Femtoscopic results in Au+Au & p+p from PHENIX at RHIC

M. Csanád
for the PHENIX Collaboration

Eötvös University, Budapest, Hungary

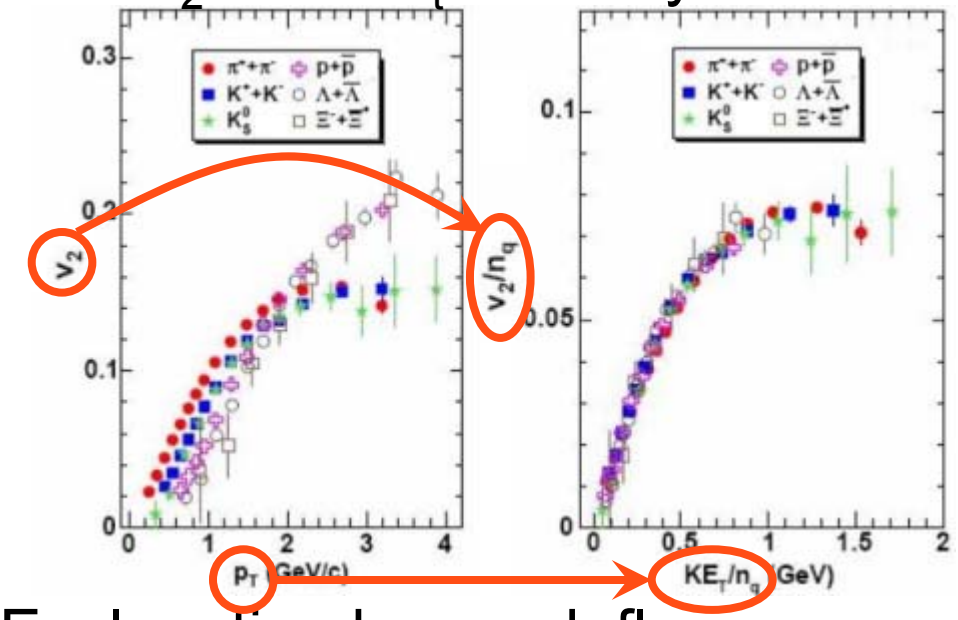
- Milestones of research at PHENIX
- Bose-Einstein correlations of charged kaons in 200 GeV Au+Au collisions
- Bose-Einstein correlations of charged pions in 200 GeV p+p collisions
- Squeezed particle-antiparticle correlations
- Photon HBT prospects

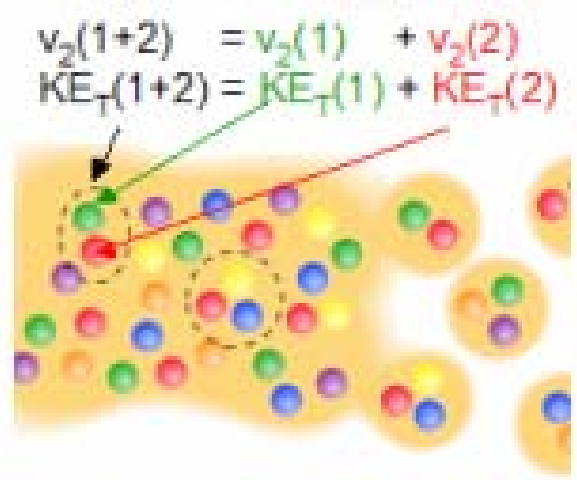
Milestones of RHIC results

- Jet suppression in A+A: new phenomenon
  - Phys. Rev. Lett. 88, 022301 (2002)
- No jet suppression in d+A: matter strongly interacting
  - Phys. Rev. Lett. 91, 072303 (2003)
- Summary of the results: matter is a liquid
  - Nucl. Phys. A 757, 184-283 (2005)
- Elliptic flow scaling: quark degrees of freedom
  - Phys. Rev. Lett. 98, 162301 (2007)
- Heavy quark flow: viscosity near lower limit
  - Phys. Rev. Lett. 98, 172301 (2007)
- Initial temperature: high above critical temperature
  - Phys. Rev. Lett. 104, 132301 (2010)

Quark degrees of freedom

- Elliptic flow (v_2) is a central observable
  - measure of momentum space asymmetry
  - sign of collective behavior
- Measured for several types of particles, $v_2(p_t)$
- Scaling variable suggested by hydro: KE_t
- Both v_2 and KE_t scale by the number of quarks

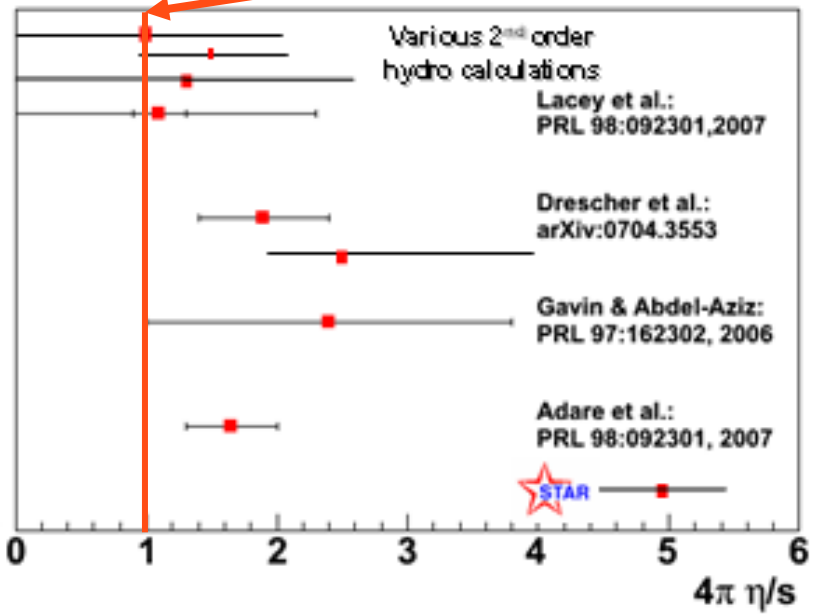


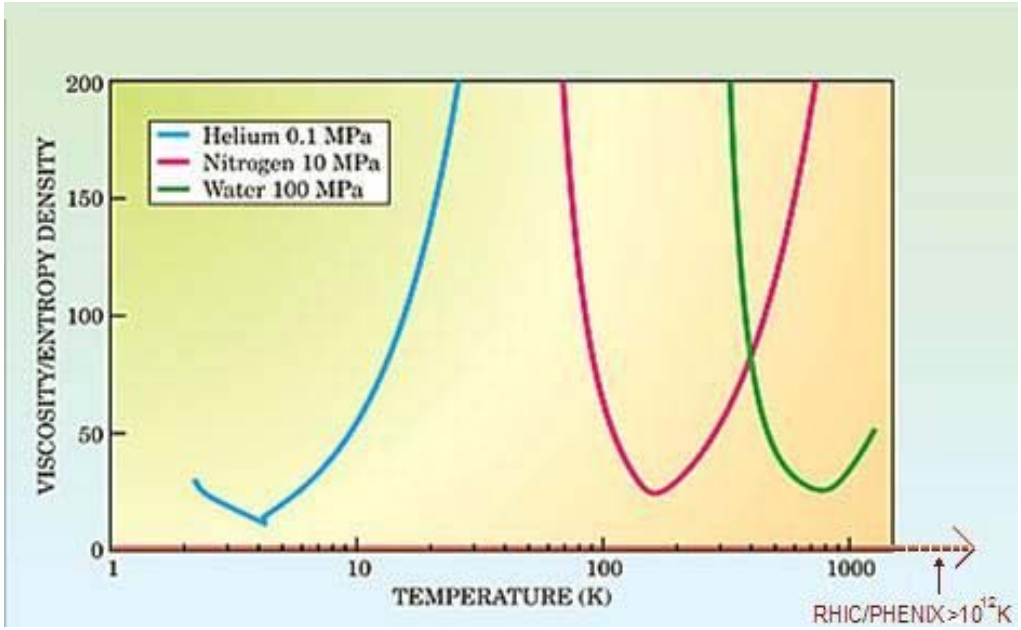


- Explanation by quark flow
- Indirect sign of quark degrees of freedom

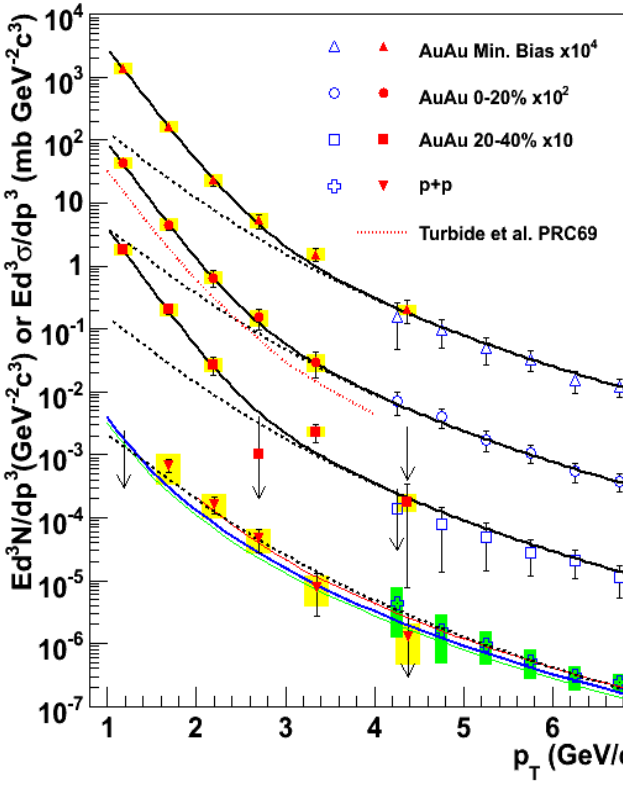
As perfect fluid as possible

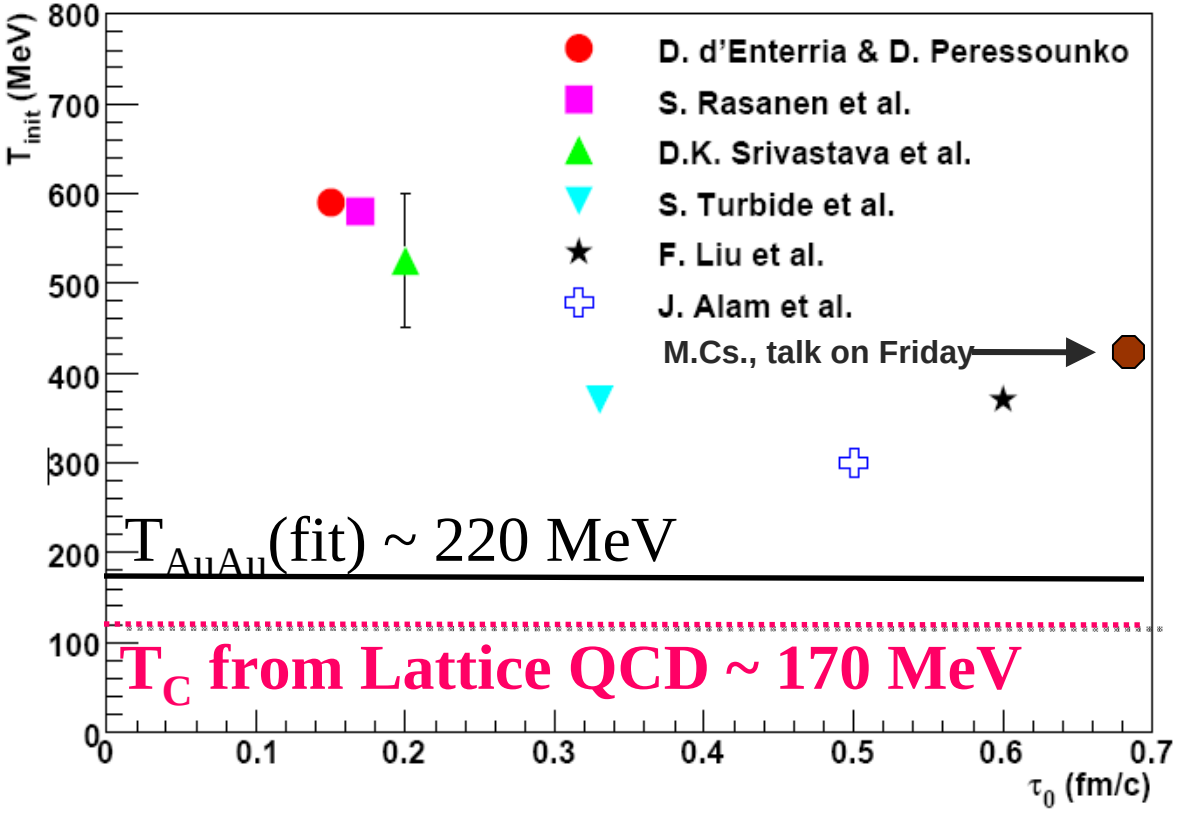
- Kinematic viscosity η/s lower than that of superfluid helium
- Conjectured limit: $1/4\pi$ (via AdS/CFT)





Initial temperature from direct γ





Directly from data: $T_{ini} > T_{AuAu} \sim 220$ MeV

Modell-calculations: $T_{ini} = 300 - 600$ MeV (with $\tau_0 = 0.15 - 0.6$ fm/c)

