Time reconstruction and performance of Crystal ECAL

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Outline

Describing the paper:

- Motivations
- Time extraction with ECAL
- Time measurement resolution studies using TB
- Synchronization of the detector
- Cross-check of resolution and linearity using cosmics
- Conclusions

Details on issues raised during SEB reading

Motivations for This Paper

ECAL timing relevant for bkg rejection
- cosmics, beam halo, electronic noise

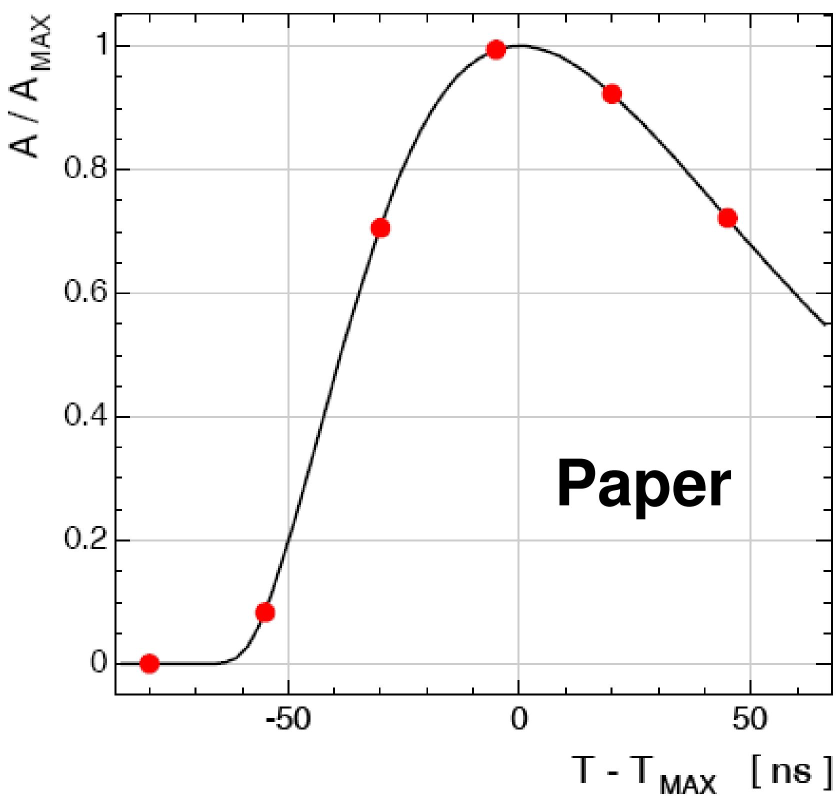
ECAL timing to be used for new physics searches
- heavy stable charged particle with small beta
- photon from neutralinos with long lifetimes

Nice opportunity to have single paper with
- Description of timing extraction
- Evaluation of performance of the method
- Description of calibration
- First synchronization in view of LHC collisions and systematics evaluation
- Use of cosmics to evaluate goodness of synchronization and cross-check resolution and linearity

Coherent picture and combination of different datasets (TB, beam splashes, cosmic ray muons) to show robustness of the detector

ECAL pulse shape and timing

Traditional pulse representation $A(T)$
Time measurement: find T_{MAX} using 10 amplitude samples



experimental measurement of pulse shape using asynchronous events (testbeam) or synchronous events (LHC) + delay scan

amplitude of each sample defined by

- pulse shape
- A_{MAX}
- T_{MAX} phase

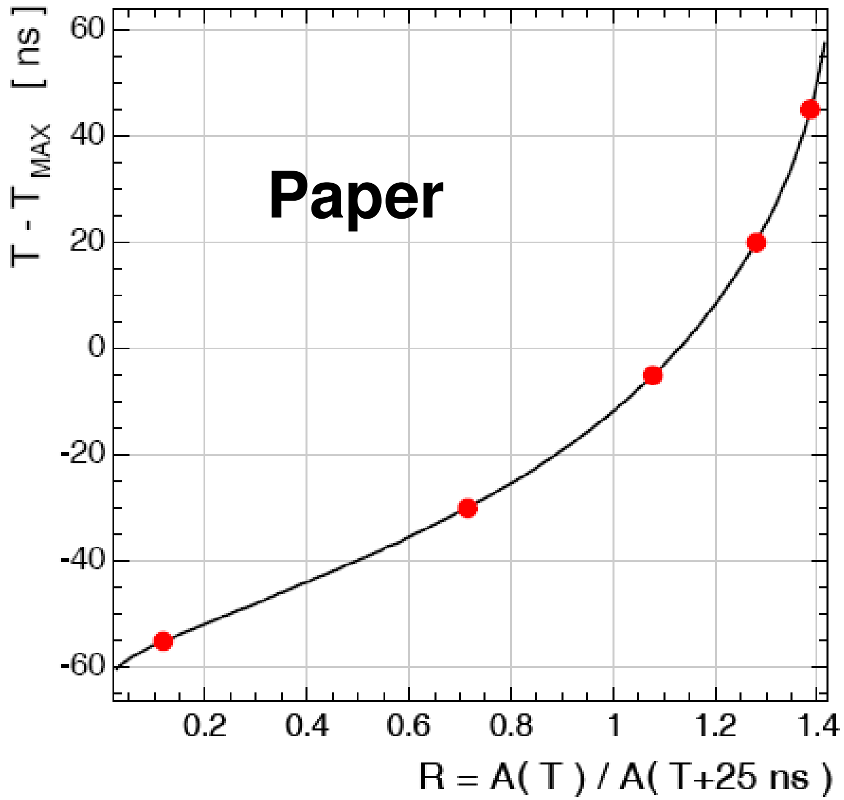
Do the analytical fit for A_{MAX} and T_{MAX} (impractical, too slow, need analytical approximation of the pulse shape)

the relative position of T_{MAX} between time samples referred to as a "T_{MAX} phase;"

Ratios to Describe Pulse Shape

new variable $R(T) = A(T)/A(T+25ns)$
same pulse in $T - T_{MAX}$ vs R
consecutive samples A_i and A_{i+1} give

$$R_i = \frac{A_i}{A_{i+1}}$$



experimental measurement of pulse shape using asynchronous events (testbeam) or synchronous events (LHC) + delay scan

pulse shape $T(R)$ can be parameterized as polynomial of 7th order. Systematics due to this parameterization $\sim 10ps$

each R_i gives quick and accurate time measurement

$$T_{MAX} = T_i - T(R_i)$$

Combination of Ratios

There are 4-5 ratios R_i per pulse, each R_i gives a timing measurement $T_{MAX,i}$ with its uncertainty $\sigma_{T,i}$.

We combine them using weighted average for uncorrelated measurements

$$T_{MAX} = \frac{\sum \frac{T_{MAX,i}}{\sigma^2_{T,i}}}{\sum \frac{1}{\sigma^2_{T,i}}}$$

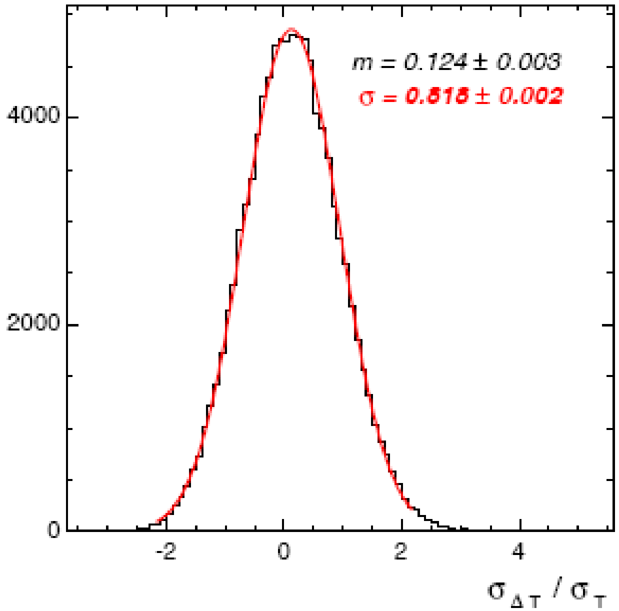
$$\frac{1}{\sigma^2_T} = \frac{1}{\sigma^2_{T,i}}$$

anti-correlations between R_i cancell each other resulting in negilgible bias and slight overestimation of errors, $< 20\%$

calculation of errors σ_T on T_{MAX} after averaging all available measurements of $T_{MAX,i}$. This plot shows distribution of

