Muon g-2

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Calorimeter Algorithms

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(g-2) computing review

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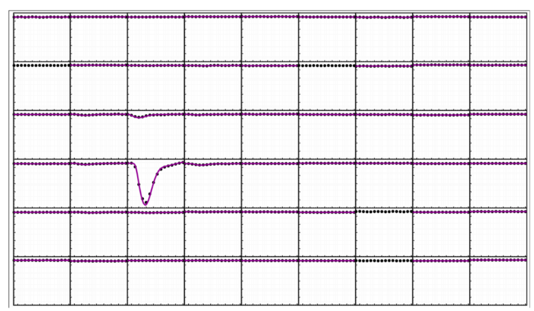
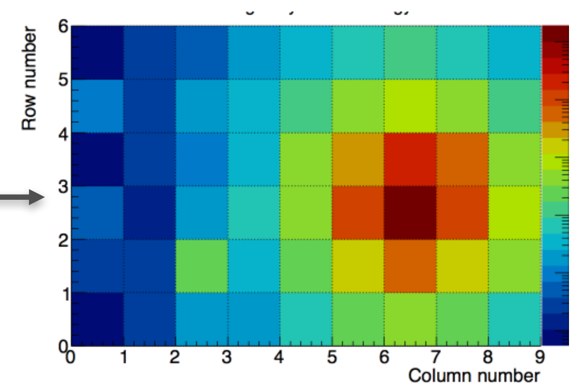
Requirements: overview

- Transform digitized detector waveforms into reconstructed decay events
  - pulse finding: pulse island -> pulse area [ADC counts] & time
  - calibration: pulse area -> pulse photoelectrons
  - clustering: pulse collection -> decay event energy, time, position

positron impact →  → 

→ (E,t)

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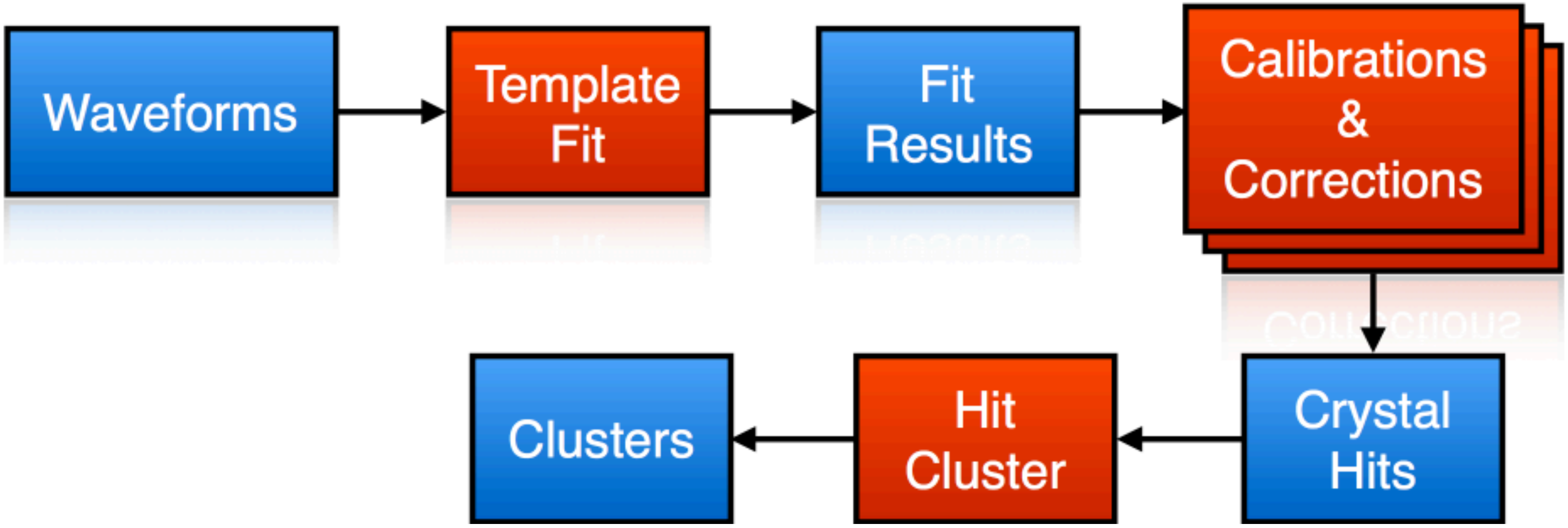
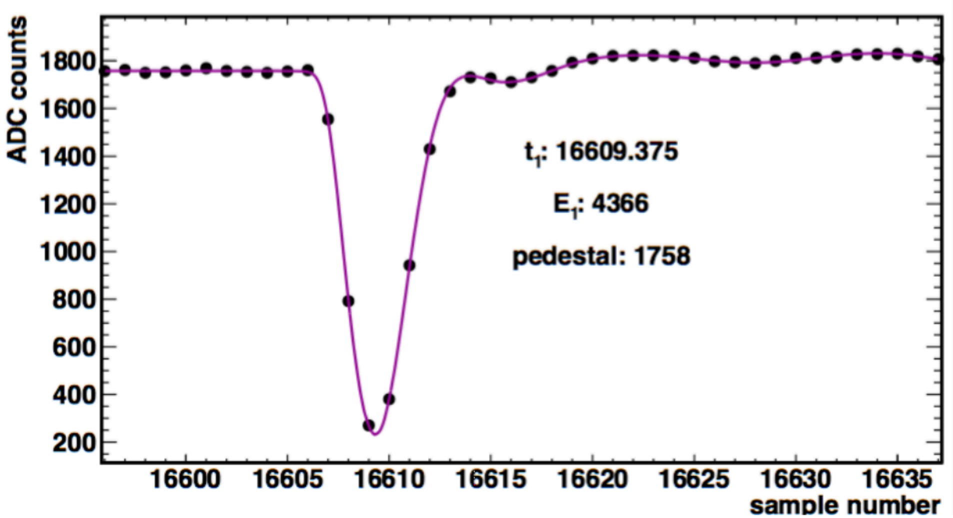


Requirements: pulse finding

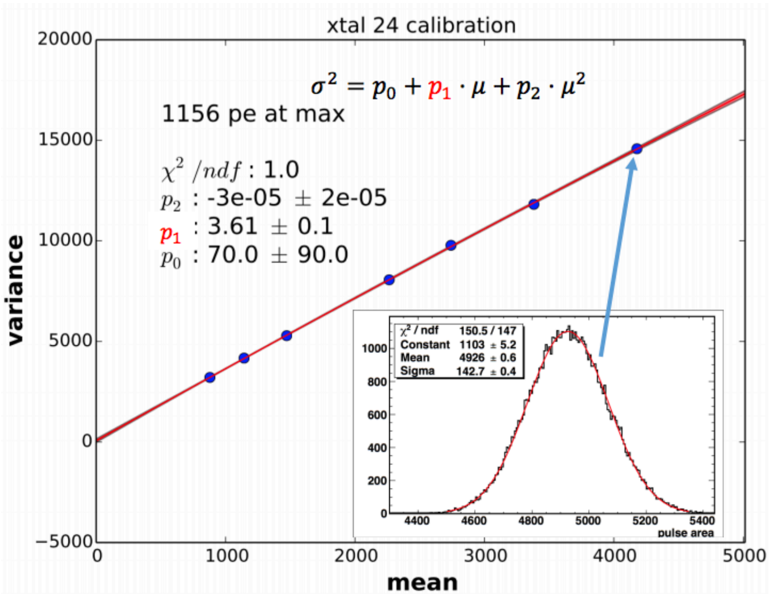
- separate distinct events for all $\Delta t > 5\ \mathrm{ns}$ (pileup separation)
- do not introduce early-to-late systematic timing shifts
- have low energy threshold for pulse reconstruction