M. Cs. talk on Friday ($T_{ini} \approx 440$ MeV from photon spectra)

Lattice QCD: $T_c \sim 170$ MeV

A. Adare et al., PHENIX Collaboration
Phys. Rev. C81, 034911 (2010)
Phys. Rev. Lett. 104, 132301 (2010)

HBT nomenclature

$$C_2(\mathbf{q}) = A(\mathbf{q})/B(\mathbf{q}) \qquad \mathbf{q} = \mathbf{p_1} - \mathbf{p_2}$$

$$= 1 + \int d\mathbf{r} K(\mathbf{q},\mathbf{r}) S(\mathbf{r})$$

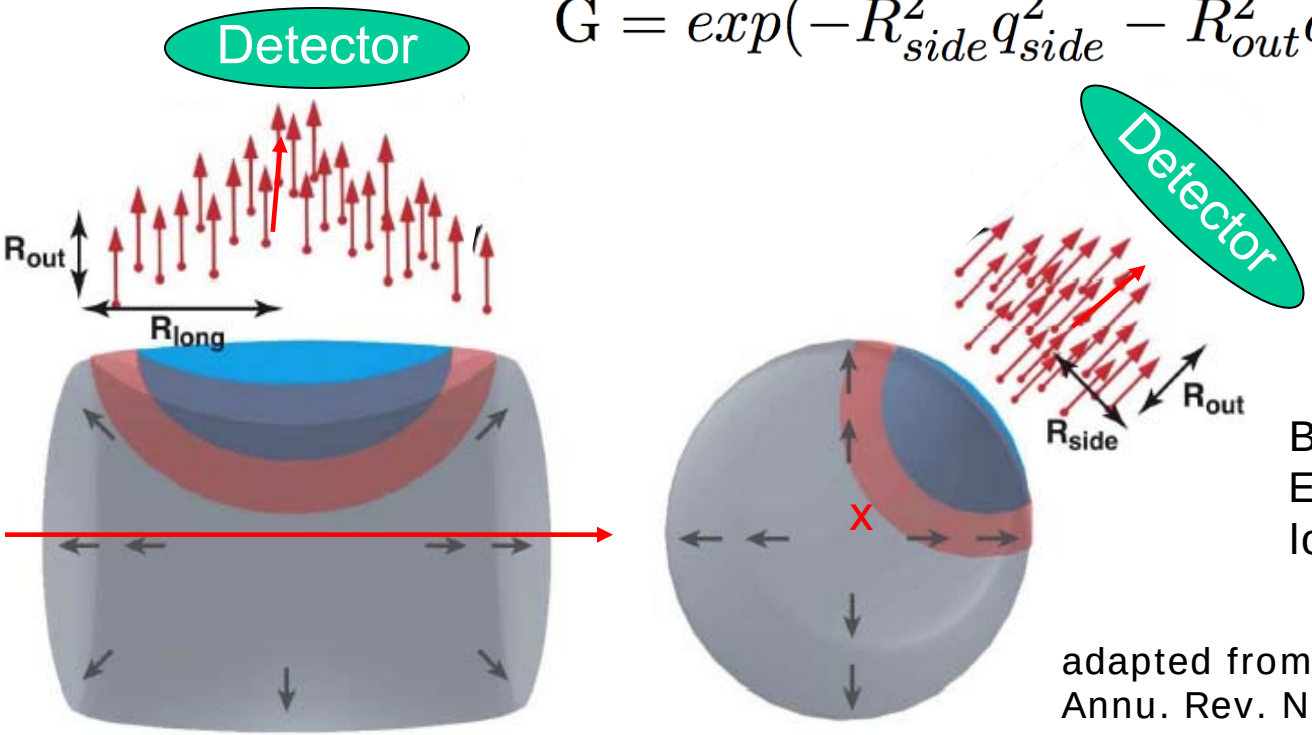
$$= \lambda(1 + \mathrm{G})\mathrm{F_C} + 1 - \lambda$$

The source S can be directly recovered with imaging

or

Make assumptions about the source

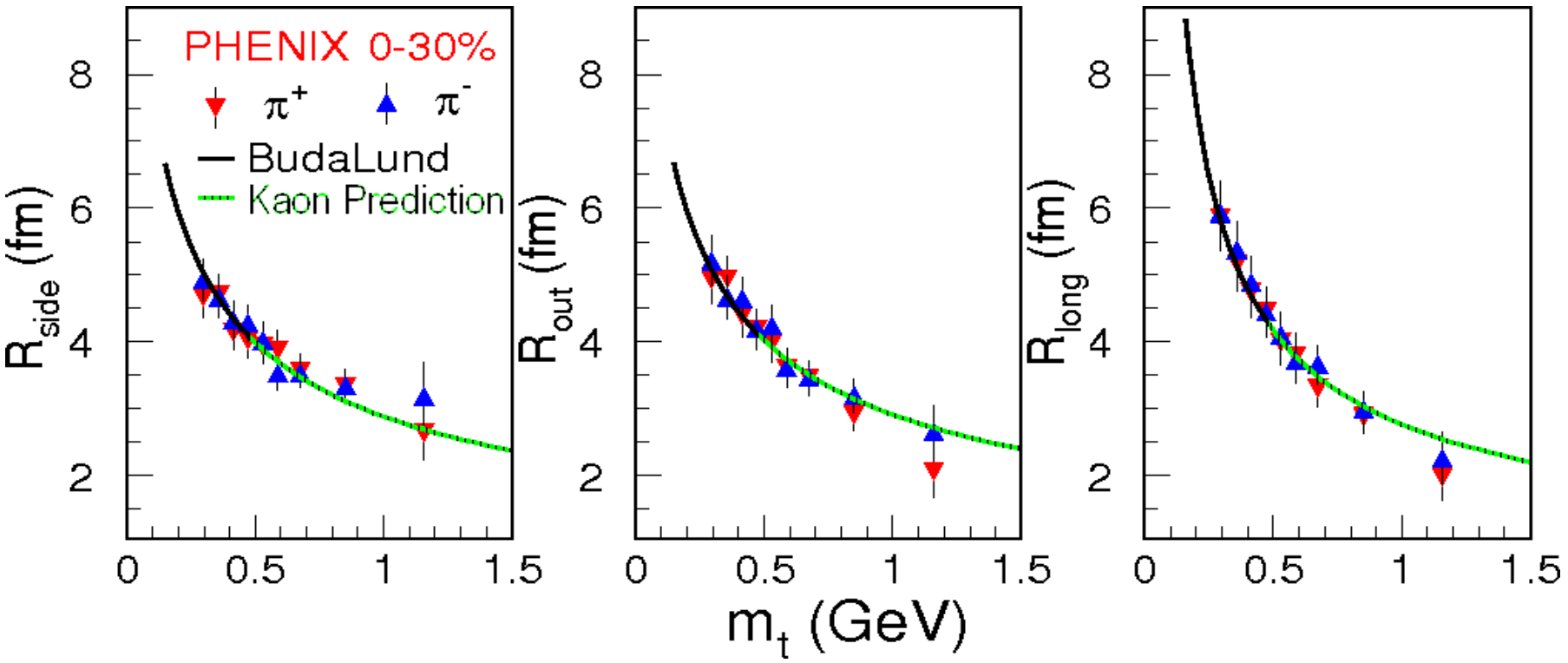
$$\mathrm{G} = exp(-R^2_{side}q^2_{side} - R^2_{out}q^2_{out} - R^2_{long}q^2_{long})$$



Bose-Einstein Enhancement at low relative momentum q

adapted from
Annu. Rev. Nucl. Part. Sci. 2005. 55:357-402

Kaon HBT in Au+Au at RHIC



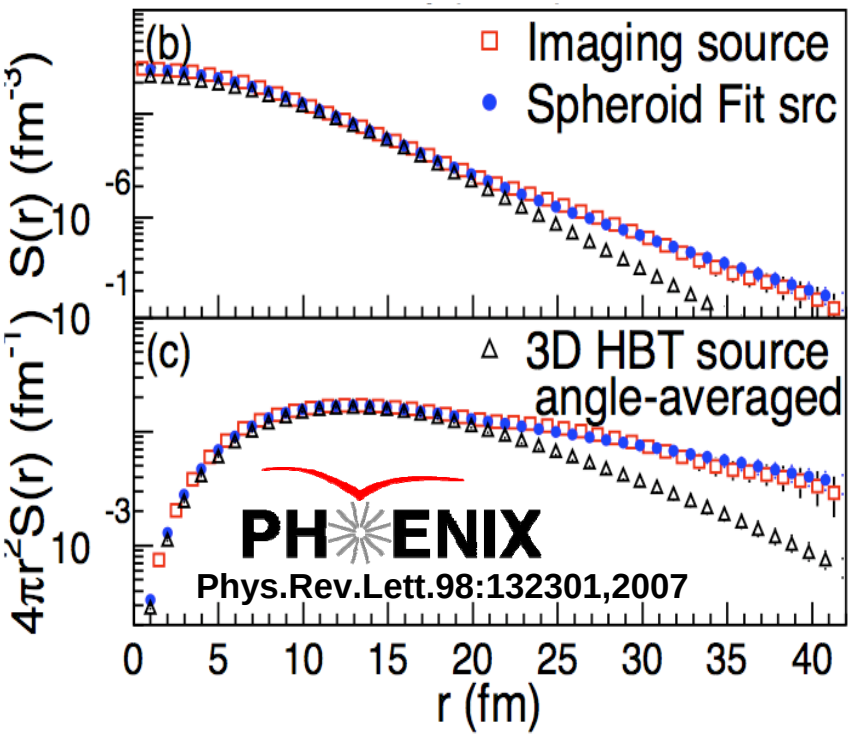
From M. Csanád, T. Csörgő, Acta Phys.Polon.Supp.1:521-524,2008

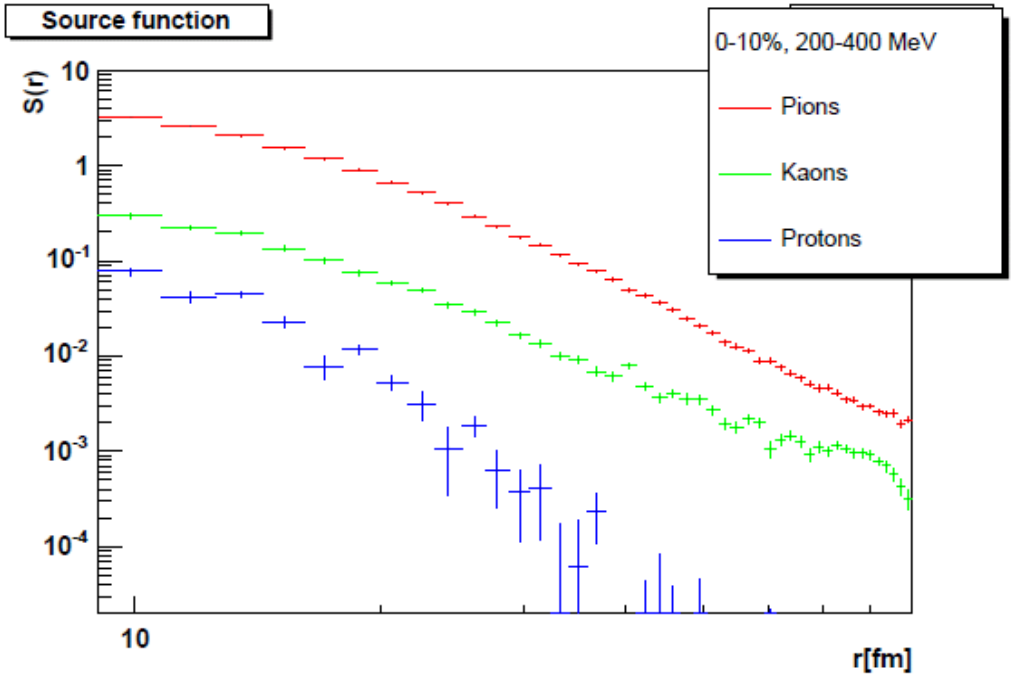
Kaon interferometry: M. Gyulassy, Sandra S. Padula, PRC 41, R21 (1990)

- Kaons less effected by decays of long lived resonances, than pions.
- A clearer distinction between QGP formation and resonance dynamics

But kaons follow m_T scaling at CERN SPS: NA44 Collab, PRL 87:112301, (2001)

Kaon imaging in Au+Au





M. Csanád et al., Braz.J.Phys.37:1002-1013,2007

FIG. 20: Source distribution of pion, kaon and proton pairs with 0.2 GeV/c < p_t < 0.4 GeV/c and 0-10% centrality.

