VERY HIGH RESOLUTION HADRON CALORIMETRY

OR

PHYSICS PRINCIPLES OF HOMOGENOUS CALORIMETERS

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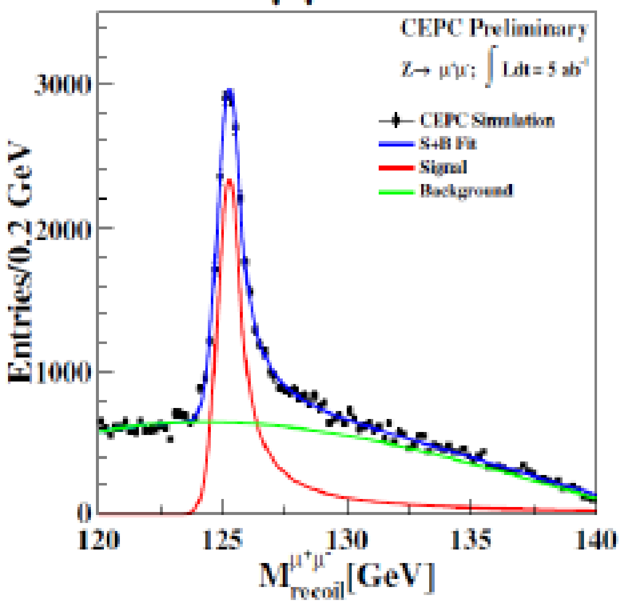
Is Hadron Calorimetry Important ?

- Hadrons are not fundamental, jets are
- Jet (nor a color singlet) definition/clustering is the major source of the uncertainity/errors
- Pile-up and underlying event fluctuations at hadron colliders spoil the energy resolution
- The hadron energy resolution of the in the 'modern' experiments (CMS, ATLAS) in far worse then it was attained 30 years ago (AFS, CDHS,ZEUS,SPACAL)

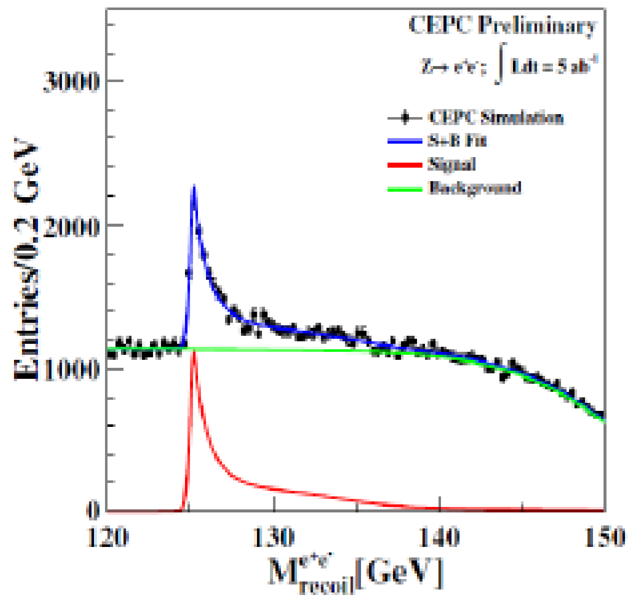
XinChou Lou & CEPC team

CEPC simulation & physics

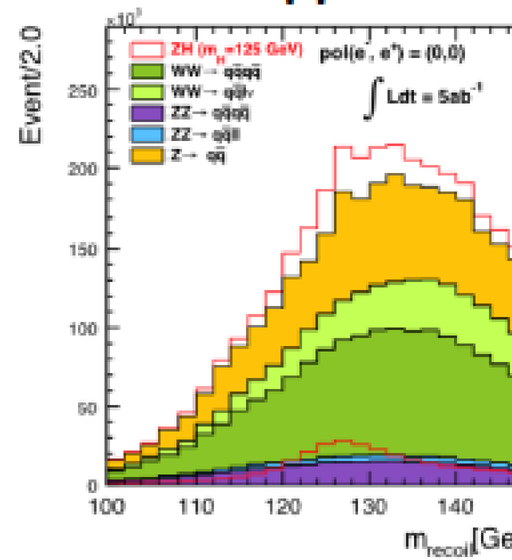
Z→μμ recoil



Z→ee recoil



Z→qq recoil



$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} \qquad = s - 2\sqrt{s}E_{ff} + M_{ff}$$

Assuming unrealistically good performance of PFA

Z decay mode	ΔM_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$	$\Delta g($
ee	14	2.1%	
$\mu\mu$	6.5	0.9%	
$ee+\mu\mu$	5.9	0.8%	0.4%
$q\bar{q}$		0.65%	0.32%
$ee+\mu\mu+q\bar{q}$		0.51%	0.25%

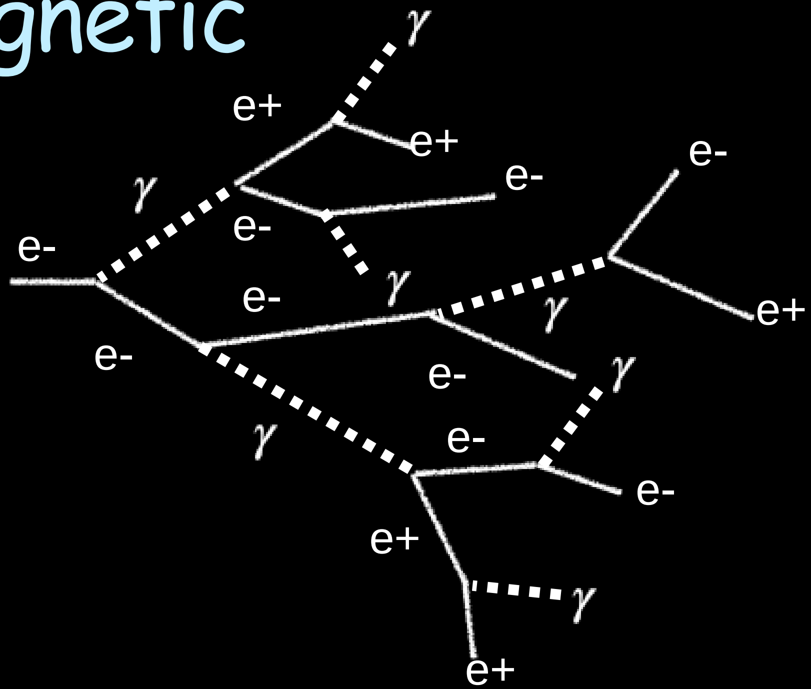
Future e+e- Higgs Factories

- Most of the ZH events have Z decaying in hadronic modes
- Missing mass resolution is of primary importance
- Energy resolution is not enough, need granularity to provide topological information

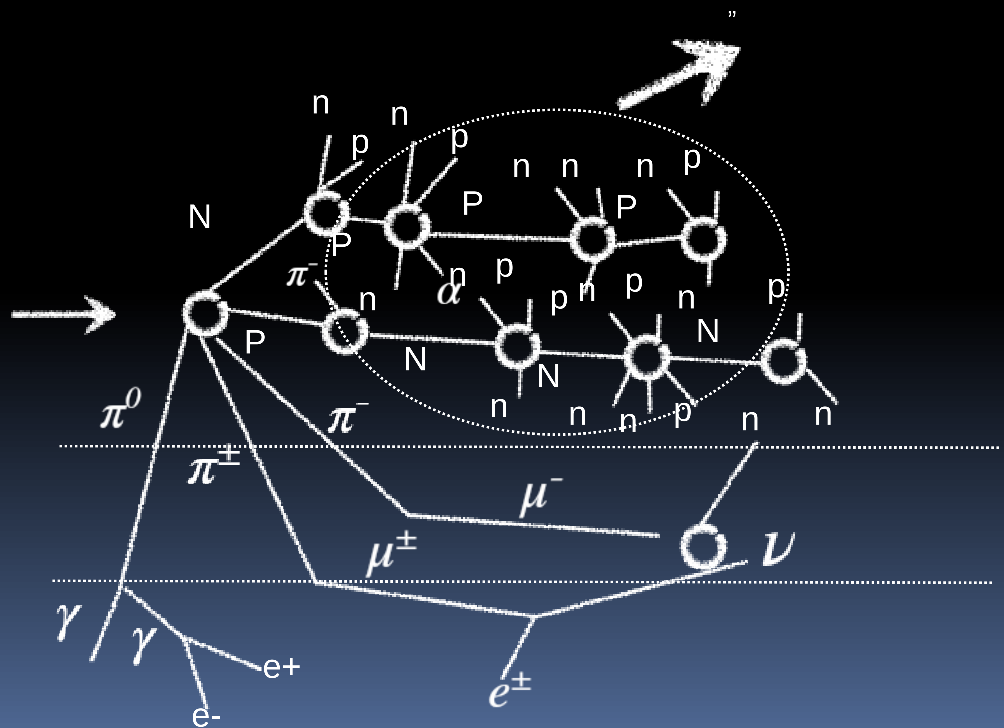
Why are Hadron Calorimeters so poor?

