Onset of radial flow in p+p collisions

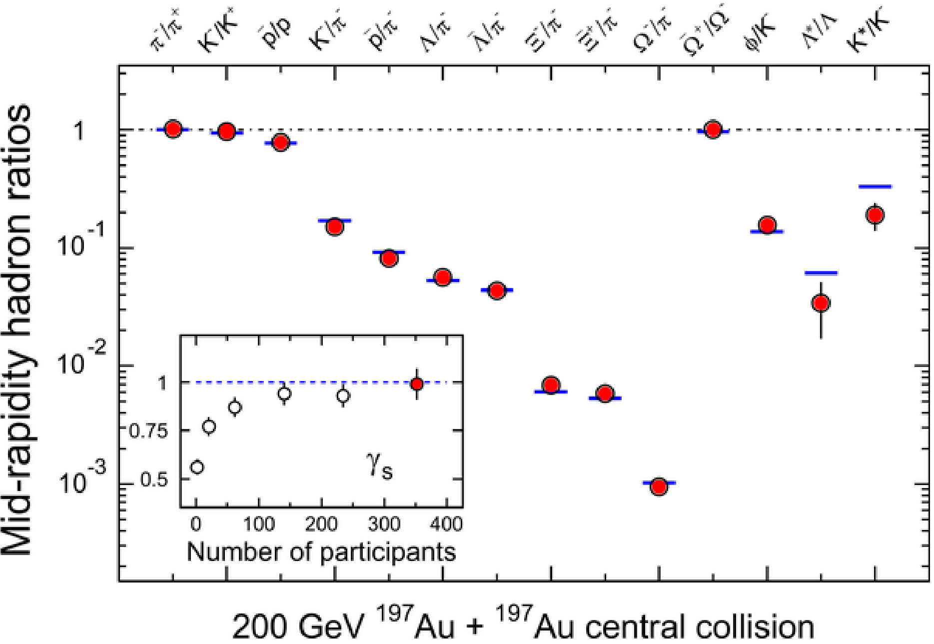
Kun Jiang, Zebo Tang, Zhangbu Xu

Zebo Tang et al.,
arXiv: 1101.1912 [nucl-ex]
JPG 37 (2010) 085104
PRC 79 (2009) 051901

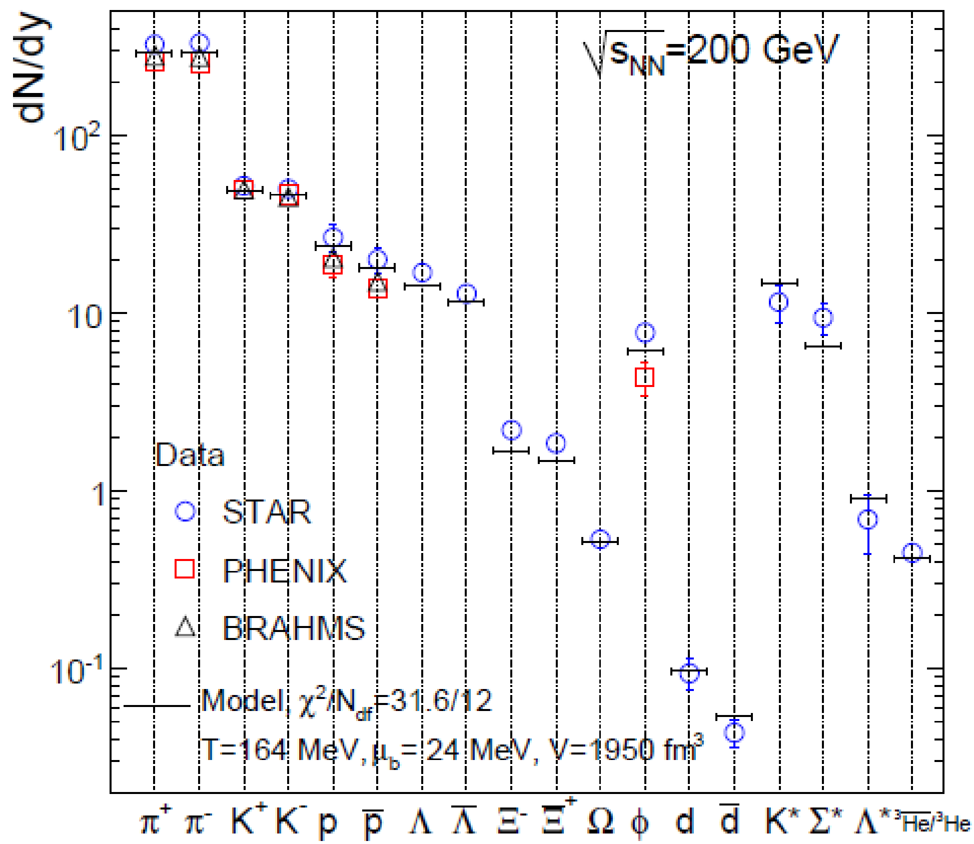
- Why do we need a new BlastWave model and non-equilibrium
- Parameterize data with least-$\chi 2$ fit
- Radial flow in A+A collisions
- Practical definition of radial flow in p+p?
- Onset of radial flow in p+p collisions
- Summary and Outlook

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
U.S. DEPARTMENT OF ENERGY

Statistical description of hadron yields



STAR whitepaper, NPA757(2005)



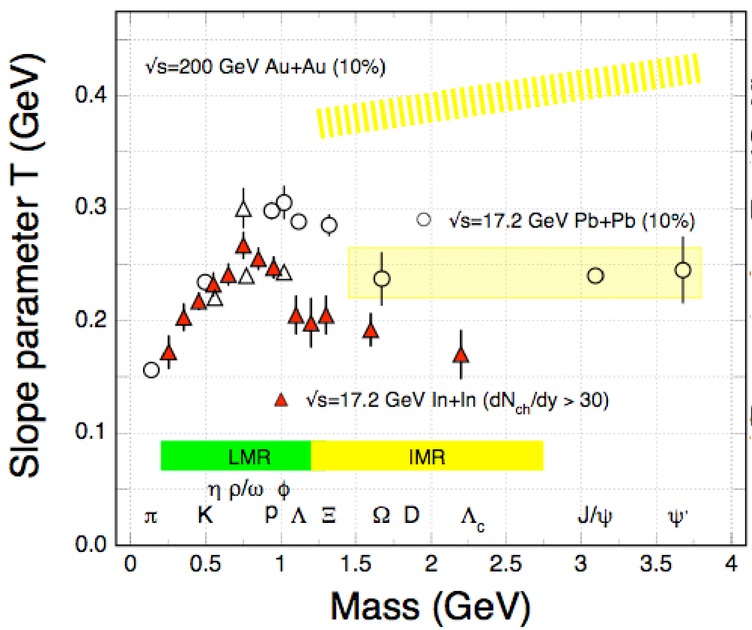
J. Rafelski and B. Muller, Phys.Rev.Lett.48:1066,1982

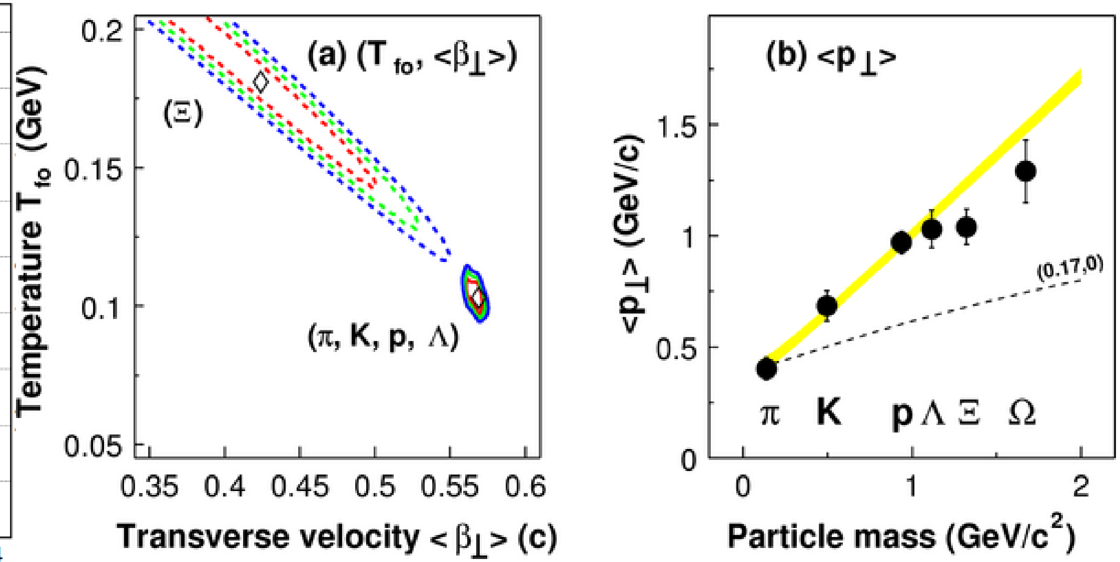
A. Andronic, P.Braun-Munzinger, J.Stachel, Phys. Lett. B 673 (2009) 142

A. Andronic, P.Braun-Munzinger, K.Redlich, J.Stachel, Phys. Lett. B 652 (2007) 259; B 678 (2009) 350; arXiv:1002.4441

m_T slope vs mass

Nu Xu's plot





Nu Xu, QM2008

STAR whitepaper, PRL92(2004)

$T_{eff} = T + 1/2 m\beta^2$

Radial flow

Spectral shape depends on PID mass
Higher mass => larger inverse slope
More central => larger inverse slope

	Central	Mid-central	Peripheral
data			
π, K, p spectra [79]	0-5%	15-30%	60-92%
Λ spectra [80]	0-5%	20-35%	35-75%
pion radii [67]	0-12%	12-32%	32-72%
Elliptic flow [38]	0-11%	11-45%	45-85%
χ^2/(# data points)			
π^+ & π^- spectra	7.2/10	26.5/10	13.0/9
K^+ & K^- spectra	24.2/22	21.4/22	10.1/10
p & $\overline{p}$ spectra	10.6/18	23.2/18	28.0/12
Λ & $\overline{\Lambda}$ spectra	9.5/16	12.8/16	11.0/16
$\pi\ v_2$	14.6/12	29.8/12	5.2/12
$p\ v_2$	1.6/3	9.2/6	0.8/3
$\pi\ r_{out}$	1.9/6	0.4/2	0.4/2
$\pi\ r_{side}$	2.7/6	0.07/2	0.06/2
$\pi\ r_{long}$	5.3/6	0.003/2	0.1/2
Total	77.6/99	107.7/90	68.7/68
parameters			
T (MeV)	106 ± 3	107 ± 2	100 ± 5
ρ_0	0.89 ± 0.02	0.85 ± 0.01	0.79 ± 0.02
$\langle\beta_T\rangle$	0.52 ± 0.01	0.50 ± 0.01	0.47 ± 0.01
ρ_2	0.060 ± 0.008	0.058 ± 0.005	0.05 ± 0.01
$R_x(fm)$	13.2 ± 0.3	10.4 ± 0.4	8.00 ± 0.4
$R_y(fm)$	13.0 ± 0.3	11.8 ± 0.4	10.1 ± 0.4
$\tau(fm/c)$	9.2 ± 0.4	7.7 ± 0.9	6.5 ± 0.6
$\Delta t(fm/c)$	0.003 ± 1.3	0.06 ± 1.3	0.6 ± 1.8

TABLE II: Upper section: data used in the fit. Middle section: number of χ^2/ data points for each measure. Lower section: best fit parameters. Note that $\langle\beta_T\rangle$ is not a fit parameter, but it is calculated from ρ_0.

