Recent results in dual-readout calorimetry: test beam data and simulations

- Fibers as light collectors with perfect separation of light
  - i. basic DREAM performance
  - ii. lateral shower sizes in Cerenkov and Scintillation light
  - iii. neutrons in DREAM module

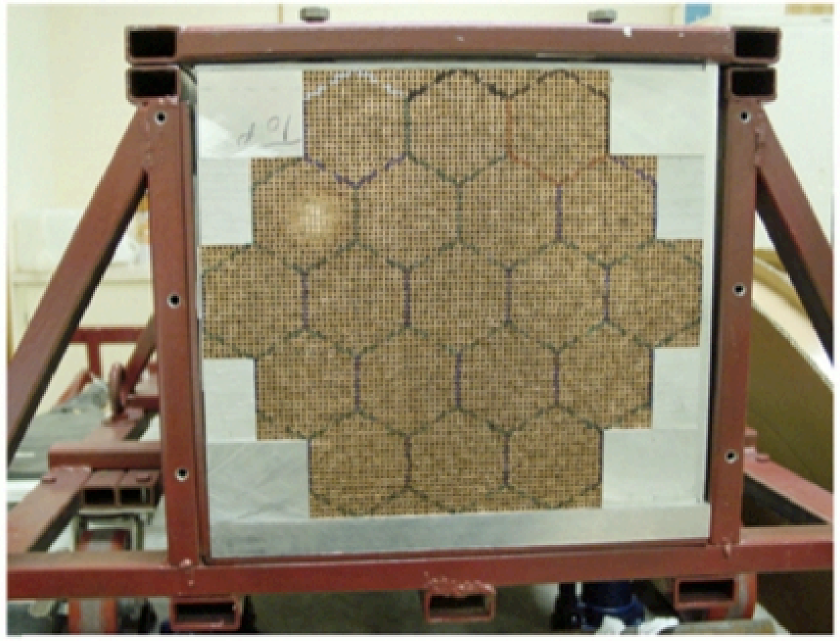
- Crystals as more efficient light collectors, but mixed light
  - i. PbWO4 crystals:
    - a. Temperature dependence (single crystal)
    - b. PbWO4 + DREAM "as a calorimeter"
  - ii. BGO crystals: single crystal
    - a. separation of Cerenkov and Scintillation light
      - cosmic muon and in beam beam
    - b. as an EM+Hadronic "calorimeter"

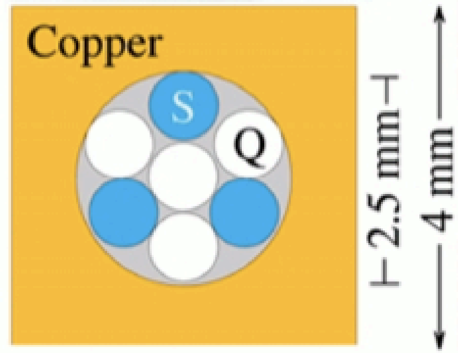
- 4th Letter of Intent

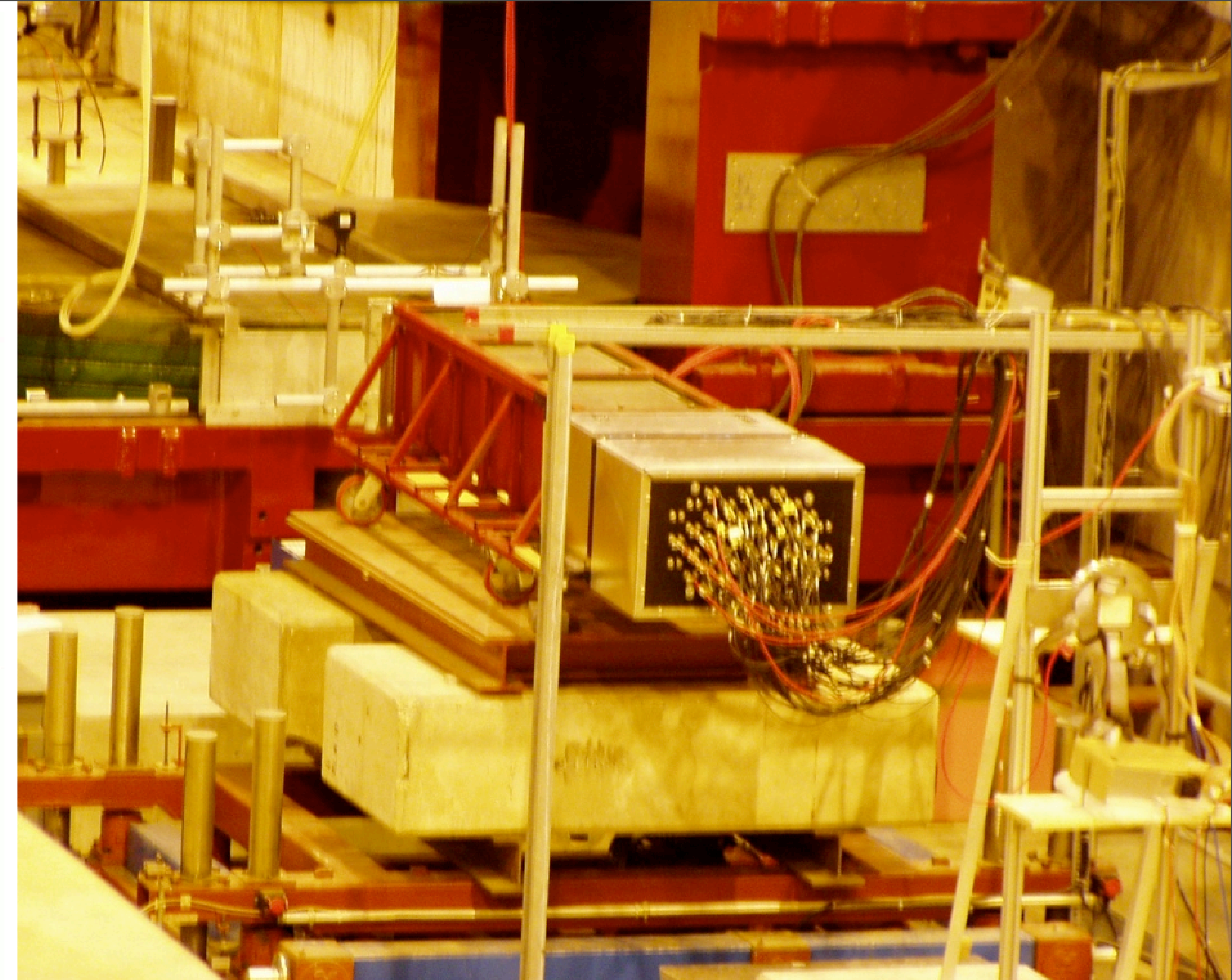
This is not a comprehensive dual-readout talk

We measure, we calculate, we agree.

