Anti-nuclei and Nuclei Production in Pb+Pb Collisions at CERN SPS Energies

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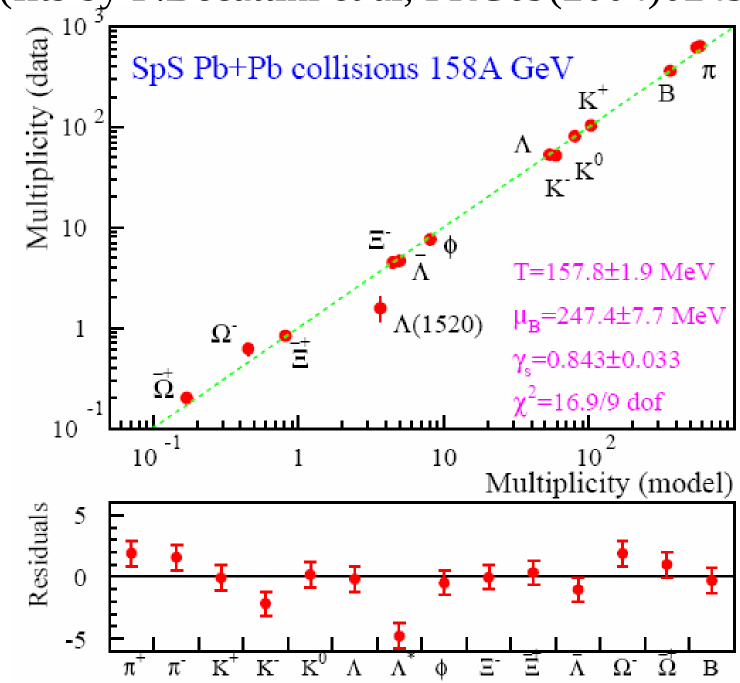
Motivation

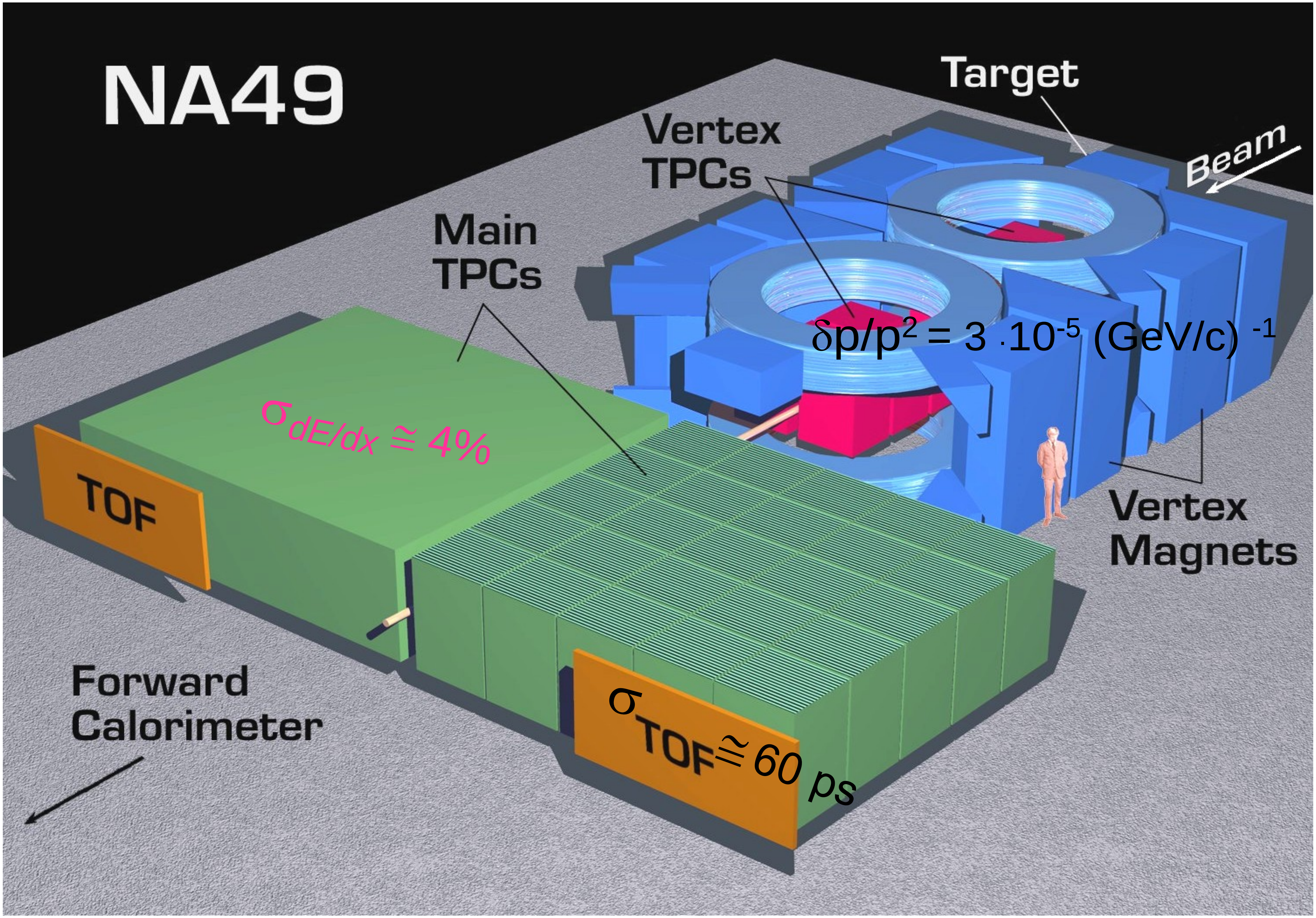
- Space-time structure of the freeze-out region
- Collective effects in dense and hot nuclear matter
- Reaction volume and freeze-out nucleon density
- Final state interactions and nuclear cluster production mechanism

Particle yields and ratios reproduced by statistical models.

Is the thermal model able to predict the yields of composite particles?

(fits by F.Becattini et al, PRC69(2004)024905)




NA49
Target
Vertex
TPCs
Beam
Main
TPCs
$\delta p/p^2 = 3 \cdot 10^{-5}$ (GeV/c) $^{-1}$
$\sigma_{dE/dx} \cong 4\%$
TOF
Vertex
Magnets
Forward
Calorimeter
$\sigma_{TOF} \cong 60$ ps

Data sets

^{3}He, t, p – 7% central Pb+Pb at E/A=20-80 GeV (300k each)

dbar (d, pbar) - 23% central Pb+Pb at E/A=158 GeV (2.6M)

Analysis

Particle identification via dE/dx and TOF measurements

Corrections: TOF efficiency (including quality cuts) > 70%,
dE/dx efficiency > 98%, acceptance (GEANT),
feeddown for (anti)protons (20-30%)

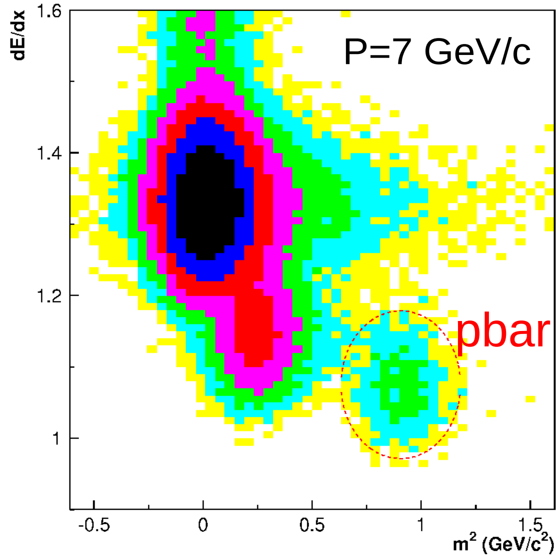
Systematic errors (clusters):

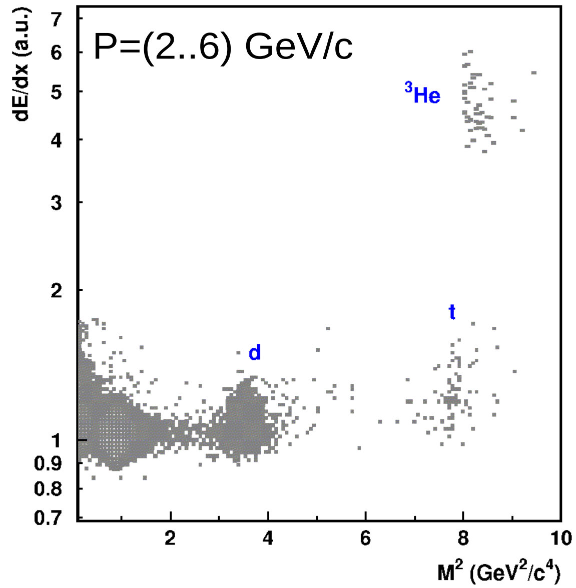
Spectra – 15% (normalization), 10% - slopes ($\langle m_t \rangle$-m)

Coalescence – 20-30%

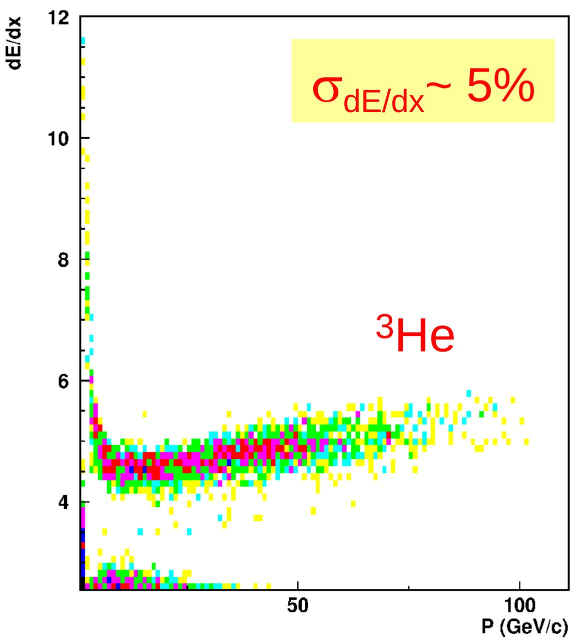
Details can be found: Phys. Rev. C69, 024902 (2004)
Phys. Rev. C73, 044910 (2006)

