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Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part IV)

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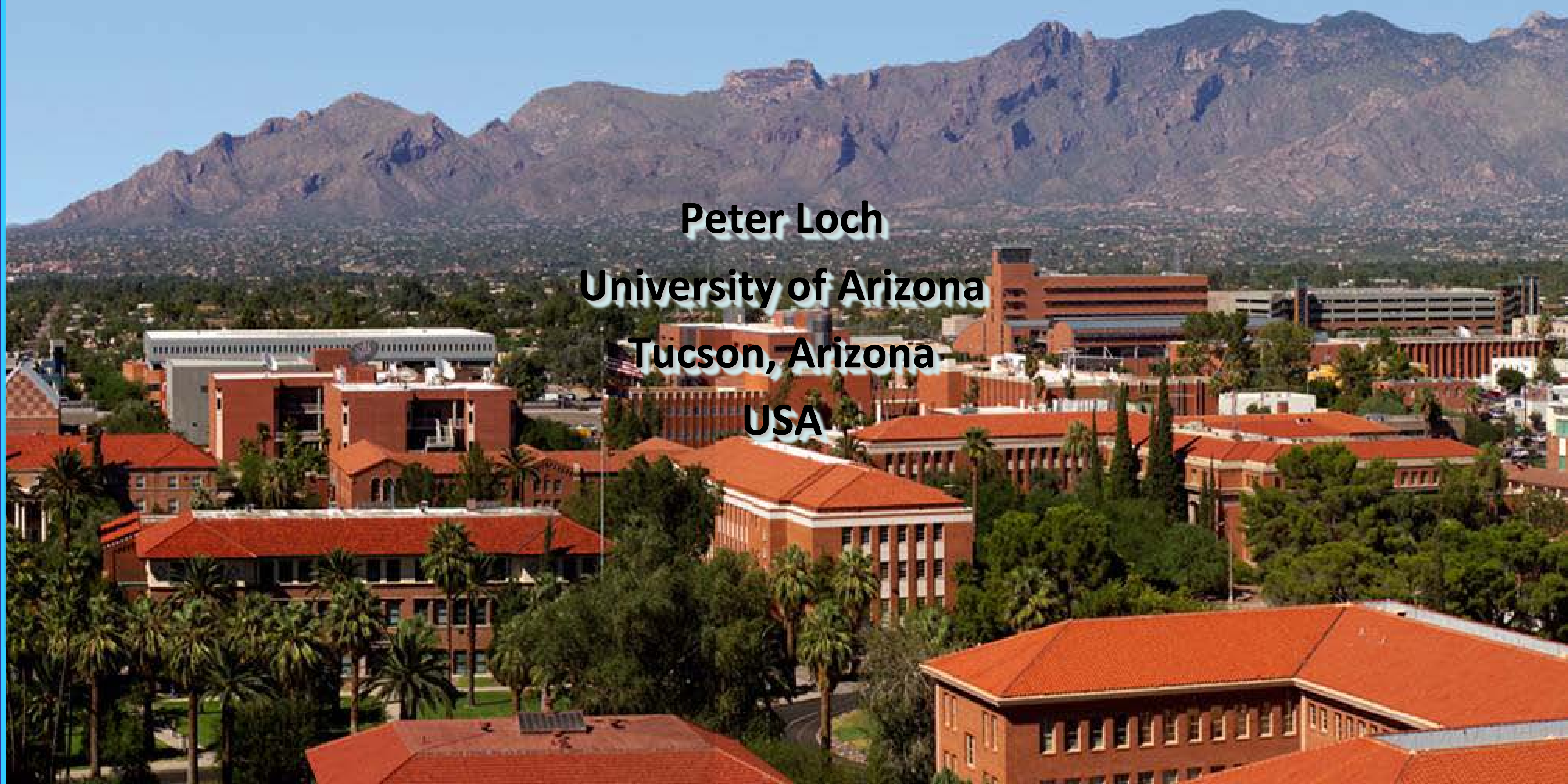

ATLAS

Calorimeter Response

P. Loch
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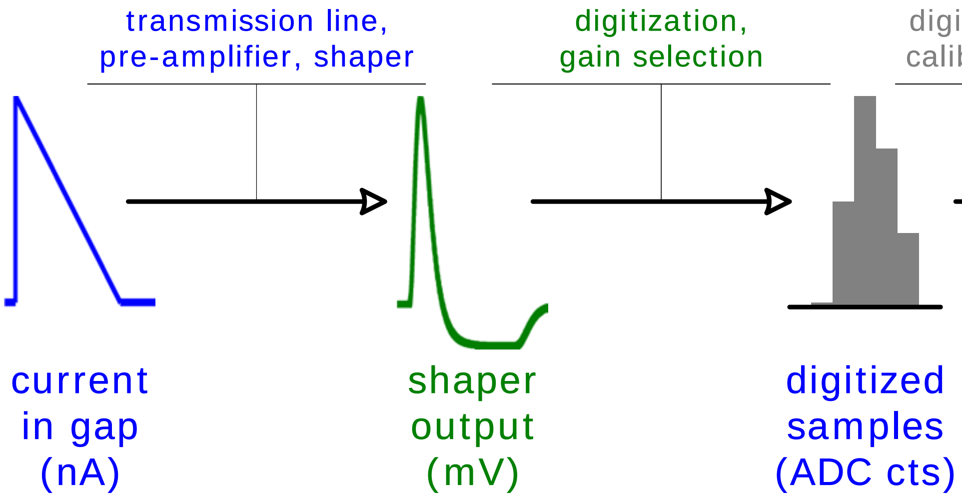
February 18, 2010



Raw Channel Data

- energy E_{raw} (MeV)
- time t (ns)
- quality Q
- selected gain g
- online id id_{online}

What is response?

- Reconstructed calorimeter signal
  - Based on the direct measurement – the raw signal
  - May include noise suppression
- Has the concept of **signal** (or **energy**) **scale**
  - Mostly understood as the basic signal before final calibrations
- Does not explicitly include particle or jet hypothesis
  - Uses only calorimeter signal amplitudes, spatial distributions, etc.

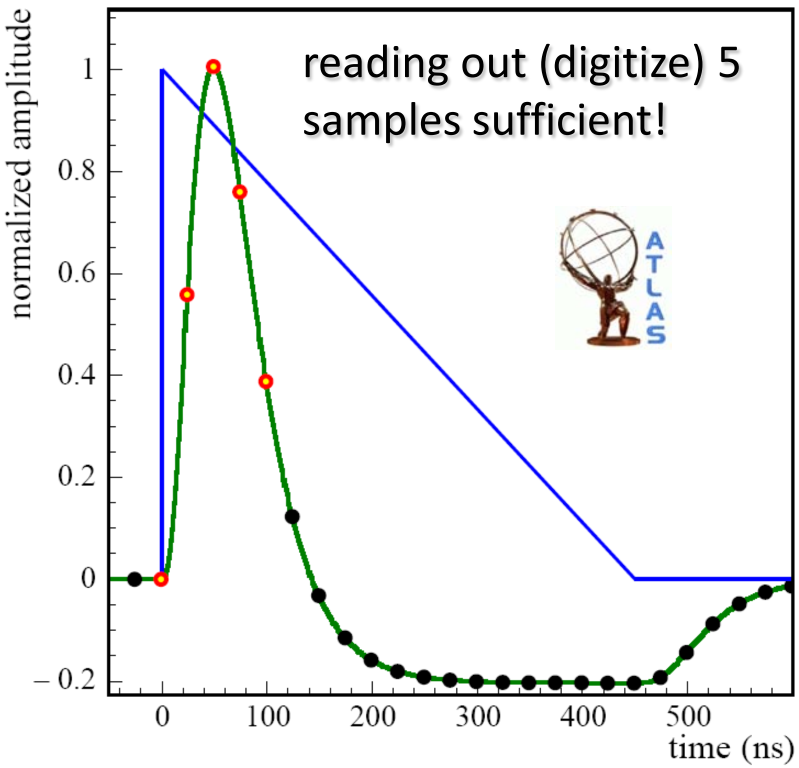
$$E_{raw} = A_{peak} \times \underbrace{\left[\mathrm{ADC} \rightarrow \mathrm{nA}\right]}_{\text{current calibration}}$$

