Gflash as a Parameterized Calorimeter Simulation for CMS

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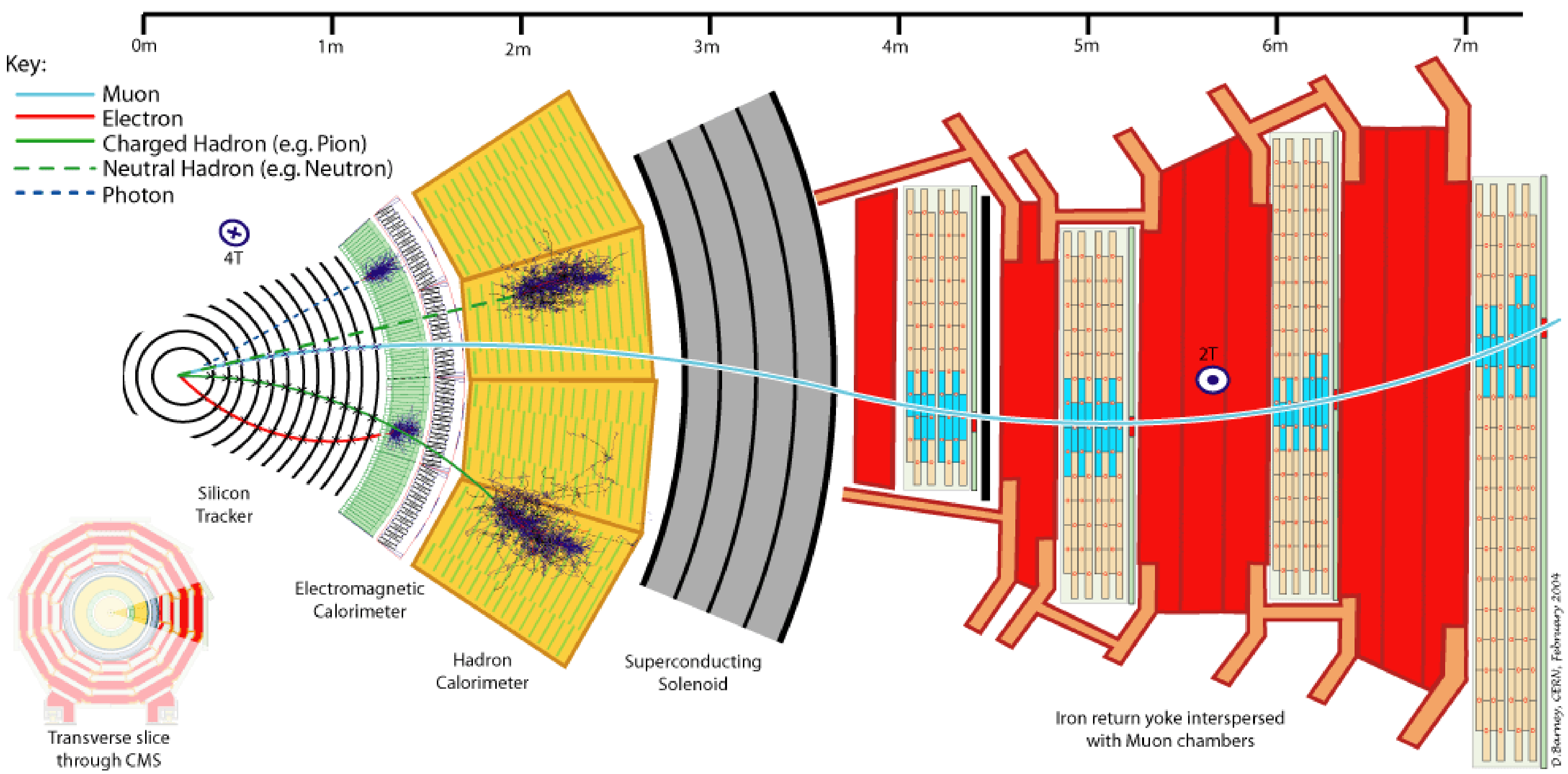
XIV International Conference on Calorimetry in High Energy Physics

May 10-14, 2010

IHEP, Beijing, China

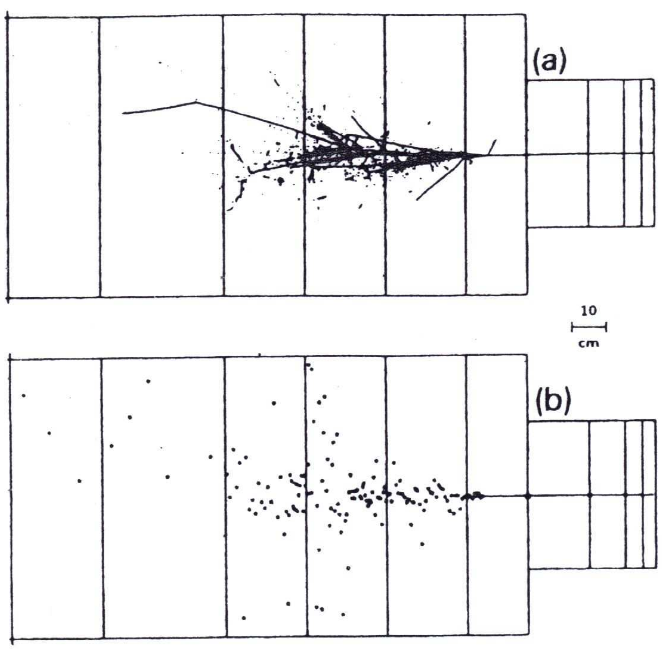
Introduction

- CMS detector simulation
  - primarily uses the Geant4 (G4) toolkit to simulate the passage of particles
  - tracks the primary particles and all their secondaries using a physics list consisting of a number of models to describe different types of interactions
  - CPU needed for simulation of particle showers in calorimeter increases linearly with the energy (high multiplicity and energetic particles at CMS)