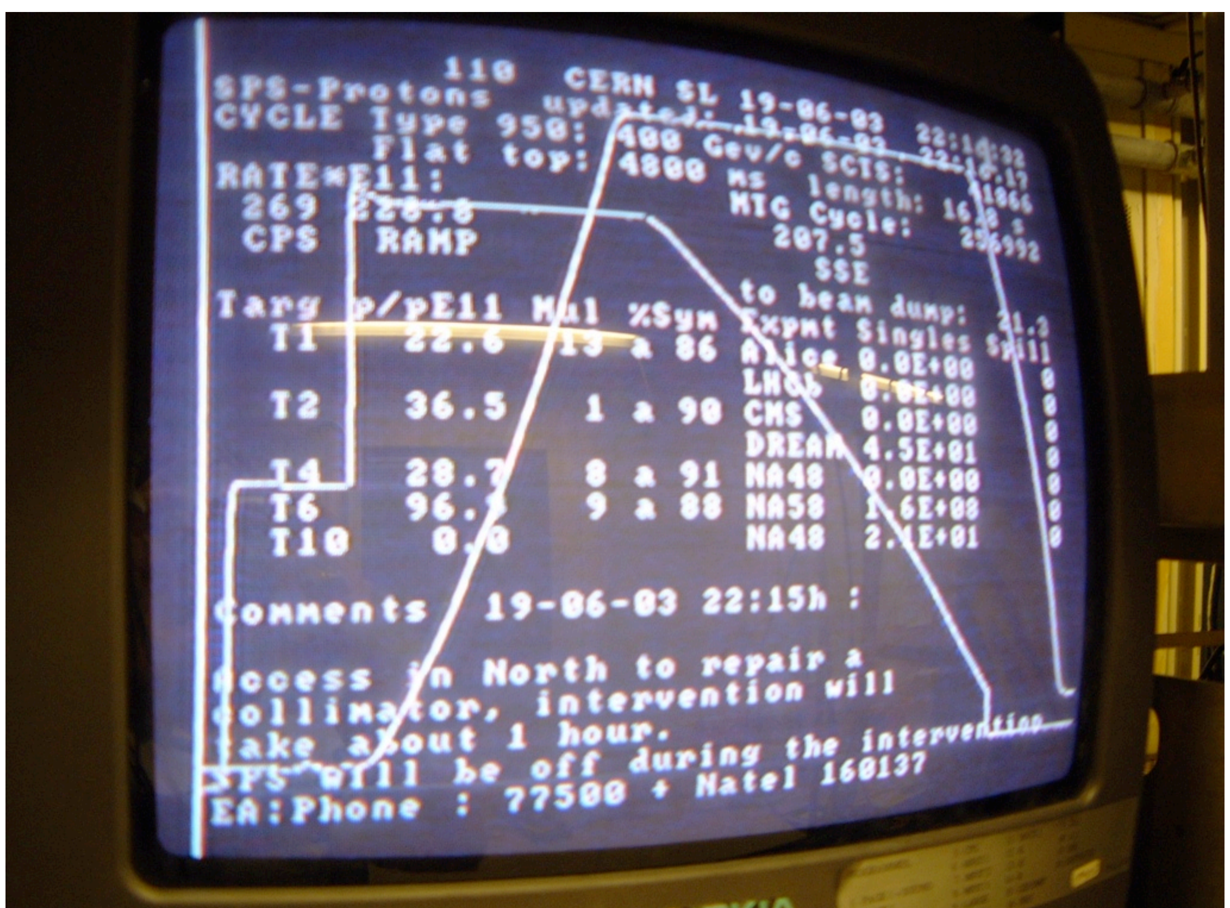
Dual-readout DREAM: Structure

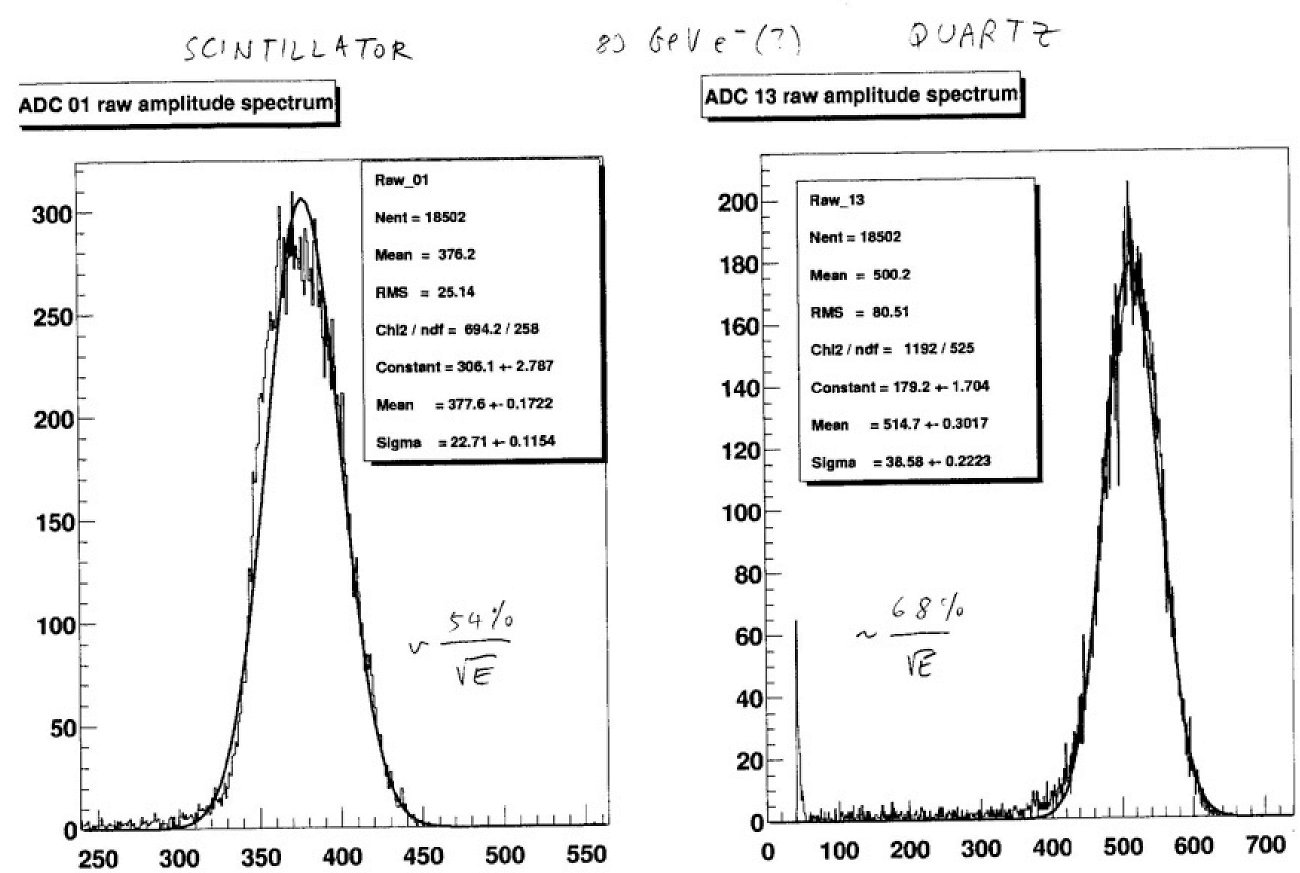






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

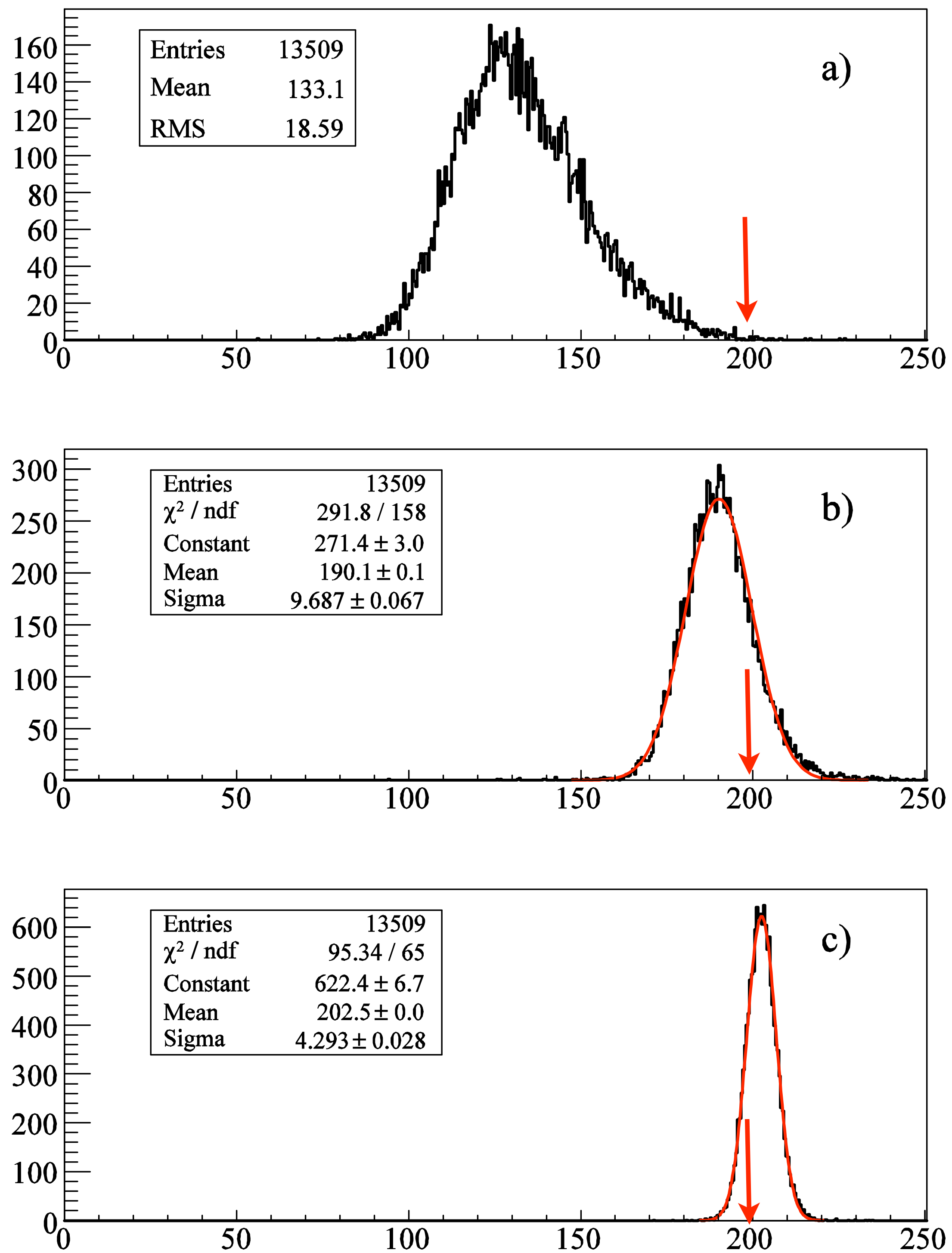




DREAM collaboration papers

1. **"Hadron and Jet Detection with a Dual-Readout Calorimeter"**, N. Akchurin, K. Carrell, J. Hauptman, H. Kim, H.P. Paar, A. Penzo, R. Thomas, R. Wigmans, *Nucl. Instrs. Meths.* **A537** (2005) 537-561.
2. **"Electron Detection with a Dual-Readout Calorimeter"**, *Nucl. Instrs. Meths.* **A536** (2005) 29-51.
3. **"Muon Detection with a Dual-Readout Calorimeter"**, *Nucl. Instrs. Meths.* **A533** (2004) 305-321.
4. **"Comparison of High-Energy Electromagnetic Shower Profiles Measured with Scintillation and Cerenkov Light"**, *Nucl. Instrs. Meths.* **A548** (2005) 336-354.
5. **"Separation of Scintillation and Cerenkov Light in an Optical Calorimeter"**, *Nucl. Instrs. Meths.* **A550** (2005) 185-200.
6. **"Comparison of High-Energy Hadronic Shower Profiles Measured with Scintillation and Cerenkov Light"**, *Nucl. Instrs. Meths.* **A584** (2007) 304-318.
7. **"Measurement of the Contribution of Neutrons to Hadron Calorimeter Signals,"** N. Akchurin, L. Berntzon, A. Cardini, G. Ciapetti, R. Ferrari, S. Franchino, G. Gaudio, J. Hauptman, H. Kim, F. Lacava, L. La Rotonda, M. Livan, E. Meoni, H. Paar, A. Penzo, D. Pinci, A. Policicchio, S. Popescu, G. Susinno, Y. Roh, W. Vandelli, and R. Wigmans, *Nucl. Instrs. Meths.* **A581** (2007) 643-650
8. **"Dual-Readout Calorimetry with Lead Tungstate Crystals,"** *Nucl. Instrs. Meths.* **A584** (2007) 273-284
9. **"Contributions of Cerenkov Light to the Signals from Lead Tungstate Crystals,"** *Nucl. Instrs. Meths.* **A582** (2007) 474-483.
10. **"Effects of the Temperature Dependence of the Signals from lead Tungstate Crystals"**, in draft.
11. **"Separation of Crystal Signals into Scintillation and Cerenkov Components",** in progress.
12. **"Dual-Readout Calorimetry with Crystal Calorimeters"**, in progress.
13. **"Neutron Signals for Dual-Readout Calorimetry"**, in progress.

DREAM data: 200 GeV π^- energy response



Scintillating (S) fibers only

Dual-readout of S and Cerenkov (C)

$$f_{EM} \propto (C/E_{shower} - 1/\eta_C)$$

(4% leakage + neutron BE loss fluctuations, and limited by photoelectron statistics in C)

Dual-readout of S and C:

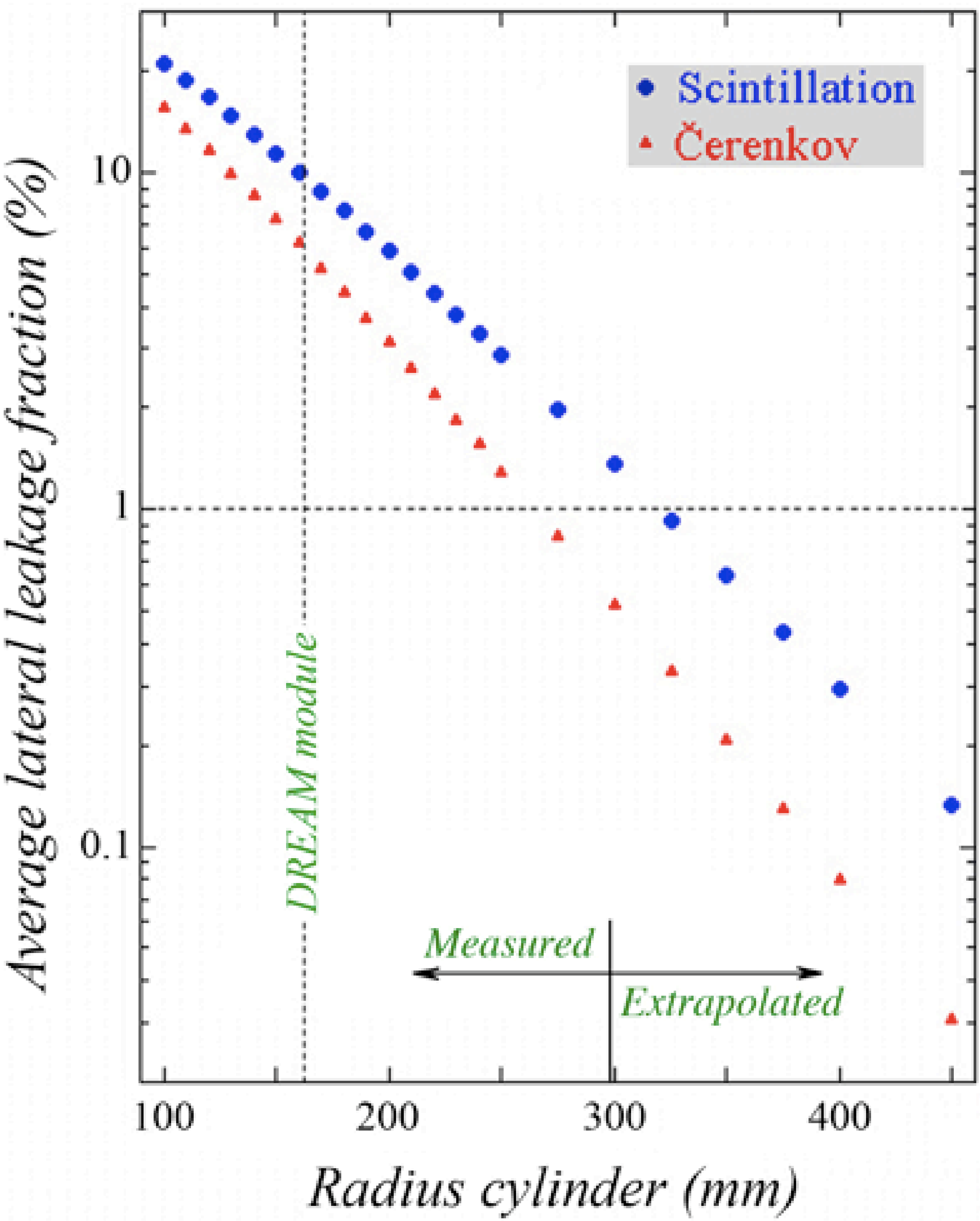
$$f_{EM} \propto (C/E_{beam} - 1/\eta_C)$$

(suppresses leakage and BE fluctuations; too optimistic)

Data NIM A537 (2005) 537.

We are measuring (DREAM) and calculating (ILCroot) (i) neutrons, (ii) a full ILC detector, (iii) Cerenkov pe statistics, and (iii) two different crystals, to understand and improve this.

DREAM data: leakage in S and C (DREAM was a small proof-of-principle test module)

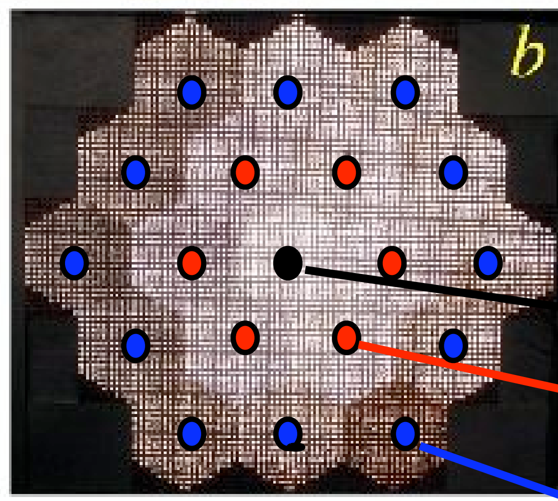


100 GeV π^+

Neutrons or "hadronic" identification: 50-300 GeV pions

DAQ was 1 GHz 4-chan digital storage scope

transfer to counting house in fast air-core cables



Scintillating fibers

"Fast 1"

"Fast 2"

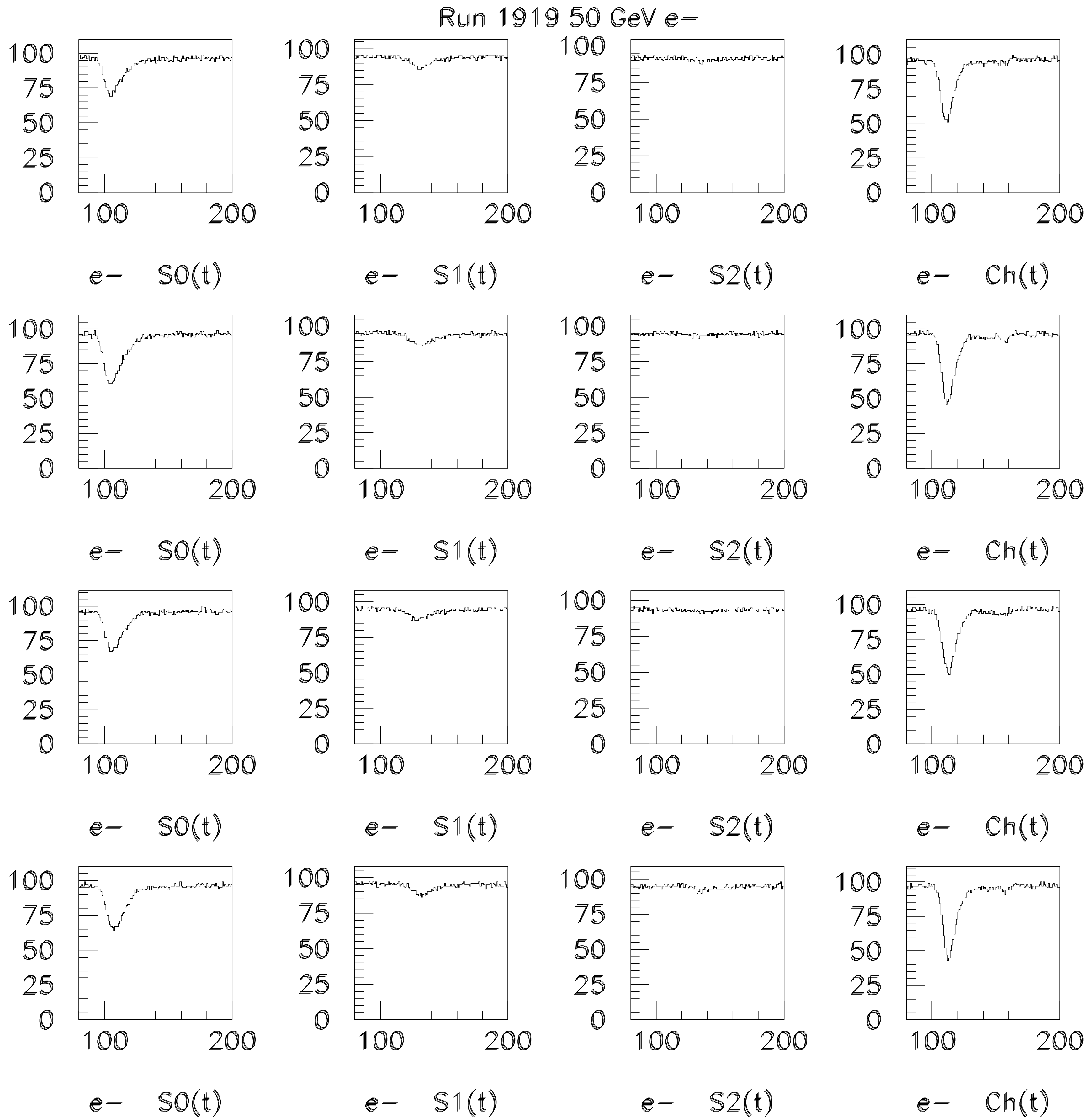
"Fast 3"

Cerenkov fibers

1● + 6● + 9● → "Fast 4"

Complete volume interrogation of DREAM: see delayed neutrons event-by-event. Analysis of data in progress.

