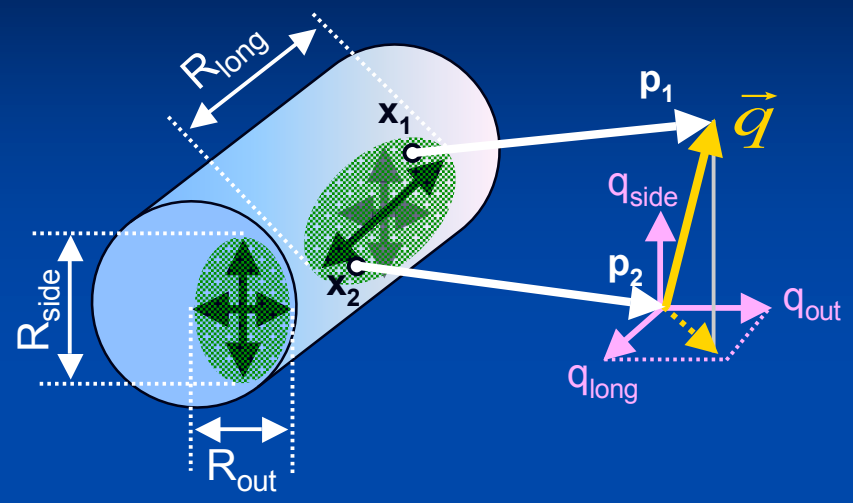
HBT: A (mostly) experimental overview

Dan Magestro, The Ohio State University

- **Overview of HBT interferometry**
- **The SPS & RHIC HBT program**
- **Recent "standard" HBT results**
- **The RHIC HBT puzzle**
- **New directions: ϕ dependence, pp vs. AuAu, non-ld, ϕHBT**

Hanbury Brown-Twiss interferometry

- **Two-particle interferometry: p-space separation □ space-time separation**



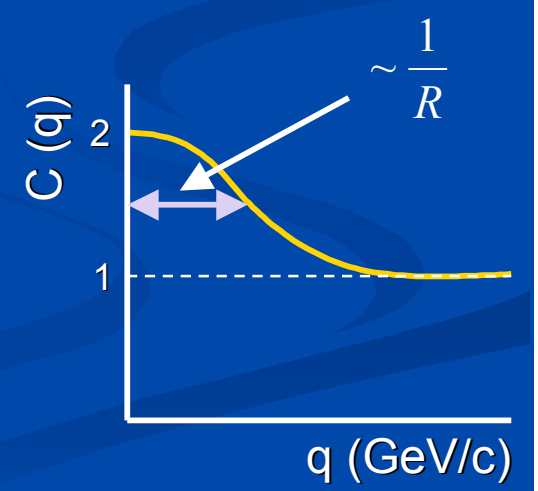
$$\vec{q} = \vec{p}_2 - \vec{p}_1$$

$$\vec{k} = \frac{1}{2}\left(\vec{p}_2 + \vec{p}_1\right)$$

- **HBT: Quantum interference between identical particles**

$$C(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \frac{\text{real event pairs}}{\text{mixed event pairs}}$$

Gaussian model (3-d): $C(\vec{q}, \vec{k}) = 1 + \lambda(\vec{k})\, e^{-q_{out}^2 R_{out}^2 - q_{side}^2 R_{side}^2 - q_{long}^2 R_{long}^2}$



- Final-state effects (Coulomb, strong) also can cause correlations, need to be accounted for

The HBT program at SPS and RHIC

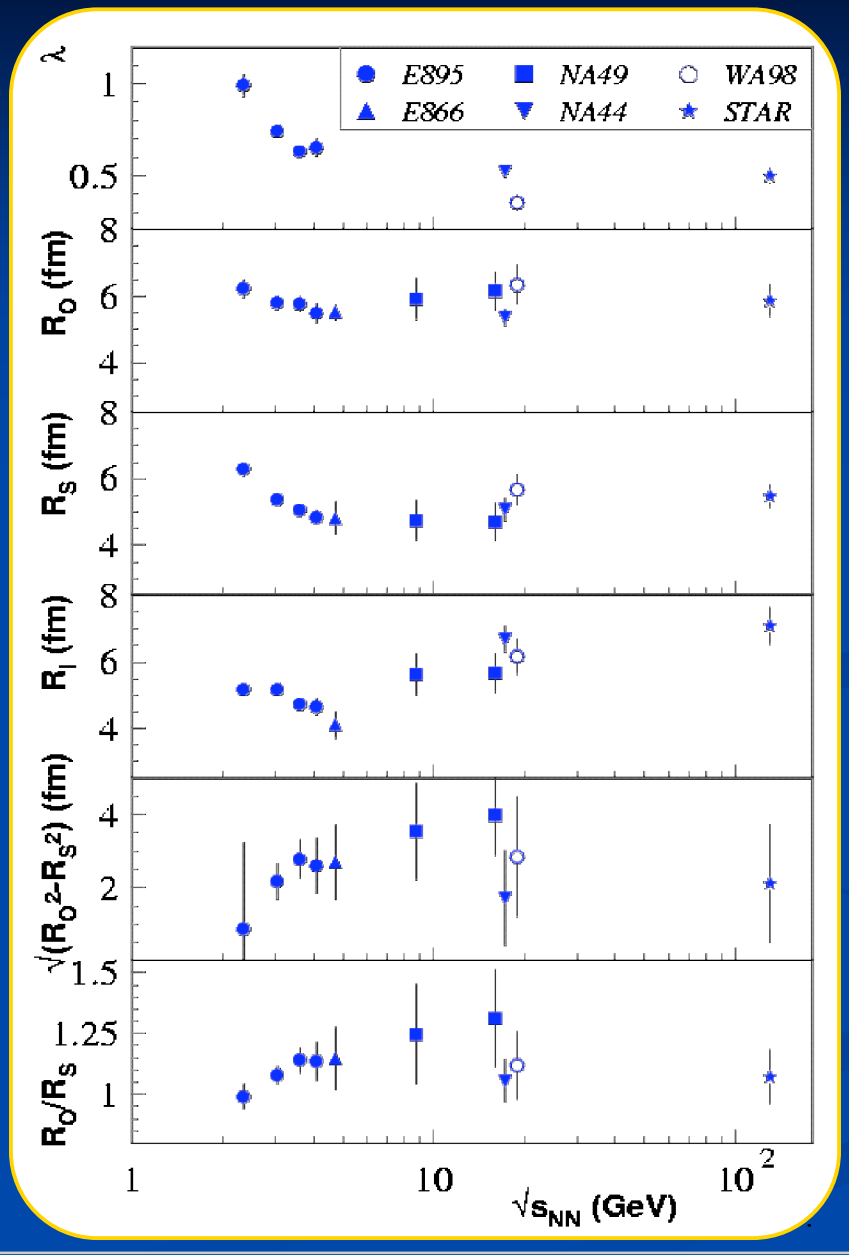
- **HBT in HI collisions: Explore space-time evolution of system**
  - Geometry: spatial distribution of emission points
  - Dynamics: hot & dense early stages reflected in freeze-out pattern
  - Lifetime: sensitive to nature of phase transition

- **Technique: Study interferometry as <u>differentially</u> as possible**

beam energy	onset effects, transition phenomena
transverse momentum (k_T)	dynamics, collective expansion
particle species	differences in emission
collision system	origins of correlations, phase space
azimuthal angle	spatial anisotropies, constrain system evolution

- **RHIC: Fertile ground for correlations studies**

HBT excitation function



STAR, PRL 87 (2001) 082301

The k_T (m_T) dependence

- **x-p correlations arise mostly due to collective expansion**
  - Radial flow pushes higher-p_T particles more at surface
- **Analytical expressions**
  - System lifetime (Sinyukov)

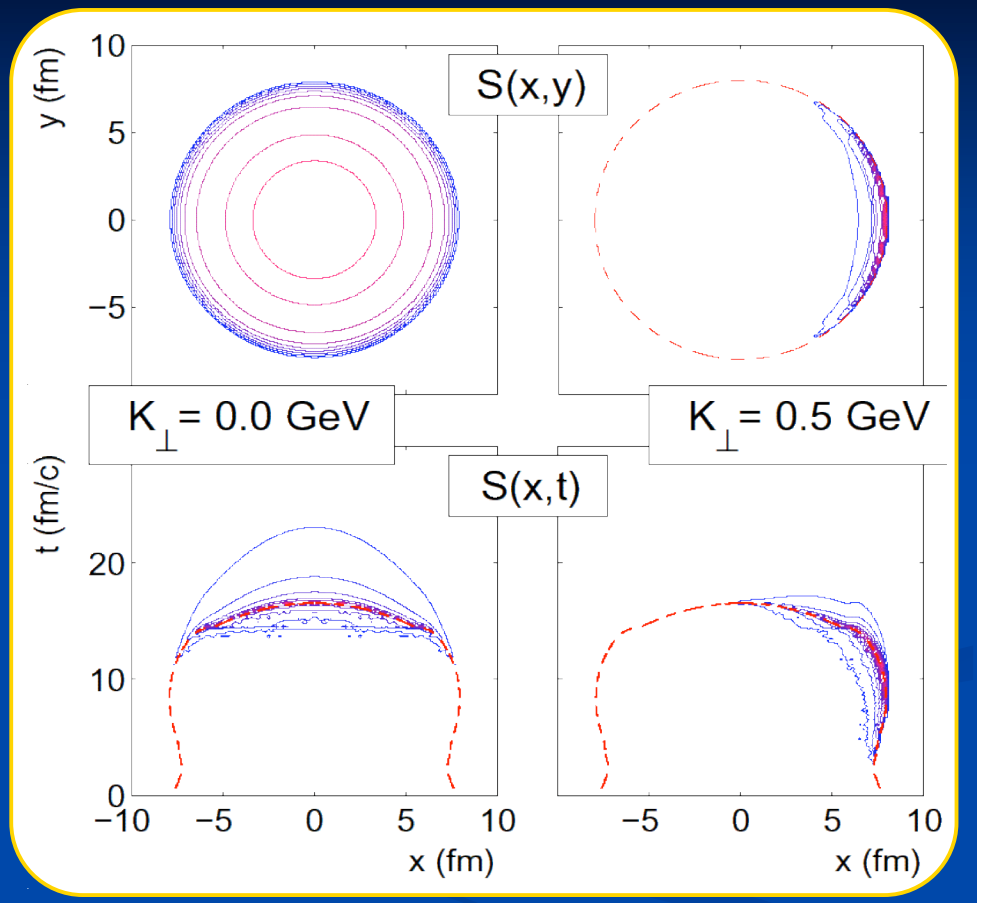
$$R_{long} = \tau_0 \sqrt{\frac{T}{m_T}\frac{K_2(m_T)}{K_1(m_T)}}$$

expansion duration

  - Transverse flow velocity, system size

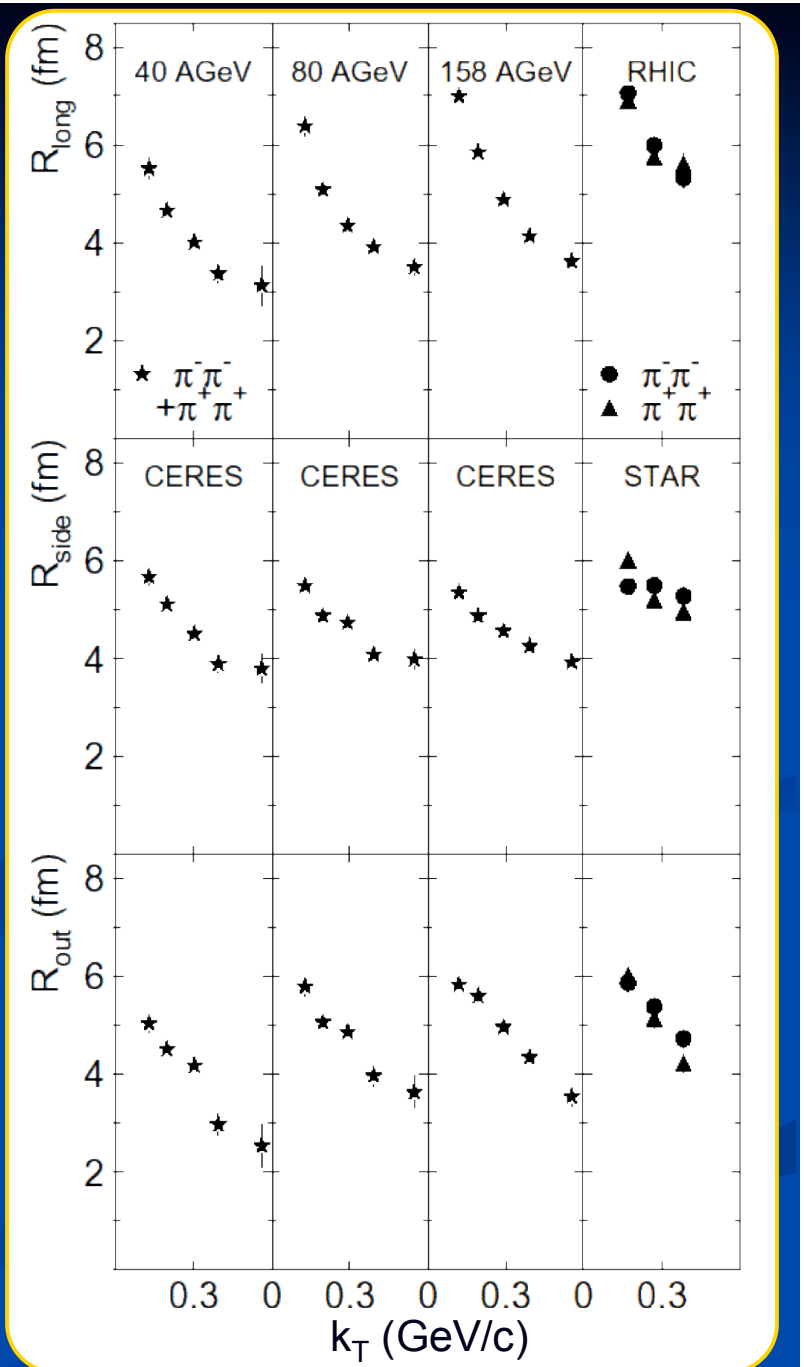
$$R_{side} = \frac{R_{geom}}{\sqrt{1+\frac{m_T}{T}\rho_f^2}}$$

transverse rapidity



Kolb & Heinz, QGP3 (nucl-th/0305084)