$$\times \underbrace{\left(\left[\mathrm{HV}\right] \times \left[\text{cross-talk}\right] \times \left[\text{purity}\right]\right)}_{\text{electronic and efficiency corrections}}$$

$$\times \underbrace{\left[\mathrm{nA} \rightarrow \mathrm{MeV}\right]}_{\text{energy calibration}}$$

Slow signal collection in liquid argon calorimeters

- ~450 ns @ 1 kV/mm drift time versus 40 MHz/25 ns bunch crossing time
  - Measure only $I_0 = I(t_0)$ (integrate <25 ns)
- Applying a fast bi-polar signal shaping
  - Shaping time ~15 ns
    - With well known shape
  - Shaped pulse integral = 0
    - Net average signal contribution from pile-up = 0
    - Need to **measure the pulse shape** (time sampled readout)
  - Total integration ~25 bunch crossings
    - 23 before signal, 1 signal, 1 after signal



ATLAS Digital Filtering

P. Loch
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What is digital filtering

- Unfolds the expected (theoretical) pulse shape from a measured pulse shape

Determines signal amplitude and timing

- Minimizes noise contributions
  - Noise reduced by ~1.4 compared to single reading
  - Note: noise depends on the luminosity
- Requires explicit knowledge of pulse shape
  - Folds triangular pulse with transmission line characteristics and active electronic signal shaping
  - Characterized by signal transfer functions depending on *R*, *L*, *C* of readout electronics, transmission lines

Filter coefficients from calibration system

- Pulse "ramps" for response
  - Inject known currents into electronic chain
  - Use output signal to constrain coefficients
- Noise for auto-correlation
  - Signal history couples fluctuations in time sampled readings

Signal amplitude A_{peak} (energy):

$$A_{\mathrm{peak}} = \sum_{i=1}^{N_s} a_i \left(s_i - p \right), \text{ with } \begin{cases} a_i & \text{digital filter coefficient} \\ s_i & \text{reading in time sample} \\ p & \text{pedestal reading} \end{cases}$$

Signal peak time t_{peak}:

$$A_{\mathrm{peak}} t_{\mathrm{peak}} = \sum_{i=1}^{N_s} b_i \left(s_i - p \right)$$

W.E. Cleland and E.G. Stern, Nucl. Inst. Meth. **A338 (1994) 467.**

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Constraints for digital filter coefficients a_i:

$$\sum_{i=1}^{N_s} a_i g_i = 1$$, with g_i being the normalized physics pulse shape

$$\sum_{i=1}^{N_s} a_i \frac{\partial g_i}{\partial t} = 0$$

ATLAS Digital Filter Coefficients

S_i .... signal amplitude in sample i
P .... analog-to-digital converter pedestal
N_s .... number of digital samples (def. 5)
a_i .... digital filter coefficient
R_{ij} .... noise auto-correlation
g_i .... normalized physics pulse shape:

Filter Coefficients

Determined by:

- Known pulse shape
- Minimizing noise

to 1st order independent of time jitter!

$$\sum_{i=1}^{N_s} a_i g_i = 1$$

$$\sum_{i=1}^{N_s} a_i \frac{\partial g_i}{\partial t} = \sum_{i=1}^{N_s} a_i g_i' = 0$$

$$\sum_{i=1}^{N_s}\sum_{j=1}^{N_s} a_i a_j \sigma_i \sigma_j R_{ij} \rightarrow \min$$

Lagrange Multipliers

$$a_i = \sum_{j=1}^{N_s} R_{ij}^{-1}\left(\lambda g_j - \mu g_j'\right) \begin{cases} \lambda = \frac{1}{\Delta}\sum_{i=1}^{N_s}\sum_{j=1}^{N_s} R_{ij}^{-1} g_i' g_j' \\ \mu = \frac{1}{\Delta}\sum_{i=1}^{N_s}\sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j' \\ \Delta = \left(\sum_{i=1}^{N_s}\sum_{j=1}^{N_s} R_{ij}^{-1} g_i' g_j'\right)\cdot\left(\sum_{i=1}^{N_s}\sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j\right) - \left(\sum_{i=1}^{N_s}\sum_{j=1}^{N_s} R_{ij}^{-1} g_i g_j'\right)^2 \end{cases}$$

Calorimeter Response

What does signal or energy scale mean?

- Indicates a certain level of signal reconstruction
  - Standard reconstruction often stops with a **basic signal scale**
- **Electromagnetic energy scale** is a good reference
  - Uses direct signal proportionality to electron/photon energy
  - Accessible in test beam experiments
  - Can be validated with isolated particles in collision environment
  - Provides good platform for data and simulation comparisons
  - Does not necessarily convert the electron signal to the true photon/electron energy!
- Hadronic signals can also be calculated on this scale
  - Good platform for comparisons to simulations
  - But does not return a good estimate for the deposited energy in non-compensating calorimeters – see later discussion!
- Is not a fundamental concept of physics!
  - Is a calorimeter feature
  - Definition varies from experiment to experiment

Recall electrons/photons in sampling calorimeters:

$$E_{\mathrm{vis}} = N_{\times} \int_{0}^{d_{\mathrm{active}}} \frac{dE}{dx} dx = N_{\times} \Delta E \propto E_0$$

Electron sampling fraction S_{e} relates signal and deposited energy:

$$S_{\mathrm{e}} = \frac{E_{\mathrm{vis}}}{E_{\mathrm{dep}}} \approx \frac{E_{\mathrm{vis}}}{E_0} \rightarrow E_{\mathrm{rec}}^{\mathrm{em}} = \frac{1}{S_{\mathrm{e}}} E_{\mathrm{vis}} = c_{\mathrm{e}} A \overset{!}{\equiv} E_{\mathrm{dep}} \approx E_0$$

with c_{e} being the electron calibration constant.