Fast-1 Fast-2 Fast-3 Fast-4



50 GeV e-
data events

#1

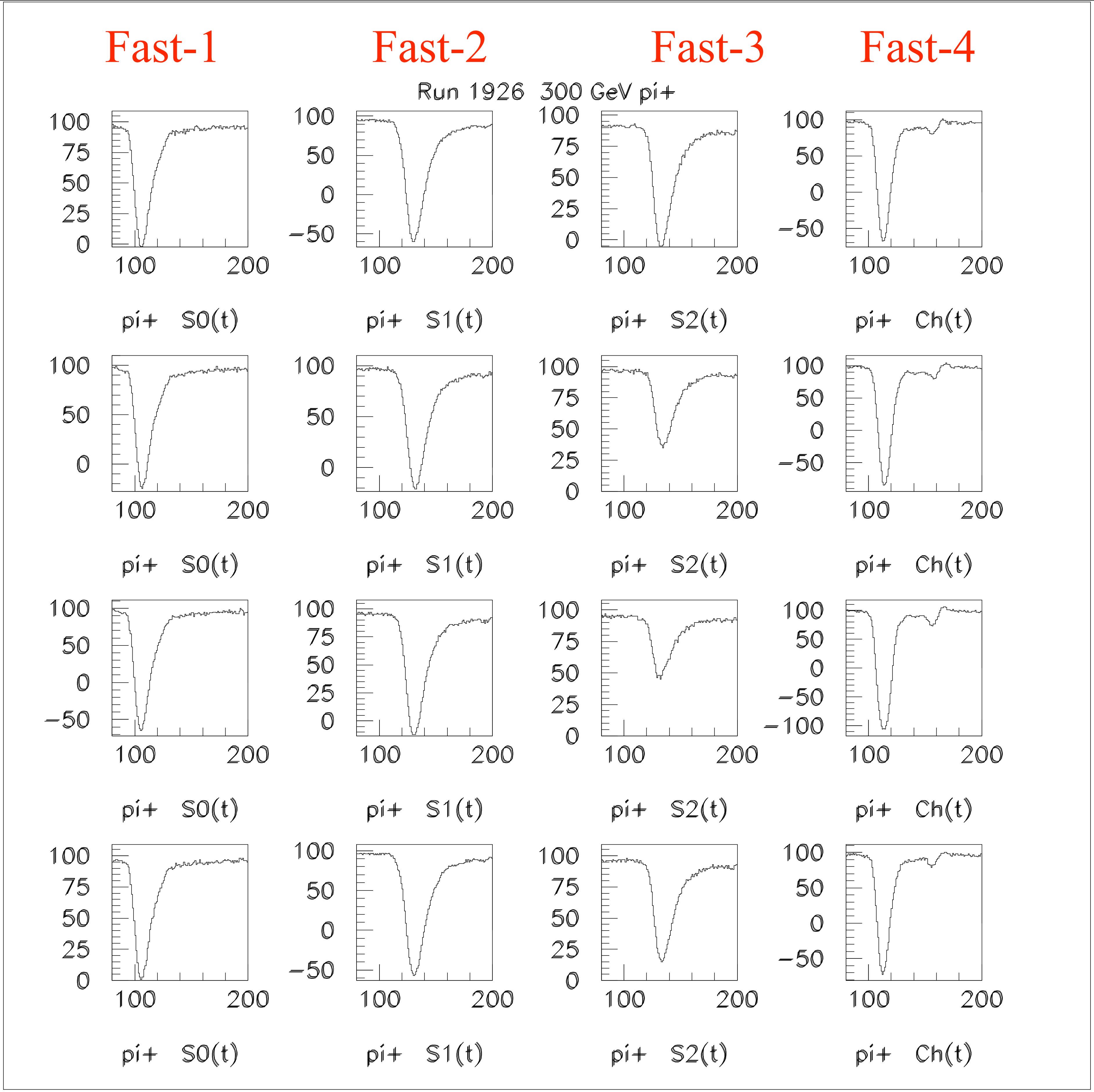
#2

#3

#4

clearly
electrons

300 GeV pi- data events



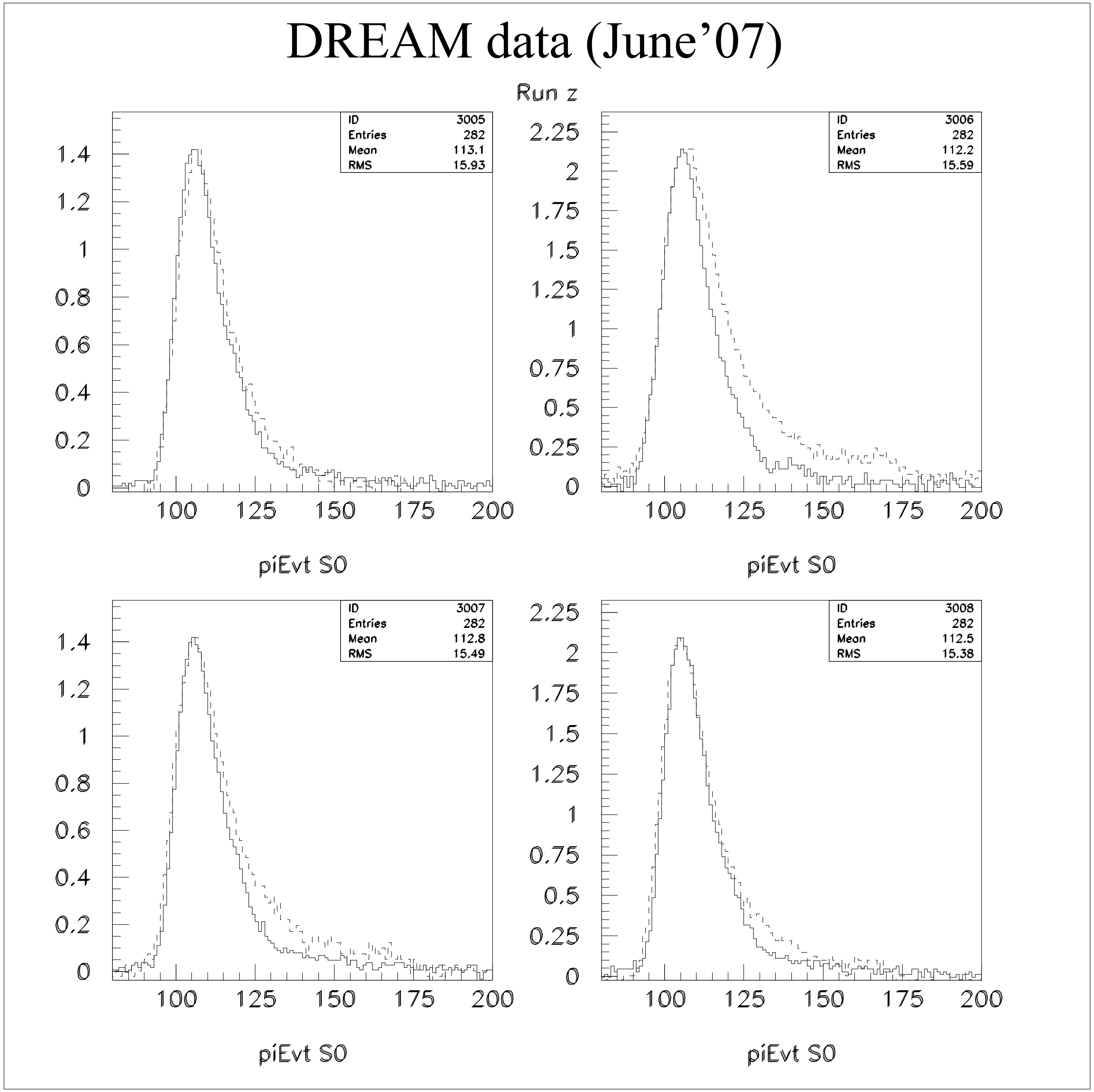
#1

#2

#3

#4

clearly pions

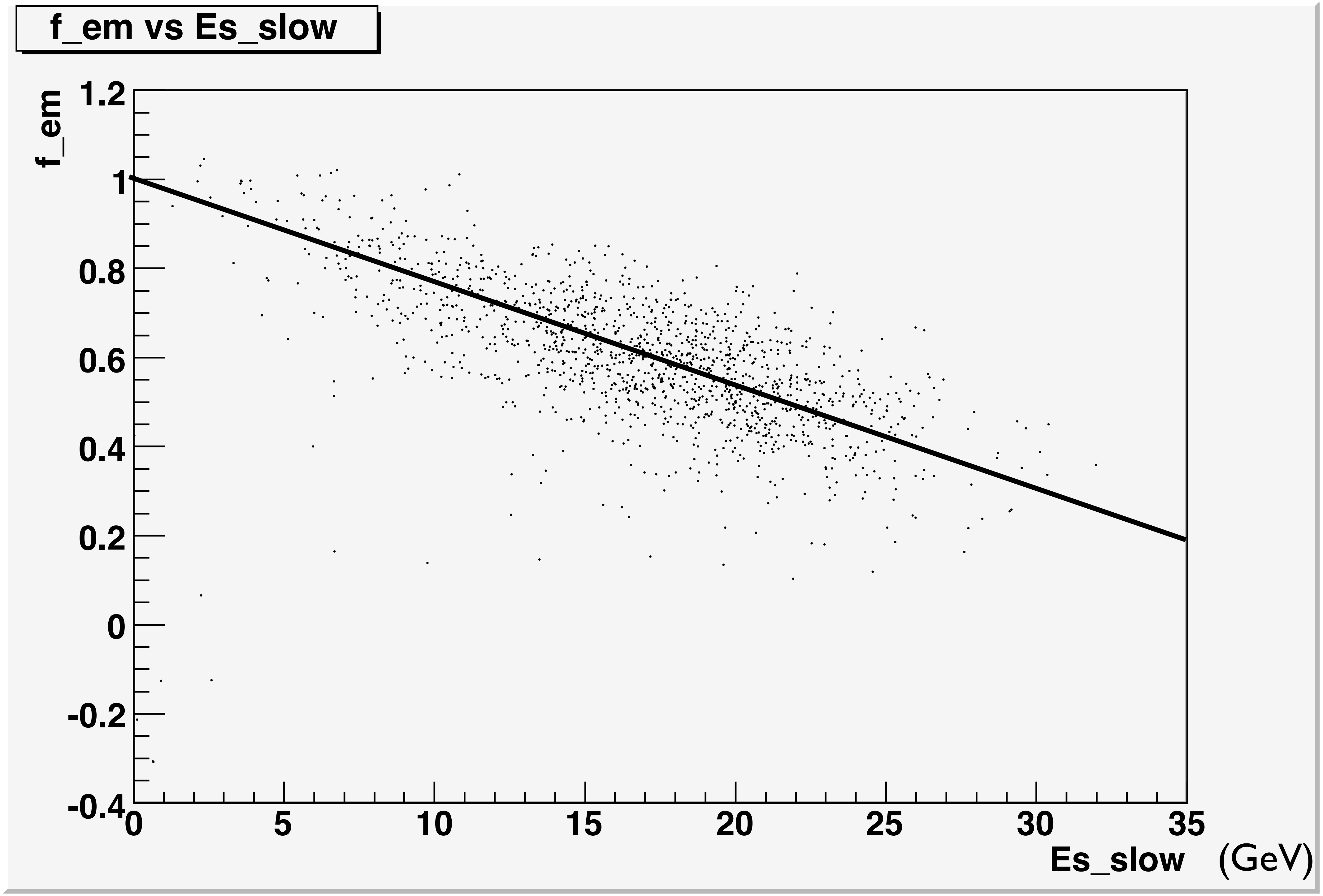


(S0-S2) pulses:

S0 ~ n x 1
S2 ~ n x 12

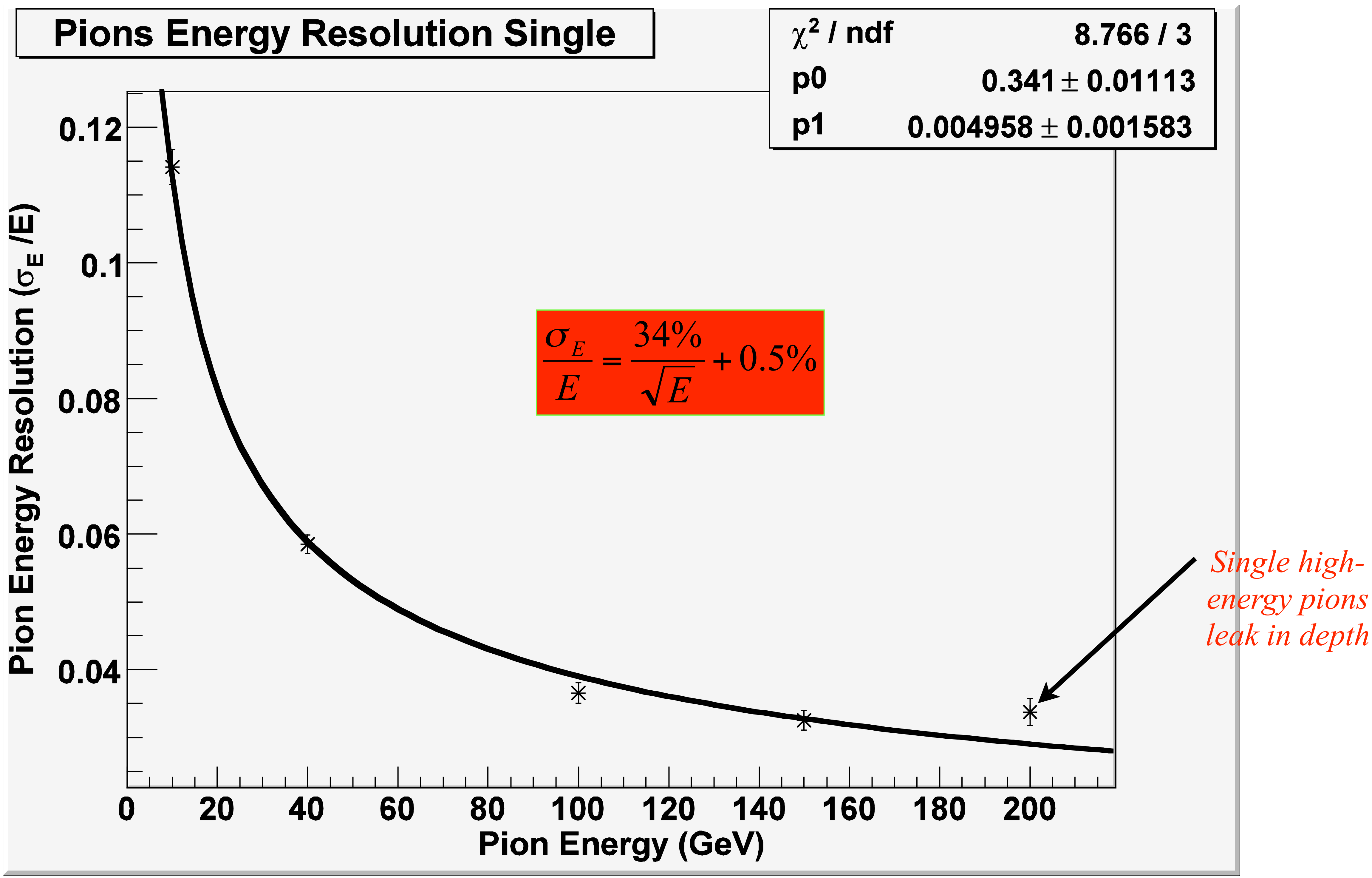
neutrons are hard (~10% in DREAM) but measureable

4th ILCroot ... calculating neutrons ... Vito Di Benedetto



f_{EM} anti-correlated with neutron fraction:
slow and late np-->np scatters in scintillating fibers

ILCroot: this is real resolution, and it scales with 1/sqrt(E). (neutrons not used yet)



Evolution: fibers ---> crystals --> both --> ...

