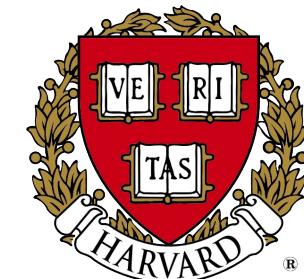


Oscillating HBT radii and the time evolution of the source

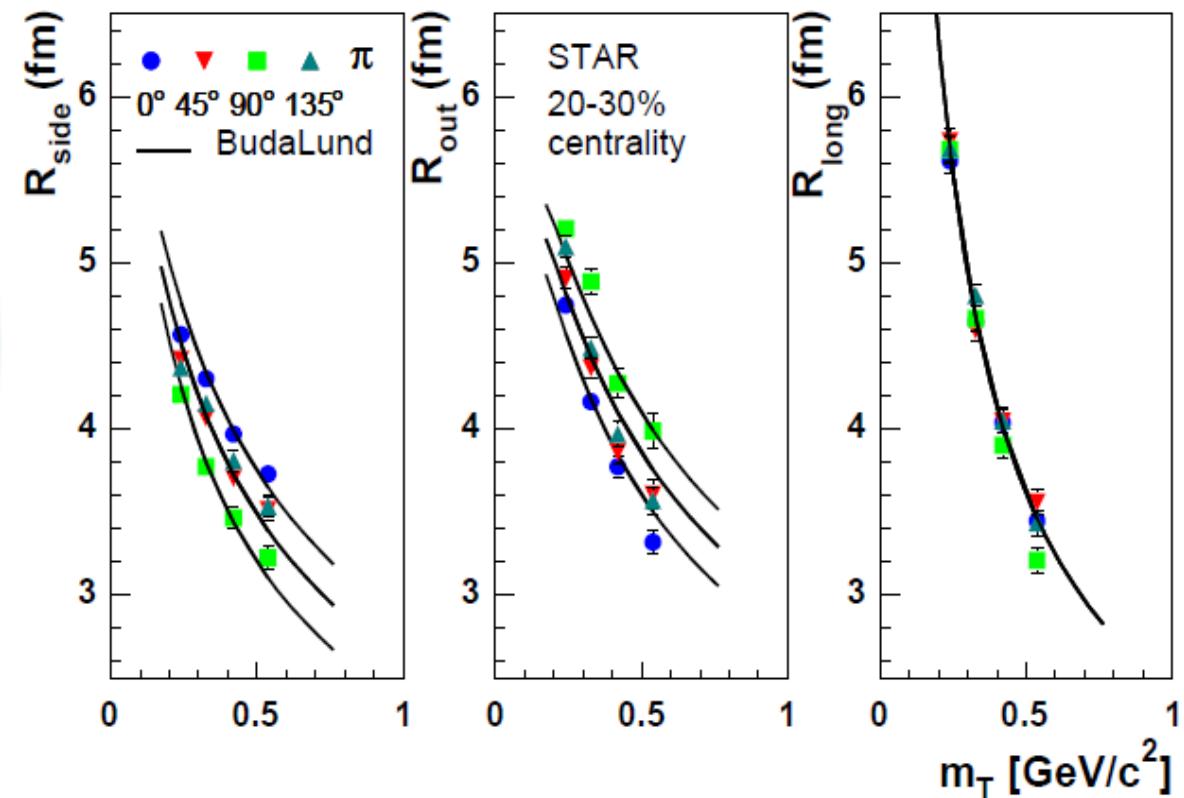
200 GeV Au+Au data analyzed with asBuda-Lund



T. Csörgő^{1,2}, A. Ster, M. Csanad, B. Lorstad, B. Tomaszik

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Motivation

- Exact solutions of 1+3d NR hydro with ellipsoidal symmetry

Spherical → Ellipsoidal symmetry

From fluid of nucleons → exact simple models for RHIC

Refs: J. Bondorf, S. Garpman and J. Zimányi, Nucl. Phys. A296:320-332,1978
T. Cs, S. V. Akkelin, Y. Hama, Yu. Sinyukov, Phys.Rev.C67:034904,2003
T. Cs, Acta Phys.Polon.B37:483-494,2006

Viscous solution: in preparation

Hydrodynamically evolving core + halo of resonances

Ref: T. Cs, B. Lörstad and J. Zimányi, Z.Phys.C71:491-497,1996

- Generalization to relativistic solutions

Ref: T. Cs, L.P. Csernai, Y. Hama, T. Kodama, Heavy Ion Phys.A21:73-84,2004 , but for Hubble flows only

- Observation: elliptic flow scaling laws

first from non-rel 3d perfect fluid solution

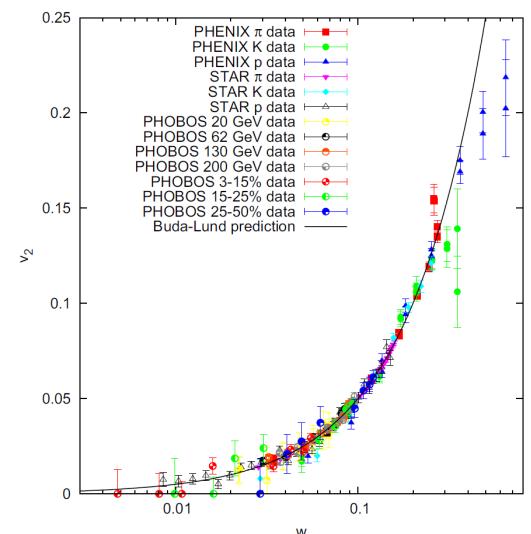
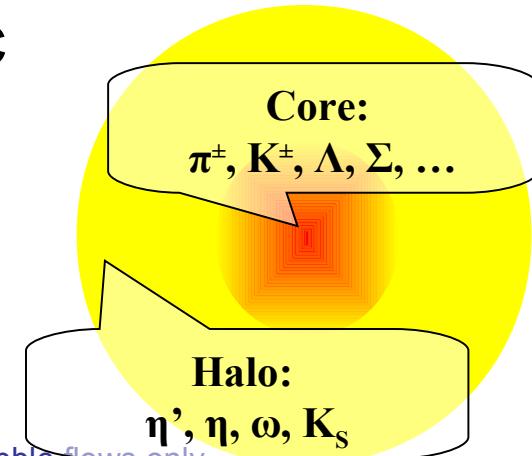
$v_2(w)$: dimensionless(dimensionless)

recent result:

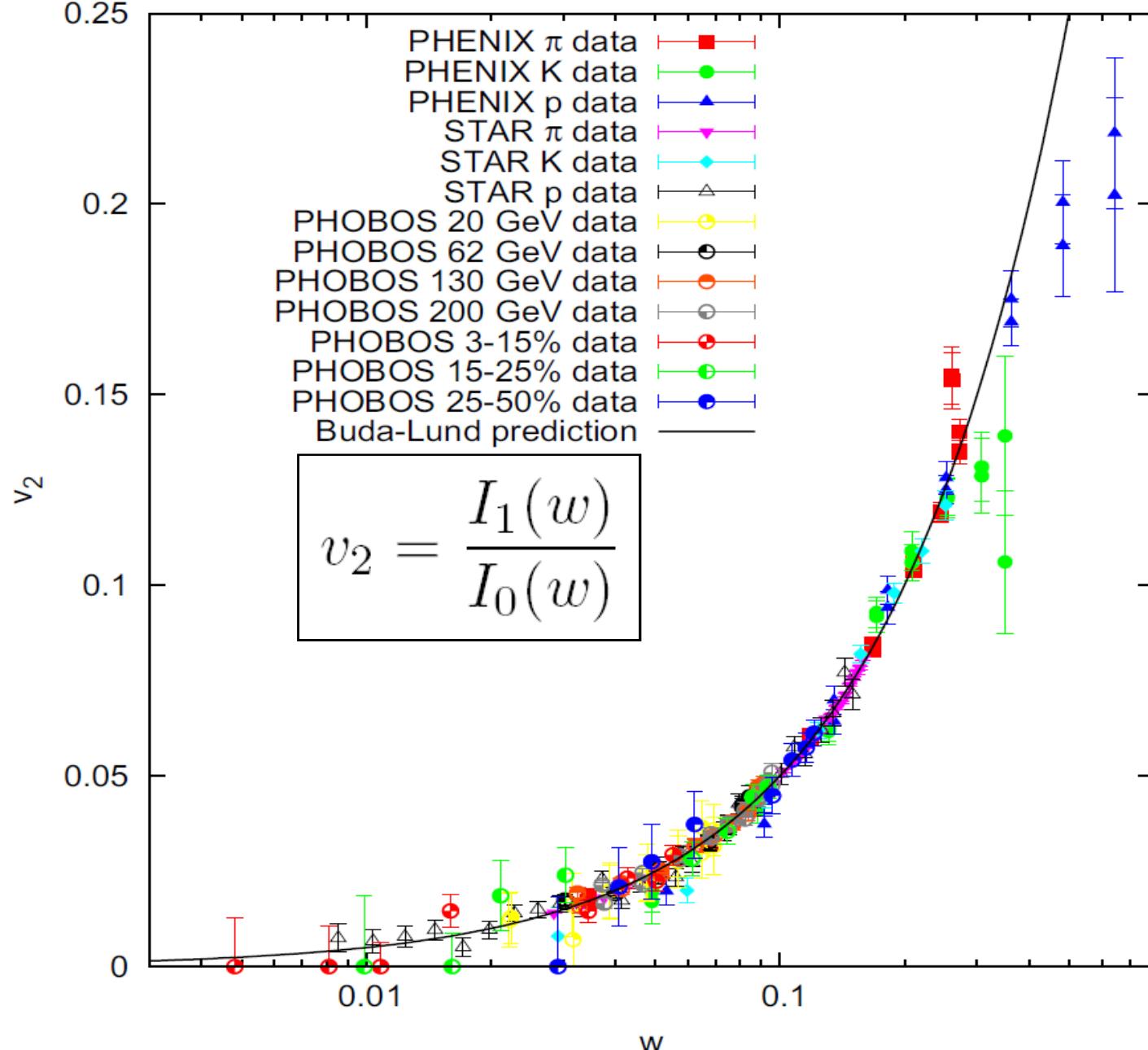
$$v_2 = \frac{I_1(w)}{I_0(w)}$$

holds for exact Navier-Stokes solutions, too

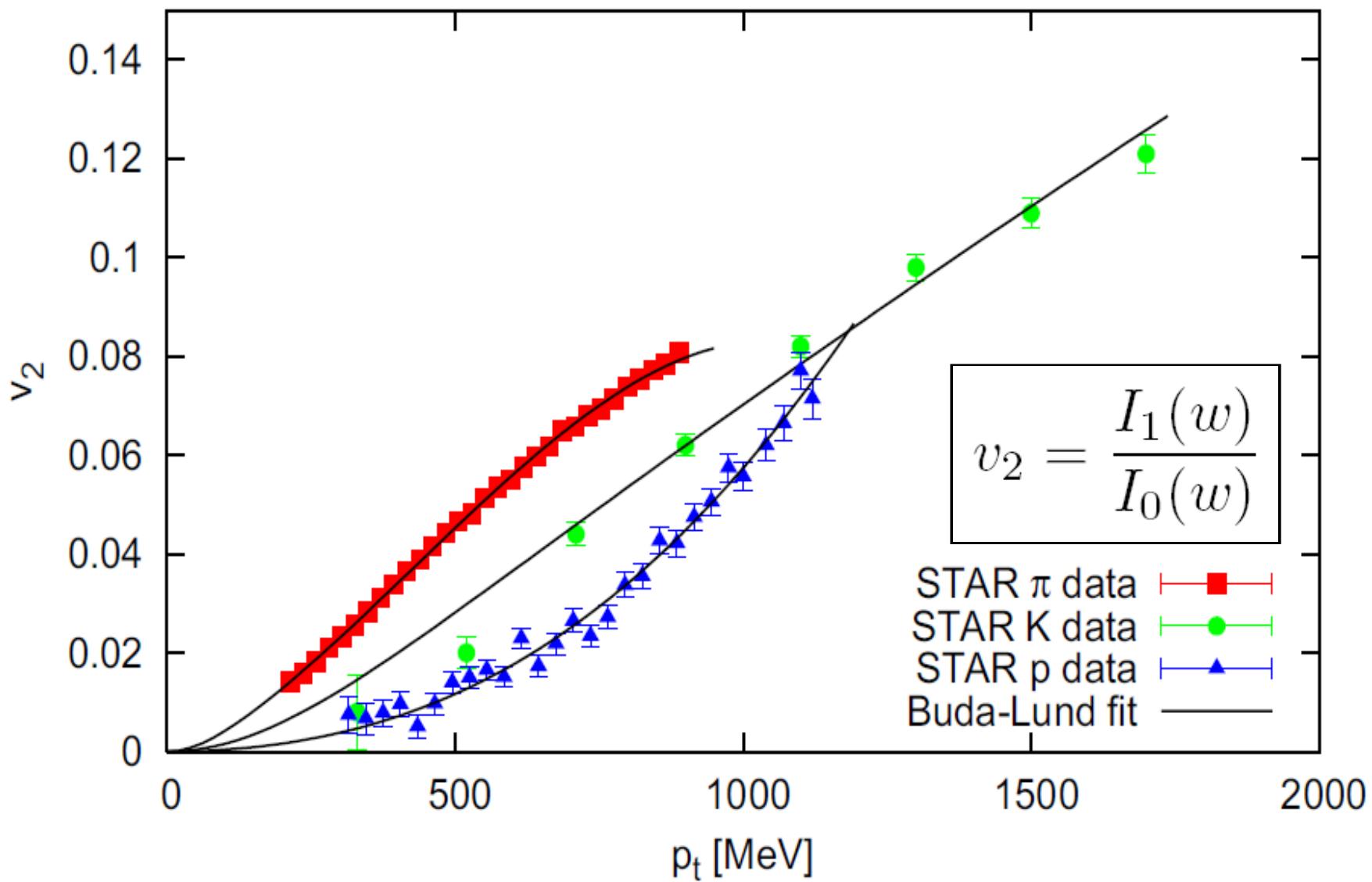
Ref: M. Csanad et al, Eur.Phys.J.A38:363-368,2008, + T. Cs. in prep.



