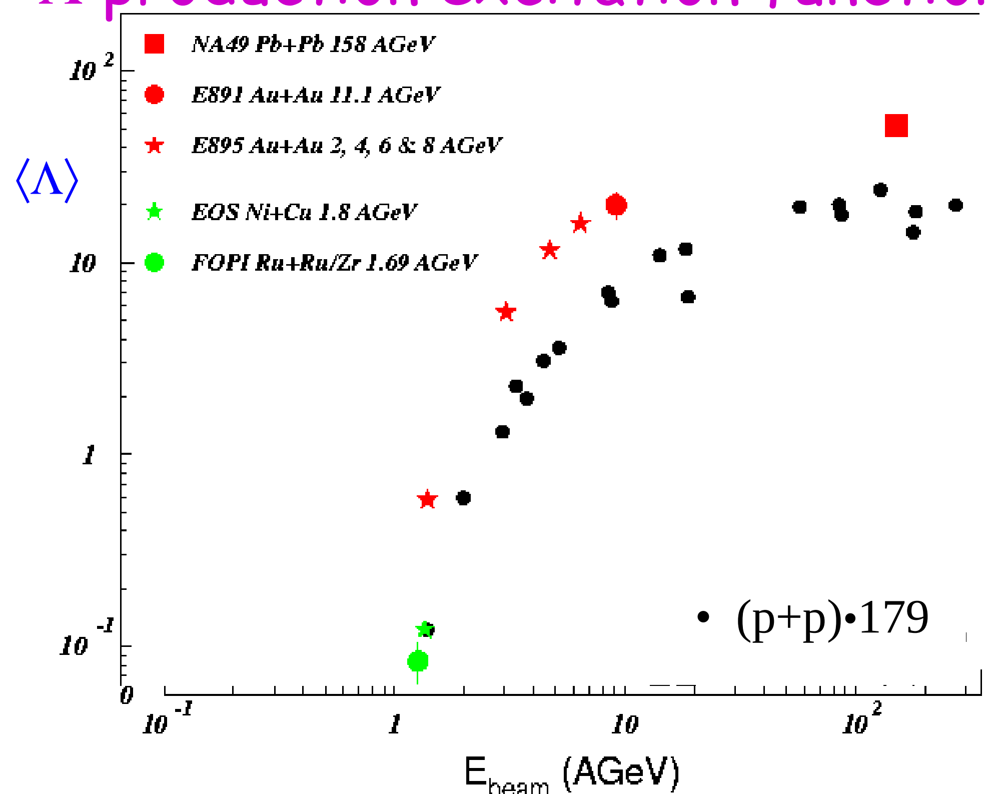
Beyond protons...

neural networks identify
decays of neutral strange particles





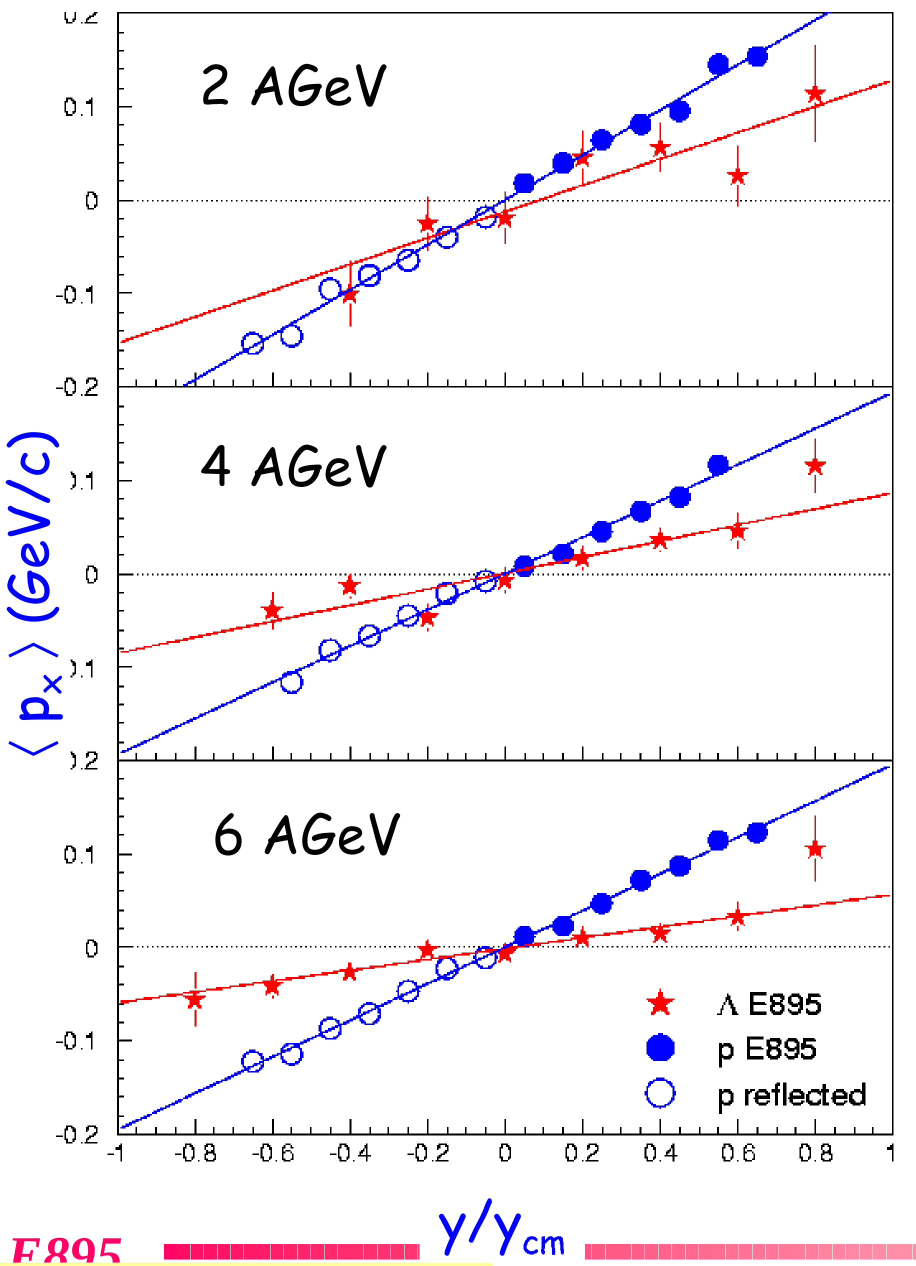
Λ production excitation function



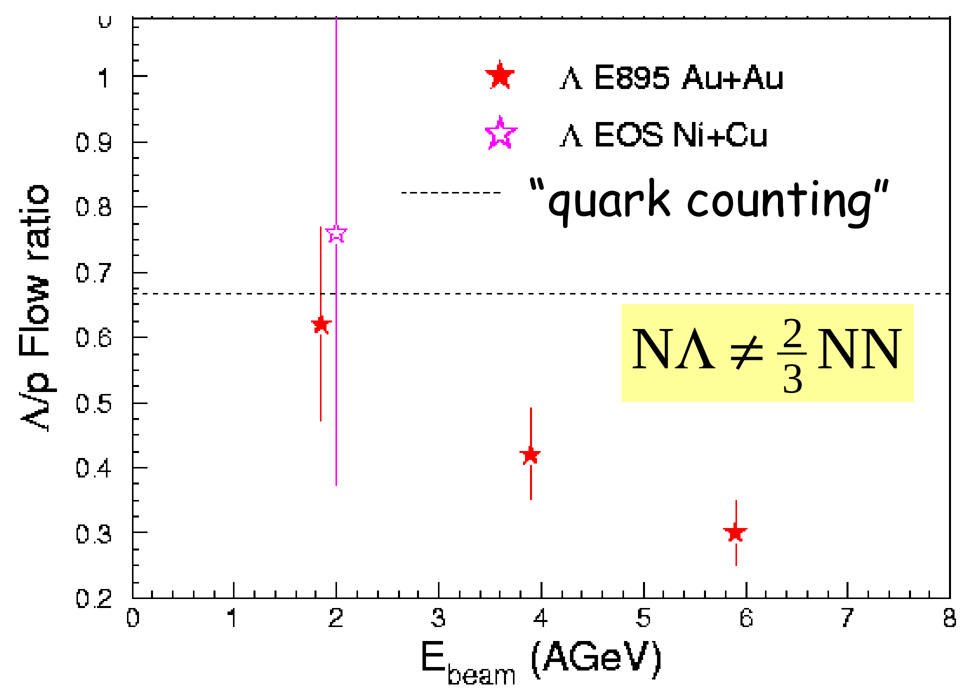
E895

see talk of Chris Pinkenburg today

Λ flow

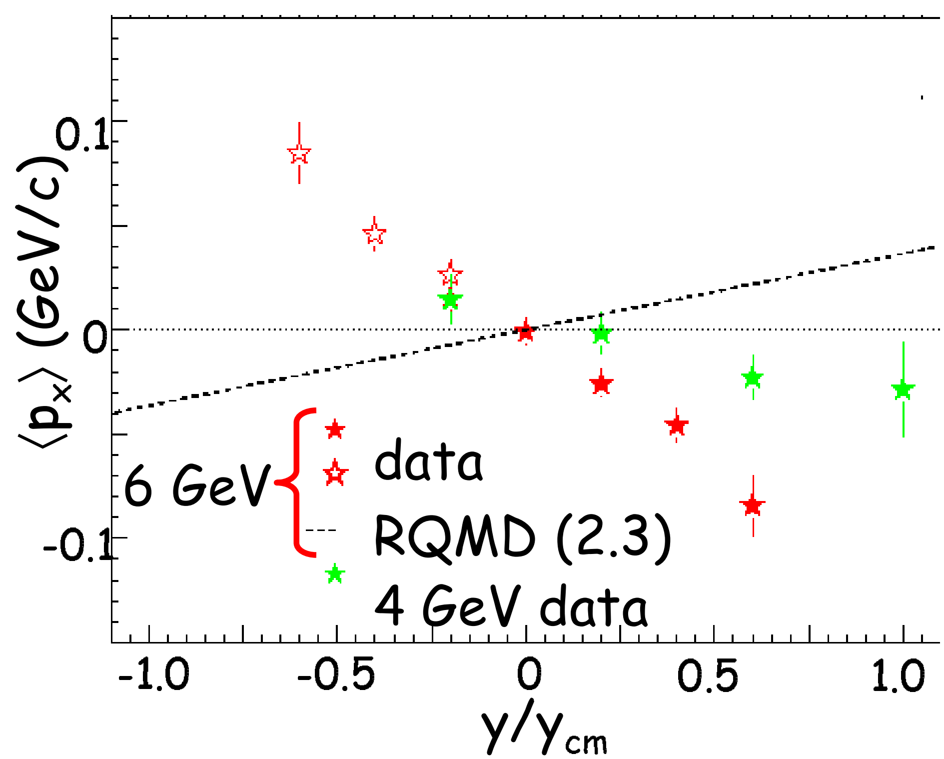


- "positive" Λ flow
- decreases with E_b (more than p)
- RQMD (without Λ potential) underpredicts effect
- probe Λ potential at high ρ (complements hypernuclei studies) $\rightarrow$ astrophysical models



