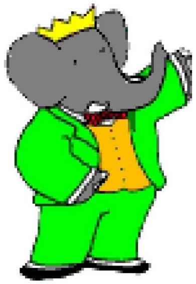
BABAR Electromagnetic Calorimeter Energy Calibration

Ringberg Workshop

Sven Menke, MPI München

22. July 2002

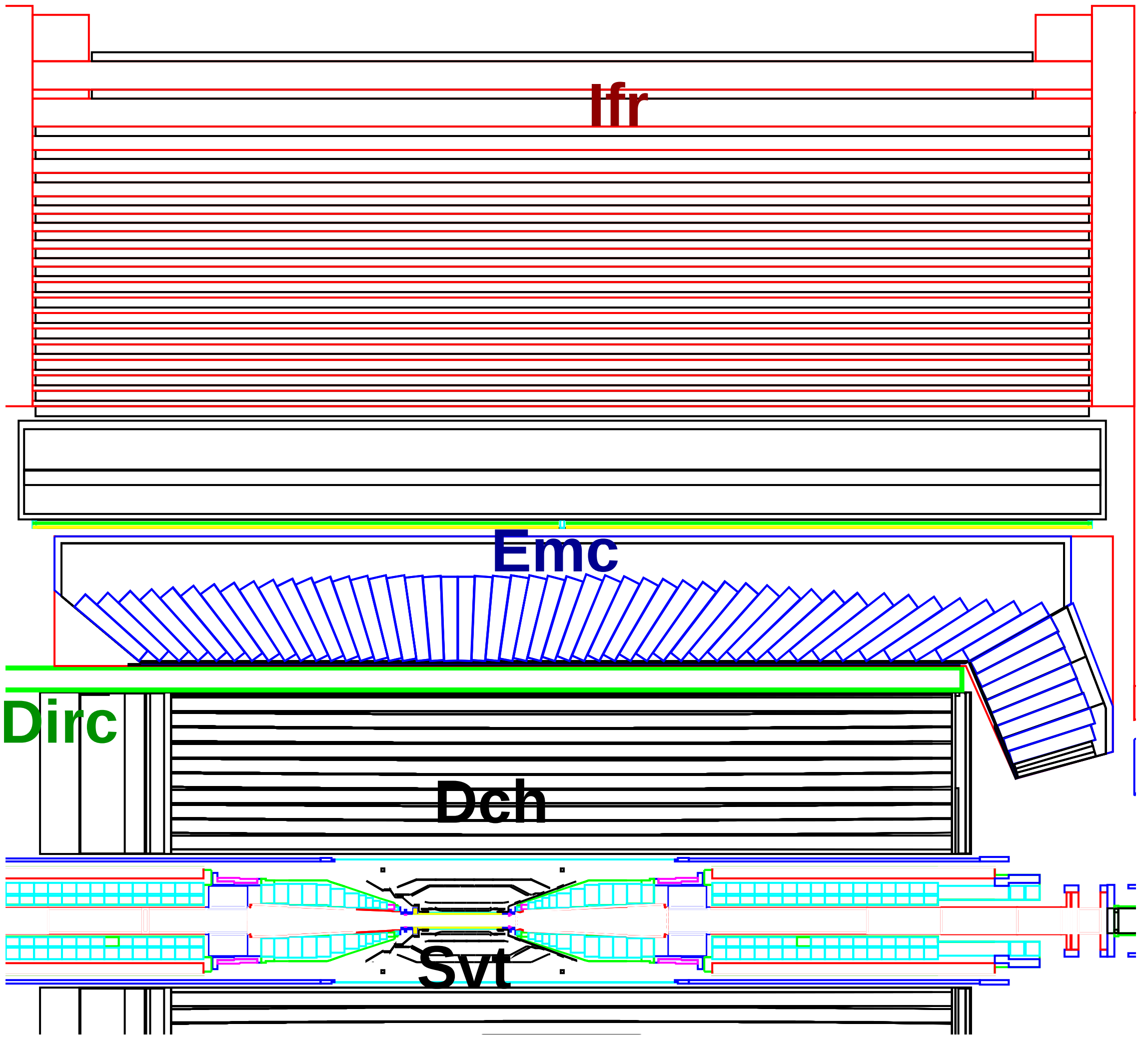
- Introduction
- 'Digi'-calibration
  - ▷ Radiative source calibration
  - ▷ Bhabha calibration
- 'Cluster'-calibration
  - ▷ π^0 calibration
  - ▷ Radiative Bhabha calibration
- Electronics non-linearities
- Performance
- Conclusion



Why do we need an energy calibration?

- Standard B decays lead on average to 5.5 charged particles and 5.5 photons, 50 % of which have less than 200 MeV
- Converting ADC counts into MeV
- Compensate various effects, which alter the linearity of the readout signal
  - ▷ back and side leakage
  - ▷ radiaton damage
  - ▷ crystal non-uniformities
  - ▷ electronics

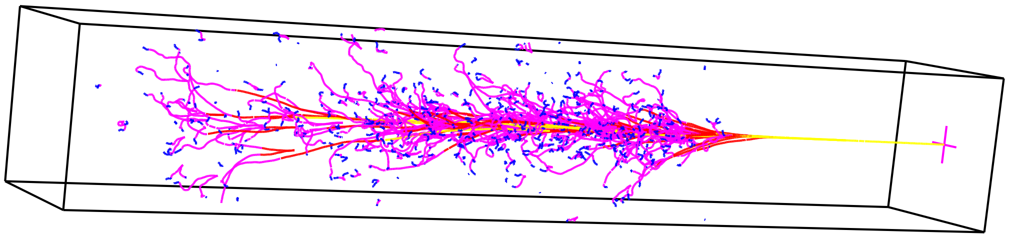
BABAR detector



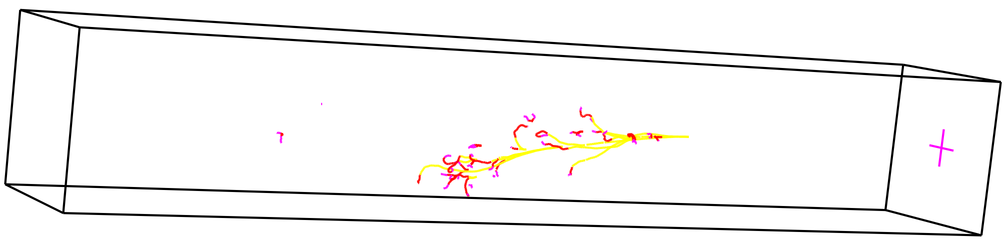
Ifr:	Instrumented flux return
Emc:	Electromagnetic calorimeter
Dirc:	Detector of internally reflected cherenkov light
Dch:	Driftchamber
Svt:	Silicon vertex tracker

