

**Possibility to Study
the Energy Correlators
for Very High Multiplicity Events
with the ATLAS at LHC**

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The notion of equilibrium was introduced.

1 Characteristic Features of VHM Events

- VHM domain:

Inelasticity coefficient:

$$n \gg \bar{n}(s)$$

$$\kappa = \frac{E - \epsilon_{\max}}{s}$$

$$1 - \kappa \ll 1$$

- VHM region:

- To exclude the phase space boundaries:

$$n \ll n_{\max} = \frac{\sqrt{s}}{m}, \quad m \approx 0.2 \text{ GeV}$$

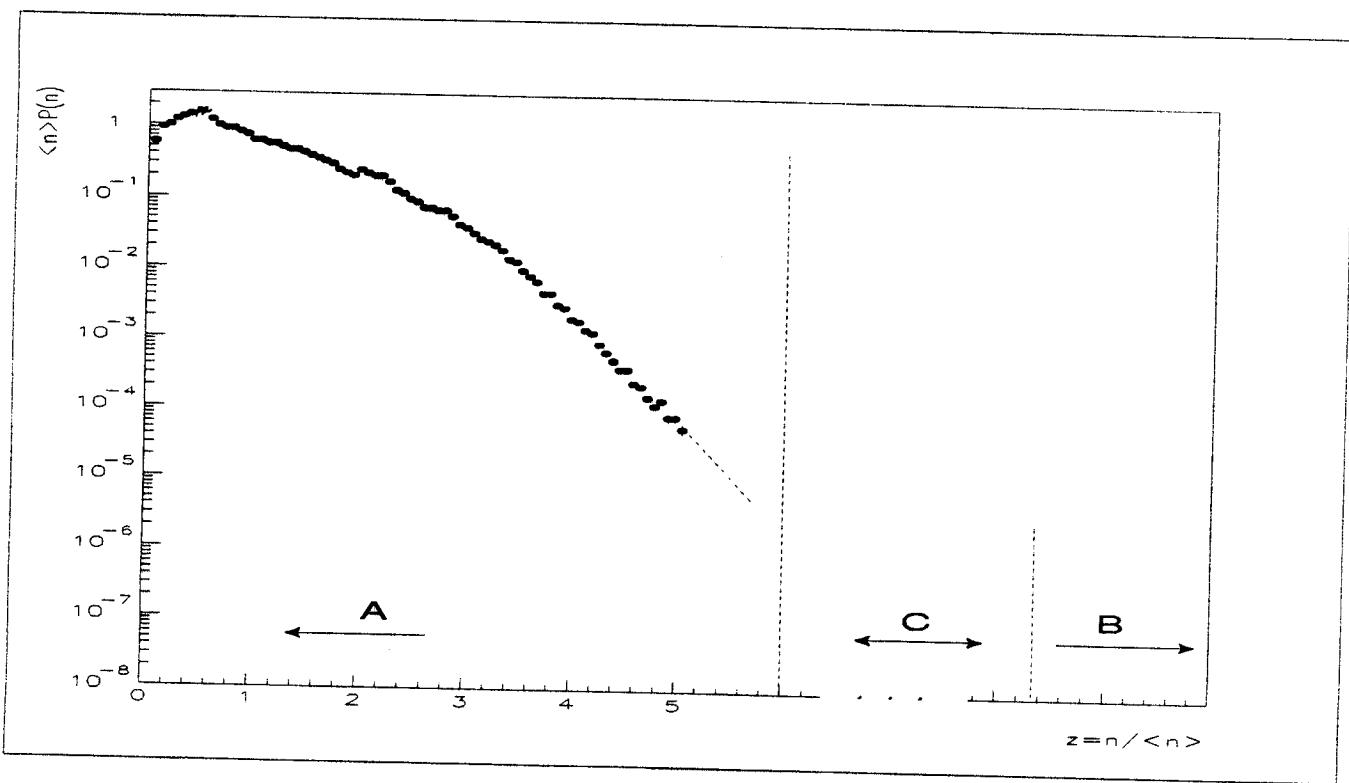


Figure 1: Multiplicity distribution: E-735 (Tevatron) data.

- A: Multiperipheral domain: $n \sim \bar{n}(s)$;
- B: Thermodynamical domain: $n \rightarrow n_{\max}(s)$;
- C: $A \Leftrightarrow B$ is the VHM domain ($\sigma_{VHM} \lesssim 10^{-7} \sigma_{tot}$).

2 Thermalization in VHM Final State

- Multiplicity n measures the thermalization rate.

For this reason:

- VHM final state should be *close* (?) to "equilibrium",
- VHM should be "calm" and "cold",

- Range of validity of the thermodynamical description.

If: $|K_l(E, n)|^{2/l} \ll K_2(E, n)$, $l = 3, 4, \dots$,

then thermodynamical interpretation is acceptable.

\Rightarrow Correlations relaxation condition of N.N.Bogolyubov

$$K_2(n, E) = \langle \varepsilon^2; n, E \rangle - \langle \varepsilon^1; n, E \rangle^2,$$

$$K_3(n, E) = \langle \varepsilon^3; n, E \rangle - 3\langle \varepsilon^2; n, E \rangle \langle \varepsilon^1; n, E \rangle + 2\langle \varepsilon^1; n, E \rangle^3,$$

etc.

$$\langle \varepsilon^l; n, E \rangle = \frac{\int \varepsilon(q_1)d^3q_1\varepsilon(q_2)d^3q_2\dots\varepsilon(q_l)d^3q_l \{d^{3l}\sigma_n(E)/d^3q_1d^3q_2\dots d^3q_l\}}{\int d^3q_1d^3q_2\dots d^3q_l \{d^{3l}\sigma_n(E)/d^3q_1d^3q_2\dots d^3q_l\}},$$

where $\frac{d^{3l}\sigma_n(E)}{d^3q_1d^3q_2\dots d^3q_l}$ – differential cross section.

3 Experimental Perspectives of VHM

As follow J.Manjavidze, A.Sissakian, Phys. Rep. 346 (2001) 1.

- **For what values of multiplicity at a given energy the VHM processes become hard?**

$$R(n) = \frac{K_3^{2/3}}{K_2} \lesssim 1; n = ?;$$

In this case it will be appear possibility to estimate:

- the role of multiperipheral contribution;
 - the jet production rate;
 - the role of vacuum instabilities.
-
- **For what values of multiplicity does the VHM final state become equilibrium?**

$$R(n) = \frac{K_3^{2/3}}{K_2} \ll 1; n = ?$$

If we will have answer then we would be able

- to investigate the status pQSD;
- to observe the phase transition phenomena directly;
- to estimate the role of confinement constraints.

The **equilibrium** means that the energy correlation function mean values are small.

4 Correlation Functions

- $K_1(E, n) = \langle \varepsilon \rangle = \int \frac{d^3 p}{(2\pi)^3 2\varepsilon(p)} \varepsilon(p) \frac{d^3 \sigma_n}{dp^3} = \int d\varepsilon \varepsilon \frac{dN}{d\varepsilon}$

If $d\varepsilon \rightarrow 0$

then $K_1(E, n) = \langle \varepsilon \rangle = \frac{1}{N} \sum_{i=1}^N E_i$

where E_i is i-particle energy.

- $K_2(E, n) = \langle (\varepsilon_1 - \langle \varepsilon \rangle) \cdot (\varepsilon_2 - \langle \varepsilon \rangle) \rangle = \langle \varepsilon^2 \rangle - \langle \varepsilon \rangle^2$

- $K_3(E, n) = \langle (\varepsilon_1 - \langle \varepsilon \rangle) \cdot (\varepsilon_2 - \langle \varepsilon \rangle) \cdot (\varepsilon_3 - \langle \varepsilon \rangle) \rangle = \langle \varepsilon^3 \rangle - 3\langle \varepsilon^2 \rangle \langle \varepsilon \rangle + 2\langle \varepsilon \rangle^3$

- Manjavidze-Sissakian prediction for VHM: $R = \frac{K_3^{2/3}}{K_2} \ll 1$

- If $R = \frac{K_3^{2/3}}{K_2} \ll 1$

then the particle energy spectrum is Gaussian, with

- "temperature": $K_1^{-1}(E, n)$

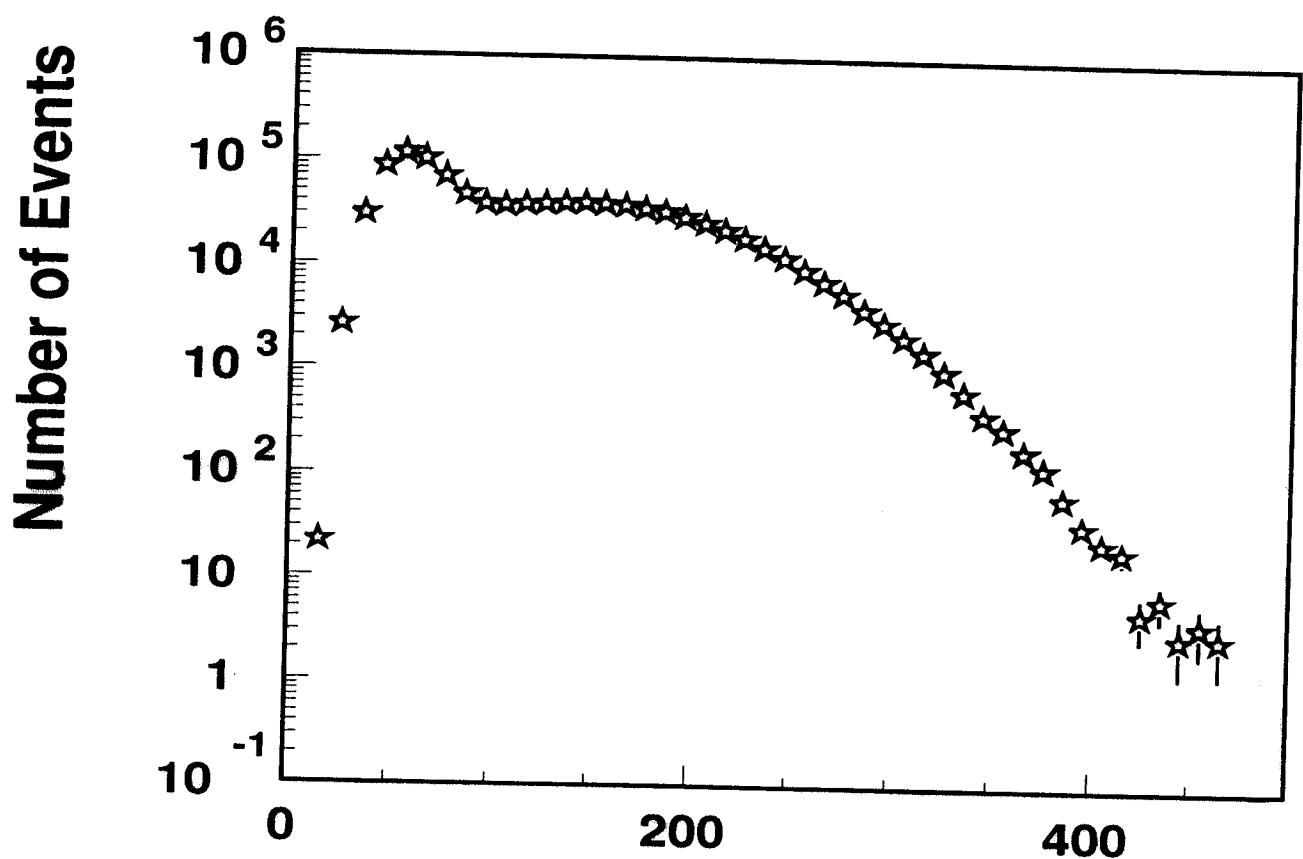
- dispersion: $\sqrt{K_2(E, n)}$

5 PYTHIA Prediction

Alushta, Ukraine, 12 September 2002

PYTHIA Sub-processes:

- $q_i q_j \rightarrow q_i q_j$
- $q_i \bar{q}_i \rightarrow q_j \bar{q}_j$
- $q_i \bar{q}_i \rightarrow g g$
- $q_i g \rightarrow q_i g$
- $g g \rightarrow q_i \bar{q}_i$
- $g g \rightarrow g g$

Figure 2: PYTHIA: Multiplicity distribution at $\sqrt{s} = 14$ TeV.