- Take ~2.5 cm iron + scintillator
- $\Delta E/E \sim A/\sqrt{E} + B$
- For electrons: $A \sim 0.23$ $B \sim 0.01$-0.02
- For hadrons: $A \sim 0.55$, $B \sim 0.05 - 0.06$
- The same calorimeter has much larger stochastic term and the constant term
- Need to improve <u>both</u> terms

Hadronic and electromagnetic showers



Incident primary particle



Key:

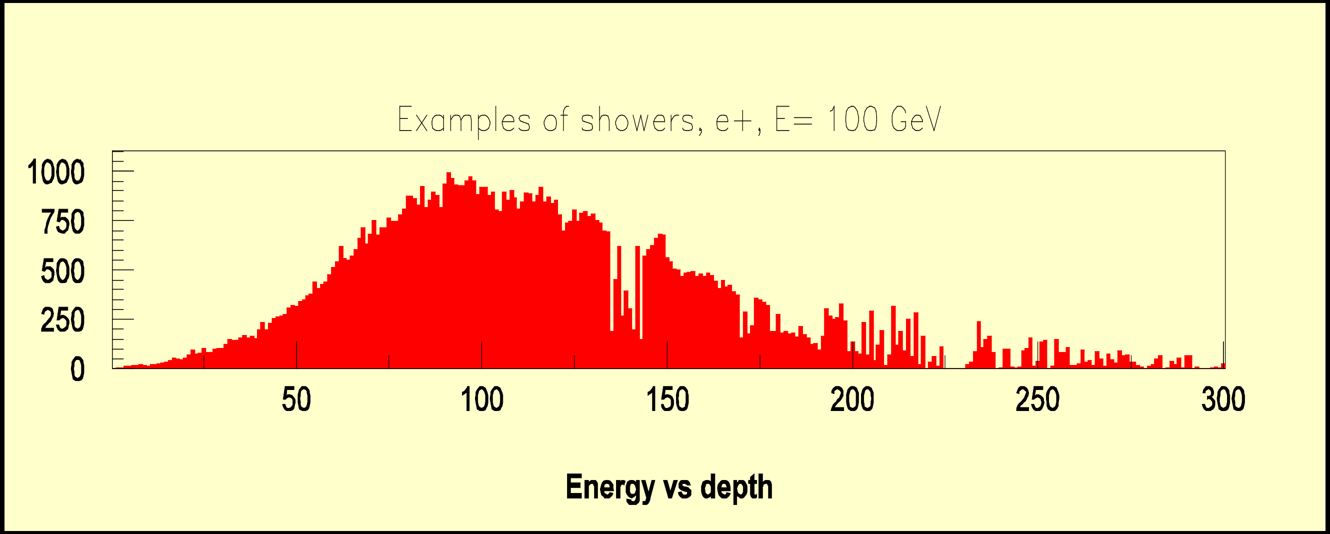
N & P = high energy nucleons

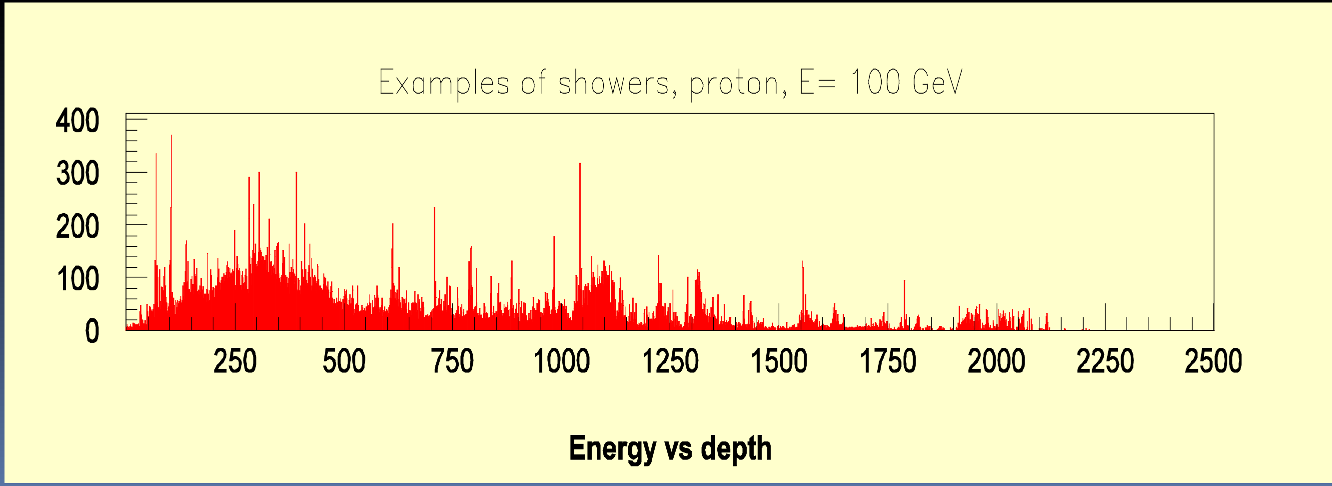
n & p = disintegration-product nucleons

= nuclear disintegration

*Nucleon: proton or neutron

Stochastic Term (Sampling Fluctuations)



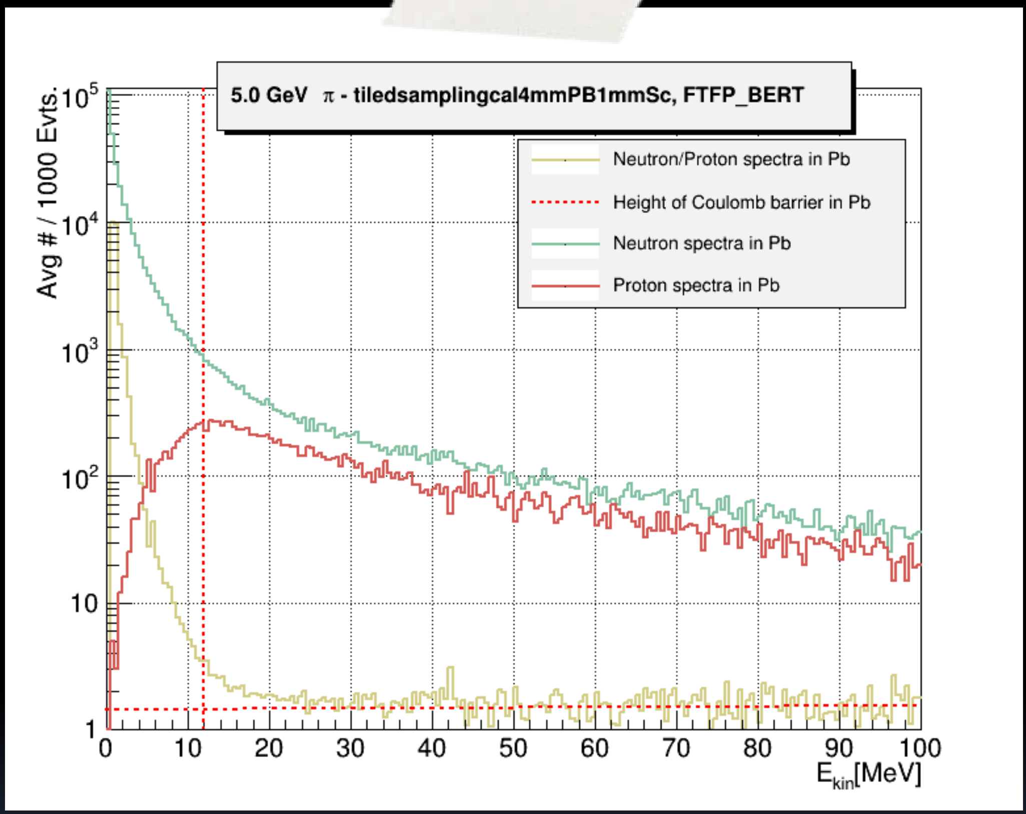


(Relatively) high energy spallation protons carry significant fraction of shower energy. They have short range in the absorber, thus causing additional contribution to sampling fluctuations.

Nucleons produced in hadronic showers

Two step process:

- Intra-nuclear cascade: incoming hadrons makes quasi-free collisions with nucleons inside the struck nucleus: spallation
- Evaporation or de-excitation: most of the particles involved are free nucleons and it goes on until excitation energy is less than binding energy.