Electromagnetic showers in CsI

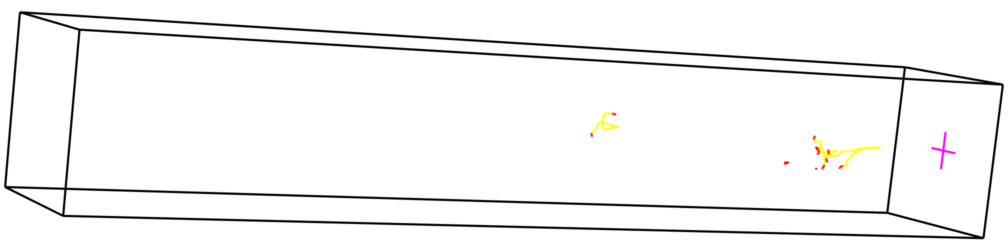
- 8 GeV electron



- 500 MeV photon

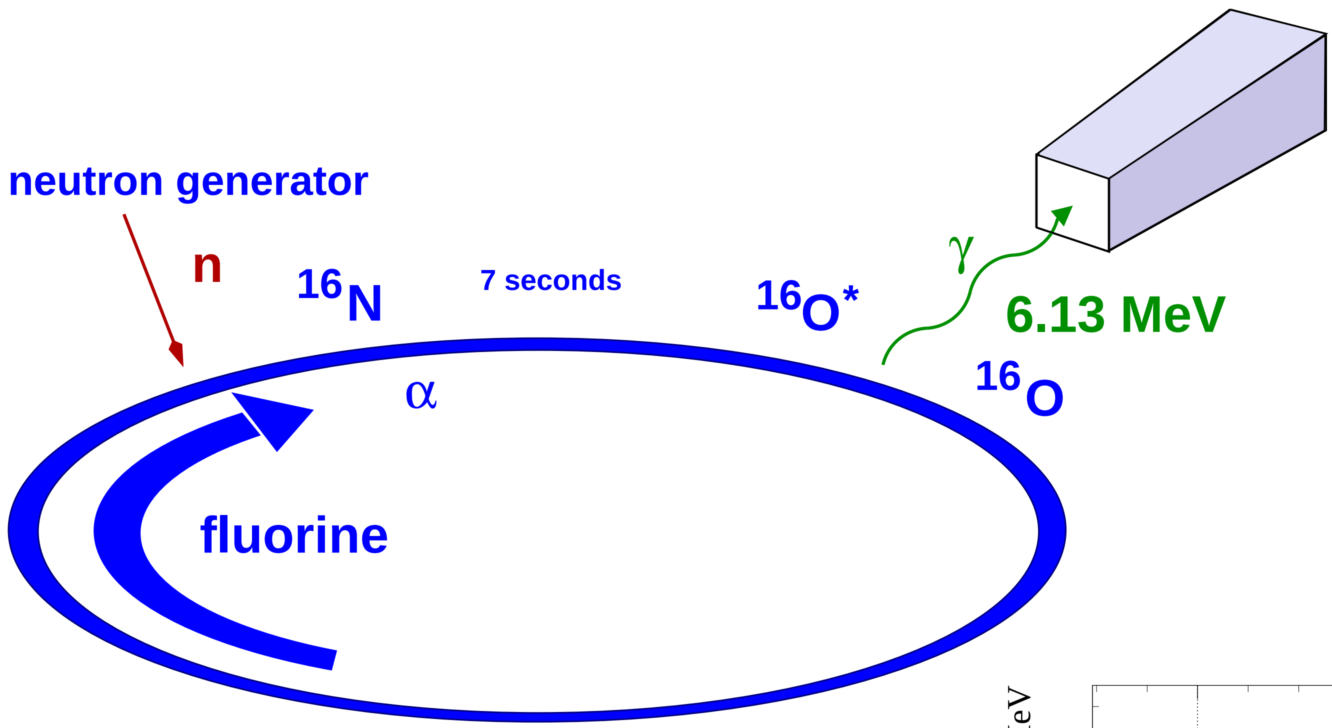


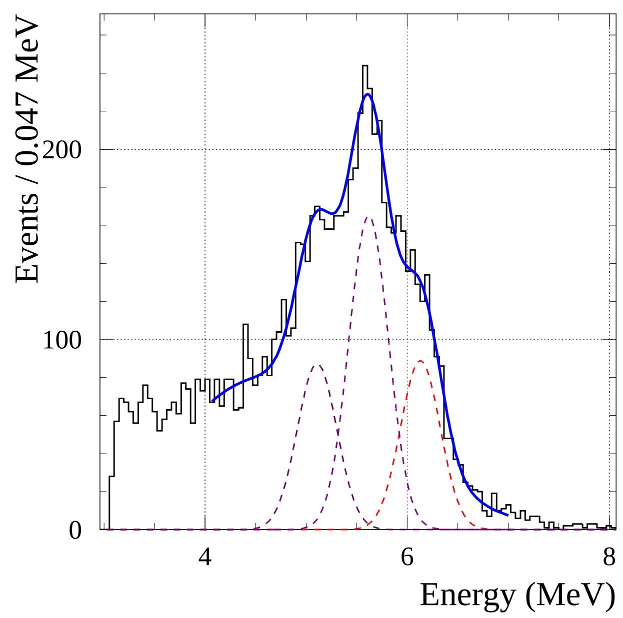
- 100 MeV photon



- Radiation damage
  - ▷ non-uniform light gain
  - ▷ energy dependence
  - ▷ Calibration at 6 MeV (radioactive fluid) and 3 − 8 GeV (Bhabha-events)

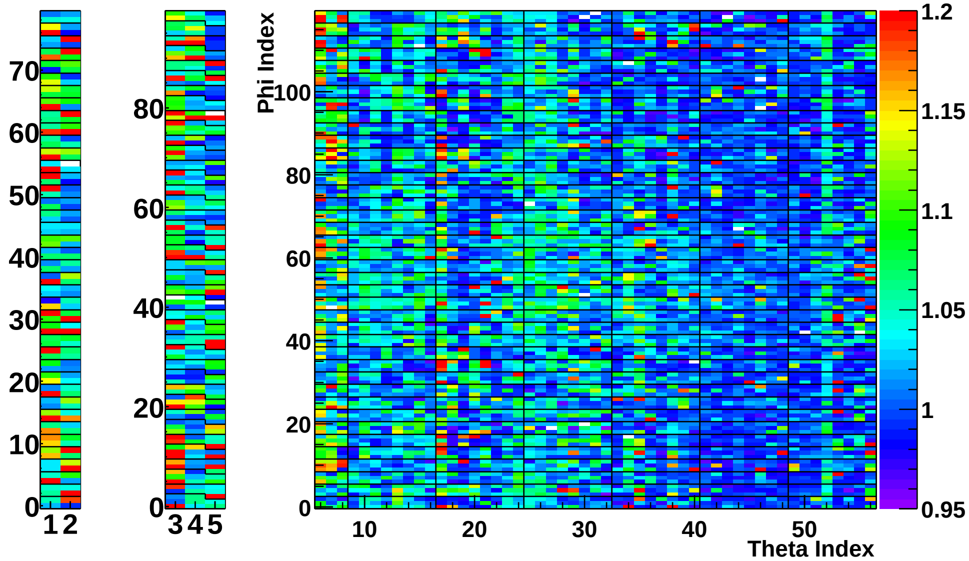
‘Digi’ calibration with radioactive source

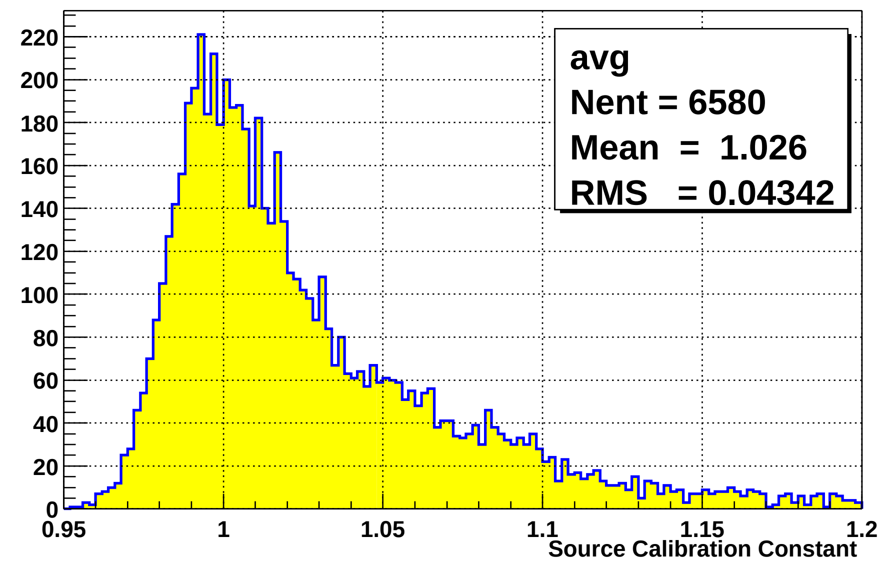




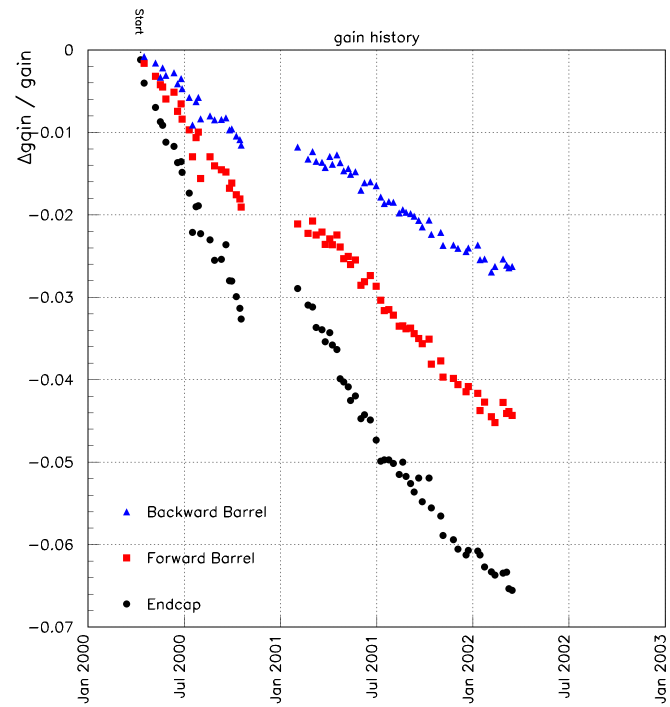
- Fit to energy spectra in each crystal
- One calibration constant per crystal
- Defines energy scale at 6 MeV

