FAST SIMULATION of HADRONIC SHOWERS for ATLAS HCAL

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Motivation

Challenge in present high energy physics:

- Insufficient to know a particle process on theory level (X-sections)
- It should be known also on experimental level:
  - ✓ Detectors resolutions and reconstruction efficiencies
  - ✓ Capability of experiment to distinguish signal process from bkgd one

Two approaches:

- Full simulation of the wanted processes
  - ✓All available physics taken into account
  - ✓Powerful computing system + team of people + time consuming

Due to shower simulations

- Fast simulation
  - ✓Full simulation of showers in calorimeter replaced by fast parametrisation tuned by experiment
  - ✓Reliable results obtained much faster (> 1000× Full simulation)

Principles of Fast MC

Goal: find spatial energy deposition in calorimeter without full simulation - using 3D parametrisation of hadronic shower (for ATLAS Had-Calorimeter)

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Main principles of our approach:

- Incident energy is devided into a certain # energy spots
- The spots are distribured according to known shower topology
- Electromagnetic and hadronic components are treated separately
- Realistic fluctuations of shower profile: individual shower profile constructed for each incident particle

Simulation algorithm

For each incident particle:

- Position of the 1st interaction (shower origin) is found
- Shower profile is constructed from a few sub-shower profiles (electromagnetic, hadronic)
- Incident energy is divided into EM and HD components
- Proper number of energy spots and their size is found (Depends on Cal. energy resolution and sampling fraction)
- The spots are distributed and energy of spots absorbed in active medium is accumulated

Resolution vs # of energy spots

Calorimeter energy resolution:

$$\varepsilon = \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b$$

sampling term

constant term

If N spots is distributed in calorimeter $\Rightarrow$ $N_A = s_f N$ spots is absorbed in active medium

Sampling fraction

N_A is a random variable obeying Poisson law: st.dev.$=\sqrt{N_A}$

Energy resolution: $$\frac{\sigma_E}{E} = \frac{\sqrt{N_A}}{N_A} = \frac{1}{\sqrt{N_A}} \Rightarrow \quad N = \frac{E}{a^2 s_f}$$

# of spots

Spot energy: $q_{eff} = a^2 s_f$

Shower Profiles

3-dimensional parametrisation of hadronic shower profile from the 1st interaction point:

$$\Psi(x,r) = w \cdot \Psi_e(x,r) + (1-w) \cdot \Psi_h(x,r)$$

Electromagnetic component

Hadronic component

w ≡ share of electromag. energy in shower – big fluctuations !

$$\Psi_{e,h}(x,r) = \frac{1}{E_{0_{e,h}}} \cdot \frac{dE_{e,h}}{dx}(x) \cdot \phi_{e,h}(x,r)$$

dE/dx ≡ longitudinal profile, ϕ ≡ radial profile

Fraction of el-mag energy

Mean EM fraction <w> depends on energy of π^0 produced (f_{π^0}):

$$\langle w \rangle = \frac{e/h \cdot \langle f_{\pi^0} \rangle}{(e/h - 1)\cdot \langle f_{\pi^0} \rangle + 1}$$

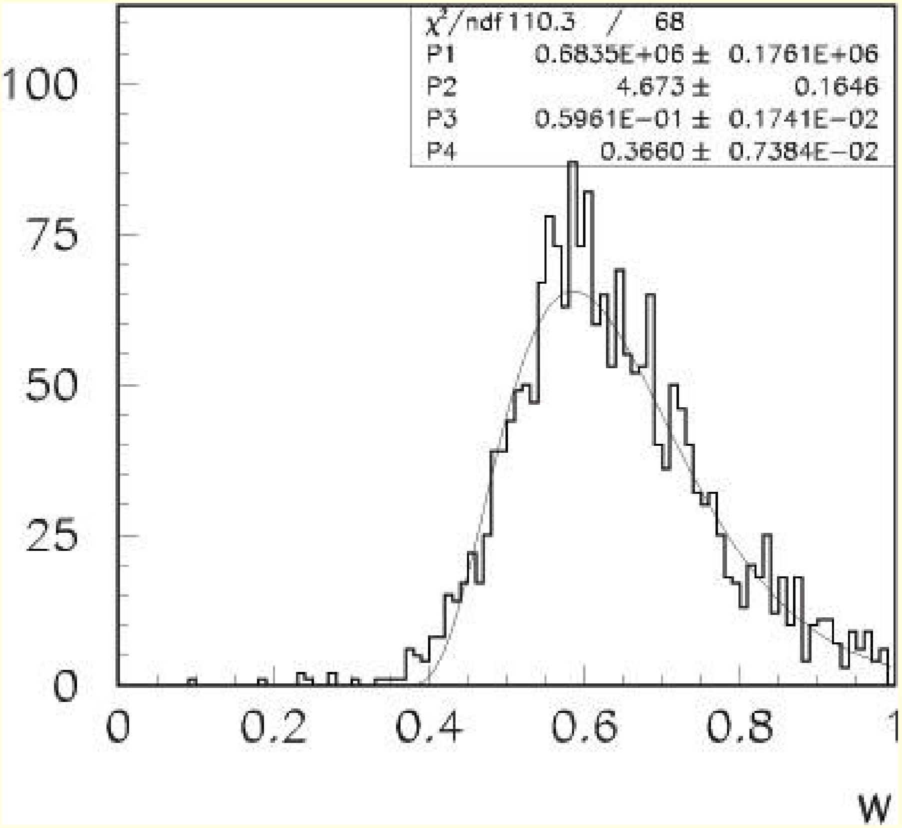
$$\langle f_{\pi^0} \rangle = 0.11 \cdot \ln E$$

Fluctuation of EM fraction:

$$p(w) = \frac{(w - w_0)^{\alpha_w - 1} \cdot e^{-(w - w_0)/\beta_w}}{(\beta_w)^{\alpha_w}\,\Gamma(\alpha_w)}$$

$$\langle w \rangle = w_0 + \alpha_w \beta_w$$

α_w, β_w ≡parameters



Fluctuation of EM fraction w: pions 100 GeV

Longitudinal profile of HD component

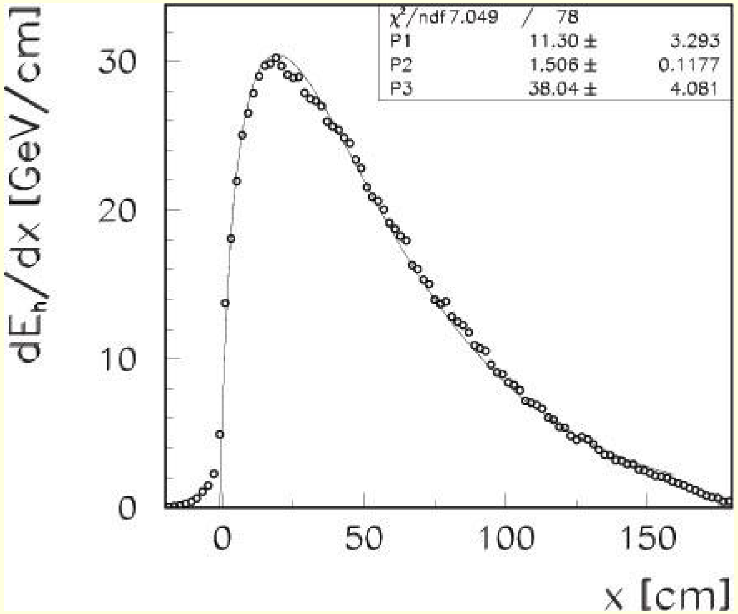
- Position of the shower beginning is sampled from $\frac{e^{-x/\beta_h}}{\beta_h}$
- Average profile of hadronic shower:

$$\frac{dE_h}{dx}(x) = \frac{x^{\alpha-1} e^{-x/\beta_h}}{\beta_h^{\alpha}\Gamma(\alpha)}$$

$[x] \equiv \lambda_I$ (interaction length)