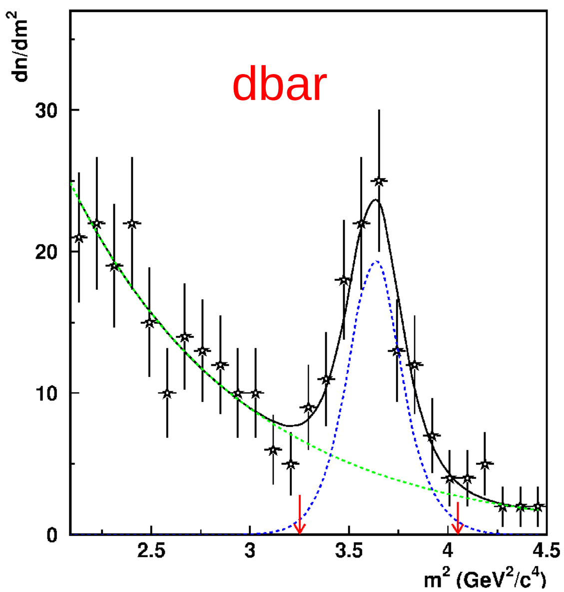
Particle ID in NA49





$dE/dx+M^2(TOF)$ → hadrons and clusters at midrapidity $0<p_t<2$ GeV/c

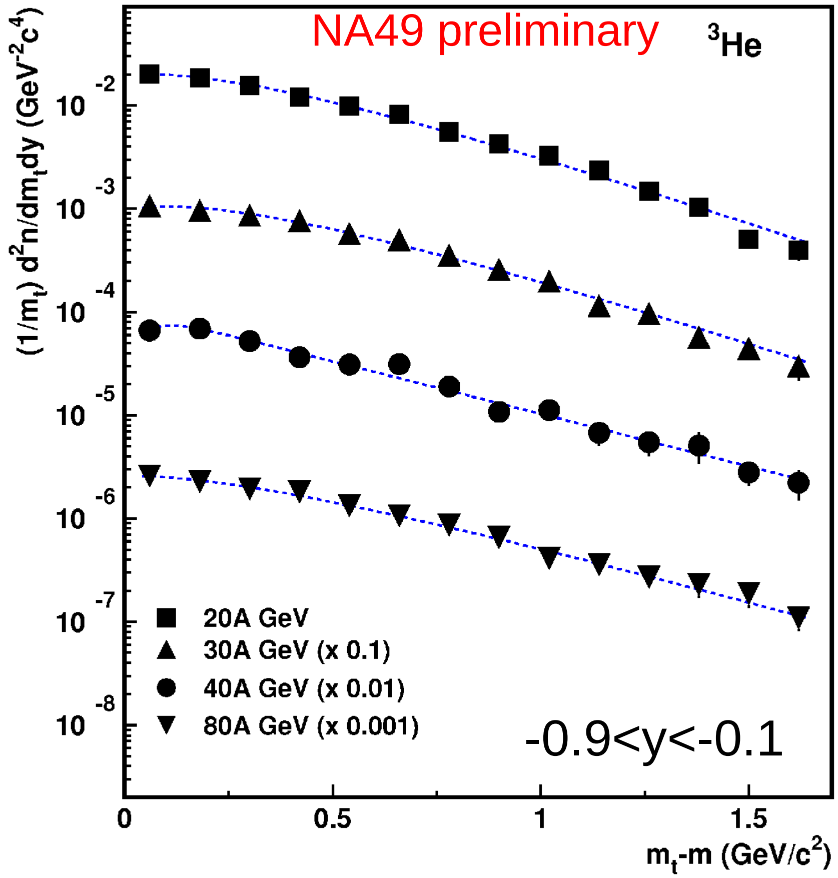


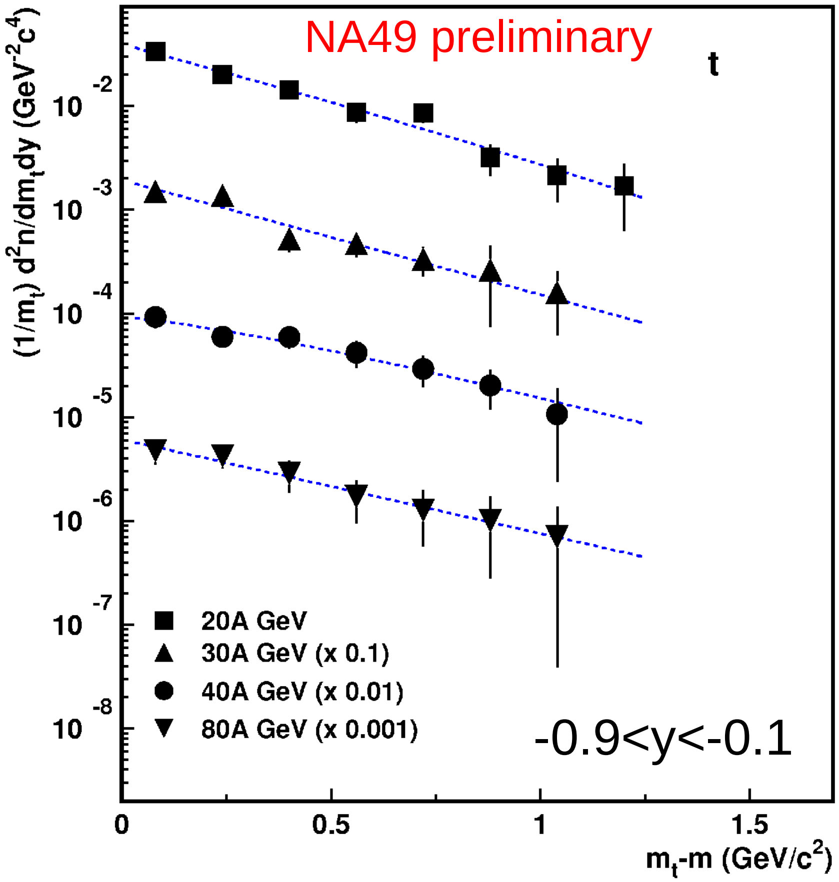


dE/dx → ^{3}He in the entire TPC acceptance $0.5<Y<Y_{beam}-0.5$ $0<p_t<3$ GeV/c

M^2 (with dE/dx cut) → dbar $-1<y<-0.5$, $0<p_t<0.9$ GeV/c

M_t-distributions for ^{3}He and t (E/A=20-80 GeV)





- m_t-spectra deviate from thermal distribution due to a large flow component
- 2-exponential fit function used for extrapolation

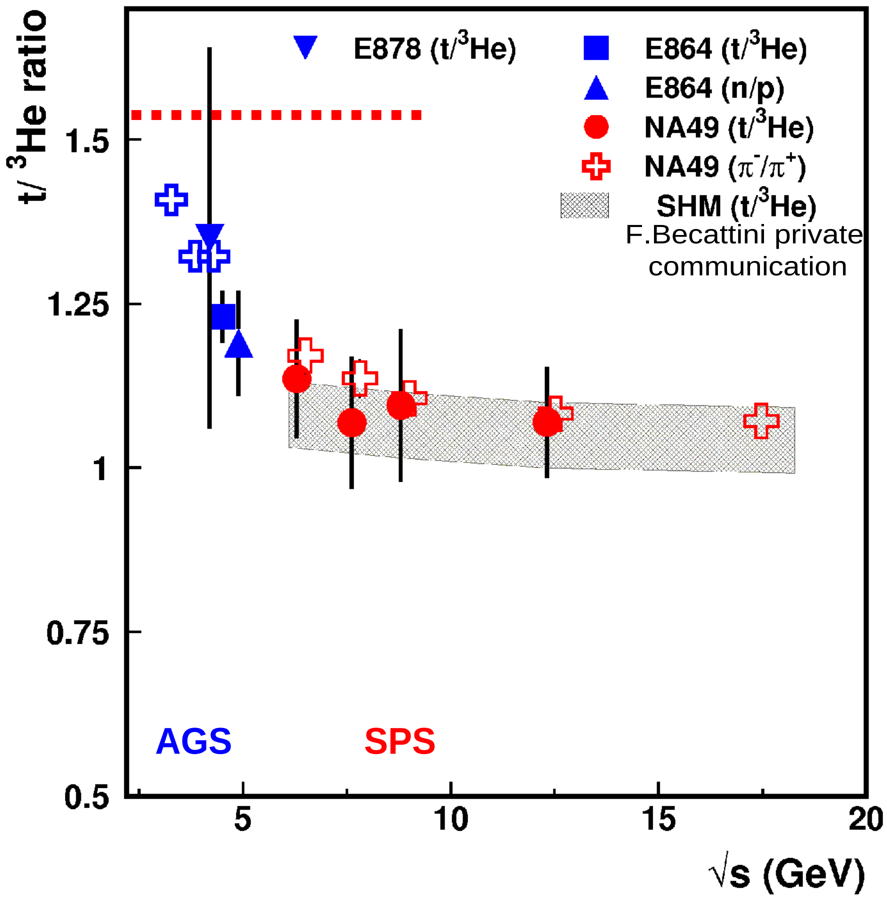
t / ^{3}He ratio in central A+ A collisions

Primordial (A-Z)/Z-asymmetry (=1.54) goes towards equilibrium in the course of the fireball evolution

$$\frac{t}{^3\mathrm{He}} = \frac{(npn)}{(npp)} \approx \frac{n}{p}$$

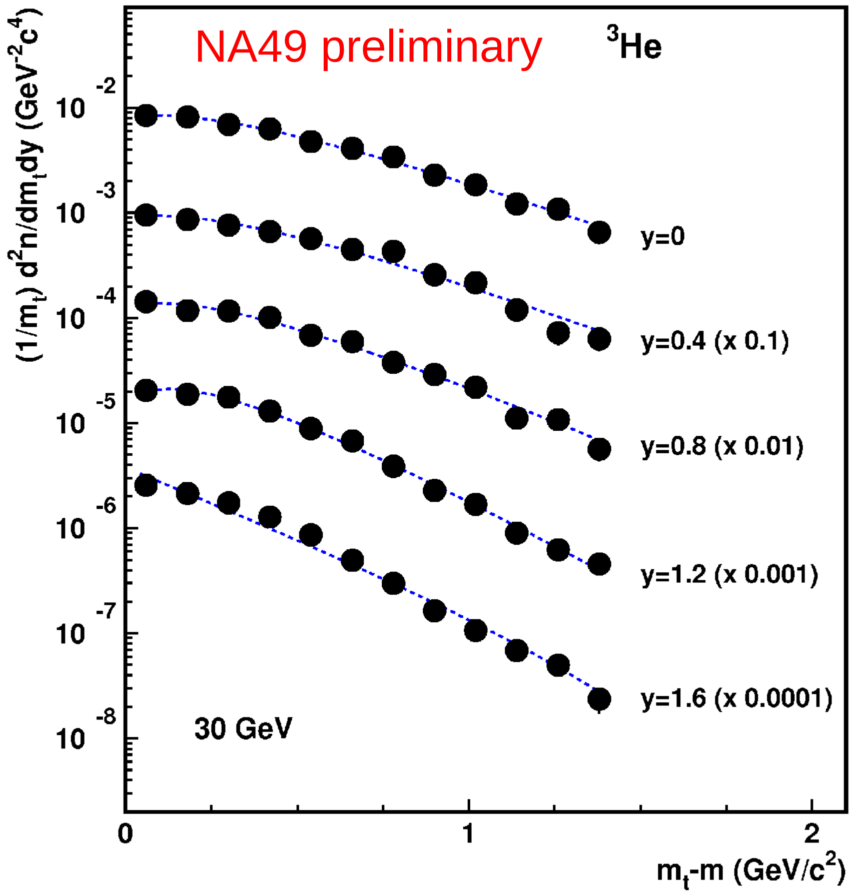
Initial isospin imbalance can be transferred to an excess of π^- over π^+

