Indication for deconfinement at RHIC

Buda-Lund hydro fits to spectra and HBT radii

M. Csanád, T. Csörgő, B. Lörstad and A. Ster

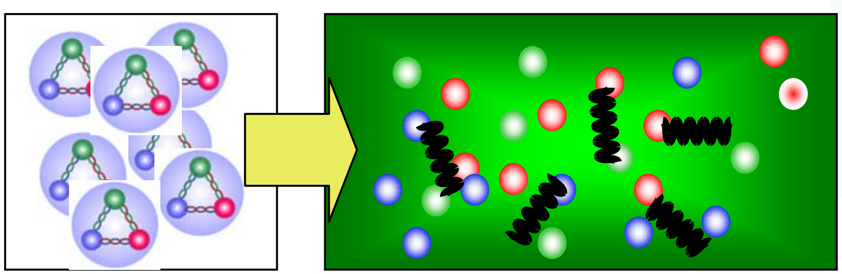
(Budapest & Lund)

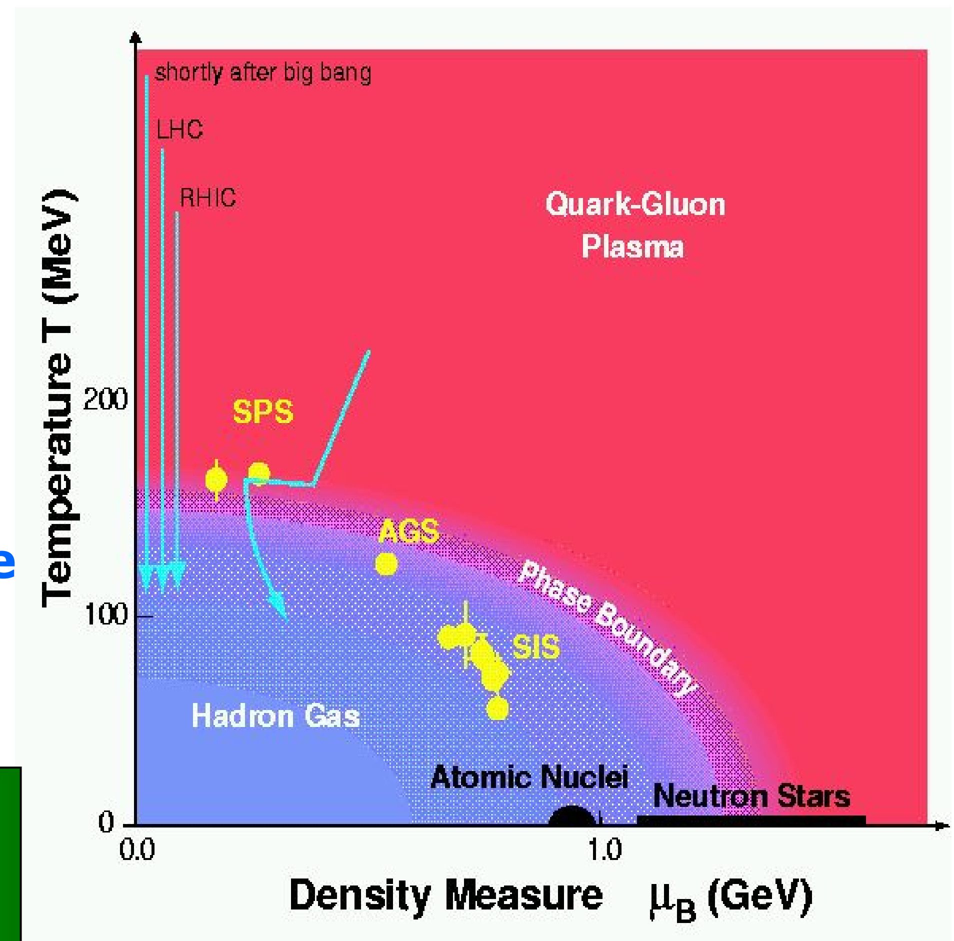
- Buda-Lund hydro model
- Buda-Lund fits to final RHIC Au+Au data
- A resolution of the “RHIC HBT puzzle”
  - Indication for a hot center, $T > T_c$
  - Confirmation by independent measurement
  - Prediction for new observables

Phases of QCD Matter

- **Quark Gluon Plasma**
  - **“Ionize” nucleons with heat**
  - **“Compress” them with density**
- **New state of matter**

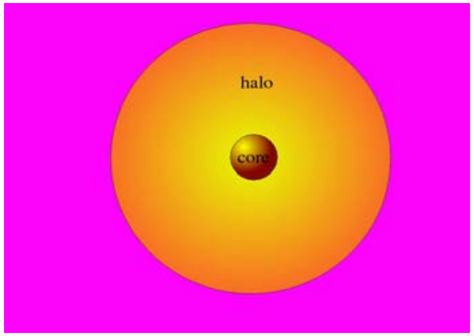
Z. Fodor and S.D. Katz:
T_c = 172 ± 3 MeV even at finite baryon density,
Cross over like transition.
(hep-lat/0106002)

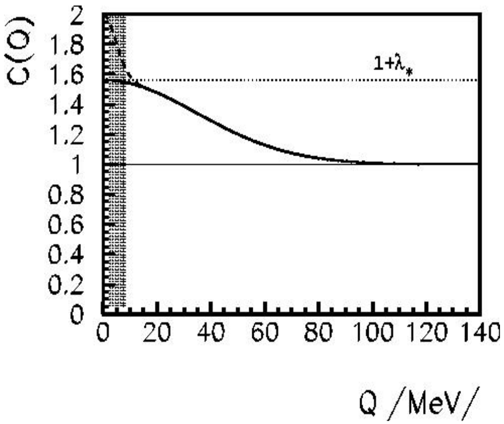




Principles for Buda-Lund hydro model

- Analytic expressions for all the observables
- 3d expansion, local thermal equilibrium, symmetry
- Goes back to known hydro solutions in nonrel limit
- Separation of the Core and the Halo
    - Core: hydrodynamic evolution
    - Halo: decay products of long-lived resonances





Buda-Lund hydro model

The general form of the emission function:

$$S_c(x,p)d^4x = \frac{g}{(2\pi)^3}\frac{p^\mu d^4\Sigma_\mu(x)}{\exp\left(\frac{p^\nu u_\nu(x)}{T(x)} - \frac{\mu(x)}{T(x)}\right) + s_q}$$

Calculation of observables with core-halo correction:

$$\mathrm{N}_1(p) = \frac{1}{\sqrt{\lambda_*}}\int d^4x S_c(p,x)$$

$$C(Q,p) = 1 + \left|\frac{\tilde{S}(Q,p)}{\tilde{S}(0,p)}\right|^2 = 1 + \lambda_*\left|\frac{\tilde{S}_c(Q,p)}{\tilde{S}_c(0,p)}\right|^2$$

Assuming special shapes for the flux, temperature, chemical potential and flow:

Buda-Lund hydro model

Invariant single particle spectrum:

$$N_1 = \frac{d^2n}{2\pi m_t dm_t dy} = \frac{g}{(2\pi)^3}\overline{E}\,\overline{V}\,\overline{C}\,\frac{1}{exp\left(\frac{p^\mu u_\mu(x_s)-\mu(x_s)}{T(x_s)}\right)+s_q}$$

Invariant Buda-Lund correlation function: oscillating, non-Gaussian prefactor!

$$C_2(k_1,k_2) = 1+\lambda_*\Omega(Q_{||})\exp\left(-Q_{||}^2R_{||}^2 - Q_{=}^2R_{=}^2 - Q_{\perp}^2R_{\perp}^2\right)$$

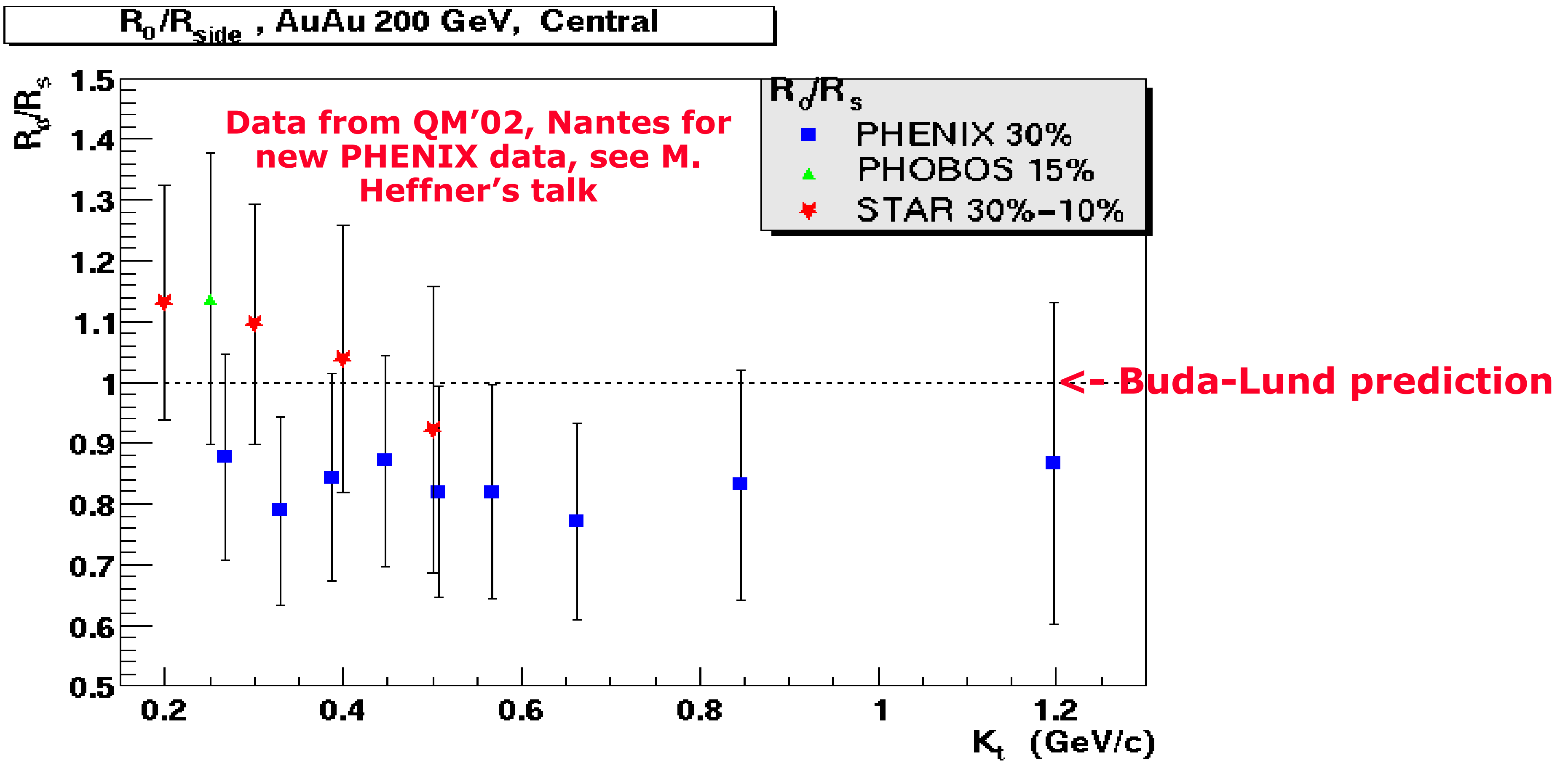
Non-invariant Bertsch-Pratt parameterization, Gaussian approximation:

$$C_2(k_1,k_2) = 1+\lambda_*\exp\left(-Q_o^2R_o^2 - Q_s^2R_s^2 - Q_l^2R_l^2 - 2Q_{os}^2R_oR_s\right)$$

Non-Gaussian BL form $\longrightarrow$ Gaussian BP *approximation*:

$$R_{||,\Omega}^2 = R_{||}^2\left(1+\frac{\overline{\Delta\eta}^2}{\overline{\eta}}\right)$$

R_{out}/R_{side} ratios at 200 GeV



- This reflects **symmetry** of the flow!
  (T. Csörgő & B. Lörstad, PRC54(1996)1390, NPA590(1995)465)
- Note also: R_{side}/R_{long} -> const (~1) as m_t>>T_0 is another BL prediction
- **Predicted** by a dynamical model with supercooling, hep-ph/940636