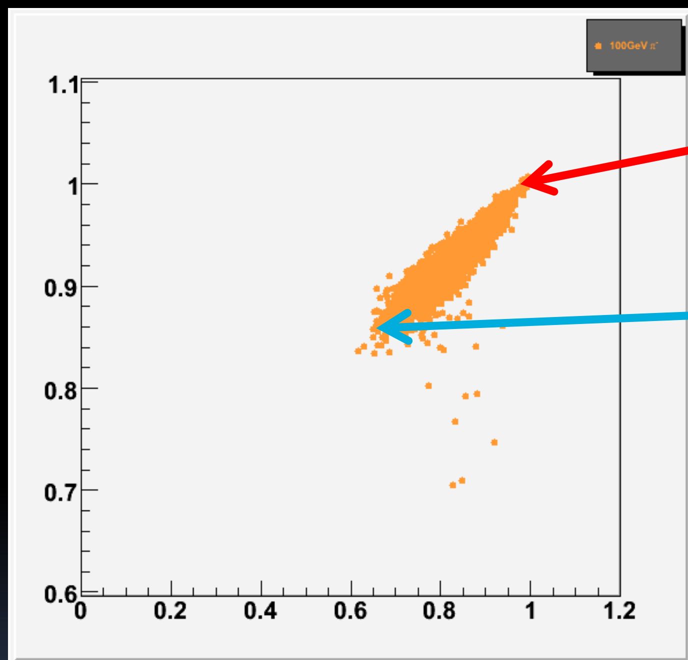
Large and fluctuating number of neutrons cause large and fluctuating deficit of observed energy (used to overcome binding energy)

Two Physics Principles of High Resolution, Hadron Calorimetry

- Total absorption: no sampling fluctuations and other sampling-related contributions. The dominant contribution to resolution: fluctuations of nuclear binding energy losses.
- 'Dual readout' : find an observable (in addition to the total energy) which is correlated with the total number of nucleons (mostly neutrons) released in the shower and us the correlation to make a correction to the observed energy. The resulting energy resolution will be limited by the degree of the correlation.
- An example of a possible second observable: Cherenkov – to Scintillation signal ratio

Mechanics of Dual Readout Correction (Total Absorption Case)

S(cintillation)/B(eam Energy)
= fraction of energy detected



Cherenkov/Scintillation

π^o-rich showers: almost all energy detected

π^o-poor showers: ~85% of the energy detected

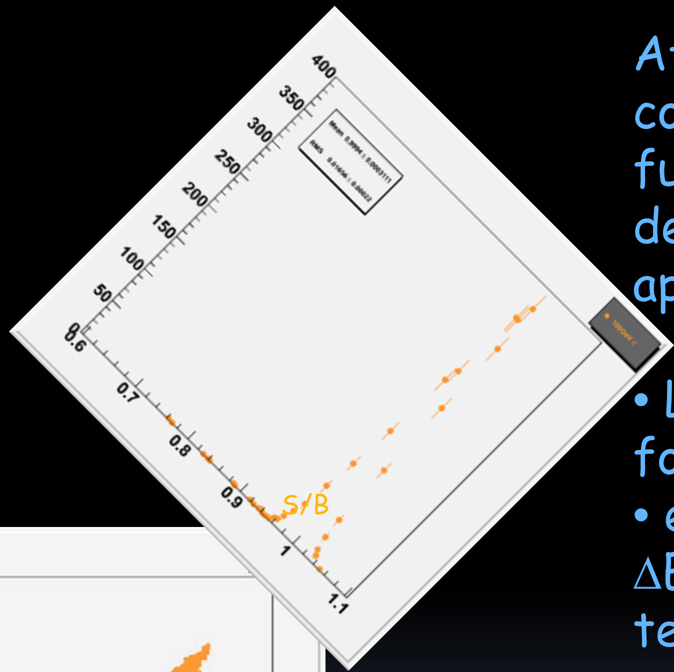
- Use C/S to correct every shower
- The resulting resolution limited by the local width of the scatter plot

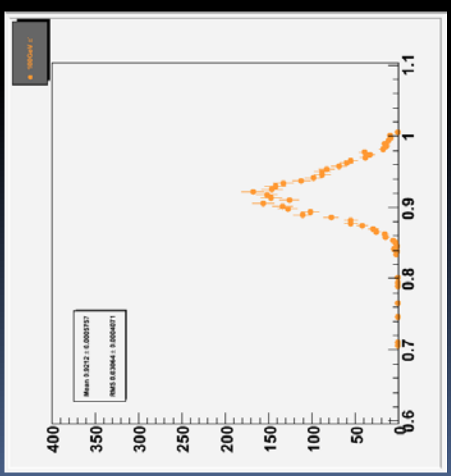
Dual Calorimetry at Work: Single Particle Measurement

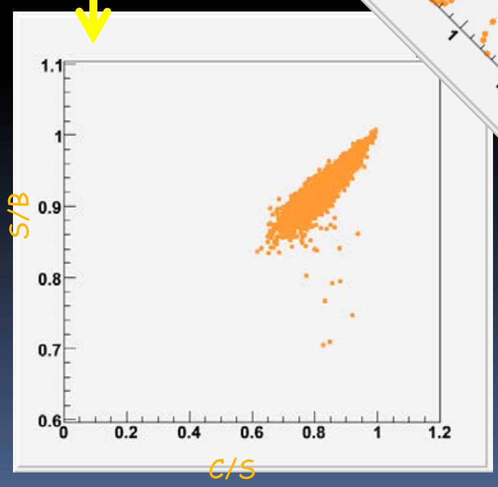
- 100 GeV π-
- Full Geant4 simulation

- Raw (uncorrected) $\Delta E/E \sim 3.3\%$

- but significant non-linearity, E~ 92 GeV



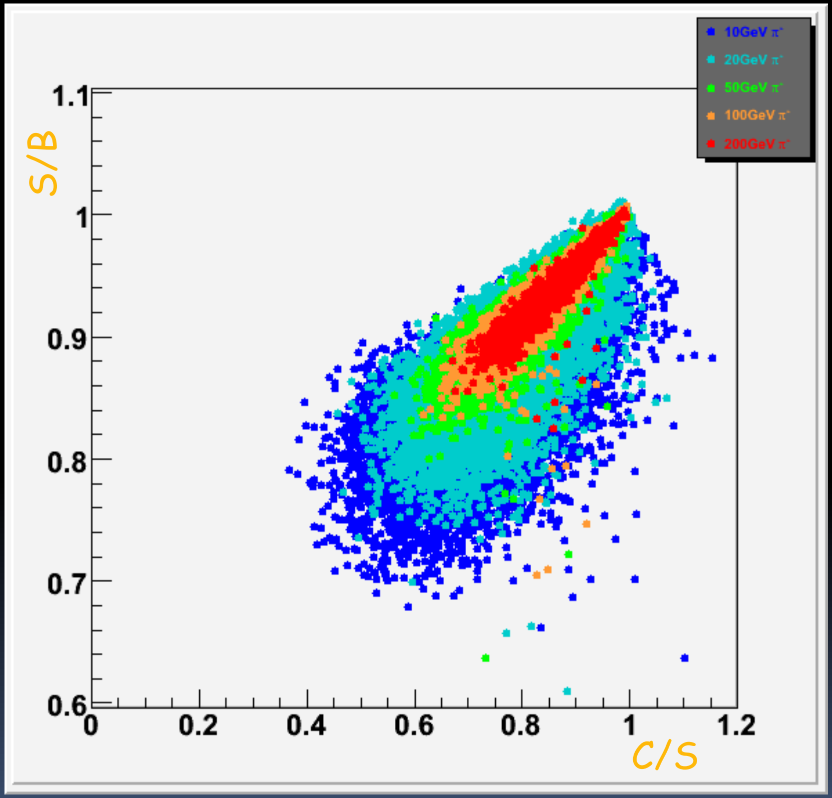




After dual readout correction, correction function (C/S) determined at the appropriate energy:

- Linear response: S/B=1 for all energies
- energy resolution $\Delta E/E \sim \alpha/\sqrt{E}$ (no constant term)
- α~12-15% or $\Delta E/E$=1.2-1.5% at 100 GeV

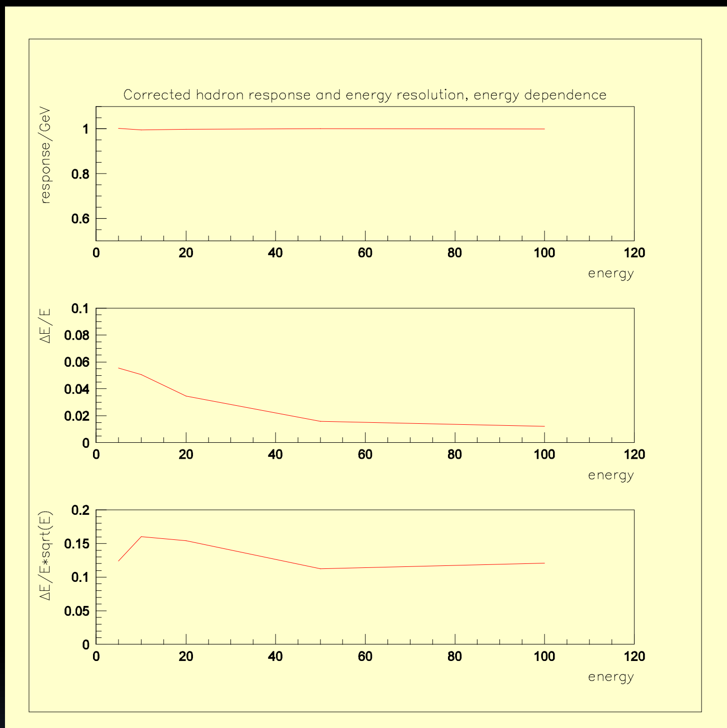
Does the Dual Readout Correction Depend on Energy

