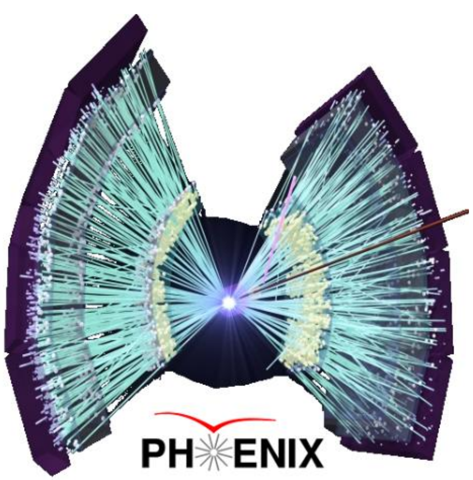
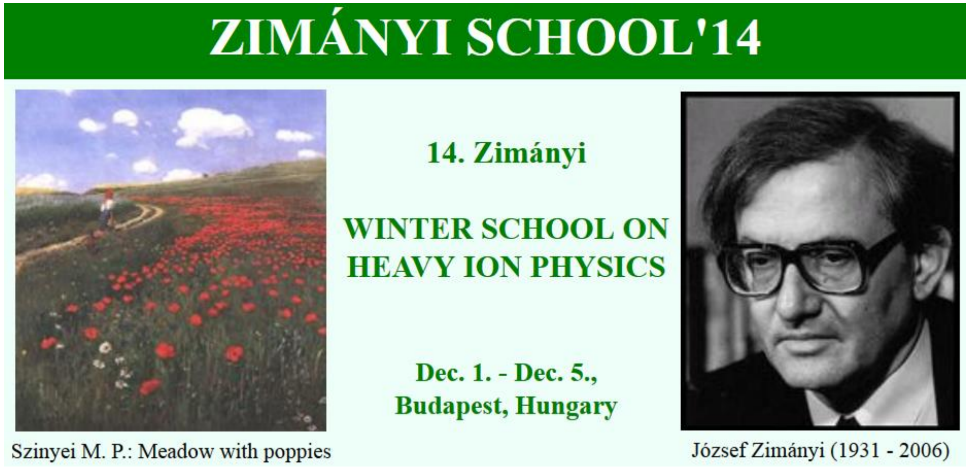
# Bose-Einstein correlations in the Beam Energy Scan with the PHENIX Experiment

Máté Csanád for the PHENIX Collaboration

Eötvös University, Budapest



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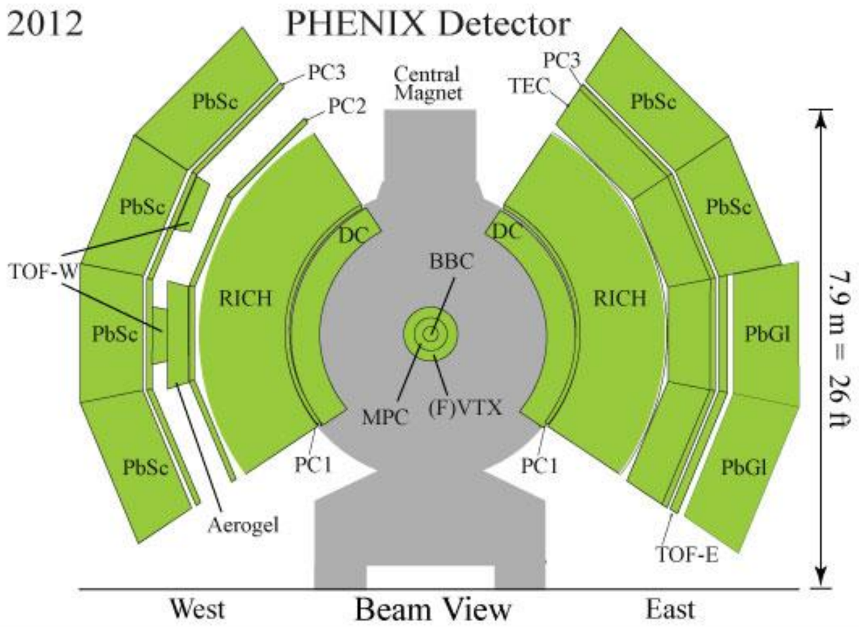
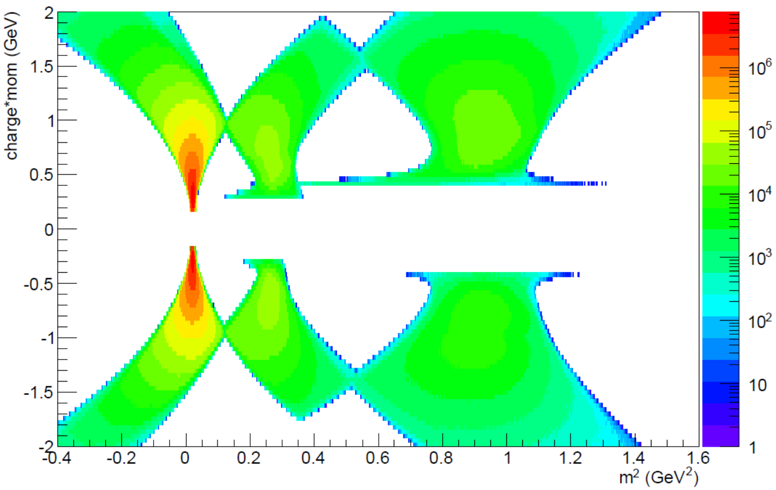
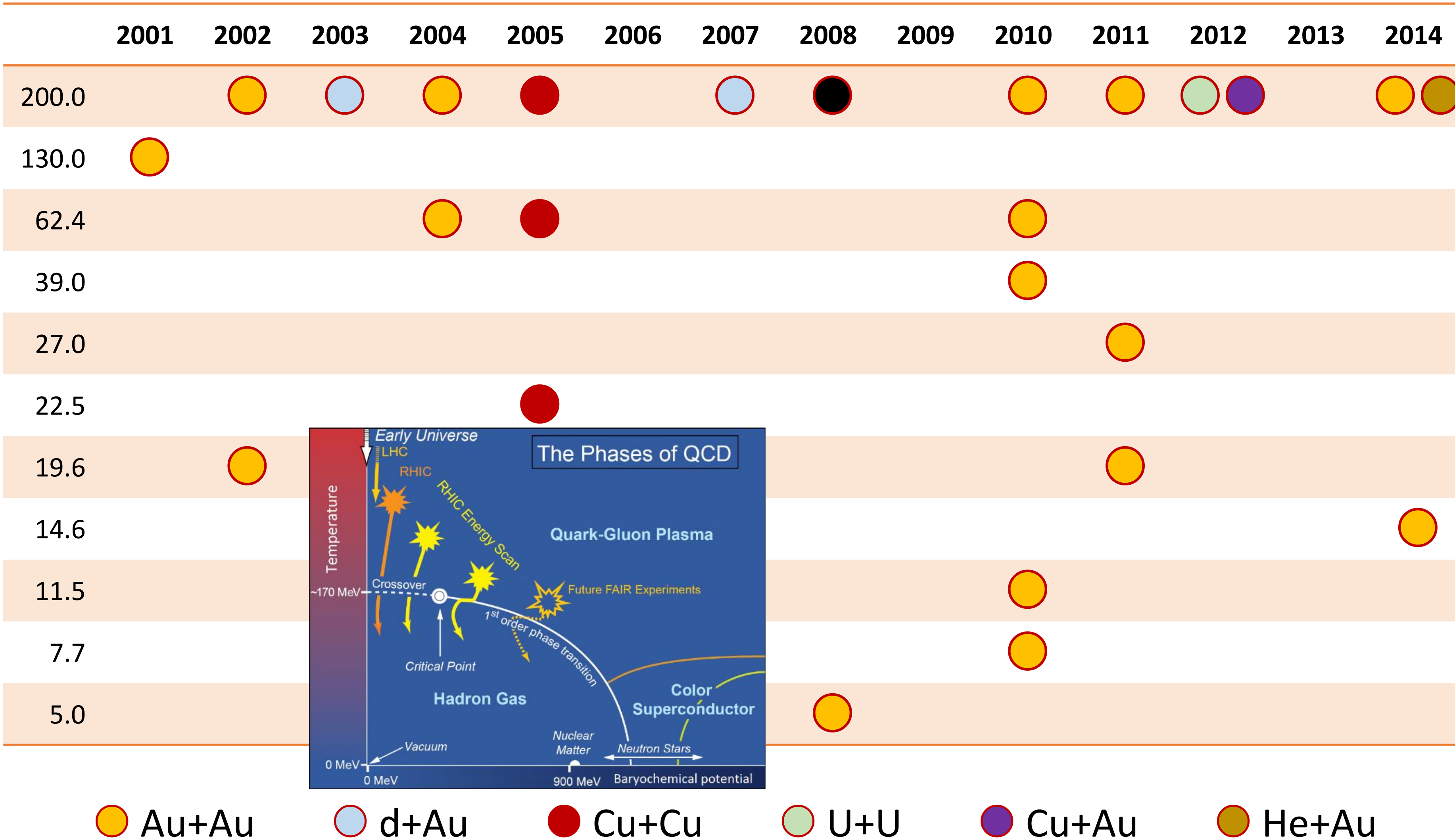
# The PHENIX Experiment at RHIC

- Observing collisions of p, d, Cu, Au, U
- Beam Beam Counters
  - Centrality, zvertex
- Pad and Drift Chambers
  - Tracking
- EM calorimeters
  - Electron and photon energy
  - Time of flight: hadron ID
- Time of Flight detectors
  - Hadron ID
- Charged pion ID for ~ 0.2 – 2 GeV/c$^2$
- Charged kaon ID for a similar range
- Beam energy scan!



# PHENIX & the RHIC Beam Energy Scan




See details at http://www.rhichome.bnl.gov/RHIC/Runs/

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# Bose-Einstein correlations

- R. H. Brown & R. Q. Twiss: intensity interferometry in radio astronomy
  - Angular diameter of a main sequence star measured
- In high energy physics: Goldhaber et al.
  - Searched for $\rho^0 \to \pi^+\pi^-$, found Bose-Einstein corr.
- Basic principle: symmetrization (QFT: comm. rel.)
- Simple QM description (QFT exists as well):

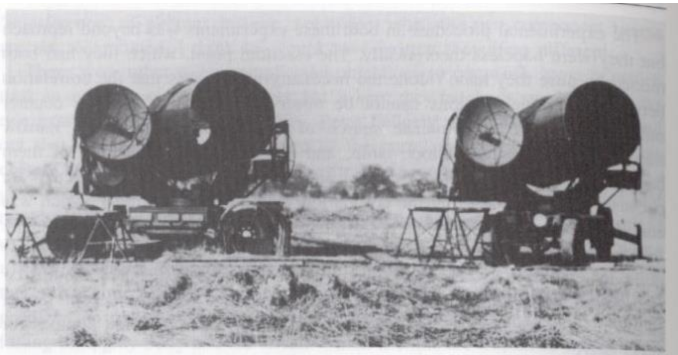


**Figure 10.1** The first stellar intensity interferometer; the pilot model of the stellar intensity interferometer at Jodrell Bank in 1955. Two Army searchlights were used to make the first measurement of the angular diameter of a main sequence star (Sirius).

$$\Psi(x) \sim e^{-ikx}, \Psi_2(x_1, x_2) \sim \left(e^{-ik_1x_1}e^{-ik_2x_2} + e^{-ik_1x_2}e^{-ik_2x_1}\right)$$

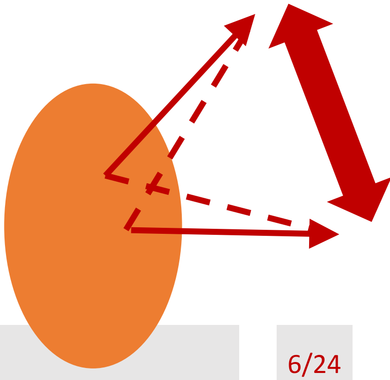
$$N_1(k) = \int S(x,k)|\Psi(x)|^2 d^4x$$

$$N_2(k_1, k_2) = \int S(x_1,k_1)S(x_2,k_2)|\Psi_2(x_1,x_2)|^2 d^4x_1 d^4x_2$$

$$C_2(k_1, k_2) = \frac{N_2(k_1,k_2)}{N_1(k_1)N_1(k_2)} \cong 1 + \left|\frac{\tilde{S}(q,K)}{\tilde{S}(0,K)}\right|^2$$