6580 constants every week



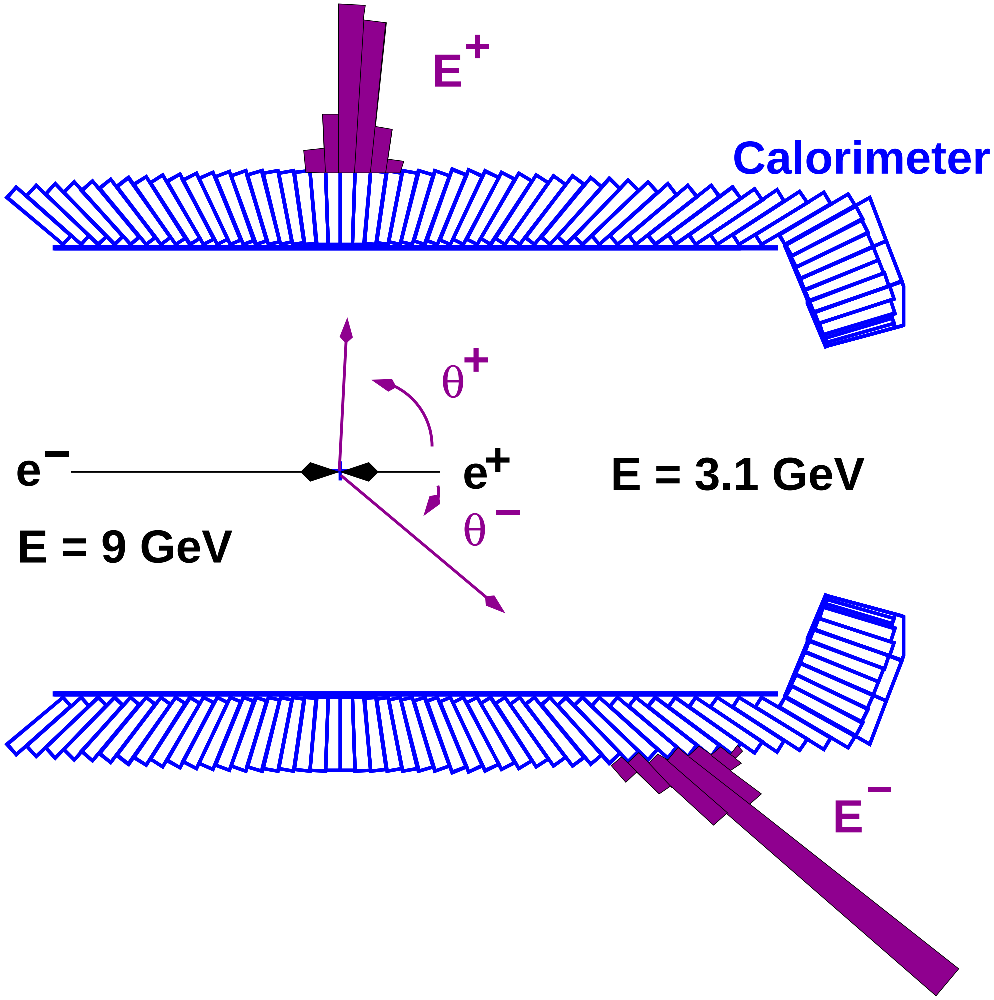


- Radiation damage
  - Differences of the constants now compared to April 2000 6.5 % in the endcap
  - 4.5 % in forward barrel
  - 2.5 % in backward barrel



- Accuracy of single crystal constants better than 0.7 %

Bhabha calibration

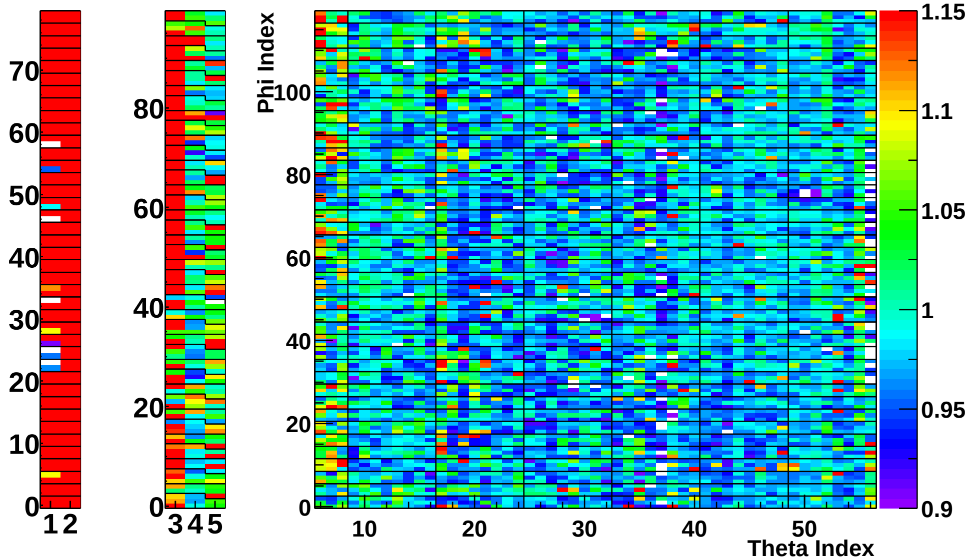


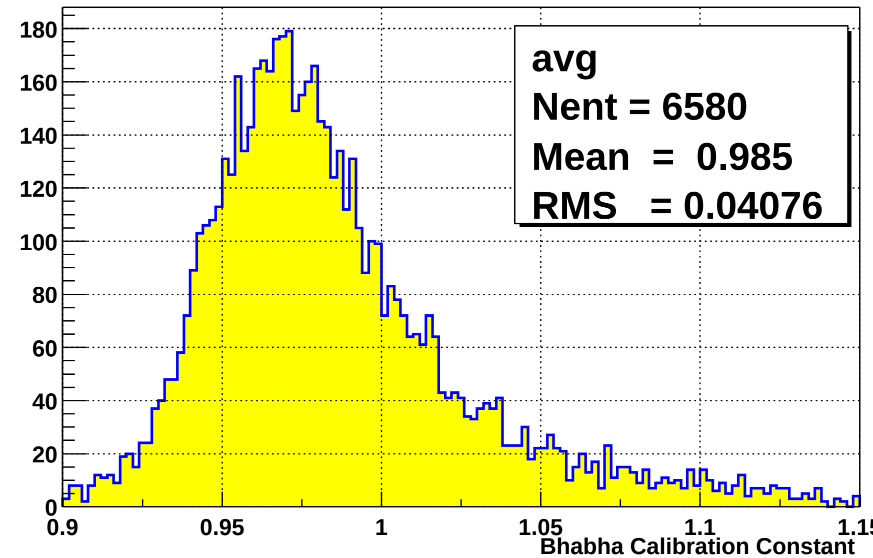
- Polar angle of the cluster determines the expected energy
  - ▷ small deviation of BABAR origin in $x - y$ plane from $(0,0)$ is taken into account

- Find constants c_i minimizing $\chi^2 = \sum_{\text{Events}} \left(\left(E_{\text{expected}} - \sum_{\text{Crystals}} c_i \, E_i \right)^2 / \sigma^2 \right)$

- Defines energy scale at $3 - 6\,\text{GeV}$

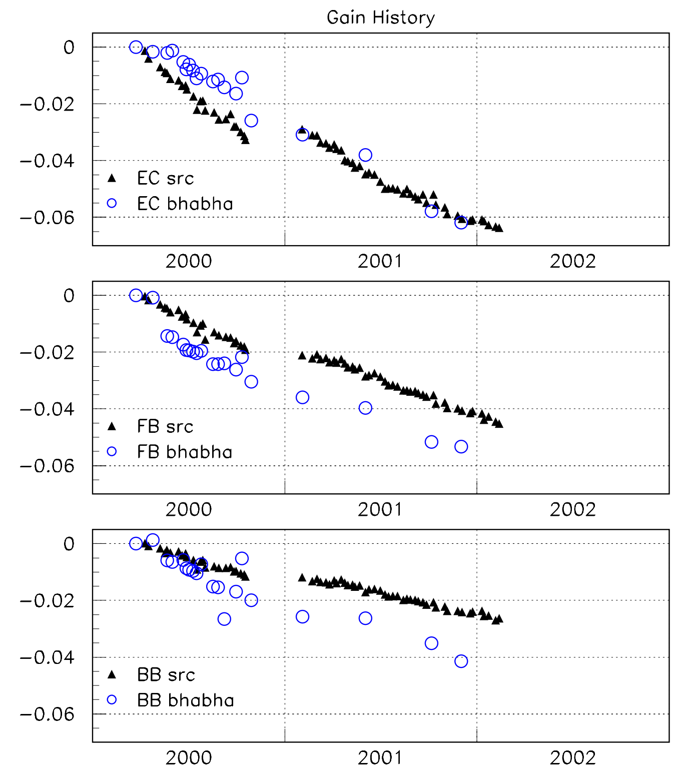
6580 constants every (two) month(s)