Introduction

- Gflash is an alternative option for the CMS calorimeter simulation
  - a parameterized simulation of electromagnetic (EM) and hadronic showers
  - replaces the standard tracking (G4) by parameterized physics at the first inelastic interaction within defined detector envelopes (calorimeters)
  - parameterized shower profiles $\rightarrow$ energy spots $\rightarrow$ hits/digitization
  - flexible to tune and fast
  - example: simulation of the H1 test calorimeter



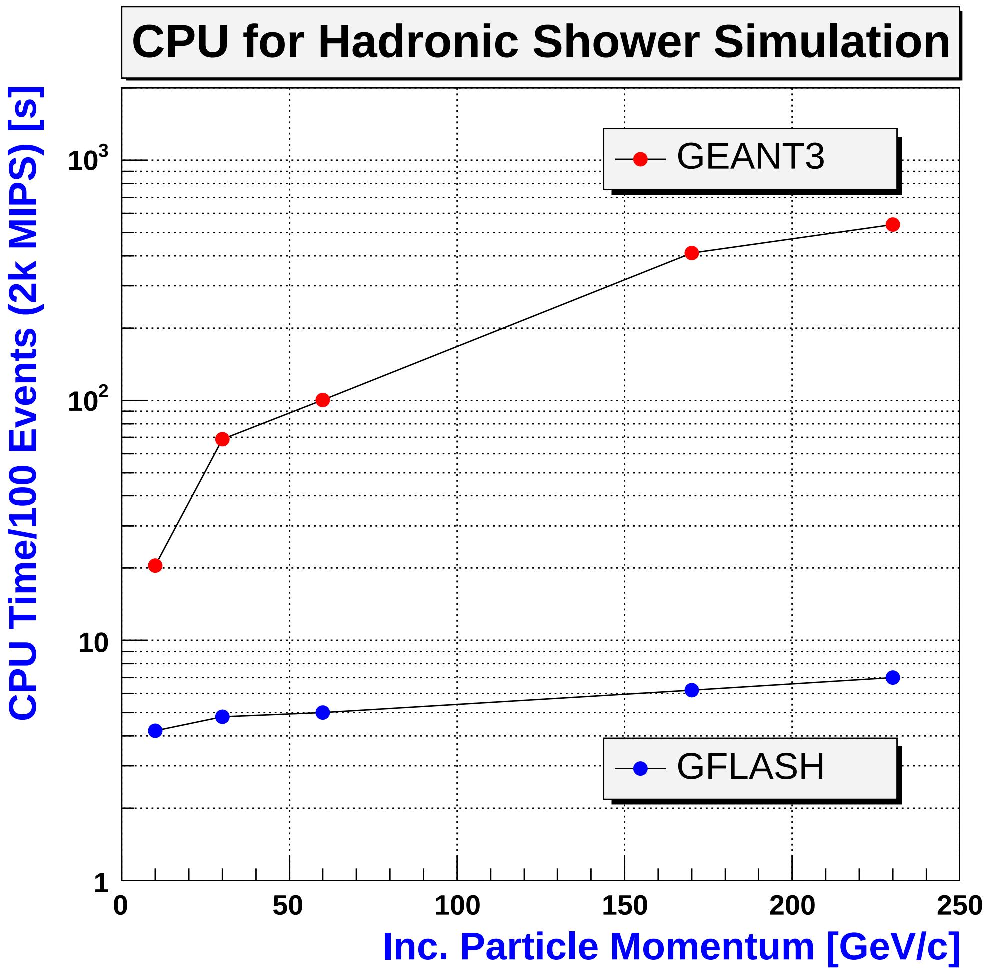
(a) Standard (Geant) tracking

(b) Parameterized energy spots

Gflash - History

Fast Simulation of Electromagnetic and Hadronic Showers

- G. Grindhammer, M. Rudowicz and S. Peters, *NIM* **A**290 (1990) 469-488
- H1 calorimeter for H1 at HERA
- Sophisticated, but fast
- Adapted for CDF calorimeter simulation at Tevatron Run–II
  - CPU gain up to 100 (CDF)
- Ideal for
  - simple geometry
  - repetitive sampling structure
  - single effective medium



GFLASH in a Nutshell

- Parameterize the spacial distribution of energy

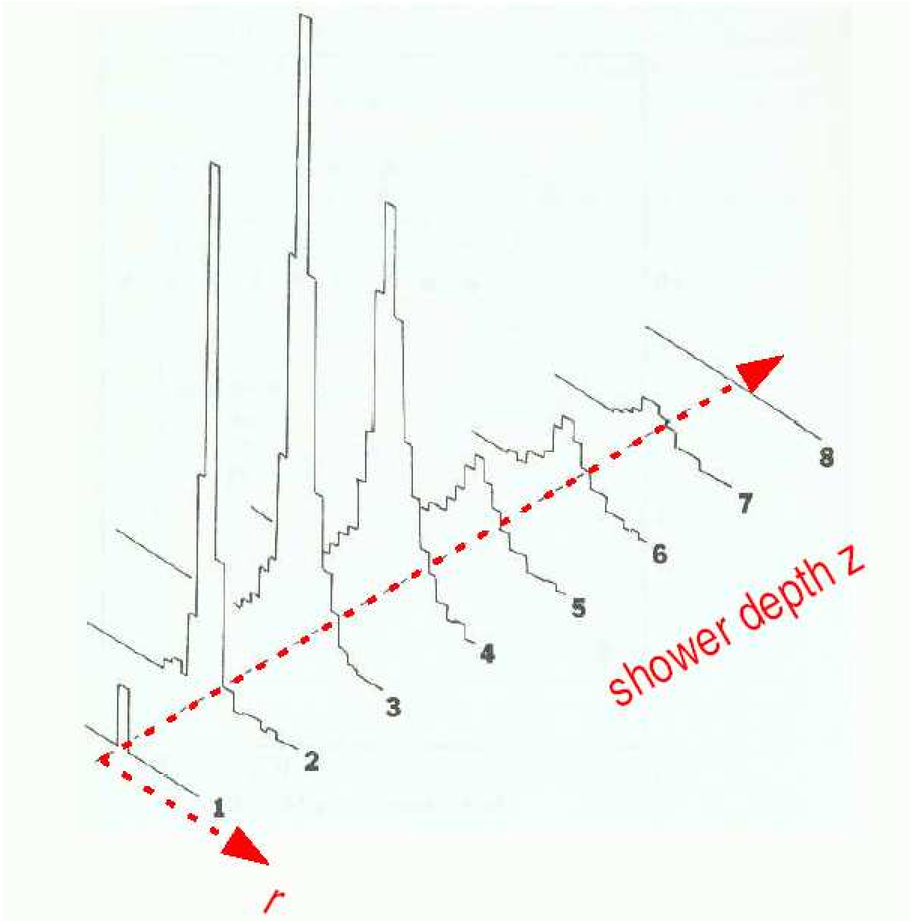
$$dE_{dp}(\vec{r}) = \frac{E_{dp}}{2\pi} f(z)dz f(r)dr$$

