HBT and Fluctuations

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Outline

- ☆ HBT
- ☆ Fluctuations

QM2001

HBT - Outline

- ★Overview of the new results
  - AGS, SPS, RHIC
- ★Emerging systematics in data
  - HBT Excitation function
  - Phasespace densities
- ★Trends in Analyses
  - Combined analyses
  - Rare particles
  - .....
- ★Summary and outlook

HBT-Results

NA 49

- Central Pb+Pb @ 40 and 158 *A*GeV

  $y = 2.2 - 2.7$ for 40 *A*GeV

  $y = 2.9 - 3.4$ for 158 *A*GeV

- Bertsch-Pratt (LCMS):

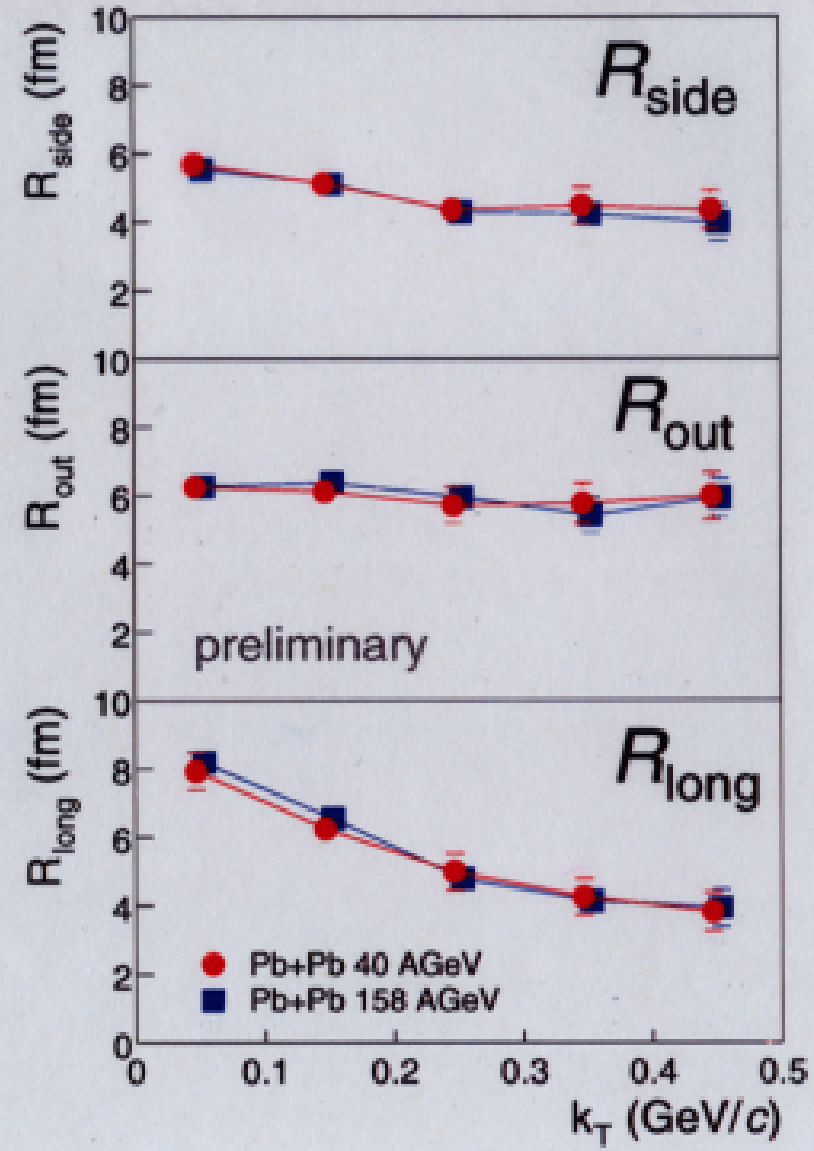
$$C_{BP} = 1 + \exp(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - 2 R_{outlong} q_{out} q_{long})$$

- Fit includes Coulomb correction:

$$C_2 = C_{Coulomb}(Q_{inv} \mid R_{side}, R_{out}, R_{long}) \cdot C_{BP}$$

Sinyukov et al.,
Phys. Lett. B432 (1998), 248 - 257

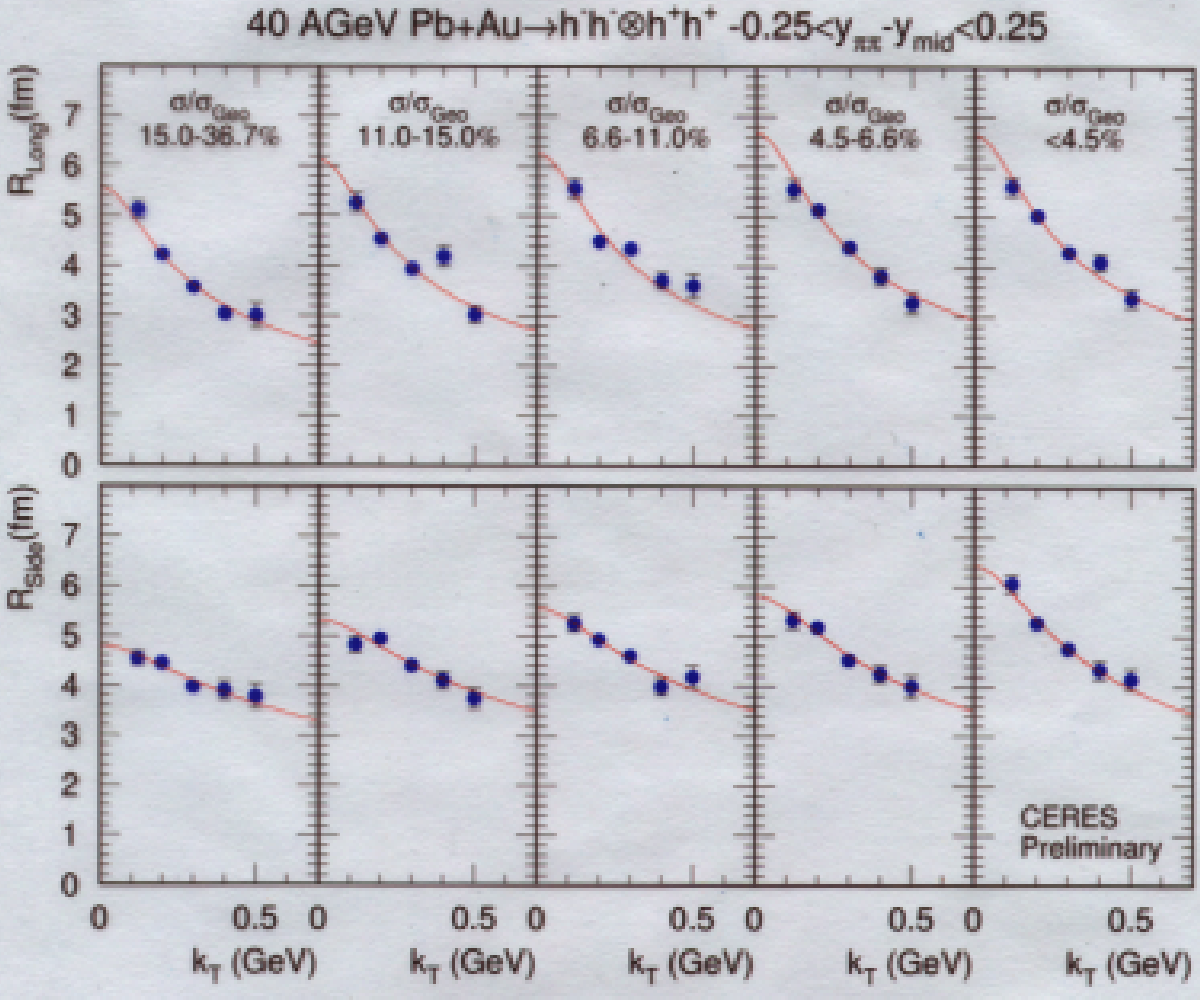
Sys. error on $R = 0.5$ fm



CERES

Transverse Momentum Dependence

$$k_T = \frac{1}{2}(\vec{p}_{T,1} + \vec{p}_{T,2})$$



Longitudinal boost-invariant expansion:

$$R_{\rm Long} = \tau_0 \sqrt{\frac{T}{m_T}}$$ Sinyukov

Radial flow:

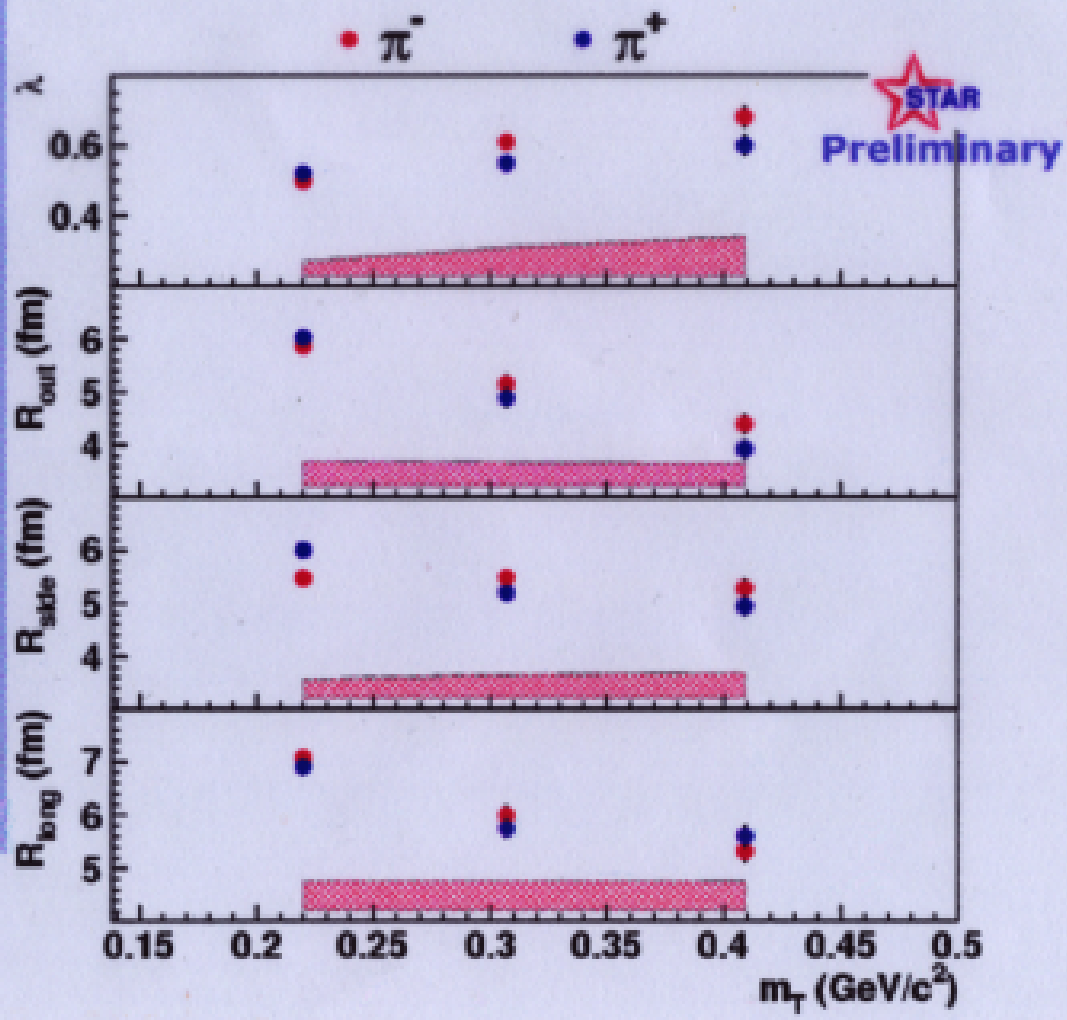
$$R^2_{\rm Side} = \frac{R^2_{\rm Geo}}{1 + \frac{\eta_f^2}{T} m_T}$$ Heinz, Tomasik, Wiedemann