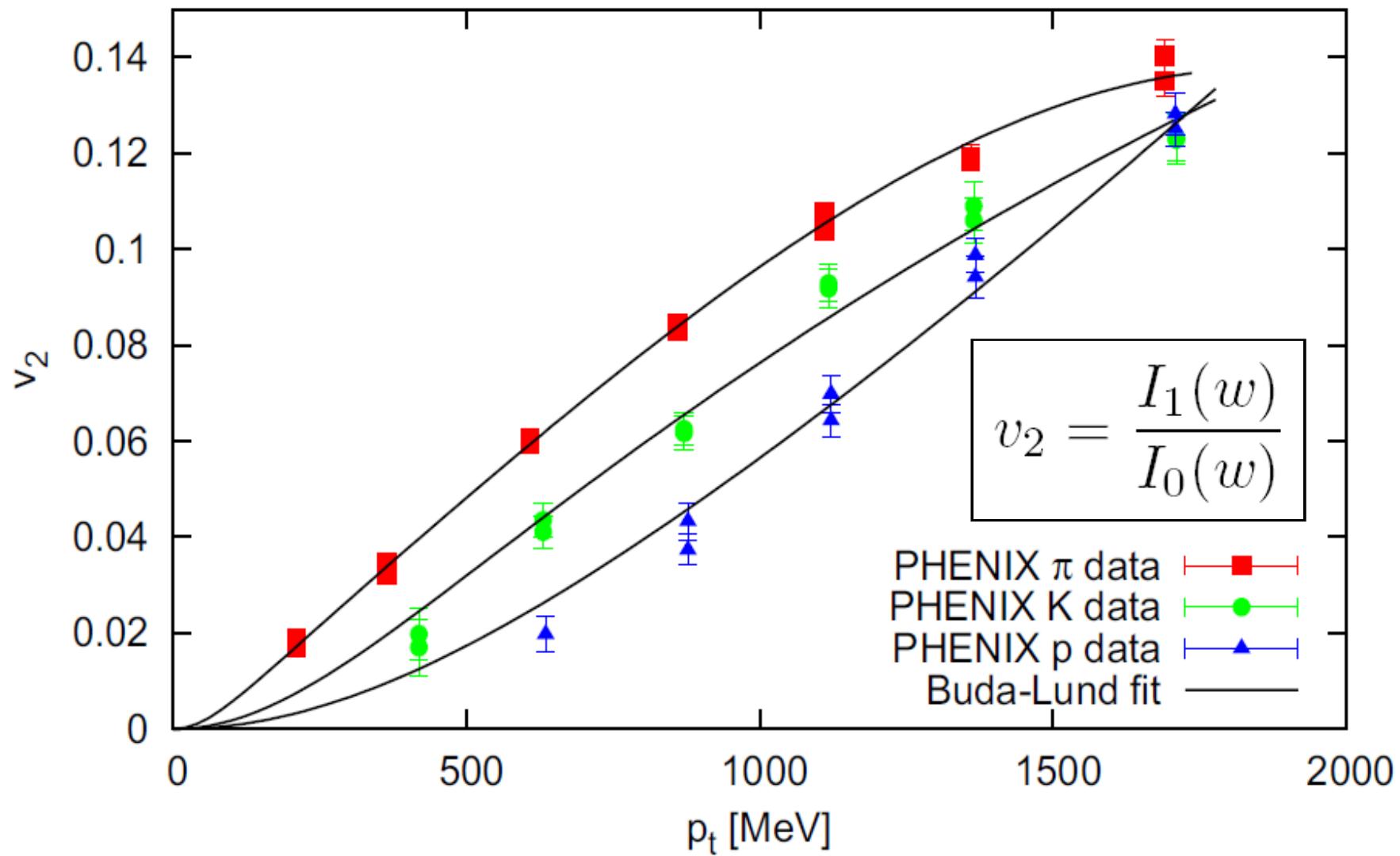
Buda-Lund: universal scaling of v_2



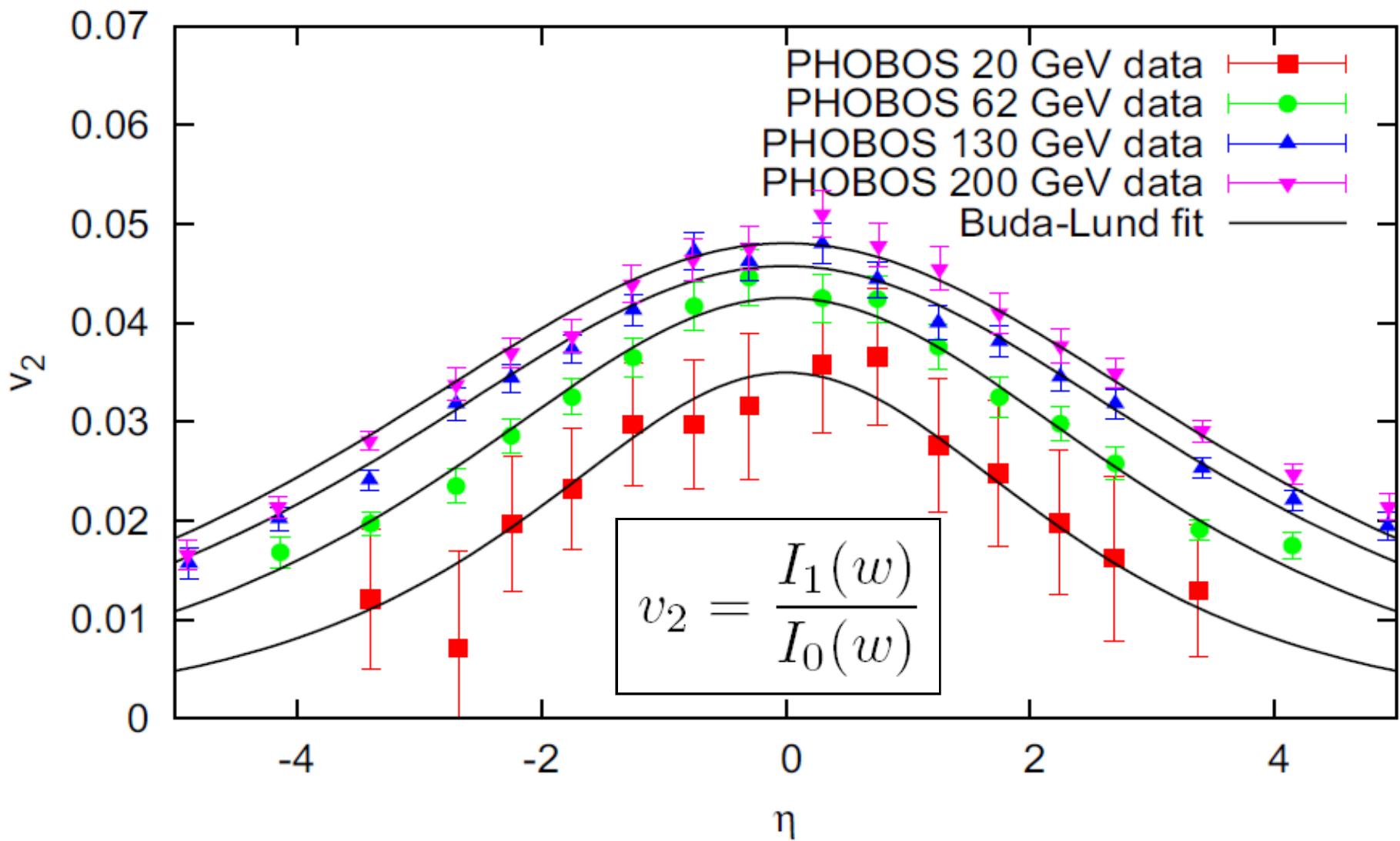
Motivation



Motivation



Motivation



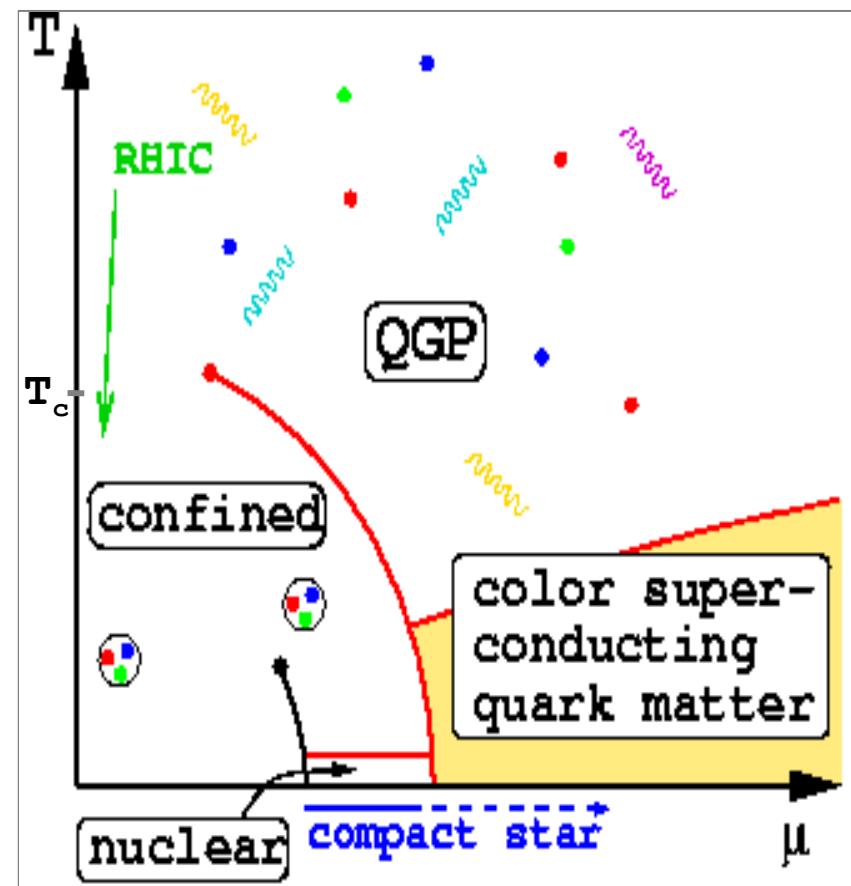
Input from lattice: EoS of QCD Matter

Old idea: Quark Gluon Plasma
More recent: Liquid of quarks

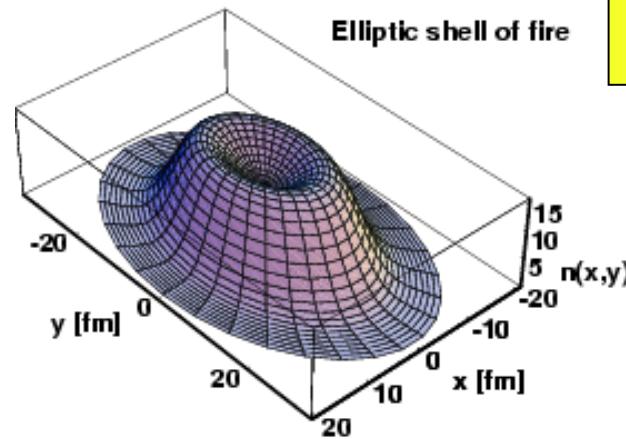
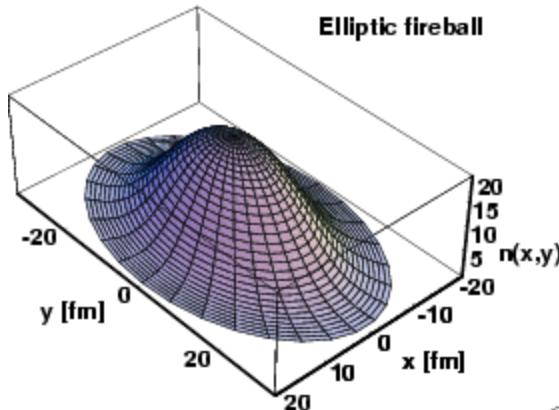
$T_c = 176 \pm 3$ MeV (~ 2 terakelvin)
([hep-ph/0511166](#))
at $\mu = 0$, a cross-over