see talk of Chris Pinkenburg today

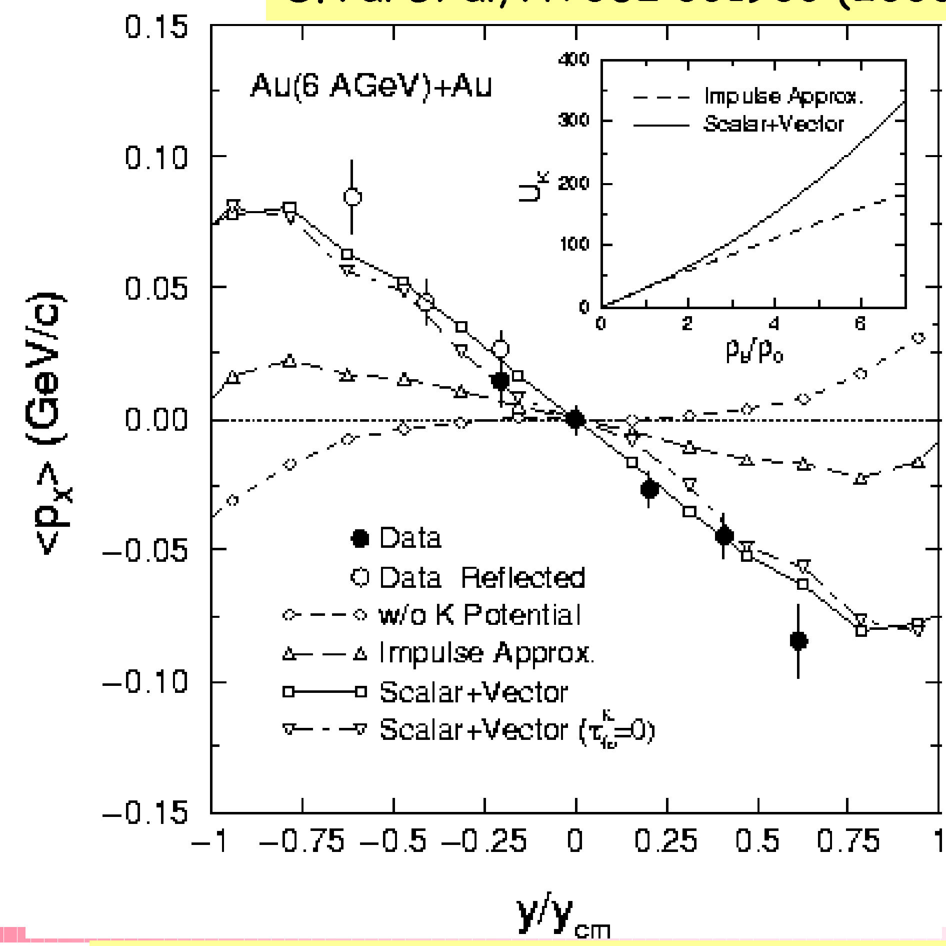
K^0_S (anti-)flow



Surprise— strong antiflow

- grows with collision energy

S. Pal et al, PR **C62** 061903 (2000)



Transport models:

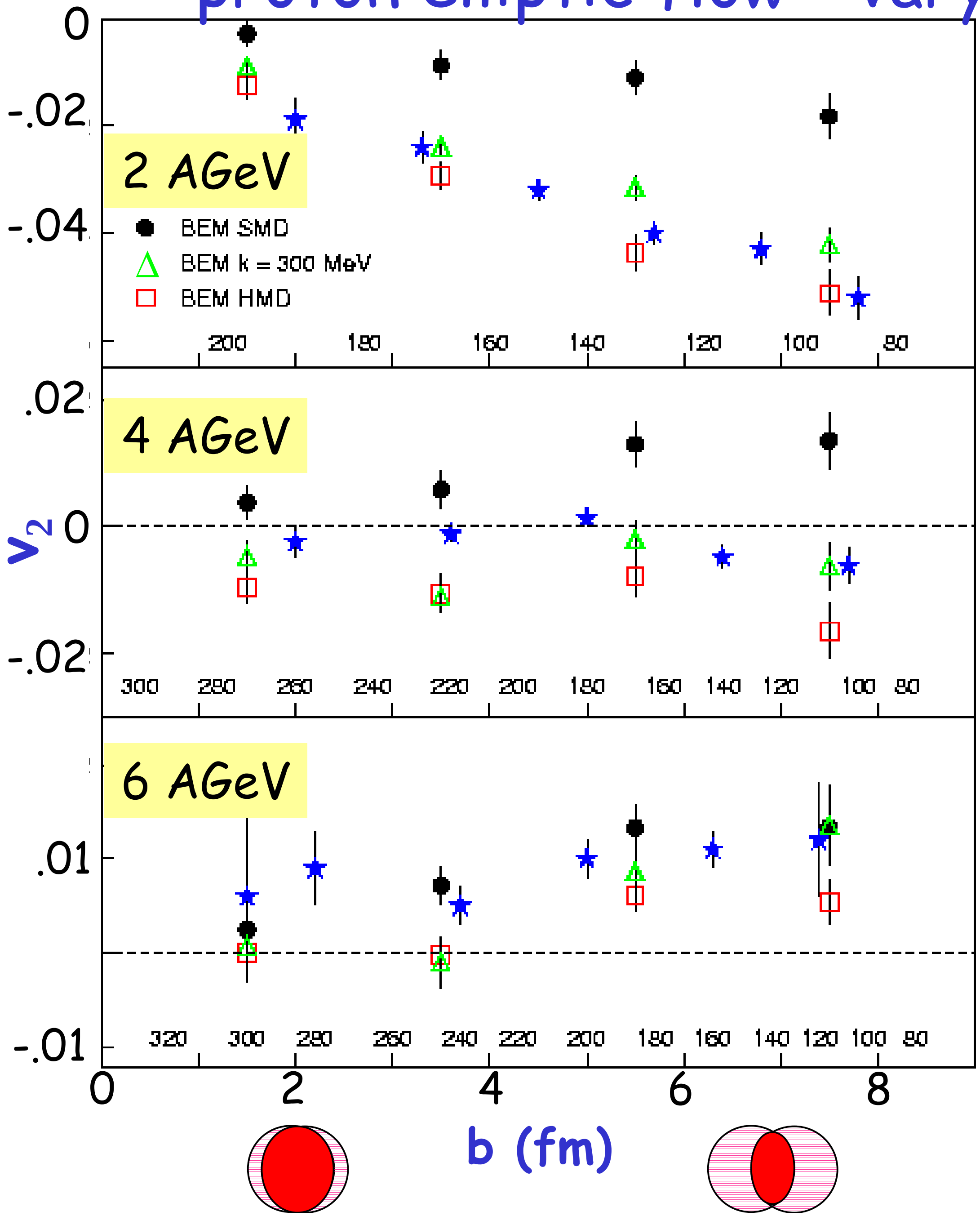
- rescattering insufficient (results in *positive* flow)
- strong repulsive vector potential required

PRL **85** 940 (2000)

Mike Lisa, Quark M

see talk of Chris Pinkenburg today

proton elliptic flow - varying the geometry



"min-bias" flow measurements do not constrain models

→ geometry provides another handle on flow

increasing spatial asymmetry produces larger signal

Can HBT give geometrical information on flow??

HBT: probing freeze-out space-time structure I
- Cylindrical sources

$$R_o^2(\vec{K}) = \left\langle \left(\tilde{x}_{out} - \beta_\perp \tilde{t}\right)^2 \right\rangle(\vec{K})$$

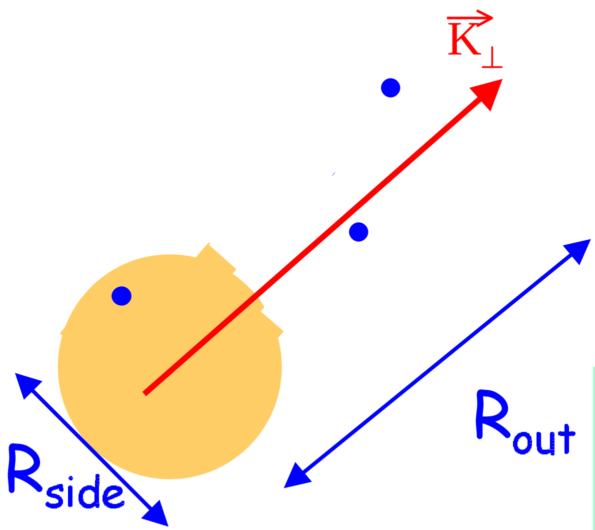
$$R_s^2(\vec{K}) = \left\langle \tilde{x}_{side}^{\,2} \right\rangle(\vec{K})$$