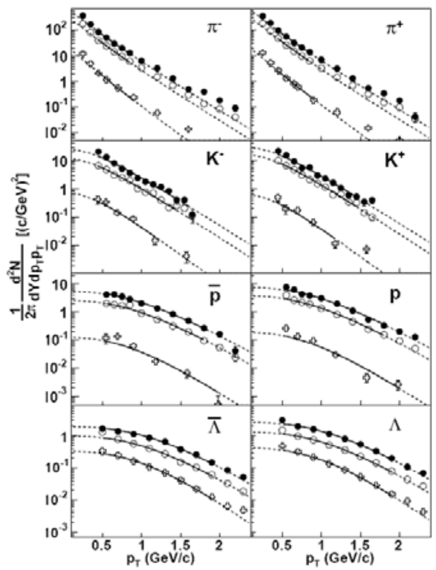
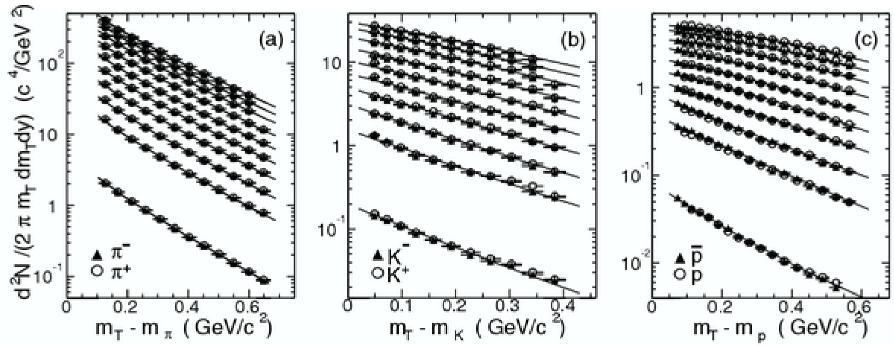
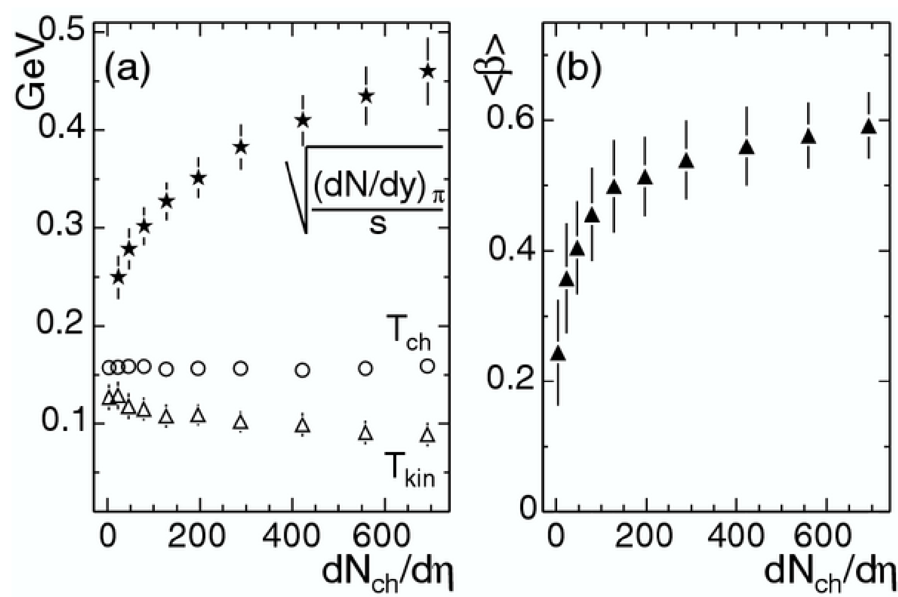


FIG. 49: Comparison of the data with the blast-wave calculations performed with the best fit parameters in three centrality bins. The closed circles are central data, the open circles are mid-central data and the crosses are peripheral data. The plain lines show the blast wave calculation within the fit range while the dash lines show the extrapolation over the whole range.



STAR PRL92



F. Retiere and M. Lisa PRC70; PHENIX PRL88

Blast Wave

Because of azimuthal symmetry we can integrate over ϕ making use of the modified Bessel function $I_0(z) = (2\pi)^{-1} \int_0^{2\pi} e^{z\cos\phi}\, d\phi$:

$$E\frac{d^3n}{d^3p} = \frac{g}{(2\pi)^2}\int_{-\mathcal{Z}}^{\mathcal{Z}} d\zeta \left[m_T \cosh y \frac{\partial z}{\partial \zeta} - m_T \sinh y \frac{\partial t}{\partial \zeta} \right] \times \int_0^R r\,dr\, \exp\left(-\frac{m_T \cosh\rho \cosh(y-\eta) - \mu}{T} \right) I_0\left(\frac{p_T \sinh\rho}{T} \right) \quad (14)$$

For the transverse mass spectrum we integrate with the help of another modified Bessel function $K_1(z) = \int_0^\infty \cosh y\, e^{-z\cosh y} dy$:

$$\frac{dn}{m_T dm_T} = \frac{g}{\pi} m_T \int_{-\mathcal{Z}}^{\mathcal{Z}} d\zeta \left[\cosh\eta \frac{\partial z}{\partial \zeta} - \sinh\eta \frac{\partial t}{\partial \zeta} \right] \int_0^R r\,dr\, K_1\left(\frac{m_T \cosh\rho}{T} \right) I_0\left(\frac{p_T \sinh\rho}{T} \right) = \frac{2g}{\pi} m_T Z_{\tilde{t}} \int_0^R r\,dr\, K_1\left(\frac{m_T \cosh\rho}{T} \right) I_0\left(\frac{p_T \sinh\rho}{T} \right) \quad (15)$$

E. Schnedermann, J. Sollfrank, U. Heinz, nucl-th/9307020, PRC48 (cited 364)

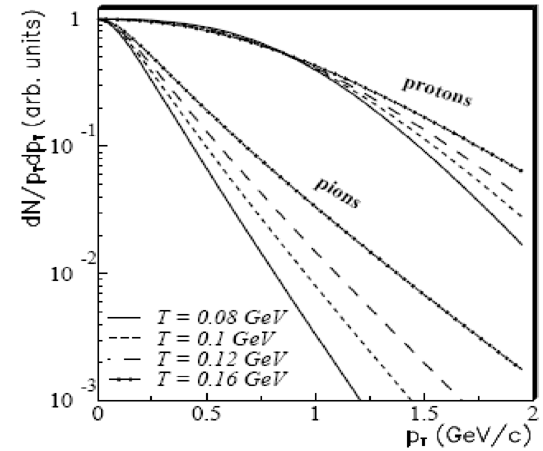


FIG. 4: Transverse momentum spectra for protons (upper curves) and pions (lower curves), as calculated by Equation 19, for several values of the temperature parameter T. Other parameters follow the "round" source defaults of Table I. All spectra are arbitrarily normalized to unity at $p_T = 0$.

F. Retiere, M. Lisa, PRC70

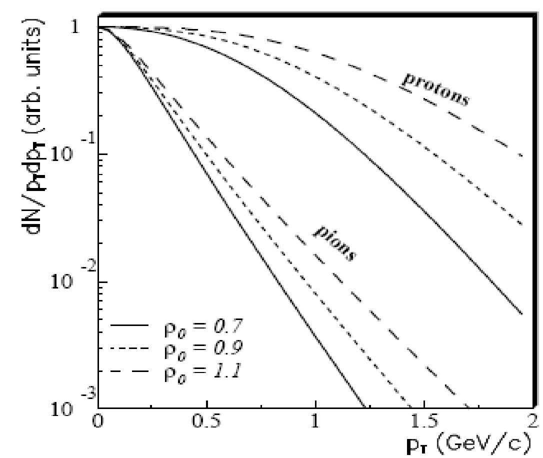


FIG. 5: Transverse momentum spectra for protons (upper curves) and pions (lower curves), as calculated by Equation 19, for several values of the radial flow parameter ρ_0. Other parameters follow the "round" source defaults of Table I. All spectra are arbitrarily normalized to unity at $p_T = 0$.

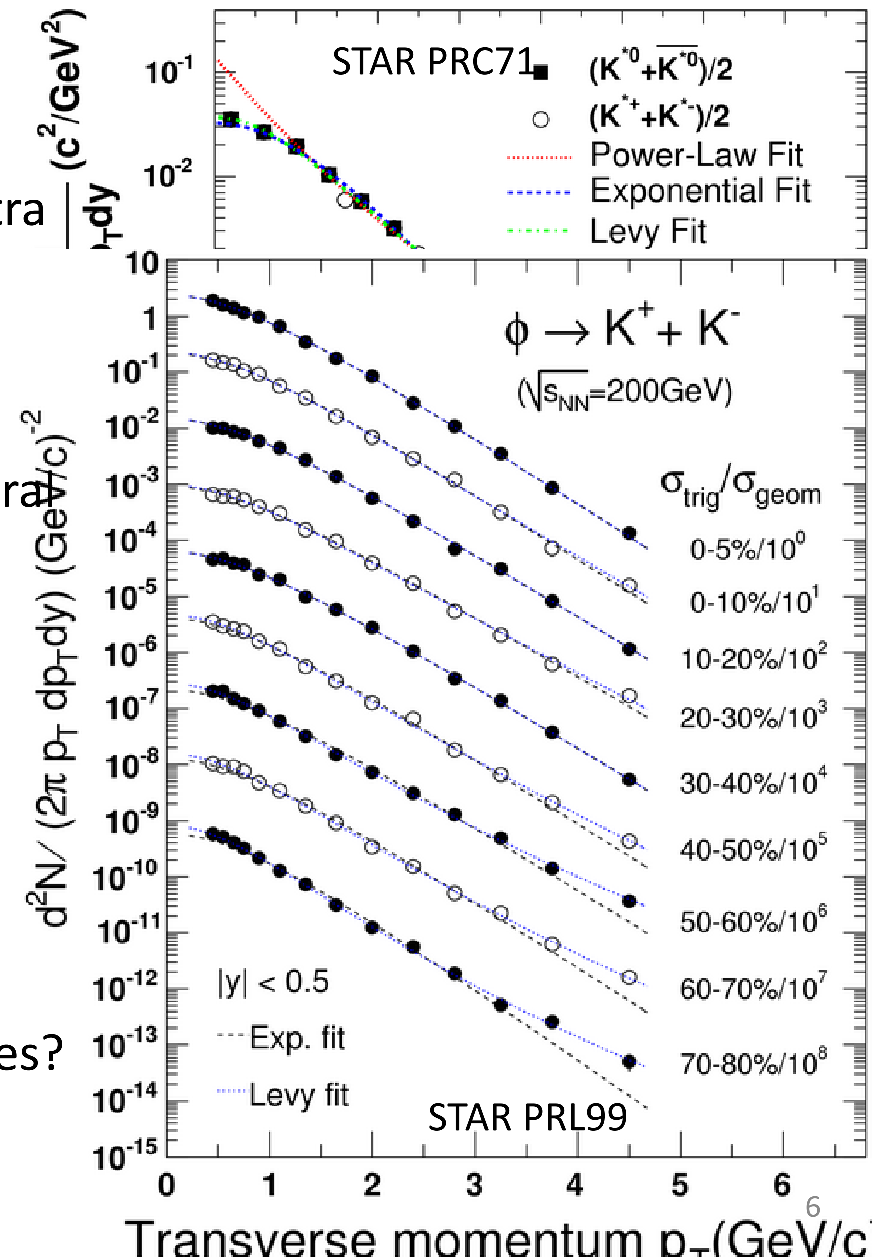
Assumptions:

1) Local thermal equilibrium ➔ Boltzmann distribution
2) Longitudinal and transverse expansions (1+2)
3) Radial flow profile $\rho(r) \propto \mathrm{Atanh}(\beta_m (r/R)^n)$, (n=1)
4) Temperature and $<\beta>$ are global quantities

BGBW: Boltzmann-Gibbs Blast-Wave

Limitations of THE BlastWave

- Strong assumption on local thermal equilibrium
- Arbitrary choice of p_T range of the spectra (low and high cuts)
- Flow velocity $<\beta>=0.2$ in p+p
- Lack of non-extensive quantities to describe the evolution from p+p to central A+A collisions
- example in chemical fits:
  canonical to grand canonical ensemble
- m_T spectra in p+p collisions:
  Levy function or m_T power-law
- m_T spectra in A+A collisions:
  Boltzmann or m_T exponential
- What function can capture these features?



Does macroscopic hydrodynamic approach fail?