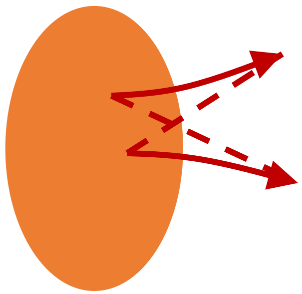
with $q = k_1 - k_2, K = (k_1+k_2)/2$

- Correlation function measures Fourier transform of the source
- Only for identified particles!
- Usually measured versus $q_{\rm inv} = \sqrt{-(k_1 - k_2)^2}$

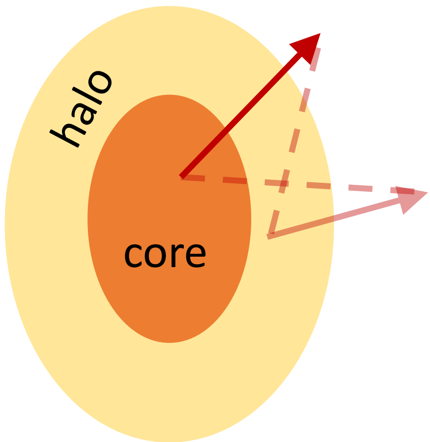


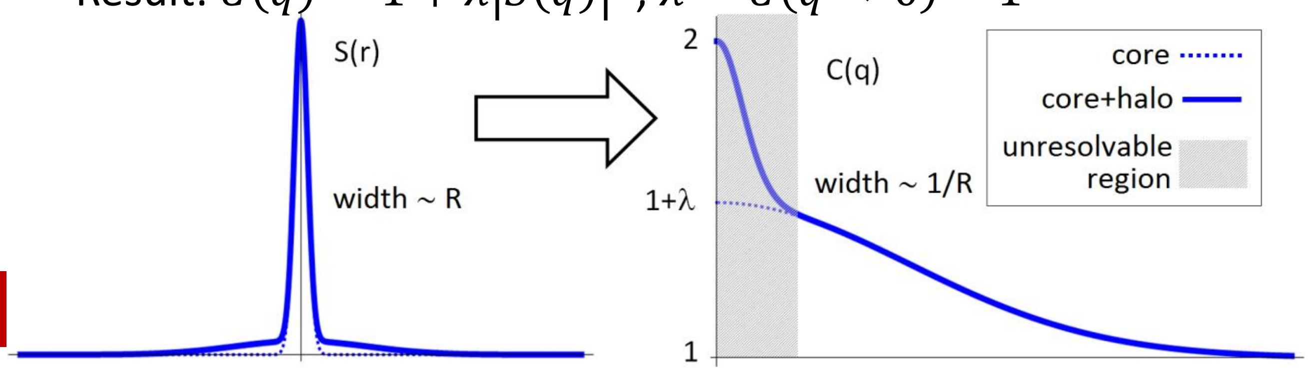
# Final state interactions, resonances

- Final state interactions distort the simple Bose-Einstein picture
  - For charged pions: Coulomb-interaction
- Instead of plane-waves: solve two-particle Schrödinger-eq. with $V(r) = -\alpha/r$
  - Simple approximation, neglects retardation, many-particle correlations, mean field, …
  - Use result in calculating $C(q)$ from $S(r)$
  - Details in Csörgő, Alt, Lörstad, PLB458 (1999)
  - An usual practice: Coulomb-correction, $C_{\text{Bose-Einstein}}(q) = K(q) C_{\text{measured}}(q)$

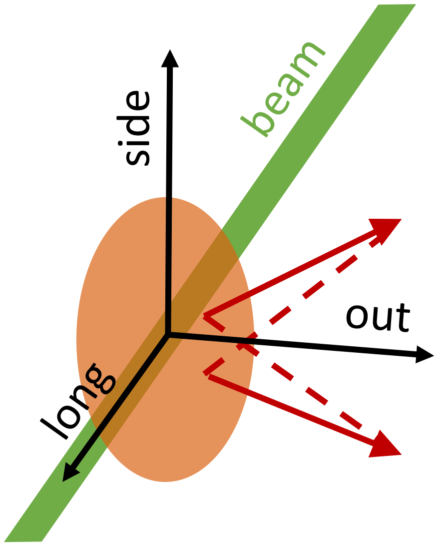


- Resonance pions: reduce correlation function
  - „Primordial" pions: coming from an 5-10 fm sized region
  - Resonance pions: from very far regions
  - Ref: Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996) and Boltz et al., PRD47 (1993)
  - Result: $C(q) = 1 + \lambda \left|\tilde{S}(q)\right|^2, \lambda = C(q \to 0) - 1$



# The out-side-long system, HBT radii




- Extract 3 or 4 dimensional information?
- Correlation function: $C_2(q) = 1 + \lambda e^{-R^2_{\mu\nu}q^\mu q^\nu}$
- Pair-coordinate system (Bertsch NPA498, Pratt PRD33)
  - Out: direction of average transverse momentum
  - Long: beam direction
  - Side: perpendicular to both
- In this system: no average side momentum, $K_{\text{side}} = 0$
- Usually used: LCMS (longitudinally comoving system)
  - Defined in Pratt, Csörgő, Zimányi, Phys.Rev. C42 (1990) 2646
  - No average longitudinal momentum, i.e. $K^\mu = (M_t, K_t, 0{,}0)$
  - Mom. diff: $q_0 = \frac{m^2_{1t}-m^2_{2t}}{2M_t}$, $q_{\text{out}} = \frac{p^2_{1t}-p^2_{2t}}{2K_t}$, $q_{\text{side}} = \frac{p_{2x}p_{1y}-p_{1x}p_{2y}}{K_t}$, $q_0 = \frac{E_2 p_{1z}-E_1 p_{2z}}{M_t}$
  - Mass shell condition: $q^\mu K_\mu = 0 \;\Rightarrow\; q_0 = \frac{K_t}{M_t} q_{\text{out}} = \beta_t q_{\text{out}}$
- From the $R^2_{\mu\nu}$ matrix, $R_{\text{out}}, R_{\text{side}}, R_{\text{long}}$ nonzero, the usual HBT radii
  - If angle dependence analyzed: $R_{\text{os}}$ also appears

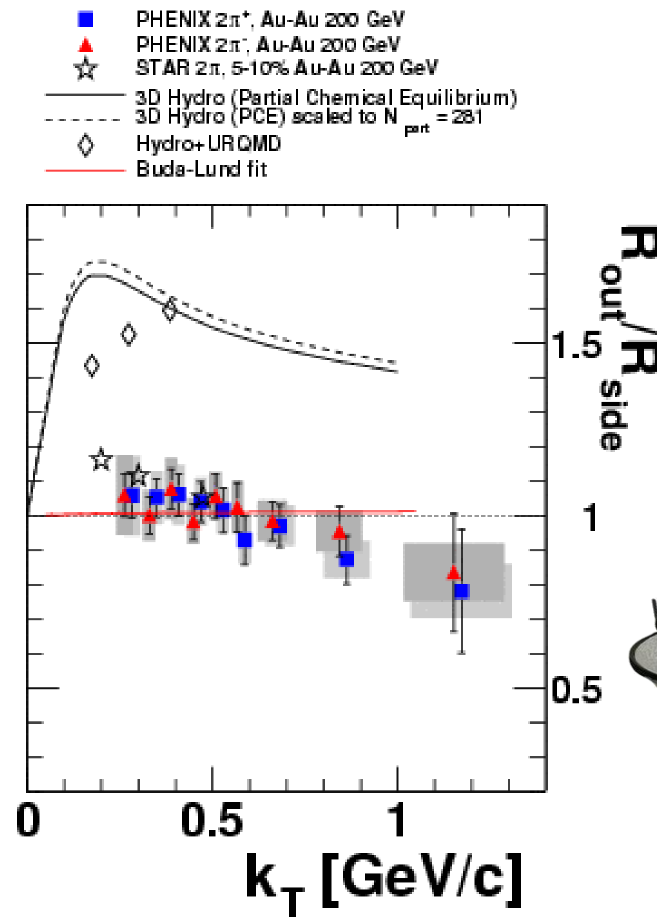
# Emission duration and out vs. side

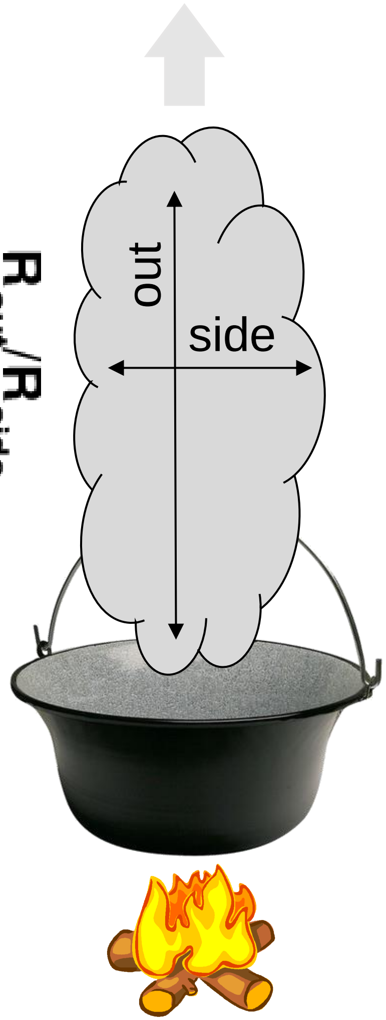
- Simple hydrodynamic result (Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390):

$$R_{\mathrm{out}}^2 = \frac{R^2}{1+\frac{m_t}{T_0}u_t^2} + \beta_t^2 \Delta\tau^2$$

$$R_{side}^2 = \frac{R^2}{1+\frac{m_t}{T_0}u_t^2}$$

- Scaling with $\sqrt{m_t}$
- Out-side diff: $\Delta\tau$ emission duration (for static source)
- RHIC: ratio is near one
  - Theoretically challenging
  - Many components for resolution
- No strong 1st order phase trans.
- What kind of transition then?
- Cross-over at 200 GeV