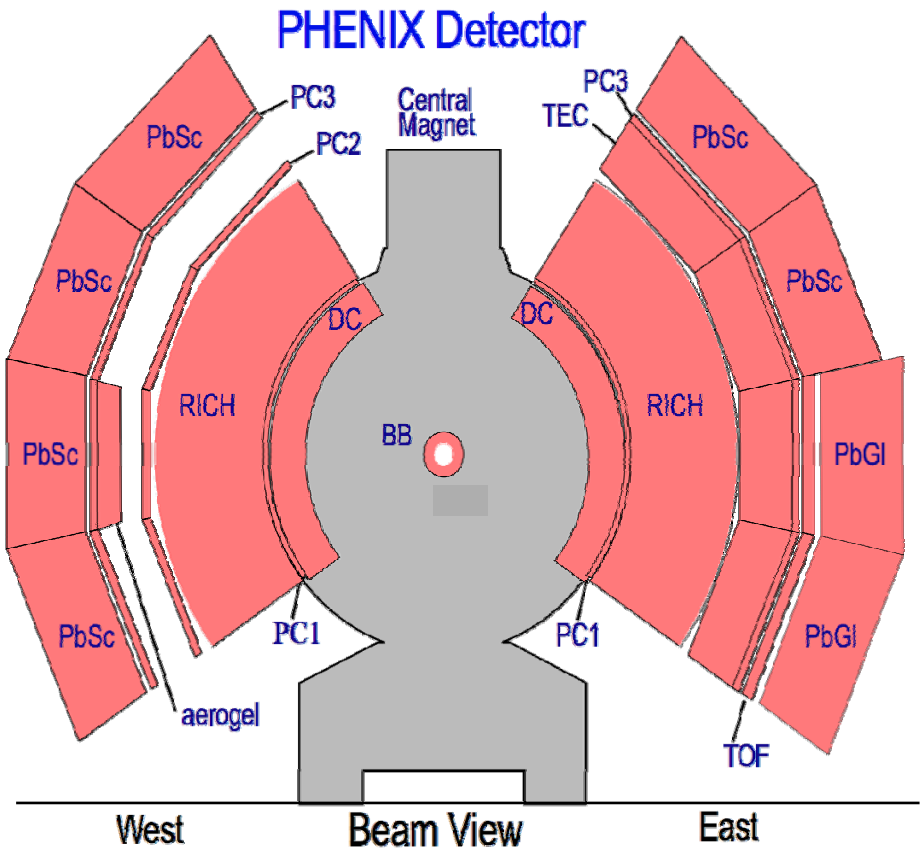
First imaging data: extended tail of pion emission in S(r)

Long lived resonances? Pions have longer tail, than kaons.

Hadronic rescattering? Pions larger cross sections, than kaons.

Anomalous diffusion in HRC simulation: kaon's tail is longer, than pions!(?)

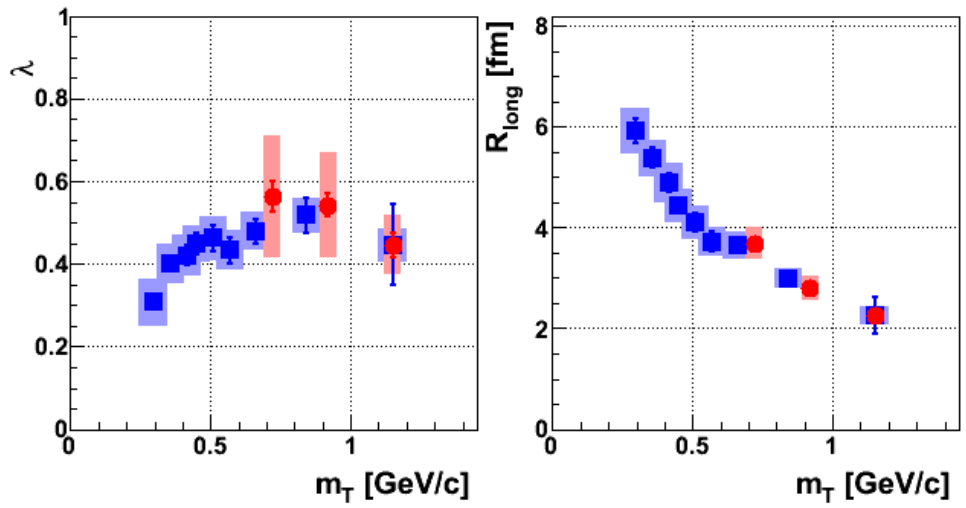
Analysis details



- 600M events, Au+Au 200 GeV minimum bias dataset of 2004 (~30M like sign kaon pairs)
- Charged kaons tracked by DC, PC1, PC3, identified by time of flight from PbSc
- Kinematic cuts:
  $|\eta| < 0.35$, $\Delta\pi = \pi/2(\pi/4)$
  in West(East) arm
- Matching cuts reduce backgrounds
- Pair selection cuts to remove merging and splitting
- Monte Carlo based corrections to extend into regions with reduced pair efficiency
- Phys.Rev.Lett.103,142301

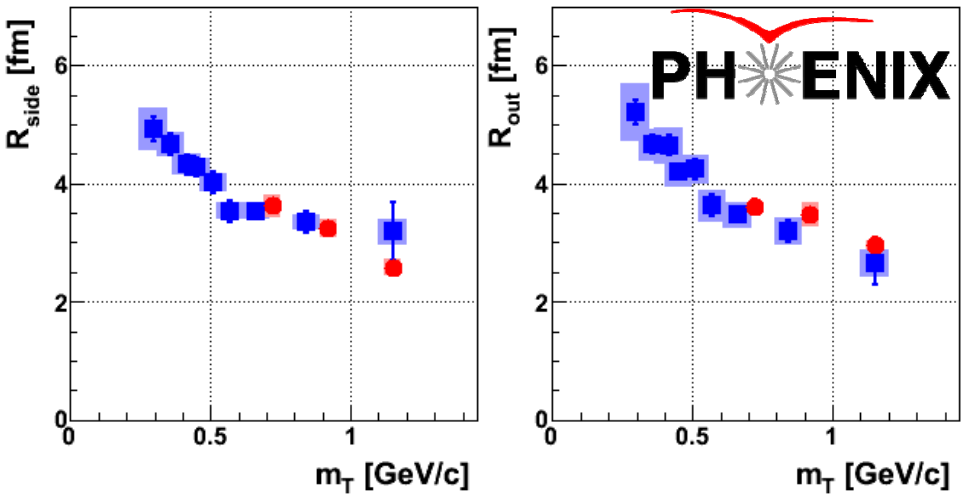
Transverse mass scaling

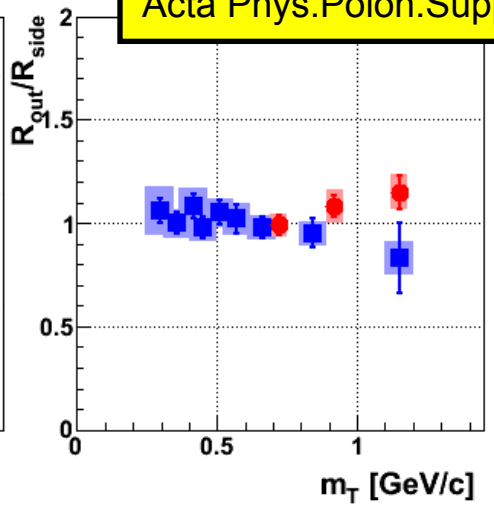
PHENIX charged kaon HBT data:
Phys. Rev. Lett. 103, 142301 (2009)



Au+Au $\sqrt{s_{NN}}$=200 GeV
0-30% Central
$K^+K^+ + K^-K^-$
$\pi^-\pi^-$ PRL 92 152302 (2004)

Particle type independent m_T scaling
Predicted by T. Csörgő and B.Lörstad
Phys.Rev.C54:1390-1403 (1996)
Calculated by M. Csanád and T. Csörgő
Acta Phys.Polon.Supp.1:521-524,2008



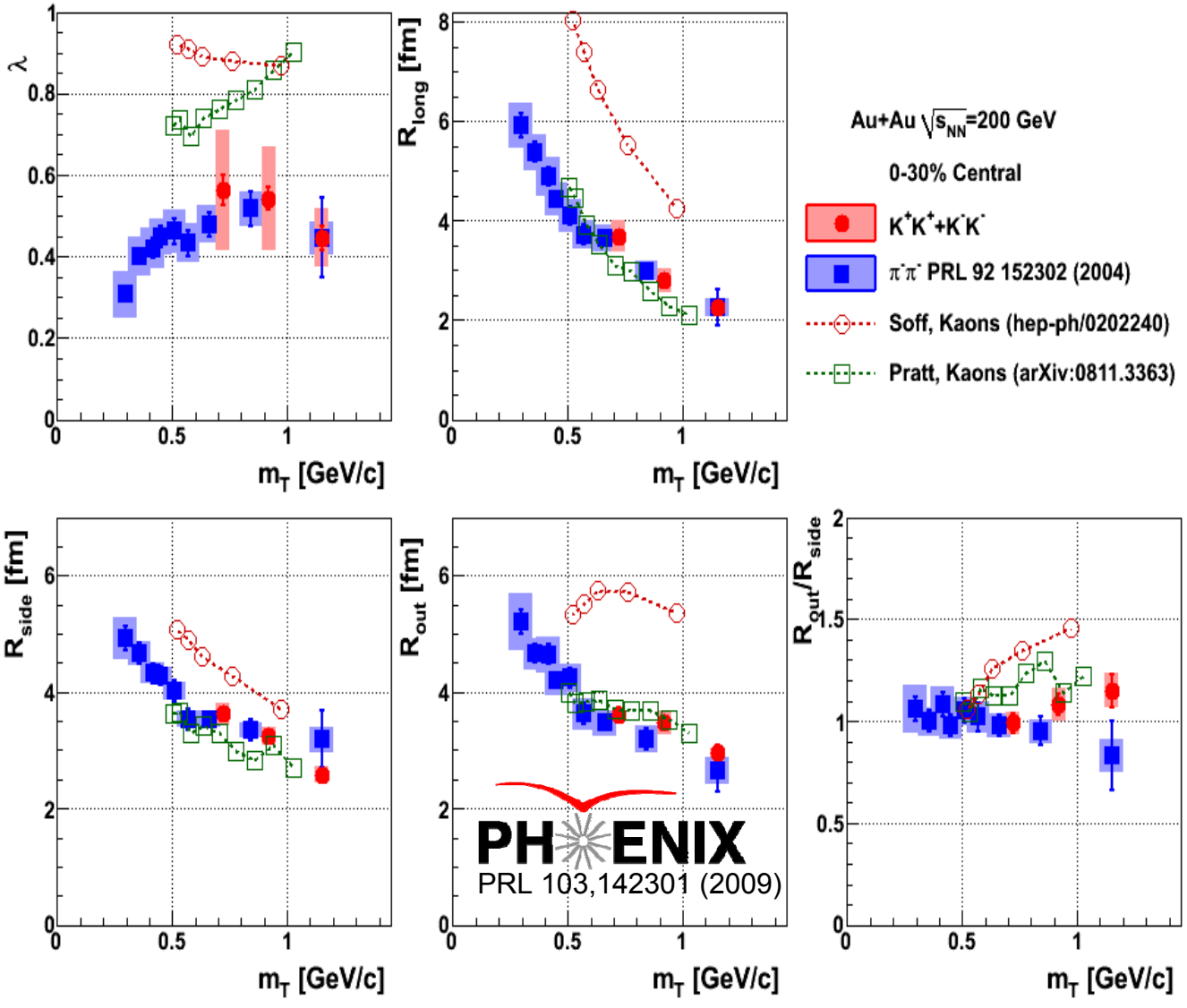


$$m_T = \sqrt{k_T^2 + m^2}$$

$$k_T = (p_{1T} + p_{2T})/2$$

In 200 GeV Au+Au, m_T dependent HBT radii for charged kaons and pions follow the same universal m_T scaling curve

