The DREAM Project
results & plans

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LCWS 05, Stanford, March 18 - 22

Outline:

- Why DREAM?
- The DREAM calorimeter
- Beam test results
- R&D plans in the context of ILC

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Ultimate Hadron Calorimetry

- Why not aim for hadron calorimetry with the same level of precision as achievable in electromagnetic calorimeters?

⇒ Need to eliminate /reduce *hadron-specific* fluctuations

- Fluctuations in *electromagnetic shower content* (f_{em})
- Fluctuations in *"visible energy" (nuclear breakup)*

- Achievable limit: $\sigma/E \sim 15\%/\sqrt{E}$

Fluctuations in the em shower component (f_{em})

- *Why are these important ?*
  - Electromagnetic calorimeter response ≠ non-em response *(e/h ≠ 1)*
  - Event-to-event fluctuations are large and *non-Gaussian*
  - *$\langle f_{em} \rangle$ depends on* shower *energy* and *age*

- *Cause of all common problems in hadron calorimeters*
  - *Energy scale* different from electrons, in energy-dependent way
  - Hadronic *non-linearity*
  - *Non-Gaussian* response function
  - Poor energy *resolution*
  - *Calibration* of the sections of a longitudinally segmented detector

- *Solutions*
  - *Compensating* calorimeters (*e/h* = 1), *e.g.* Pb/plastic scintillator
  - Measure *f_{em} event-by-event*

Measuring the electromagnetic shower content

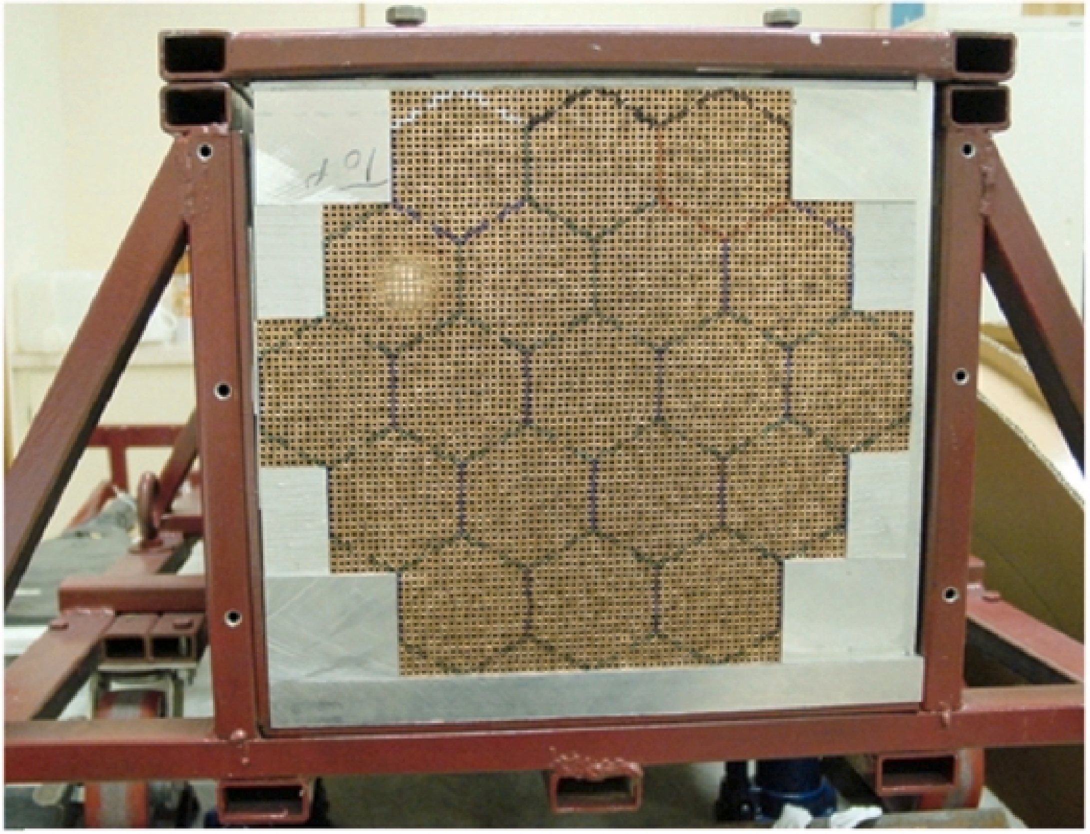
- *Measure f_{em} event by event*
  - Pioneered by WA1 around 1980
  - Used characteristics of energy deposit profile to disentangle em/non-em shower components
  - Does *not* work well $\lesssim$ 20 GeV
  - Does *not* work for jets
    (collection of γs, πs showering simultaneously in the same area)

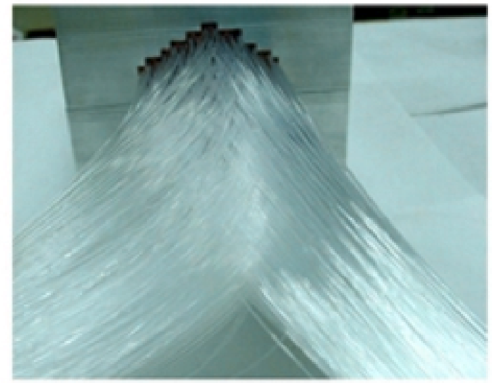
The DREAM principle

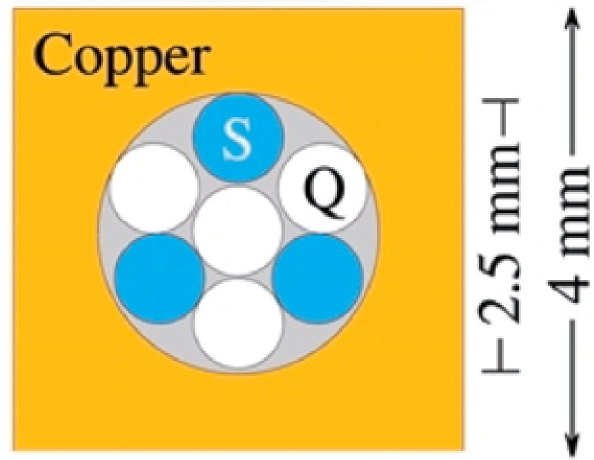
- *Quartz fibers are only sensitive to em shower component!*
  - CMS prototype: e/h ~ 5 NIM A399 (1997) 202
  - ➡ Use dual-readout system:
  - Regular readout (scintillator, LAr,...) measures *visible* energy
  - Quartz fibers measure em shower component E_{em}
  - Combining both results makes it possible to determine f_{em} and the energy E of the showering hadron
  - *Eliminate dominant source of fluctuations*