PYTHIA: $K_1(\varepsilon, n_h)$

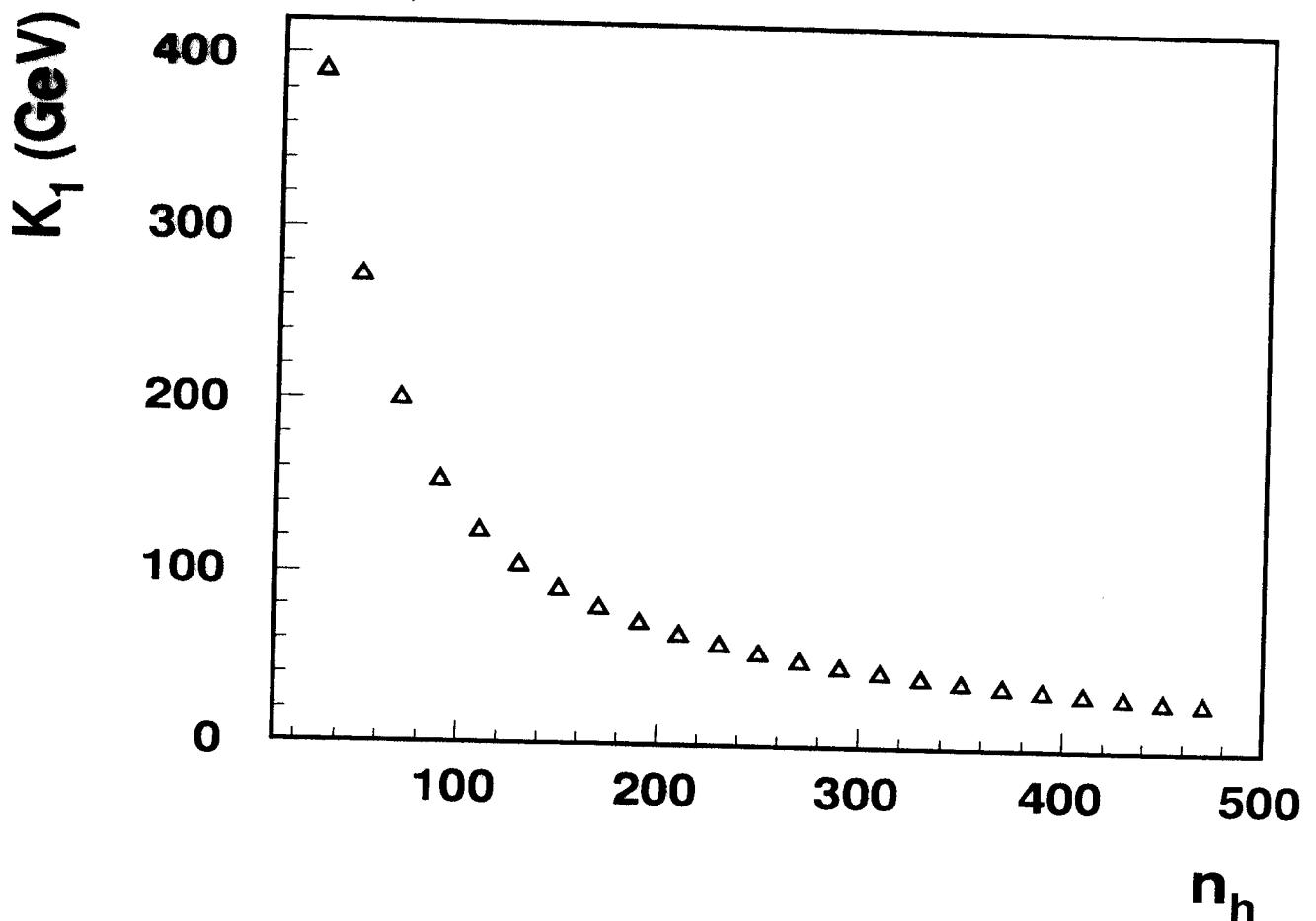


Figure 3: **Dependent of $K_1(\varepsilon, n_h)$ from number of hadrons.**

$$K_1(\varepsilon, n_h) = \langle \varepsilon; n \rangle = \frac{1}{N_n} \int \varepsilon d\varepsilon \frac{dN_n(\varepsilon)}{d\varepsilon} = \frac{1}{N_n} \sum_{i=1}^{N_n} E_i$$

- n – number of particles (hadrons);
- ε – particles energy;
- N_n – number of events with multiplicity n_h ;
- $dN_n(\varepsilon)/d\varepsilon$ – number of events with multiplicity n and particle with energy ε .

PYTHIA: $K_2(\varepsilon, n_h)$

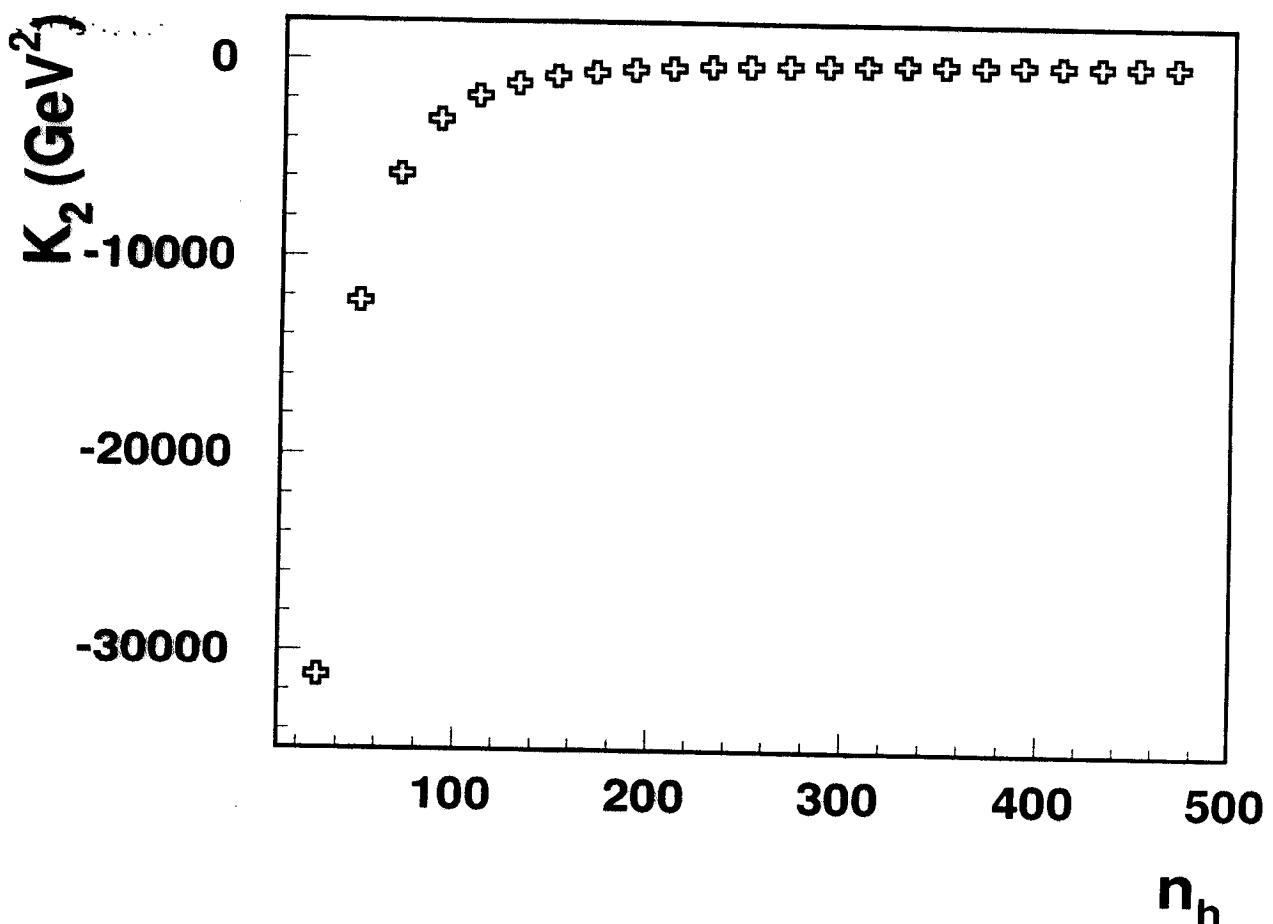


Figure 4: **Dependent of $K_2(\varepsilon, n_h)$ from number of hadrons.**

$$\begin{aligned} K_2(\varepsilon_1, \varepsilon_2; n_h) &= \langle [(\varepsilon_1; n_h) - \langle \varepsilon; n_h \rangle][(\varepsilon_2; n_h) - \langle \varepsilon; n_h \rangle] \rangle \\ &= \langle \varepsilon^2; n_h \rangle - \langle \varepsilon; n_h \rangle^2 \end{aligned}$$

$$\langle \varepsilon^2; n_h \rangle = \frac{1}{N_n} \int \varepsilon_1 d\varepsilon_1 \varepsilon_2 d\varepsilon_2 \frac{d^2 N_n}{d\varepsilon_1 d\varepsilon_2}$$

— $d^2 N_n / d\varepsilon_1 d\varepsilon_2$ - number of events with multiplicity n_h and particles with energy ε_1 and ε_2

