Probing spatial anisotropy at freeze-out with HBT

Dan Magestro
The Ohio State University

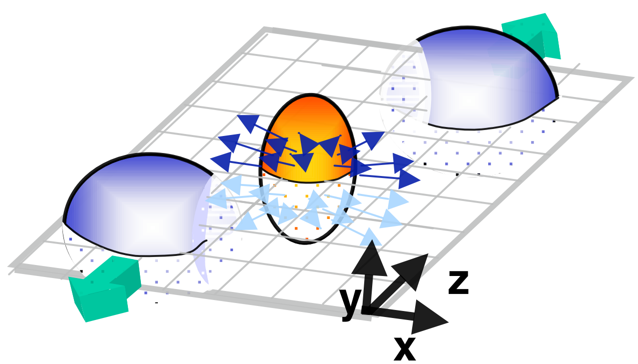
Riken/BNL Flow Workshop, 11/03

HBT in the context of a flow workshop

HBT relative to the reaction plane in Au+Au collisions

Sensitivity of HBT(□) to freeze-out parameters

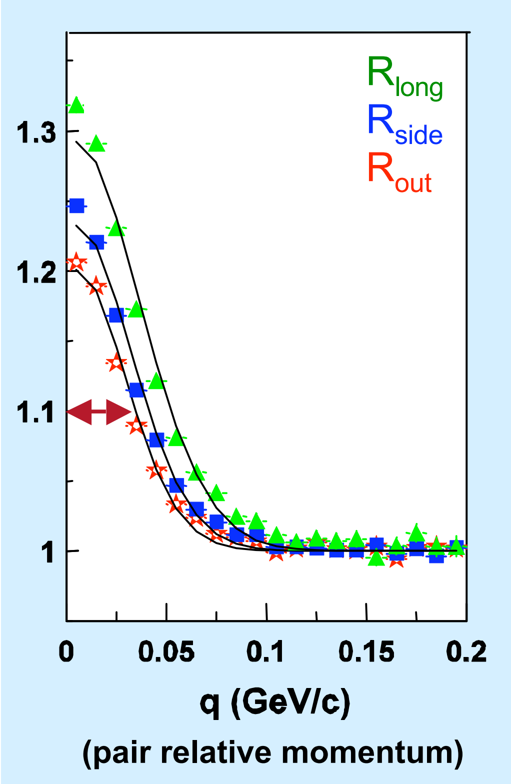
Initial vs. final eccentricity of source



HBT

- Goal: quantify contributions to space-time evolution (**STE**) of system
  - Lifetime and duration of emission
  - Spatial extent of system
  - Collective flow
- Single-particle p_T spectra & v_2 also determined by STE, but...
- Bose-Einstein $\vec{p}$ correlations **disentangle STE**

  1. Pairs of identical pions experience B-E correlations
  2. Hanbury-Brown Twiss interferometry: characterize correlations through intensity interferometry
  3. Width of correlation peak as q 0 reflects "length of homogeneity"



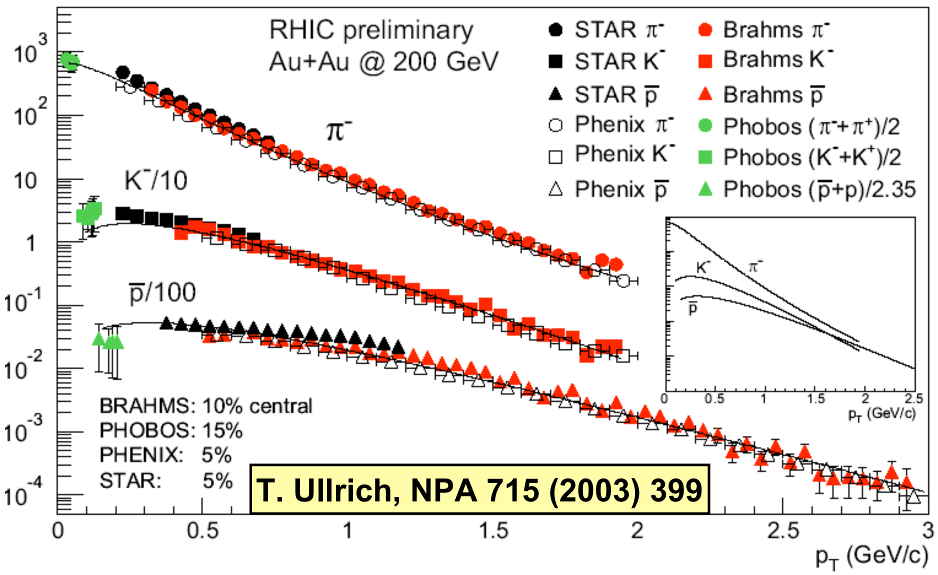
static source: HBT radii _ true geometrical size of system

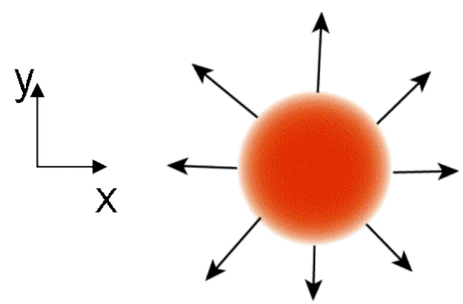
dynamic source: HBT radii _ x-p correlations reduce observed radii

Transverse flow & HBT - 1

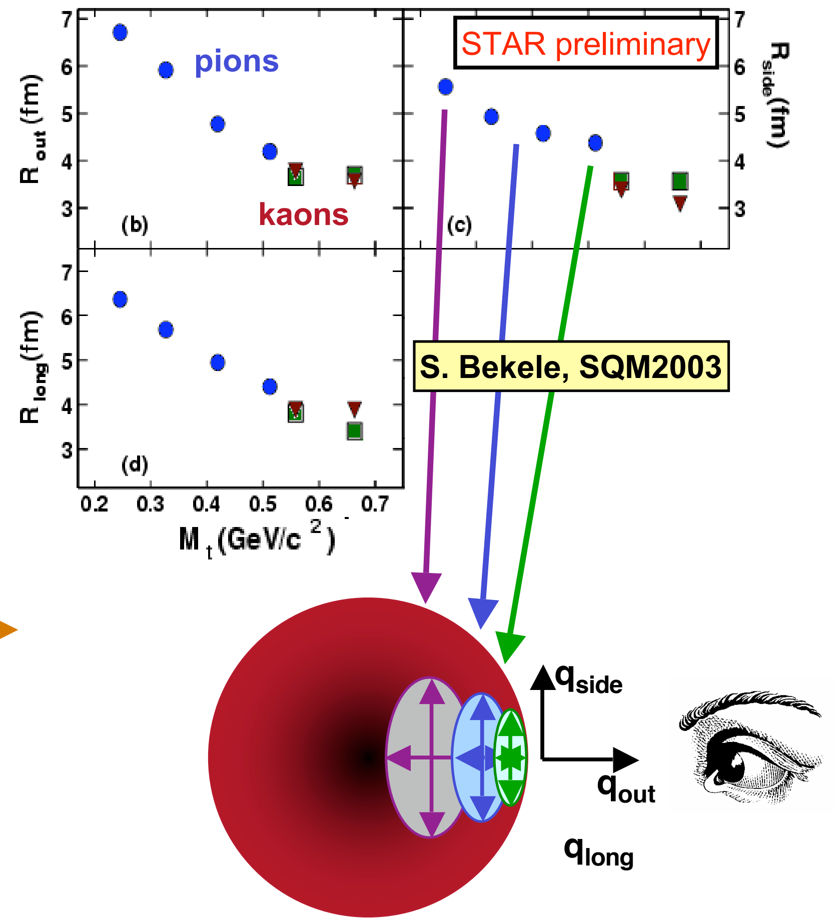
Radial flow

p_T spectra





m_T dependence of HBT radii



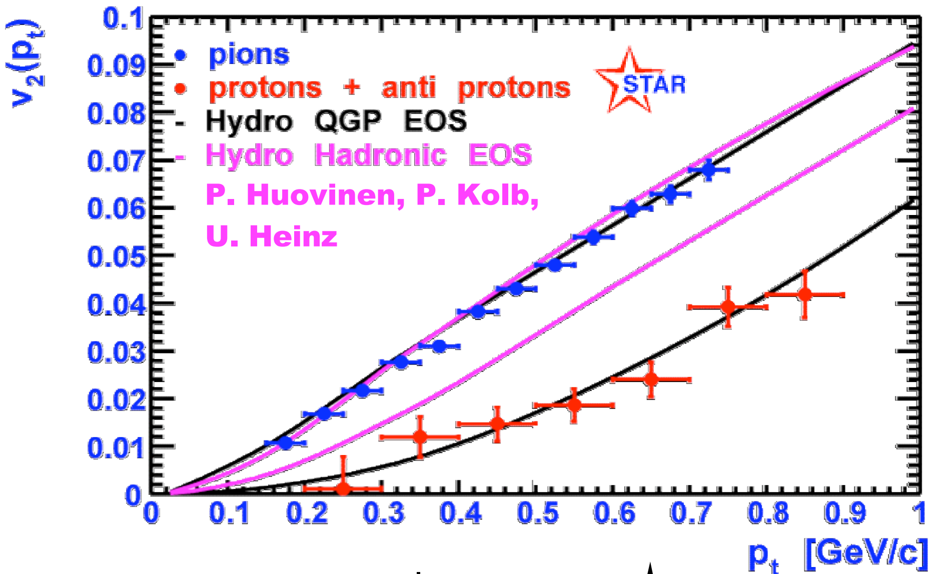
- Integrates pressure history over complete expansion phase

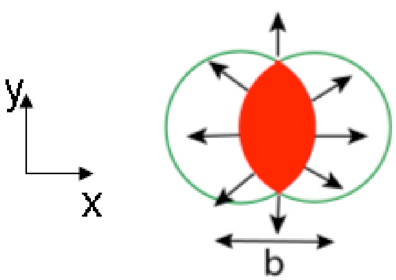
- m_T dependence of transverse HBT radii arises primarily from transverse flow
- Flow pattern, emission duration, source opacity, etc. (model-dependent)

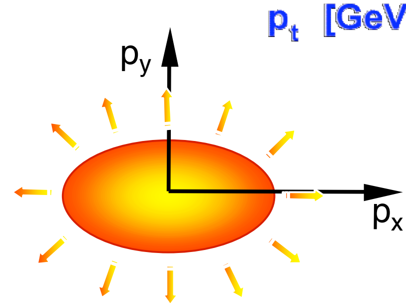
Transverse flow & HBT - 2

Elliptic flow

p-space anisotropy



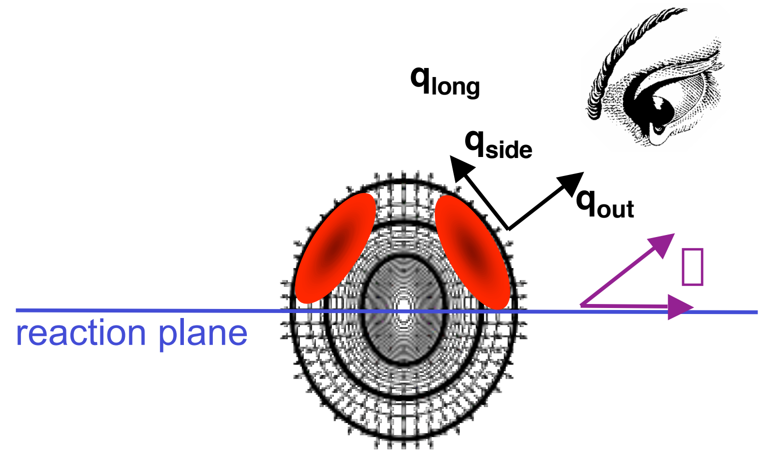




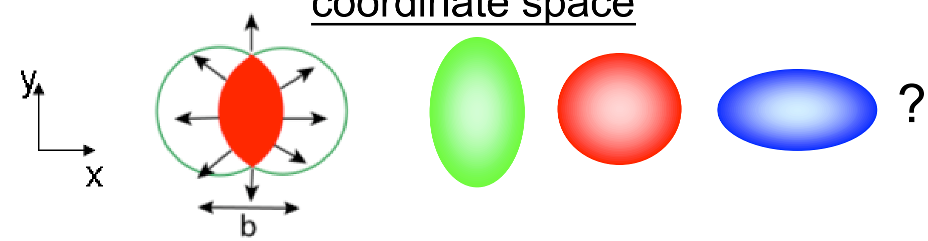
- Sensitive to EOS, probes pressure at early stages of collision