STAR HBT m_T Dependence

- $\pi+\pi+$, $\pi-\pi-$, HBT parameters similar
- Grossly similar to AGS/SPS

With increasing m_T

- λ increases → fewer resonances
- radii decrease → x-p correlations
- stronger effect in R_o tha at AGS/SPS



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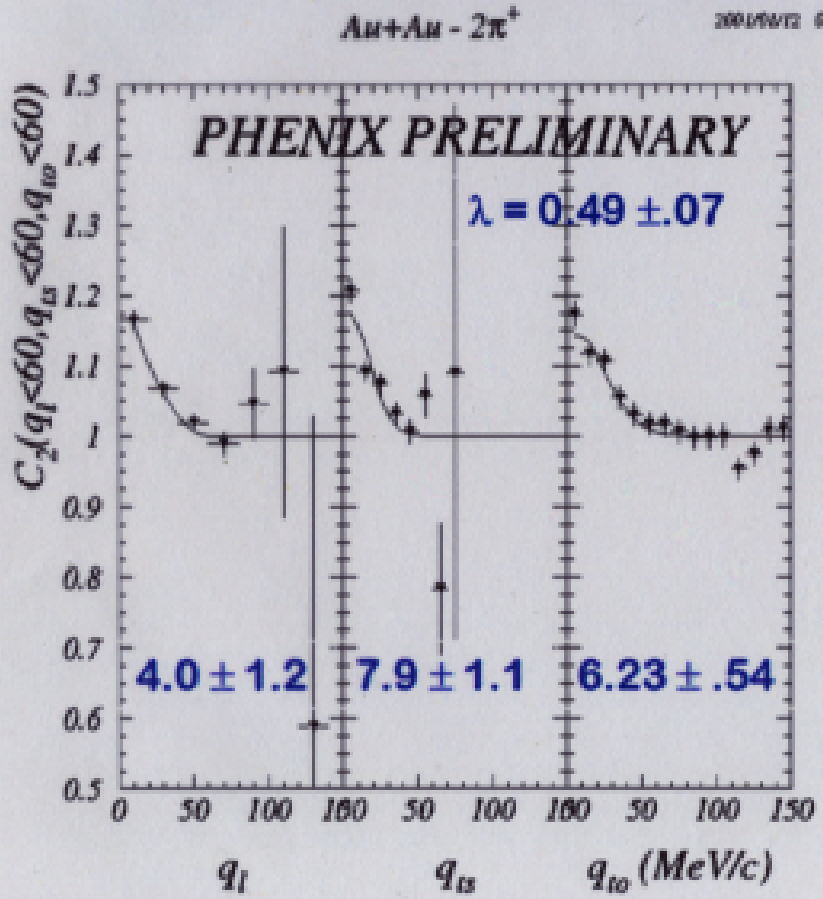
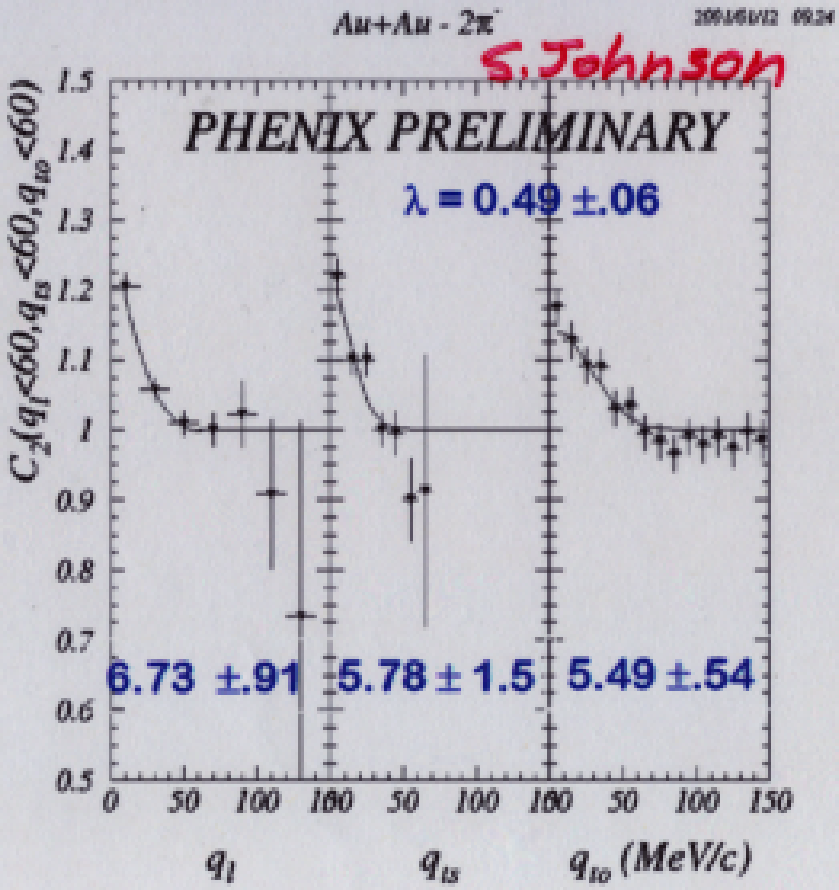
First Phenix HBT results

★ A proof of principle analysis
- 20% most central
- Full Coulomb Correction
- No evidence for large expansion





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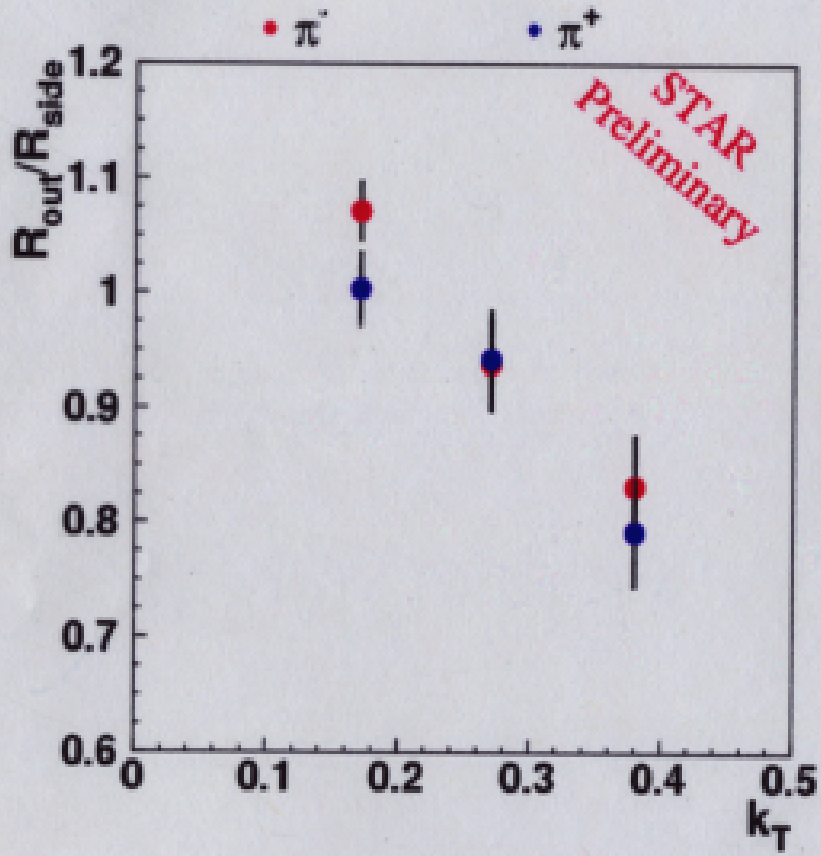
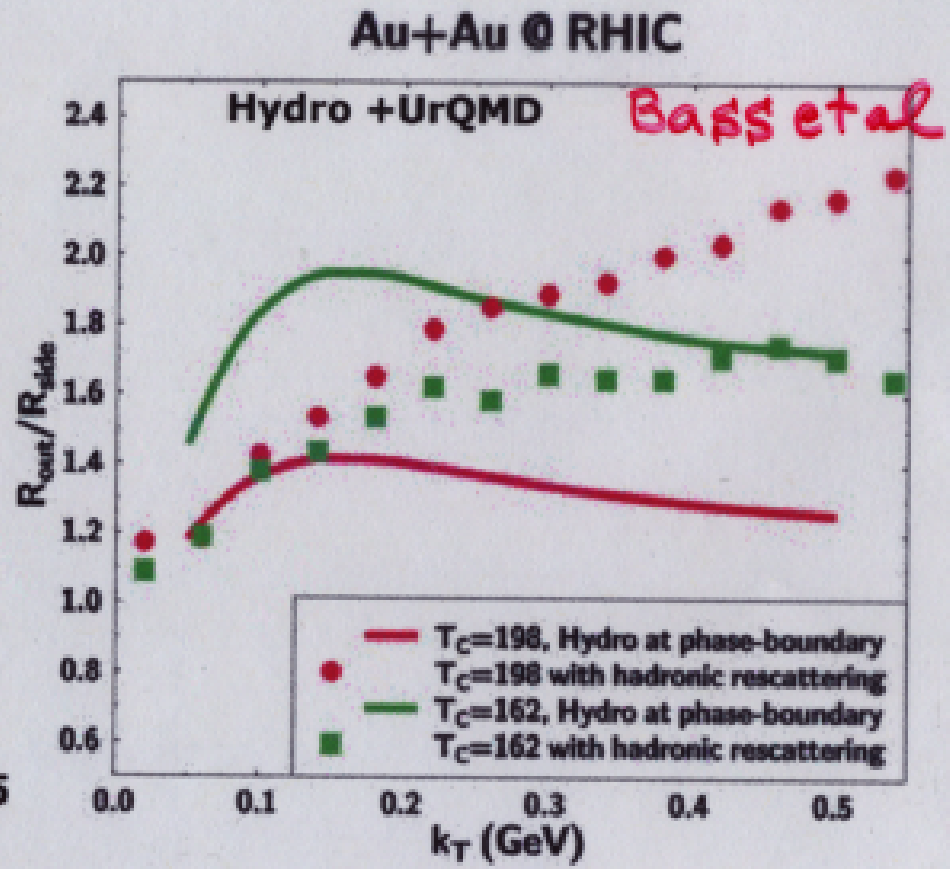
The R_{out}/R_{side} Ratio