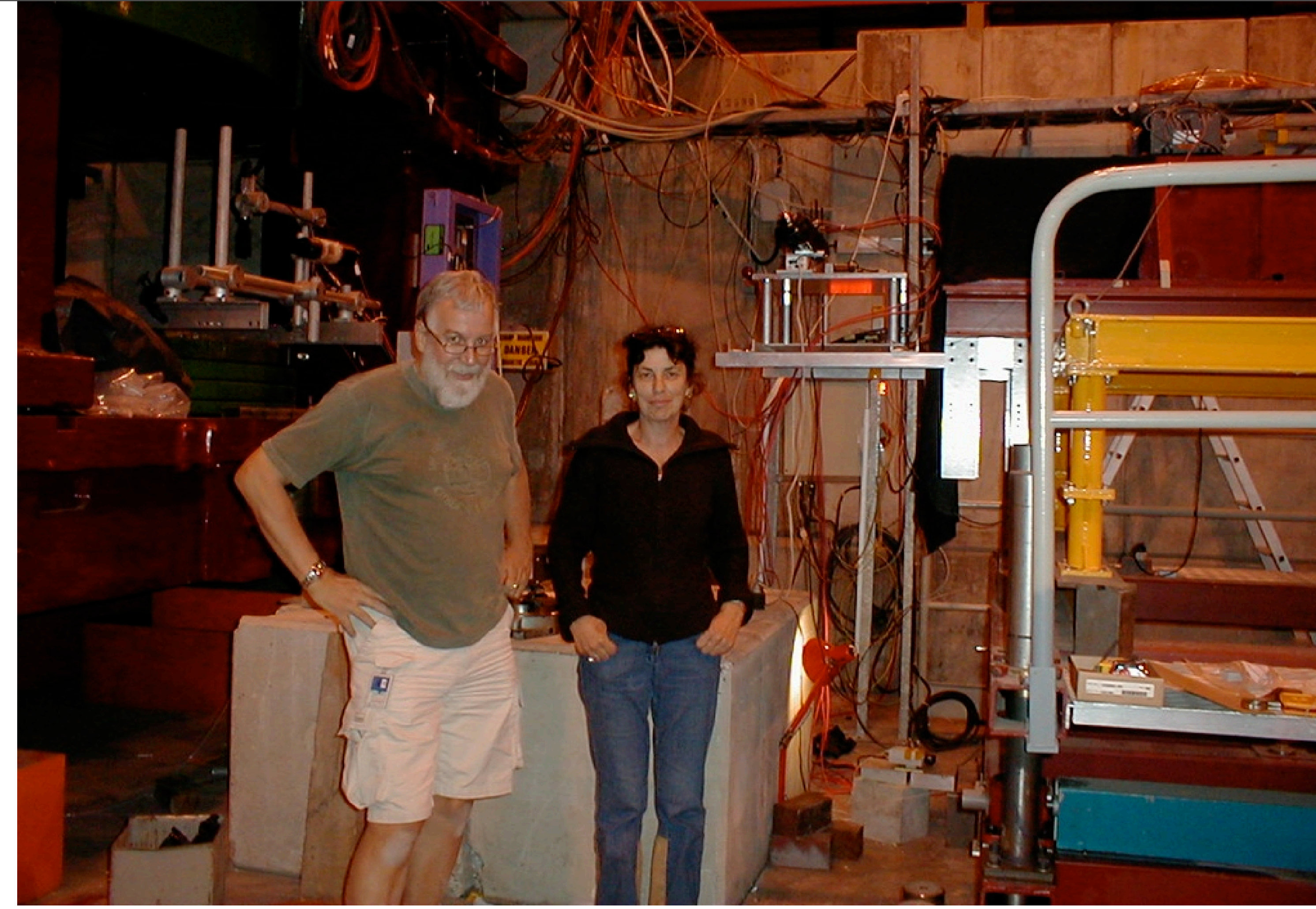
- The recognition from the first DREAM data in 2004 that the limiting measurement (NIM paper) was the Cerenkov photostatistics (due to the small numerical aperture of the quartz fibers) led the DREAM collaboration naturally to consider crystals and glasses as dual-readout media. We had already mixed light in the fibers in the 2005 beam test, and then un-mixed them (NIM paper).

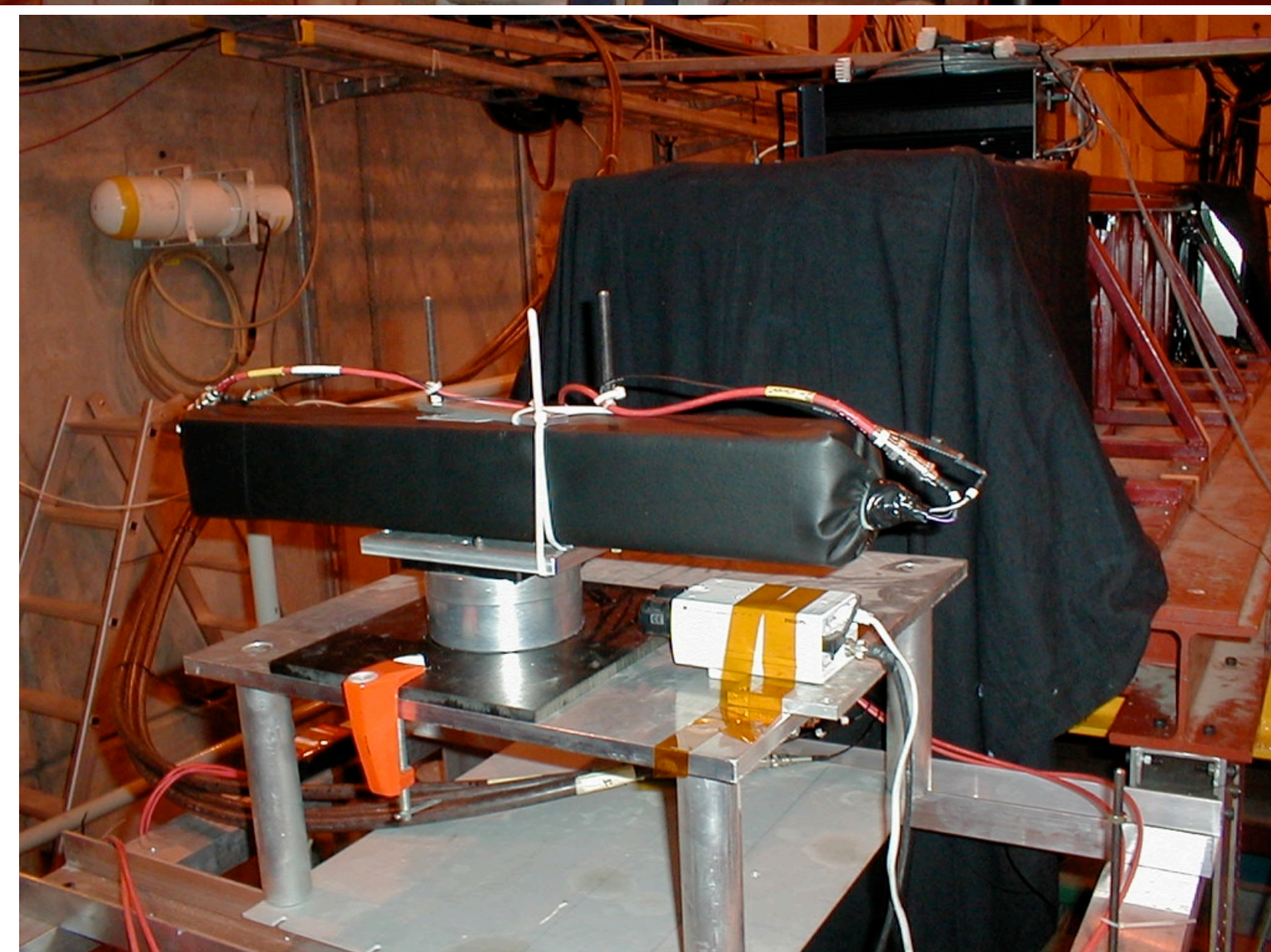
- Without funds, the DREAM collaboration studied those crystals it could borrow - PWO (from ALICE) and, later, BGO (from L3). We achieved usable dual readout in both (NIM papers).

- We are thinking of all-fiber, all-crystal, and crystal-plus-fiber, most of which are Wigmans' ideas. And, in both measurements and calculations. For 4th, we want to optimize the physics.

Dual-readout of BGO crystals

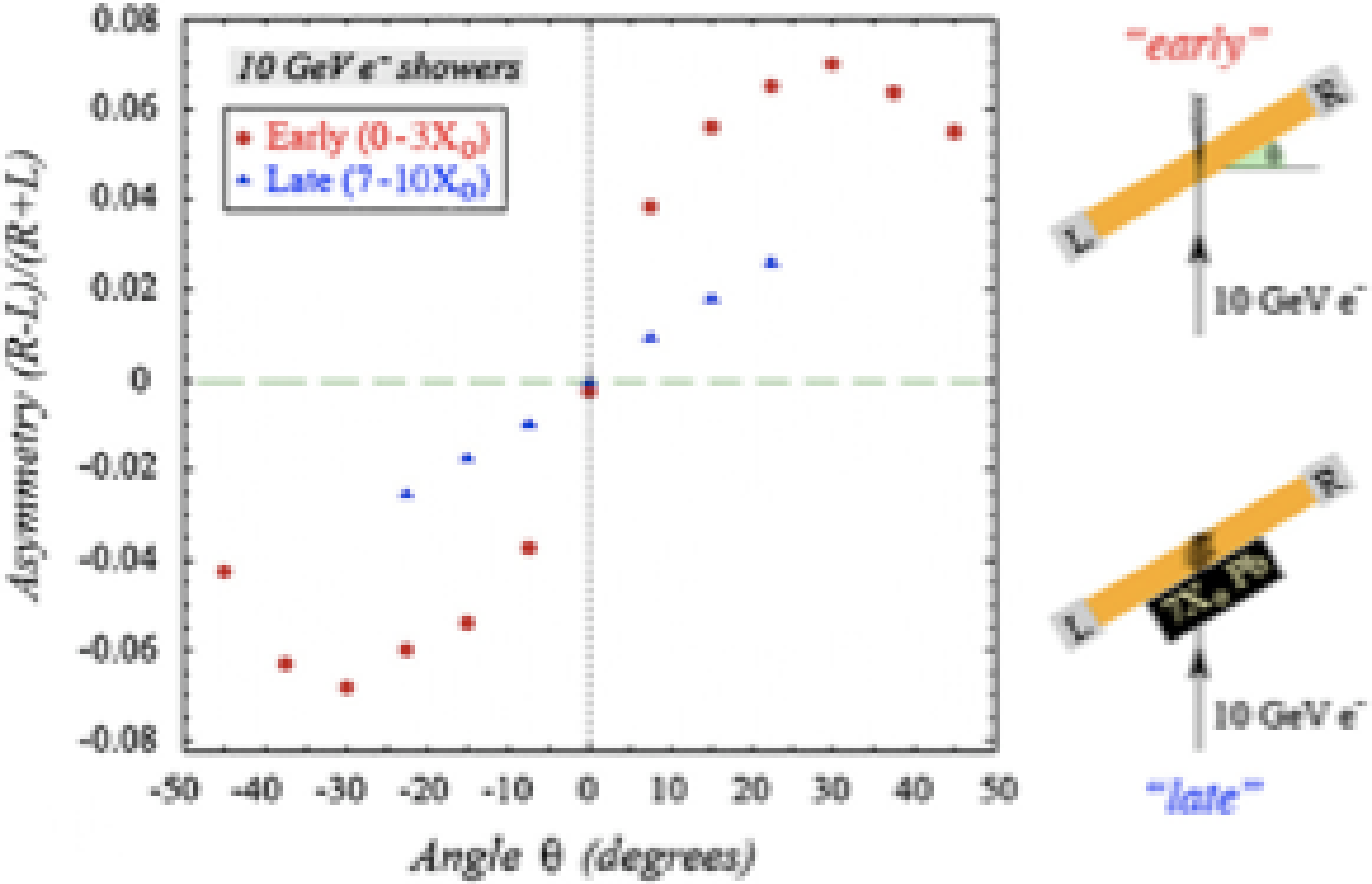
BGO crystal, its housing, and in the beam in front of DREAM module