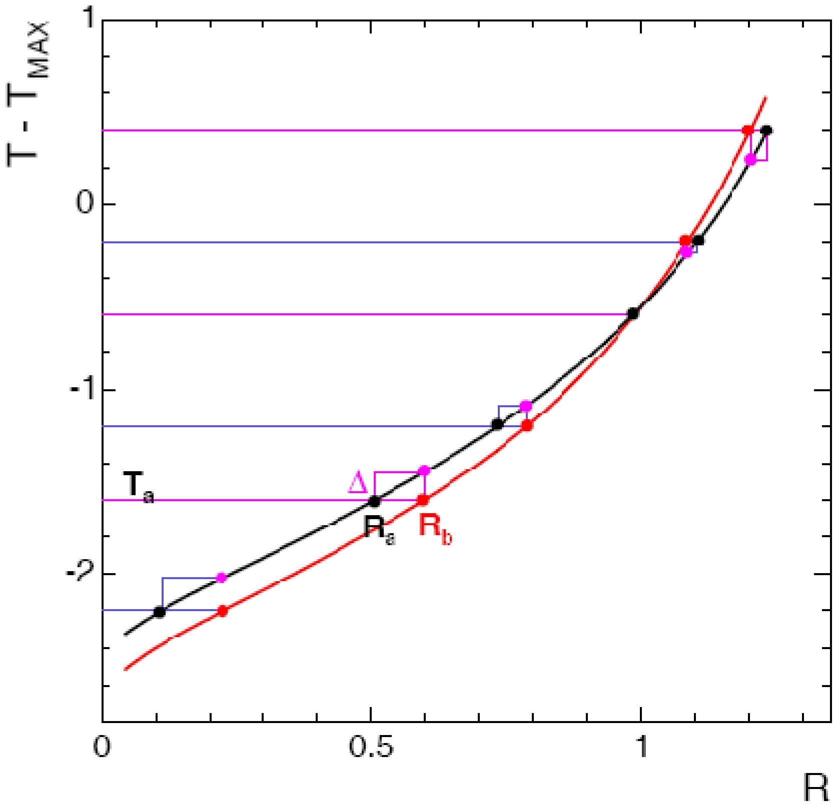
$$\frac{T_{MEAS} - T_{TRUE}}{\sigma_T}$$

from Toy Monte Carlo and a Gaussian fit.



Syst. Induced by Pulse Shape Modeling

systematics arising from applying universal calibration to all ECAL channels



pulse shapes vary from channel to channel

this systematics manifests as a bias that vary with magnitude of T_{MAX} phase with respect to LHC clock

effect of this systematics dissapears when measured time is small

T Measurement Reso: Parameterization

$$\sigma^2(t) = \left(\frac{N\sigma_n}{A}\right)^2 + \left(\frac{S}{\sqrt{A}}\right)^2 + C^2$$

Noise term:
induced by high and low frequency noise

Stochastic term:
induced by photo-statistics and finite time scint. emission

Constant term:
induced by effects vs Tmax phase, entrance pos., and any syst. in synchronization

Does this parameterization work and how big are the different terms?

Checked on toy MC studies

$$\sigma_T^2 = \frac{(2.4 - 4.2)\ ns^2 \cdot MeV}{E} + \frac{33\ ns^2}{(E/\sigma_n)^2} + c^2$$

(details on backup slides)

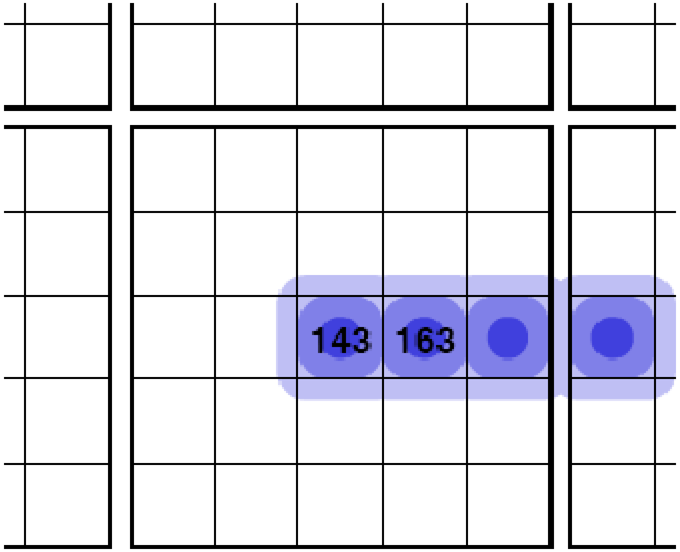
TB Electrons to Extract Resolution

- Use of 230GeV TB electrons on EE
- Compared time between crystals of the same electron cluster
  - ⇒ Synchronous by definition (modulo shower propagation)
- Use time difference to extract resolution
- Approach is much less sensitive to constant term
- Effects due to synchronization or differences in pulse shape affect only mean

$$\sigma^2(t_1 - t_2) = \left(\frac{N\sigma_n}{A_{eff}}\right)^2 + 2\bar{C}^2$$

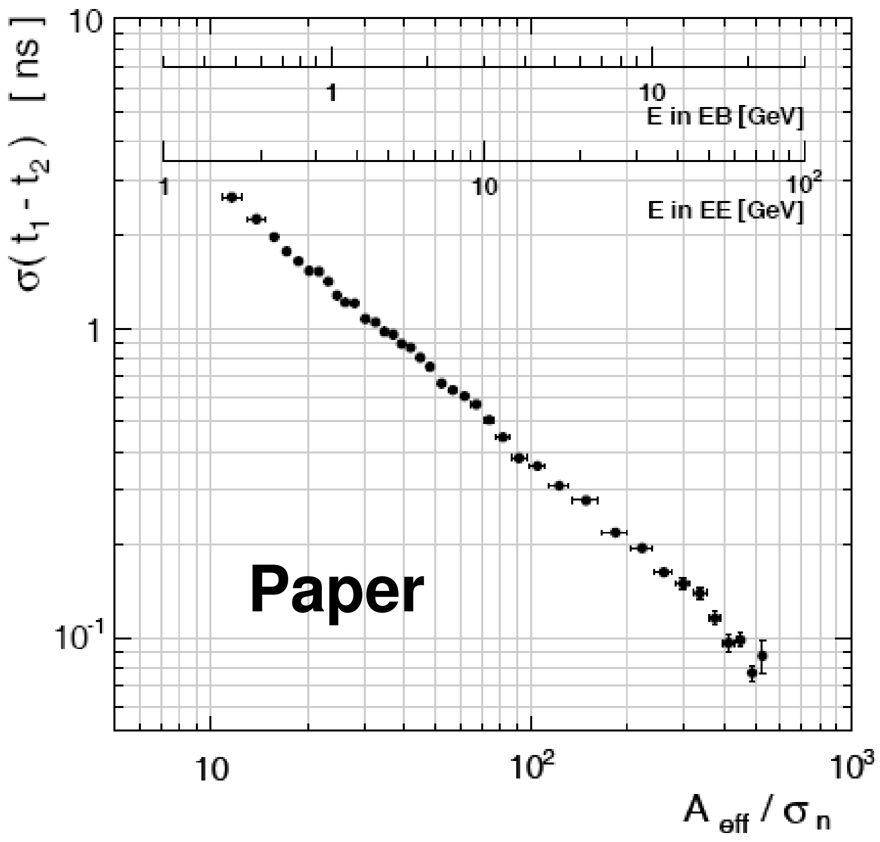
$$A_{eff} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$$

Residual contrib. to constant term (method)



Results

uniform calibration to several channels, 230 GeV electrons in TB07, apply TDC cut to select the same T_{MAX} phase (LHC-like conditions)



direct measurements of sub-100ps resolution in ECAL.

This performance will be reached at 15-20 GeV in EB and 60 GeV in EE

no indications for constant term

we expect to achieve this performance with uniform calibration for all ECAL channels!

$N = (35 \pm 1)$ ns
$a < 7.9\ ns \cdot MeV^{1/2}$ (90% C.L.)
good agreement with MC
$a = (2.4 - 4.2)\ ns \cdot MeV^{1/2}$

(see backup for details)

Synchronization of ECAL

- T_{MAX} phase for a given channel does not change with time
  - Collisions synchronized with clock
  - Time of flight from IP fixed
- Possible to use corrections to synchronize all channels
- Synchronization crucial to reduce biases of amplitude and timing reco

- Two synchronizations:
  - Hardware: step=1.04ns
  - Software: limited by time measurement resolution (extraction method) and systematics (synchronization technique)

- What's needed: physics events with known T phase vs eta

How to Synch with LHC collisions

- Excellent candidates given by minimum bias events
  - Synchronous
  - Illuminating whole ECAL with large stat and energy

- No systematics induced by large T_{MAX} phase (i.e. they are in synch. with LHC clock by definition)