□ dependence of HBT radii

(subject of this talk)



coordinate space



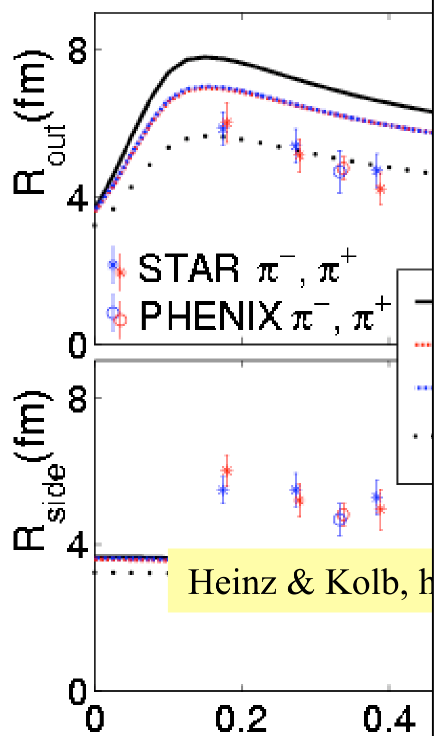
- Source shape at freeze-out _ constrains evolution of system
- Probes pressure gradients, expansion time, flow profile, etc.
- *Does the strong elliptic flow "quench" the initial spatial anisotropy?*

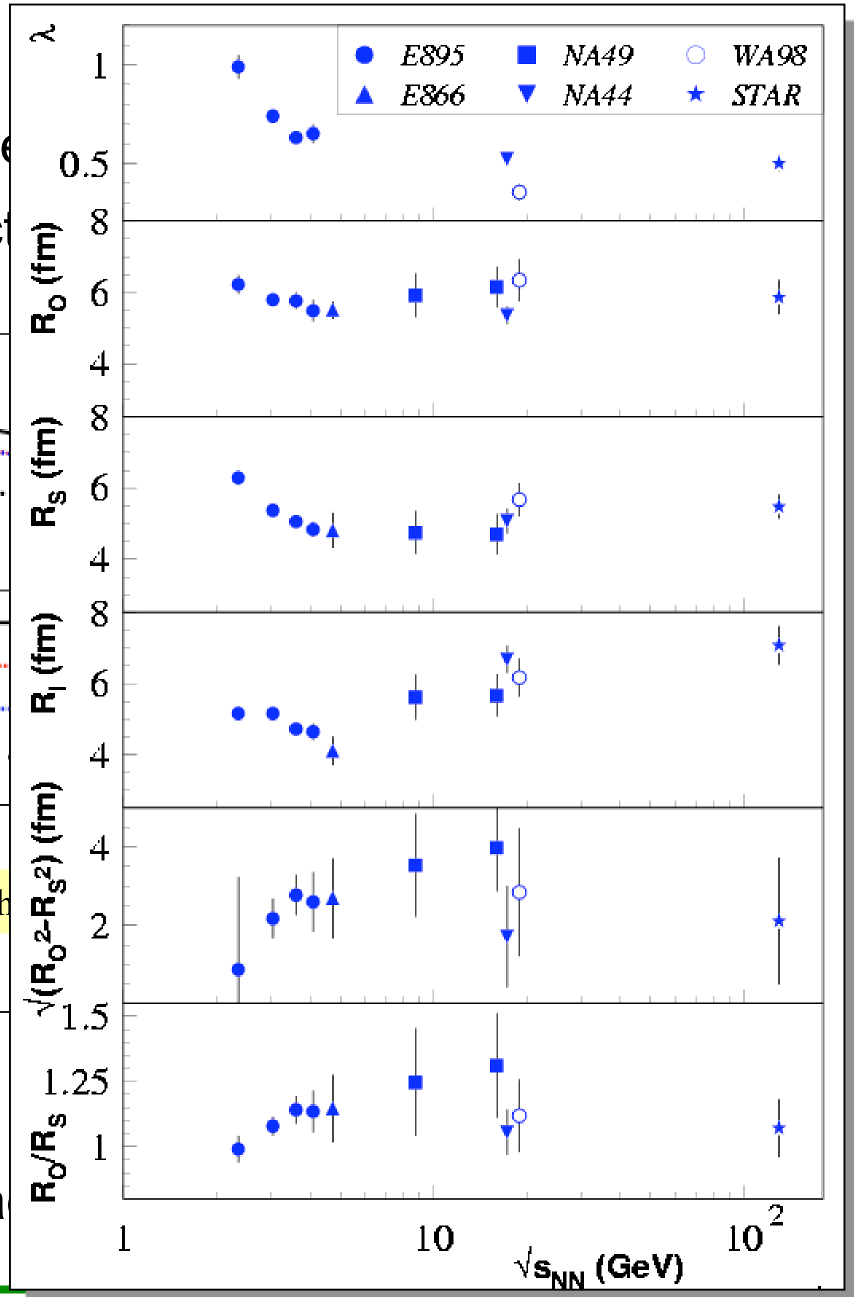
Hydrodynamics and HBT at RHIC

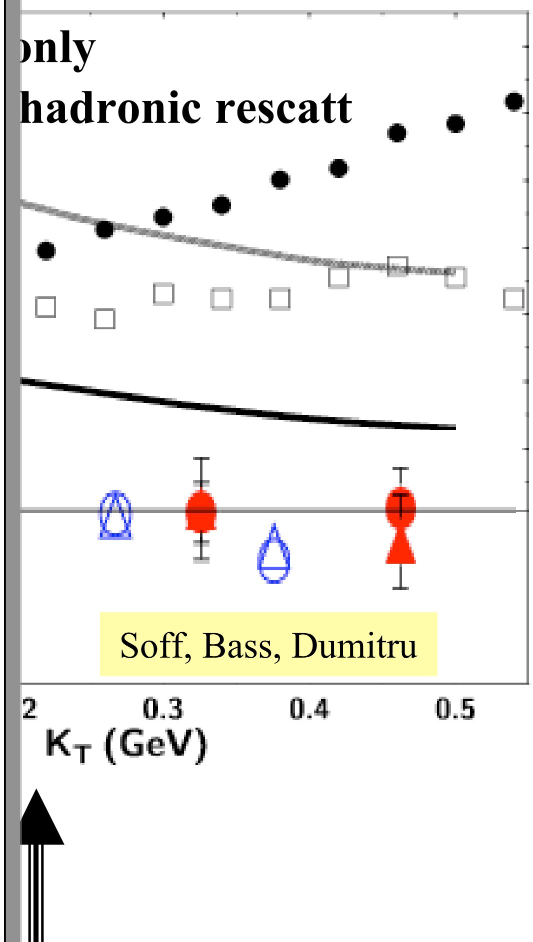
Hydrodynamics

- Successfully r
- ☹ Fails to predict

"HBT Puzzle"



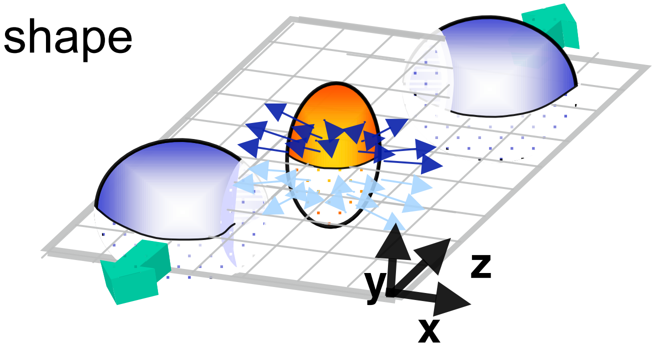




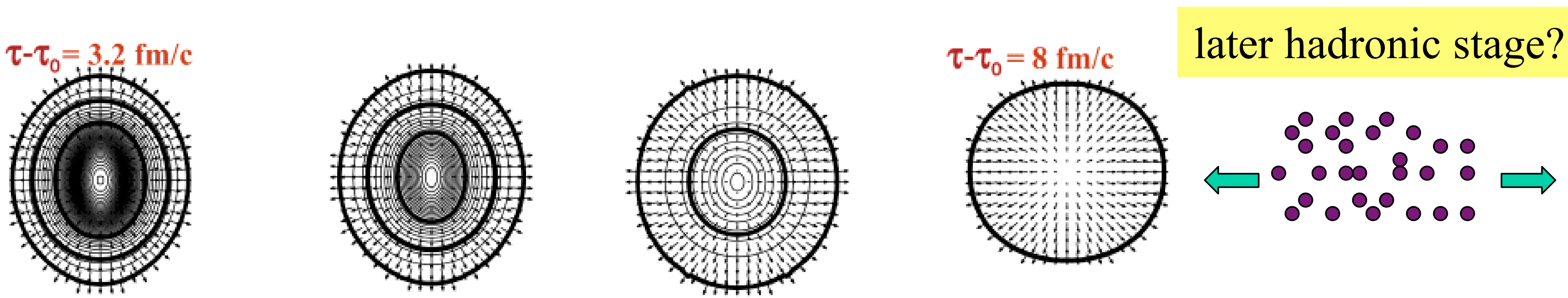
- ☹ Including ha

Why study HBT(□)?

- HBT(□) provides measure of anisotropies in source shape
- Source shape at freeze-out □ evolution of system
  "How much of initial spatial deformation still exists (if any) at freeze-out?"



The (transverse) Hydro Picture



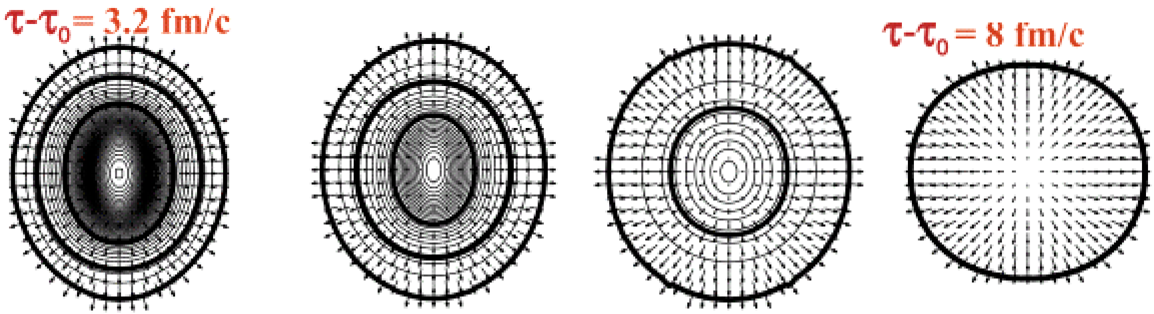
1. Initial geometry _ aniosotropies in pressure gradients
2. Preferential in-plane expansion _ decreases spatial anisotropy
3. Freeze-out source shape via HBT _ measure of pressure, expansion time

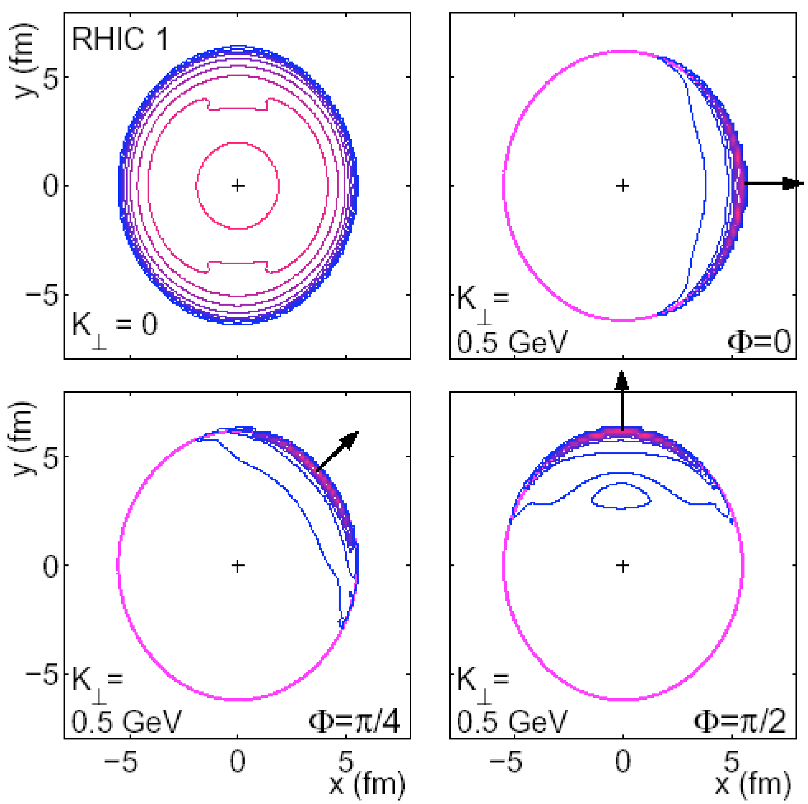
(model-dependent)