Aoki, Endrődi, Fodor, Katz, Szabó
[hep-lat/0611014](#)

LQCD input for hydro: $p(\mu, T)$
LQCD for RHIC region: $p \sim p(T)$,
 $c_s^2 = \delta p / \delta e = c_s^2(T) = 1/\kappa(T)$
It's in the family exact hydro solutions!

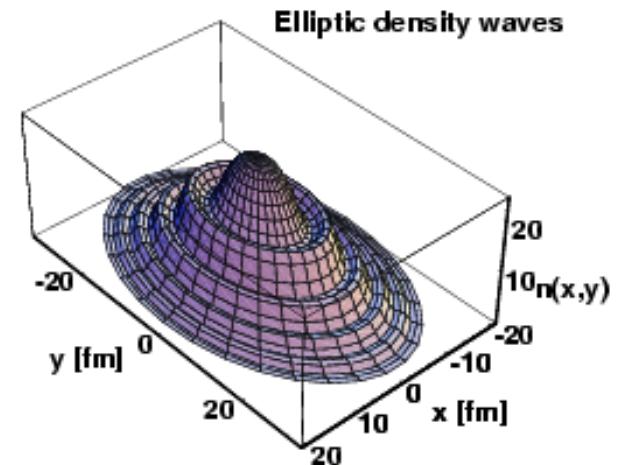


Illustrated initial T-> density profiles

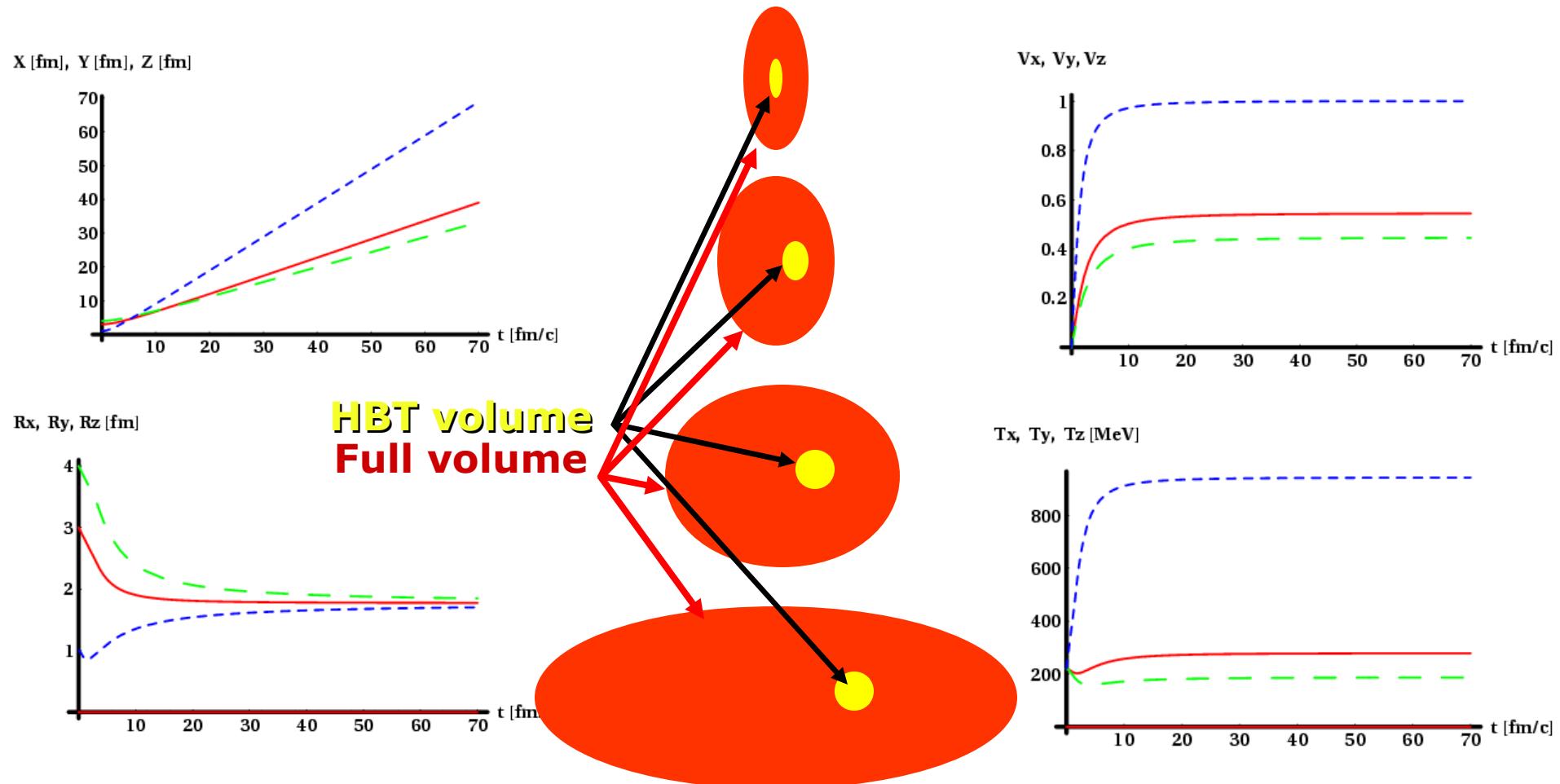


Determines density profile!
Examples of density profiles
- Fireball
- Ring of fire
- Embedded shells of fire
Exact integrals of hydro
Scales expand in time

Time evolution of the scales (X,Y,Z) follows a classic potential motion.
Scales at freeze out \rightarrow observables.
info on history LOST!
No go theorem - constraints
on initial conditions
(penetrating probels) indispensable.



Solution of the “HBT puzzle”



Geometrical sizes keep on increasing. Expansion velocities tend to constants.
 HBT radii R_x , R_y , R_z approach a direction independent constant.
 Slope parameters tend to direction dependent constants.
 General property, independent of initial conditions - a beautiful exact result.

Scaling from exact hydro

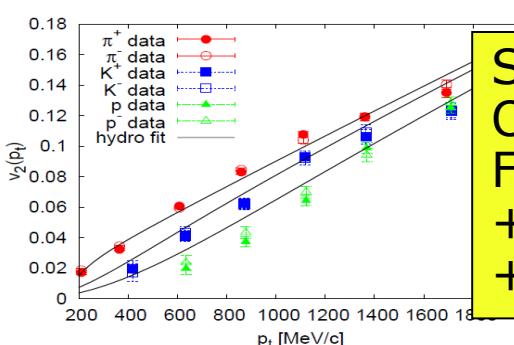
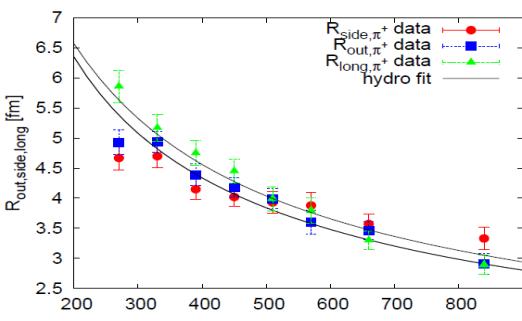
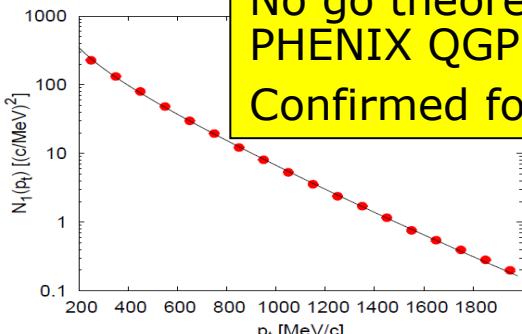
M. Csand, M. Vargyas