1.25 ns / sample

Requirements: calibration

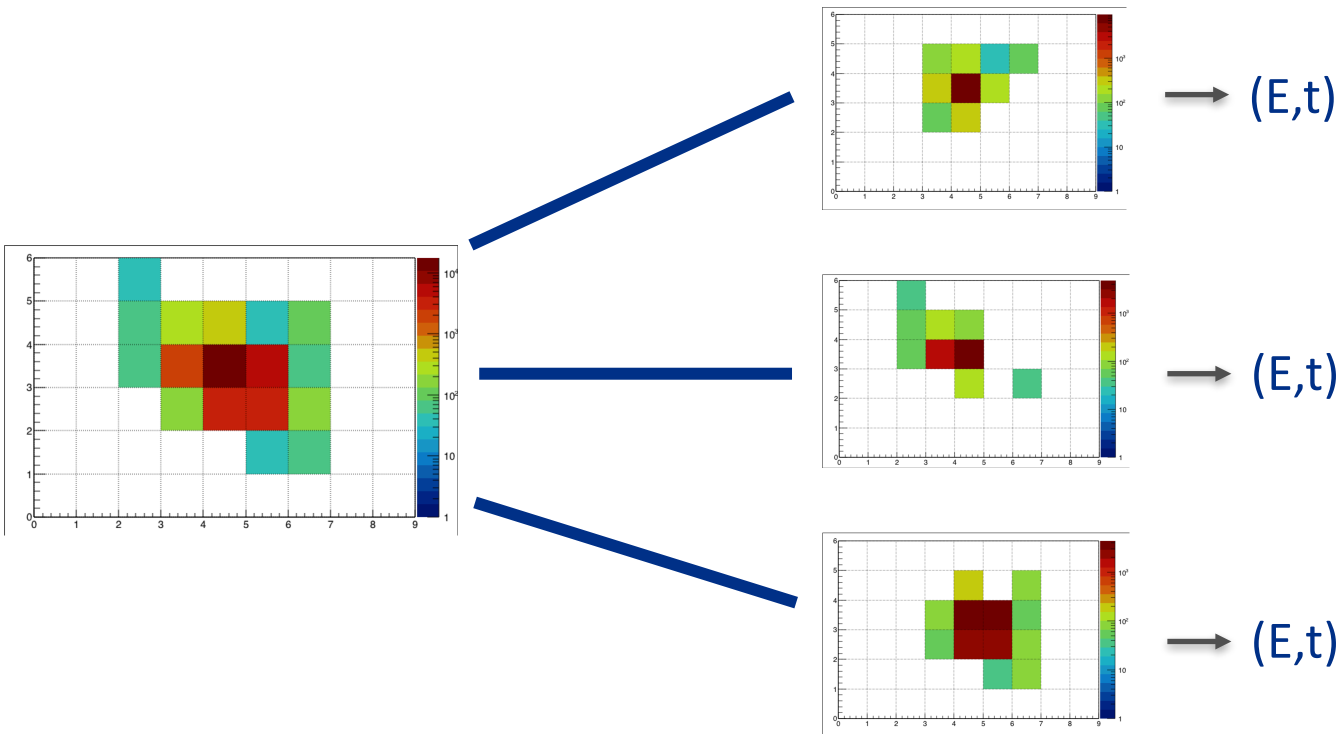
- achieve absolute calibration in energy units
- control long term, short term, rate dependent gain changes
- 20 ppb budget for gain related systematic error



Requirements: clustering

- combine calibrated pulses from each decay positron

- spatially resolve at least 2/3 of pileup events remaining after time separation, correctly partition energy



Status: pulse finding overview

baseline pulse finding algorithm is **template fitting**
a **template** is an empirical pulse shape extracted from data

template fitting entails:
- building beam and laser template for each SiPM
- using template to fit pulse islands for time, energy, pedestal
- fitting additional pulses as needed, 2*nPulses + 1 parameters

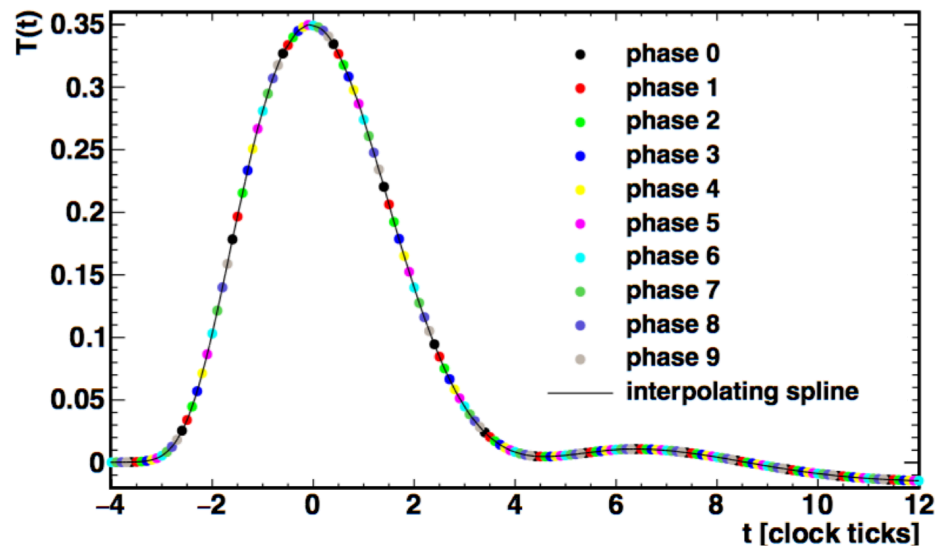
advantages:
- fast
- precise time and energy extraction

potential disadvantage:
- requires assumption of consistent, energy independent shape

Status: template building

Template building is the process of generating an empirical pulse shape model from a set of digitized waveforms

- sort pulses based on "phase" (where peak falls between samples)
- normalize each pulse by area
- average pulses with the same "phase"
- recombine average pulse shapes for each "phase", offset appropriately
- interpolate these more finely binned samples with a cubic spline to obtain template function, $T(t)$
- templates will be stored in database



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Status: template fitting

$$\chi^2 = \sum_{i=0}^{m} \sigma_i^{-2} \left(D_i - \sum_{j=0}^{n} s_j T\left(t_i - t_{0,j}\right) - P \right)^2$$

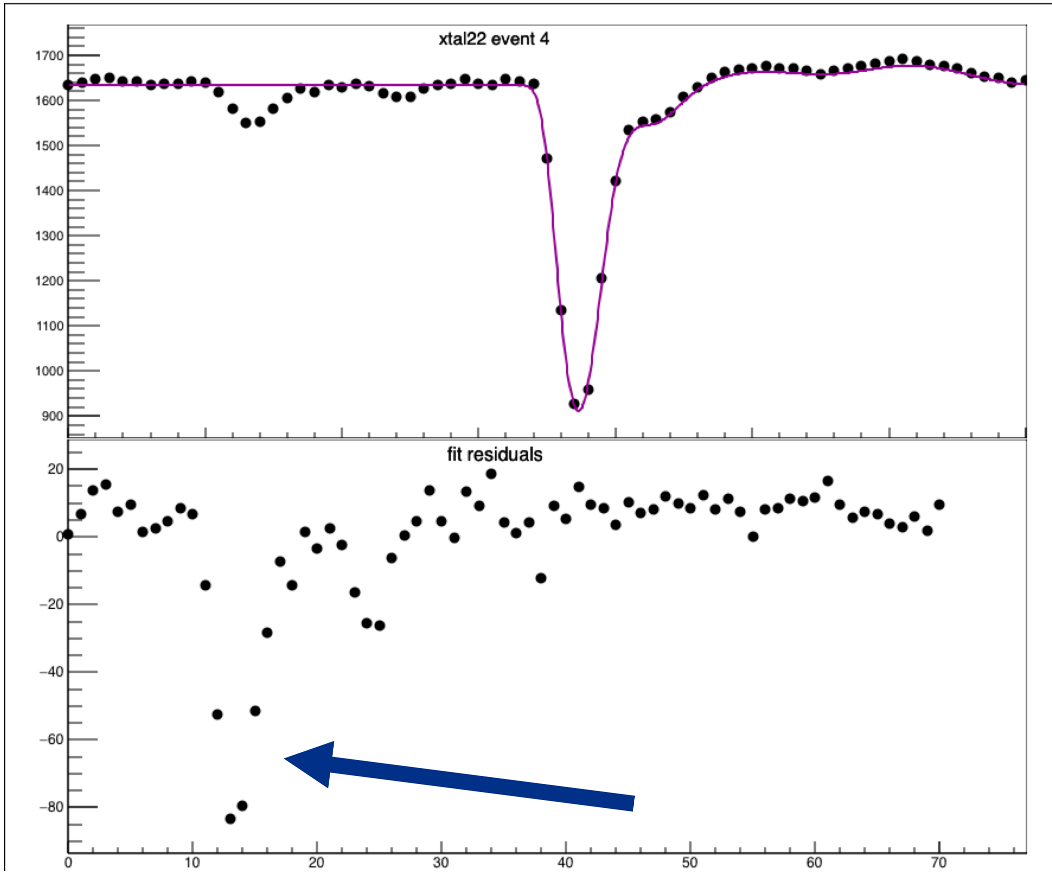
- fit traces with χ^2 minimization
- for given time guess(es), energy and pedestal parameters are linear and can be found analytically; numerical analysis needed only for times
- number of pulses to fit and initial time guesses must be provided as input
- use eigen c++ library for linear algebra