More theory comparisons



S. Soff, hep-ph/0202240:

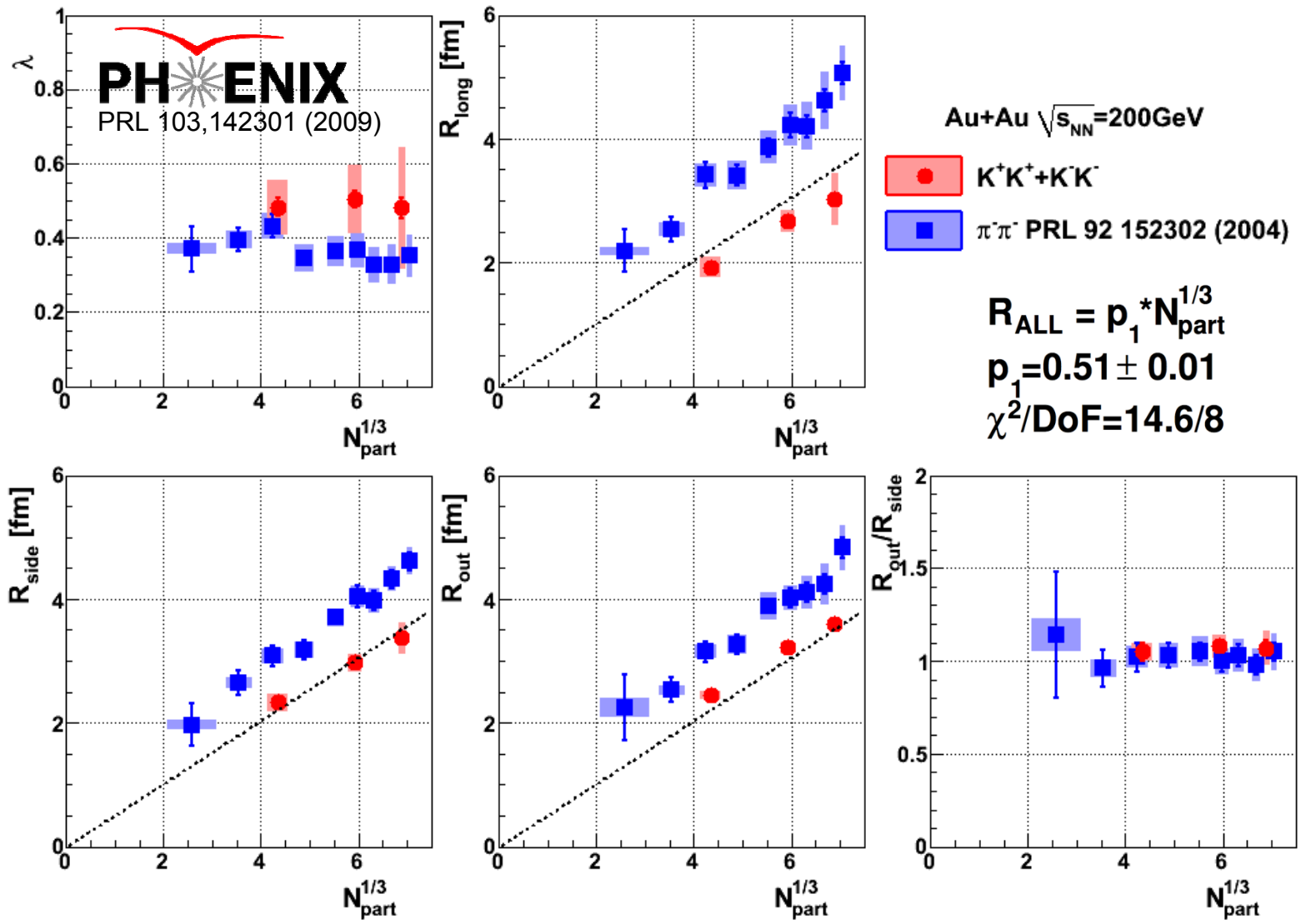
2 d +1 hydro+UrQMD
Example of "HBT puzzle"

S. Pratt,
nucl- th/0811.3363
~ m_t scaling

1 d +1 hydro+cascade
with.pre-equilibrium flow
& lattice inspired
equation of state.

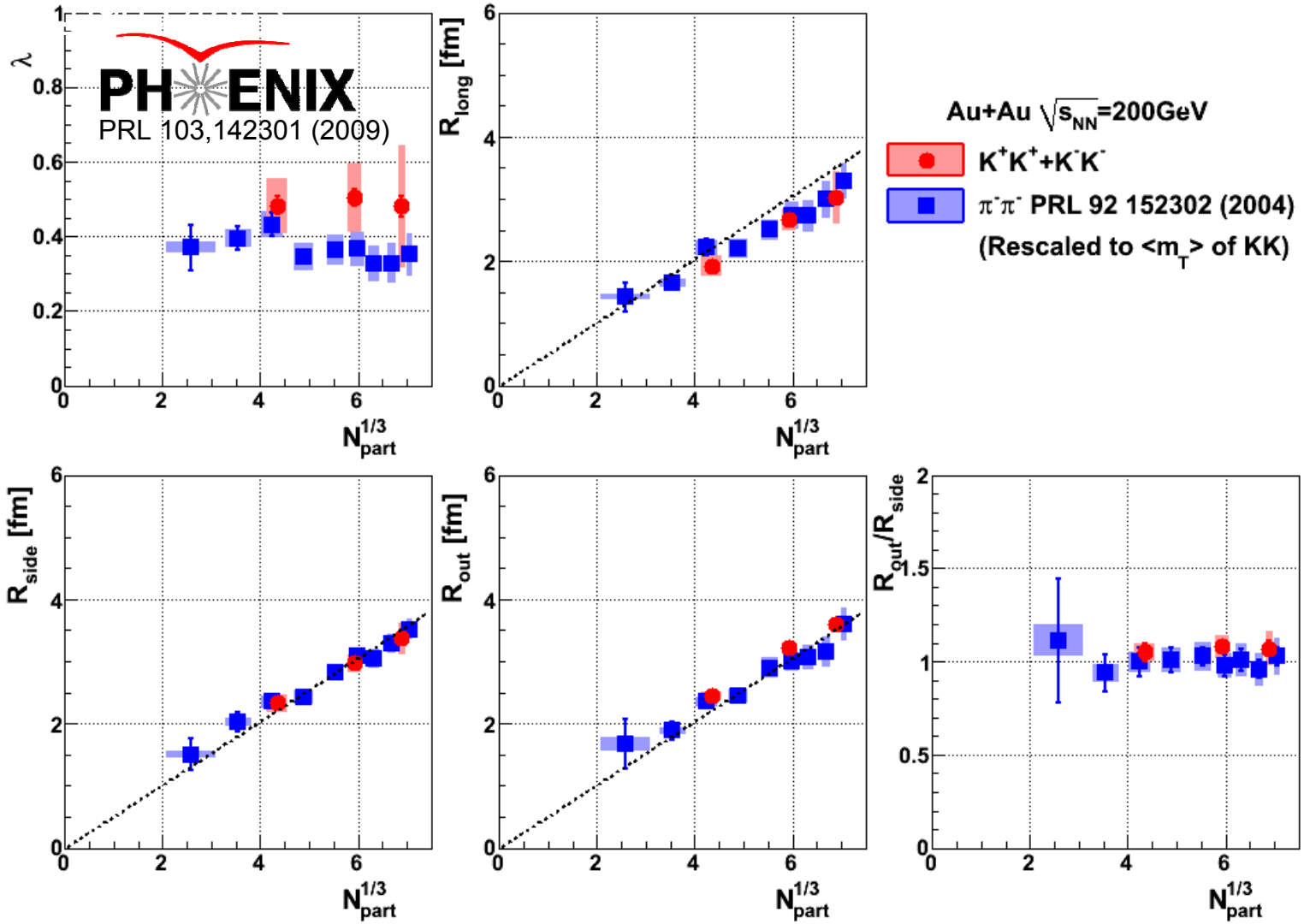
not tuned to kaons!

Centrality Dependence



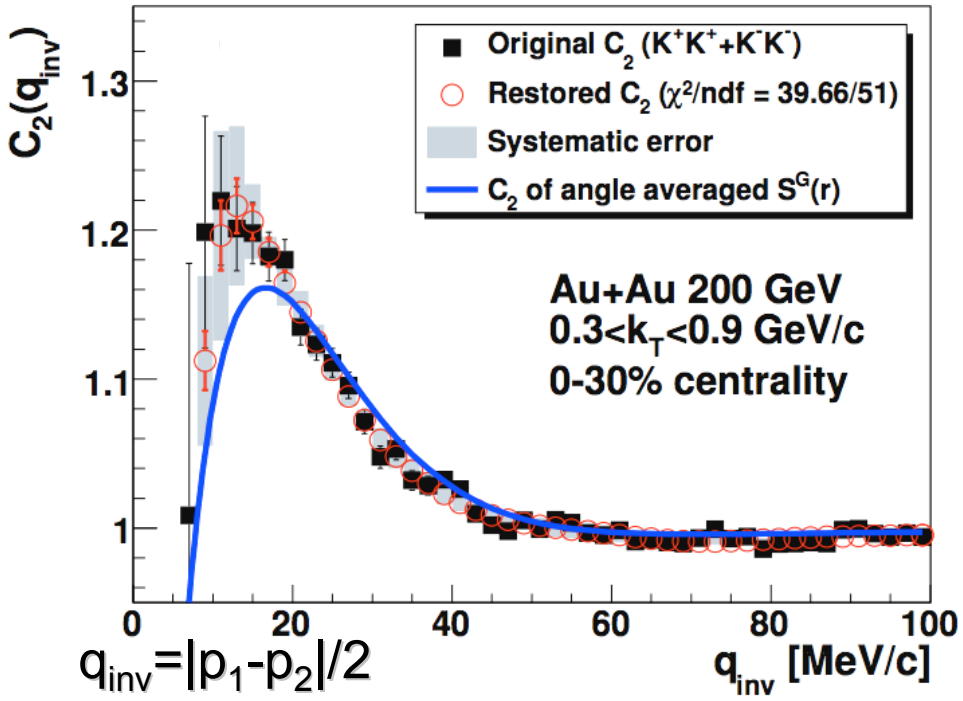
Similar slope as π-s, agrees well with linear extrapolation, R=0 for N_{part}=0

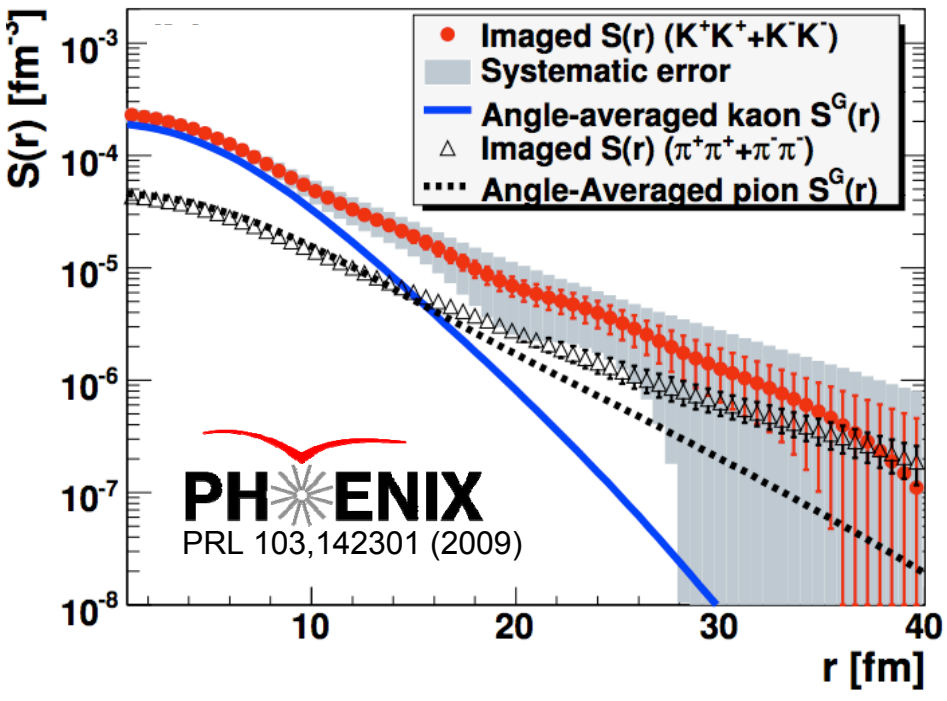
If rescaled by average m_t



Consistent with previous pion measurement

Kaon Source Imaging





Significant tail for r>10 fm for kaon source
Pion source is not only from long lived resonance (ω) decays
Larger kaon tail consistent with hadronic resonance cascade models
M. Csanád et al, hep-ph/0702032, T. Csörgő et al, nucl-th/051206.0298

Summary, $K^{\pm}K^{\pm}$ in Au+Au

Kaon m_T and m_T scaled centrality dependence consistent with pions.

Kaon HBT radii scale as $R_{HBT} = p_1 N_{part}^{1/3}$

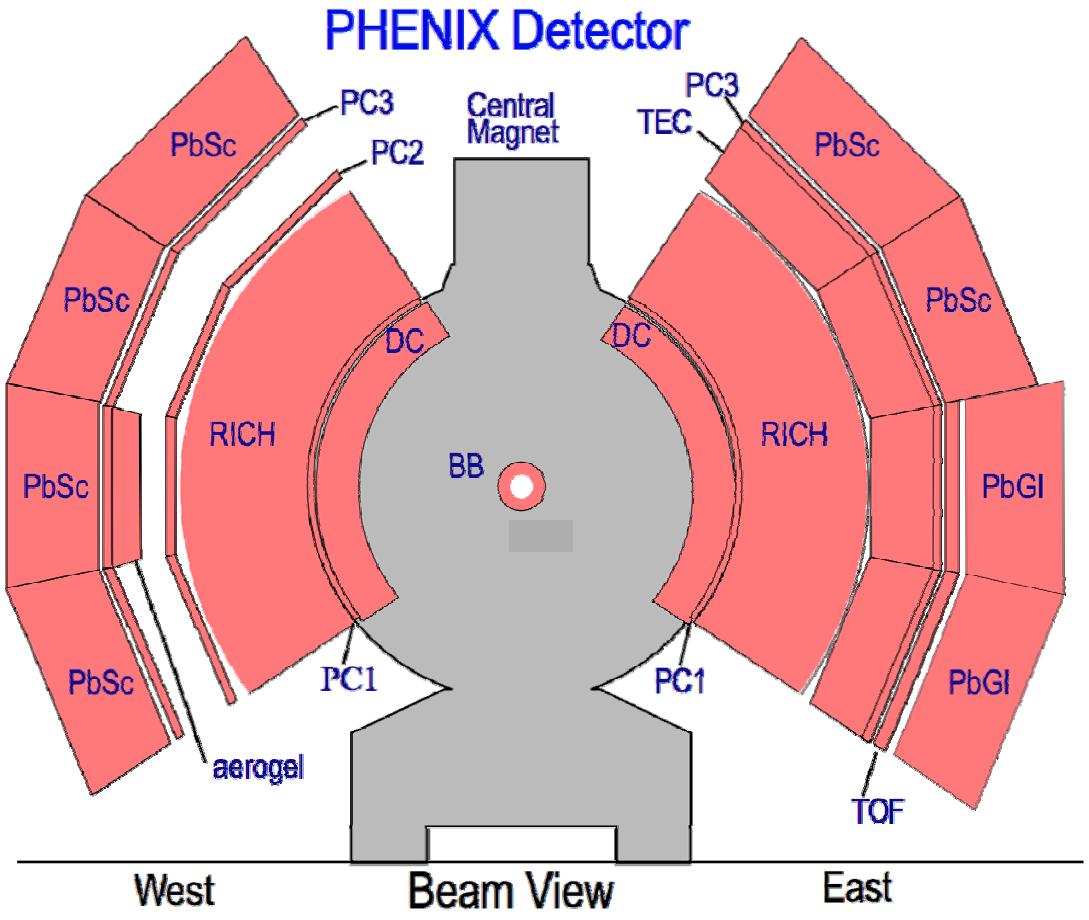
i.e. $R_{HBT}=0$ at $N_{part}=0$

Bulk production in agreement with predictions on m_T scaling, and with a promising 1+1D+hydro+cascade with initial flow