Buda-Lund fits to RHIC data

Calculation program packages:

Version 1.0: Calculation of IMD & Radii, linearized saddle-point equations
(NA22, NA44, NA49, prel. RHIC run-1)

Version 1.4: Calculation for $dN/\Delta\eta$ added

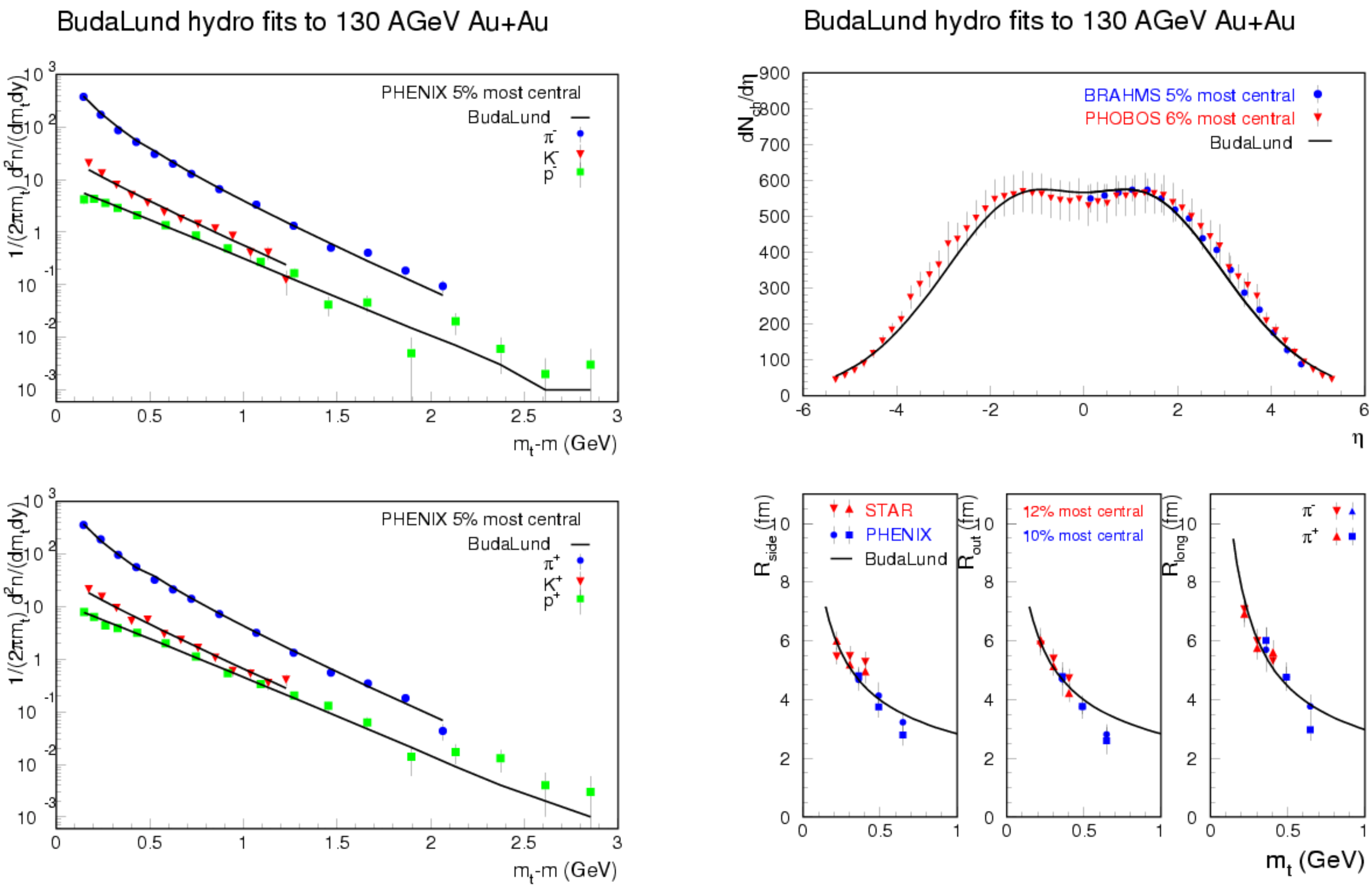
Version 1.5: Saddle point found exactly in direction η

http://www.kfki.hu/~csorgo/budalund/

Version 2.0: Exact analytic calculation (in progress)

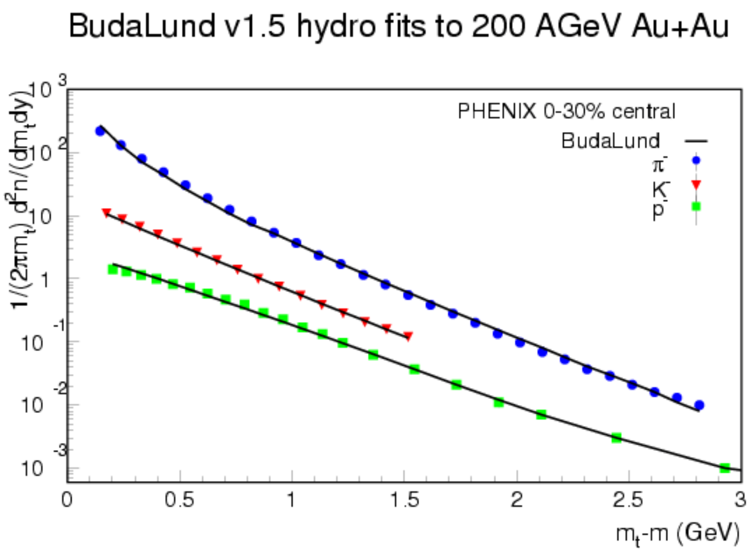
All versions: Analytic expressions for all observables and simultaneous fits to all the observables

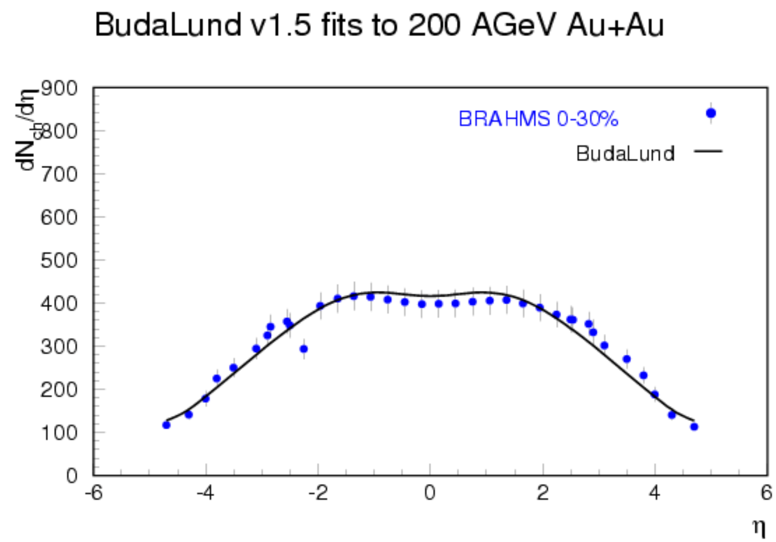
BudaLund fits, 130 GeV RHIC data

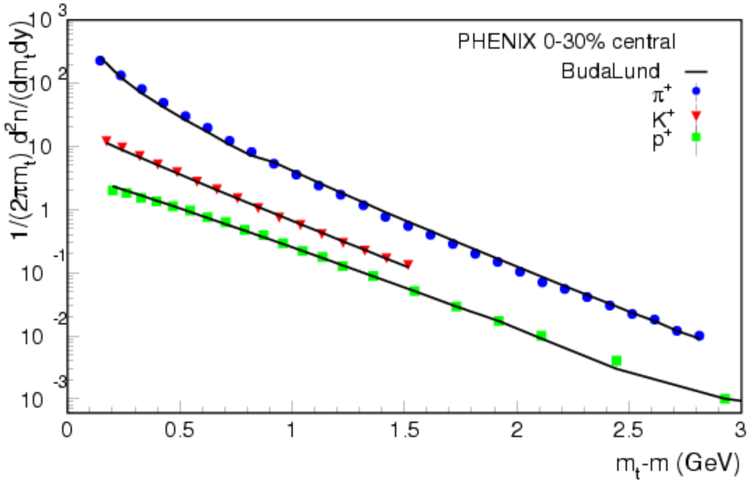


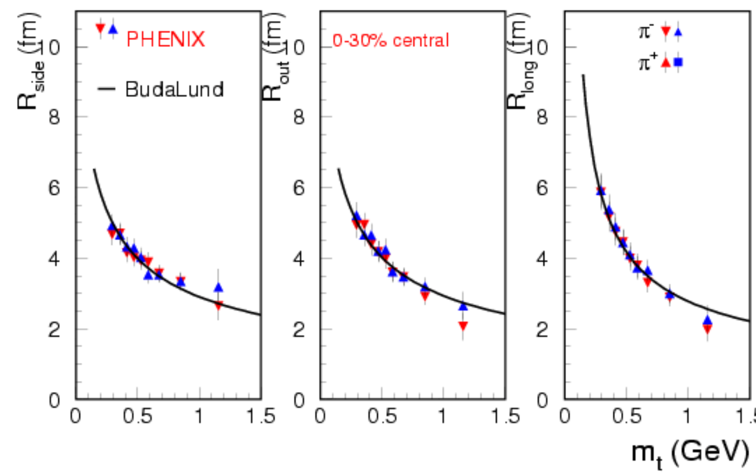
nucl-th/0311102, nucl-th/0207016

BudaLund fits, 200 GeV RHIC data









M. Csanád at QM'04

Comparing RHIC Au+Au to SPS results

BL v1.5 parameters	RHIC 200 GeV Au+Au		RHIC 130 GeV Au+Au		Pb+Pb SPS		h+p SPS	
T_0 [MeV]	200	$\pm$ 9	214	$\pm$7	139	$\pm$ 6	140	$\pm$ 3
$\langle u_t \rangle$	1.5	$\pm$ 0.1	1.0	$\pm$ 0.1	0.55	$\pm$ 0.06	0.20	$\pm$ 0.07
R_s [fm]	11.6	$\pm$ 1	8.6	$\pm$ 0.4	7.1	$\pm$ 0.2	0.88	$\pm$ 0.13
T_{surf} [MeV]	0.5 T_0	fixed	0.5 T_0	fixed	131	$\pm$ 8	82	$\pm$ 7
τ_0 [fm/c]	5.7	$\pm$ 0.2	6.0	$\pm$ 0.2	5.9	$\pm$ 0.6	1.4	$\pm$ 0.1
$\Delta\tau$ [fm/c]	1.9	$\pm$ 0.5	0.3	$\pm$ 1.2	1.6	$\pm$ 1.5	1.3	$\pm$ 0.3
$\Delta\eta$	3.1	$\pm$ 0.05	2.3	$\pm$ 0.4	2.1	$\pm$ 0.4	1.36	$\pm$ 0.02
T_{evap} [MeV]	127	$\pm$ 13	102	$\pm$ 11	87	$\pm$ 24	-	
μ_0^{π} [MeV]	-2	$\pm$ 14	63	$\pm$ 11				
μ_0^{K+} [MeV]	16	$\pm$ 19	98	$\pm$ 19				
μ_0^{p-} [MeV]	97	$\pm$ 28	315	$\pm$ 27				
μ_B [MeV]	61	$\pm$ 39	77	$\pm$ 38				
χ^2/NDF	126/208=0.61		158/180=0.9					
CL	100	%	88	%				

A 5σ effect, $T_0 > T_c$

T_0 (RHIC) > T_0 (SPS)

Indication for quarks & hard EOS

μ_B = 77 ± 38 MeV

M. Csanád at QM’04

Comparison of expansion rates:

RHIC and the universe

Universality of the Hubble expansion: u = H r

Hubble constant of the Universe: H_0= (71 ± 7) km/sec/Mpc

converted to SI units: H_0= (2.3 ± 0.2)x10^{-18} sec^{-1}

Hubble constant at Au+Au collisions with 200 GeV

Method a) $H_{RHIC} = \langle u_t \rangle / R_G \sim (3.8 \pm 0.5) \times 10^{22}\ sec^{-1}$