  - $f(z)$: longitudinal shower profile
  - $f(r)$: lateral shower profile

- Take into account correlation and fluctuation of individual showers

- Distribute N_{spot} with the sampling structure with fluctuation a

$$\frac{\sigma}{E} = \sqrt{\frac{a^2}{E} + \frac{N^2}{E^2} + C^2}, \qquad E_{spot} = a^2$$



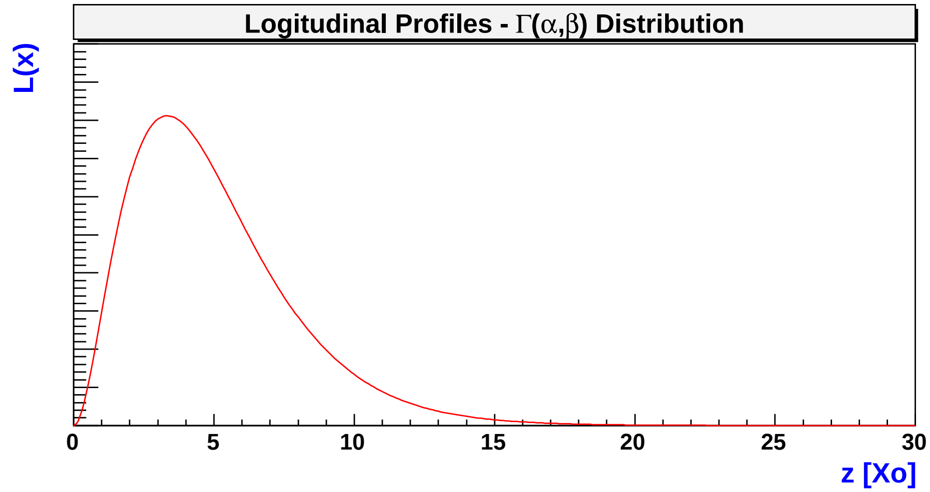
- Visible energy with the relative sampling fraction to mip

GFLASH in a Nutshell - EM Shower

- Longitudinal profile along the shower depth (z) in radiation length $[X_0]$

$$f(x) = \frac{1}{E}\frac{dE}{dx} = \frac{x^{\alpha-1}e^{-x}}{\Gamma(\alpha)} \qquad x = \beta z$$

where the correlated pair (α, β) characterizes the shower shape (tune-on, tail)



- Lateral Profile: radial distribution of energy in each longitudinal $f(x)dx$

$$f(r) = \frac{1}{dE(x)}\frac{dE(x,r)}{dr} = \frac{2rR_0^2}{(r^2+R_0^2)^2}, \qquad \langle R_0 \rangle = [R_1 + (R_2 - R_3 \ln E) \cdot z]^2$$

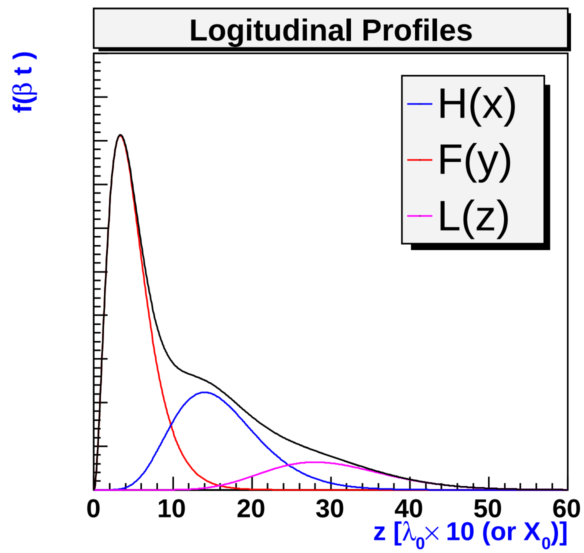
- Parameterization is material–independent if E in E_c and z in X_o units (Rossi)

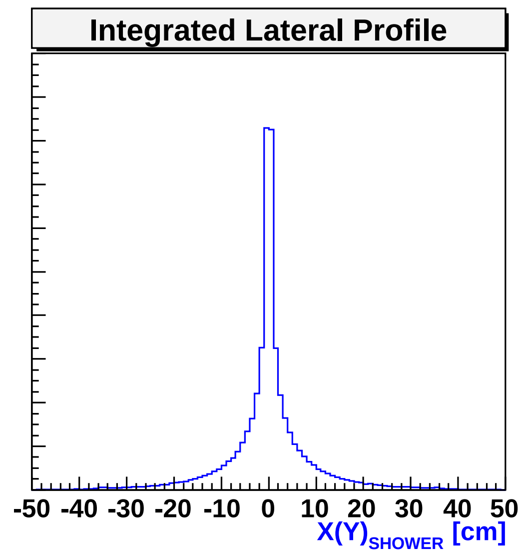
GFLASH in a Nutshell - Hadron Showers

- Longitudinal profile: three $\Gamma(\alpha, \beta)$–functions for three different shower classes
  - $H(x)$: pure hadronic shower
  - $F(y)$: π^0 contribution in the first inelastic interaction
  - $L(z)$: π^0 contribution in the later interactions

$$E_{dp} = f_{dp} E_{inc}[(1 - f_{\pi^0}) \cdot H(x)dx + f_{\pi^o}(1 - f^l_{\pi^0}) \cdot F(y)dy + f_{\pi^o} f^l_{\pi^0} \cdot L(z)dz]$$

where f_{dp} (f_{π^o}, $f^l_{\pi^0}$): fraction of deposited energy (by all π^0, late π^0)