PYTHIA: $K_3(\varepsilon, n_h)$

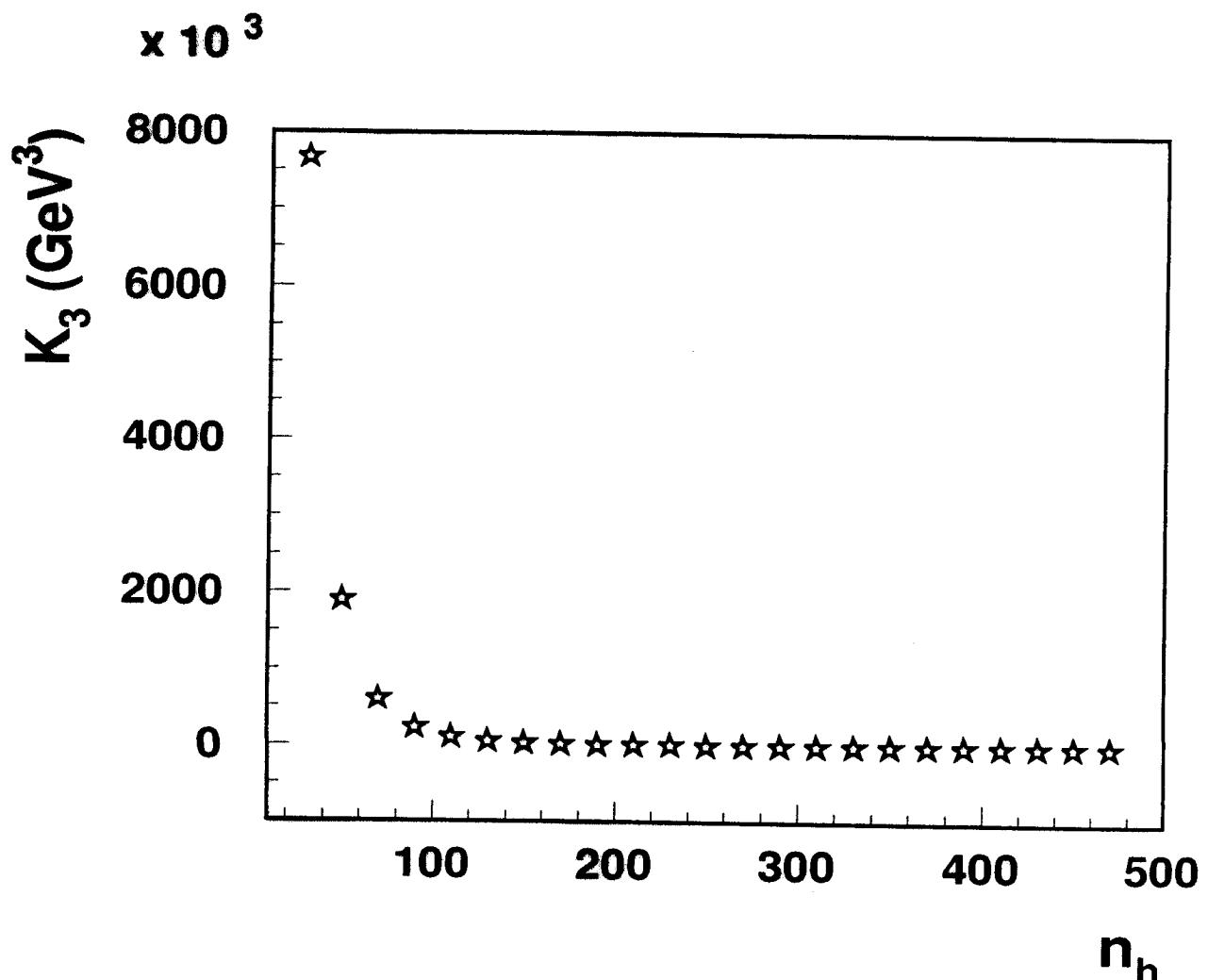


Figure 5: **Dependent of $K_3(\varepsilon, n_h)$ from number of hadrons.**

$$\begin{aligned}
 & K_3(\varepsilon_1, \varepsilon_2, \varepsilon_3; n_h) = \\
 &= \langle [(\varepsilon_1; n_h) - \langle \varepsilon; n_h \rangle] [(\varepsilon_2; n_h) - \langle \varepsilon; n_h \rangle] [(\varepsilon_3; n_h) - \langle \varepsilon; n_h \rangle] \rangle = \\
 &= \langle \varepsilon^3; n_h \rangle - 3\langle \varepsilon^2; n_h \rangle \langle \varepsilon; n_h \rangle + 2\langle \varepsilon; n_h \rangle^3
 \end{aligned}$$

PYTHIA Prediction for $R = K_3^{2/3}/K_2$

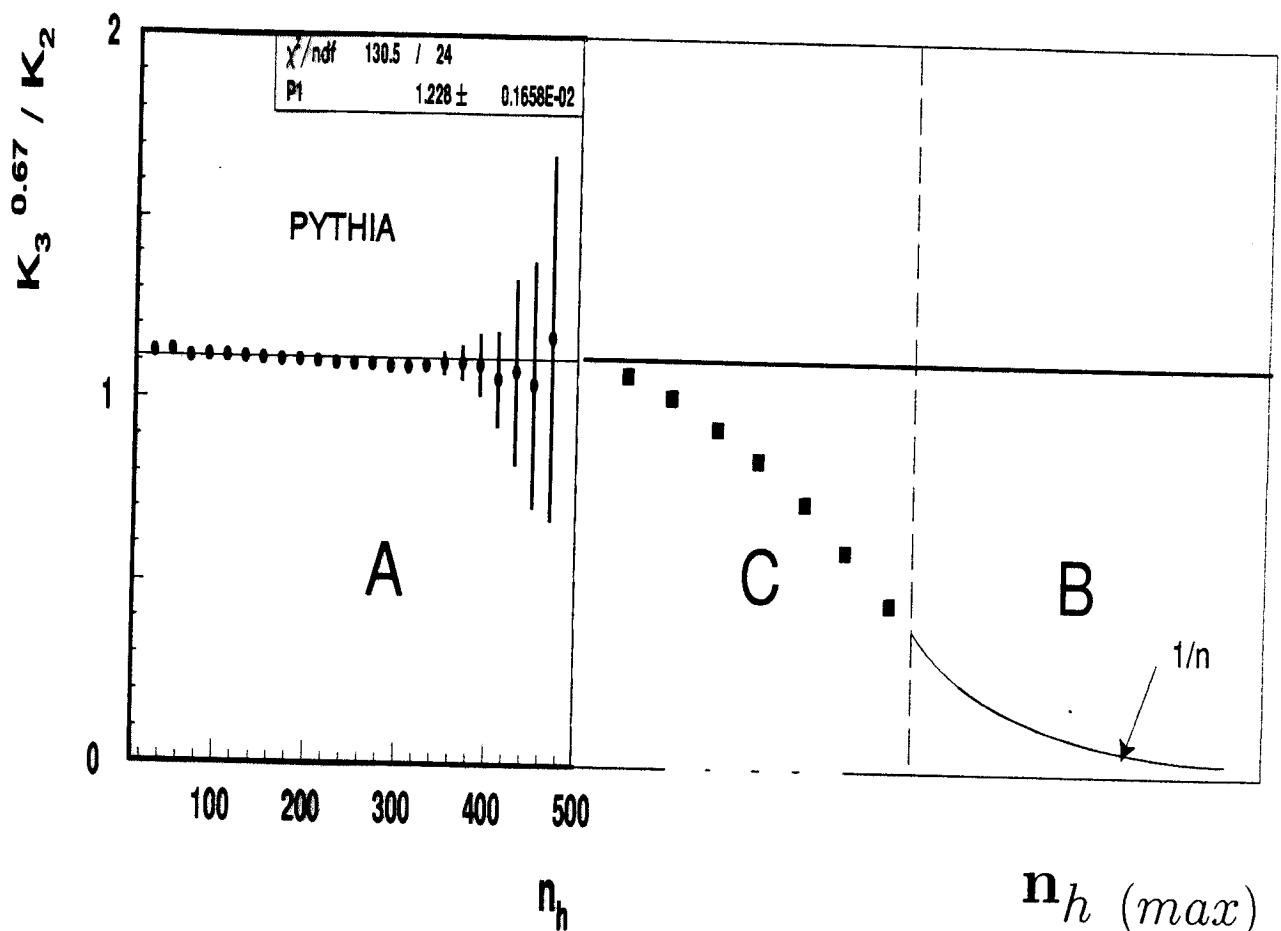


Figure 6: Ratio $R = K_3^{2/3}/K_2$; A: PYTHIA, B: theory. C: VHM.

A \Rightarrow PYTHIA: $n \sim \bar{n}$ $(n = (3 \div 5) \bar{n})$

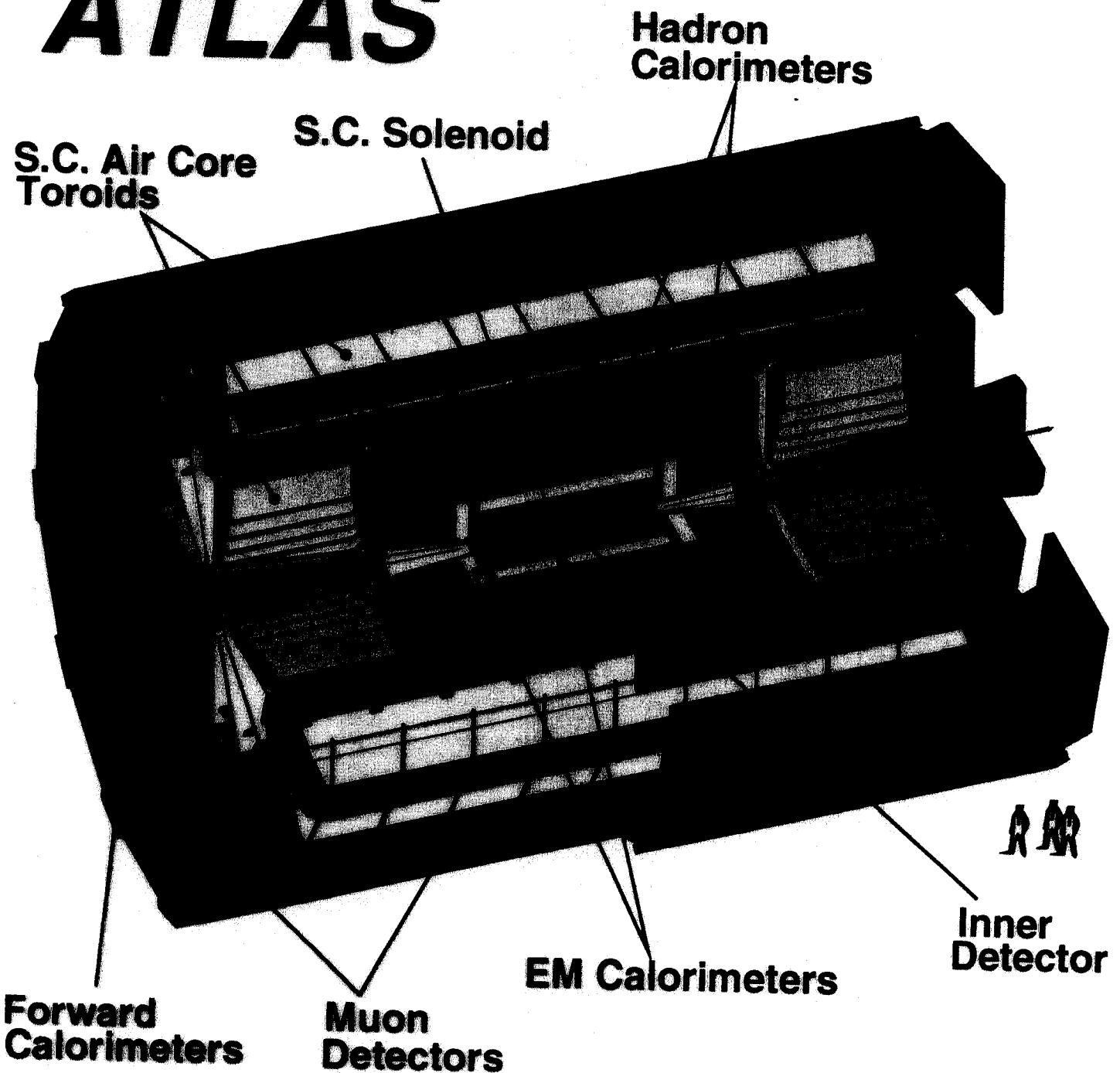
B \Rightarrow Theory: $n \rightarrow n_{max}$ ($|p_i| < m$, $i = 1, 2, \dots, n$)