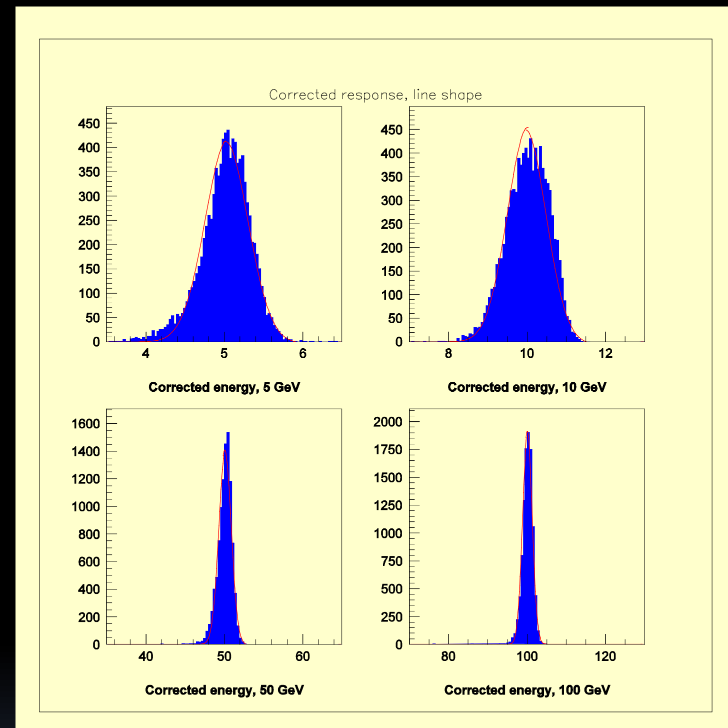


Correlation of the fraction of 'missing energy' and Cherenkov-to-scintillation ratio for showers of different energies: 10 – 200 GeV:

- high energy showers contain more EM energy (range of C/S confined to higher and higher values)
- overall shape quite similar, but significant differences present.
- (Weak) Energy dependence can be implemented iteratively (0^{th} order sufficient)
-

Response and Resolution, Corrected





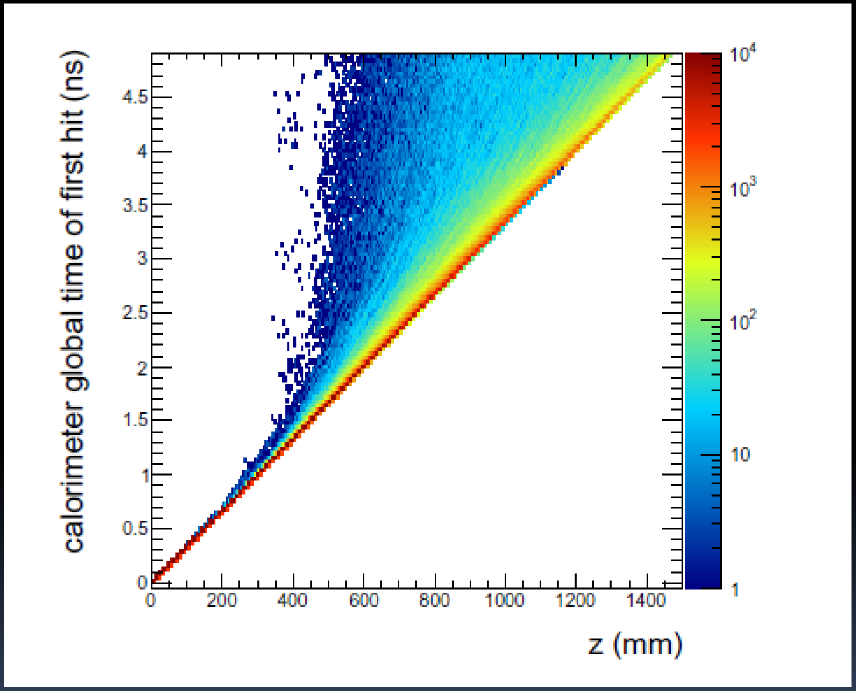
After dual readout correction:

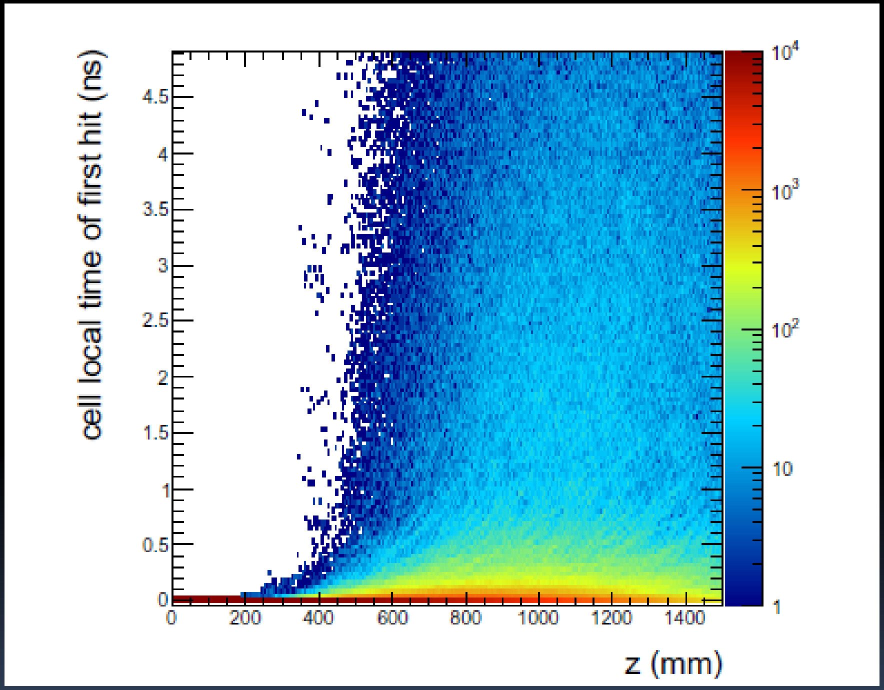
- good linearity of the corrected response
- good energy resolution ~ $0.12/\sqrt{E}$
- no sign of a constant term up to 100 GeV
- Gaussian response function (no long tails)

Homogenopus Hadron Calorimeter with Dual Readout

- Can be constructed thanks to the advances in sensors technology (inorganic scintillators, compact photodetectors)
- Almost arbitrary granularity possible, as required by the physics-driven arguments
- Several 'practical' issues (mostly related to Cherenkov detection): cost, calibration of the segmented calorimeter
- Look for an alternative 'correcting observable'

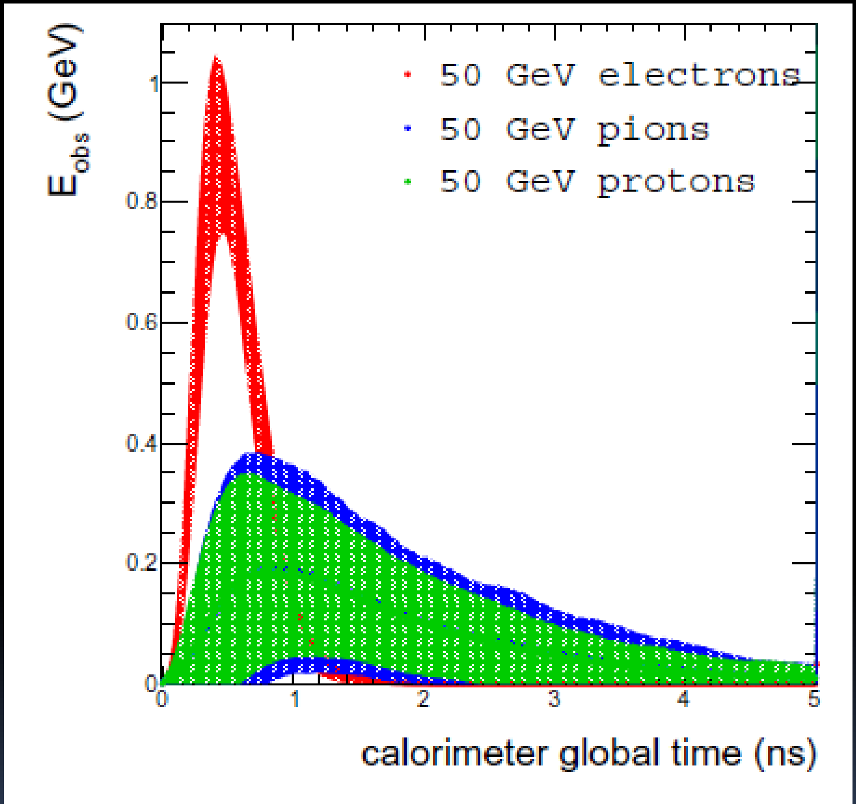
Time Development of Energy Deposition in Hadronic Showers