Heinz & Kolb, Nucl.Phys. A702 (2002) 269-280

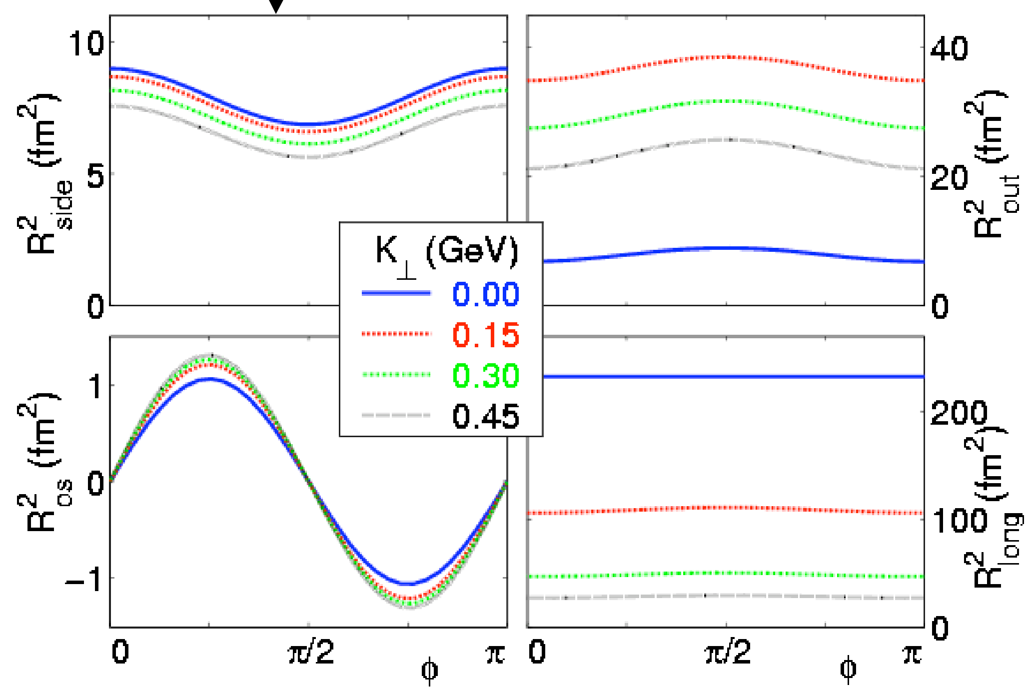
Predictions from hydrodynamics

- Hydrodynamics: initial out-of-plane anisotropy may become in-plane





Hydro calculations initialized with fits to spectra, v_2



Heinz & Kolb, PLB 542 (2002) 216

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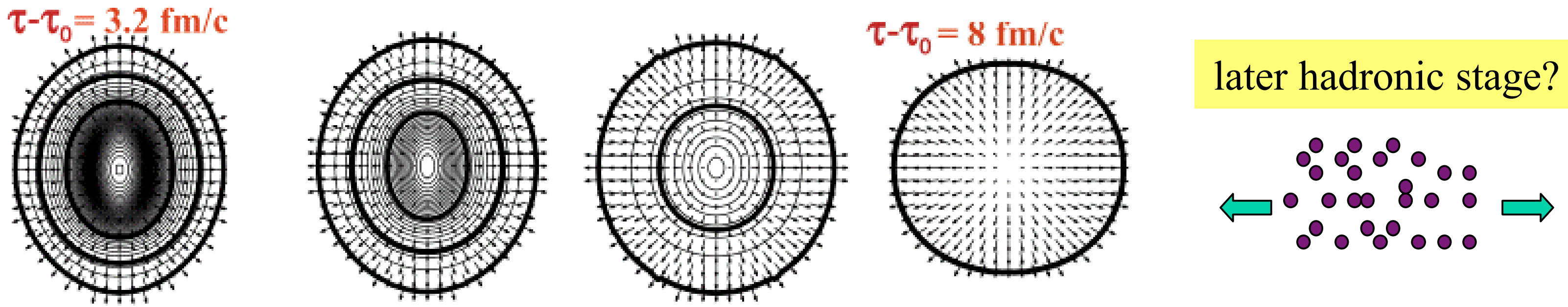
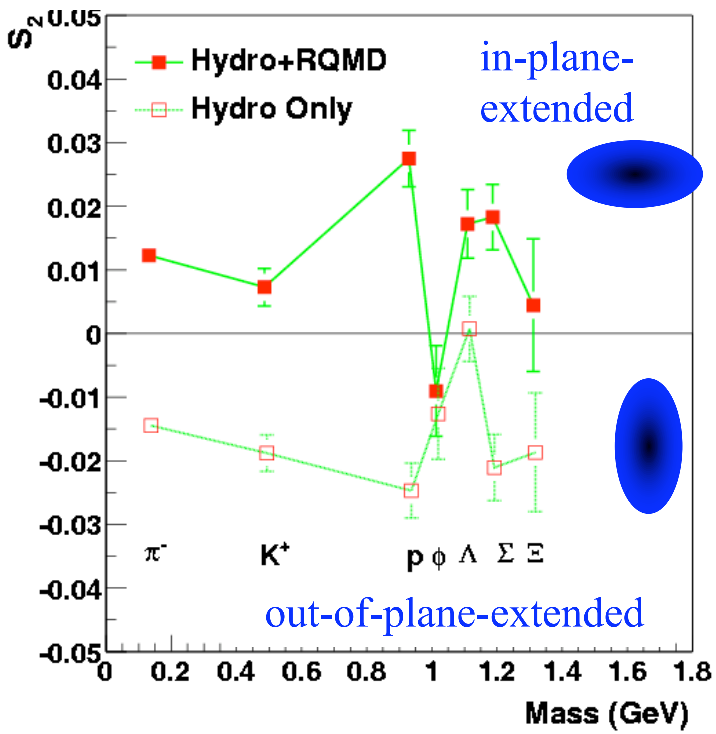


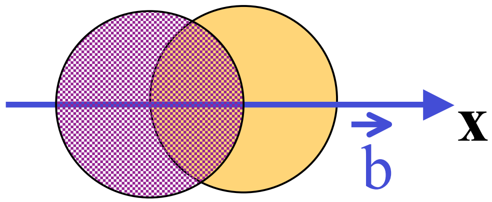


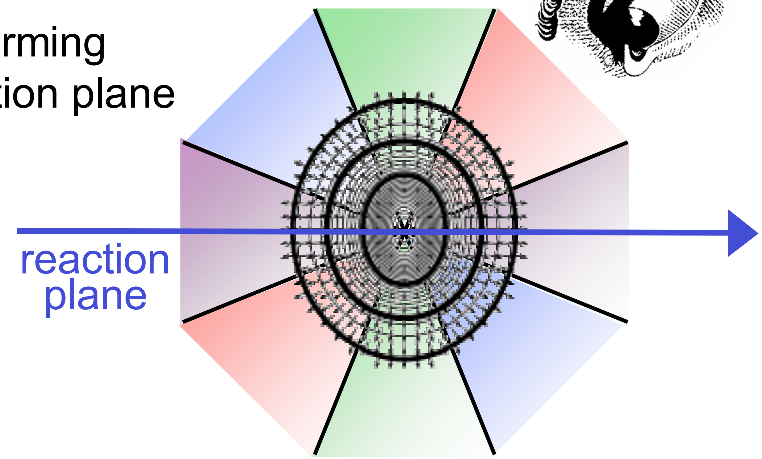
Teaney, Lauret, & Shuryak, nucl-th/0110037

The HBT(□) experimental technique

1. Study (transverse) source at different angles by performing two-pion interferometry separately for bins w.r.t. reaction plane

beam into screen

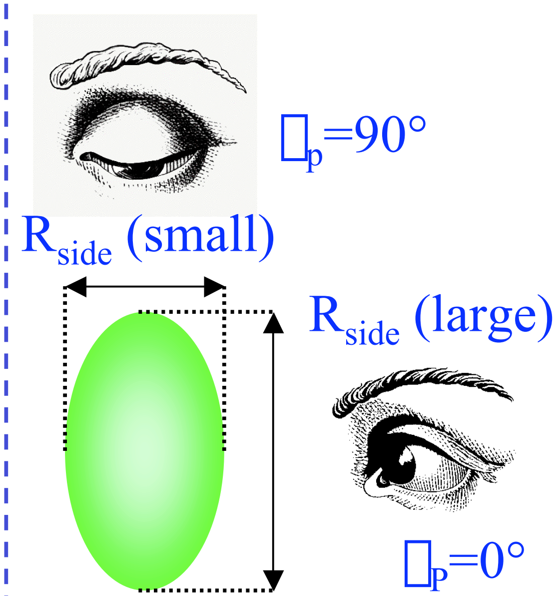




2. Apply HBT formalism for non-central collisions to extract "HBT radii" for each bin

□ fraction of correlated pairs are fit to Coulomb + Gaussian

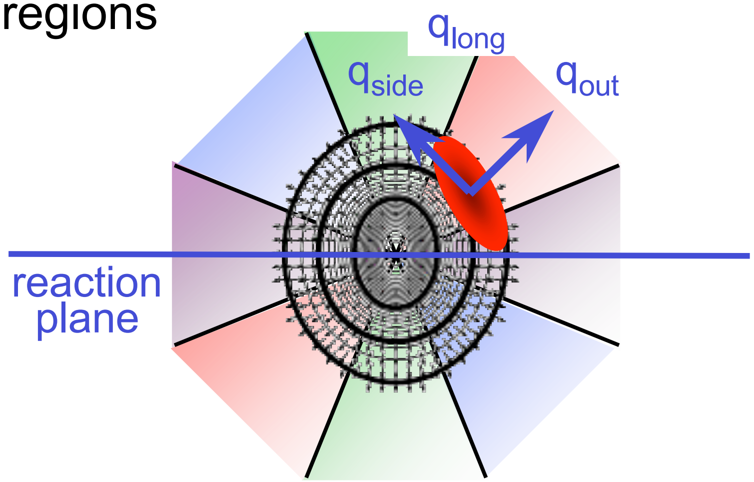
3. Oscillations of radii w.r.t. RP indicate if source is in-plane or out-of-plane extended



Summary of HBT(□) procedure

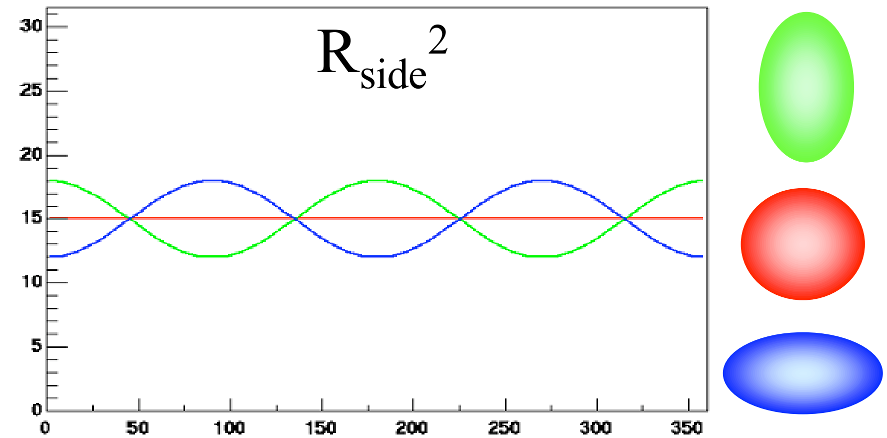
❶ What we measure

HBT radii as a function of emission angle – corresponds to homogeneity regions



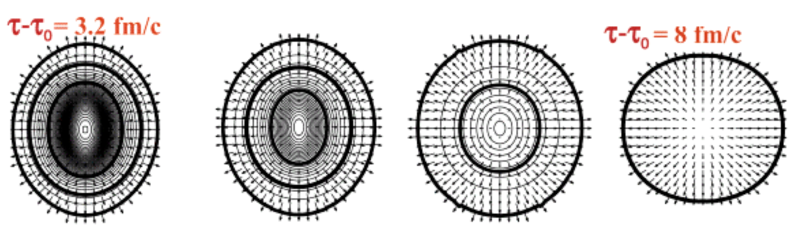
❷ What we expect to see:

2^{nd}-order oscillations in HBT radii analogous to momentum-space (flow)



❸ Why we're interested

The size and orientation of the source at freeze-out places tight constraints on expansion/evolution

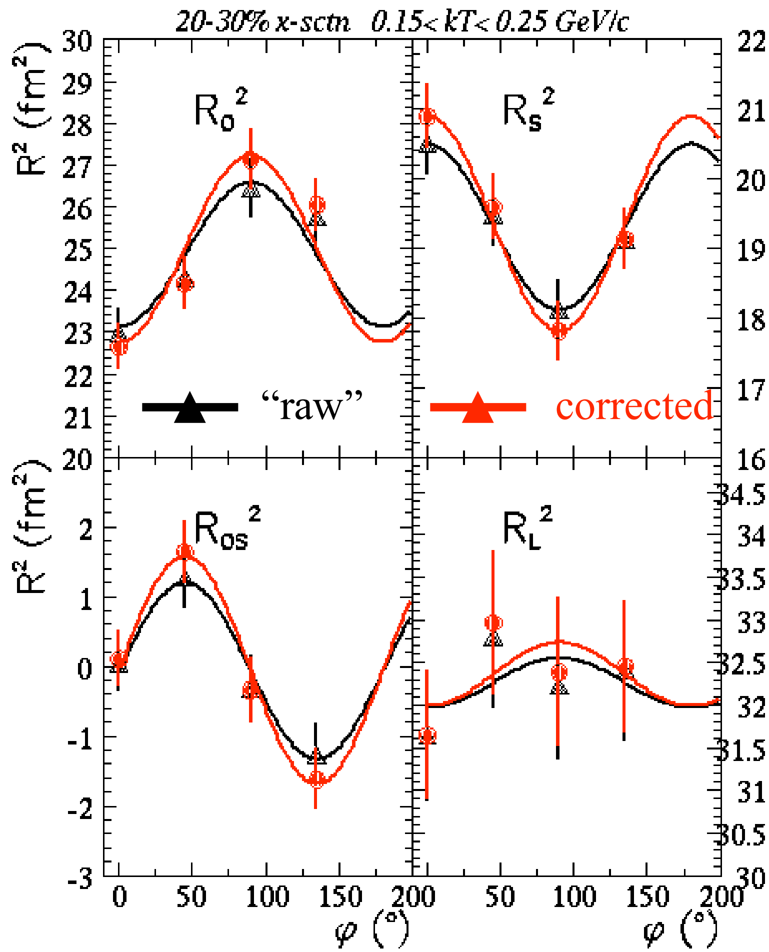


❹ What should be remembered

The form of the oscillations (sin vs. cos, harmonics) are governed by geometrical symmetries of the source.

Corrections applied to data

- Reaction plane resolution correction
  - Observed HBT() oscillations are reduced due to finite r.p. res.
  - Model-independent correction to Num's & Den's of CF increases oscillations; increase ~ inv. proportional to resolution
    Heinz et al, Phys. Rev. **C66** 044903 (2002)



- Momentum resolution correction
  - Single particle *p*-resolution (p/p ~ 1%) slightly redu and R_i's
  - Correlation functions corrected for this effect, HBT increase 1-3%

Centrality dependence of HBT(Φ) oscillations

- **12 Φ-bin analysis, 0 < Φ < π**
  (0.15 < k_T < 0.60 GeV/c)

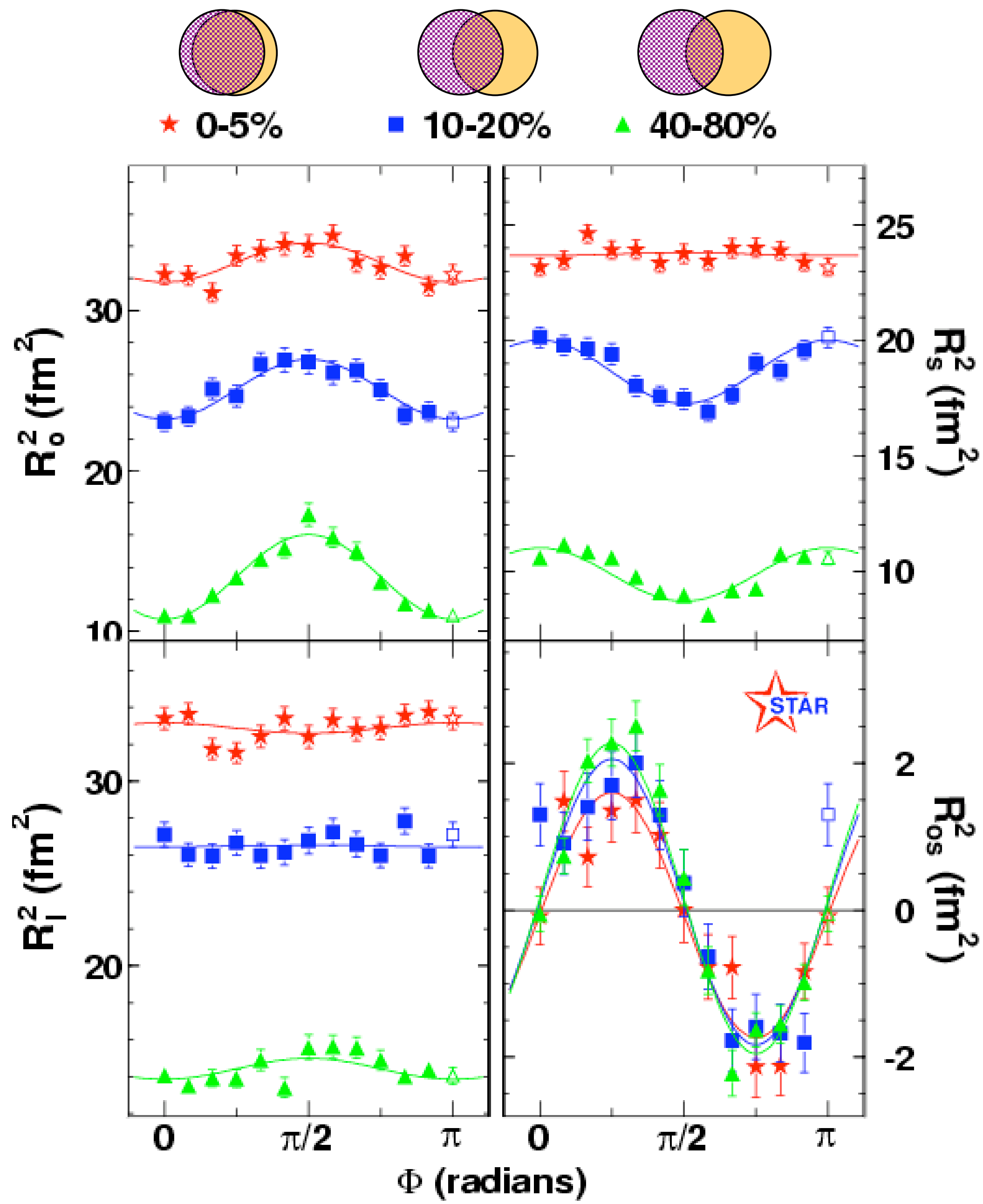
- 15° bins, **72 independent CF's**

- 2nd-order oscillations of HBT radii are observed

- Lines are fits to allowed oscillations:

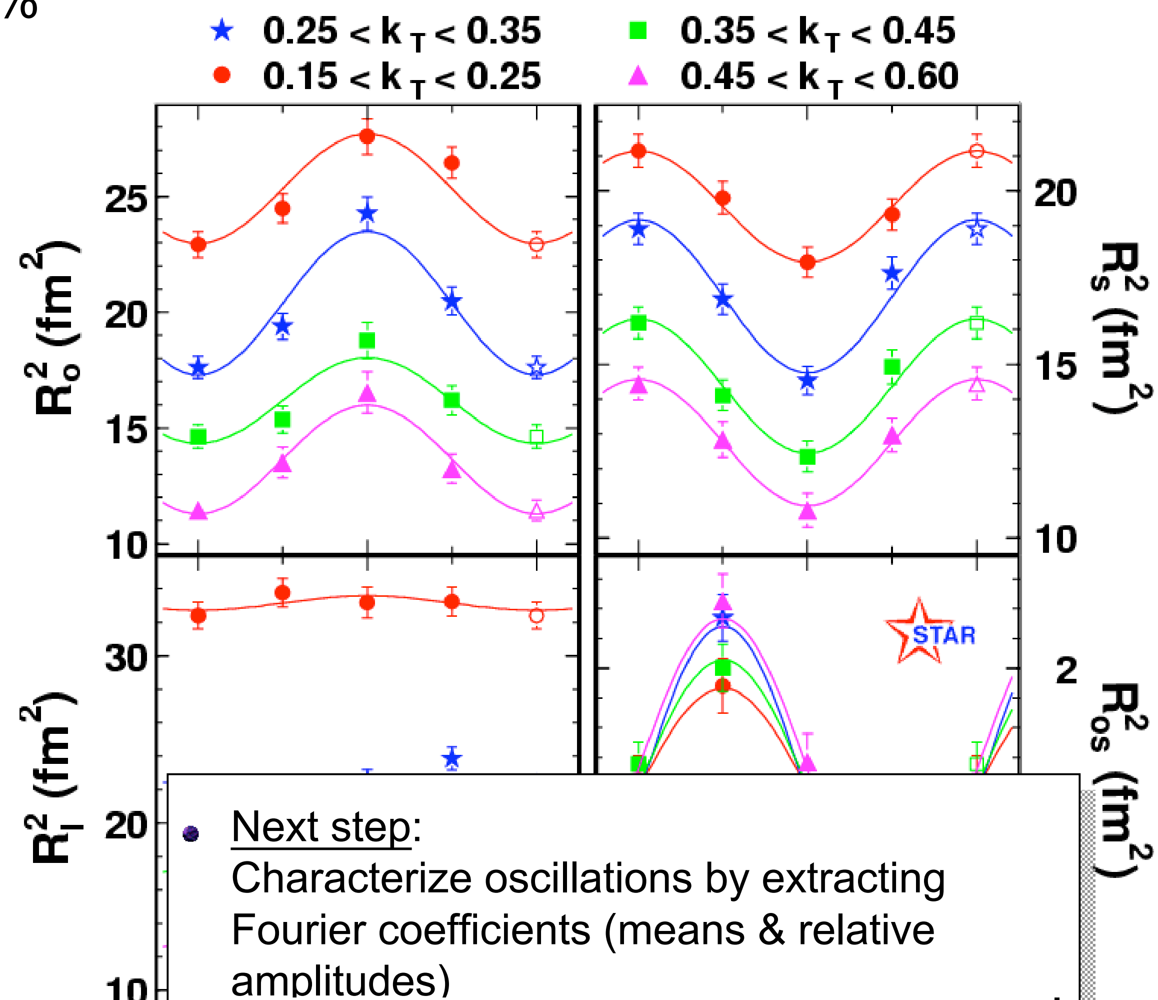
  out, side, long go as **cos(2Φ)**
  out-side goes as **sin(2Φ)**

- Amplitudes weakest for 0-5% (makes sense)



k_T dependence of HBT(□) oscillations

Au+Au, 20-30%



- Next step:
  Characterize oscillations by extracting Fourier coefficients (means & relative amplitudes)

$$R^2_{\mu,n}(k_T) = \begin{cases} \langle R^2_\mu(k_T,\phi_p)\cos(n\phi_p)\rangle & (\mu = o,s,l) \\ \langle R^2_\mu(k_T,\phi_p)\sin(n\phi_p)\rangle & (\mu = os) \end{cases}$$