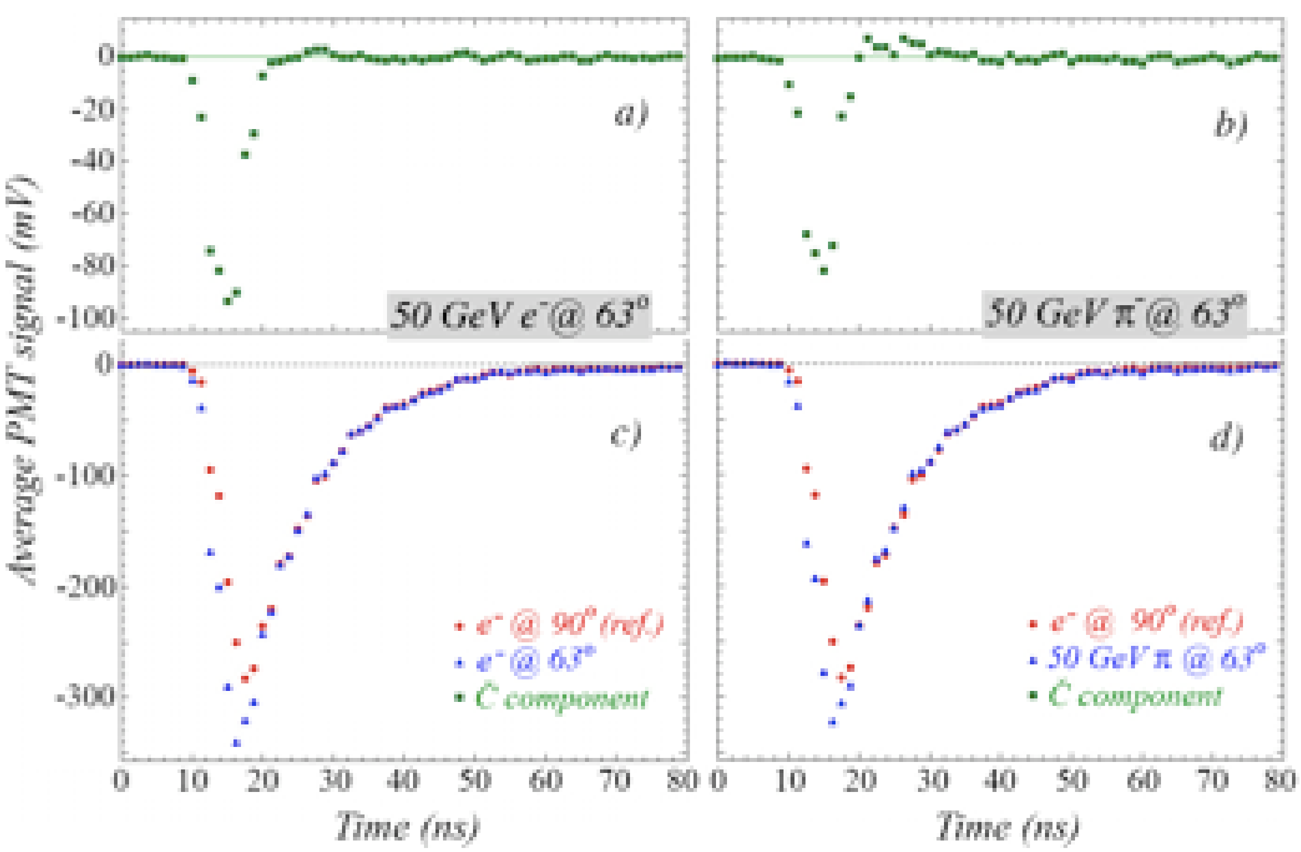


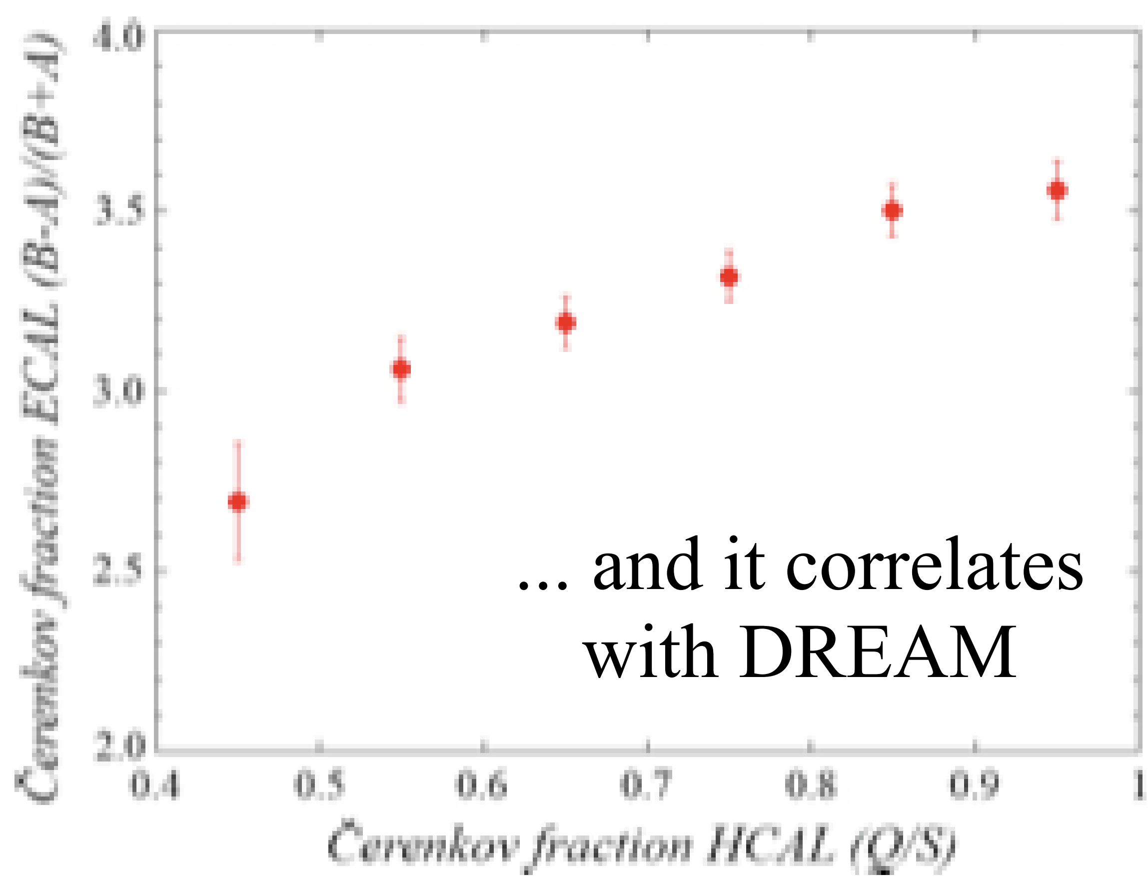
Lead Tungstate (PWO)

... by direction



... by time

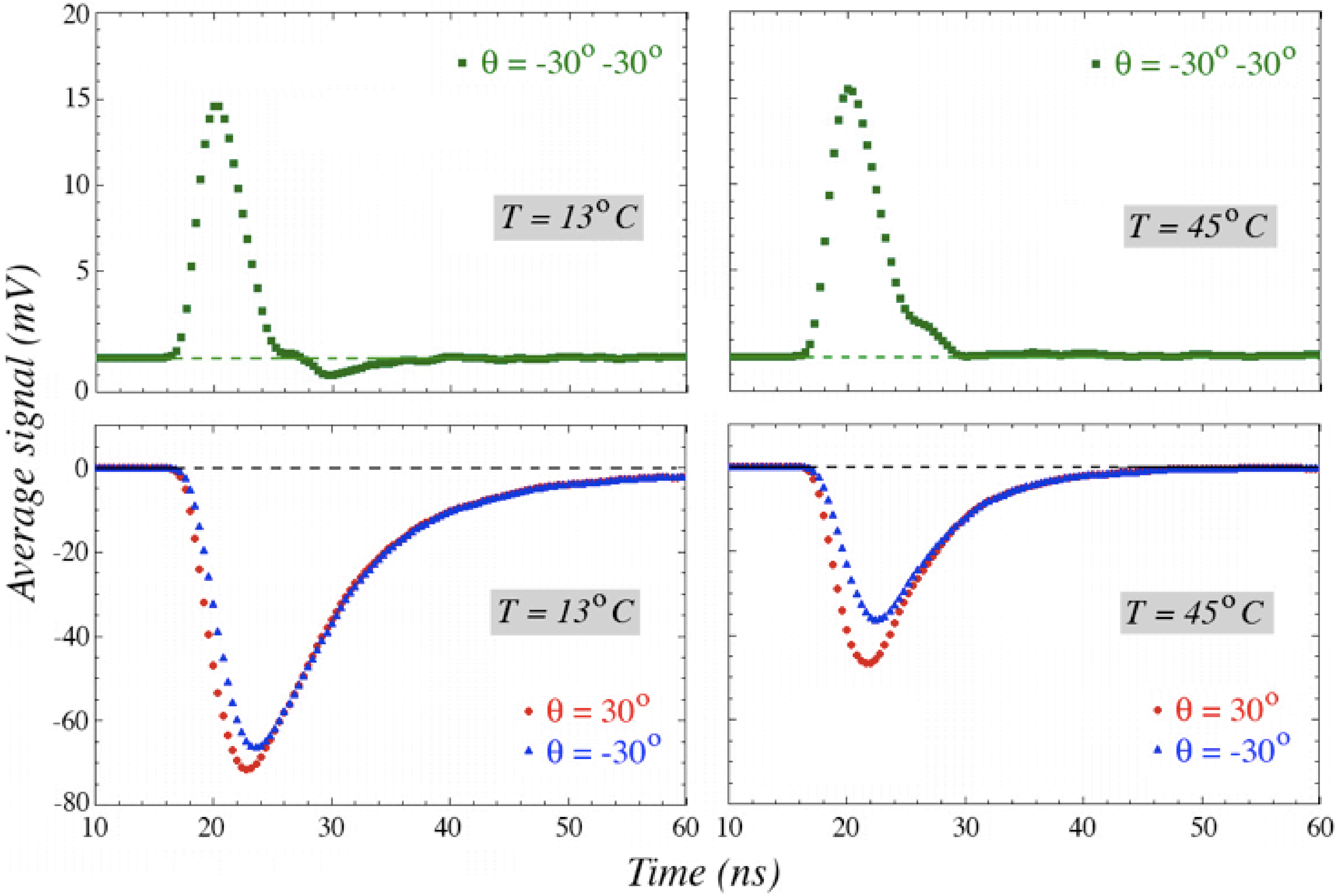


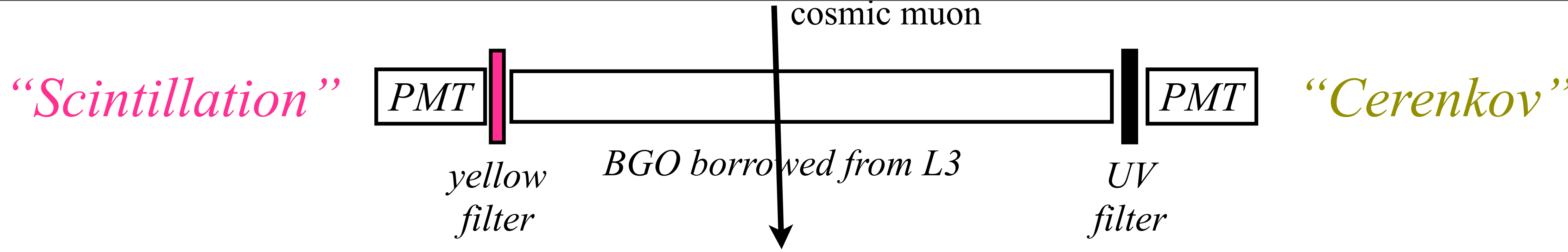


... and it correlates with DREAM

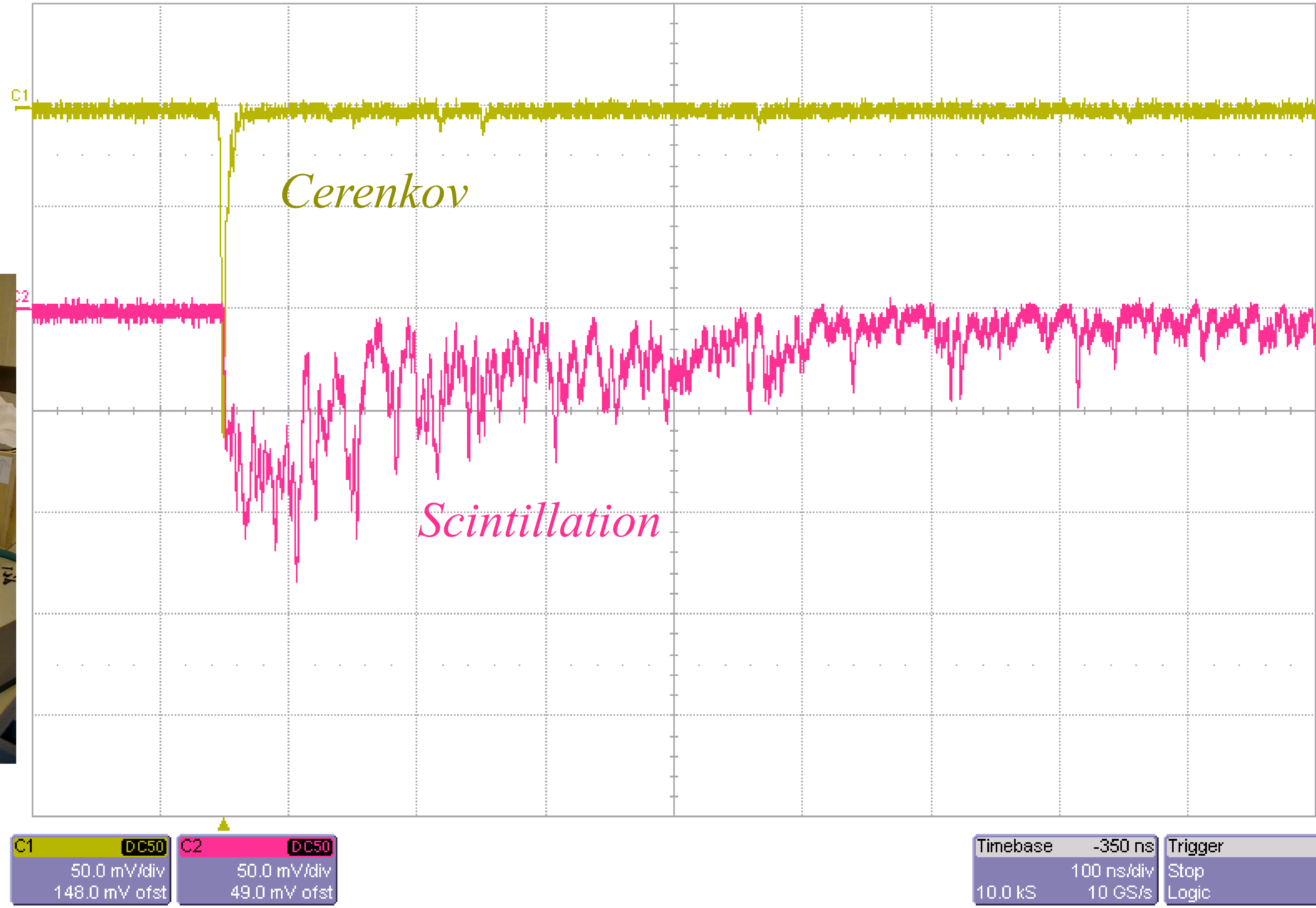
Lead Tungstate (PWO) - Temperature effects on S and C

a. S goes down at T goes up
b. C independent of T
c. S becomes faster as T goes up, slow components die