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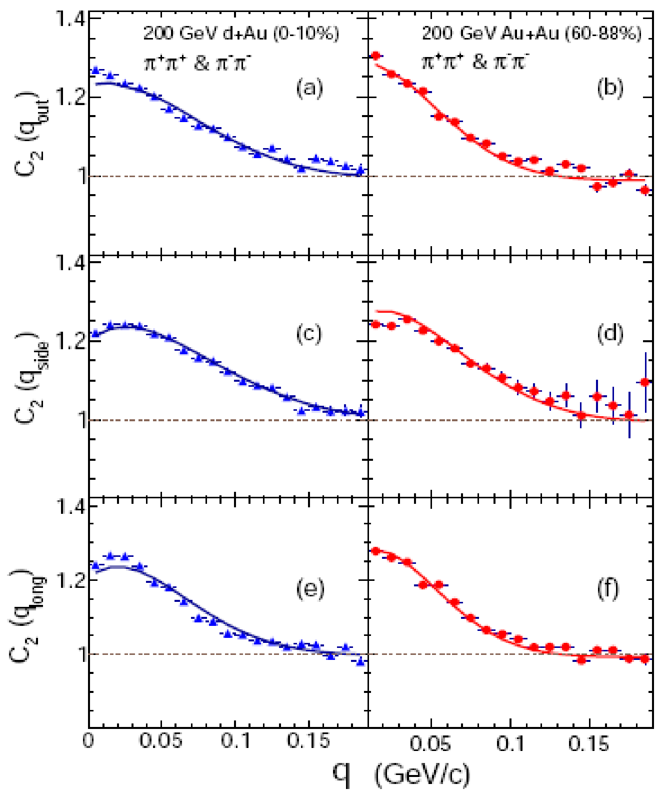
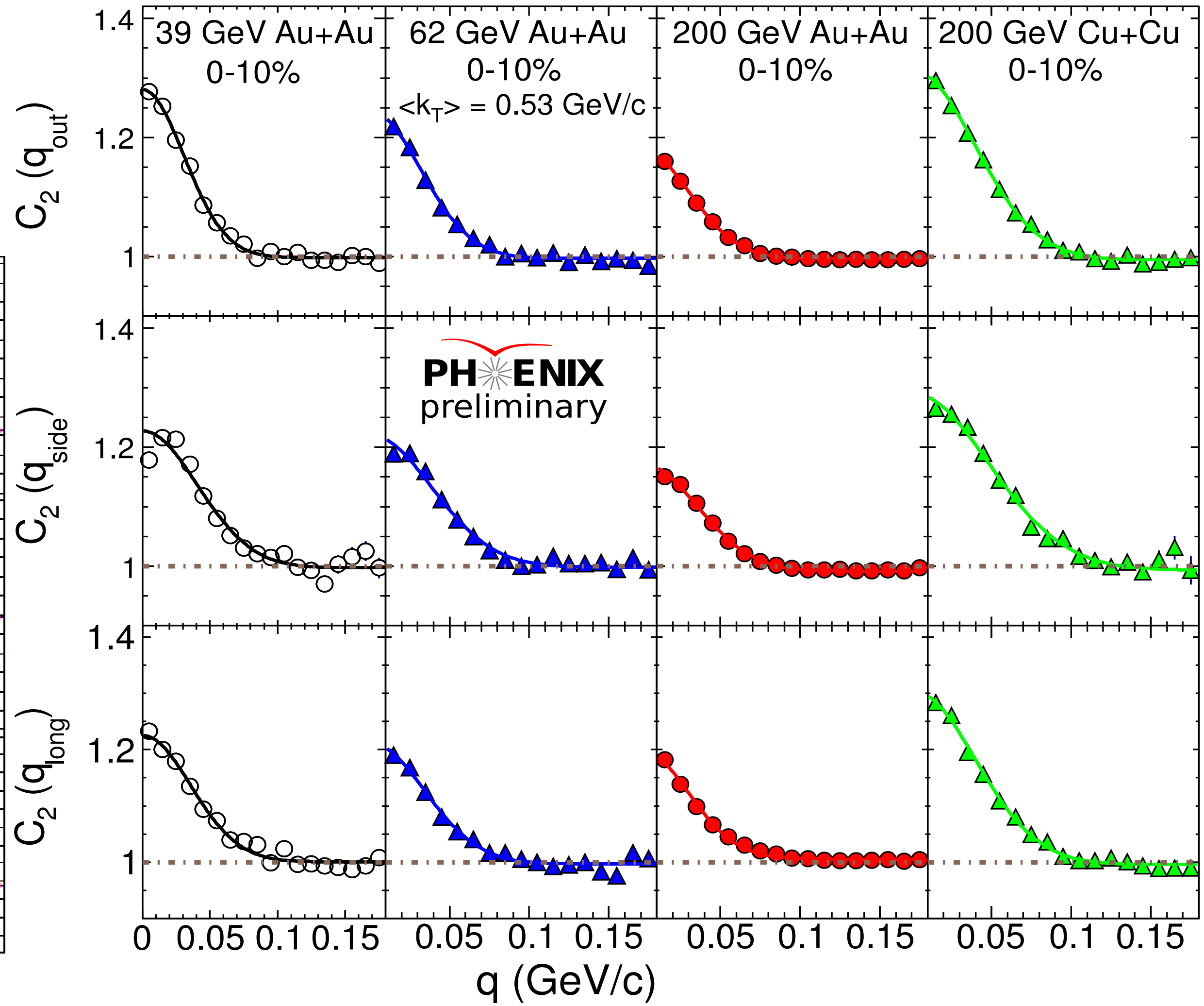
- The PHENIX Experiment
- Basics Bose-Einstein correlations and HBT radii
- PHENIX HBT results
  - Transverse momentum scaling
  - Azimuthally dependent HBT
  - Geometric scaling
  - Excitation function
- Beyond HBT
- Summary

# Bose-Einstein correlation results at a glance

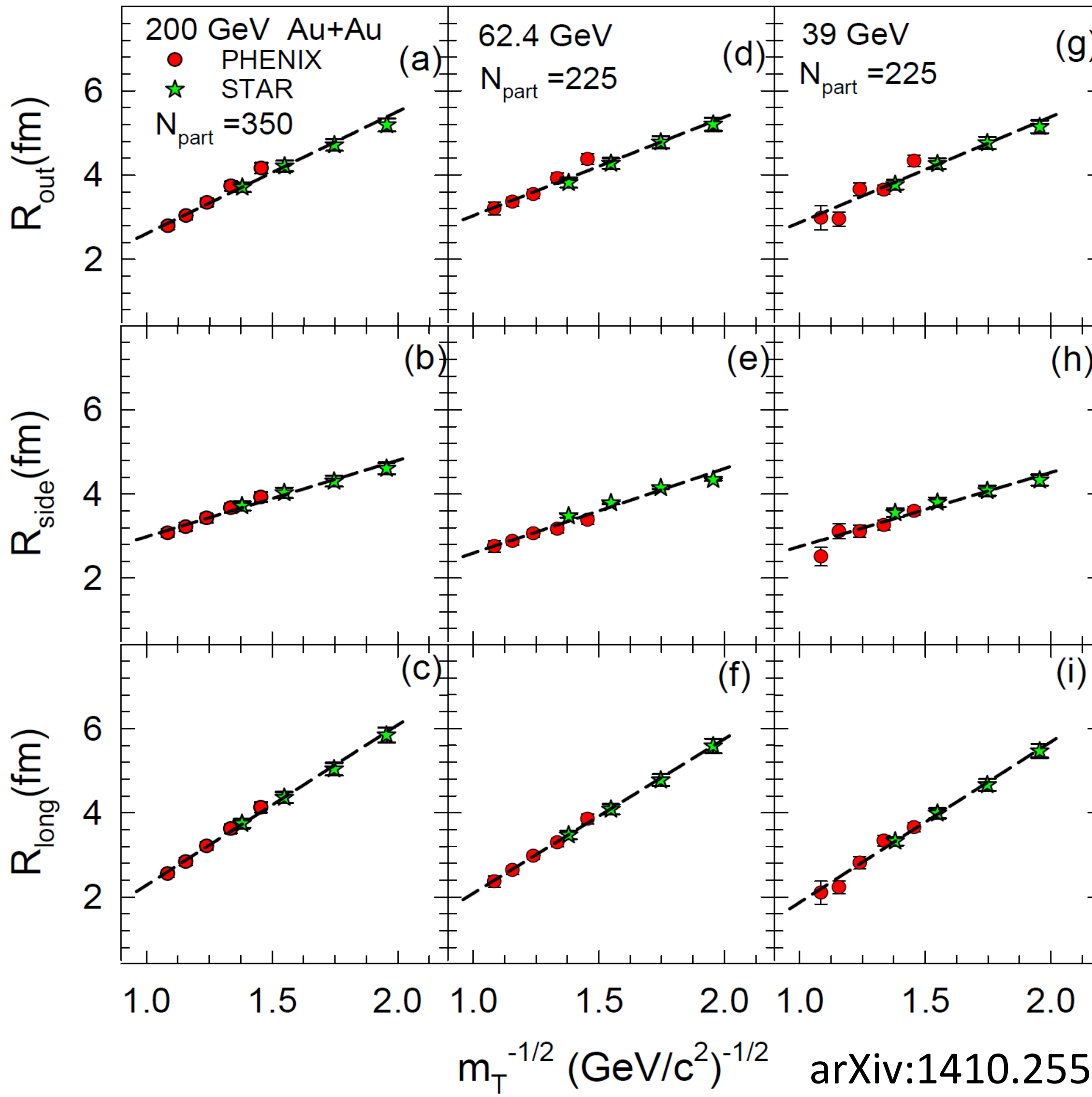
- Corr. func. in 3D, Gaussian fit ⇒ HBT radii (details e.g.: arXiv:1410.2559)
- Systematics:
  - Beam species
  - Coll. energy
  - Centrality



# Transverse momentum (hydro) scaling

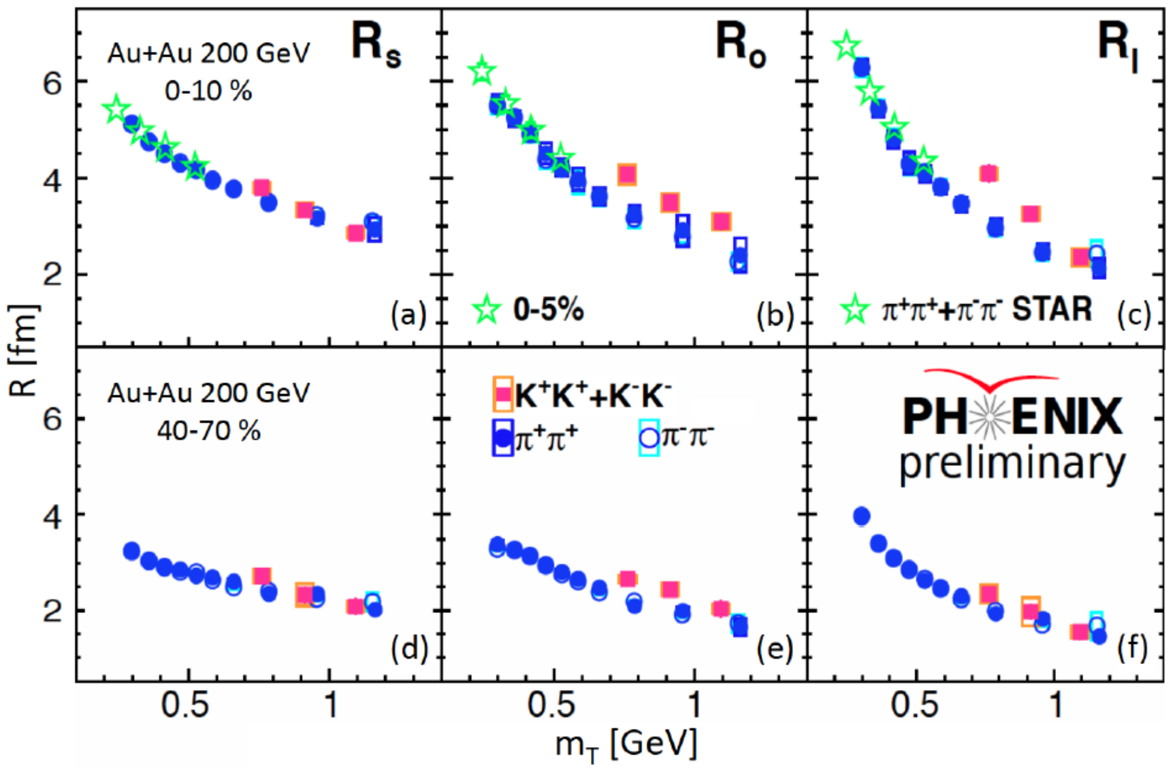
- Linear dependence observed for all systems and directions
- Recall $R_i = a + \frac{b}{\sqrt{m_t}}$
- Works 39 to 200 GeV
- Consistent with STAR
- Interpolation to common transverse momentum!
- How about kaons?



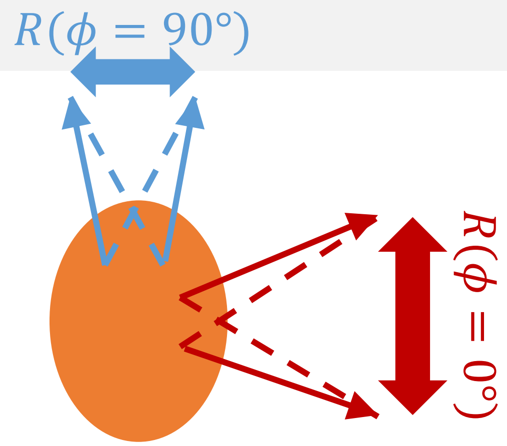

arXiv:1410.2559

# Transverse momentum scaling of kaons?

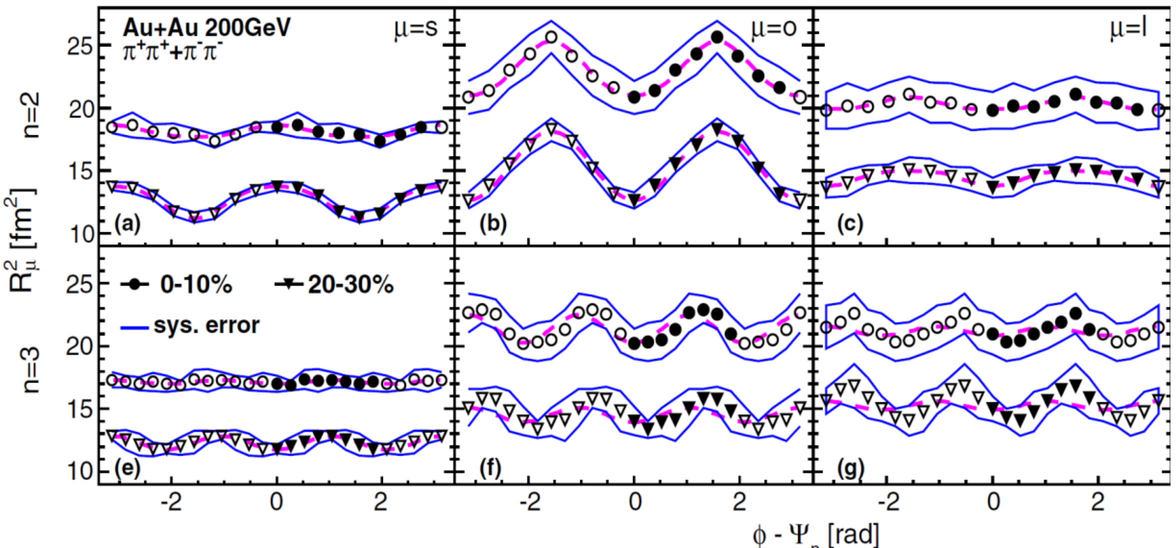
- Transverse momentum scaling approximately conserved
- Visible differences for the out and long directions
- Larger differences for central events
- Kaon emission duration longer?