- **Little difference from SPS to RHIC**
  - Consistent lifetimes: τ ~ 8-10 fm/c



CERES, Nucl.Phys. A 714 (2003) 124

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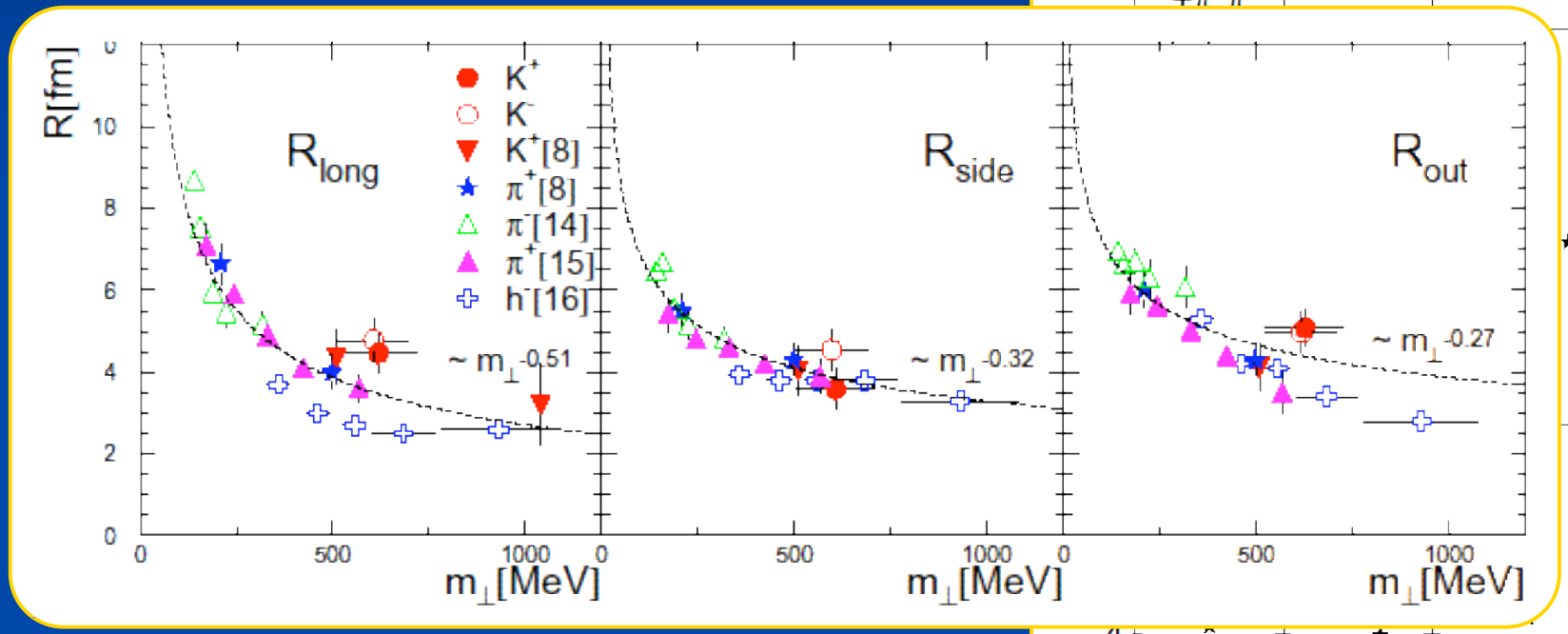
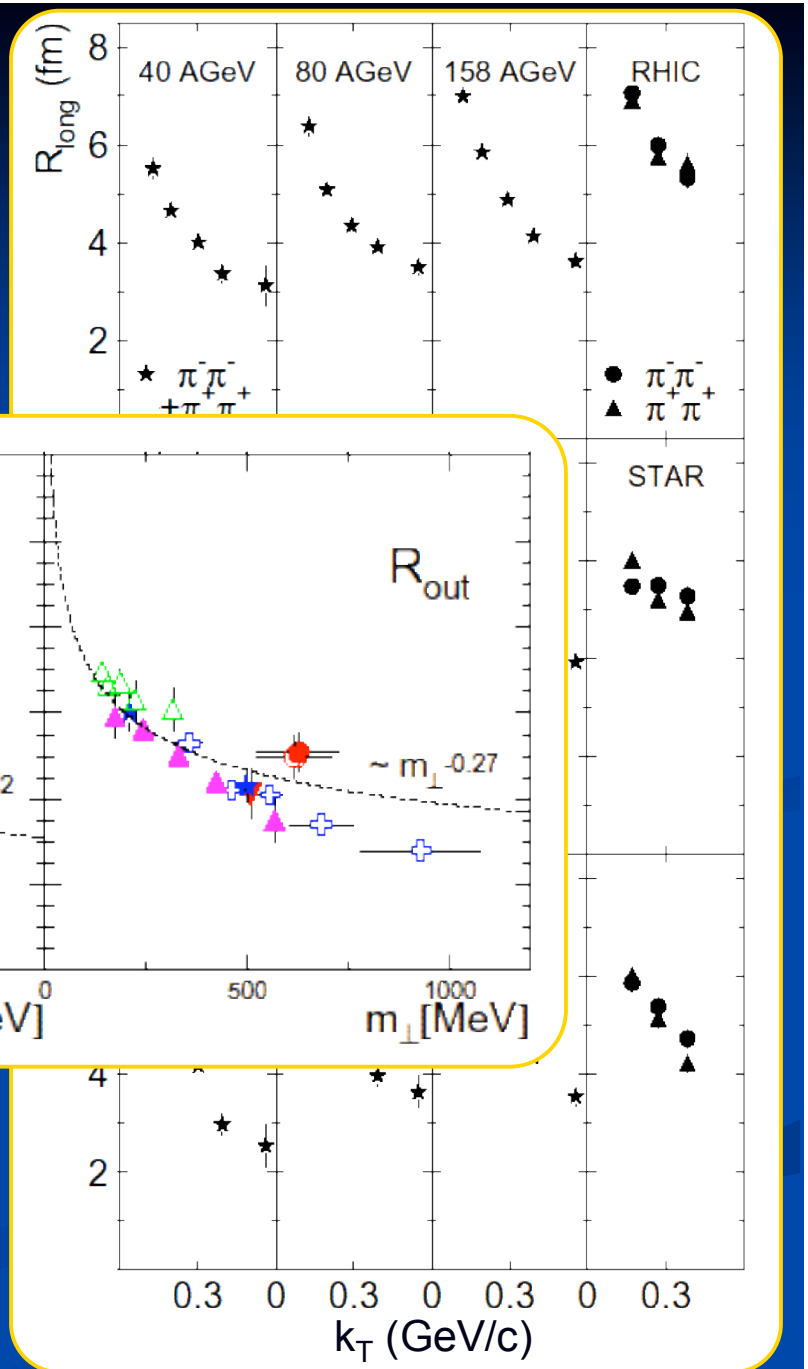


NA49, Phys.Lett. B 557 (2003) 157

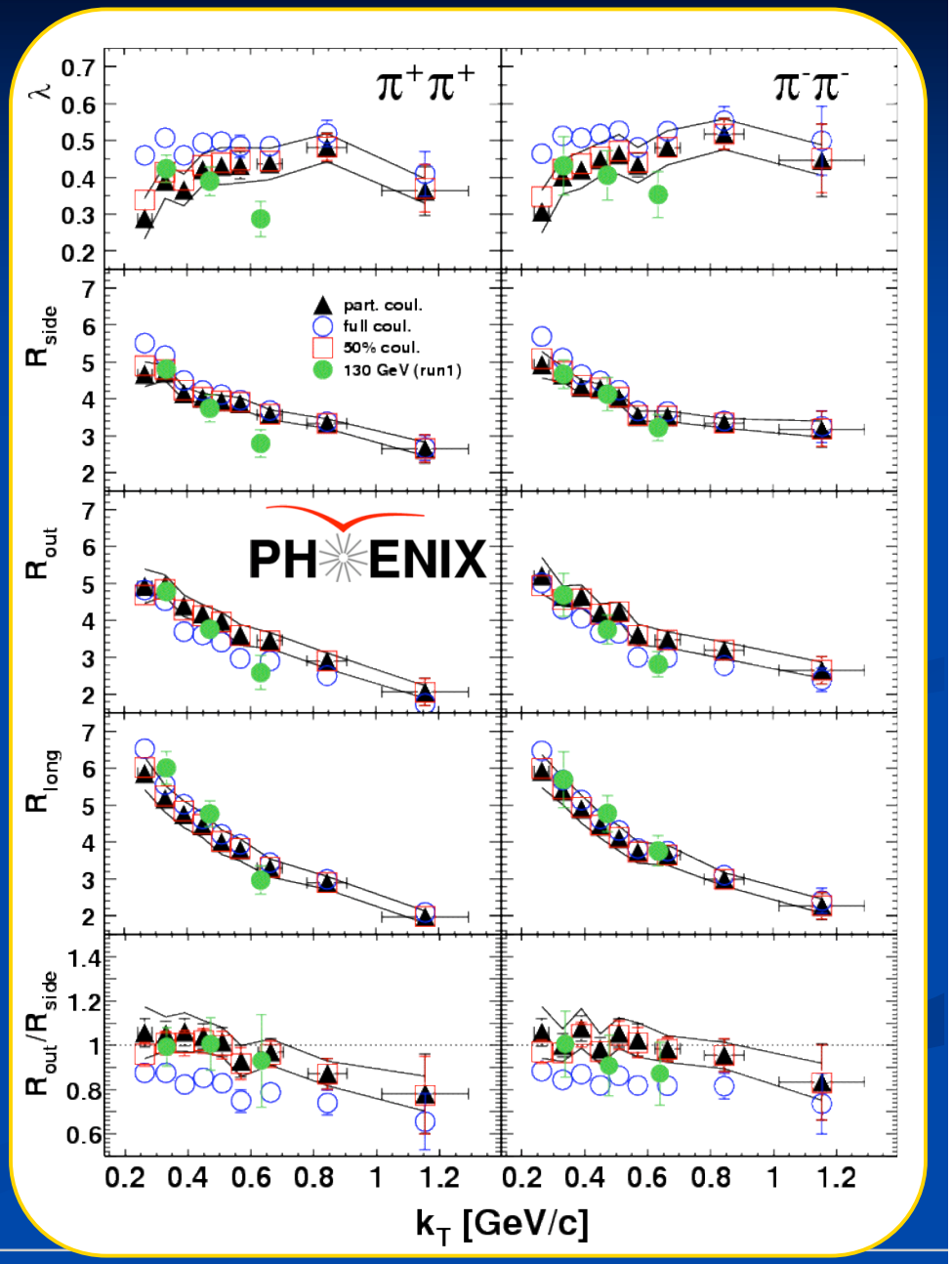


CERES, Nucl.Phys. A 714 (2003) 124

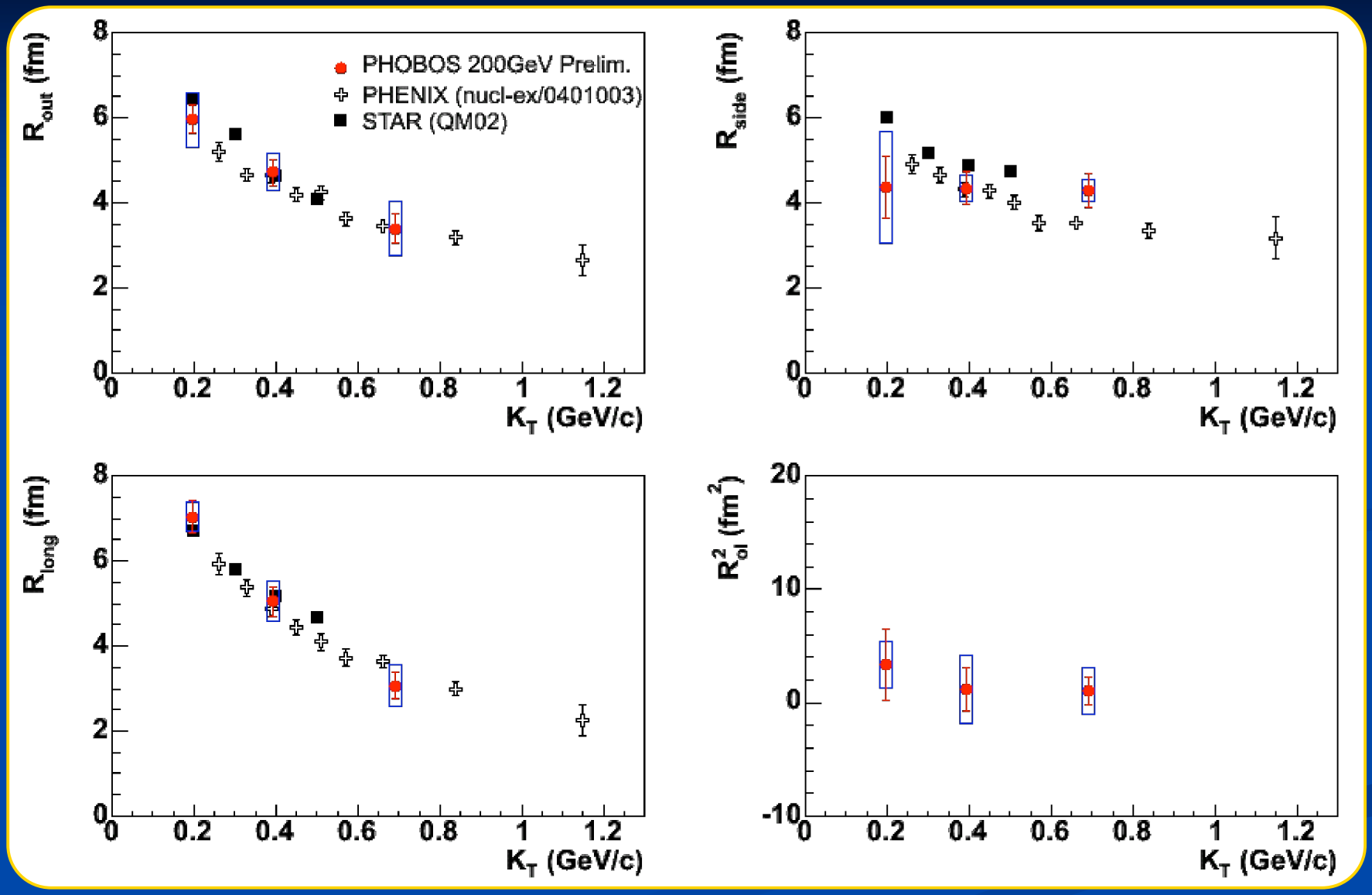
- **m_T scaling ~ holds up to 1 GeV at SPS**

HBT at $\sqrt{s}$ = 200 GeV

- **PHENIX π-HBT: k_T , centrality dependence at 200 GeV (nucl-ex/0401003)**
  - New Coulomb treatment causes ~ 10-15% change in R_{out}/R_{side}
- **STAR π-HBT: k_T , centrality and π dependence at 200 GeV (later) (nucl-ex/0312009)**
  - Sufficient statistics for triple-differential analysis!



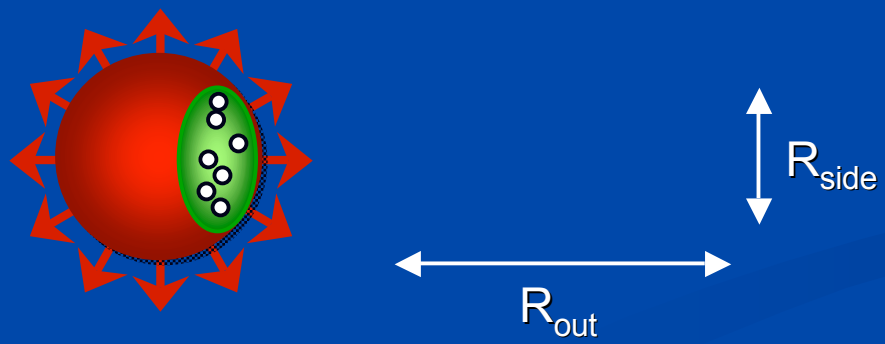
A highlight from this week

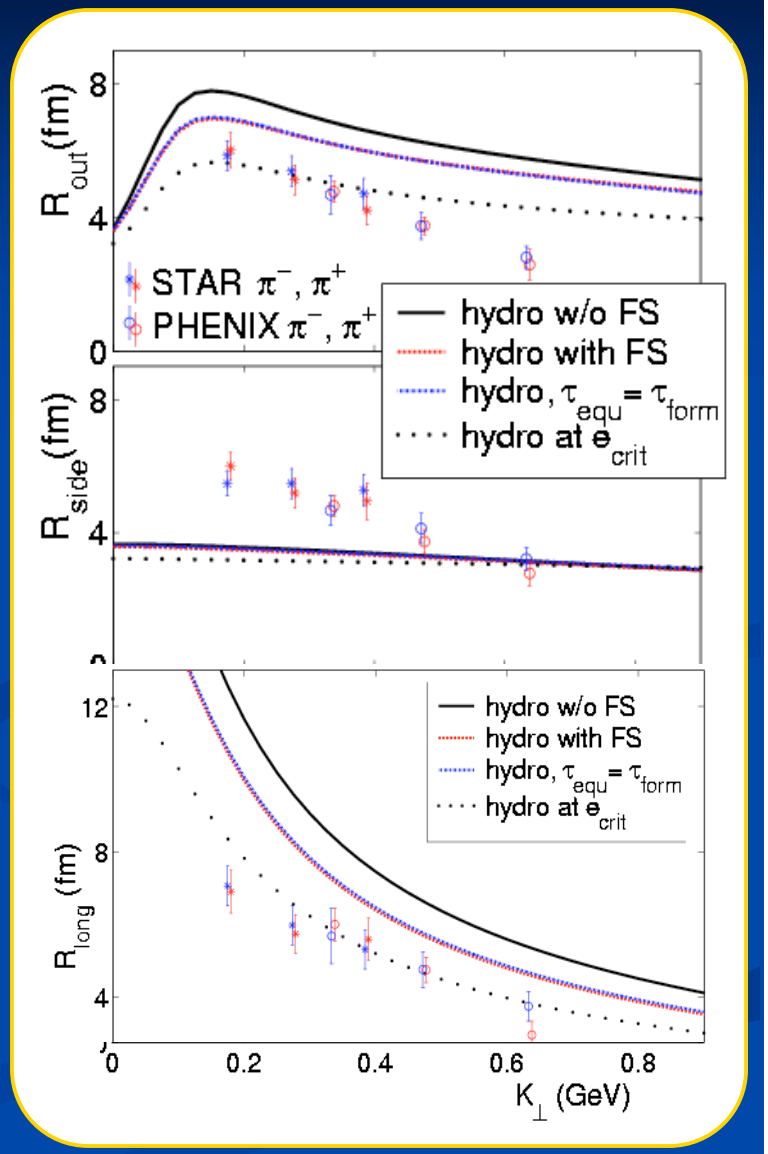


Burt Holzman, PHOBOS

The RHIC HBT Puzzle - 1

- **Hydrodynamics at RHIC**
  - ☑ Can describe soft p_T spectra and v_2 consistently, for several particle species
    - Fast thermalization in partonic phase (~_ fm/c), lives for ~15 fm/c
  - ☐ Underpredicts R_{side} and its k_T dependence
  - ☐ Overpredicts R_{out} and R_{long} by factor ~2
- **Hydro doesn't work. Why is this a puzzle?**
  - Expanding fireball, undergoing phase transition, should <u>at least</u> cause $R_{out} > R_{side}$





Kolb & Heinz, QGP3 (nucl-th/0305084)

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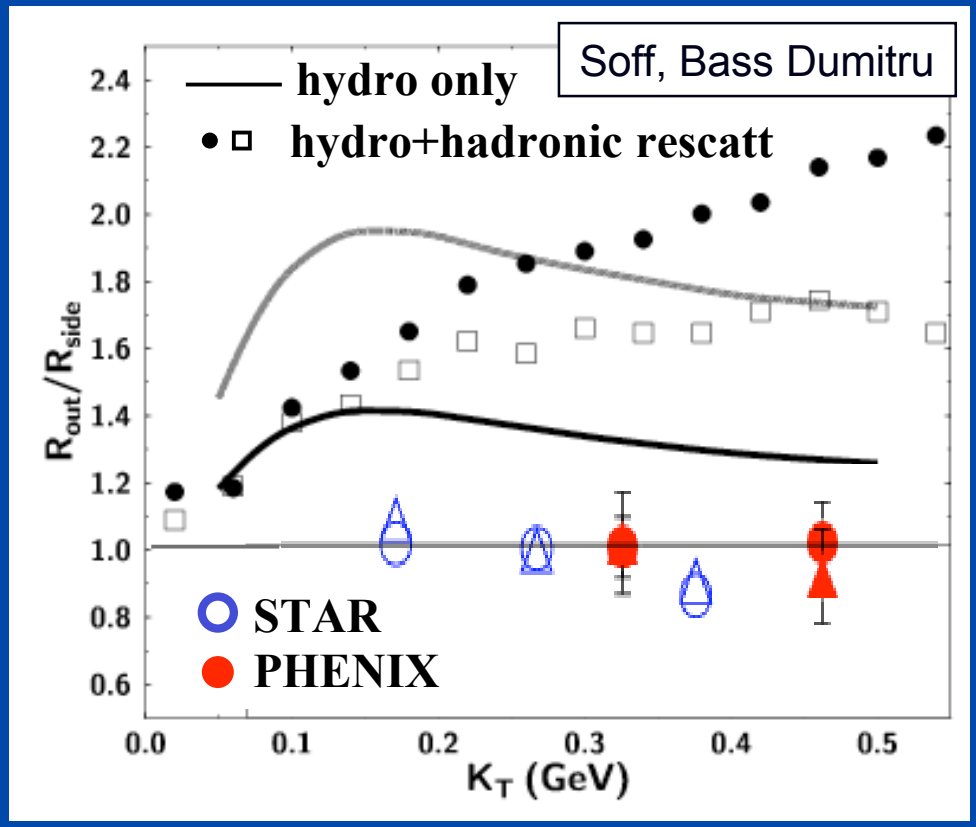
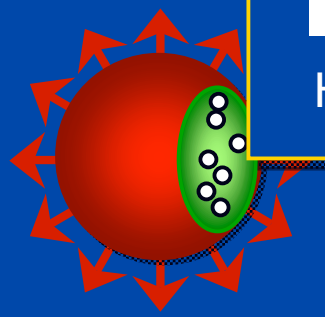
- **Hydrodynam**
  - ☑ Can descr consistentl
    - Fast th (~_ fm/
  - ☐ Underpred
  - ☐ Overpredic
- **Hydro doesn puzzle?**
  - Expanding transition, s