(S_{e} is a unitless fraction, c_{e} converts a signal unit into an energy unit, e.g. nA $\rightarrow$ MeV)

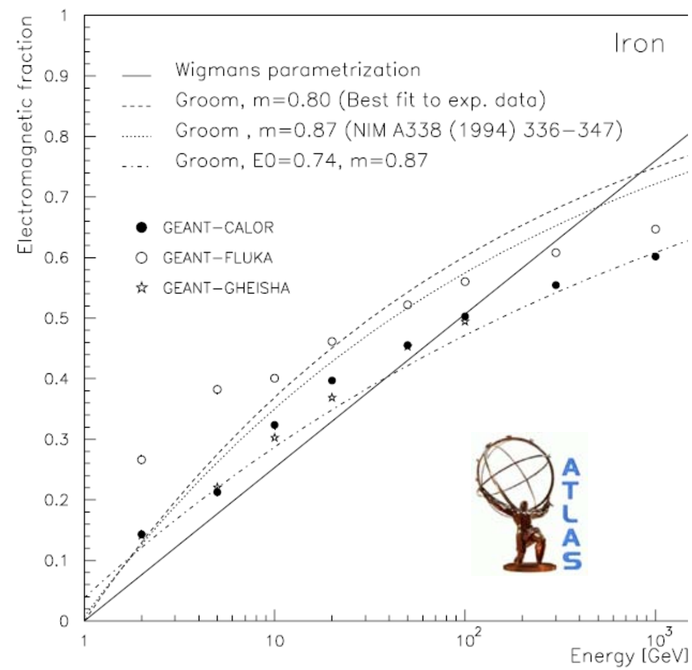
Response often denoted $e = e(E_{\mathrm{dep}}) = E_{\mathrm{rec}}^{\mathrm{em}}(c_{\mathrm{e}}, A)$

Hadronic Response (1)

Single hadron reponse:

$$\pi(E_0) = f_{\mathrm{em}}(E_0)\cdot e + \left(1 - f_{\mathrm{em}}(E_0)\right)\cdot h$$

$$\text{with } \begin{cases} f_{\mathrm{em}}(E_0) & \text{intrinsic em fraction} \\ h & \text{response of pure hadronic shower branch} \end{cases}$$



Non-compensation measure:

$$\frac{e}{\pi} = \frac{1}{f_{\mathrm{em}}(E_0) + \left(1 - f_{\mathrm{em}}(E_0)\right)\cdot h/e}$$

Popular parametrization by Groom et al.:

$$f_{\mathrm{em}}(E_0) = 1 - \left(E_0/E_{\mathrm{base}}\right)^{m-1}$$

$$m = 0.80 - 0.85,\ E_{\mathrm{base}} = \begin{cases} 1.0\ \mathrm{GeV} & \text{for } \pi^{\pm} \\ 2.6\ \mathrm{GeV} & \text{for } p \end{cases}$$

D.Groom et al., NIM A338, 336-347 (1994)

Hadronic Response (2)

Observable

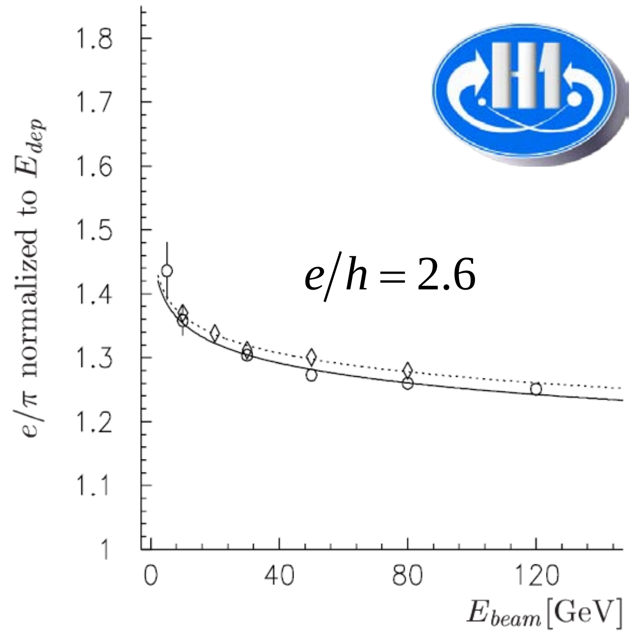
$$\frac{e}{\pi} = \frac{e}{\left(E_0/E_{\mathrm{base}}\right)^{m-1} h + \left(1-\left(E_0/E_{\mathrm{base}}\right)^{m-1}\right) e}$$

$$= \frac{1}{1-\left(1-h/e\right)\left(E_0/E_{\mathrm{base}}\right)^{m-1}}$$

provides experimental access to characteristic calorimeter variables in pion test beams by fitting *h/e*, E_{base} and *m* from the energy dependence of the pion signal on electromagnetic energy scale:

$$\frac{e}{\pi} = \frac{E_0}{E_{\mathrm{rec}}^{\mathrm{em}}(\pi)} \approx \frac{E_{\mathrm{dep}}}{E_{\mathrm{rec}}^{\mathrm{em}}(\pi)}$$

Note that *e/h* is often constant, for example: in both H1 and ATLAS about 50% of the energy in the hadronic branch generates a signal independent of the energy itself



Complex mixture of hadrons and photons

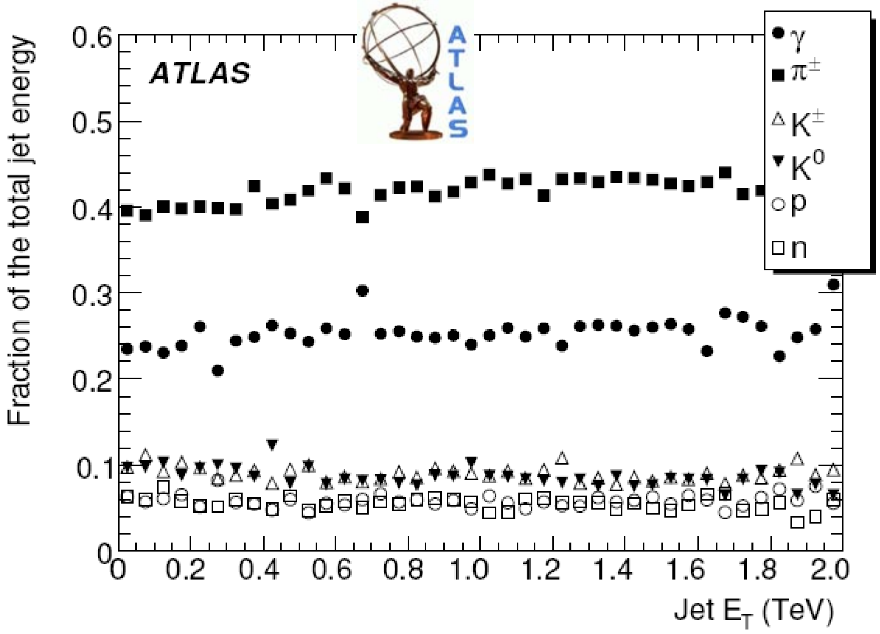
- Not a single particle response
- Carries initial electromagnetic energy
  - Mainly photons

Very simple response model

- Assume the hadronic jet content is represented by 1 particle only
  - Not realistic, but helpful to understand basic response features

More evolved model

- Use fragmentation function in jet response
  - This has some practical considerations
    - E.g. jet calibration in CDF
- Gets non-compensation effect
  - Does not address acceptance effect due to shower overlaps