Method b) $H_{RHIC} = 1/\tau_0 \sim (5.1 \pm 0.1 \times 10^{22})\ sec^{-1}$

Ratio of expansion rates:

$$H_{RHIC} / H_0 \sim 2 \times 10^{40}$$

**approx. the ratio of the ages of the objects,
without correction for inflation...**

New ways of plotting the results

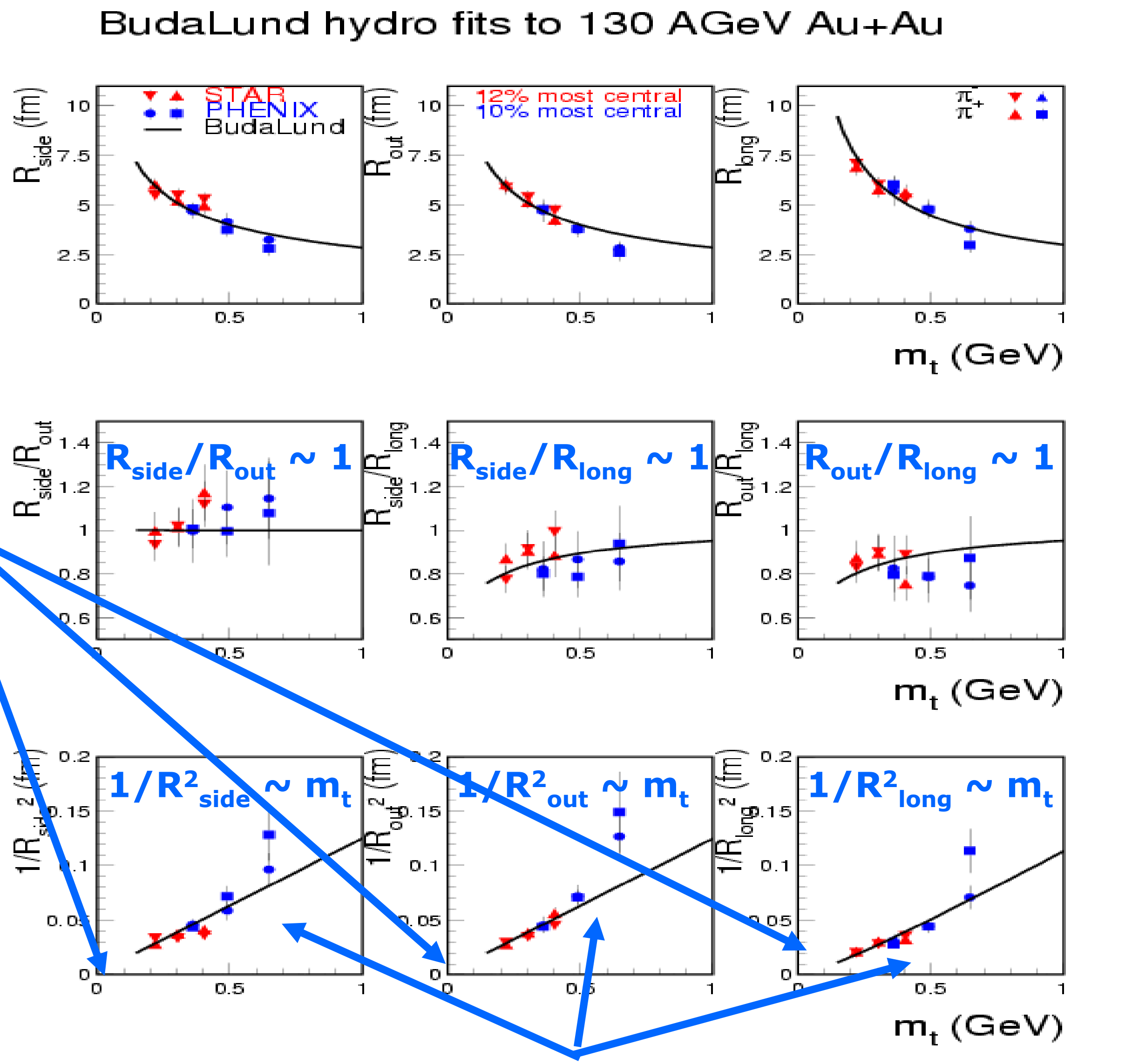
$1/R^2_{eff} = 1/R^2_{geom} + 1/R^2_{therm}$
and $1/R^2_{therm} \sim m_t$

$\Downarrow$

intercept is nearly 0,
indicating $1/R_G^2 \sim 0$,

thus $\mu(x)/T(x)$ = const!

reason for success of
thermal models @ RHIC!



same slopes ~ fully developed, **3d Hubble flow**

SUMMARY

The analysis of RHIC Au+Au data from BRAHMS, PHOBOS, PHENIX and STAR show:

- **succesful Buda-Lund hydro fits**

  (also at h+p and Pb+Pb at SPS)

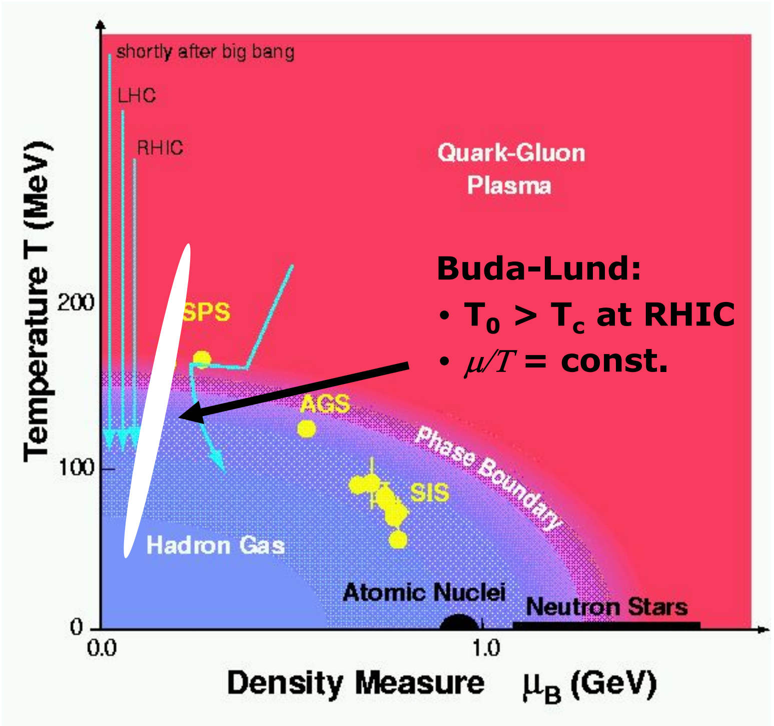
- **indication for deconfinement at RHIC**

  ($T > T_c = 172$ MeV by 3σ at RHIC, but not at SPS)

- **evidence for a developed 3d Hubble flow at RHIC**

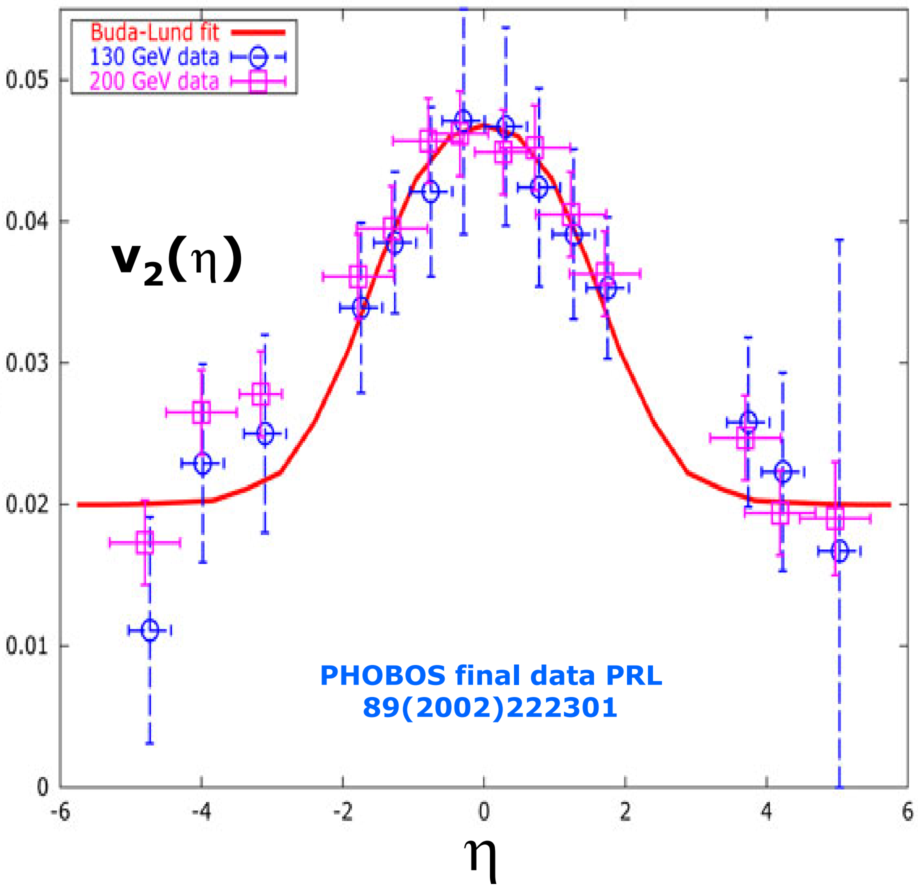
A solution of the RHIC HBT puzzle

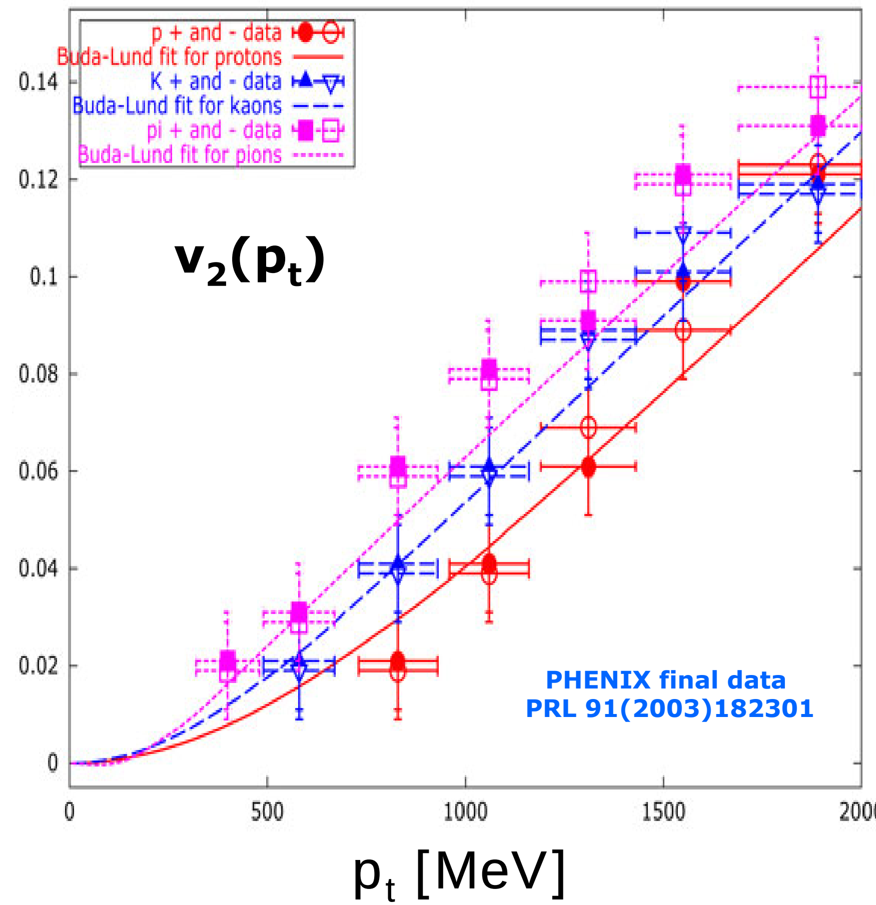
- Our answer: hot center, a fireball heated from inside
- If we **assume** a hot center, the difference between out and side vanishes



- **Confirmed** in fits for the rapidity dependence of the elliptic flow, see **poster (Flow-12)** and nucl-th/0310040
- **Prediction:** $v_4(p_t)$, $v_1(\eta)$, $v_3(\eta)$