σ_i	uncertainty on sample i
D_i	digitizer sample i
s_j	scale of pulse j
t_i	time of sample i
$t_{0,j}$	time of pulse j
P	pedestal (baseline)
m	number of samples
n	number of pulses

red variables are fit parameters

Status: multi-pulse fitting

- fit single pulse first
- look for peaks in residuals
- add pulses one at a time
- use previous fit result for time guesses
- guesses must be 4 ns apart



sample number

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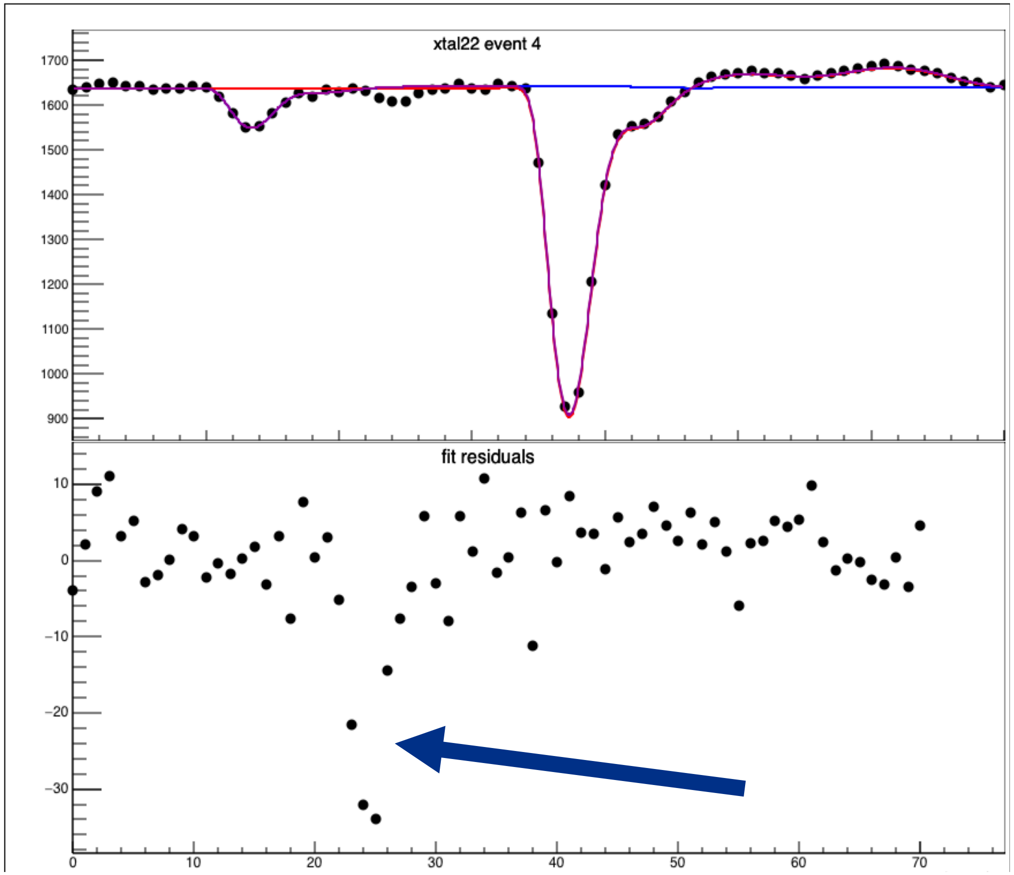

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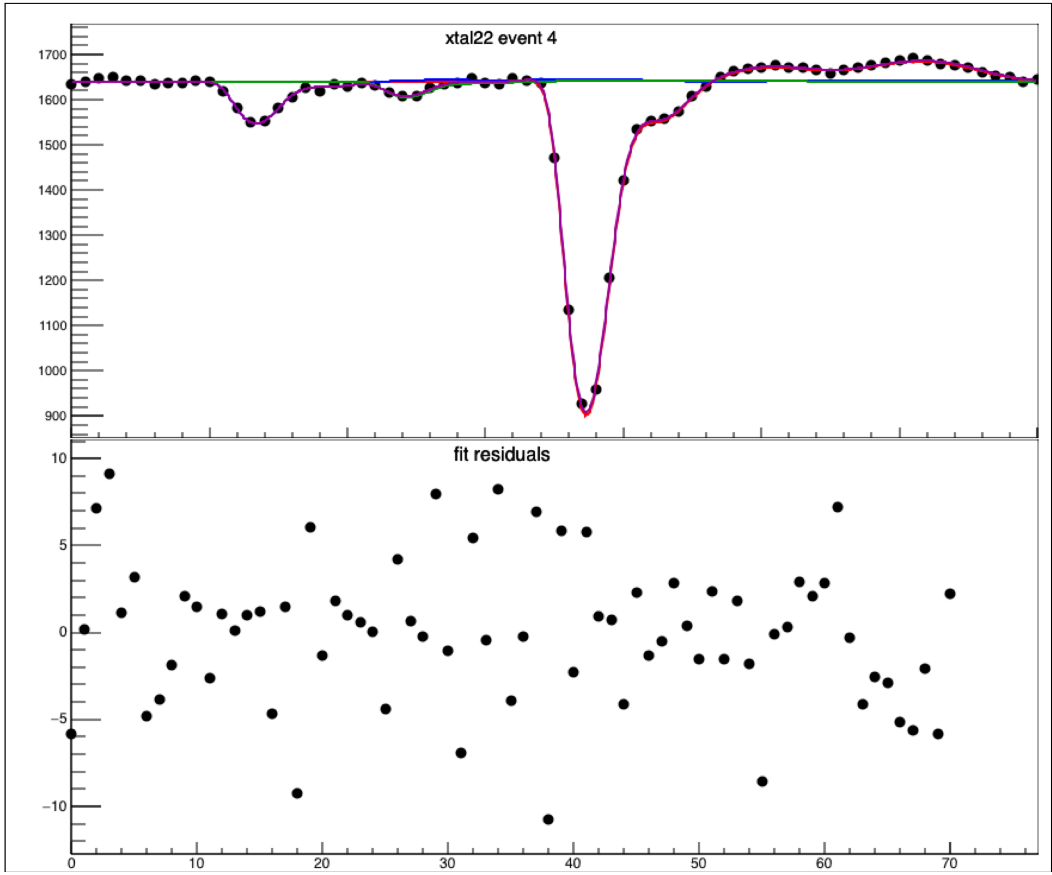
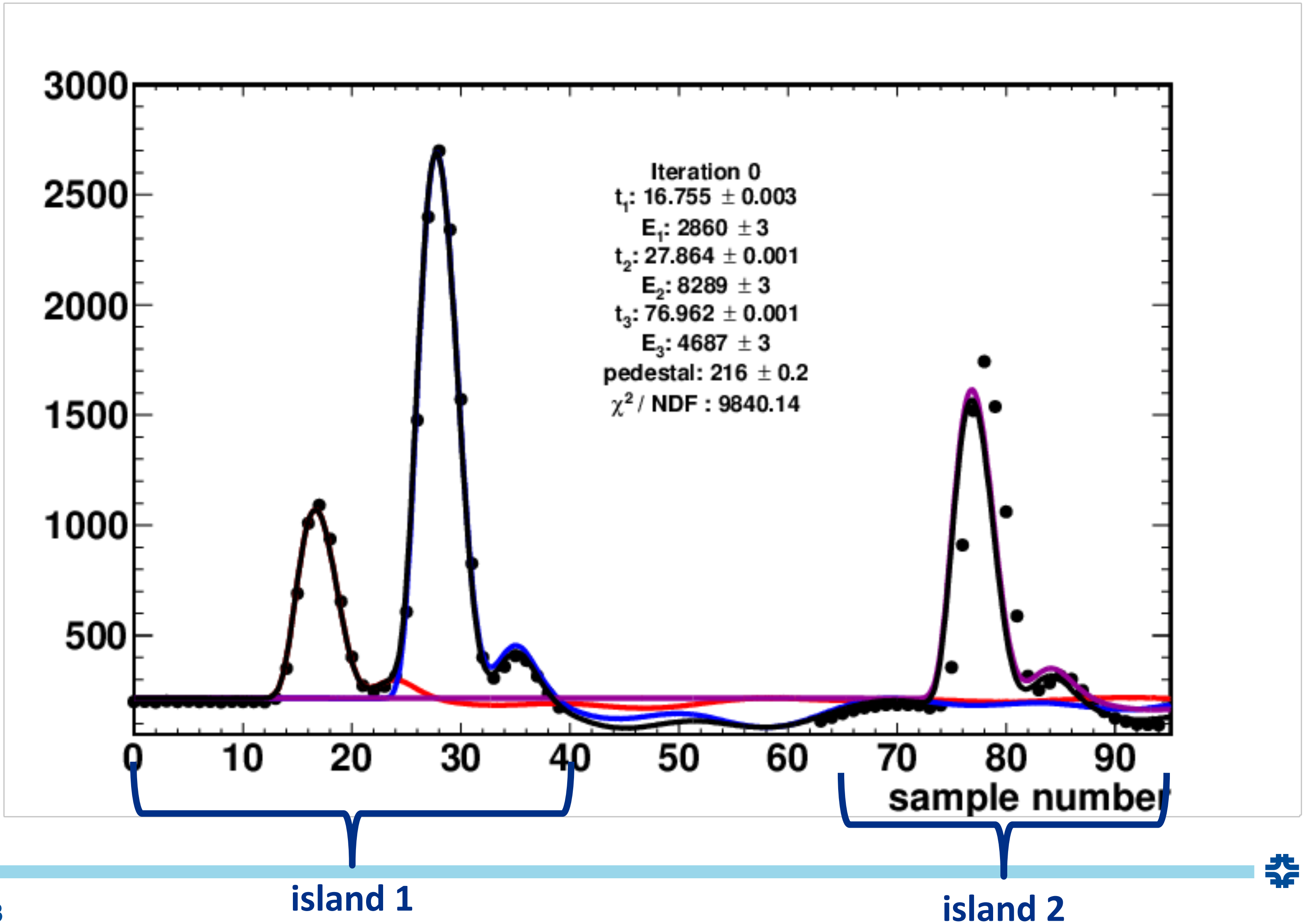
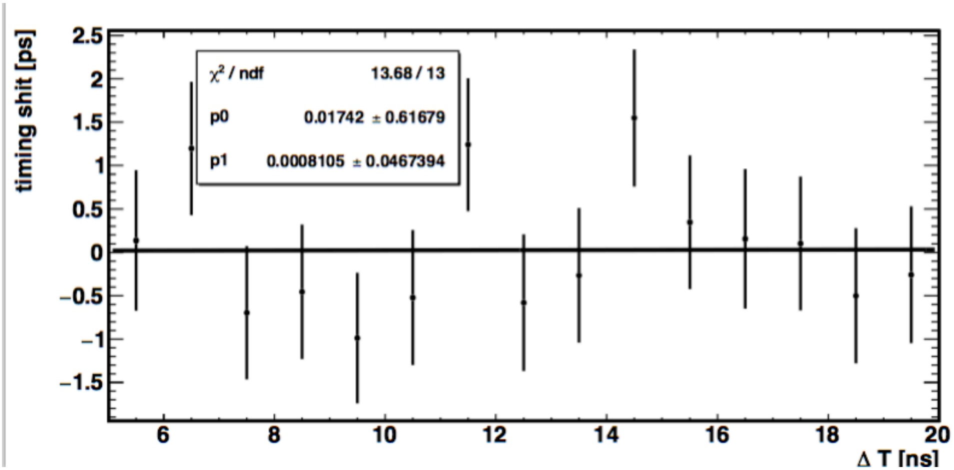