- By varying the switching temperature at which the hydrodynamic output is converted to particles for further propagation with the Boltzmann cascade we test the ability of the macroscopic hydrodynamic approach to emulate the microscopic evolution during the hadronic stage and extract the temperature dependence of the effective shear viscosity of the hadron resonance gas produced in the collision.
We find that the extracted values depend on the prior hydrodynamic history and hence do not represent fundamental transport properties of the hadron resonance gas.
- We conclude that viscous fluid dynamics does not provide a faithful description of hadron resonance gas dynamics with predictive power, and that both components of the hybrid approach are needed for a quantitative description of the fireball expansion and its freeze-out.
-------------------- Song, Bass and Heinz, arXiv: 1012.0565

1. Hybrid of microscopic cascade + viscous hydrodynamics
2. Non-equilibrium hydrodynamics

Viscous Correction in Hydrodynamics

other nuisance parameters. However, we want to point out here that these studies have all made a common assumption about the way that the asymmetry in the stress tensor is manifested in the particle distribution after freezeout. In particular, the particle distribution after freezeout is locally of the form $f = f_0 + \delta f$ where f_0 is the equilibrium distribution and δf is the first correction. All groups have assumed that $\delta f(p) \propto p^2 f_0$ and that the coefficient of proportionality is independent of particle type.

Dusling, Moore, Teaney, PRC 81 (2010)

Model	Physics	Formula
Relaxation time, $\tau_R \propto p$	Relaxation time grows with particle momentum.	$\chi(p) \propto p^2$
Relaxation time , $\tau_R = \mathrm{const}$	Relaxation time independent of momentum.	$\chi(p) \propto p$
Scalar theory	Randomizing collisions which happen rarely	$\chi(p) \propto p^2$
QCD Soft Scatt.	Soft $q \sim gT$ collisions lead to a random walk of hard particles.	$\chi(p) \propto p^2$
QCD Hard Scatt.	Hard $q \sim \sqrt{pT}$ collisions lead to a random walk of hard particles.	$\chi(p) \propto \frac{p^2}{\log(p/T)}$
QCD Rad. E-loss	Radiative energy controls the approach to equilibrium. In the LPM regime $\hat{q}$ controls the radiation rate.	$\chi(p) \propto \frac{p^{3/2}}{\alpha_s \sqrt{\hat{q}}}$

TABLE I: Summary of the functional dependence of the departure from equilibrium on the theory and approximation considered.

$$\delta T_{\mu\nu}(n,t) = \exp\left(-\beta n^2\right)\delta T_{\mu\nu}(0), \quad \beta = \frac{2}{3}\frac{\eta}{s}\frac{1}{\bar{R}^2}\frac{t}{T}$$

$$f = f_0 + \delta f(\tilde{p}_T), \quad \tilde{p}_T = \frac{p_T}{T}$$

$$\frac{v_n(p_T)}{\varepsilon_n} \propto \exp\left(-\beta' n^2\right),$$

Roy Racey et al., 1301.0165

Tsallis Statistics

- **Nice web based notebooks: Tsallis Statistics, Statistical Mechar… for Non-extensive Systems and Long-Range Interactions** **http://www.cscs.umich.edu/~crshalizi/notabene/tsallis.html**
- http://tsallis.cat.cbpf.br/biblio.htm

Grupo de Física Estatística - Group of Statistical Physics - Windows Internet Explorer

http://tsallis.cat.cbpf.br/biblio.htm

Nonextensive Statistical Mechanics and Thermodynam…

E-Mail: tsallis@cbpf.br

BIBLIOGRAPHY

FURTHER INFORMATION

AVAILABLE BOOKS

TABLE OF FOUNDATIONS

SET OF MINI-REVIEWS (Special issue of Europhysics News, European Physical S…
- Europhysics News 36 (6) (Nov-Dec 2005)
- Erratum: Europhysics News 37 (1) (Jan-Feb 2006), page 25

MEXICO PRIZE FOR SCIENCE AND TECHNOLOGY
- Speeches and photos

INSTITUTO NACIONAL DE SISTEMAS COMPLEXOS

Number of visits since 14 March 1997: 40527

Last updating: 18 Sep 2008

Group of Statistical Physics (CBPF) CBPF

ENTROPY AND STATISTICAL MECHANICS: FOUNDATIONS

	BG (thermal equilibrium)	$q \neq 1$ (thermal metaequilibrium, nonequilibrium)
Distribution of velocities at equilibrium	Maxwell 1860	R. Silva, A.R. Plastino, J.A.S. Lima Phys Lett A 249, 401 (1998); R.S. Mendes and C. Tsallis Phys Lett A 285, 273 (2001)
Kinetic equation Molecular chaos hypothesis	Boltzmann 1872	J.A.S. Lima, R. Silva, A.R. Plastino Phys Rev Lett 86, 2938 (2001)
	Khinchin 1949	cond-mat/0606038 and /0606040; S. Abe and A.K. Rajagopal Europhys Lett 52, 610 (2000)

Let us thus concentrate on the other class, systems with fluctuations. Consider a system of ordinary statistical mechanics with Hamiltonian H. Tsallis statistics with $q > 1$ can arise from this ordinary Hamiltonian if one assumes that the temperature β^{-1} is locally fluctuating. From the integral representation of the gamma-function one can easily derive the formula [7,15]

$$(1+(q-1)\beta_0 H)^{-\frac{1}{q-1}} = \int_0^\infty e^{-\beta H} f(\beta)\, d\beta, \qquad (3)$$

where

$$f(\beta) = \frac{1}{\Gamma\left(\frac{1}{q-1}\right)} \left\{\frac{1}{(q-1)\beta_0}\right\}^{\frac{1}{q-1}} \beta^{\frac{1}{q-1}-1} \exp\left[-\frac{\beta}{(q-1)\beta_0}\right] \qquad (4)$$

is the probability density of the χ^2 distribution. The above formula is valid for arbitrary Hamiltonians H and thus of great significance. The left-hand side of eq. (3) is just the generalized Boltzmann factor emerging out of nonextensive statistical mechanics. It can directly be obtained by extremizing S_q. The right-hand side is a weighted average over Boltzmann factors of ordinary statistical mechanics. In other words, if we consider a nonequilibrim system (formally described by a fluctuating β), then the generalized distribution functions of nonextensive statistical mechanics are a consequence of integrating over all possible fluctuating inverse temperatures β, provided β is χ^2 distributed.

Negative Binomial Distribution: $\kappa=1/(q-1$

Temperature fluctuation: $$\frac{\langle 1/T^2\rangle - \langle 1/T\rangle^2}{\langle 1/T\rangle^2} = 1-q$$

G. Wilk: arXiv: 0810.2939; C. Beck, EPL57(2002)3

It is all about the q-statistics

BASIC QUANTITIES
q-exponential : $\exp_q(x) \equiv [1+(1-q)\,x]^{\frac{1}{1-q}} \longrightarrow_{q\to 1} e^x$
q-logarithm : $\ln_q(x) \equiv \frac{x^{1-q}-1}{1-q} \longrightarrow_{q\to 1} \ln x$
Boltzmann-Gibbs entropy : $S_{BG} \equiv -k\sum_{i=1}^{W} p_i \ln p_i$
q-entropy : $S_q \equiv k\frac{1-\sum_{i=1}^{W} p_i^q}{q-1} = k\sum_{i=1}^{W} p_i \ln_q(1/p_i) = -k\sum_{i=1}^{W} p_i^q \ln_q p_i \longrightarrow_{q\to 1} S_{BG}$
Escort distribution : $P_i \equiv p_i^q / \sum_{j=1}^{W} p_j^q$
Ensemble q-average : $\langle A\rangle_q \equiv \sum_{i=1}^{W} A_i P_i = \sum_{i=1}^{W} A_i p_i^q / \sum_{j=1}^{W} p_j^q$

◄ **Box:** The two basic functions that appear in Nonextensive Statistical Mechanics are the q-exponential and the q- logarithm with $\ln_q(\exp_q x) = \exp_q(\ln_q x) = x$. They are simple generalizations of the usual exponential and logarithmic functions which are retrieved by performing a $|1 - q| << 1$ expansion. Similarly the q-entropy generalizes the standard Boltzmann-Gibbs entropy. The escort distribution is a generalization of the usual ensemble averaging function to which it reduces for $q = 1$.

europhysics news NOVEMBER/DECEMBER 2005 185

- Why is this relevant to us (Heavy-ion physics)?
  - We have dealt with Boltzmann distribution
    But the spectra are clearly non-Boltzmann
  - It is easy to make a change
  - It is easy to compare
  - Change m_T exponential to m_T power law

$$(1+\frac{q-1}{T}m_T)^{-1/(q-1)}$$

Tsallis statistics in Blast Wave model

Because of azimuthal symmetry we can integrate over ϕ making use of the modified Bessel function $I_0(z) = (2\pi)^{-1} \int_0^{2\pi} e^{z\cos\phi}\, d\phi$:

$$E\frac{d^3n}{d^3p} = \frac{g}{(2\pi)^2}\int_{-\mathcal{Z}}^{\mathcal{Z}} d\zeta \left[m_T \cosh y \frac{\partial z}{\partial \zeta} - m_T \sinh y \frac{\partial t}{\partial \zeta}\right] \times \int_0^R r\,dr\ \exp\left(-\frac{m_T \cosh\rho \cosh(y-\eta) - \mu}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right) \quad (14)$$

For the transverse mass spectrum we integrate with the help of another modified Bessel function $K_1(z) = \int_0^\infty \cosh y\, e^{-z\cosh y}\, dy$:

$$\begin{aligned}\frac{dn}{m_T dm_T} &= \frac{g}{\pi} m_T \int_{-\mathcal{Z}}^{\mathcal{Z}} d\zeta \left[\cosh\eta \frac{\partial z}{\partial \zeta} - \sinh\eta \frac{\partial t}{\partial \zeta}\right] \int_0^R r\,dr\, K_1\left(\frac{m_T\cosh\rho}{T}\right) I_0\left(\frac{p_T\sinh\rho}{T}\right) \\ &= \frac{2g}{\pi} m_T Z_{\tilde{t}} \int_0^R r\,dr\, K_1\left(\frac{m_T\cosh\rho}{T}\right) I_0\left(\frac{p_T\sinh\rho}{T}\right) \quad (15)\end{aligned}$$

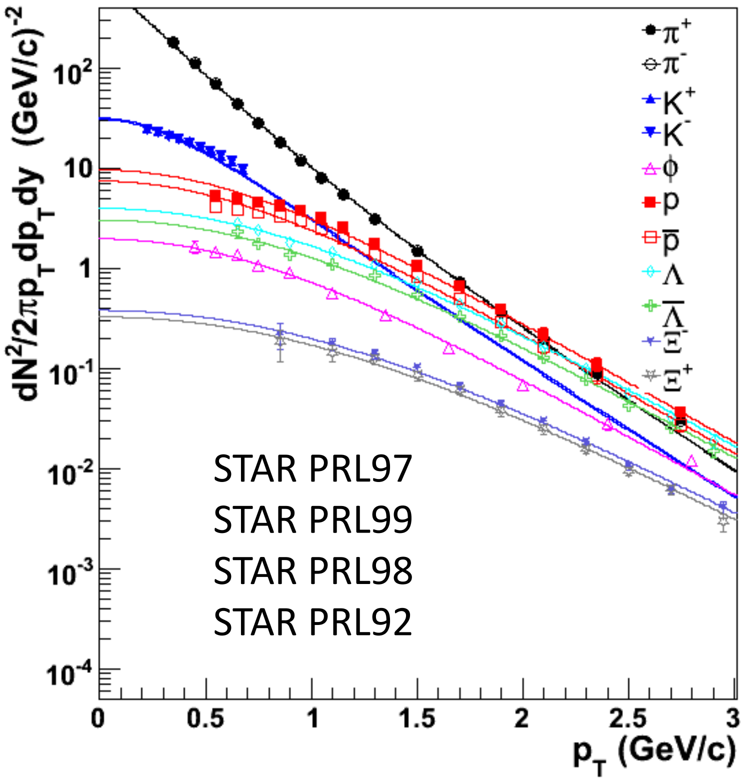
With Tsallis distribution, the BlastWave equation is:

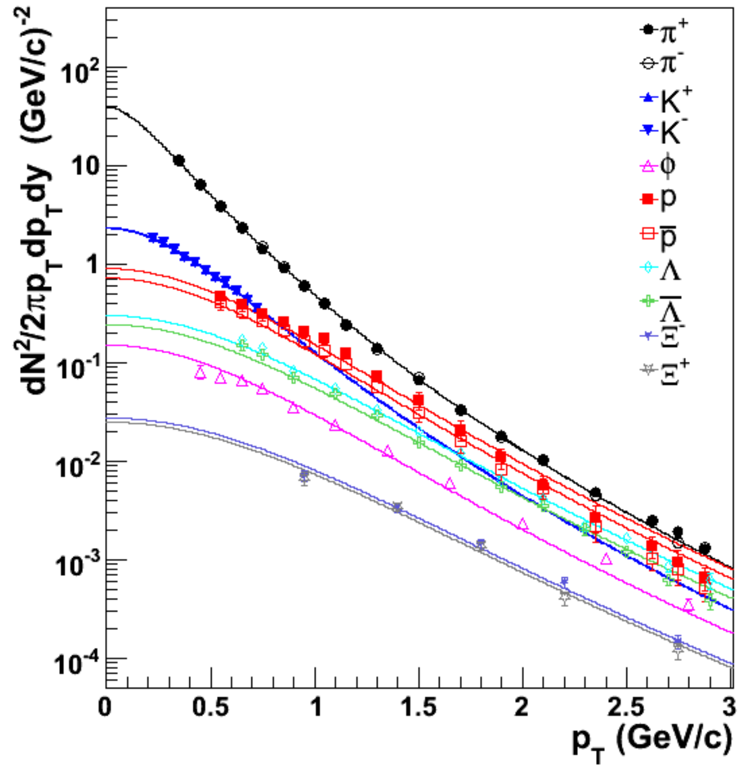
$$\frac{dN}{m_T dm_T} \propto m_T \int_{-Y}^{+Y} \cosh(y)dy \int_{-\pi}^{+\pi} d\phi \int_0^R rdr \left(1 + \frac{q-1}{T}\left(m_T \cosh(y)\cosh(\rho) - p_T \sinh(\rho)\cos(\phi)\right)\right)^{-1/(q-1)}$$

Where $\rho = \mathrm{Atanh}(\beta_m (r/R)^n)$, n=1 ; any of the three integrals is HypergeometryF1

β: flow velocity

Fit results in Au+Au collisions

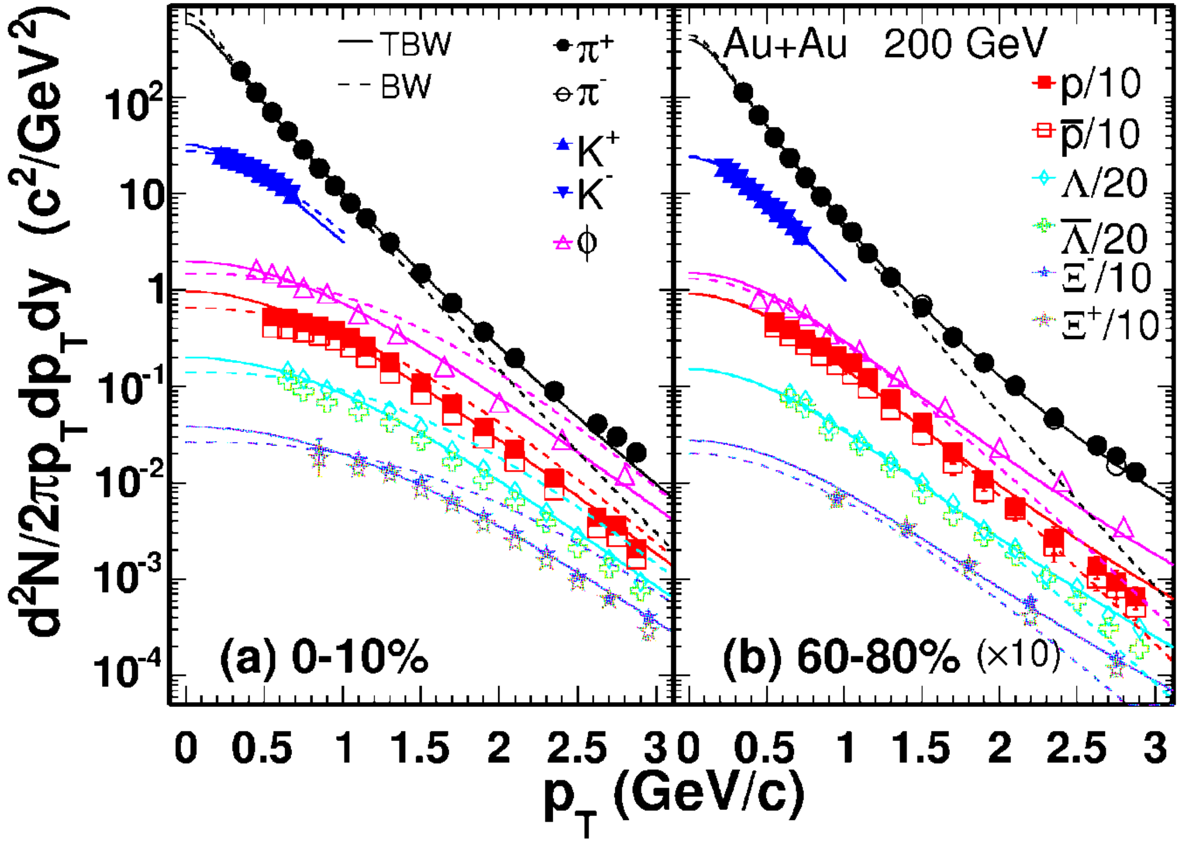




Au+Au 0—10%:
<β> = 0.470+- 0.009
T = 0.122 +- 0.002
q = 1.018 +- 0.005
chi^2/nDof = 130 / 125

Au+Au 60—80%:
<β>=0
T = 0.114 +- 0.003
q = 1.086 +- 0.002
chi^2/nDof = 138/ 123

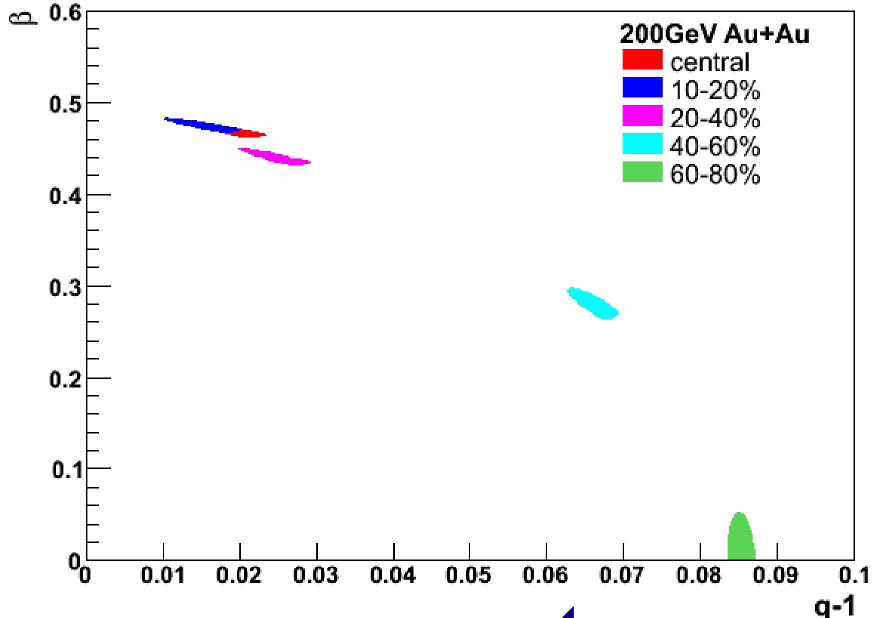
How is result different from BGBW?

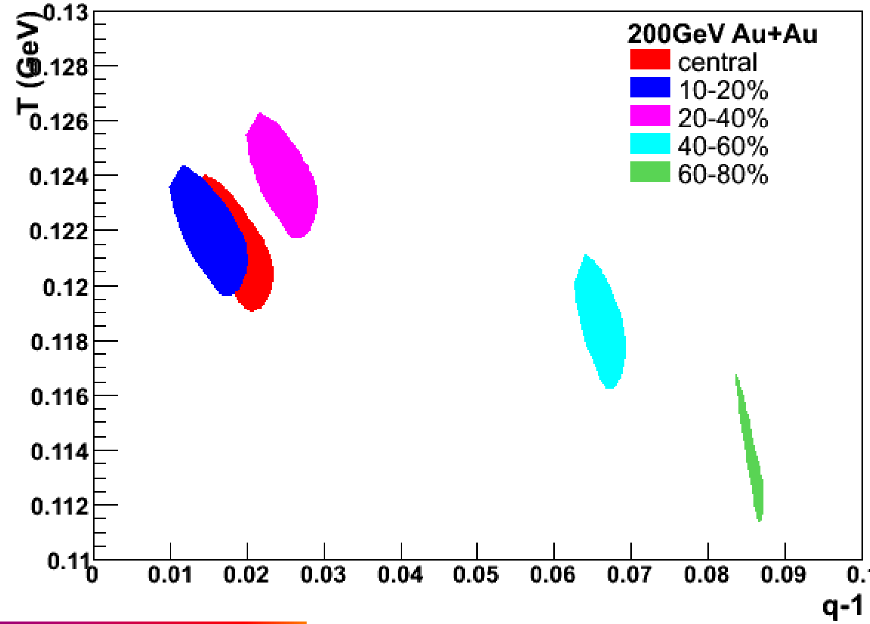


Central Au+Au collisions
BGBW: underpredict low mass particles at high pt
overpredict high mass particles at high pt

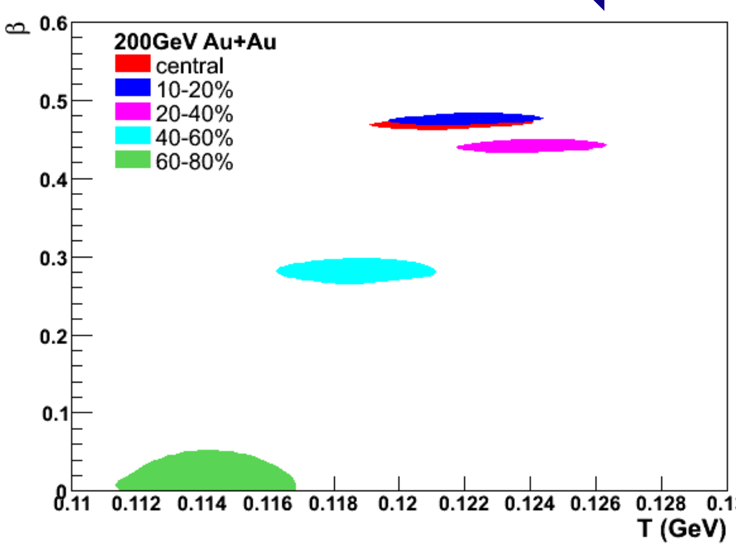
Peripheral Au+Au collisions
BGBW: underpredict low mass particles at high pt
underpredict high mass particles at high pt

Dissipative energy into flow and heat





More thermalized



1. Decrease of q➔1, closer to Boltzmann
2. Increase of radial flow (0➔0.5)
3. Increase of temperature
4. T, $\beta \propto (q\text{-}1)^2$, NOT linear (q-1)