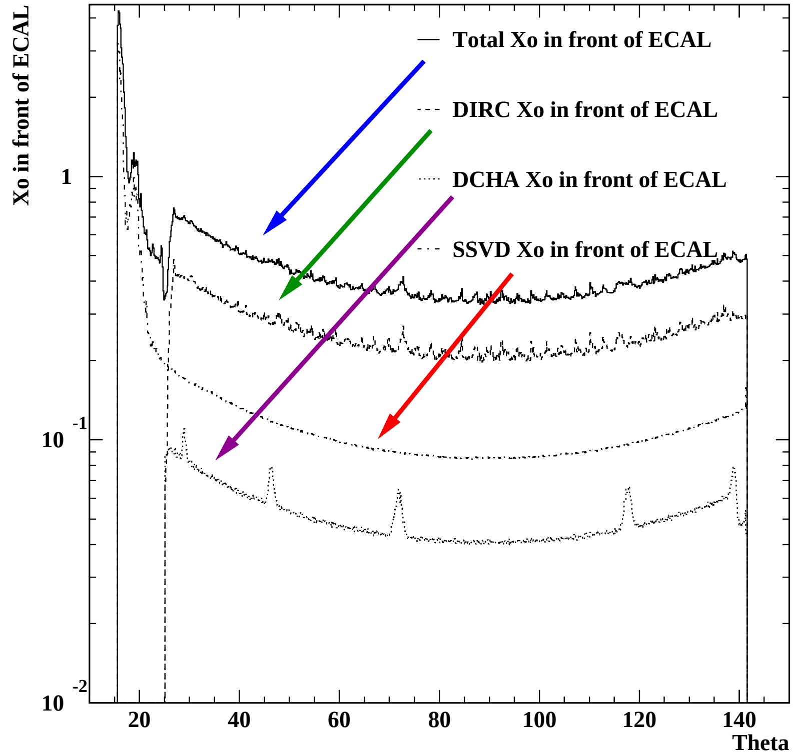
- Radiation damage
  - Differences of the constants now compared to April 2000 similar to source calibration except for inner most endcap rings
- Accuracy 1 – 2 % (statistical: 0.35 %)
- Calibration function for crystals:

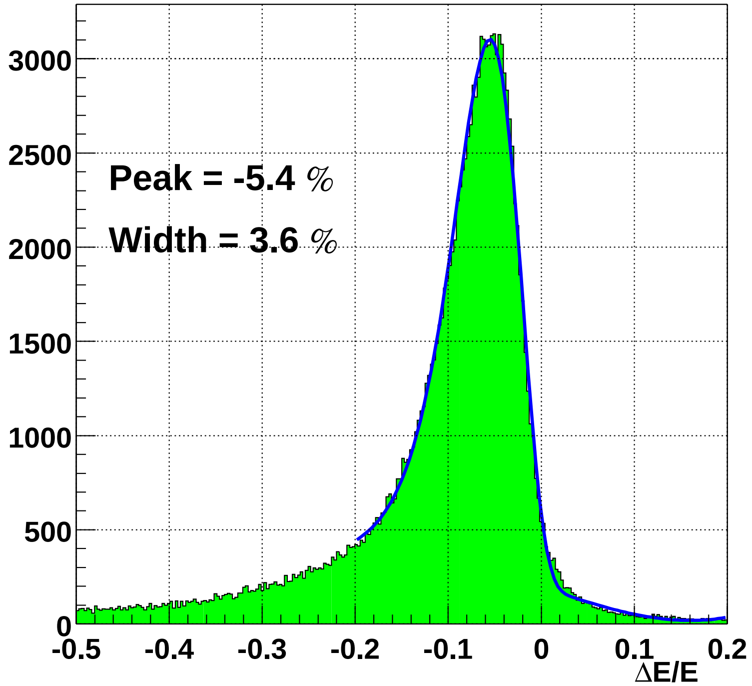
$$E'_i = E_i \left(\frac{\ln(E_i) - \ln(6.13\ \mathrm{MeV})}{\ln(E_i^{\mathrm{Bhabha}}) - \ln(6.13\ \mathrm{MeV})} \left(c_i^{\mathrm{Bhabha}} - c_i^{\mathrm{Source}}\right) + c_i^{\mathrm{Source}} \right)$$



'Cluster' calibration

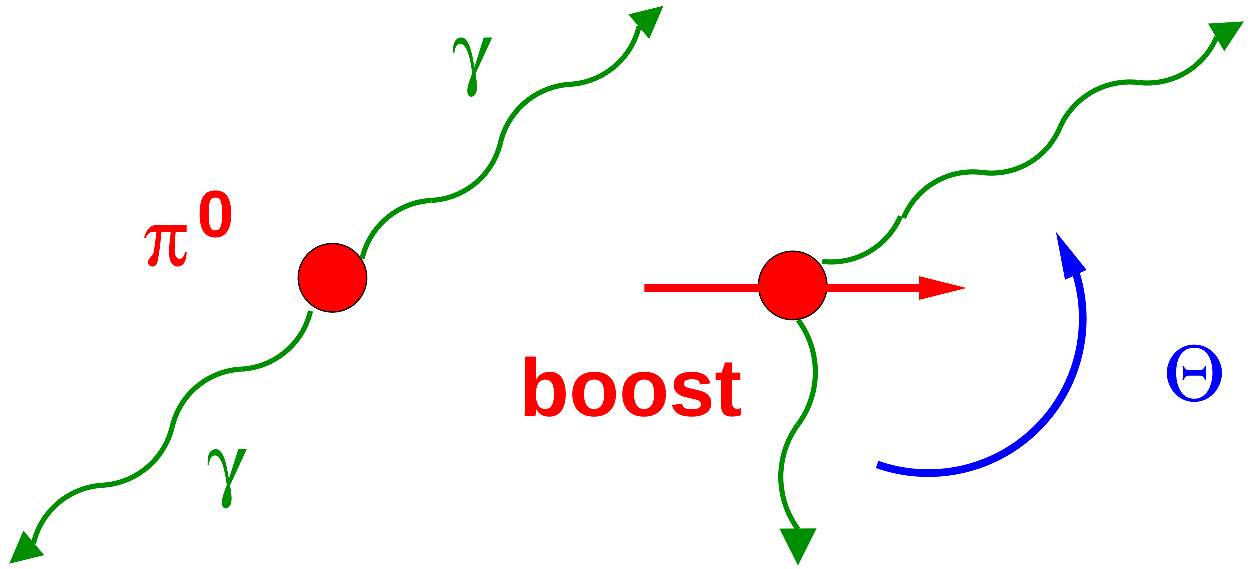
- energy losses in material in front of the Emc
  - ▷ on average reduced deposited energy
  - ▷ energy losses fluktuate
  - ▷ reduced energy resolution





- need known energy processes over the entire physics range to calibrate clusters
- π^0 deacys and radiative Bhabha events are used in BABAR

π^0 calibration



$E_1 = E_2$ $= 67.5$ MeV

$(E-p)/2 < E_1 \neq E_2 < (E+p)/2$

- Use the known π^0 mass $m_{\pi^0} = \sqrt{2E_1E_2(1-\cos\theta)}$, to correct E_1 and E_2.
- Correct from deposited photon energy to true energy of the photon

Energy correction function

$$
\begin{aligned}
E' &= E \times \exp(a_0 \\
&+ a_1 \ln E + a_2 \ln^2 E + a_3 \ln^3 E \\
&+ a_4 \cos\theta + a_5 \cos^2\theta + \ldots + a_8 \cos^5\theta \\
&+ a_9 \ln E \cos\theta)
\end{aligned}
$$