sample number

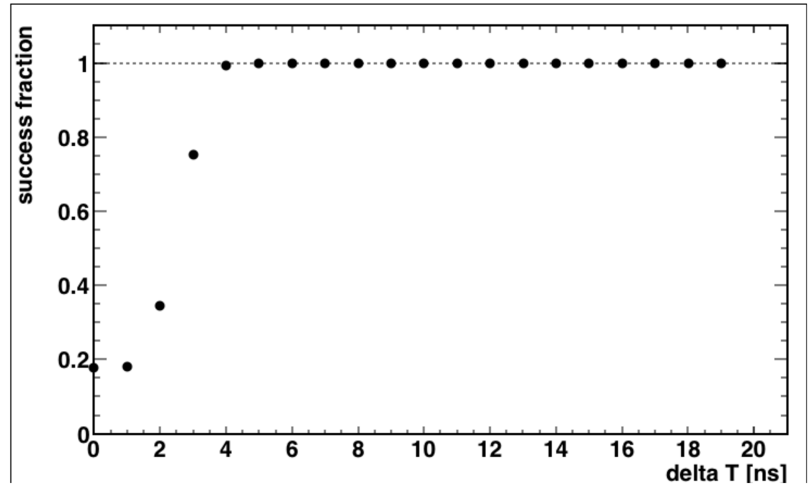
Three pulses, separate islands



Status: pulse finding performance

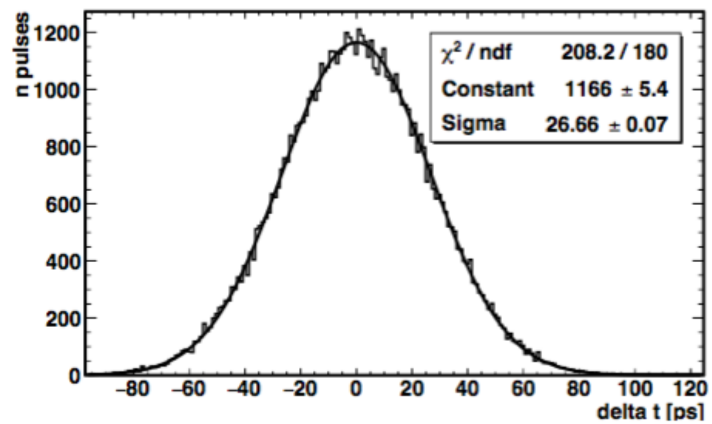


time extraction unbiased by multi-pulse fit



100% pileup separation at 5 ns

- negligible contribution to E resolution
- processes single pulses at about 100 kHz per CPU (recon bottleneck)



20 ps single detector timing resolution

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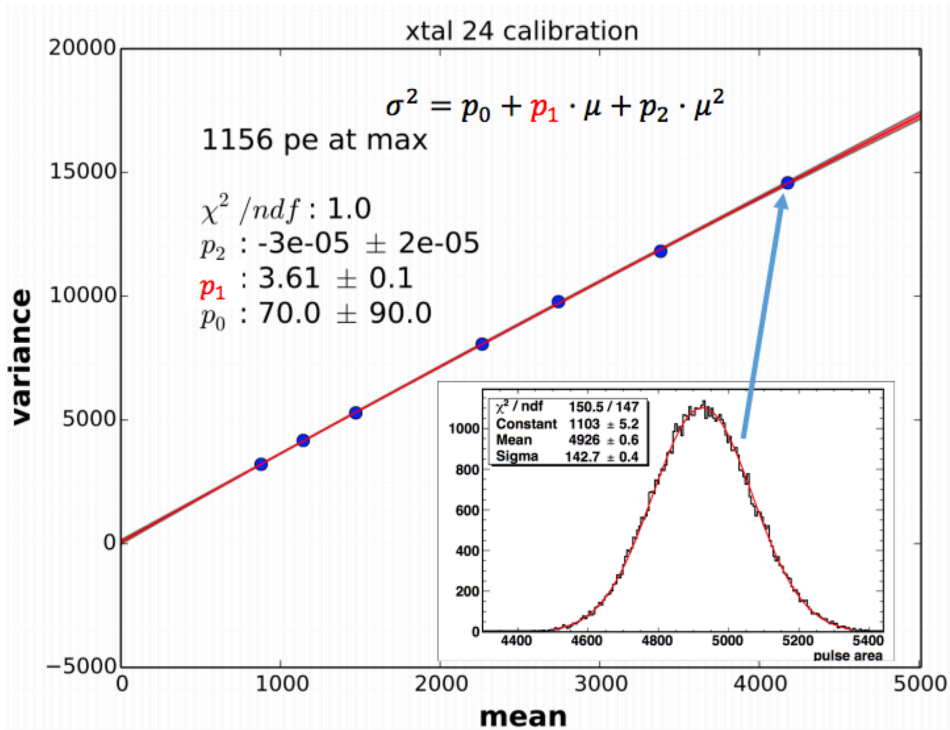
Status: absolute calibration