- Estimate:
  - About 1000hits/channel/day
  - About 500MeV/channel in average

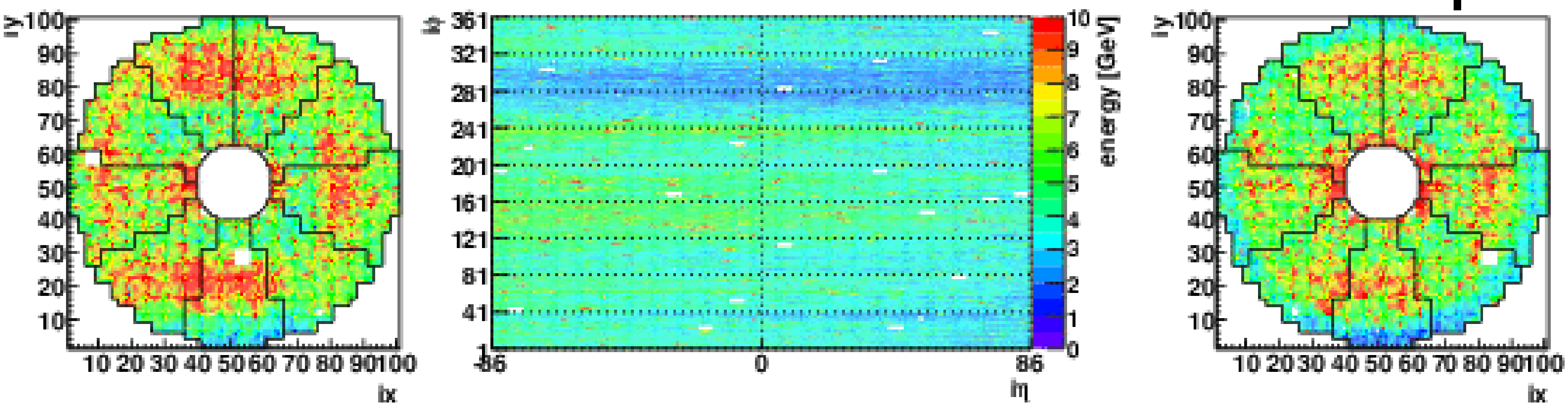
  $\Rightarrow$ 100ps precision in one day of running

First Synch. Using Beam Splash Events

- Nice sample to be used to synchronize already available:
  - for a single event all horizontal muons are in synch
  - Correction for TOF vs eta needed
  - All crystals illuminated
  - Many muons cross each crystal: <E>~few GeV's

Figure illustrates energy map for a single beam splash event

Paper



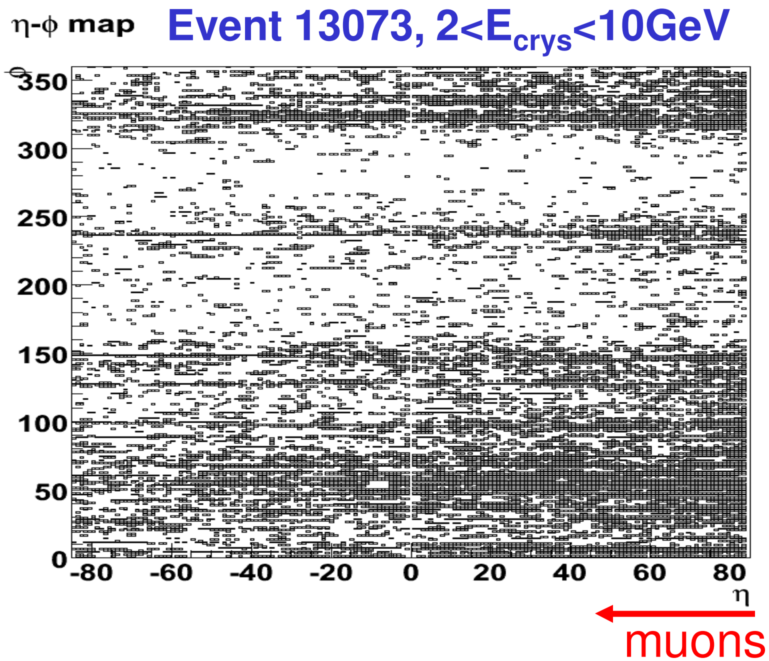
Beam Splash TOF

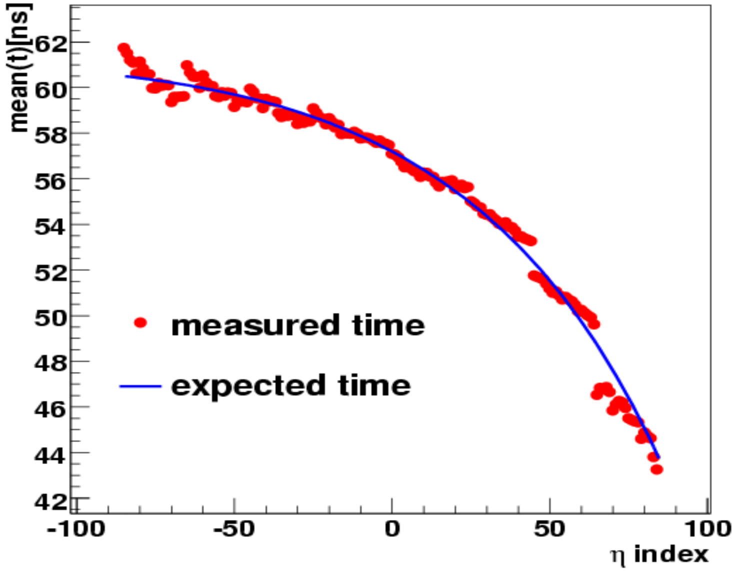
- Formula for expected time (correction for the barrel)

$$t_{\exp} = const + \frac{z + \sqrt{z^2 + R^2}}{c}$$

where:

- z is the z coordinate of the front face of the crystal
- R is the distance of ECAL barrel from beam axis



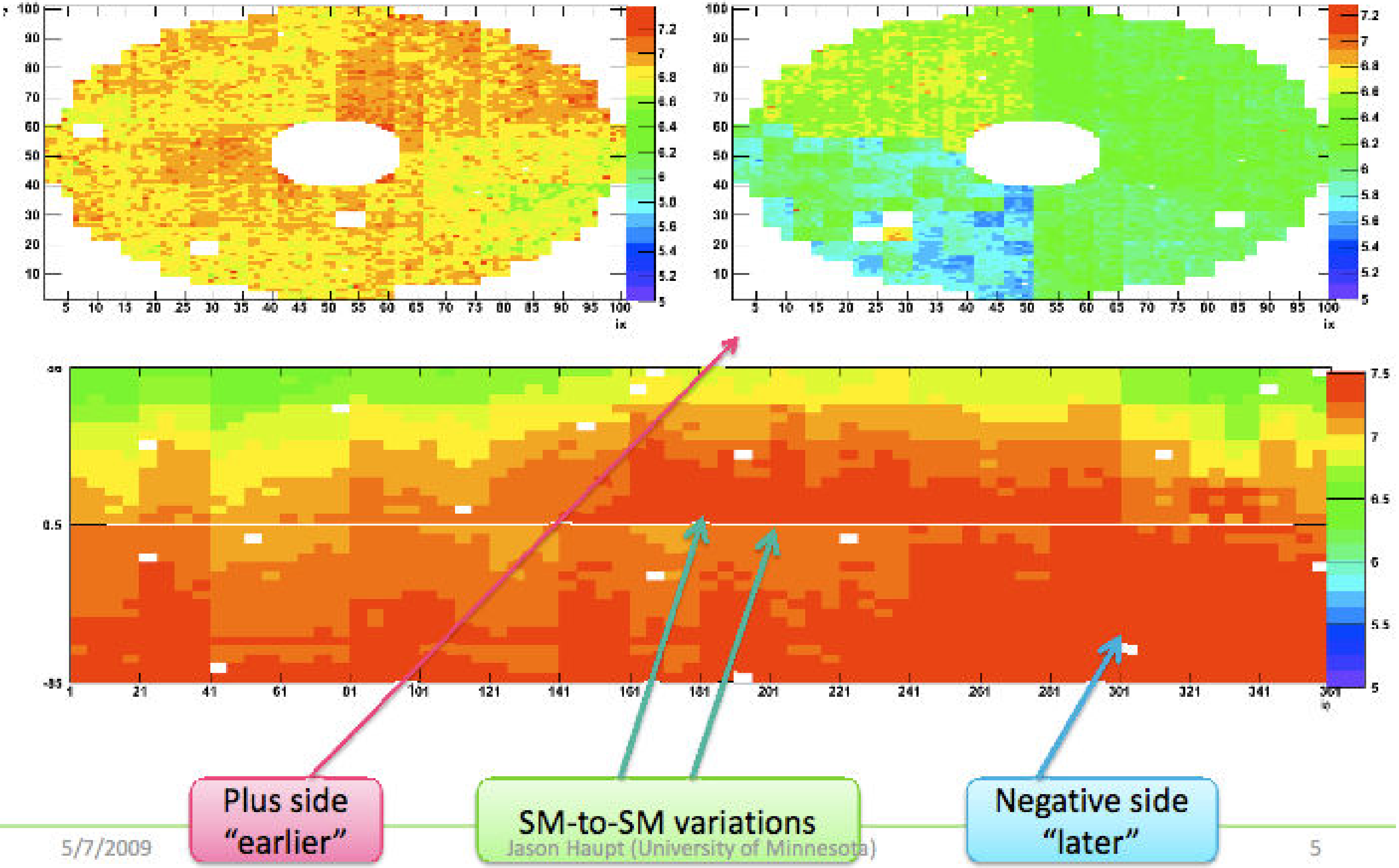


Calibration Procedure

For each splash event:

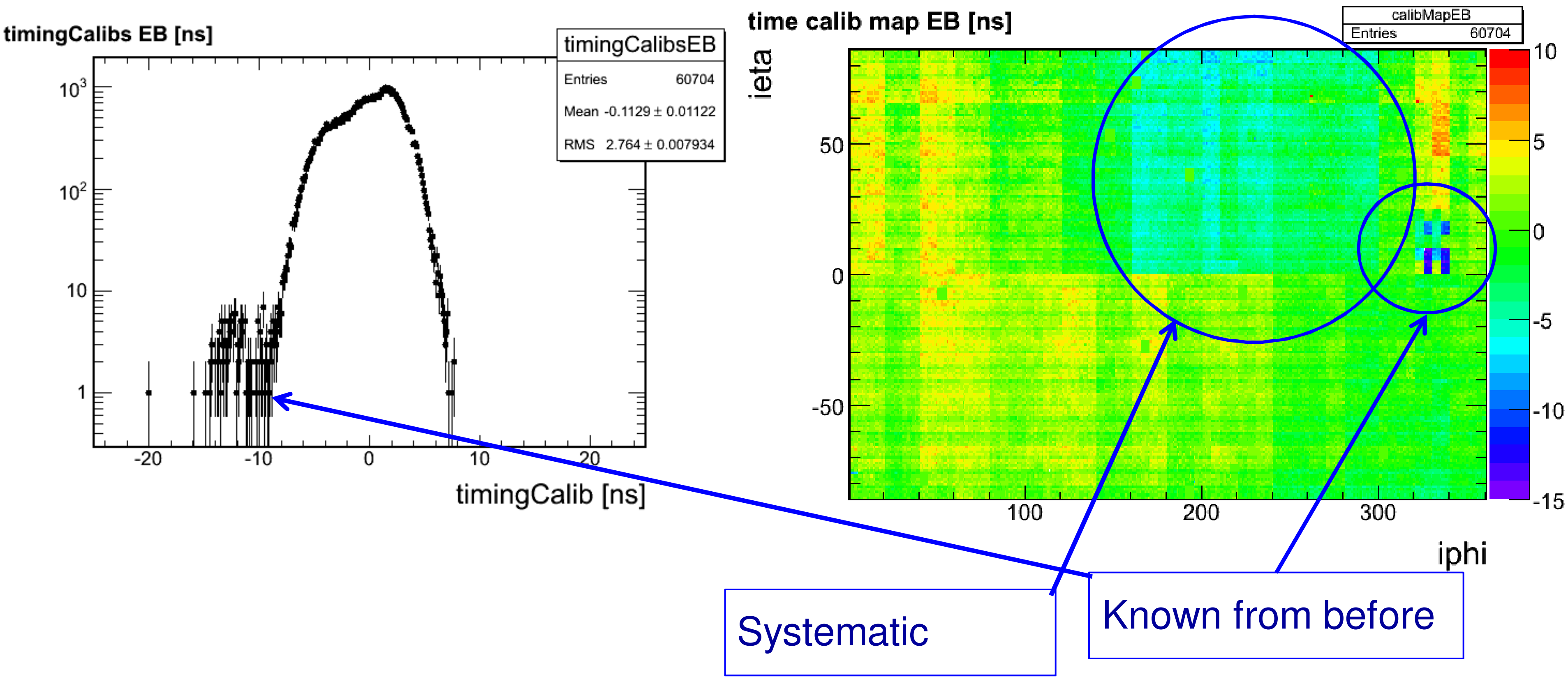
- Correct for trigger jitter (typically few hundred ps)
- Apply time-of-flight and ECAL readout corrections to each crystal (z-corrections, previous slide)
- Apply amplitude > 25 ADC and chi2 cuts
- Generate timing distribution for each crystal
- Obtain mean and uncertainty on mean (weighted average)
- Uncertainty on final mean is also compared with expectations (given N_{events} and $\langle E \rangle$)

Time Map (w/o z-corrections)



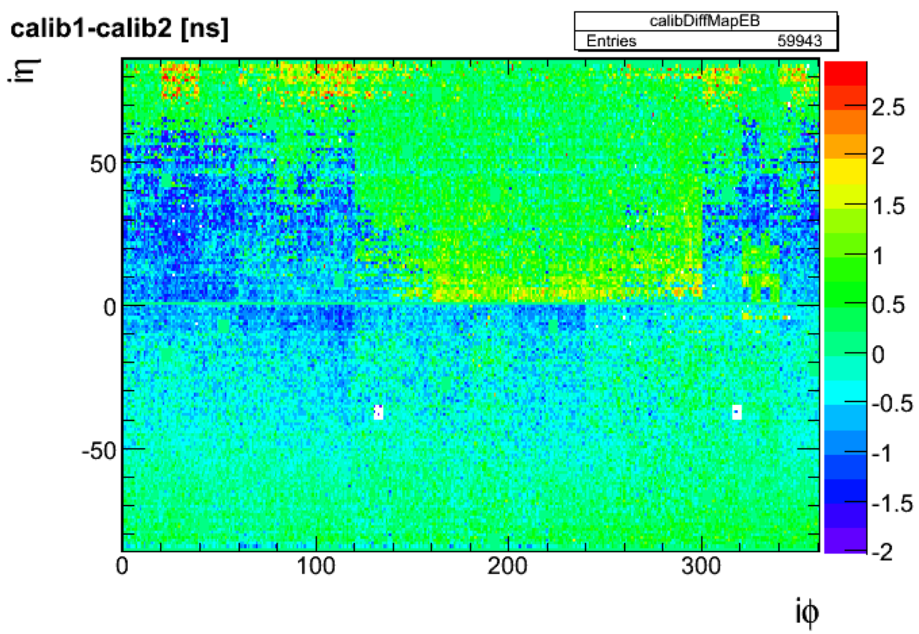
Calibration Map

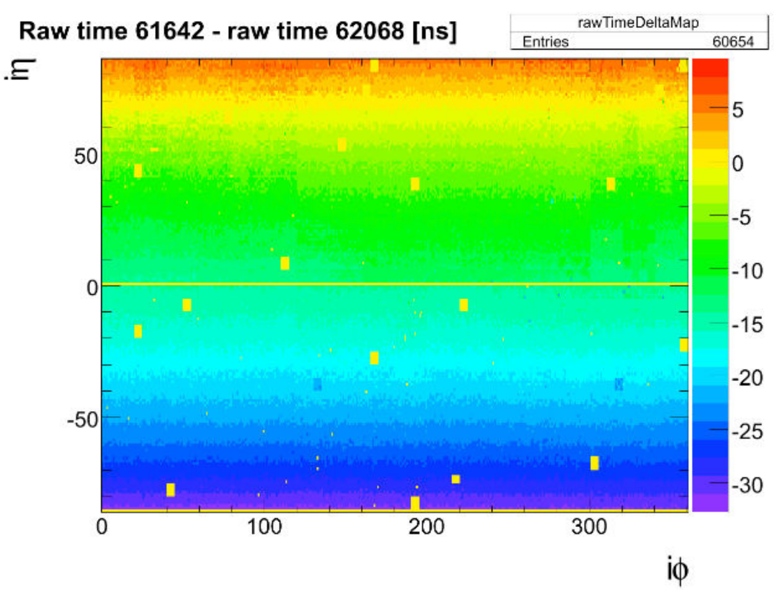
- Calibration obtained using all beam splash events (O(50))
  - ~20 events with muons traveling in neg. z dir. ("- beam")
  - ~35 events with muons traveling in pos. z dir. ("+ beam")



Systematics Evaluations

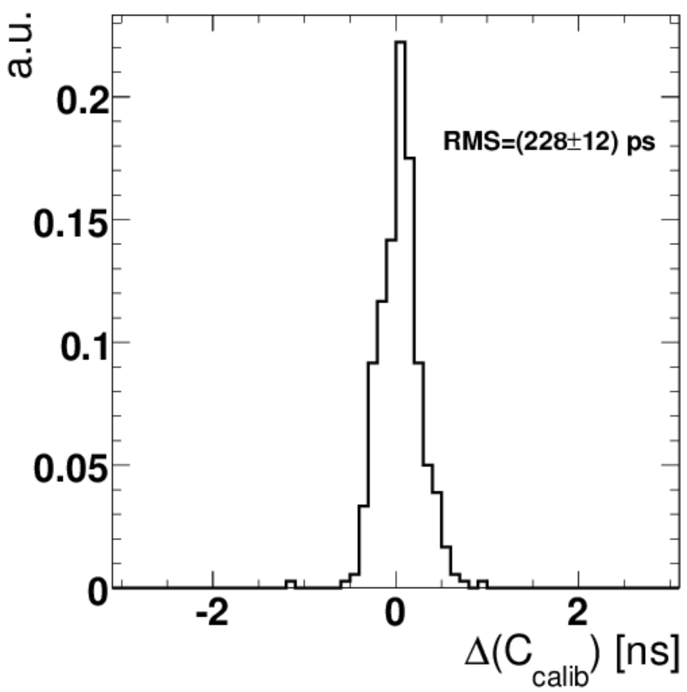
- This method is affected by the "T_{MAX} phase" systematics
  - Muon TOF >10ns
- Goodness and systematics on calibration evaluated comparing "- beam" and "+ beam" calibration constants
  - Very different "T_{MAX} phase" due to different muon propagation



