Recent results from the DREAM project*

Richard WIGMANS (TTU)
Università di Roma (1), March 14, 2008

Outline :

- High-precision (hadron) calorimetry
- The DREAM approach
- Results
- Future plans
- Conclusions

---

* DREAM is a collaboration of US and Italian institutions
TTU, UCSD, ISU (USA), PV, RM1, CS, CG, PI (I)

High-resolution hadron calorimetry
(for jet spectroscopy)

- *Very relevant for Linear high-energy e^+e^- Colliders*

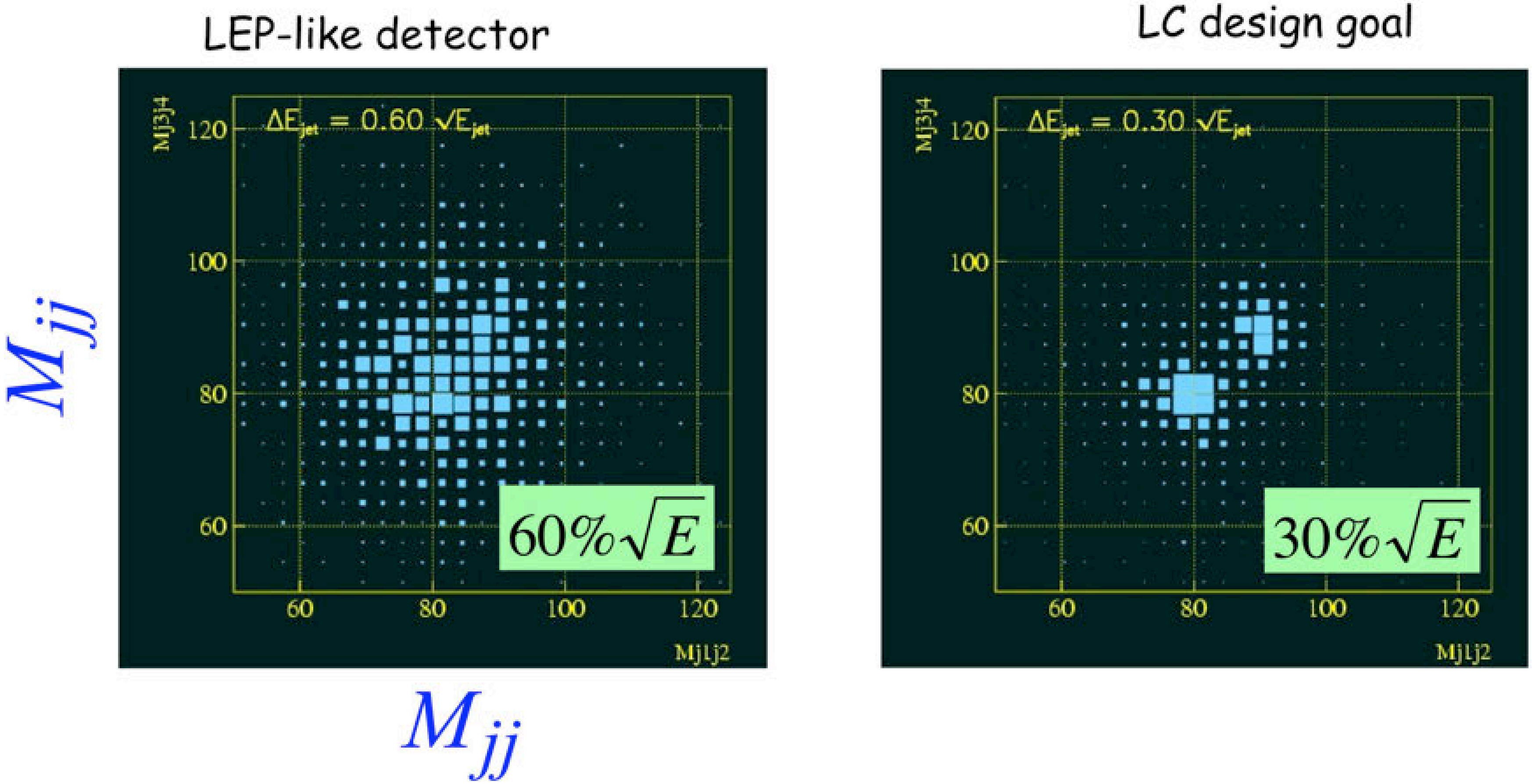
  Benchmark: Separate hadronically decaying W, Z