C \Rightarrow VHM: $R \ll 1 \Leftrightarrow$ Coloured Plasma

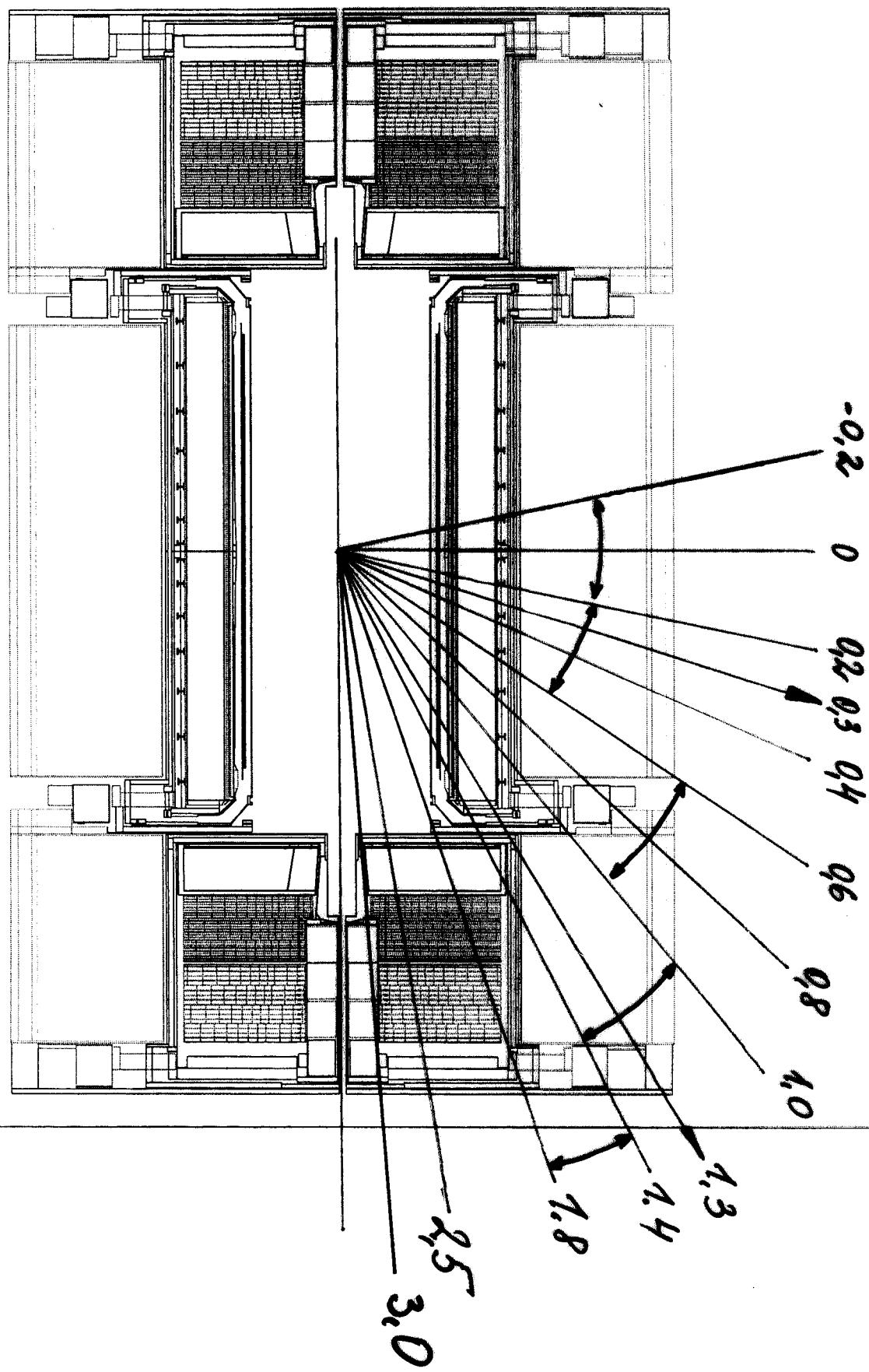
Hadron Collisions: ATLAS (CERN), CDF (Tevatron)

Heavy Ion Collisions: STAR (RHIC)

ATLAS



$$\gamma = -\ln(\tan \frac{\theta}{2})$$



PYTHIA: $R = K_3^{2/3}/K_2$.

Colored partons transverse momentum cutoff is $p_t > 2500$ GeV.

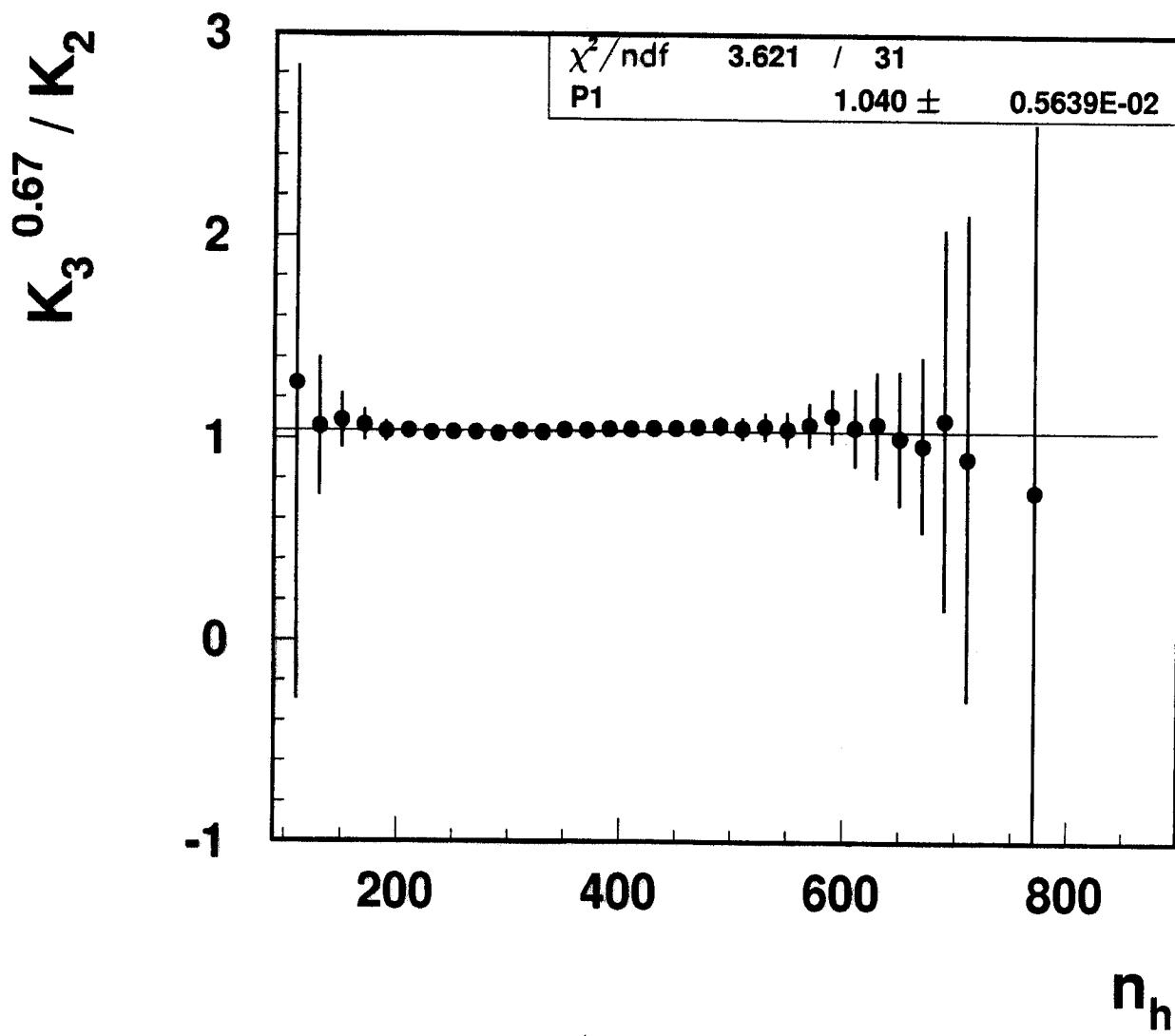


Figure 7: Dependent of ratio $K_3^{2/3}/K_2$ from number of hadrons.