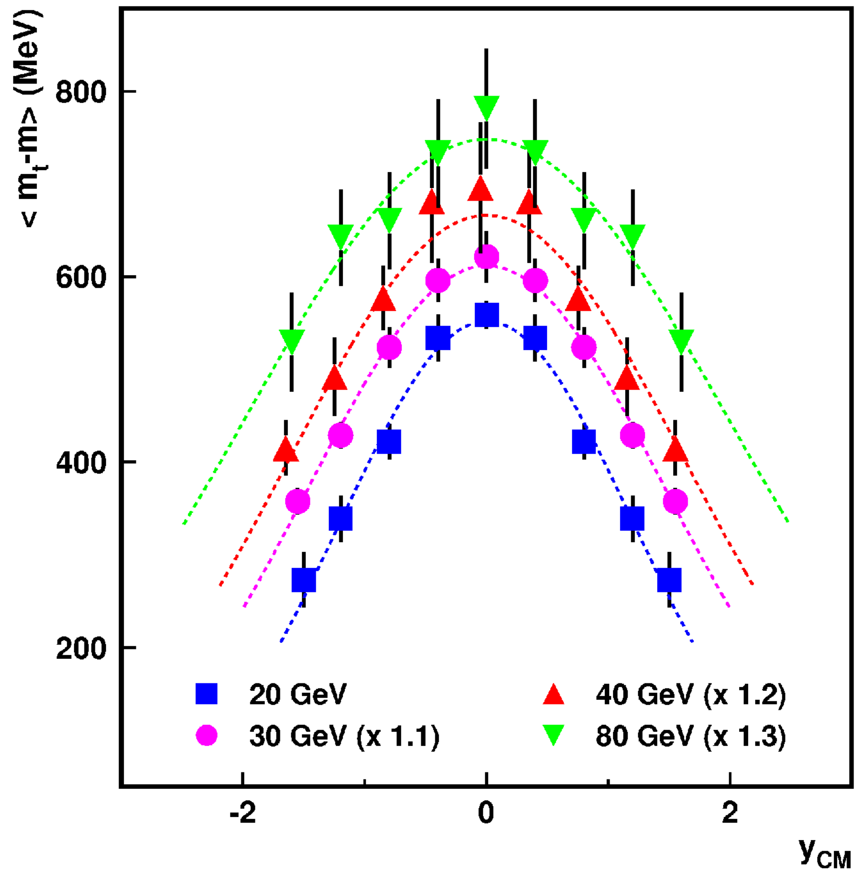
SHM: F.Becattini et al., PRC73, 044905 (2006)



- t/^{3}He ratio decreases with increasing energy (t/^{3}He ≅ 1.09 +/- 0.05 at SPS)
- t/^{3}He ratio is consistent with π^-/π^+
- data agree with SHM predictions

^{3}He m_t-spectra (rapidity dependence)

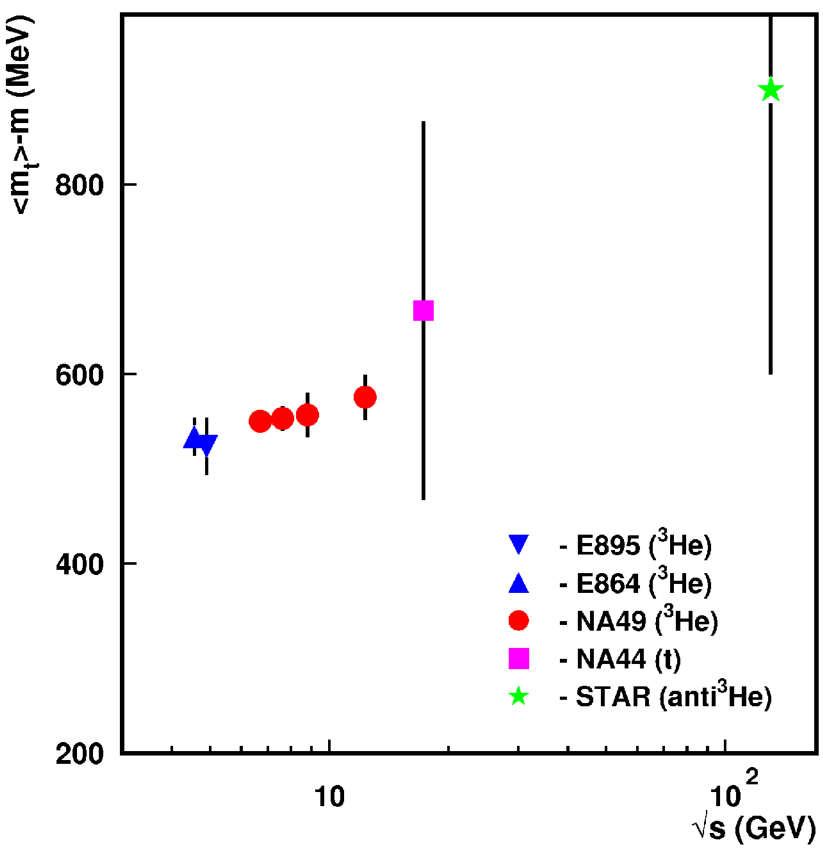


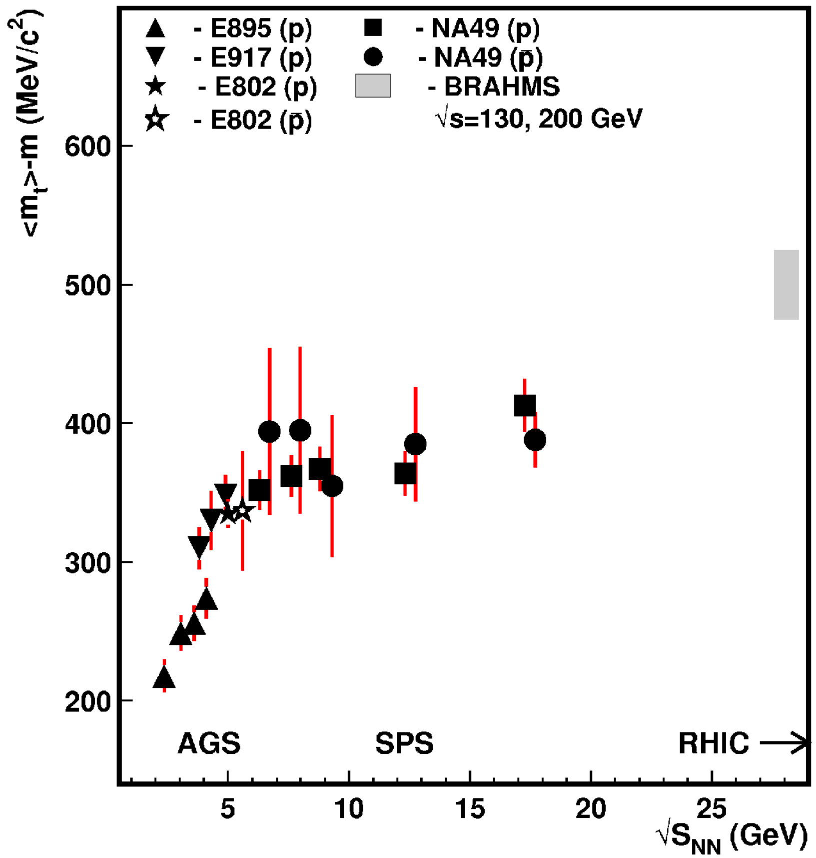


$<m_t>$-m decreases with rapidity

Gaussian functions fitted to the data

Midrapidity < m_t> - m (energy dependence)





Gradual increase of <m_t> for ^{3}He with collision energy at SPS

The same trend (plateau at SPS) observed for (anti)protons
NA49, Phys. ReV. C73, 044910 (2006)

Midrapidity $\langle m_t \rangle$ - m (mass dependence)

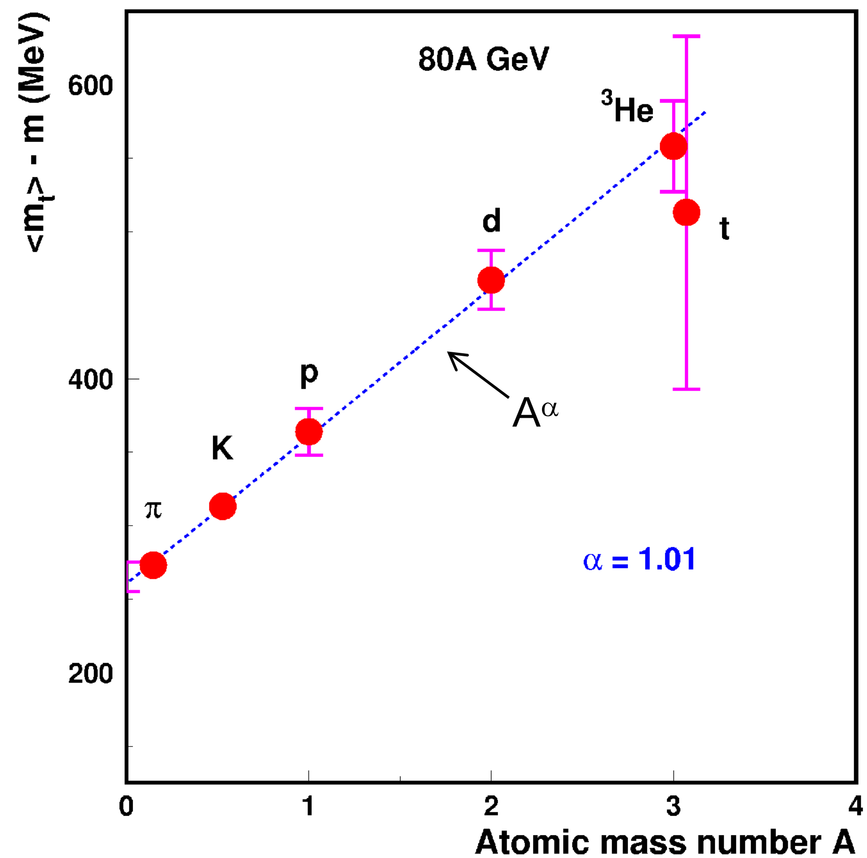
Different density and flow profiles result in a different A-dependence of $\langle m_t \rangle$-m for clusters (A – mass number of a cluster):
A. Polleri *et al.* Phys. Lett. B419 (1998) 19-24