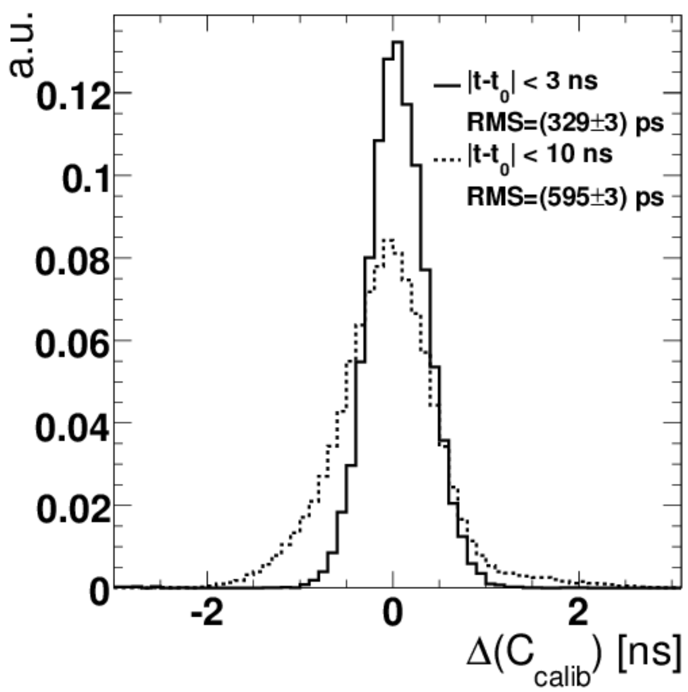


Synchronization Results

- In eta ring where arrival times are the same, total spread is in good agreement with prediction from statistics alone (215 ps)
- Remaining systematic (~ 500 ps) due to pulse shape differences combined with large range of absolute times



Paper



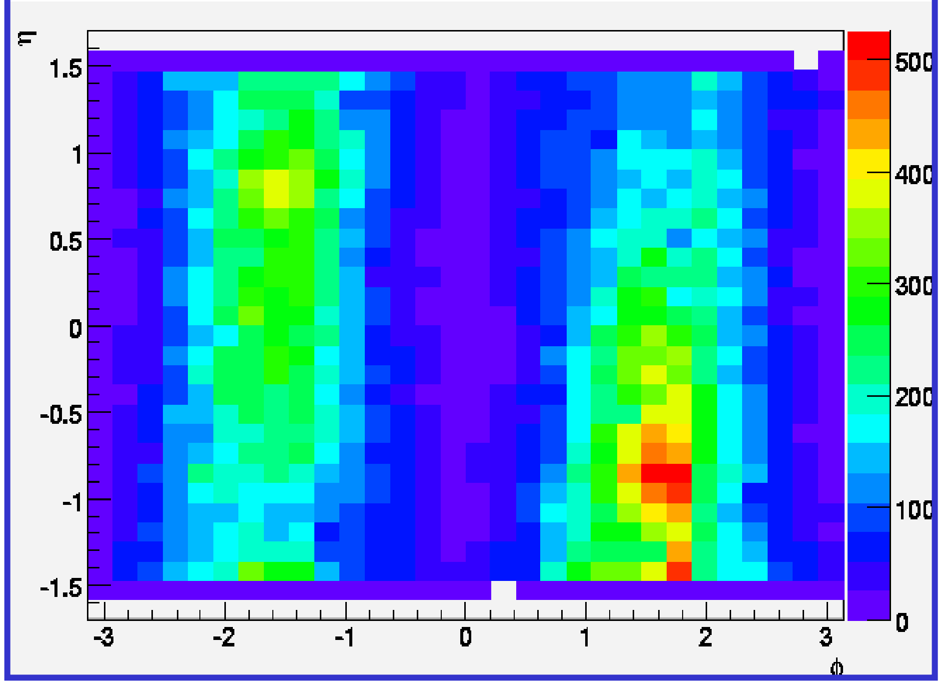
Study on Cosmics

- Idea is to verify the resolution parameters (N and C) and the linearity of the time measurement using real data
- Use of calibration constants extracted with beam splash events
- Use of CRUZET 3 and 4 data without magnetic field
  - Runs 50908, 50911, 50914, 51020 and 58537

Selection of Good Muon Clusters

- Use of SuperClusters (SC)
  - island with fixed matrix
- Good SC selected by association with tracking
  - Small distance between μ-track @ ECAL and SC required
  - Criteria: $\Delta\phi<0.1$ && $\Delta\eta<0.1$

$\eta-\phi$ map for associated clusters



Resolution

- Δ(time) between seed crystal and other crystals of SC
- Δ(time) distribution fitted using 2 gaussians
  - First one for core, second one for small amount of tails (fixed sigma=8ns)
- Exact same TB method to extract statistical (N) and constant term (C), i.e.

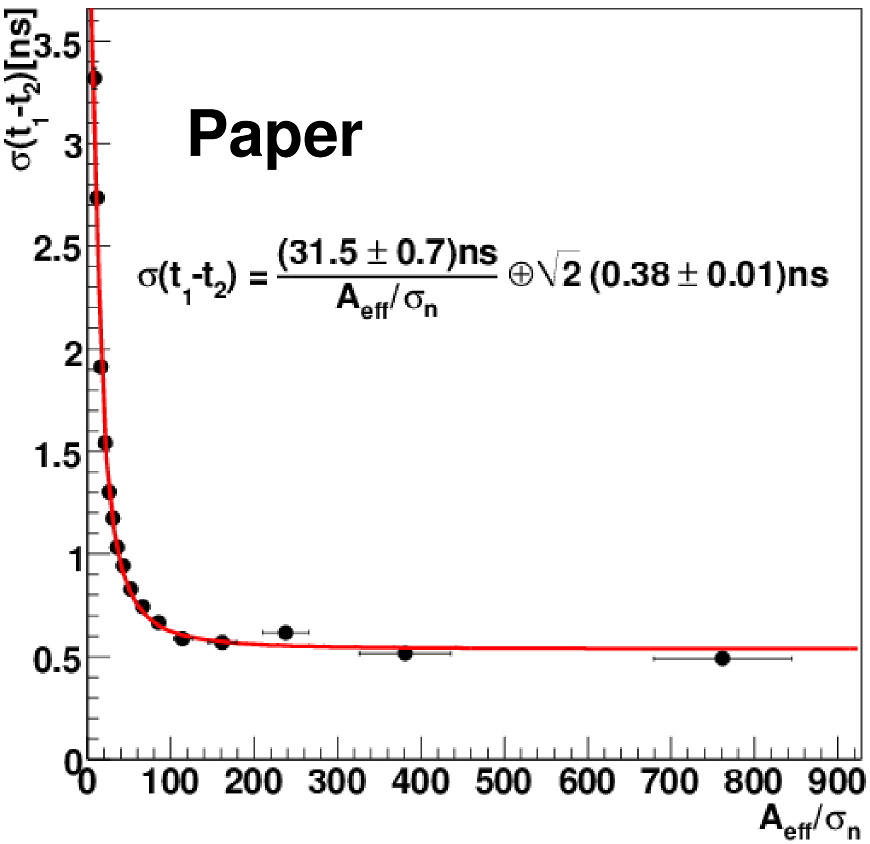
$$\sigma(\Delta t)^2 = N^2\left(\frac{1}{A_1{}^2}+\frac{1}{A_2{}^2}\right)+2C^2 = N^2\left(\frac{1}{A_{eff}{}^2}\right)+2C^2$$

Linearity

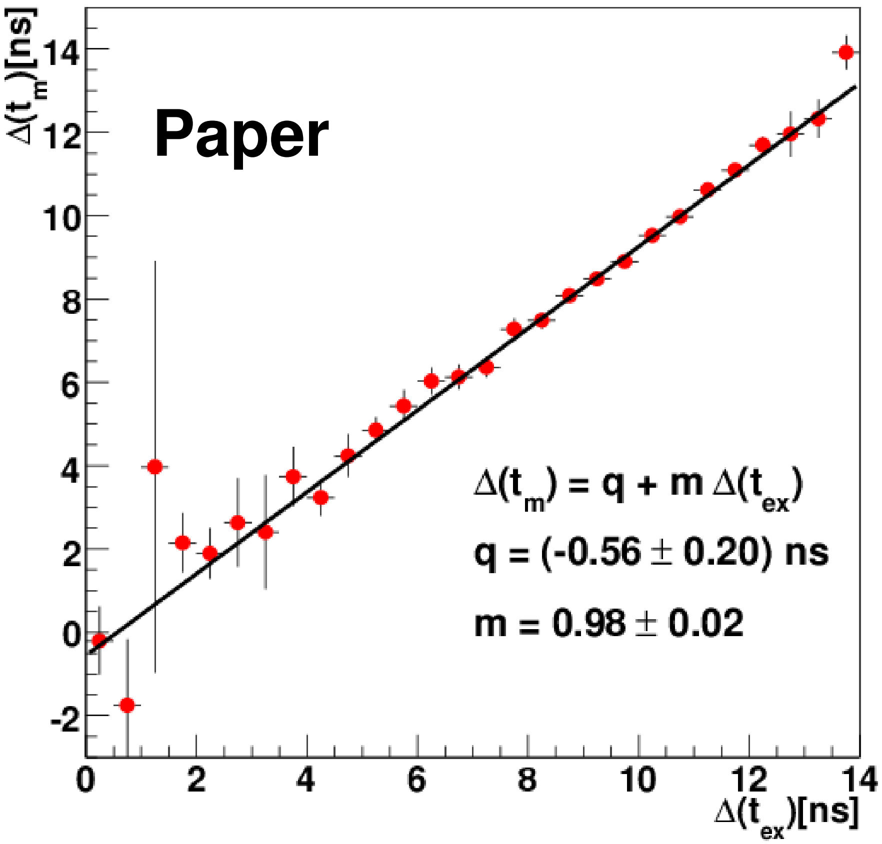
- Measured vs expected correlation using two seeds belonging to up and down SCs (depending on their y coordinate) associated to the same muon
  - TOF based on muon @ ECAL positions assuming that in average muon enters from the middles of a side of the crystal
  - The TOF range between 0ns (basically tangent to ECAL) and 14ns