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$$\frac{j(E_{\text{jet}})}{e} = f_{\gamma}^{\text{jet}} + \left(1 - f_{\gamma}^{\text{jet}}\right) \cdot \left(f_{\text{em}} + \left(1 - f_{\text{em}}\right)\frac{h}{e}\right)$$

$$f_{\text{em}} = f_{\text{em}}(E_{\text{jet}}^{\text{had}}),\ E_{\text{jet}}^{\text{had}} = \left(1 - f_{\gamma}^{\text{jet}}\right) E_{\text{jet}}$$

[single particle approximation]

$$f_{\text{em}} = 1 - \left(\frac{E_{\text{jet}}^{\text{had}}}{E_{\text{base}}}\right)^{1-m}$$

[Groom's parameterization]

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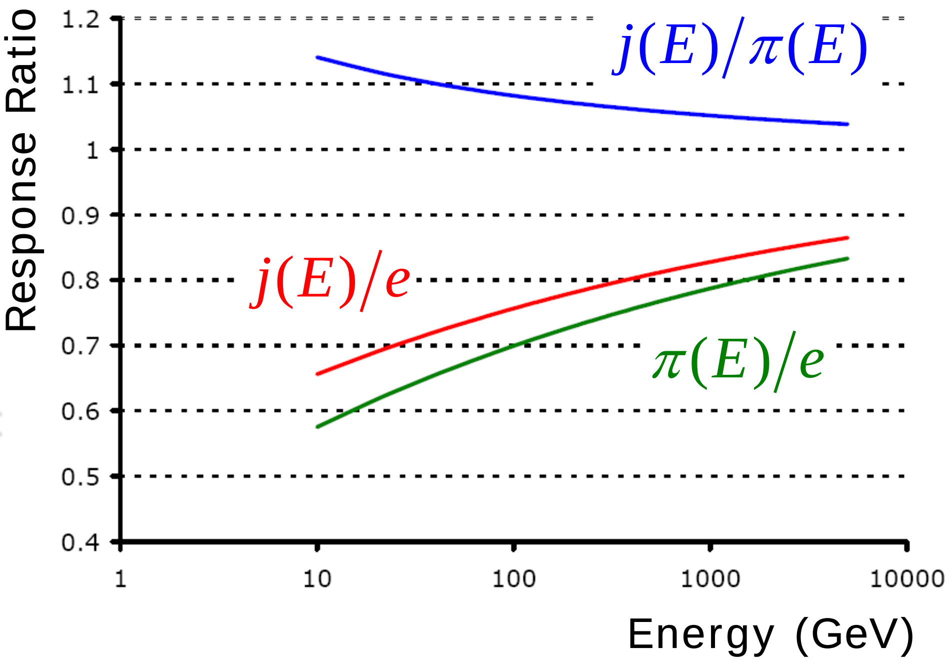

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$$= f_{\gamma}^{\text{jet}} + \left(1 - f_{\gamma}^{\text{jet}}\right) \sum_{\text{hadrons}} \left[1 - \left(\frac{E_{\text{had}}}{E_{\text{base}}}\right)^{m-1} + \left(\frac{E_{\text{had}}}{E_{\text{base}}}\right)^{m-1} h/e \right]$$

$$= f_{\gamma}^{\text{jet}} + \left(1 - f_{\gamma}^{\text{jet}}\right) \sum_{\text{hadrons}} \left(1 + \left(E_{\text{had}}/E_{\text{base}}\right)^{m-1} \left(h/e - 1\right)\right)$$

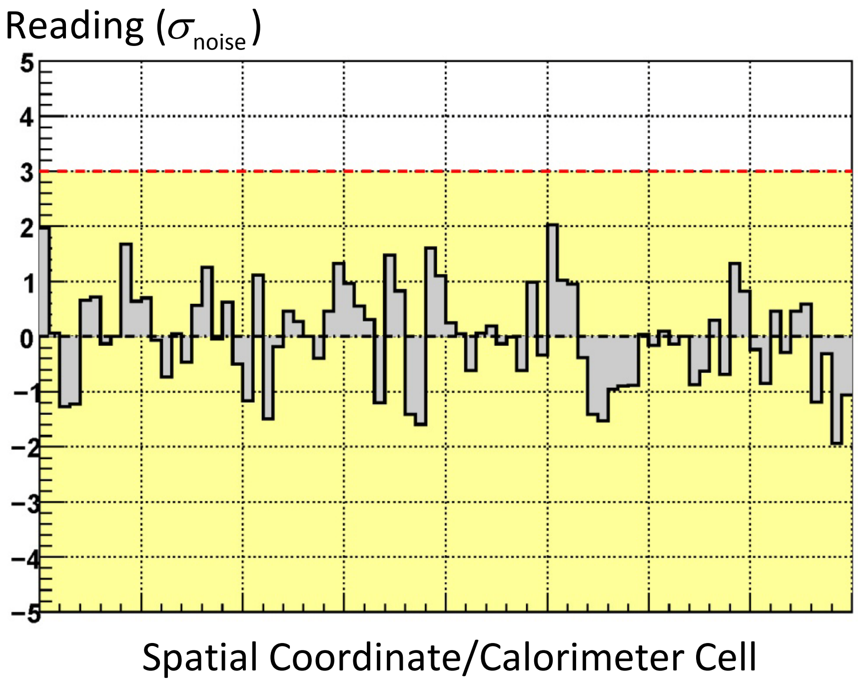
Acceptance and Noise in Jet Response

Noise

- Fluctuations of the “zero” or “empty” signal reading
  - Pedestal fluctuations
- Independent of the signal from particles
  - At least to first order
- Mostly incoherent
  - No noise correlations between readout channels
    - Noise in each channel is independent oscillator
- Gaussian in nature
  - Pedestal fluctuations ideally follow normal distribution around 0
  - Width of distribution (1 σ) is noise value

Signal significance

- Noise can fake particle signals
  - Only signals exceeding noise can be reliably measured
- Signals larger than 3 $\times$ noise are very likely from particles
  - Gaussian interpretation of pedestal fluctuations
- Calorimeter signal reconstruction aims to suppress noise
  - Average contribution = 0, but adds to fluctuations!



Small signal:

- Noise only
- Signal on top of noise
- Sum of noise and signal
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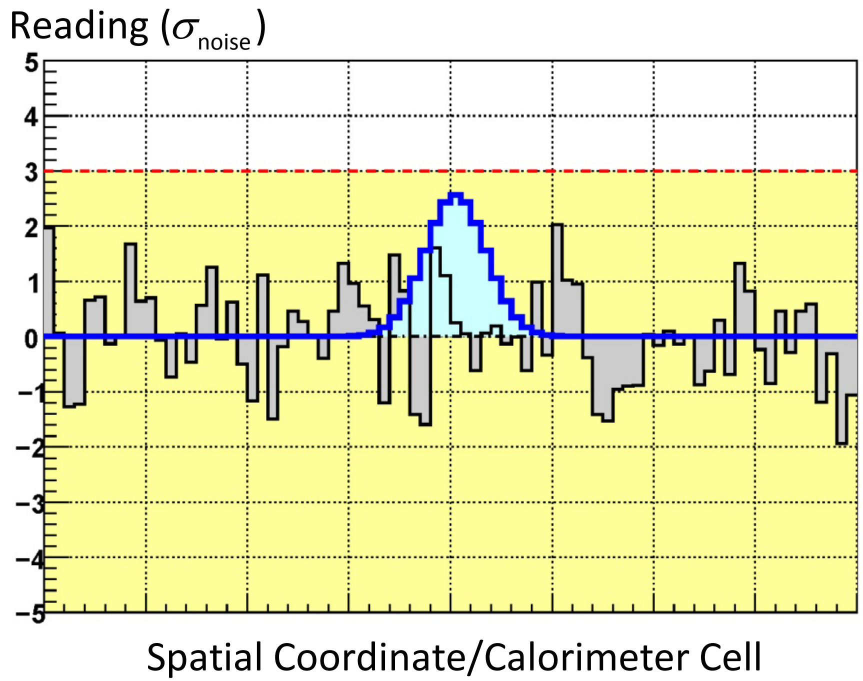