DREAM = Dual REAdout Module

DREAM: Structure

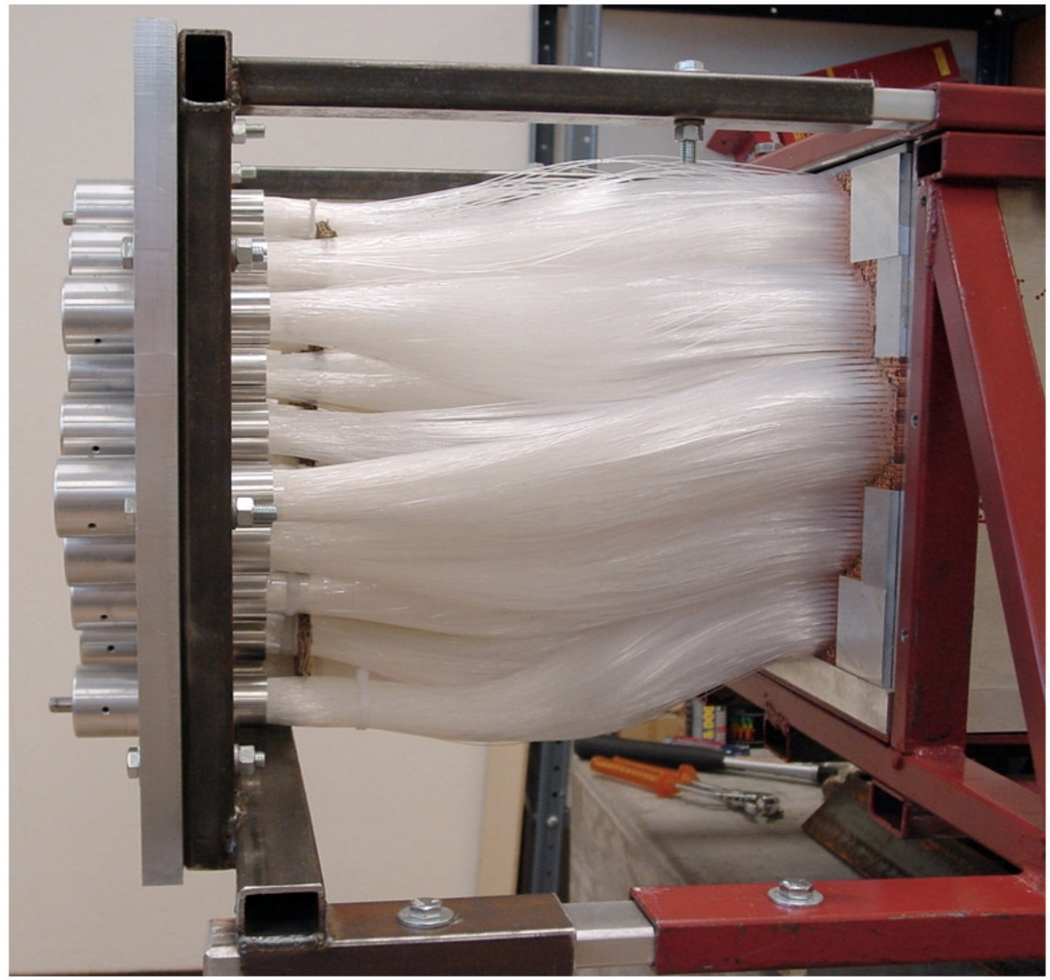


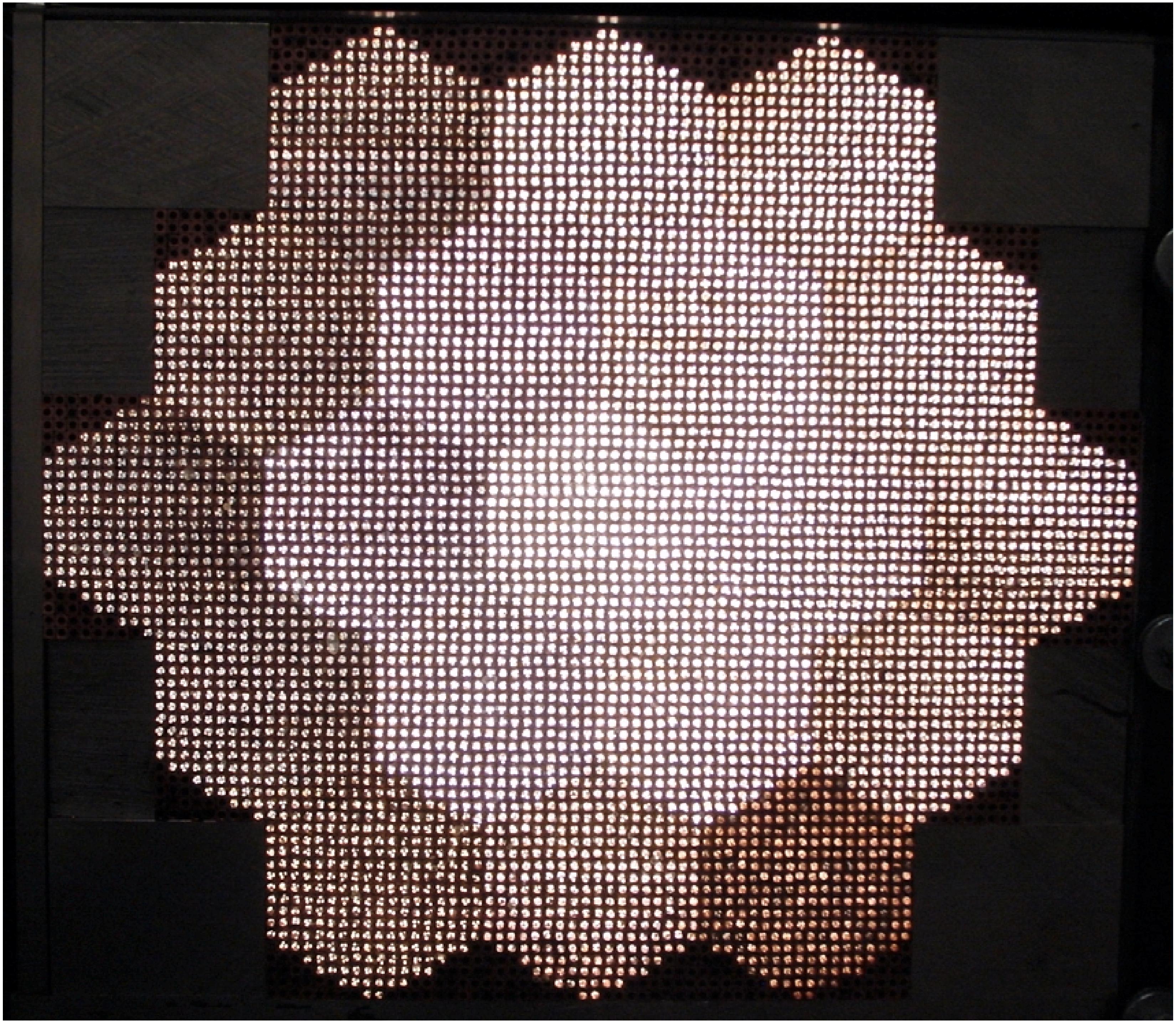


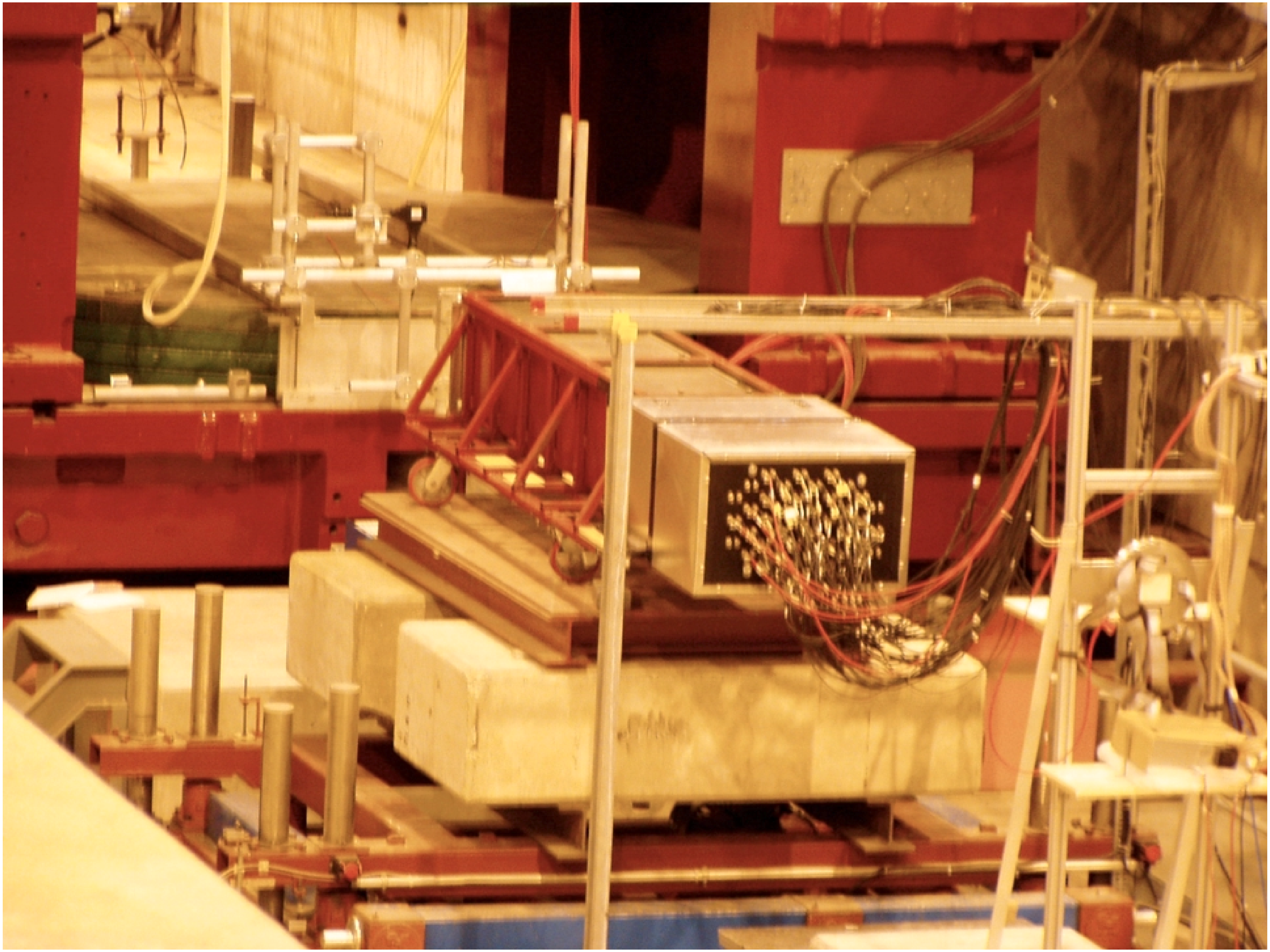


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