Smaller observed ratio than expected ?!
Different K_T dependence ?!

need other handles → HBT relative to the reaction plane

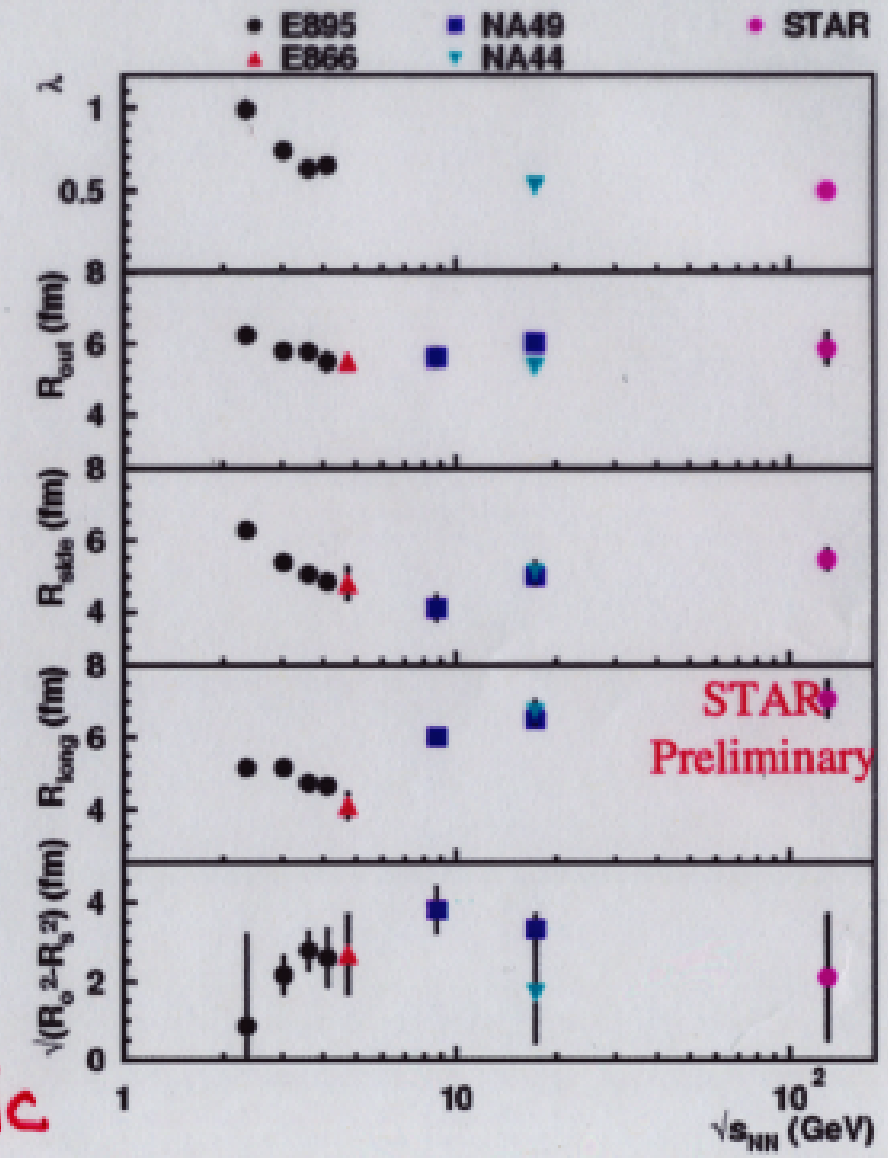
The HBT Excitation function

Compilation of world BP 3D ππ-HBT parameters as a function of √s

- ~10% Central AuAu(PbPb) events
- y ~ 0
- k_T ≈0.17 GeV/c

no significant rise in spatio-temporal size of the π emitting source

rapid change @ AGS
smooth evolution SPS-RHIC



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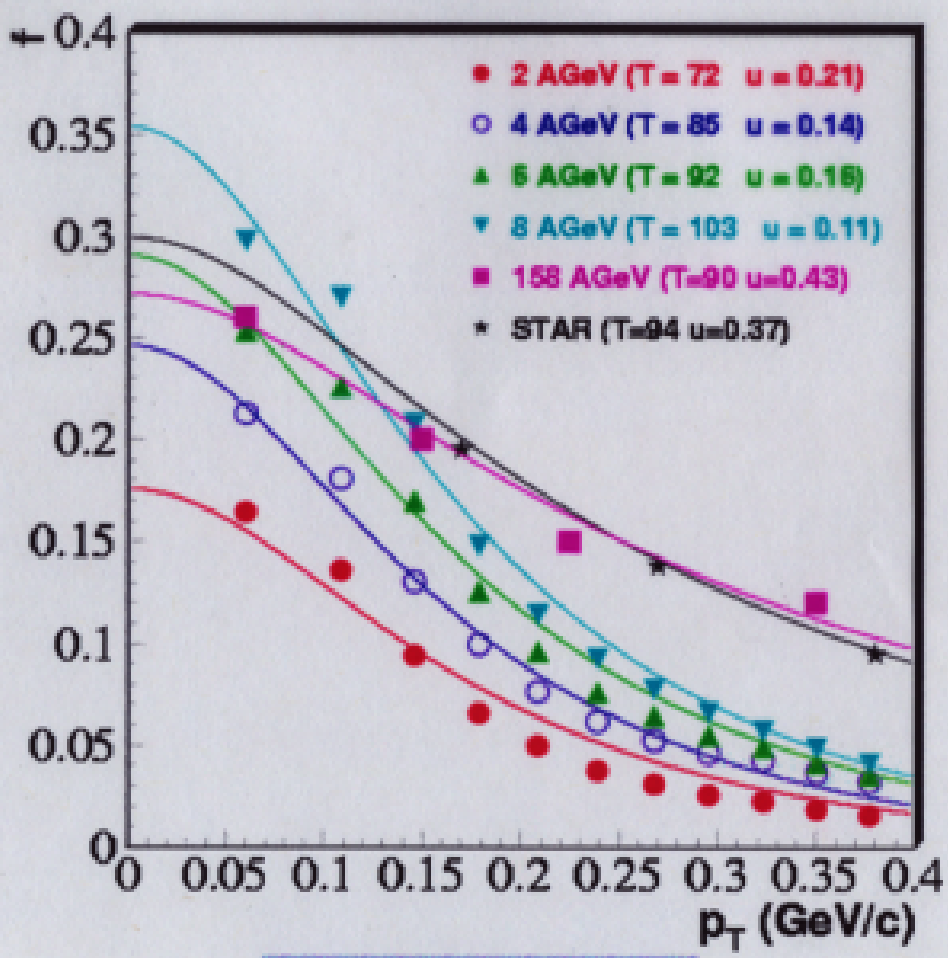
Pion Phasespace Densities

- non-universal growth of ⟨f⟩ with collision energy
- f<1 → no condensate
- low-p_T saturation of ⟨f⟩ as E_{beam} → 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

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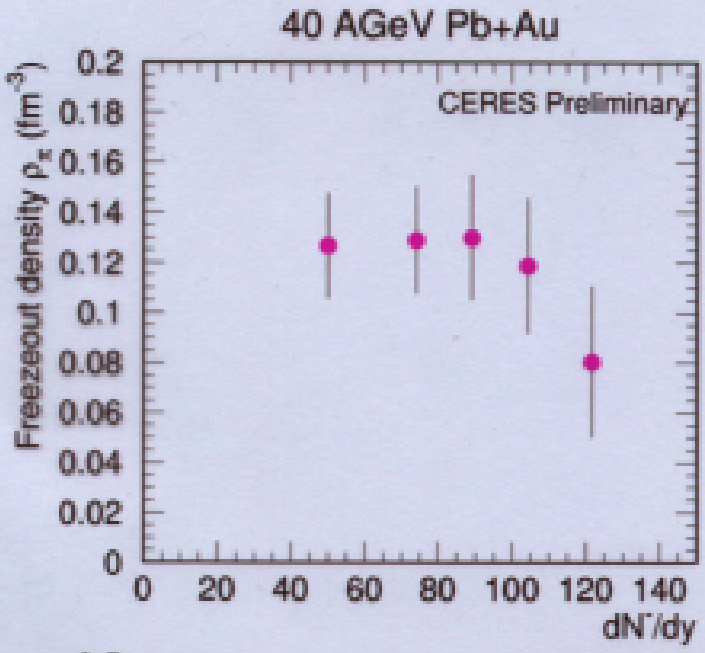
Pion Freeze-out

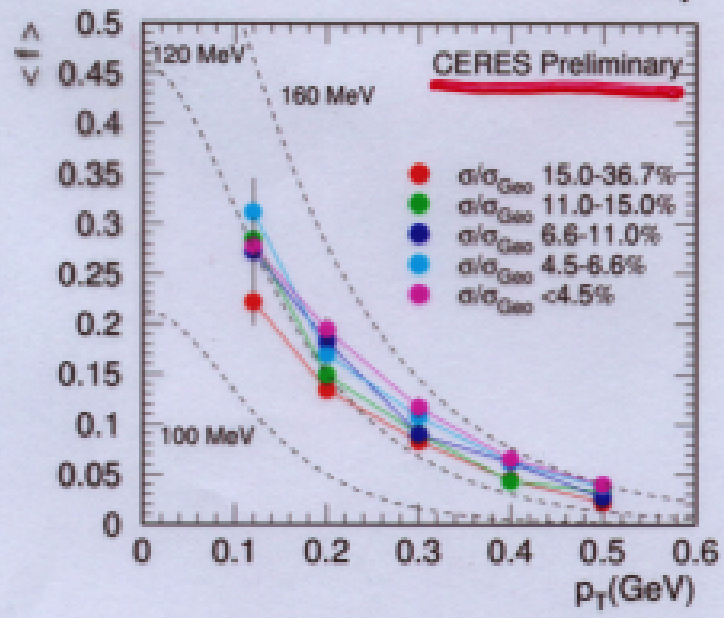
Freeze-out density:

$$\rho_\pi = \frac{\mathrm{d}n/\mathrm{d}y}{2\pi \cdot R^2_{\mathrm{Geo}} \cdot \tau_0}$$