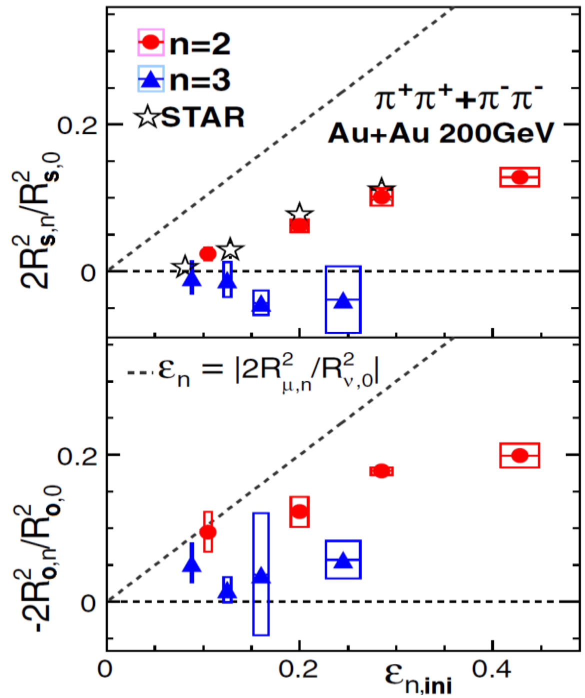


# Azimuthally dependent HBT results




- Correlation functions as a function of azimuth angle
- HBT radii parameterized as
  $R_\mu^2 = R_{\mu,0}^2 + R_{\mu,n}^2 \cos[n(\phi - \Psi_n)]$
- Higher order contributions ($\cos[n(\phi - \Psi_{2,3})]$ for $n = 4, 6$ also possible)
- Final eccentricity measure $\epsilon_{n,\text{final}} = 2R_{\mu,n}^2/R_{\mu,0}^2$
- Eccentricity dynamics: $\epsilon_{\text{ini}}$ versus $\epsilon_{\text{final}}$

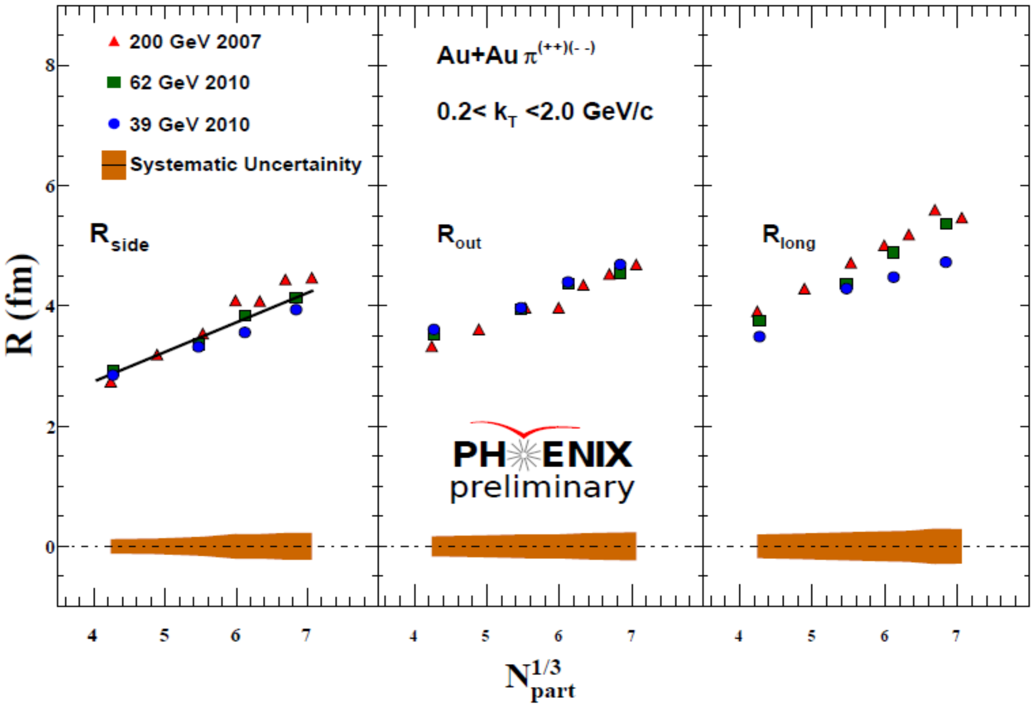


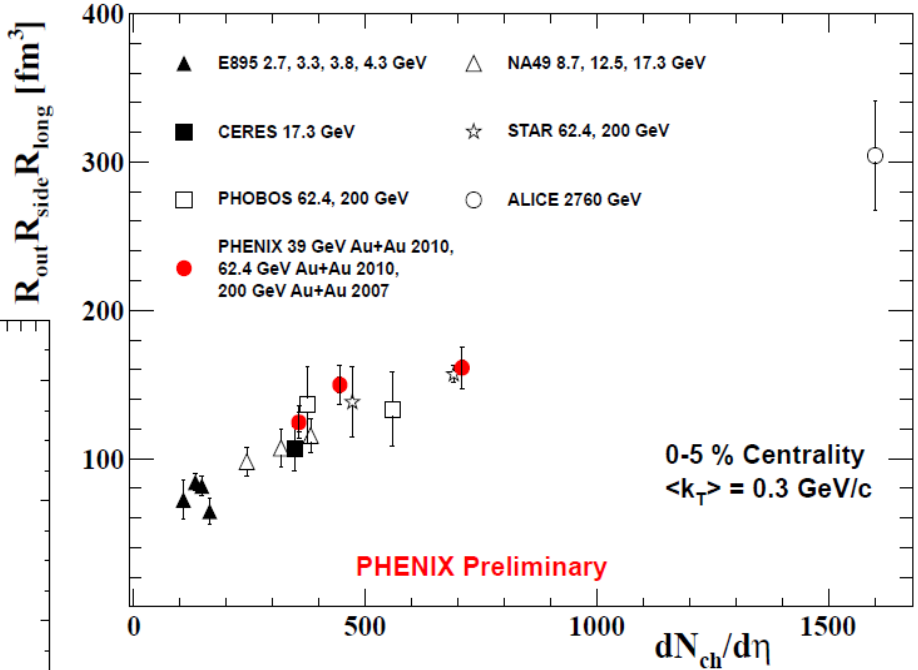




Phys.Rev.Lett 112, 222301 (2014)

# System size dependence

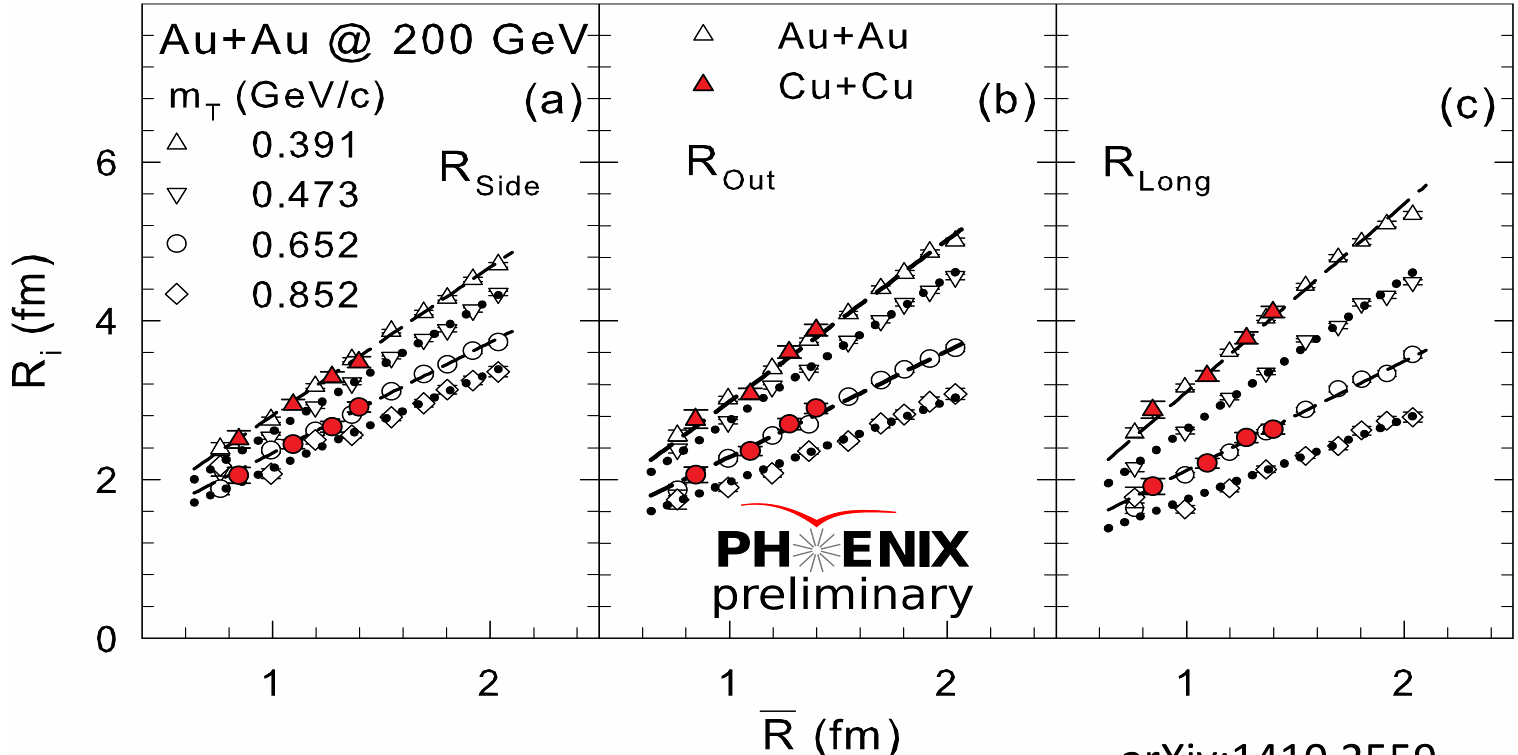
- Linear increase with $N_{\rm part}^{1/3}$: system volume information, $R_o R_s R_l \sim V \sim N_{\rm part}$
- Approximate scaling observed
- Similar trend for 39, 62 and 200 GeV
- Linear rise in volume versus $N_{\rm ch}$