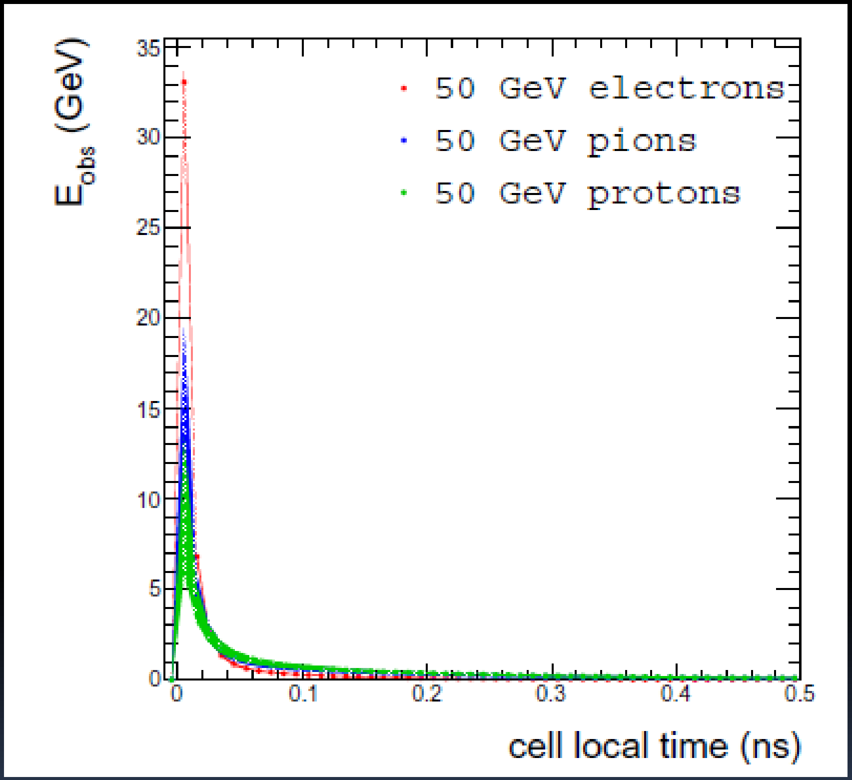




At short times (nsec scale) the timing is dominated by geometry (time of flight) even for hadronic showers. 'Local' time = T – z/c

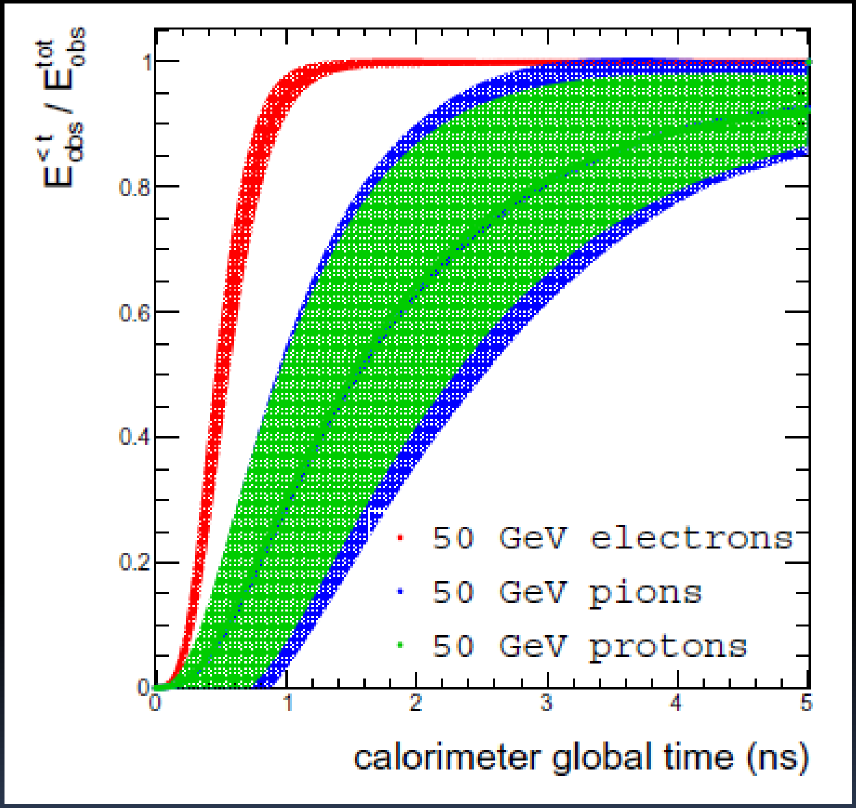
Fast Component of Showers

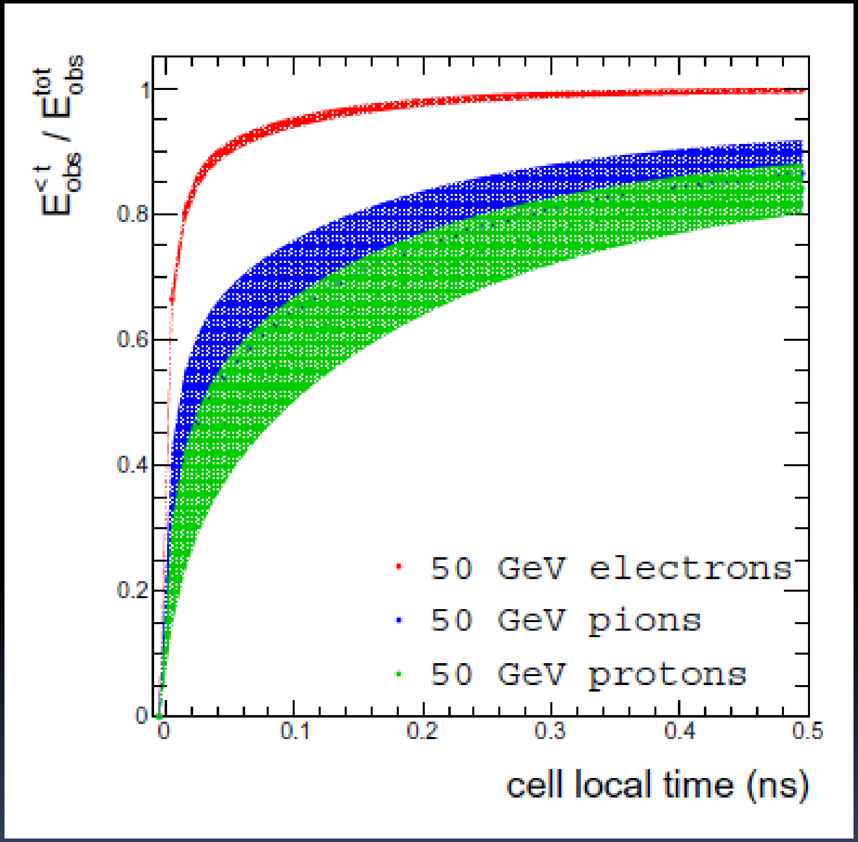




After the time-of-flight correction the core of the shower develops at the time scales of tens of picoseconds. Even for hadronic showers.