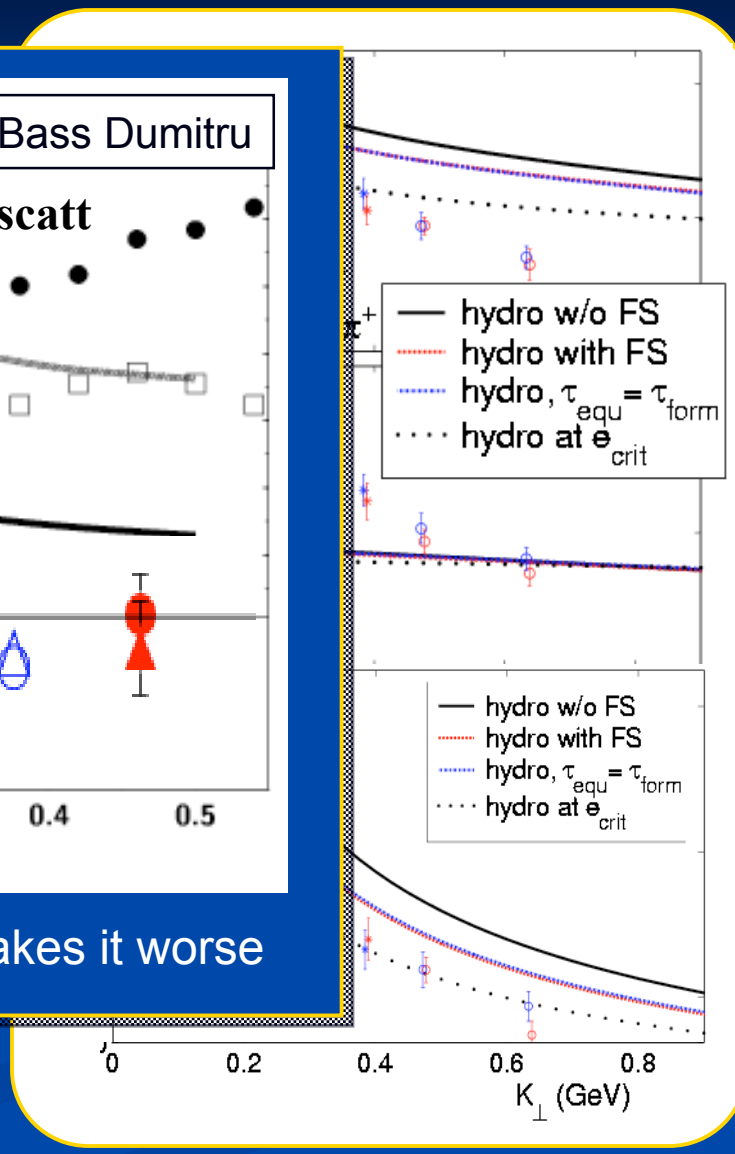


Hadronic rescattering phase makes it worse



R_{side}

R_{out}



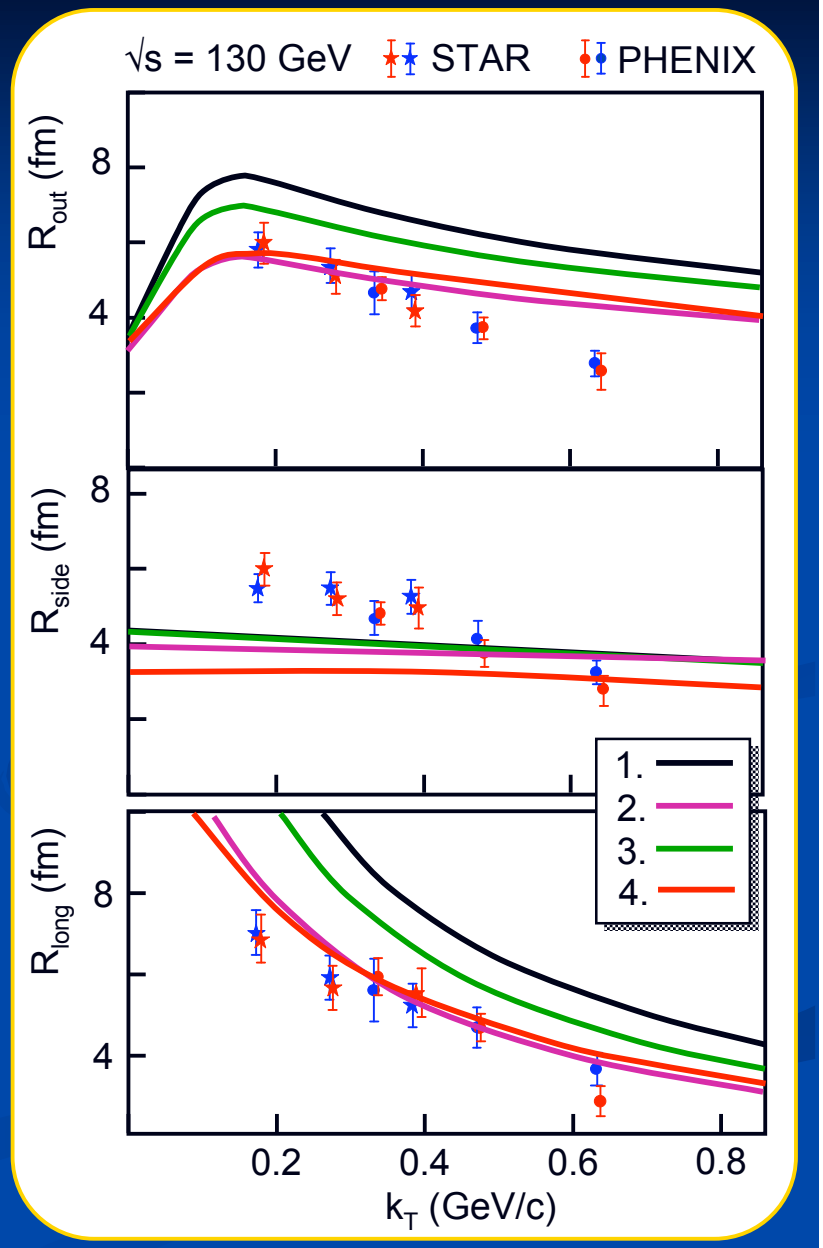
Kolb & Heinz, QGP3 (nucl-th/0305084)

The RHIC HBT Puzzle - 2

Can HBT puzzle be resolved in Hydro?

Kolb & Heinz, QGP3 (nucl-th/0305084)

1. **Default initial conditions (fit p_T & v_2)**
2. **Freeze-out directly at hadronization**
   - Conflicts with fits to particle spectra
3. **Thermalize faster, or initialize Hydro with non-zero flow**
4. **Hydro + partial chemical equilibrium**
   Hirano and Tsuda, PRC 66 (2002) 054905
   - Chemical potentials maintain proper abundances through hadronic evolution
   - Smaller R_{long}, but fails R_{out} , R_{side}



The RHIC HBT Puzzle - 3

Alternative approaches

5. **Parton cascade with opacity**
   Molnar and Gyulassy, nucl-th/0211017
   - Pion freeze-out distribution sensitive to transport opacity □

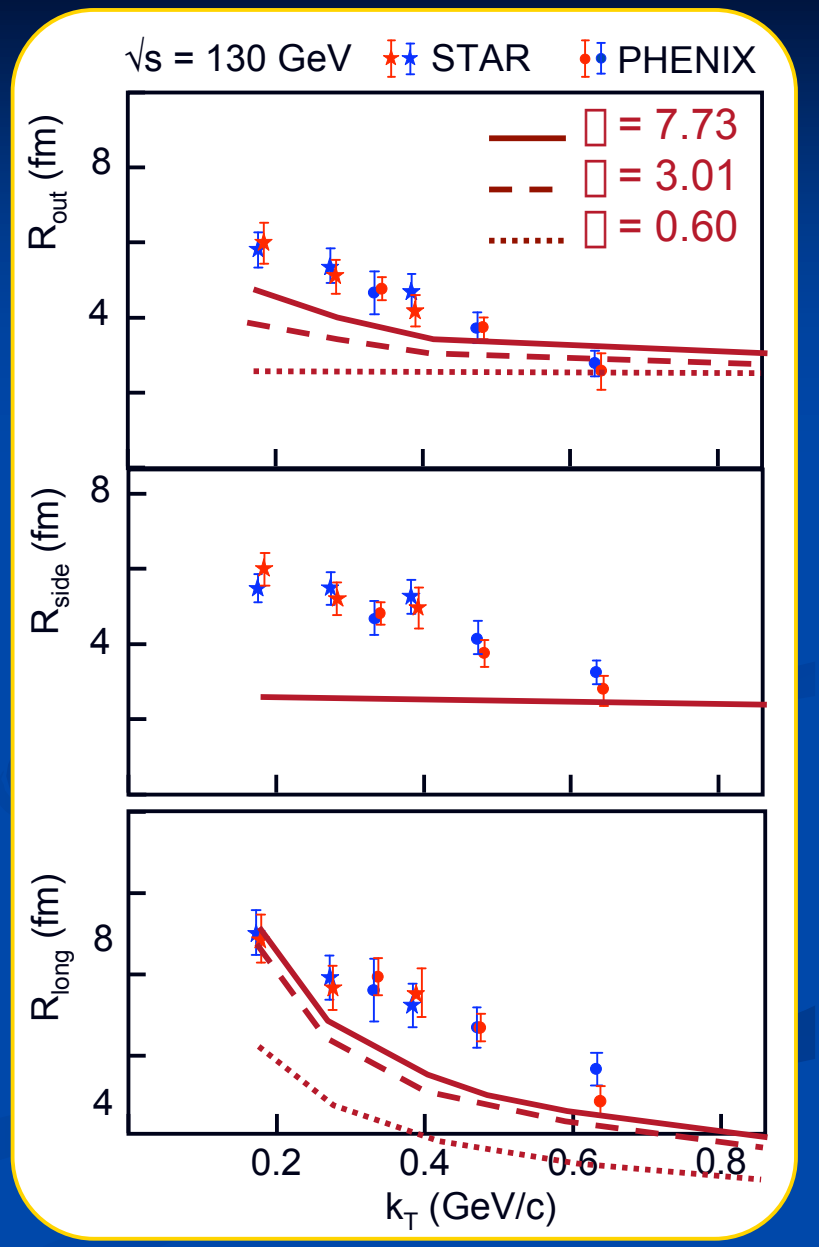
6. **Positive x_o-t correlation ?!**
   Lin, Ko and Pal, PRL 89 (2002) 152301

$$R_o^2(K) = \langle \tilde{x}_o^2 \rangle \square 2\square_T \langle \tilde{x}_o t \rangle + \square_T^2 \langle t^2 \rangle$$

±

$$R_s^2(K) = \langle \tilde{x}_s^2 \rangle$$

$$R_l^2(K) = \langle \tilde{z}^2 \rangle \quad \left(= \square^2 + t^2\right)$$



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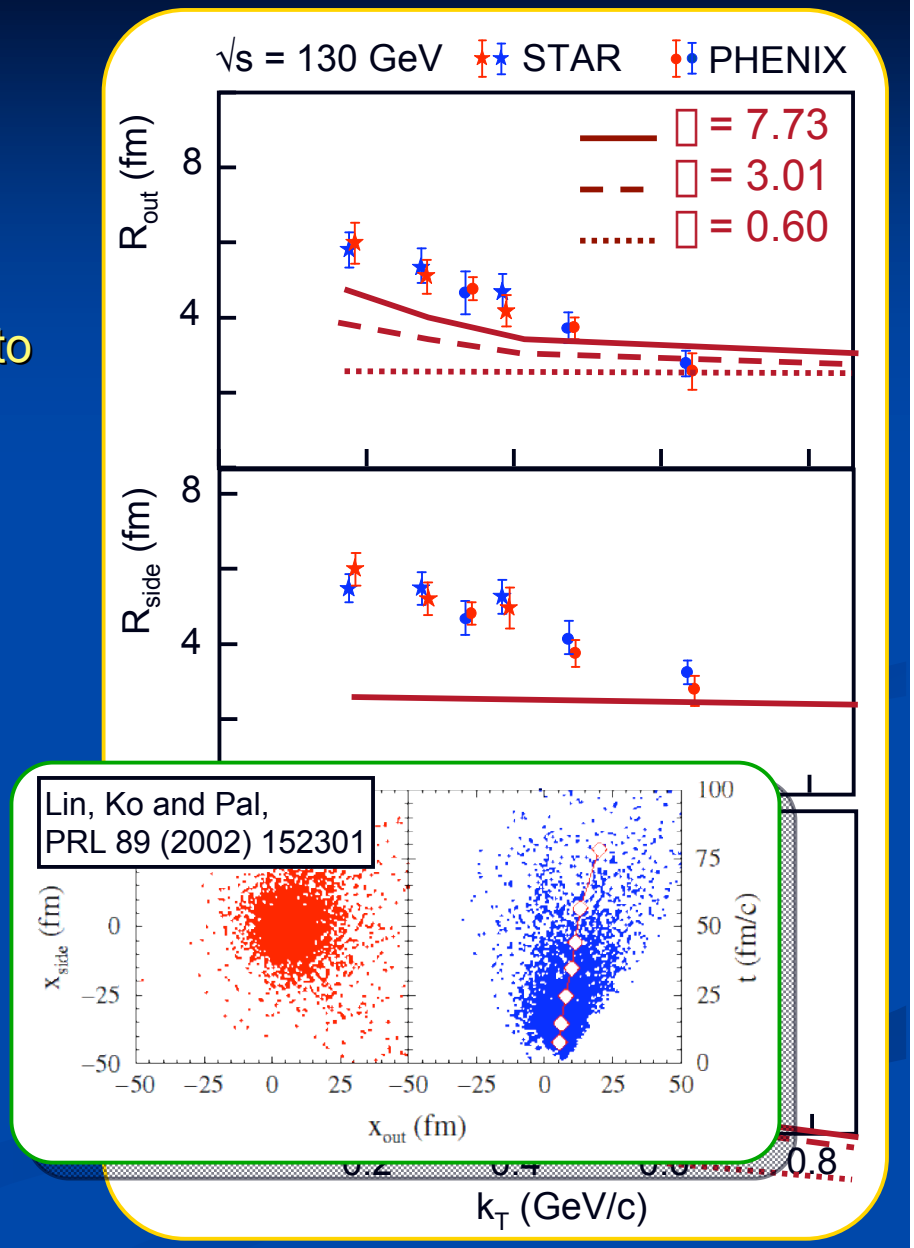


The RHIC HBT Puzzle - 4

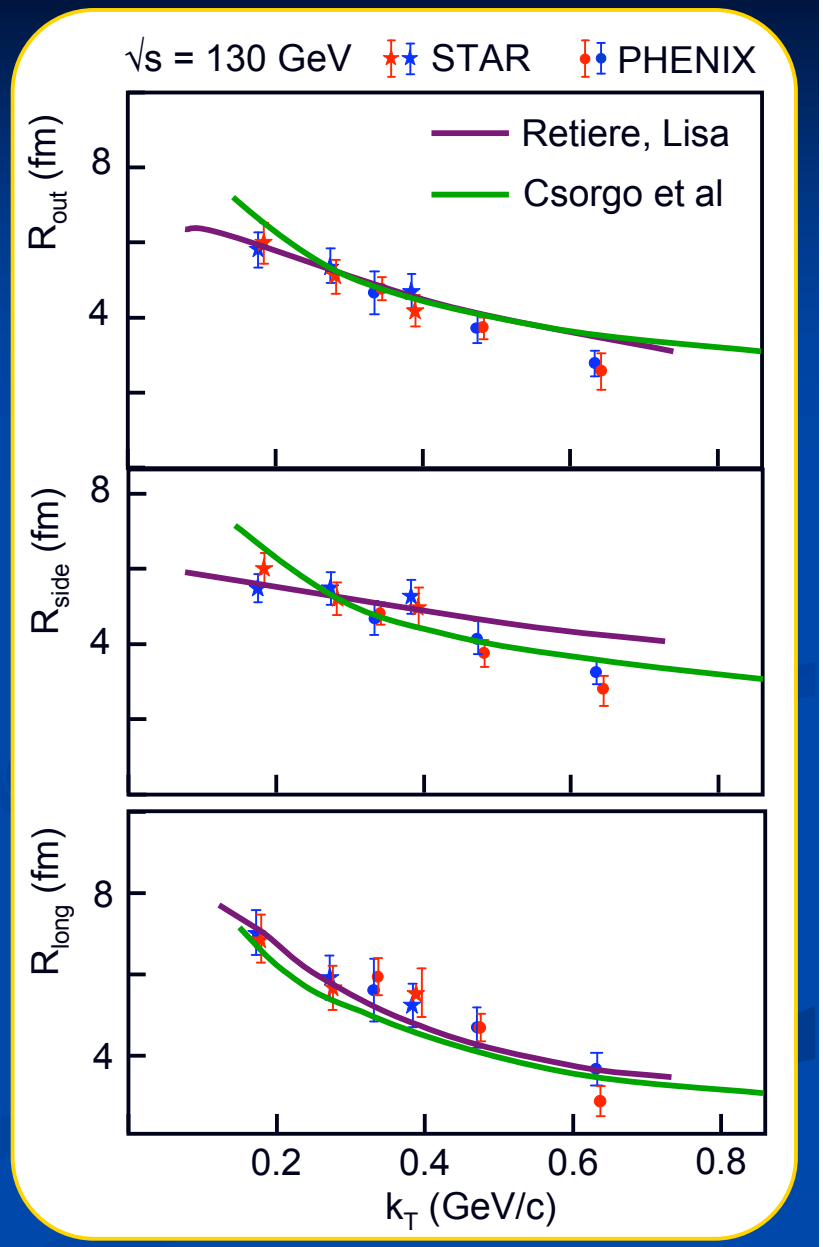
Hinting at the solution

- **Blast-wave parametrization**
  Retiere and Lisa, nucl-th/0312024
  - Longitudinal boost invariance
  - Relative particle abundances not fixed
  - Constant parameters at freeze-out