# Geometric scaling

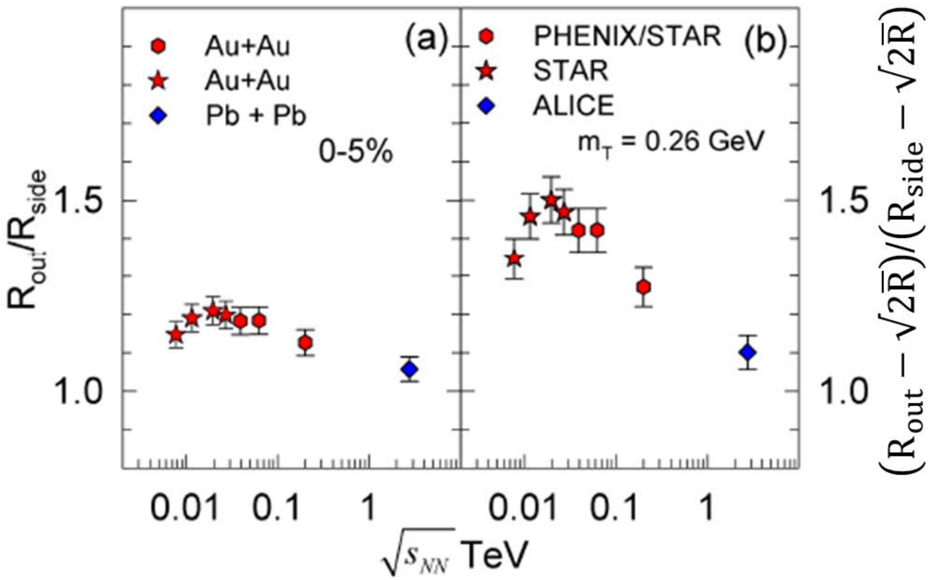
- Initial transverse size $\bar{R}^{-2} = \sigma_x^{-2} + \sigma_y^{-2}$ (average density RMS)
- Scaling observed!
- Better predictor of final state homogeneity length, than $N_{\text{part}}$
- HBT sensitive to expansion dynamics

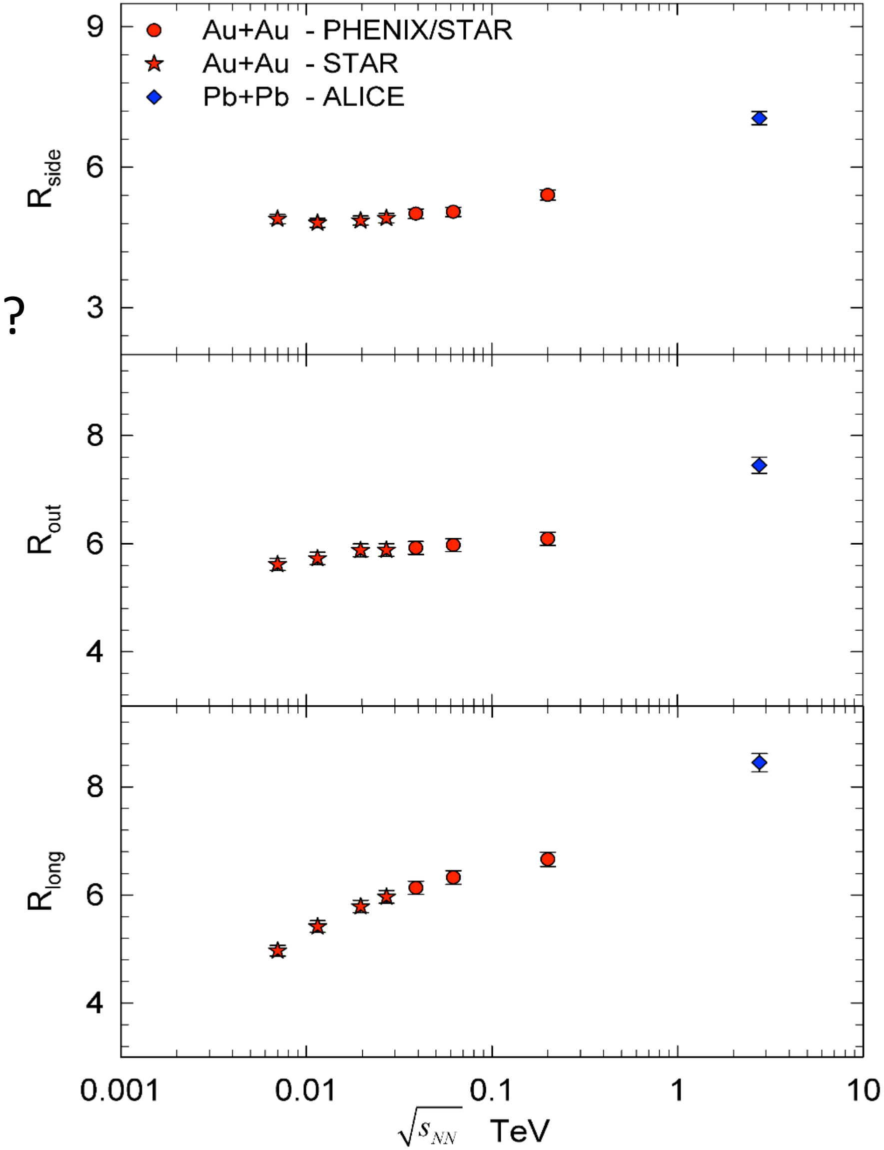



arXiv:1410.2559

# Excitation function of HBT radii

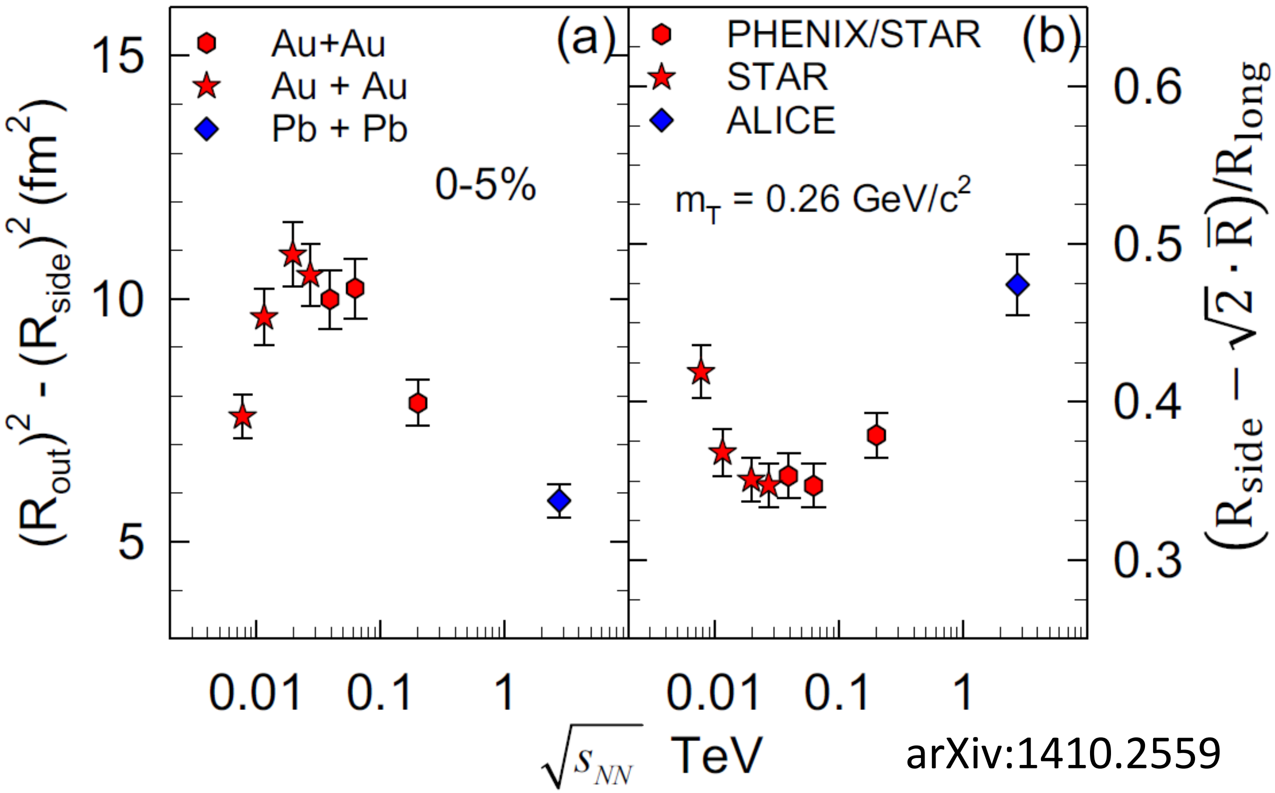
- Radii all increase
- What happens with $R_{\text{out}}/R_{\text{side}}$?
- Plot $(R_{\text{out}}-\sqrt{2}\bar{R})/(R_{\text{side}}-\sqrt{2}\bar{R})$
- Something happening around 30-40 GeV?



# Excitation function of emission duration

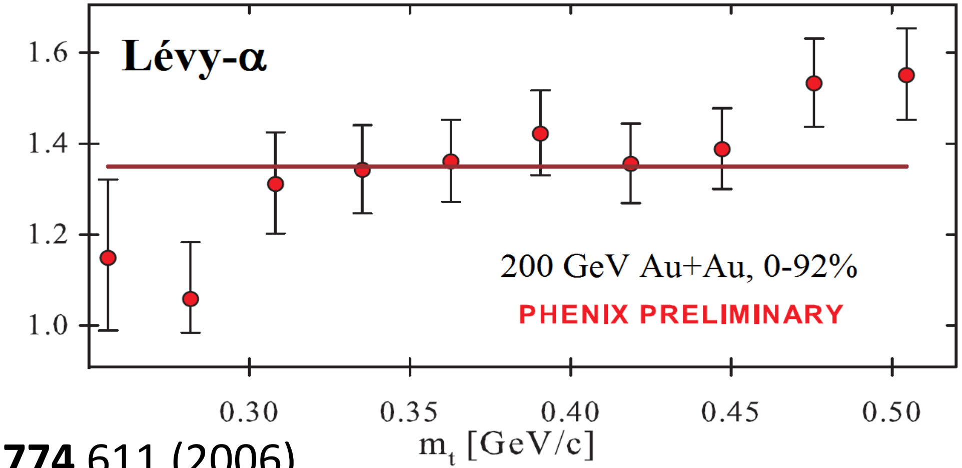
- Measure $R_{\text{out}}^2 - R_{\text{side}}^2$ and $(R_{\text{side}} - \sqrt{2}\bar{R})/R_{\text{long}}$
- Very non-monotonic behavior!
- Theoretically challenging: HBT radii smaller than actual sizes (dynamics!)
- Full hybrid modelling needed to interpret the data (models at low $\sqrt{s_{NN}}$ ?)



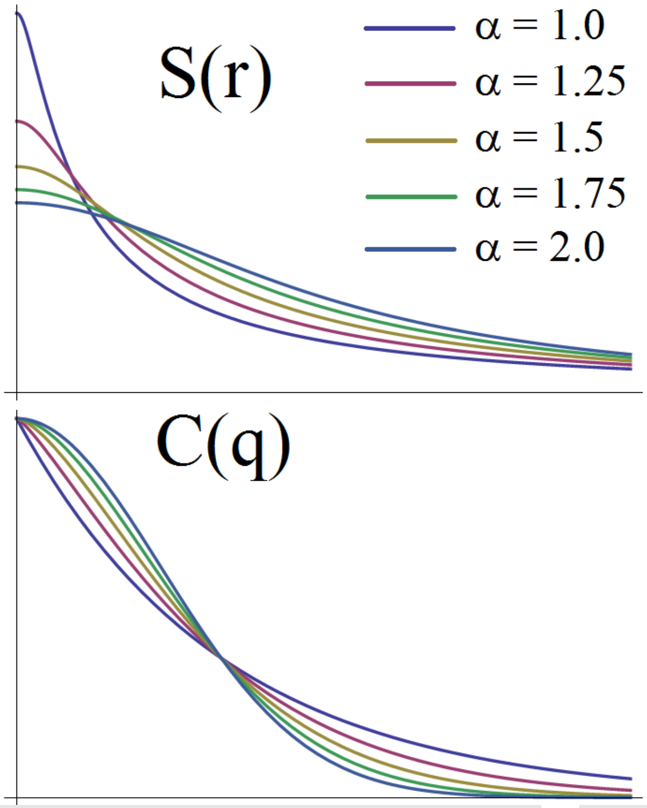

arXiv:1410.2559

# Other prospects in HBT versus critical point

- Gaussian assumption: $C(q) = 1 + \lambda e^{-q^2 R^2} \Leftrightarrow S(r) = e^{-r^2/R^2}$
- Two-particles source identical to correlation function, $\langle\Psi(0)\Psi(r)\rangle$
- At the critical point: $\langle\Psi(0)\Psi(r)\rangle \propto r^{-d+2-\eta}$, with critical exponent $\eta$
- If source is Lévy-stable: stability exponent $\alpha = \eta$!
  - Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67
- Universality class? Conjecture: $\alpha = \eta = 0.5$
- Excitation function of $\alpha$?
- $\alpha(m_t)$ available at 200 GeV