density: Box or Gauss; $\text{flow}: v(r) = v_f \left(\frac{r}{R}\right)^{\alpha}$

$$\langle m_t \rangle - m \propto A \quad - (\text{Box})$$

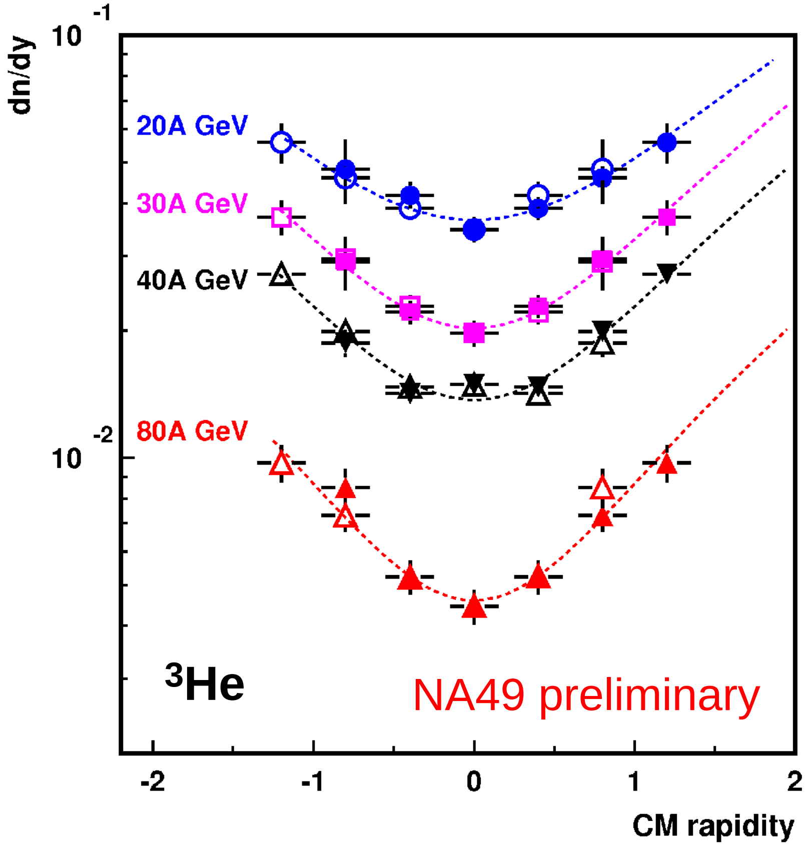
$$\langle m_t \rangle - m \propto A^{1-\alpha} \quad - (\text{Gauss})$$

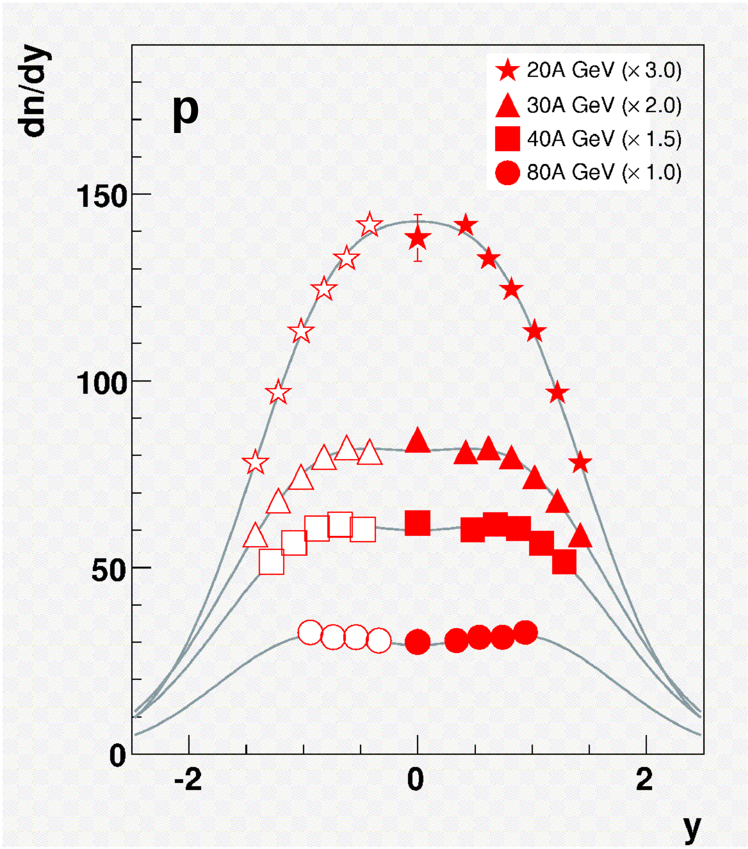
$\alpha \approx 0.9 \div 1.0$ favours a box-like nucleon density profile at SPS



π,K : NA49, J.Phys.G31,S911,2005
NA49, Phys. Rev. C66, 054902 (2002)
p,d : NA49, Phys. Rev. C69, 024902 (2004)

^{3}He yields (rapidity distributions)



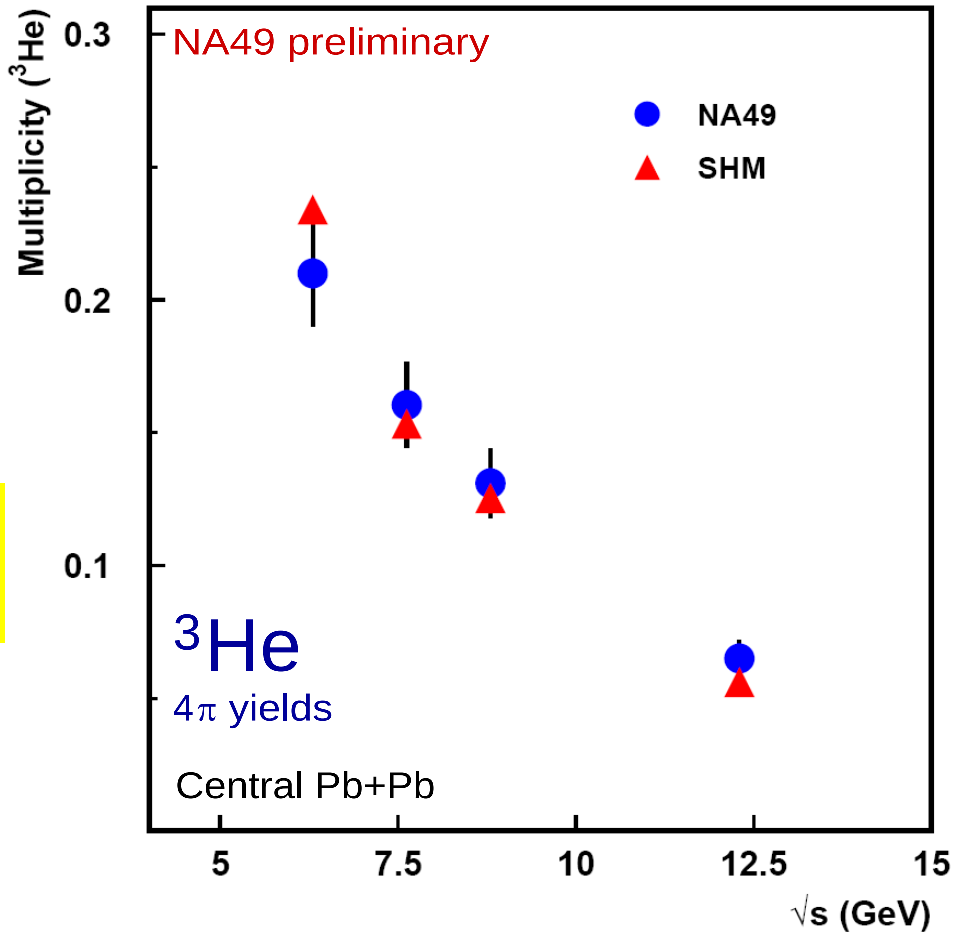


- **Concavity of y-distributions for ^{3}He (in contrast to protons) → increase of cluster formation probability away from Y_{CM} (smaller volume, larger correlations)?**

4π yield of ^{3}He in central Pb+Pb

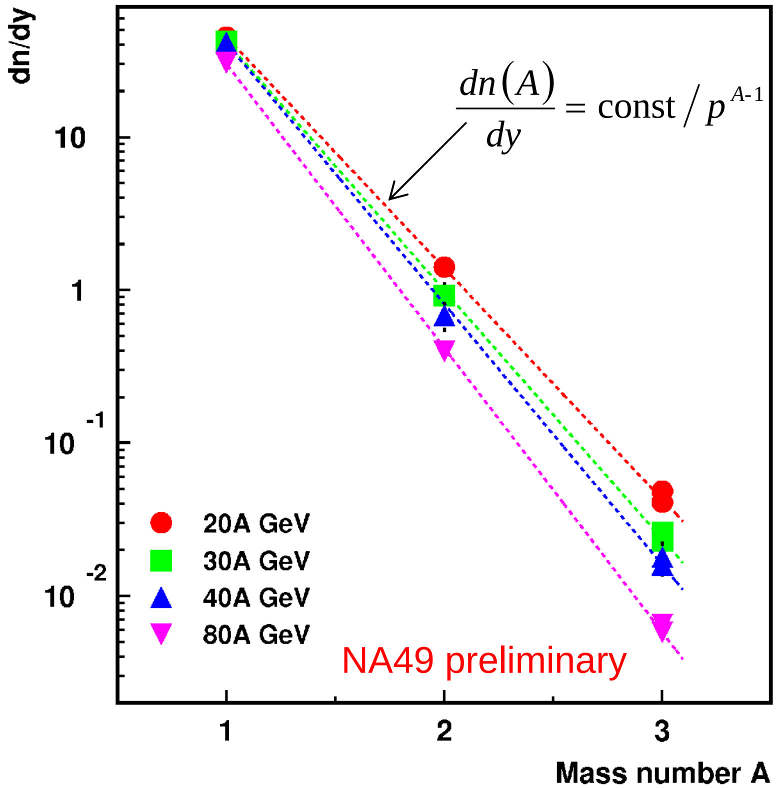
SHM: F.Becattini et al., PRC73 (2006) 044905