Significant tail in imaged K source for r>10fm

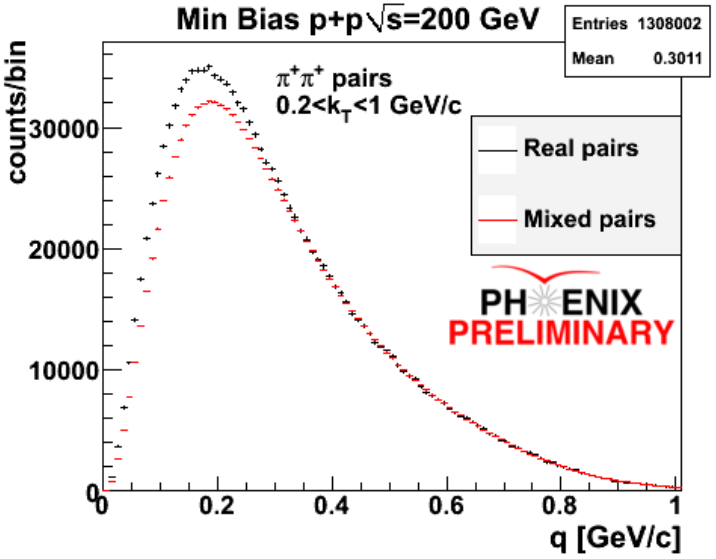
- Tail stronger for kaons than for pions !
- Tail in pions not just from resonances!
- Further checks needed for other particles (protons)!

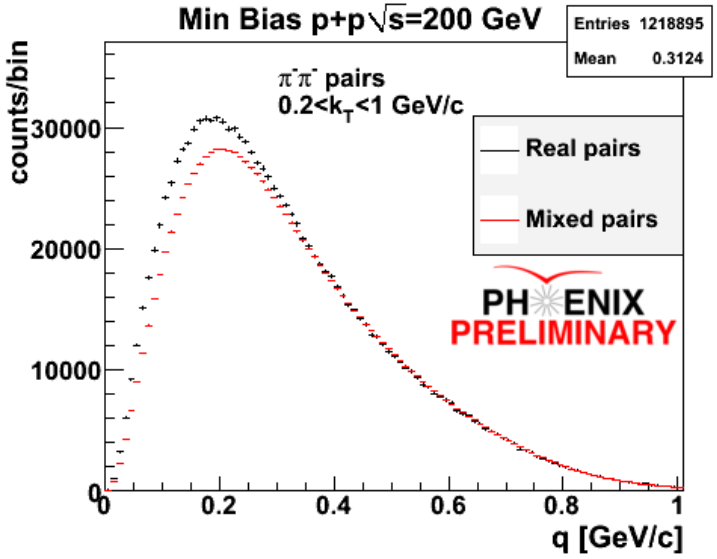
Pion HBT in p+p

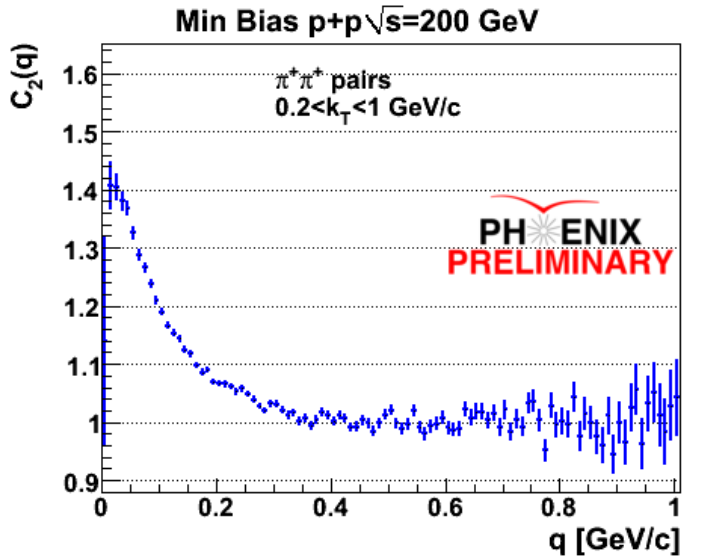


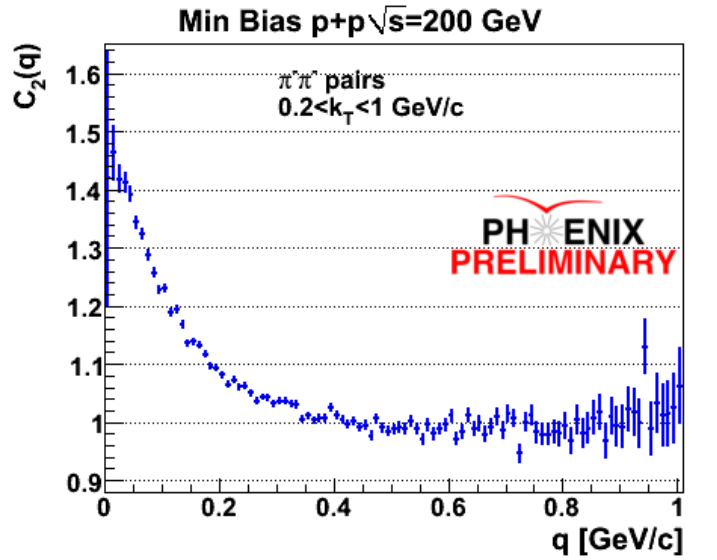
- Baseline measurement
- Run5 p+p minimum biased (~2.5M like sign pion pairs)
- Charged pions identified by time of flight from West PbSc
- Matching cuts reduce backgrounds
- Pair selection cuts to remove merging and splitting
- No Monte Carlo based corrections so more selective pair cuts

1-D Correlations









Slices of 3-D Correlation

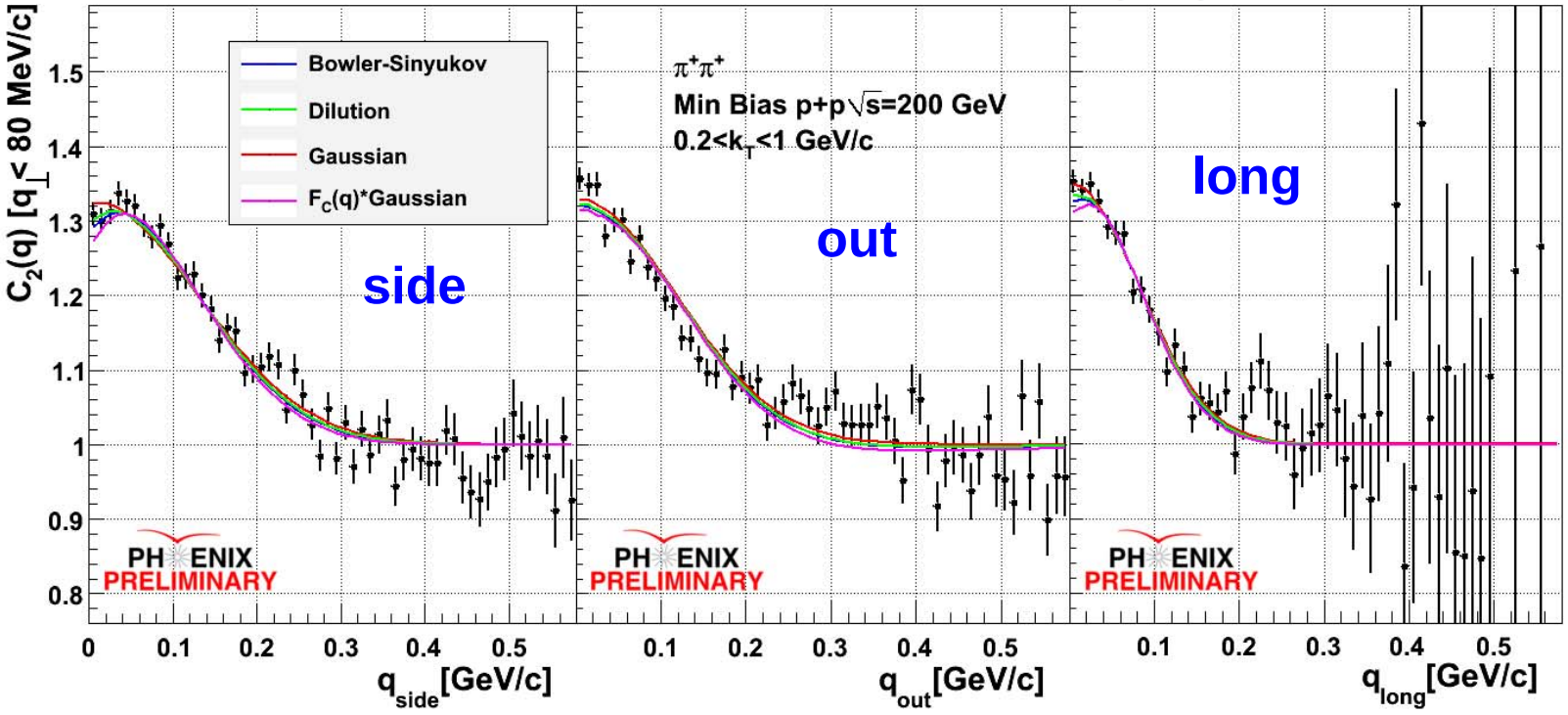
Bowler-Sinyukov: $C_2 = [\lambda(1+G)]F_c(q_{inv}) + [1+\lambda]$