NP**A774** 611 (2006)



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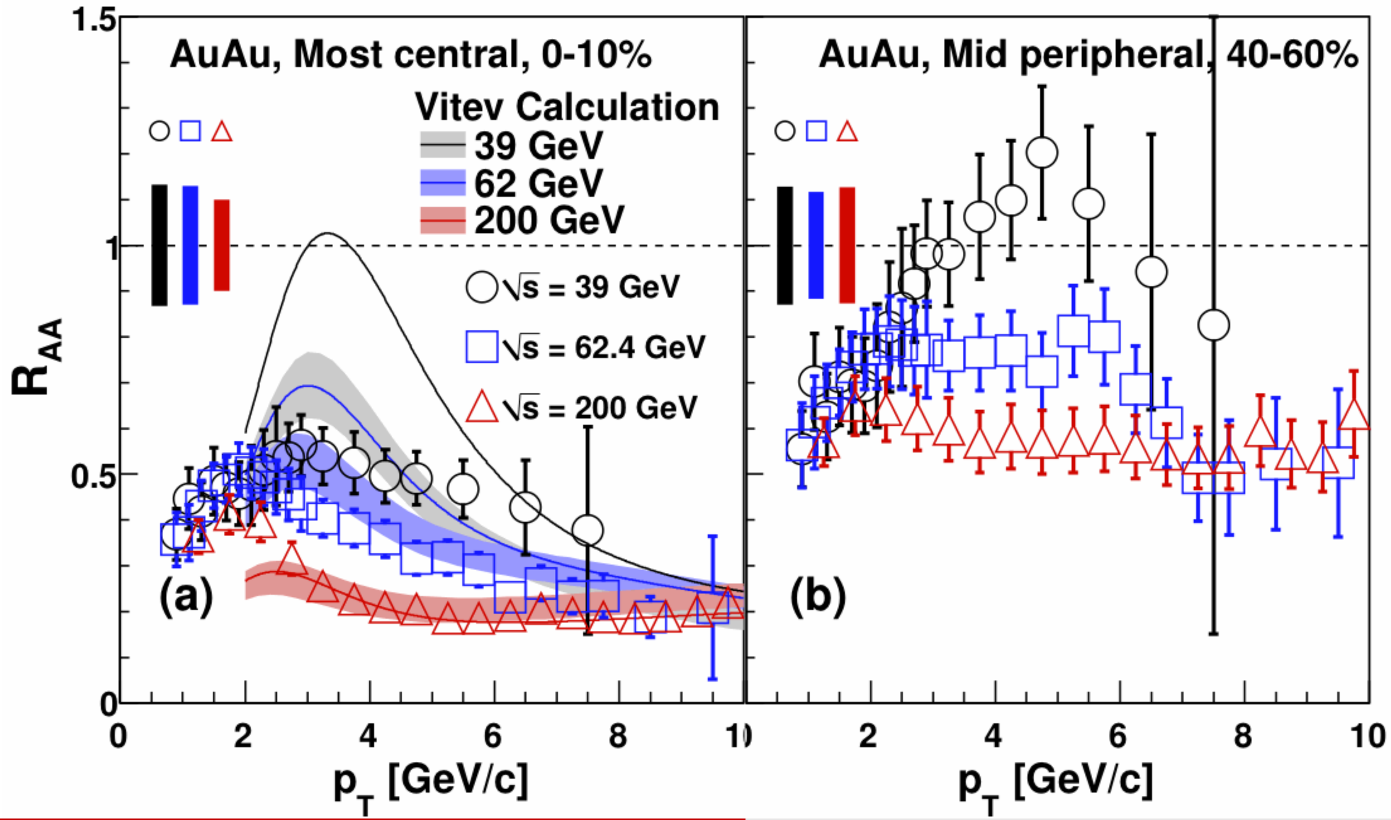
# Neutral pion energy loss in Au+Au

- Strong suppression in central 39 GeV as well
- Suppression pattern similar at 62 GeV and 200 GeV
- No suppression in peripheral 39 GeV collisions!
- Details in Phys.Rev.Lett. 109 (2012) 152301

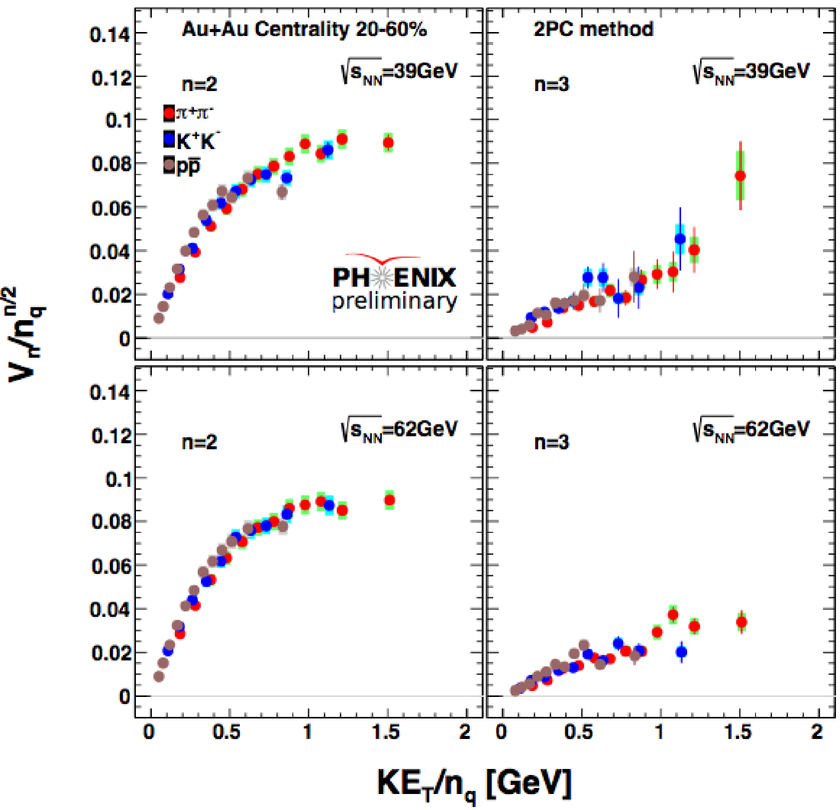


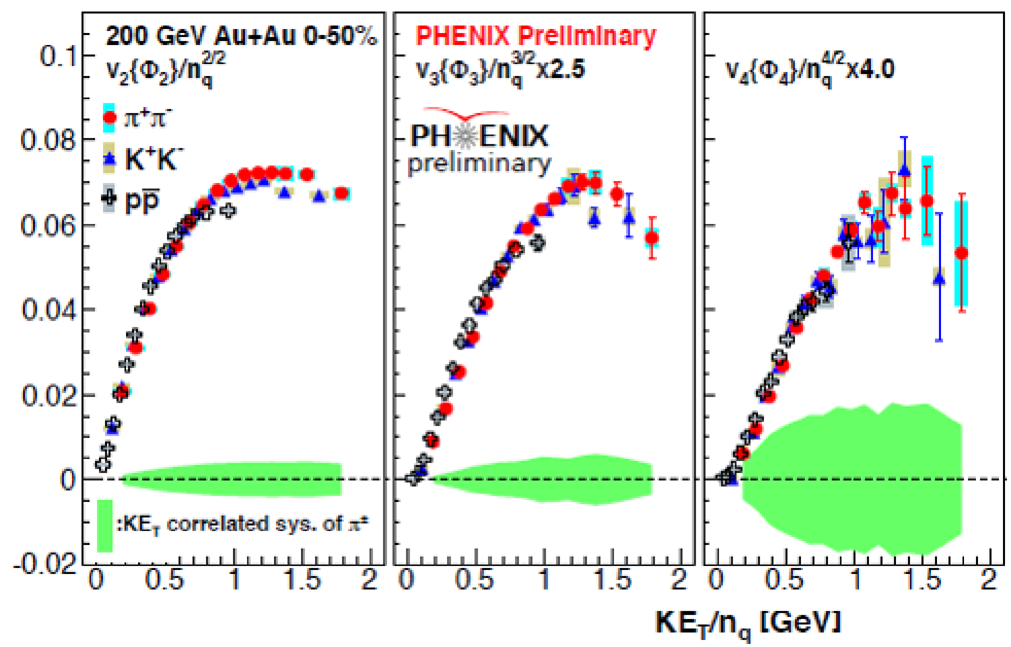
# Quark number scaling

- Observed for higher order anisotropies in

$$N(p_t,\phi) = N(p_t)\left[1 + \sum_n v_n(p_t)\cos\left(n(\phi - \Psi_n)\right)\right]$$

- Quark number scaling: $v_n/\sqrt{n_q}^{\,n}$ versus $KE_T/n_q$
- Preserved from 200 to 39 GeV; breakdown: when & how?



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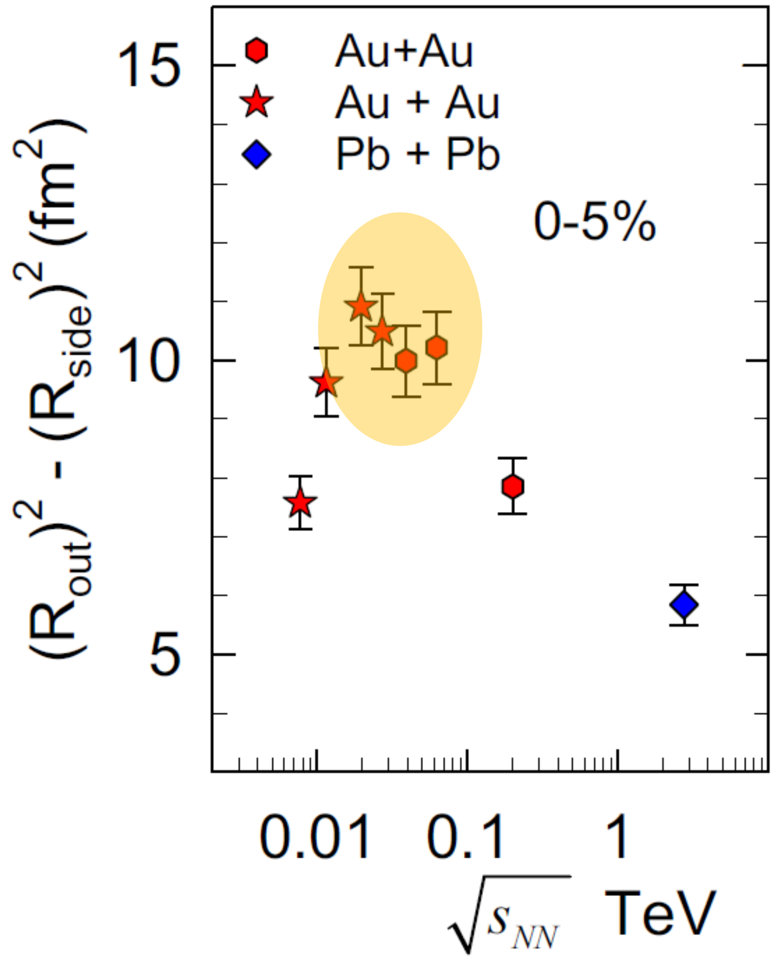
# Summary

- A wide variety of HBT data now available
- Scaling observed for wide $s_{NN}$ range
  - Transverse mass
  - System size
  - Geometric scaling
- Excitation function of HBT radii
  - Non-monotonicity of emission duration?
  - Maximum at around $\sqrt{s_{NN}} = 40$ GeV
- How about correlation exponent $\eta$?
- Support beyond HBT?
  - Quark number scaling observed
  - Non-monotonic behavior in $R_{AA}$

