# *Systematic measurements of HBT radii at RHIC*

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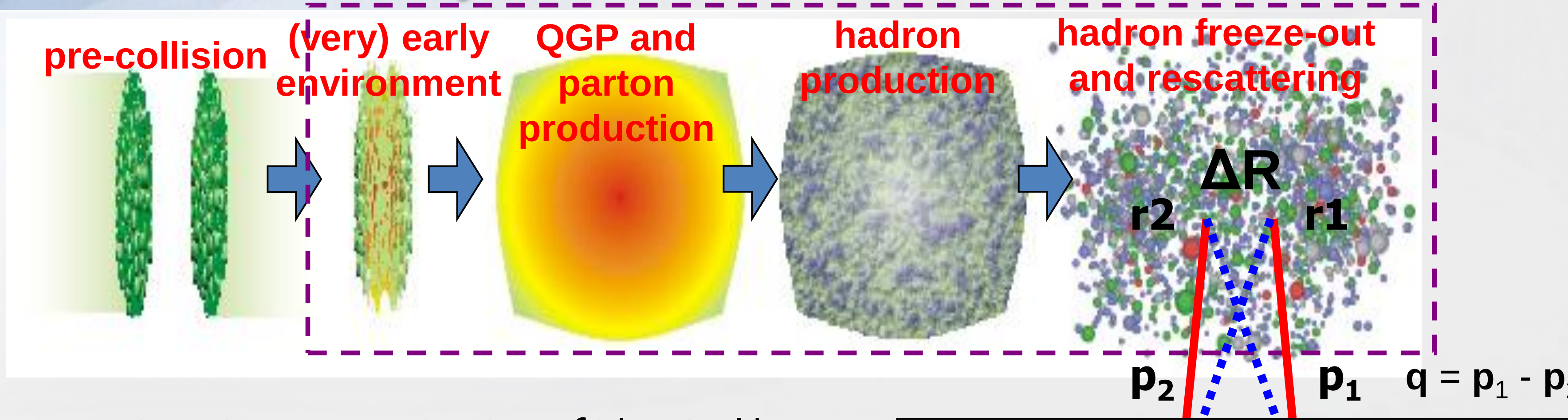
Oak Ridge National Laboratory
Akitomo Enokizono

# Outline

- Physics motivation and introduction of HBT femotoscopy
- Experimental results (HBT radii)
  - as functions of
    - collision centrality ($N_{part}$), multiplicity ($N_{ch}$)
    - reaction plane ($\Delta\phi$), eccentricity ($\varepsilon$)
    - momentum ($m_T$)
    - PID (pion vs kaon)
- Comparison with theoretical models
- Summary

# Physics motivation



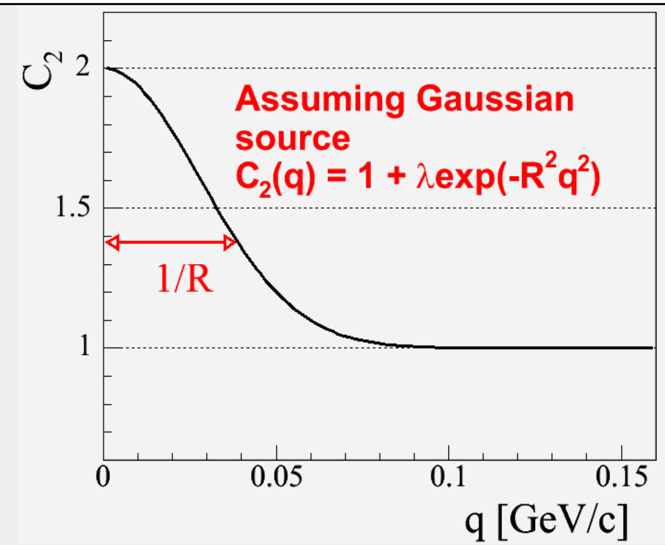

The Bose-Einstein symmetrization of identical bosons:

$$\psi_2(p_1, p_2) = \frac{1}{\sqrt{2}}\left(e^{ip_1(x_1-r_1)}e^{ip_2(x_2-r_2)} \pm e^{ip_1(x_1-r_2)}e^{ip_2(x_2-r_1)}\right)$$

$$C_2(p_1, p_2) \equiv \frac{P_2(p_1, p_2)}{P(p_1)P(p_2)} \approx 1 + |\rho(q)|^2$$

- HBT radii represent Gaussian extents (durations) of particle emissions at the time they kinetically freeze-out.

- The properties of the space-time evolution in heavy-ion collisions change the HBT radii for hadrons.



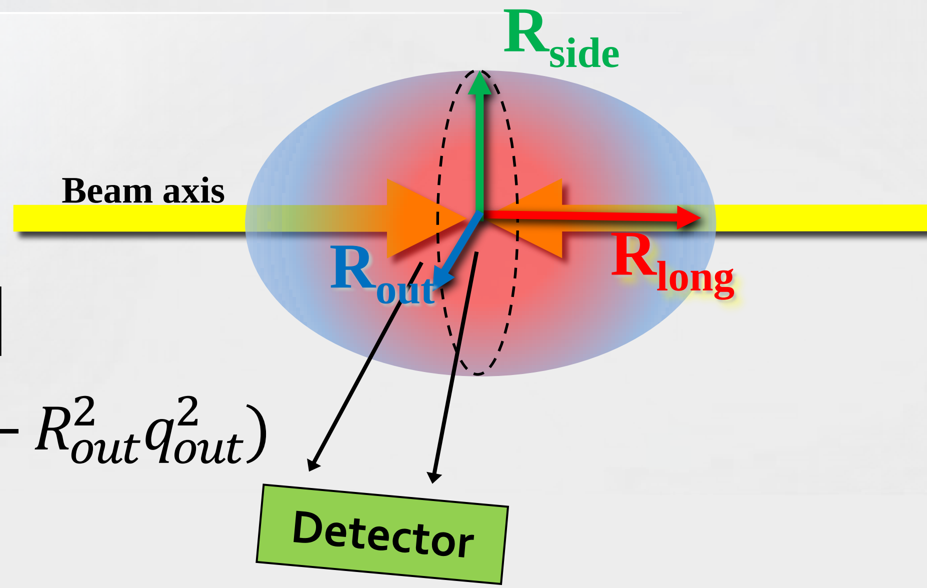
# 3D HBT radii

*"Long-Side-Out" space*
*with "core-halo" parameterization*

$$C_2 = C_2^{core} + C_2^{halo}$$
$$= [\lambda(1+G)]F_c + [1-\lambda]$$

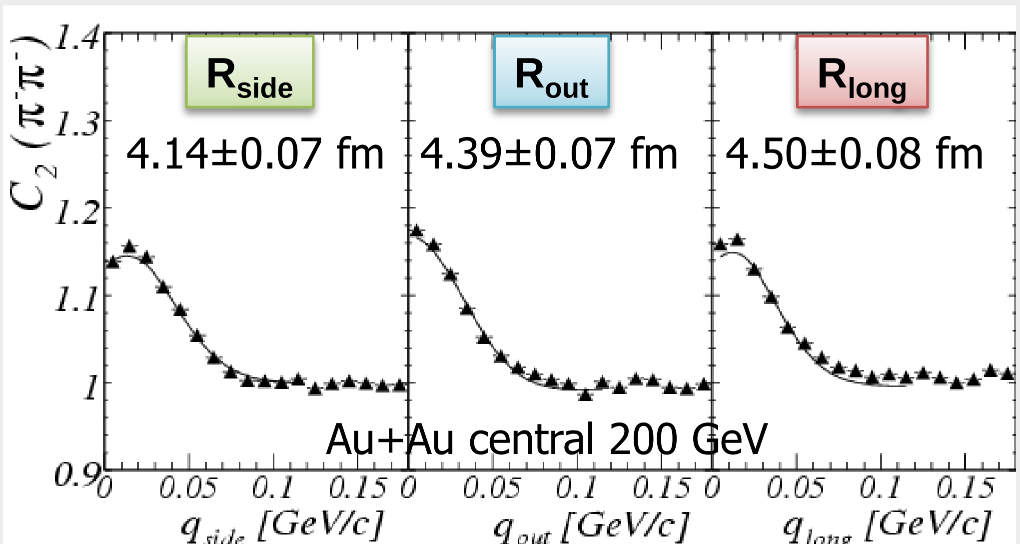
$$\boldsymbol{G} = exp(-R_{long}^2 q_{long}^2 - R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2)$$