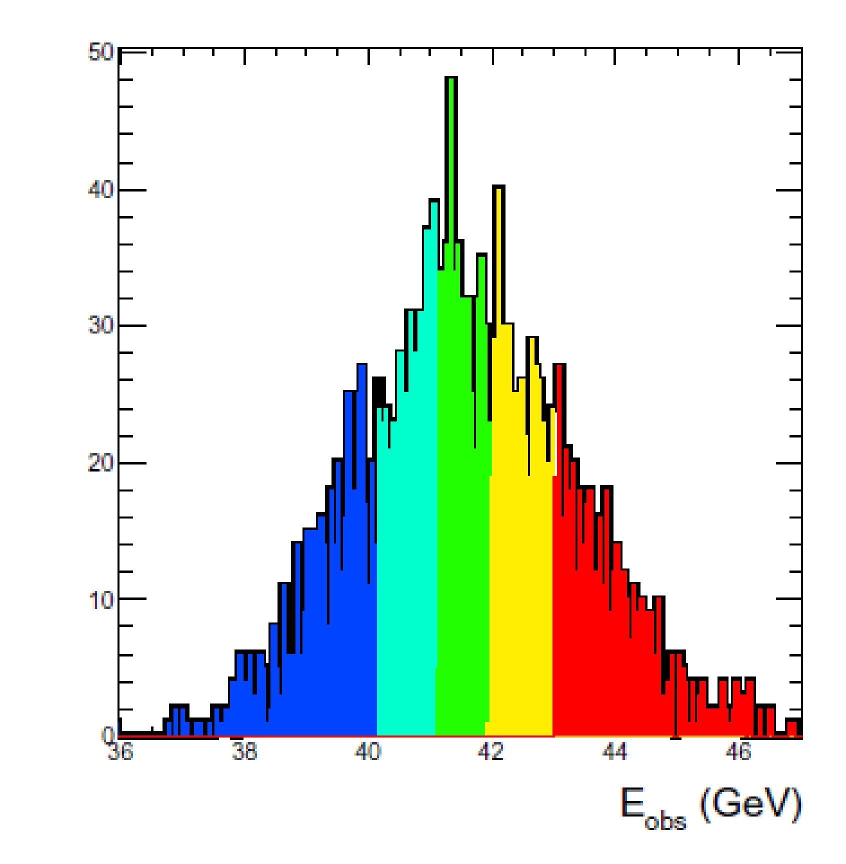
Fast Component of Showers

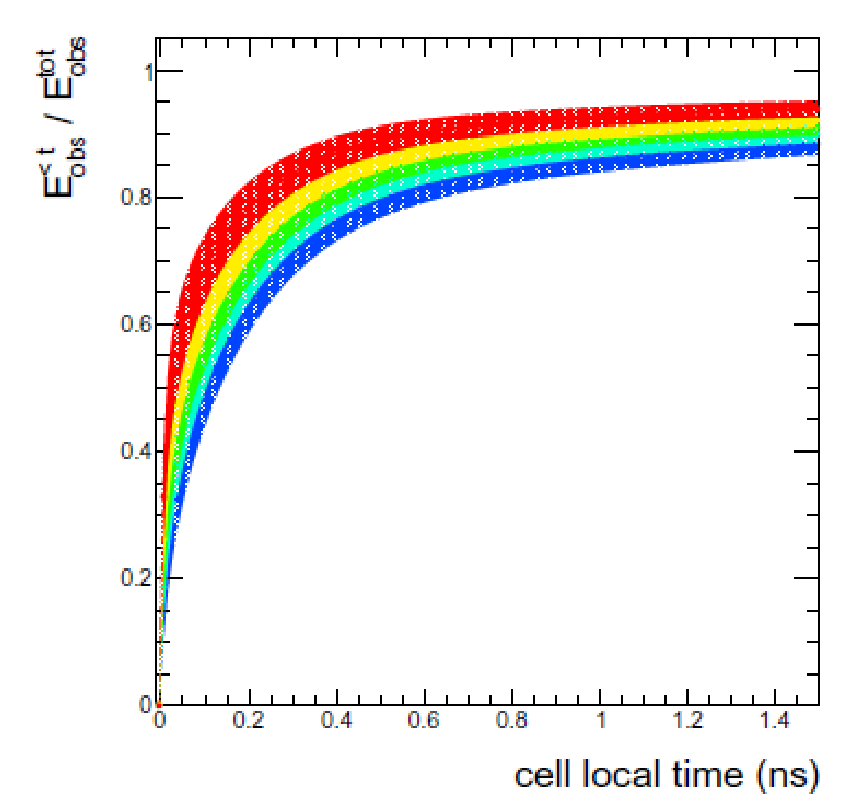




About 80% (on average) of the energy of hadronic showers is deposited within 0.5 nses)

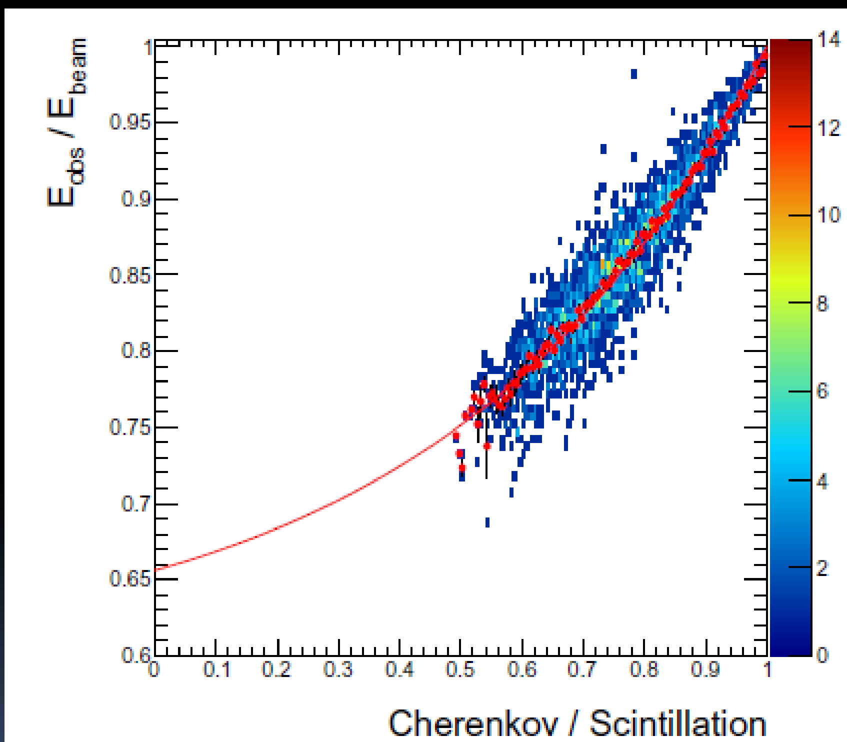
Correlation of the Time Evolution and Total Observed Energy (50 GeV pion)

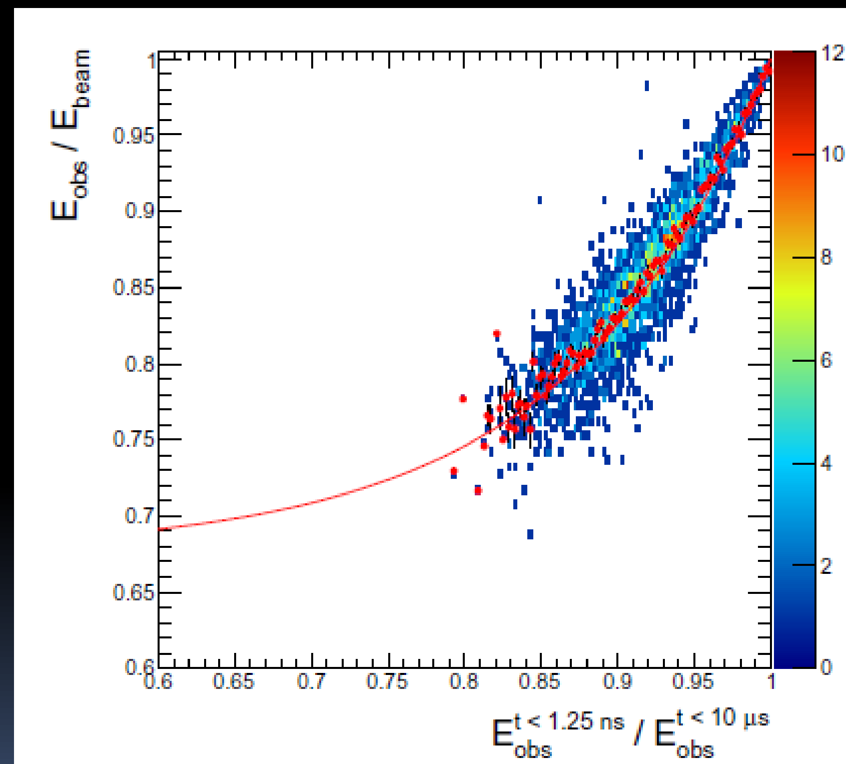




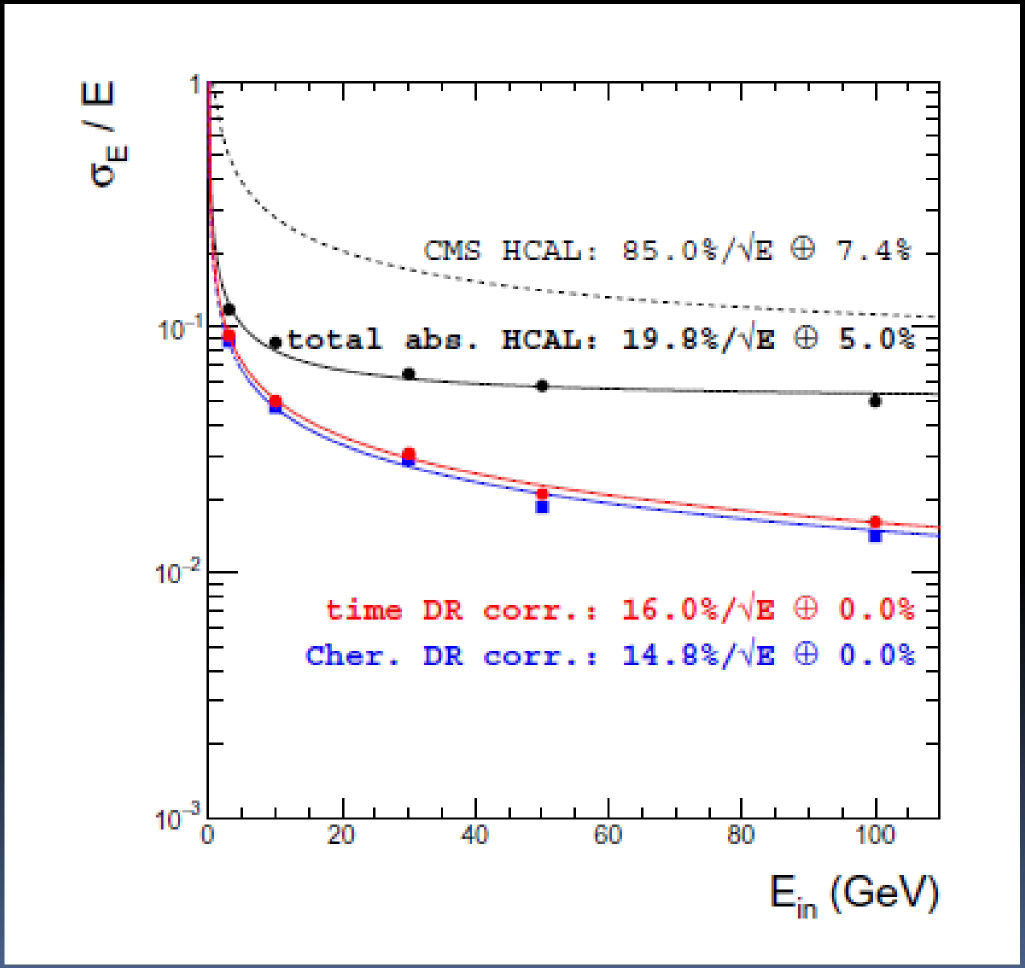
Late energy depositions are related to neutron component: Use dual time gate to make the energy correction.