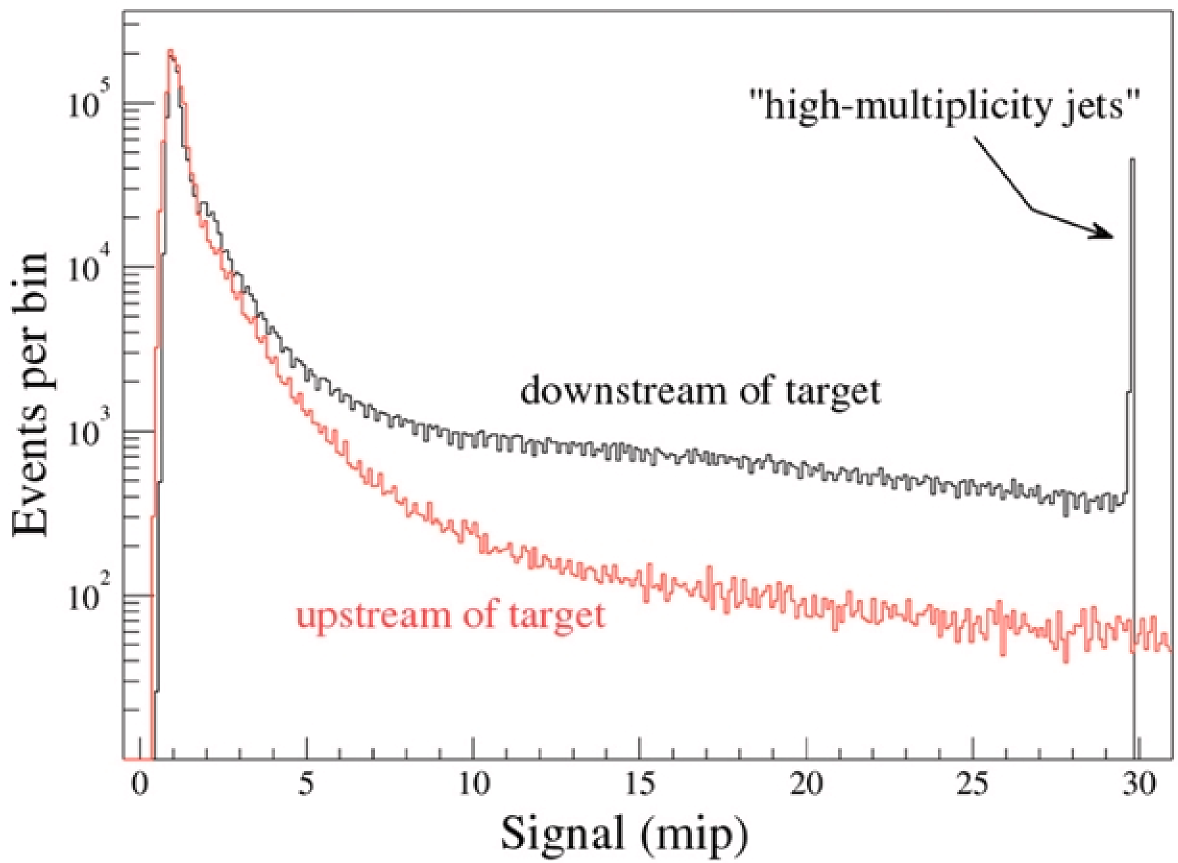
DREAM readout





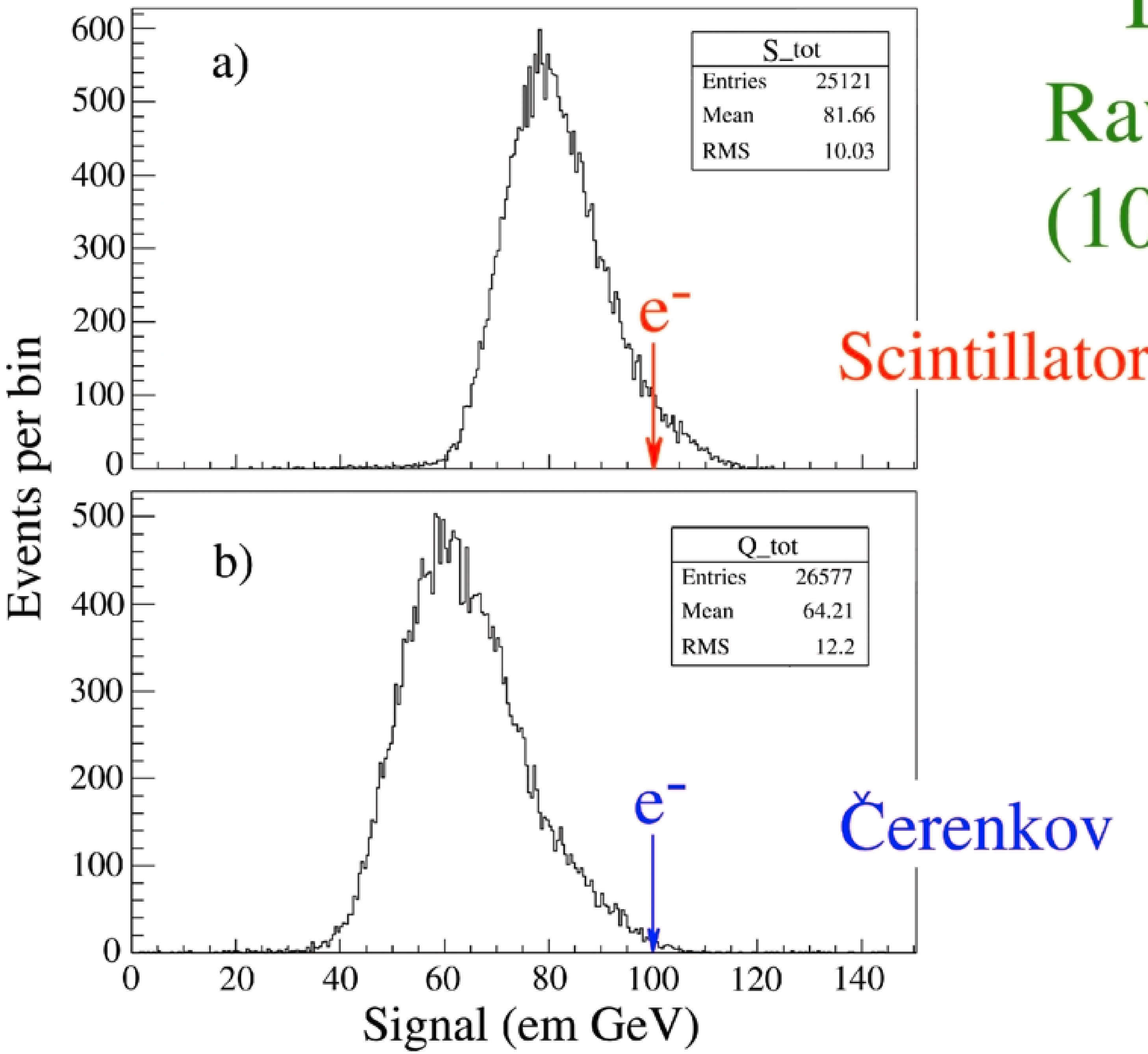


Experimental setup for DREAM beam tests

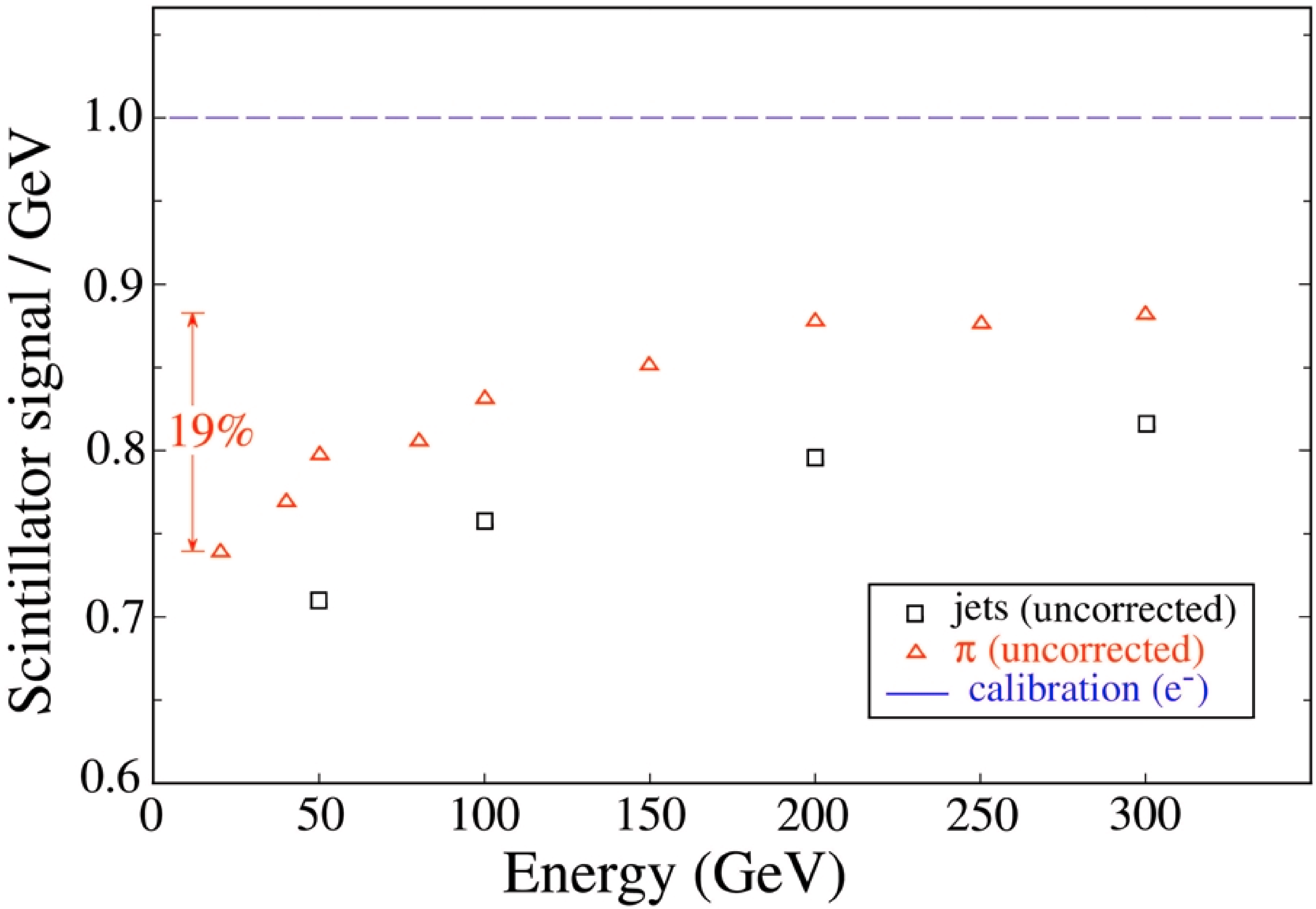


"JET" Measurements

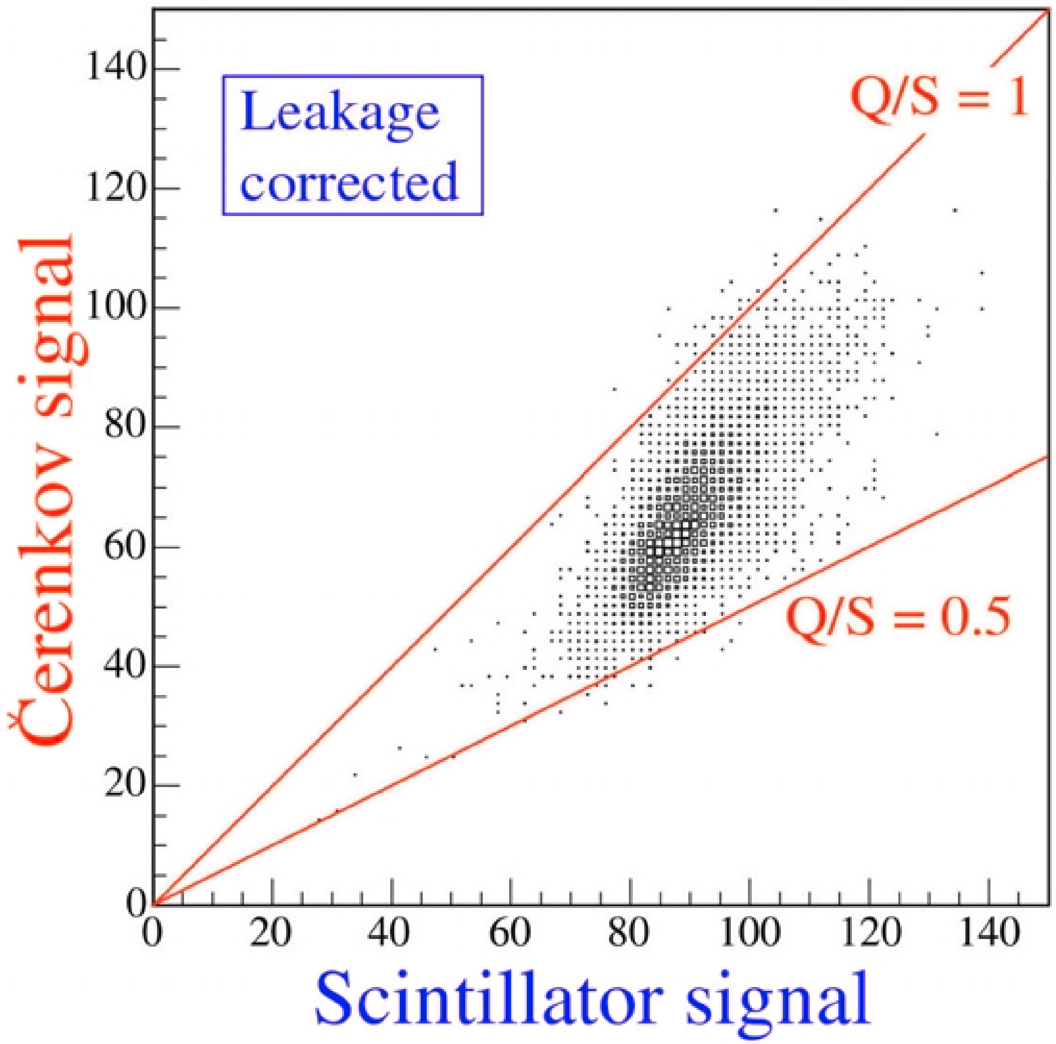