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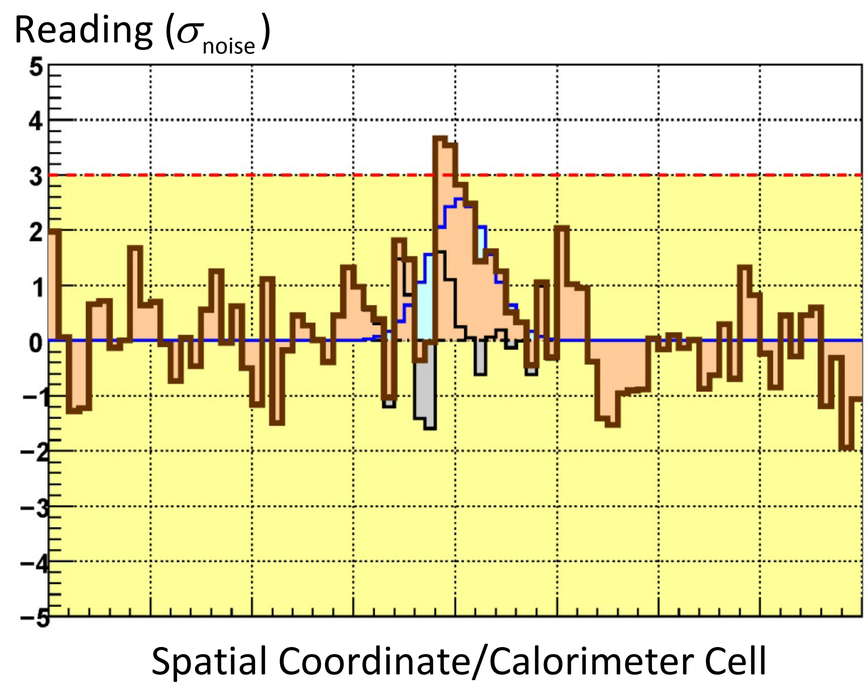

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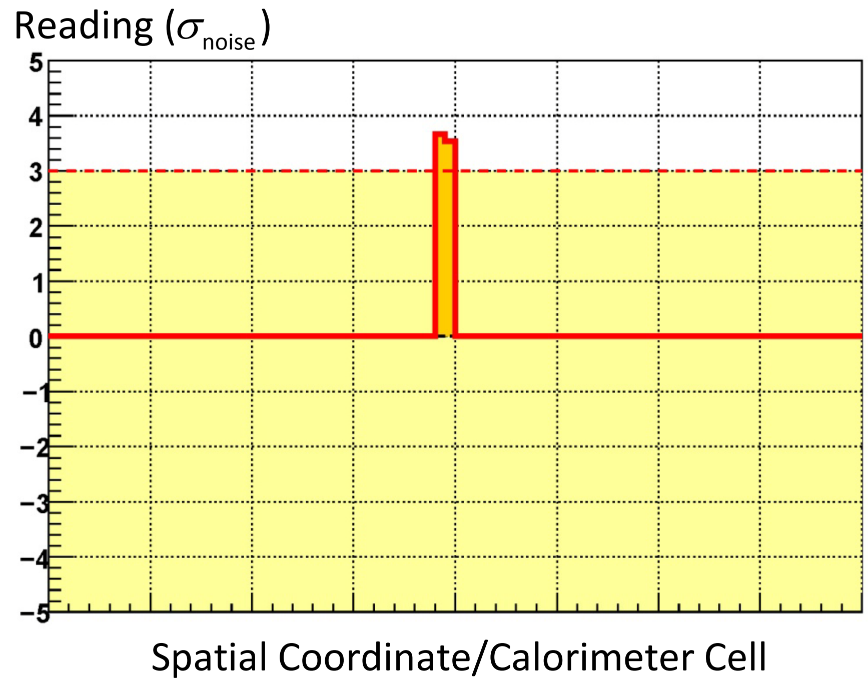

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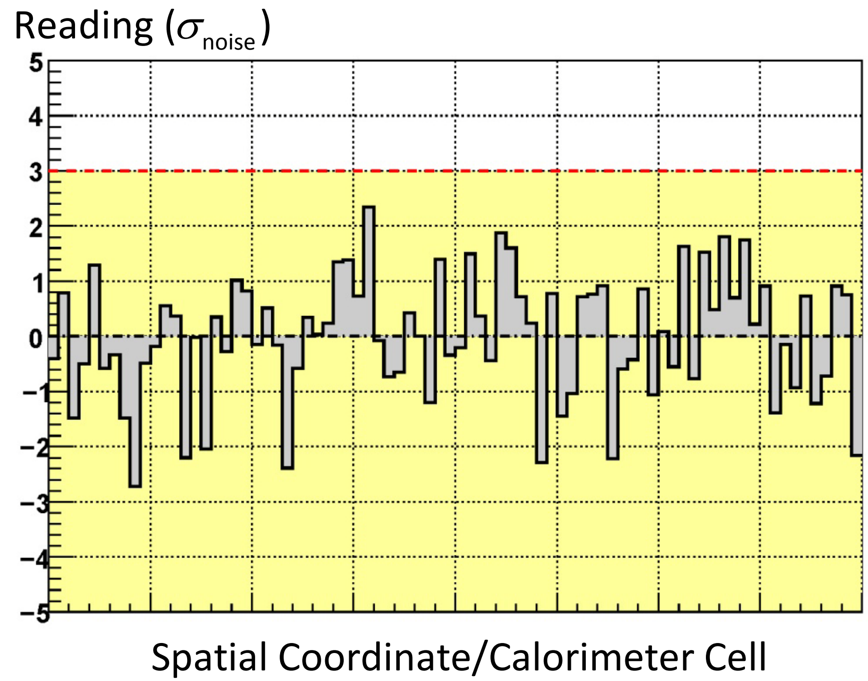