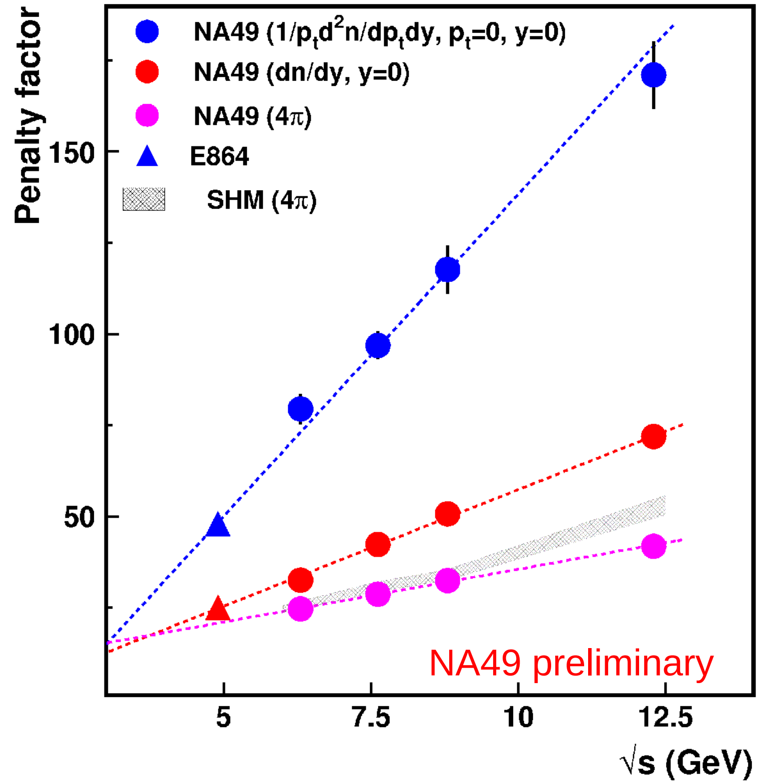
total yields estimated from parabolic fits up to $|y_{beam}|$
motivated by RQMD and
F.Becattini, J.Cleymans, hep-ph/0701029



yields show surprising agreement with statistical hadron gas model

Penalty factor for nuclear cluster production



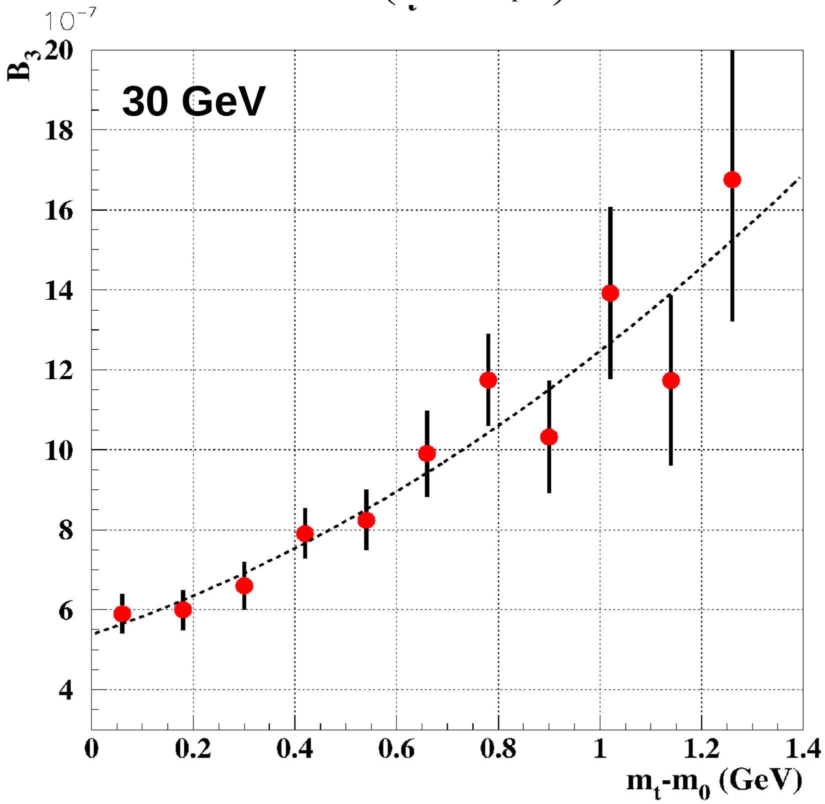


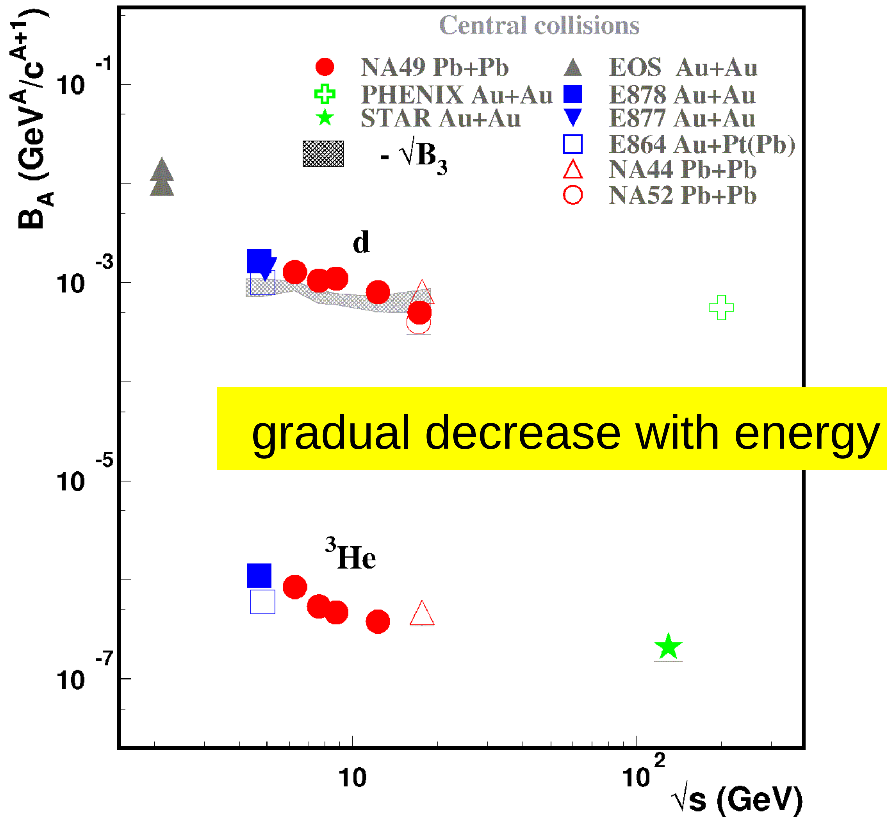
- **Exponential A-dependence for cluster yields**
- **Penalty factor (p) increases with collision energy**
- **p-factor hierarchy reflects different phase space distributions for clusters**
- **Measured penalties for 4π yields agree with the SHM predictions (** $p_{SHM} \approx e^{(m_N - \mu)/T}$ **)**

Coalescence parameter B_A in central A+ A

$$E_A \frac{d^3 N_A}{dP_A^3} = B_A \cdot \left(E_p \frac{d^3 N_p}{dP_p^3} \right)^A, \quad P_A = A \cdot P_p$$

proton spectra: NA49, PRC 73, 044910 (2006)





- Increasing of B_3 with m_t suggests collective flow and agrees with a box density profile
- Same trend (decreasing with energy) for B_2 and B_3 → increase of the source volume
- B_2 agrees (within 25-30%) with $\sqrt{B_3}$

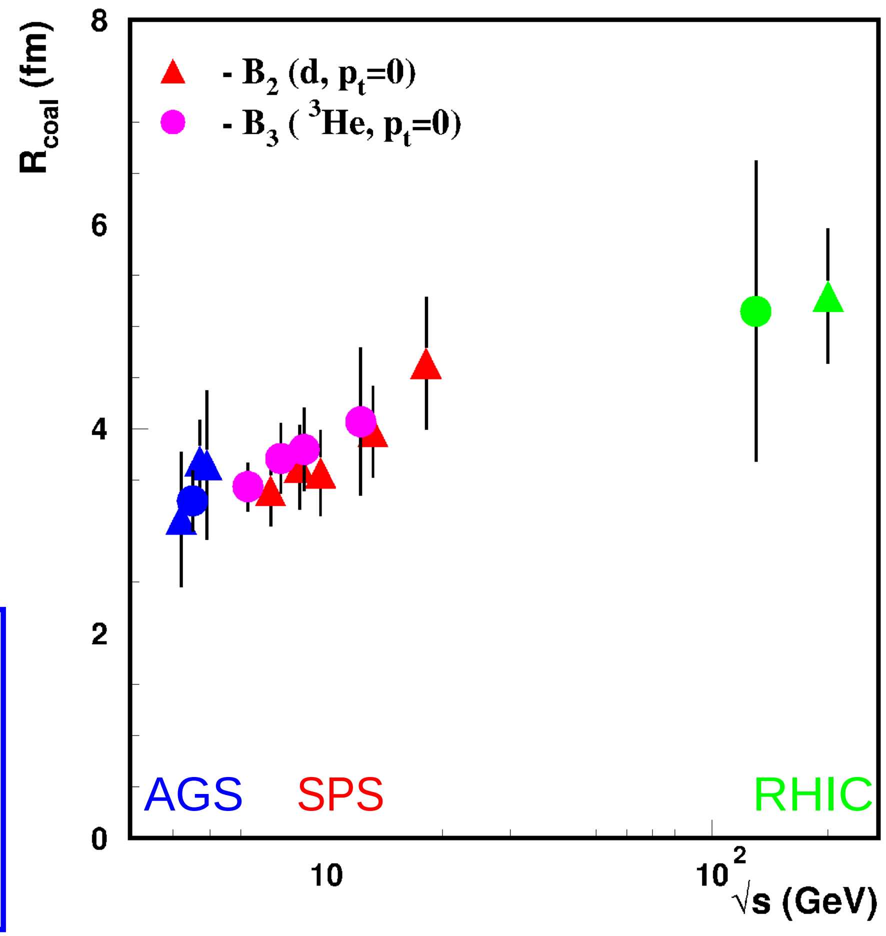
Coalescence radii R_{coal} for d and ^{3}He

In a coalescence approach:

$$V_{coal} = \frac{3\pi^{3/2}\langle C_A \rangle}{2 m_t B_A}$$

$\langle C_A \rangle$ - quantum-mechanical correction factor
$\langle C_d \rangle=0.8$, $\langle C_{^3He} \rangle=0.7$

R.Scheibl and U.Heinz, Phys.Rev.C59, 1585 (1999)