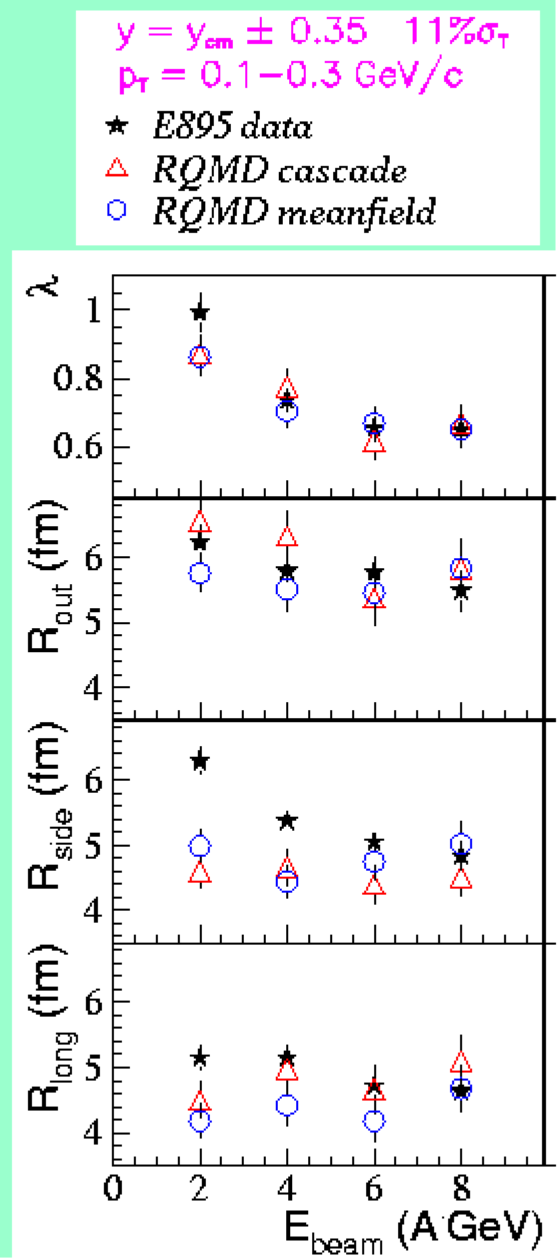
$$R_l^2(\vec{K}) = \left\langle \left(\tilde{x}_{long} - \beta_l \tilde{t}\right)^2 \right\rangle(\vec{K})$$

$$\tilde{x} \equiv x - \langle x \rangle$$

$$\langle f \rangle \equiv \frac{\int d^4x \cdot S(x,K) \cdot f(x)}{\int d^4x \cdot S(x,K)}$$

$$(x_{out}, x_{side}) \neq (x, y)$$



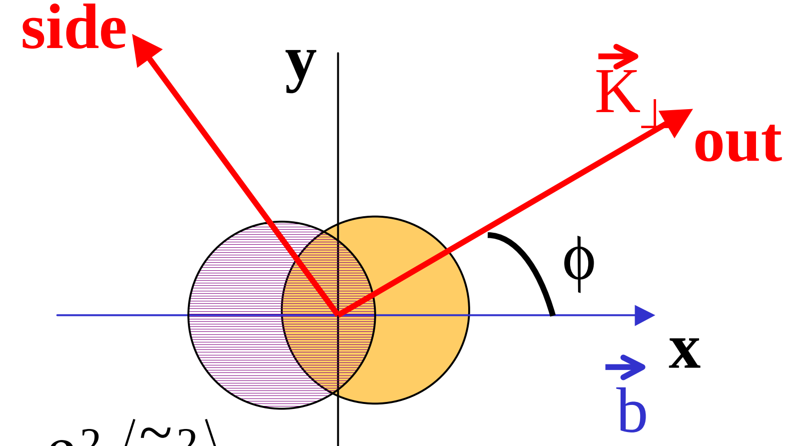


HBT @ AGS mapped by E895 (QM99)

PRL **84**, 2798 (2000)
NPA **661**, 444c (1999)

E895

HBT: probing freeze-out space-time structure II - Collisions at b≠0



- Source in **b**-fixed system: (x,y,z)
- Space/time entangled in pair system (x_O,x_S,x_L)

$$R_o^2 = -\tfrac{1}{2}\left(\langle\tilde{y}^2\rangle - \langle\tilde{x}^2\rangle\right)\cos 2\phi + \tfrac{1}{2}\left(\langle\tilde{y}^2\rangle + \langle\tilde{x}^2\rangle\right) + \beta_\perp^2\langle\tilde{t}^2\rangle$$

$$R_s^2 = +\tfrac{1}{2}\left(\langle\tilde{y}^2\rangle - \langle\tilde{x}^2\rangle\right)\cos 2\phi + \tfrac{1}{2}\left(\langle\tilde{y}^2\rangle + \langle\tilde{x}^2\rangle\right)$$

$$R_{os}^2 = +\tfrac{1}{2}\left(\langle\tilde{y}^2\rangle - \langle\tilde{x}^2\rangle\right)\sin 2\phi$$

$$R_l^2 = \langle\tilde{z}^2\rangle + \beta_L^2\langle\tilde{t}^2\rangle$$

$$R_{ol}^2 = \langle\tilde{x}\cdot\tilde{z}\rangle\cos\phi$$

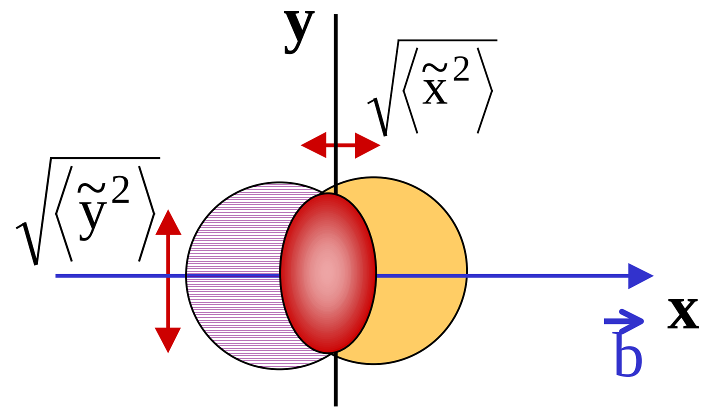
$$R_{sl}^2 = -\langle\tilde{x}\cdot\tilde{z}\rangle\sin\phi$$

(several terms vanish @ p_T = y = 0)

U. Wiedemann, PRC **57**, 266 (1998)
MAL, U. Heinz, U. Wiedemann PLB **489**, 287 (2000)
See Poster by U. Heinz

First-order information in HBT(ϕ)

2nd-harmonic oscillations from elliptical transverse shape



$$R_o^2 = -\tfrac{1}{2}\left(\langle\tilde{y}^2\rangle - \langle\tilde{x}^2\rangle\right)\cos 2\phi + \tfrac{1}{2}\left(\langle\tilde{y}^2\rangle + \langle\tilde{x}^2\rangle\right) + \beta_\perp^2\langle\tilde{t}^2\rangle$$

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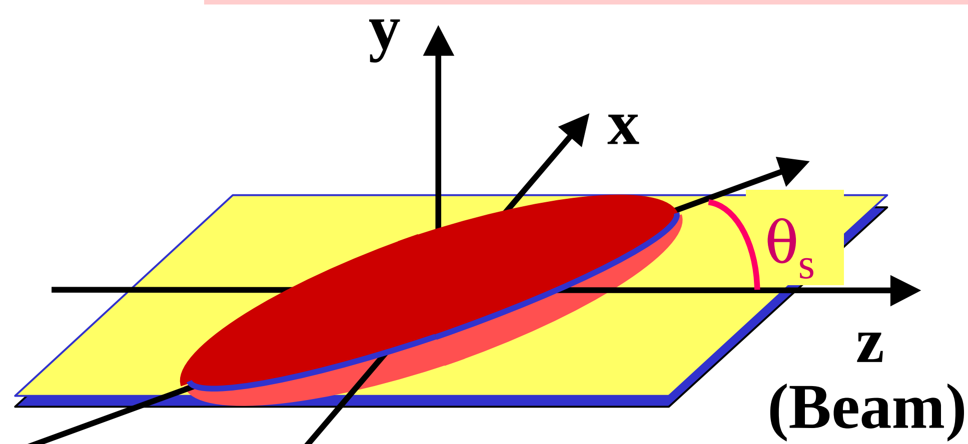
$$R_{ol}^2 = \langle\tilde{x}\cdot\tilde{z}\rangle\cos\phi$$

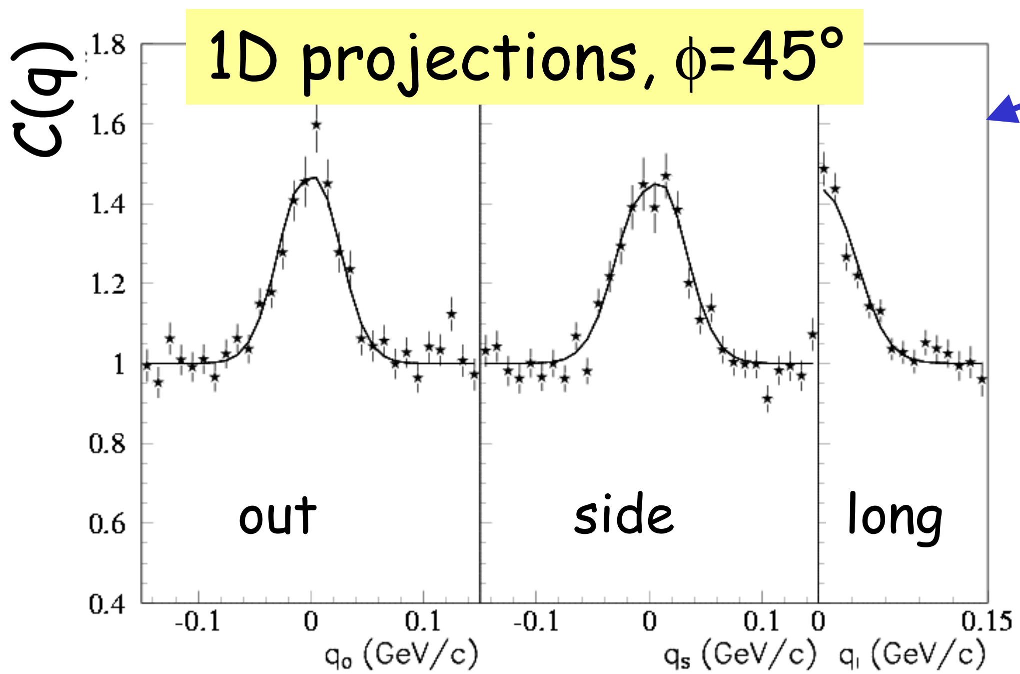
$$R_{sl}^2 = -\langle\tilde{x}\cdot\tilde{z}\rangle\sin\phi$$