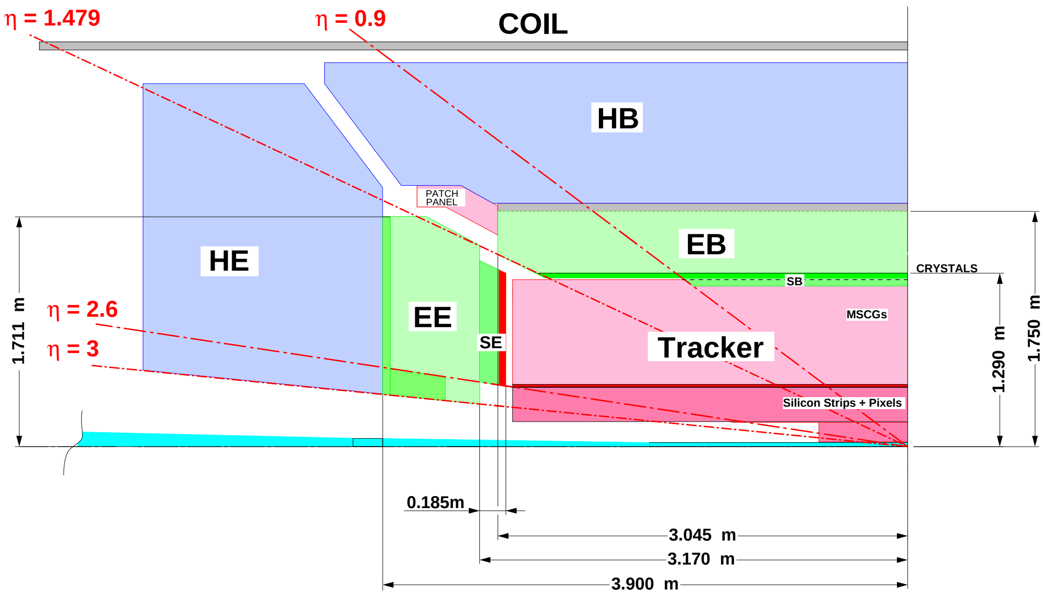




- Lateral profile: same form to that of EM except $\langle R_0 \rangle = R_1 + (R_2 - R_3 \ln E)z$

Gflash at CMS

- Geant4 interface and Gflash Models
  - use G4 Fast Simulation Manager
  - replace G4 for calorimeter simulation
  - regions for parameterization (envelopes: EB,EE,HB,HE,HO)
  - particle type ($e^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p, \bar{p}$)
  - kinematic/geometrical conditions



- Challenge for CMS
  - geometry (gaps between Ecal and Hcal)
  - magnetic field (calorimeter inside 3.8T)
  - new hadronic parameterization

Calorimeter Type	Thickness
Ecal Barrel ($PbWO_4$)	25.8 X_o, 1.1 λ
Ecal Endcap ($PbWO_4$)	24.7 X_o, 1.1 λ
Hcal Barrel (Brass)	5.7 λ
Hcal Endcap (Brass)	8.1 λ
Hcal Outer (Scint. tiles)	1(2)×1.0cm

- Tuning Gflash to data
  - 2006 e^- test beam data
  - 2006 hadron test beam data
  - *in-situ* collision data (underway)

New Parameterization of Hadron Shower for CMS

- Longitudinal profile: a combination of sub-profiles in Ecal and Hcal

$$F = f_{\rm ecal} F_{\rm ecal} + f_{\rm hcal} F_{\rm hcal}$$

where f_i $(i = {\rm ecal},\ {\rm hcal})$ is related to the fraction of deposited energy in i-detector

- Functional hypothesis: F_i is the superposition of two Γ–distributions:

$$F_{\rm ecal}\ ({\rm or}\ F_{\rm hcal}) = [cL(x_e; \alpha_e, \beta_e)dx_e + (1-c)L(x_h; \alpha_h, \beta_h)dx_h],$$

$$L(x_i; \alpha_i, \beta_i) = \frac{x_i^{\alpha_i - 1} e^{-x_i}}{\Gamma(\alpha_i)}, \qquad x_i = \frac{\beta_i z}{d_i} \qquad (d_e = X_0, d_h = \lambda_0)$$

- Build sets of longitudinal parameters, $\vec{x} = \{c, \ln\alpha_e, \ln\beta_e, \ln\alpha_h, \ln\beta_h\}$ using the $n^{\rm th}$ moment of Γ distribution (m_n) and the hit energy (E_j) of $G4$ steps

$$m_n = \sum_{j=1}^{nhit} (z/d_j)^n E_j / \sum_{j=1}^{nhit} E_j \qquad n = 1, 2, 3...$$

$$\alpha = m_1^2/(m_2 - m_1^2)$$

$$\beta = m_1/(m_2 - m_1^2)$$

- Individual fluctuations (μ_i, σ_i) and their corrections (ρ_{ij}): $\vec{x} = \{x_i\}$, $\vec{\mu} = \langle\vec{x}\rangle$, $\vec{\sigma} = \delta\vec{x}$, $\vec{\phi}$: a vector of normal random

$$\vec{x} = \vec{\mu} + \vec{\sigma}\mathbf{C}\vec{\phi} \quad \text{with} \quad \rho = \mathbf{C}\mathbf{C}^T$$

where $\mathbf{C}$ is Cholesky decomposed matrix of correlation matrix ρ.