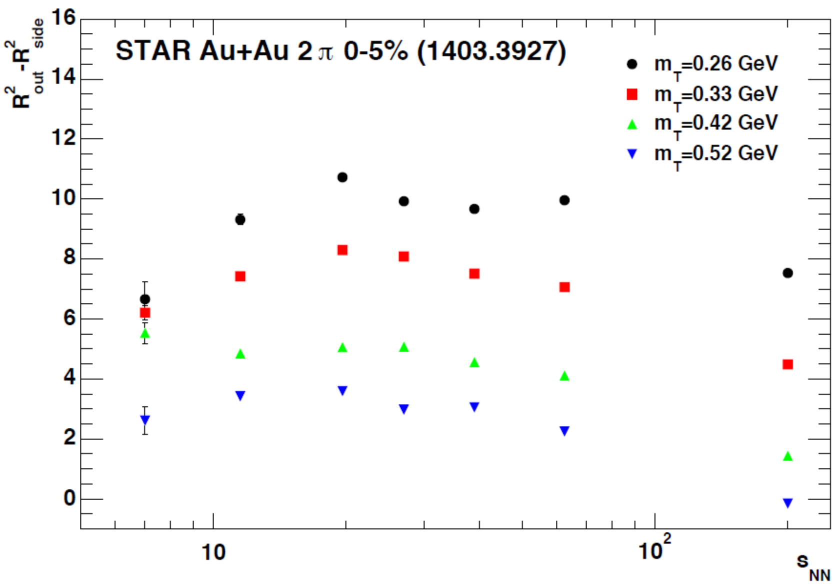


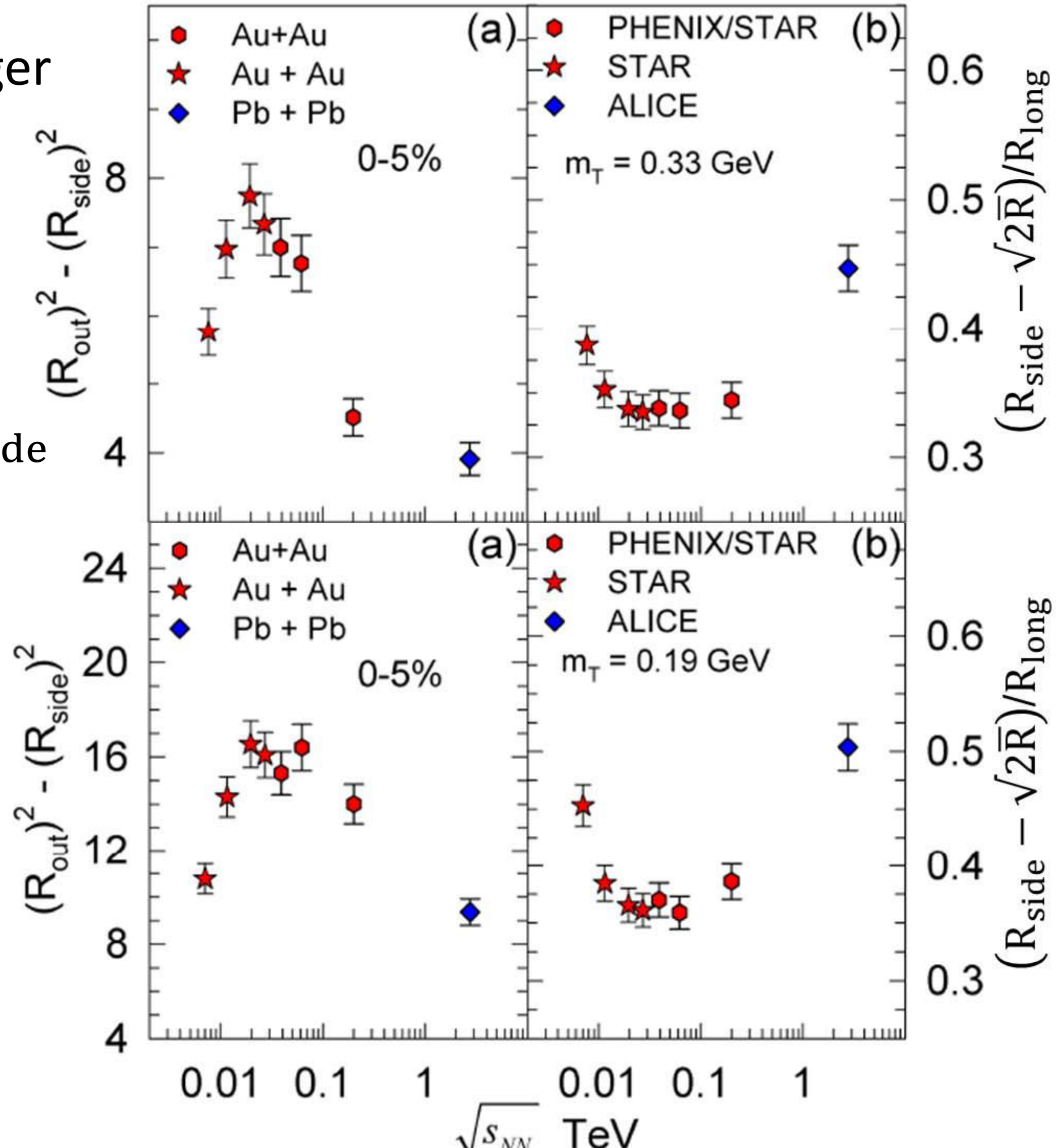
# Thank you for your attention!


14 countries, 73 institutions, January 2013

# Excitation function for other transverse masses

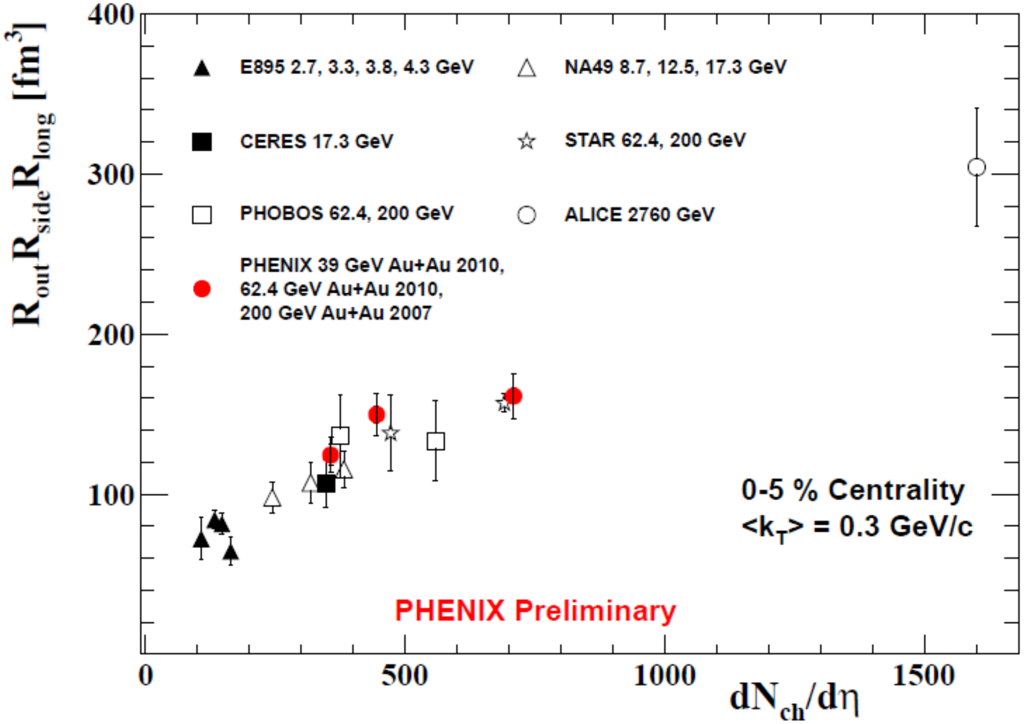
- Similar results for smaller and larger transverse momenta
- Maximum also seen at STAR
- Again, full hybrid+hydro models needed for interpretation
- Remember challanges in $R_{\text{out}}/R_{\text{side}}$

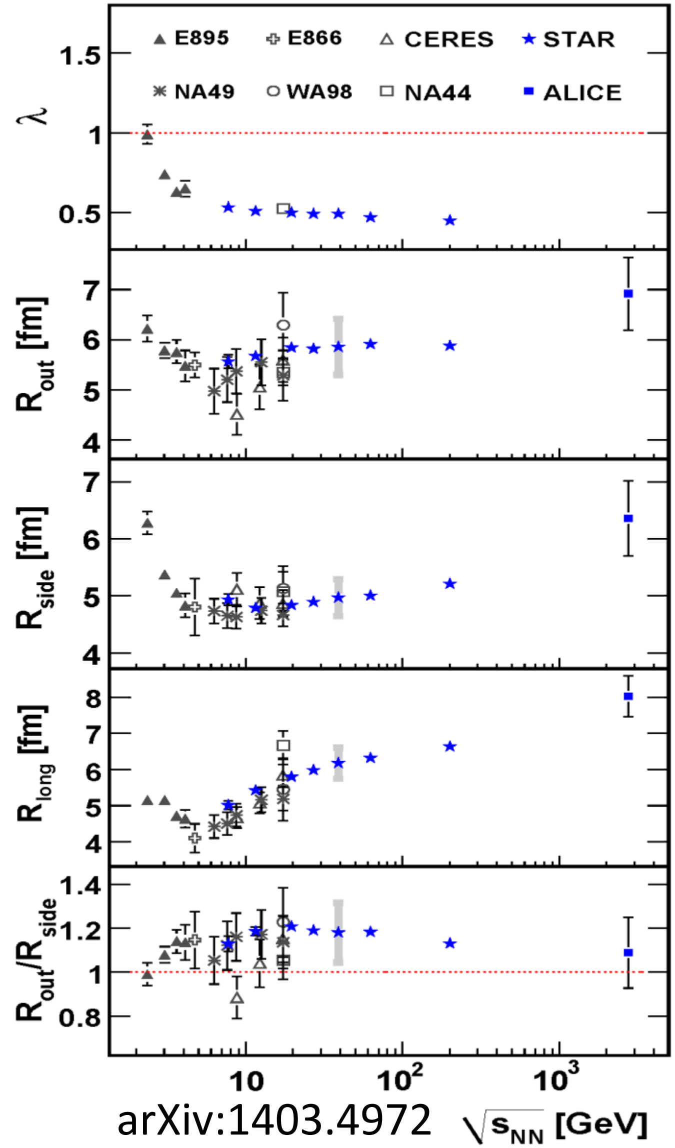


# Excitation function of HBT radii

- Systematics not apparent
- System Volume linearly increases with $dN_{\mathrm{ch}}/d\eta$