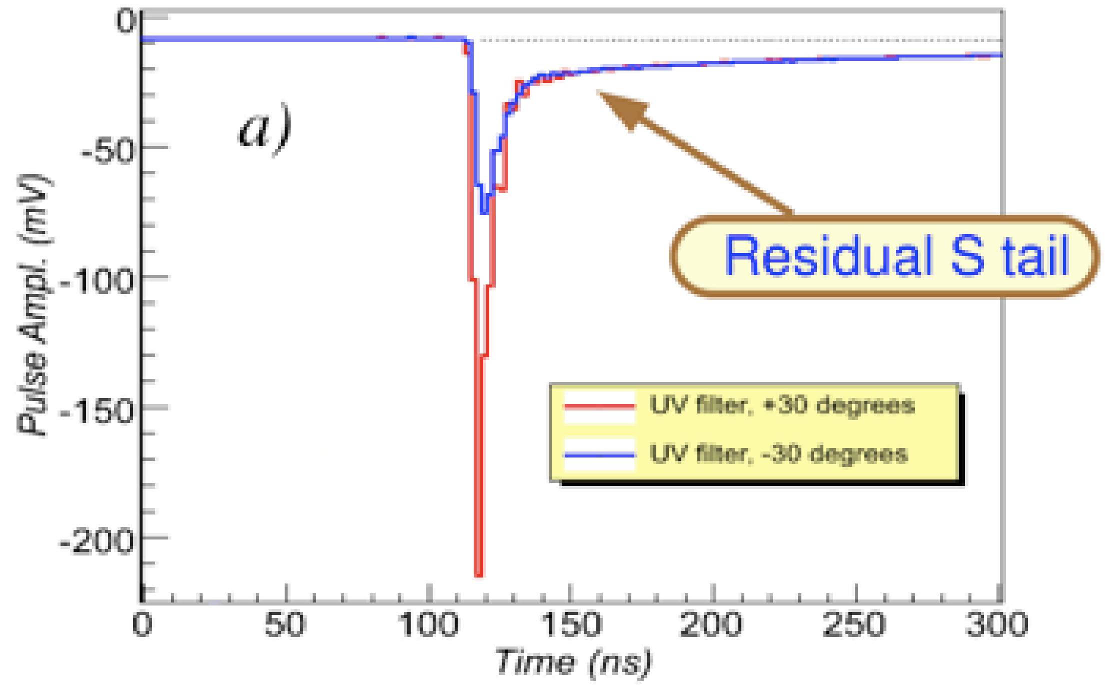
BGO ...
by time and wavelength



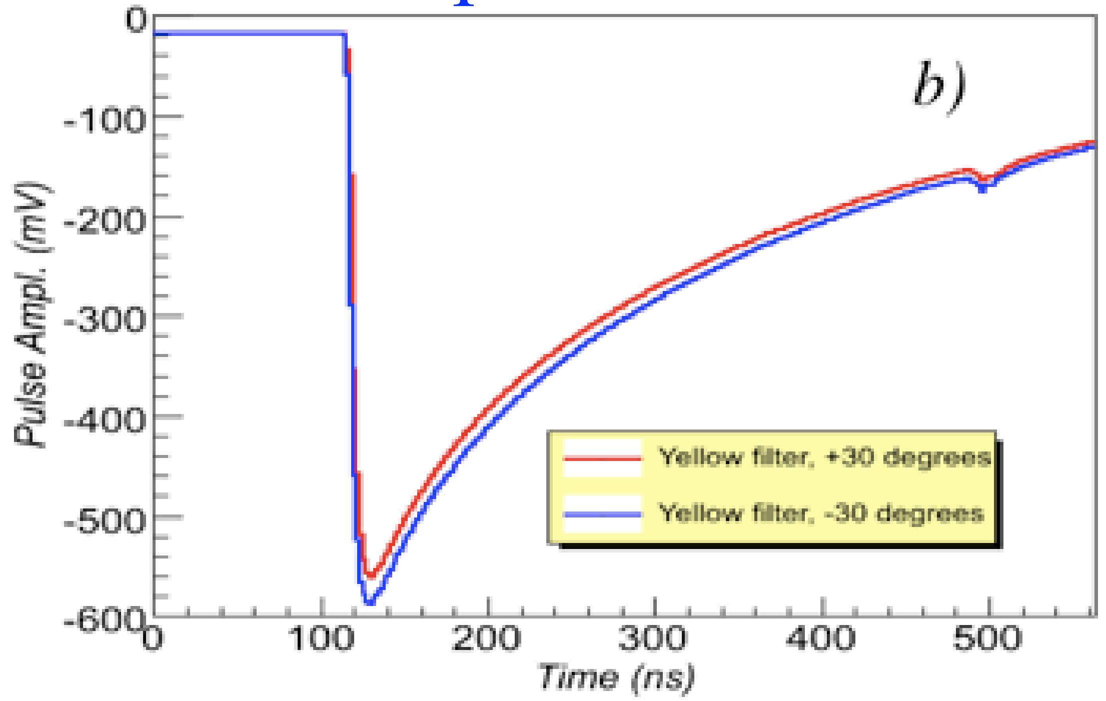
We can now do dual-readout in a single crystal ==> EM precision

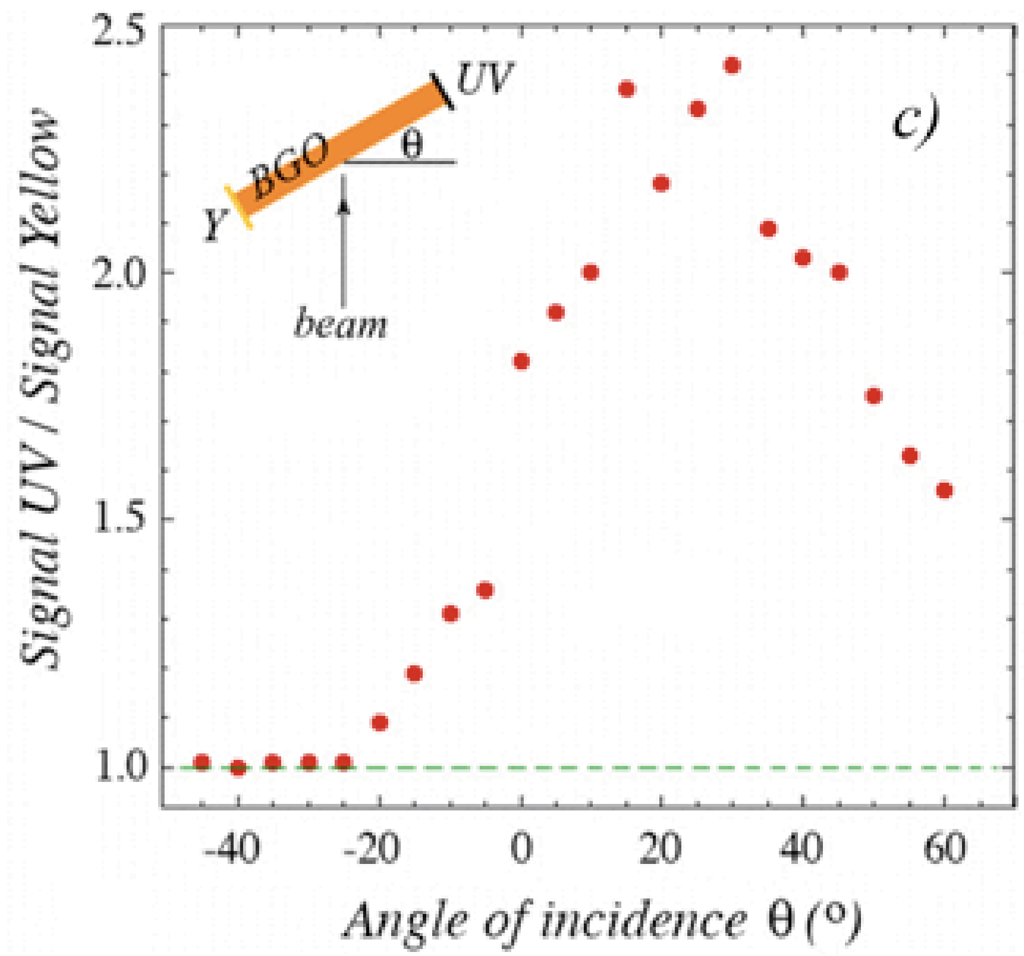
BGO ... by wavelength, direction and time