Dual Gate (Scintillation Only) vs Dual Readout Correction



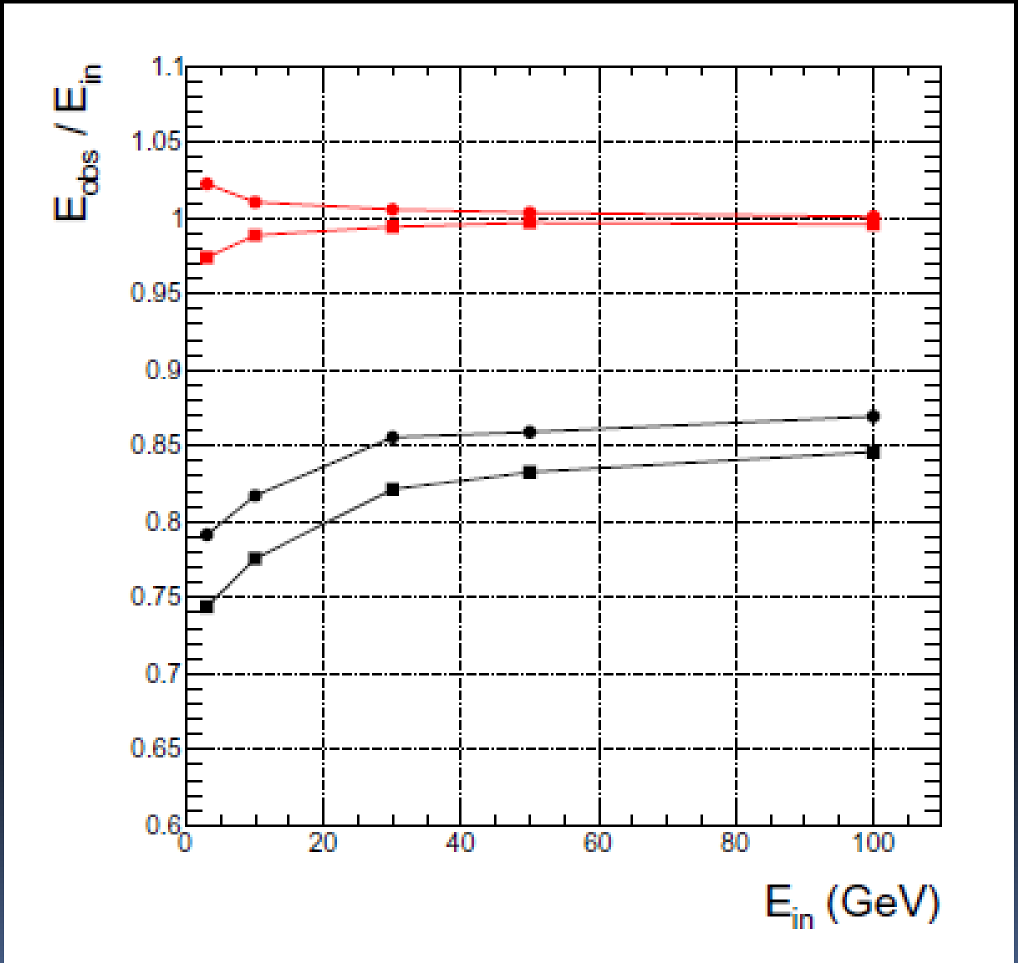


Energy Resolution of Dual Readout and Dual Gate Calorimeters



Energy resolution for single hadrons is important, but linearity and equality of resposnse to different particles is critical for jets

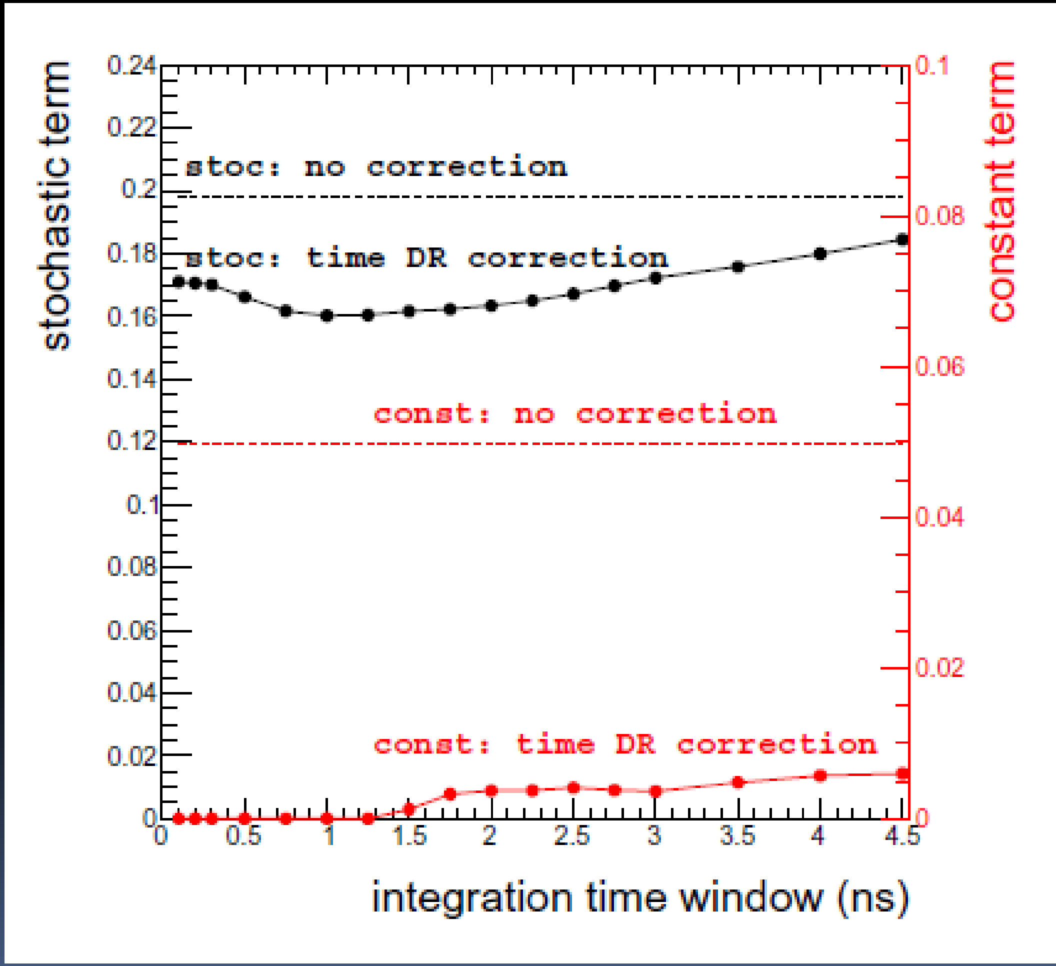
Linearity and Response to Protons and Pions of Dual Gate Calorimeter



Circles: pions
Squares: protons
Black: before correction
Red: After correction

Response linear within ~2% in the range 1 – 100 GeV

Gate Optimization

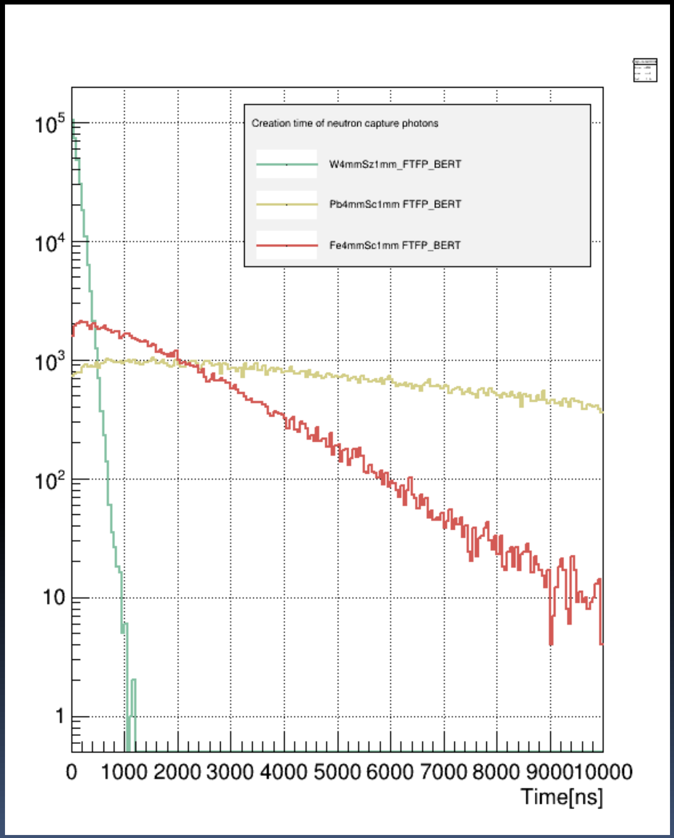


- The resolution is best for the 'short' time gate of the order of 1 ns
- The stochastic term depends very weakly on the gate length
- The constant term is below ~1% for gates shorter than 5 nsec