*$F_C$ (Coulomb correction factor)*

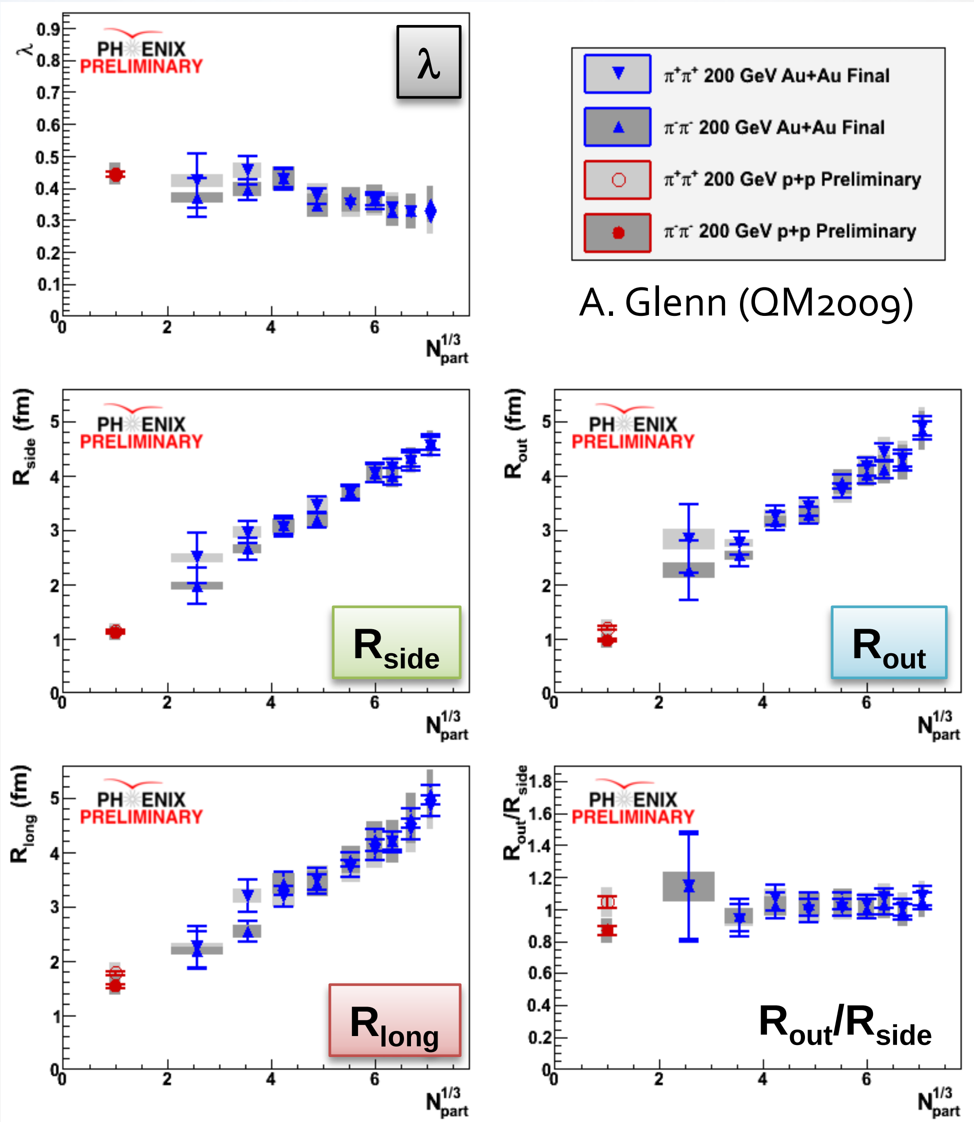



- $\boldsymbol{\lambda}$ = Chaoticity
- $R_{long}$ = Longitudinal HBT radius
- $R_{side}$ = Transverse HBT radius
- $R_{out}$ = Transverse HBT radius + $\Delta\tau$
  ($\Delta\tau$ = emission duration)

$$\Delta\tau > 0 \rightarrow \frac{R_{out}}{R_{side}} > 1$$



# HBT radii VS collision centrality

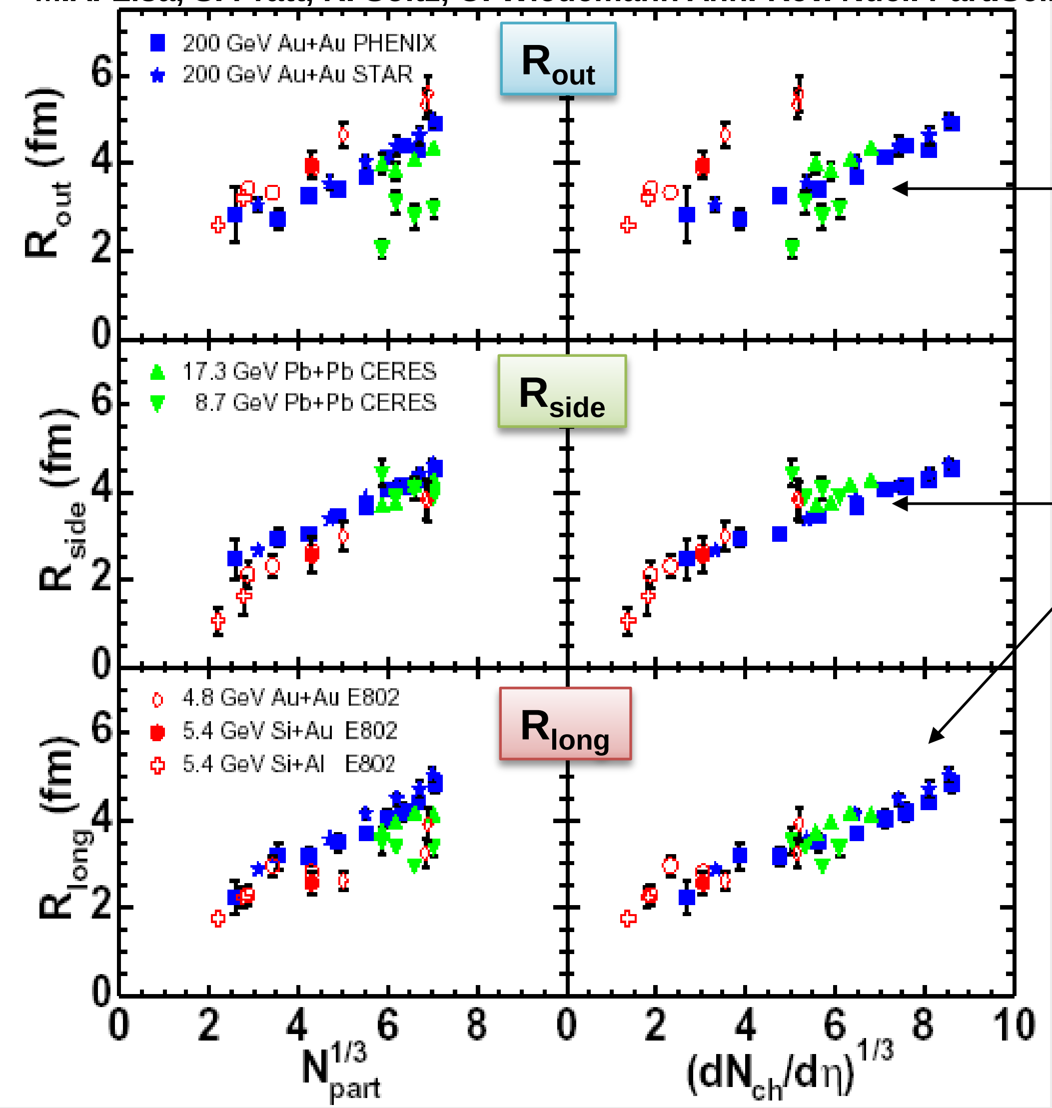



A. Glenn (QM2009)

- HBT radii show linear increase as the cube-root of the number of participants ($N_{part}^{1/3}$)
  - $N_{part}^{1/3}$ ~ Geometrical radius of the initial volume.
- The linearity is valid from p+p to central Au+Au collisions.
- Spherically symmetric source $R_{side} \sim R_{out} \sim R_{long}$.
- $R_{out}/R_{side} \sim 1$ for the entire $N_{part}^{1/3}$ region.
  - **Short emission duration**

# Multiplicity scaling

M.A. Lisa, S. Pratt, R. Soltz, U. Wiedemann Ann. Rev. Nucl. Part.Sci.55:357-402,2005