Confirmation of hot center



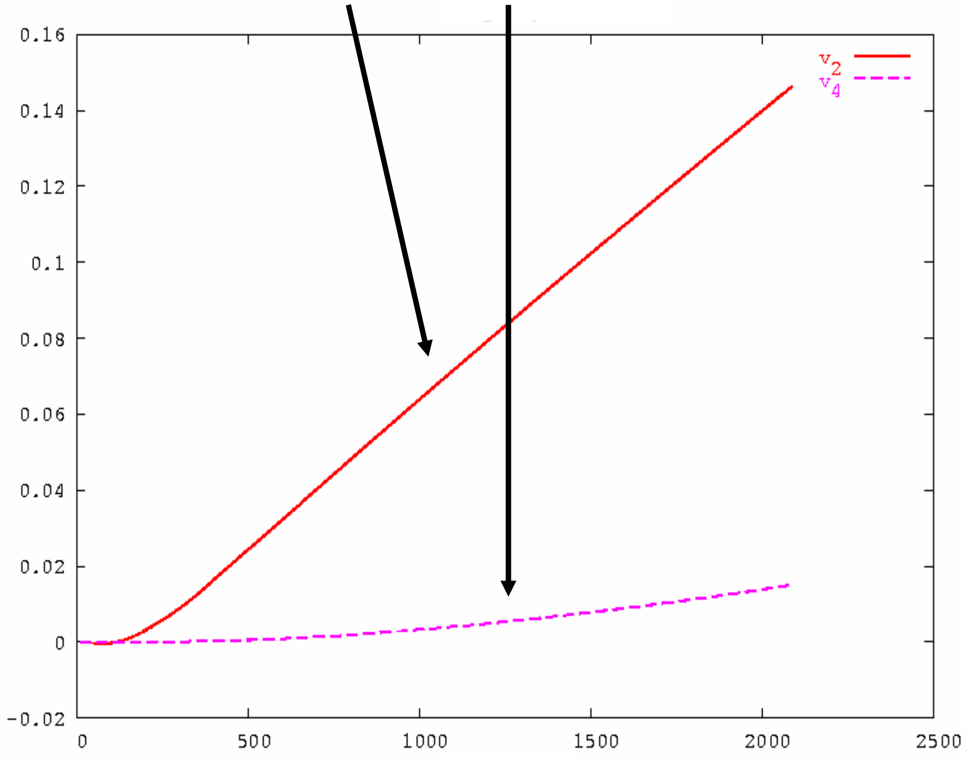


$$T_s = 105\ \mathrm{MeV},\ T_0 = 210\ \mathrm{MeV},\ \tau_0 = 7\ \mathrm{fm/c},\ \vartheta = 0.09$$
$$\dot{X} = 0.57,\ \dot{Y} = 0.45,\ \dot{Z} = 2.4$$
$$X_f = 8.6\ \mathrm{fm},\ Y_f = 10.5\ \mathrm{fm},\ Z_f = 17.5\ \mathrm{fm}$$

poster Flow-12, nucl-th/0310040

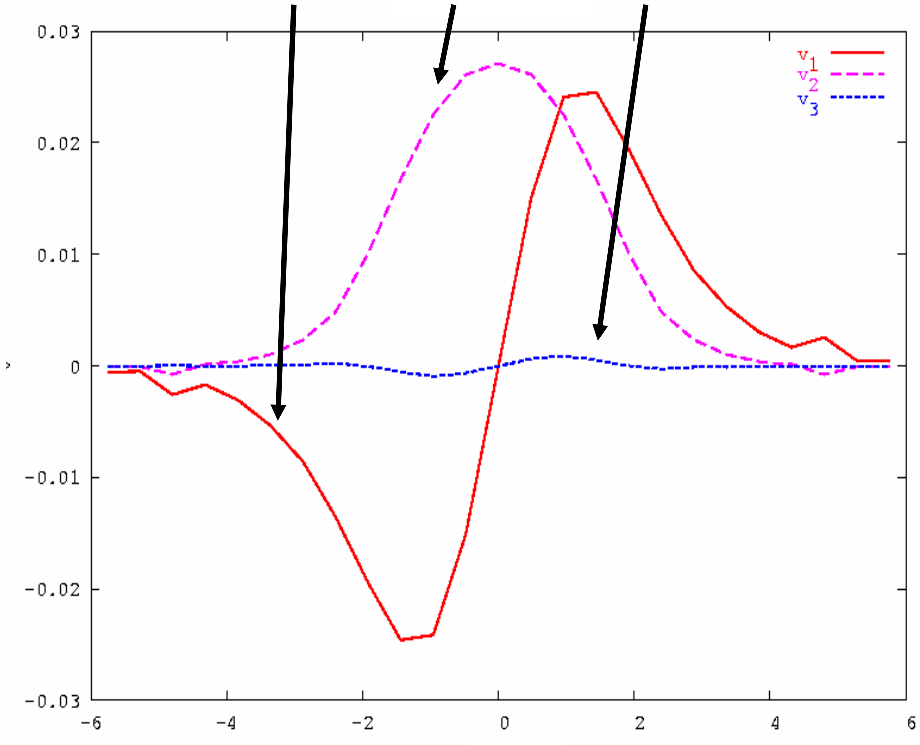
Prediction

$v_2(p_t)$, $v_4(p_t)$



p_t [MeV]

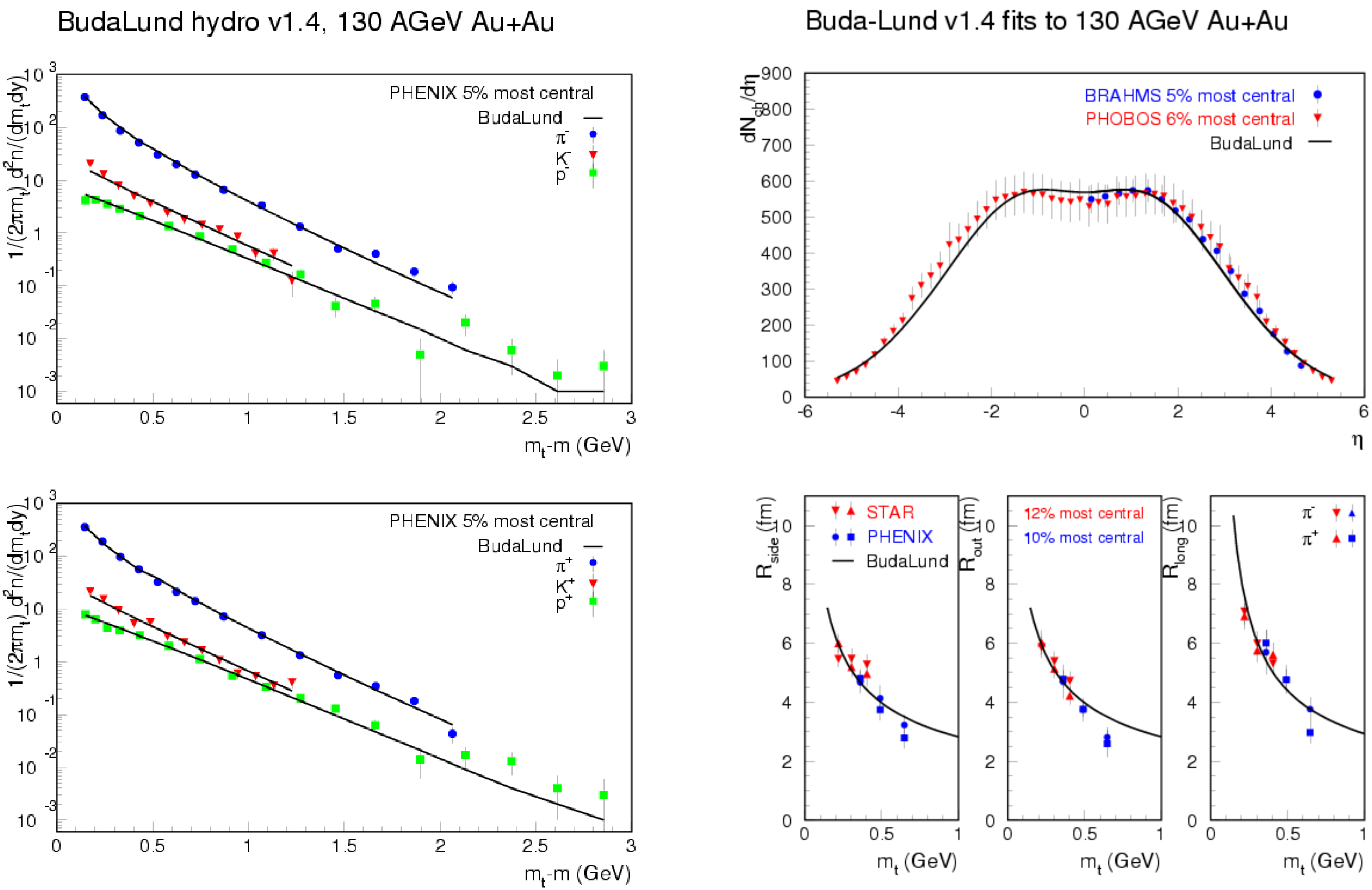
$v_1(\eta)$, $v_2(\eta)$, $v_3(\eta)$



η

Thank you for your attention.

BudaLund fits to final run-1 RHIC data



M. Csanád at QM'04

BudaLund fits to final run-1 RHIC data

BL-H source	Buda-Lund v1.0	Buda-Lund v1.4
T_0 [MeV]	202 $\pm$ 13	232 $\pm$ 16
$\langle u_t \rangle$	1.0 $\pm$ 0.2	0.9 $\pm$ 0.06
R_G [fm]	9.8 $\pm$ 1.2	10.0 Fixed
τ_0 [fm/c]	6.1 $\pm$ 0.3	6.1 $\pm$ 0.3
$\Delta\tau$ [fm/c]	0.0 $\pm$ 1.5	0.0 $\pm$ 1.0
$\Delta\eta$	2.5 Fixed	2.3 $\pm$ 0.04
T_{surf} [MeV]	110 $\pm$ 24	94 $\pm$ 4
T_{eva} [MeV]	88 $\pm$ 25	98 $\pm$ 11
$\mu_0^{\pi-}$ [MeV]	75 $\pm$ 19	97 $\pm$ 16
μ_0^{K-} [MeV]	107 $\pm$ 14	89 $\pm$ 27
μ_0^{p-} [MeV]	305 $\pm$ 41	272 $\pm$ 47
$\mu_0^{\pi+}$ [MeV]	-	79 $\pm$ 13
μ_0^{K+} [MeV]	-	123 $\pm$ 27
μ_0^{p} [MeV]	-	353 $\pm$ 46
χ^2/NDF	74/68 =1.08	226/18 =1.25
CL	28.9 %	1.3 %

V1.0 fits to STAR & PHENIX data at midrapidity, Deta fixed

V1.4 Rg fixed as data determine <ut>/Rg dependence only

NEXT TO DO

Fits to :

new NA49 data (with Kaon correlation),

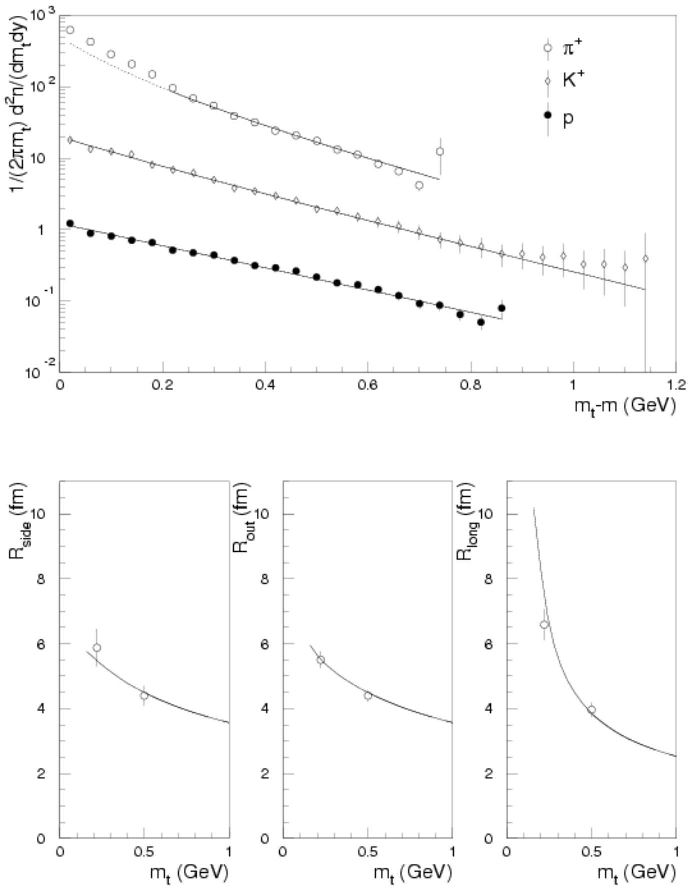
NA44 data,

CERES data

at SPS.