  - Uncertainties due to jet algorithms/underlying event small
  - No constrained fits as in LEP

➡ *Intrinsic detector properties limiting factor*

Design goal ILC/CLIC: separate $W,Z \rightarrow q\bar{q}$

- *Hadronic energy resolution very important for this multi-jet spectroscopy.*



- *No kinematic constraints as in LEP (beamstrahlung)*

The importance of energy resolution

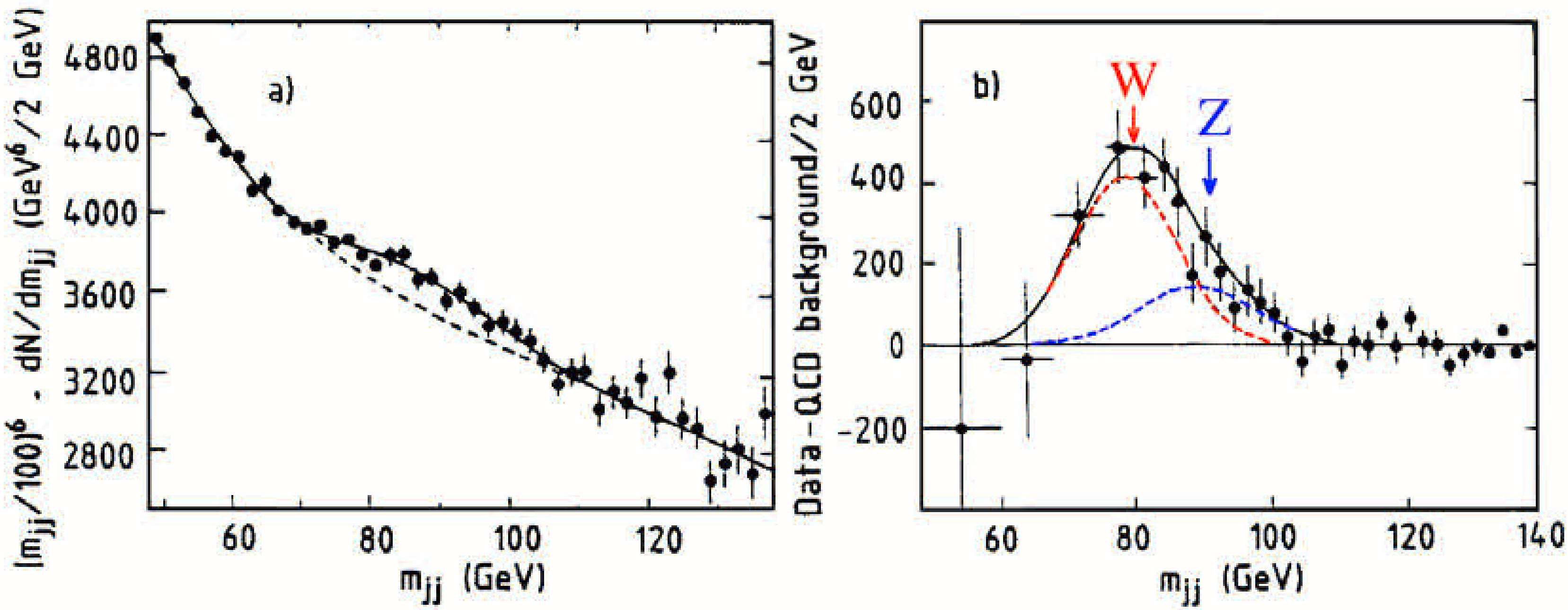