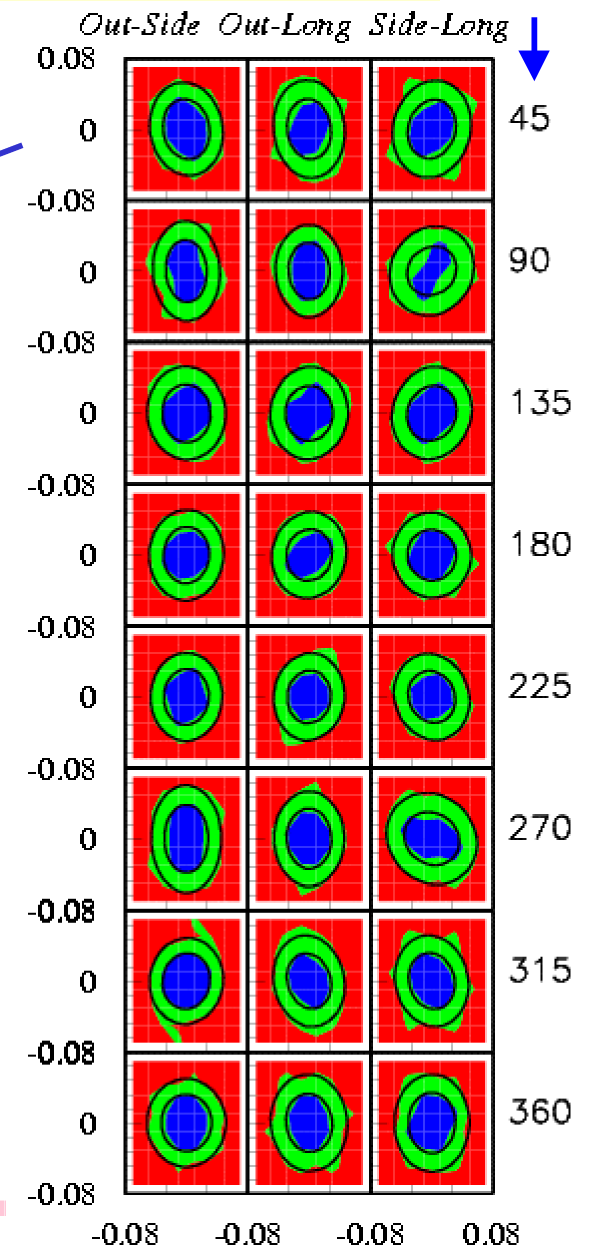
1st-harmonic oscillations: spatial tilt angle θ_s



Coordinate space!

Data: π^- correlation functions
Au(4 AGeV)Au, b≈4-8 fm





lines: projections of 3D Gaussian fit

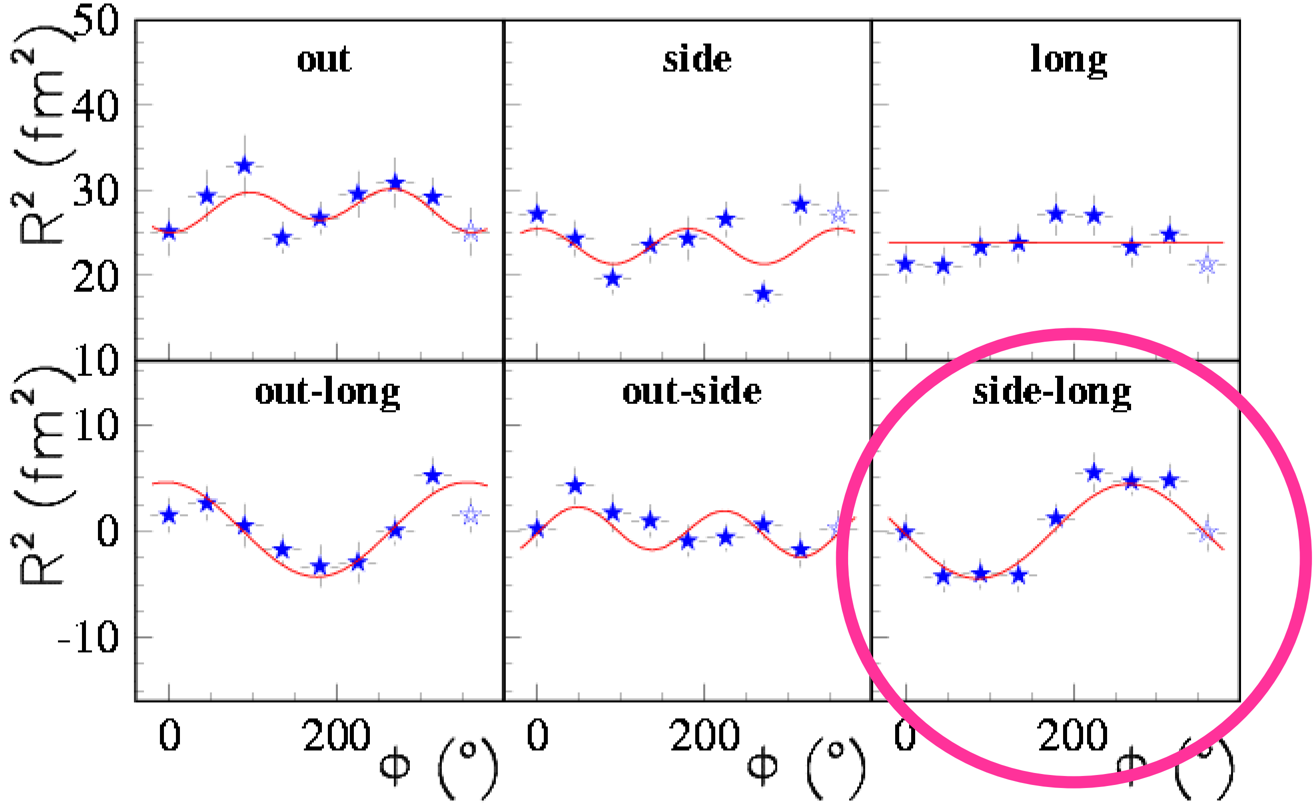
$$C(\vec{q},\phi) = 1 + \lambda(\phi) \cdot e^{-q_i q_j R_{ij}^2(\phi)}$$

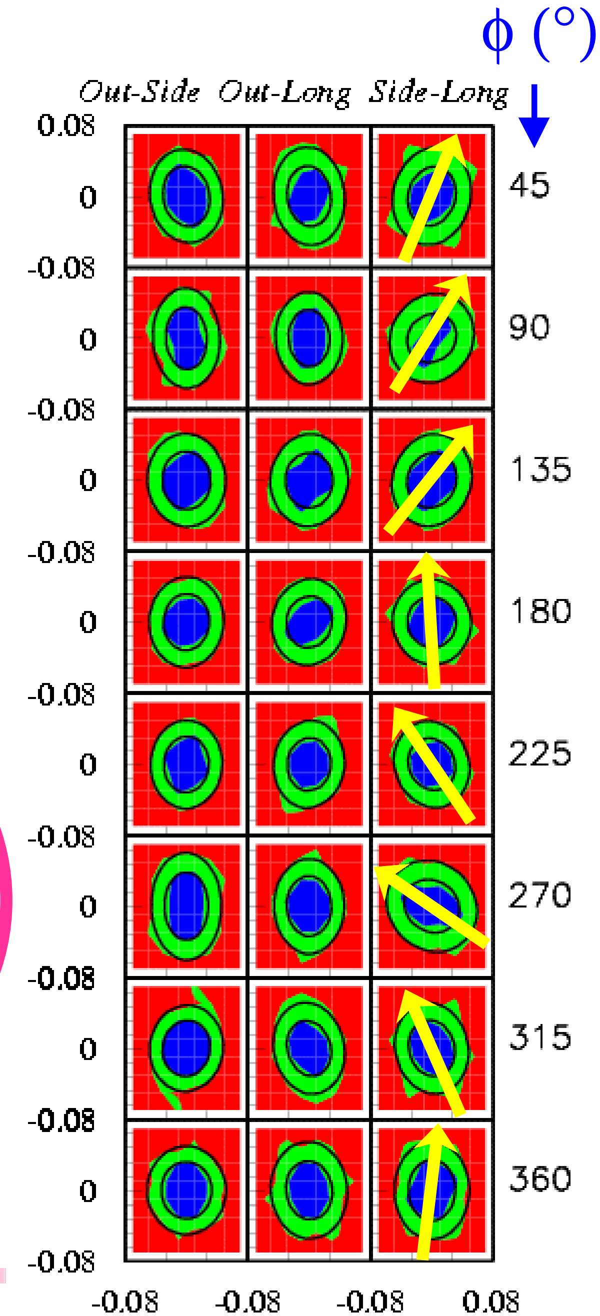
- 6 components to radius tensor: i, j = o,s,l

E895, PLB **496** 1 (2000)

Cross-term radii R_{ol}, R_{os}, R_{sl} quantify "tilts" in correlation functions