T_f	104 ± 3 MeV
τ_f	8.9 ± 0.3 fm/c

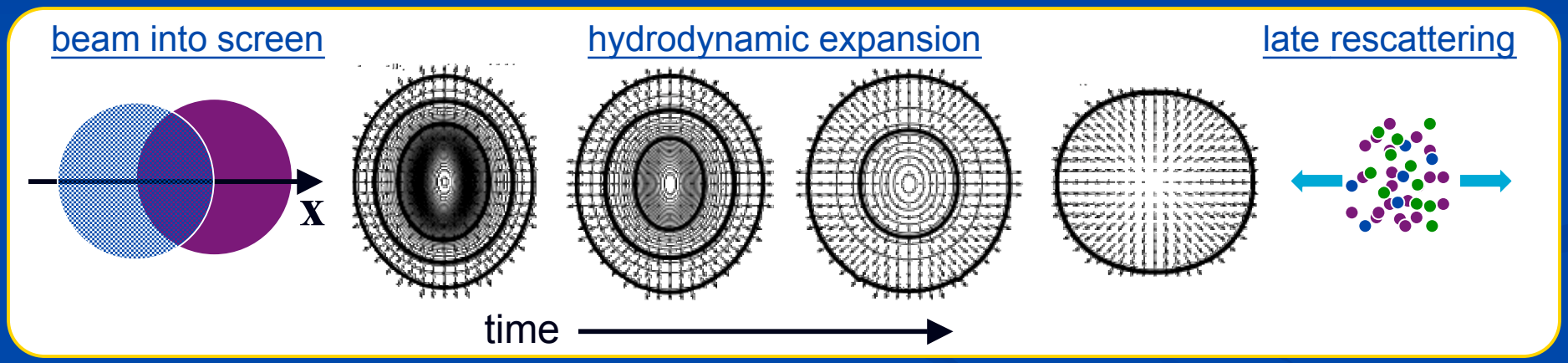
- **Buda-Lund Hydro parameterization**
  Csorgo et al, nucl-th/0311102
  - Not boost invariant (Hubble flow)
  - Freeze-out smeared in temperature

T_o	214 ± 7 MeV
τ_f	6.0 ± 0.2 fm/c



Azimuthally sensitive □ HBT

- **HBT(□): probe spatial anisotropy at freeze-out**
  Wiedemann, PRC 57 (1998) 266
  - Freeze-out shape probes nature & timescale of system evolution
  - How much (if any) initial spatial deformation survives system expansion?



❶ Initial geometry _ aniosotropies in pressure gradients

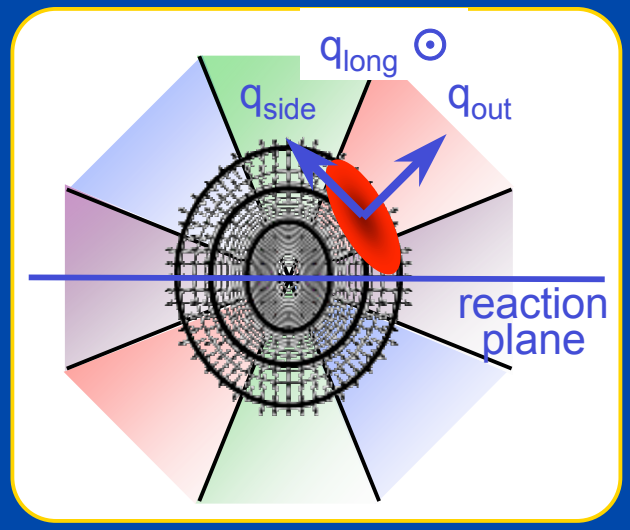
❷ Preferential in-plane expansion _ decreases spatial anisotropy

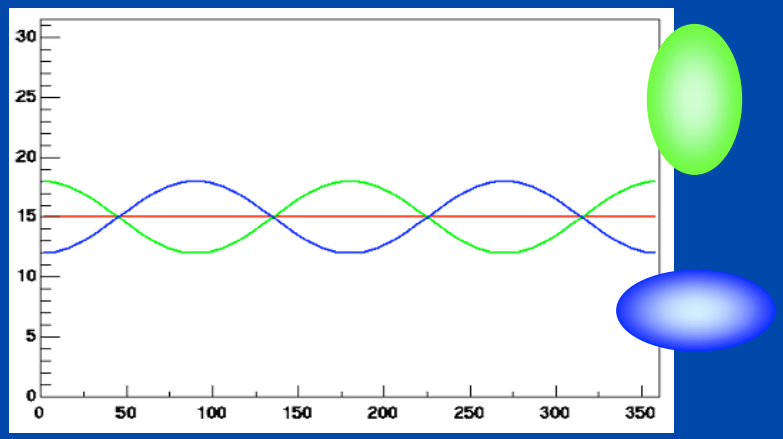
❸ Freeze-out source shape via HBT _ measure of pressure, expansion time

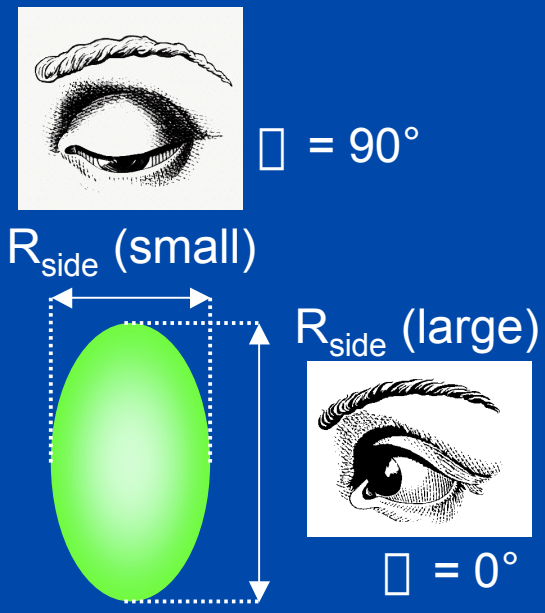
(model-dependent)

Azimuthally sensitive □ HBT

- **HBT(□): probe spatial anisotropy at freeze-out**

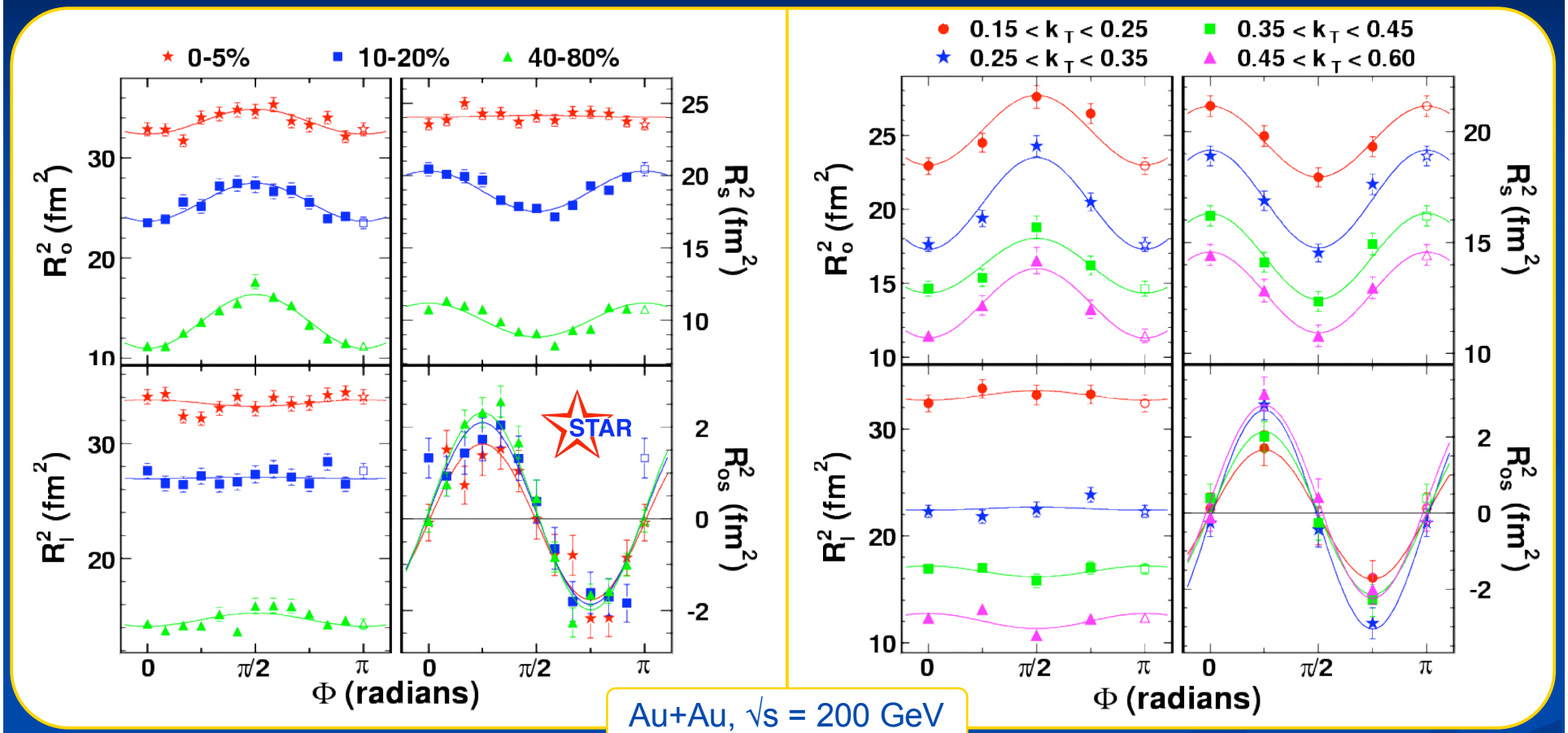






(model-dependent)

HBT(Φ): Centrality & k_T dependence



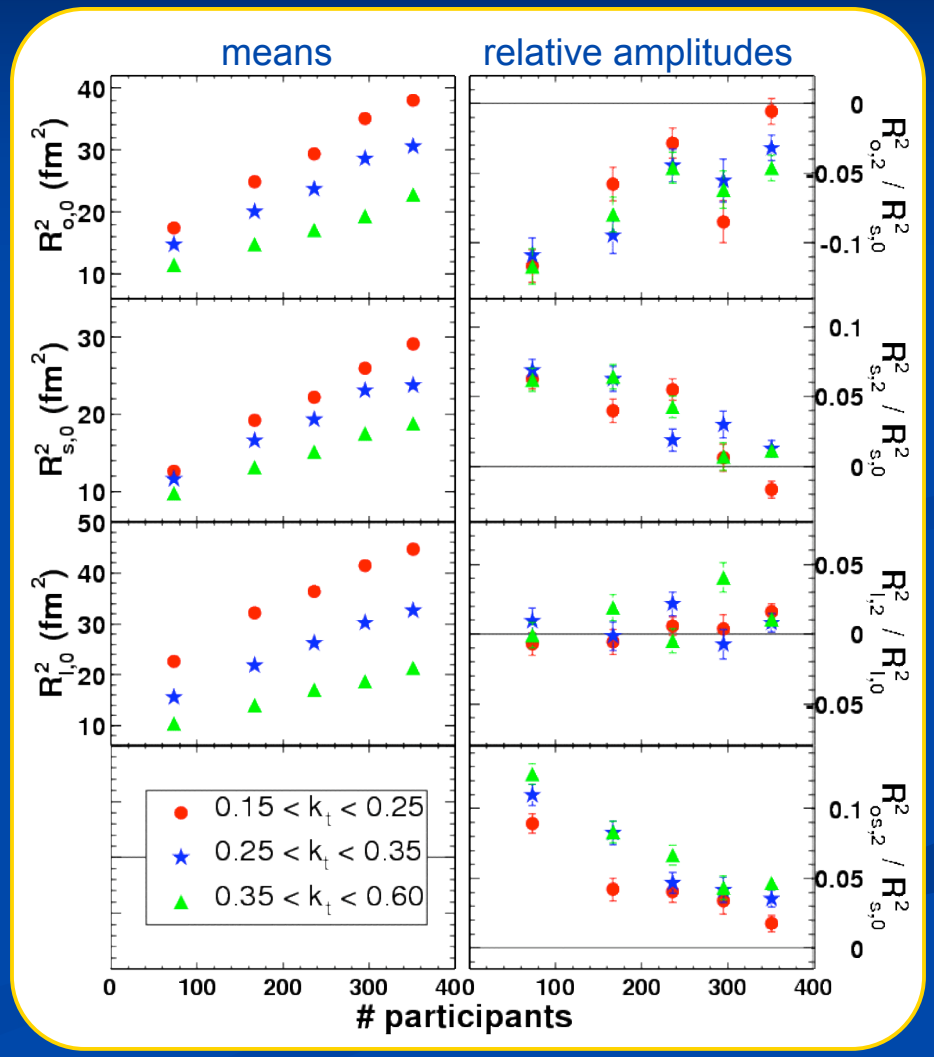
Au+Au, √s = 200 GeV

STAR Collaboration, nucl-ex/0312009

Fourier coefficients of HBT(□) oscillations

- 0th-order FC: centrality & k_T dependence mirrors □-integrated analyses; quantitatively consistent
- Relative amplitudes increase from central to peripheral collisions

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



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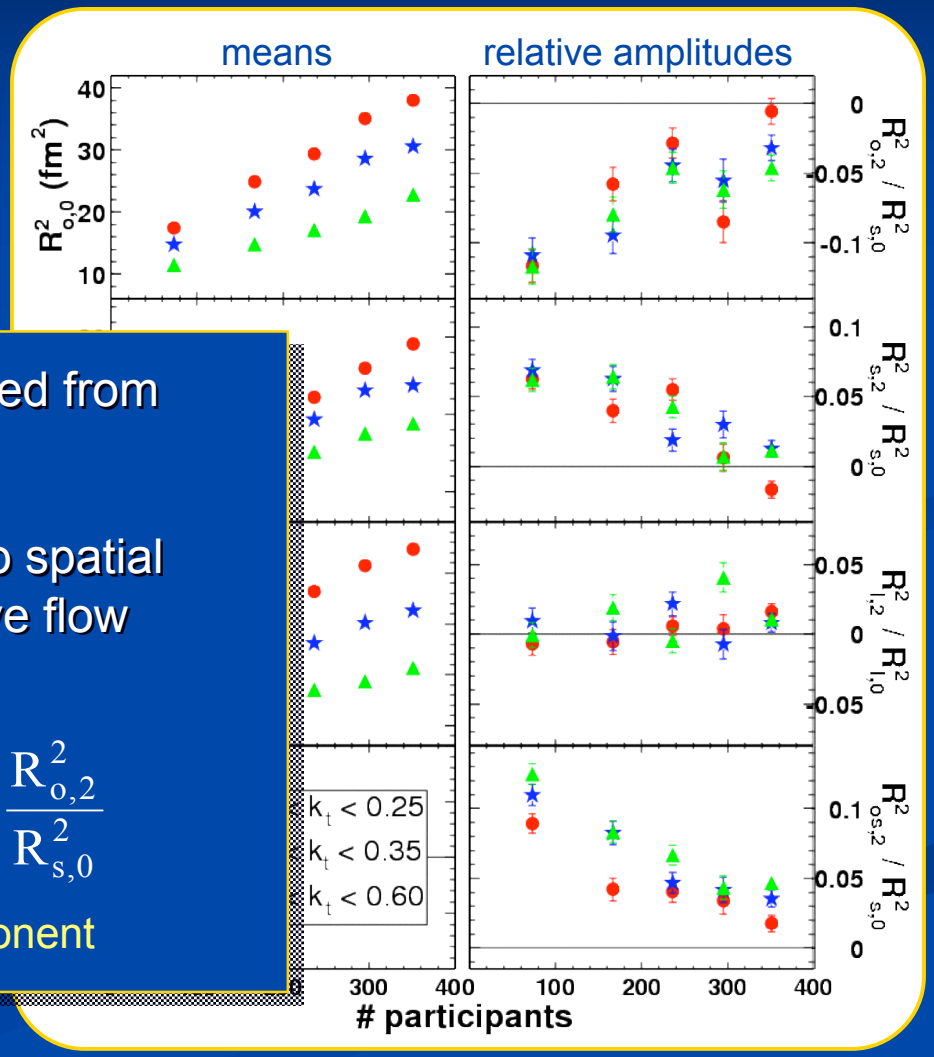