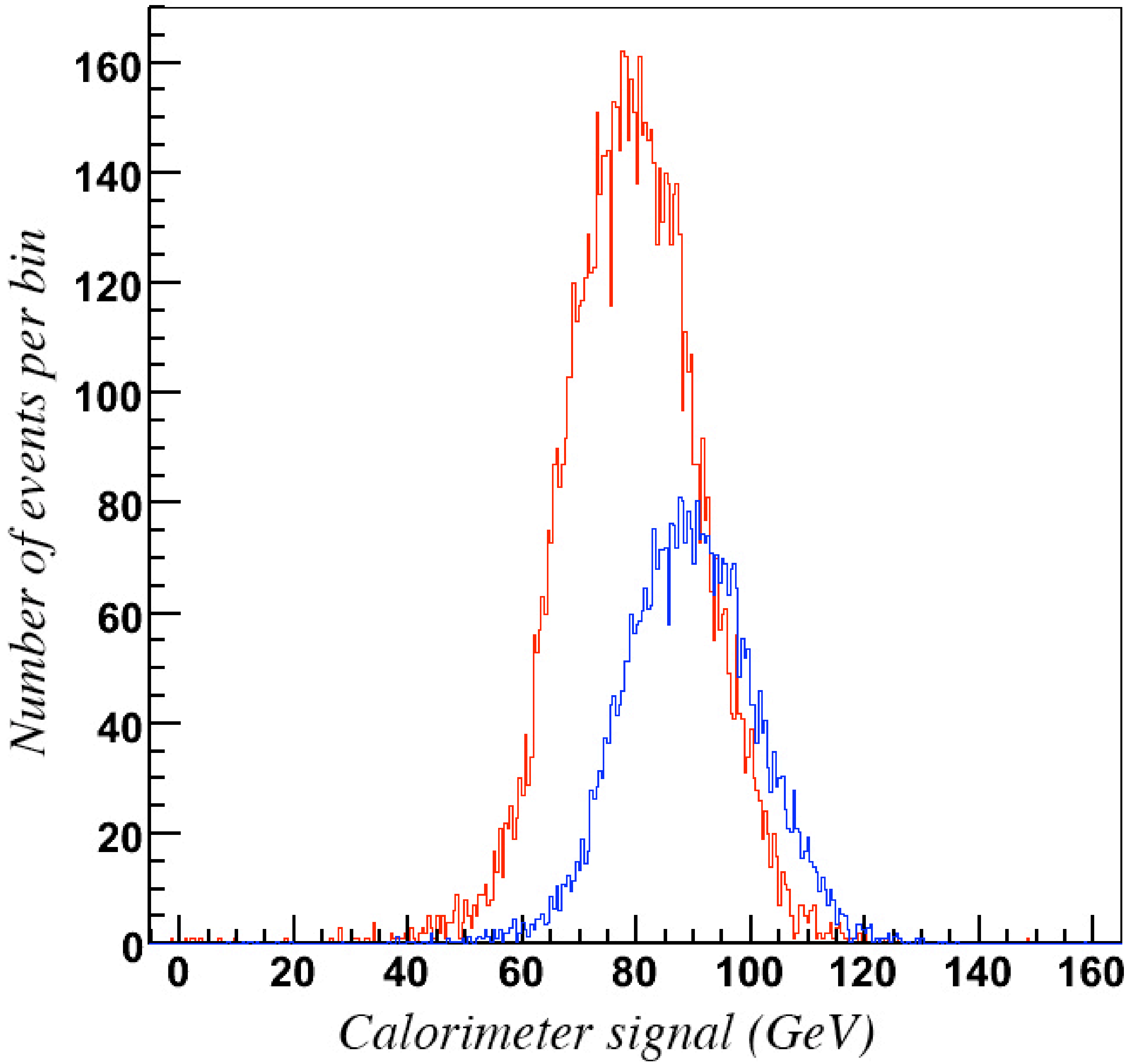


FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \rightarrow q\bar{q}$ decays. Diagram b) shows the same data after subtracting the QCD background. The data are compatible with peaks at $m_W = 80$ GeV and $m_Z = 90$ GeV. The measured width of the bump, or rather the standard deviation of the mass distribution, was 8 GeV, of which 5 GeV could be attributed to non-ideal calorimeter performance [Jen 88].