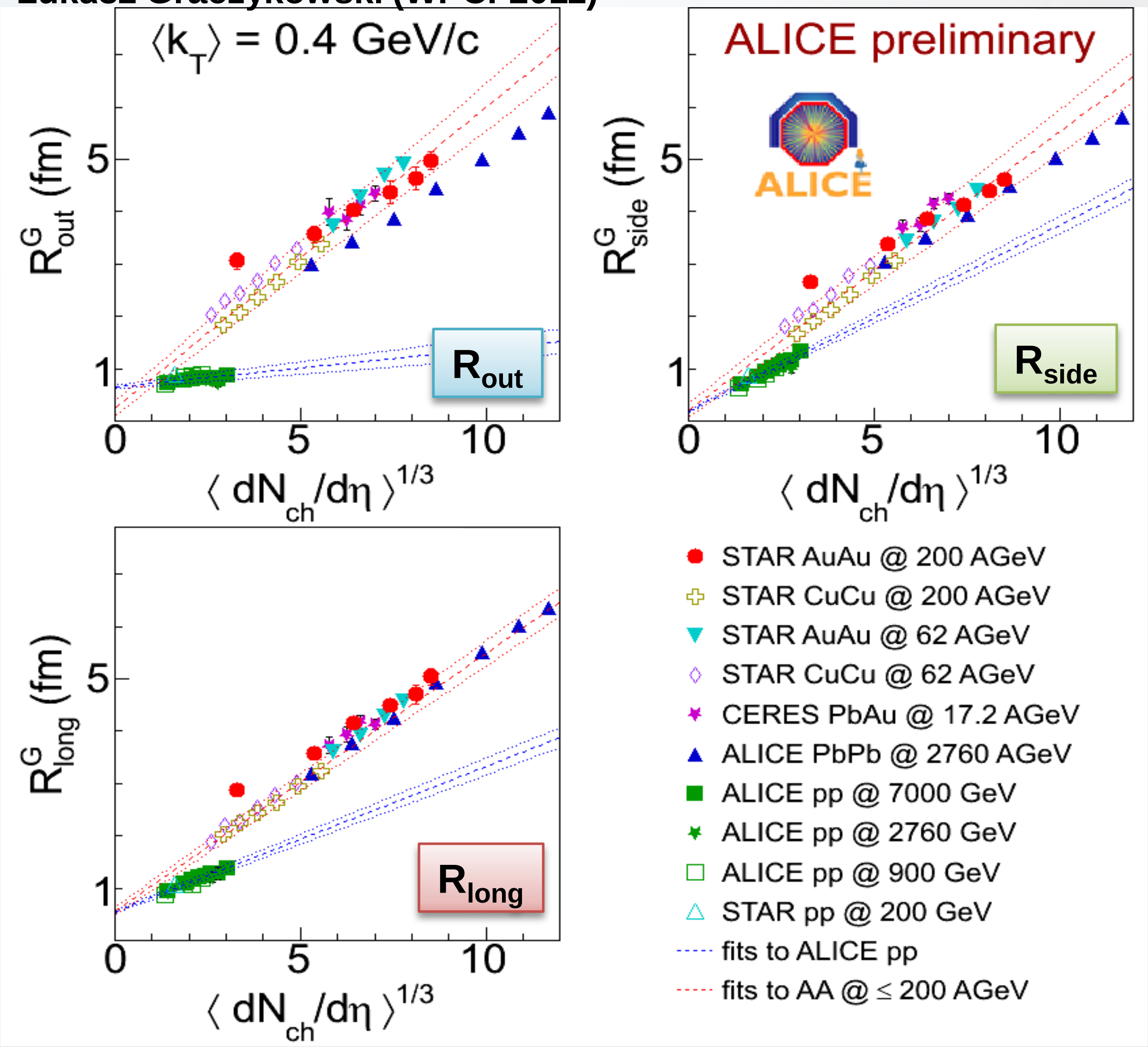

$R_{out}$ is not scaled with dN/dy from AGS to SPS energy. Emission duration is significantly changed from AGS to SPS?

$R_{side}$, $R_{long}$ are scaled well with multiplicity dN/dy rather than $N_{part}$.

*Nature of phase transition could be changed at energy between AGS to SPS region. Detailed studies by energy scan is being performed at RHIC.*

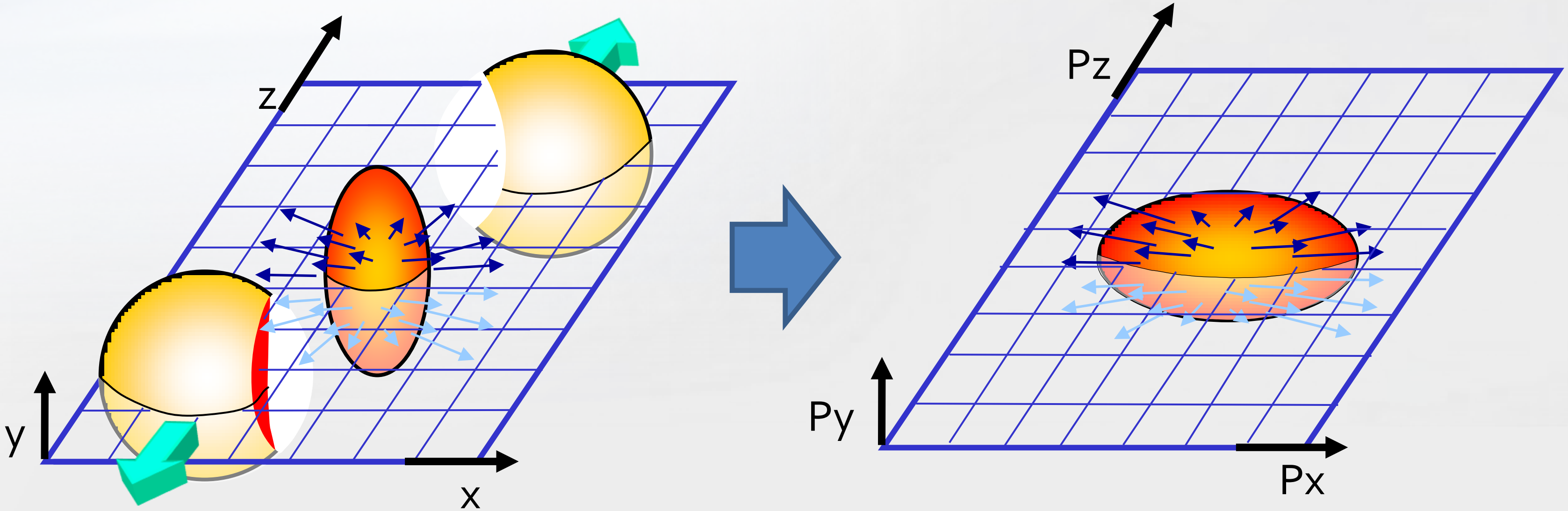
# Multiplicity scaling VS $\sqrt{s_{NN}}$

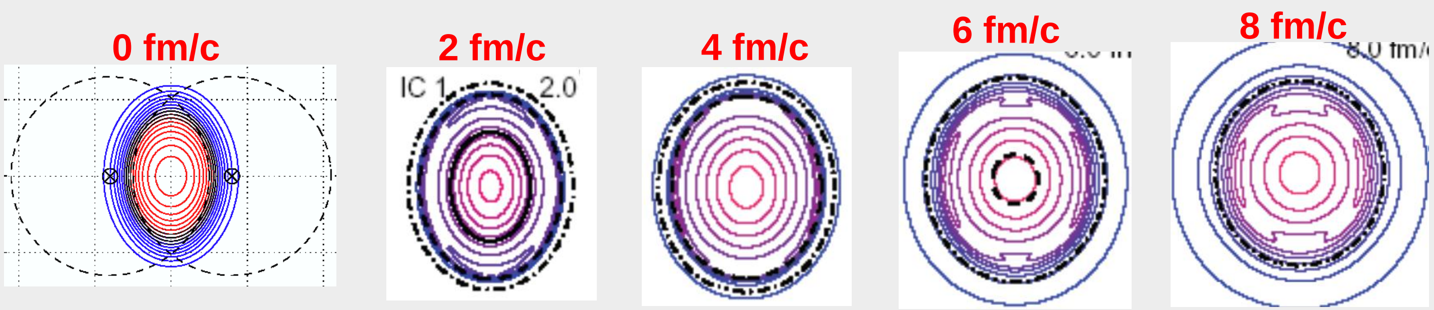
Łukasz Graczykowski (WPCF2011)




- Multiplicity scaling is valid for $R_{side}$ and $R_{long}$ up to LHC energy, but not $R_{out}$.
  - $R_{out}$(AGS) > $R_{out}$(RHIC) > $R_{out}$(LHC)
- Multiplicity dependence of HBT radii in p+p collisions DO NOT scale with those for heavy-ion collisions.
  - Different mechanism for the hadronic freeze-out for A+A and p+p?
  - Contribution from jet?