- enregy loss/leakage is shower depth dependent
  - ▷ energy dependency as polynoimal in $\ln E$
- material in front of the Emc / tilt of the Crystals varies with polar angle
  - ▷ angular dependency as polynomial in $\cos\theta$

Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $\mathrm{fNov}(m) + \mathrm{poly}(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $\mathrm{fNov}(m) + \mathrm{poly}(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $\mathrm{fNov}(m) + \mathrm{poly}(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $\text{fNov}(m) + \text{poly}(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $\mathrm{fNov}(m) + \mathrm{poly}(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $\mathrm{fNov}(m) + \mathrm{poly}(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $\mathrm{fNov}(m) + \mathrm{poly}(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

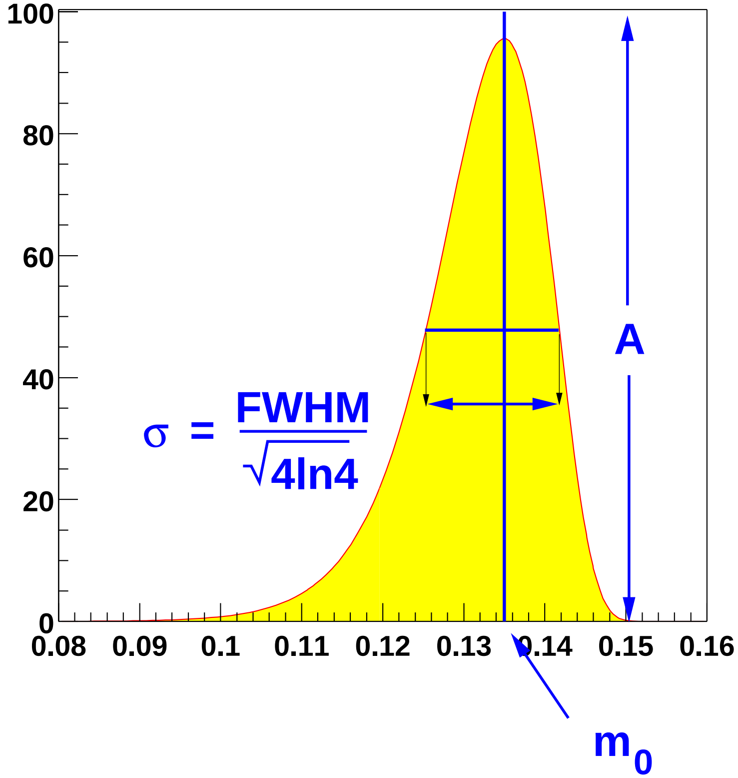
Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $fNov(m) + poly(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

Iterative procedure to obtain the coefficients

1. select photon candidates and calibrate their energies with the old calibration function
2. build all possible two-photon combinations
3. histogram the 2-photon-mass in bins of E_1, E_2 (2 entries per combination) and inbins of $(\cos\theta_1 + \cos\theta_2)/2$ (1 entry per combination)
4. fit the function $\mathrm{fNov}(m) + \mathrm{poly}(m)$ to the histograms
5. use the 'peak'-masses m_0 from the fits and plot $\ln(m_{\pi^0}/m_0)$ as function of $\ln E$ or $\cos\theta$
6. fit a 3rd order polynomial in $\ln E$ to $\ln(m_{\pi^0}/m_0)(\ln E)$ and a 2nd order polynomial in $\cos\theta$ to $\ln(m_{\pi^0}/m_0)(\cos\theta)$
7. add the coefficients of the polynomials to the old coefficients
8. repeat from step 1 until coefficients don't change anymore

‘Novosibirsk’ function



$$A \exp\left[-\frac{1}{2}\left(\frac{\ln^2\left(1 + t\,\frac{\sinh(t\sqrt{\ln 4})}{t\sqrt{\ln 4}}\,\frac{m - m_0}{\sigma}\right)}{t^2} + t^2\right)\right]$$

- “Gauß plus exponential tail”
- becomes a Gaußian for $t \rightarrow 0$
- Normalization such that the integral $(-\infty, +\infty)$ is identical to integrated Gaußian with (A, m_0, σ)

Why $\ln(m_{\pi^0}/m_0)$?

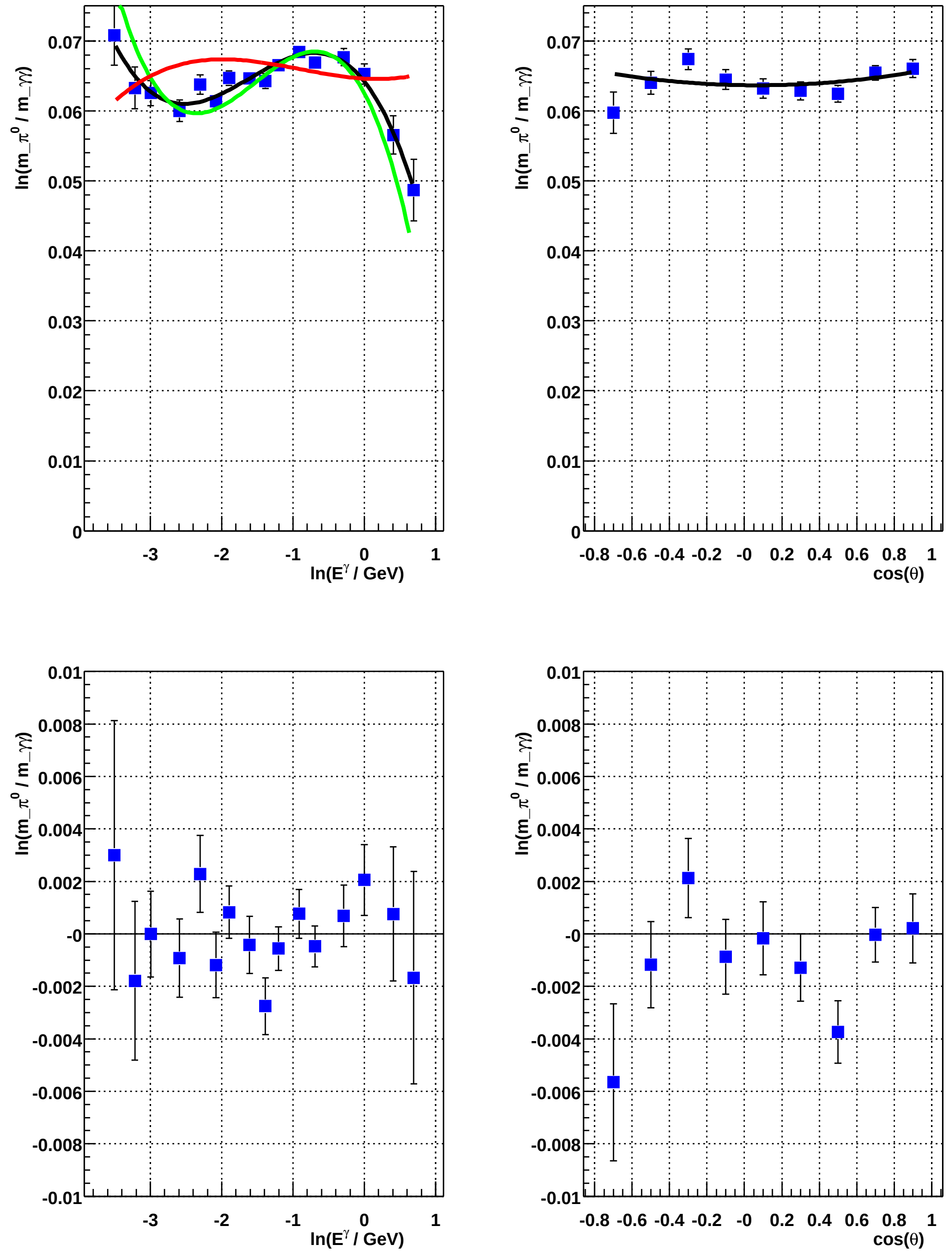
- Example iteration

$$
\begin{aligned}
\ln\frac{m_{\pi^0}}{m_0} &= \ln m_{\pi^0} - 0.5 * (\ln 2 + \ln E_1 + \ln E_2 \\
&\qquad + \ln(1-\cos\theta)) \\
&= 0.5 * (\ln(E_1'/E_1) + \ln(E_2'/E_2)) \\
&= \quad a_0 \\
&\quad + a_1\,(\ln E_1 + \ln E_2)/2 \\
&\quad + a_2\,(\ln^2 E_1 + \ln^2 E_2)/2 \\
&\quad + a_3\,(\ln^3 E_1 + \ln^3 E_2)/2 \\
&\quad + a_4 (\cos\theta_1 + \cos\theta_2)/2 \\
&\quad + a_5 (\cos^2\theta_1 + \cos^2\theta_2)/2 + \ldots
\end{aligned}
$$