- Freeze-out eccentricity can be estimated from relative amplitudes
- Blast-wave: rel. amplitudes sensitive to spatial anisotropy, depend weakly on collective flow
  Retiere and Lisa, nucl-th/0312024

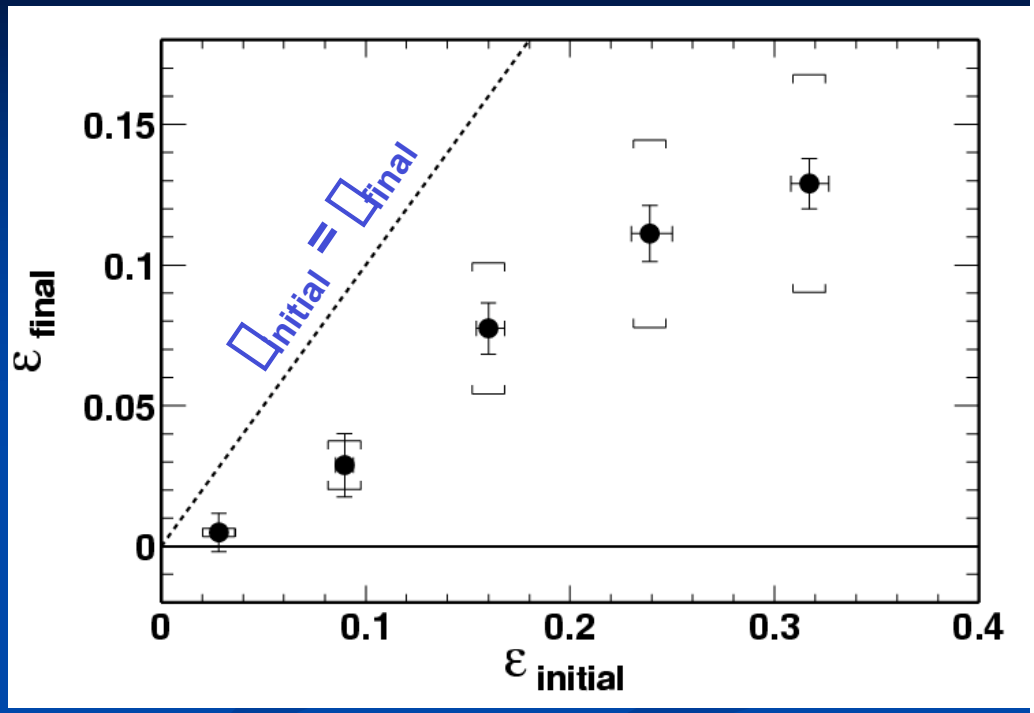
$$\square \equiv \frac{R_y^2 \square R_x^2}{R_y^2 + R_x^2} = 2\frac{R^2_{s,2}}{R^2_{s,0}} = 2\frac{R^2_{os,2}}{R^2_{s,0}} = \square 2\frac{R^2_{o,2}}{R^2_{s,0}}$$

no temporal component

STAR Collaboration, nucl-ex/0312009

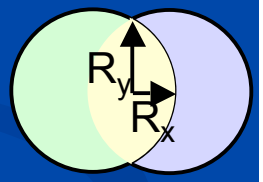
Fourier coefficients of HBT(□) oscillations

- **Out-of-plane sources at freeze-out**
  - Pressure and/or expansion time was not sufficient to quench initial shape
- **From v_2 we know...**
  - Strong in-plane flow _ significant pressure build-up in system



STAR Collaboration, nucl-ex/0312009

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



- **Evolution of eccentricity _ consistent with □~ 9 fm from R_{long} Sinyukov fit**

Universal pion freeze-out

- **CERES proposed a simple ansatz to investigate if critical mean free path for pions λ_f drives freeze-out**
  - Mean free path can be estimated from these two relations:

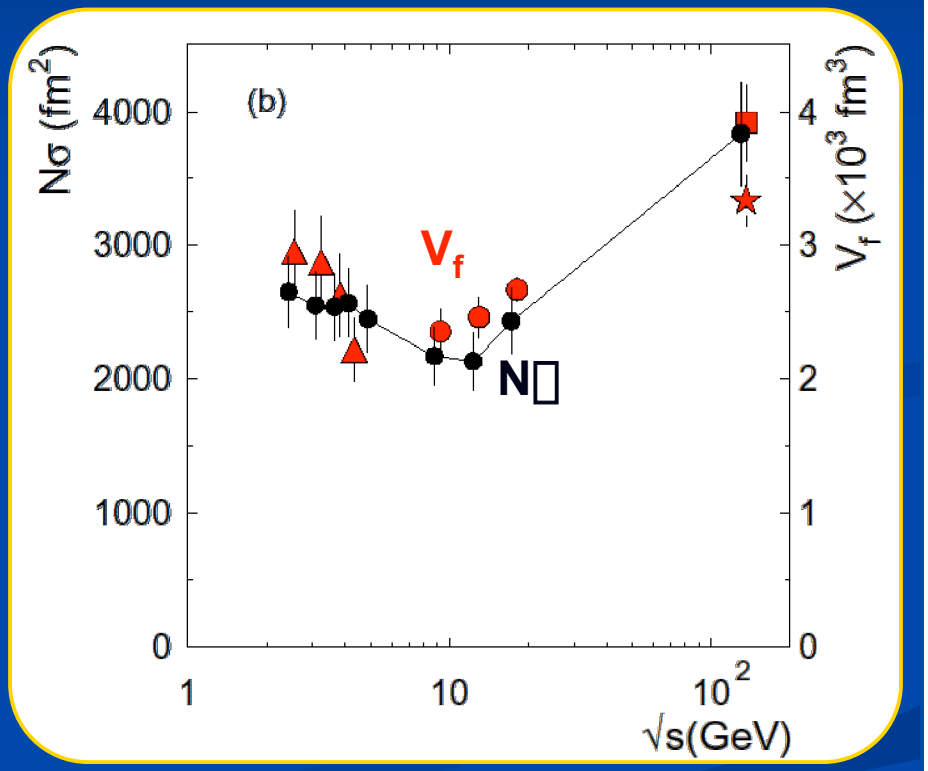
$$\lambda_f = \frac{\lambda_f}{\lambda} = \frac{V_f}{N\lambda} \lambda \sim 1\,\text{fm}$$

  - Use HBT radii to estimate freeze-out volume V_f

$$V_f \equiv (2\pi)^{3/2} R_{\text{long}} R_{\text{side}}^2$$

  - Fold π-π and π-N cross sections with experimentally-measured dN/dy's

$$N\lambda \equiv \sum_i N_i \lambda_{\pi i} = N_N \lambda_{\pi N} + N_\pi \lambda_{\pi\pi}$$

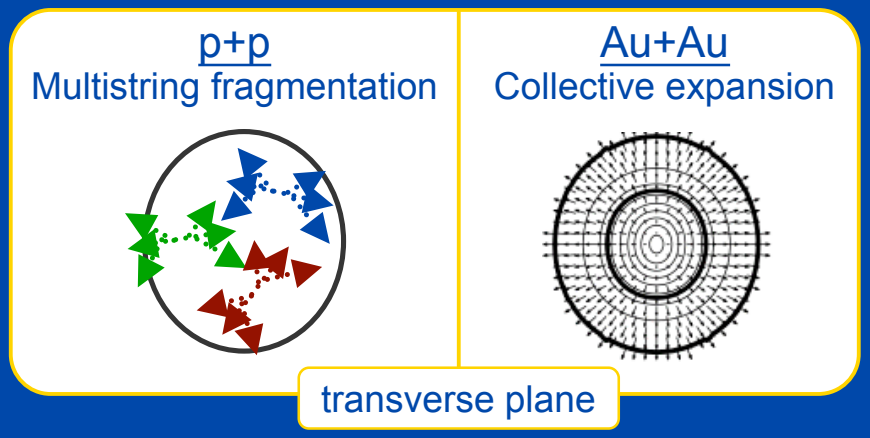


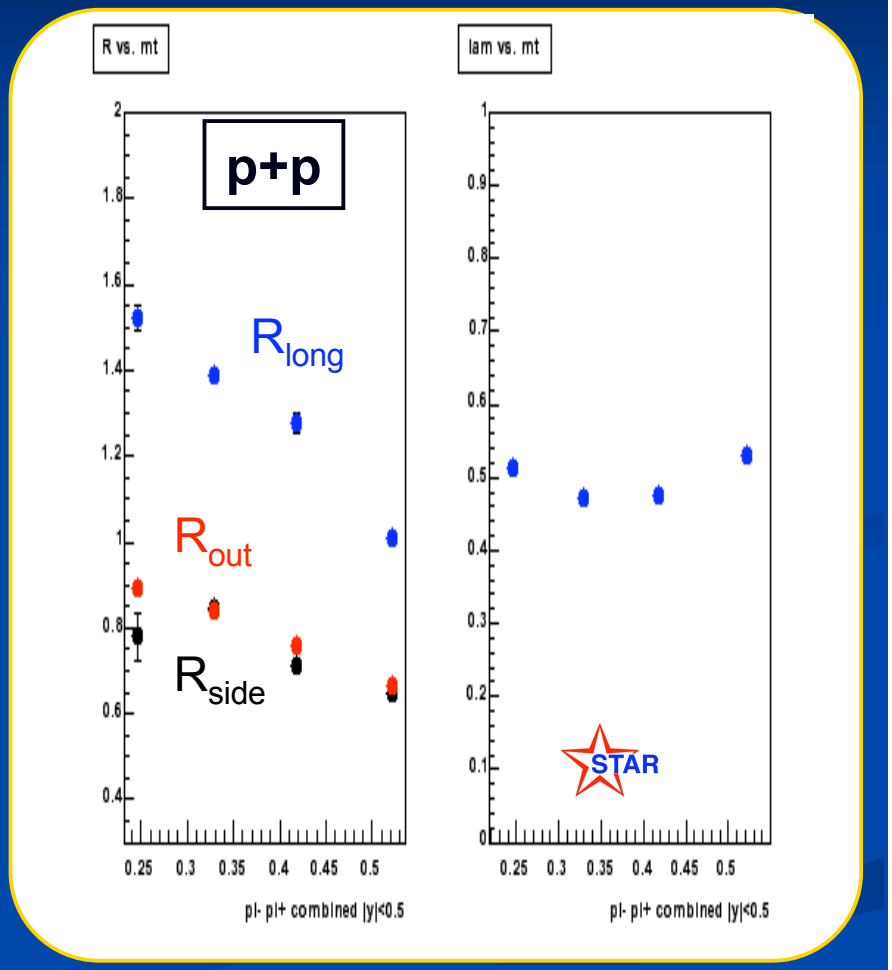
CERES, PRL 90 (2003) 022301

- **Does this work for lighter systems?**

HBT in p+p collisions at RHIC

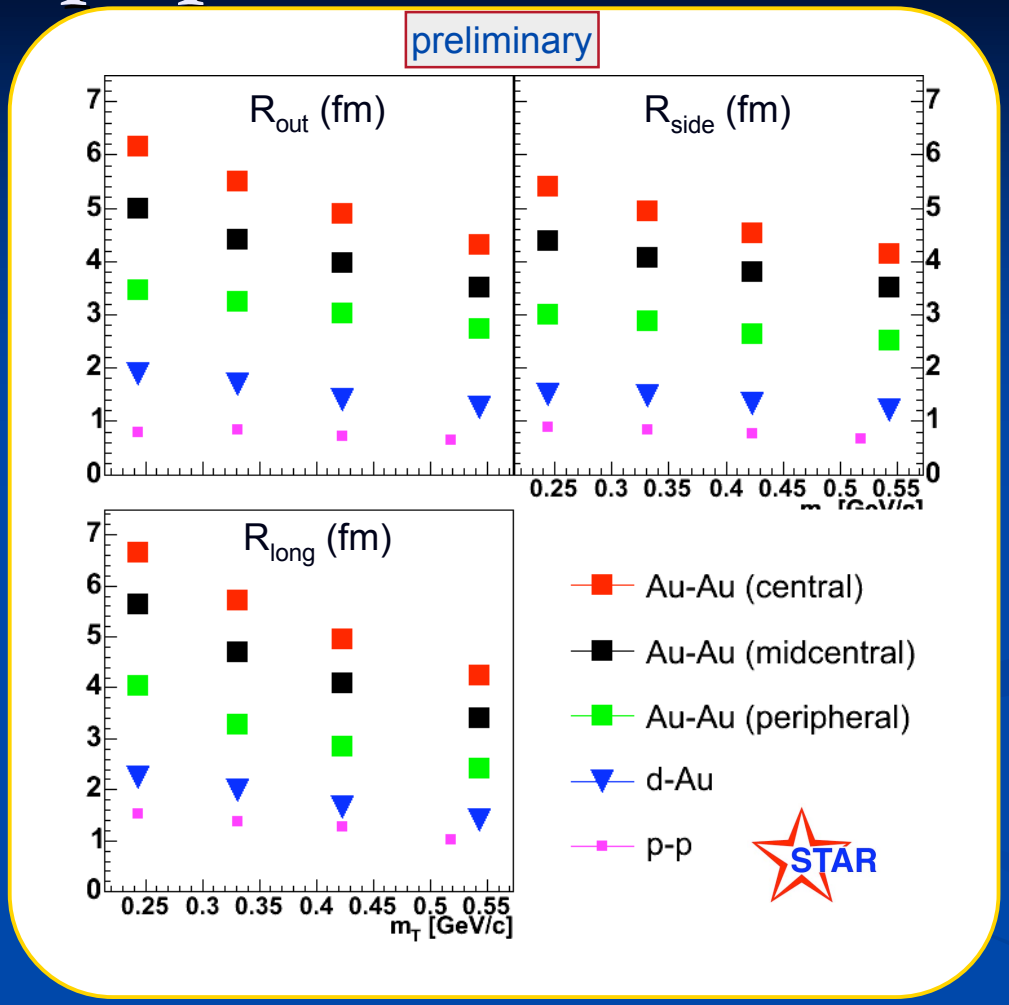
- **RHIC: HBT for 3 very different systems at same c.m. energy & with same detector**
- **k_T dependence of HBT radii presumably arises in different ways**





T. Gutierrez for STAR Coll, poster

p+p _ d+Au _ Au+Au



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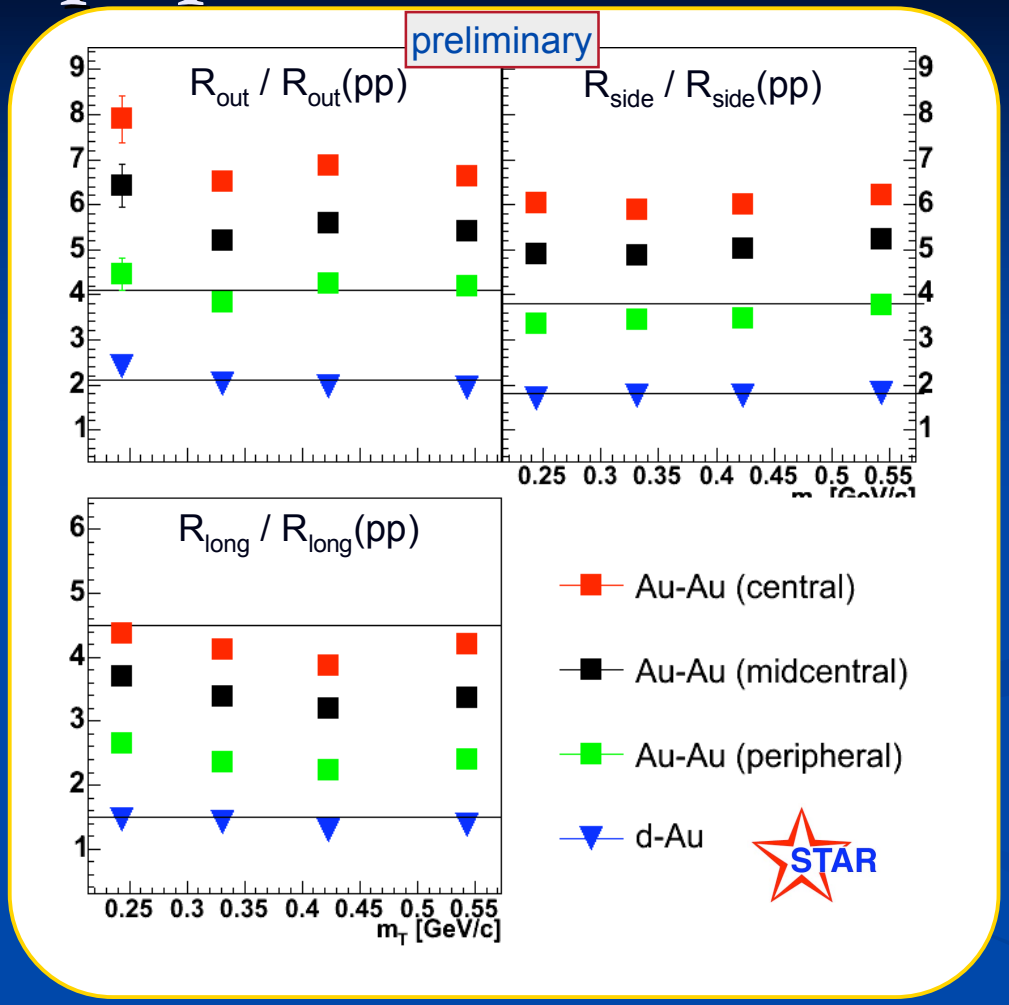
- All three systems exhibit similar k_T dependence (?!)
- Systematic study underway to assess “Gaussian-ness” of correlation