- fit results to correlation functions





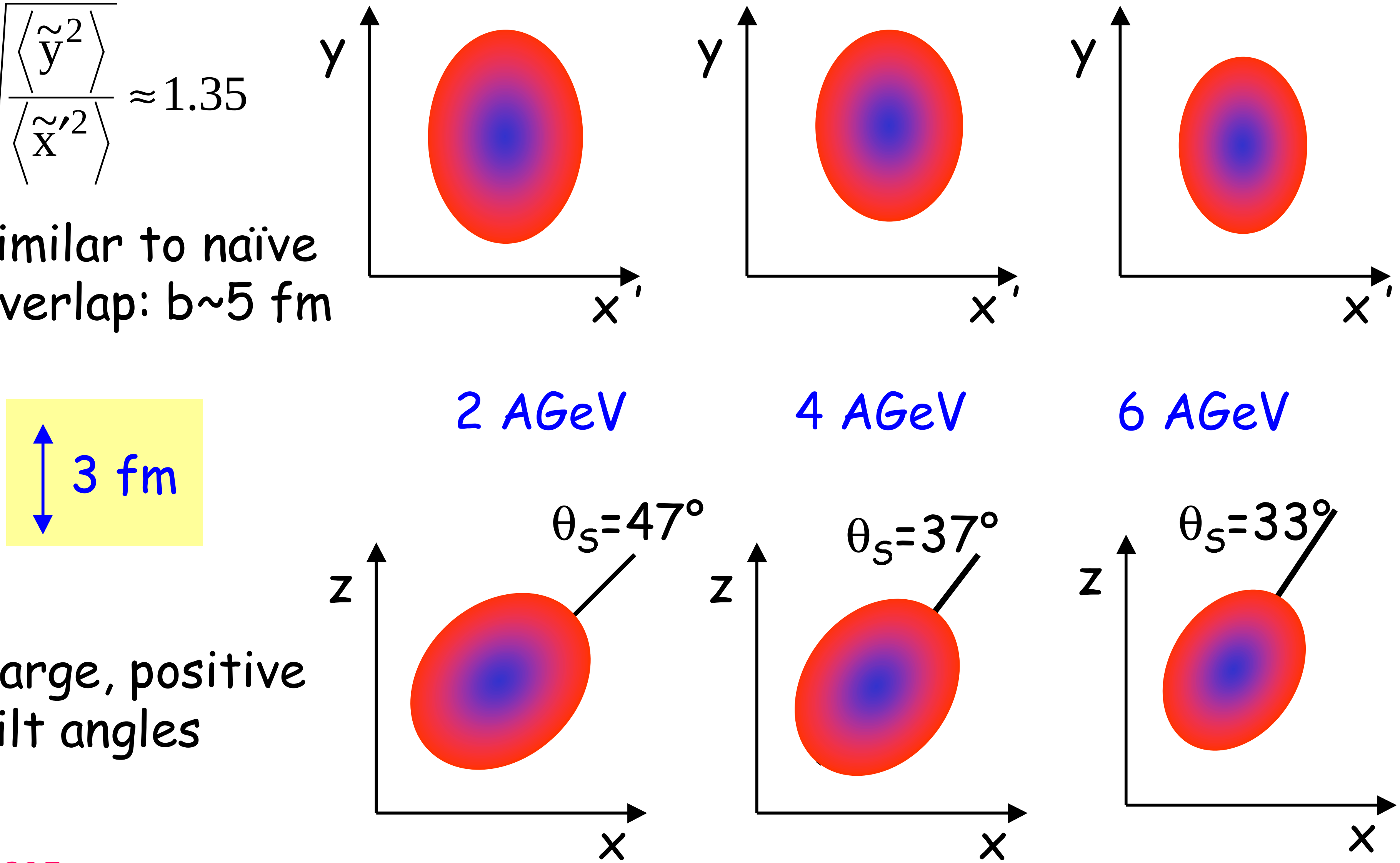
Lines: Simultaneous fit to HBT radii to extract underlying geometry

E89...

Images of π^--emitting sources (scaled ~ x10^{14})

$$\sqrt{\frac{\langle \tilde{y}^2 \rangle}{\langle \tilde{x}'^2 \rangle}} \approx 1.35$$

similar to naïve
overlap: b~5 fm

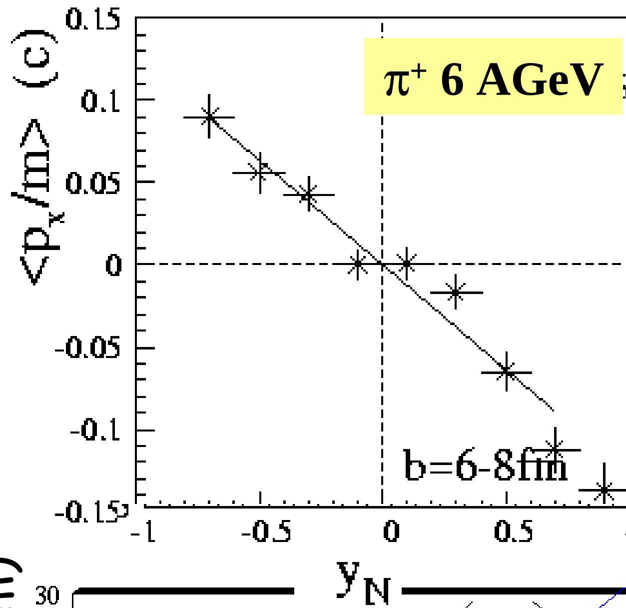


Large, positive
tilt angles

Opposing average tilts in **p**, **x** and the physics of π flow

- π "antiflow" (*negative* tilt in **p**-space)
- **x**-space tilt in positive direction

→ non-hydro nature of π flow



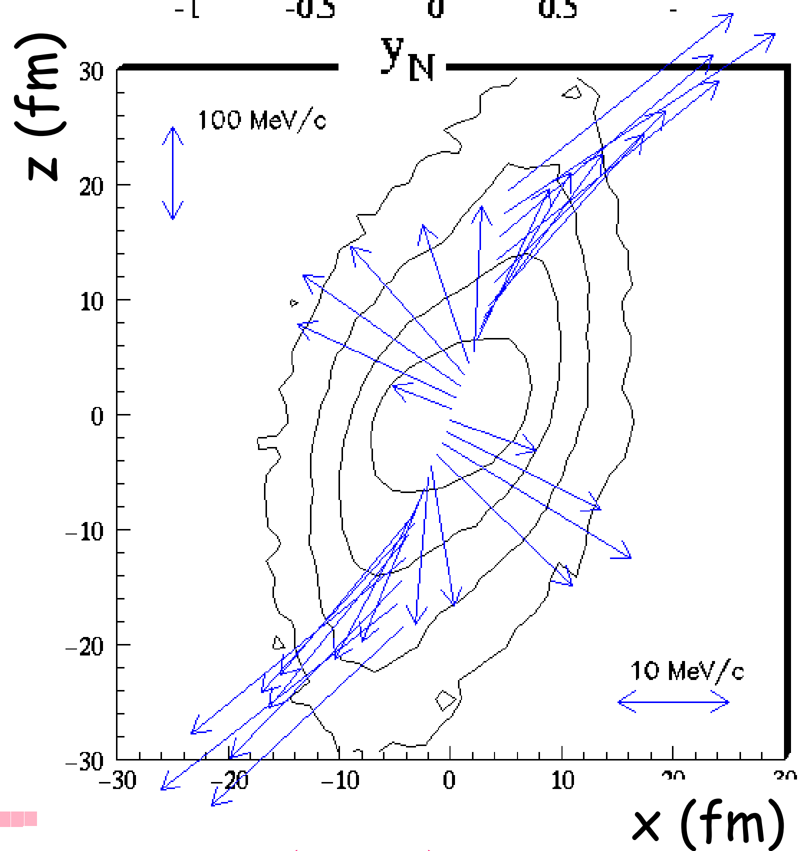
RQMD transport model:

- Antiflow reflects dense region z~0
- (dilute large-|z| show <u>positive</u> flow)

pion momentum anisotropies due to reflection from flowing baryons

(πN→Δ →πN)

π tilt reflects x-space structure of <u>proton</u> flow



RQMD Au(2GeV)Au

E895

Bass et al [PLB **302** 381 (93)]:

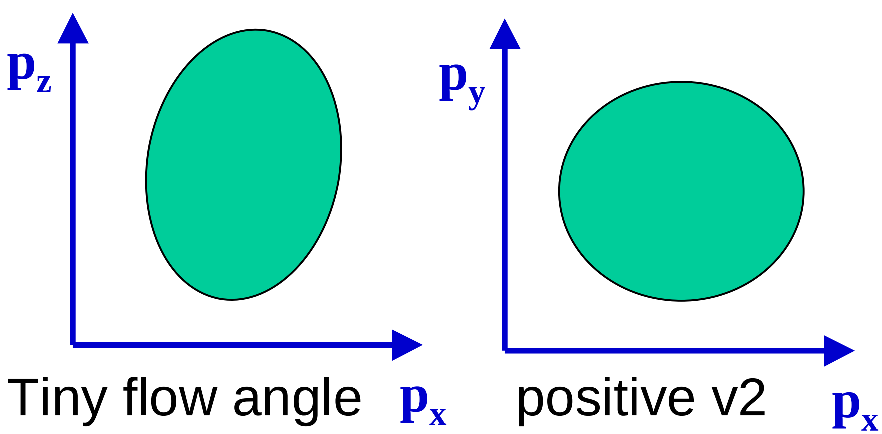
Tomography in 6 Dimensions

Flow analysis and HBT relative to the reaction plane allow a complete characterization of the final state in phase space, get space-momentum correlations

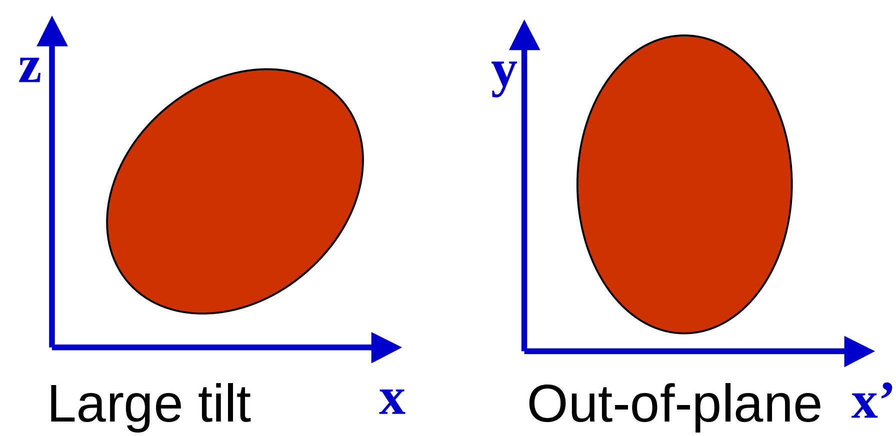
→ **6 dimensional Tomography of proton flow**

6 AGeV

Momentum Space (Flow)



Coordinate Space (HBT)



More on position - momentum space relationship the phasespace density

f = occupation of 6-D position$\otimes$momentum cell, volume $\hbar^3$

- determines magnitude of multi-particle correlations (lasers)
- provides a test of thermalization/consistency

$$f(x,p) = \frac{1}{e^{p \cdot u(x)/T(x)} - 1}$$

← T determines <u>number</u> of π, as well as spectral shape

Experimental access to spatially averaged density

$$\langle f \rangle (p_T, y) = \sqrt{\lambda \pi^3} \cdot \frac{\frac{1}{E} \cdot \frac{d^3N}{dy \cdot p_T dp_T \cdot d\phi}}{R_{out} \cdot R_{side} \cdot R_{long}}$$