Dilution: $C_2 = [\lambda(1+\lambda G)]F_c(q_{inv}) + [1+\lambda]$

Coulomb corrected Gaussian: $C_2 = (1+\lambda G)F_c(q_{inv})$

Gaussian: $C_2 = 1+\lambda G$

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



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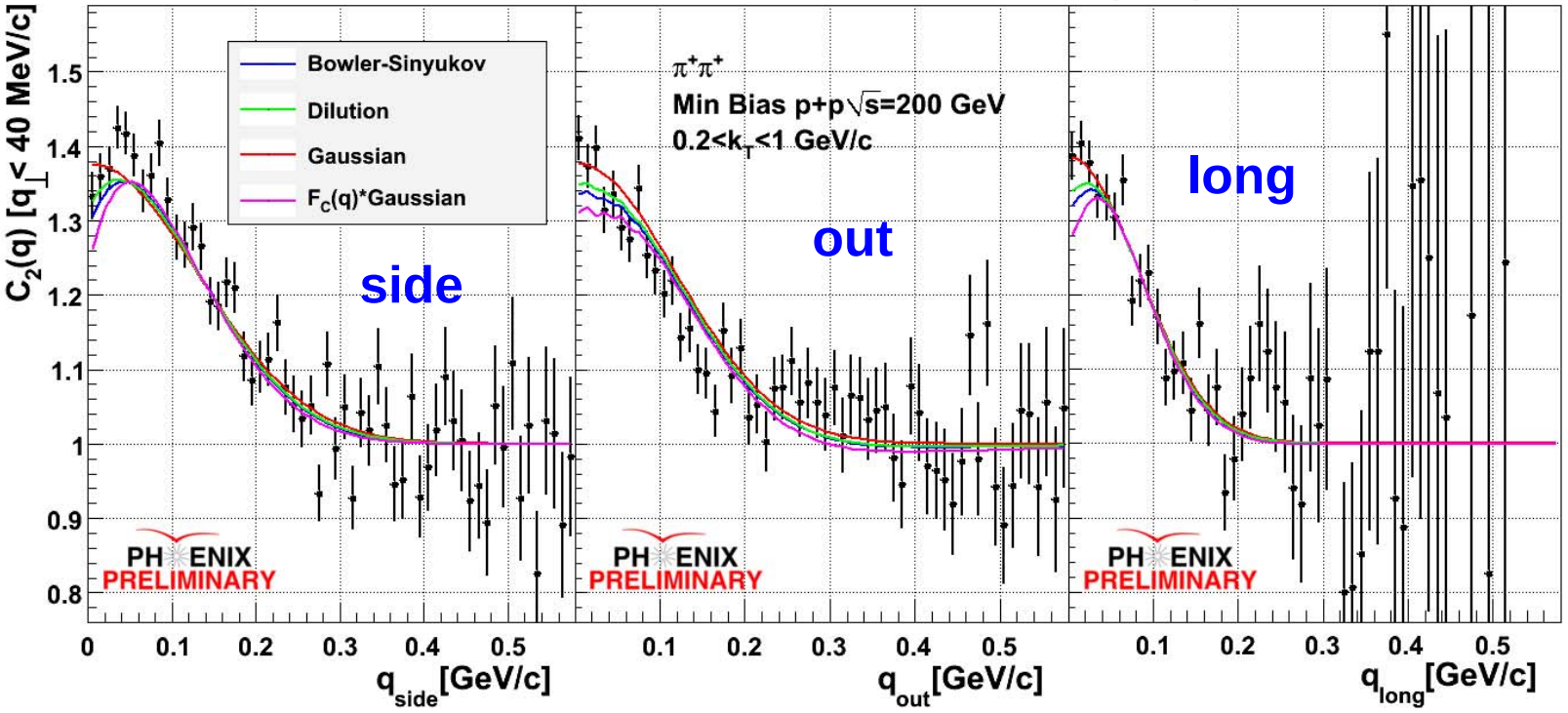
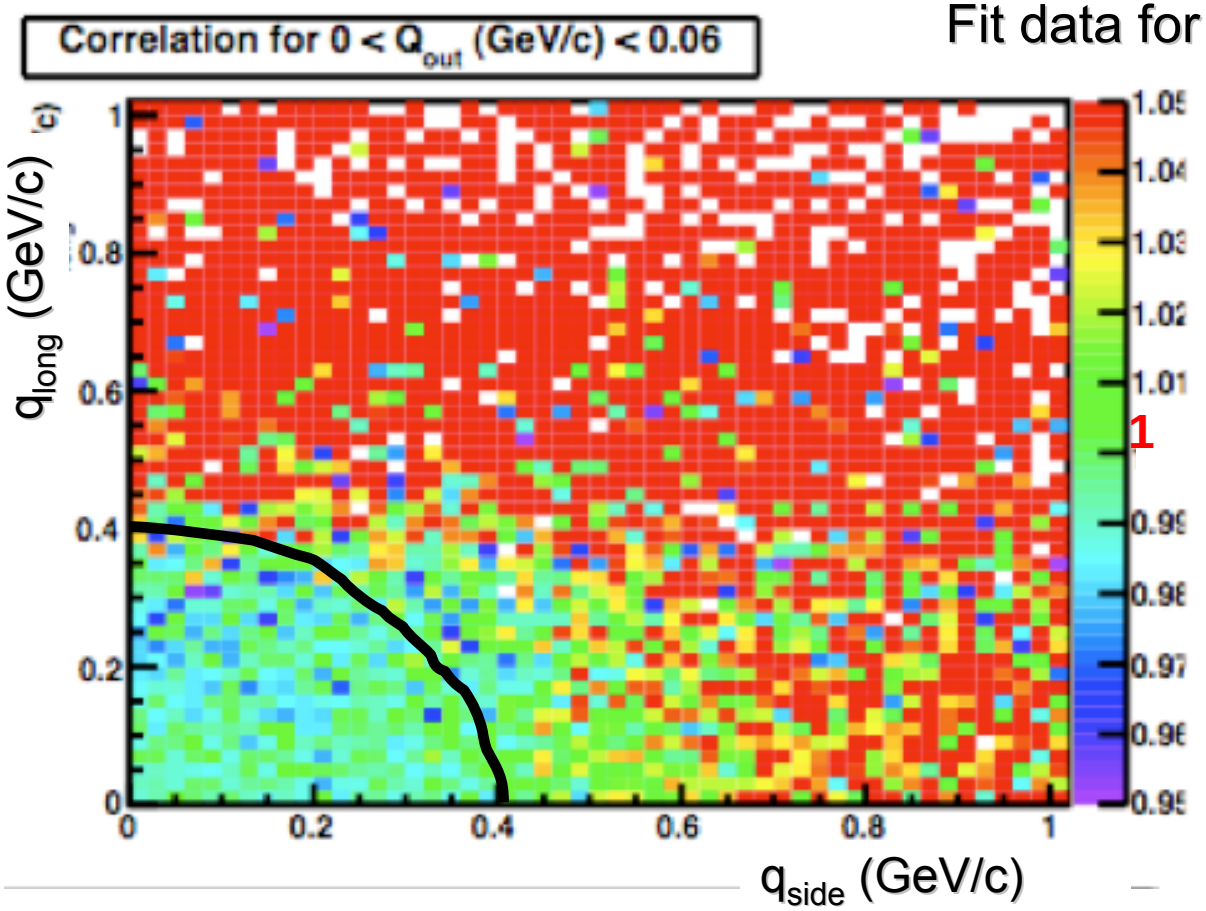


A few words on fitting

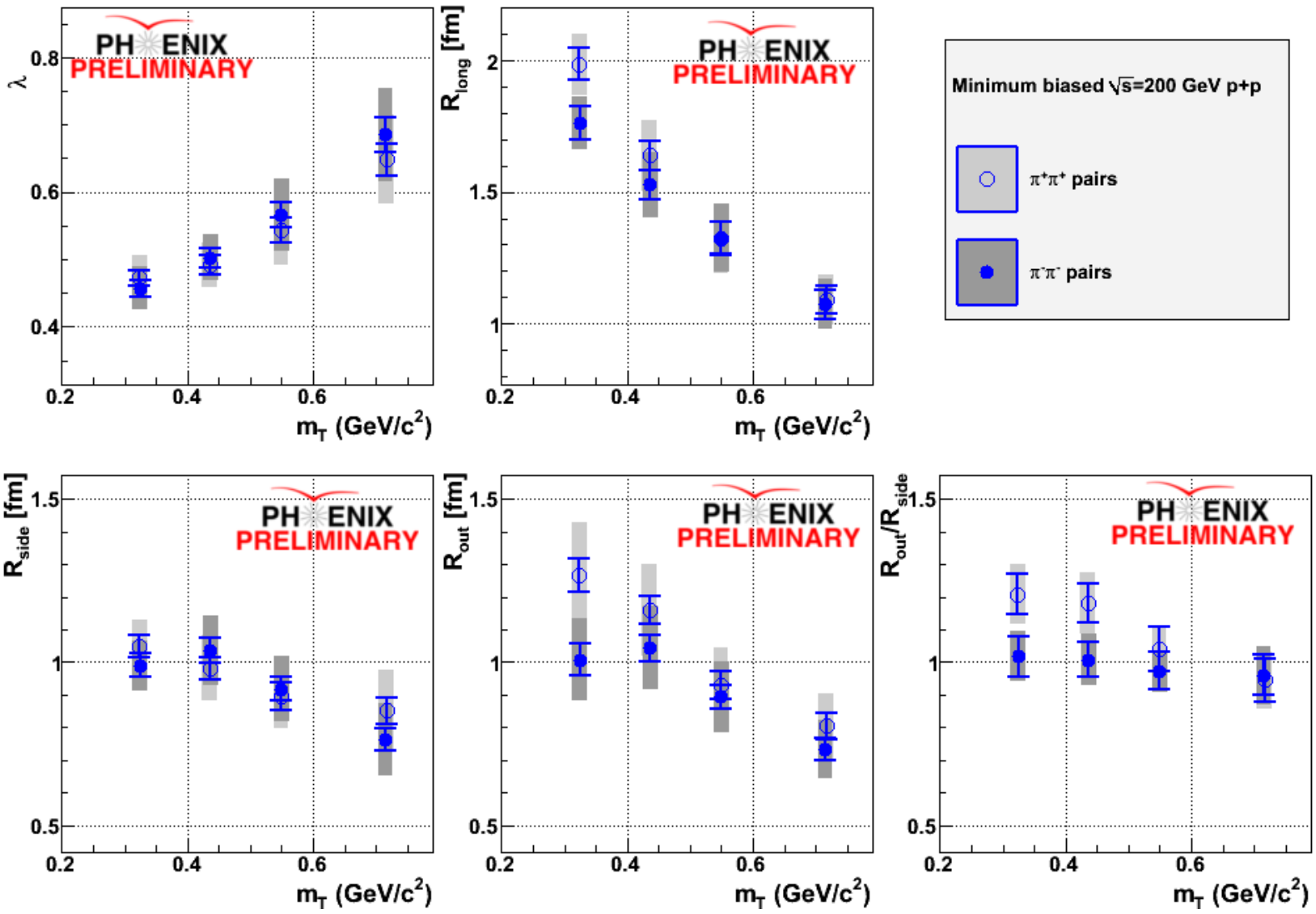
PYTHIA used as sanity check to limit fit range
and help minimize impact of non-HBT correlations

Fit data for $q_o^2+q_l^2+q_s^2<(0.4\text{GeV/c})^2$

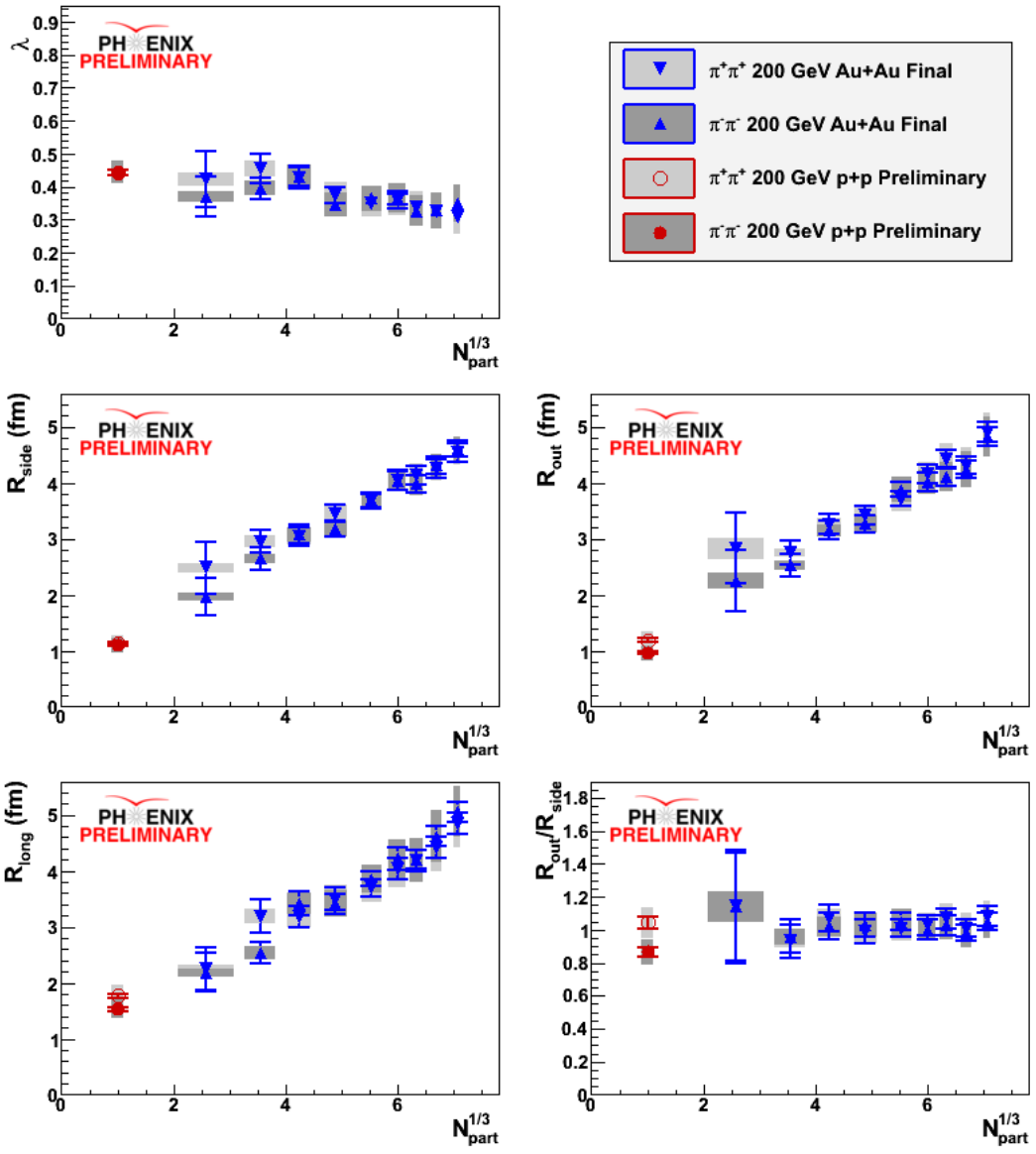


one example of
many slices

Transverse Mass Dependence



p+p and Au+Au comparison



Summary: $\pi\pi$ in p+p

Pion correlations in min. bias collisions for PHENIX west arm acceptance do not show significant energy momentum contamination.