p+p _ d+Au _ Au+Au



T. Gutierrez for STAR Coll, poster

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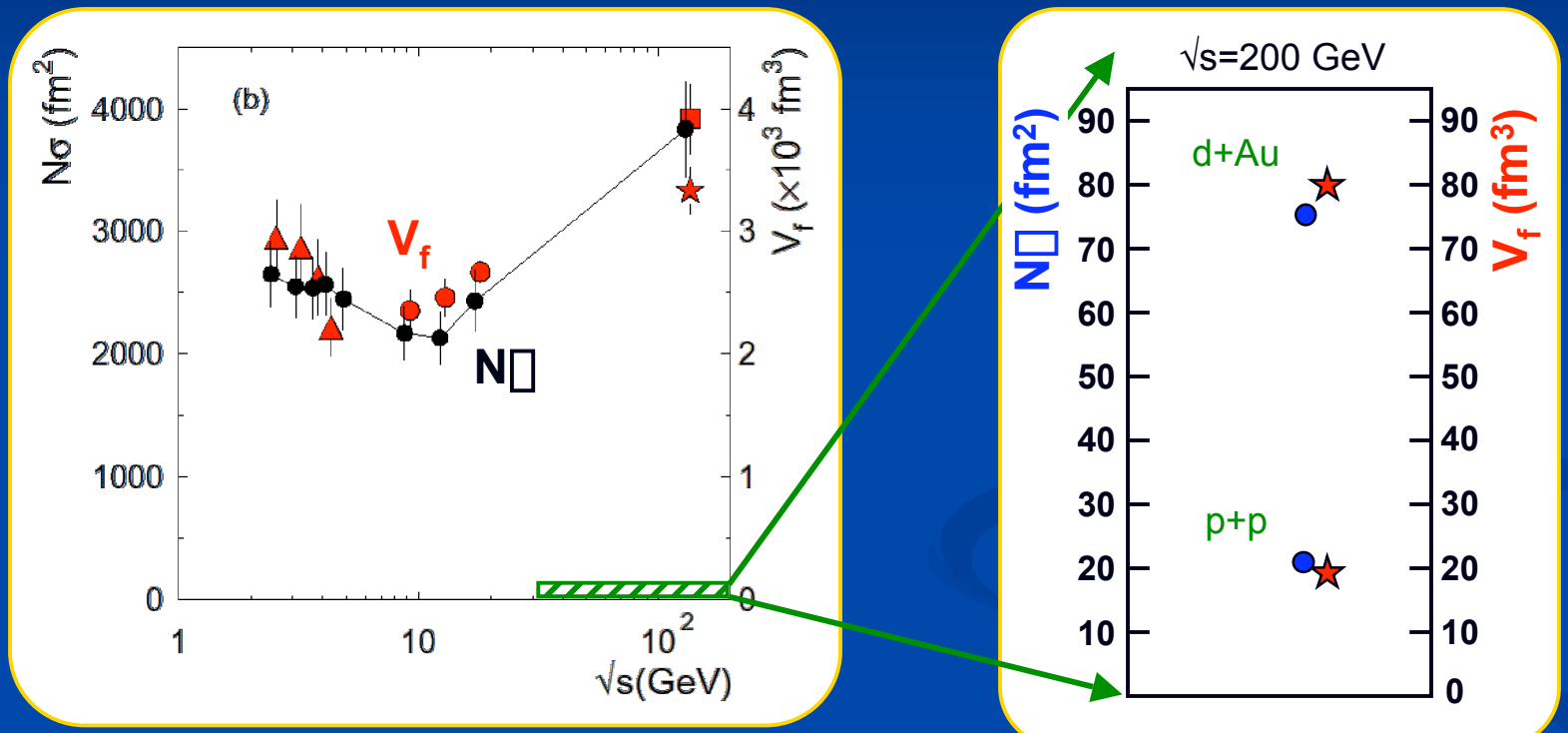
Same universal freeze-out in p+p, d+Au ?

- **Check CERES' ansatz using dN/dy's and HBT radii for p+p and d+Au**
  - dN/dy's taken from power-law fits to STAR p_T spectra (nucl-ex/0309012)



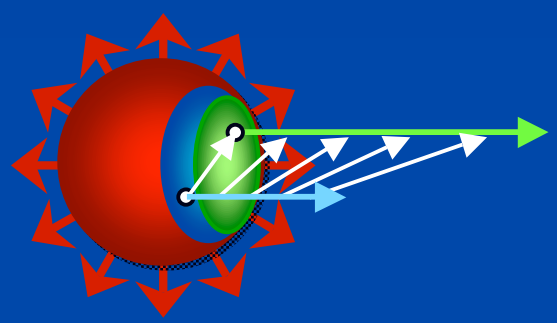
CERES, PRL 90 (2003) 022301

- **τ_f ~ 1 fm seems to hold for light systems as well (!)**
- **Why are p+p, d+Au and Au+Au so similar?**

Non-identical particle correlations

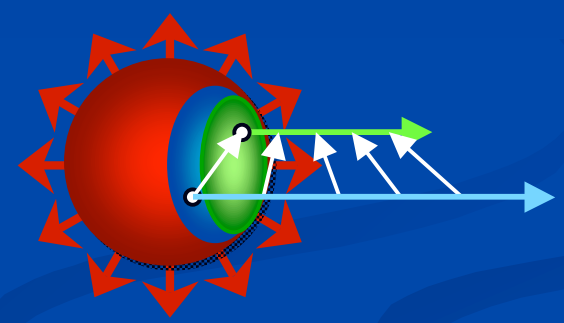
- **Study emission asymmetries with final-state interactions**
  - Strong radial flow induces species-dependent x-p correlations

Case 1
Particle emitted closer to center is **slower**



- Effective interaction time shorter
- Weaker correlation

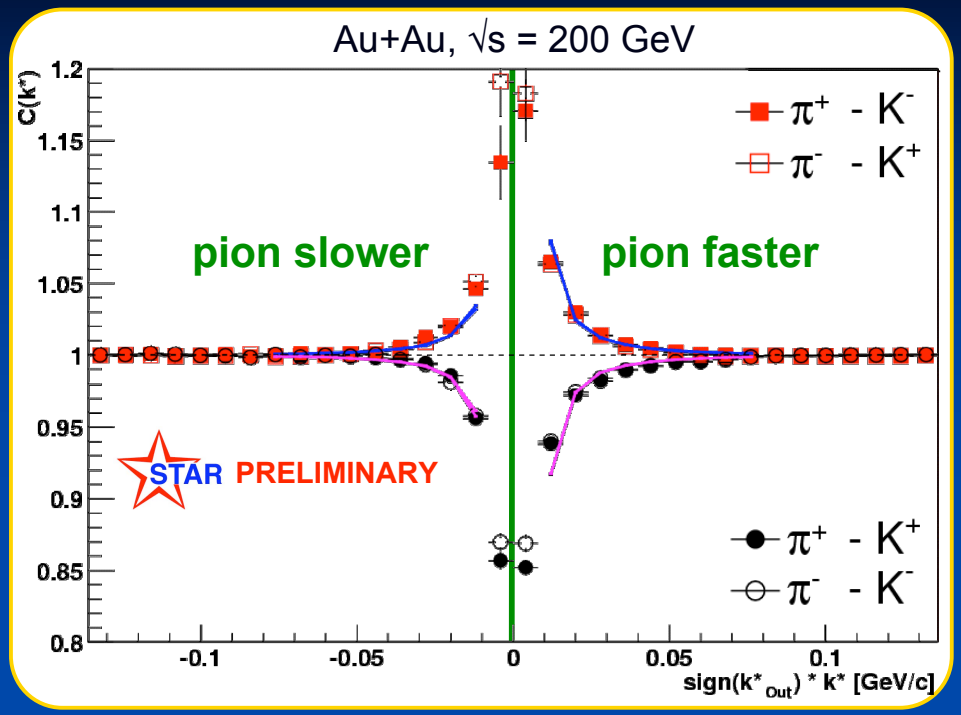
Case 2
Particle emitted closer to center is **faster**

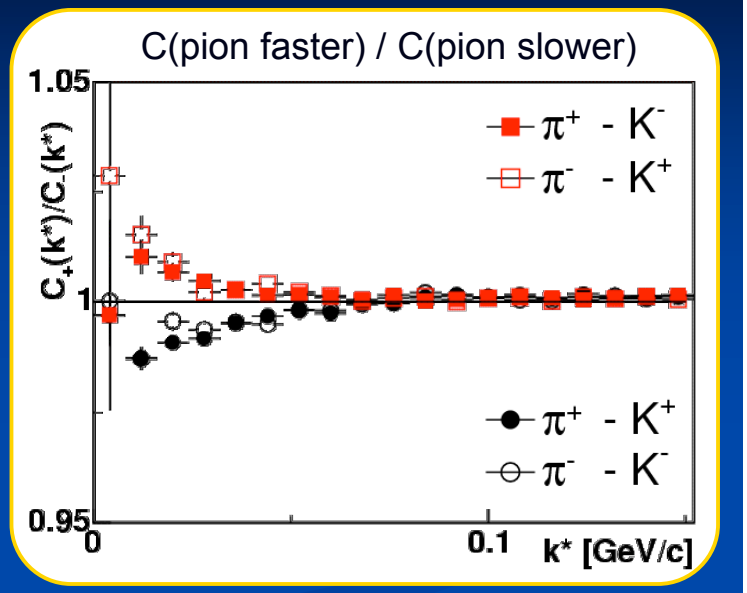


- Effective interaction time larger
- Stronger correlation

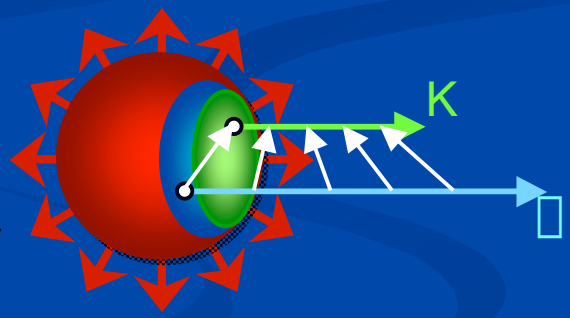
- **The two cases can be discriminated**
  - Two correlation functions: “lighter particle faster”, “lighter particle slower”
  - Compare correlation strength of two CF’s

Non-identical particle correlations



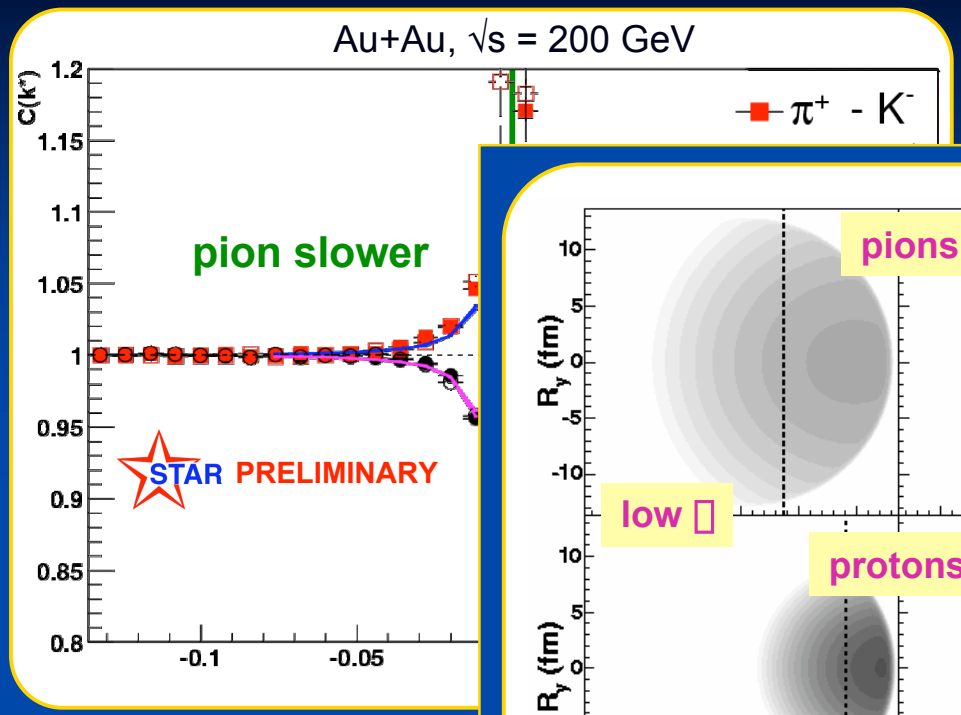


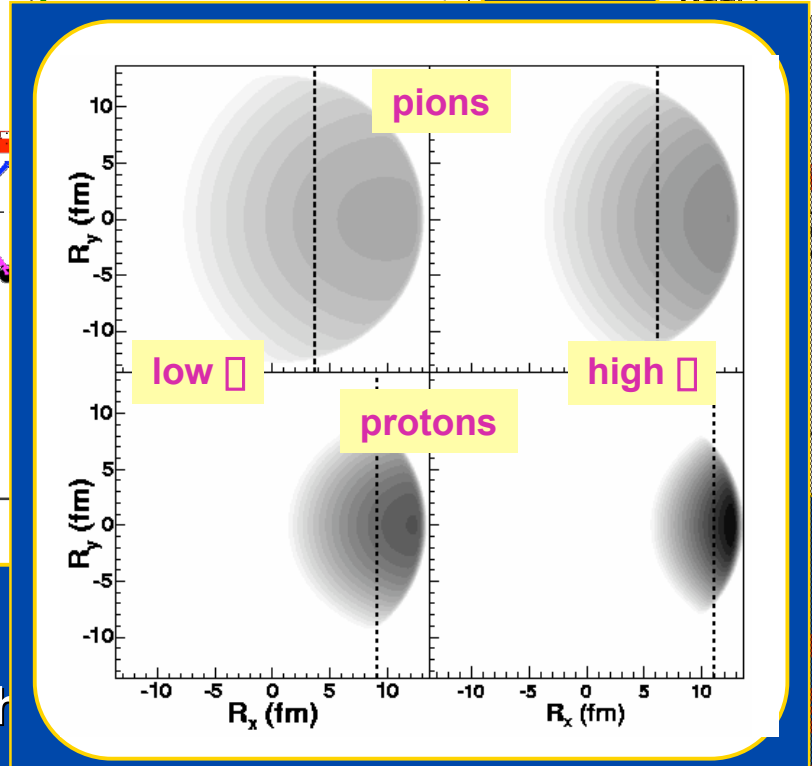
A. Kisiel for STAR

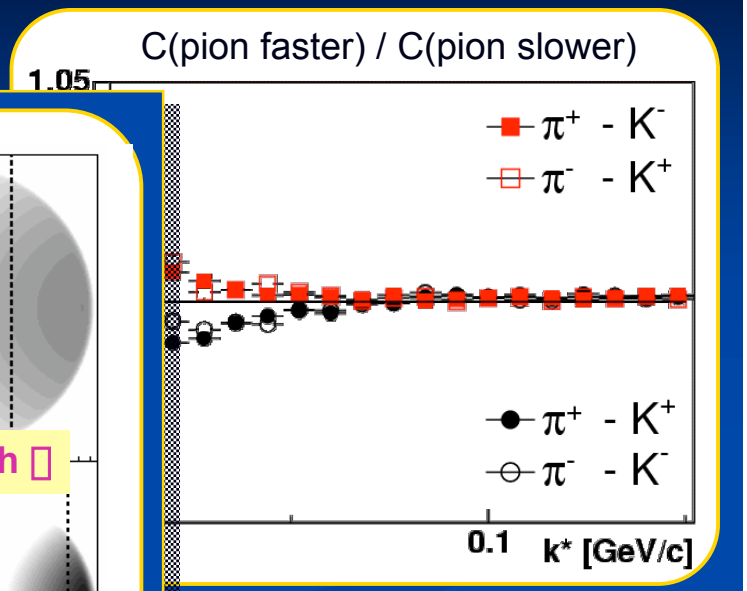


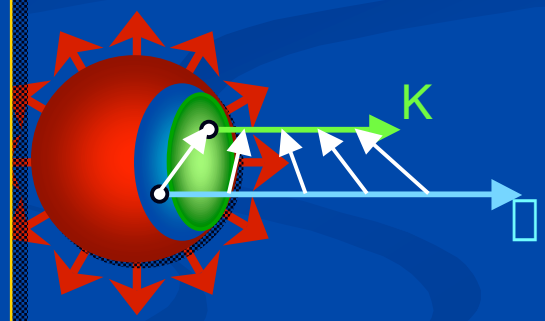
- **"pion faster" shows stronger correlation**
  - pions on average emitted nearer to source center
  - Arises naturally in collective expansion picture
- **Similar studies are underway for many particle combinations**
  - Exotic correlations like - can yield information about nature of flow

Non-identical particle correlations







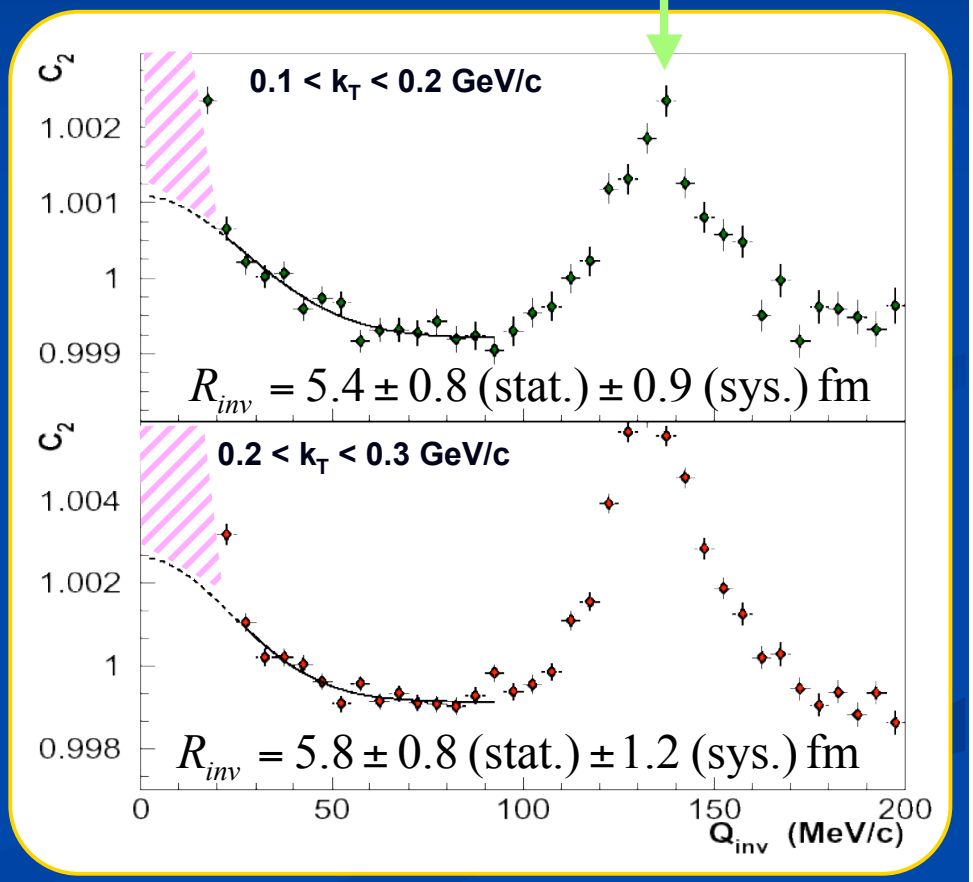


- **"pion faster" sh**
  - pions on aver
  - Arises naturall
- Blast-wave picture
- **Similar studies are underway for many particle combinations**
  - Exotic correlations like - can yield information about nature of flow

HBT of direct photons

- **Photon interferometry in heavy ion collisions**
  - Probes initial state, not final-state interactions
    Srivastava and Kapusta; Timmerman *et al*; Peressounko PRC 67 (2003) 014905
  - A major challenge experimentally!
  - Low relative direct photon yield
  - Many sources of small-Q_{inv} pairs: photon conversions, π^0 HBT, mis-id πs, resonance decays, etc.