No flow pattern in J/ψ spectra

J. Phys. G: Nucl. Part. Phys. 37 (2010) 085104 M Shao *et al*

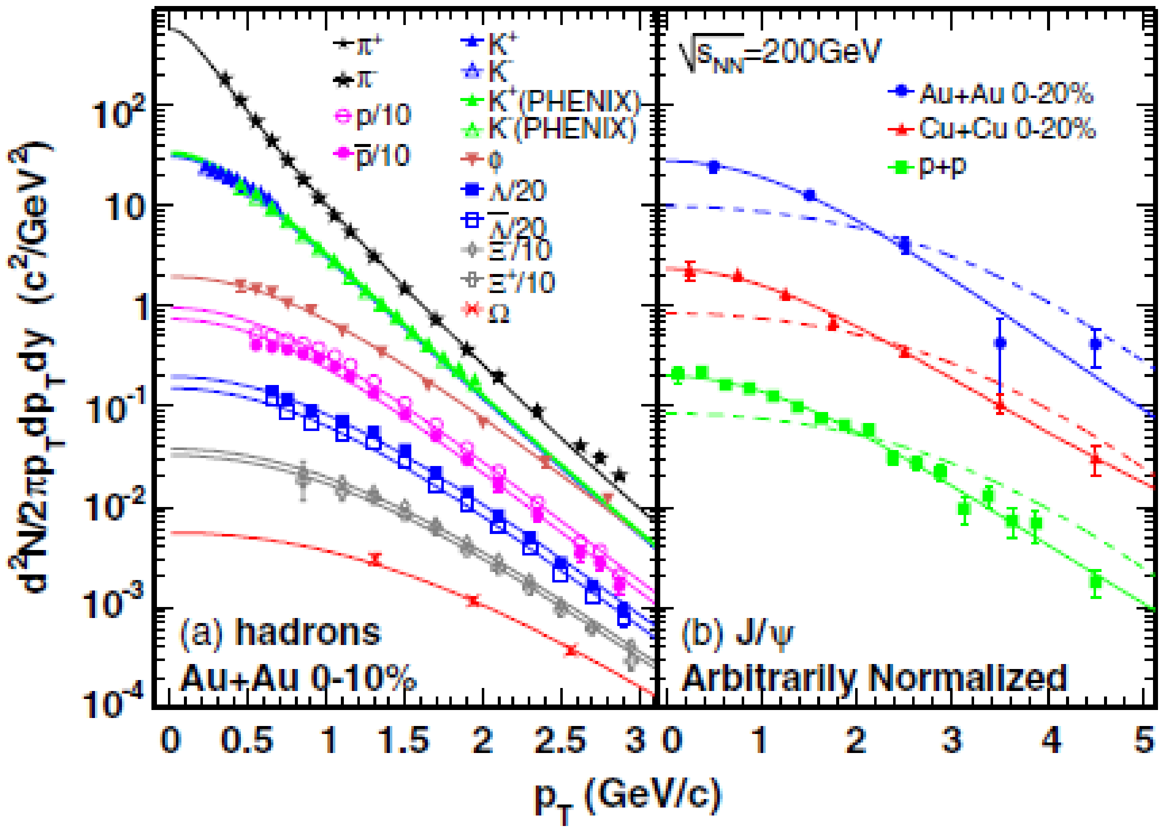


Figure 1. Identified particle spectra from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Left panel: spectra of light hadrons and strange hadrons. The solid curves are results from the TBW fit. Right panel: *J/ψ* spectrum, the dashed line is the TBW prediction using parameters from the fit to other hadrons, and the solid curve is a TBW fit to *J/ψ* alone.

No sign of flow at SPS either

J. Phys. G: Nucl. Part. Phys. 37 (2010) 085104 M Shao *et al*

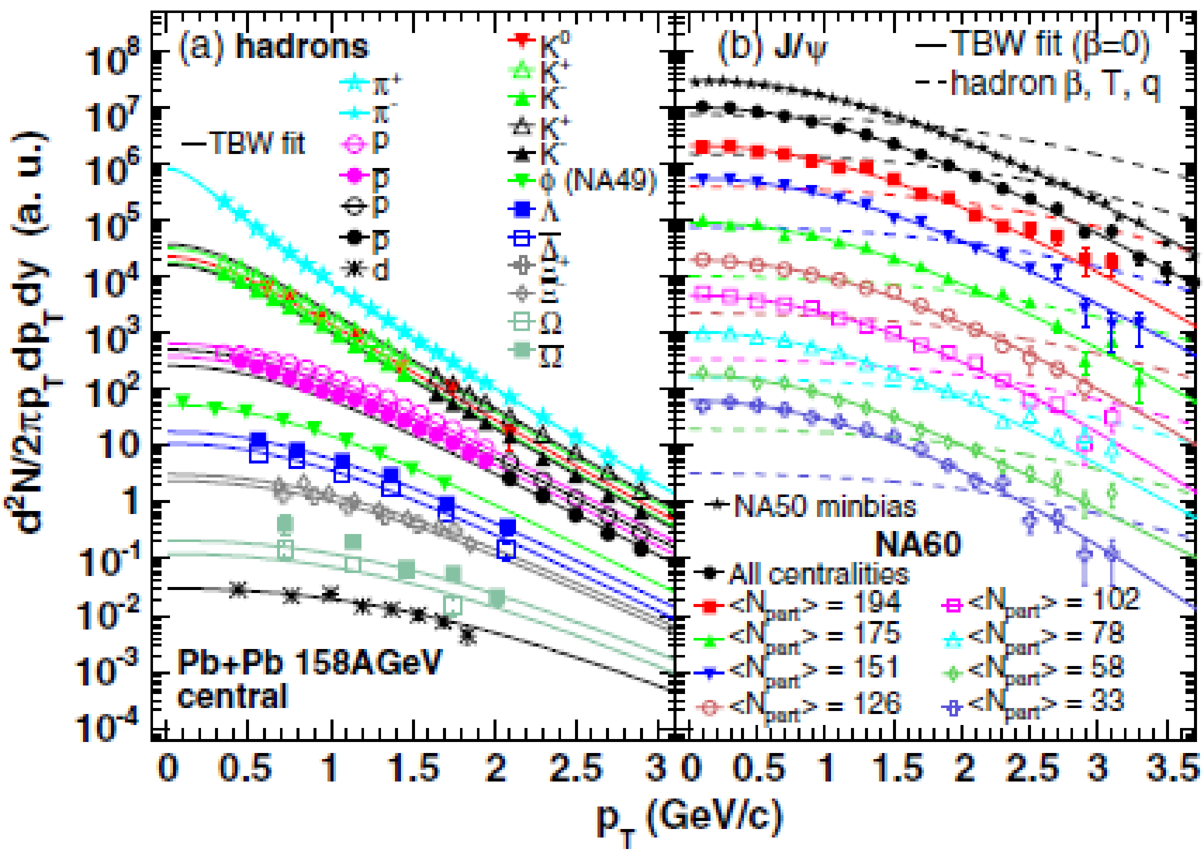
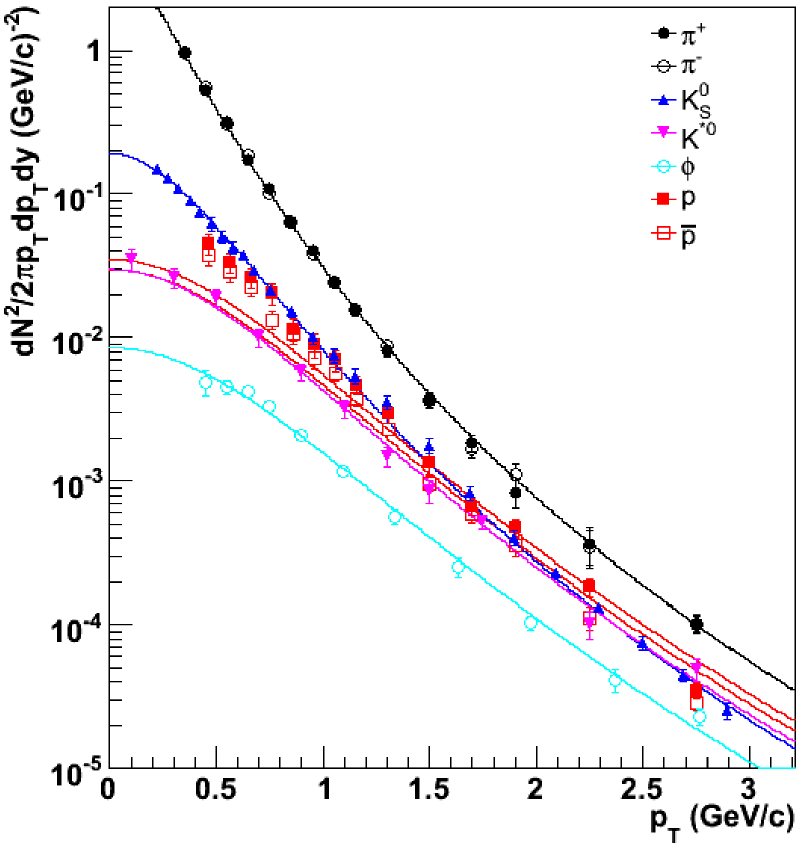
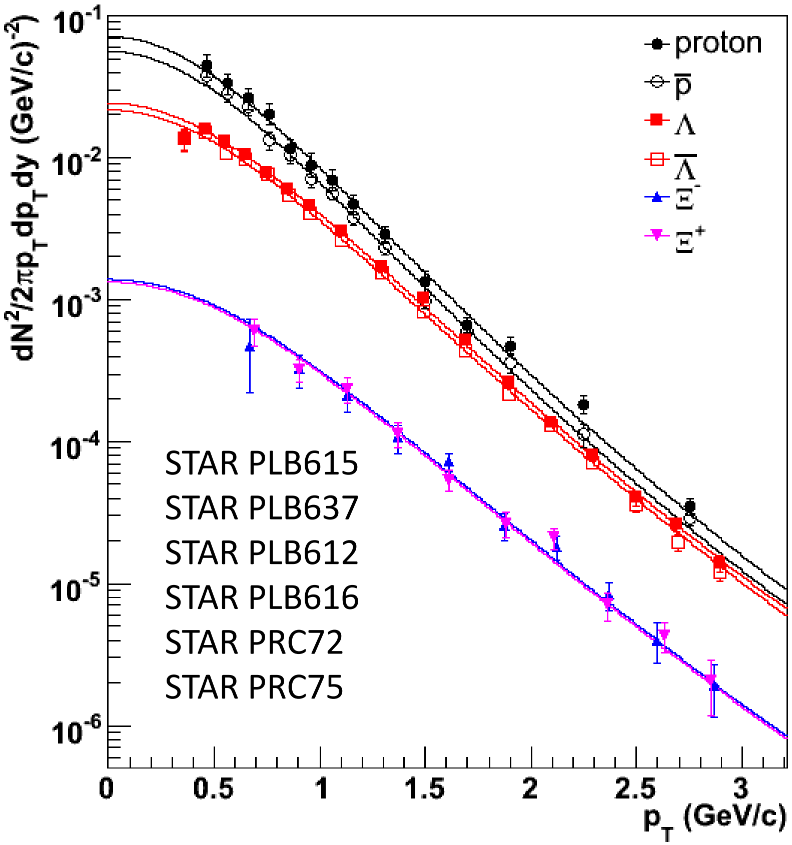


Figure 2. Identified particle spectra in central Pb+Pb collisions at the beam energy of 158 A GeV from the fixed-target experiments at SPS. Left panel: spectra of light hadrons and strange hadrons. The solid curves are results from the TBW fit. Right panel: *J/ψ* spectra, the dashed line is the TBW prediction using parameters from the fit to other hadrons, and the solid curve is a TBW fit to *J/ψ* alone.