Fourier coefficients of HBT(□) oscillations

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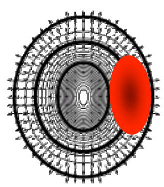
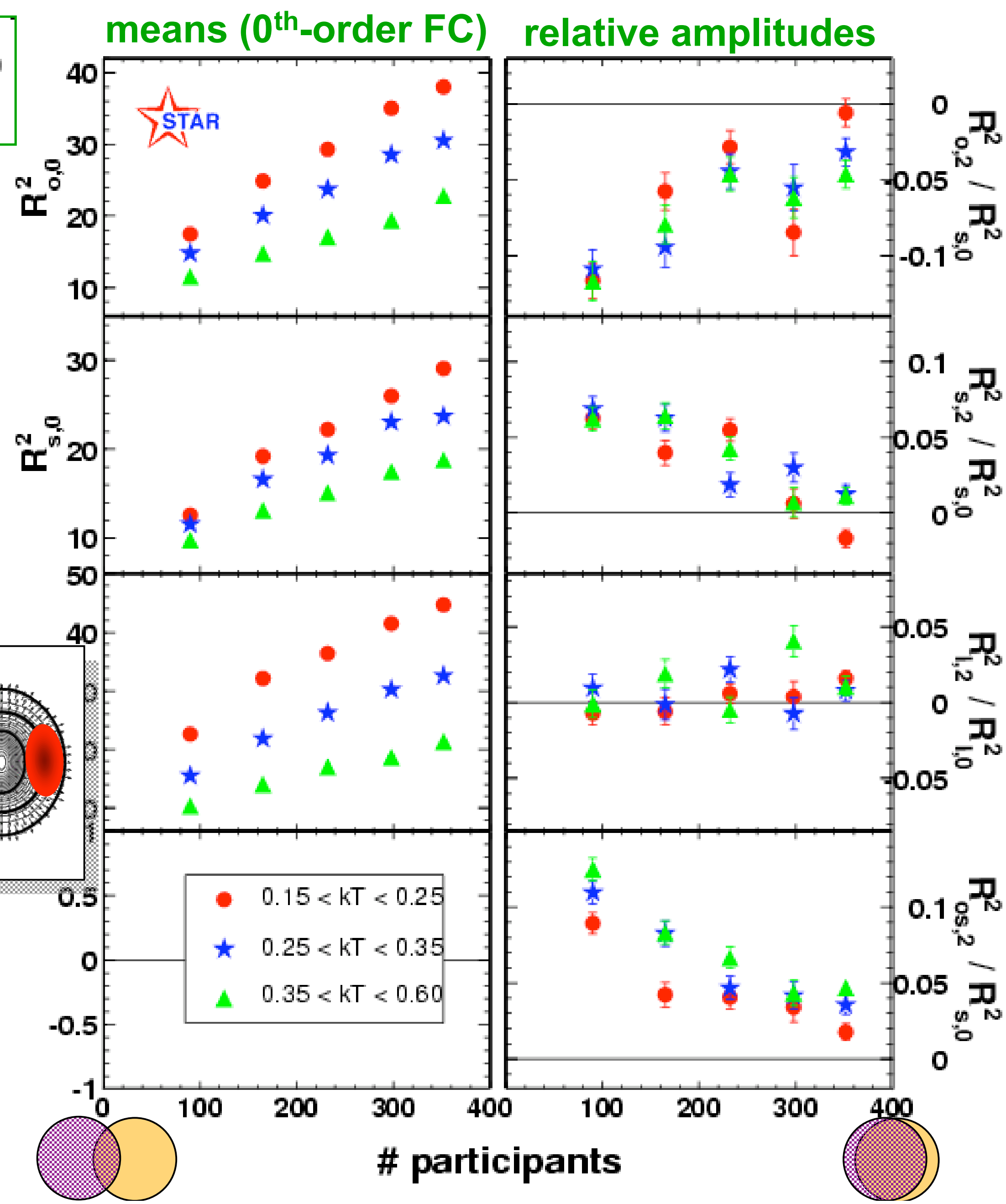
- Relative amplitudes increase in magnitude as centrality decreases
- **Source at freeze-out reflects initial spatial anisotropy!**

- Next step:
  Relate the relative amplitudes from HBT(□) to eccentricity of source at freeze-out



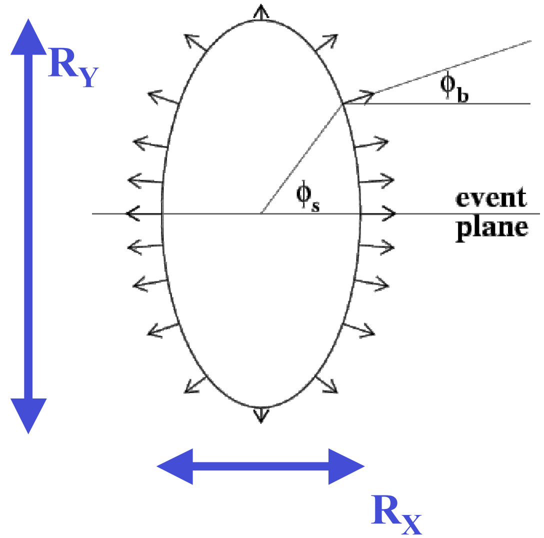


Blast-wave studies of HBT(□)

- Blast-wave: Hydro-inspired <u>parameterization</u> of freeze-out

[illegible]

	momentum space	x-space	time
7 parameters:	T, $\square_0$, $\square_a$	R_x, R_y	□, □t



- Source anisotropy enters in two independent ways:
  - $\square_a \neq 0$ _ *e.g.* boost stronger in-plane for $\square_a > 0$
  - $R_y \neq R_x$ _ *e.g.* more sources emitting in-plane for $R_y > R_x$

- Use Blast-wave to relate HBT(□) measurements to source freeze-out shape & orientation

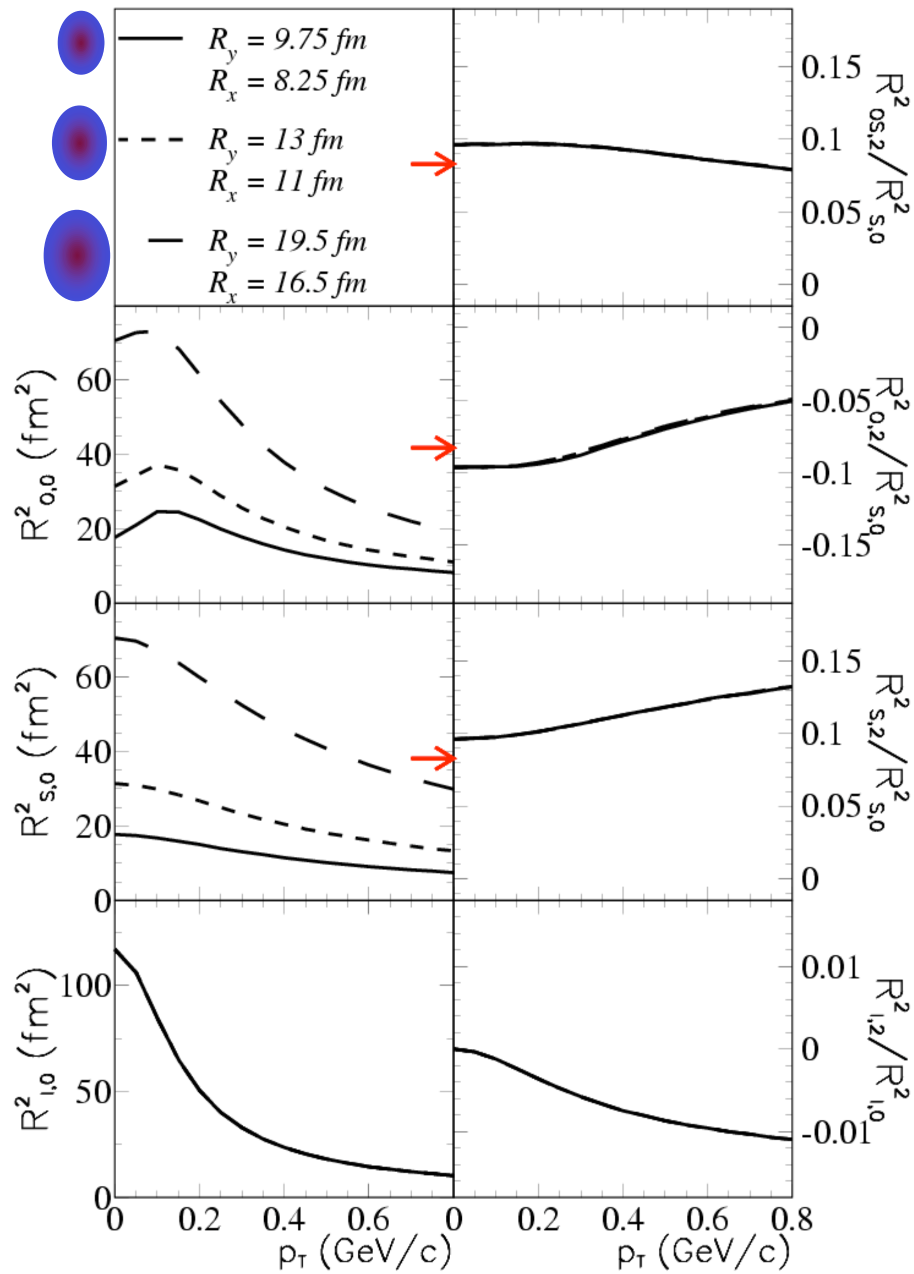
First, how sensitive are the HBT(□) relative oscillation amplitudes to Blast-wave parameters?

F. Retiere and M.A. Lisa, in preparation

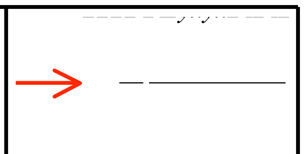
Sensitivity of HBT(φ) to b-w parameters

What drives the relative amplitudes?

1. Freeze-out size $R_y^2+R_x^2$ (fixed R_y/R_x)
   - No sensitivity of relative amplitudes to source size



$$R^2_{\mu,n}(p_T) = \begin{cases} \langle R^2_\mu(p_T,\Phi)\cdot\cos(n\Phi)\rangle & (\mu = o,s,l) \\ \langle R^2_\mu(p_T,\Phi)\cdot\sin(n\Phi)\rangle & (\mu = os) \end{cases}$$



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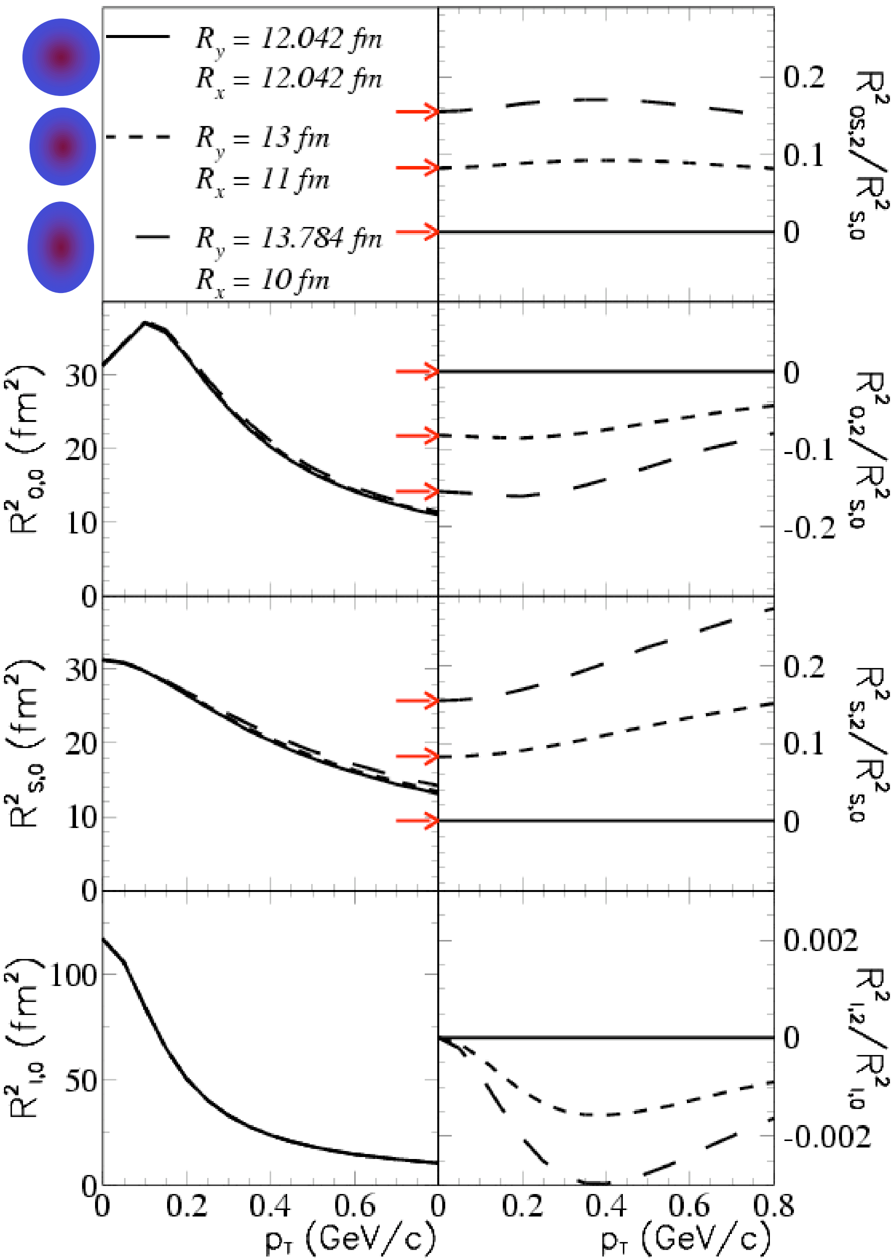