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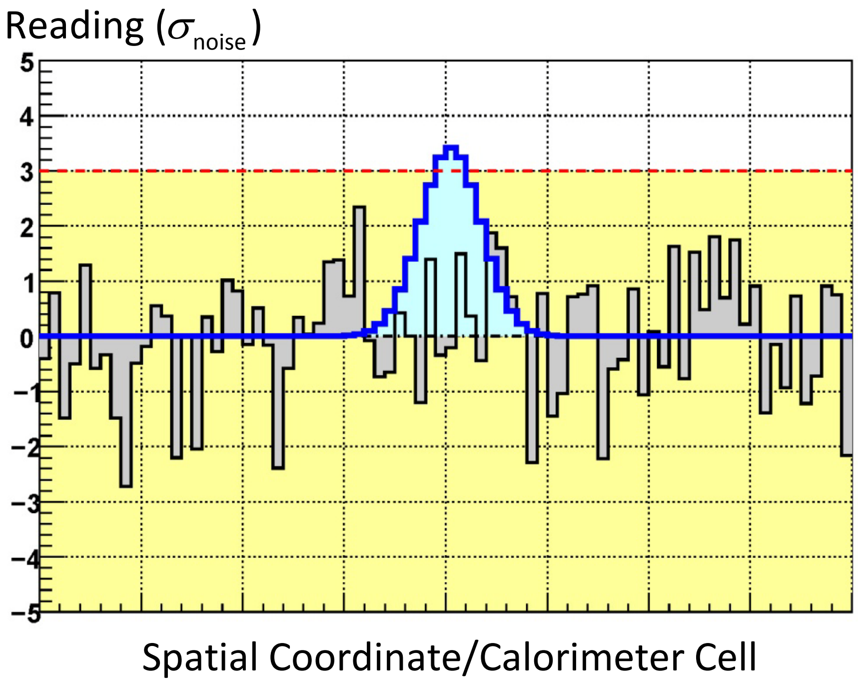

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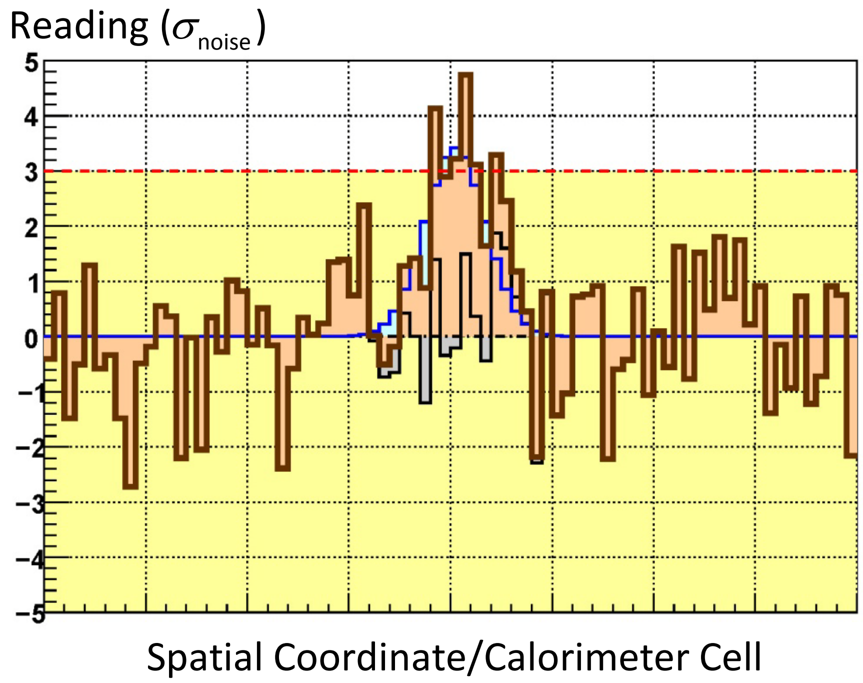

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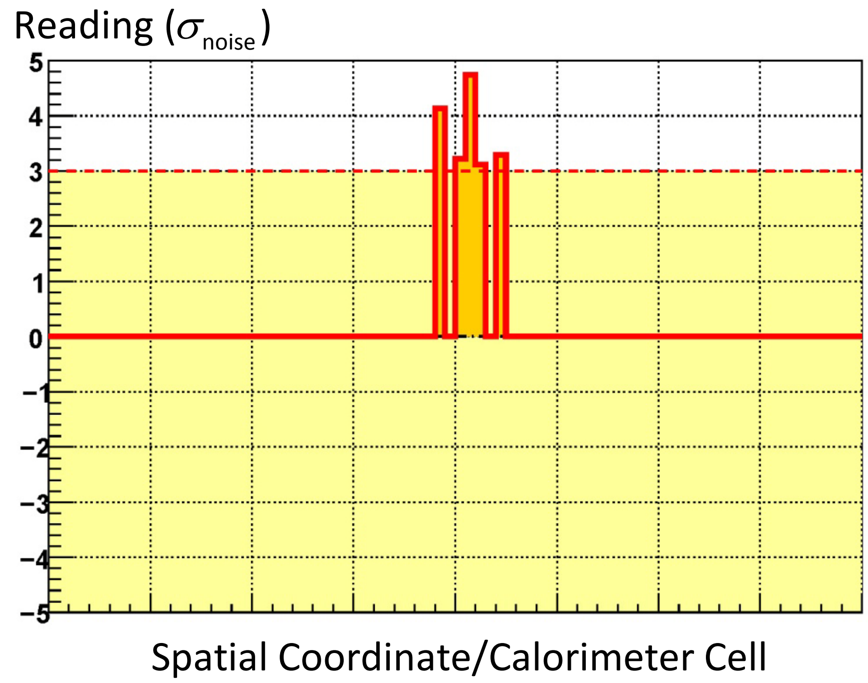

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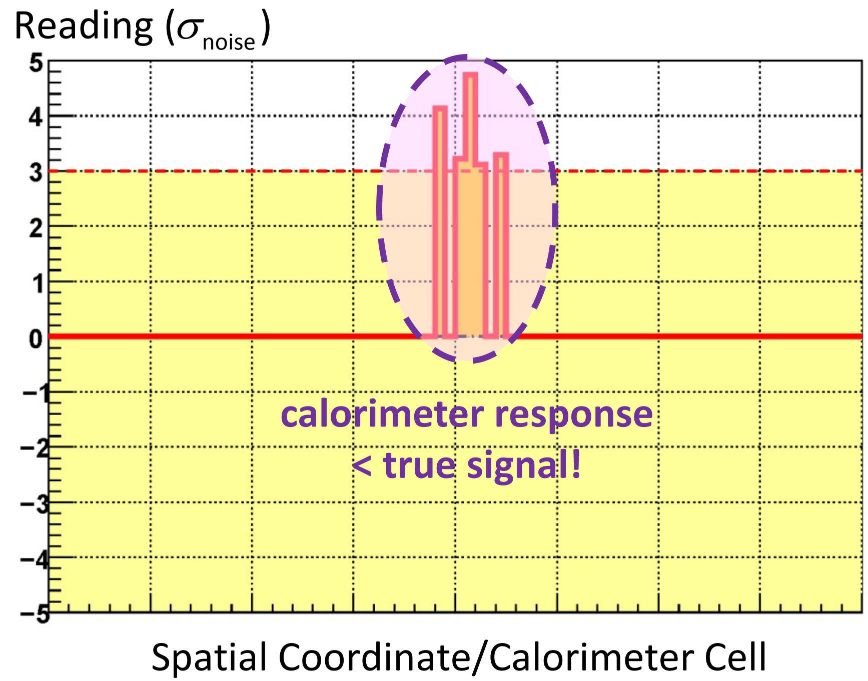