Phase-space density (Bertsch):

$$< f > (p_T, y) = \sqrt{\lambda(p_T, y)} \frac{\frac{\mathrm{d}n^-}{\mathrm{d}y} \frac{1}{2\pi T^2_{\mathrm{eff}}(y)} e^{-p_T/T_{\mathrm{eff}}(y)}}{\pi^{-3/2} m_T \cosh y \cdot R^2_{\mathrm{Side}}(p_T, y) \cdot R_{\mathrm{Long}}(p_T, y)}$$





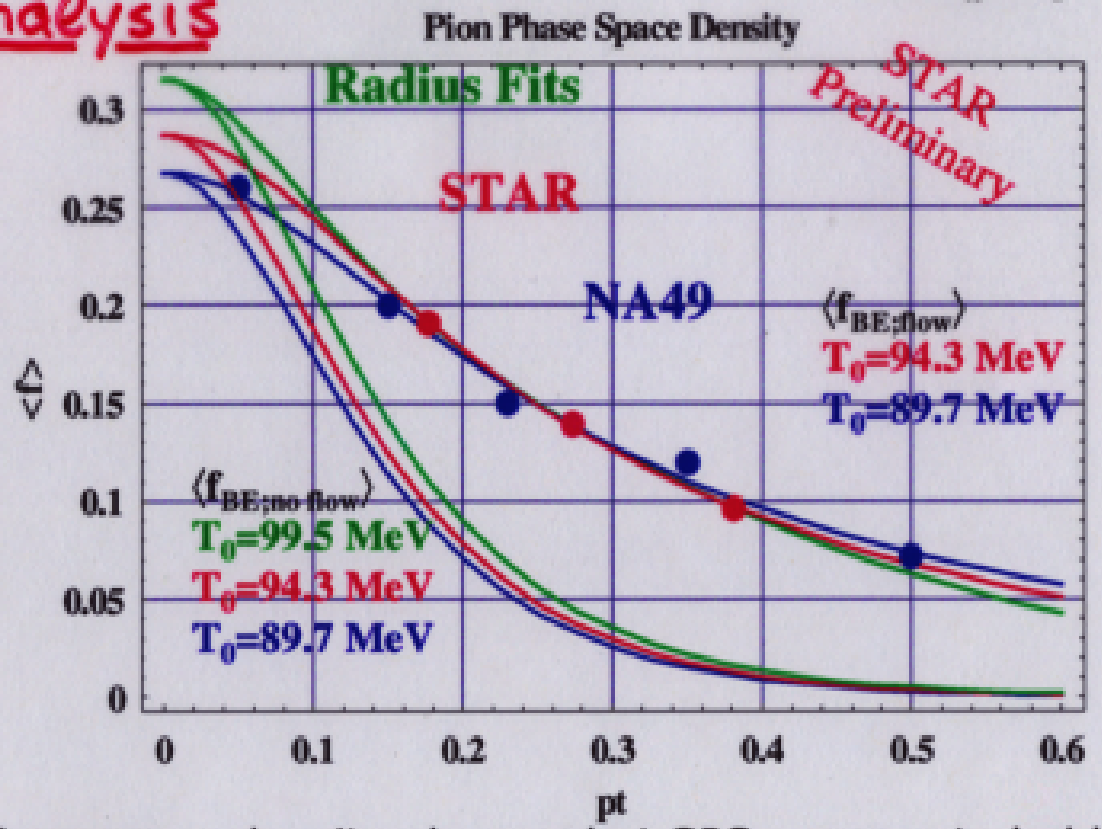
Consistent with universal P.S.D.

Pion Phasespace Density

pion occupation of cell in coordinate⊗momentum space:

$$\langle f \rangle (m_T) = \frac{(\hbar c)^3}{2\, E_\pi\, m_T} \frac{d^2N}{dy\, dm_T} \frac{(\lambda\, \pi)^{1/2}}{R_O\, R_S\, R_L}$$

combined analysis
HBT + specta



- "Universal" phasespace density observed at SPS appears to hold at RHIC as well
- Consistent with thermal distribution (T≈94MeV) and strong collective flow (β ≈0.58)
- Fundamental phasespace saturation may relate increases in geometry, temperature, multiplicity

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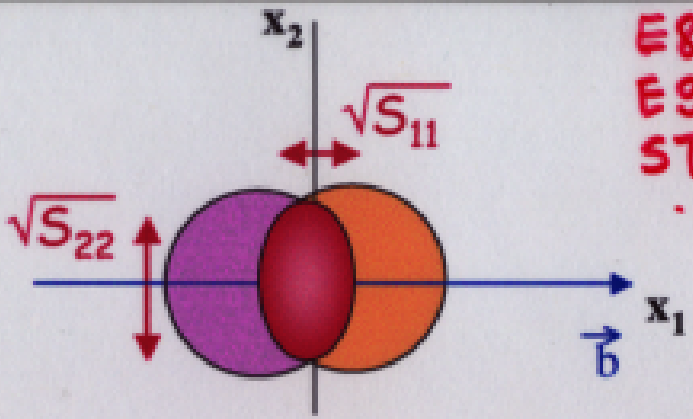
HBT relative to the Reaction Plane

combined analysis: HBT + flow

2nd-harmonic oscillations from elliptical transverse shape



E895
E917
STAR
. . . .

$$R_o^2 = -\tfrac{1}{2}(S_{22} - S_{11})\cos 2\phi + \tfrac{1}{2}(S_{11} + S_{22}) + \beta_\perp^2 S_{00}$$

$$R_s^2 = +\tfrac{1}{2}(S_{22} - S_{11})\cos 2\phi + \tfrac{1}{2}(S_{11} + S_{22})$$

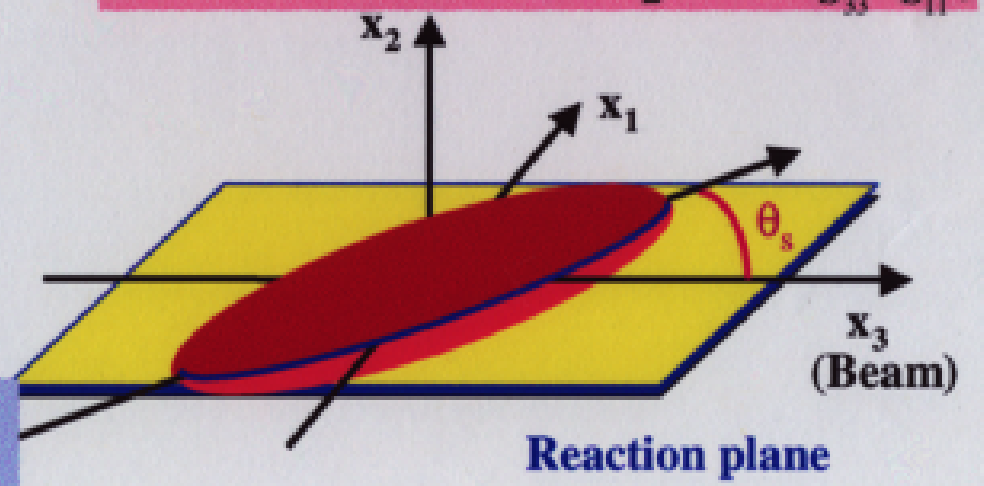
$$R_{os}^2 = +\tfrac{1}{2}(S_{22} - S_{11})\sin 2\phi$$

$$R_l^2 = S_{33} + \beta_L^2 S_{00}$$

$$R_{ol}^2 = S_{13}\cos\phi$$

$$R_{sl}^2 = -S_{13}\sin\phi$$

1st-harmonic oscillations reveal spatial tilt angle $\theta_s = \frac{1}{2}\tan^{-1}\left(\frac{2S_{13}}{S_{33} - S_{11}}\right)$



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

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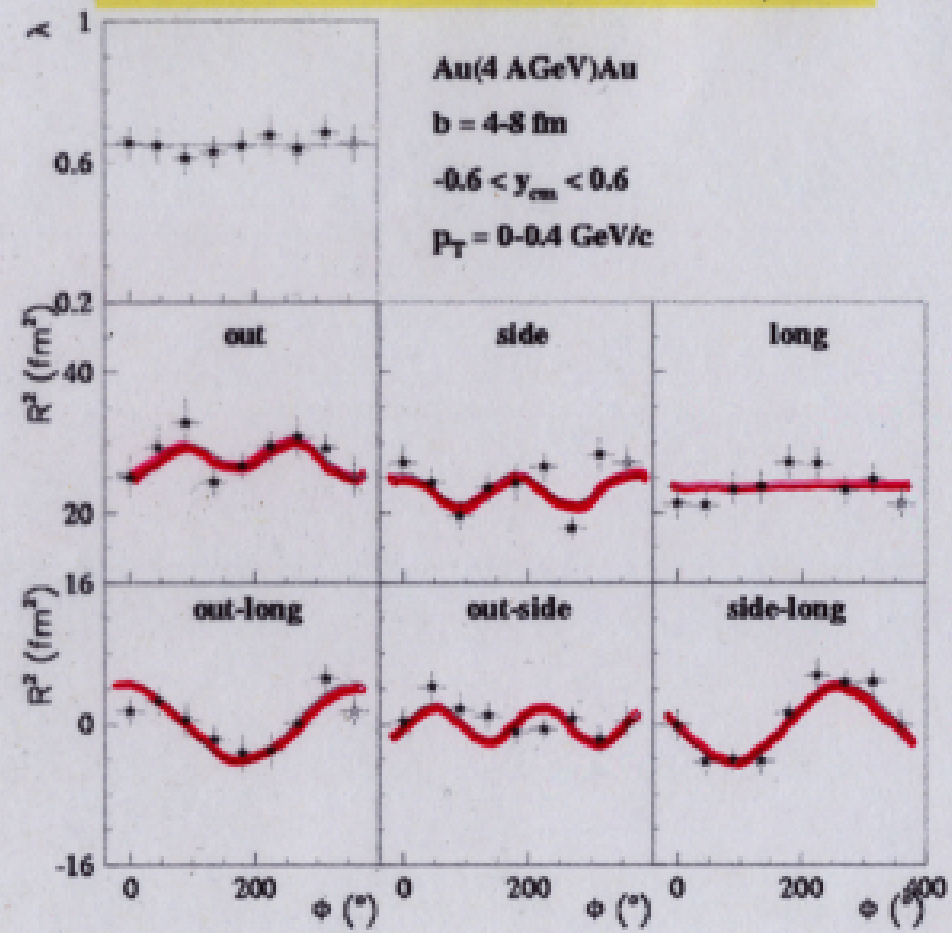
Extracting the underlying geometry