Longitudinal profile of H-component
Can be found by GEANT

✓ dots: Geant simulation
✓ full line: fit by the function



Individual longit. shower profile

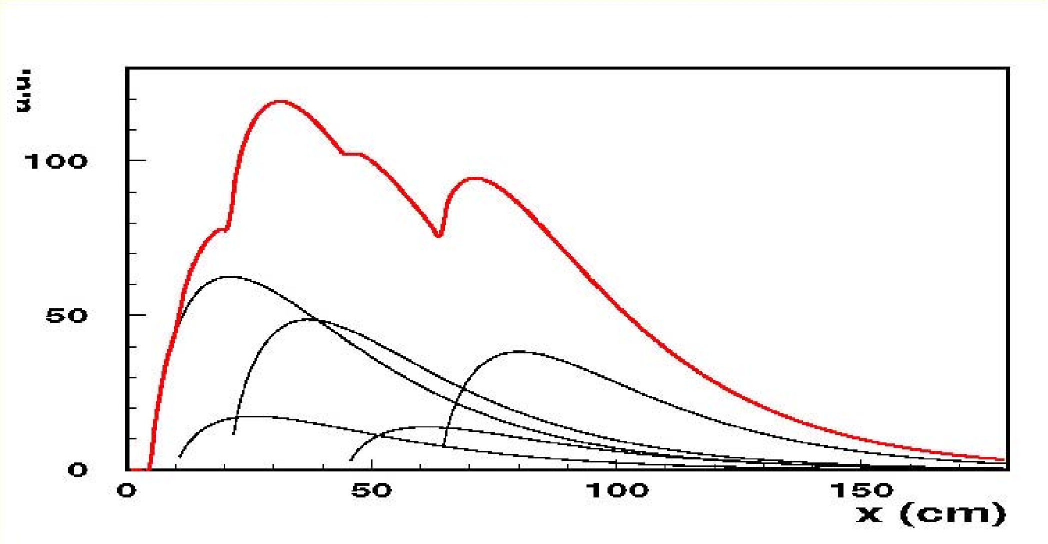
- From the origin a few "principal" particles emerge
- Each of them starts sub-shower at its interaction place
- Individual HD-shower is a sum of the sub-showers:

$$\frac{dE_h(x)}{dx} = \sum_i f_i \cdot G(x - x_i, \alpha_h - 1, \beta_h)$$

Energy fraction carried by i^{th} particle

Origin of i^{th} sub-shower

An example of individual hadronic shower:
— sub-showers
— full shower



Longitudinal profile of EM component

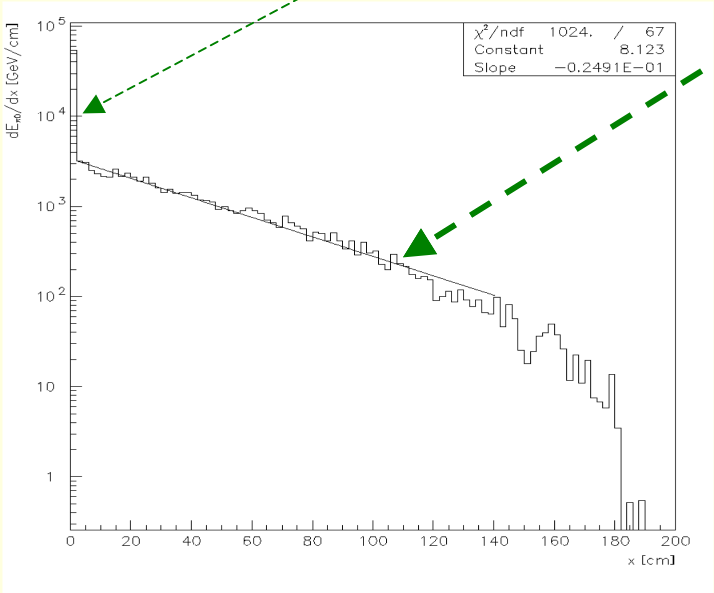
EM longitudinal shower profile

$$\frac{dE_e}{dx} = E_{\pi^0}\left(f_1 \cdot G(x,\alpha_e,\beta_e) + (1-f_1)\cdot \int_0^x e^{-\frac{t}{\lambda}} \cdot G(x-t,\alpha_e,\beta_e)dt \right)$$

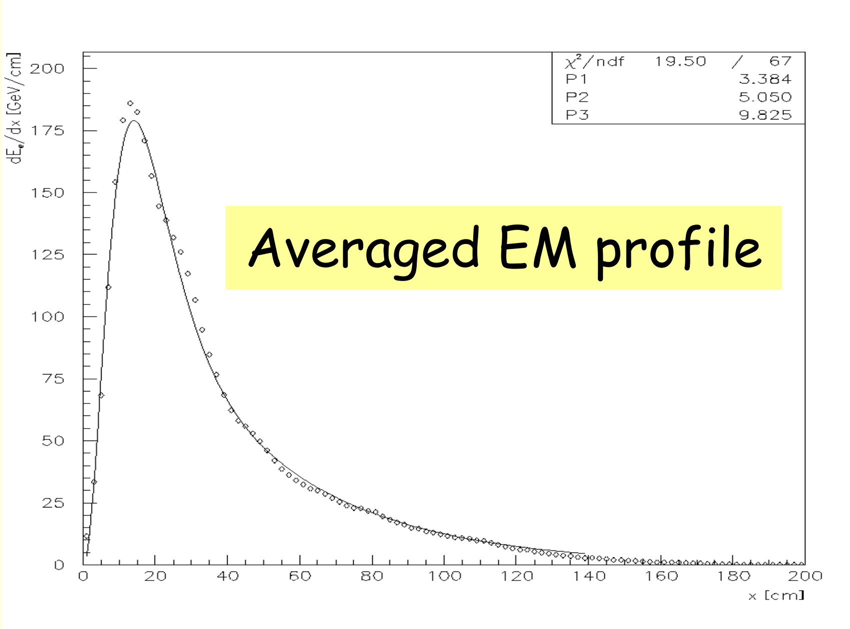
$$p(f_1) = N\exp\left(-\frac{(f_1-\mu_{f1})^2}{\sigma_{f1}^2}\right)$$

f_1 fluctuations

$$G(x,\alpha,\beta) = \frac{x^{\alpha-1}\cdot e^{-x/\beta}}{\beta^\alpha \cdot \Gamma(\alpha)}$$



produced π^0 vs depth:



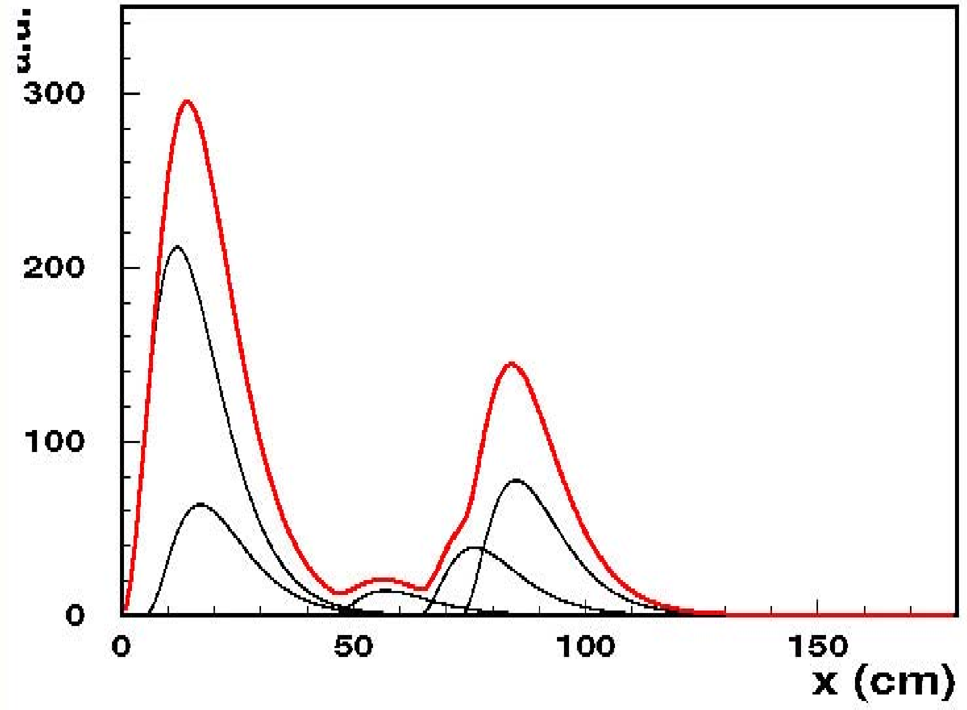
Individual EM profile

An example of individual EM shower profile:

—— EM sub-showers
—— Full EM shower

$$\frac{1}{E_{\pi^0}}\frac{dE_e(x)}{dx} = f_1 \cdot G(x,\alpha_e,\beta_e) + \sum_{i\geq 2} f_2 \cdot G(x - x_i,\alpha_e,\beta_e)$$

$G(x,\alpha,\beta) \equiv$ gamma distribution



Individual longitudinal shower profile
incident energy: 100 GeV

Radial shower profiles

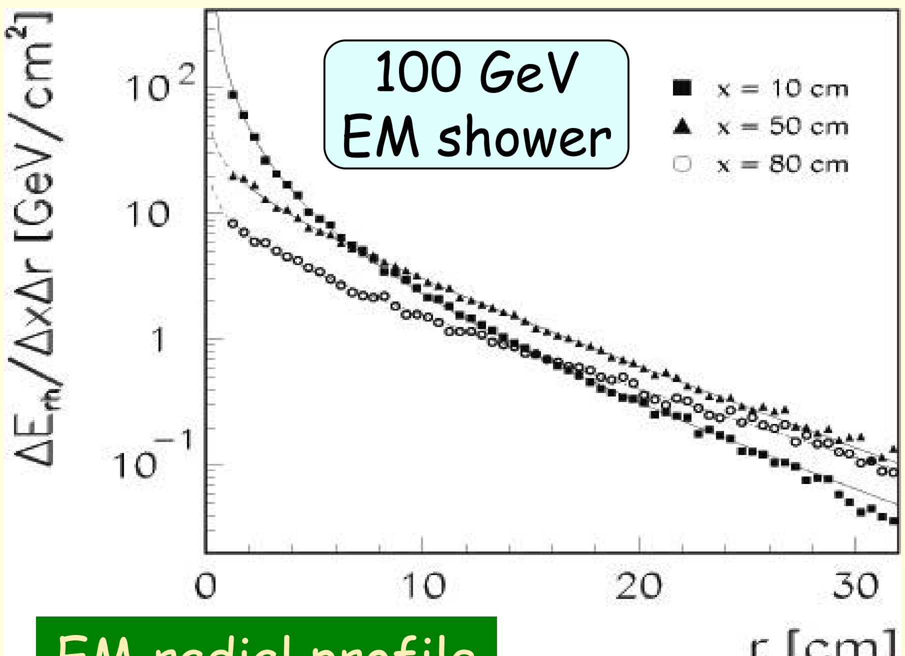
Parametrization of radial profile:

$$\frac{\Delta E_r(x,r)}{\Delta r \Delta x} = c \cdot r^{\alpha_r(x)-1} e^{-r/\beta_r(x)}$$