# Azimuthal HBT radii

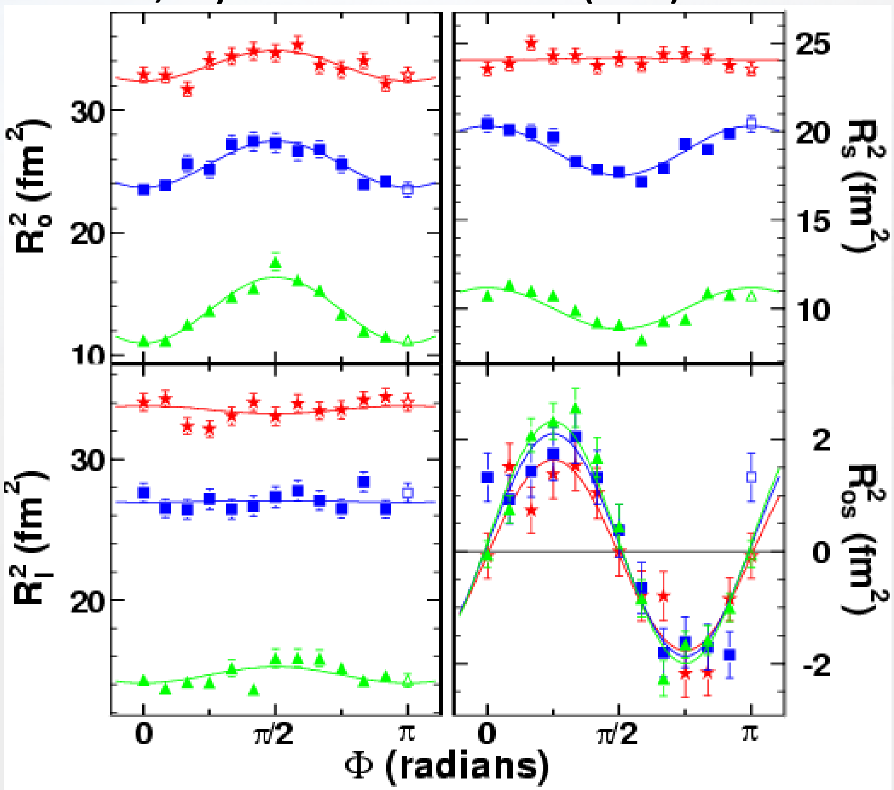


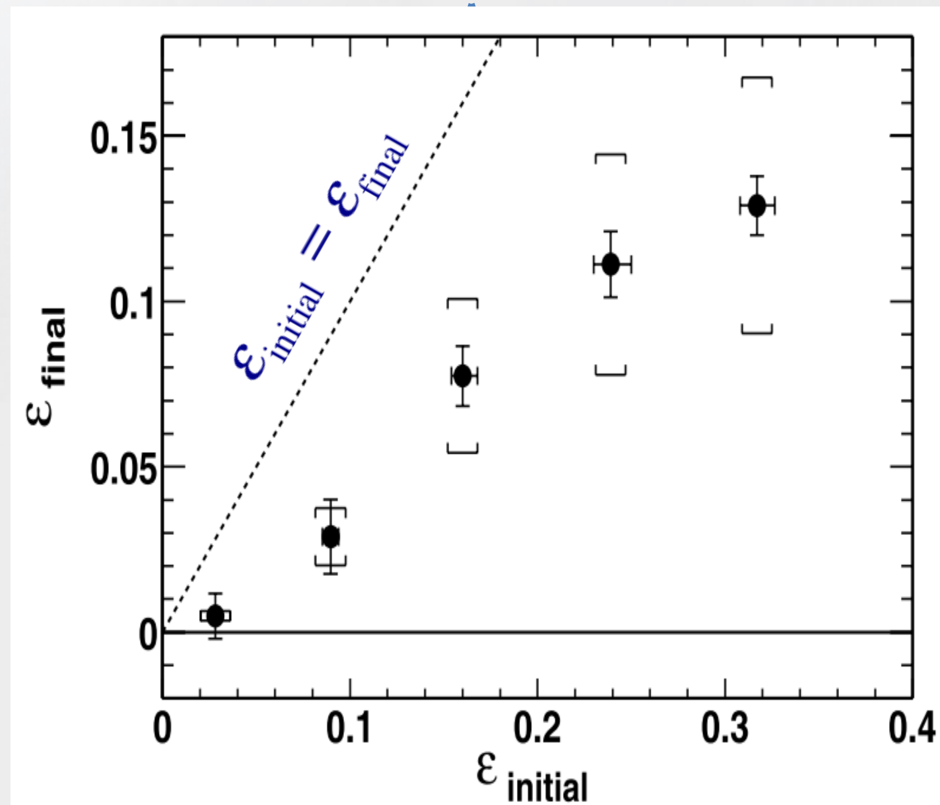




What we measure: **eccentricity at freeze-out**, which depends initial eccentricity, pressure anisotropy, life time etc…

# Freeze-out eccentricity

STAR, Phys. Rev. Lett. 93 012301 (2004)