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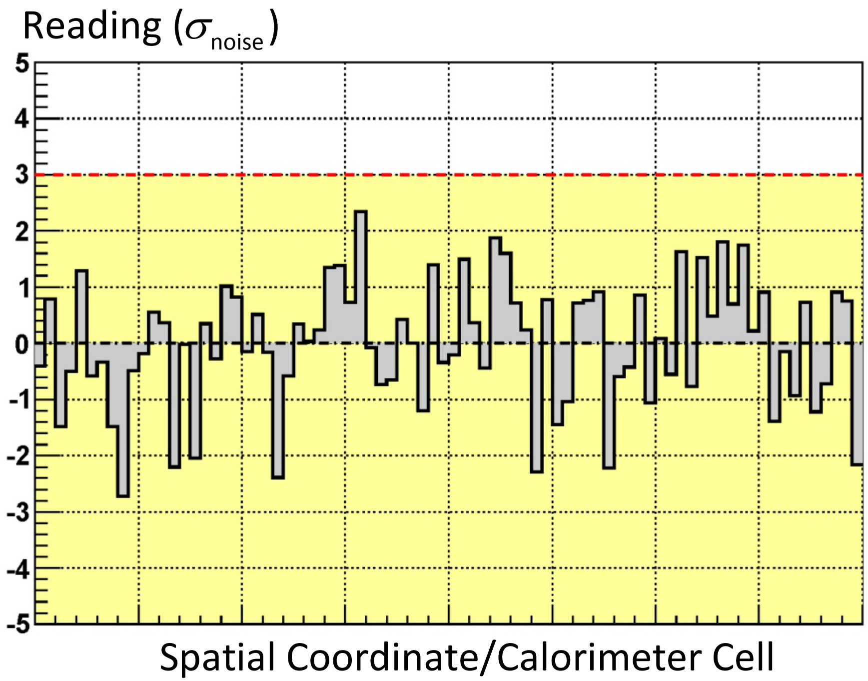

Small signal, two particles:

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- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

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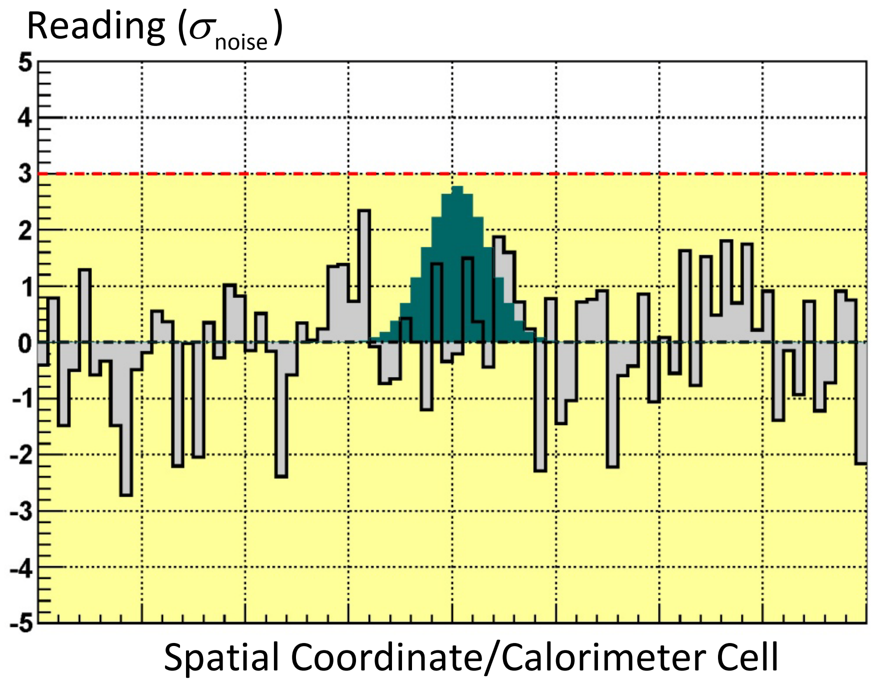
  - Pedestal fluctuations ideally follow normal distribution around 0
  - Width of distribution (1 σ) is noise value

Signal significance

- Noise can fake particle signals
  - Only signals exceeding noise can be reliably measured
- Signals larger than 3 × noise are very likely from particles
  - Gaussian interpretation of pedestal fluctuations
- Calorimeter signal reconstruction aims to suppress noise
  - Average contribution = 0, but adds to fluctuations!



Small signal, first particle:

- Noise only
- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

ATLAS

Acceptance and Noise in Jet Response

P. Loch
U of Arizona
February 18, 2010

Noise

- Fluctuations of the “zero” or “empty” signal reading
  - Pedestal fluctuations
- Independent of the signal from particles
  - At least to first order
- Mostly incoherent
  - No noise correlations between readout channels
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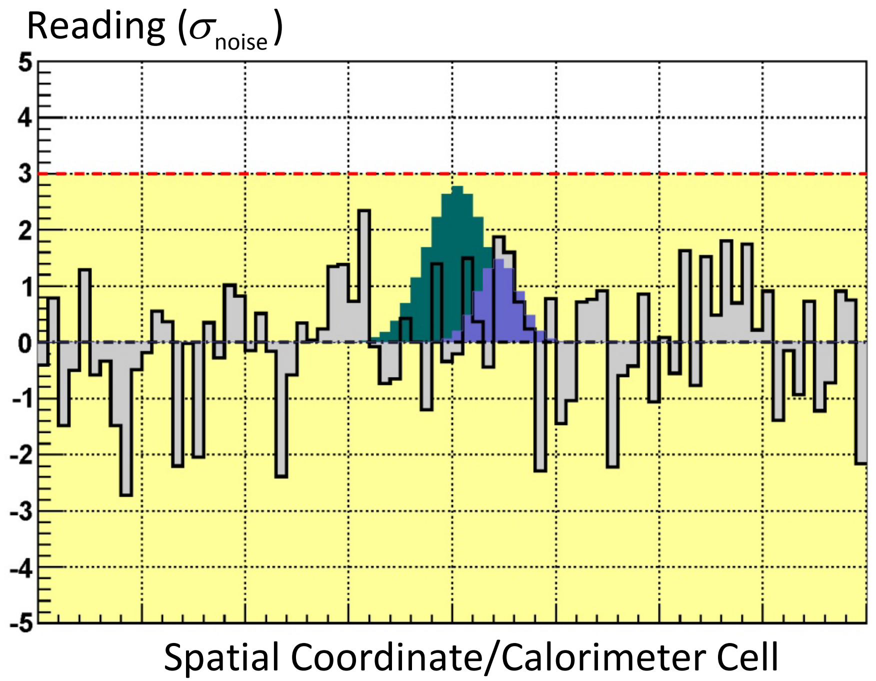

Small signal, first and second particle:

- Noise only
- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

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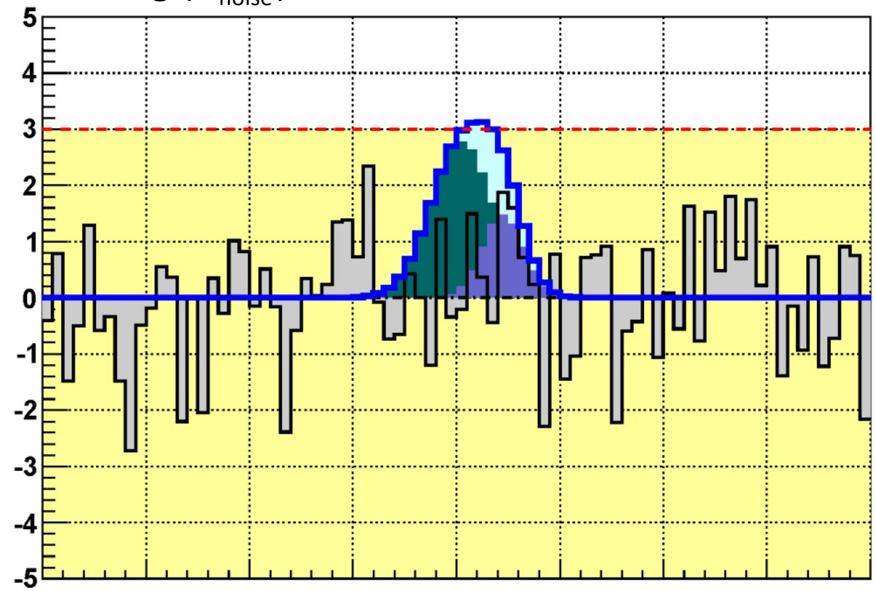

Small signal, two particle, sum:

- Noise only
- Signal on top of noise
- Sum of noise and signal
- Signal after noise suppression

Acceptance and Noise in Jet Response

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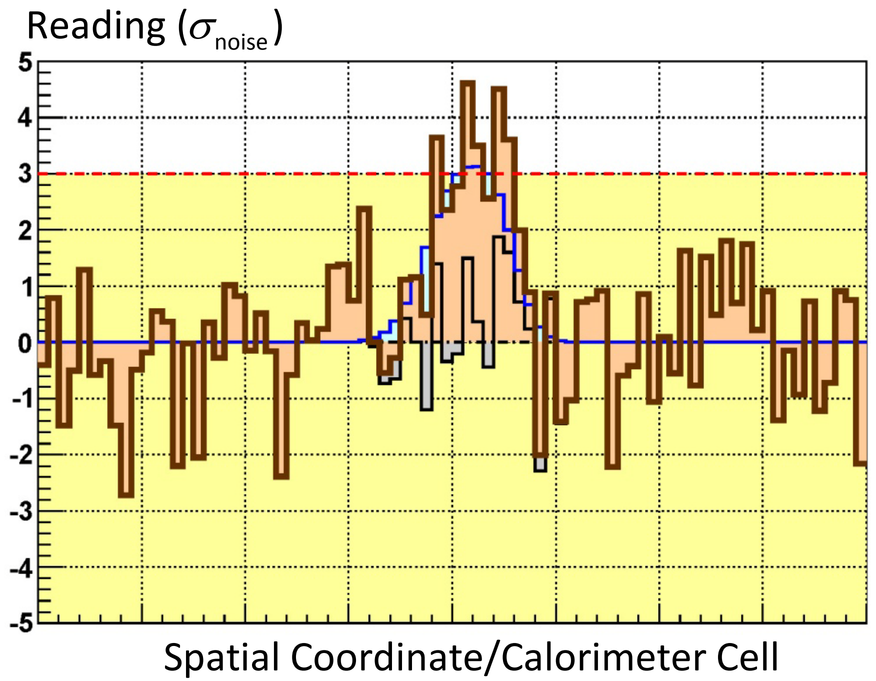

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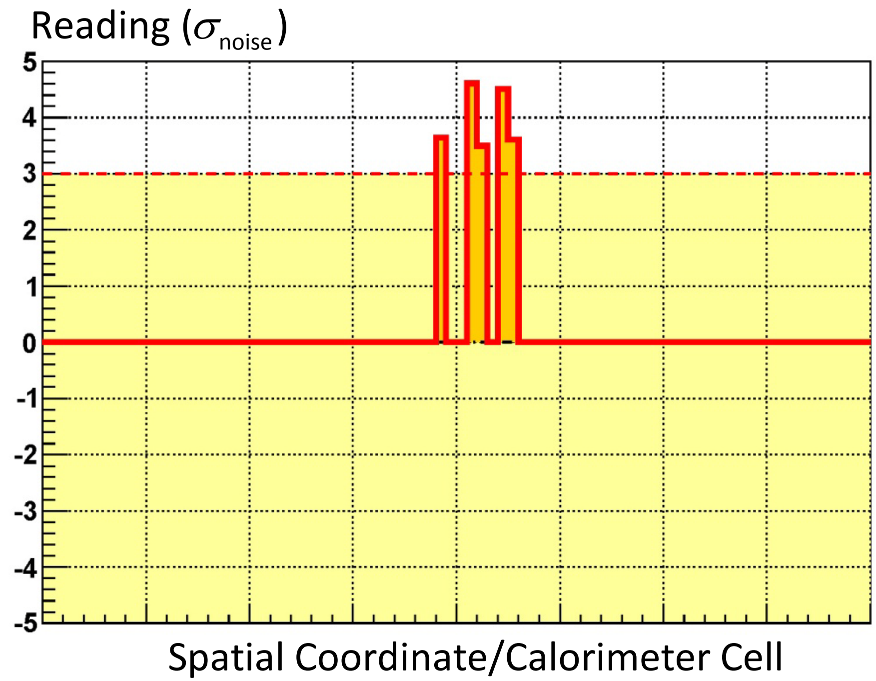

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THE UNIVERSITY OF ARIZONA.

Acceptance and Noise in Jet Response

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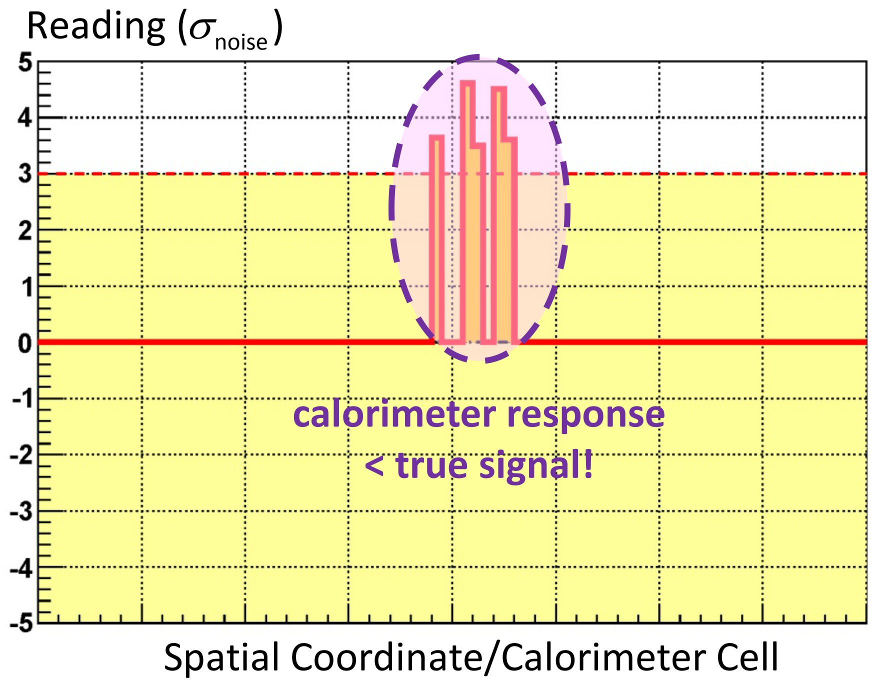

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