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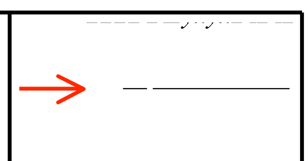

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3. Flow anisotropy $\Box_a$ ($R_y = R_x$)
   - Weak sensitivity in comparison to spatial anisotropy

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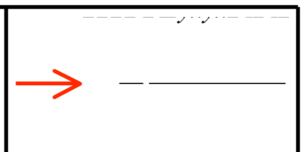

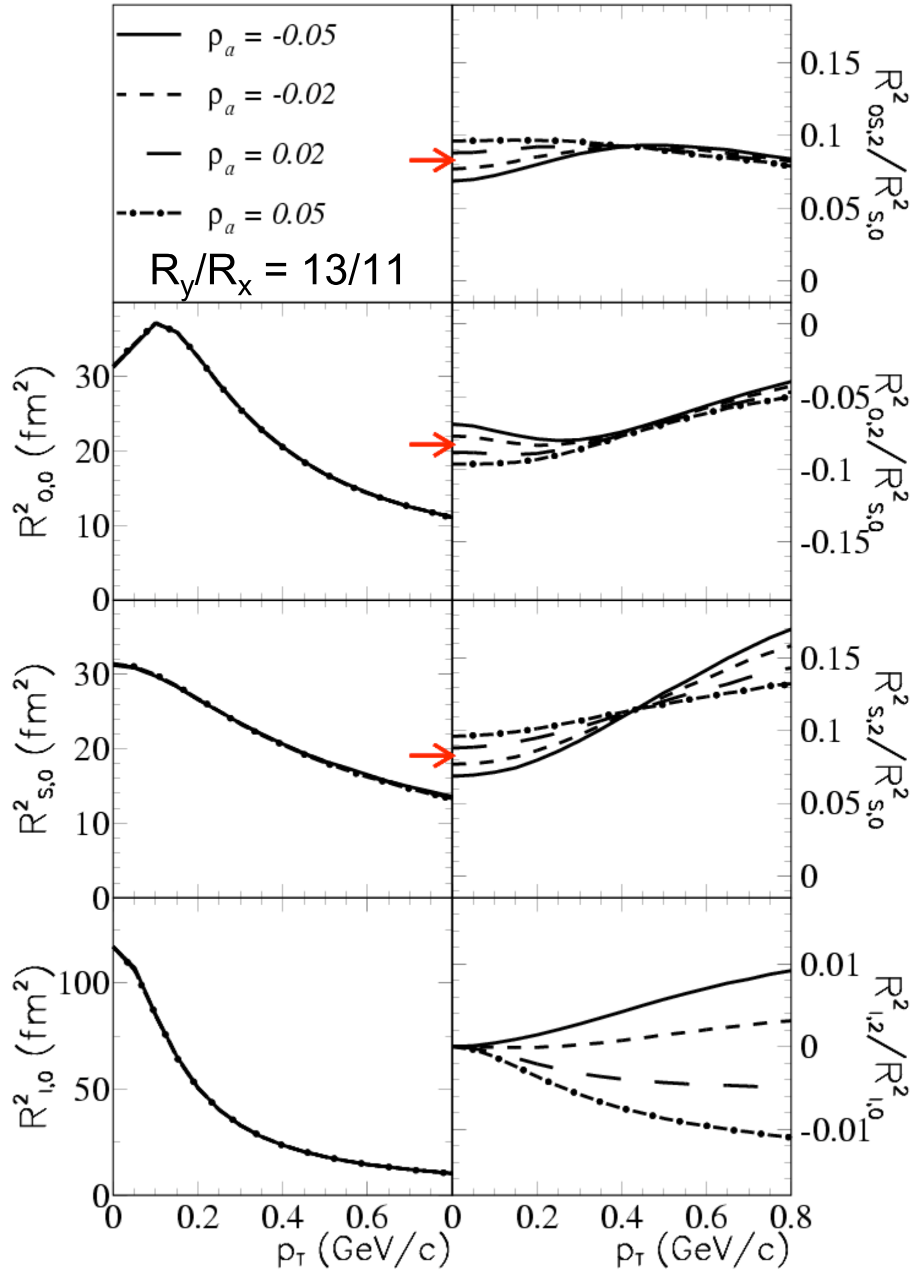

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   - Weak sensitivity in comparison to spatial anisotropy
4. Temperature T
   - ~ Weak sensitivity

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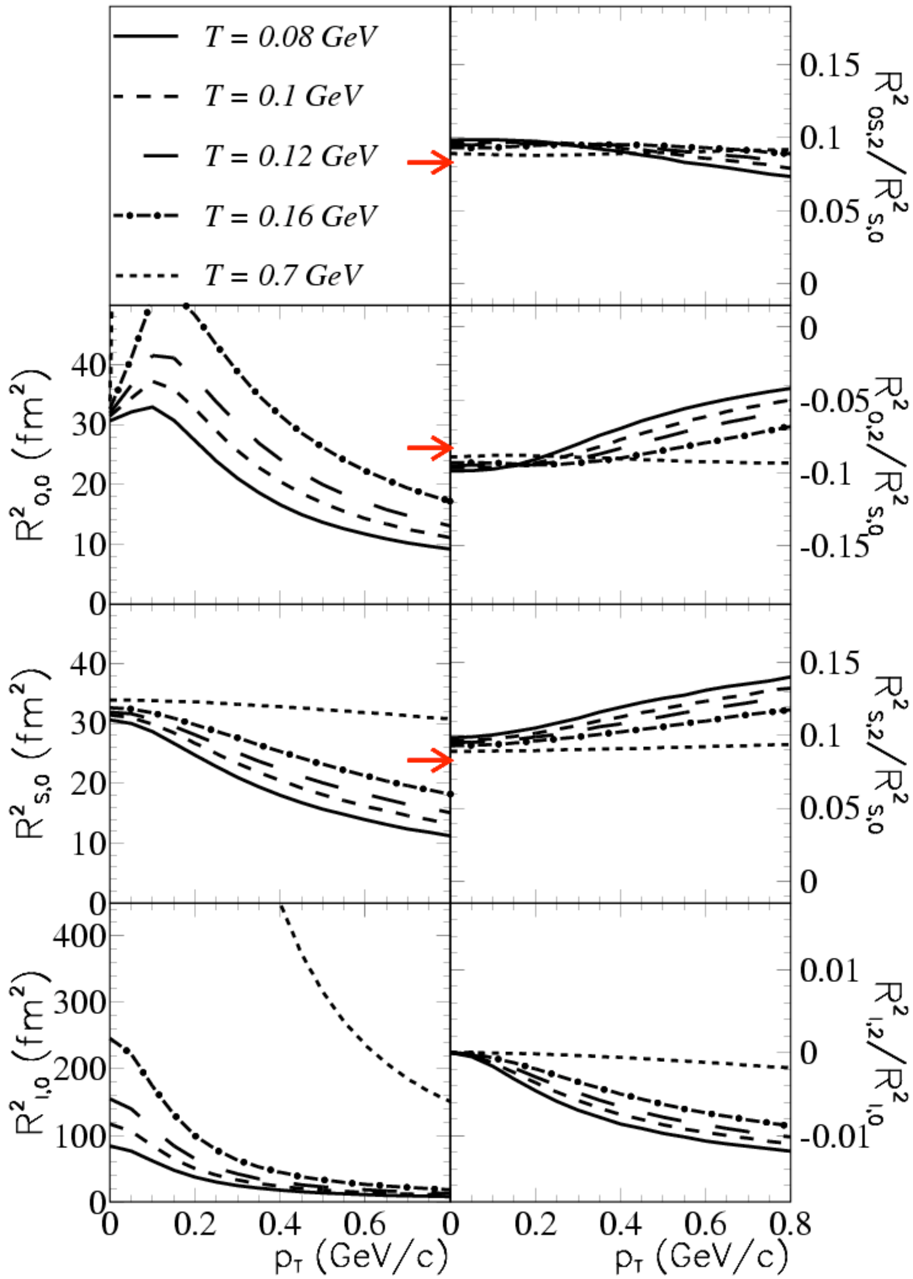

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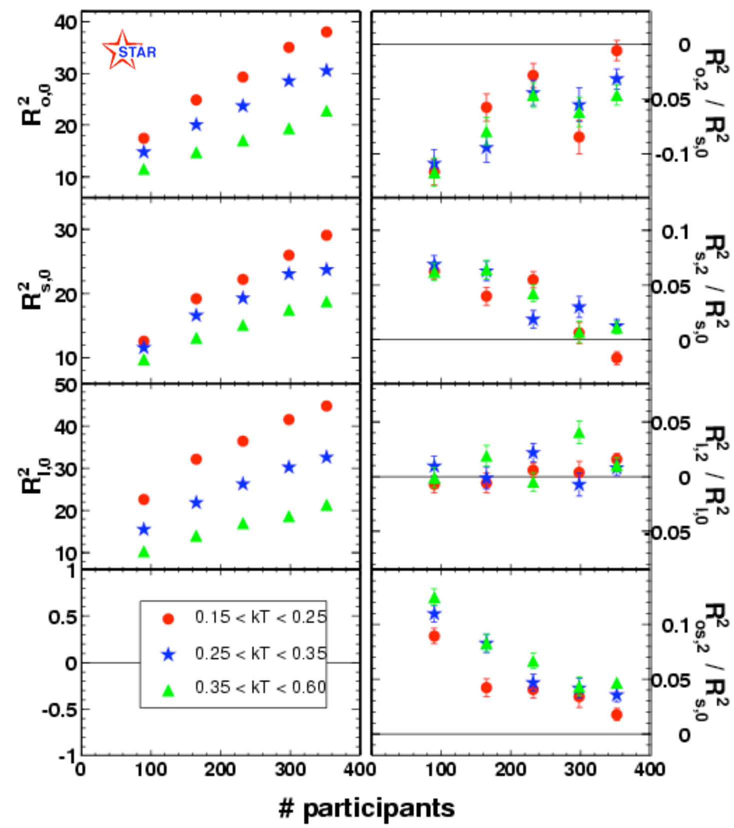
4. Temperature T
   - ~ Weak sensitivity