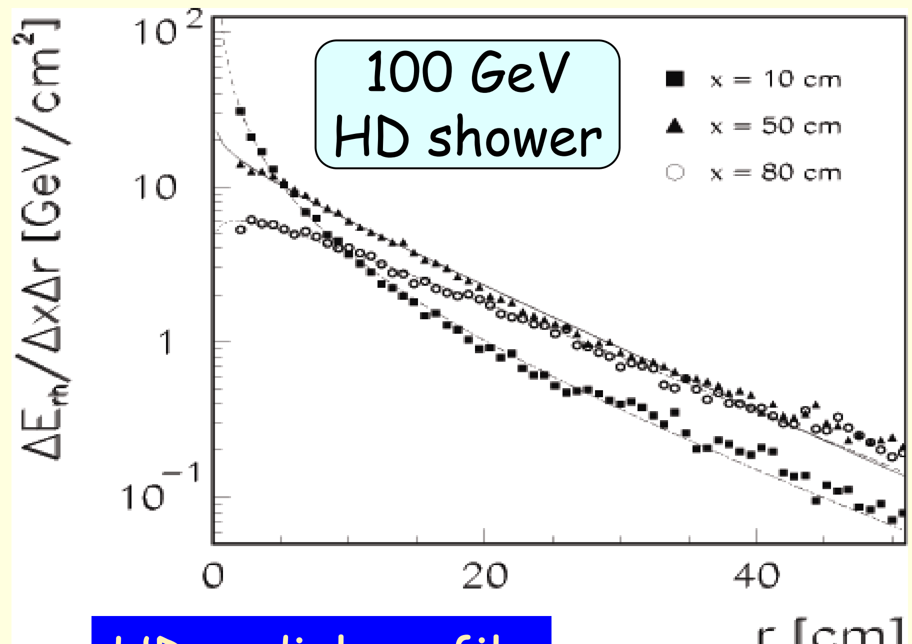
Related to the profile function as:

$$\phi(x,r) = \frac{\Delta E_r(x,r)}{2\pi r \cdot \Delta x \Delta r \cdot \frac{dE(x)}{dx}}$$

No fluctuations of radial profile included !



EM radial profile



HD radial profile

Parameters of the method

For shower profile and its fluctuations - 25 parameters:

- ✓ Fluctuation of π^0 energy fraction (2)
- ✓ Longitudinal profile of EM component (3)
- ✓ and its fluctuations (4)
- ✓ Longitudinal profile of H component (2)
- ✓ and its fluctuations (2)
- ✓ Radial EM component (6)
- ✓ Radial HD component (6)

} *At given energy*

Dependence of parameters on energy:

$P_i(E) = p_i + q_i \ln E$ or $P_i(E) = p_i + q_i E$ or $P_i(E) = \text{const}$

Parameters values

Shower parameters values + energy dependence

Parameter	Energy dependence
α_w	5.0
β_w	$0.102 - 0.0095 \cdot \ln E$
$\lambda_{\pi 0}$	$14.9 + 5.08 \cdot \ln E$
α_e	$1.83 + 0.333 \cdot \ln E$
β_e	$4.53 + 0.120 \cdot \ln E$
α_h	$0.81 + 0.147 \cdot \ln E$
β_h	$26.5 + 2.48 \cdot \ln E$
c_h	$0.455 - 0.181 \cdot \ln E$
d_h	0.20
σ_{f1}	$0.72 - 0.068 \cdot \ln E$
μ_{f1}	$0.69 - 0.064 \cdot \ln E$
c_e	$0.014 - 0.096 \cdot \ln E$
d_e	$0.38 - 0.039 \cdot \ln E$

Longitudinal parameters

Parameter	Energy dependence
α_{e0}	$0.741 - 0.0811 \cdot \ln E$
α_{e1}	$-10.9 + 8.51 \cdot \ln E$
β_{e1}	$4.50 + 1.06 \cdot \ln E$
β_{e2}	$0.00130 - 0.0207 \cdot \ln E$
β_{e3}	$5.43 + 0.00177 \cdot E$
β_{e4}	0.0274
α_{h0}	$-0.806 - 0.000581 \cdot E$
α_{h1}	$0.571 - 0.0186 \cdot \ln E$
β_{h1}	$1.88 + 2.58 \cdot \ln E$
β_{h2}	$0.138 - 0.0601 \cdot \ln E$
β_{h3}	$2.80 + 1.16 \cdot \ln E$
β_{h4}	0.0527

Radial parameters

Fast MC vs Testbeam data

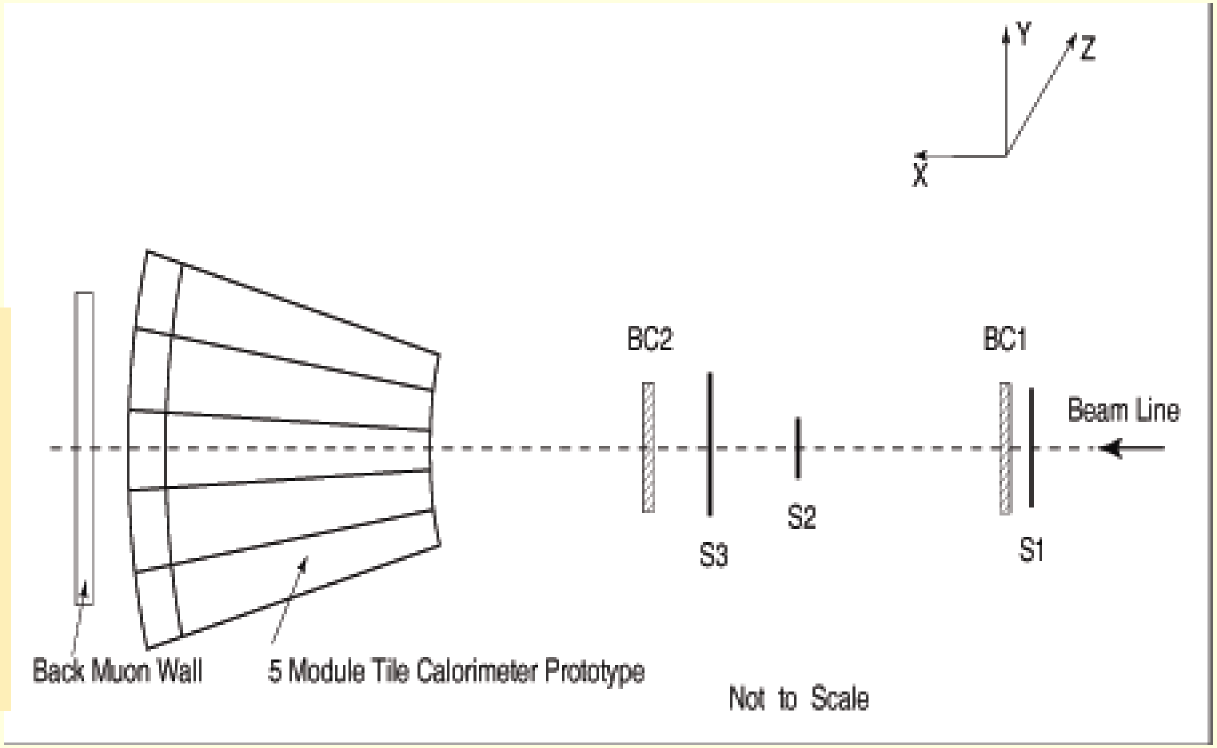
The fast MC is compared with the test beam data of 5 1m-modules for different incident pion energies (20 – 300) GeV and different input conditions

– varied:

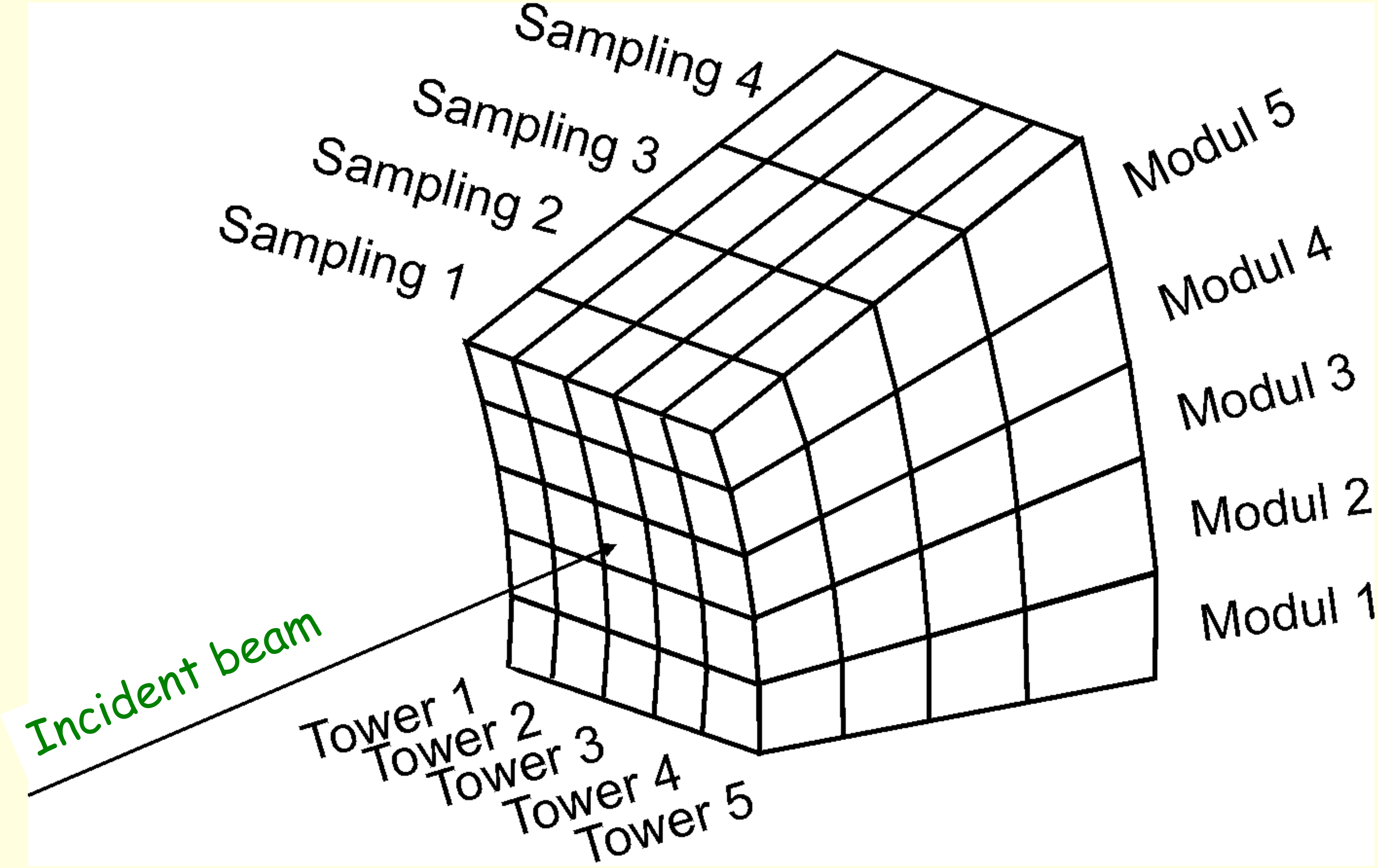
- ✓ Tilt angle
- ✓ Beam position

Test beam setup:

- 5 modules
- Each dided into 20 cells (4 samplings, 5 towers)
- Cell read by 2 PMT



Calorimeter structure

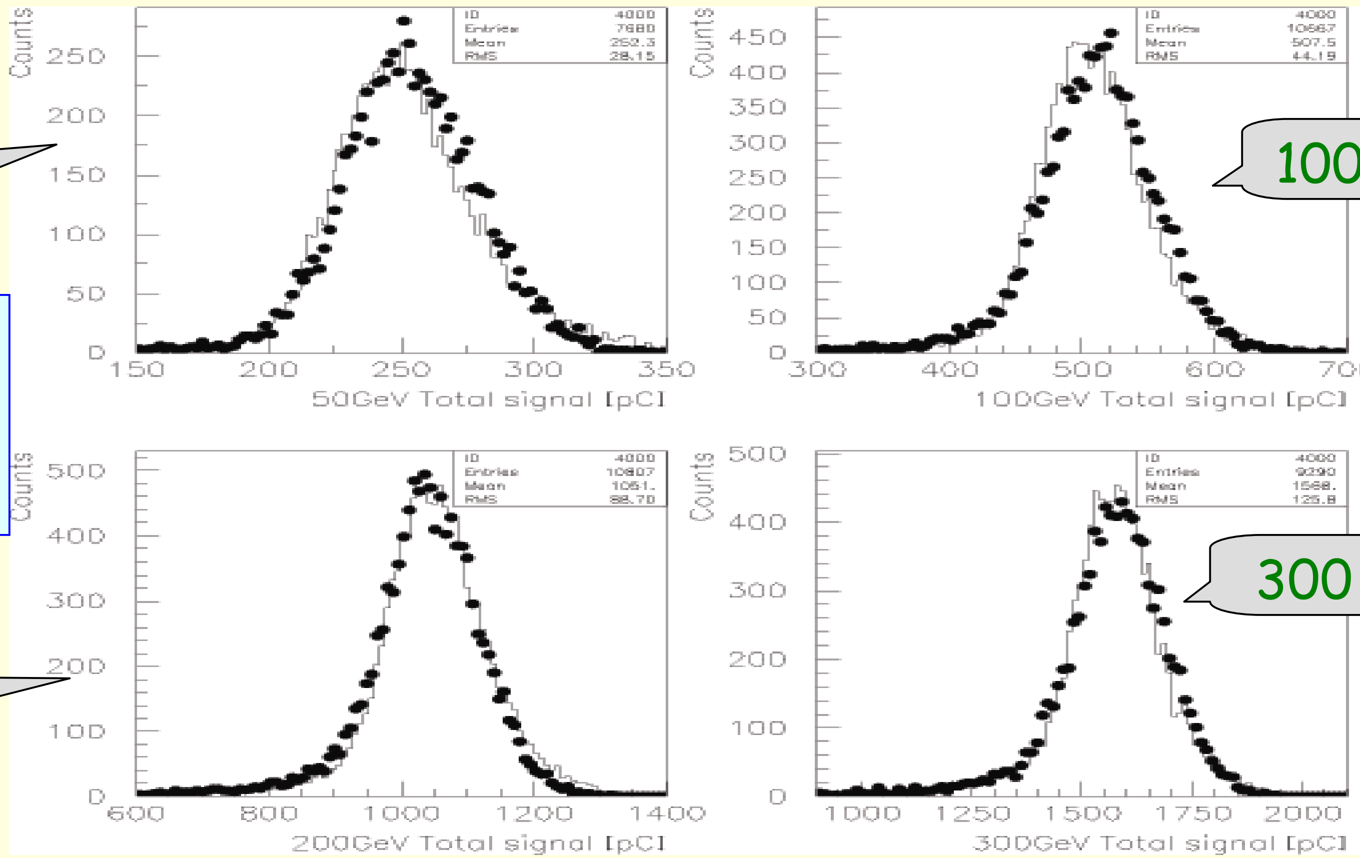


Fast MC vs Data - full responses

Full responses: Fast MC vs Test beam data for incident pion energies: 50, 100, 200 and 300 GeV, tilt angle: 10°

50 GeV

100 GeV



—TB data
● Fast MC

200 GeV

300 GeV

Fast MC vs TB data - samplings

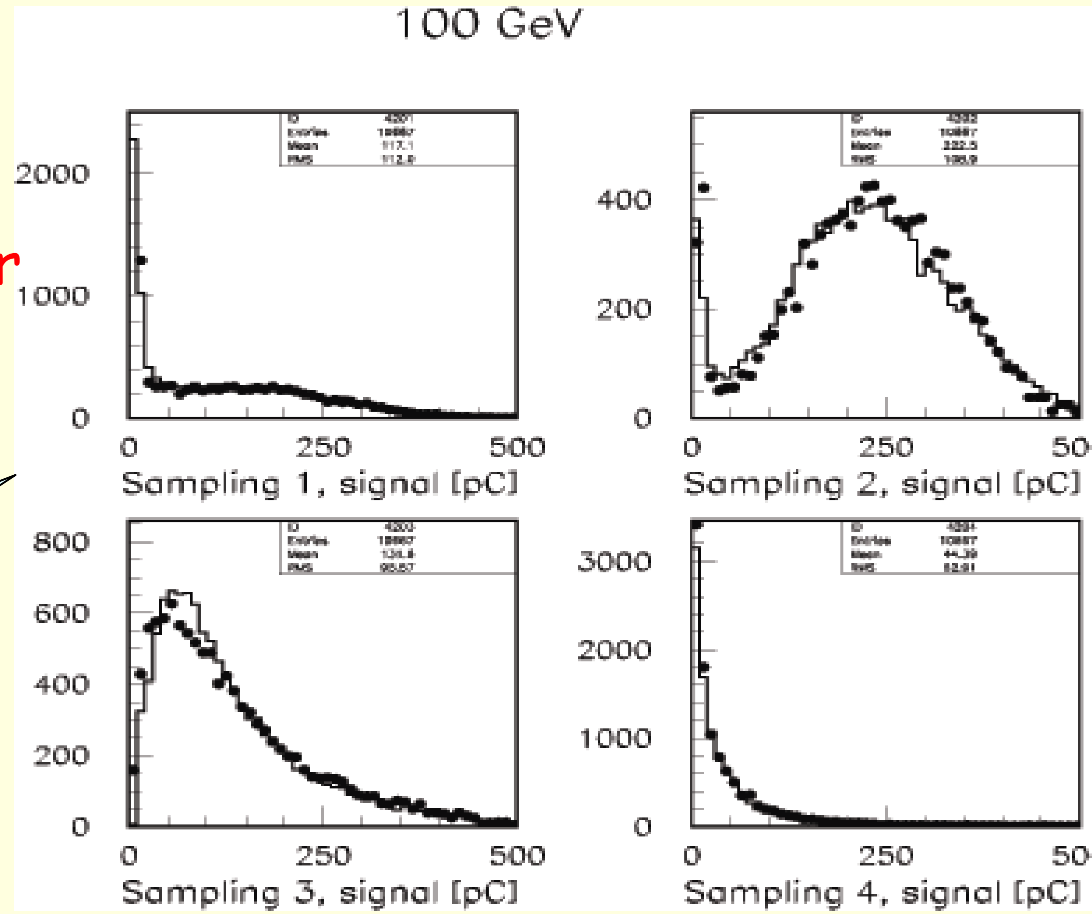
Sampling responses: Fast MC vs Test beam data