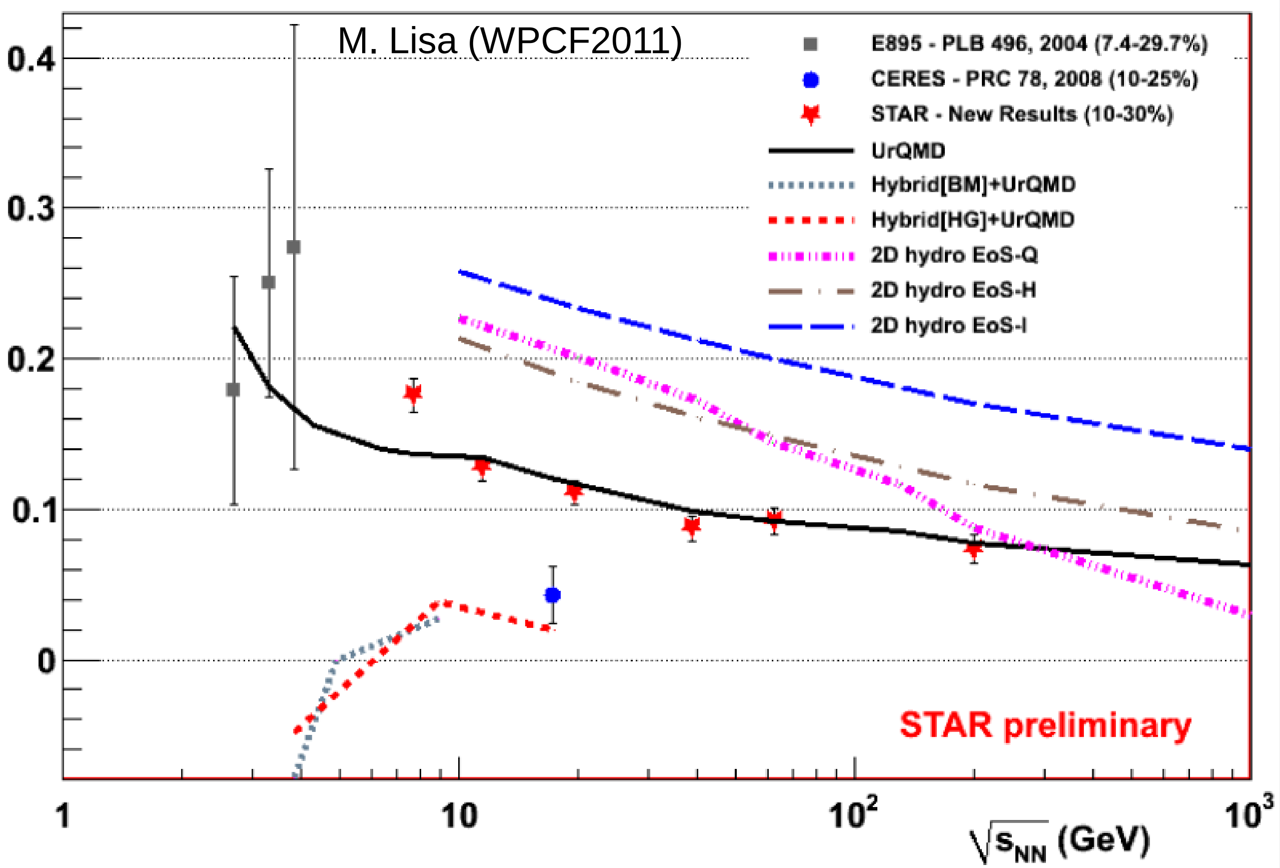

$$R_{s,n}^2 \equiv \langle R_s^2(\phi) \cdot \cos(n\phi) \rangle$$

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

$$\varepsilon_{final} \sim \varepsilon_{initial}/2$$

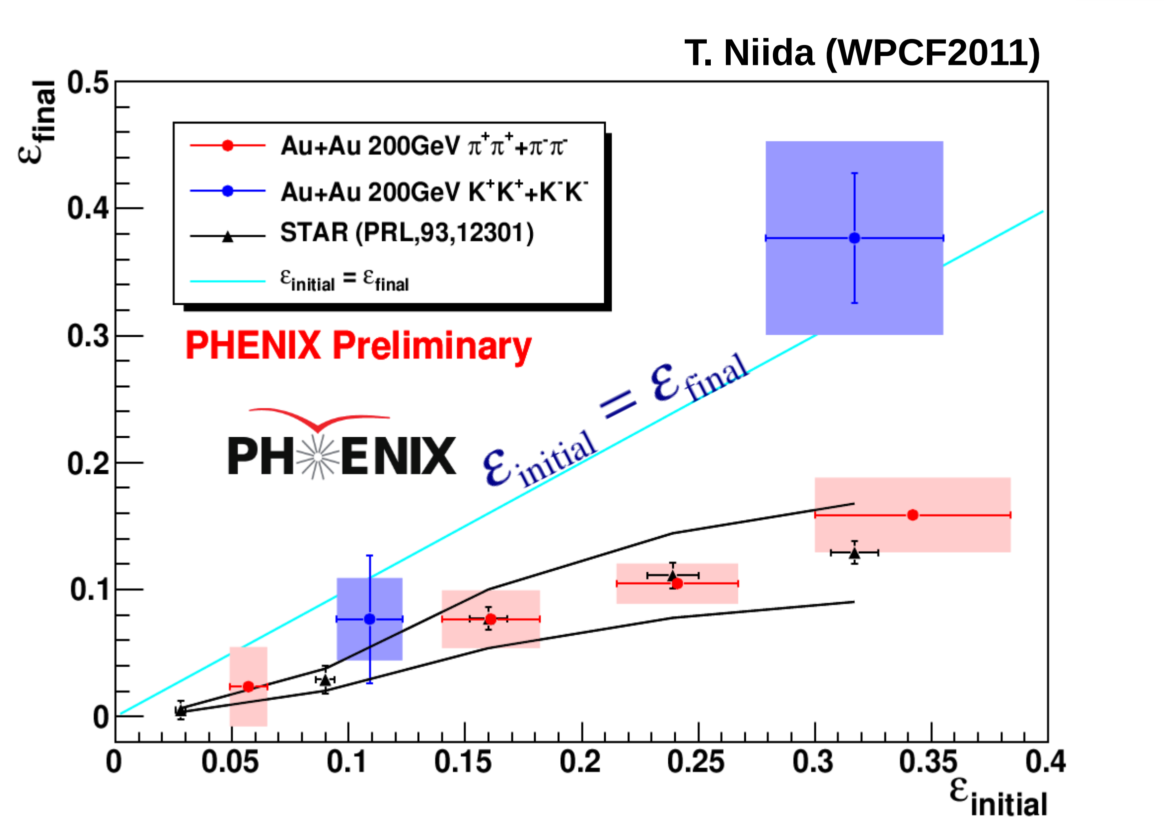
Retiere&MAL PRC70 (2004) 044907

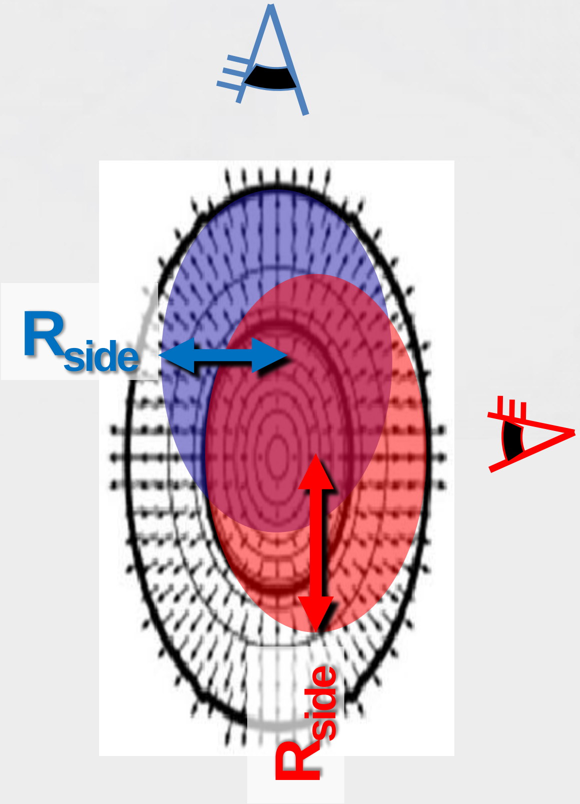
# Eccentricity VS collision energy




- Monotonic decrease of freeze-out eccentricity is reasonably described by UrQMD model
- CERES result which raised hope for finding of critical point seems to be excluded by STAR's new result with energy scan

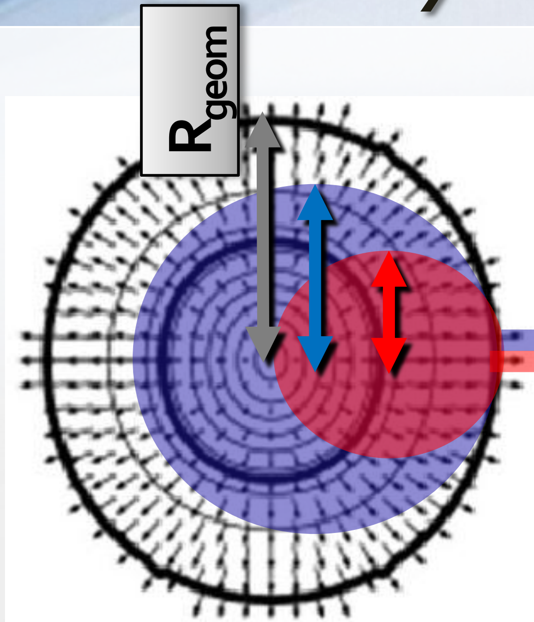
# Freeze-out eccentricity of Kaon



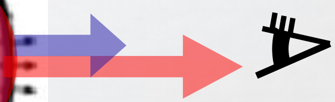




- Kaon radii indictates $\varepsilon_{final} \sim \varepsilon_{initial}$
  - Different freeze-out mechanism between pion and kaon, e.g faster freeze-out for kaon
  - Different (higher) $m_T$ region than pion, and looking at different correlation region?

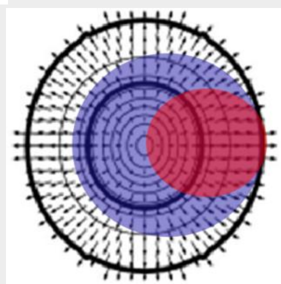
# Dynamical HBT radii



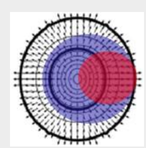

Au+Au



$$m_T = \sqrt{k_T^2 + m_0^2}$$



Cu+Cu



p+p

***How the $m_T$ dependence of HBT radii change as functions of $N_{part}$ or collision energy?***

## *For collectively expanding source*

HBT size is not the geometrical size ($R_{geom}$) but the "length of homogeneity" size (x-p correlation)

Static source: $R_{geom} = R_{HBT}$
Expanding source: $R_{geom} > R_{HBT}$

HBT size decreases as the transverse mass momentum ($m_T$) or collective flow of source (v) increases.