← volume in **p**-space

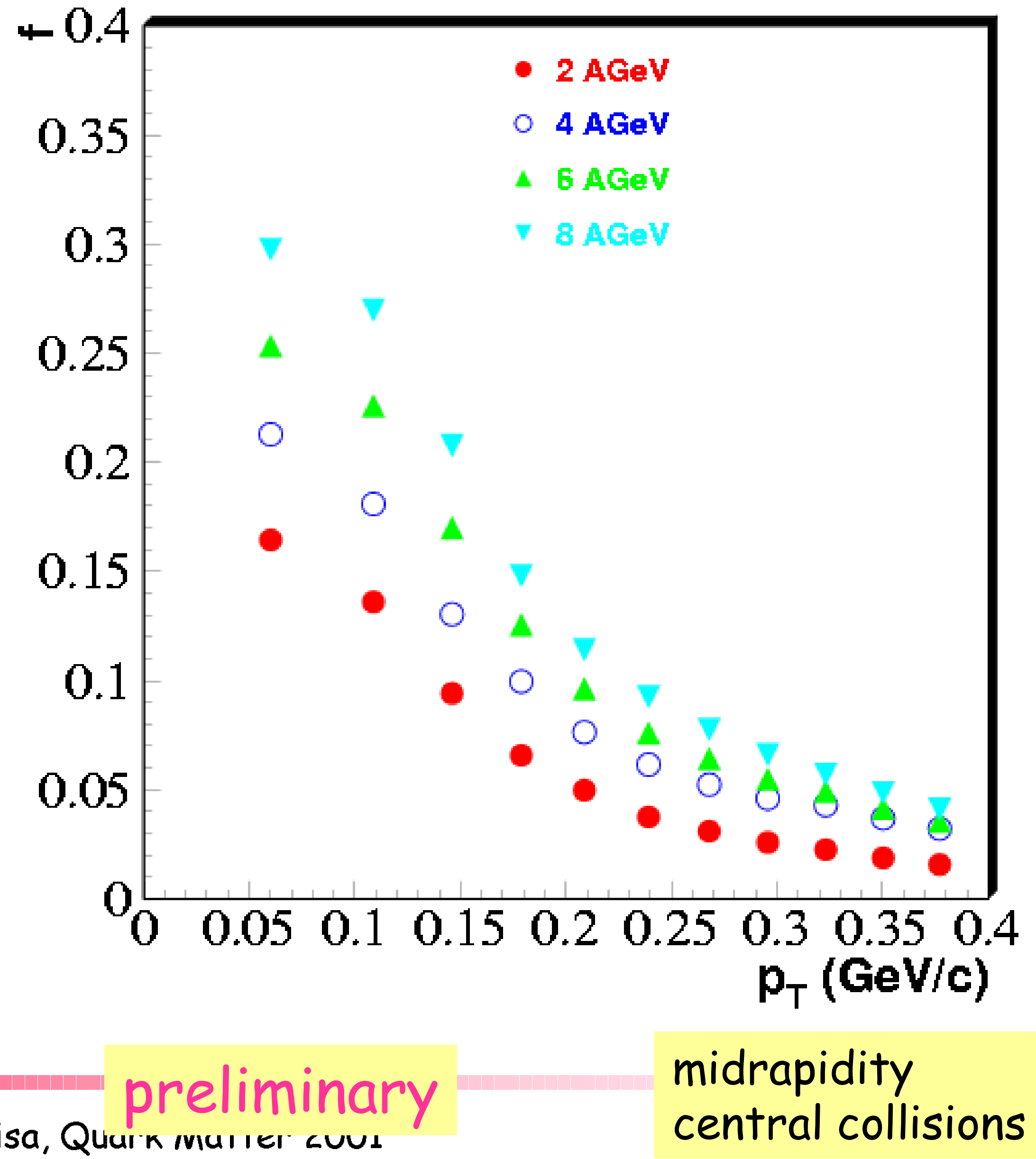
← volume in **x**-space

G. Bertsch, PRL **72** 2349 (94)
D. Ferenc *et al*, PL **B457** 347 (99)

- observation @ SPS, AGS: "Universal" π freeze-out density
  - breaks down at lower energies?

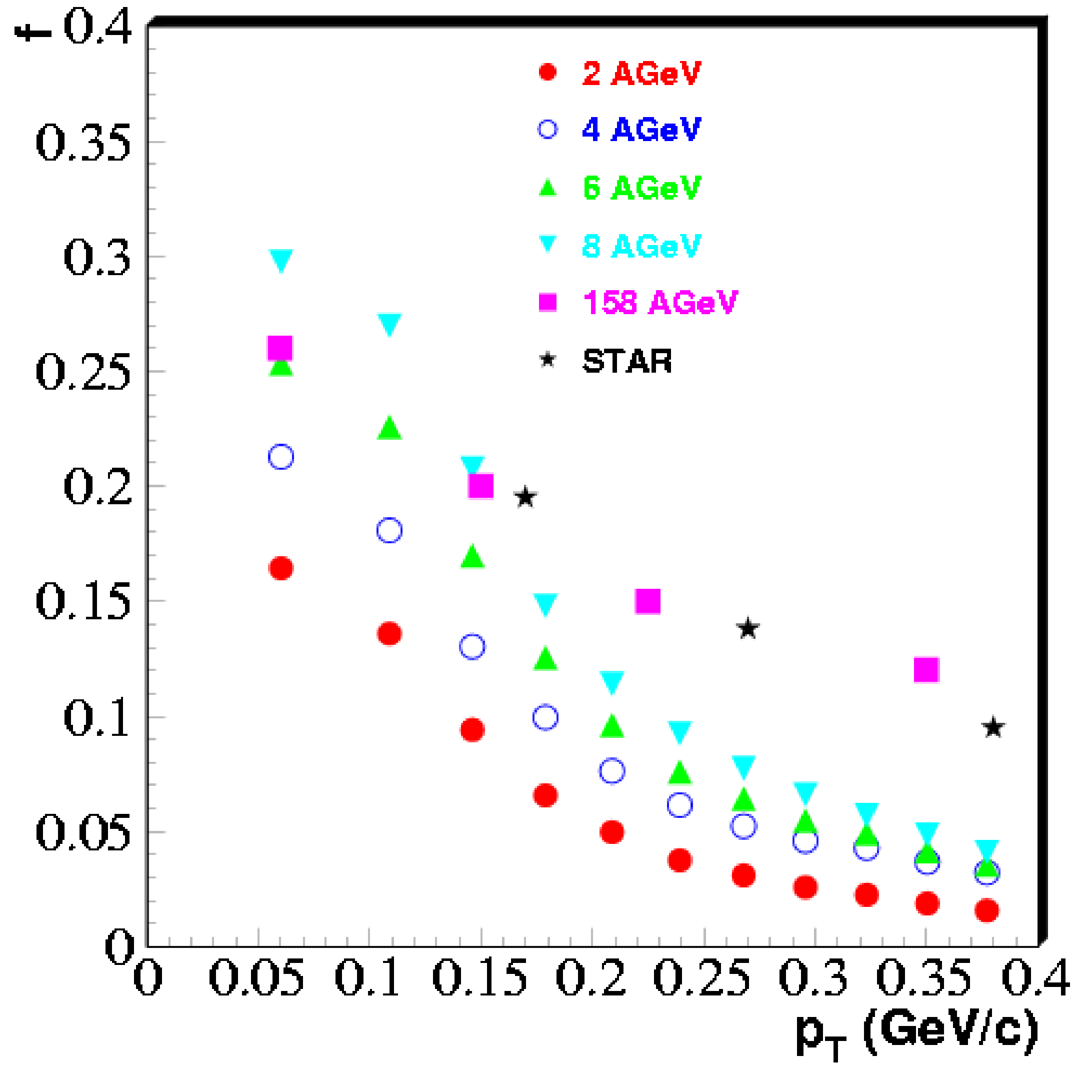
Measured phasespace densities

- non-universal growth of ⟨f⟩ with collision energy
- f<1 → no condensate



Measured phasespace densities

- non-universal growth of $\langle f \rangle$ with collision energy
- f<1 $\rightarrow$ no condensate
- low-p_T saturation of $\langle f \rangle$ as $E_{beam} \rightarrow$ 8 AGeV
  - same occupancy as STAR!



preliminary

midrapidity
central collisions

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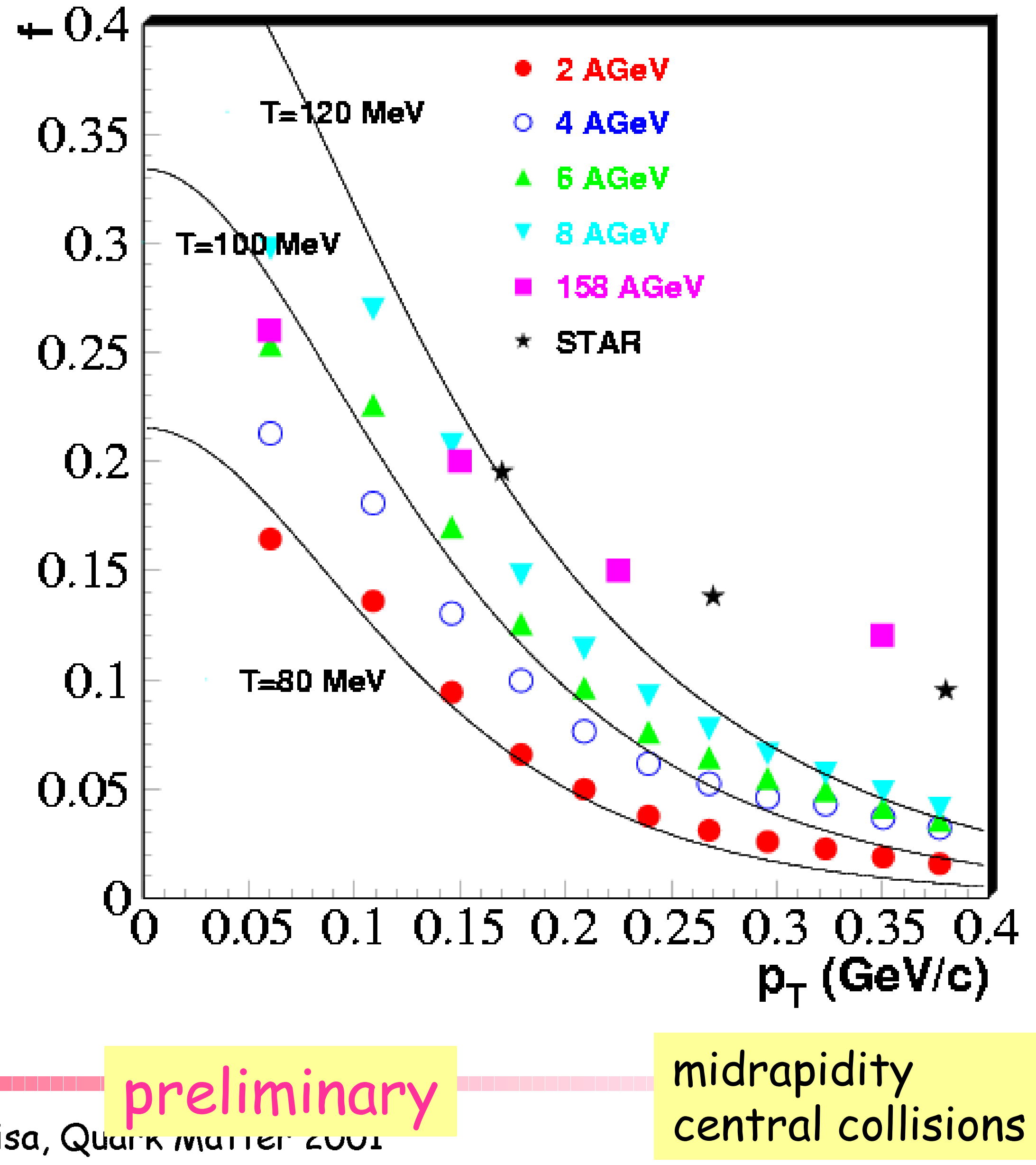
- low-p_T saturation of $\langle f \rangle$ as $E_{beam} \rightarrow 8$ AGeV
  - same occupancy as STAR!
- Rough agreement with thermal Bose-Einstein
  - high-p_T excess @ high E_b