Spatial anisotropy drives relative amplitudes

Use relative amplitudes to estimate eccentricity of freeze-out source

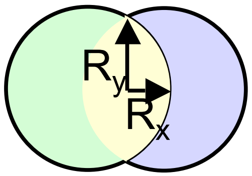
$$\varepsilon \equiv \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} = 2\frac{R_{s,2}^2}{R_{s,0}^2} = 2\frac{R_{os,2}^2}{R_{s,0}^2} = -2\frac{R_{o,2}^2}{R_{s,0}^2}$$

doesn't have temporal component



Evolution of source eccentricity

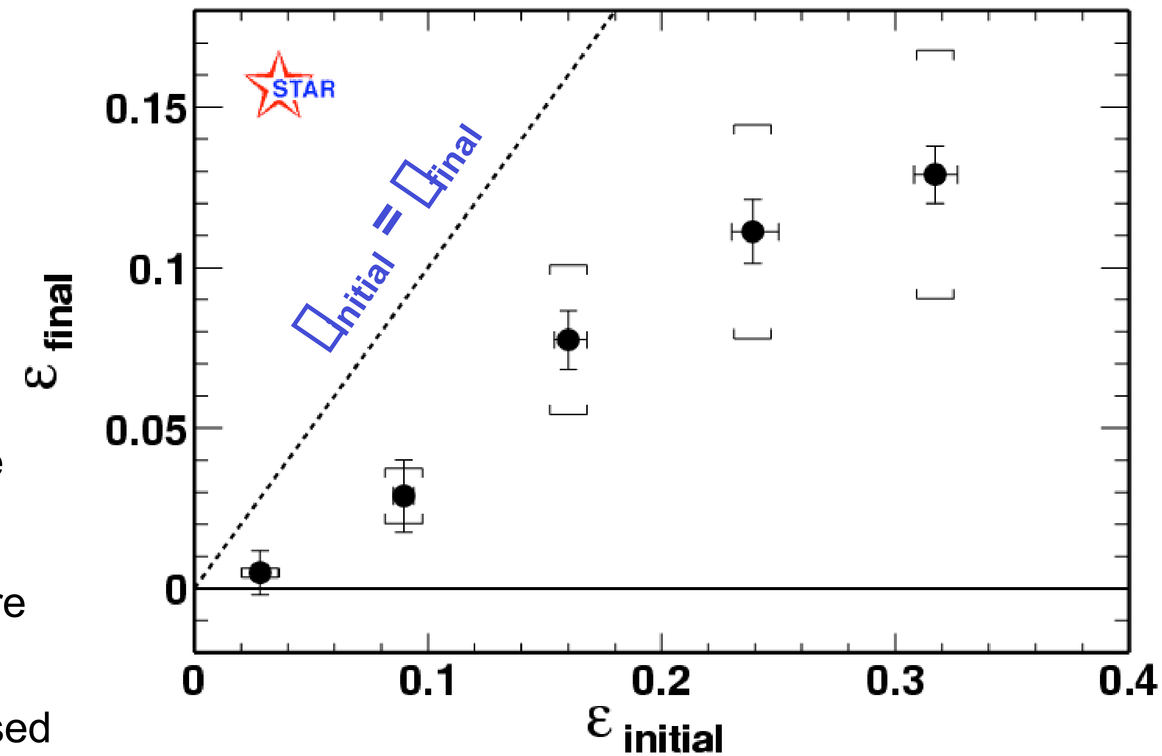
Initial eccentricity



- Estimate $\varepsilon_{initial}$ from nuclear overlap model
- Weight events by ≈ # pairs

Final eccentricity

- **HBT(ϕ)**: Estimate ε_{final} from relative amplitudes ($\varepsilon_{final} = 2\, R_{s,2}^2/R_{s,0}^2$)
- **Blast-wave**: Relative amplitudes are driven by spatial anisotropy
- 30% sys. error assigned to ε_{final} based on variation of rel. amplitudes with other b-w parameters



- Monotonic relationship between $\varepsilon_{initial}$ and ε_{final}
- Freeze-out spatial anisotropy reflects greater initial spatial anisotropy

HBT(): Physics interpretation

Out-of-plane sources at freeze-out

- Indicate pressure and/or expansion time was not sufficient to quench initial shape

But from v_2 measurements we know...

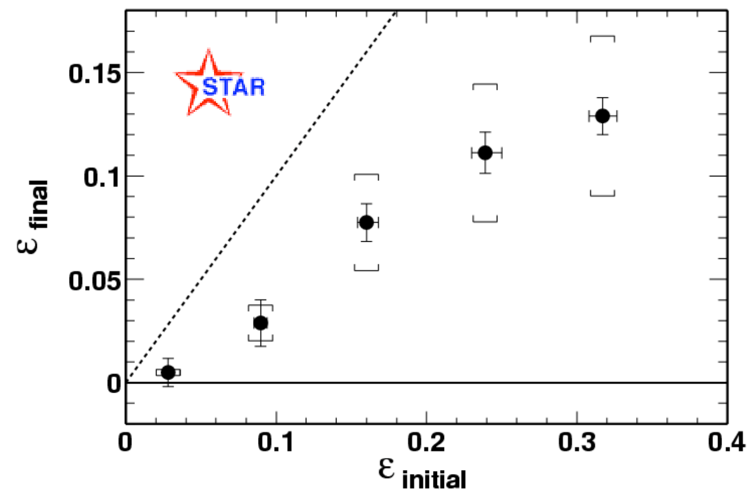
- Strong in-plane flow _ significant pressure build-up in system

 Short expansion time plays dominant role in out-of-plane freeze-out source shapes

Short system lifetime consistent with blast-wave fits to spectra/v_2 & "standard" HBT radii

 However, late-stage contributions to v_2 signal, though likely quite weak, cannot be exlcuded

 In framework of Teaney *et al* (Hydro+RQMD), late-stage rescattering stage is short-lived...



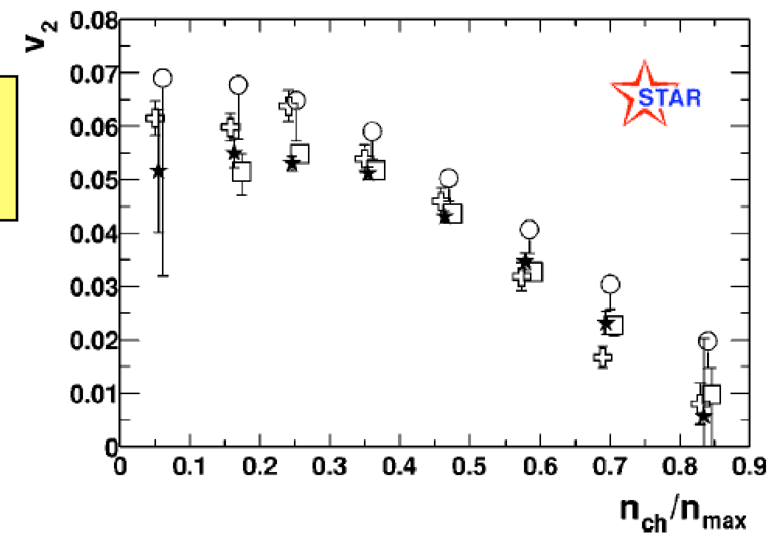


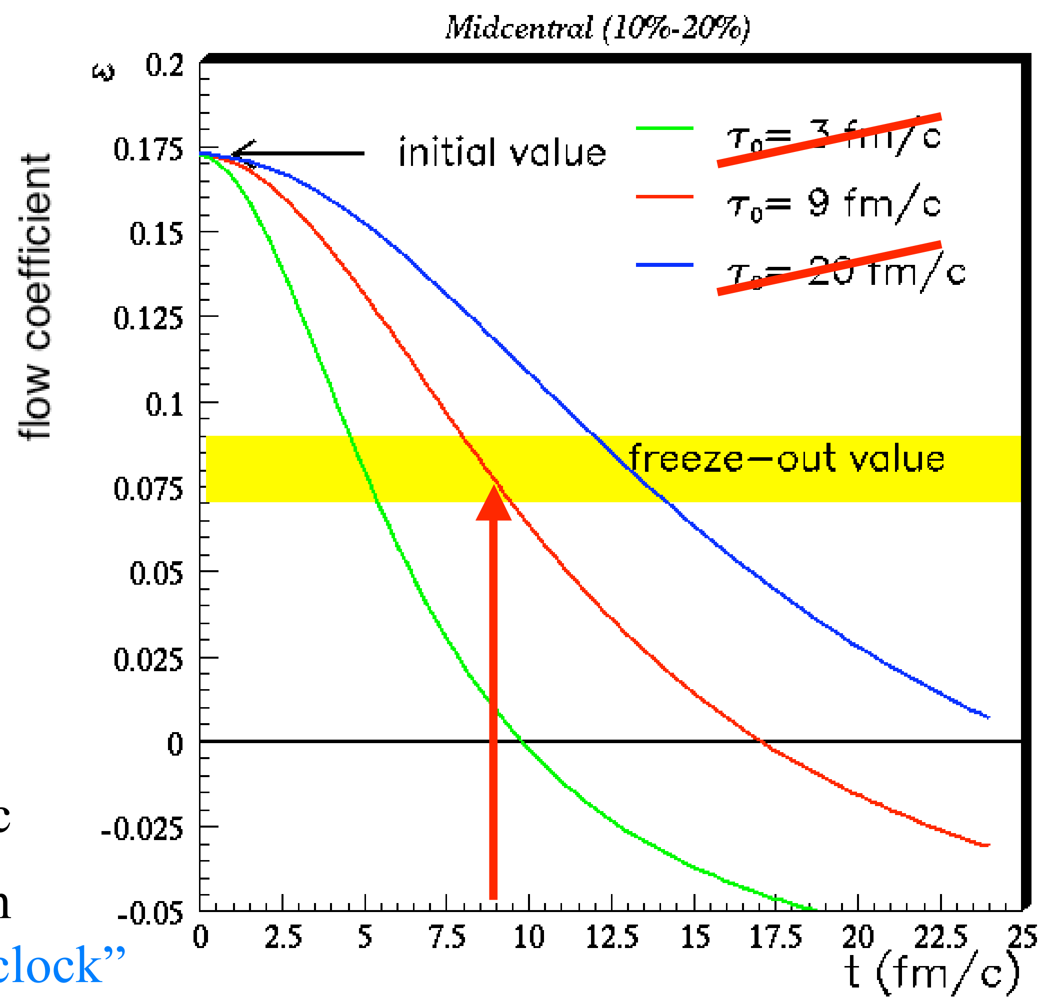
FIG. 13. Measured elliptic flow vs centrality for Au+Au at $\sqrt{s_{NN}}$ = 130 GeV. The circles show the conventional v_2 with estimated systematic uncertainty due to nonflow [37], the stars show the fourth-order cumulant v_2 from the generating function, the crosses show the conventional v_2 from quarter events, and the squares show the fourth-order cumulant v_2 from the four-subevent method.

A simple estimate – $\square_0$ from $\square_{init}$ and $\square_{final}$

- BW _ $\square_X$, $\square_Y$ @ F.O. ($\square_X > \square_Y$)
- hydro: flow velocity grows ~ t

$$\square \quad \square_{X,Y}(t) = \square_{X,Y}(F.O.) \cdot \frac{t}{\square_0}$$

- From $R_L(m_T)$: $\square_0$ ~ 9 fm/c
  - □ consistent picture
- Longer or shorter evolution times
  - X inconsistent



□ toy estimate: $\square_0$ ~ $\square_0$(BW)~ 9 fm/c

- But need a real model comparison
  _ asHBT valuable "evolutionary clock" constraint for models

Conclusions

- Azimuthal dependence of HBT _ Oscillations of HBT radii observed as fcn of centrality, k_T
- Blast-wave study _ relative amplitudes most sensitive to freeze-out spatial anisotropy
- Freeze-out source out-of-plane extended _ indicates pressure and/or expansion time not sufficient to quench initial almond shape
- In context of strong elliptic flow observed at RHIC, measurement points to short expansion times