PYTHIA: $K_1(\varepsilon, n_h)$ with pile-up

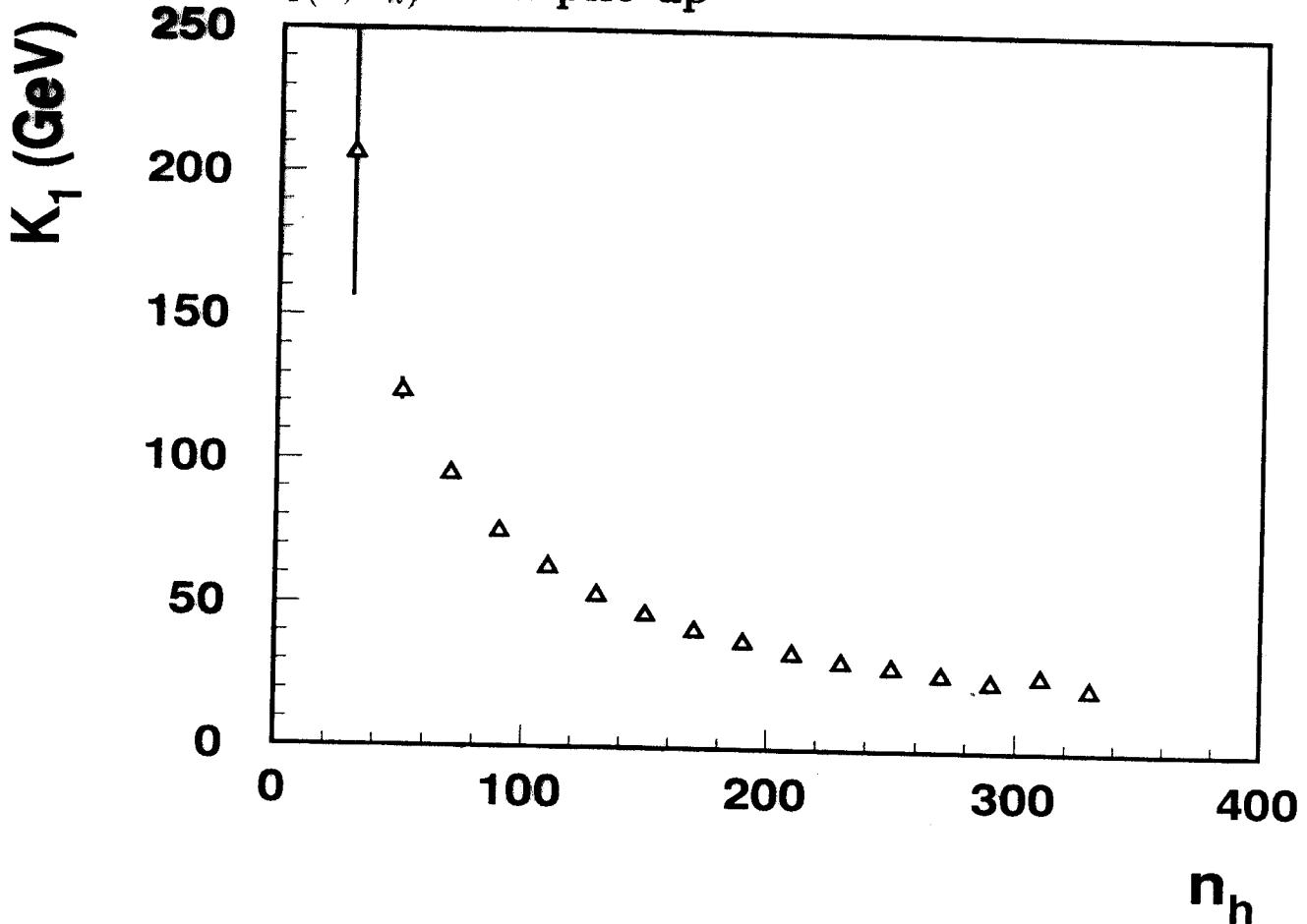


Figure 8: Dependent of $K_1(\varepsilon, n_h)$ from number of hadrons.

$$K_1(\varepsilon, n_h) = \langle \varepsilon; n \rangle = \frac{1}{N_n} \int \varepsilon d\varepsilon \frac{dN_n(\varepsilon)}{d\varepsilon} = \frac{1}{N_n} \sum_{i=1}^{N_n} E_i$$

- n — number of particles (hadrons);
- ε — particles energy;
- N_n — number of events with multiplicity n_h ;
- $dN_n(\varepsilon)/d\varepsilon$ — number of events with multiplicity n and particle with energy ε .

$5bc = 5 \times 23 = 115 ; |\gamma| < 3 ; p_T^h > 2 \text{ GeV}$

$p_T^h > 10 \text{ GeV}$

PYTHIA: $K_2(\varepsilon, n_h)$ with pile-up

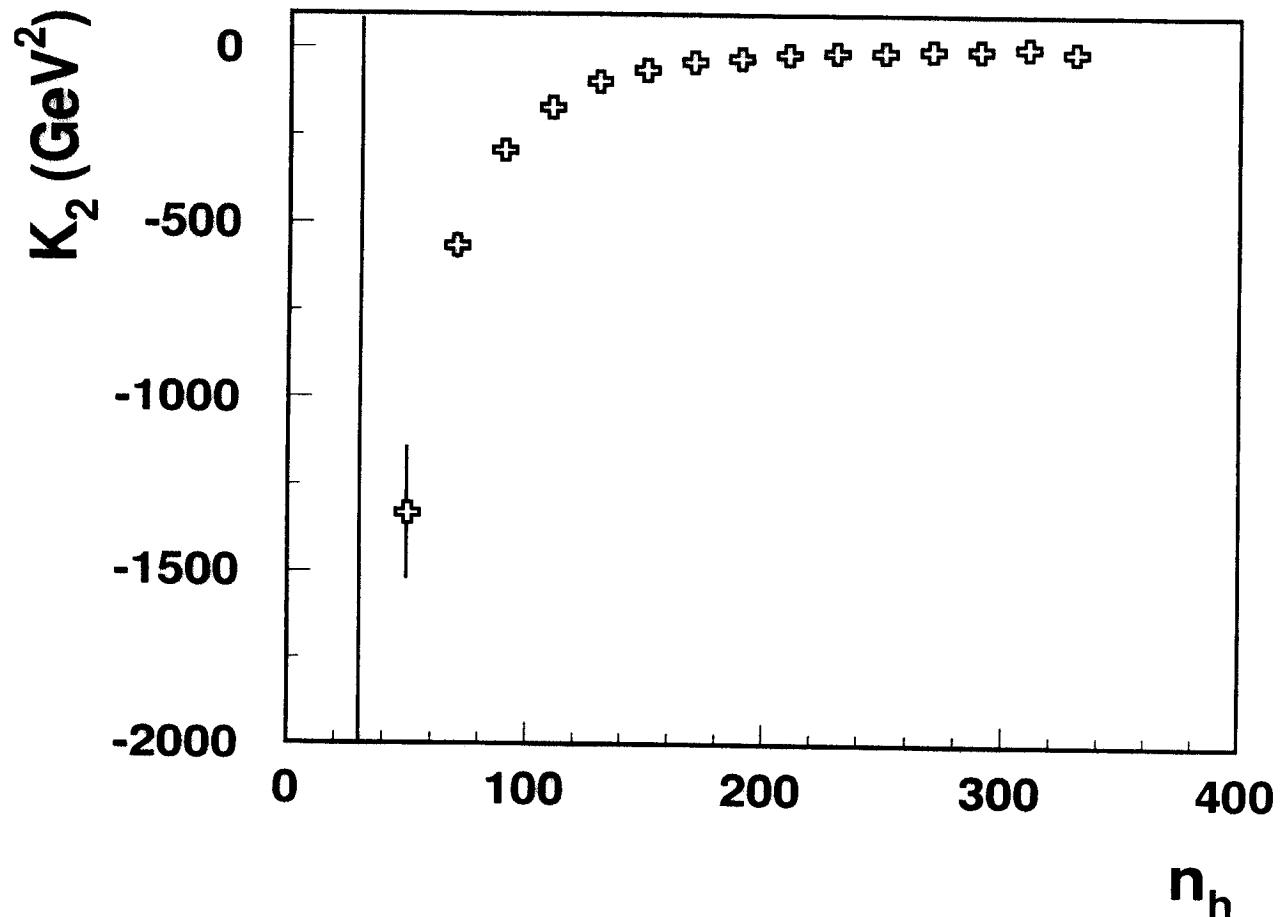


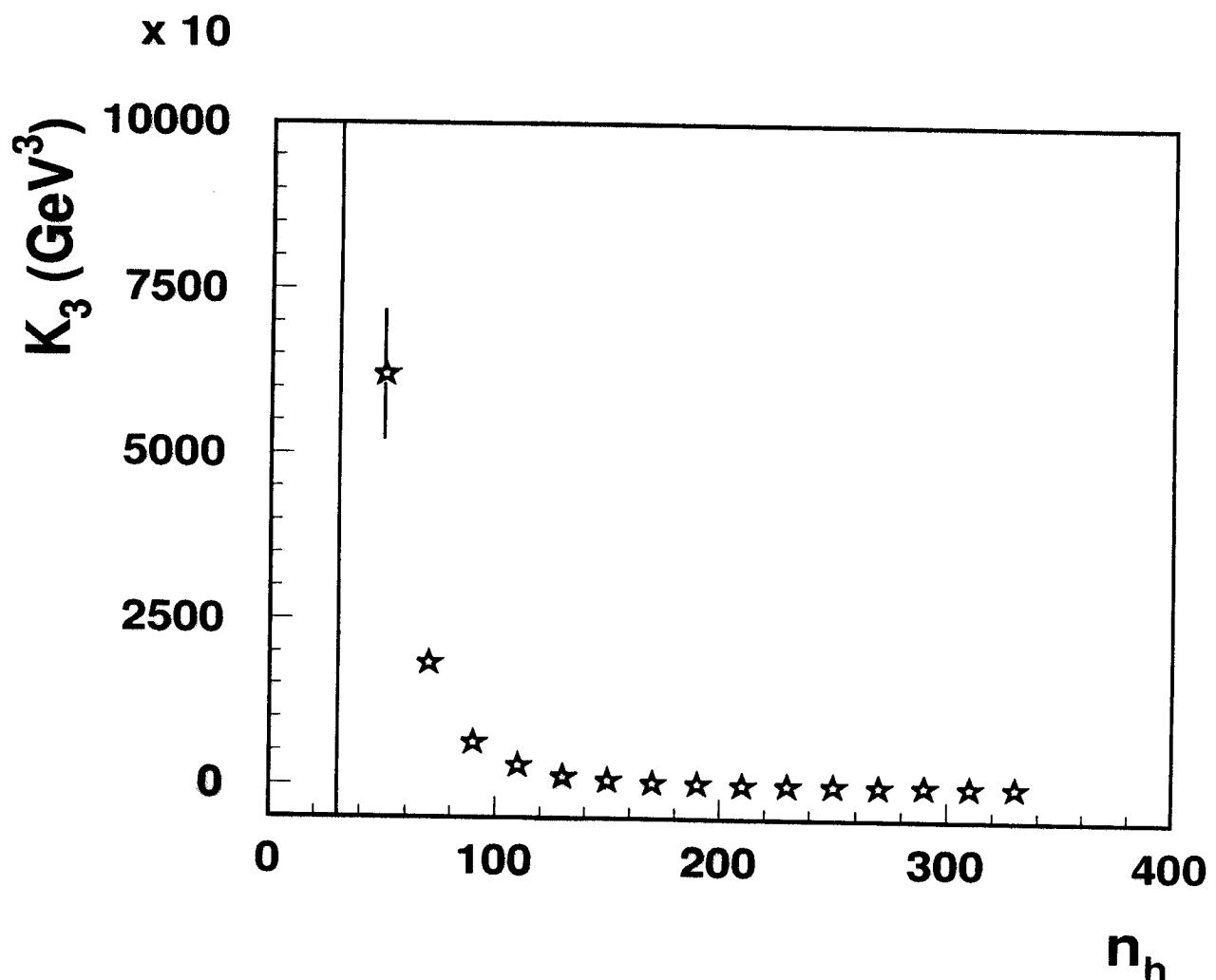
Figure 9: **Dependent of $K_2(\varepsilon, n_h)$ from number of hadrons.**

$$\begin{aligned} K_2(\varepsilon_1, \varepsilon_2; n_h) &= \langle [(\varepsilon_1; n_h) - \langle \varepsilon; n_h \rangle][(\varepsilon_2; n_h) - \langle \varepsilon; n_h \rangle] \rangle \\ &= \langle \varepsilon^2; n_h \rangle - \langle \varepsilon; n_h \rangle^2 \end{aligned}$$

$$\langle \varepsilon^2; n_h \rangle = \frac{1}{N_n} \int \varepsilon_1 d\varepsilon_1 \varepsilon_2 d\varepsilon_2 \frac{d^2 N_n}{d\varepsilon_1 d\varepsilon_2}$$