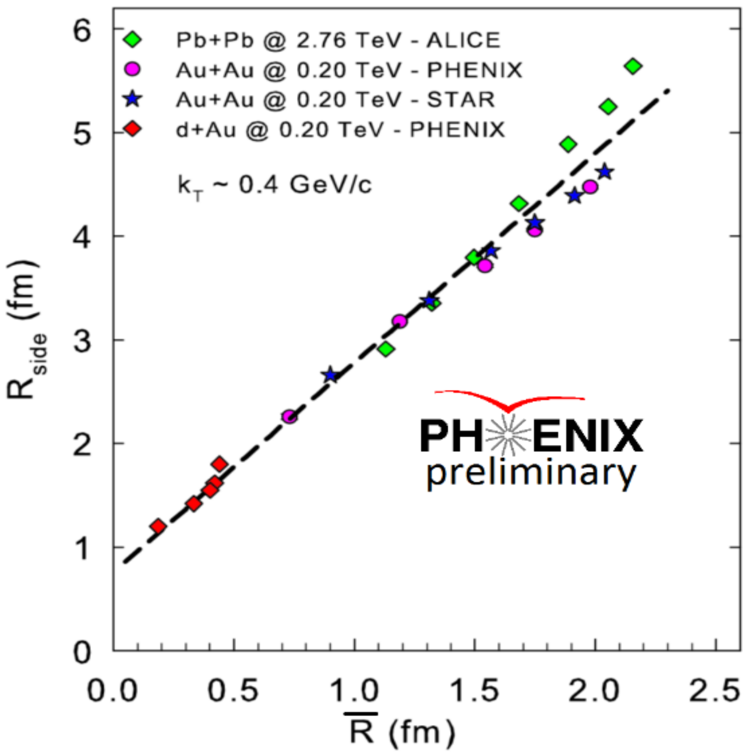


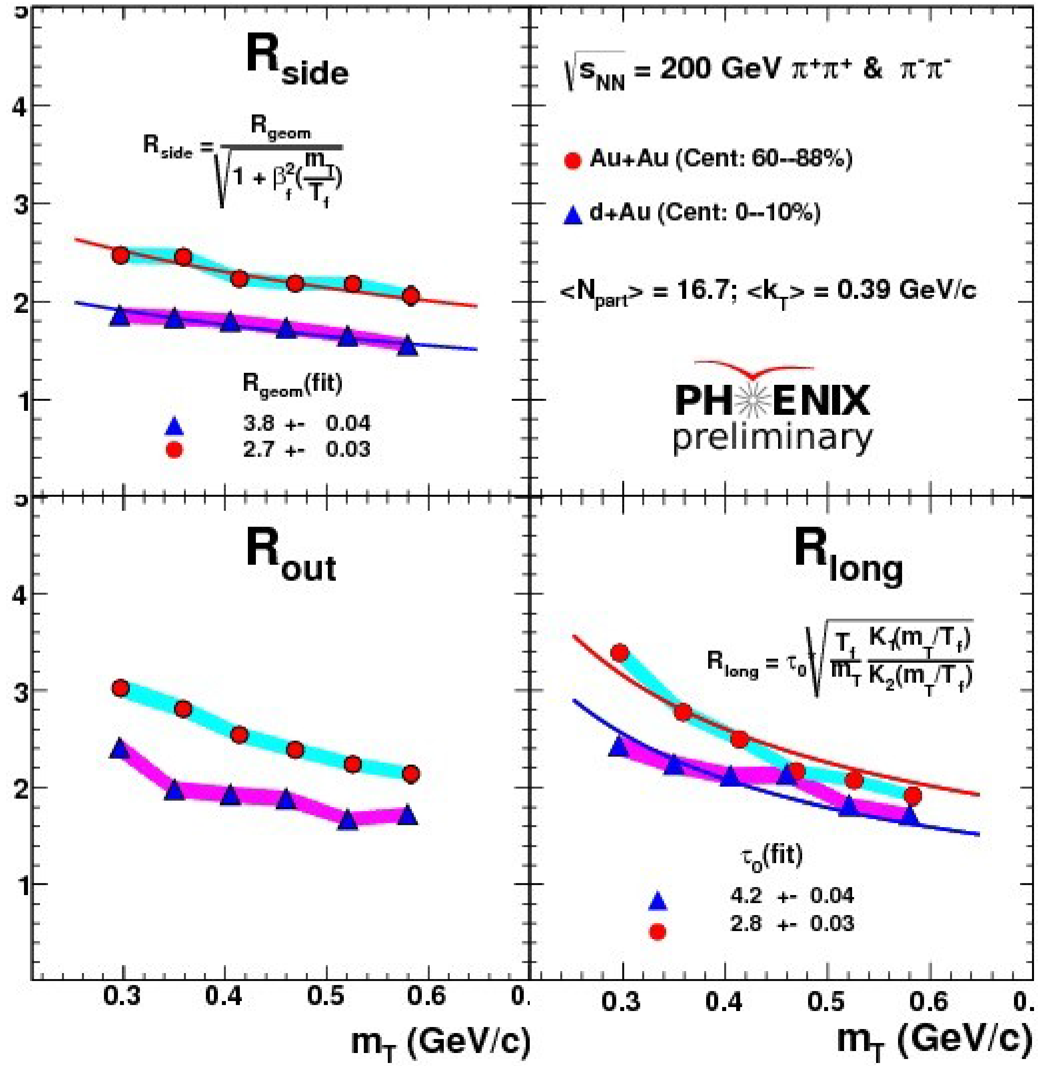




arXiv:1403.4972

# Scaling in d+Au

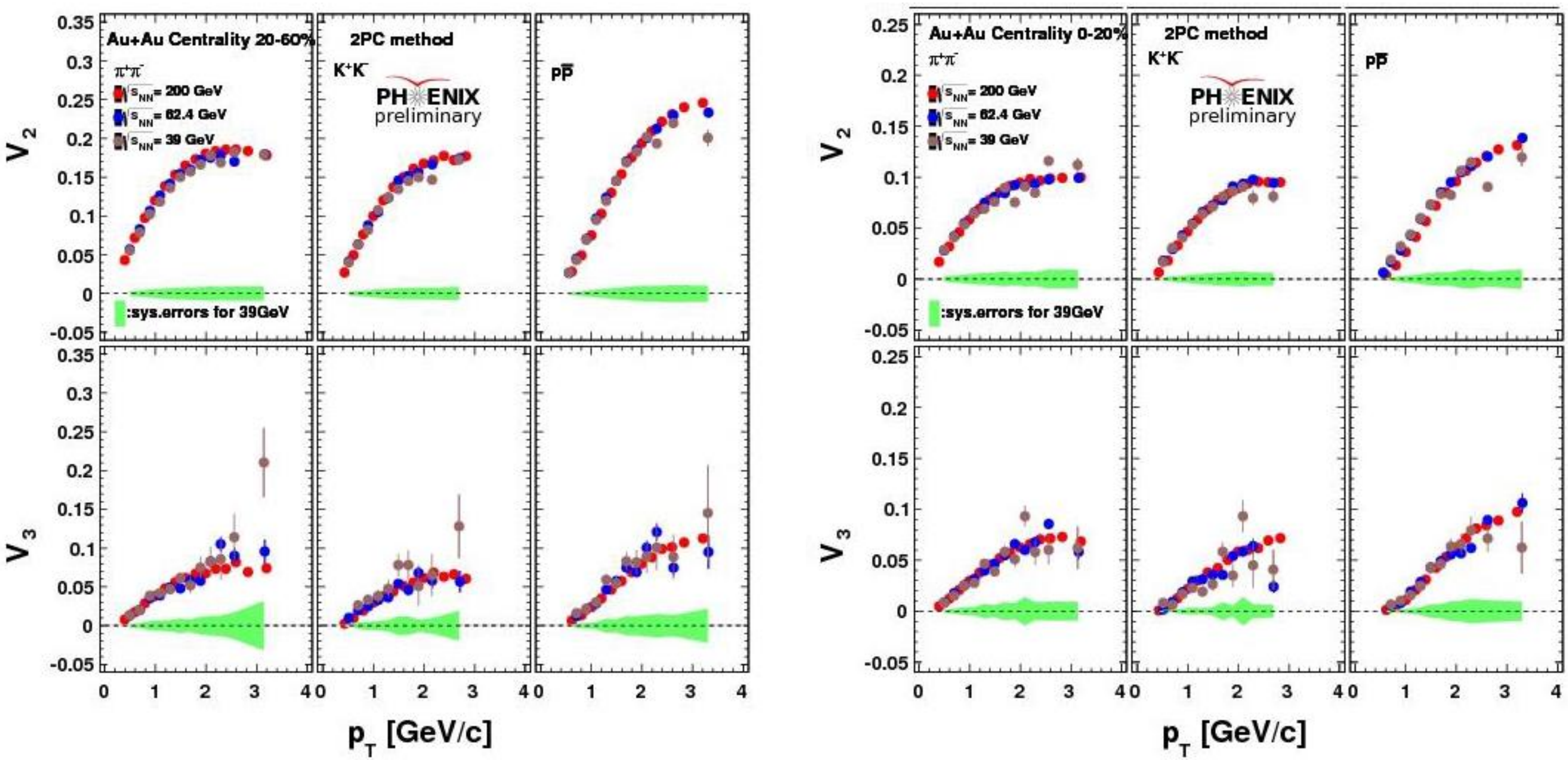
- Similar to Au+Au
- Geometric scaling fits into the picture



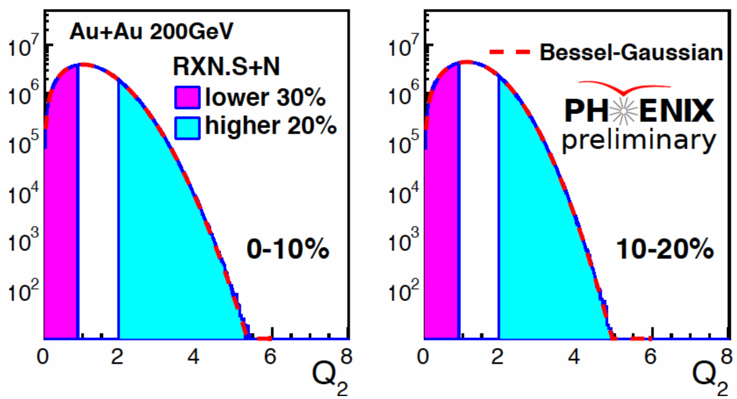
# Momentum space anisotropy

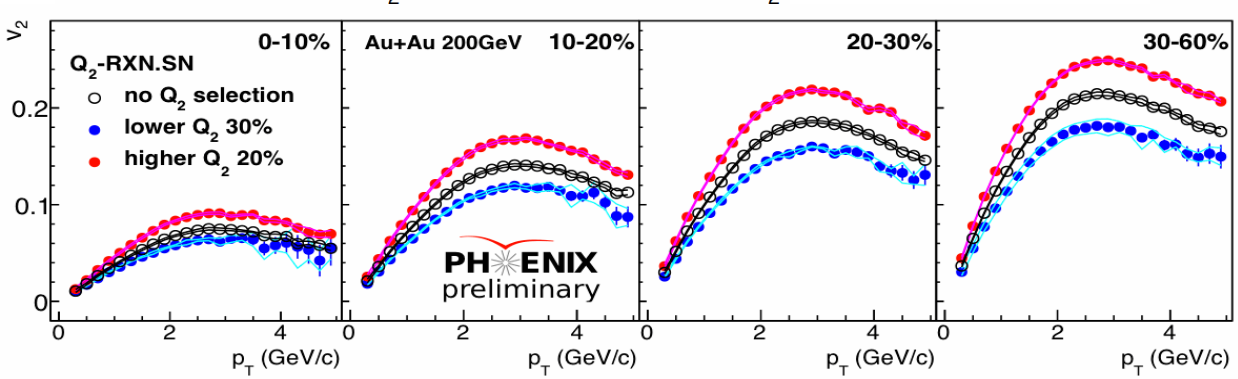
- Magnitude of elliptic and triangular anisotropy changes only a little

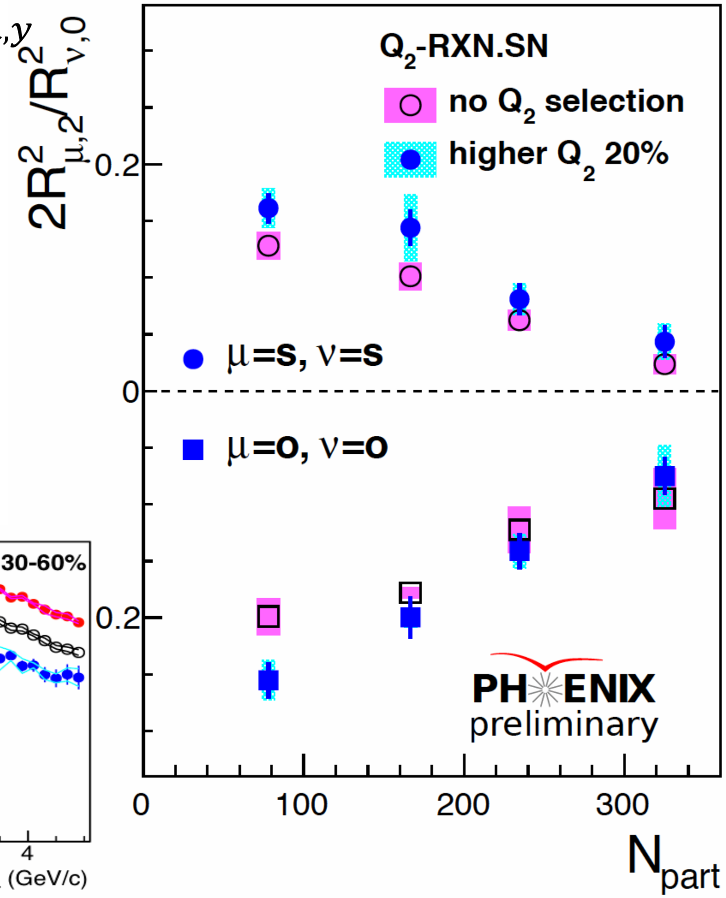


# Shape engineered HBT

- Same centrality, different geometry: shape fluctuations
- A shape vector defined as $Q_n = \frac{1}{\sqrt{N}} \sum_i^N (\cos n\phi_i , \sin n\phi_i)$
- Event plane: direction of $Q_n$, i.e. $\Psi_n = \arctan \frac{q_{n,x}}{q_{n,y}}$
- Magnitude of $Q_n$ also controls geometry!



# Neutral pion energy loss in Cu+Cu

- Significant suppression in central 62 & 200 GeV collisions
- Enhancement in 22 GeV collisions for ($p_t$ of 2.5 to 3.5 GeV/c)
- Details in Phys.Rev.Lett.101 (2008) 162301