DREAM Raw signals (100 GeV π^-)



DREAM: Hadronic response (non-linearity)



DREAM: The (energy-independent) Q/S method



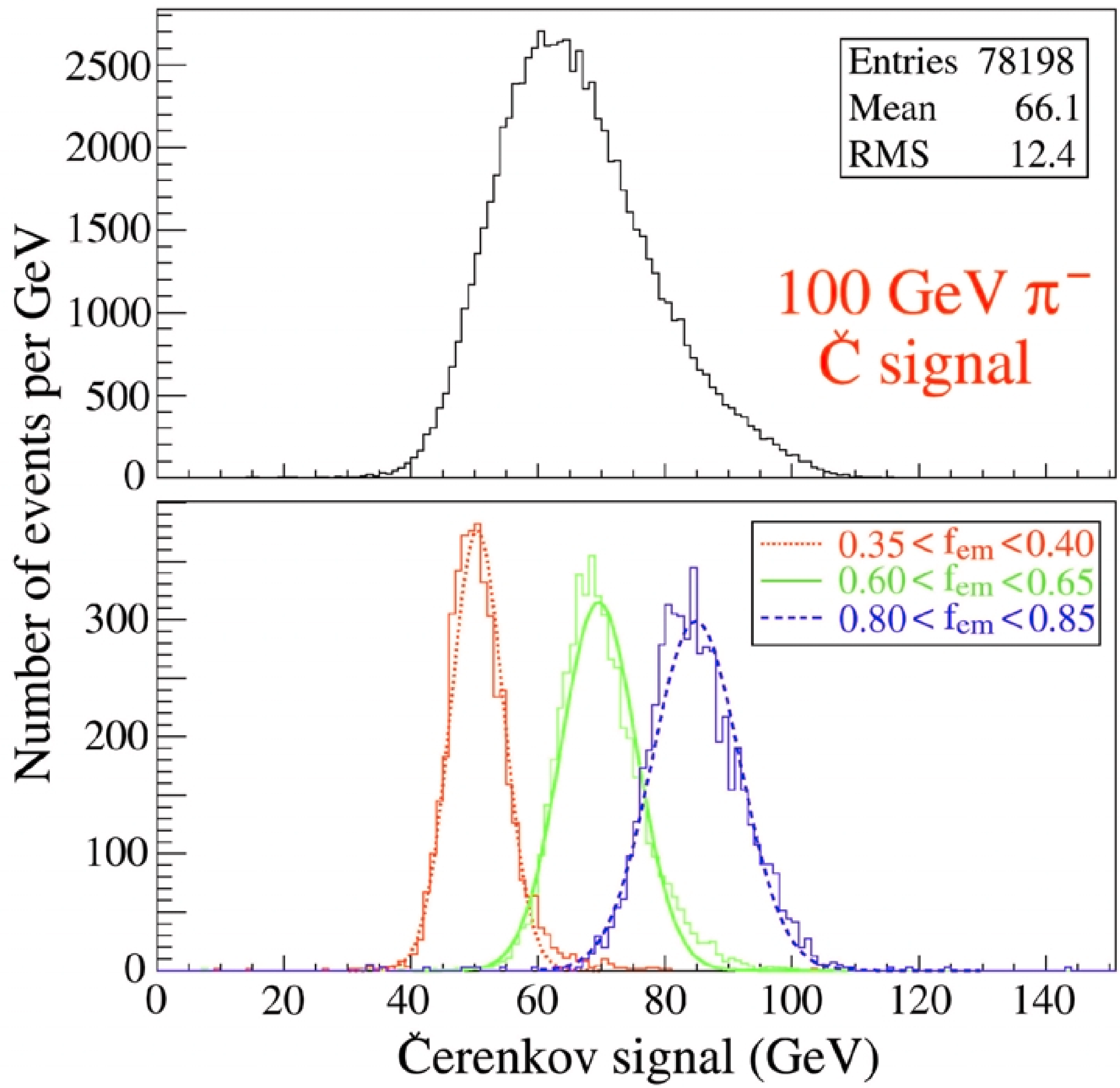
$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_{\rm S}}(1 - f_{\rm em})\right]$$