— $d^2 N_n / d\varepsilon_1 d\varepsilon_2$ - number of events with multiplicity n_h and particles with energy ε_1 and ε_2

$$5 \text{ bc} = 5 \times 23 = 115; |\eta| < 3; p_T' > 2 \text{ GeV}$$

PYTHIA: $K_3(\varepsilon, n_h)$ with pile-upFigure 10: Dependent of $K_3(\varepsilon, n_h)$ from number of hadrons.

$$\begin{aligned}
 K_3(\varepsilon_1, \varepsilon_2, \varepsilon_3; n_h) &= \\
 &= \langle [(\varepsilon_1; n_h) - \langle \varepsilon; n_h \rangle] [(\varepsilon_2; n_h) - \langle \varepsilon; n_h \rangle] [(\varepsilon_3; n_h) - \langle \varepsilon; n_h \rangle] \rangle = \\
 &= \langle \varepsilon^3; n_h \rangle - 3\langle \varepsilon^2; n_h \rangle \langle \varepsilon; n_h \rangle + 2\langle \varepsilon; n_h \rangle^3
 \end{aligned}$$

$5bc = 5 \times 23 = 115$; $|\gamma| < 3$; $p_T^h > 2 GeV$

PYTHIA: $R = K_3^{2/3}/K_2$ for events with pile-up background

Number of pile-up events: $23 \times 5 = 115$;
 $p_t > 2$ GeV for every hadron at $|\eta| < 3$.

Colored partons transverse momentum cutoff is $p_t > 200$ GeV.

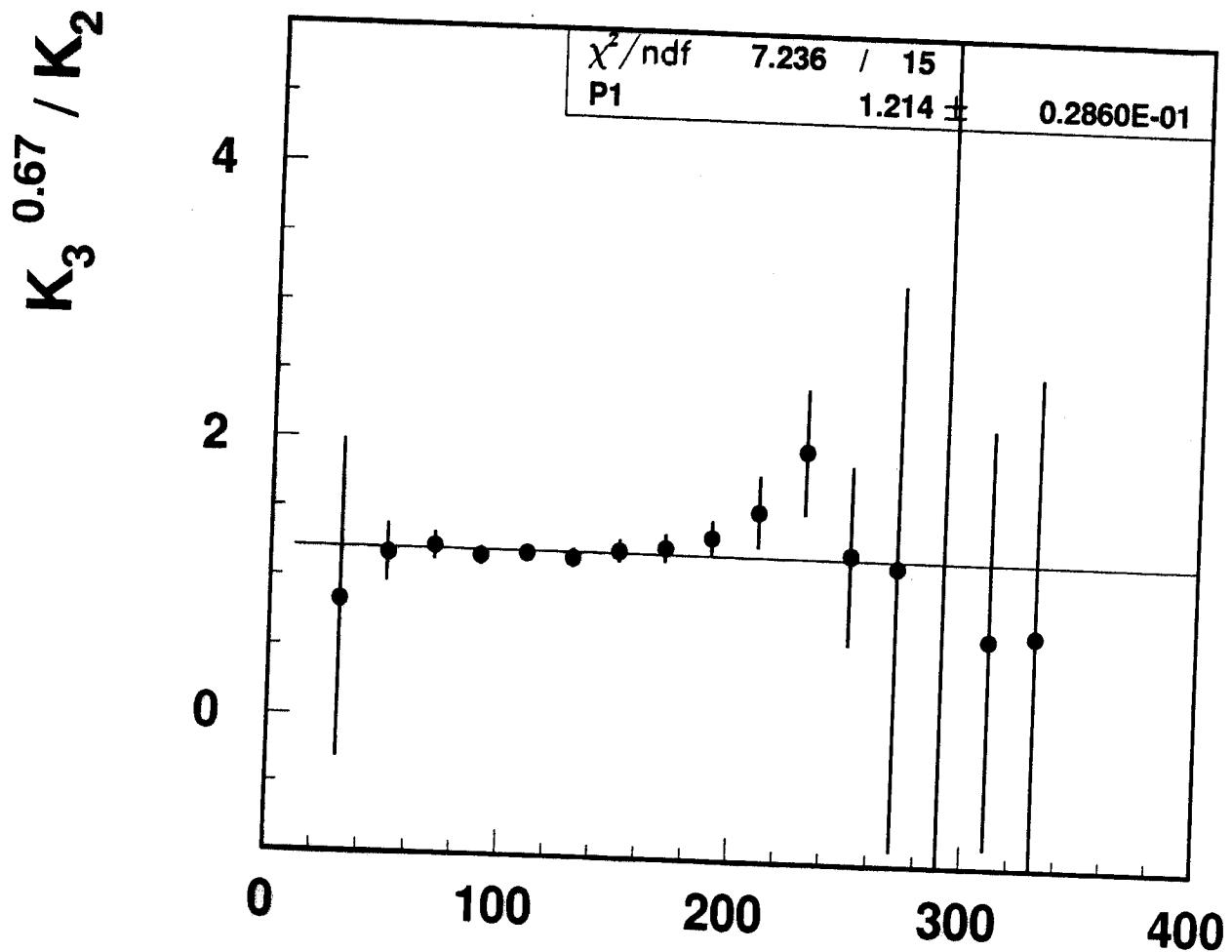
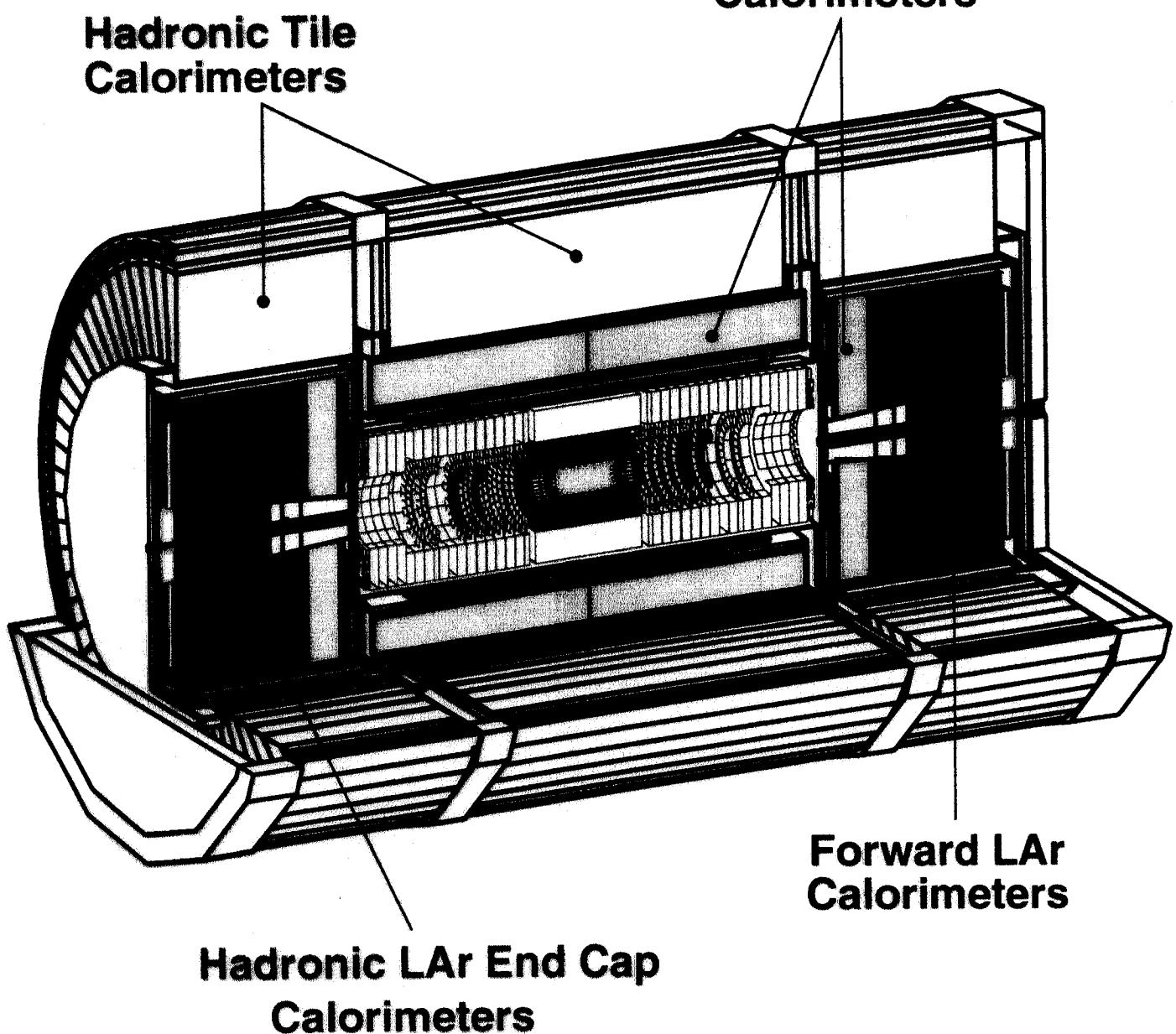
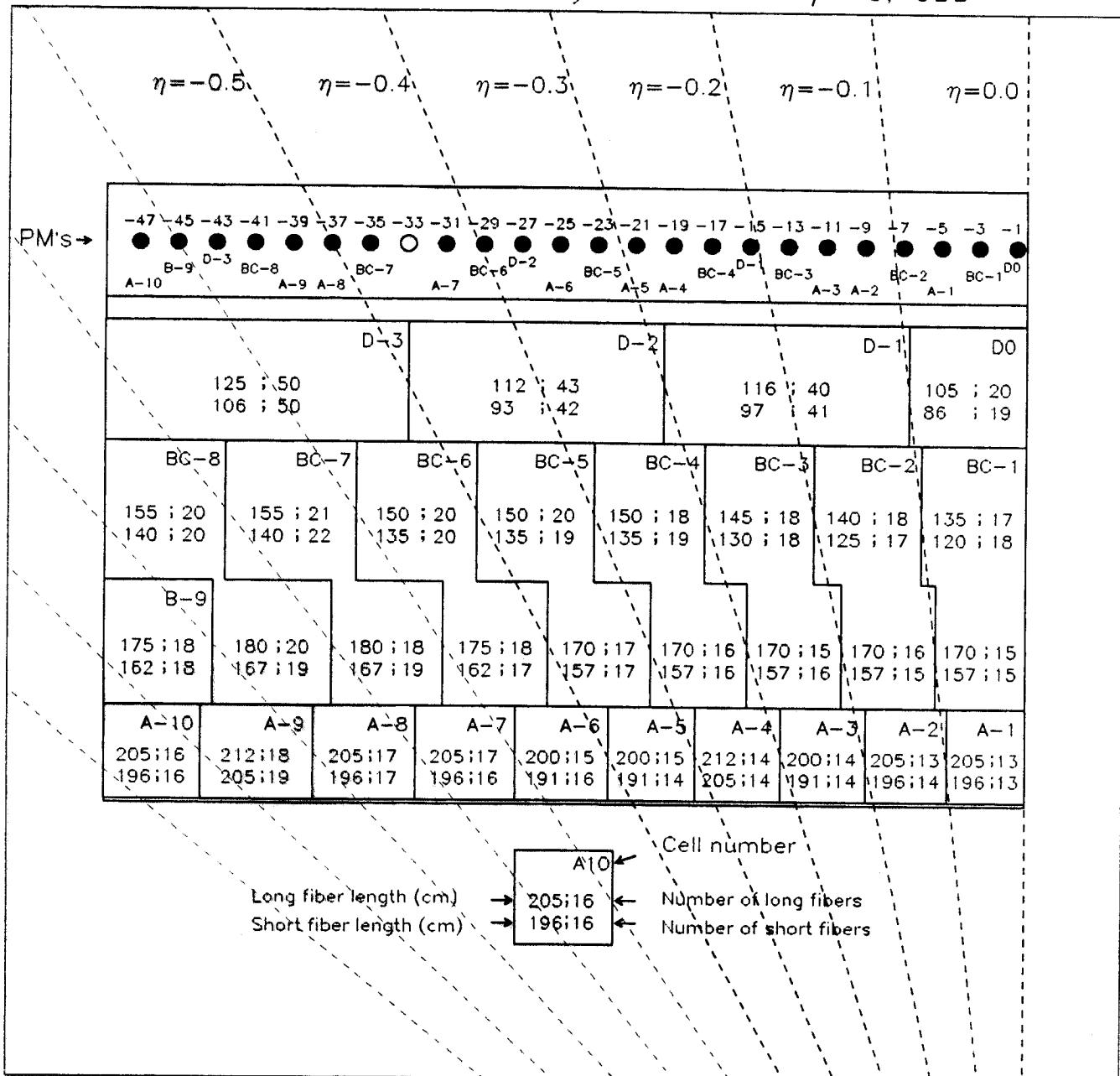