$$R_{side}^2 = \frac{R_{geom}^2}{1 + (m_T/T_0)v^2}$$

# $m_T$ dependence of HBT radii

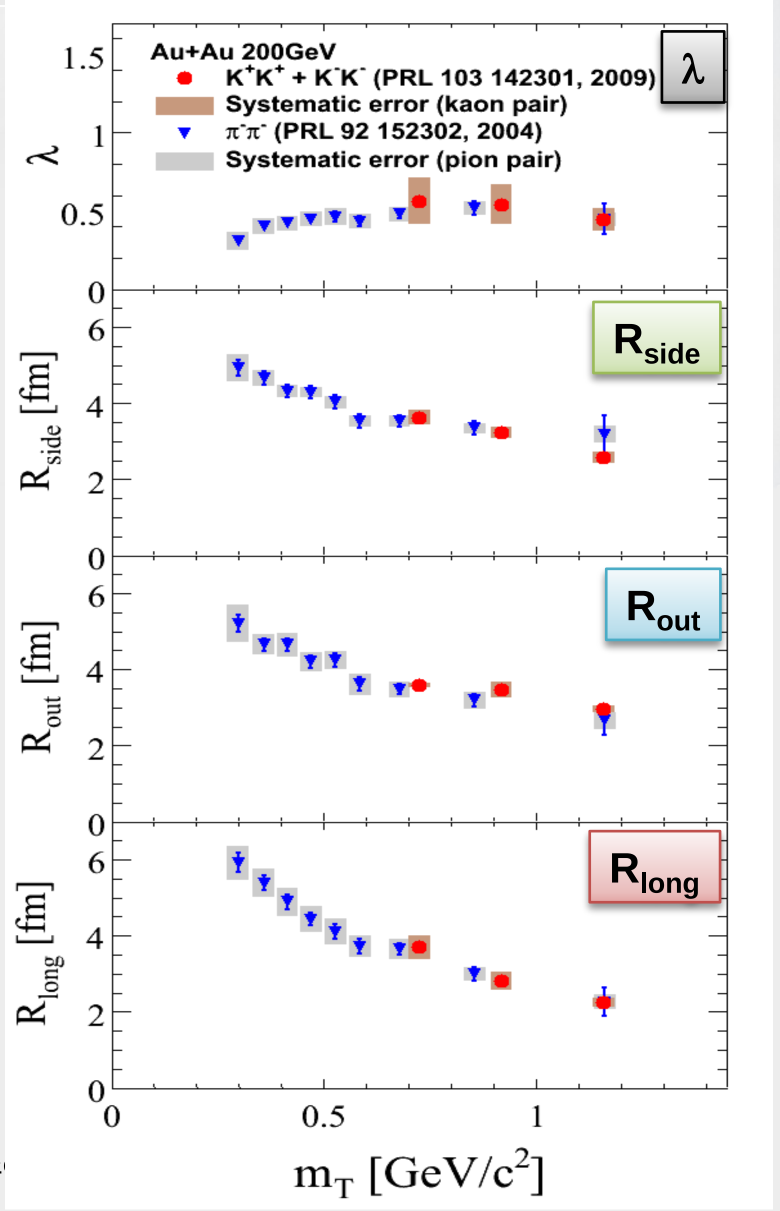
- All HBT radii decrease as a function of momentum ($m_T$).
- Pion and Kaon radii are well scaled with $m_T$.
  - A clear evidence of the hadronic collective flow

$$R_{side}^2 = \frac{R_{geom}^2}{1 + (m_T/T_0)v^2}$$

($T_0$~120MeV $\beta_f$~0.7 at Au+Au 200GeV)

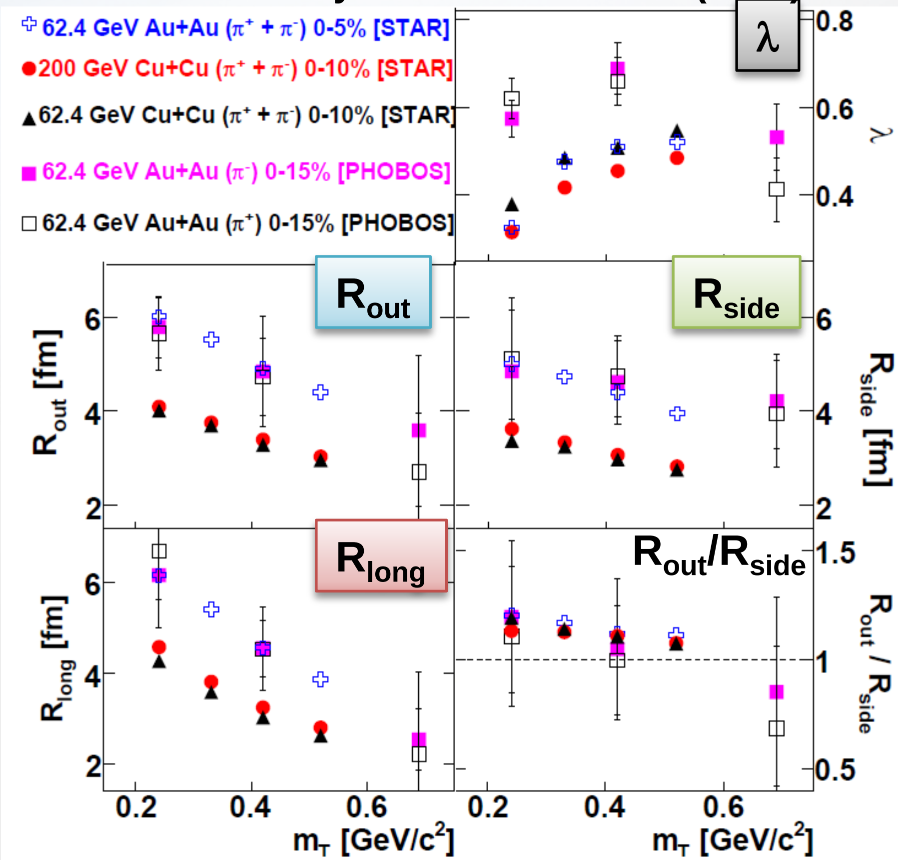
$R_{geom}$ ~ 7.1 fm

(Au RMS = 3.07 fm)

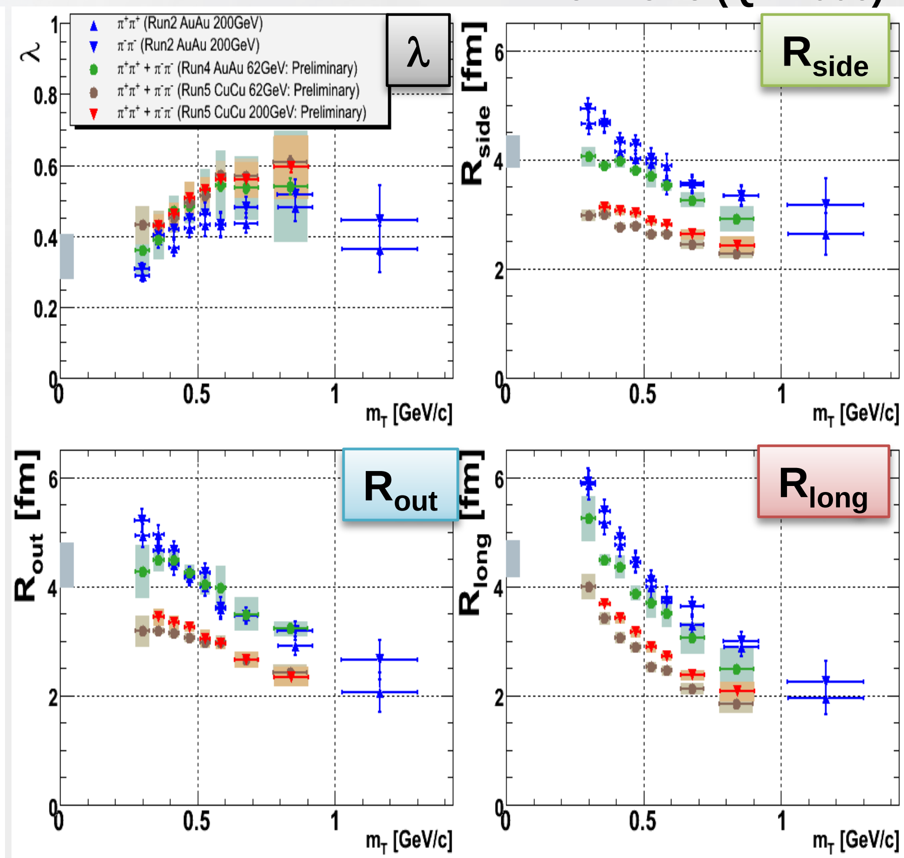


# $m_T$ dependence VS $N_{part}$ & $\sqrt{s_{NN}}$

STAR Phys. Rev. C80 024905 (2009)