$$Q = E\left[f_{\rm em} + \frac{1}{(e/h)_{\rm Q}}(1 - f_{\rm em})\right]$$

$e/h = 1.3$ (S), 5 (Q)

$$\frac{Q}{S} = \frac{f_{\rm em} + 0.20\ (1 - f_{\rm em})}{f_{\rm em} + 0.77\ (1 - f_{\rm em})}$$

DREAM: Effect of event selection based on f_{em}



Dual-Readout Calorimetry in Practice

The (energy-independent) Q/S method

- Hadronic response (normalized to electrons):

$$R(f_{em}) = f_{em} + \frac{1}{e/h}\left[1 - f_{em}\right], \qquad e/h = 1.3 \text{ (S)}, \quad 5 \text{ (Č)}$$

- Q/S response *ratio* related to f_{em} value → find f_{em} from Q/S:

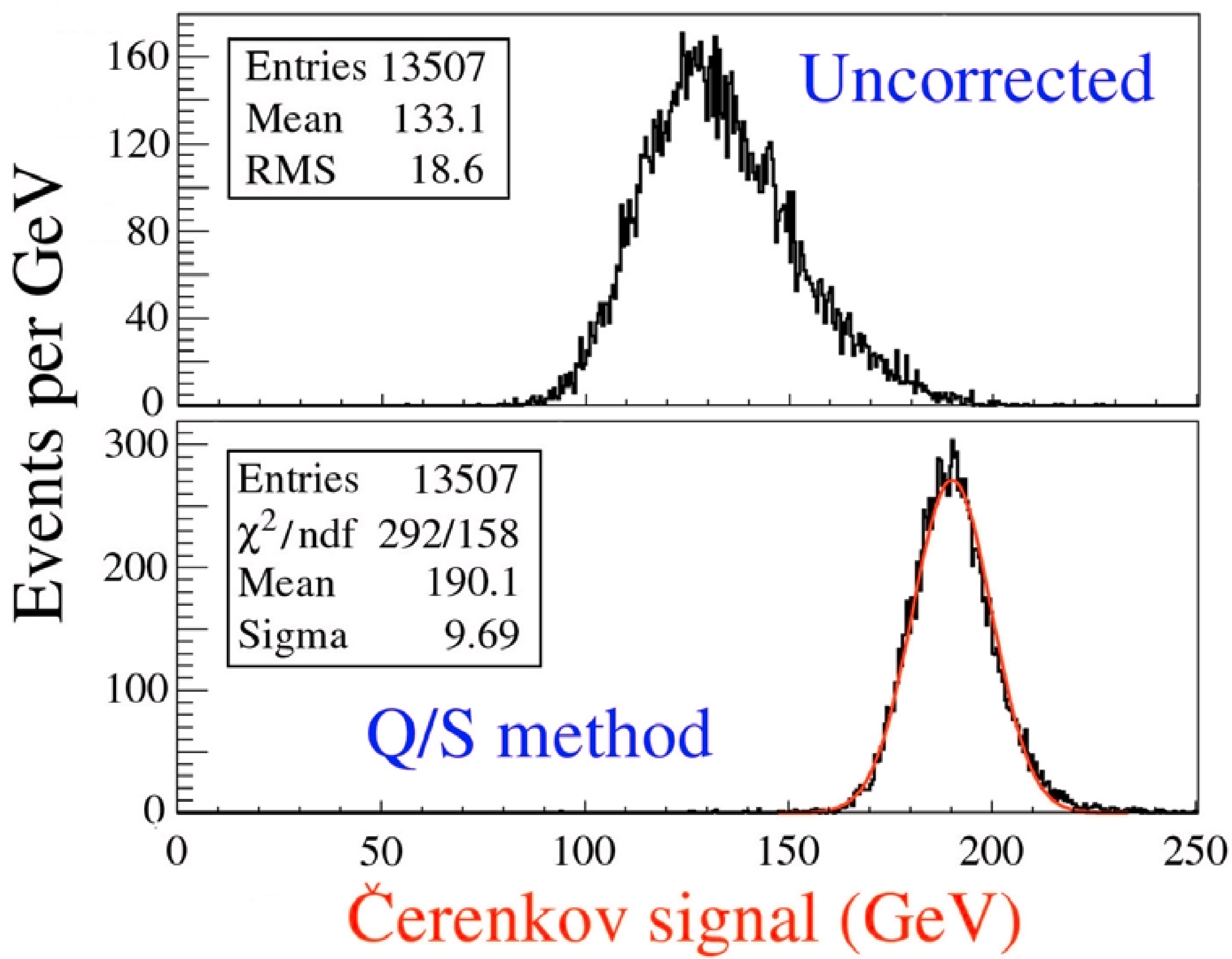
$$\frac{Q}{S} = \frac{R_Q}{R_S} = \frac{f_{em} + 0.20\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}$$

- Correction to measured signals (regardless of energy):

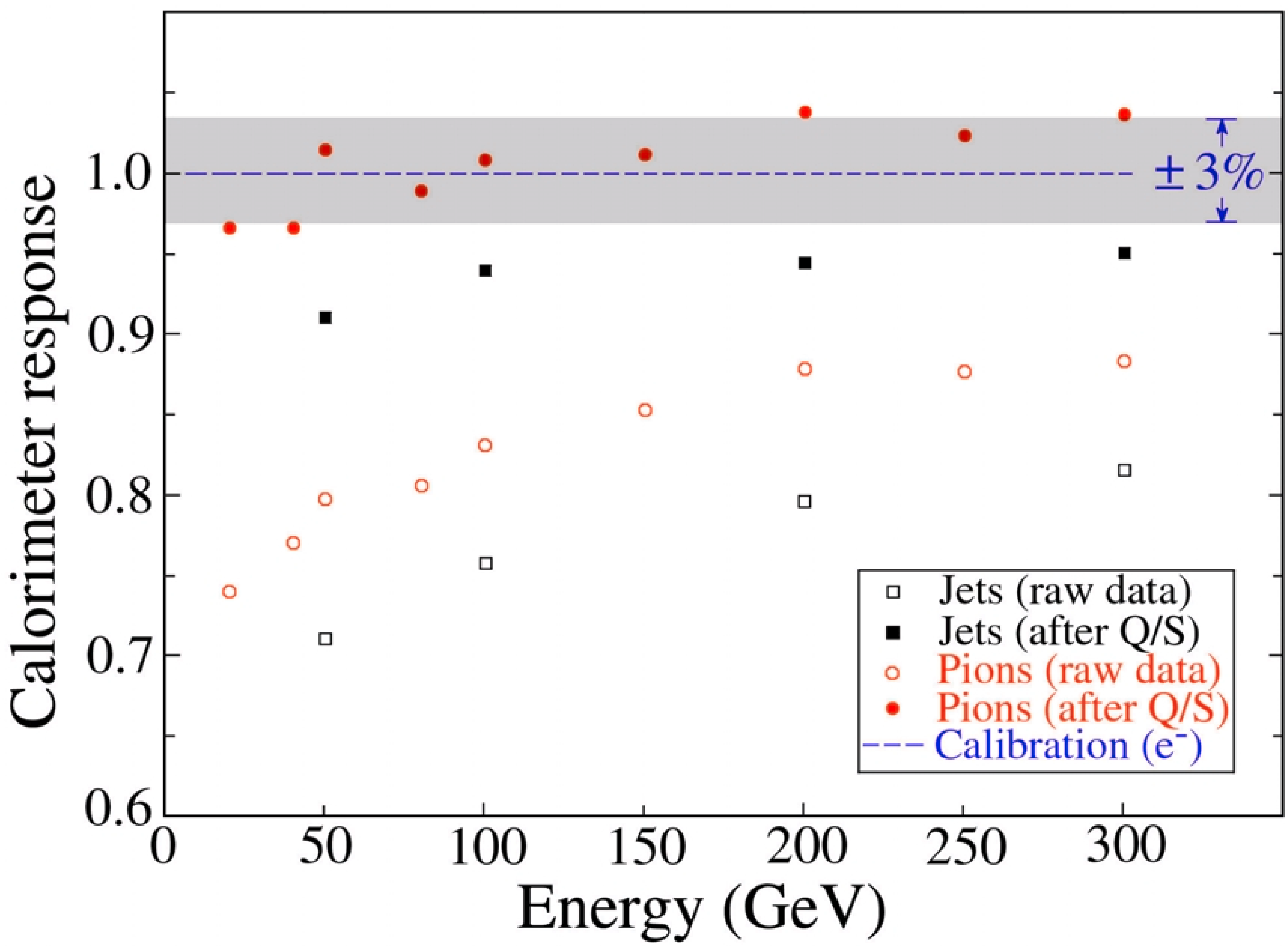
$$S_{corr} = S_{meas}\left[\frac{1 + p_1/p_0}{1 + f_{em} \cdot p_1/p_0}\right], \qquad \text{with} \quad \frac{p_1}{p_0} = (e/h)_S - 1$$