Measured radii: consistent with centrality extrapolation from Au+Au

Plenty to look at

(multiplicity dependence, jets…)

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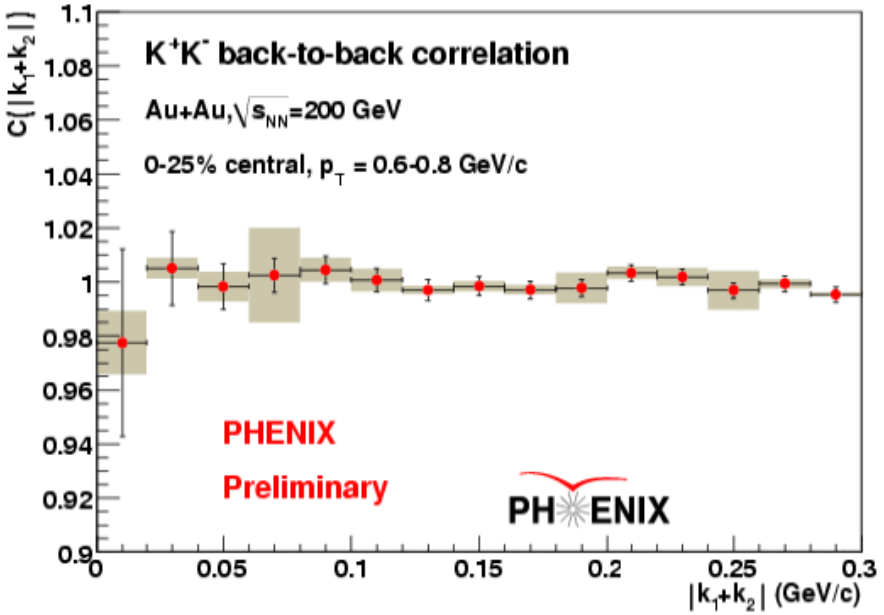
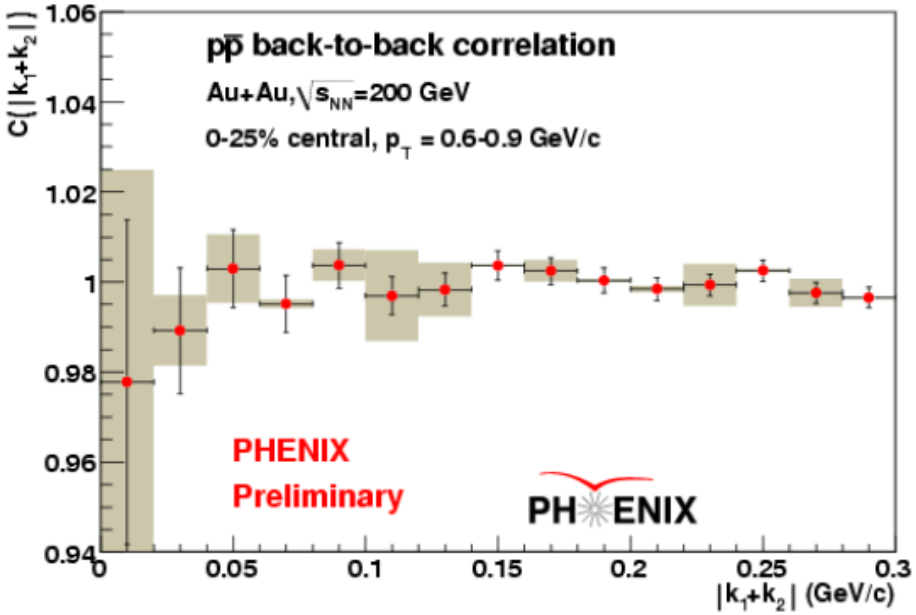
Squeezed particle-antiparticle correlations

- Back-to-back correlation: $q_{back}=|k_1+k_2|$, particle-antiparticle
- Expectation:
  - **In-medium mass modification → back-to-back correlations**
    - **M. Asakawa, T. Csörgő, M. Gyulassy, Phys. Rev. Lett. 83, 40134016, (1999)**
    - **S. S. Padula, T. Csörgő, Braz. J. Phys. 37, 949962, (2007)**
  - **Question: $C_2(q_{back})\neq 1$??**
  - **New type of QM correlations, different from:**
    - HBT ↔ back-to-back
    - Jetjet correlations ↔ soft phenomenon, not from hard scattering
    - Only between particles and antiparticles
- Predicted signal is sensitive to:
  - **mass modification (prerequisite)**
  - **freezeout characteristics, phase transition ...**
  - **detailed simulations show dependence on flow, system size, etc. Importantly: freezeout time & distribution**

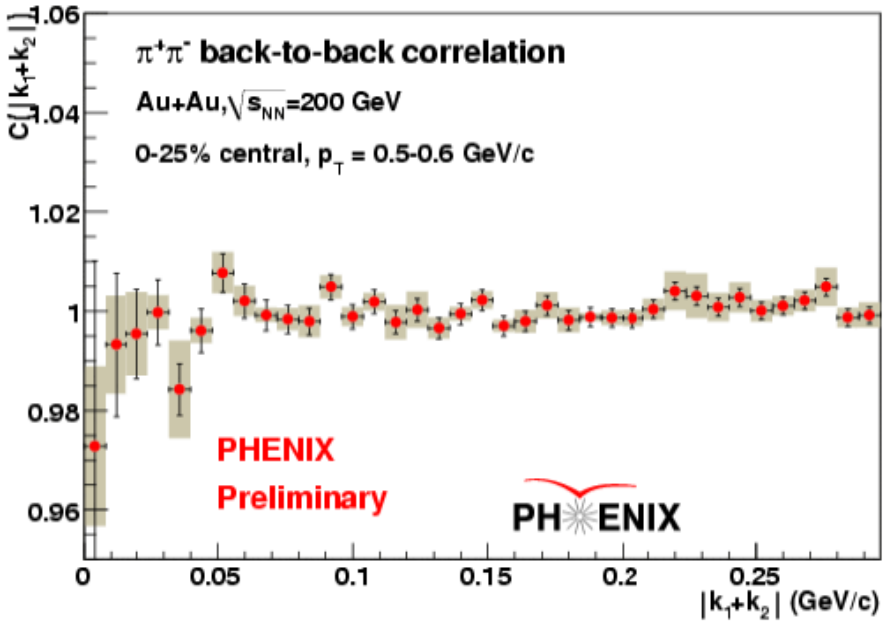
Results for kaons and protons

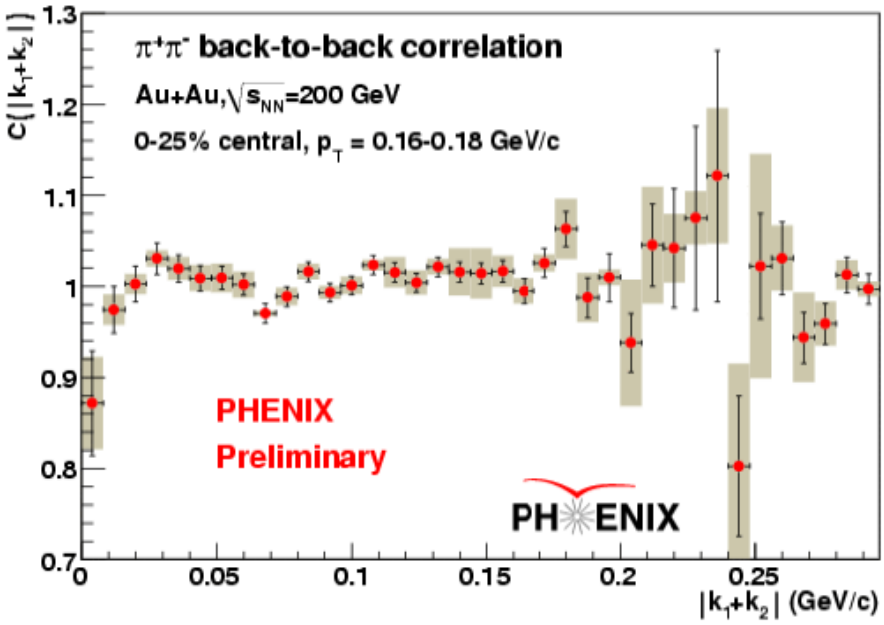




- No visible deviation from 1 is found
  - **Neither for kaons, nor for protons, using ~900M Au+Au events**
  - **Shaded bars: estimated uncertainty from PID (&other) cut variations**
  - **Reliable PID is possible only in intermediate momentum ranges**
- Low momentum pions favored by anomalous freezeout distribution

Results for pions





- Intermediate momentum
  - **No significant deviation, using ~900M Au+Au events**
  - **Shaded bars: estimated uncertainty from PID (&other) cut variations**
  - **Reliable PID is possible only in intermediate momentum ranges**
- Low momentum
  - **Some structure maybe, to be explored**

Summary of back-to-back correlations

- PHENIX measurement of new type of particle-antiparticle back-to-back correlation is analyzed
- **Basic theoretical ground well established, input theory parameters are not clear**
- No statistically significant deviation from 1 is found for pions, kaons and protons in the investigated momentum ranges
- **In principle, statement could change with improved statistics**
- **Understanding physical backgrounds is critical**
- Measurement of other particles?
- **Need more data for improved measurement, or for resonances (eg. Φ meson)**

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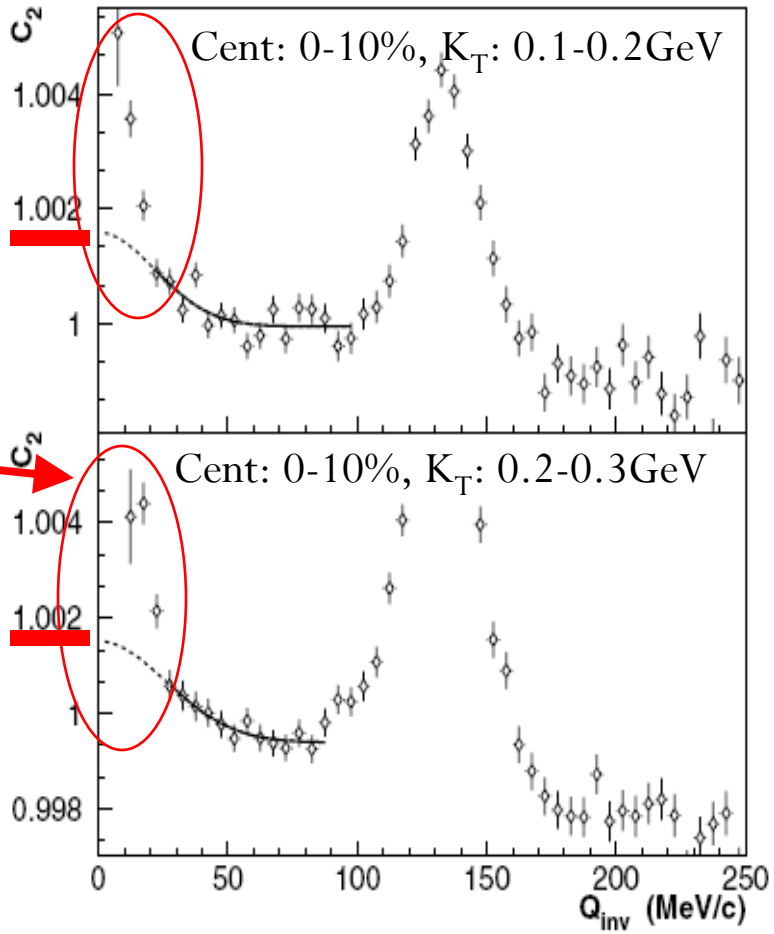
Photon HBT with PHENIX

- Direct photons image QGP
- Signal is very weak
- Try to use two photons both from EMCal
- Photons do not bend → correlated photons leave close hits
- One photon from EMCal, another photon from HBD
- Huge improvement
- Very limited statistics, any contamination destroys the signal