Incident energy: 100 GeV

Particle type: π^-

Position of beam: M3 center

Incident angle: 10°



Shower depth dependence

— TB data

● Fast MC

Fast MC vs TB data - modules

Module responses: Fast MC vs Test beam data

Incident energy: 100 GeV

Particle type: π^-

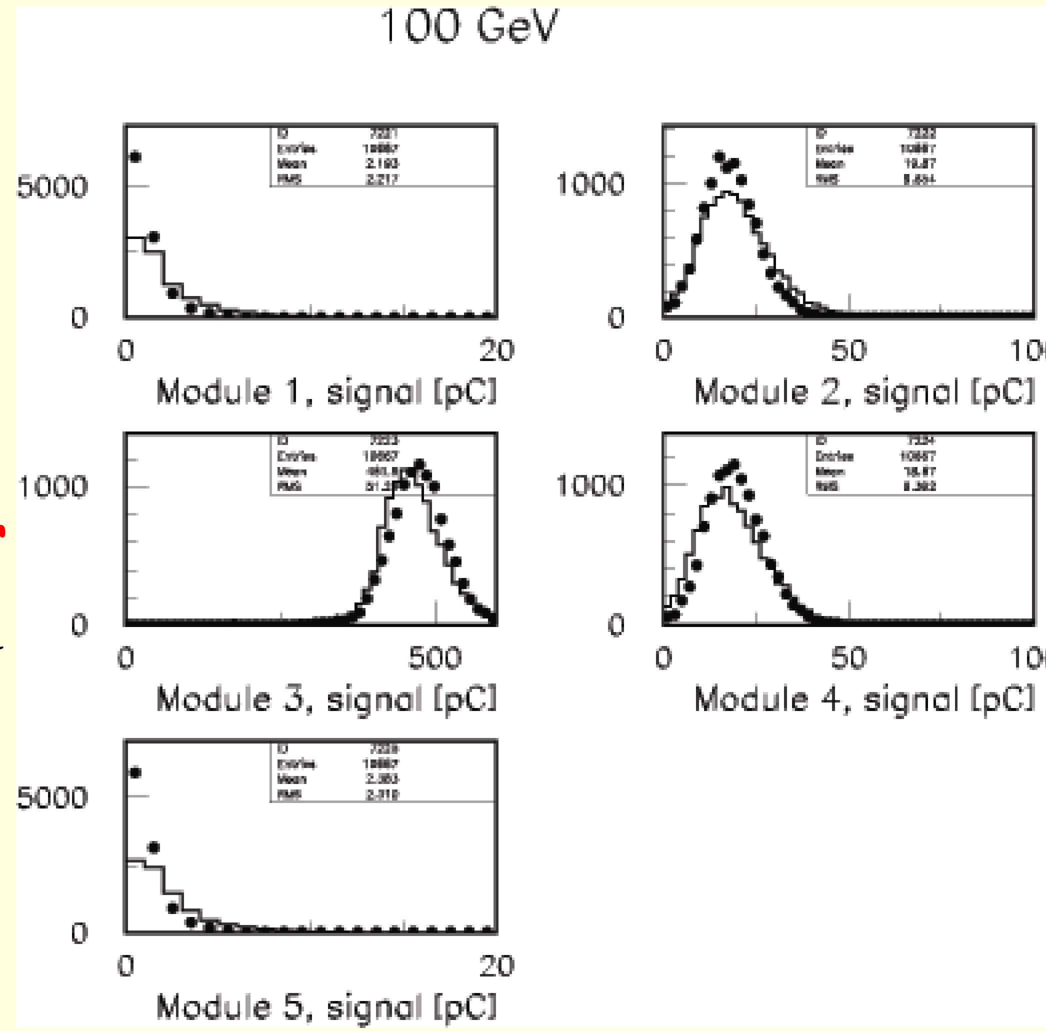
Position of beam: M3 center

Incident angle: 10°

Shower transversal dependence

— TB data

● Fast MC



Fast MC vs TB data - towers

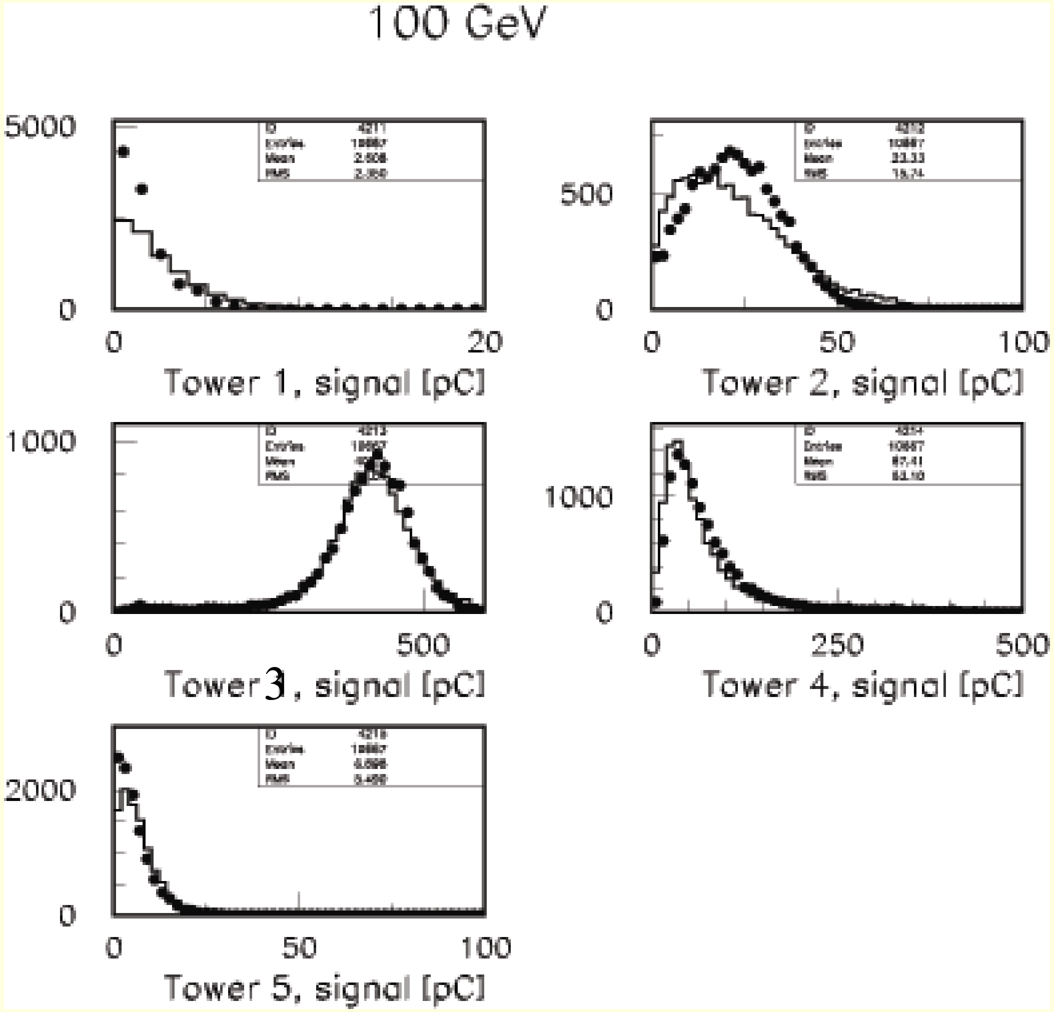
Tower responses: Fast MC vs Test beam data

Incident energy: 100 GeV

Particle type: π^-

Position of beam: M3 center

Incident angle: 10°



Shower transversal dependence

— TB data

● Fast MC

Conclusions and perspectives

- Fast MC method for sampling calorimeter based on idea of building shower from sub-showers was created
- Good description of energy response at least in the interval 50-300 GeV
- Good description of fluctuation on calorimeter cell level
- Method is easy adaptable for jets