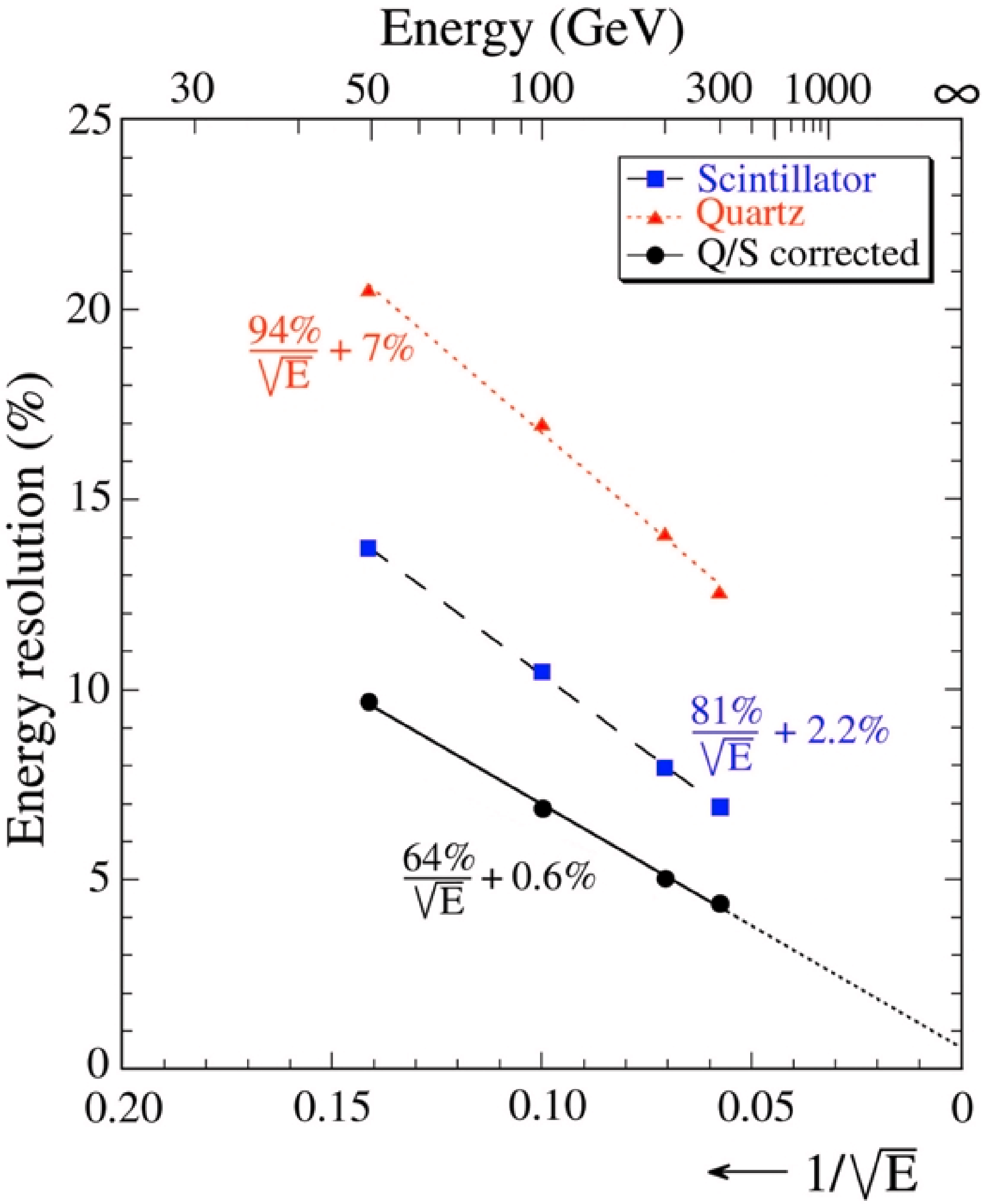
$$Q_{corr} = Q_{meas}\left[\frac{1 + p_1/p_0}{1 + f_{em} \cdot p_1/p_0}\right], \qquad \text{with} \quad \frac{p_1}{p_0} = (e/h)_{\check{C}} - 1$$

DREAM: Effect of corrections (200 GeV "jets")



Hadronic response: Effect Q/S correction





DREAM

Energy resolution "jets"

CONCLUSIONS
from tests

- DREAM offers a powerful technique to *improve* hadronic calorimeter performance:
  - Correct hadronic energy reconstruction, *in an instrument calibrated with electrons!*
  - Linearity for hadrons and jets
  - Gaussian response functions
  - Energy resolution scales with $1/\sqrt{E}$
  - $\sigma/E < 5\%$ for high-energy "jets", in a detector with a mass of only 1 ton!
    dominated by fluctuations in shower leakage

- These, and many other, experimental results are described in 3 papers:

  Hadrons & jets: Nucl. Instr. & Meth. A537 (2005) 537
  Electrons: Nucl. Instr. & Meth. A536 (2005) 29
  Muons: Nucl. Instr. & Meth. A533 (2004) 305

ILC Calorimetry

What is needed?	DREAM
1) Correct hadronic energy reconstruction	√
2) Separate W from Z ⟶ $\sigma \sim 3$ GeV	

DREAM prototype resolution (σ~7 GeV) *limited by*	*Needed*
• *Leakage fluctuations (mass 1 ton)*	*$*
• *Light yield (Quartz fibers: 8 Č.p.e./GeV* ⟶ $35\%/\sqrt{E}$*)*	*more light*
• *Fluctuations in visible energy*	TREAM

More Light

- Use fibers with *larger numerical aperture*
  (e.g. clear acrylic plastic fibers: 18 Č.p.e./GeV)

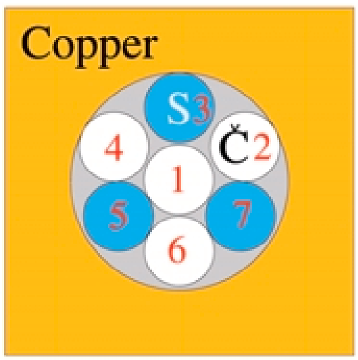
- *Increase* fiber *packing fraction* *and/or* *quantum efficiency*
  (this would necessitate different readout, e.g. SiPM)

- Use *homogeneous medium*
  There is absolutely no reason why DREAM principles should be limited to fibers
  These principles can be used in any optical calorimeter whose signals can be separated into scintillation and Čerenkov components

$\Longrightarrow$ DREAM 2

DREAM 2

- To what extent can light from an optical calorimeter be separated into its scintillaton and Čerenkov components?
- *Modified* the DREAM calorimeter