Conclusion

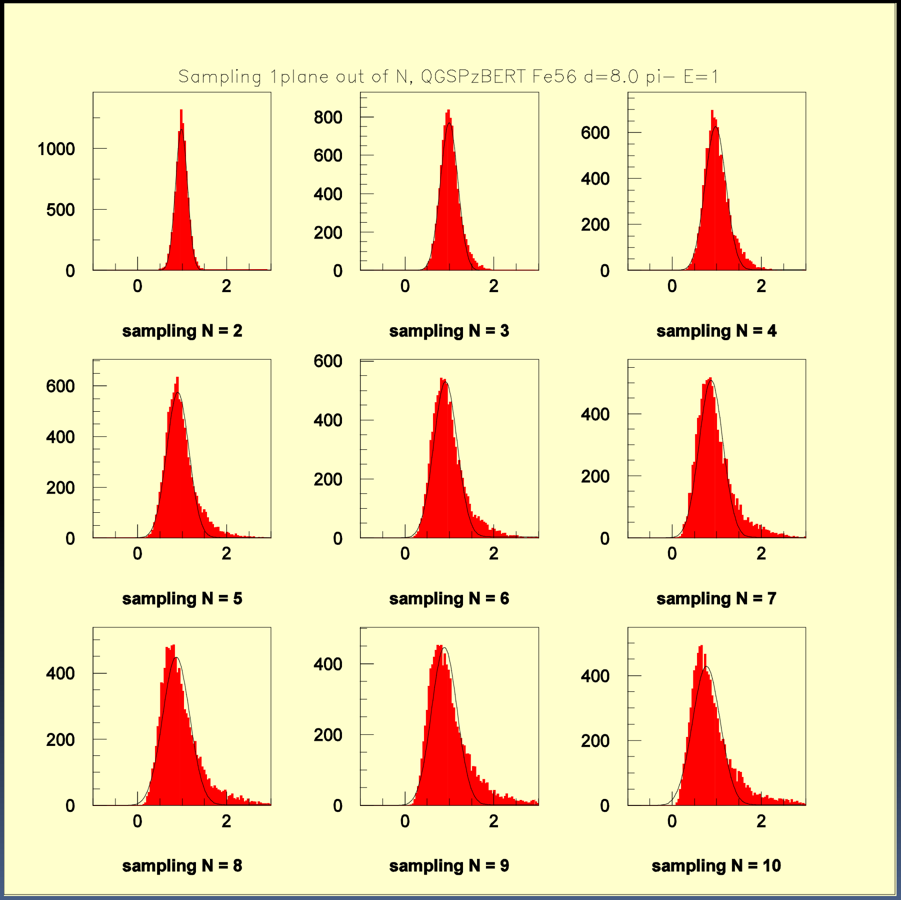
- Use of the dual integration time provides an attractive alternative to dual readout calorimetry, fast timing offering another bonus
- Excellent hadron calorimeter with very high energy resolution, linear response and uniform response to all particles can be constructed bu using dual integration time, with the short integration gate of the order of 5 nsec.
- Fast, dense, inorganic scintillators are necessary to exploit the full advantage
- The actual achievable energy resolution will be limited by various 'practical' effects: leakage fluctuations, calibration..

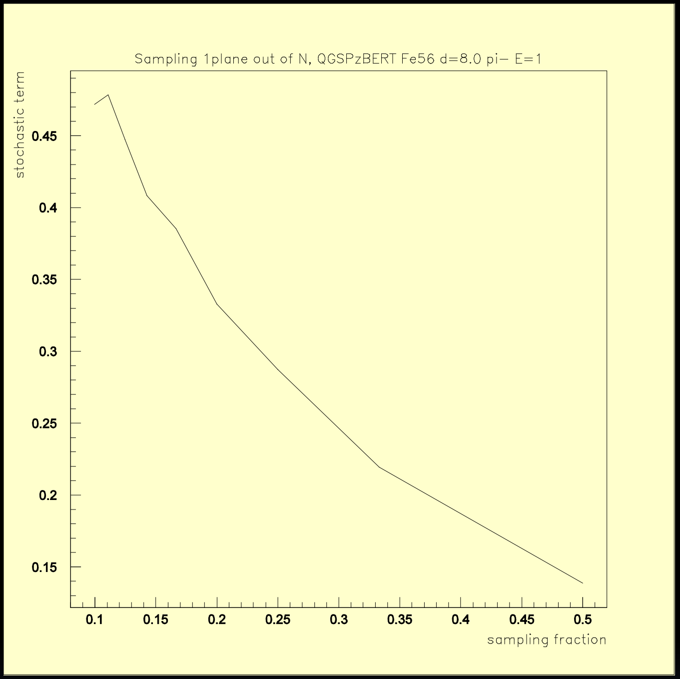
Neutron Capture (as an example of a possible physics-driven detector optimization)



- A number of neutrons produced and captured depends dramatically on the chemical compistion
- Thermalization time and capture time varies by orders of magnitude
- Possibilities of fine tuning of the chemical compositin of the calorimeter
- Need for systematic studies of a large classes of

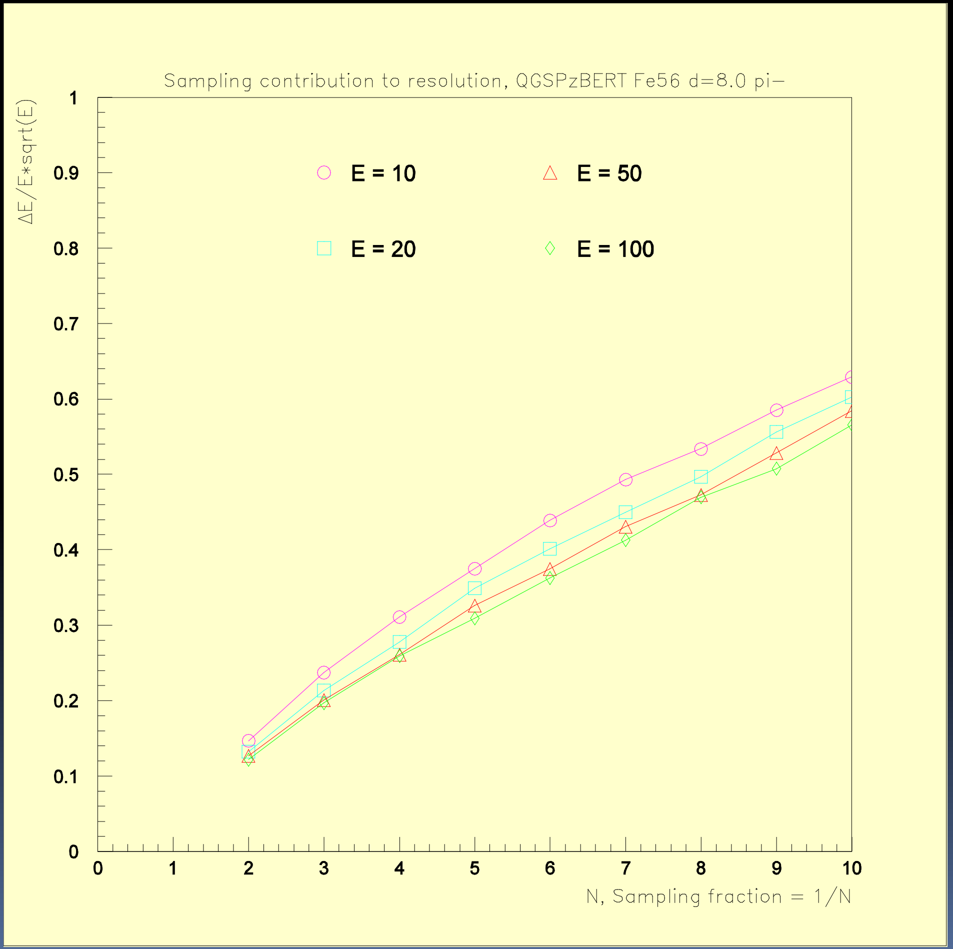
1 GeV pions, Different Sampling





- Sampling fluctuations are non-gaussian, even with fine sampling
- Stochastic term increases as the sampling worsens

How do Sampling Fluctuations Scale with the Sampling Fraction?



- $\Delta E/E$ * sqrt(E) vs N = 1/SF
- sampling fluctuations are inversely proportional to the sampling fraction
- Even a very high sampling fraction, like 25%, introduces a very significant contribution to the resolution, of the order or (0.25-0.3)/sqrt(E)