- absolute calibration through photostatistics
- illuminate SiPMs with laser
- vary laser intensity with filter wheel
- measure pulse area distribution
- fit variance vs mean with polynomial
- identify p_1 as pulse area / p.e. (gain)
- measure beam energy in p.e.
- constants stored in database



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Status: gain correction

- precise scheme for long term and fill-scale gain correction still to be defined

- proposals for fill-scale corrections:
  - measure single detector energy, time dependent gain perturbation response and apply pulse-by-pulse gain correction
  - measure average early-to-late gain perturbation over entire data set and apply correction to final histogram

- long term gain correction achieved by comparing SiPM laser responses to laser monitor signals:

$$GainCorrection = \frac{L_0}{\langle L \rangle} \cdot \frac{\langle S \rangle}{S_0},$$ L: SiPM response, S: source monitors

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Status: clustering

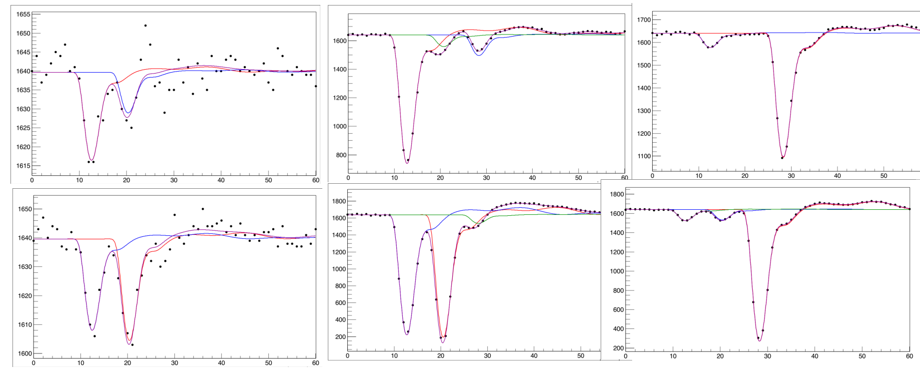
- clustering algorithm takes a collection of calibrated crystal hits and outputs an arbitrary number of reconstructed decay positron parameters, called “clusters”

- basic two step clustering algorithm in place that meets baseline requirements:
  - step one: time partitioning
  - step two: spatial separation and energy partitioning
  - Additionally, reports cluster position for single-positron clusters

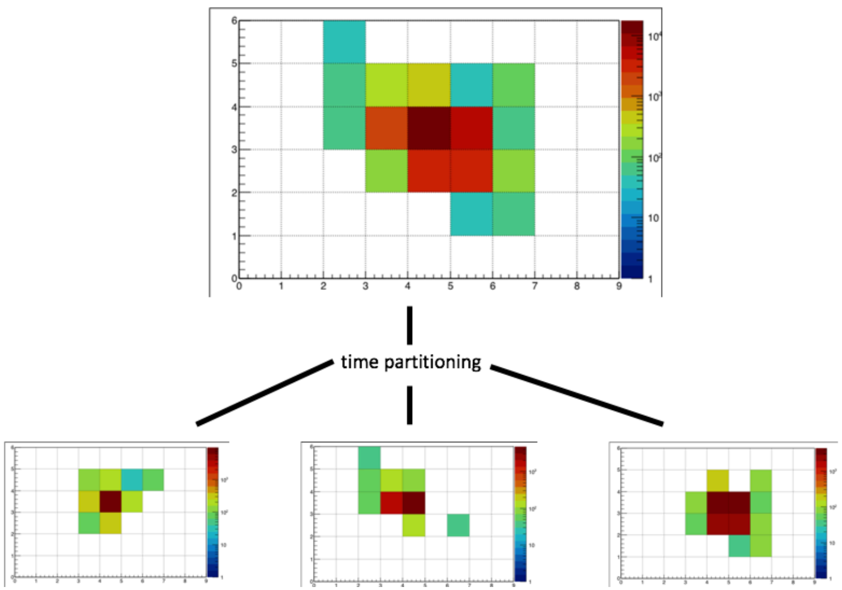
- simulation suggests spatial separation will be confused by preshowering, can machine learning techniques help?

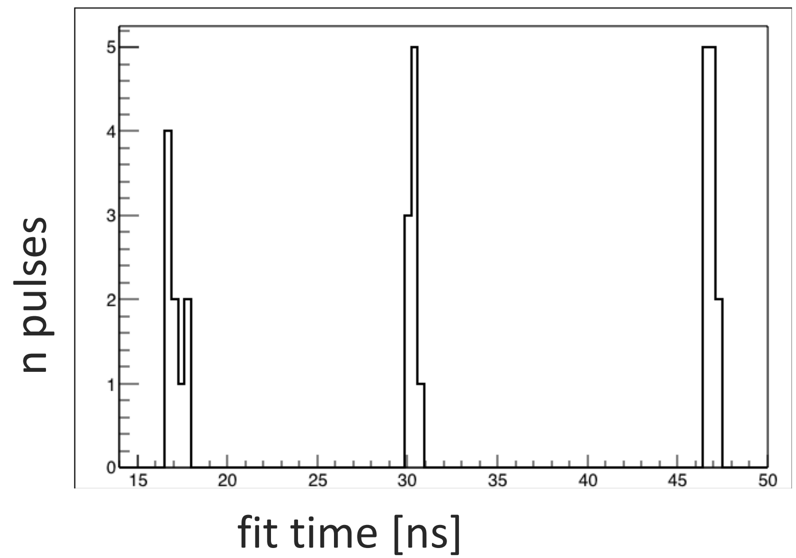
Status: cluster time partitioning

- sort fit results from a given island by time
- group results with $\Delta T < \sim 5\ ns$