E895

Lines: simultaneous fit to R(ϕ)



$$S = \begin{pmatrix} 13.4\pm3.5 & 0.7\pm0.9 & 0.2\pm1.0 & 0.0\pm1.1 \\ 0.7\pm0.9 & 21.3\pm0.9 & -0.1\pm0.6 & 4.5\pm0.6 \\ 0.2\pm1.0 & -0.1\pm0.6 & 25.5\pm1.0 & -0.3\pm0.6 \\ 0.0\pm1.1 & 4.5\pm0.6 & -0.3\pm0.6 & 22.8\pm0.9 \end{pmatrix}$$

after (small) reaction plane resolution corrections...

$$\theta_s = \frac{1}{2}\tan^{-1}\left(\frac{2S_{13}}{S_{33}-S_{11}}\right) = 37^\circ \pm 4^\circ$$

$$R^T(\theta_s)\cdot S\cdot R(\theta_s) = \begin{pmatrix} 13.4\pm3.5 & 0.5\pm1.0 & 0.2\pm1.0 & 0.4\pm1.0 \\ 0.5\pm1.0 & 15.9\pm1.0 & 0.1\pm0.6 & 0\pm0.9 \\ 0.2\pm1.0 & 0.1\pm0.6 & 27.0\pm1.4 & -0.3\pm0.6 \\ 0.4\pm1.0 & 0\pm0.9 & -0.3\pm0.6 & 26.8\pm0.8 \end{pmatrix}$$

most detailed information available with HBT so far.

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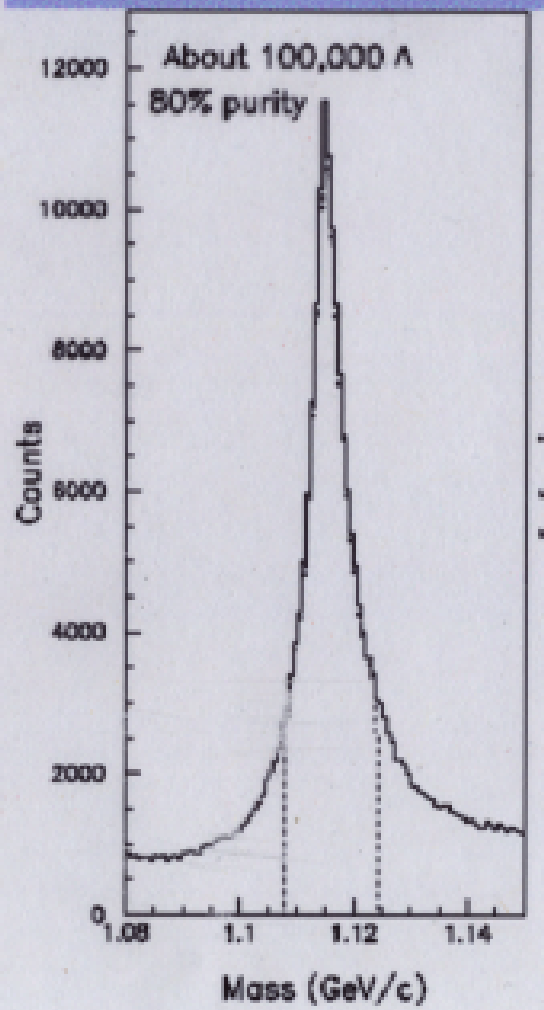
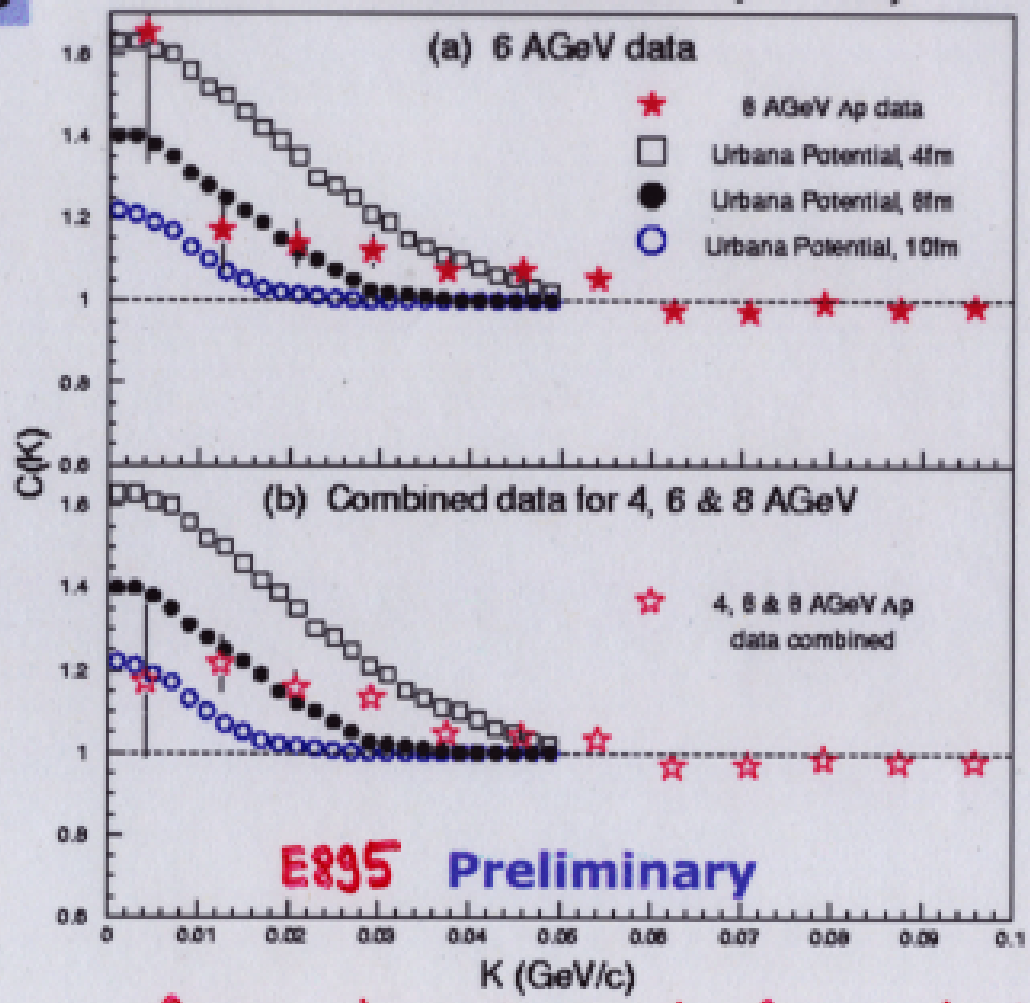
E895 - First Λp Correlations

proposed by S. Pratt, F.Q. Wang

6 AGeV Λ Invariant Mass



Λ-P Correlation Function (b < 7fm)



clear signal, not clear what it means

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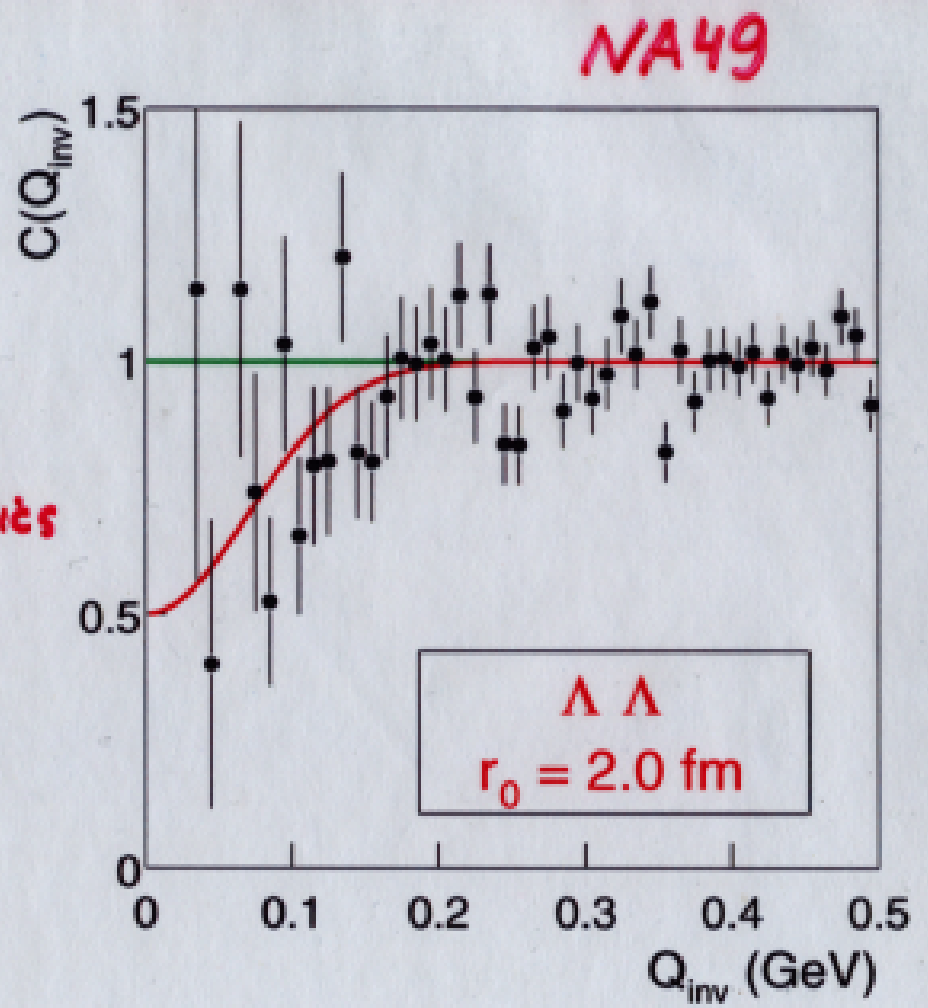
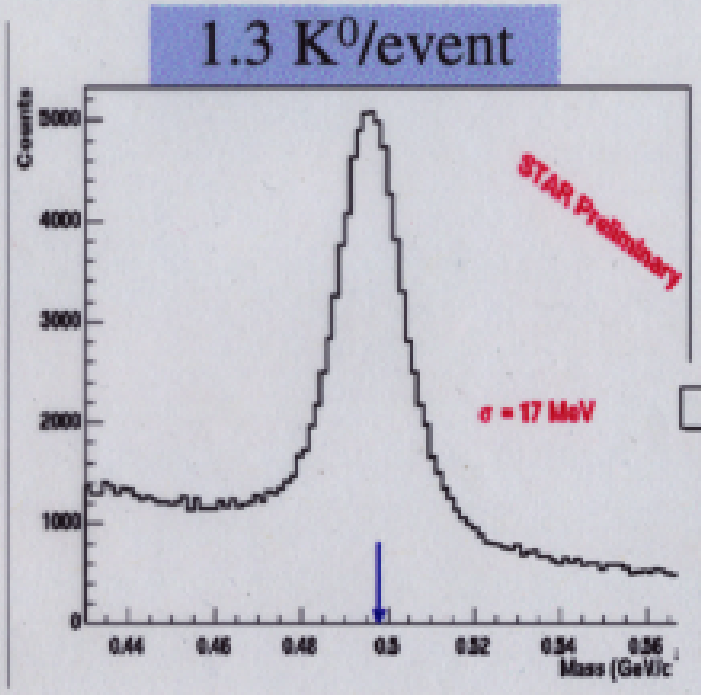
ΛΛ-Correlations