Results on Cosmics

- Noise term consistent with TB and MC
- Constant term consistent with systematics on calib. coeff.



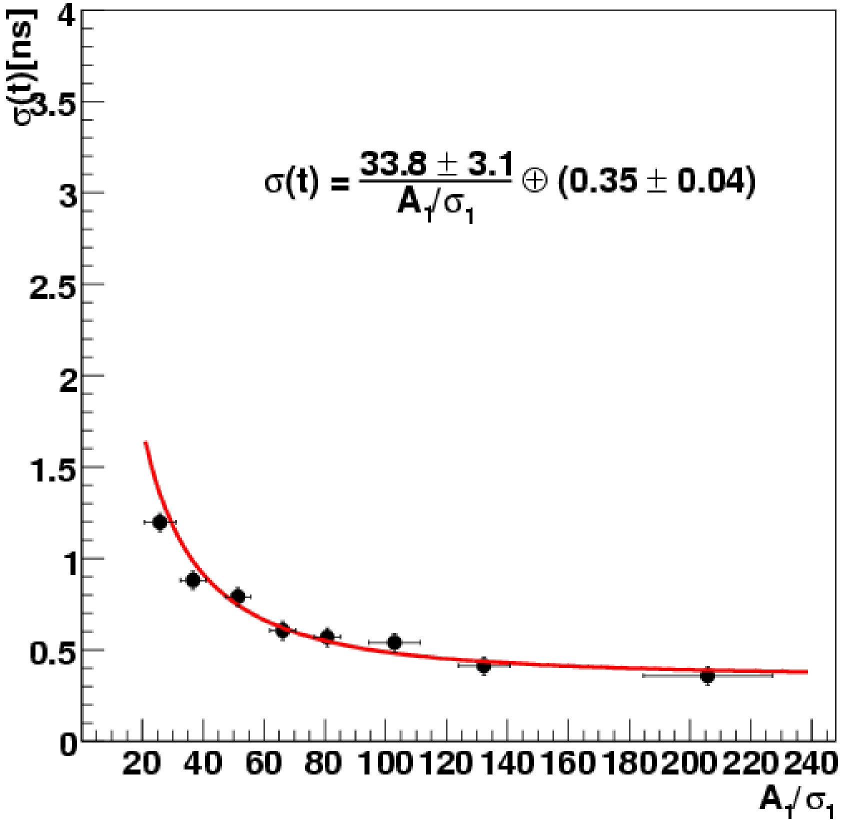
- m compatible with 1
- q compatible with 0 within systematics on calib. coeff.



Extra Cross-check on Beam Splash

(not in the paper)

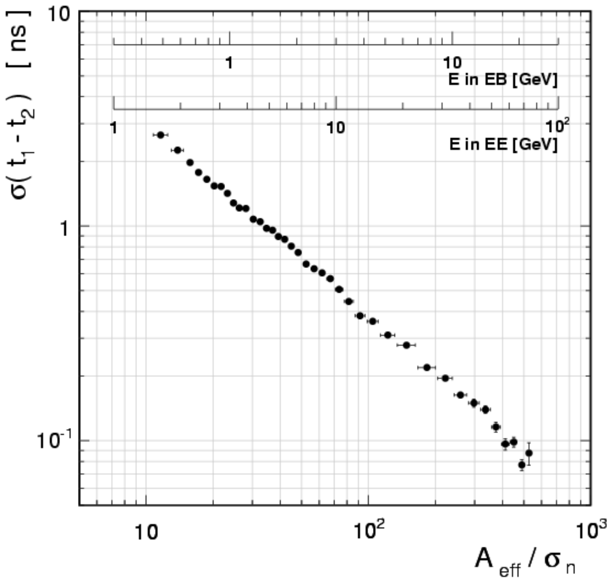
Noise and constant term consistent studying beam splash events



Issues during SEB reading

Log-log Scale and Constant Term

- It is not true that all functions are linear in log-log scale
- Main goal of this figure is to show that contribution of constant term on TB analysis is negligible

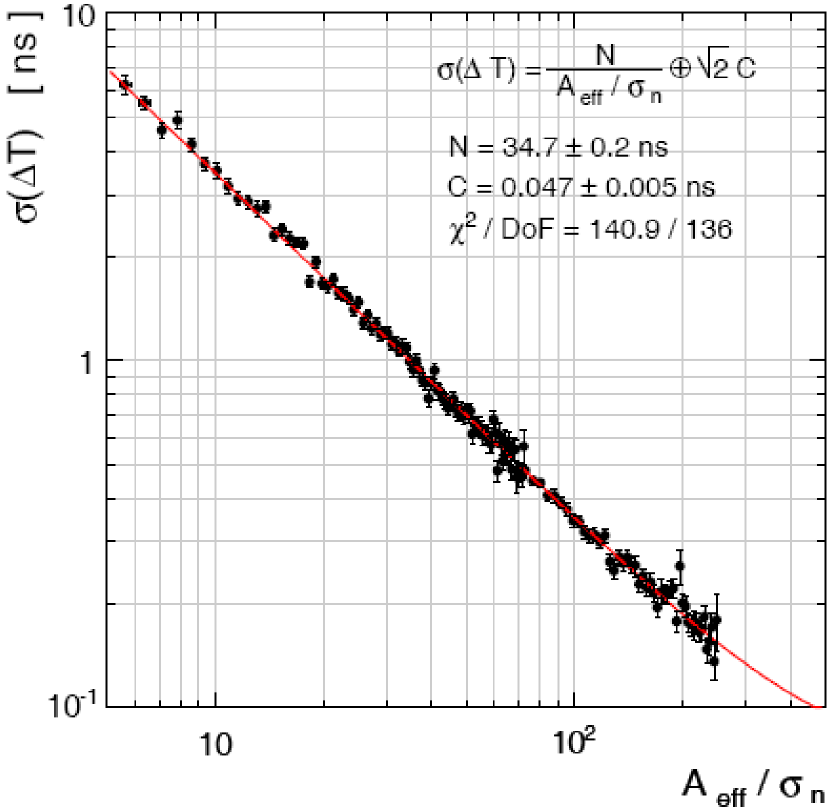


- We did additional tests on different samples and (presenting them in log-log and linear-linear scale, next slides)

Check on 120GeV TB electrons

Plot $\sigma(t_1 - t_2)$ as a function of A_{EFF}/σ_n

$$\frac{1}{A_{EFF}^2} = \frac{1}{A_1^2} + \frac{1}{A_2^2}$$



Fit results:

n	=	34.7 ± 0.2
c	=	0.047 ± 0.005
χ^2/dof	=	140.9/136

Two estimations

$n_{DATA} = 31.2 \pm 0.4$

$n_{DATA} = 34.7 \pm 0.2$

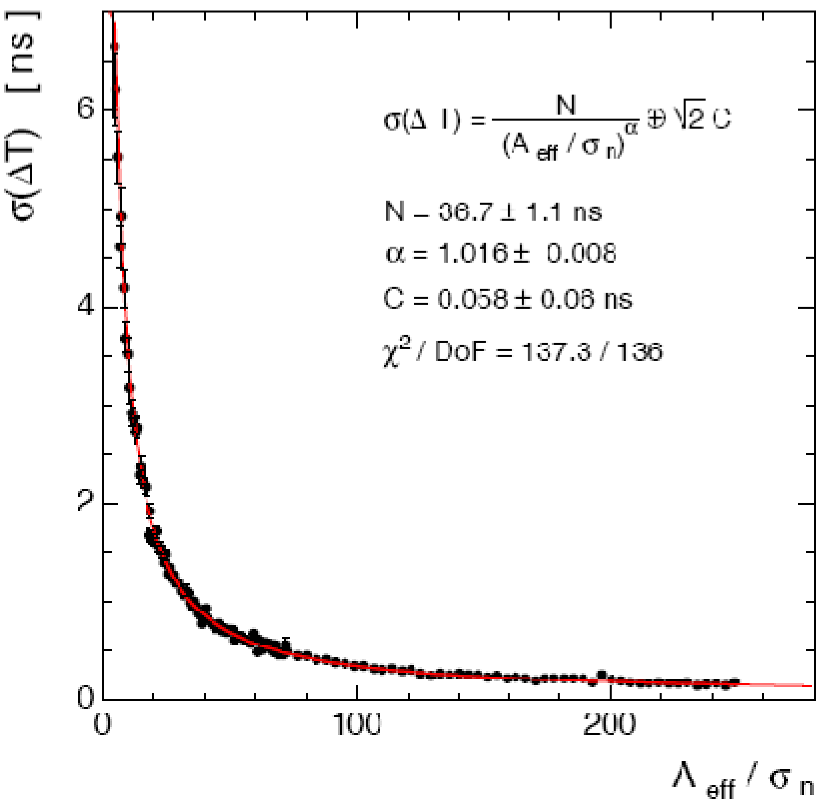
give average $n_{DATA} = 33.0 \pm 2.5$

compare to $n_{MC} = 33.0$

Check on 120GeV TB electrons (lin)

same data as on previous page,
different fit function

$$\sigma^2 = \left(\frac{N}{(A_{EFF}/\sigma_n)^\alpha}\right)^2 + 2c^2$$



Another check for validity of $1/A$ parameterization for noise term
Fit result for power law:

$$\alpha = 1.016 \pm 0.008$$

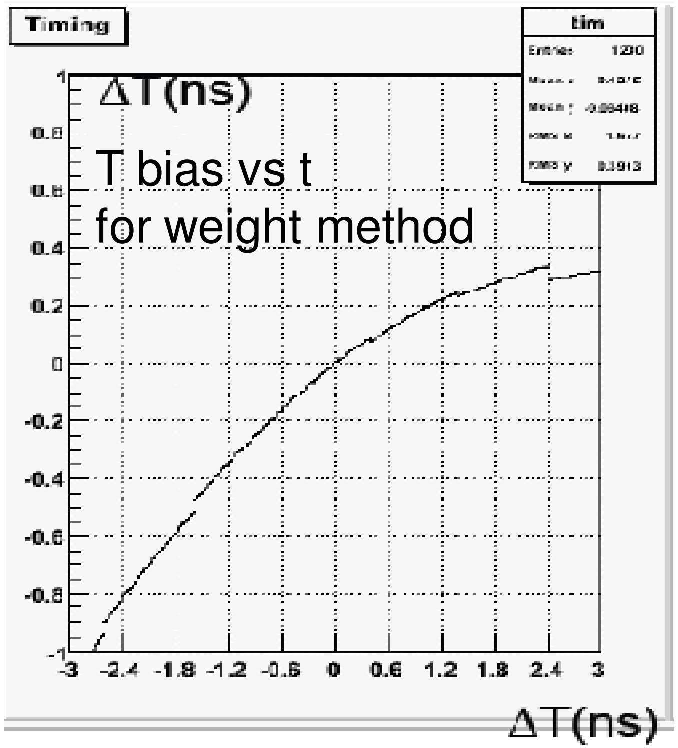
Ref. to Paper on Amplitude Reco

We put a reference just after the ratio method descritpion, saying:

"This method represents an improvement to what was previously shown in [6] since it is much less affected by the "T_{MAX} phase."

Poor Resolution at Large t Values?

- 500ps syst is small compared to weight method (see plot)



- BTW, not relevant if all hits will be synchronized (as for the LHC collisions, see slide 7)
- Could affect new physics searches but small impact (only if delay is very large)

Conclusions

- Performance of time measurement performance investigated using TB, beam splash, and cosmics events
- Resolution parameters extracted (consistent with expectations and MC studies)
  - With perfect time alignment resolution better than 100ps for large energies (>20GeV in barrel)
- Linearity verified on cosmics
- First synchronization of ECAL crystals using beam splash events
  - Uncertainty on synchronization ~500ps in average
  - Will be much improved using collision data

BACKUP

Details on Ratio Method Uncer.

we can calculate uncertainty for R_i which has three contributions:

- noise in each sample σ_n

$$R_i^2 \cdot \sigma_n^2 \cdot \left[\frac{1}{A_i^2} + \frac{1}{A_{i+1}^2}\right]$$

- uncertainty in pedestal subtraction

$$\frac{\sigma_n \cdot (1 - R_i)}{A_{i+1}}$$

- round-down in 12-bit digitization

$$\frac{1}{\sqrt{12}A_{i+1}}$$

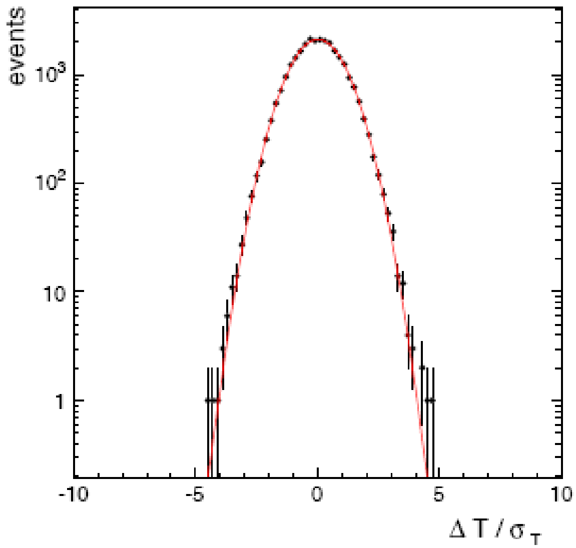
uncertainty on T_{MAX} from single ratio R

$$\sigma_T^2 = \left(\frac{dT}{dR}\right)^2 \cdot \sigma_R^2$$

calculation of errors σ_T on T_{MAX} from single ratio is verified with Toy Monte Carlo. This plot show distribution of

$$\frac{T_{MEAS} - T_{TRUE}}{\sigma_T}$$

it is a *perfect* Gaussian with $m = 0$ and $\sigma = 1$



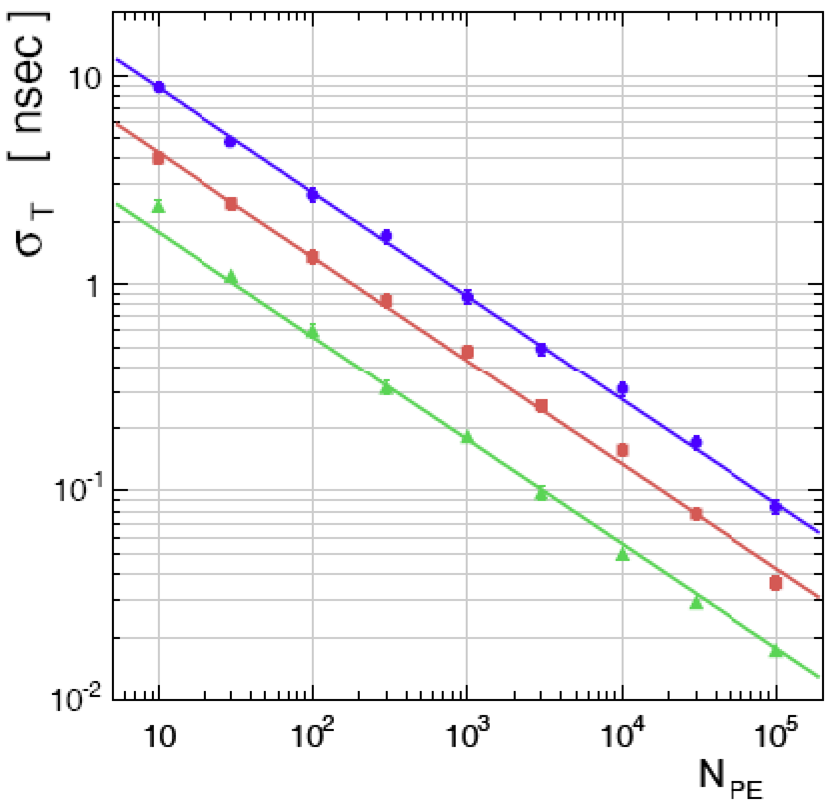
simulation of stochastic fluctuations

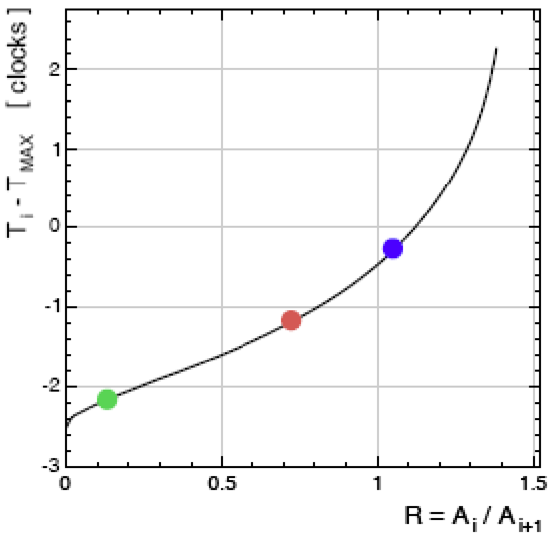
N photo-electrons generated per event. Each p.e. has time T_{GEN} according to triple exponent function from TDR