Results in p+p collisioins

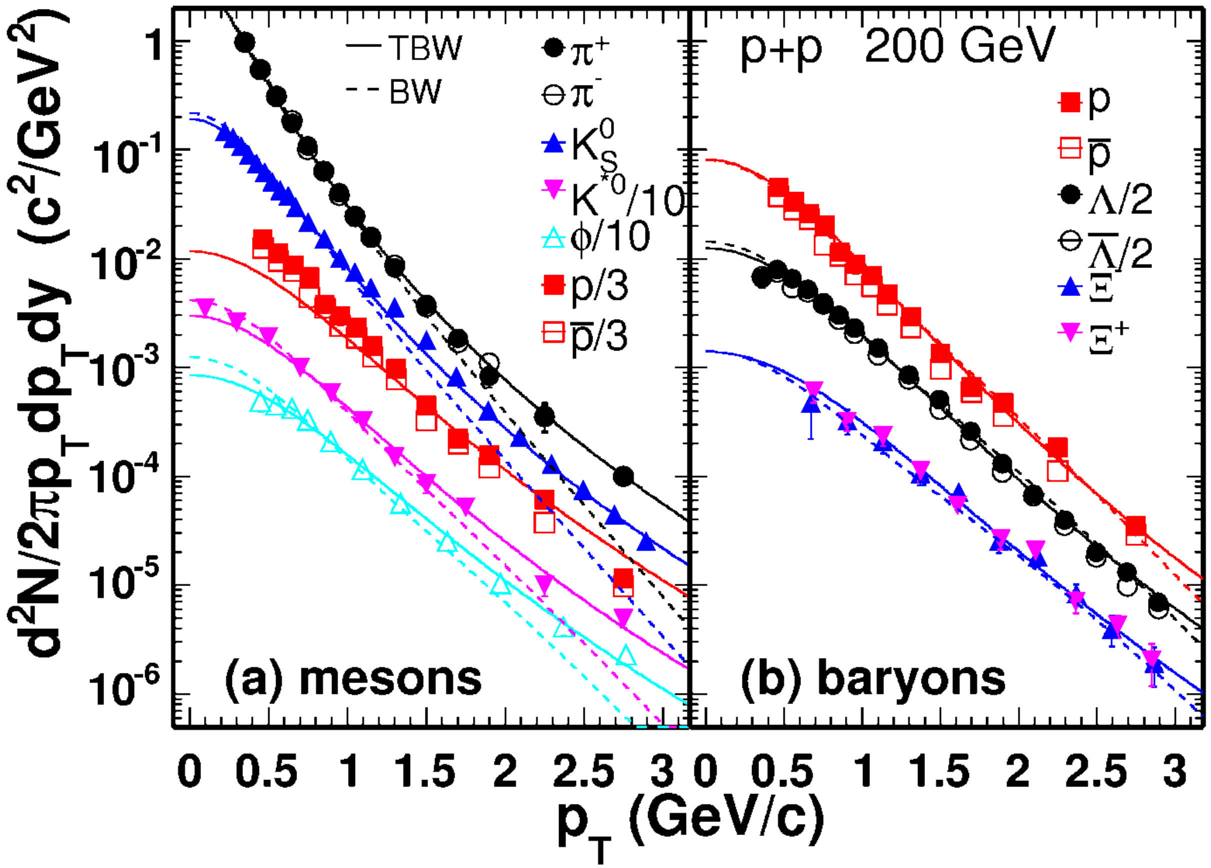




<β> = 0
T = 0.0889+- 0.004
q = 1.100 +- 0.003
chi^2/nDof = 53 / 66

<β> = 0
T = 0.097+- 0.010
q = 1.073 +- 0.005
chi^2/nDof = 55 / 73

How is result different from BGBW?



BGBW: underpredicts higher pt yields for all mesons in p+p
Baryons and mesons are created differently in p+p:
baryons from gluons and popcorn model?

Baryon and meson are different classes

The constant is determined by the ratio of Casimirs $C_A/C_F = 9/4$ and the dynamics of the QCD splitting functions. It also depends weakly on the number of quark flavors and we have quoted the two flavor case.

Motivated by this example, we have postulated that the baryon and meson components of the medium have different equilibration rates. Indeed, there is no reason to expect that these species would equilibrate at the same rate. Then we fitted (by eye) the ratio of relaxation rates to reproduce the baryon and meson elliptic flows. If the ratio of relaxation times is

$$\frac{\chi_m}{\chi_b} \simeq 1.5\,, \tag{57}$$

meaning that baryons relax to equilibrium 1.5 times faster than mesons, then the resulting viscous hydrodynamic calculation effortlessly reproduces the universal "constituent quark scaling" curve. Physically what is happening is that in ideal hydrodynamics the baryons and mesons have approximately the same elliptic flow which is approximately described by a linear rise in m_T. The viscous correction then dictates that the baryons will follow this ideal trend 1.5 times farther than the mesons. Although it is not obvious from the data shown

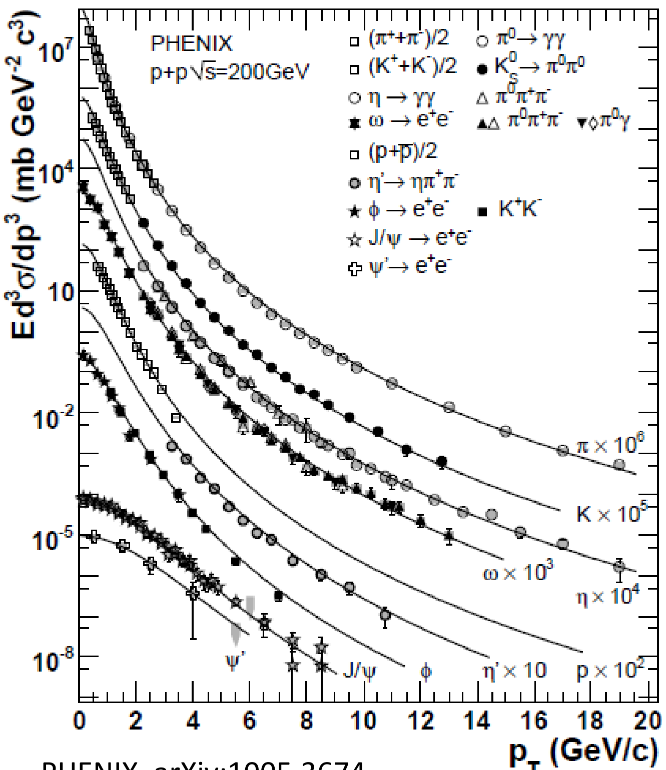
In p+p collisions, the m_T spectra of baryons and mesons are in two groups
Maybe we should not call p+p system as a whole global system
However, equilibrated toward more central Au+Au collisions

Observations from the q-statistics

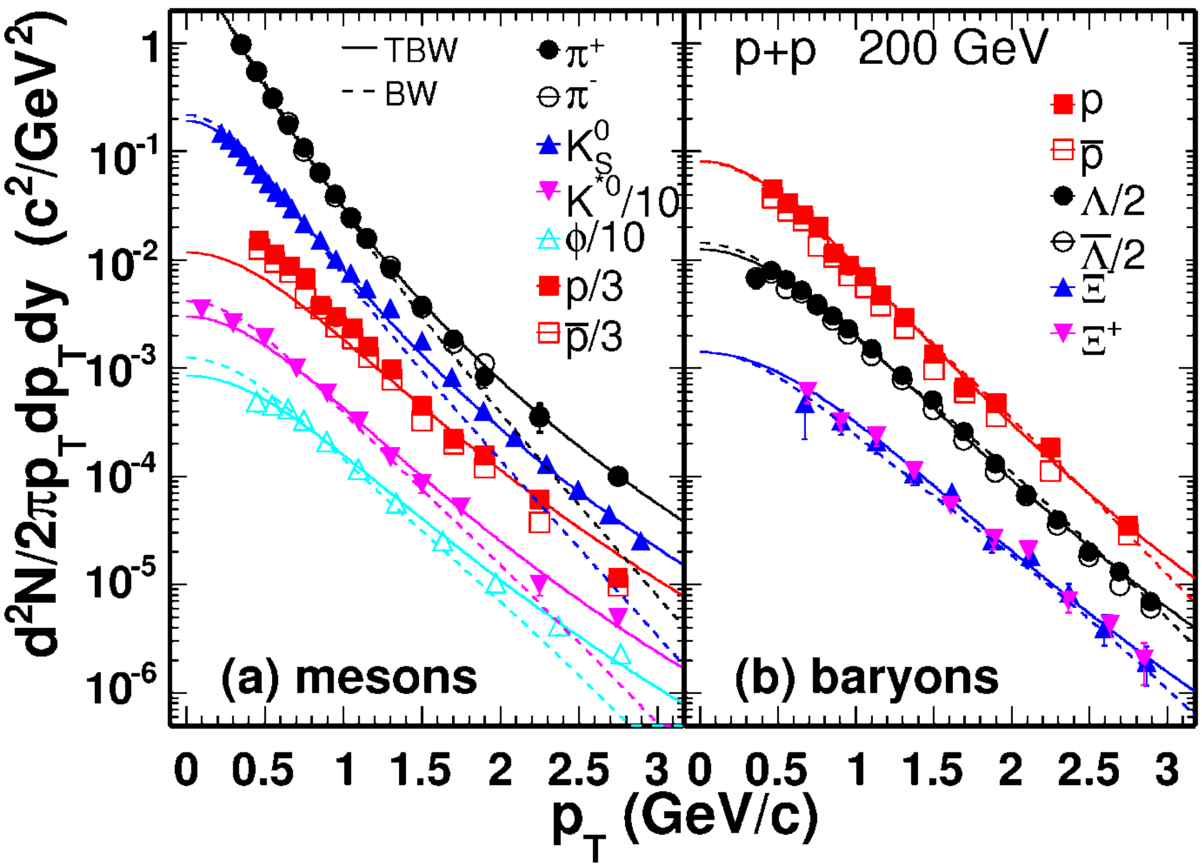
- Fit spectra well for all particles with p_T<~ 3 GeV/c
- Radial flow increases from 0 to 0.5c
- Kinetical freeze-out temperature increases from 90 (110) to 130 MeV
- q-1 decreases from 0.1 to 0.01
- T and β depend on $(q-1)^2$
- p+p collisions are very different, split between mesons and baryons

- Tsallis statistics describes the data better than Boltzmann-Gibbs statistics
- Radial flow is zero in p+p and peripheral Au+Au collisions
- Evolution from peripheral to central Au+Au collisions:
  hot spots (temperature fluctuation) are quenched toward a more uniform Boltzmann-like distribution
- dissipative energy into heat and flow, related to bulk viscosity
- Energy conservation is a built-in requirement in any statistical model (that is where you get the temperature)

Extend to high p_T



PHENIX, arXiv:1005.3674



$$\left(1+\frac{q-1}{T}m_T\right)^{-1/(q-1)}$$

$$\xrightarrow{q\to 1} e^{-m_T/T}$$

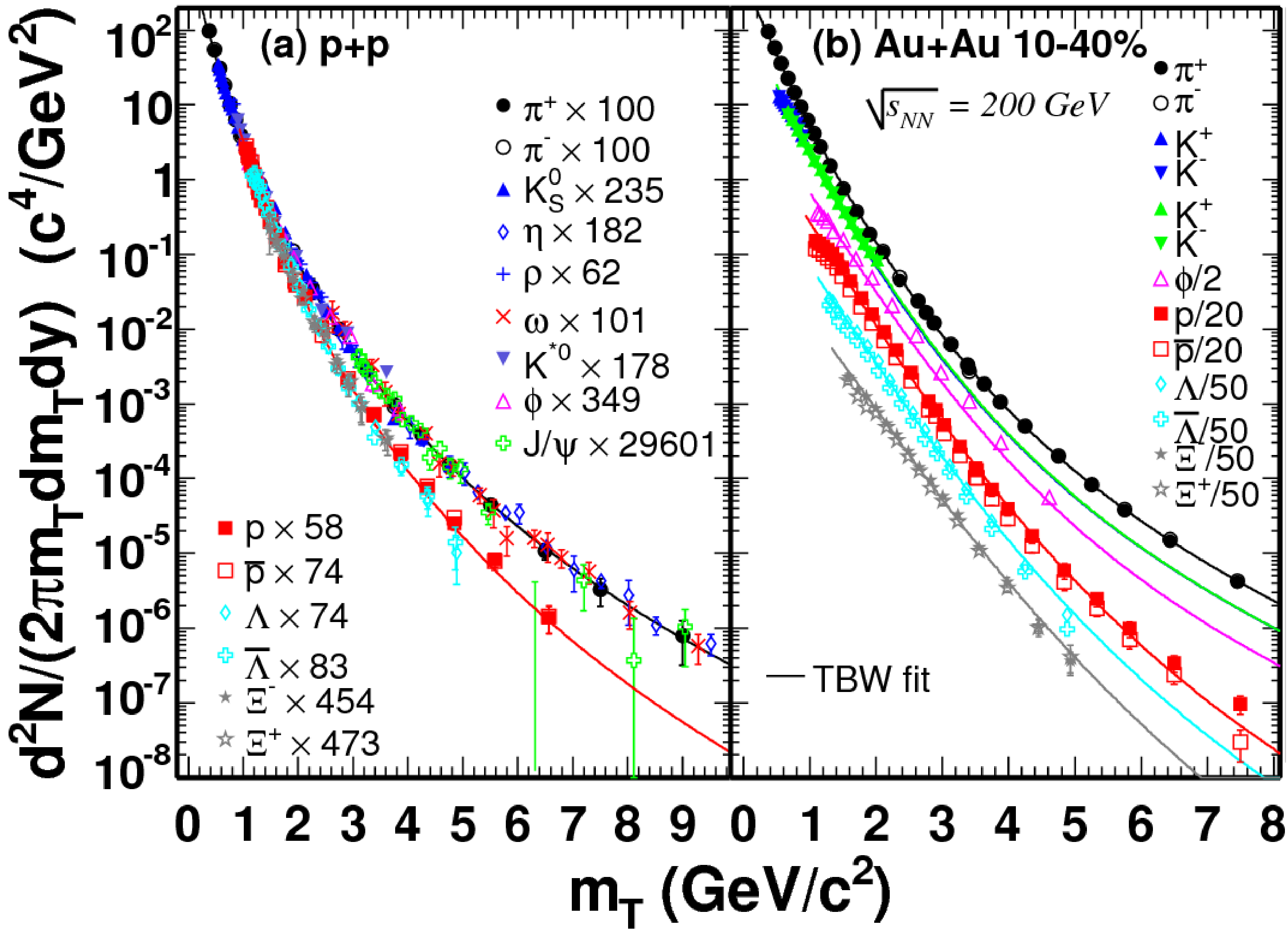
q-1=0.10+-(~0.01)