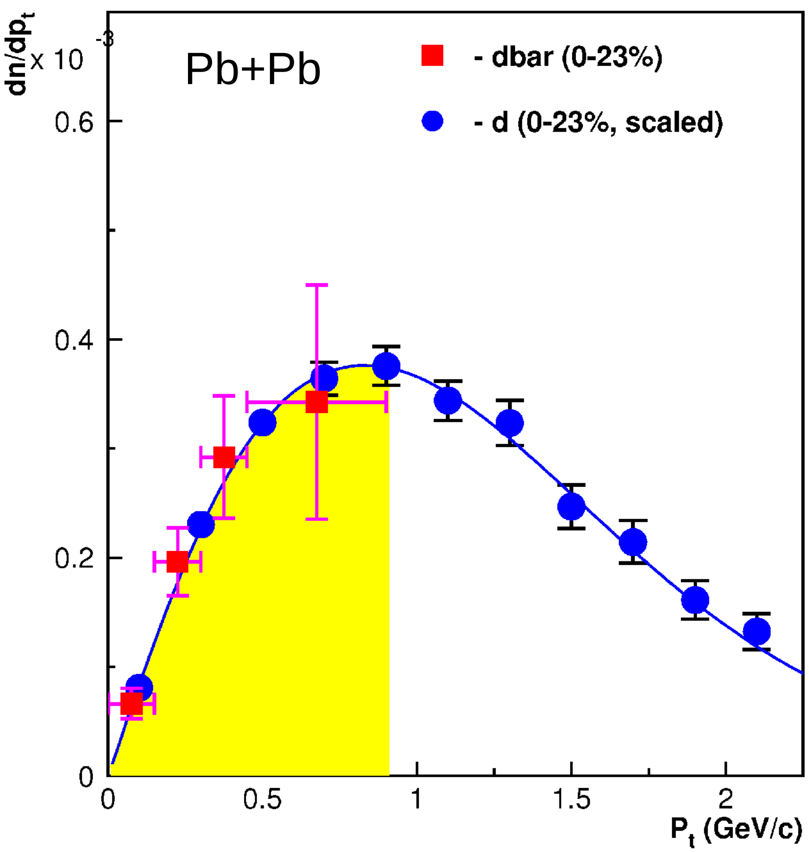


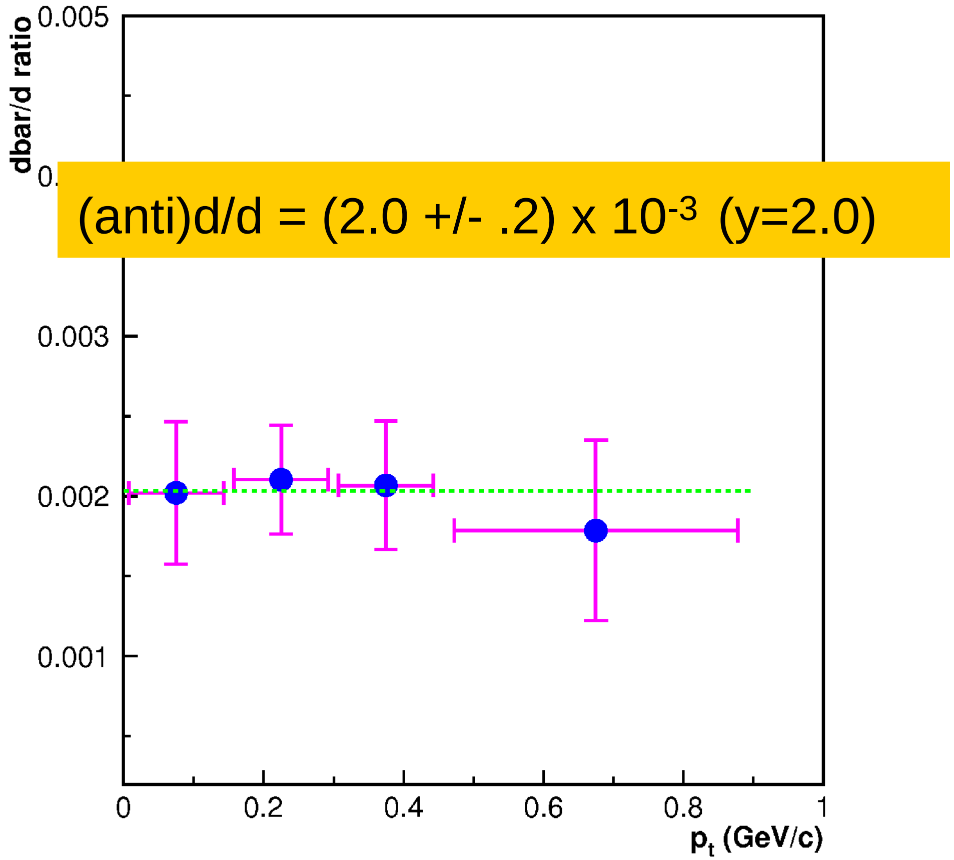
- R_{coal} for d and ^{3}He agree within errors
- Both increase with energy gradually

Antideuterons

(0-23% central Pb+Pb at E/A=158 GeV)

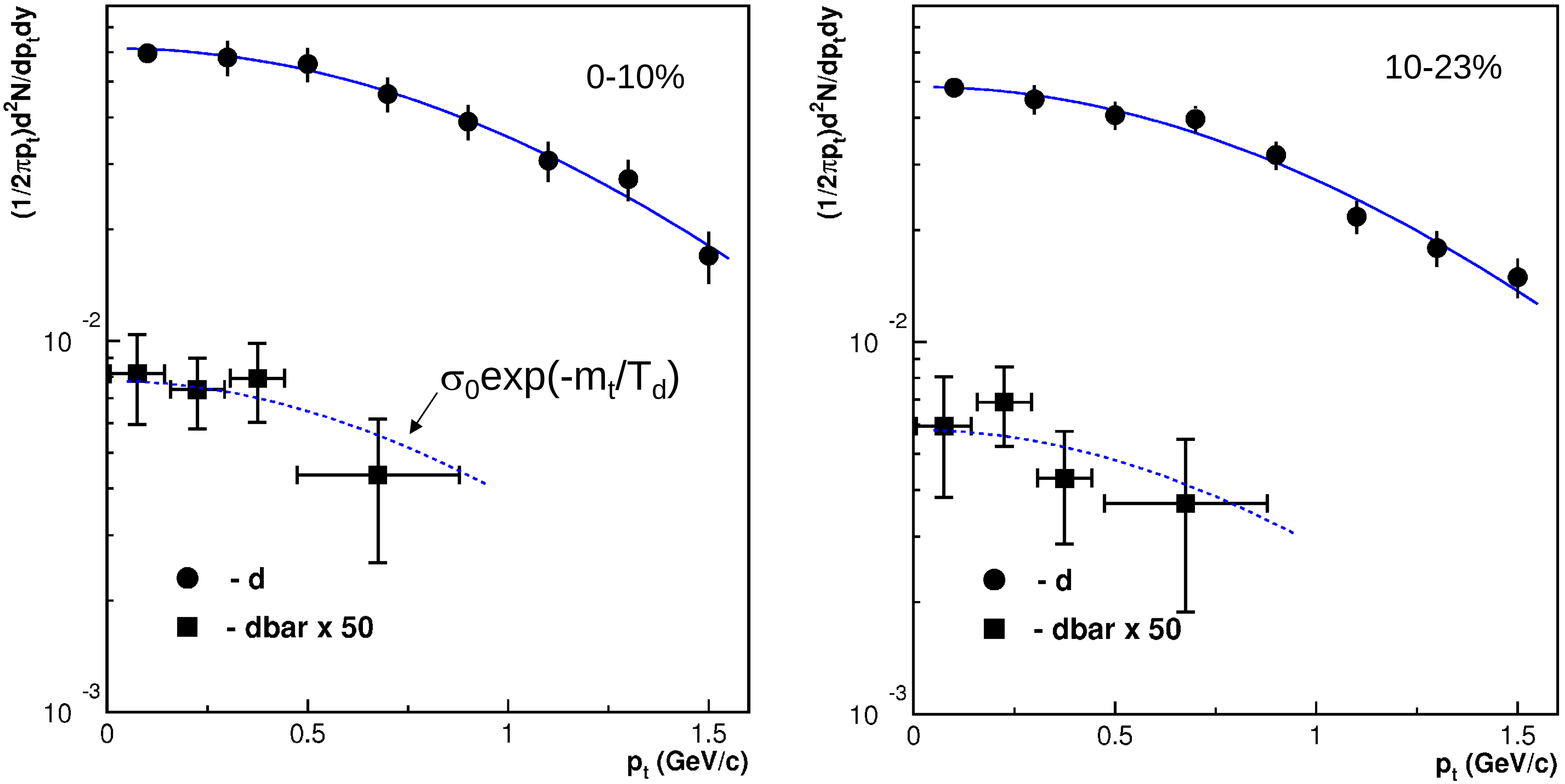
Comparison of shapes of the p_t-distributions for $\bar{d}$ and d





Similar shapes of the p_t-distributions for d and dbar (up to $p_t = 0.9$ GeV/c) ⟹ dbar/d ratio independent on p_t

Dbar invariant yield (central Pb+Pb @ E=158A GeV)

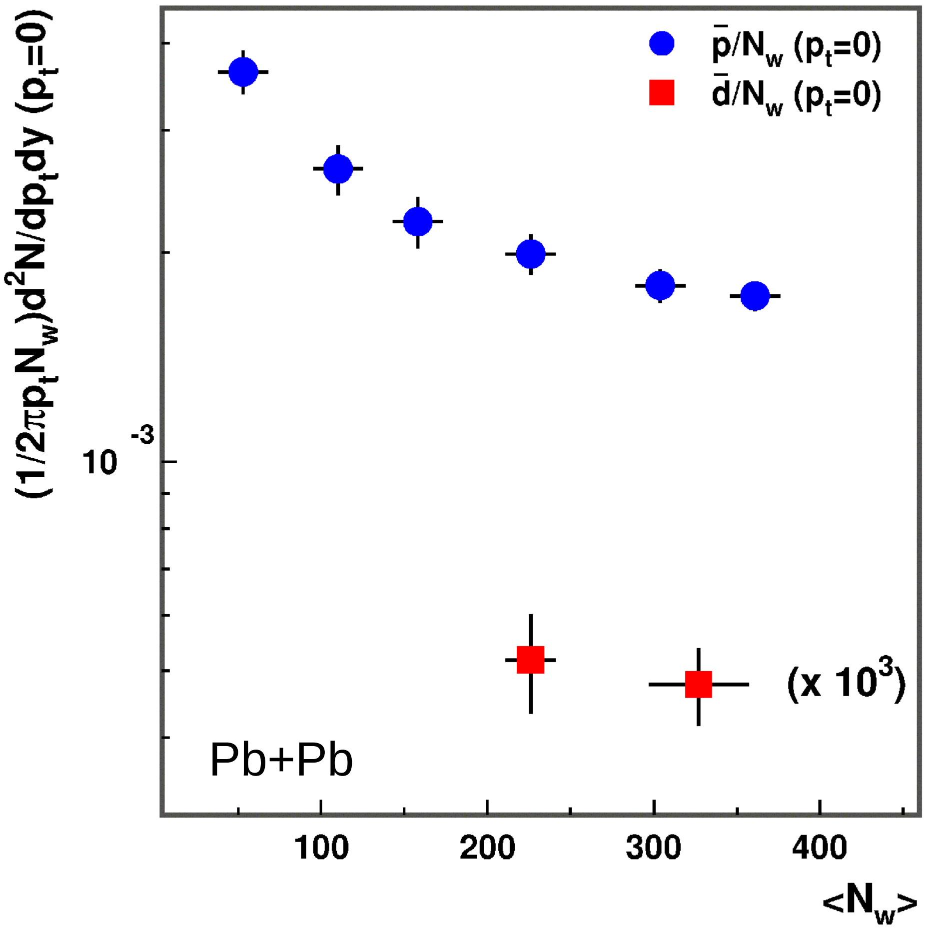


T_d fixed to the deuteron slope

σ_0 – invariant yield at p_t=0

Dbar invariant yield (centrality dependence)