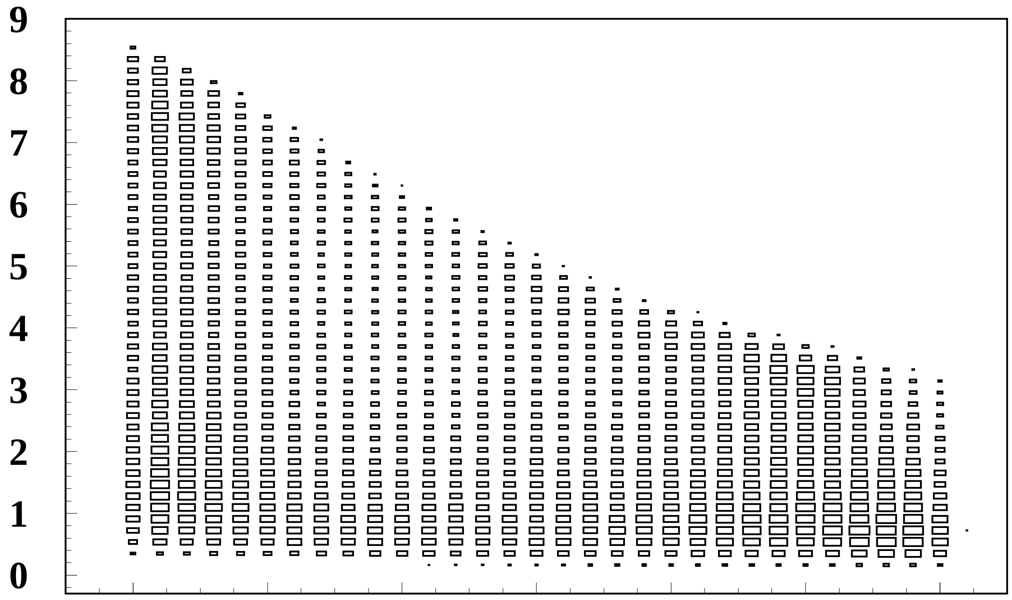
- Fit to $\ln E$ yields a_{0-3}
- Fit to $(\cos\theta_1 + \cos\theta_2)/2$ yields $a_{4,5}$

Result after 1(2) iteration(s)

- 1. iteration
  - red: MC calibration function
  - black: after one iteration
  - green: after two iterations
- 2. iteration



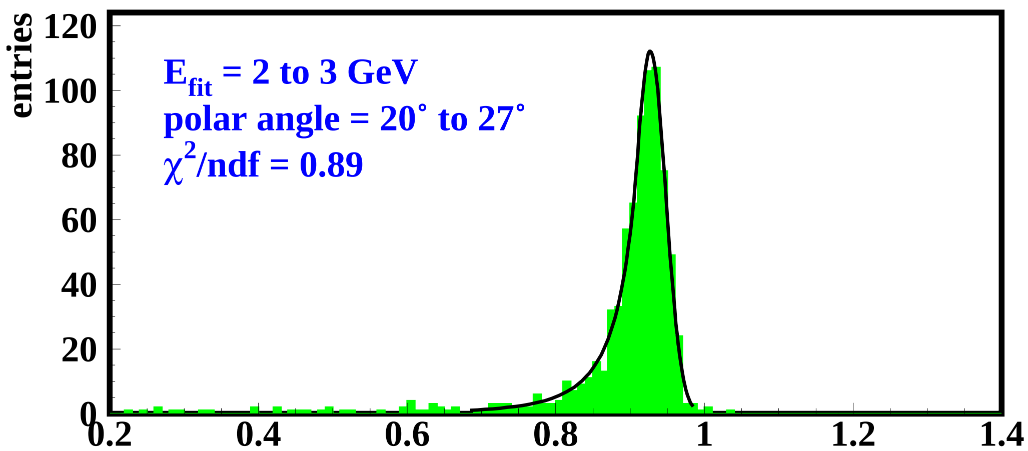
Radiative Bhabha calibration



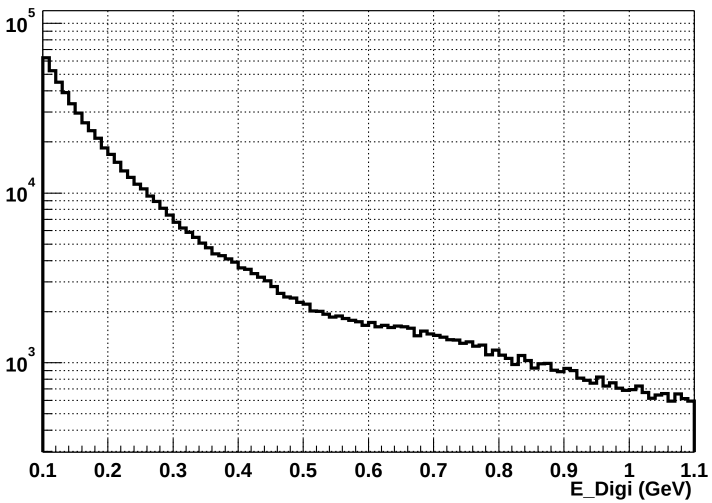
photon lab E_{fit} vs. lab θ_{fit}

- radiative Bhabha events provide photons > 0.5 GeV
- could therefore complement the π^0 calibration, which is mainly sensitive to low energetic photons
- use track momenta and the direction of the photon to (over)constrain the photon energy

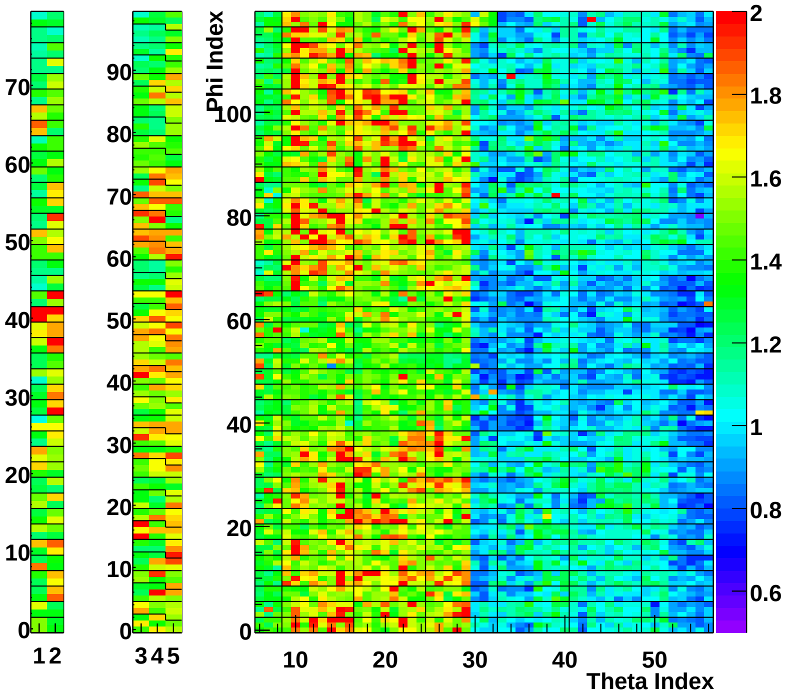
- fit results look consistent
- but: some non understood biases prohibit use of this calibration method for now
- detailed MC studies are needed to understand/correct the bias