Directional Cerenkov

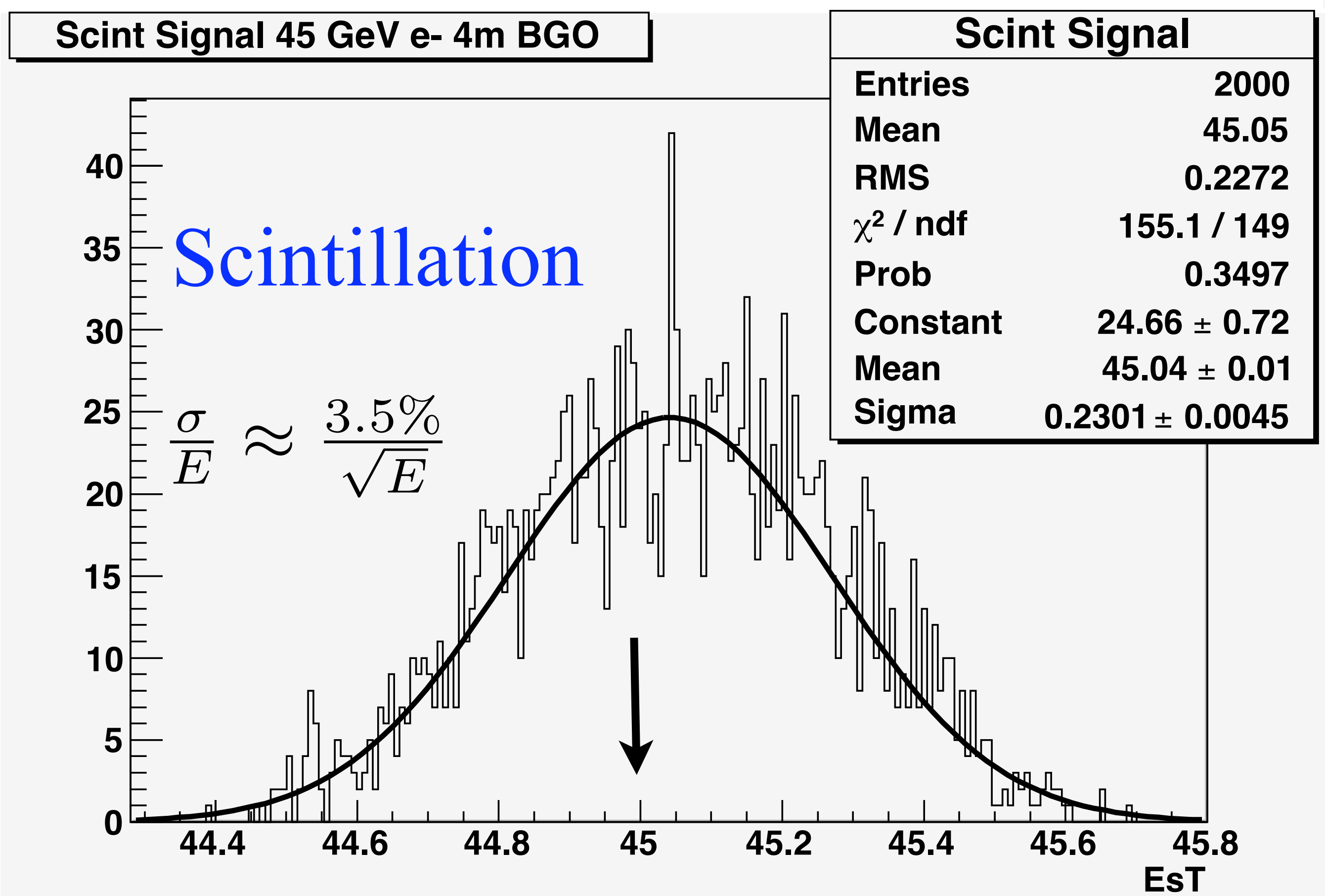


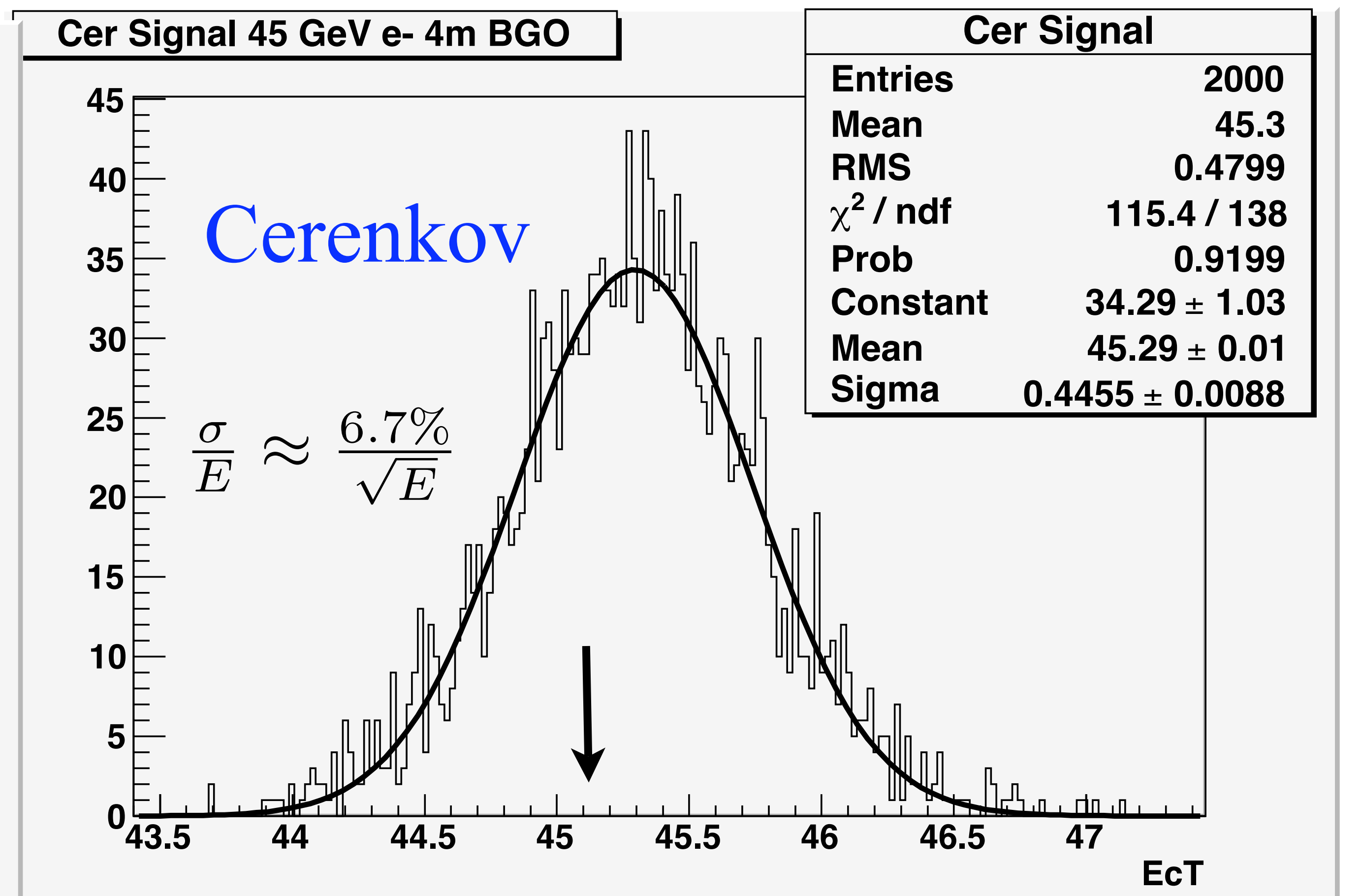
Isotropic scintillation

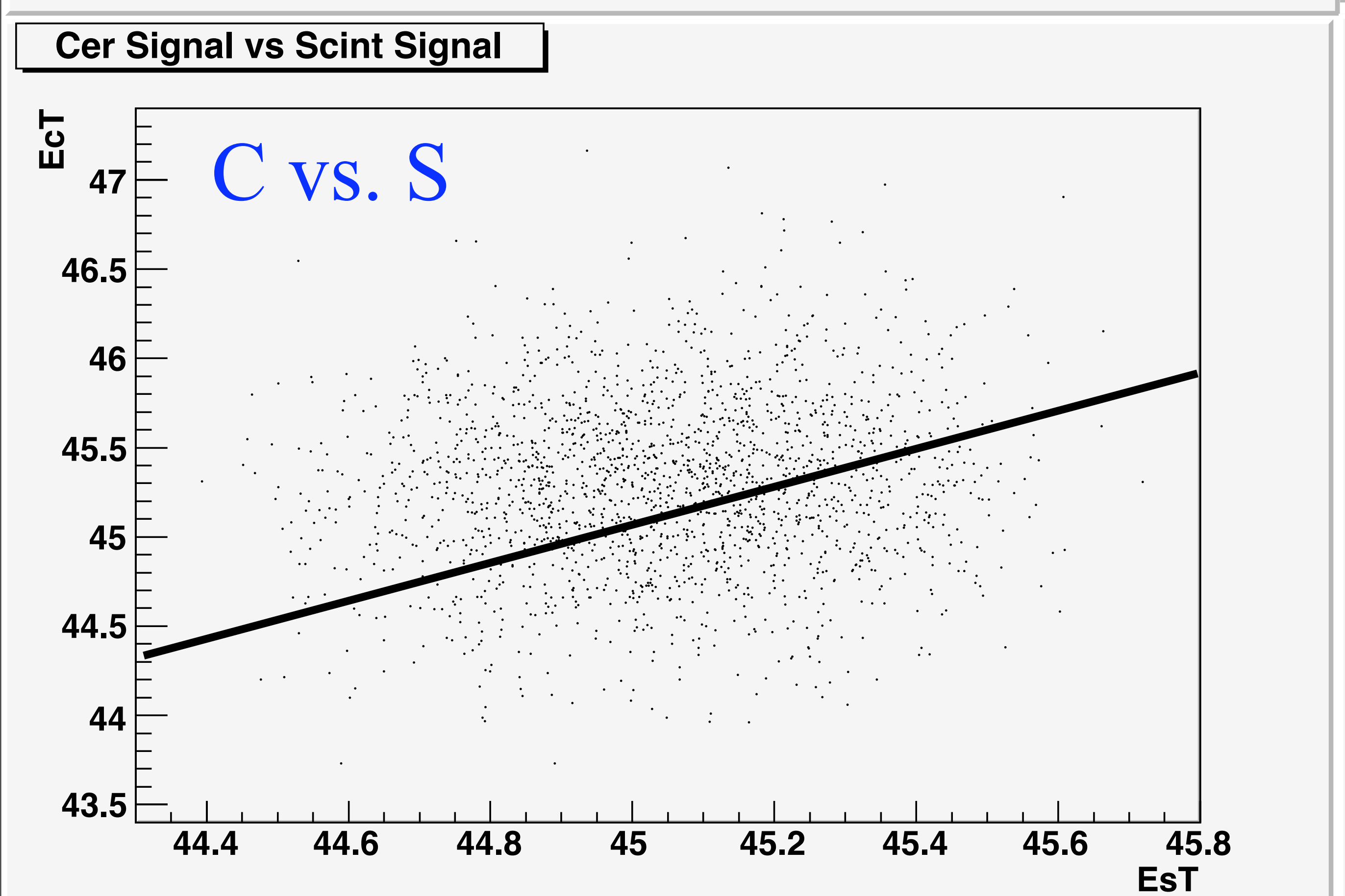


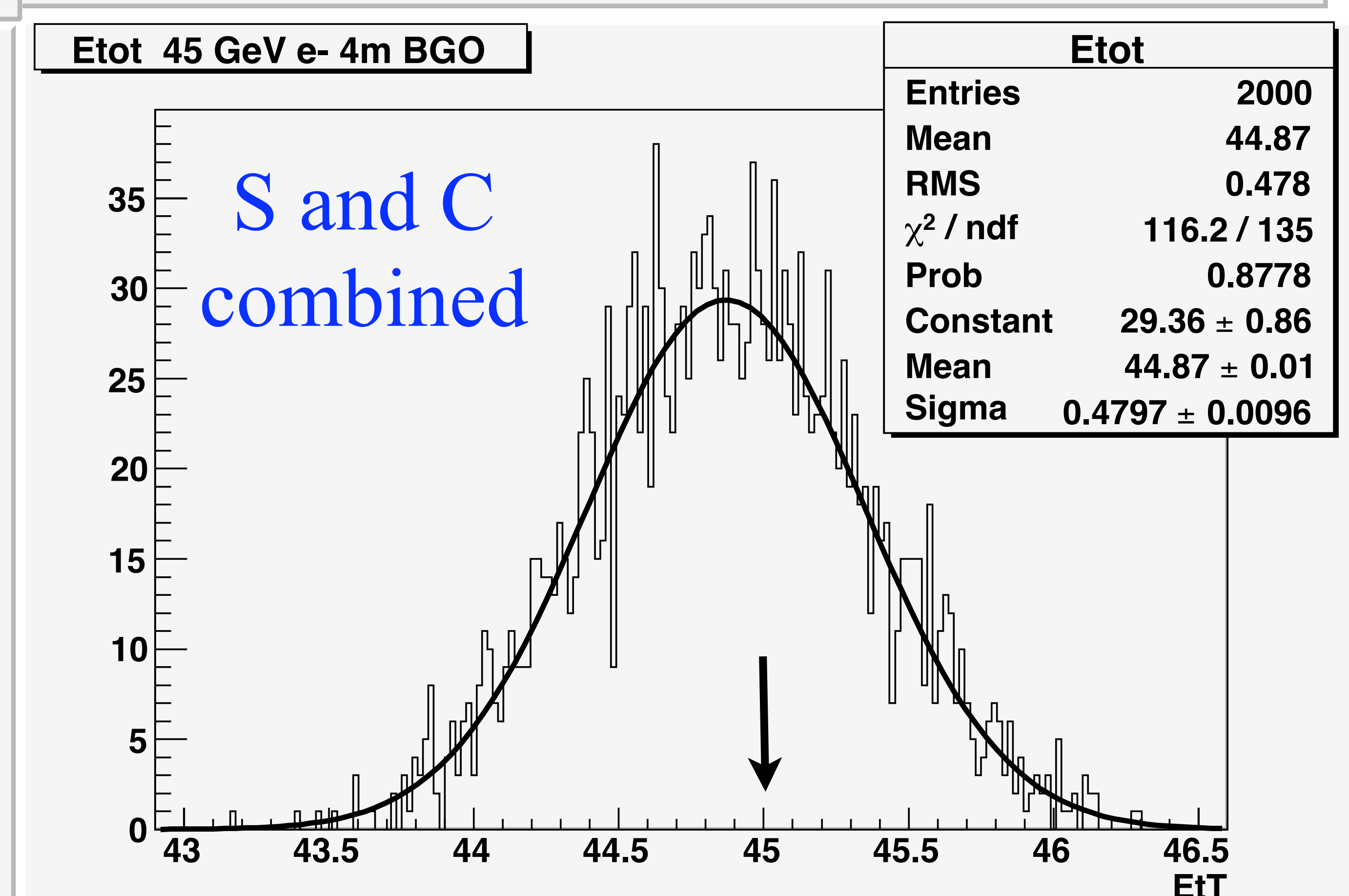


"BGO calorimeter" 45 GeV e- 4th ILCroot: Vito Di Benedetto

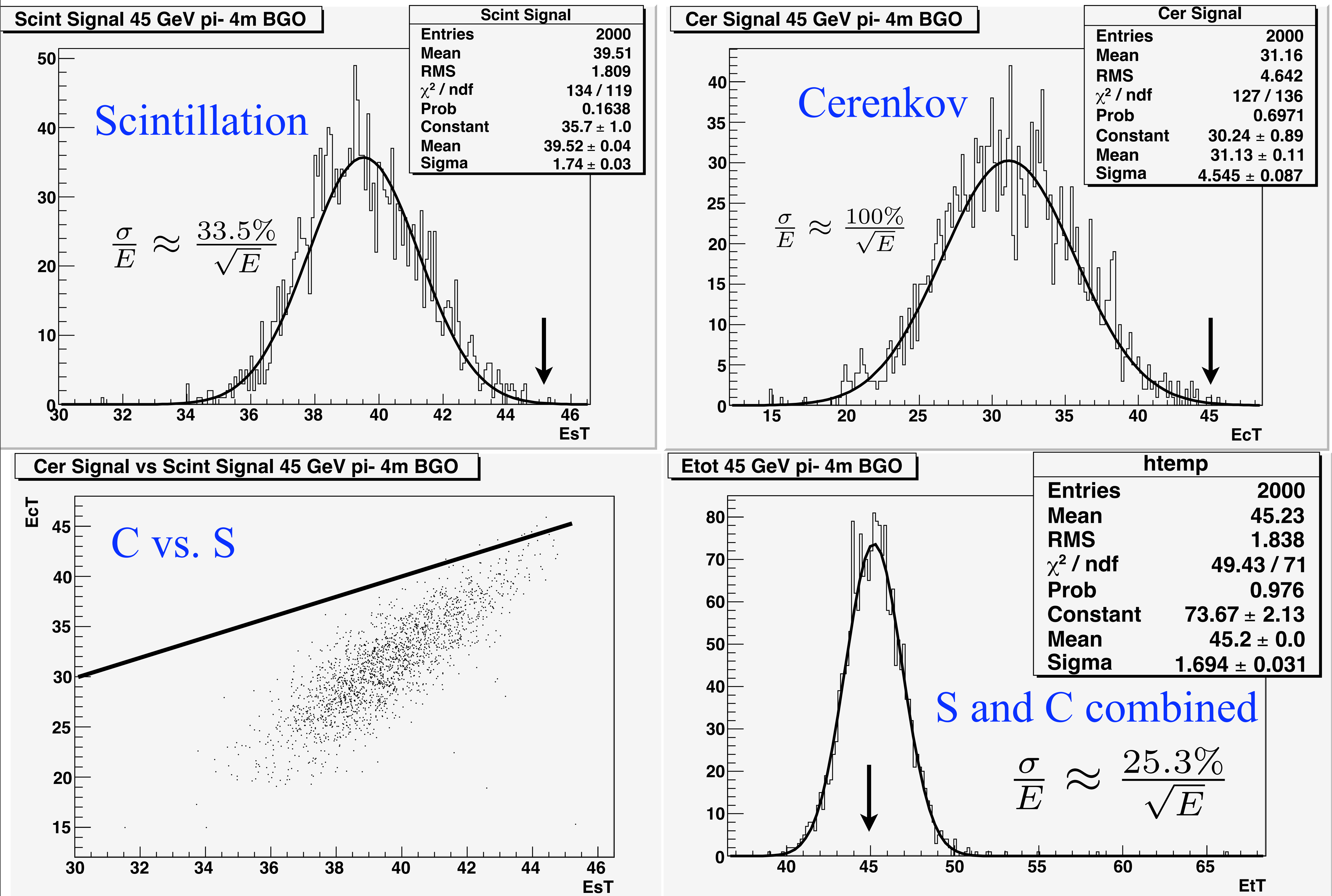




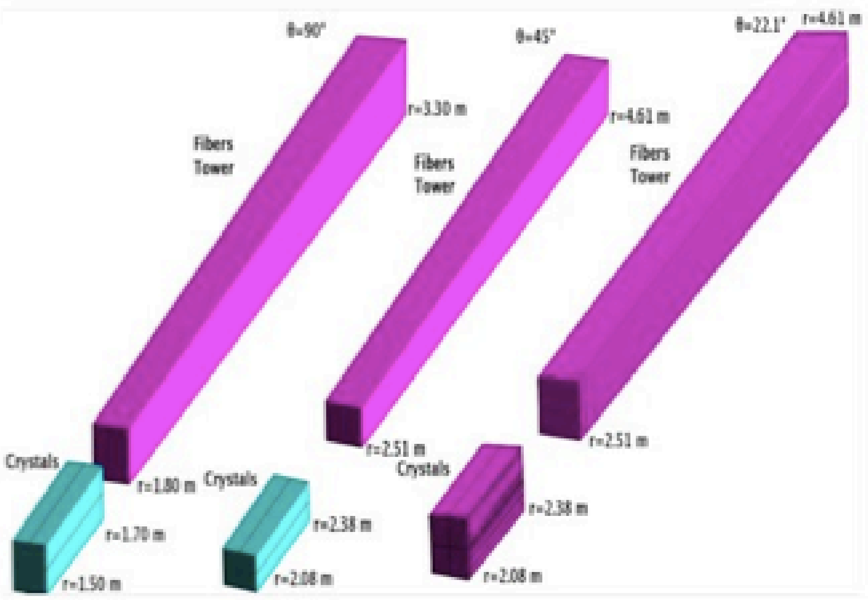


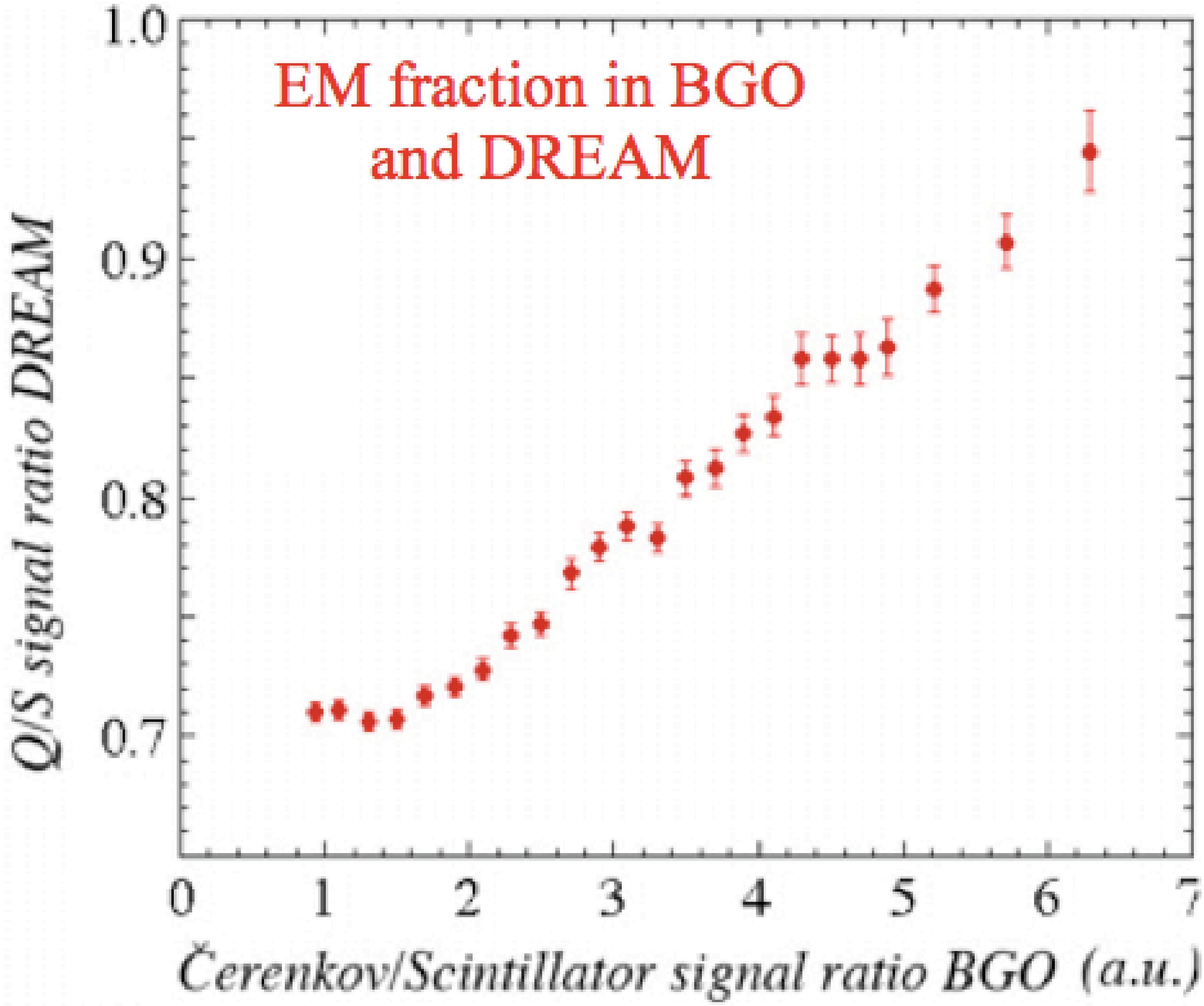


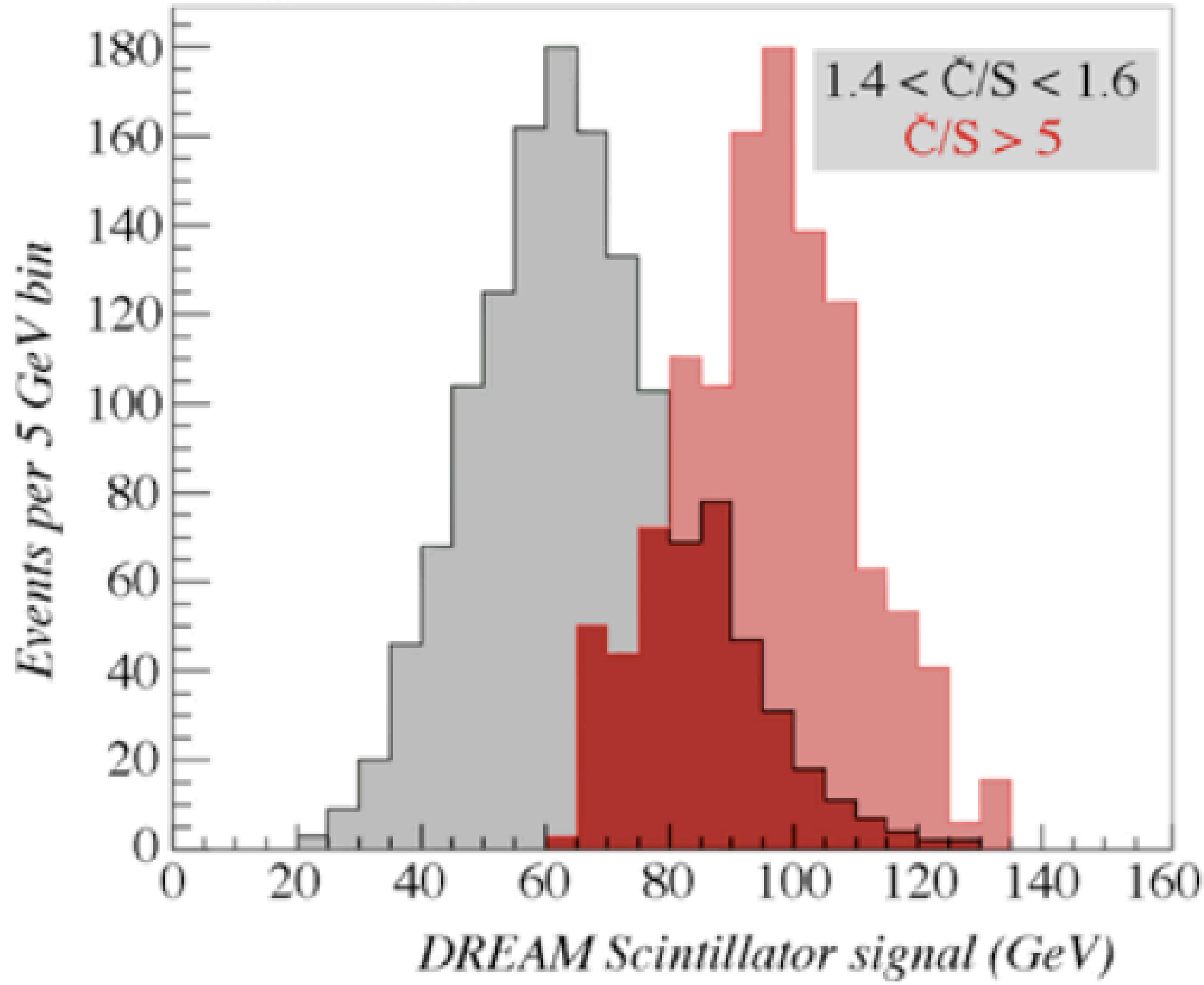
“BGO calorimeter” 45 GeV pi- 4th ILCroot: Vito Di Benedetto



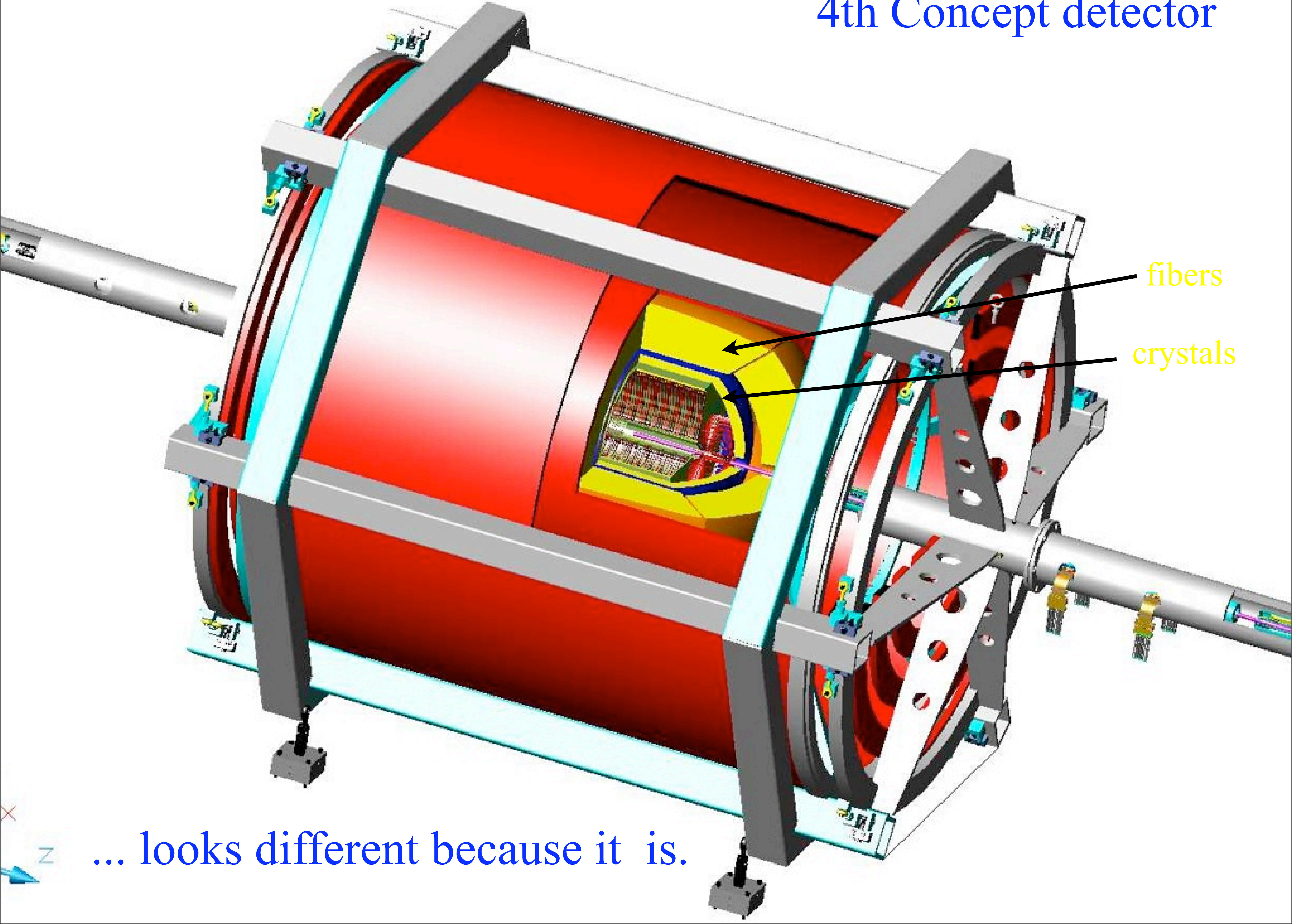
An “ILC calorimeter” BGO+DREAM = 4th LoI







4th Concept detector



... looks different because it is.

Particle identification in 4th: *e-pi-mu, em-had, n-x, mu-x, e-pi-K-p, tau, W/Z, ...*

Table 1:

Physical measurement	Partons/particles discriminated	Subsystems used
C *vs.* S	$e^\pm$ *vs.* $\pi^\pm$ *vs.* $\mu^\pm$	dual-readout calorimeters
$\chi^2 \sim \frac{1}{n}\sum_i^n [C_i - S_i]^2$	EM *vs.* "hadronic"	dual-readout calorimeters
$f_n \sim E_n/E_{\mathrm{shower}}$ (slow neutrons by time-history)	"hadronic" *vs.* EM or "muonic"	calor. scintillating fibers
$(S - C)$ *vs.* $(S + C)$	μ *vs.* π	dual readout calorimeters
dN/dx cluster counting	$e - \mu - \pi - K - p$ in GeV region	CluCou tracking chamber
$p_{\mathrm{tracking}} \approx E_{\mathrm{dual-readout}} + p_{\mathrm{muon}}$	μ *vs.* any track exiting calrimeter	CluCou, dual-readout, muon
$\tau^\pm \to \rho^\pm \nu \to \pi^\pm \gamma\gamma$	τ *vs.* hadronic debris	BGO dual-readout calorimeter
$W, Z \to jj$ mass	W, Z from QCD jj background	dual-readout calorimeter

4th Letter of Intent (regarding calorimetry)

- We will submit a Letter of Intent with dual-readout calorimetry;
- We understand (well enough) the simulations of dual-readout in ILCroot, but have yet to verify the crystal+fiber combination;
- For the next CERN beam test, we will test a multi-crystal readout;
- The 4th configuration will be a BGO-like dual-readout crystal with a improved DREAM-like fiber calorimeter behind. This secures particle ID, very good EM and hadronic resolutions, and ns-ToF (not discussed here).
- We are assembling a simulation-physics team from four institutions (which depends on the non-existent LCRD funding).