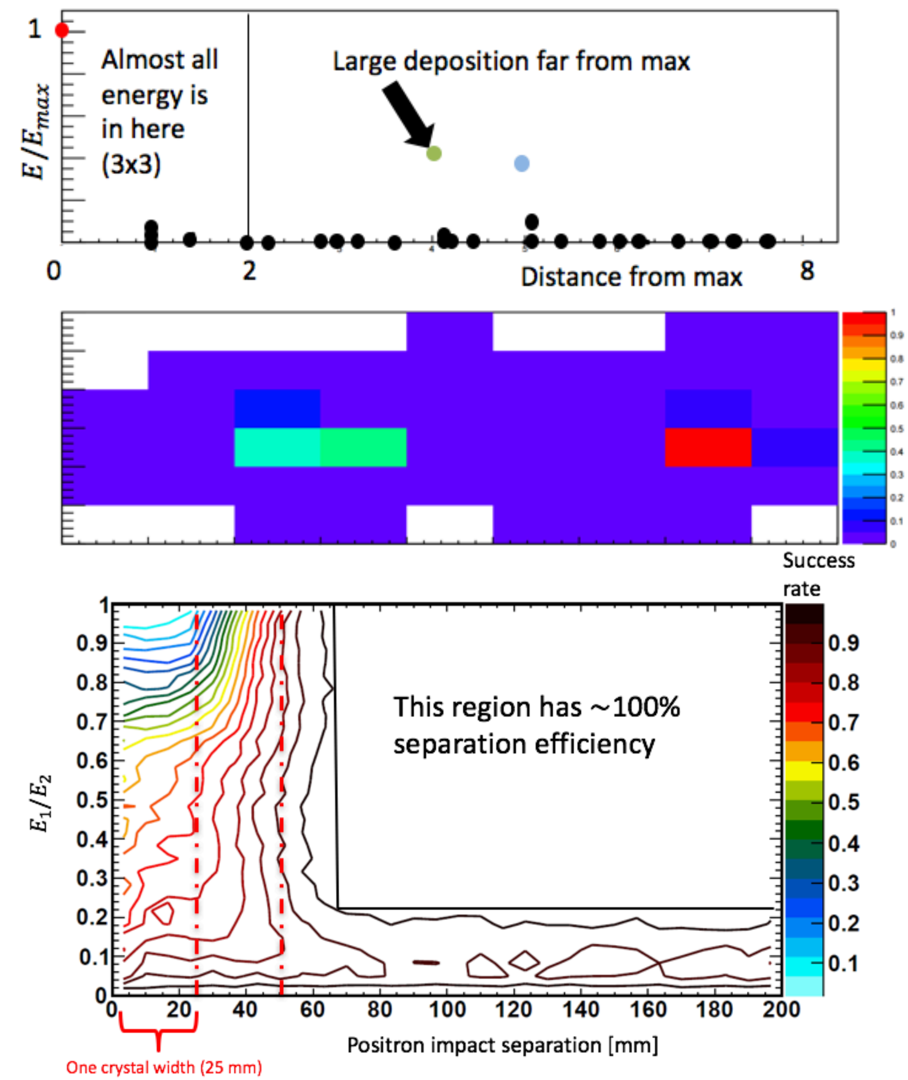
fits from a triple pileup event





Status: cluster spatial separation

- spatial separation runs on hits grouped by time partitioning
- current algorithm based on finding peaks in E / Emax far from max crystal
- iterative procedure, will find arbitrary number of separate clusters (tested on up to four)
- energy partition according to 3x3 sums surrounding cluster centers, scaled to match overall total energy
- Successfully resolves 75% of over-threshold pileup events
- Negligible contribution to computation time



Status: cluster position extraction

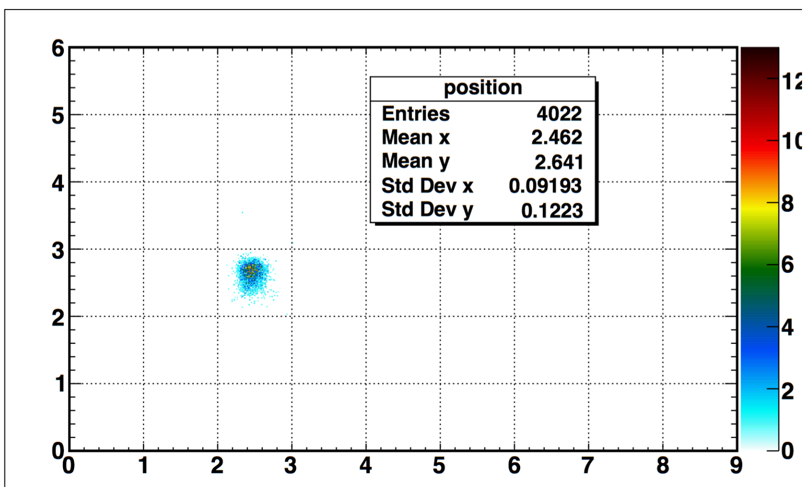
- logarithmic weighting provides best compromise between precision and position bias
- achieved 2 mm resolution at 2 GeV according to simulation, consistent with test beam data

$$x_{\text{reco}} = \frac{\sum_i w_i \cdot x_i}{\sum_i w_i},$$

crystal center

$$w_i = \max\left\{0, \left(W_0 + \log\frac{E_i}{\sum_j E_j}\right)\right\}$$

fraction of deposited energy

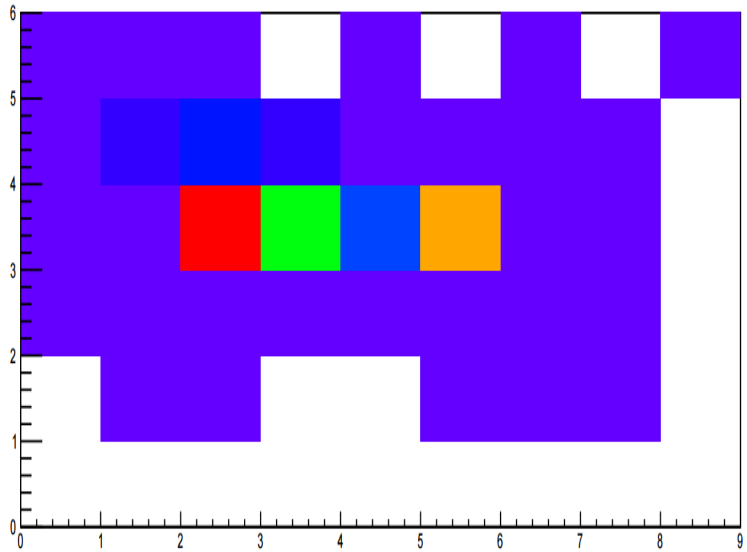


Status: spatial pileup confusion

Effects that confuse the spatial separation algorithm:

- "false pileup," false positives on single decay events that preshower before reaching a calorimeter
  (about 0.1% of events, according to simulation)

- extreme impact angles for low energy decays



a false pileup event

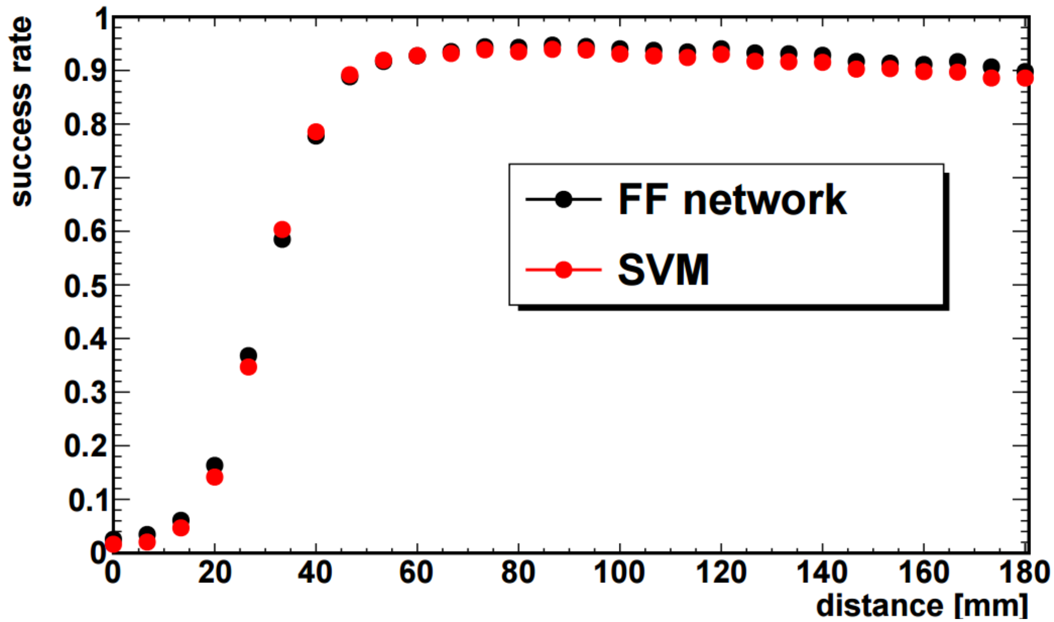
Status: machine learning experimentation

we briefly experimented with feed forward (FF) neural networks and support vector machines (SVM) to see if they can distinguish false pileup

- classification success rate improved, but classification doesn't help with energy partitioning

- false pileup remains an issue

- merits further investigation



double event classification success rate for NN and SVM
downward slope due to energy-position correlations
(the positrons far away are generally low energy)

Future plans

- develop alternative analysis chain and alternative algorithms
  - alternative clustering techniques
  - further machine learning investigation
  - one-step fitting-clustering algorithms
- build offline chain for Q-method analysis
- implement and test database integration
- stress test current system with simulation data and laser data as we build the calorimeters