Figure 11: Dependent of ratio $K_3^{2/3}/K_2$ from number of hadrons.
Pile-up — 115 events; $p_t > 2$ GeV for every hadron at $|\eta| < 3$.

ATLAS Calorimetry



Barrel Readout Cell Geometry in Module 0 - $\eta < 0$, ODD



Cell-PMT configuration, fiber lengths, fiber nums.

Figure 13: The layout of ATLAS Barrel Tile Calorimeter cell geometry.

7 ATLFAST: Energy Correlators for “Towers”

ATLFAST: $K_1(\varepsilon, n_h)$

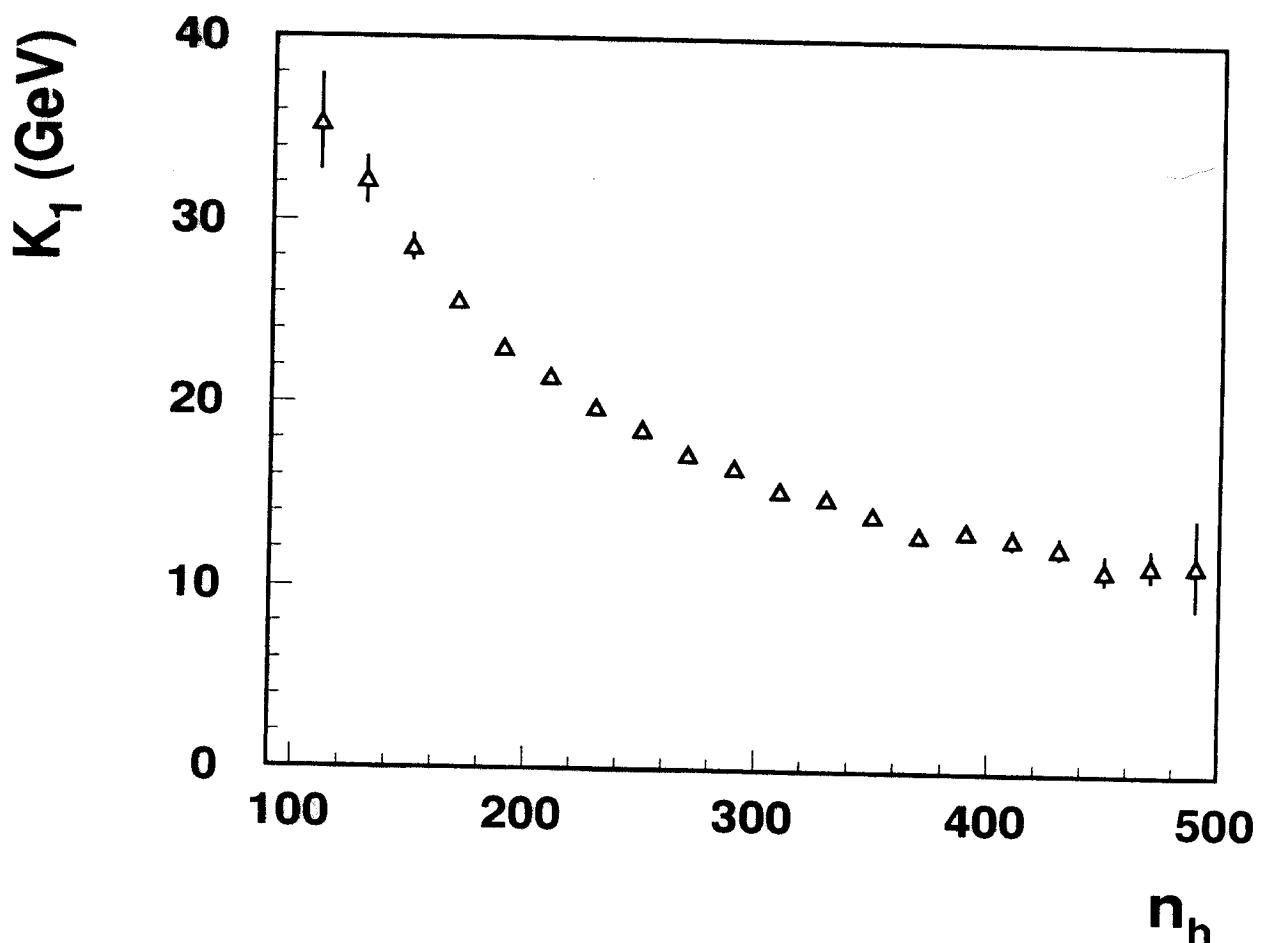


Figure 14: **Dependent of $K_1(\varepsilon, n_h)$ from number of calorimeter towers.** Colored partons transverse momentum cutoff is $p_t > 1000$ GeV.

- ε - energy deposited in the "tower"
- $dN_n/d\varepsilon$ - number of events with energy ε in the "tower"

ATLFAST: $K_2(\varepsilon, n_h)$

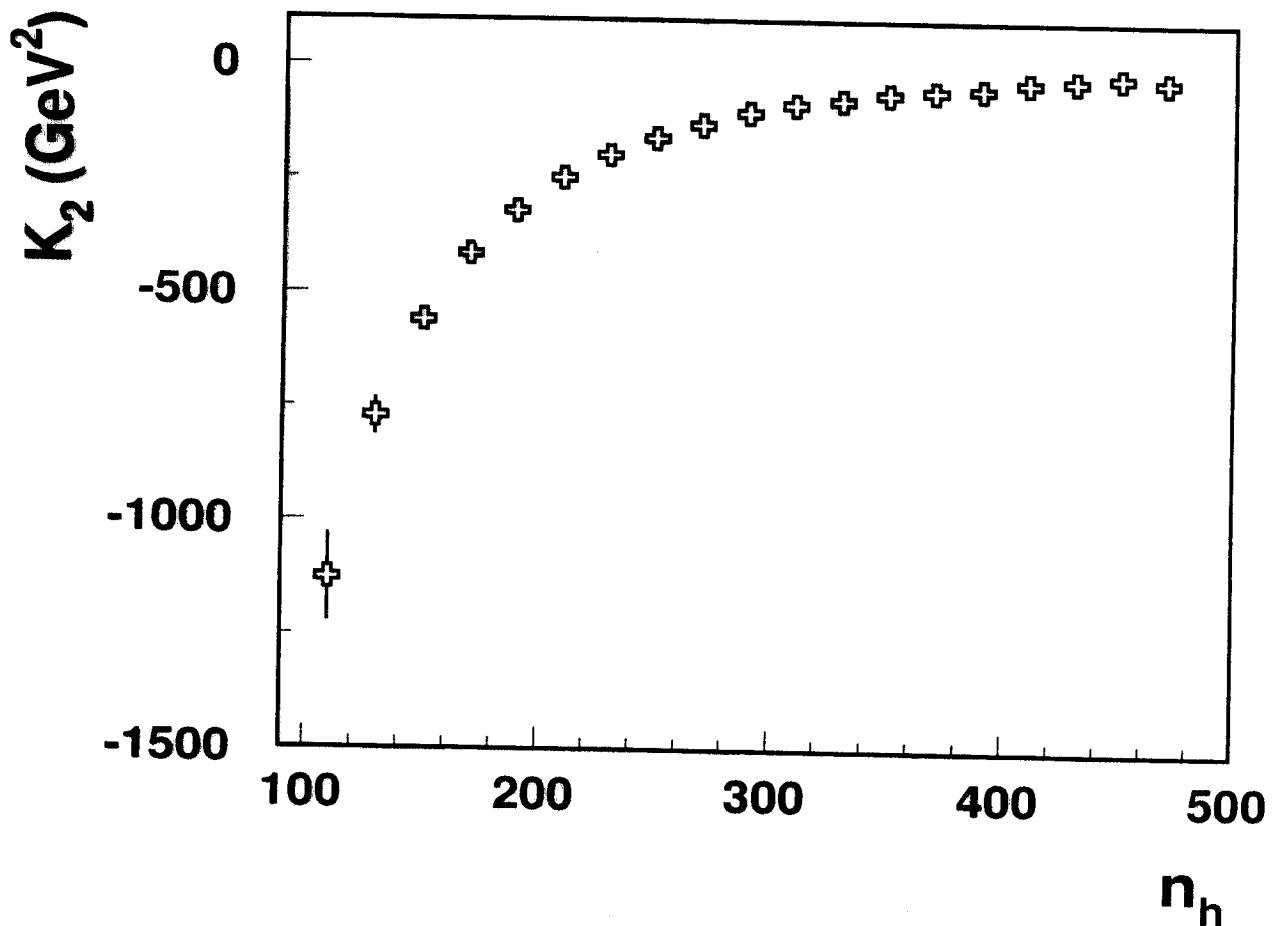


Figure 15: Dependent of $K_2(\varepsilon, n_h)$ from number of calorimeter towers. Colored partons transverse momentum cutoff is $p_t > 1000$ GeV.