- Interaction of strange baryons
- Analyzed: 900k central Pb+Pb events @ 158 *A*GeV
  - 0.44 Λ/event
  - 5700 ΛΛ-pairs with $Q_{inv} < 0.5$ GeV
- Indication for anti-correlation
  consistant with Fermi-Dirac statistics
  → no or weakly repulsive FSI
- Existence of H^0-dibaryon questionable



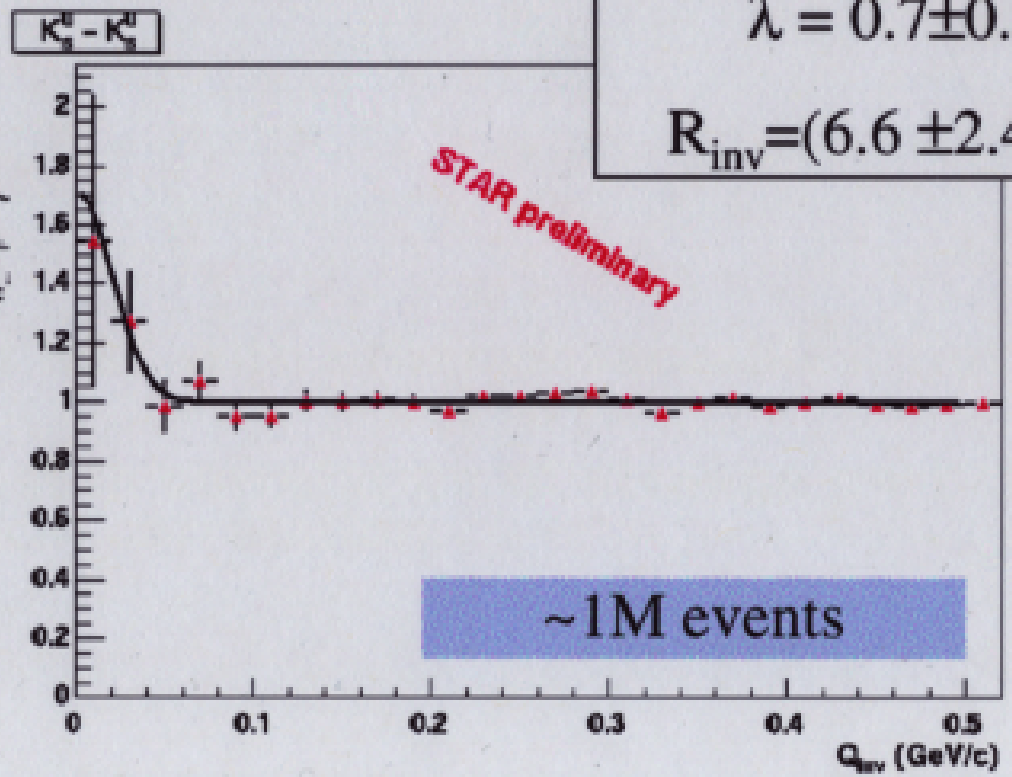
$K^0_S K^0_S$ - Correlations (Poster by T.Humanic)



- no coulomb repulsion problems
- less 2 track resolution problems
- few distortions from resonance decays

$\lambda = 0.7 \pm 0.5$

$R_{inv} = (6.6 \pm 2.4)$fm



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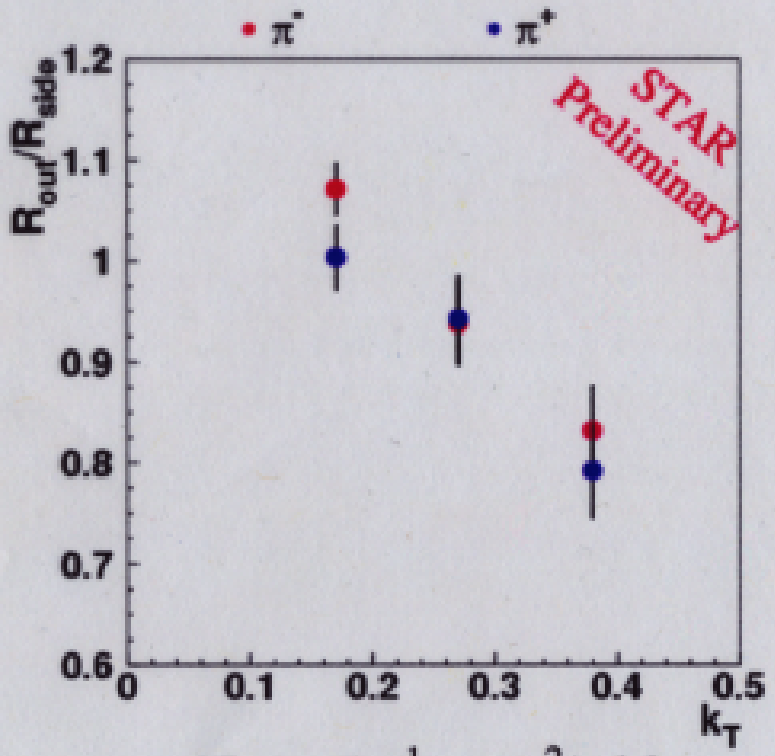
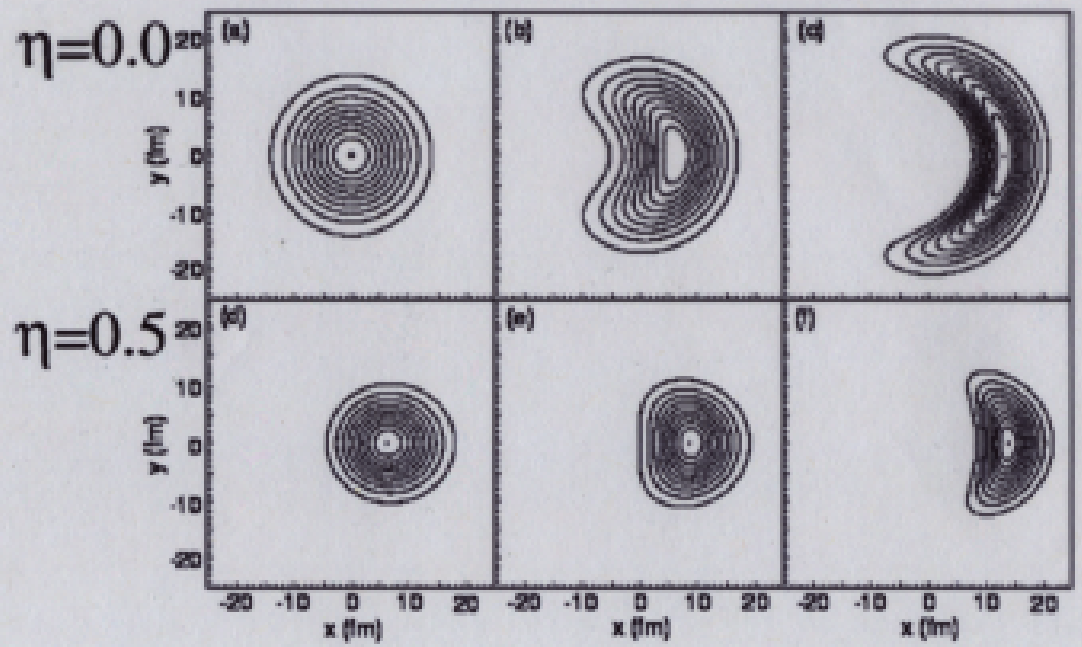
The Rout/Rside Ratio

emission duration for transparent sources: $\tau = \sqrt{R_{Out}^{\ 2} - R_{Side}^{\ 2}} \Big/ \beta_T$



$$K_T = (p_T^1 + p_T^2)/2$$

Tomášik, Heinz nucl-th/9805016



ω=0 ω=1 ω=10

$$\eta(r) = \eta_f \left(\frac{r}{R} \right) \qquad \omega = R/\lambda$$

flow / opaqueness

explosive SOURCE

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HBT Summary

- ★ Impressive HBT systematics emerged since QM99
- ★ New data from AGS, SPS and RHIC
- ★ Similar HBT signals at 40 and 158 AGeV at SPS
- ★ Smooth HBT excitation function between SPS and RHIC
- ★ Universal freeze-out phasespace density holds at RHIC (and 40 AGeV SPS)
- ★ Evolution of phasespace density at AGS
- ★ No dramatic increase in apparent size and lifetime at RHIC
- ★ Rout/Rside puzzle at RHIC -> explosive source?
- ★ New analysis trends:
  - Combination of HBT with other observables: flow, spectra
  - Growing interest in correlation of strange particles and non-identical correlation..

★ Stay Tuned! Work is in Progress.

Fluctuations

- ★ **Theoretical activities**
  - Conserved quantities fluctuations
  - Study of the real world complications
  - Balance functions
- ★ **SPS results**
  - $\langle P_t \rangle$ Fluctuation - Na45, NA49
  - Charge ratios fluctuations - NA49
  - DCC search, N_γ N_{ch} fluctuations- WA98
  - Event texture analysis - NA44
- ★ **STAR results**

Theory I

- ★ E-by-E Fluctuations in relativistic heavy ion collisions have attracted a lot of attention
- ★ Strong interest in conserved quantities (charge, baryon number, strangeness) fluctuations

  (Talks by V. Koch, M. Asakava, M. Stephanov, S. Gavin, ...)
- ★ Use intensive variables to avoid volume fluctuations
- ★ Ratio fluctuations: π^+/π^-, N^+/N^-, K+/K-, baryon number, ...