Eur.Phys.J.A44:473-478,2010

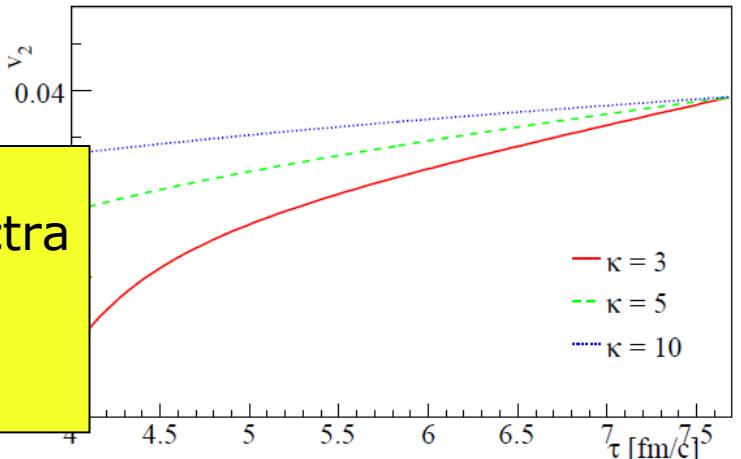
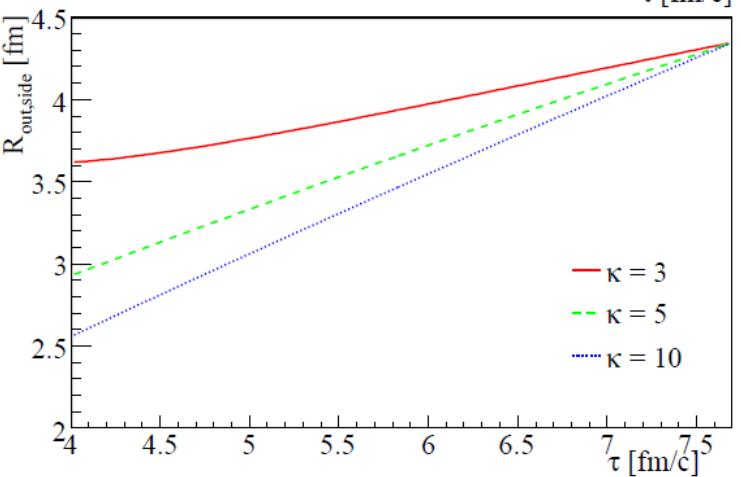
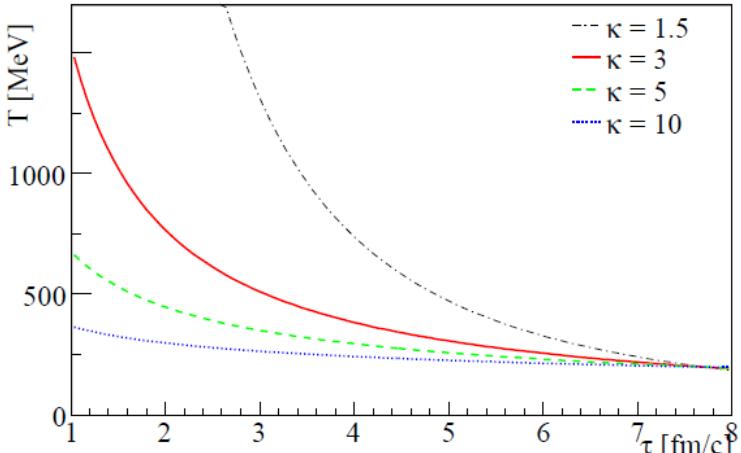
Scales at freeze out -> observables.
info on history [LOST!](#)

No go theorem - illustrated, BUT
PHENIX QGP claim, $T_{\text{int}} \geq 330$ MeV

Confirmed for any reasonable $p/e \geq 0.1$



See talk of M. Csand
On analysis of photon spectra
For more details
+ constraints on evolution
+ constraints on EoS



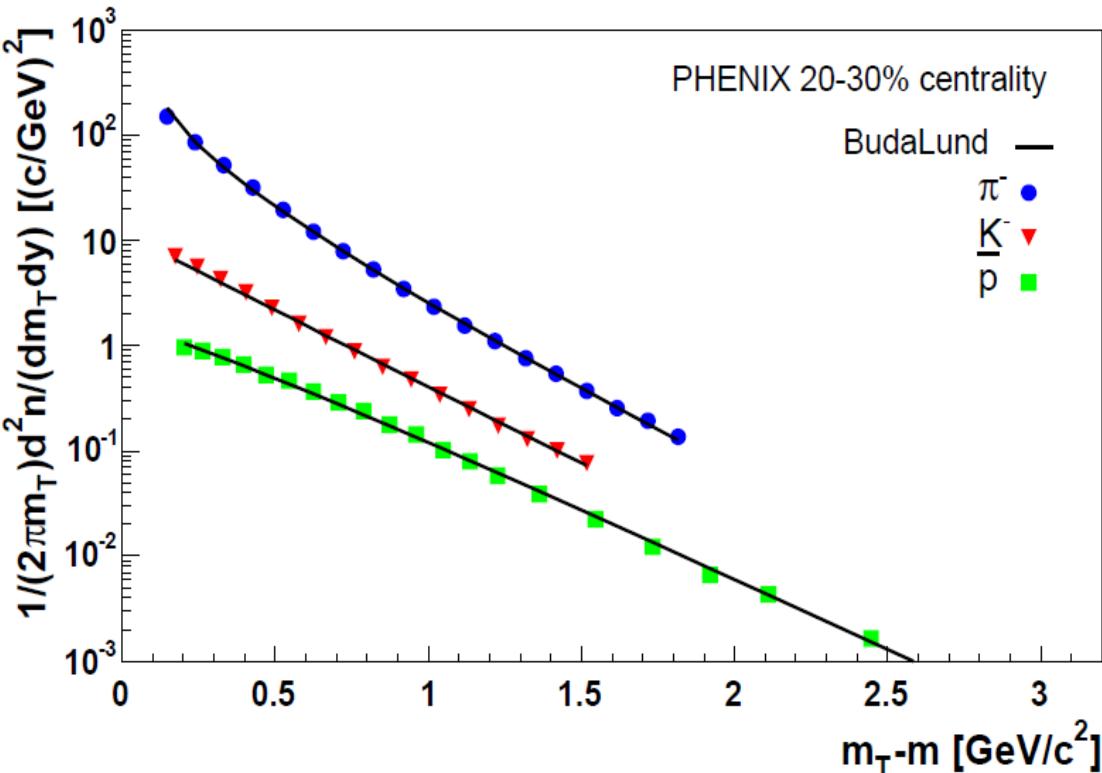
Intro/Reminder, Buda-Lund hydro model

If the finite source sizes are large compared to the thermal length-scales and if we also have $a^2 + b^2 \approx 1$, one obtains an M_t -scaling for the parameters of the BECF,

$$R_{side}^2 \simeq R_{out}^2 \simeq R_L^2 \simeq \tau_0^2 \frac{T_0}{M_t}, \quad \text{valid for } \beta_t \ll \frac{1}{b}. \quad (82)$$

Axially symmetric: T. Cs, B. Lörstad, hep-ph/9509213
Ellipsoidal generalization:
M. Csanad, T.Cs., B. L rsrad, nucl-th/0310040