Hadron Detection in CMS



An attractive option for improving the quality of hadron calorimetry:

Use Čerenkov light!! *Why?*

Hadron showers < *em* component (π^o) / *non-em* component (mainly soft p)

Calorimeter response to these components not the same *($e/h \neq 1$)*

$< f_{em} >$ energy dependent → *hadronic signal non-linearity*

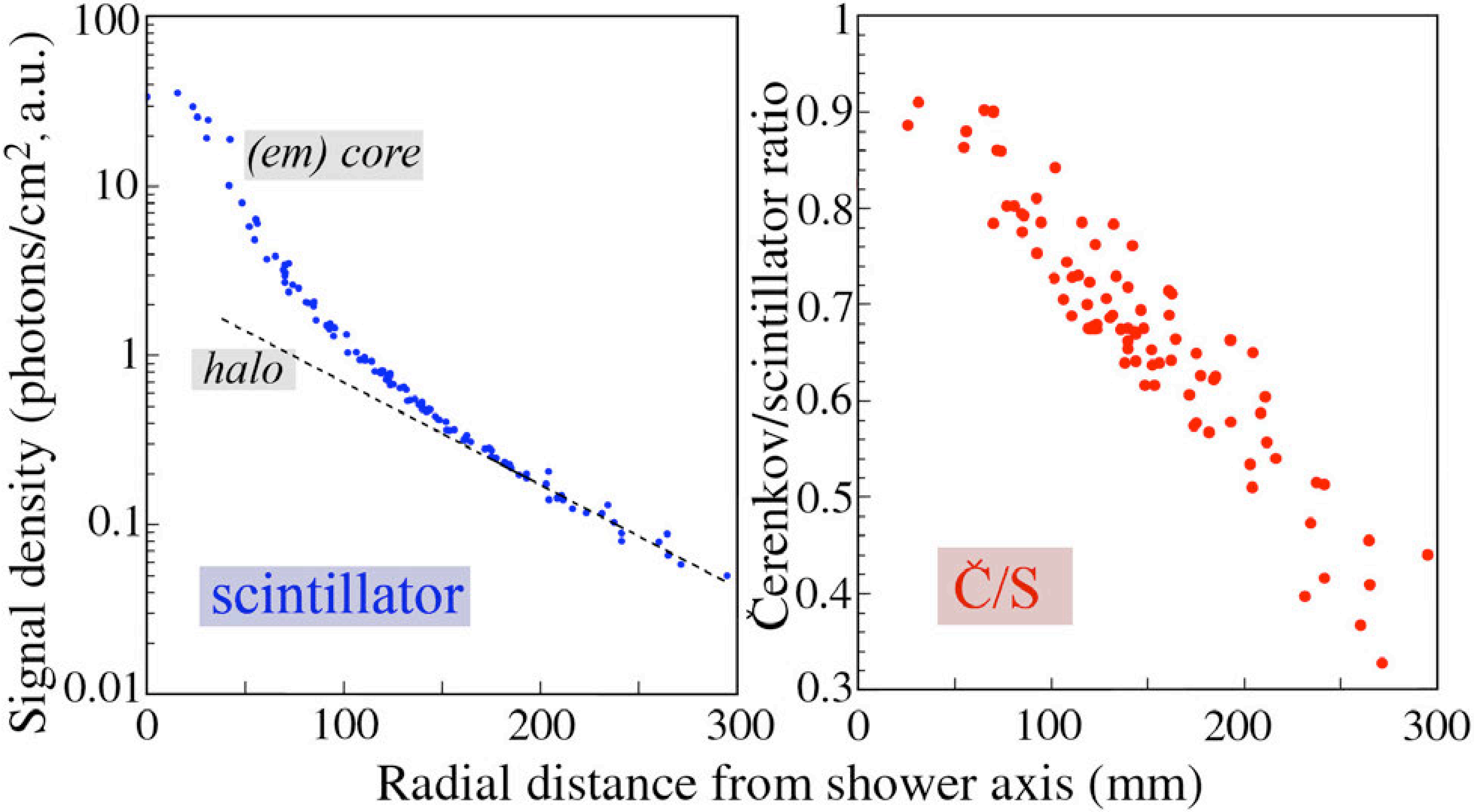
Fluctuations in f_{em} large, non-Gaussian → *poor resolution, etc.*