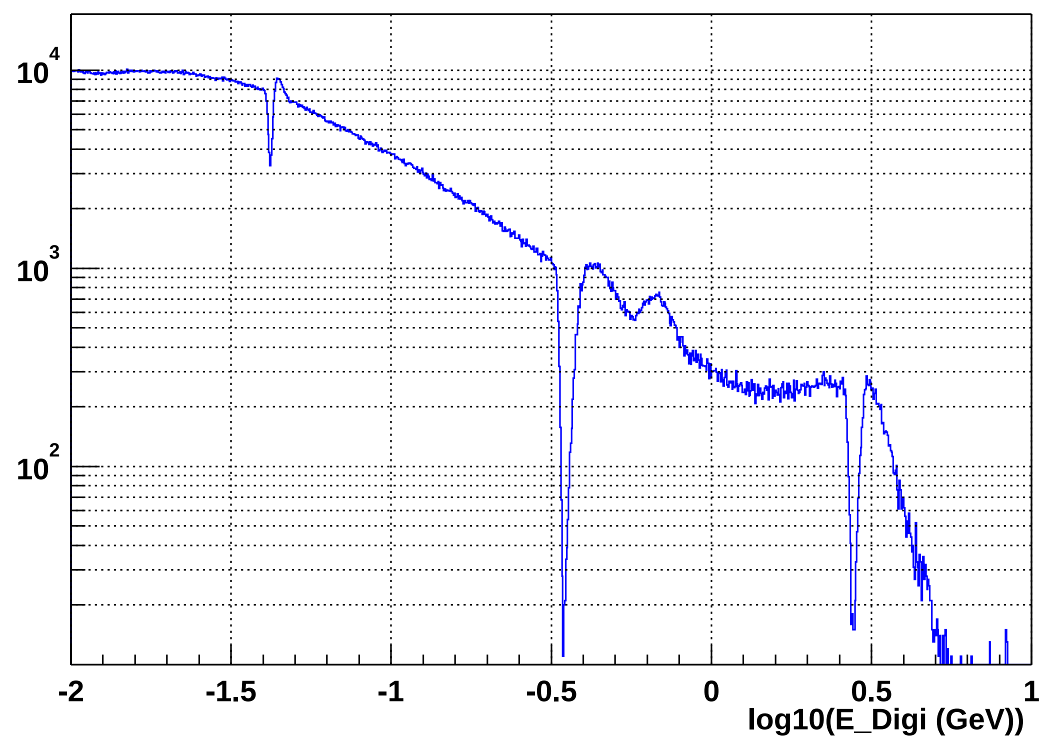


Electronics non-linearities



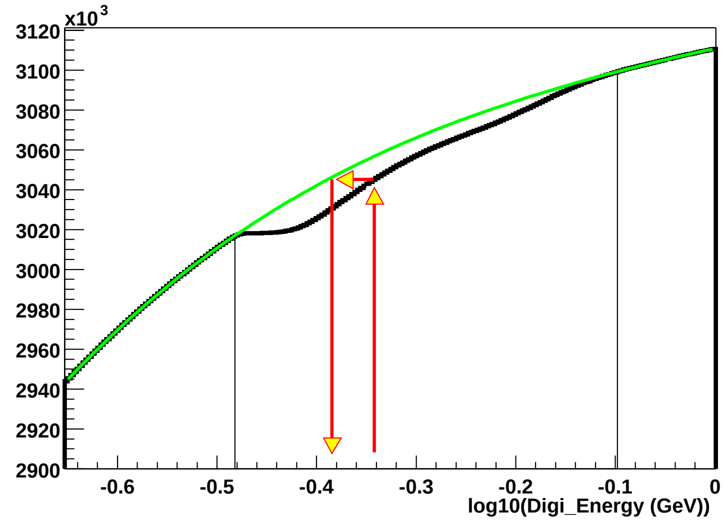
- a look at the crystal energy spectrum averaged over all crystals
- nothing unusual visible
- energy over lightyield spectrum shows problems with the electronics and electronics calibration at range switches