To be done:

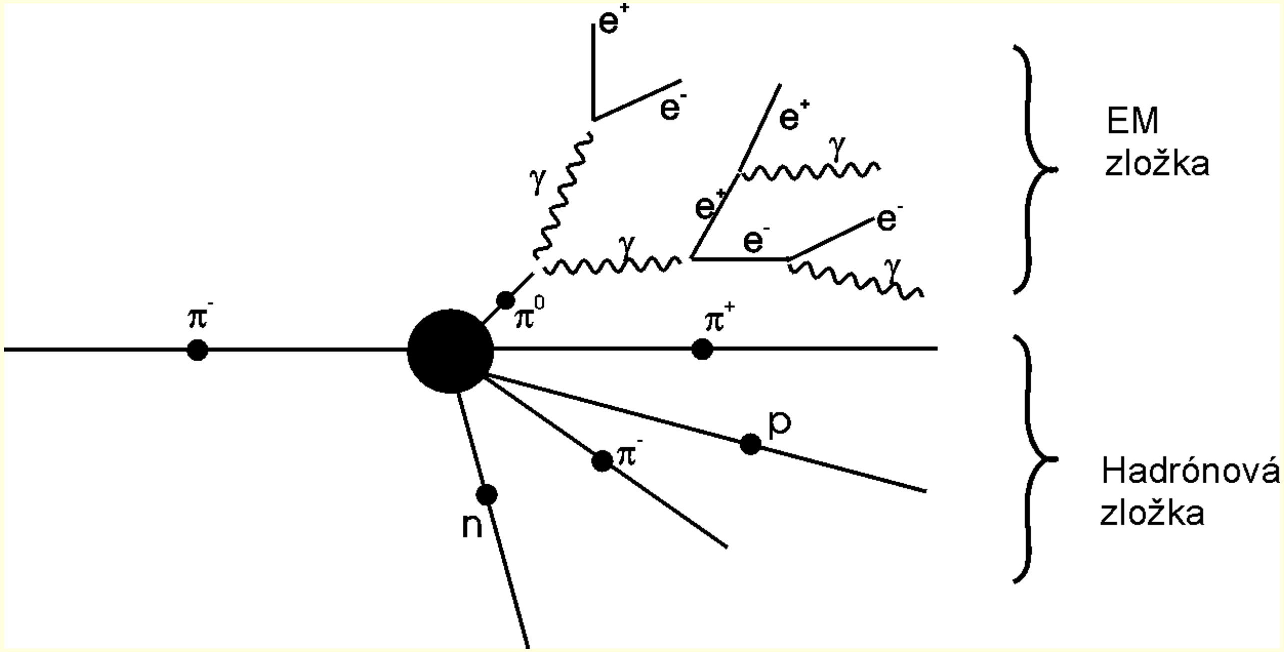
- ✓ Test method for low energies (1-20) GeV
- ✓ For application in ATLAS to include Elektromag. Cal.

Thank you very much!

Bol'šoje spasibo !!!

KALORIMETRIA

- Meranie energie častíc
- Fyzika hadrónovej spŕšky
- Modelovanie spŕšky - programový balík GEANT



D) Radiálny profil

•parametrizácia pre EM aj hadrónovú zložku:

$$\frac{\Delta E(x,r)}{\Delta x \Delta r} = \begin{cases} c r^{\alpha_r(x)-1} e^{-r/\beta_r(x)} & r > r_0 \\ r \cdot c r_0^{\alpha_r(x)-1} e^{-r_0/\beta_r(x)} & r < r_0 \end{cases}$$

•závislosť α_r od x pre EM zložku:

$$\alpha_{re}(x) = \alpha_{e0}\left(1 - 2e^{-x/\alpha_{e1}}\right)$$

$$\beta_{re}(x) = \begin{cases} \beta_{e1} + \beta_{e2} x & x \in (0,30) \\ \beta_{e3} + \beta_{e4} x & x \in (30,180) \end{cases}$$

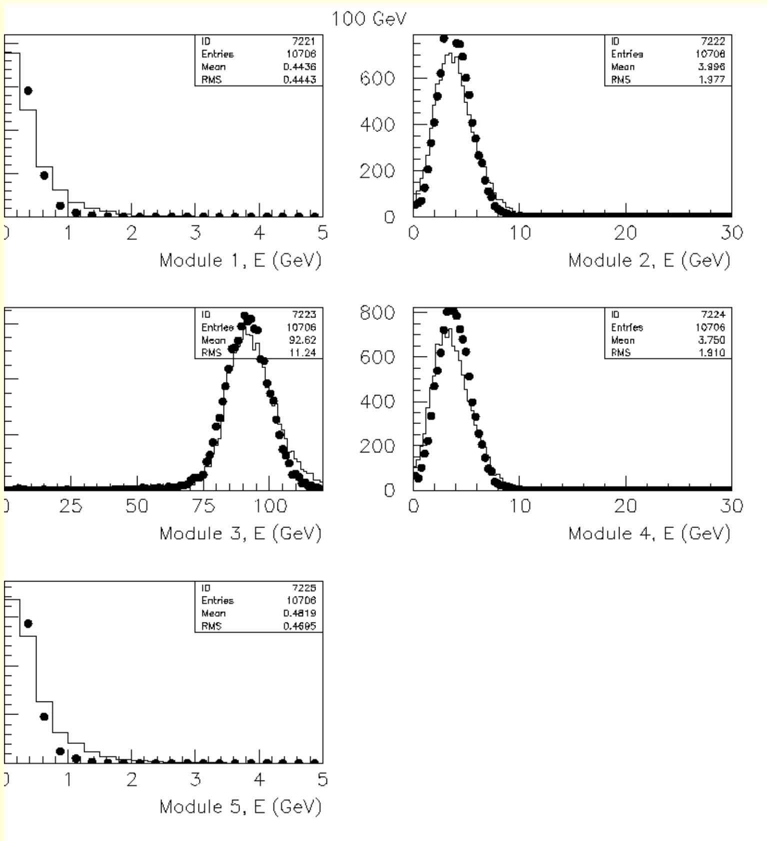
•závislosť α_r od x pre hadrónovú zložku:

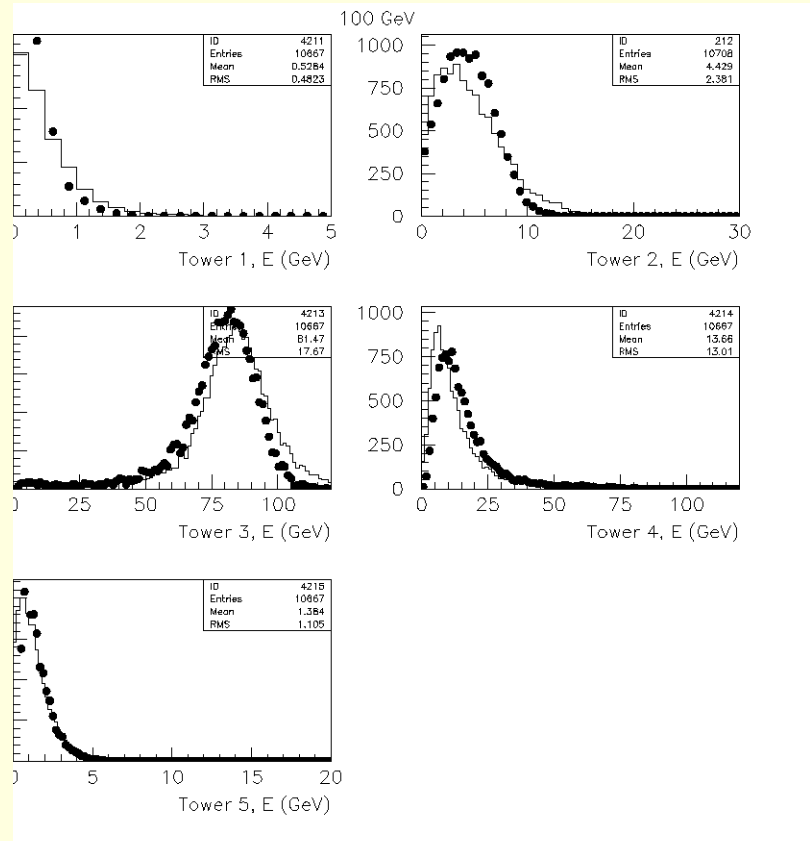
$$\alpha_{rh}(x) = \alpha_{h0} + \alpha_{h0} \ln(x)$$

$$\beta_{rh}(x) = \begin{cases} \beta_{h1} + \beta_{h2} x & x \in (0,30) \\ \beta_{h3} + \beta_{h4} x & x \in (30,180) \end{cases}$$