Čerenkov light almost exclusively produced by em component *
(~80% of non-em energy deposited by non-relativistic particles)

➡ DREAM (Dual REAdout Method) principle:
Measure f_{em} event by event by comparing Č and dE/dx signals

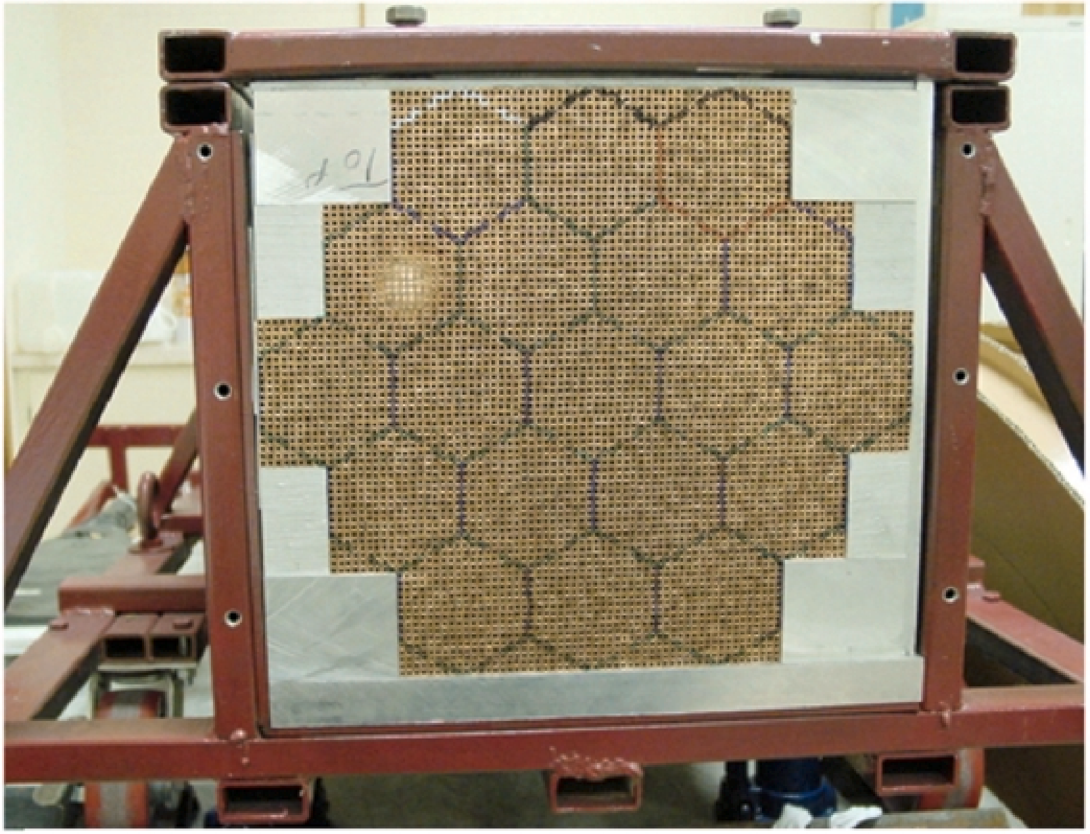
* How do we know this?
- CMS HF: $e/h \sim 5$
- Lateral profiles of hadronic showers

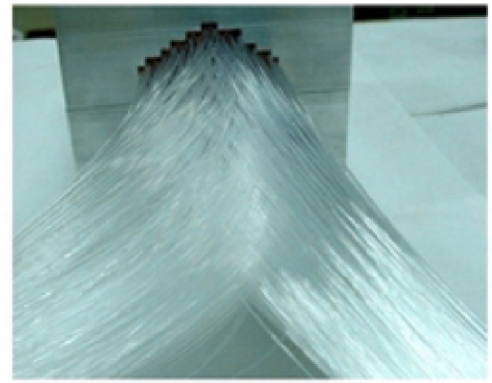
Radial hadron shower profiles (DREAM)