new run-2 data at RHIC

Buda-Lund fits to NA44 Pb+Pb data

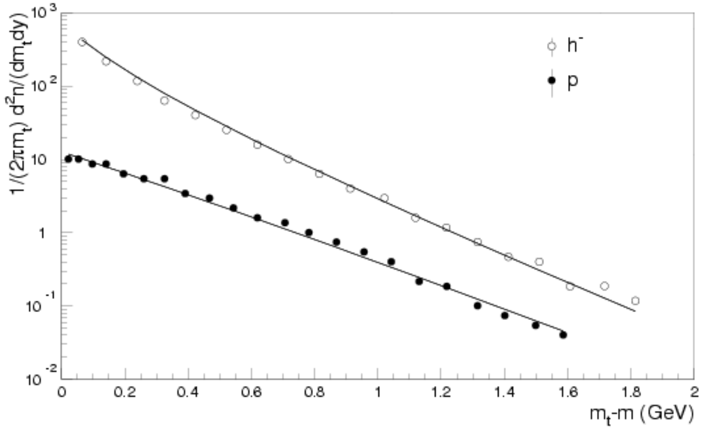


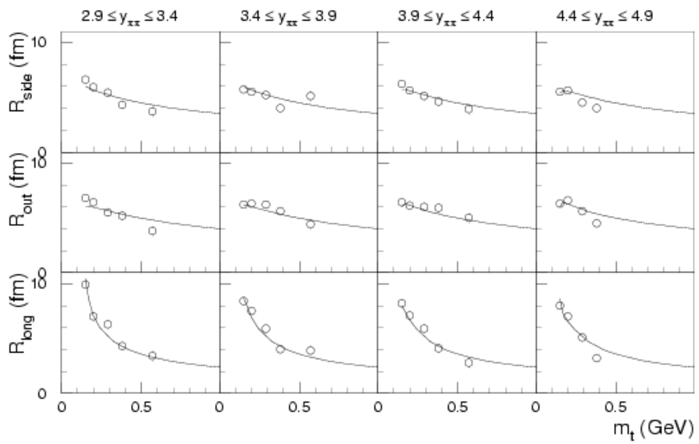
BL-H source parameters		
T_0	145	$\pm$ 3 MeV
$<u_t>$	0.57	$\pm$ 0.12
R_G	6.9	$\pm$ 1.1 fm
τ_0	6.1	$\pm$ 0.9 fm/c
$\Delta\tau$	0.1	$\pm$ 2.2 fm/c
$\Delta\eta$	2.4	$\pm$ 1.6
$<\Delta T/T>_r$	0.08	$\pm$ 0.08
$<\Delta T/T>_t$	0.87	$\pm$ 0.72
χ^2/NDF	63/71	= 0.89

Final data
Absolute normalization,
Boltzmann approx.,
$\Omega \sim 1$, $\mu_0 = 0$ approx.

A. Ster, T. Cs, B. Lörstad, hep-ph/9907338

Buda-Lund fits to NA49 Pb+Pb data



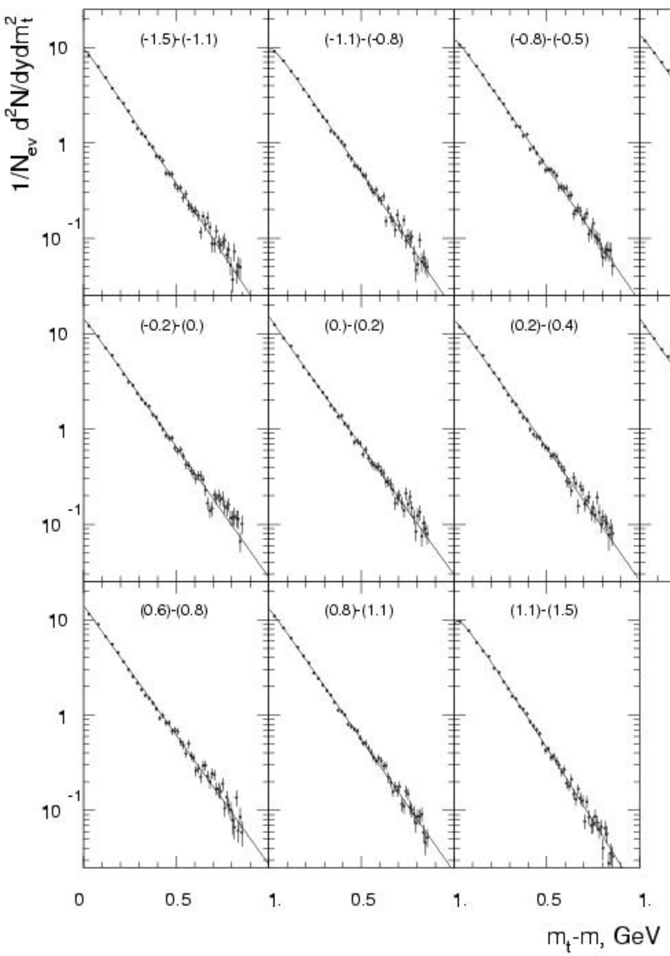


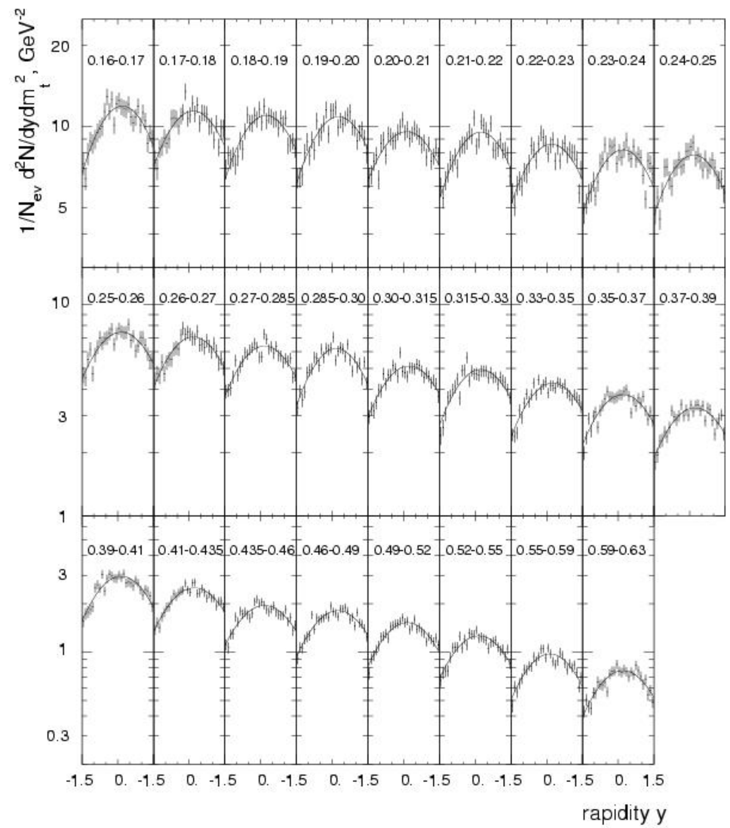
BL-H source parameters		
T_0	134	$\pm$ 3 MeV
$<u_t>$	0.61	$\pm$ 0.05
R_G	7.3	$\pm$ 0.3 fm
τ_0	6.1	$\pm$ 0.2 fm/c
$\Delta\tau$	2.8	$\pm$ 0.4 fm/c
$\Delta\eta$	2.1	$\pm$ 0.2
$<\Delta T/T>_r$	0.07	$\pm$ 0.02
$<\Delta T/T>_t$	0.16	$\pm$ 0.05
χ^2/NDF	163/98	= 1.66

Final data
Absolute normalization,
Boltzmann approx.,
$\Omega \sim 1$, $\mu_0 = 0$ approx.