- Laternal profile is well modeled by $f(r) = 2rR^2/(r^2+R^2)^2$ where R is to be a log-normally distributed with the mean (μ) and standard deviation σ related to the expected value of (R_0) and its variance (V)

$$\mu = \ln R_0 - \sigma^2, \qquad \sigma^2 = \ln(V/R_0^2 + 1).$$

- Constructed p.d.f., $f(r)$ of energy density using parameters E_i^{jk} for the i-th lateral interval (r_i), the j-th depth segment and the k-th beam energy bin. Then, R_0 and V are calculated using E_i^{jk}

$$R_0^{jk} = \frac{2}{\pi}\sum_i E_i^{jk} r_i, \qquad V^{jk} = \sum_i E_i^{jk}(r_i - R_0^{jk})^2$$

- R_0 and V are parameterized as the shower depth (z) and the energy

$$R_0 = R_c(E) + R_s(E)z, \qquad V = [S_c(E) + S_s(E)z]^2 R_0^2.$$

Tuning Gflash to Test Beam Data

- Gflash tuning to 2006 test beam data
  - use the detector geometry used for test beam set-up
  - simulate single particle events at a fixed energy
  - follow the same procedure and calibration consistent with test beam analysis

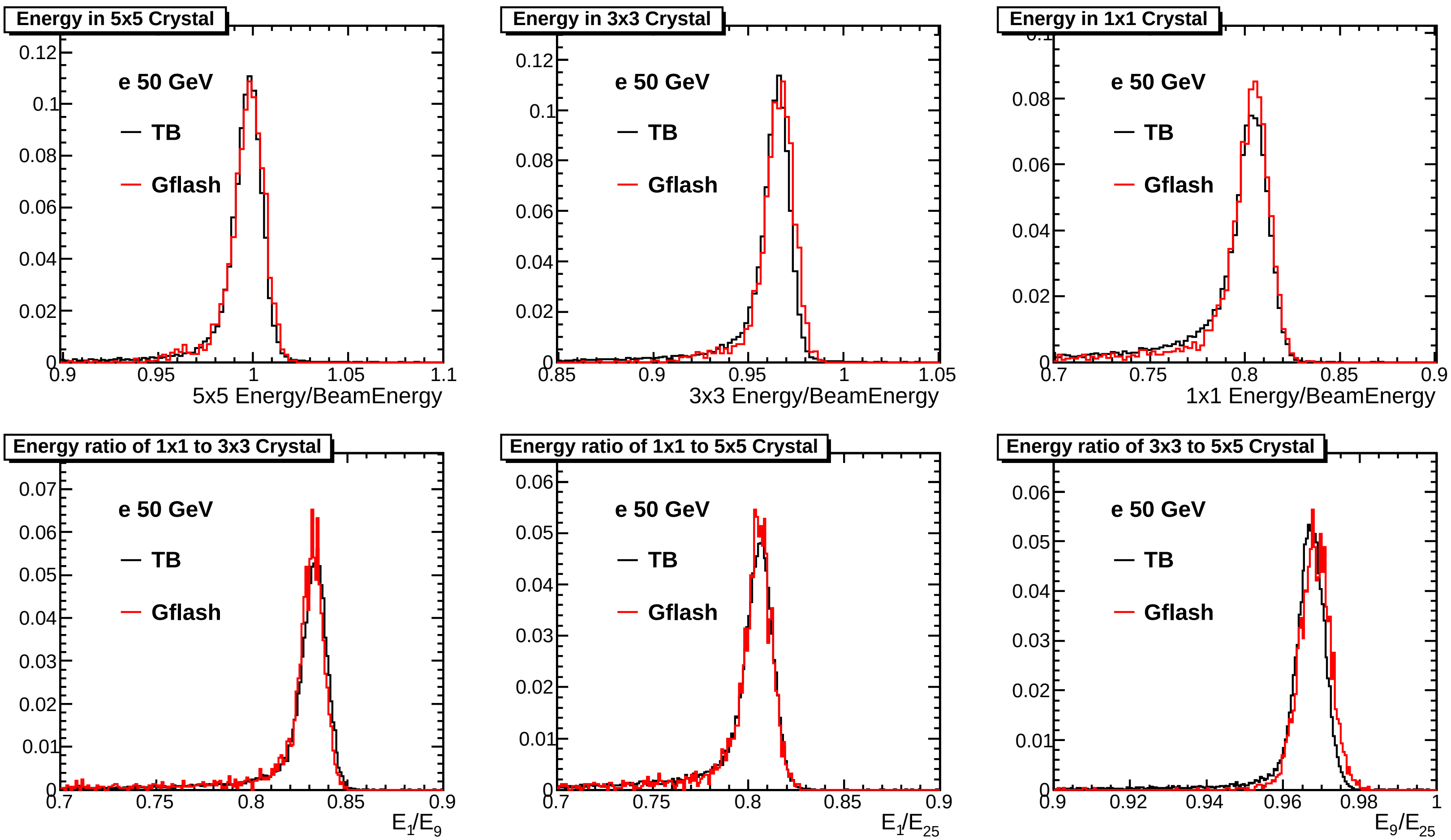
- e^- test beam data and tuning
  - beam energies: 20, 30, 50, 80, 120 GeV
  - compare energy responses in $N \times N$ crystals ($N = 1, 3, 5$)

- hadron test beam data and tuning
  - low energy ($2 - 9$ GeV) beams: mainly $\pi^\pm$, p and some $K^\pm$, $\bar{p}$
  - high energy ($20 - 350$ GeV) beams: π^-, p, $\bar{p}$
  - compare energy responses with Ecal (7×7 crystals) and Hcal (3×3 towers)