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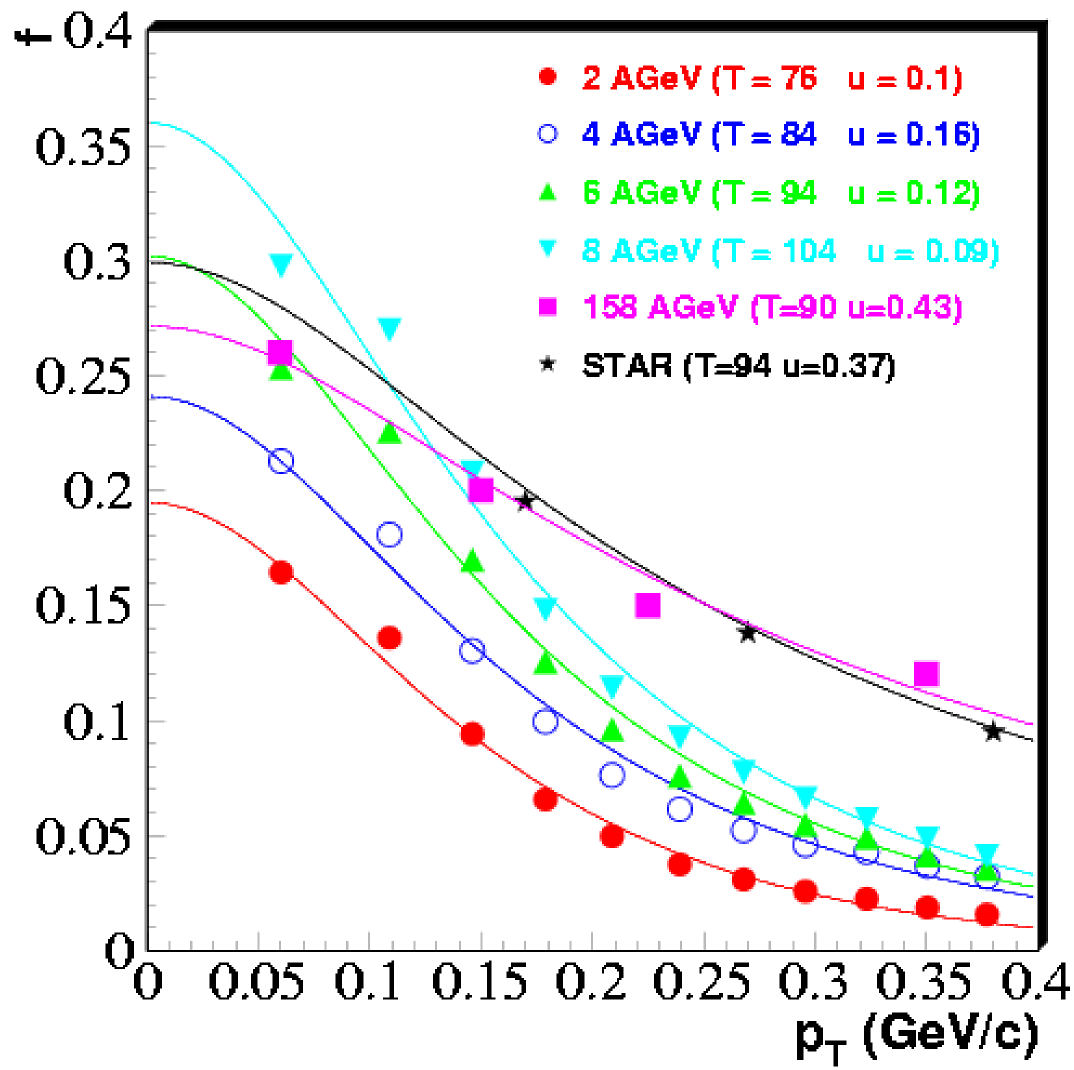
- low-p_T saturation of $\langle f \rangle$ as $E_{beam} \rightarrow$ 8 AGeV
  - same occupancy as STAR!
- Rough agreement with thermal Bose-Einstein
  - high-p_T excess @ high E_b
- Better description by inclusion of radial flow [B. Tomasik, Ph.D. thesis]
- Substantial experimental & theoretical uncertainties

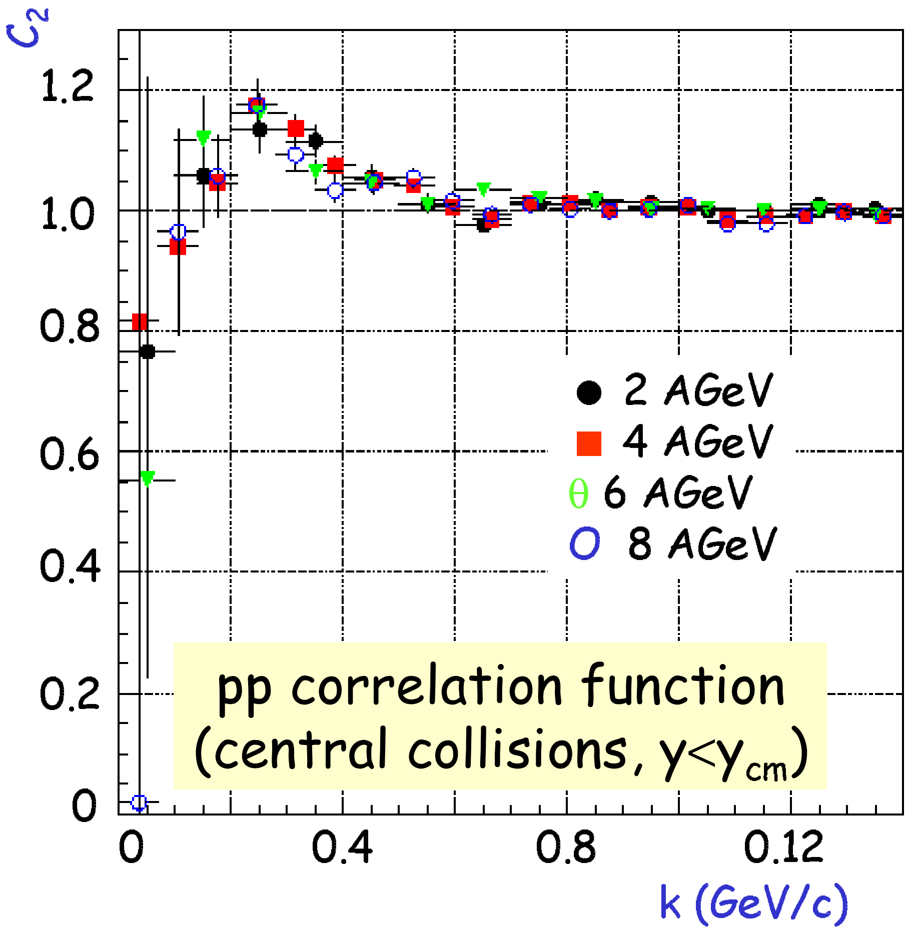


preliminary

midrapidity
central collisions

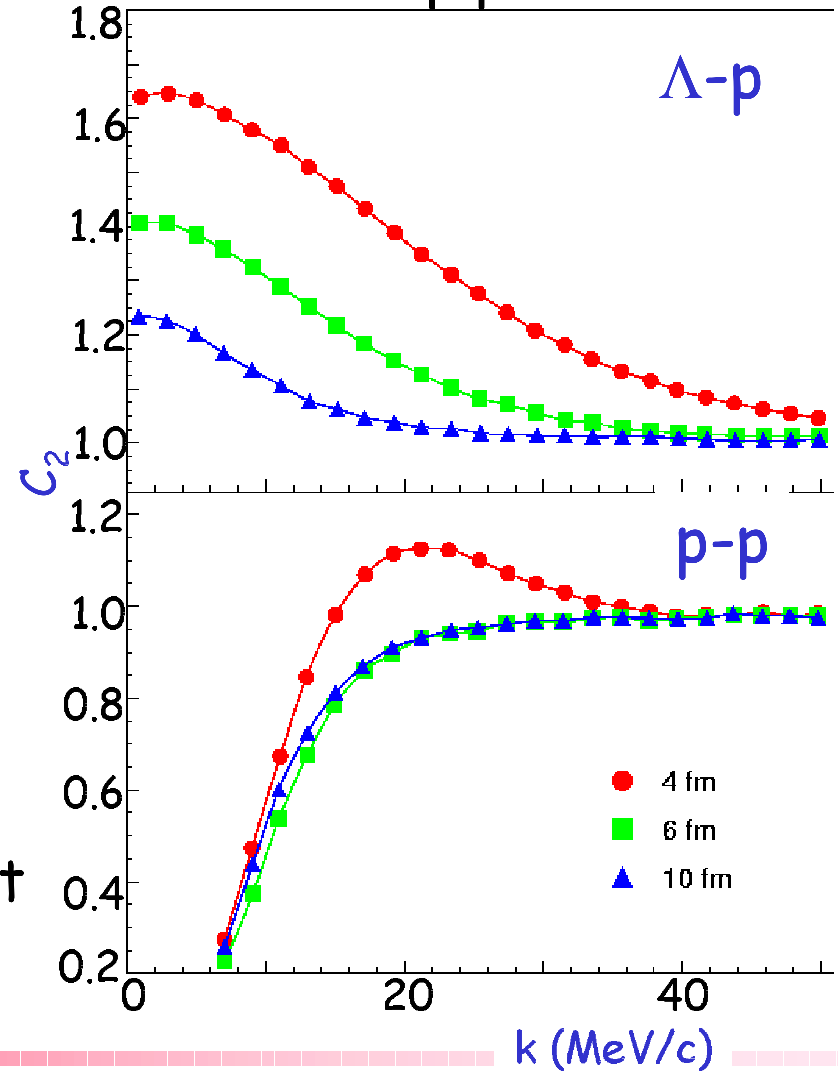
also see poster of D. Cebra

Baryon correlations



- pp correlations ~ E_{beam} independent
- another handle on baryon source?