For example for charge fluctuations:

$\langle Nch\rangle\langle(\delta R)^2\rangle \sim 3$ for HG

$\langle Nch\rangle\langle(\delta R)^2\rangle \sim 1$ for QGP

Theory II. Real world effects

★ Rescattering in the hadronic phase (talks by Asakawa, Stephanov, Gavin, Koch)

Rescattering in hadronic phase reduces signal

Use large rapidity window Dy!

Study signal as a function of Dy

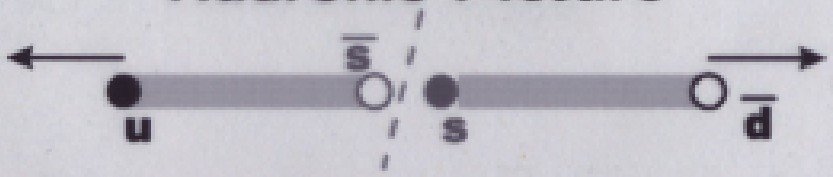
Acceptance corrections are essential (Koch)

Waiting for the data....

Motivation

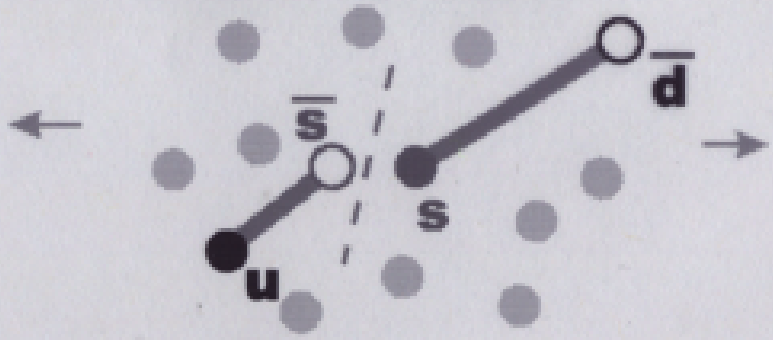
Suppose one could identify *balancing* charges? (e.g. K^+, K^-)

Hadronic Picture



- Hadrons appear at $\tau \approx$ 0.5 fm/c.
- String dynamics separate balancing $Q-\bar{Q}$ by $\Delta y \sim 1$.
- Strangeness annihilates with time, reduces probability of small Δy.

QGP Picture



- Hadronization at 5-10 fm/c into collision, $T \approx 165$.
- Many $q\bar{q}$ pairs created during hadronization.
- Balancing charges separated by $\Delta y \sim v_{\text{therm.}}$

Narrow distribution in Δy signals late production of $q\bar{q}$ pairs.
$\rightarrow$ novel phase persisted substantial time.

What are Balance Functions?

Given the existence of a particle with momentum p_1, balance functions describe the probability of seeing a particle of opposite charge with momentum p_2.

$$B(p_2|p_1) \equiv \frac{1}{2}\{\rho(+Q,p_2|-Q,p_1) - \rho(-Q,p_2|-Q,p_1) + \rho(-Q,p_2|+Q,p_1) - \rho(+Q,p_2|+Q,p_1)\}$$

Here $\rho(b,p_2|a,p_1)$ is the conditional probability,

$$\rho(b,p_2|a,p_1) = \frac{N(a,p_1;b,p_2)}{N(a,p_1)}$$

Common binning choice:

1. p_1 is anywhere in detector.
2. p_2 refers to relative rapidity.

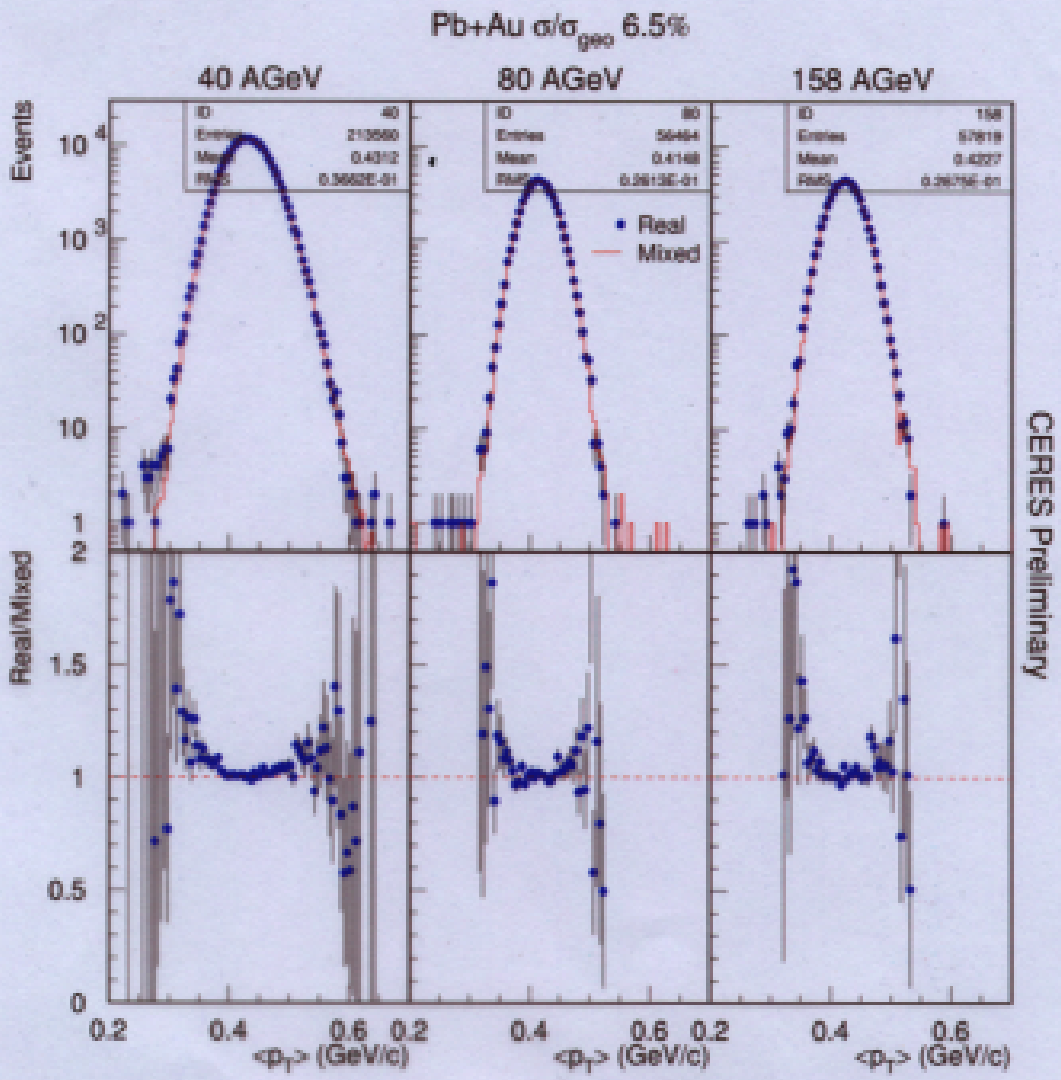
Can be applied to specific particle/antiparticle pairs, e.g. π^+/π^-, or to specific charges, e.g. (all antibaryons)/(all baryons).

CERES H. Appelshaeuser

Event-by-Event $< p_T >$ Fluctuations

	N_{events}	$< N_{tracks} >$	Φ_{p_T}real (MeV)	Φ_{p_T}mix (MeV)
40 AGeV	216881	77.8	5.5 ± 0.7	0.0 ± 0.2
80 AGeV	56464	128.7	3.7 ± 0.9	-0.5 ± 0.8
158 AGeV	57819	129.4	7.8 ± 0.9	1.0 ± 0.9

$$0.05 < p_T < 1.5 \text{ GeV}$$



⇒ Upper limit for dynamical fluctuations: $\frac{\sigma_{dyn}}{<p_T>} < 3\%$

Charge-Fluctuations

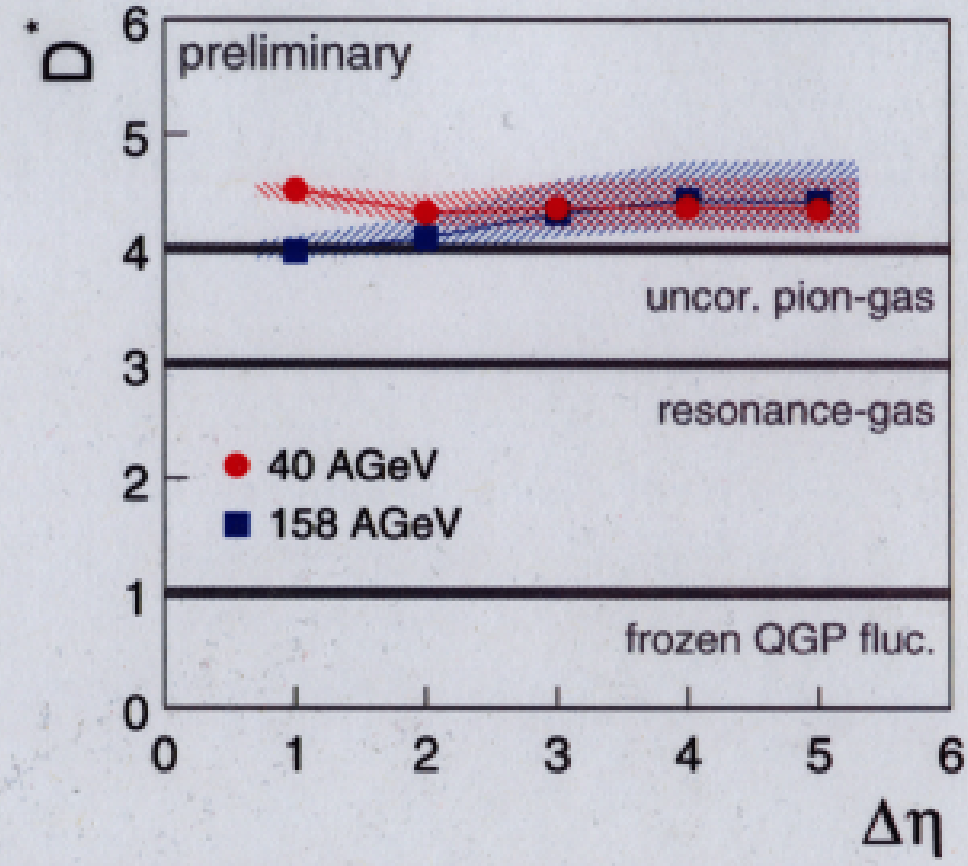
- Event-by-event charge-fluctuations in central Pb+Pb