- Precision tuning with single particle responses with in-$situ$ collision data from CMS is also underway

EM Energy Shape Tuned to Test Beam Data

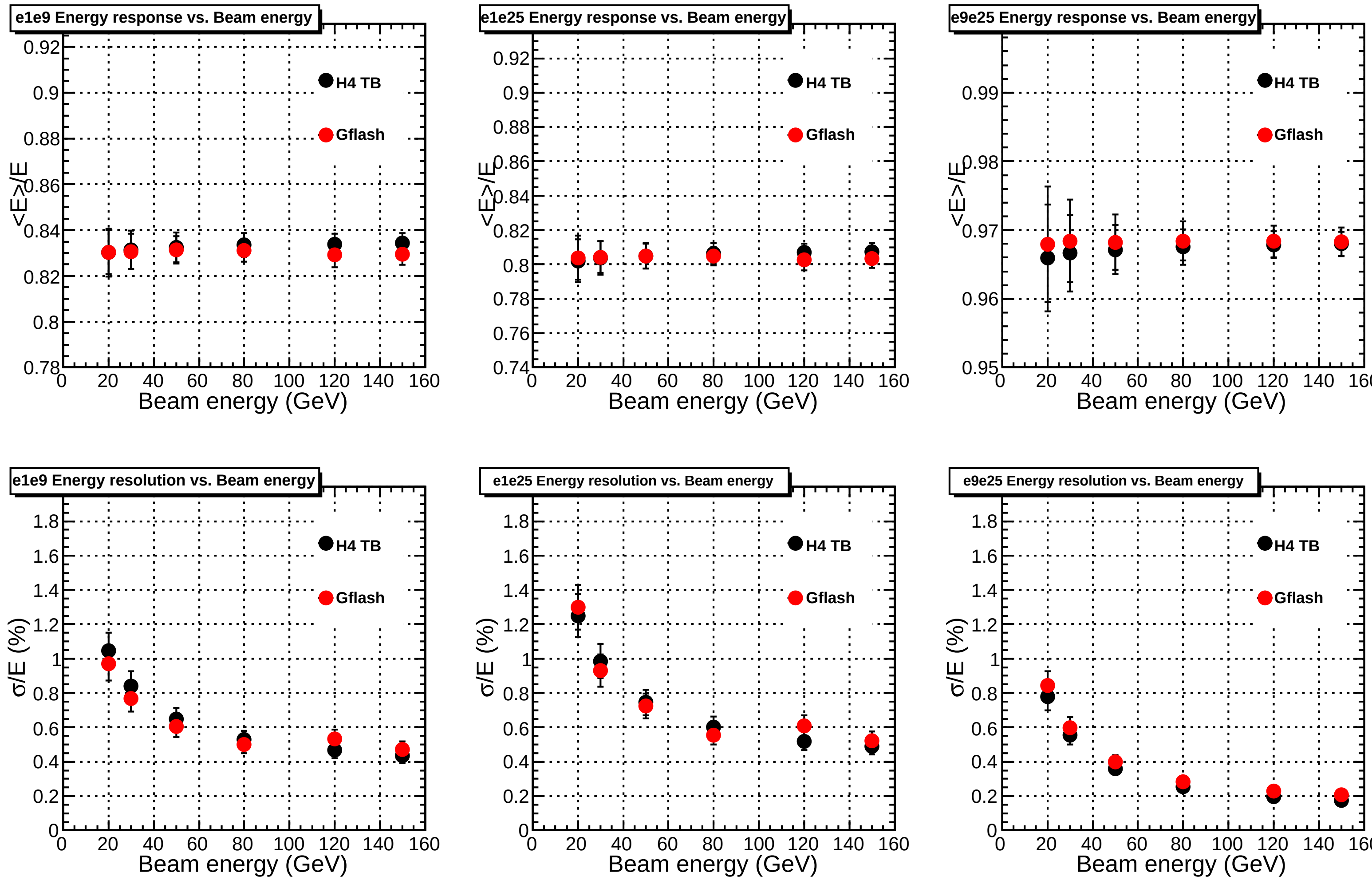
$n \times n$ crystal response of 50 GeV e^- compared to 2006 e^- test beam data



- Both absolute response and relative response are in good agreement
  - longitudinal containment and lateral spread are well modeled and tuned