POROVNANIE S EXPERIMENTÁLNYMI DÁTAMI

100 Gev



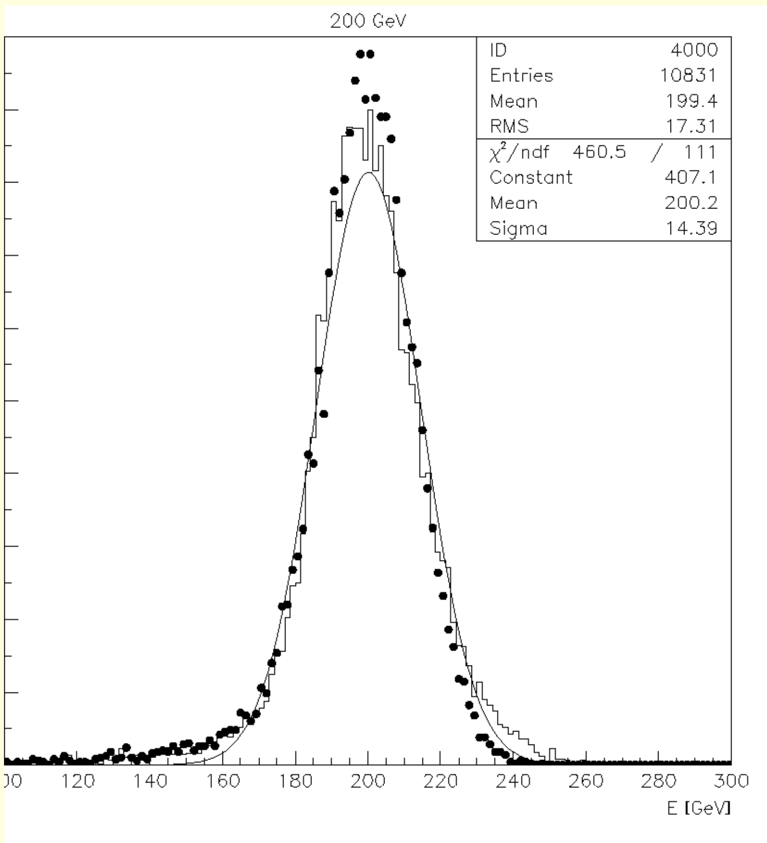


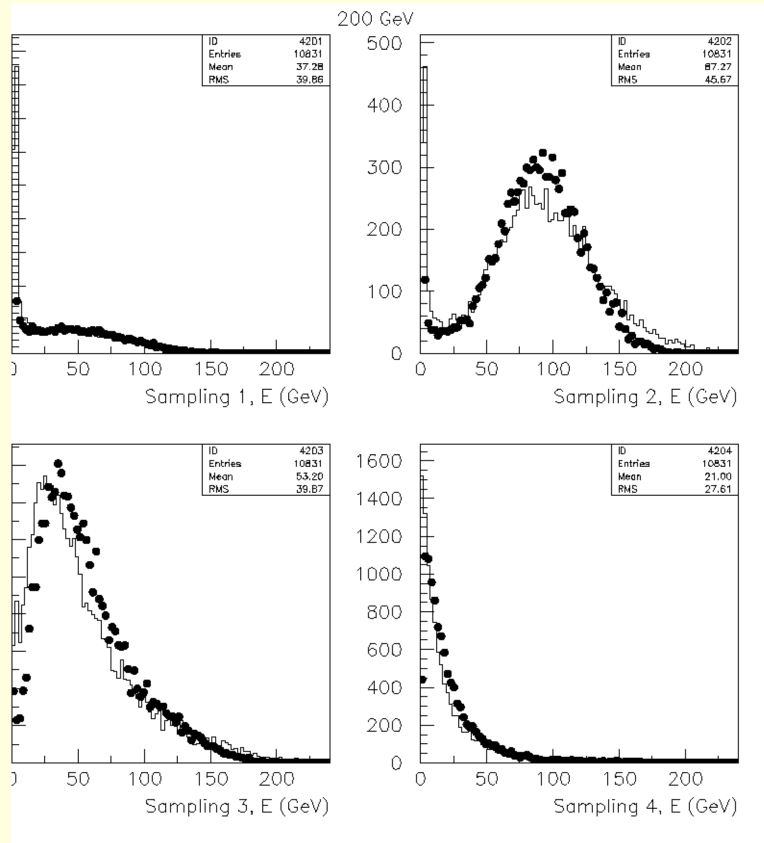
Energia uložená v moduloch, plná čiara – experimentálne dáta, body – rýchle simulácie

Energia uložená v toweroch, plná čiara – experimentálne dáta, body – rýchle simulácie

POROVNANIE S EXPERIMENTÁLNYMI DÁTAMI

200 Gev



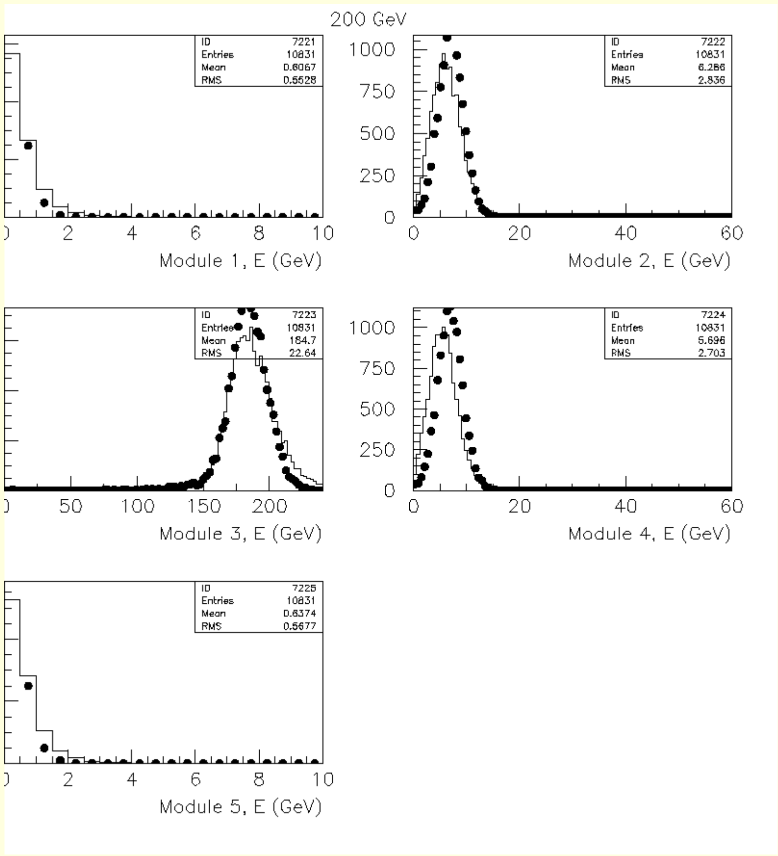


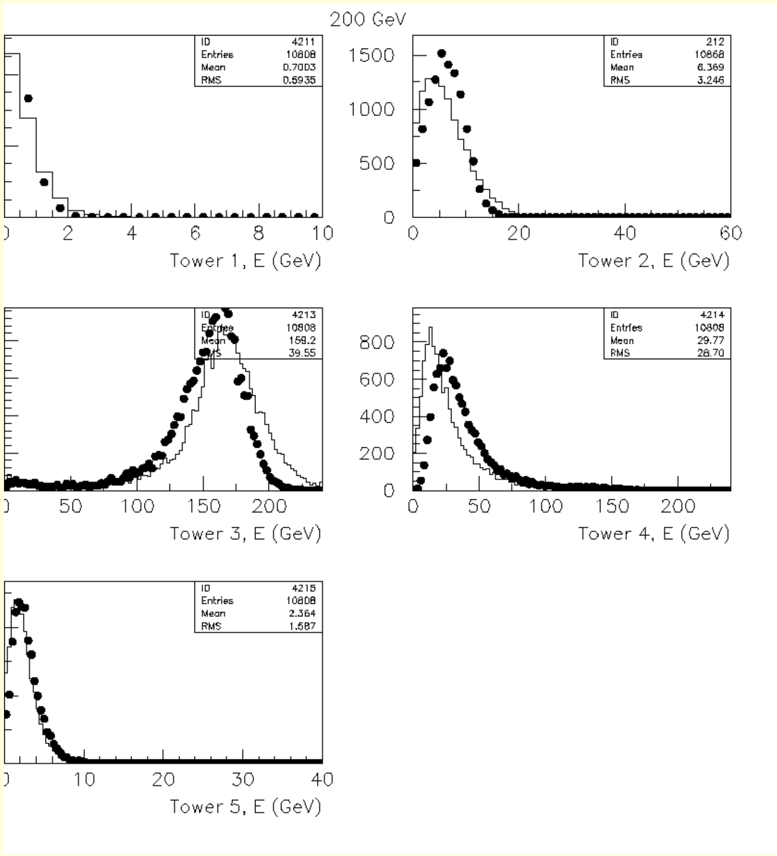
Celková uložená energia,
plná čiara – experimentálne dáta,
body – rýchle simulácie

Energia uložená v samplingoch,
plná čiara – experimentálne dáta,
body – rýchle simulácie