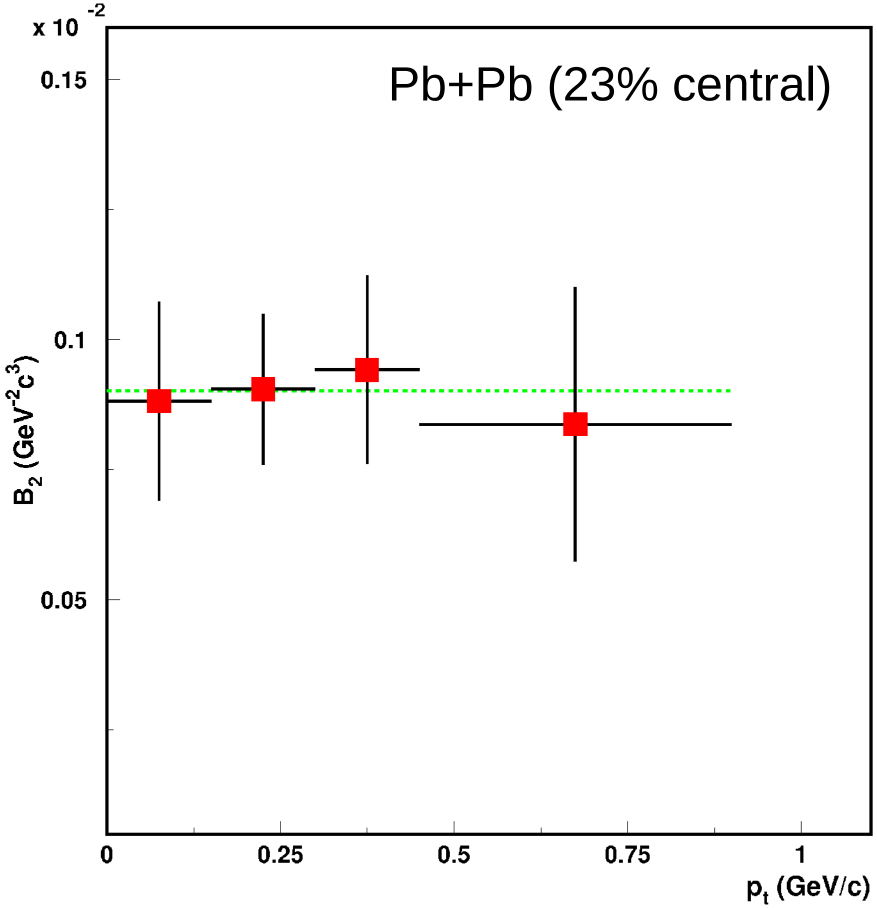
antiprotons: NA49, PRC 73, 044910 (2006)



- dbar cross-section increases with centrality
- approx. scales with $\langle N_w \rangle$

B_2 for anti-d (p_t-dependence)

antiproton spectra: NA49, PRC 73, 044910 (2006)



B_2(dbar) = (9.1 +/- 0.9) 10^{-4} GeV^2/c^3

Coalescence radius (dbar):

R_{coal} =3.97 +/- 0.24 fm (0-23% central)

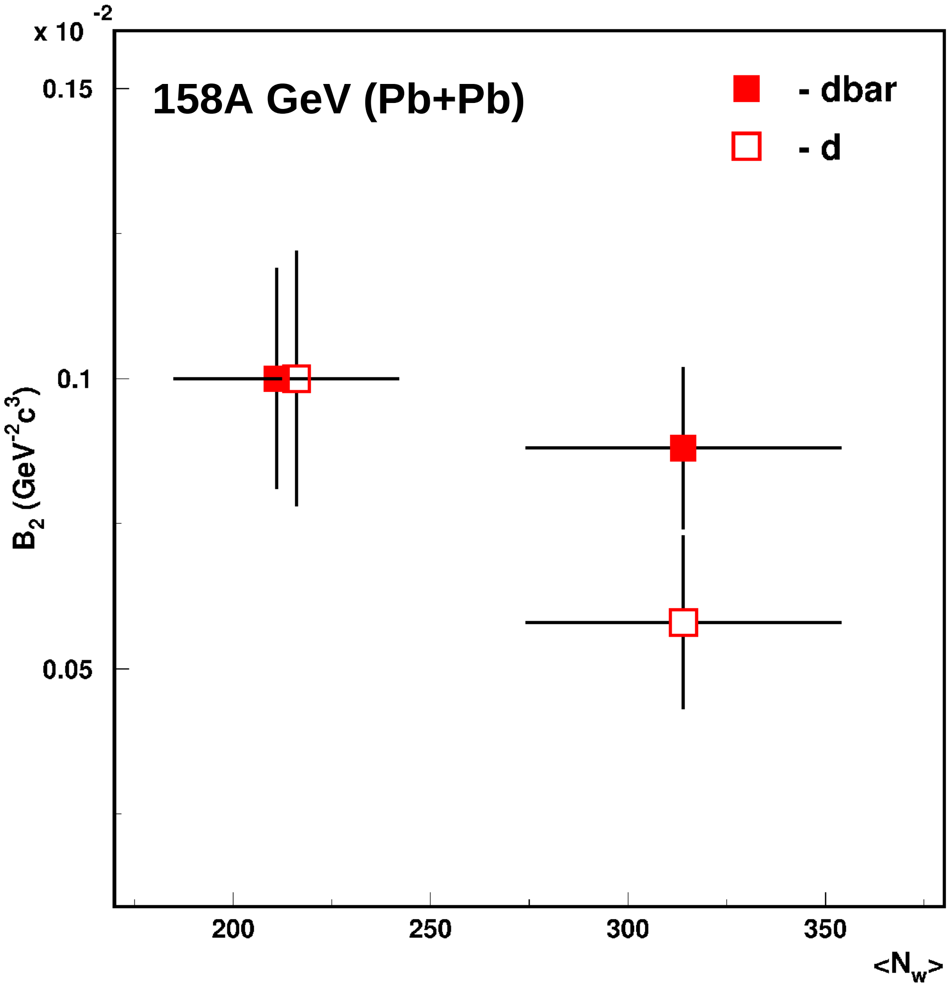
R.Scheibl and U.Heinz, Phys.Rev. C59, 1585 (1999)

RHIC data (PRL 87, 262301 (2004)):
Rcoal = 4.75 +/- 0.1 fm
(18% central Au+Au @ 130 GeV)

Increase of V_{eff} by 1.7 from SPS to RHIC

weak dependence in the measured p_t-interval

B_2 (centrality dependence)



- B_2 decreases with centrality for d and anti-d
- centrality dependence for deuterons is stronger than for anti-d
- both agree within the errors (20% for d and 30% for anti-d

SUMMARY

- Production of ^{3}**He** and **t** clusters has been studied by the NA49 experiment in 7% most central Pb+Pb collisions @ E/A=20-80 GeV. Measurements of antideuterons in 23% central Pb+Pb @ E/A=158 GeV are also presented.
- An average midrapidity t/^{3}He ratio of 1.09+/-0.05 is observed representing a considerable equilibrium at SPS.
- For the first time total 4π multiplicities for ^{3}He as well as scaling (penalty) factors for cluster yields in the entire phase space have been measured. Those agree with the predictions of the Statistical Hadronization Model.
- An observed linear rise of midrapidity $\langle m_t \rangle - m$ with particle (cluster) mass and increase of B_3 with m_t is consistent with strong transverse flow and a box-shaped fireball.
- B_2 and B_3 (R_{coal}) for clusters decreases (increases) gradually with collision energy indicating an increasing source size at SPS.
- Coalescence fireball radii for A=2 and A=3 clusters, derived from the B_A parameters, are consistent with each other within errors.
- Shapes of p_t-distributions for d and dbar are similar up to p_t = 0.9 GeV/c.
- Dbar invariant yield increases with centrality linearly with $\langle N_w \rangle$.
- B_2 for antideuterons decreases towards central collisions indicating increase of the source volume.

The NA49 collaboration

C. Alt[9], T. Anticic[21], B. Baatar[8],D. Barna[4], J. Bartke[6], L. Betev[10], H. Białkowska[19], C. Blume[9], B. Boimska[19], M. Botje[1], J. Bracinik[3], R. Bramm[9], P. Bunčić[10], V. Cerny[3], P. Christakoglou[2], O. Chvala[14], J.G. Cramer[16], P. Csató[4], P. Dinkelaker[9], V. Eckardt[13], D. Flierl[9], Z. Fodor[4], P. Foka[7], V. Friese[7], J. Gál[4], M. Gaździcki[9,11], V. Genchev[18], G. Georgopoulos[2], E. Gładysz[6], K. Grebieszkow[20], S. Hegyi[4], C. Höhne[7], K. Kadija[21], A. Karev[13], M. Kliemant[9], S. Kniege[9], V.I. Kolesnikov[8], E. Kornas[6], R. Korus[11], M. Kowalski[6], I. Kraus[7], M. Kreps[3], M. van Leeuwen[1], P. Lévai[4], L. Litov[17], B. Lungwitz[9], M. Makariev[17], A.I. Malakhov[8], M. Mateev[17], G.L. Melkumov[8], M. Mitrovski[9], J. Molnár[4], St. Mrówczyński[11], V. Nicolic[21], G. Pálla[4], A.D. Panagiotou[2], D. Panayotov[17], A. Petridis[2], M. Pikna[3], D. Prindle[16], F. Pühlhofer[12], R. Renfordt[9], C. Roland[5], G. Roland[5], M. Rybczyński[11], A. Rybicki[6,10], A. Sandoval[7], N. Schmitz[13], T. Schuster[9], P. Seyboth[13], F. Siklér[4], B. Sitar[3], E. Skrzypczak[20], G. Stefanek[11], R. Stock[9], H. Ströbele[9], T. Susa[21], I. Szentpétery[4], J. Sziklai[4], P. Szymanski[10,19], V. Trubnikov[19], D. Varga[4,10], M. Vassiliou[2], G.I. Veres[4,5], G. Vesztergombi[4], D. Vranić[7], A. Wetzler[9], Z. Włodarczyk[11] I.K. Yoo[15], J. Zimányi[4]