Schedule

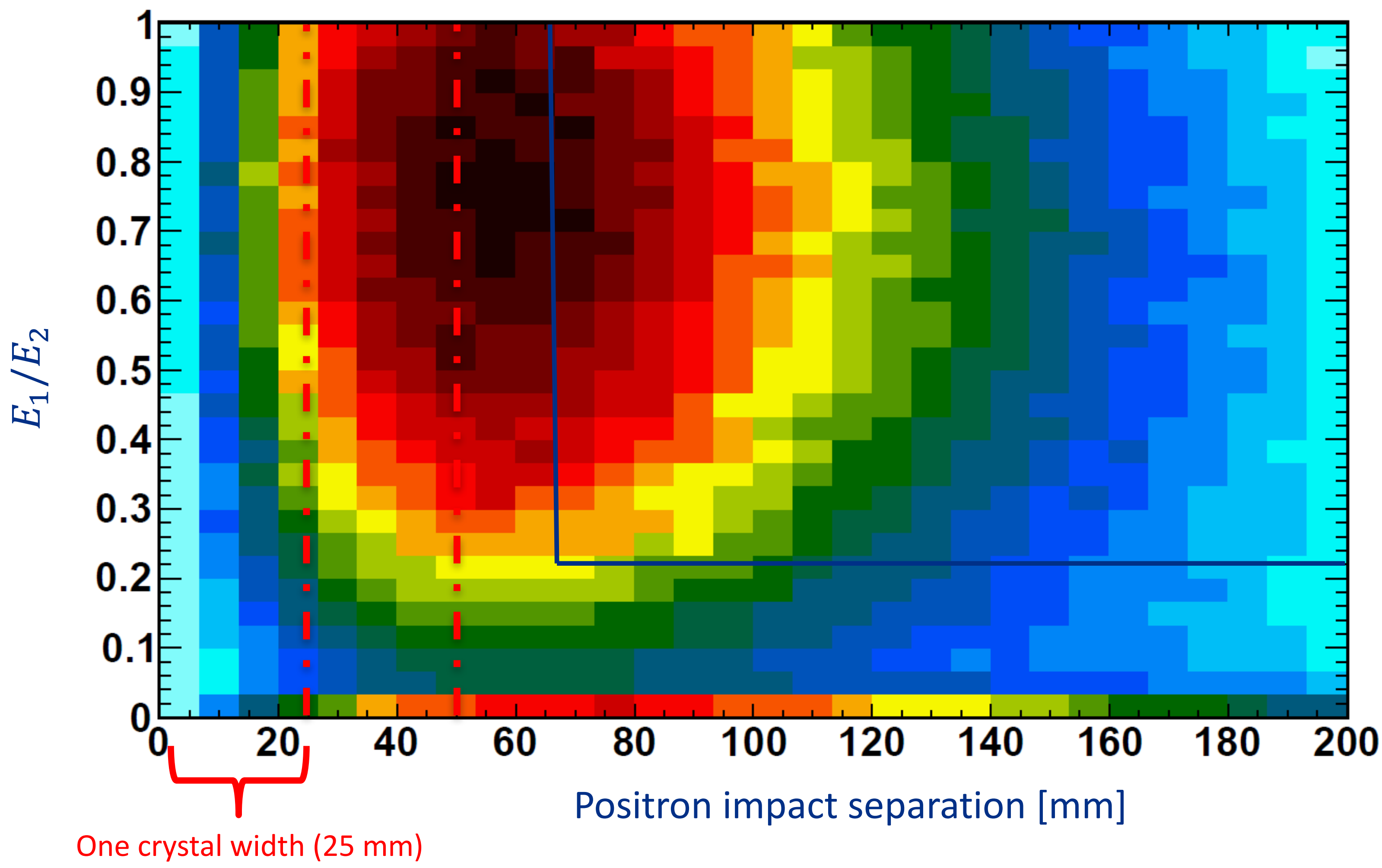
- Baseline analysis chain mostly ready; following shakedown over next months, it will be ready before beam arrives

- Q-method analysis chain must be defined in time to modify DAQ as needed

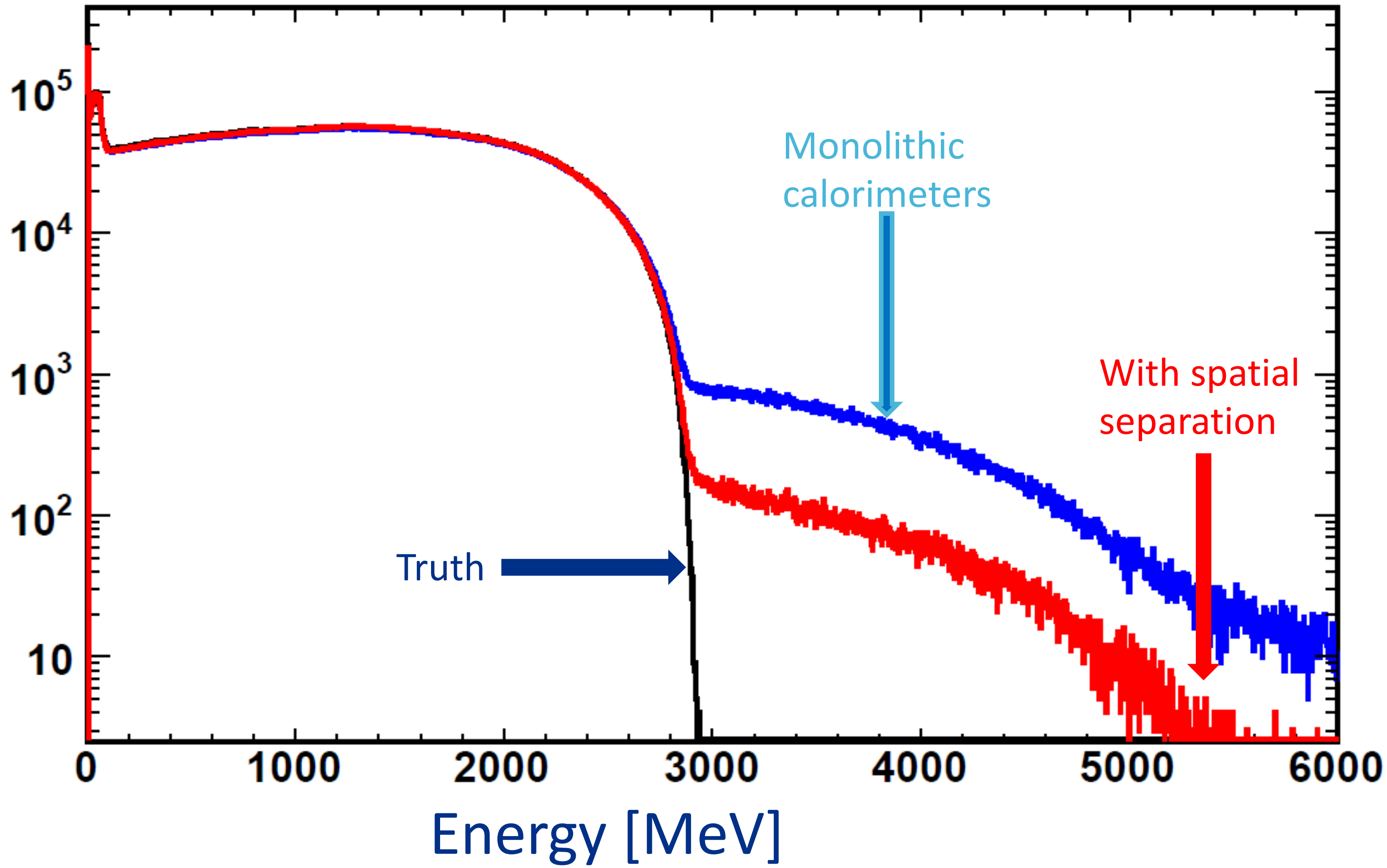
- Thank you!

Backups

Overall distribution



Spatial separation pileup reduction



Linear parameters given by:

$$\boldsymbol{T}\boldsymbol{T}^T \cdot \begin{pmatrix} S_1 \\ \vdots \\ P \end{pmatrix} = \boldsymbol{T} \cdot \boldsymbol{D}$$

$$T_{ij} \equiv \sigma_j^{-1} T(t_j - t_{0,i}) \qquad \boldsymbol{D} \equiv \begin{pmatrix} D_0/\sigma_0 \\ \vdots \\ D_m/\sigma_m \end{pmatrix}$$

Never have to guess for pulse sizes, only times.
This is regardless of how many pulses you are trying to fit.