Relative Response and Resolution of EM Shower

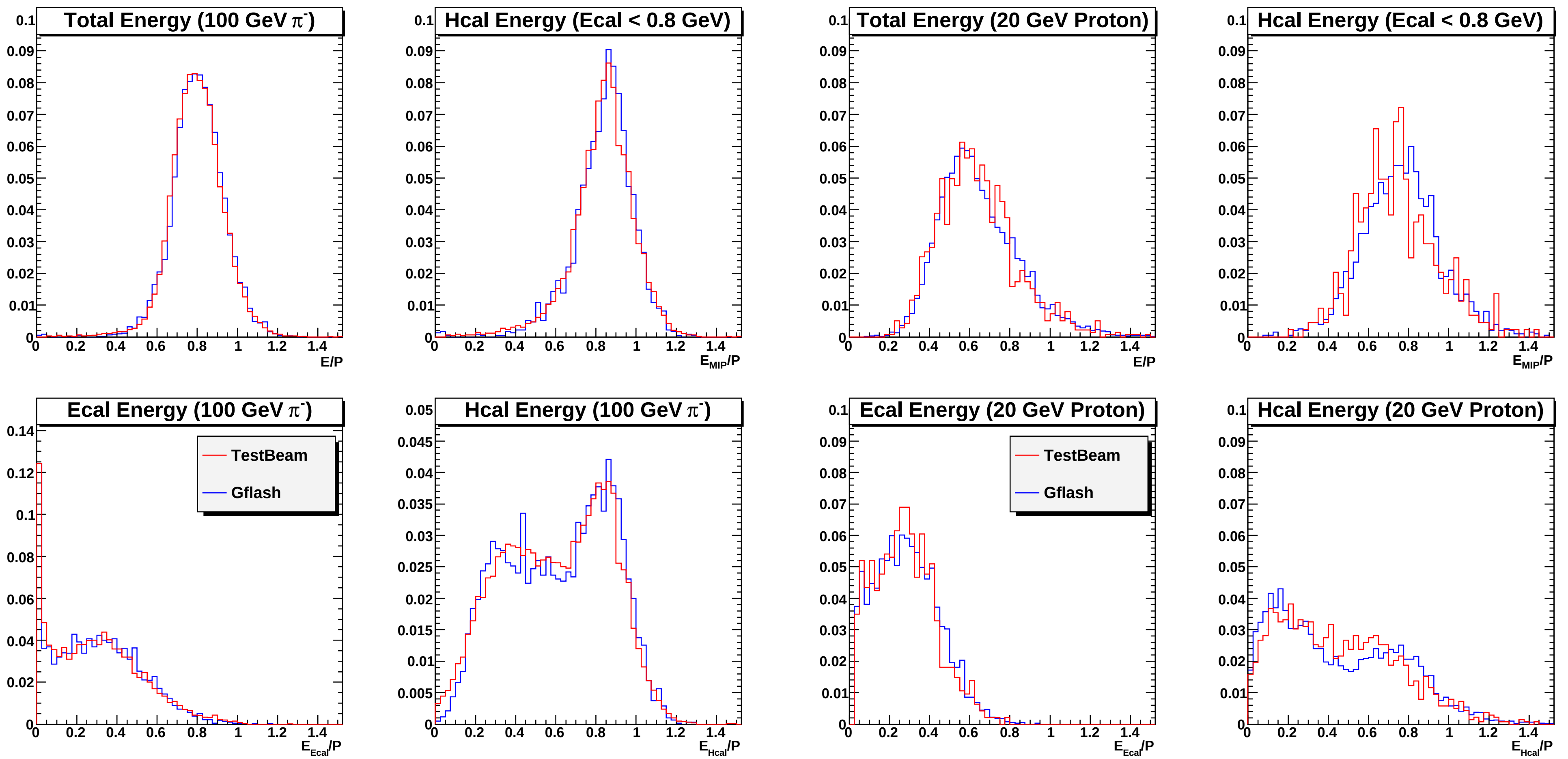
$\frac{E_{n\times n}}{E_{N\times N}}$ compared to 2006 e^- test beam data (20,30,50,80,120,150 GeV)



- Scale independent lateral response and resolution as the beam momentum

Hadronic Energy Shape Tuned to Test Beam Data

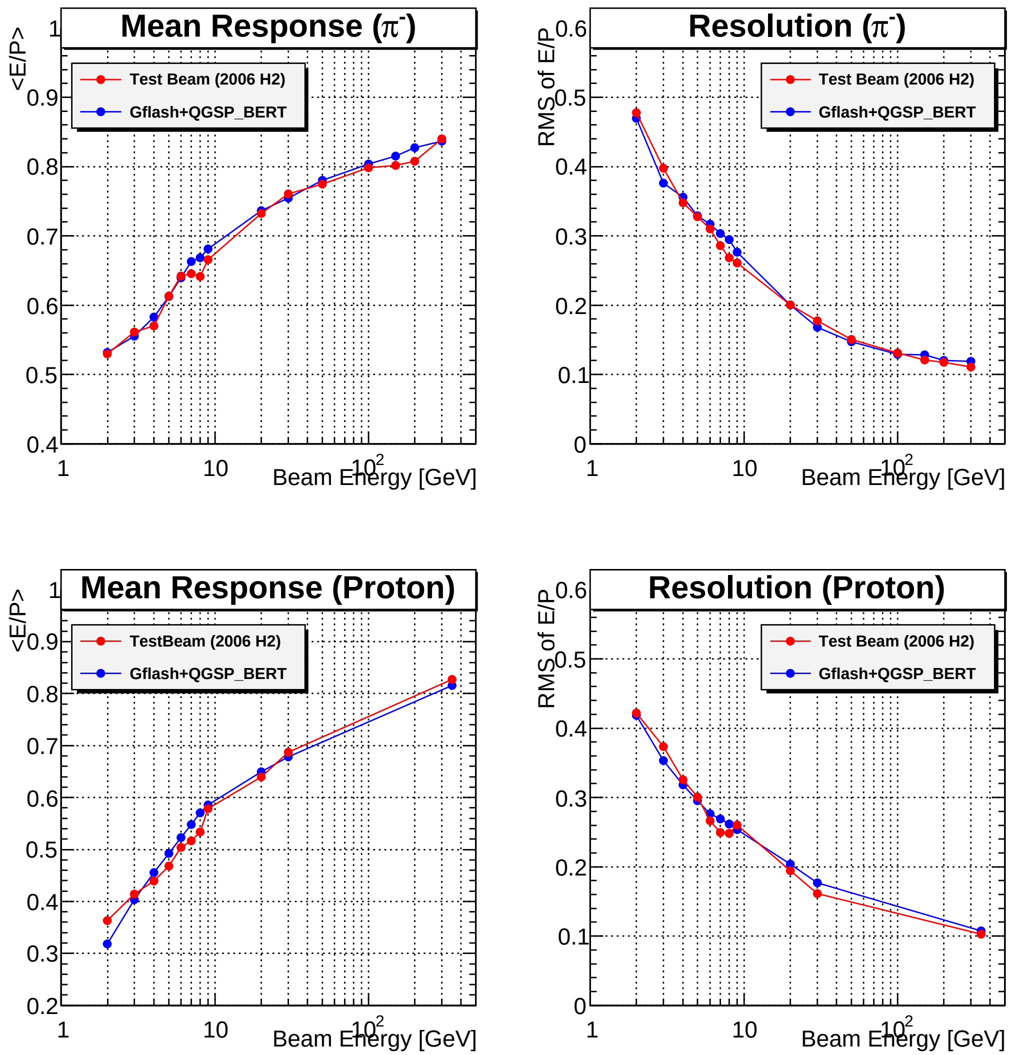
energy response of 100 GeV π^- and 20 GeV p compared to 2006 test beam data