A. Ster, T. Cs, B. Lörstad, hep-ph/9907338

Buda-Lund fits to NA22 h + p data

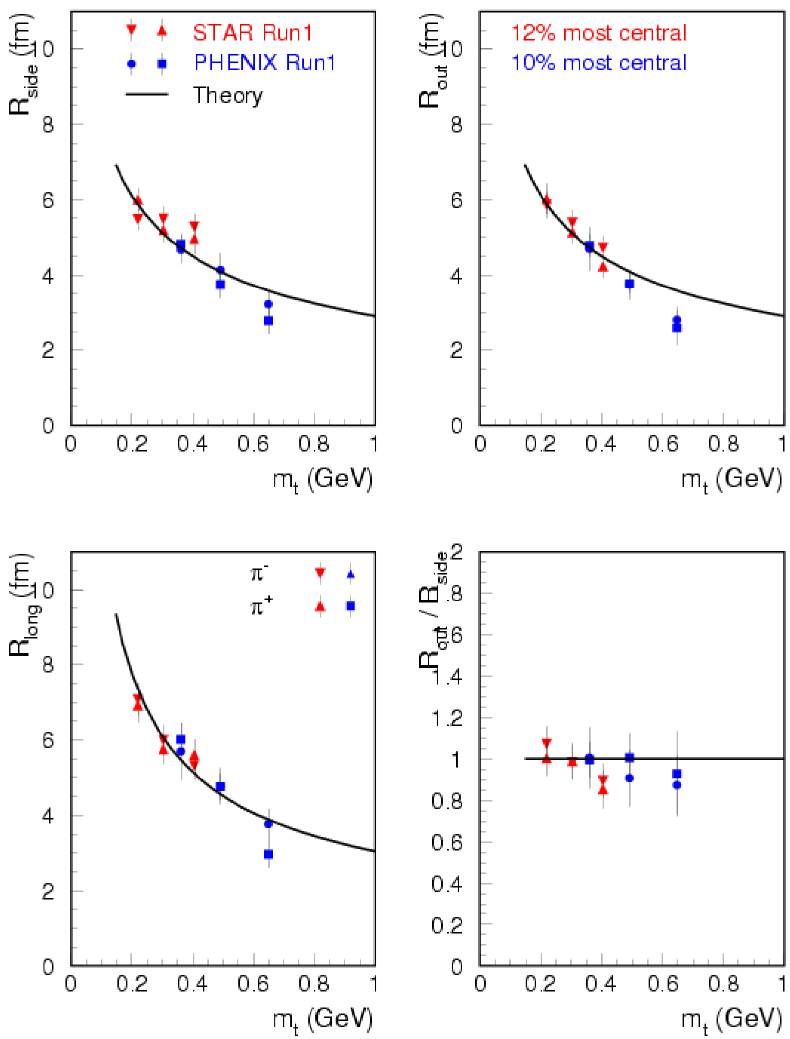




N. M. Agababyan et al, EHS/NA22 , PLB 422 (1998) 395
T. Csörgő, hep-ph/001233, Heavy Ion Phys. 15 (2002) 1-80

Comparison of results of models

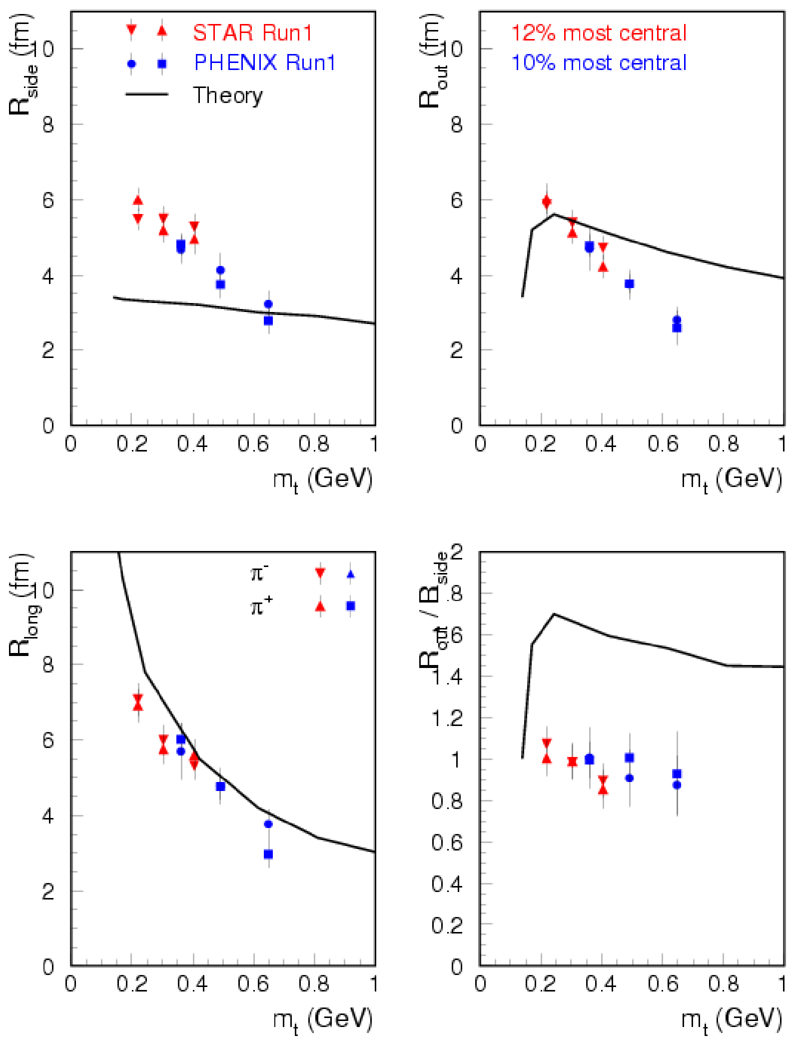
nucl-th/0207016-1 fits to 130 AGeV Au+Au



Acceptable

Comparison of results of models

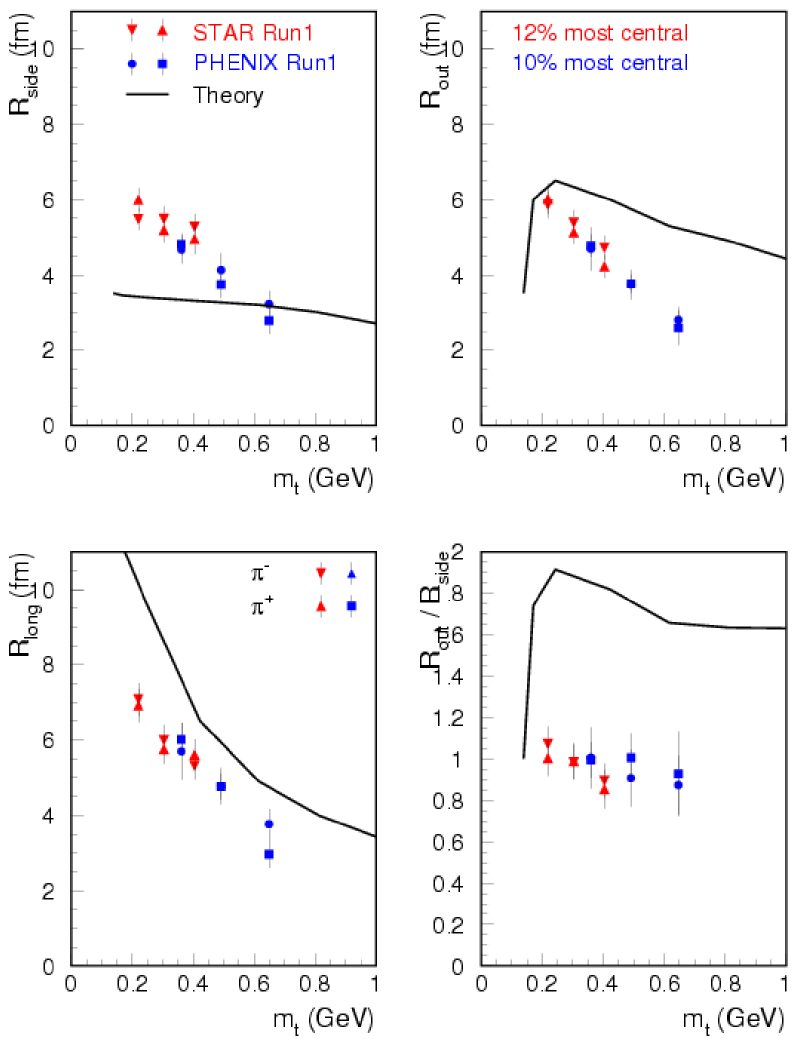
nucl-th/0208068-1 fits to 130 AGeV Au+Au