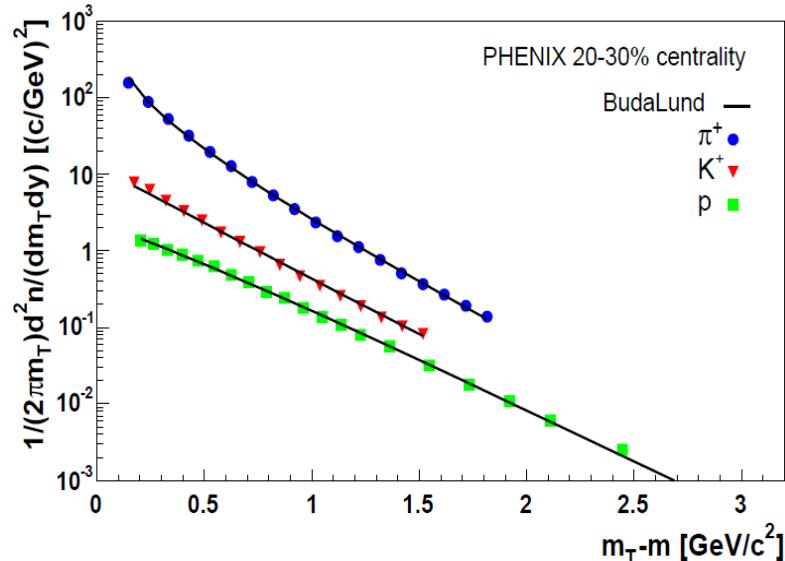
Results, asBuda-Lund fits to spectra



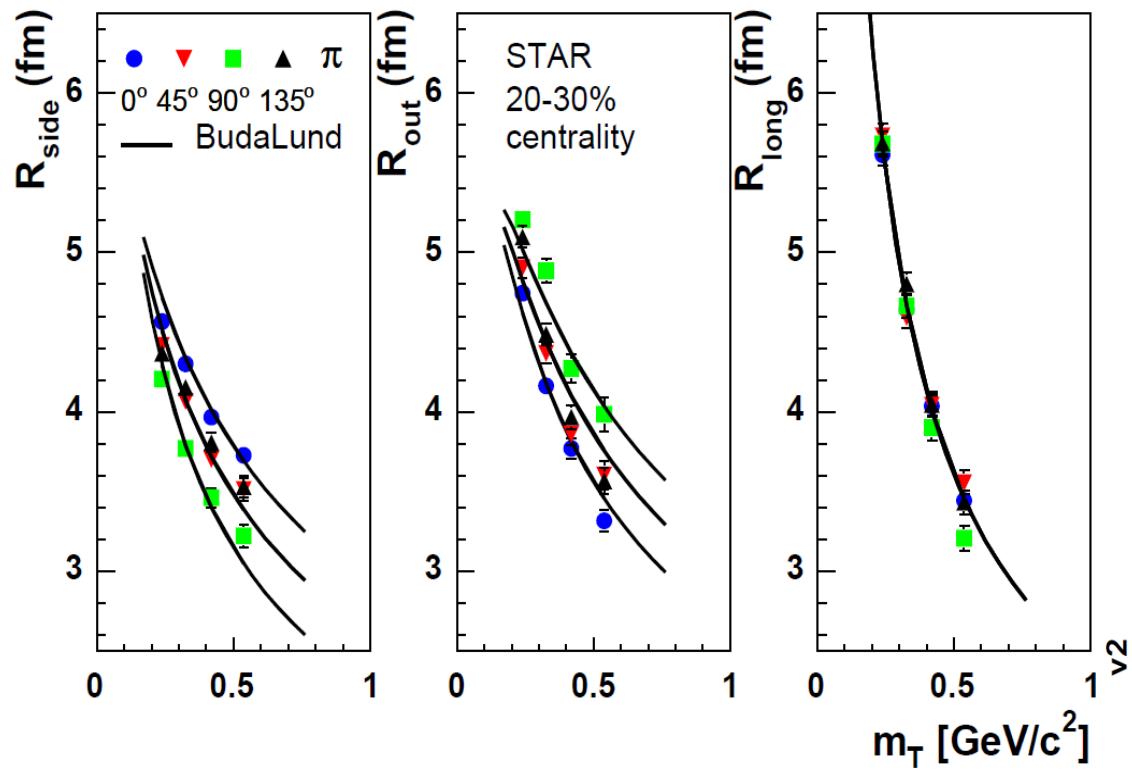
Spectra are corrected for long-lived Resonance effects using core-halo model.

Both positive and negative spectra described in stat. acceptable way

Fits 20-30 % centrality
Fits are done simultenously
To spectra, v_2 and asHBT
Analytic formulas,
precision < 2-4 %
Buda-Lund parameters
Optimized by CERN Minuit

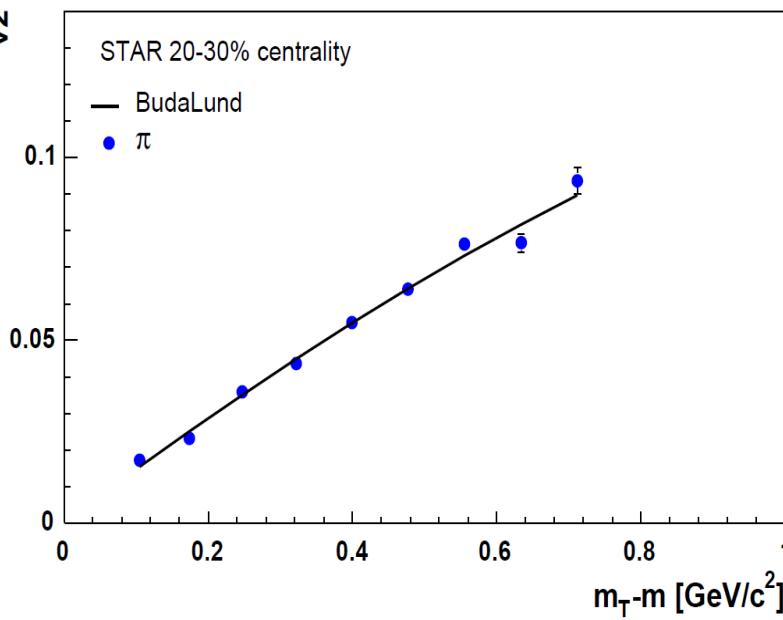


Results, asBuda-Lund fits to asHBT

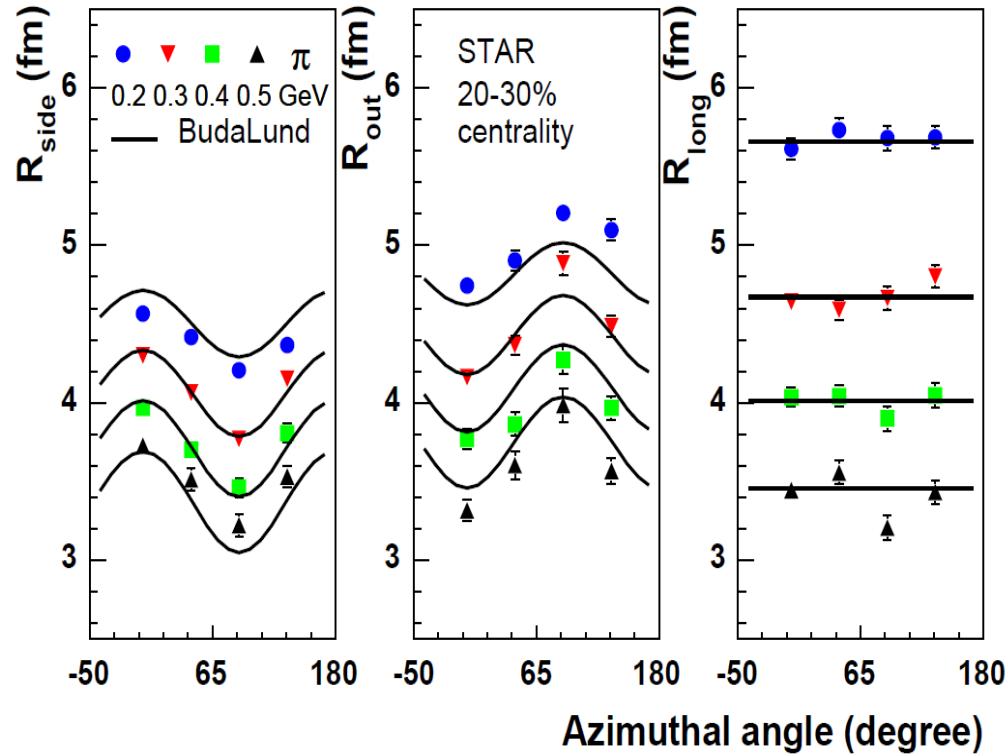


Fits 20-30 % centrality
Fits are done simultaneously
To spectra, v_2 and asHBT
Analytic formulas,
precision < 2-4 %
Buda-Lund parameters
Optimized by CERN Minuit

Oscillations of HBT radii are described reasonably well, as a function of transverse mass. Simultaneously with charged particle elliptic flow and spectra.