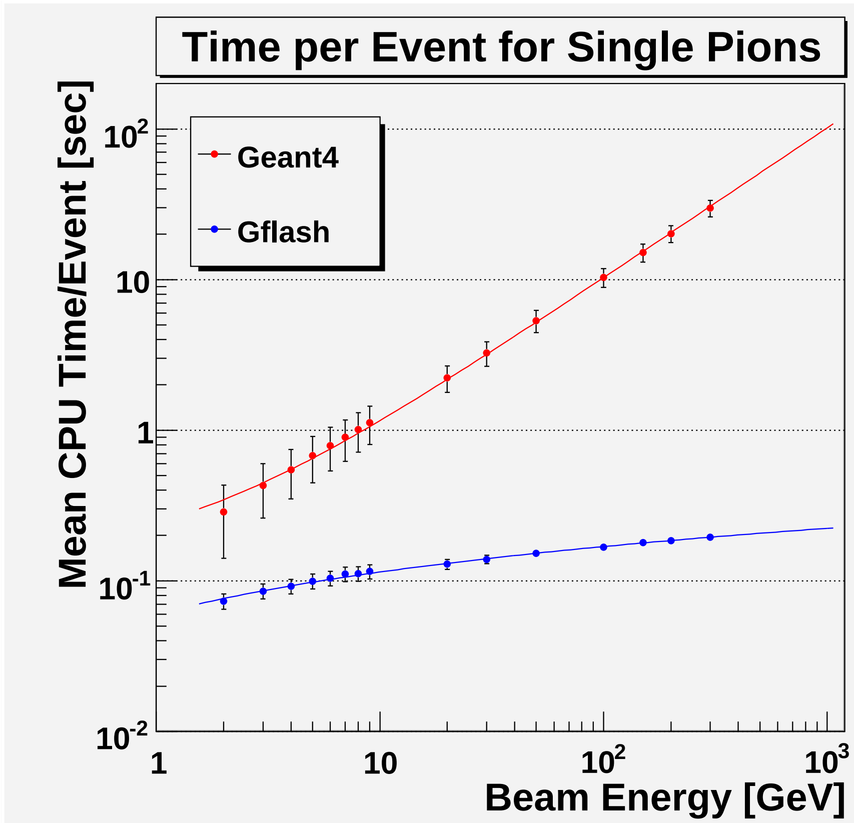
- Energy sharing (correlation) between Ecal and Hcal as well as the pure hadronic (MIP like in EM) response are well described

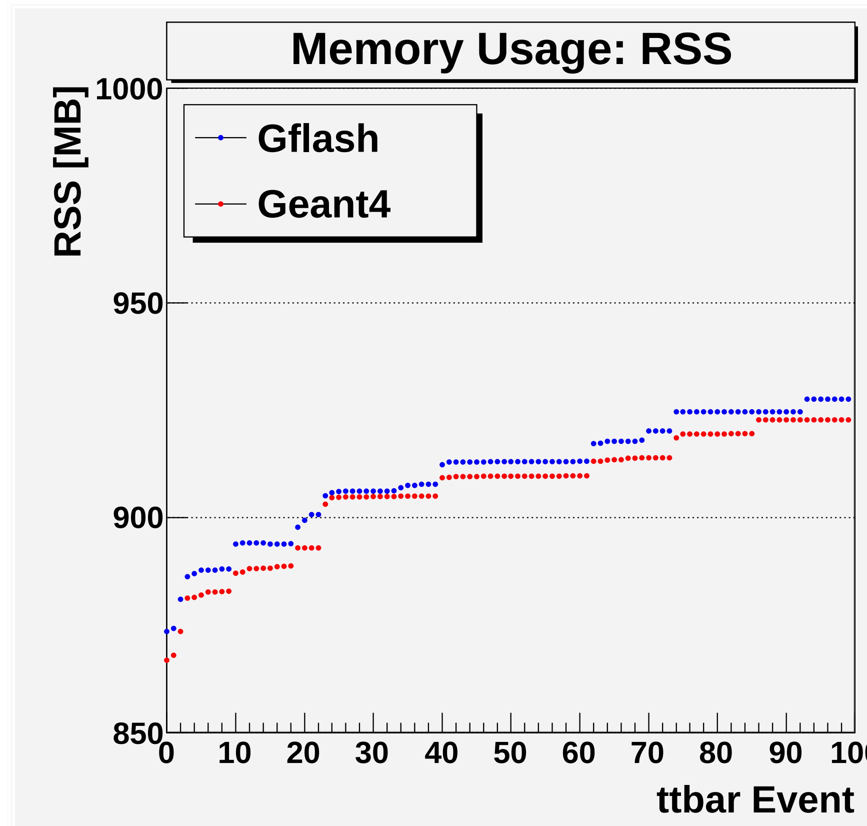
Hadronic Energy Response and Resolution

$\langle E/P \rangle$ as P and its RMS compared to 2006 test beam data (π^- and p)



Performance for Single Pions: CPU and Memory Usage





- CPU: Gflash $\propto \ln E$ vs. Geant4 (QGSP_BERT) $\propto E$
- Memory usage (RSS or VSIZE): marginal increase compared to Geant4
- CPU performance will be further optimized for general physics processes

Summary

- Gflash is successfully implemented for the CMS calorimeter simulation
- Preliminary tuning to 2006 test beam data (e^- and charged hadrons) is done
- Promising computing performance compared to full Geant4 without loss of generality
- Precision tuning to $in\text{-}situ$ collision data from CMS is underway