- **WA98: First γ-HBT in R.H.I.C.**
  - R_{inv} quantitatively similar to π HBT in same k_T region
  - _ Soft photons arise in late stages of collision



WA98 Collaboration, nucl-ex/0310022

HBT of direct photons

- **Photon inter**
  - Probes ini
    Srivastava ar
  - A major ch
  - Low relati
  - Many sour
    photon co
    mis-id □s,
- **WA98: Firs**
  - R_{inv} quar
    □ HBT in
  - _ Soft ph
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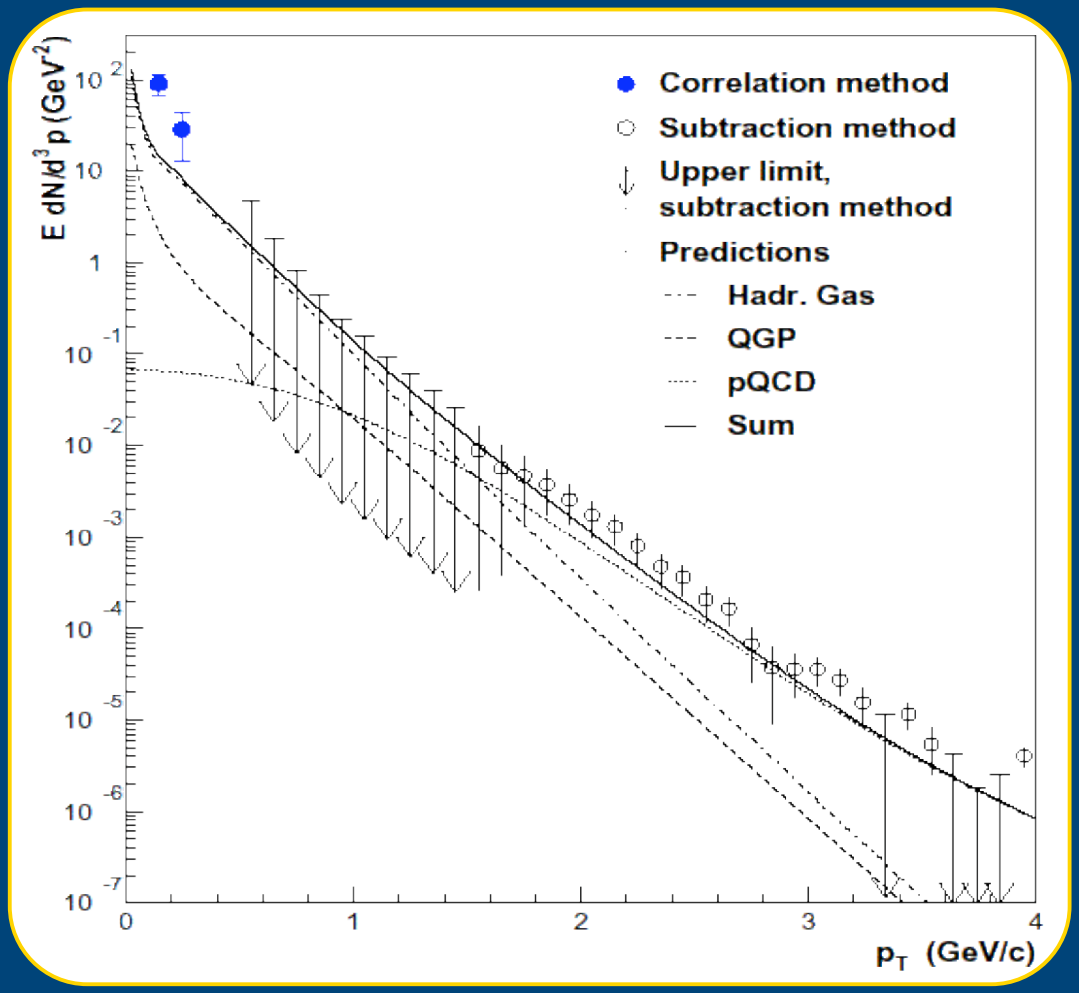
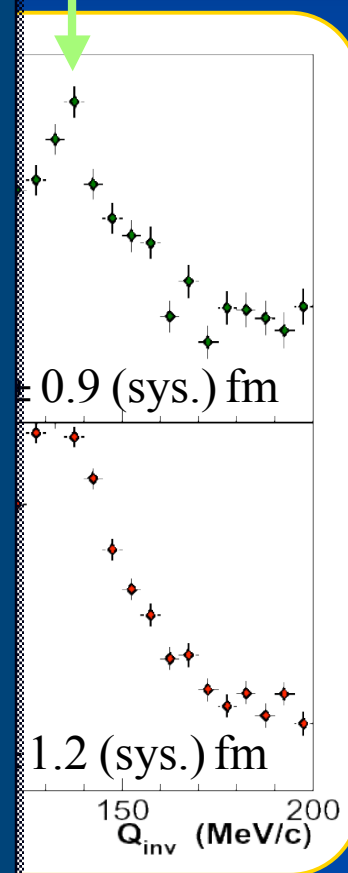


WA98 Collaboration, nucl-ex/0310022

- **Direct photon yield can be accessed with □**

$$N_{\square}^{\text{Direct}} / N_{\square}^{\text{Total}} = \sqrt{2\square}$$



cl-ex/0310022

Conclusions

- **Identical-meson HBT interferometry**
  - HBT is <u>the</u> observable that doesn't fit into dynamic picture at low p_t
  - p+p, d+Au and Au+Au exhibit similar k_T dependence, similar freeze-out pion mean free path
- **Azumithally sensitive HBT**
  - Evidence for out-of-plane extended sources at freeze-out
  - Short-lived system "remembers" its initial spatial anisotropy
- **Non-identical particle correlations**
  - Lighter particles emitted closer to center
- **Direct photon interferometry**
  - Similar R_{inv} for π- and γ-HBT; access to low-p_T direct photon yield

“HBT brings us from enlightenment to tragedy, and back to enlightenment, on a time scale of four years.”

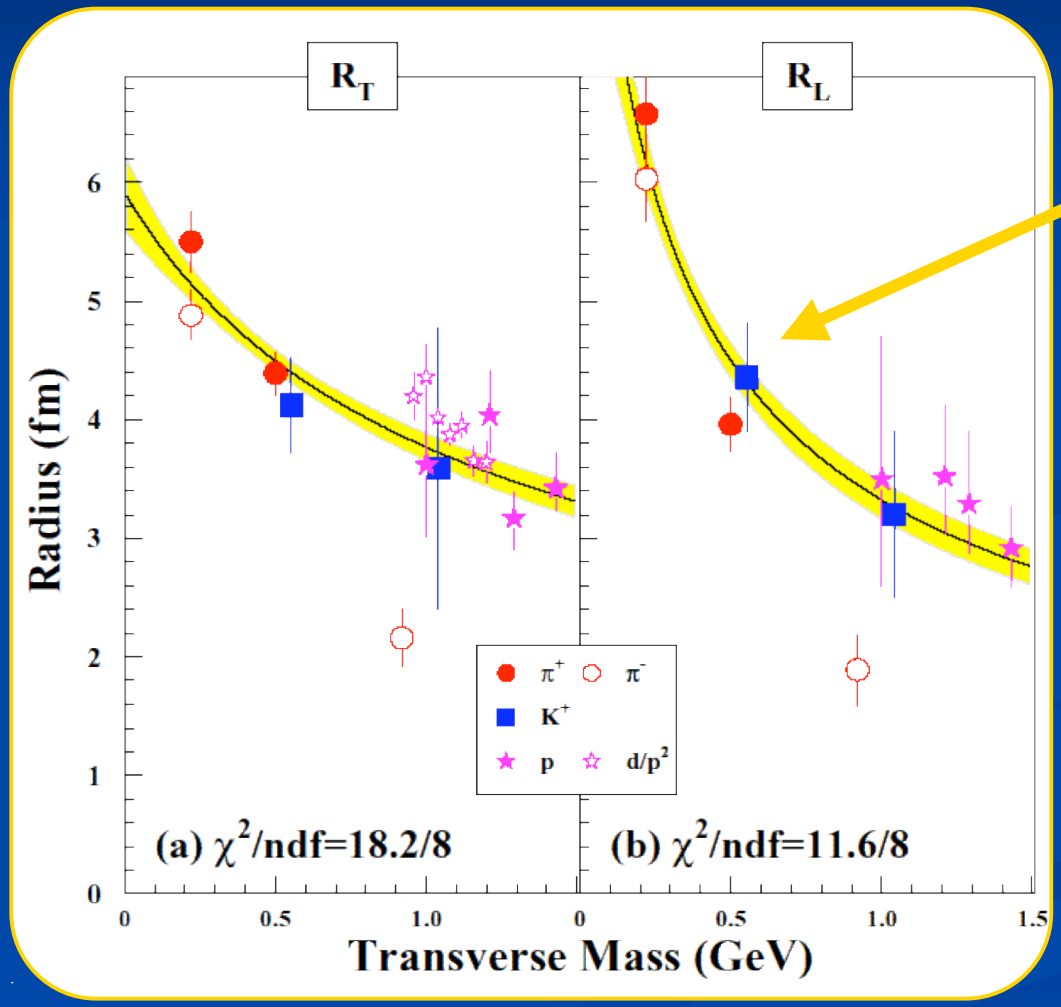
Reinhard Stock

The HBT puzzle is three years old.
 2004 is looking promising!

BACK-UPS

Recent "standard" HBT results - SPS

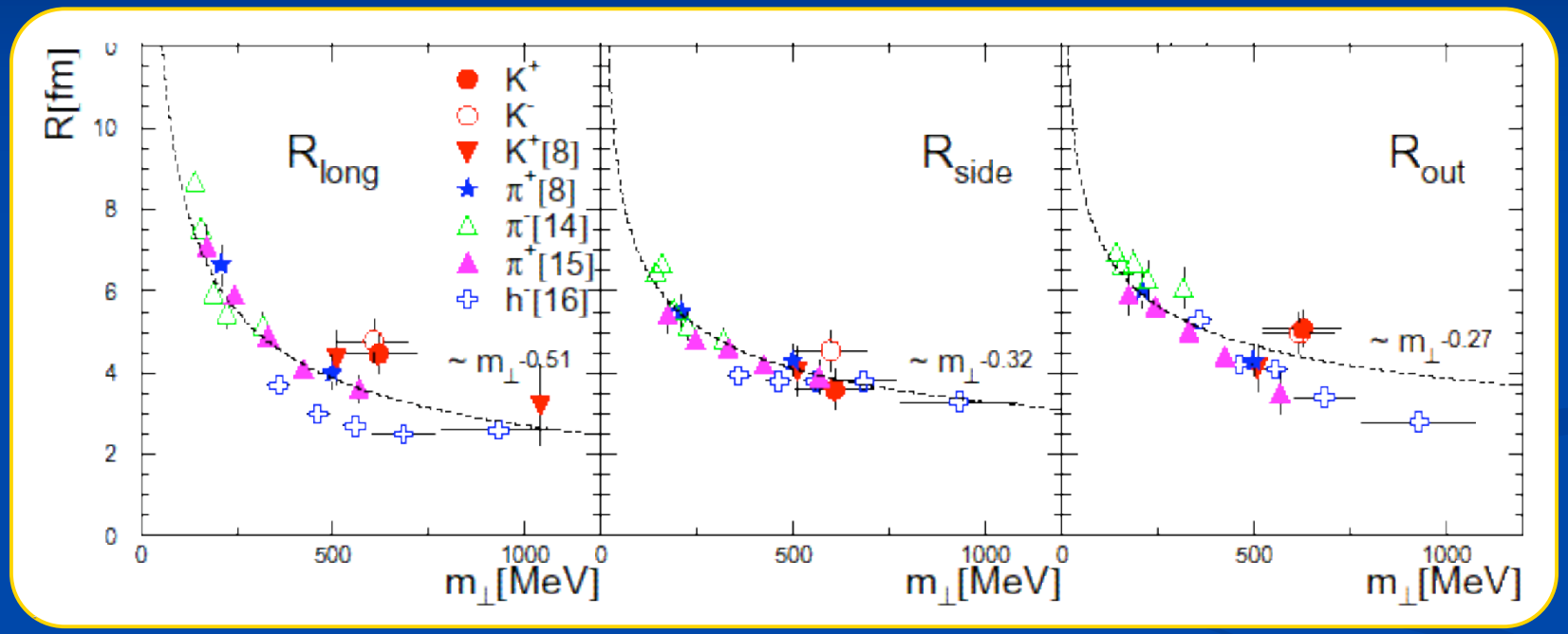
- **NA44: High m_T π- and p-HBT** (nucl-ex/0305014)



$$\frac{1}{R^2} = p_0 + p_1 m_T$$

Recent "standard" HBT results - SPS

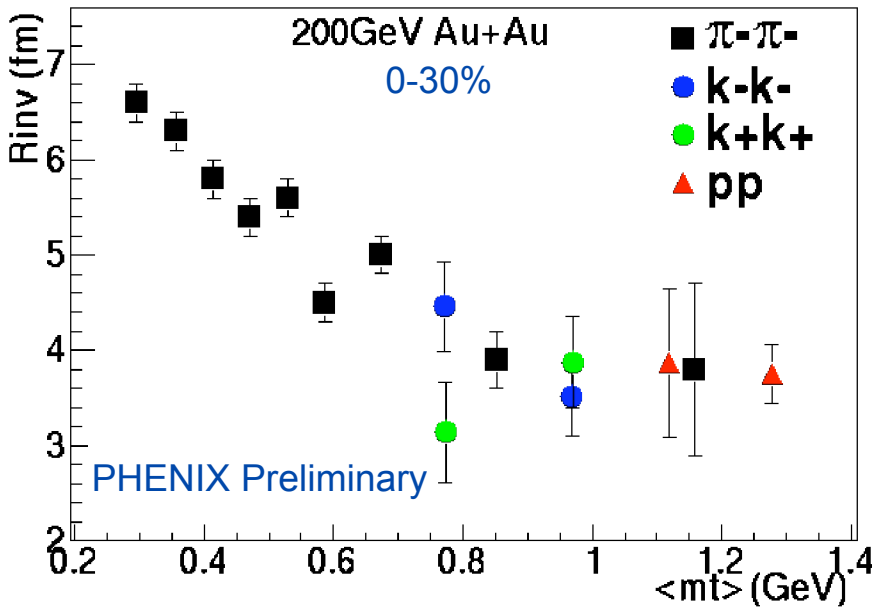
- **NA49: Kaon HBT** (Phys.Lett. B 557 (2003) 157)
  - Less influence from resonances & feeddown



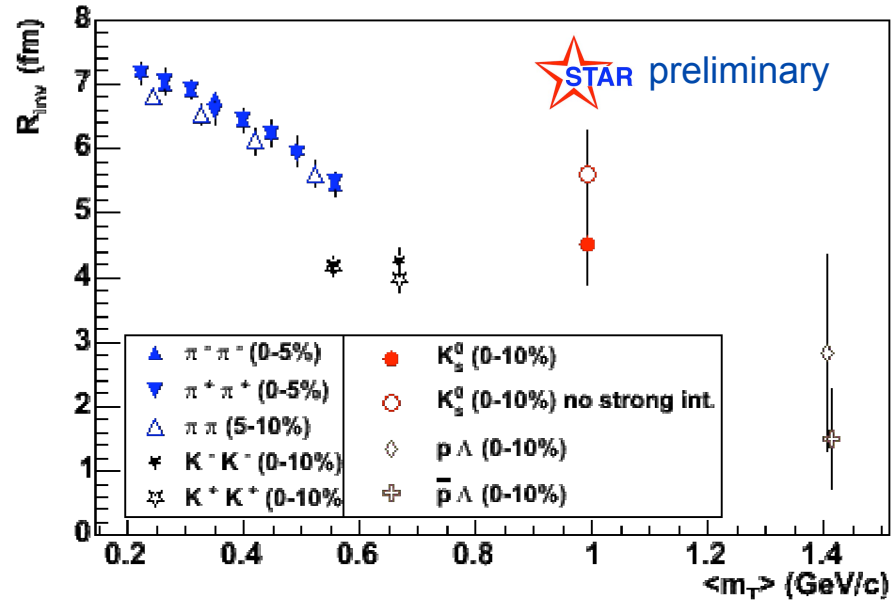
T = 120 ± 12 MeV _ $\square_f$ ~ 9.5 ± 1 fm, $\square_T$ ~ 0.55

- **New results shown this week**
  - HBT @ 20, 30, 40, 80, 158 AGeV (!)