Velocity β =0

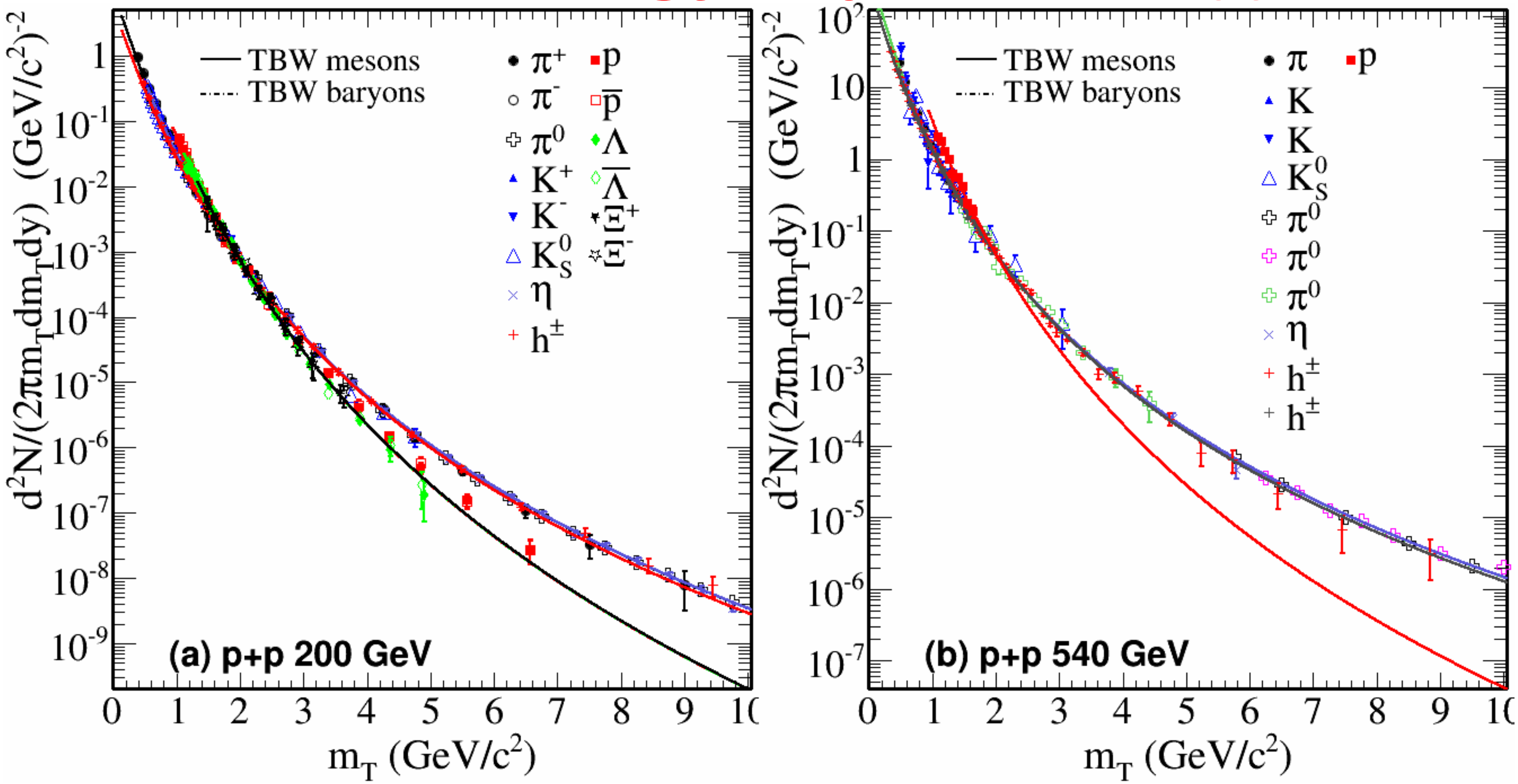
Blast-Wave with Tsallis Statistics

Z. Tang et al., PRC 79 (2009) 051901

Fit to p+p Spectra in 200 GeV

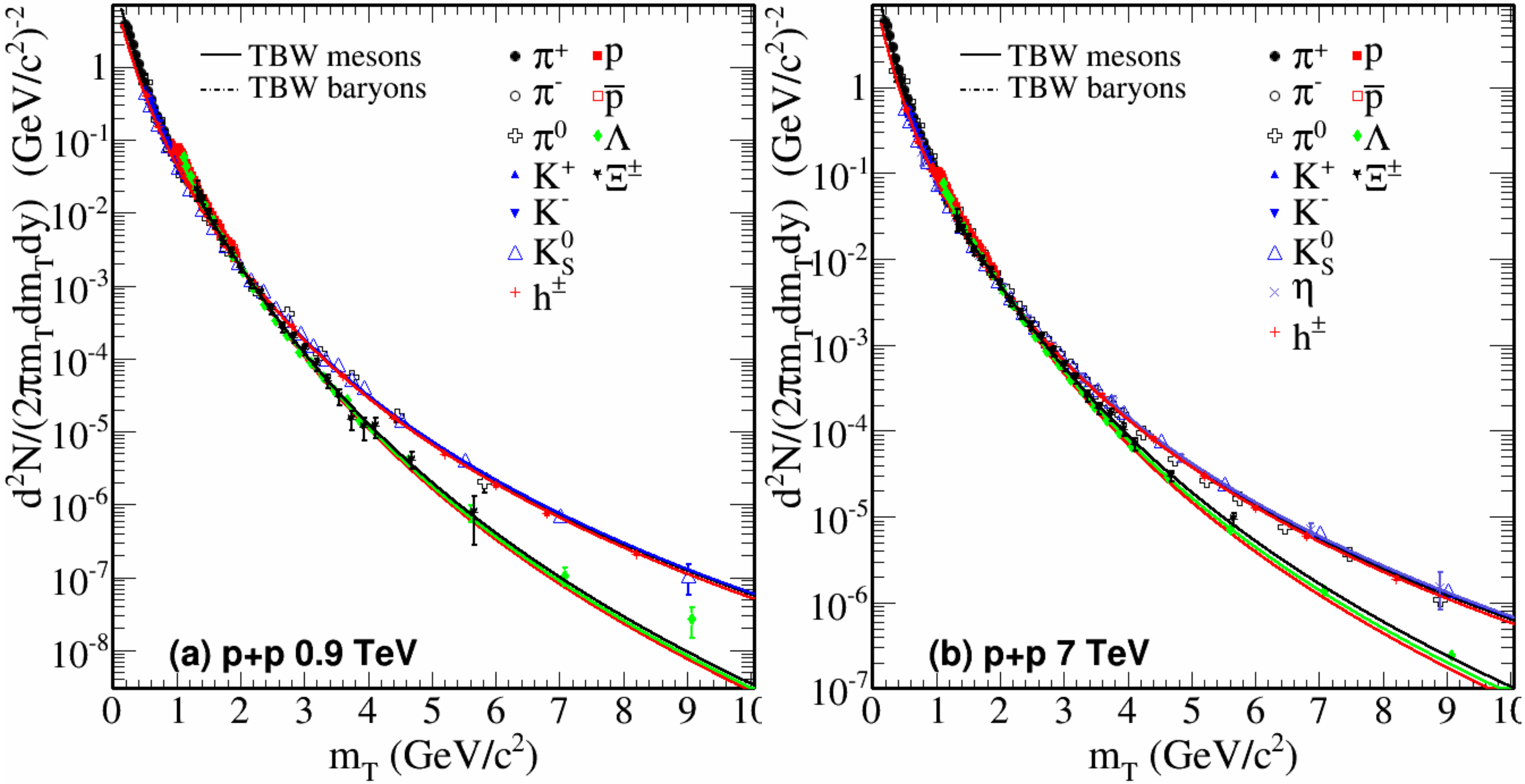


Beam Energy Dependence (i)



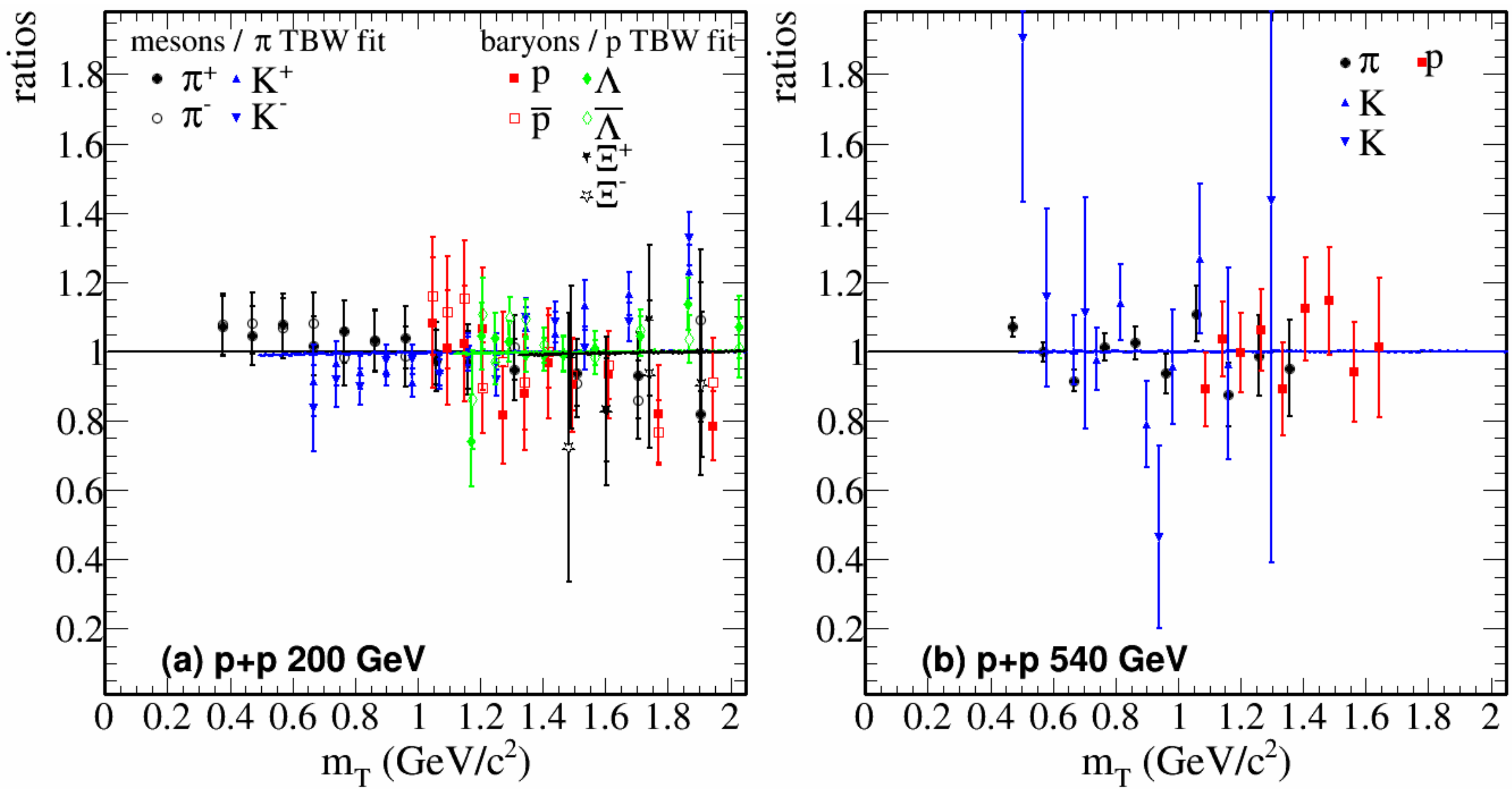
Energy	$\langle\beta\rangle$ (c)	T (MeV)	$q_M - 1$	$q_B - 1$	χ^2/ndf
7 TeV	0.337 ± 0.006	67.6 ± 0.8	0.1316 ± 0.0004	0.1019 ± 0.0011	276/250
900 GeV	0.258 ± 0.009	75.8 ± 0.9	0.1134 ± 0.0004	0.0837 ± 0.0013	182/220
540 GeV	$0.000^{+0.105}_{-0.000}$	81.8 ± 0.6	0.1158 ± 0.0007	0.0841 ± 0.0036	205/168
200 GeV	$0.000^{+0.067}_{-0.000}$	93.9 ± 0.2	0.0939 ± 0.0012	0.0752 ± 0.0011	156/165