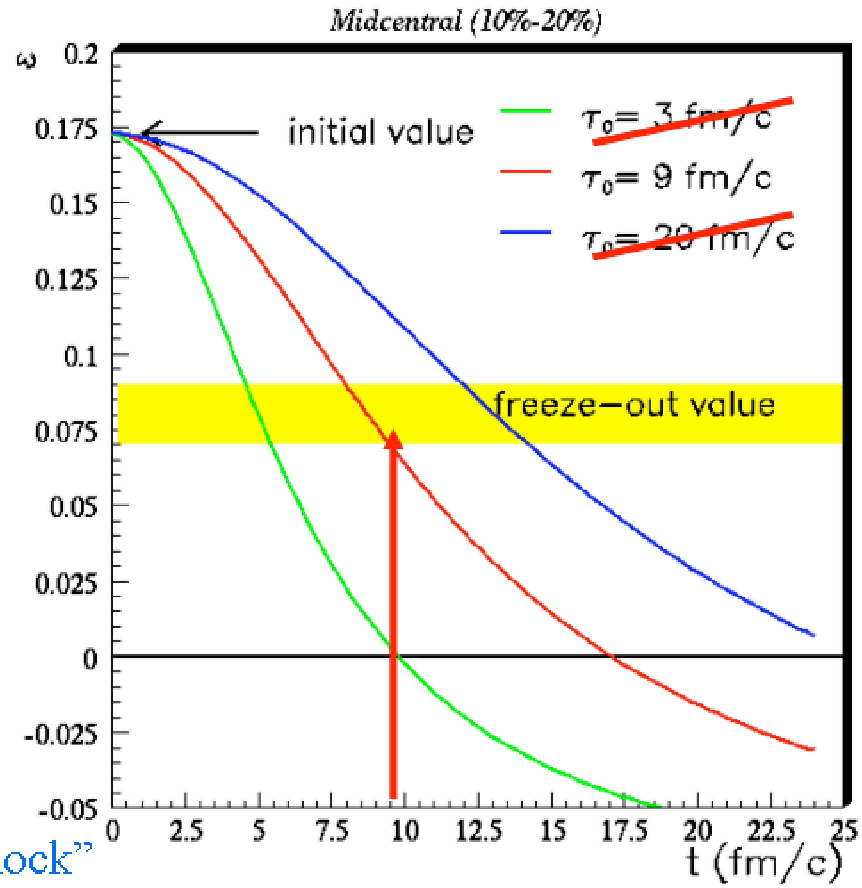
Back-up slides

A simple estimate - τ_0 from ε_{init} and ε_{final}

- BW → β_X, β_Y @ F.O. ($\beta_X > \beta_Y$)
- hydro: flow velocity grows ~ t

$$\rightarrow \beta_{X,Y}(t) = \beta_{X,Y}(F.O.) \cdot \frac{t}{\tau_0}$$

- From $R_L(m_T)$: $\tau_0 \sim 9$ fm/c
  - ✓ consistent picture
- Longer or shorter evolution times
  - X inconsistent



✓ toy estimate: $\tau_0 \sim \tau_0$(BW)~ 9 fm/c

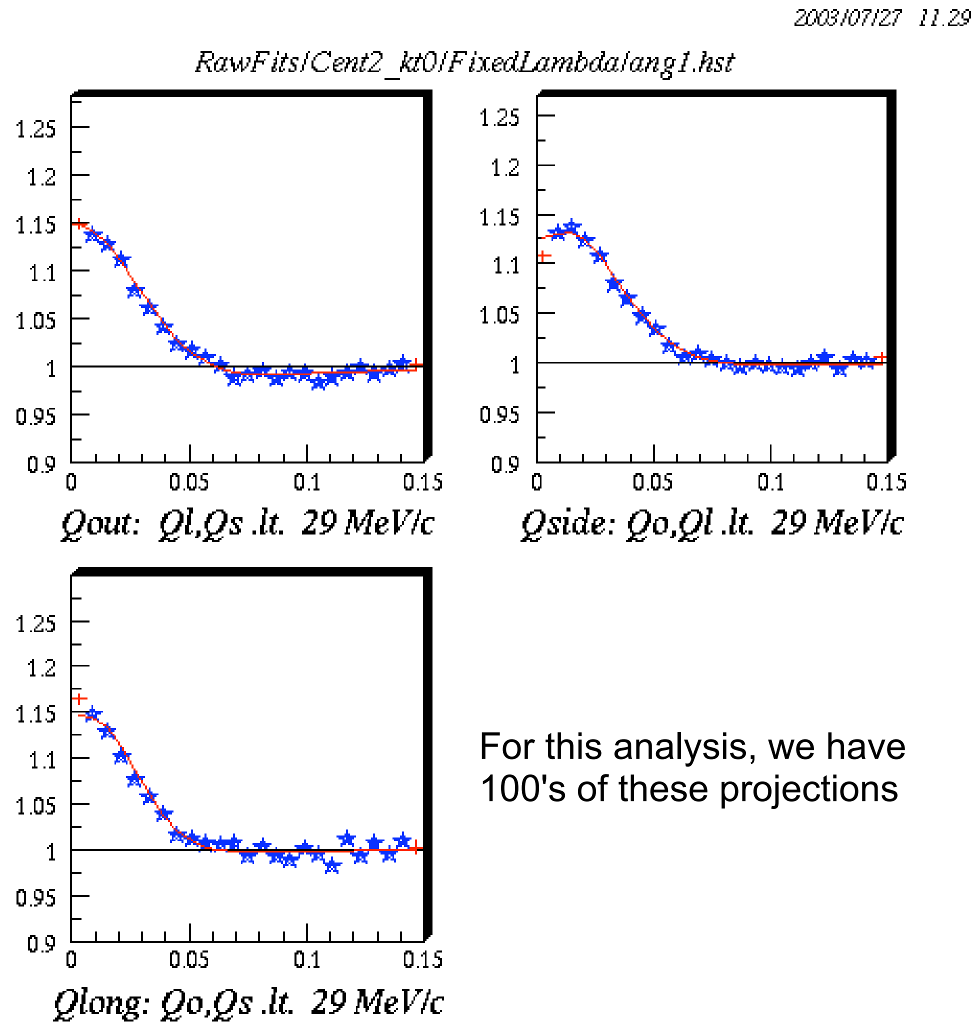
- But need a real model comparison

→ asHBT valuable "evolutionary clock" constraint for models

STAR HBT

Projections of correlation function

- Remember: CF & projections shouldn't be perfectly Gaussian

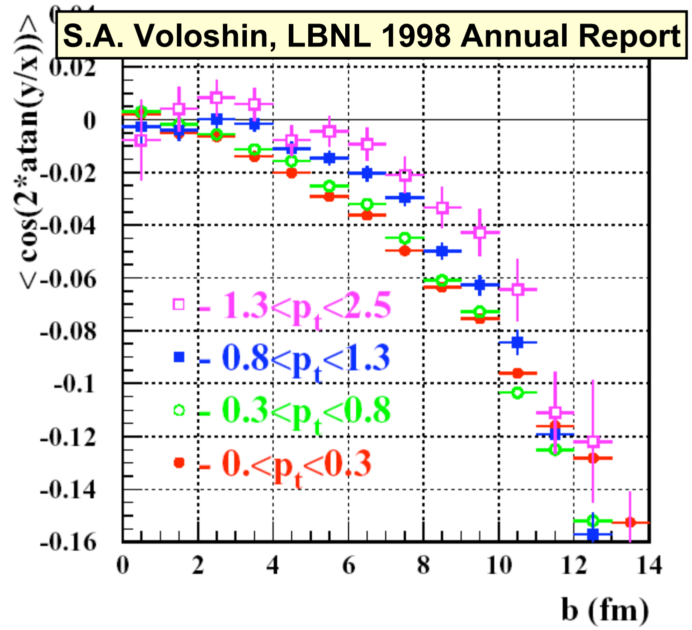


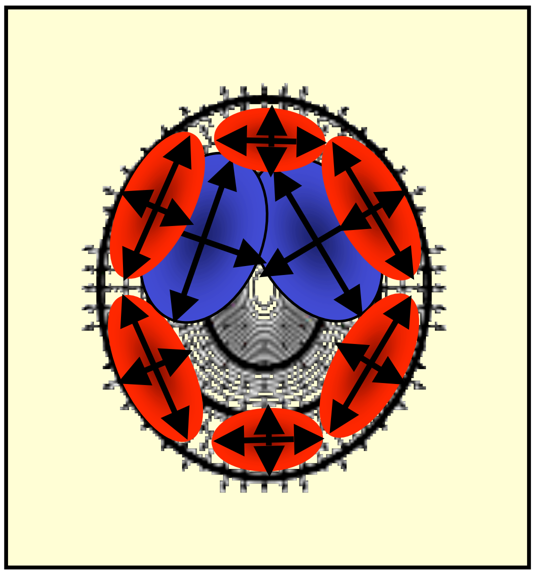
For this analysis, we have 100's of these projections

Clarification: what we mean by 'source'

i.e. slice in p_T

- **S. Voloshin**: **"effective" source** may be in-plane for high pT particles, though HBT measurement would still yield out-of-plane oscillations





We measure: **homogeneity lengths** (R_i) as a function of $\mathbf{k_T}$ and □

We're interested in: **<u>entire</u> source** ("The Source"), NOT just a p_T slice of The Source

Getting from R_i(kT,□) to size/shape of "The Source" requires a model (more later)

Correcting for finite □-binning & □$_{RP}$-resolution

Heinz, Hummel, Lisa, Wiedemann, Phys. Rev. C66 044903 (2002)

$$C(\vec{q},\Box) = \frac{N(\vec{q},\Box)}{D(\vec{q},\Box)}$$

$$N_{exp}(\vec{q},\Box_j) = N_0^{exp}(\vec{q}) + 2\sum_{n=1}^{N_{bin}}\left[N_{c,n}^{exp}(\vec{q})\cos(n\Box_j) + N_{s,n}^{exp}(\vec{q})\sin(n\Box_j)\right]$$

$$N(q,\Box_j) = N_{exp}(q,\Box_j) + 2\sum_{n=1}^{N_{bin}} \Box_{n,m}(\Box)\left[N_{c,n}^{exp}(q)\cos(n\Box_j) + N_{s,n}^{exp}(q)\sin(n\Box_j)\right]$$

n□ / 2

— □1

p

ıs for

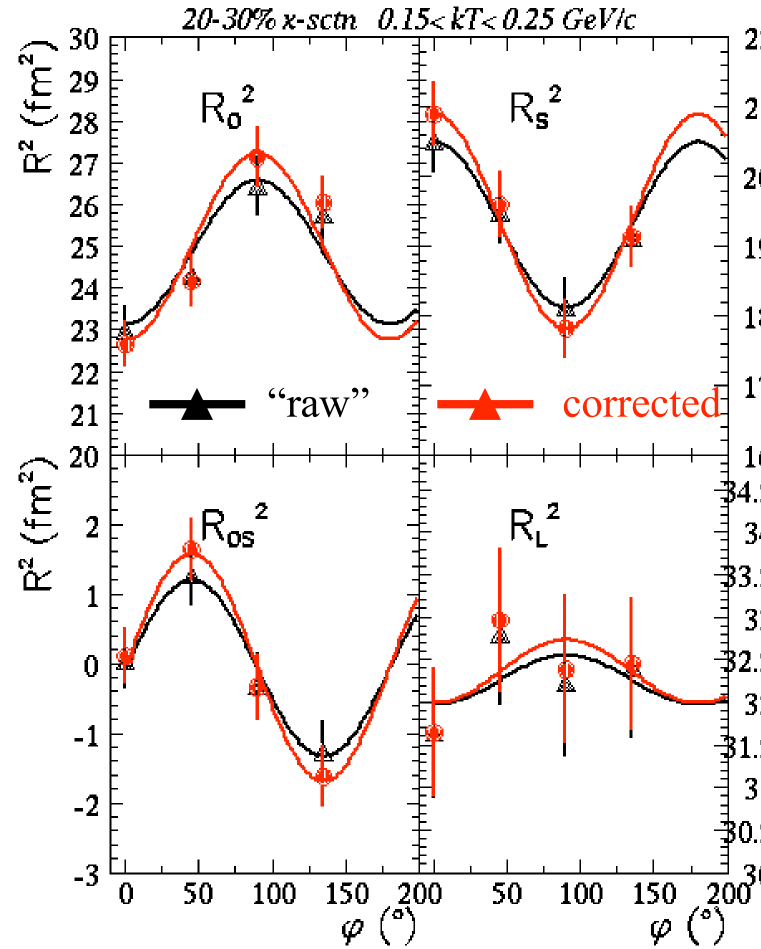
nth-

event-

Fourier coefficients for a given **q** bin

$$N_{c,n}^{exp}(\vec{q}) = \langle N_{exp}(\vec{q},\Box)\cos(n\Box)\rangle = \frac{1}{N_{bin}}\sum_{j=1}^{N_{bin}} N_{exp}(\vec{q},\Box_j)\cos(n\Box_j)$$

$$N_{s,n}^{exp}(\vec{q}) = \langle N_{exp}(\vec{q},\Box)\sin(n\Box)\rangle = \frac{1}{N_{bin}}\sum_{j=1}^{N_{bin}} N_{exp}(\vec{q},\Box_j)\sin(n\Box_j)$$



- ~ 30% effect on 2nd-order radius oscillations
- ~0% change in mean values