A highlight from this week



Mike Heffner, PHENIX

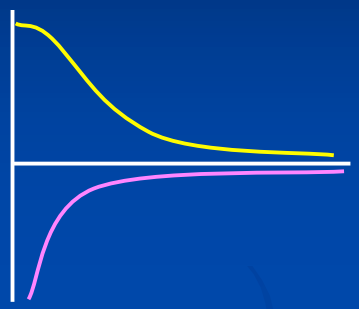


Selemon Bekele, STAR

Refined Coulomb treatment

- **Final-state interactions (Coulomb, strong) influence correlation signal**
- **Traditionally, all pairs in CF corrected for Coulomb**

$$\frac{A(\vec{q})}{B(\vec{q})} = K(\vec{q})\,\underbrace{G(\vec{q})}_{1+\lambda e^{-q_i^2 R_i^2}}$$



  - This over-corrects the CF _ increases width, decreases radii

- **CERES: Apply Coulomb correction only to pairs participating in B-E**
  (Nucl. Phys. A 714 (2003) 124)

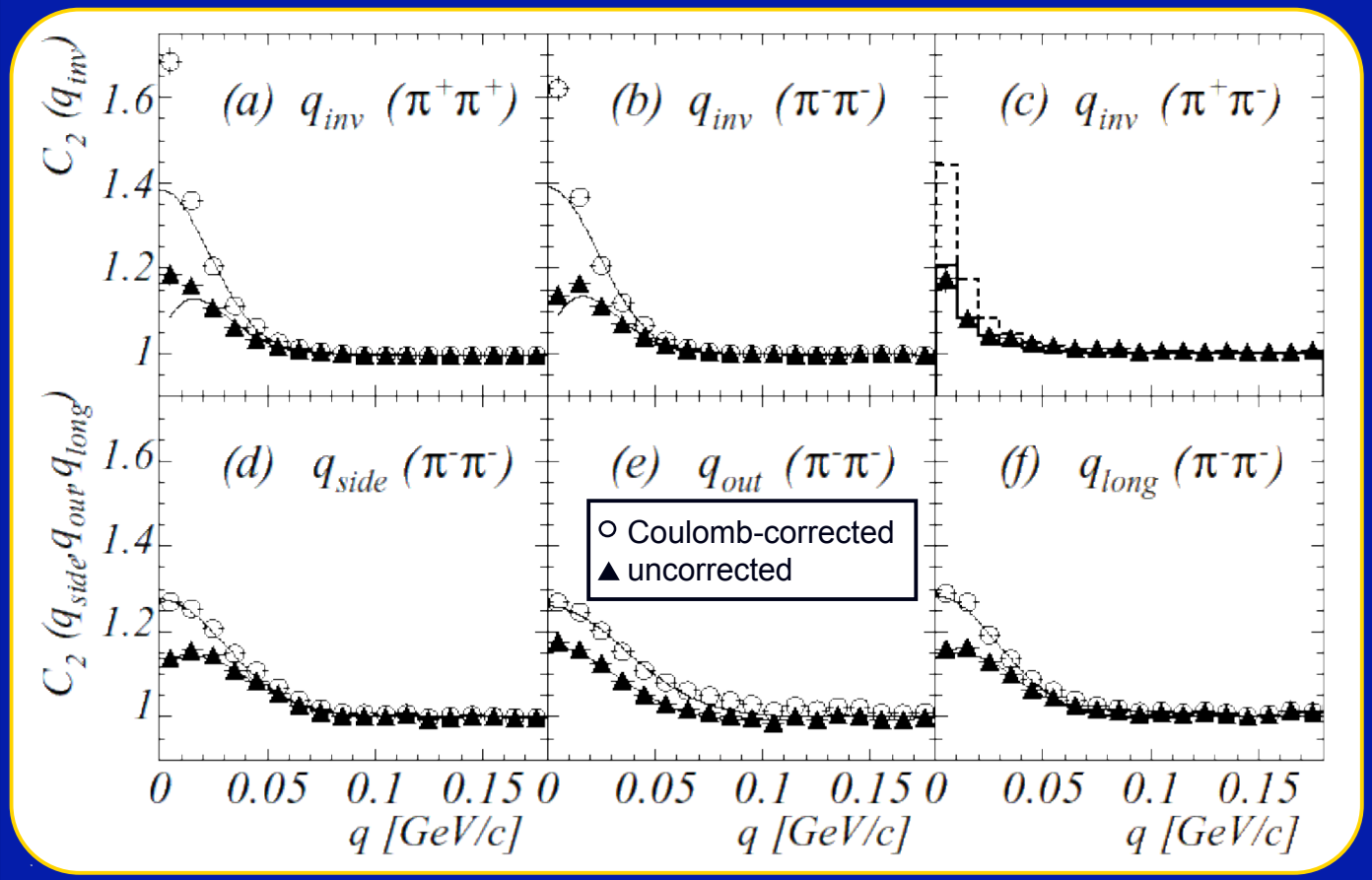
$$\frac{A(\vec{q})}{B(\vec{q})} = \underbrace{(\lambda - 1)}_{\text{fraction of non-participating pairs}} + \lambda K(\vec{q})\,G(\vec{q})$$

First proposed in:
Bowler PLB 270 (1991) 69

- **Adopted by in recent papers by STAR, PHENIX**
  STAR Coll, nucl-ex/0312009; PHENIX Coll, nucl-ex/0401003

Refined Coulomb treatment

- **Final-state interactions (Coulomb, strong) influence correlation signal**
- **Traditi**
  - Thi
- **CERE**
  (Nucl. Pl
- **Adopt**
  STAR Coll, nucl-ex/0312009; PHENIX Coll, nucl-ex/0401003



PHENIX Coll, nucl-ex/0401003

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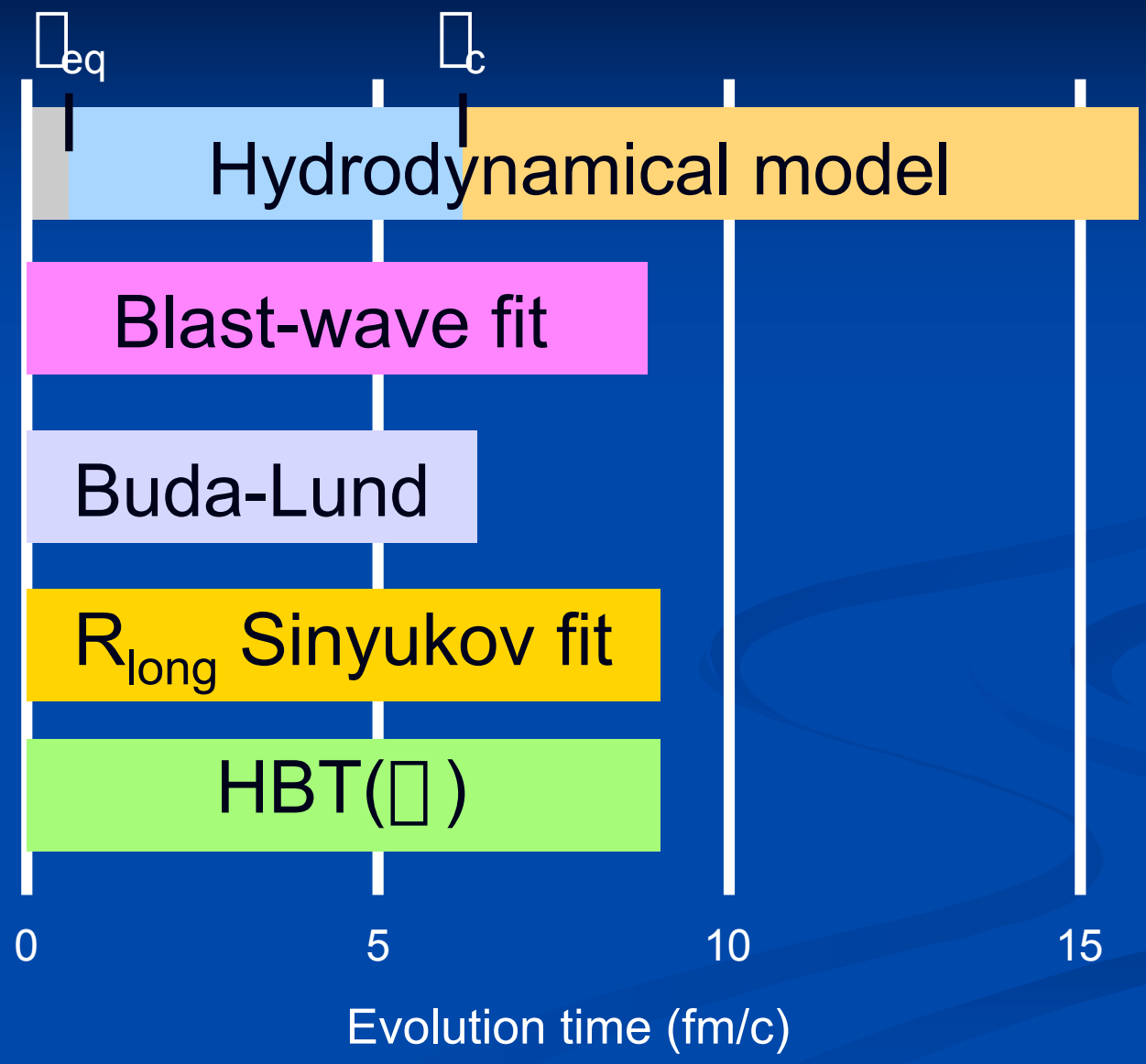
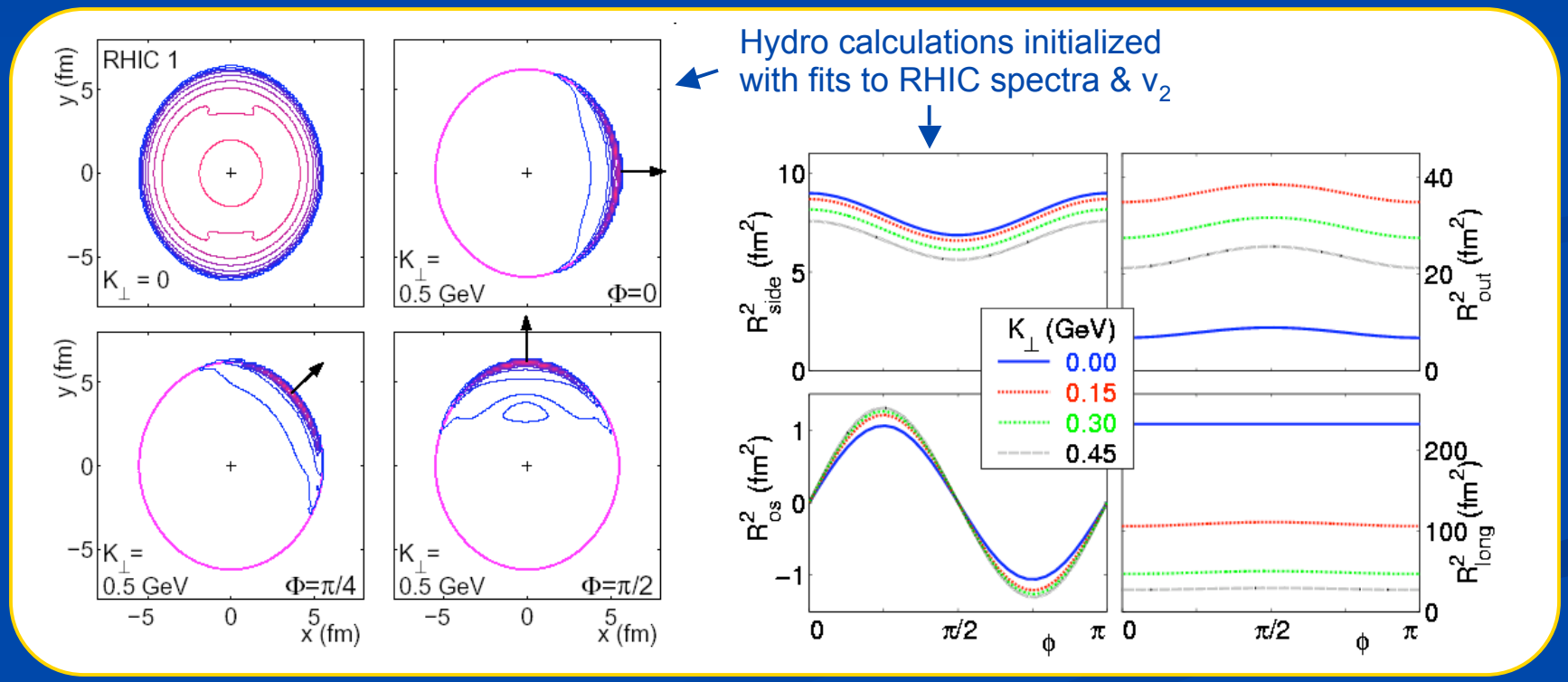
) (1991) 69

Collision timescale



HBT(Φ) predictions from hydrodynamics

- **Hydro: Freeze-out shape sensitive to lifetime, initial conditions**
  - k_T dependence probes different regions of space-time source
  - Realistic hydro parameters: Source orientation reflected in HBT(Φ) oscillations



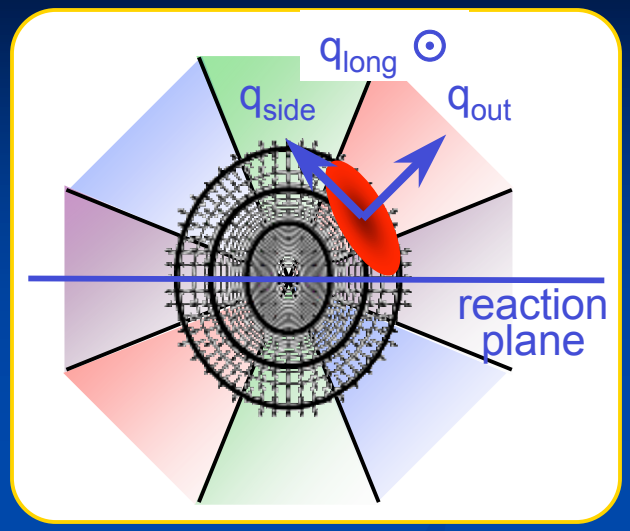
Heinz & Kolb, PLB 542 (2002) 216

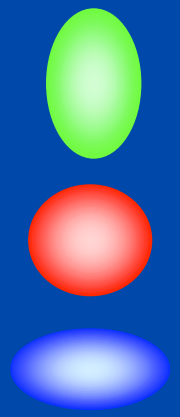
HBT(Φ) experimental technique

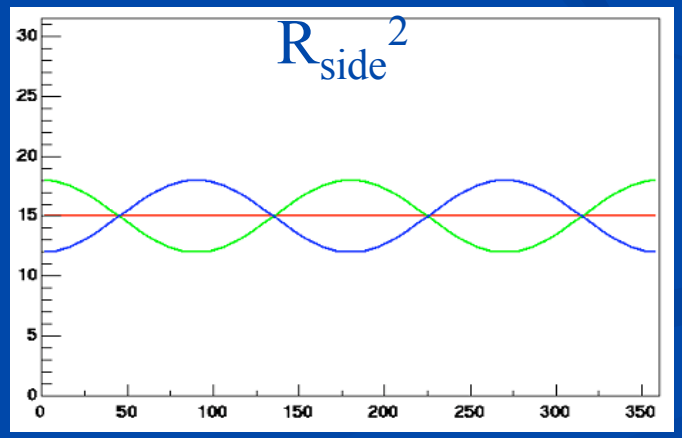
1. **Construct correlation functions for discrete bins w.r.t. reaction plane angle**

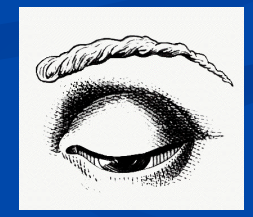
2. **Apply HBT formalism to extract R_{ij}^2 vs. Φ**
   - Additional out-side cross-term

3. **Oscillations of R_{ij}^2 reflect spatial anisotropies in system**
   - Oscillations governed by geometrical symmetries



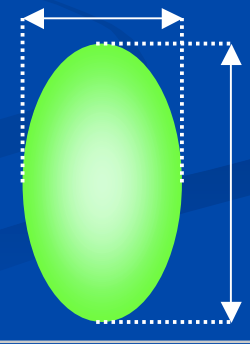




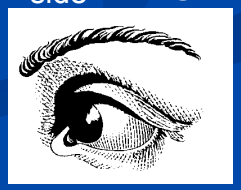


Φ = 90°

R_{side} (small)



R_{side} (large)



Φ = 0°

A simple estimate – τ_0 from τ_{init} and τ_{final}

- BW _ τ_X, τ_Y @ F.O. ($\tau_X > \tau_Y$)
- hydro: flow velocity grows ~ t

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

- From $R_L(m_T)$: τ_0 ~ 9 fm/c
  - consistent picture
- Longer or shorter evolution times
  - X inconsistent

toy estimate: τ_0 ~ τ_0(BW)~ 9 fm/c