Each photo-electron increments 10 time samples by a value of single photoelectron response from DN2008/001

Ratio method is used for T_{MAX} measurement

Fluctuations in T_{MAX} is stochastic term fluctuations in T_{MAX} vs number of photo-electrons per event (dots) and $1/\sqrt{N}$ fit (lines) for three different values of R=0.13 (green), R=0.73 (red) and R=1.08 (blue)





Good parameterization for stochastic term

$$\sigma_T = \frac{a}{\sqrt{N}}$$

R	a [ns]
0.13	5.6
0.73	13.5
1.08	27.6

assuming

measured LY of a crystal	10 p.e./MeV
PMT qe = VPT qe	
VPT geometr. acceptace	50%
EE photo-statistics	5 p.e./MeV
EB photo-statistics	5 p.e./MeV

Since reconstructed time is a weighted average from 3-4 ratios, estimated stochasitc term is

$$\sigma_T = \frac{(5.4 - 9.4)\ ns}{\sqrt{N}}$$

or

$$\sigma_T = \frac{(2.4 - 4.2)\ ns \cdot MeV^{1/2}}{\sqrt{E}}$$

- back side of EE crystal is $3 \times 3 = 9$ cm^2, VPT area is 5 cm^2, assume 50% geometrical acceptance
- APD geometrical acceptance is lower but efficiency of detecting a photon is $\times 5$ higher which results in EB photo-statistics equal to EE

simulation of noise fluctuations

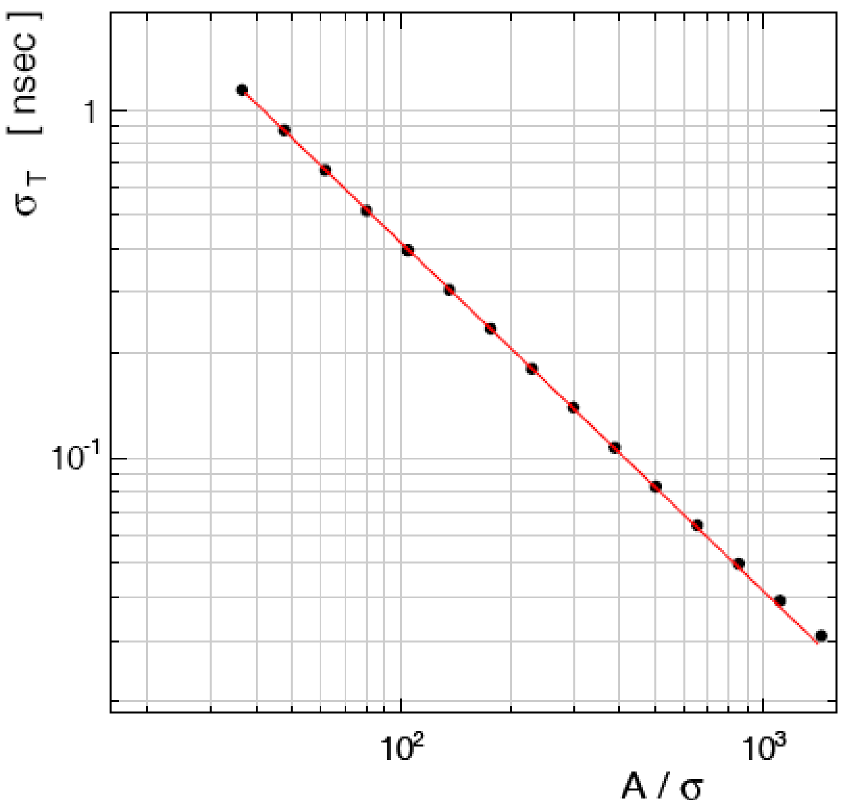
Ten time samples according to pulse shape with A_{MAX} and T_{MAX}

Gaussian noise applied to each time sample with σ_{noise}

Ratio method is used for T_{MAX} measurement

Fluctuations in T_{MAX} is noise term

fluctuations in T_{MAX} as a function of pulse amplitude normalized to noise (dots) and σ/A fit (line)



Good parameterization for noise term

$$\sigma_T = \frac{41.5\ ns}{A/\sigma_{noise}}$$

simulations apply high frequency noise only!

In EE HF noise is 1.1 adc count affects ratio calculation

Pedestal subtraction have 2 adc count uncertainties

Prediction for data

$$\sigma_T = \frac{33\ ns}{A/\sigma_{noise}}$$

Stochastic Term

assume time resolution for individual channel

$$\sigma_T^2 = \frac{a^2}{A} + \frac{b^2}{A^2} + c^2$$

fluctuations in time difference

$$\sigma_\Delta^2 = \left(\frac{a_1^2}{A_1} + \frac{a_2^2}{A_2}\right) + \left(\frac{b_1^2}{A_1^2} + \frac{b_2^2}{A_2^2}\right) + \left(c_1^2 + c_2^2\right)$$

crystals #228 and #248 in run 20283

	#228	#248
Crystal LY	11.05	10.4
VPT LY @ 0T	28.7	31.2
pedestal RMS	2.02	2.04
noise @ 25 nsec	1.08	1.10

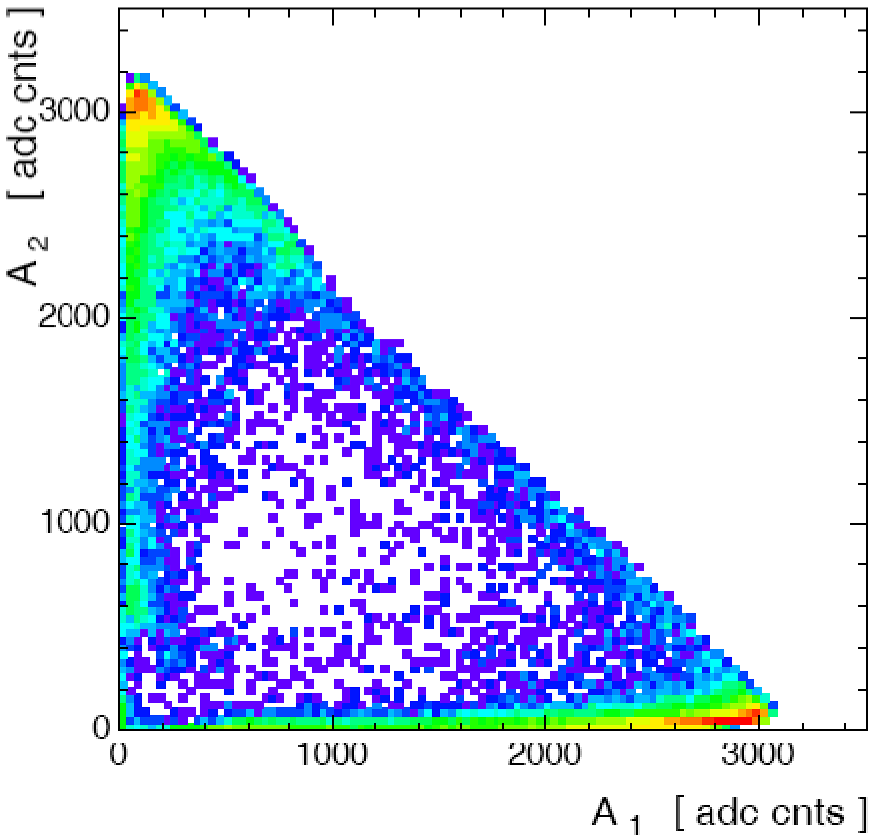
very similar crystals

$$\sigma_\Delta^2 = a^2\left(\frac{1}{A_1} + \frac{1}{A_2}\right) + b^2\left(\frac{1}{A_1^2} + \frac{1}{A_2^2}\right) + 2c^2$$

Stochastic Term

Distribution of events in A_2 vs A_1 plane. Each bin has value of σ_Δ. Fit with

$$\sigma_\Delta^2 = a^2\left(\frac{1}{A_1}+\frac{1}{A_2}\right)+b^2\left(\frac{1}{A_1^2}+\frac{1}{A_2^2}\right)+2c^2$$



Fit results:

a	=	0 ± 0.73
b	=	62.3 ± 0.7
c	=	0.148 ± 0.006

$a < 0.73\ ns \cdot ADC^{1/2}$ means
$a < 7.9\ ns \cdot MeV^{1/2}$ (90% C.L.)
good agreement with MC
$a = (2.4 - 4.2)\ ns \cdot MeV^{1/2}$
stochastic term is negligible.
Simplifies our studies a lot!

$b = 62.3$ means
$n = 31.2\ ns$
good agreement with MC
$n = 33\ ns$
we will study it further

Calc. vs. Obs. Uncertainties on the Mean