PRL, WA98 Collaboration, 93(2),2004

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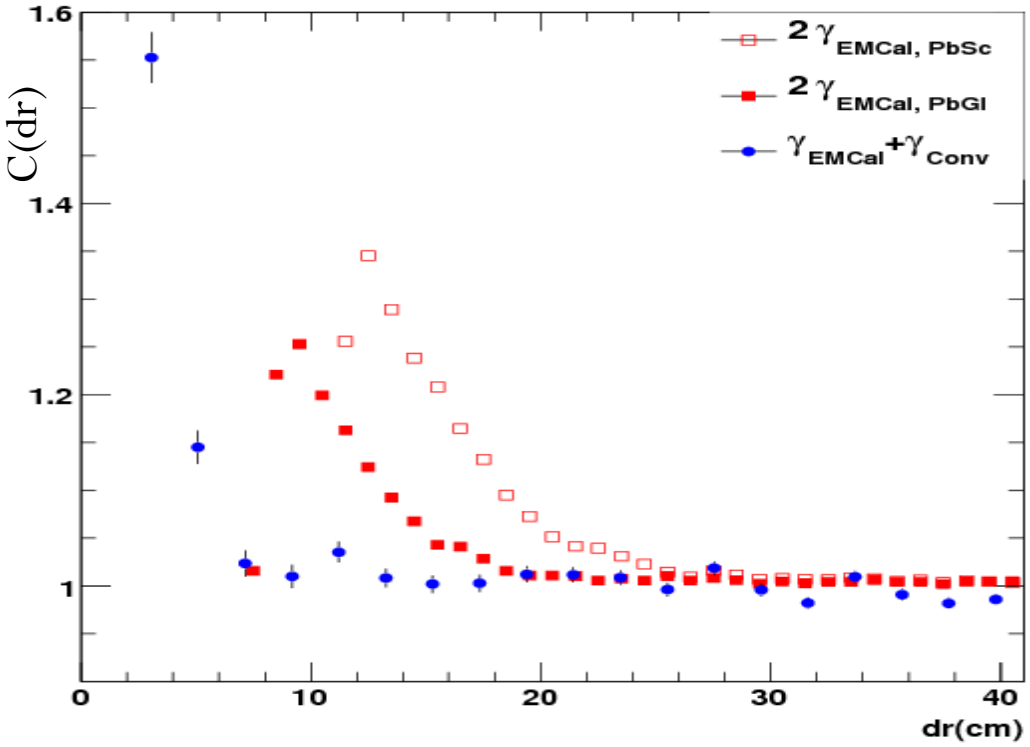
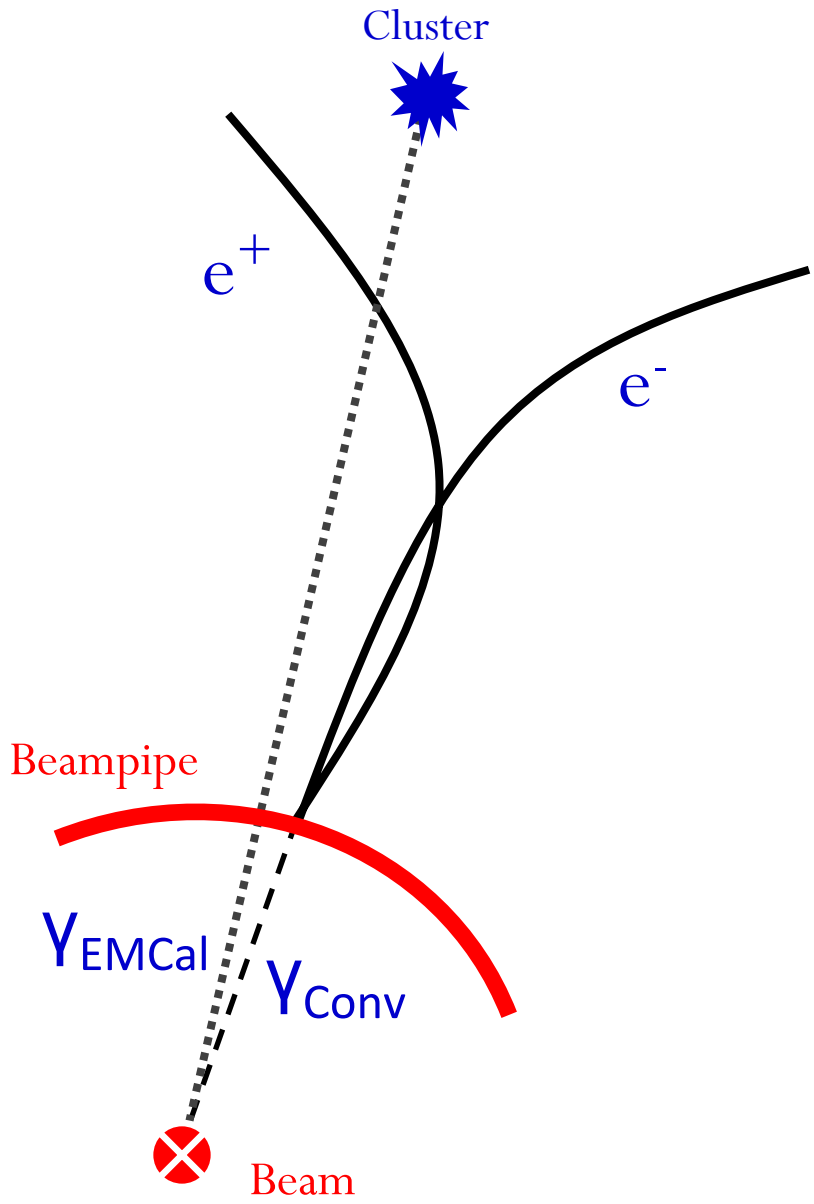
Photon HBT with PHENIX

- Cluster splitting if both photons are clusters on EMCal
- Idea: one of the two photons from conversion
- Caveat: beampipe is 0.3% radiation length
- We lose statistics.





Summary of photon HBT

- Photon HBT could provide additional insights to QGP's dynamic evolution.
- Its signal is small and distorted by detector effects.
- The detector effects could be suppressed by using one externally converted photon in the correlation.

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Summary of the summaries

- QGP created at RHIC
- Kaon HBT: done
  - Transverse mass scaling together with π's
  - Zero size at zero N_{part}
- p+p HBT: done
  - Consistent with Au+Au HBT
  - A lot to be done
- Squeezed back-to-back correlations
  - Ongoing topic, no stat. significant signal yet
- Photon HBT feasibility study
  - One photon from internal conversion
  - Doable with a larger dataset

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Thank you for your attention

PHENIX

APS 2010 announcement related articles (English)

Media	Headline
BNL News Release	'Perfect' Liquid Hot Enough to be Quark Soup
BNL YouTube	Hot Quark Soup Produced at RHIC
Google/news search	search Google News
DiscoverMagazine	The Hottest Science Experiment on the Planet, by Calla Cofield
NY Times Science	In Brookhaven Collider, Scientists Briefly Break a Law of Nature, by Dennis Overbye
Newsday	Brookhaven Lab findings eye birth of the universe, by Sumathi Reddy
Reuters UK	Hottest temperature ever heads science to Big Bang
Fox News Inside Science	Measuring the Hottest Temperatures in the Universe
PhysOrg.com	'Perfect' Liquid Hot Enough to be Quark Soup
MSNBC CosmicLog	Hottest soup in the universe, by Alan Boyle
Mirror.co.uk News	Scientists create 250,000 times the heat of the Sun by Mike Swain
Oneindia	Subatomic soup may explain why matter won over antimatter after Big Bang
USA Today	Scientists re-create high temperatures from Big Bang, by Dan Vergano
DailyMail.co.uk ScienceTech	Scientists create hottest temperature since Big Bang - 250,000 times more scorching than our Sun by David Derbyshire
ABCNews Technology	Hottest Temperature Ever Heads Science to Big Bang by Maggie Fox
ScienceDaily	'Perfect' Liquid Hot Enough to Be Quark Soup
ITWire.com Science-Energy	Record universal temperature created at Brookhaven, by William Atkins
DiscoveryNews	Scientists Cook Up Hottest 'Soup' Ever, by Irene Klotz
TGDaily Science	Scientists recreate Big Bang 'quark soup', by Jean Antonique
TheMoneyTimes	Scientists create temperature of 7.2 trillion degrees, hottest since Big Bang, by Ishita Sood
TopNews	Atom smashers create the hottest-ever lab temperature, by Justin Rorkin
WorldScience	Physicists report creating hottest temperatures ever in lab
Science a GoGo	Mirror symmetry broken at 7 trillion degrees, by Kate McVille
DigitalJournal	Scientists collide gold ions, reach hottest temp ever recorded, by Paul Wallis
IndyPosted	Scientists Create Hottest Temperatures Ever. STILL No Black Hole, by Maggie Romuld
ScienceNews.org	Hot and heavy matter runs a 4 trillion degree fever, by Laura Sanders
Interactions.org	'Perfect' Liquid Hot Enough to be Quark Soup
TheWestAustralian	Hottest temperature ever heads science to Big Bang, by Maggie Fox
NewsTrack India	Subatomic soup may explain why matter won over antimatter after Big Bang
DailyTech	Science U.S. Lab Recreates Violent Big Bang Temperatures, Makes Quark Soup by Jason Mick
ScienceBlog	'Perfect' liquid hot enough to be quark soup
Gizmodo Australia	Quark Soup Cooked At Highest Temperature In A Lab Ever, by Jesus Diaz
Popular Science	RHIC Collider Creates Quark-Gluon Plasma at 4,000,000,000,000 Degrees Celsius, by Stuart Fox

CBC News Canada	Physicists create highest-ever lab temperature
redOrbit	Scientists Create Hottest Temperature, Compare It To Big Bang
ecPulse	The highest temperature ever may unveil the universe mysterious creation
Telegraph.co.uk	US lab reaches Big Bang heat of four trillion degrees Celsius By an AFP reporter in Washington
NatureNews	Subatomic soup is hot stuff, by Eric Hand
InsideScience.org	Hottest Temperature In The Universe Measured By Devin Powell
LiveScience.com	Twisted Physics: 7 Recent Mind-Blowing Findings, select number one.

APS 2010 announcement related articles (non - English)

Media	Headline
Deutschlandfunk	Am Anfang war der Symmetriebruch, Vier Billionen Grad heiße Urknall-Suppe untersucht, von Jan Lublinski
Yomiuri Online	Successfully achieved four trillion degrees! Reproduced right after BigBang
gazeta.ru Science	It was hot in the beginning
Russian Academy of Science	Physicists have measured temperature of the Universe an it's first moments of life
Index.hu	Biggest heat since the Big Bang
Hungarian Academy of Sciences	Temperature of the Hottest Matter Measured
Origo.hu (Hungarian Portal, Science	Creation of the Original Matter of the Universe
Cernblog.worldpress.com (Hungarian)	Results from America on the Original Matter of the Universe
Cernblog.worldpress.com (Hungarian)	At least 4 Trillion Celsius: Temperature of the Primordial Matter of the Universe
Cernblog.worldpress.com (Hungarian)	Bubbles of Violate Symmetry in the Quark Soup of RHIC
HirExtra.hu (Hungarian)	Primordial Soup Boiling Again
Hirado.hu (Hungarian National Television)	Hungarian Researchers in Experiments Studying Post Big Bang State
Epresso.hu (Hungarian Education Portal)	Hungarian Participants in Measurement of Hottest Matter Ever
The-online.hu (Hungarian Science Portal)	Temperature of Hottest Ever Matter Measured

Last Updated on Tuesday, 06-Apr-2010 10:26:49 EDT by A. Franz

Charged kaon analysis details

Momentum resolution:
$\delta p/p = 0.7\ \% \oplus 1\ \% \times p\ (GeV/c)$

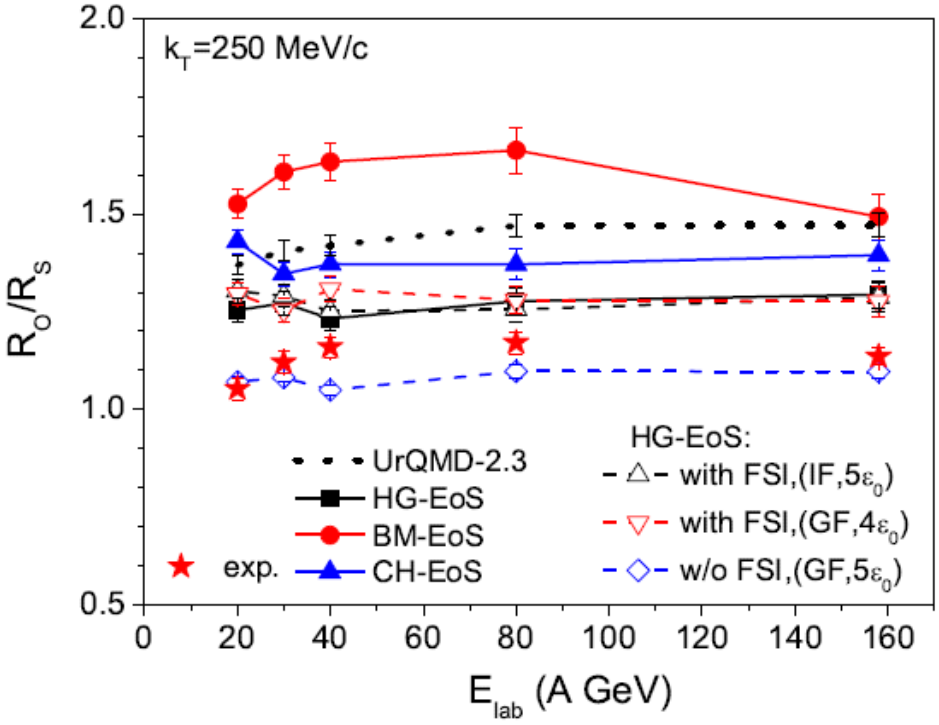
Matching cuts for tracking:
- $2\ \sigma$ position match in PbSc
- $3\ \sigma$ position match in PC3

Kaon identification based on BBC and PbSc timing signals for $p_t < 0.9$ GeV/c. For $p_t > 0.9$ GeV/c, kaons accepted if $< 2\ \sigma$ close to the invariant mass peak and $> 3\ \sigma$ from the invariant mass peak of pions and (anti)protons.

At $p_t \sim 1.5$ GeV/c,
contamination from pions: 4 %, from (anti)protons: 1 %.

After track selection and merging cuts:
$1.5 \times 10^7\ K^+K^+$ and $1.4 \times 10^7\ K^-K^-$ pairs

HBT signal of 1st order phase transitions, uses $R_{out}/R_{side}(m_t, \sqrt{s_{NN}})$



H. Petersen, QM 2009 talk:
HG= hadron gas EoS +hydro
BM= bag model EoS + hydro
CH= chiral EoS with CP+hydro
arXiv: 0812.0375

Comment:
Rischke's hydro <-> NA49
HBT puzzle is not RHIC specific
R_{out}/R_{side} sensitive to the EoS