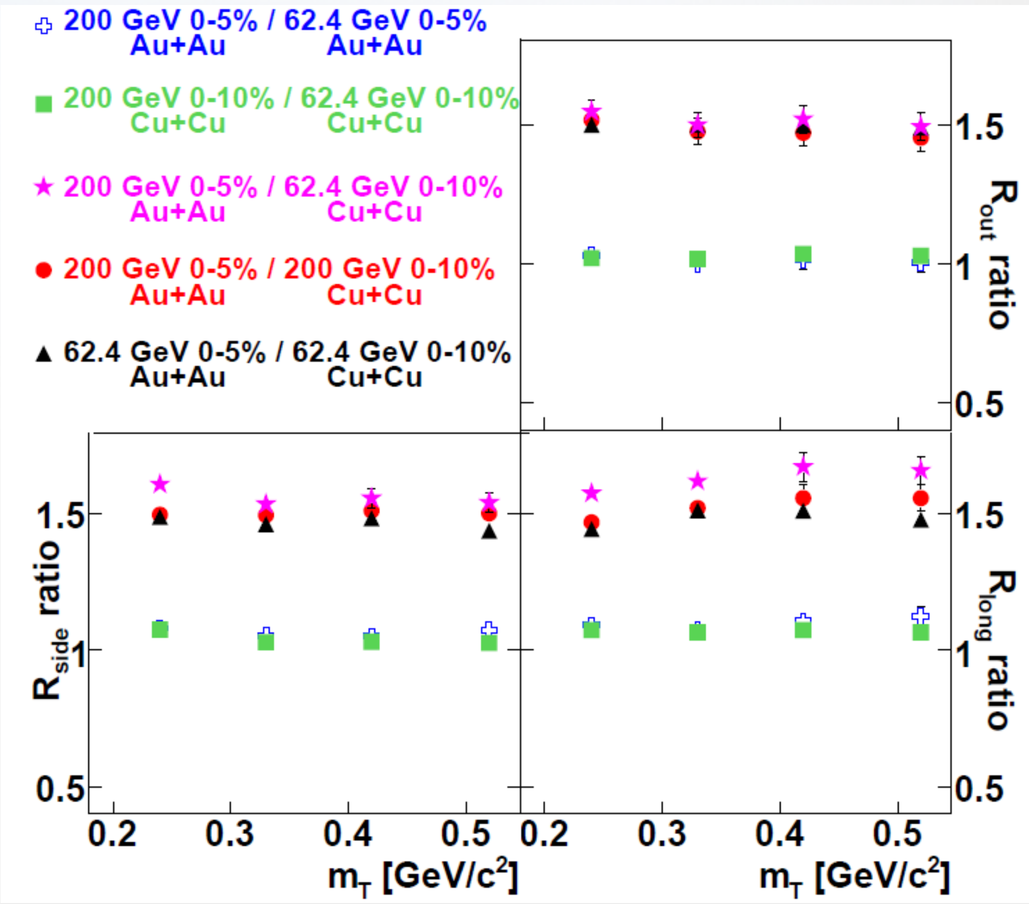

A. Enokizono (QM2006)




- HBT radii for different collision system/energy show a very similar $m_T$ dependence.
- Drop of HBT-λ at lower $m_T$ → Less chaotic source at low $m_T$?

# $m_T$ dependence VS $N_{part}$ & $\sqrt{s_{NN}}$

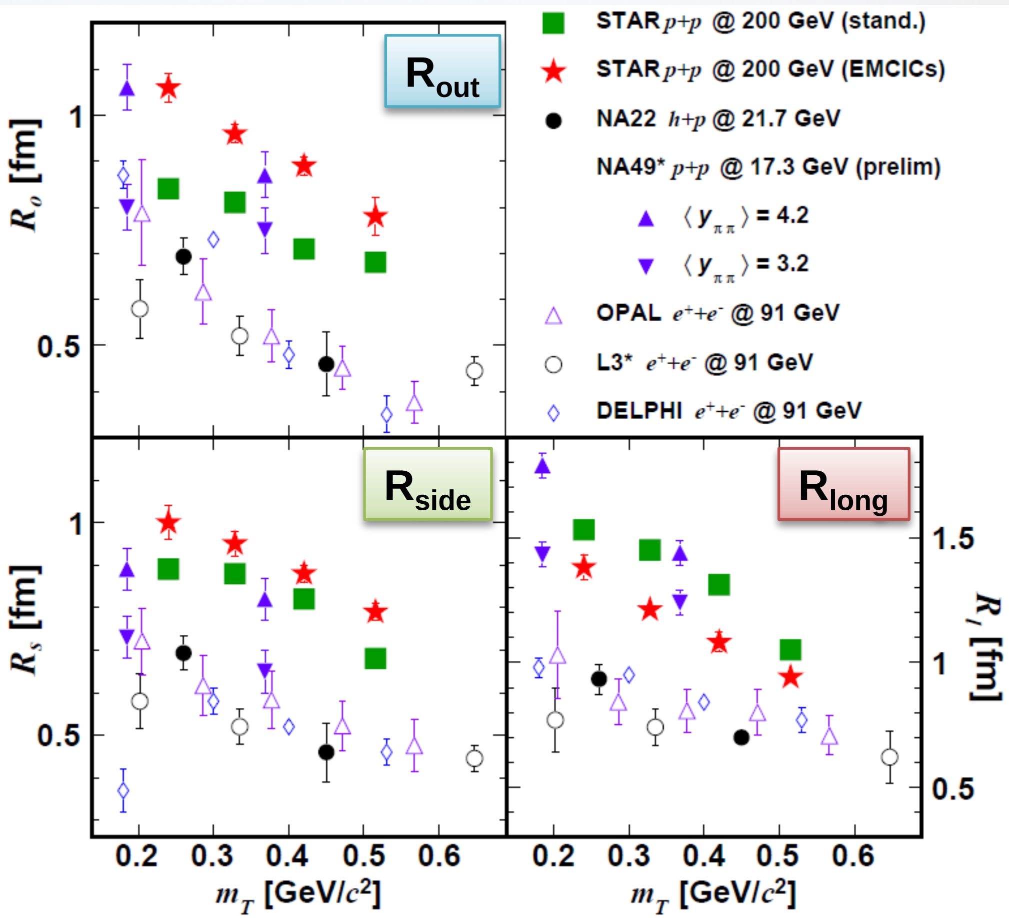
STAR Phys. Rev. C80 024905 (2009)




- Ratios of HBT radii between different $N_{part}$ and collision energy are mostly flat as a function of $m_T$
- No difference for the degree of $m_T$ dependence between 64GeV–200GeV for Au+Au and Cu+Cu data.

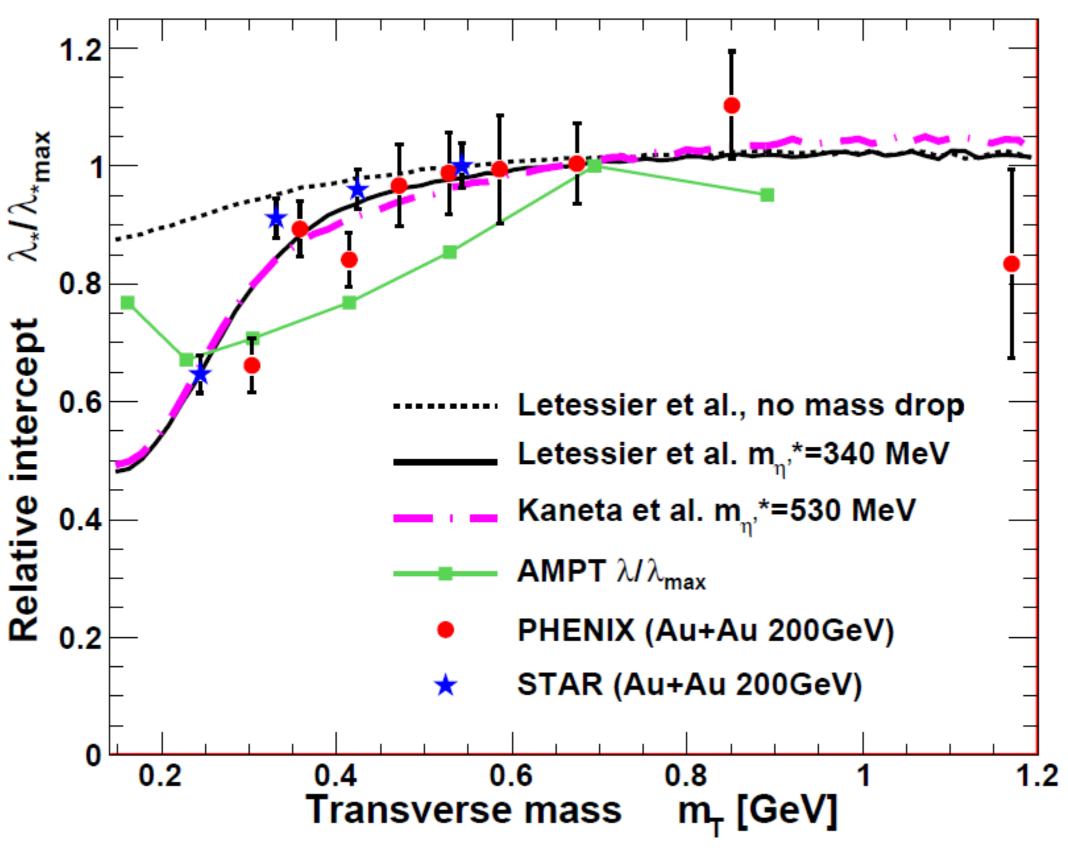
# $m_T$ dependence (small systems)