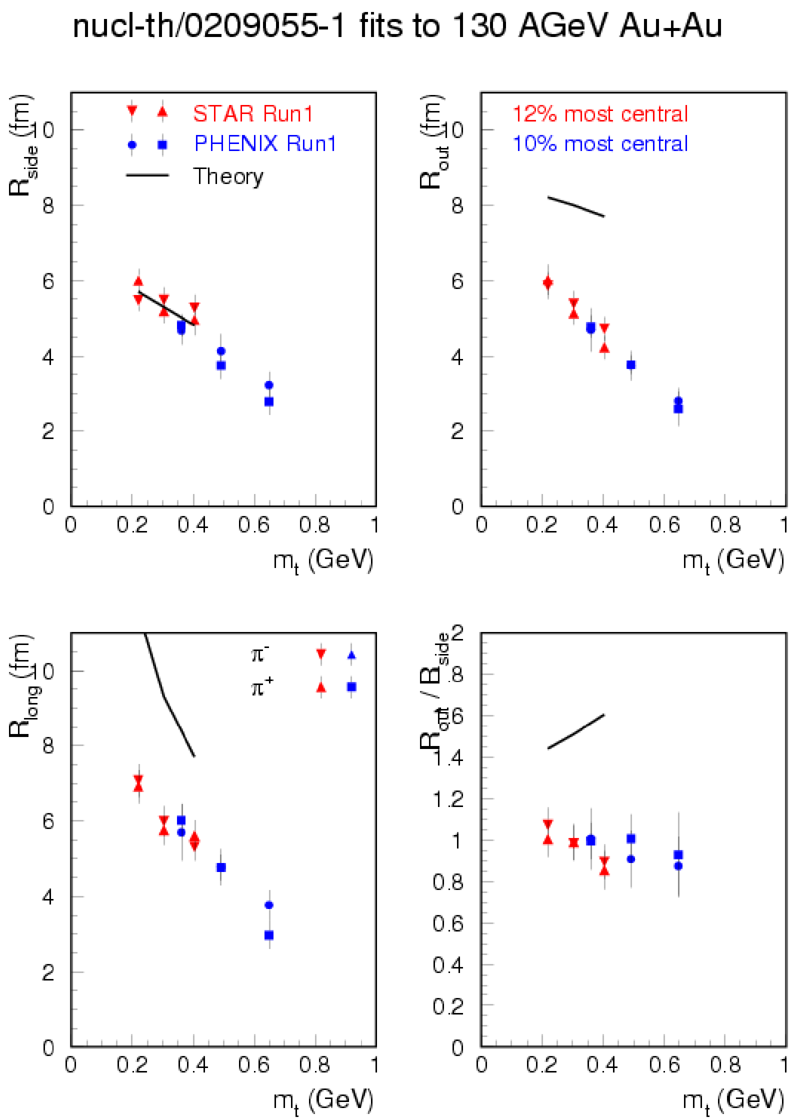
M. Csanád at QM'04

Comparison of results of models

nucl-th/0208068-2 fits to 130 AGeV Au+Au

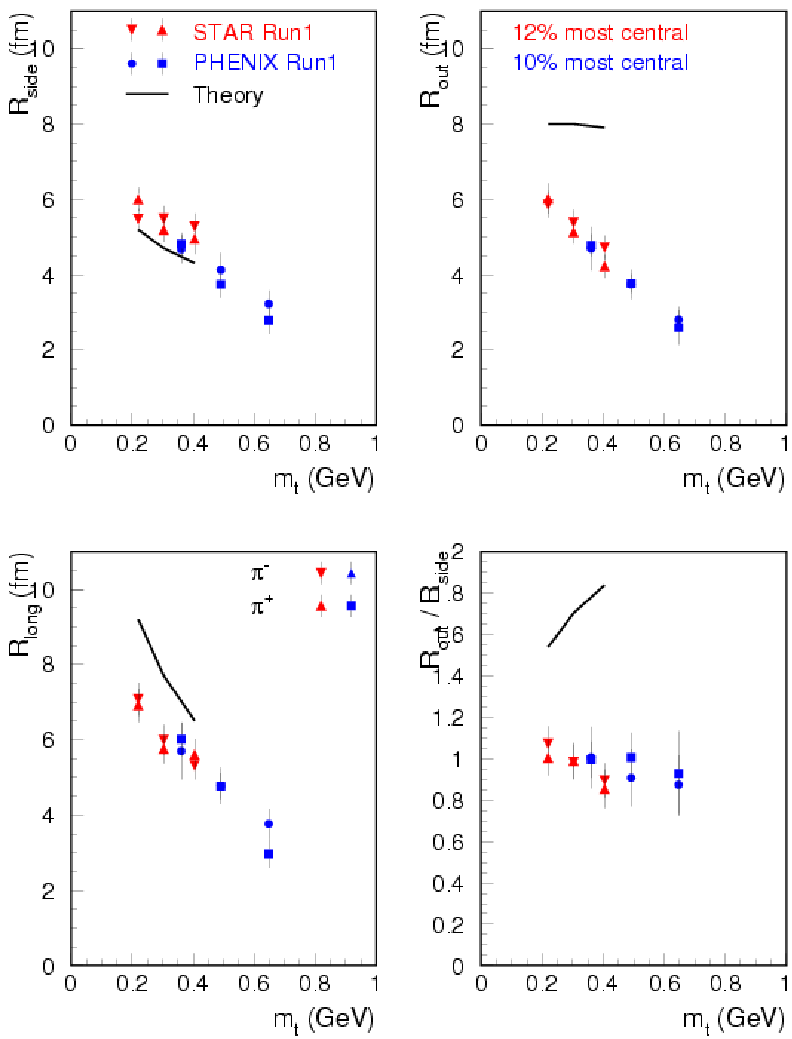


Comparison of results of models



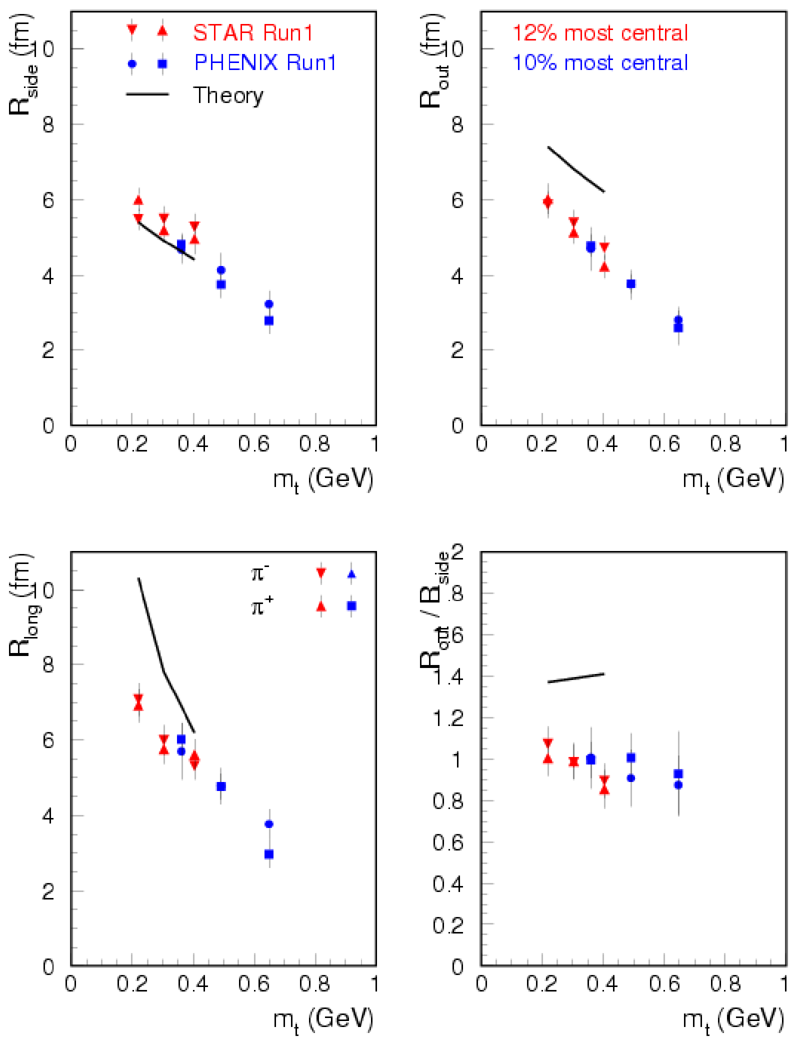
Comparison of results of models

nucl-th/0209055-2 fits to 130 AGeV Au+Au



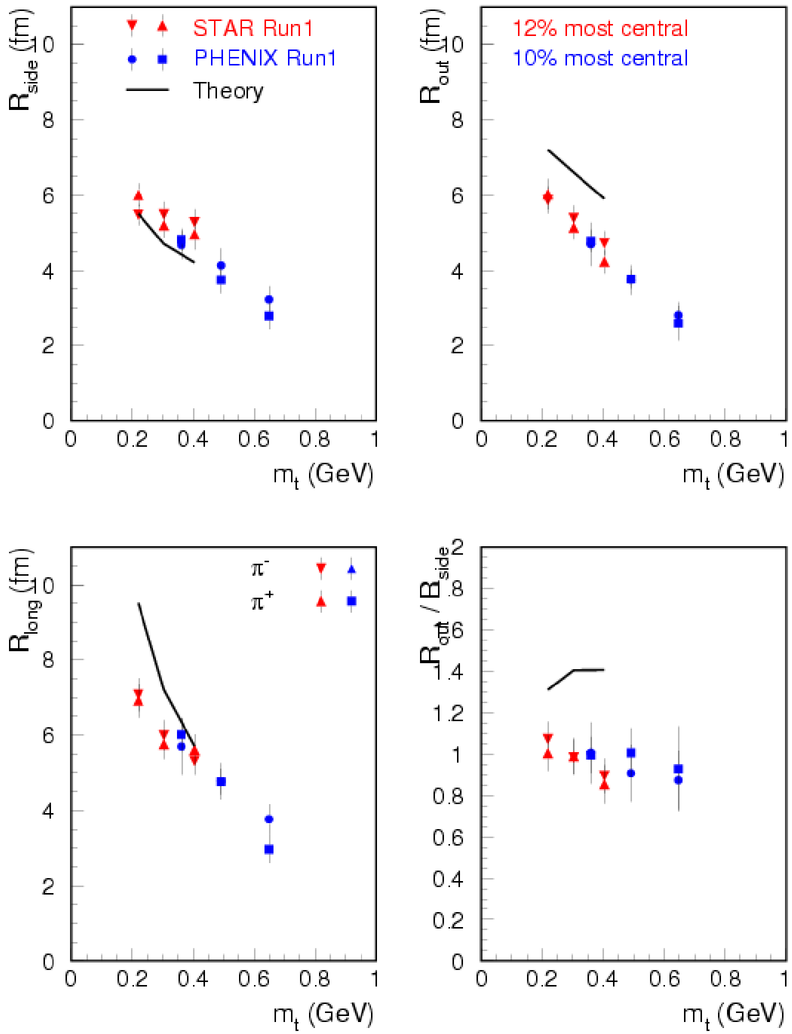
Comparison of results of models

nucl-th/0209055-3 fits to 130 AGeV Au+Au



Comparison of results of models

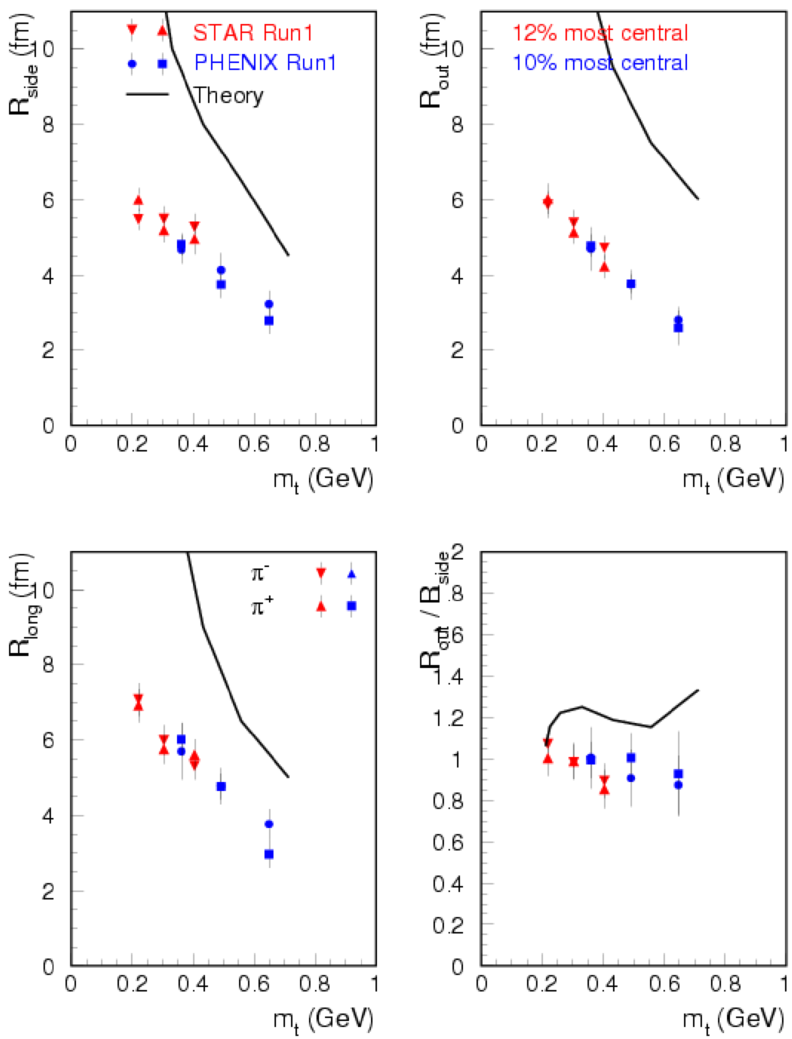
nucl-th/0209055-4 fits to 130 AGeV Au+Au