  S. Jeon and V. Koch
  Phys. Rev. Lett. 85 (2000) 2076-2079
  M. Asakawa, U. Heinz, and B. Müller,
  Phys. Rev. Lett. 85 (2000) 2072-2075

- Corrections for acceptance and net-charge:

$$R = N_+ / N_- \,|_{event}$$
$$D^* = \langle N_{ch} \rangle \langle \delta R^2 \rangle / (C_\mu \, C_y)$$
$$C_\mu = \langle N_+ \rangle^2 / \langle N_- \rangle^2$$
$$C_y = 1 - \langle N_{ch} \rangle / \langle N_{ch} \rangle_{total}$$

  M. Bleicher, S. Jeon, and V. Koch,
  Phys. Rev. C62 (2000) 061902



- Analysis done as function of the acceptance window Δη around mid-rapidity
- $D^* \approx 4 \rightarrow$ uncorrelated pion-gas
- No difference between 40 and 158 *A*GeV

NA49

WA98 Results

- ★Search for localized fluctuations in the multiplicity of charged particles and photons in $\eta-\phi$ space using PMD and SPMD
- ★Wavelet analysis + $N_\gamma - N_{ch}$ multiplicity fluctuations

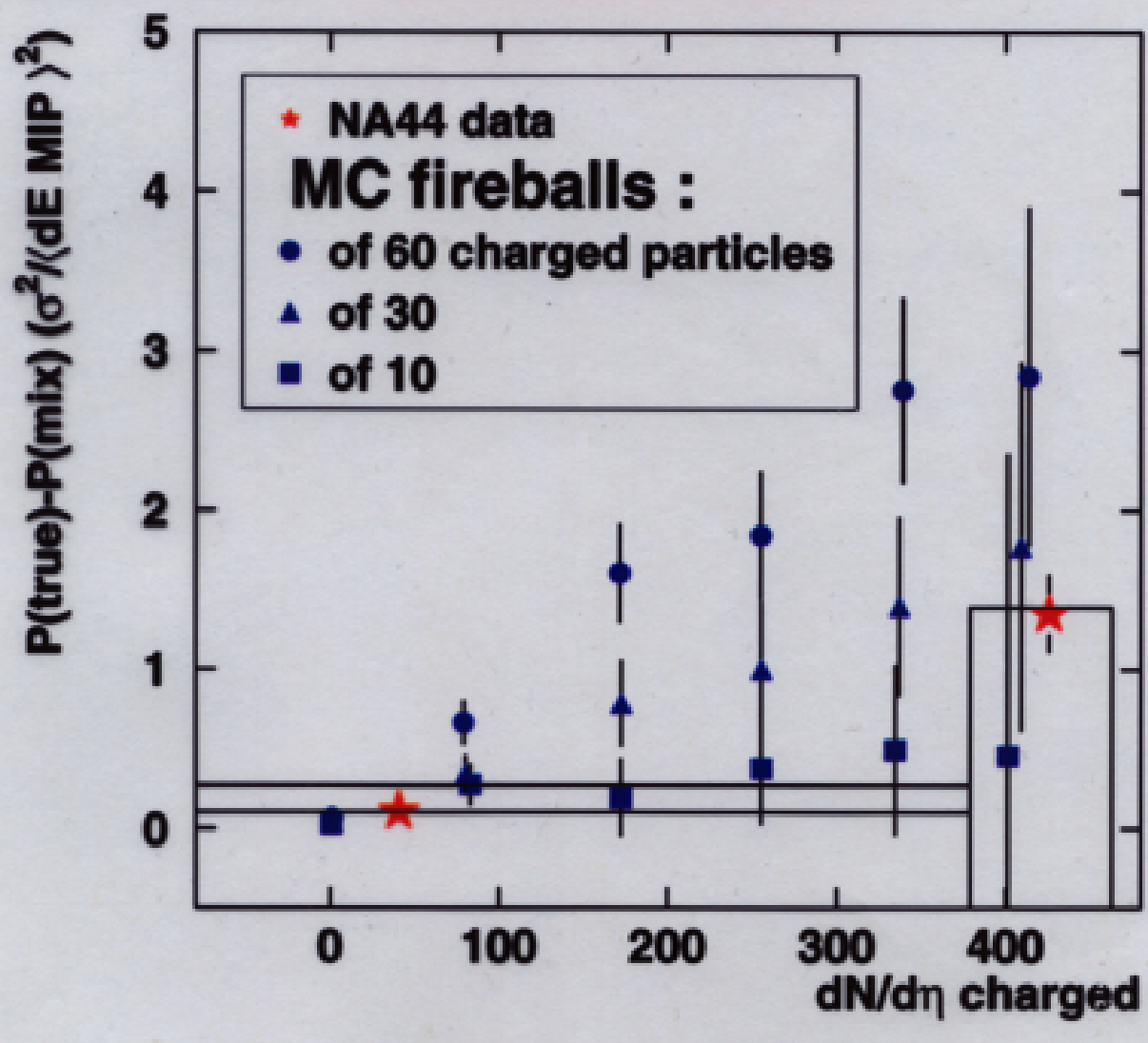
Conclusions:

- ★Upper limit on DCC ($<3\times10^{-3}$)
- ★No correlated E-by-E fluctuations of $N_\gamma - N_{ch}$
- ★Individual N_γ, Nch fluctuations
  - Not yet clear what would be the physics of it...

T. Nayak (Posters P075,P087)

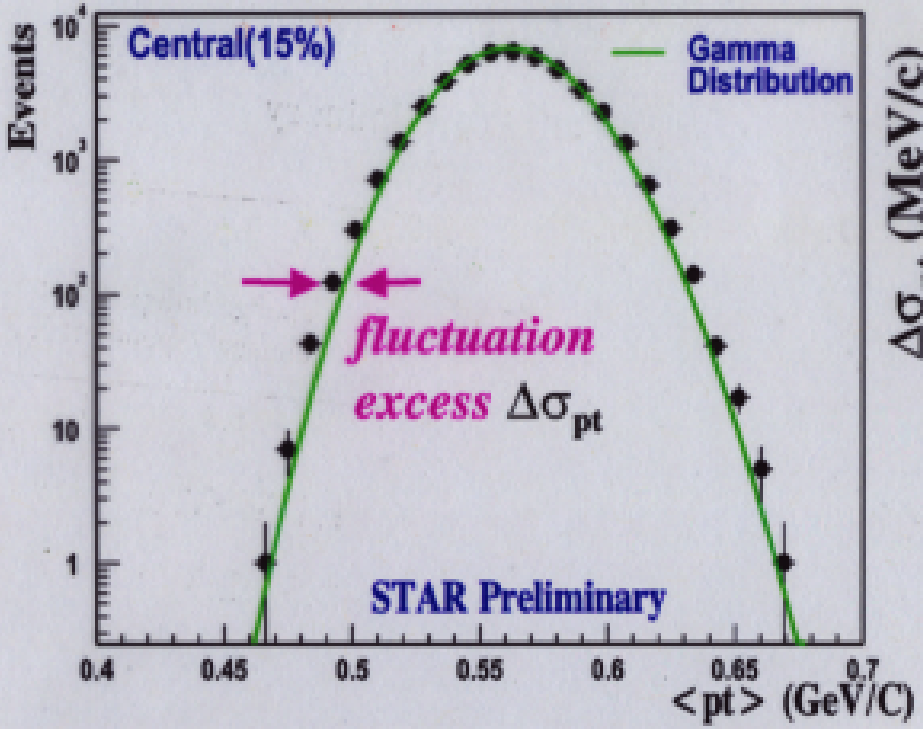
Mikhail KOPYTINE (Stony Brook) for NA44:

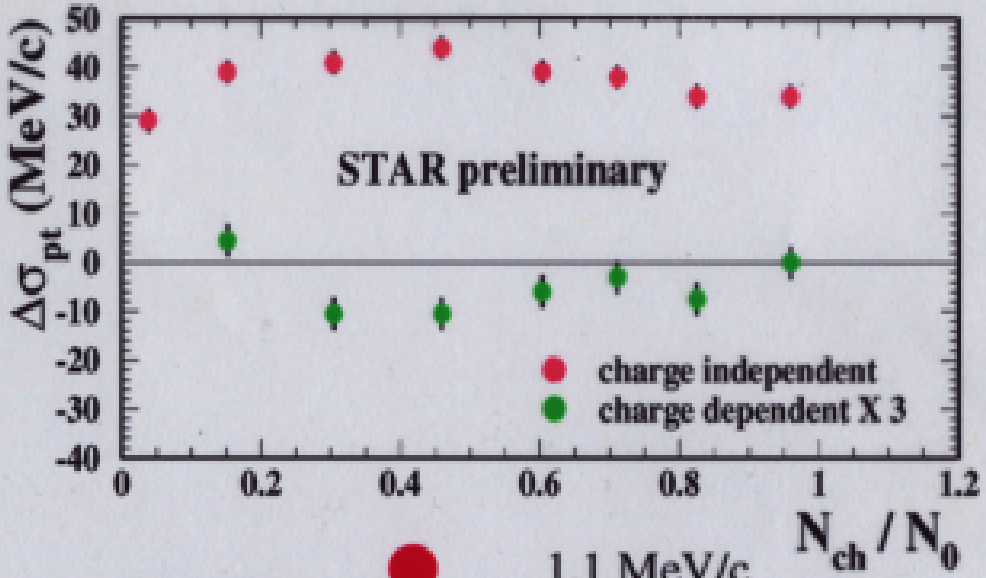
Search for local fluctuations in N_{ch} in (η, ϕ) space using *event texture analysis* .



The method is sensitive to local fluctuations; no evidence of critical phenomena.

STAR E-by-E Results





NA49: 1.1 MeV/c, −8.5 MeV/c

★ Substantial $\langle p_t \rangle$ fluctuation excess is observed over a range of collision centralities

★ Centrality dependence differs for charge-dependent ( ) and charge- independent ( ) excess

Talk by J.G. Reid: Par. Sess. III - Friday

● [(++) + (−−)] / [(+−) + (−+)] ● [(++) + (−−)] * [(+−) + (−+)]

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Fluctuations

Summary

- ☆ Intense Theoretical Activity
  - -new ideas, observables
- ☆ Many new results from SPS
- ☆ No clear message at SPS energies: <Pt>, Nch
- ☆ New data from STAR – evidence of dynamical fluctuations?!
- ☆ Stay tuned……