Beam Energy Dependence (ii)



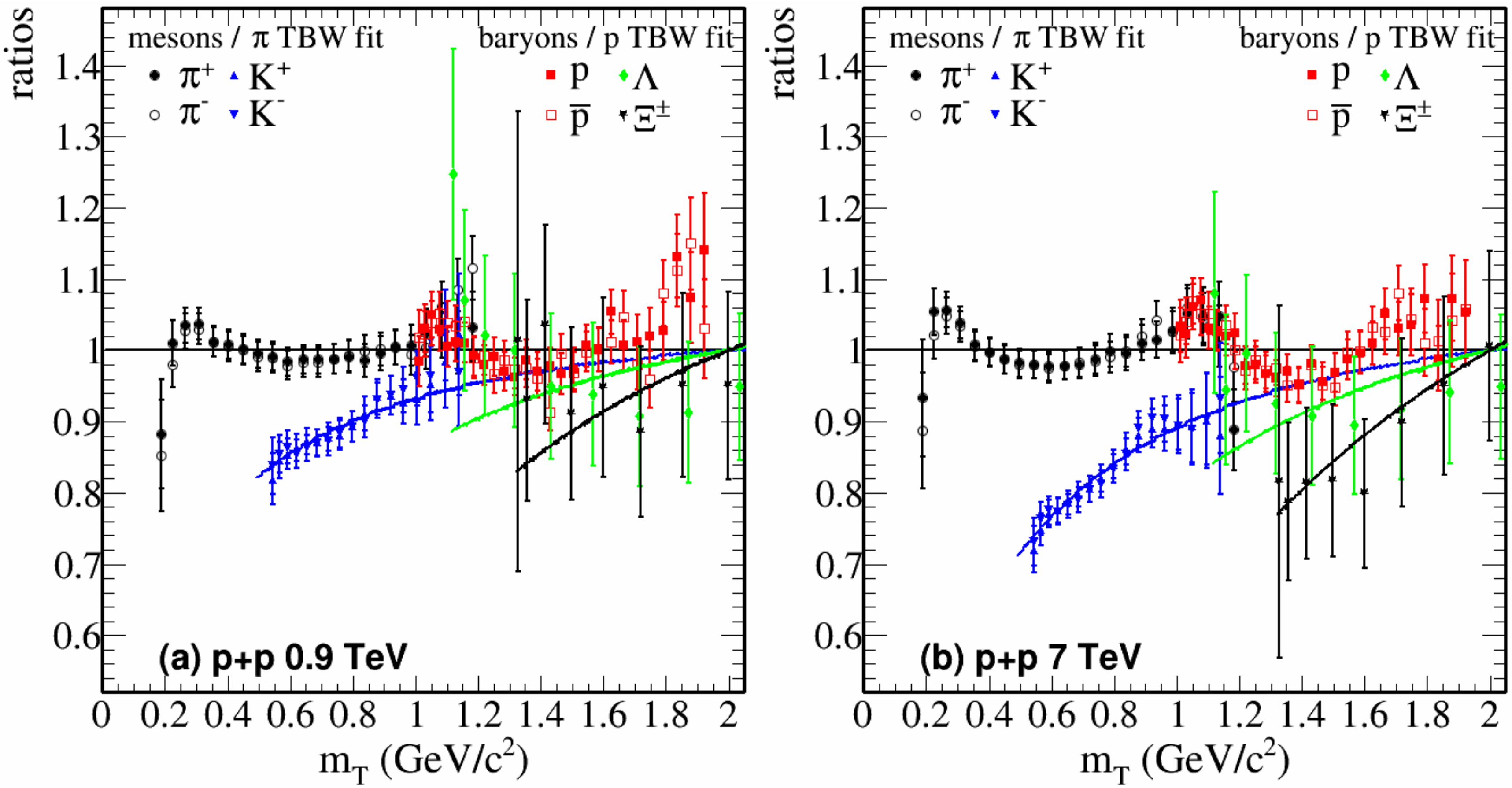
Energy	$\langle\beta\rangle$ (c)	T (MeV)	$q_M - 1$	$q_B - 1$	χ^2/ndf
7 TeV	0.337 ± 0.006	67.6 ± 0.8	0.1316 ± 0.0004	0.1019 ± 0.0011	276/250
900 GeV	0.258 ± 0.009	75.8 ± 0.9	0.1134 ± 0.0004	0.0837 ± 0.0013	182/220
540 GeV	$0.000^{+0.105}_{-0.000}$	81.8 ± 0.6	0.1158 ± 0.0007	0.0841 ± 0.0036	205/168
200 GeV	$0.000^{+0.067}_{-0.000}$	93.9 ± 0.2	0.0939 ± 0.0012	0.0752 ± 0.0011	156/165

m_T scaling



mesons / π TBW fit
baryons / p TBW fit
π+ K+
π- K-
p Λ
p̄ Λ̄
Ξ+
Ξ-
ratios
(a) p+p 200 GeV
m_T (GeV/c²)
π p
K
K
(b) p+p 540 GeV

Breaking of m_T scaling



Conclusions and Outlook

- Non-equilibrium effects are needed to describe the spectra in p+p collisions
- Non-zero radial flow (breaking of mT scaling) is observed at 900GeV and 7TeV p+p collisions
- Study of d+Au and p+Pb, and high multiplicity p+p events are on-going

Data references (p+p)

- 200 GeV RHIC data (STAR+PHENIX)
- charged pions, protons and anti-protons(STAR) (Phys.Lett.B637:161-169,2006)
- K0S, lambda, lambdabar, xiMinus, xiPlus(STAR) (Phys. Rev. C 75, 064901(2007))
- piZero(Phenix) (Phys. Rev. D 76, 051106 (2007))
- KPlus, KMinus(Phenix) (Phys. Rev. C 74, 024904 (2006))

- 540 GeV data (UA2, UA1)
- pion, kaon, proton, charged particles(UA2, 1983) (Banner M, Bloch P, Bonaudi F, et al. Inclusive charged particle production at the CERN pp collider[J]. Physics Letters B, 1983, 122(3): 322-328.)
- kaon, K0S (Alner G J, Alpg?rd K, Anderer P, et al. Kaon production in pp reactions at a centre-of-mass energy of 540 GeV[J]. Nuclear Physics B, 1985, 258: 505-539.)
- pionZero(pT<=40 GeV/c, 1.0<|eta|<1.8), pionZero(pT<=15 GeV/c, |eta|<=0.85), eta(3<=pT<=6 GeV/c, |eta|<=0.85) (Banner M, Bloch P, Bonaudi F, et al. Inclusive particle production in the transverse momentum range between 0.25 and 40 GeV/c at the CERNSp\ bar pS collider[J]. Zeitschrift f¨¹r Physik C Particles and Fields, 1985, 27(3): 329-339.)
- pionZero(1.5<pT<4.5 GeV/c, <|eta|>=0) (Banner M, Bloch P, Bonaudi F, et al. Inclusive< i> ¦Ð</i>< sup> 0</sup> production at the CERN p-p? collider[J]. Physics Letters B, 1982, 115(1): 59-64.)
- K/pion, pbar/pion (Alexopoulos T, Allen C, Anderson E W, et al. Mass-identified particle production in proton-antiproton collisions at sqrt [s]= 300, 540, 1000, and 1800 GeV[J]. Physical Review D, 1993, 48(3): 984.)
- charged particles(UA1,1982) (Arnison G, Astbury A, Aubert B, et al. Transverse momentum spectra for charged particles at the cern proton-antiproton collider[J]. Physics Letters B, 1982, 118(1): 167-172.)

- 0.9 TeV pp collisions at LHC data:
- pionPlus, pionMinus, KPlus, KMinus, proton, pbar(CMS) (Chatrchyan S, Khachatryan V, Sirunyan A M, et al. Study of the inclusive production of charged pions, kaons, and protons in pp collisions at\ sqrt {s}= 0.9, 2.76,\ mbox {and} 7~\ mbox {TeV}[J]. The European Physical Journal C, 2012, 72(10): 1-37.)
- K0S, lambda, Xi(CMS) (Khachatryan V, Sirunyan A M, Tumasyan A, et al. Strange particle production in pp collisions at\ sqrt {s}= 0.9 and 7 TeV[J]. Journal of High Energy Physics, 2011, 2011(5): 1-40.)
- pionZero(ALiCE) (Abelev B, Abrahantes Quintana A, Adamov¨¢ D, et al. Neutral pion and ¦Ç meson production in proton¨Cproton collisions at and[J]. Physics Letters B, 2012.)
- charged particles(CMS) (Charchyan S. Charged particle transverse momentum spectra in pp collisions at\ sqrt {s}= 0.9 and 7 TeV[J]. 2011.)

- 7 TeV pp collisions at LHC data:
- pionPlus, pionMinus, KPlus, KMinus, proton, pbar(CMS) (Chatrchyan S, Khachatryan V, Sirunyan A M, et al. Study of the inclusive production of charged pions, kaons, and protons in pp collisions at\ sqrt {s}= 0.9, 2.76,\ mbox {and} 7~\ mbox {TeV}[J]. The European Physical Journal C, 2012, 72(10): 1-37.)
- K0S, lambda, Xi(CMS) (Khachatryan V, Sirunyan A M, Tumasyan A, et al. Strange particle production in pp collisions at\ sqrt {s}= 0.9 and 7 TeV[J]. Journal of High Energy Physics, 2011, 2011(5): 1-40.)
- pionZero, Eta(ALiCE) (Abelev B, Abrahantes Quintana A, Adamov¨¢ D, et al. Neutral pion and ¦Ç meson production in proton¨Cproton collisions at and[J]. Physics Letters B, 2012.)
- charged particles(CMS) (Charchyan S. Charged particle transverse momentum spectra in pp collisions at\ sqrt {s}= 0.9 and 7 TeV[J]. 2011.)

Does nonextensive contradict coalescence?

- No, macroscopic vs microscopic
- Coalescence is non-extensive (T. Biro et al.)
- In fact, this non-extensive approach may provide a foundation for discussing entropy issues (Wilk, Biro, Tsallis, Maroney et al.)
- Can we describe/predict LHC results?
- J/Ψ, ϕ v_2 and R_{AA}