POROVNANIE S EXPERIMENTÁLNYMI DÁTAMI

200 Gev





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Energia uložená v toweroch,
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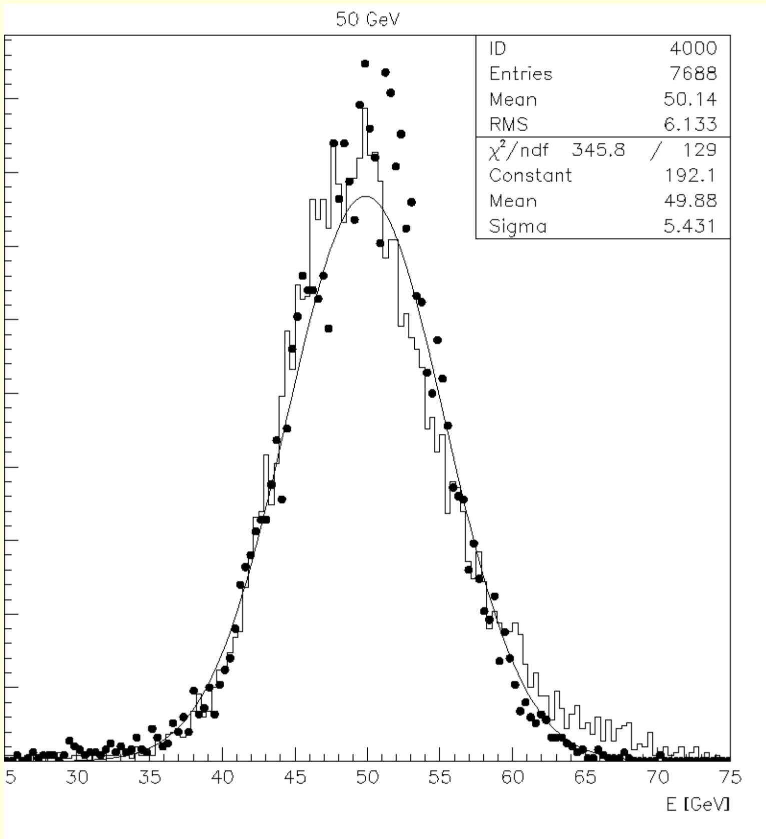
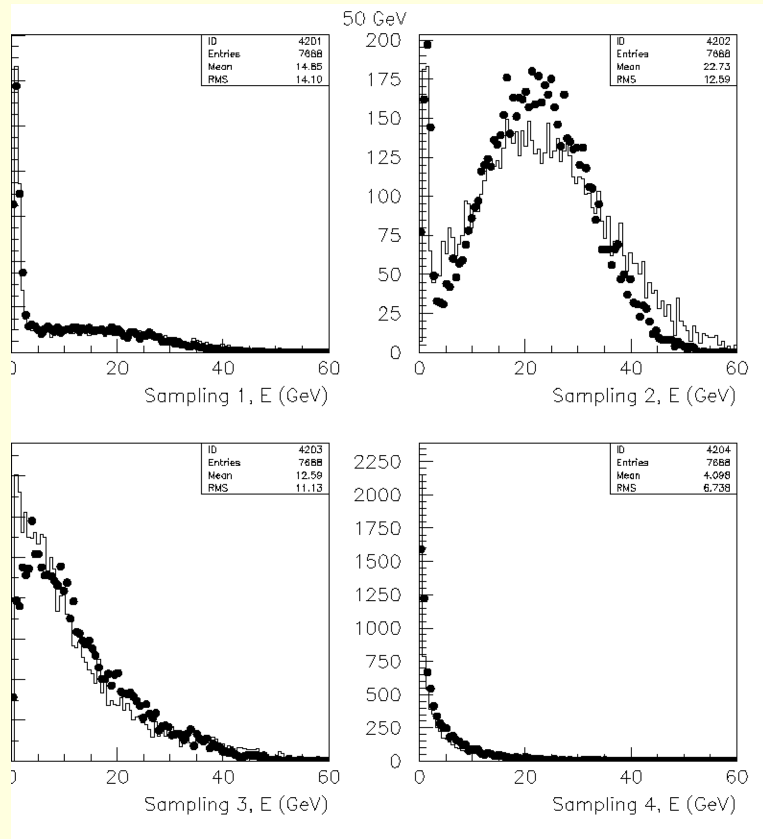
POROVNANIE S EXPERIMENTÁLNYMI DÁTAMI

50 Gev





Celková uložená energia,
plná čiara – experimentálne dáta,
body – rýchle simulácie

Energia uložená v samplingoch,
plná čiara – experimentálne dáta,
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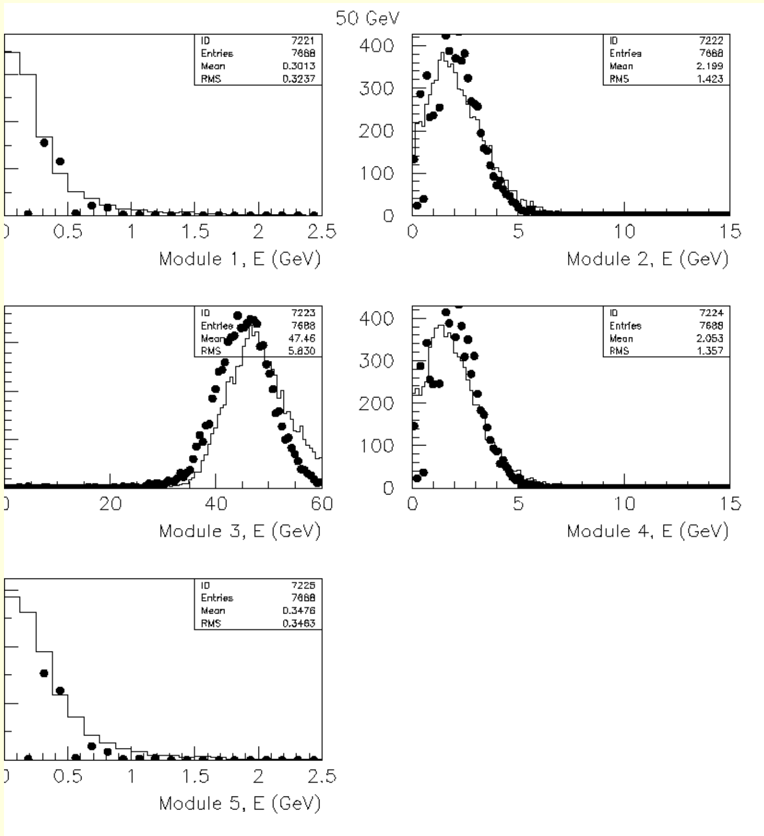
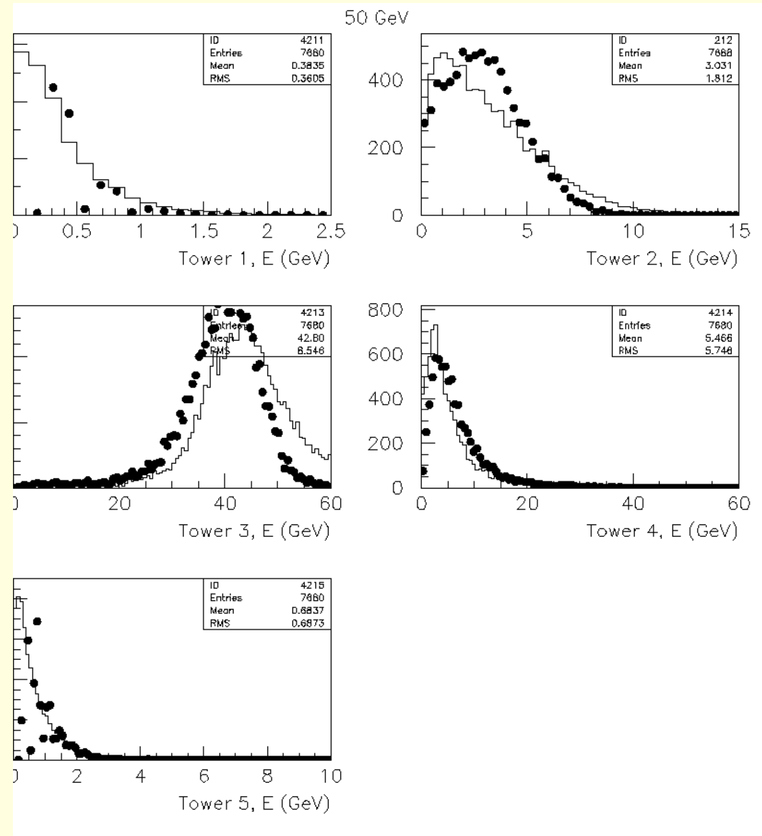
POROVNANIE S EXPERIMENTÁLNYMI DÁTAMI

50 Gev





Energia uložená v moduloch,
plná čiara – experimentálne dáta,
body – rýchle simulácie

Energia uložená v toweroch,
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body – rýchle simulácie

ZÁVER

- pomocou Monte Carlo simulácii (program GEANT) sme skúmali topológiu hadrónových spŕšok v kalorimetri s cieľom nájsť základné tendencie
- našli sme parametrizáciu profilu spŕšky a spôsob zahrnutia jeho fluktuácii
- na základe týchto znalostí bol vytvorený program pre rýchle simulácie
- dosiahli sme výbornú zhodu s reálnymi experimentál-nymi dátami

$$\frac{dE_{\pi^0}(x)}{dx} = \begin{cases} E_{\pi^0} f_1 \delta(x) \\ E_{\pi^0}(1-f_1)\dfrac{\exp\left(-x/\lambda_{\pi^0}\right)}{\lambda_{\pi^0}} \end{cases}$$