$$\begin{aligned} K_2(\varepsilon_1, \varepsilon_2; n_h) &= \langle [(\varepsilon_1; n_h) - \langle \varepsilon; n_h \rangle][(\varepsilon_2; n_h) - \langle \varepsilon; n_h \rangle] \rangle \\ &= \langle \varepsilon^2; n_h \rangle - \langle \varepsilon; n_h \rangle^2 \end{aligned}$$

$$\langle \varepsilon^2; n_h \rangle = \frac{1}{N_n} \int \varepsilon_1 d\varepsilon_1 \varepsilon_2 d\varepsilon_2 \frac{d^2 N_n}{d\varepsilon_1 d\varepsilon_2}$$

— $d^2 N_n / d\varepsilon_1 d\varepsilon_2$ - number of events with multiplicity n_h and particles with energy ε_1 and ε_2

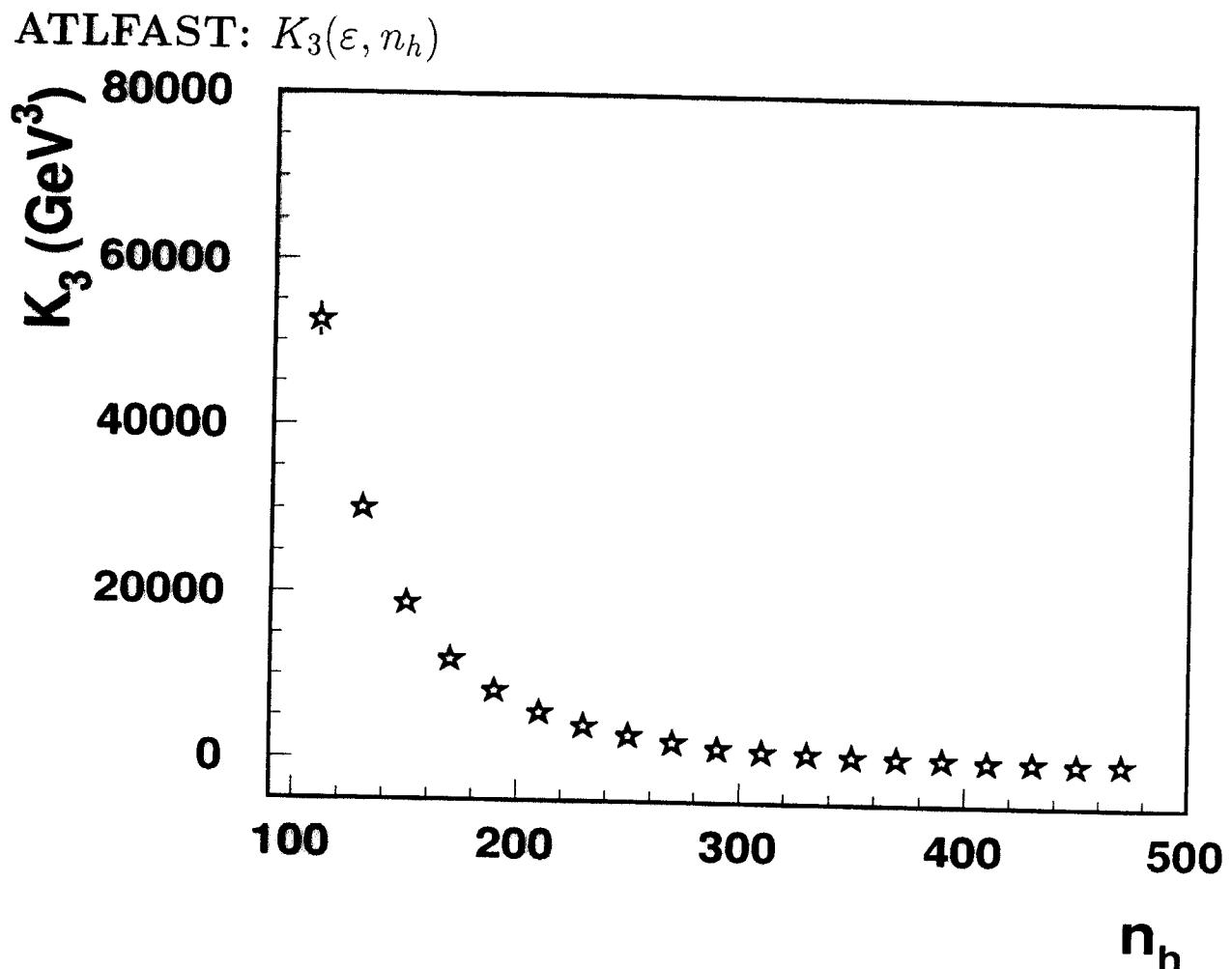


Figure 16: Dependent of $K_3(\varepsilon, n_h)$ from number of calorimeter towers. Colored partons transverse momentum cutoff is $p_t > 1000$ GeV.

$$\begin{aligned}
 K_3(\varepsilon_1, \varepsilon_2, \varepsilon_3; n_h) &= \\
 &= \langle [(\varepsilon_1; n_h) - \langle \varepsilon; n_h \rangle][(\varepsilon_2; n_h) - \langle \varepsilon; n_h \rangle][(\varepsilon_3; n_h) - \langle \varepsilon; n_h \rangle] \rangle = \\
 &= \langle \varepsilon^3; n_h \rangle - 3\langle \varepsilon^2; n_h \rangle \langle \varepsilon; n_h \rangle + 2\langle \varepsilon; n_h \rangle^3
 \end{aligned}$$

ATLFAST Prediction for $R = K_3^{2/3}/K_2$

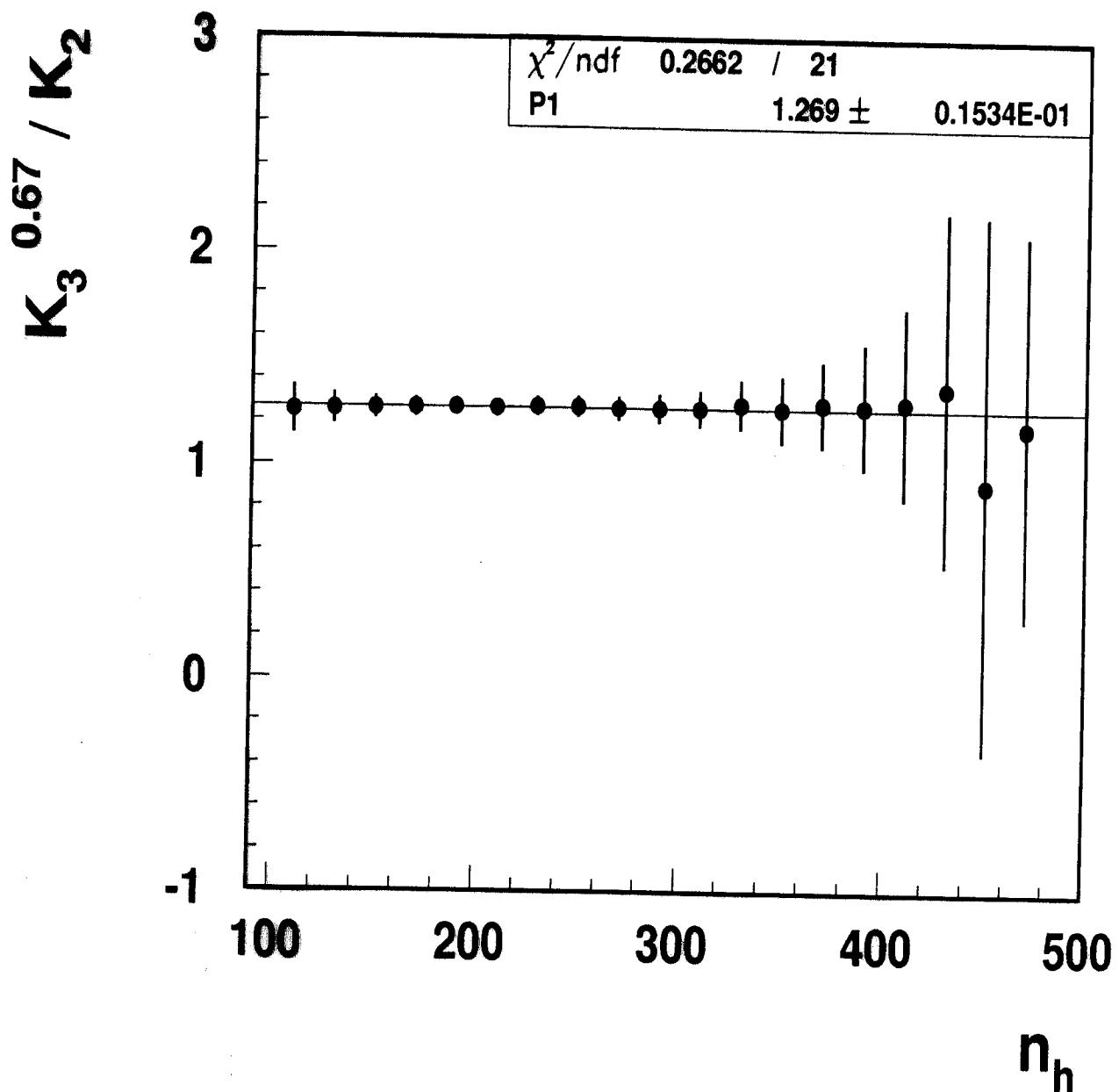


Figure 17: Dependent of Ratio $K_3^{2/3}/K_2$ from number of calorimeter towers. Colored partons transverse momentum cutoff is $p_t > 200$ GeV.

8 Conclusions

- We present the results of the calculations in the PYTHIA the energy correlators K_1, K_2, K_3 and ratio $R = \frac{K_3^{2/3}}{K_2}$ versus number of hadrons.
- The PYTHIA can not predict the **tendency** to equilibrium. $R = \frac{K_3^{2/3}}{K_2} \geq 1$ for any colored partons transverse momentum p_t cutoff with pile-up background and does not agree with the Manjavidze-Sissakian prediction for VHM $R = \frac{K_3^{2/3}}{K_2} \ll 1$.
- Using ATLFAST we calculated the energy correlators K_1, K_2, K_3 and ratio $R = \frac{K_3^{2/3}}{K_2}$ versus number of ATLAS calorimeter towers with hits.
- The energy correlators K_1, K_2, K_3 have the same dependencies for hadrons and for ATLAS calorimeter towers.
 $R_{\text{towers}} \approx 1.1 \cdot R_{\text{hadrons}}$.