Results, asBuda-Lund fits to asHBT

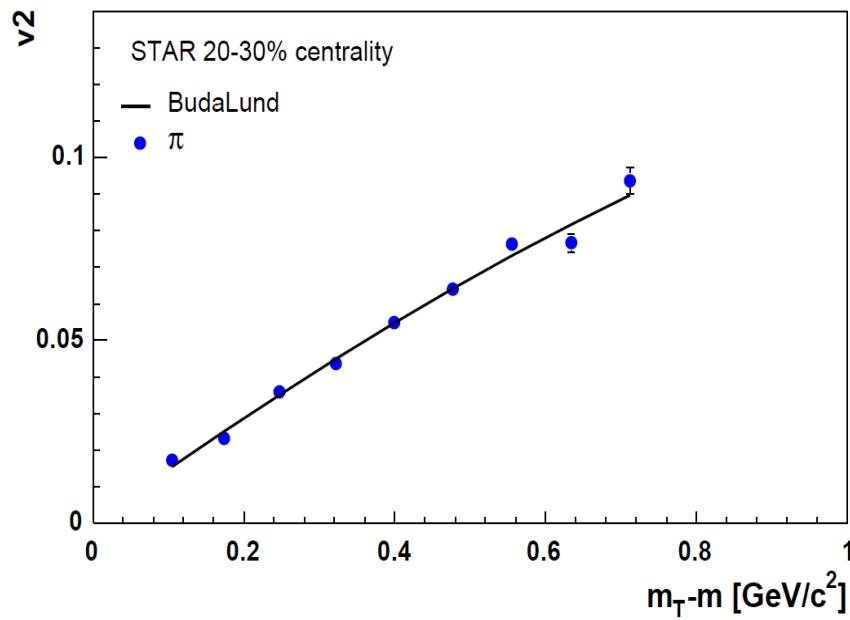


Oscillations of HBT radii are described reasonably well, as a function of angle small but systematics in out and side.

But $\chi^2/\text{NDF} = 255.6 / 152$
 $\text{CL} = 0.78 \%$ acceptable

Beyond Gaussian $H(\tau)$ distribution?

Fits 20-30 % centrality
Fits are done simultaneously
To spectra, v_2 , and asHBT
Analytic formulas,
precision < 2-4 %
Buda-Lund parameters
Optimized by CERN Minuit



Results: from spectra, v_2 , asHBT + Buda-Lund

BudaLund source parameters	RHIC 200 AGeV central (0-30%)	RHIC 200 AGeV non-central (20-30%)
T_0 [MeV]	196 ± 13	190 ± 5
T_e [MeV]	117 ± 12	118 ± 8
H_x [c/fm]	0.12 ± 0.013	0.17 ± 0.002
H_y [c/fm]		0.12 ± 0.001
H_z [c/fm]	0.17 ± 0.008	0.19 ± 0.003
R_x [fm]	13.5 ± 1.7	9.3 ± 0.5
R_y [fm]		6.7 ± 0.2
$\Delta\tau$ [fm/c]	0.9 ± 1.2	2.7 ± 0.2
$\Delta\eta$	3.1 ± 0.1	2.4 ± 0.3
$\mu_{o\pi}$ [MeV]	-2 ± 14	40 ± 8
μ_{oK} [MeV]	16 ± 19	55 ± 13
μ_{op} [MeV]	97 ± 28	178 ± 22
χ^2/NDF	$114 / 208$	$261 / 152$ CL=0.7%

CL > 0.1 %
Acceptable.
Temperatures:
Similar.

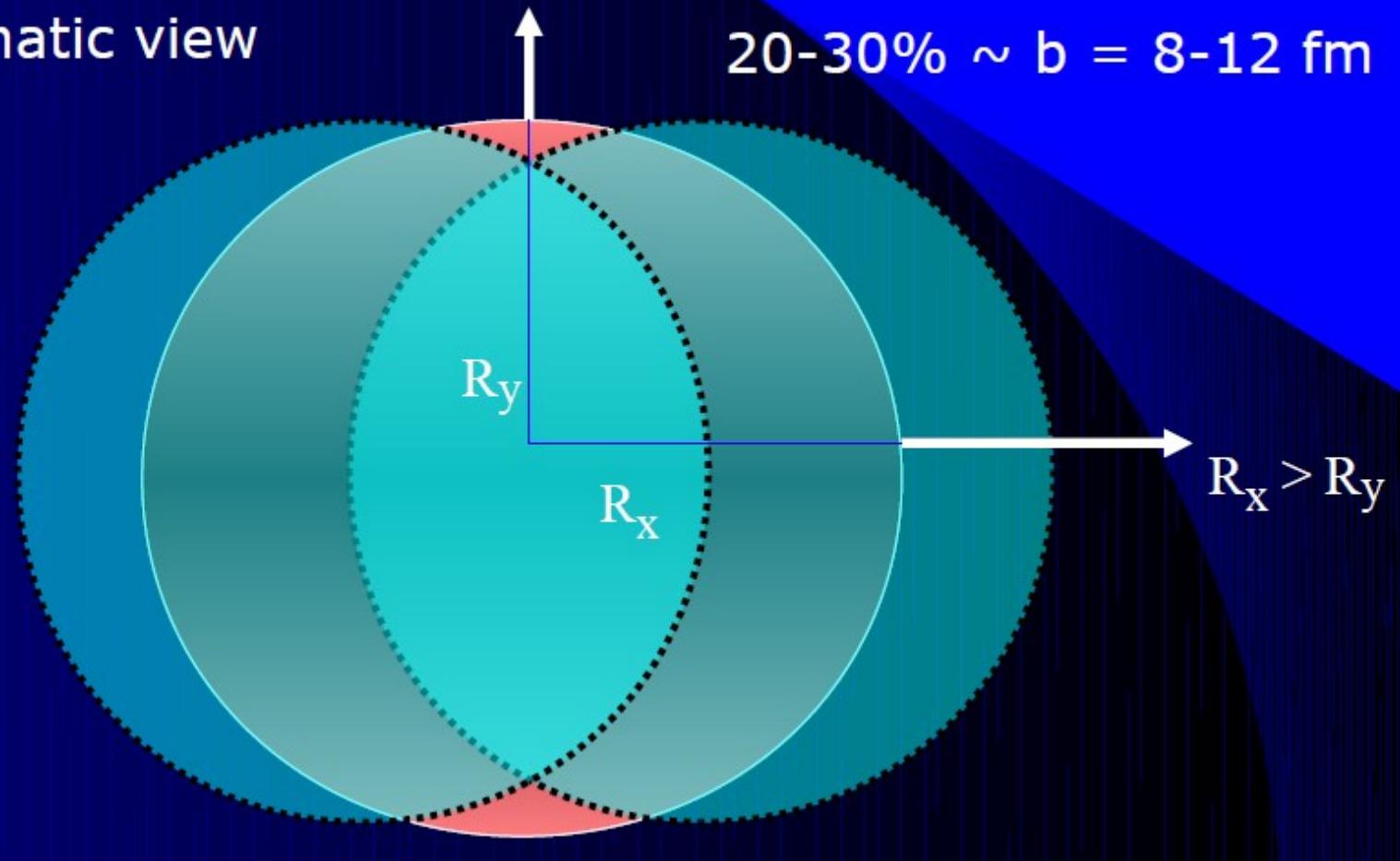
Strong expansion
in impact parameter
direction.
Homogeneity region:
out-of-plane elongated

Actual source:
in-plane elongated
a little (5 σ stat)

Illustration

Schematic view

20-30% $\sim b = 8-12 \text{ fm}$



A. Ster, talk at WPCF 2009:
Indication of in-plane extended source

Summary

**Au+Au elliptic flow data at RHIC satisfy
UNIVERSAL scaling laws
predicted in 2001, 2003 by Buda-Lund hydro model,
based on exact solutions of hydrodynamics.**