- Λp more sensitive than pp?
- Correct Λp potential?



F. Wang & S. Pratt PRL **83** 3139 (1999)

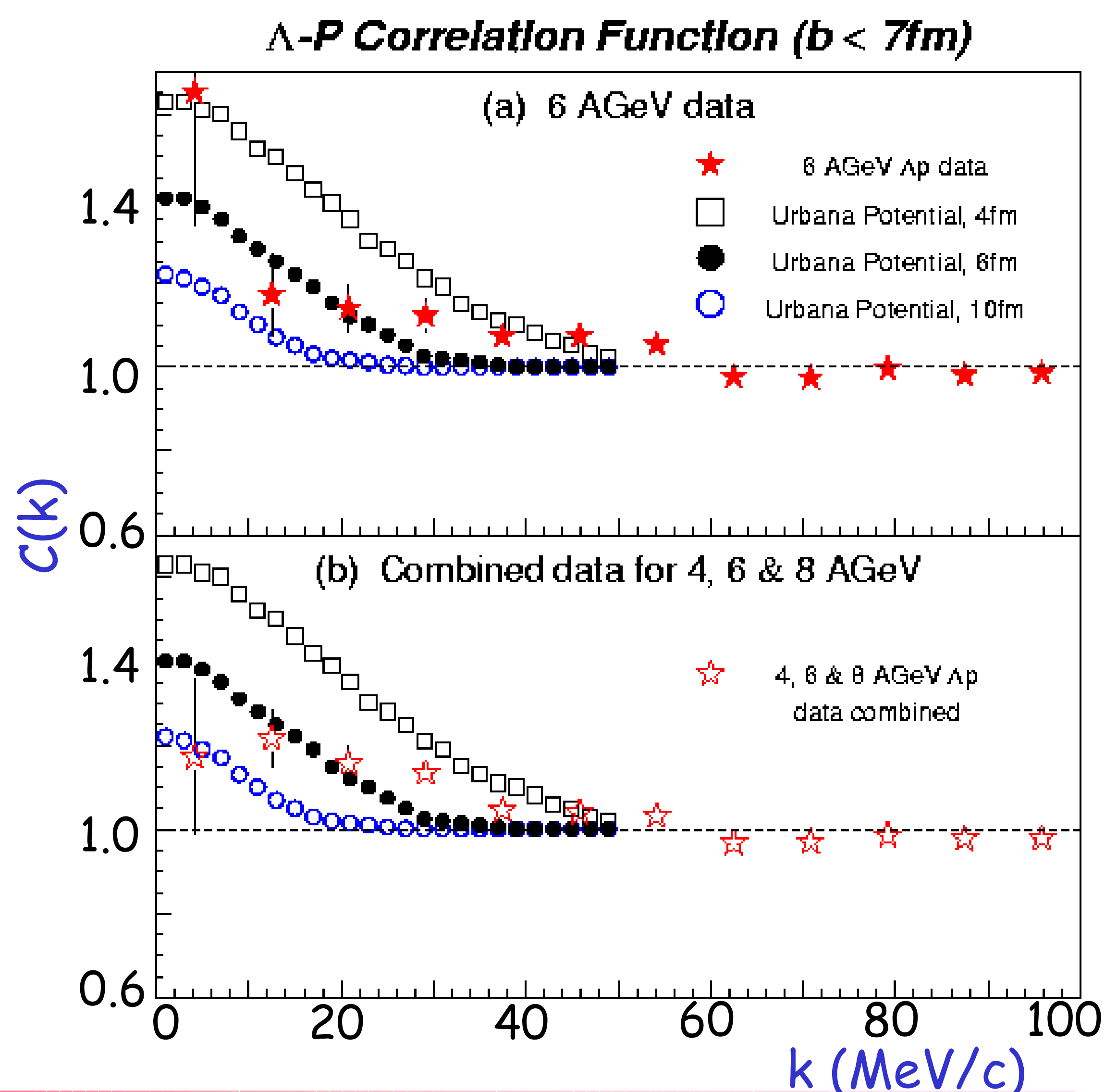
Another E895 first: Λ-p correlation function

- positive correlation observed

- qualitatively different shape than expected from Urbana p-Λ potential

→ input to the particle physics

- work in progress…



Summary I

- continuing to push the envelope…
- directed and elliptic flow excitation function
  - continue input to bulk parameterization
- strange particle flow
  - positive Λ flow
    - does not scale with proton flow (naïve 2/3 rule broken)
    - Λ potential important to describe flow
  - strong antiflow of K^0's
    - strong, repulsive vector potential indicated
- Varying geometry (impact parameter): another handle
  - increased **x** asymmetry $\rightarrow$ larger **p** asymmetry

Summary II

- azimuthally-sensitive π^- HBT
  - almond-shaped source, (~ entrance-channel geometry)
  - large positive spatial tilt angles
  - non-hydro nature of π flow
  - coordinate-space structure of proton flow

- 6-D π phasespace density
  - non-universal growth of <f> with energy
  - saturation to "universal" behaviour at 8 AGeV
  - after 8 AGeV, increased π yield pushed to high $p_T \rightarrow$ flow

- first p-Λ signal observed
  - significant positive correlation
  - inconsistent with shape expected by Urbana potential

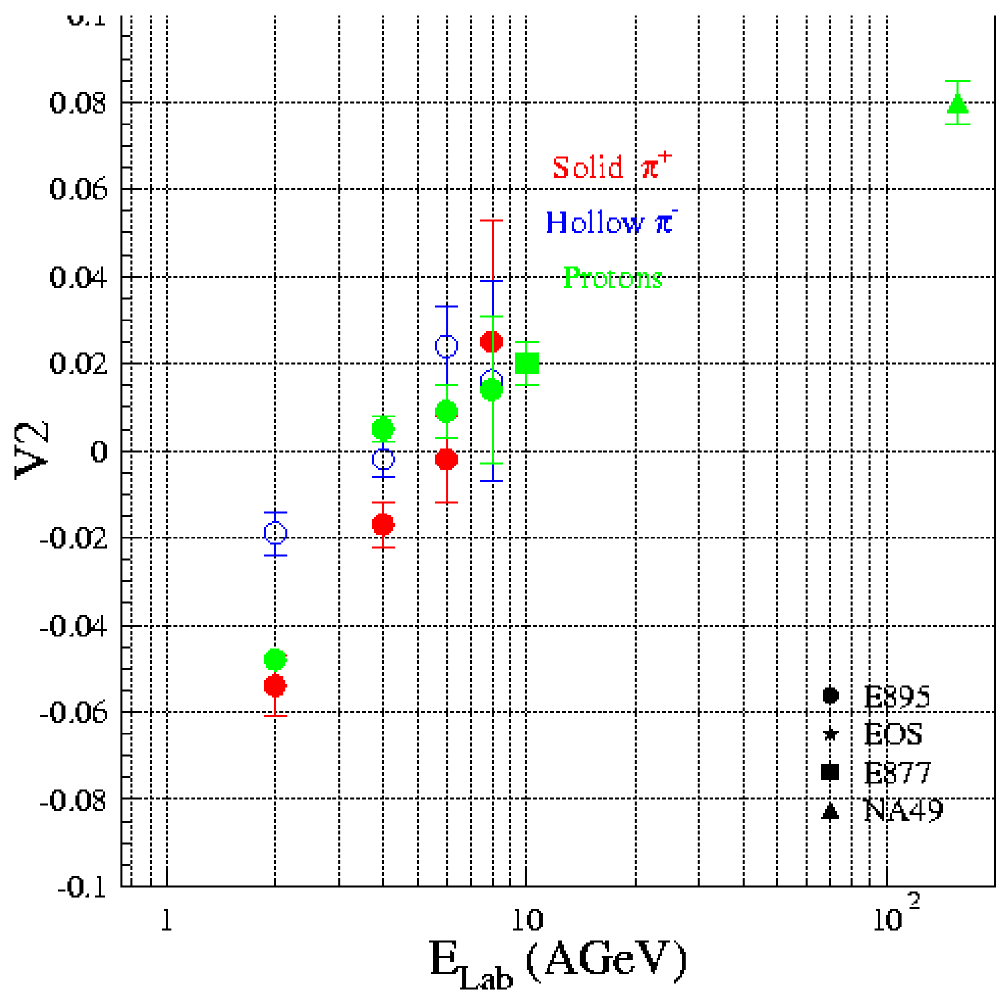
More E895 @ QM01

- Production & Collective Behaviour of Strange Particles
  Parallel session today: Chris Pinkenburg
- π Phasespace Density & Source Charge Density
  P063 Dan Cebra
- Directed, Elliptic, Radial, & Longitudinal Flow
  P069 Jenn Klay
- Azimuthally-sensitive HBT and the Tilt of the π Source
  P018 Ulrich Heinz*

* honorary E895 member

Pion and proton elliptic flow

- Ellitpic flow of both positive and negative pions follows the trends of the protons



W. Caskey, DNP98