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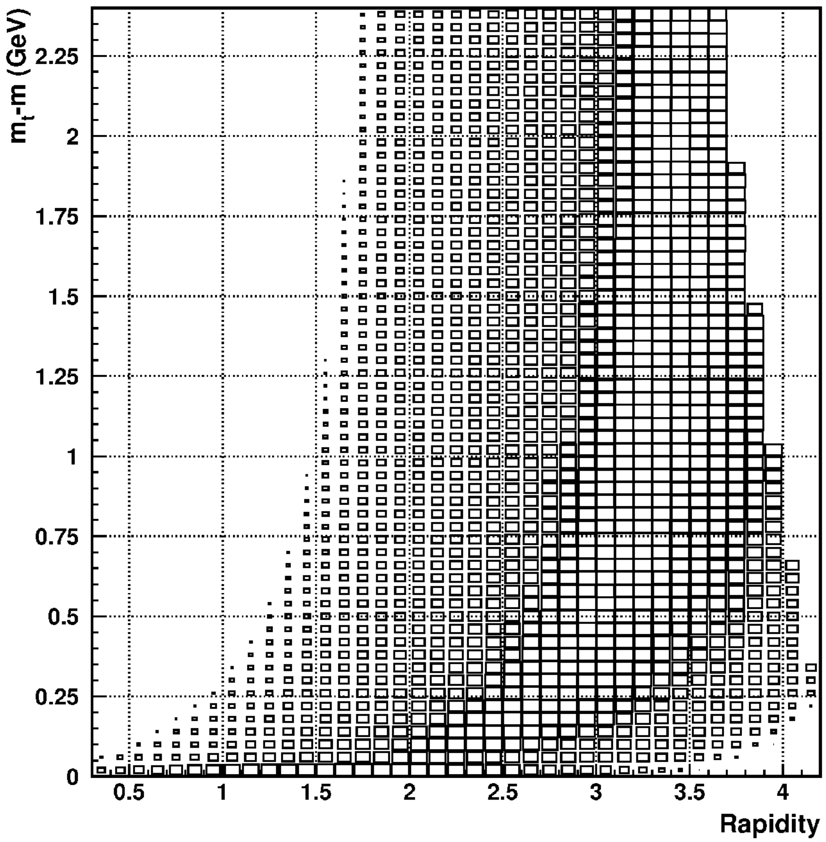
The End

Extra slide (1)

NA49 TPC acceptance (30A GeV)



Extra slide (2)

SHM : Superposition of fireballs:

$$\frac{dN_i}{dy} = \int_{-\infty}^{\infty} dY\ \rho(Y) \frac{dN_i^0}{dy}(y-Y)$$

where

$$\frac{dN_i^0}{dy} = \frac{g_i V}{2\pi^2}\left[\frac{2T^3}{\cosh^2(y-Y)} + \frac{2mT^2}{\cosh(y-Y)} + m^2 T\right] e^{\frac{\mu_i}{T}}$$

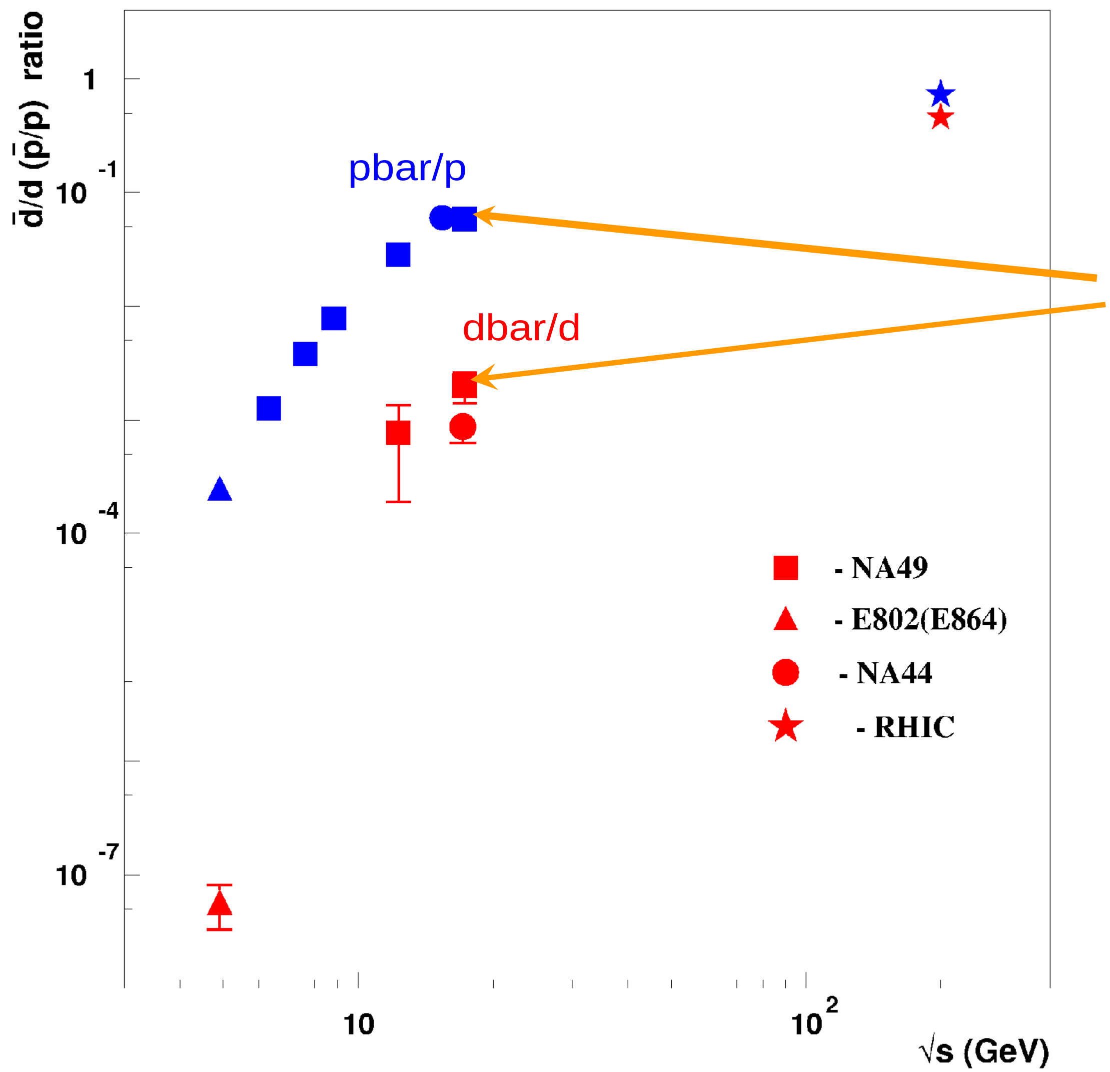
Rapidity dependence for ρ and μ_B :

$$\rho(Y) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{Y^2}{2\sigma_Y^2}\right) \qquad \mu_B = \mu_B^0 + a * Y^2$$

T varying according to the universal freezeout curve

For A=3 clusters exp(3μ_B/T) factor overcome Gaussian weight of ρ(Y) at large Y → parabolic rapidity distributions for clusters!

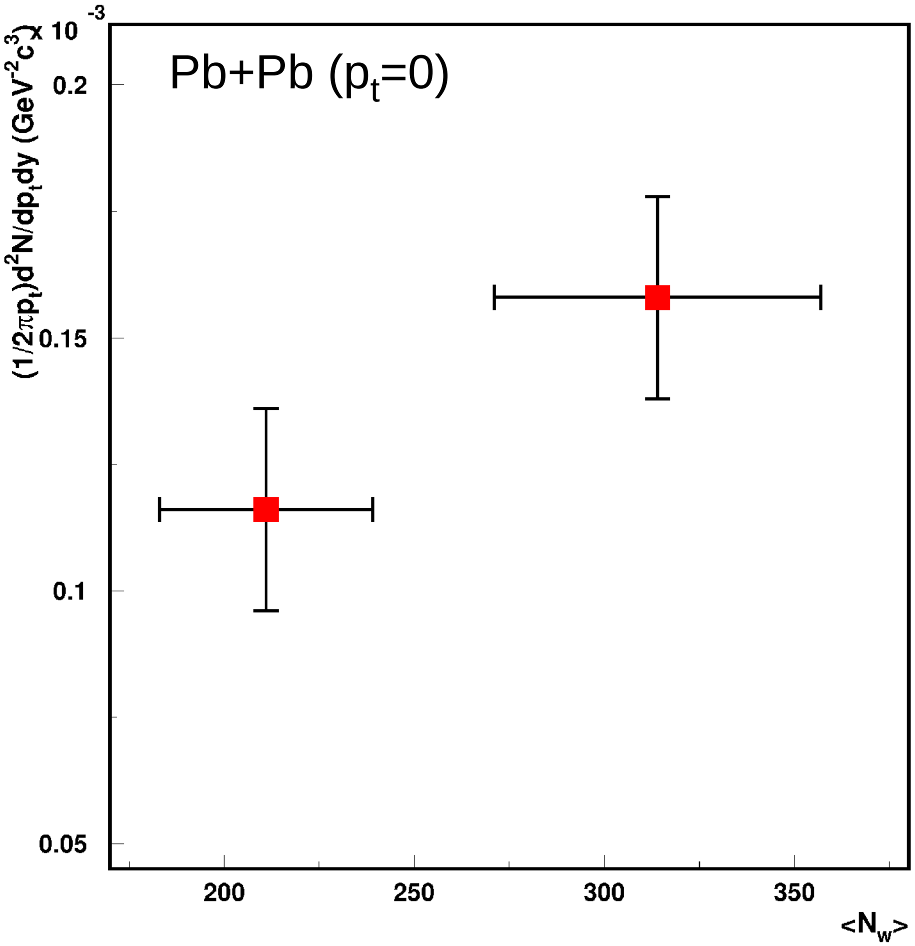
dbar/d (energy dependence)



$$\frac{\bar{d}}{d} \approx \left(\frac{\bar{p}}{p}\right)^2$$

as expected in coalescence models

Dbar invariant yield (centrality dependence)



- dbar cross-section increases with centrality
- approx. scales with $<N_w>$