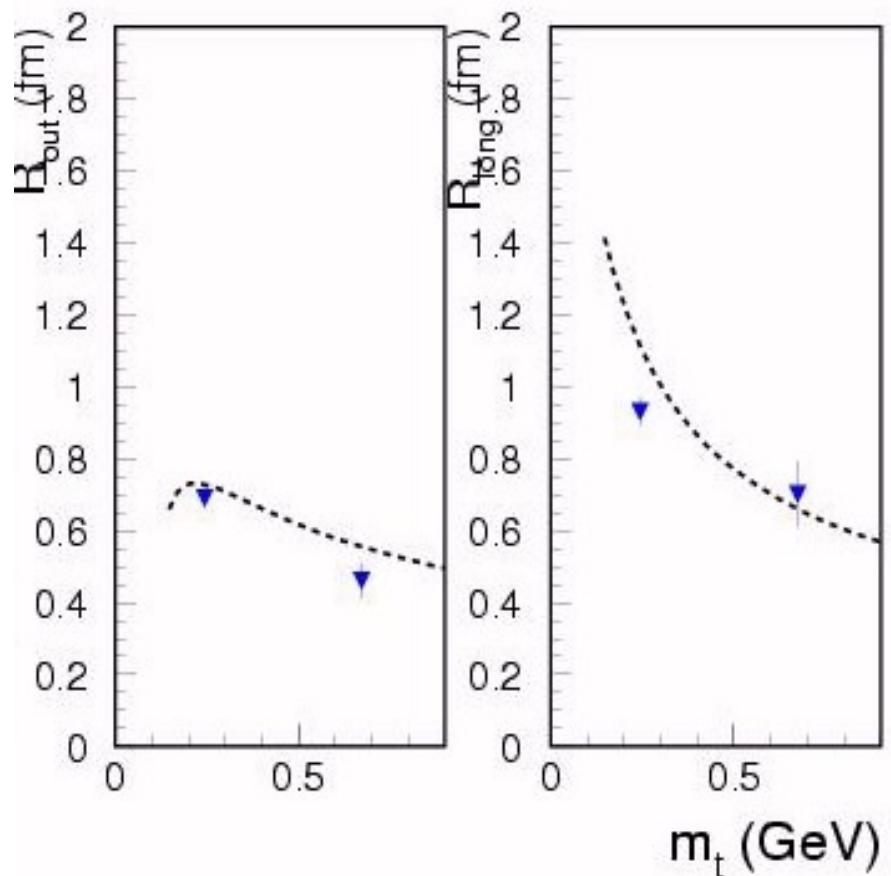
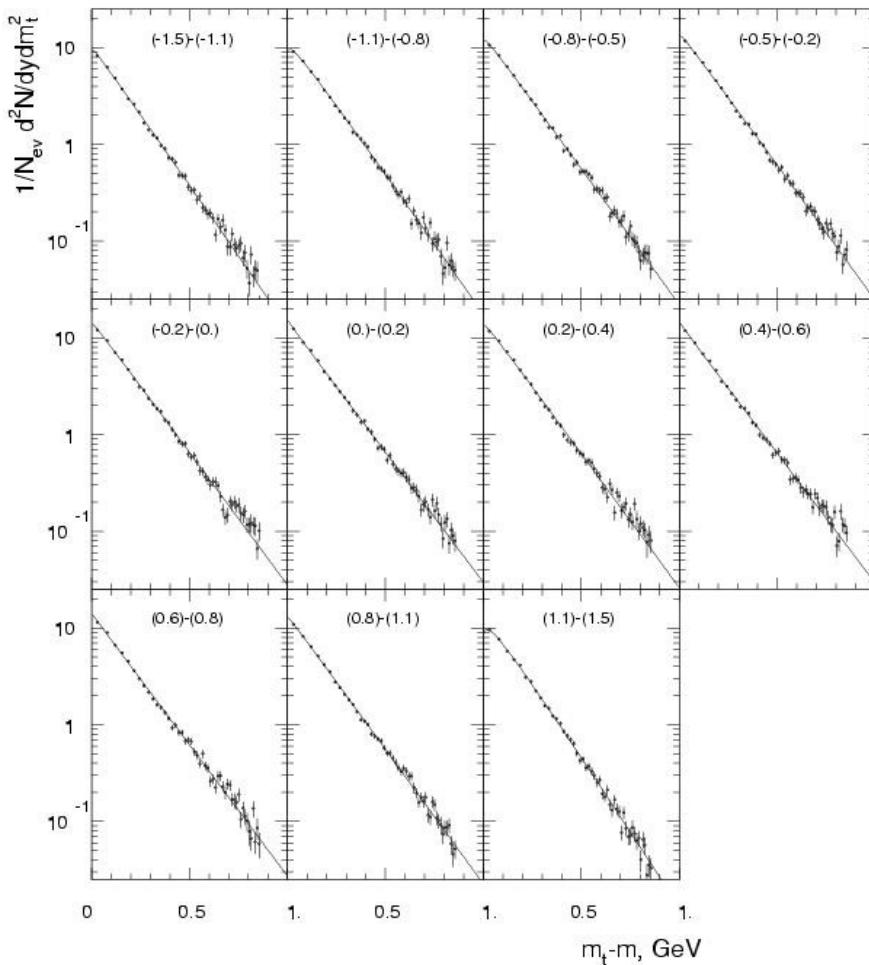
**Quantitative evidence for a perfect fluid in Au+Au at RHIC
- but quark number scaling suggests flow on quark level.**

**Buda-Lund model predicted the HBT radii successfully at RHIC,
describes azimuthal oscillations of HBT radii.**

Model specific predictions:

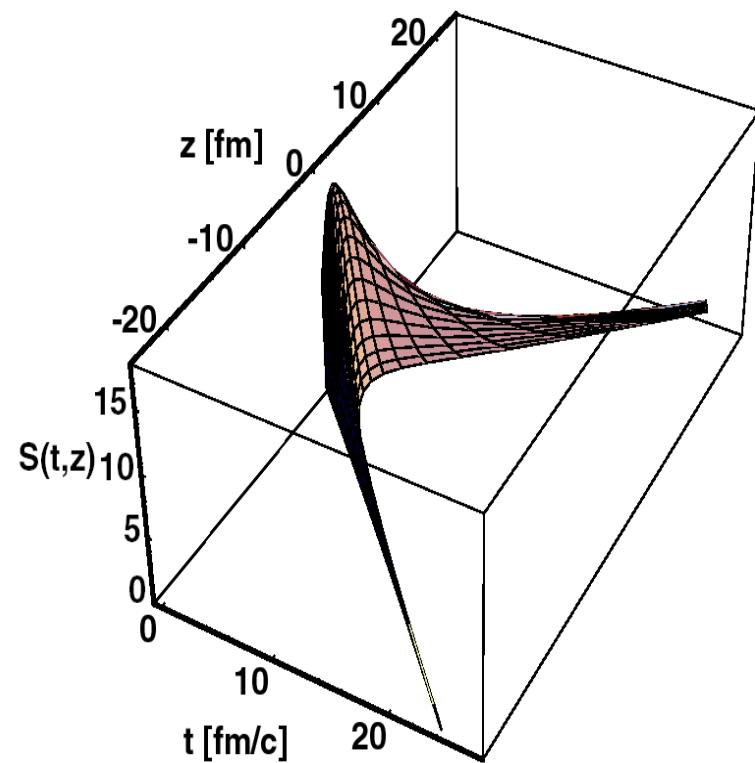
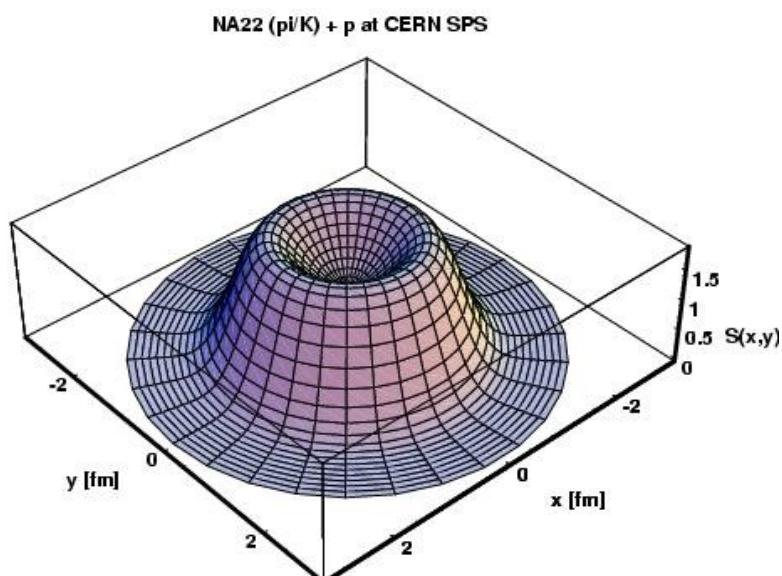
**HBT oscillation amplitudes of side, out and os are the same
 V_2 is given by flow asymmetry alone**

Buda-Lund hydro fits to NA22 h+p data



N. M. Agababyan et al, EHS/NA22 , PLB 422 (1998) 395
T. Csörgő, hep-ph/001233, Heavy Ion Phys. 15 (2002) 1-80

Buda-Lund hydro fits to NA22 h+p data



N. M. Agababyan et al, EHS/NA22 , PLB 422 (1998) 395
T. Csörgő, hep-ph/001233, Heavy Ion Phys. 15 (2002) 1-80

Back-up slides (EoS, equation for $T(t)$)