STAR Phys. Rev C.83 064905 (2011)




- $m_T$ dependence of HBT radii can be observed for small system (p+p, and e+e too!)
  - Bulk collective flow even in p+p, e+e collisions?
  - Final state hadronic rescattering effect?
- Need more detalied study using imaging analysis…

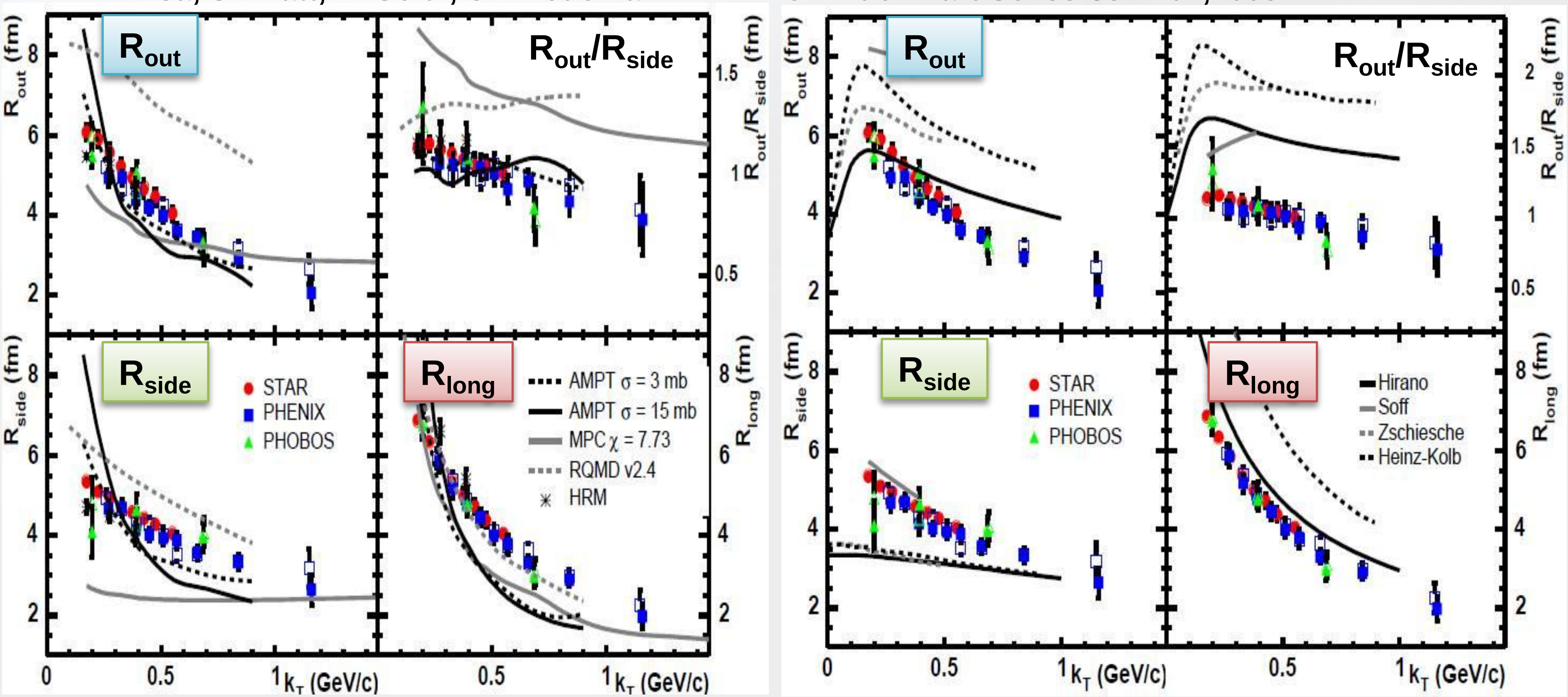
# What is HBT-$\lambda$ drop at low $m_T$?




- In hot medium η' mass could be reduced to quark model mass due to UA(1) symmetry restoration mass, resulting in enhancement of mass of η' production (decrease of HBT-$\lambda$) at low $m_T$.

# RHIC HBT puzzle

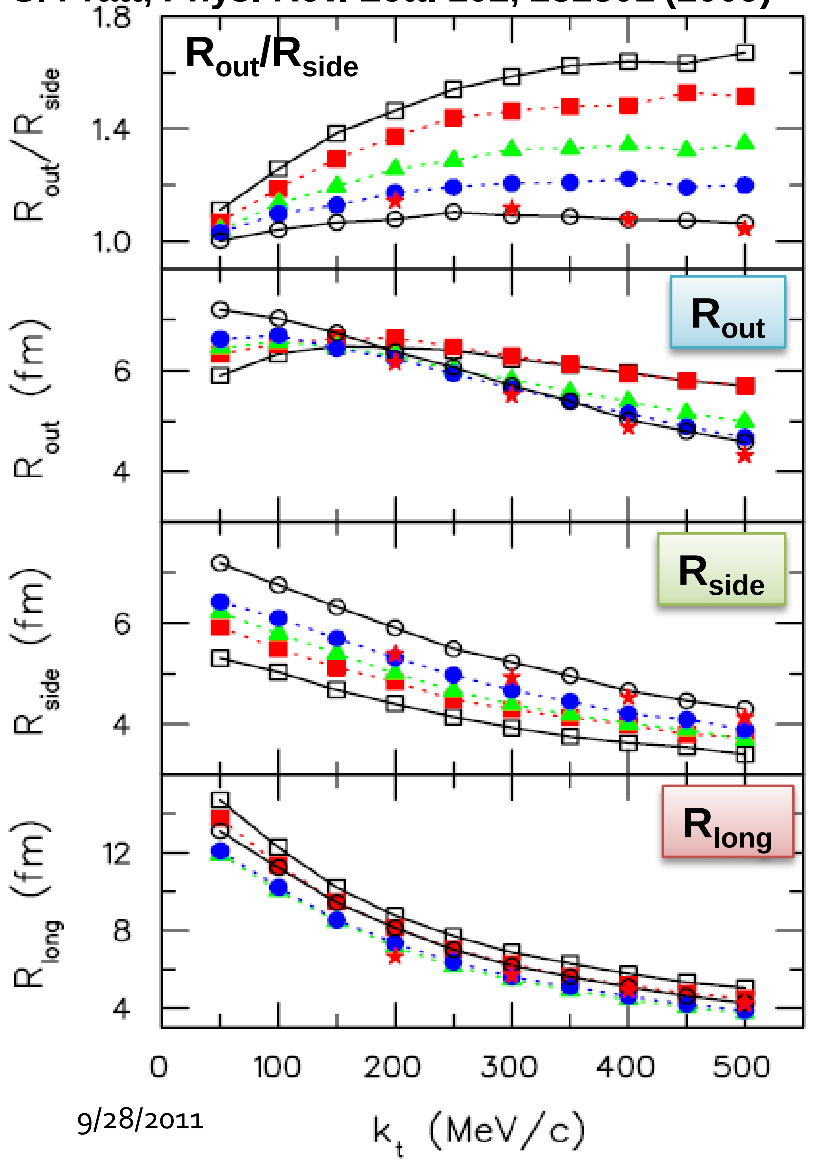
M.A. Lisa, S. Pratt, R. Soltz, U. Wiedemann Ann. Rev. Nucl. Part.Sci.55:357-402,2005




- Before recently most of the hydro-models have failed to reproduce experimental HBT radii at the same time as other observables (e.g spectra, flows) .

# Resolving HBT puzzle

S. Pratt, Phys. Rev. Lett. 102, 232301 (2009)




- □ **1st order phase transition, no pre-thermal flow, no viscosity**
- ■ **Include pre-thermal acceleration**
- ▲ **Stiffer equation of state**
- ● **Adding viscosity**
- ○ **Include all features**

- One of the recent hydrodynamics calculations which successfully reproduce HBT $R(m_T)$ at the same time as flow/spectra results.
- All of the physics features describing RHIC A+A collisions push $R_{out}/R_{side}$ toward ~1.

# Summary

- HBT radii have been extensively and systematically measured for RHIC collision systems/energies.
  - Result values are consistent between RHIC experiments
- HBT radii clearly scale with multiplicity but,
  - Rout are not scaled between AGS, RHIC and LHC energy regions.
  - Different scaling between A+A and p+p
- No sign for the critical point observed by HBT so far…
- More interesting HBT analyses (e.g. HBT radii vs. $v_3$, 3D imaging) are on-going.