Time steps given by:

$$\left[\boldsymbol{S T' T'^{T} S} - \mathrm{diag}\left(\boldsymbol{S T''} \cdot \boldsymbol{\Delta}\right)\right] \cdot \delta \boldsymbol{t_0} = -\boldsymbol{S T'} \cdot \boldsymbol{\Delta}$$

note: for single pulse fits, this is only one equation and one unknown

$$\Delta_i \equiv \sigma_i^{-1} \left(D_i - \sum_{j=0}^{n} s_j T\left(t_i - t_{0,j}\right) - P \right)$$

$$S_{ij} \equiv \delta_{ij} s_j$$

$$T'_{ij} \equiv \sigma_j^{-1} \frac{d}{dt} T(t) \bigg|_{t_j - t_{0,i}}$$

$$T''_{ij} \equiv \sigma_j^{-1} \frac{d^2}{dt^2} T(t) \bigg|_{t_j - t_{0,i}}$$

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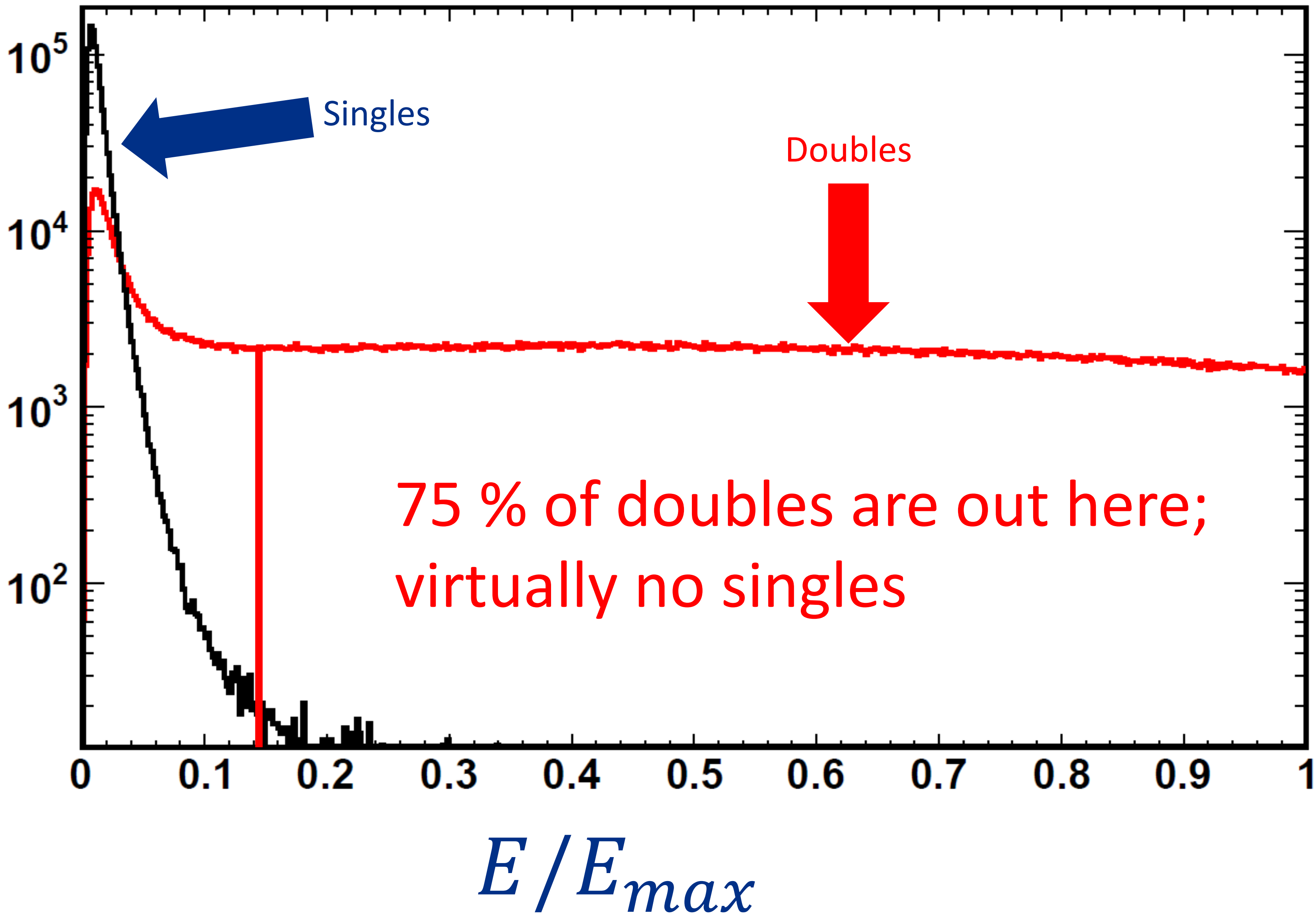
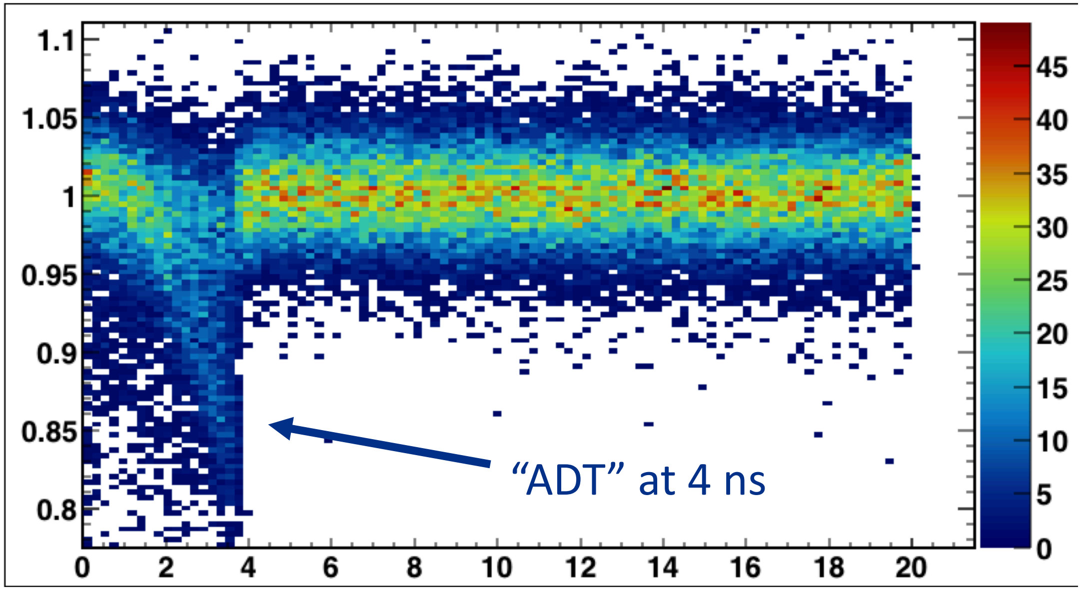


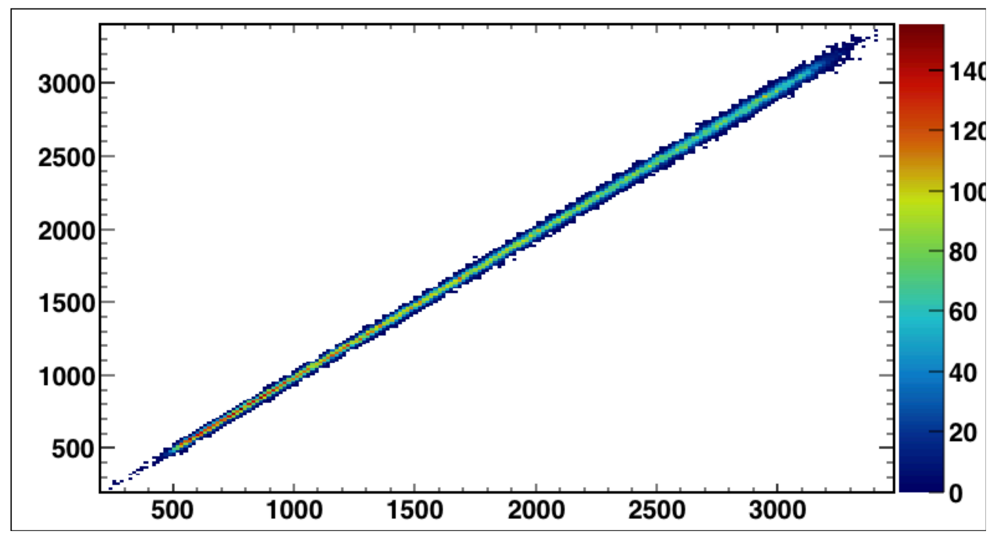
10^5
10^4
10^3
10^2
Singles
Doubles
75 % of doubles are out here;
virtually no singles
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
E/E_{max}

E_{recon} / E_{true}



ΔT [ns]

reconstructed energy [MeV]



n photons detected at all SiPMs

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