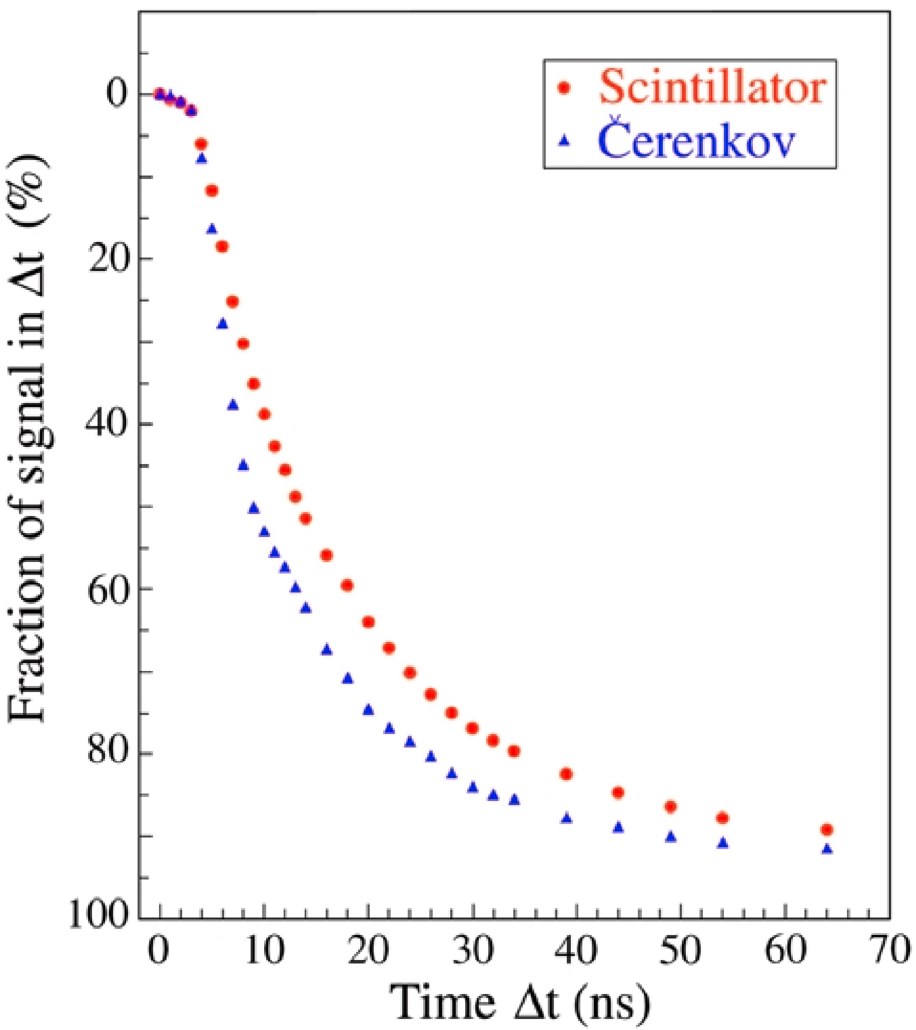


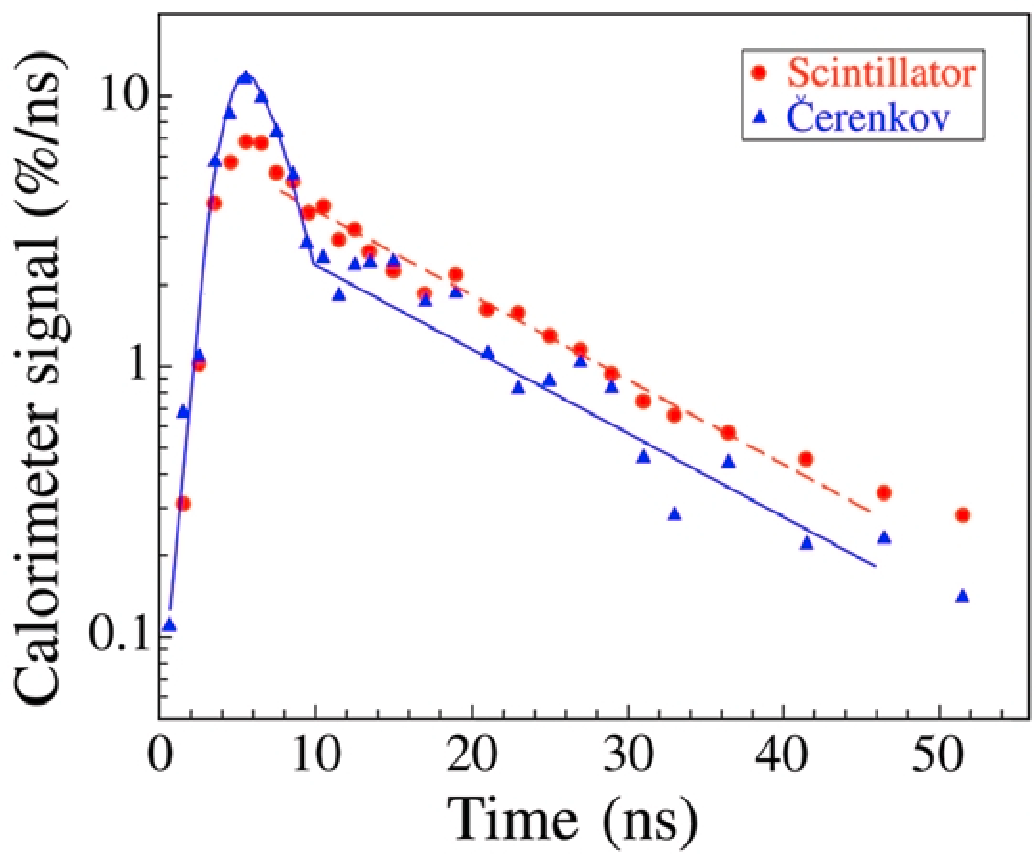
5+7	PMT1 (S)
2+4	PMT2 (Č)
1+3+6	PMT3 (mixed)

Also:
Fibers read out from both ends

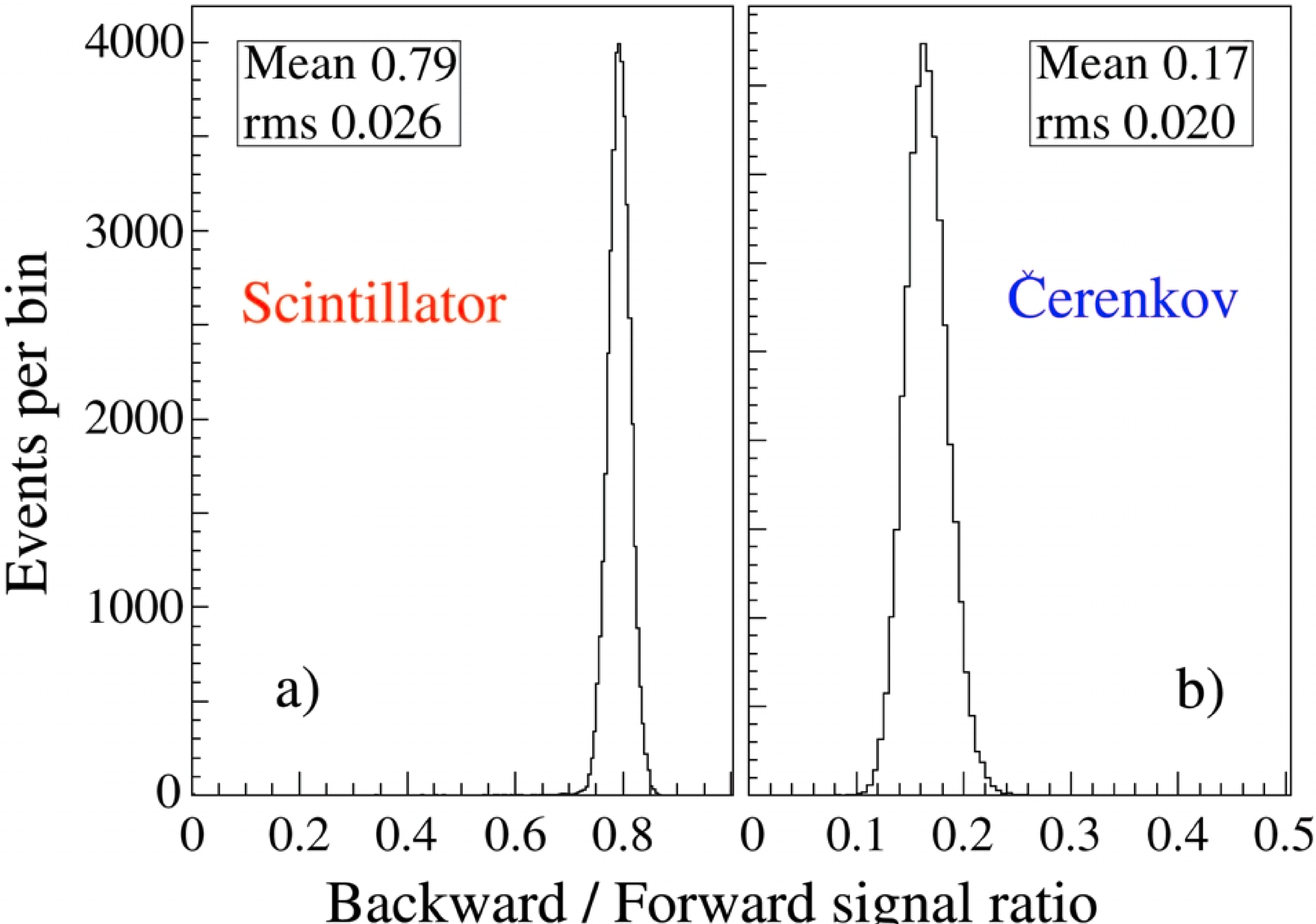
- Separation methods based on differences in:
  - Time structure of signals
  - Light directionality
  - Optical spectra
  - Polarization