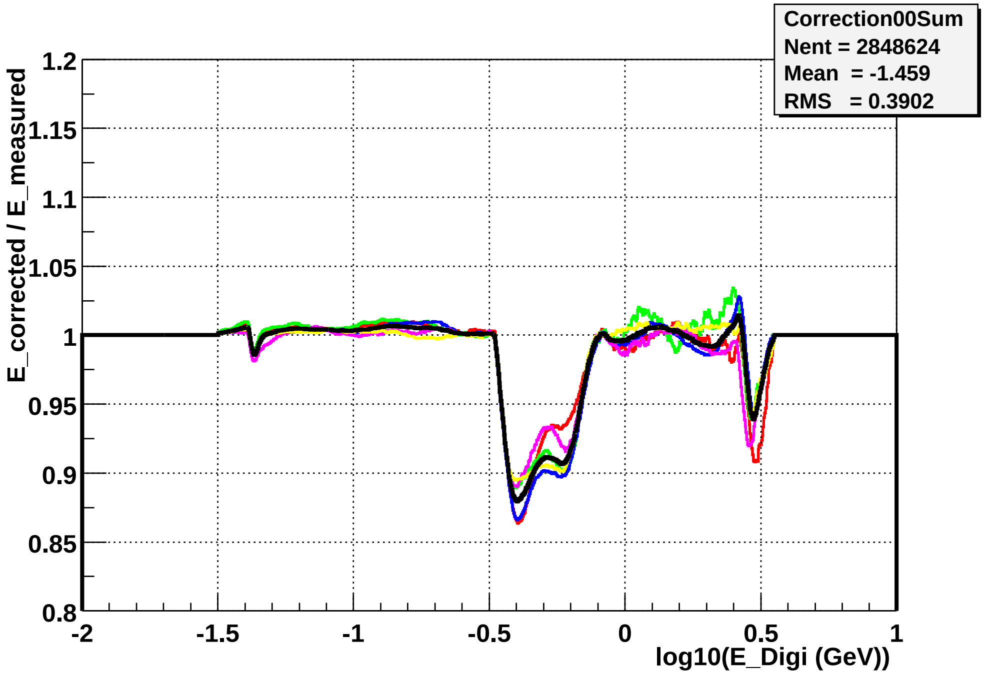


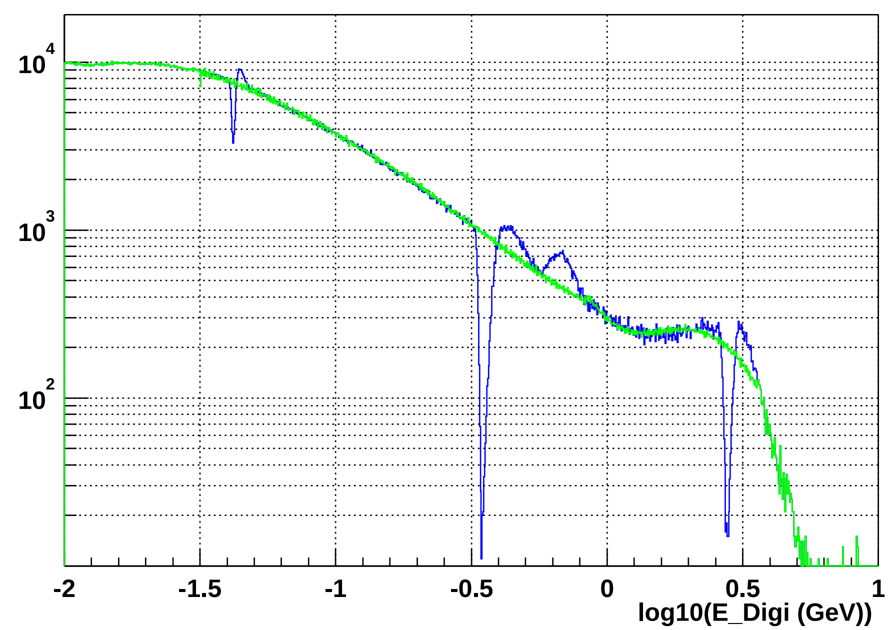


Correction of electronics non-linearities

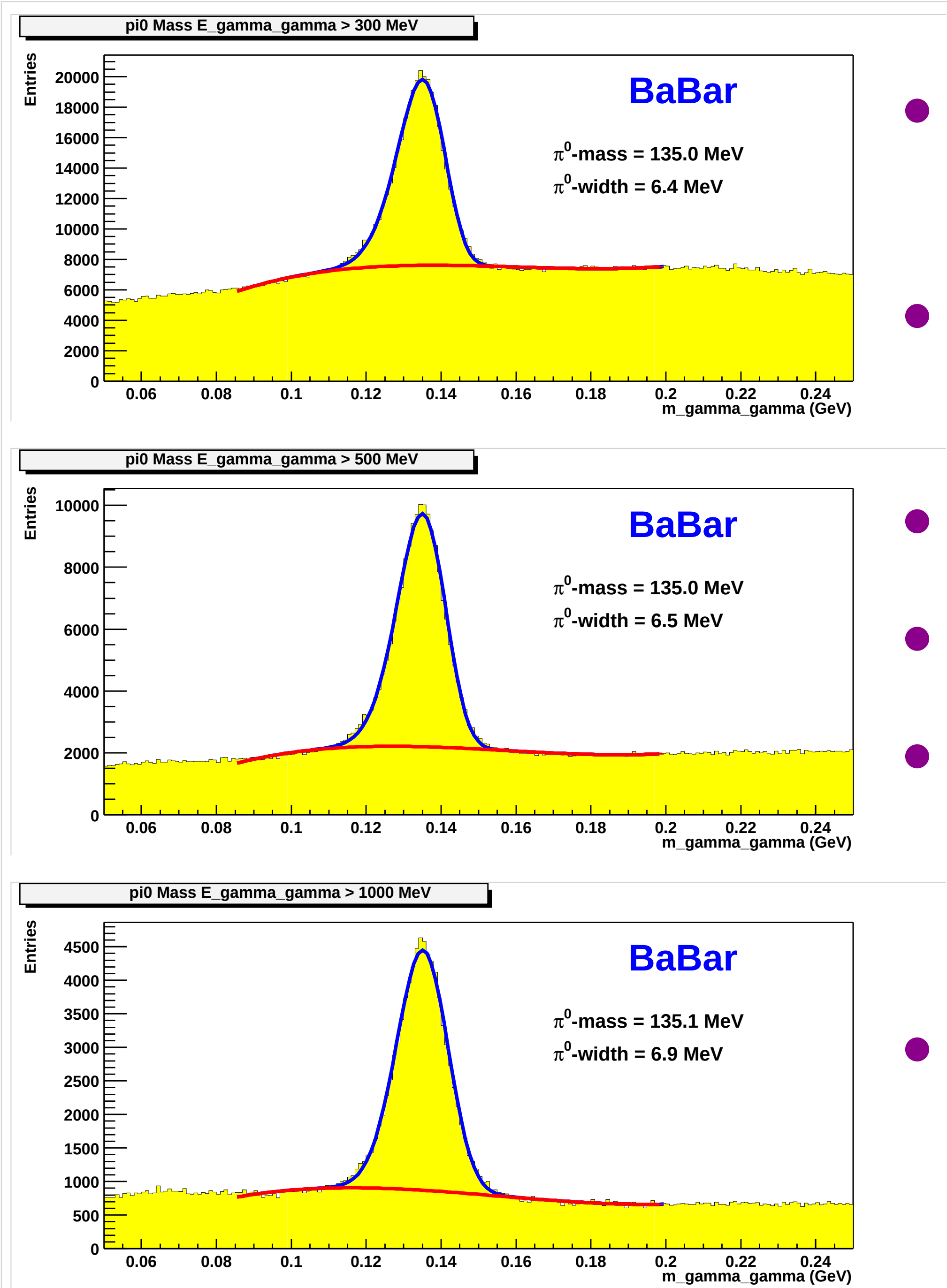
- for the correction the true shape of the energy spectrum needs to be known
- approximate correction is possible assuming the true shape is smooth
- use inverse-transform method to calculate correction







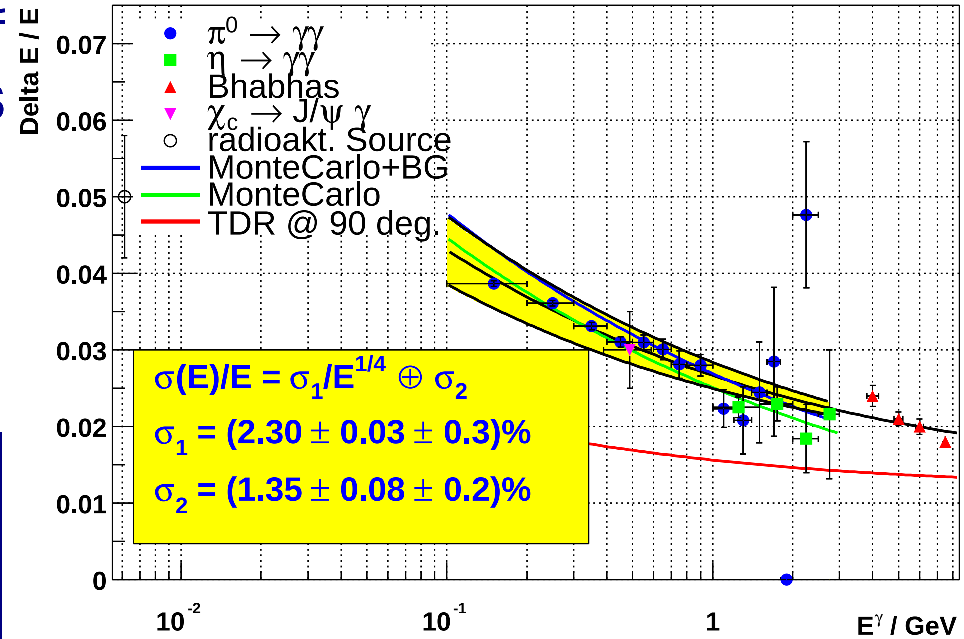
Performance

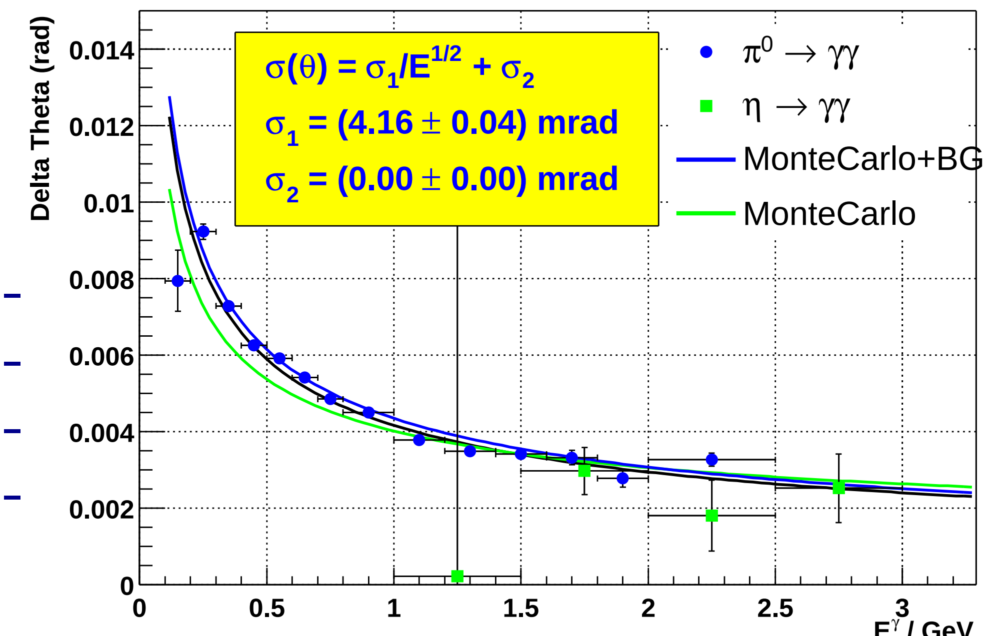


- meanwhile electronics problems also solved in hardware
- main performance monitor: π^0 mass resolution
- plots at $E_{\pi^0} > 300, 500, 1000$ MeV
- typical resolution $4.8\,\%$
- use 'symmetric' π^0, η decays to measure photon energy resolution
- needs tail-parameter (asymmetry of measured over true energy) as input

Resolution from symmetric π^0 and η decays

- 'Measure' mass and width of π^0 and η decays to 2 photons with equal energy.
- Minimize $\chi^2 = \frac{\left(\sigma_i - \sigma_i^{theo}\right)^2}{(\Delta\sigma_i)^2}$, with
  - ▷ $\sigma^{theo} = \sqrt{\frac{m^2}{2}\left(\frac{\Delta E}{E}\right)^2 + \frac{E^4 \sin^2\alpha}{m^2}(\Delta\alpha)^2}$
  - ▷ $\frac{\Delta E}{E} = \frac{e_a}{\sqrt[4]{E}} \oplus e_b$
  - ▷ $\Delta\alpha = \frac{\sqrt{2}\, t_a}{\sqrt{E}} + \sqrt{2}\, t_b$
- beam backgrounds and electronic noise (230 keV after digital filtering) make sparsification necessary: 1 MeV Digi E-cut and 5 MeV Neighbor E-cut





Conclusions

- two calibration methods for the *BABAR* calorimeter for the single-crystal calibration at different energies; accuracy:
  - ▷ $< 0.7\,\%$ (radioactive source)
  - ▷ $1 - 2\,\%$ (Bhabha events)
- global energy calibration for photons from π^0 decays; accuracy:
  - ▷ $< 1.0\,\%$
- electronics non-linearities first fixed in software; since 2001 fixed in hardware
- energy resolution of $\sigma(\mathrm{E})/\mathrm{E} \approx 2.3\,\%/\sqrt[4]{\mathrm{E}} \oplus 1.35\,\%$ limitted by sparisfication mandated by electronics noise and beam background