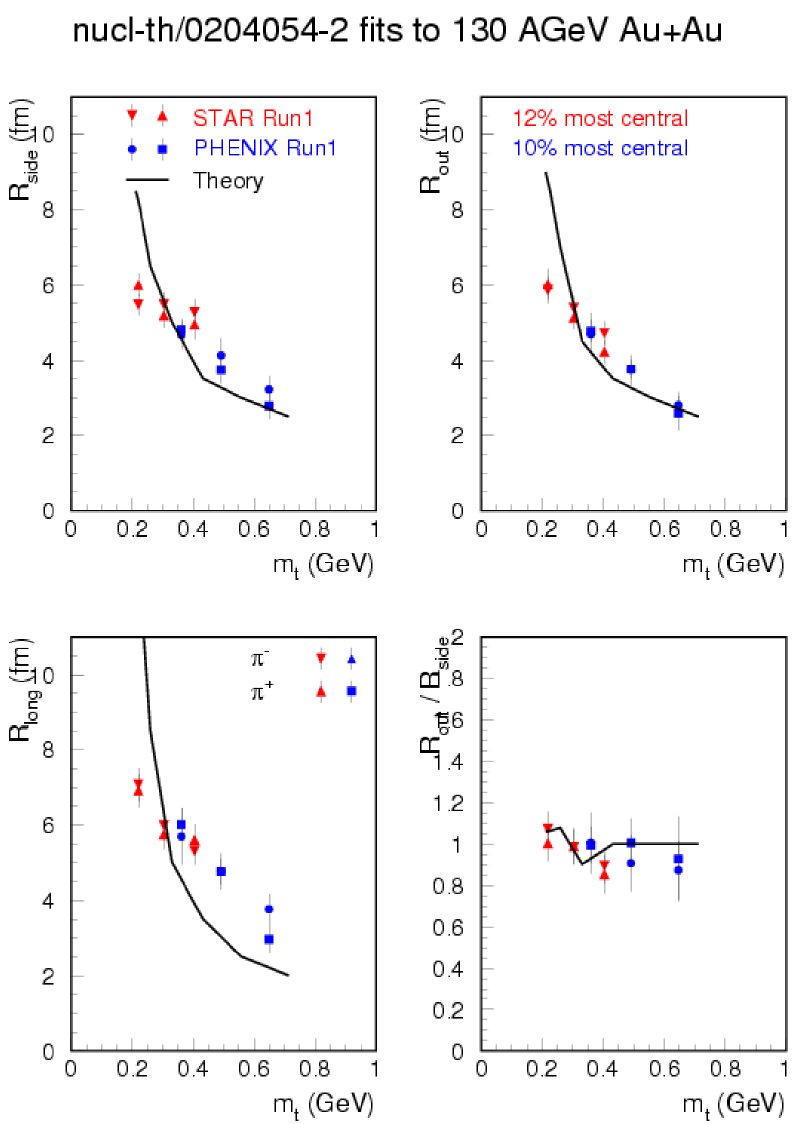
M. Csanád at QM'04

Comparison of results of models

nucl-th/0204054-1 fits to 130 AGeV Au+Au



Comparison of results of models

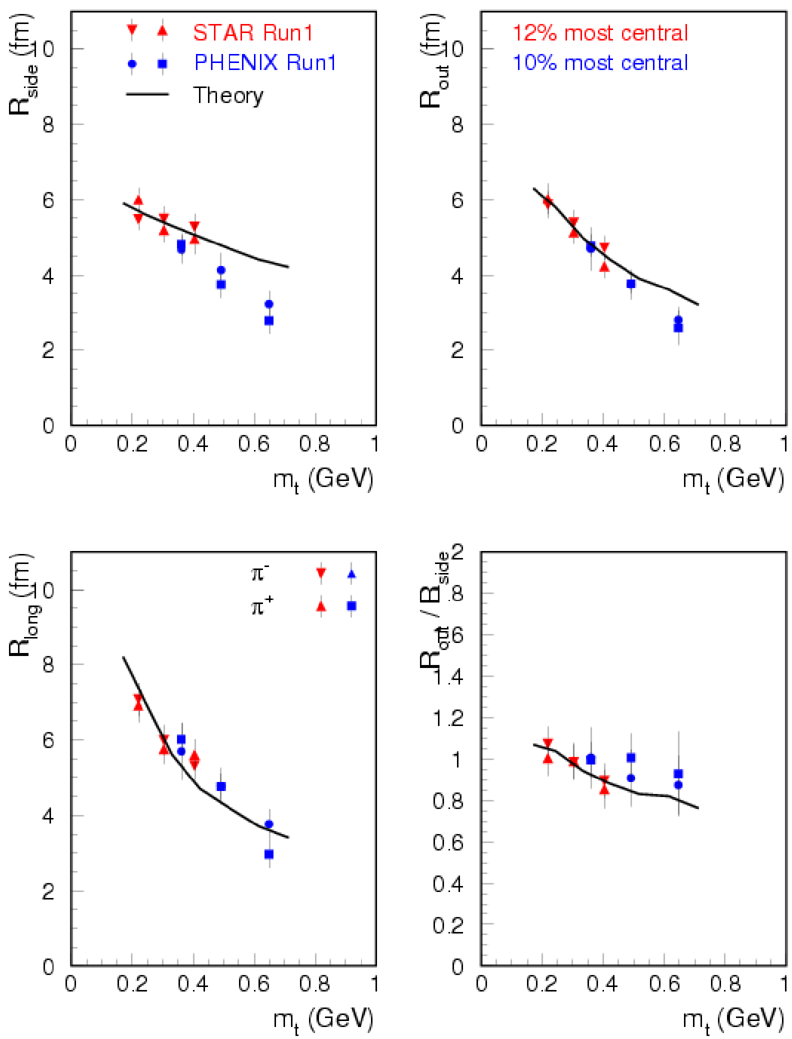


~ Acceptable

M. Csanád at QM'04

Comparison of results of models

nucl-ex/0307026-1 fits to 130 AGeV Au+Au

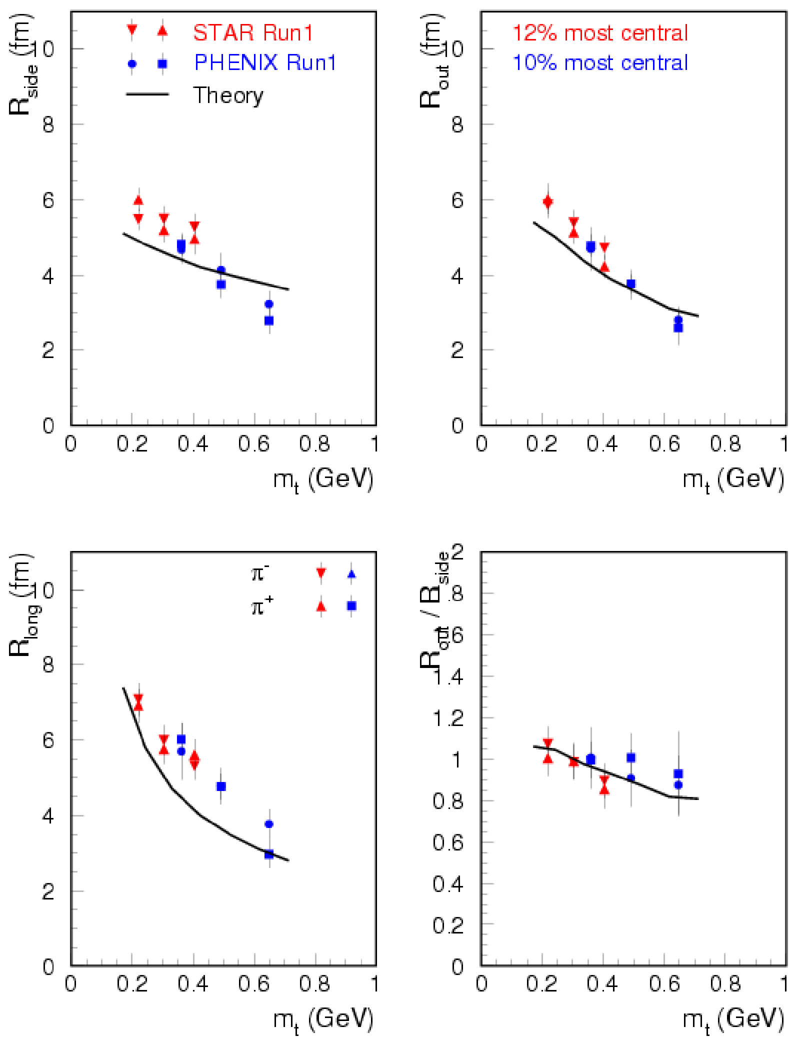


Acceptable

M. Csanád at QM'04

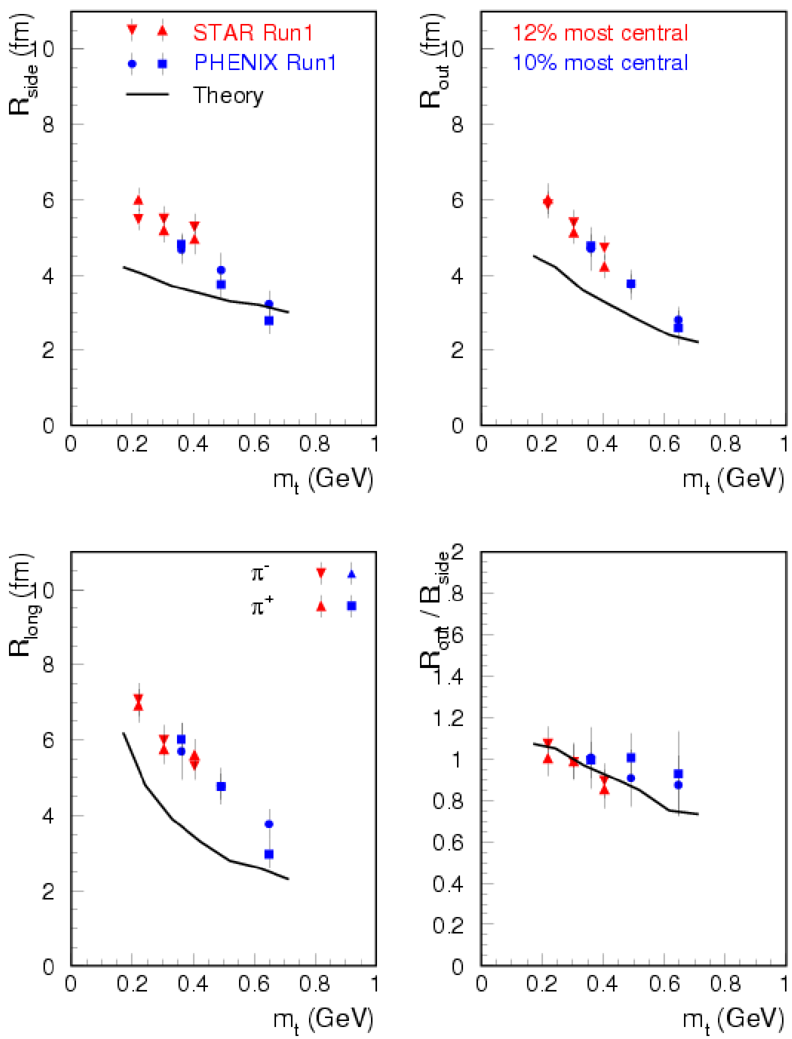
Comparison of results of models

nucl-ex/0307026-2 fits to 130 AGeV Au+Au



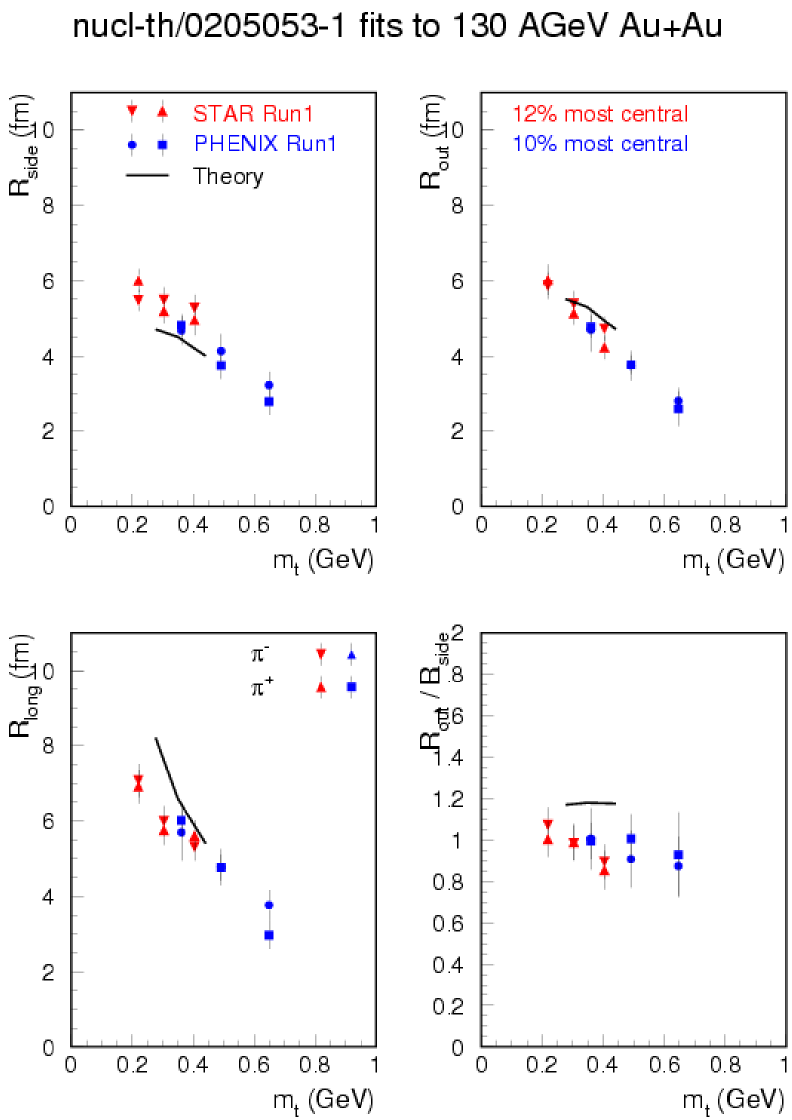
Comparison of results of models

nucl-ex/0307026-3 fits to 130 AGeV Au+Au



M. Csanád at QM’04

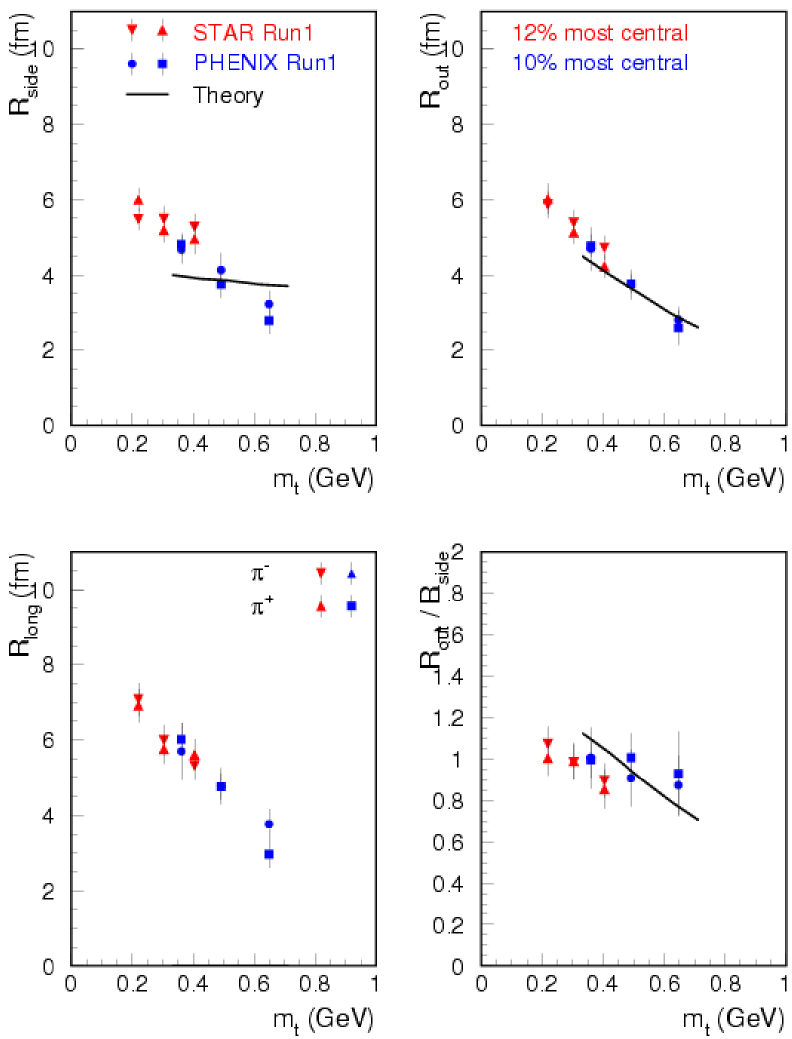
Comparison of results of models



~
Acceptable

Comparison of results of models

nucl-th/0212053-2 fits to 130 AGeV Au+Au



Comparison of results of models

Models with acceptable results:

nucl-th/0204054 Multiphase Trasport model (AMPT).
Z. Lin, C. M. Ko, S. Pal.

nucl-th/0205053 Hadron cascade model. T . Humanic.

nucl-th/0207016 Buda-Lund hydro model.
T.Csörgő. A. Ster,
Heavy Ion Phys. 17 (2003) 295-312.

nucl-ex/0307026 Blast wave model. F. Retiére for STAR.

Not shown here but acceptable:

nucl-th/0208068 3D hydro model. T. Hirano, & T.Tsuda.

hep-ph/0209054 Cracow (single freeze-out, thermal) model.
W.Broniowski, A. Baran, W. Florkowski.