DREAM - Differences in time structure



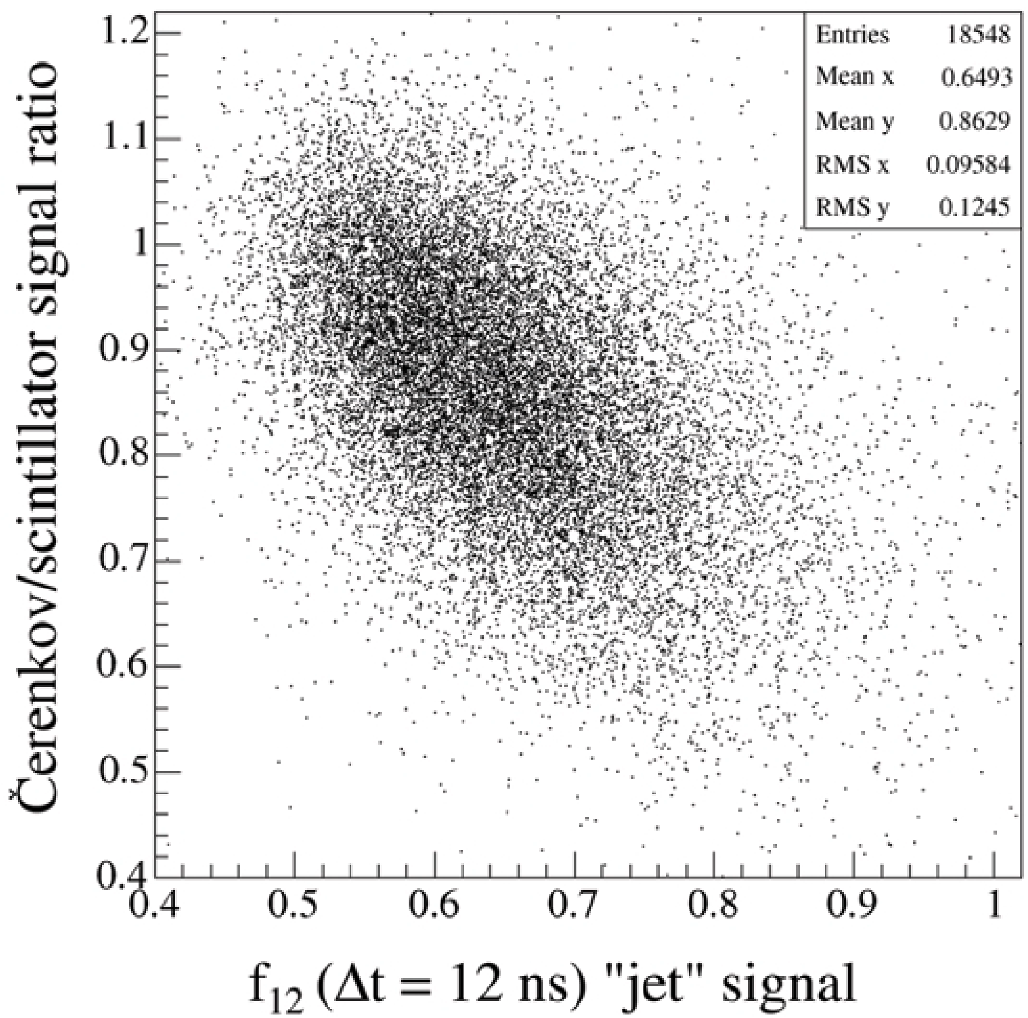


DREAM - Light directionality

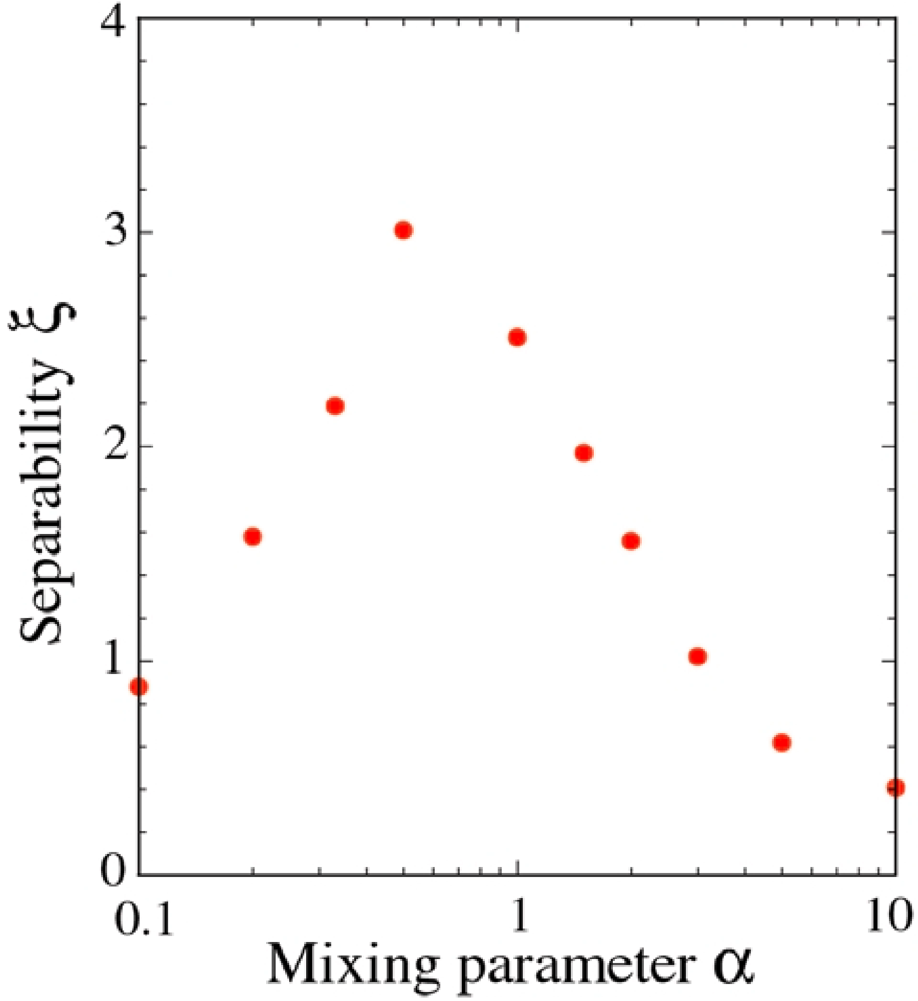


DREAM - Separation of mixed light

Time structure



Directionality



DREAM 2 & the Electromagnetic Section

- Typically, half of the jet energy is deposited in the em section
  $\longrightarrow$ *The em section should be an excellent hadron calorimeter*

- Use DREAM 2 results to optimize the design of the em section
  Example: Lead glass doped with an *appropriate* scintillating agent
  (optimized concentration and decay constant, spectrum)
  Em resolution better than $5\%/\sqrt{E}$ should be no problem

Ultimate Hadron Calorimetry

- Having eliminated all other effects, fluctuations in nuclear binding energy losses ($f_{\Delta B}$) are the main remaining challenge

- ΔB is correlated with the total kinetic energy carried by neutrons
Efficient detection of neutrons can reduce intrinsic resolution of hadron calorimeters to $\sim 15\%/\sqrt{E}$

- TREAM $\longrightarrow$ measure that kinetic energy event by event (triple readout)

TREAM

- A third type of fibers will make it possible to measure E(n) and thus reduce the effects of fluctuations in ΔB

- Two options are being studied:
  - Replace every second scintillating fiber in DREAM with a non-hydrogenous scintillating fiber (*e.g.* doped quartz)
    E(n) can be determined from a comparison of signals from hydrogenous and non-hydrogenous fibers
  - Develop dedicated fibers
    that are specifically sensitive to MeV-type neutrons

CONCLUSIONS

- D(T)REAM seems capable of meeting / exceeding ILC hadronic calorimeter performance requirements
- Bonus: Em resolution $< 5\%/\sqrt{E}$
- And: The entire detector can be calibrated with electrons!