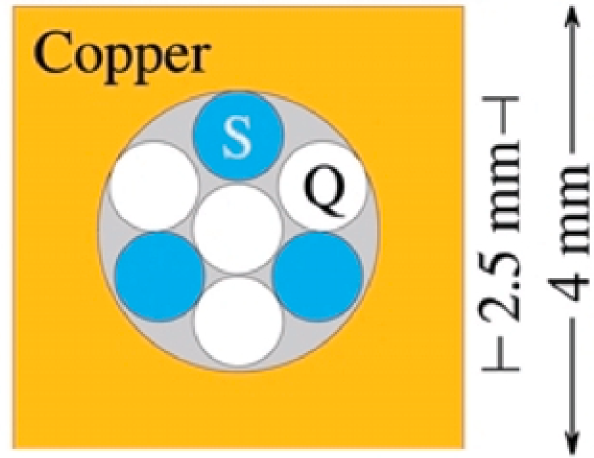


From:
NIM A584 (2008) 273

DREAM: Structure

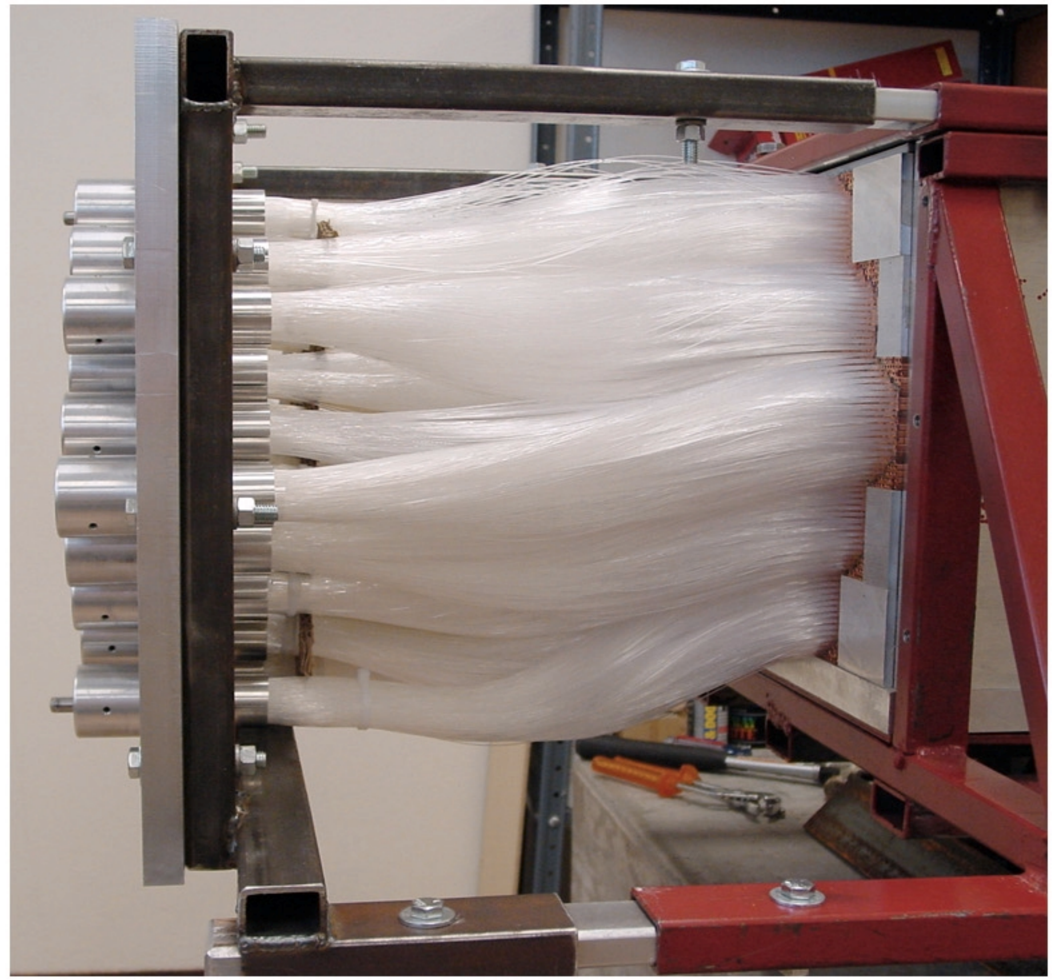


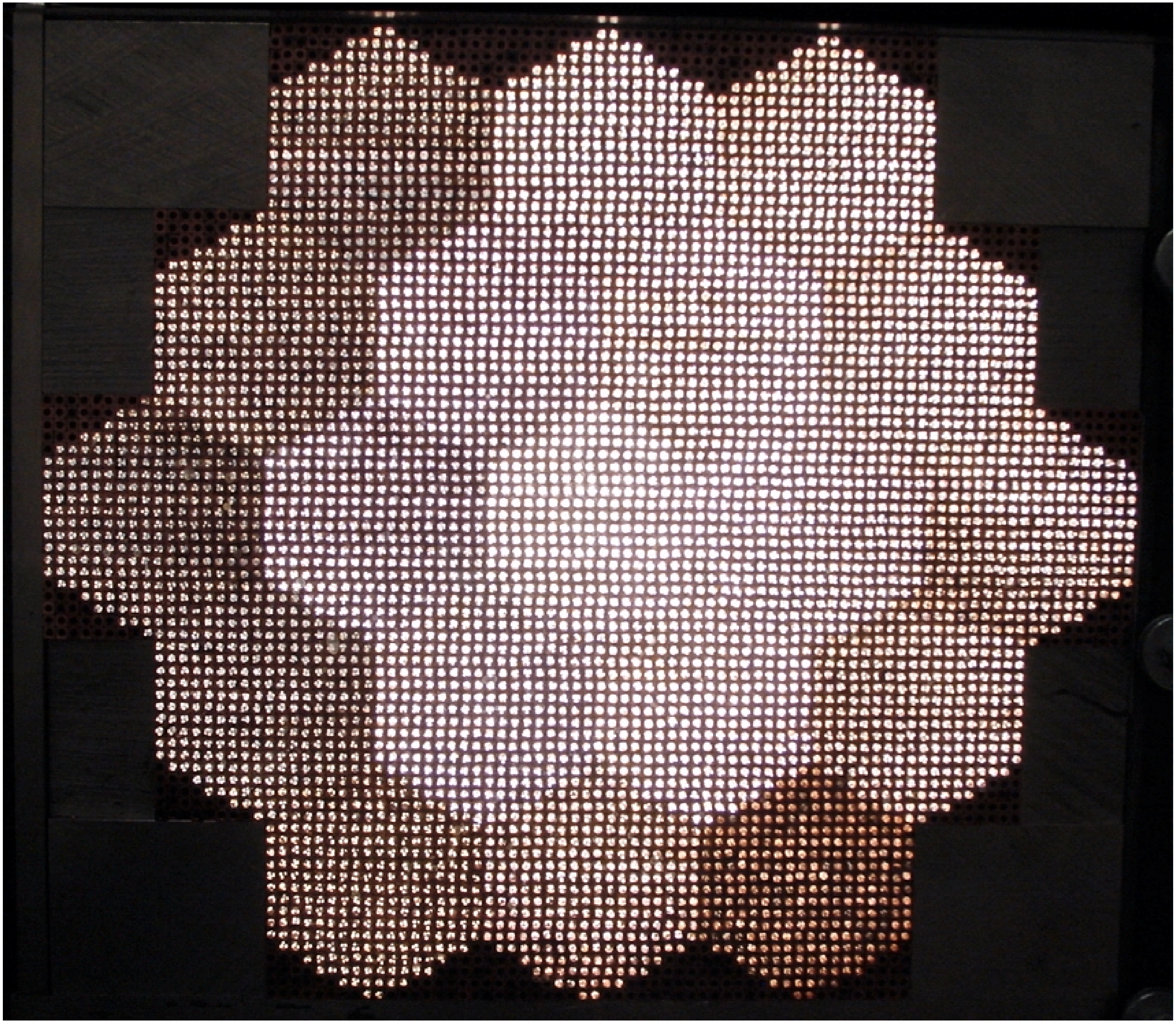


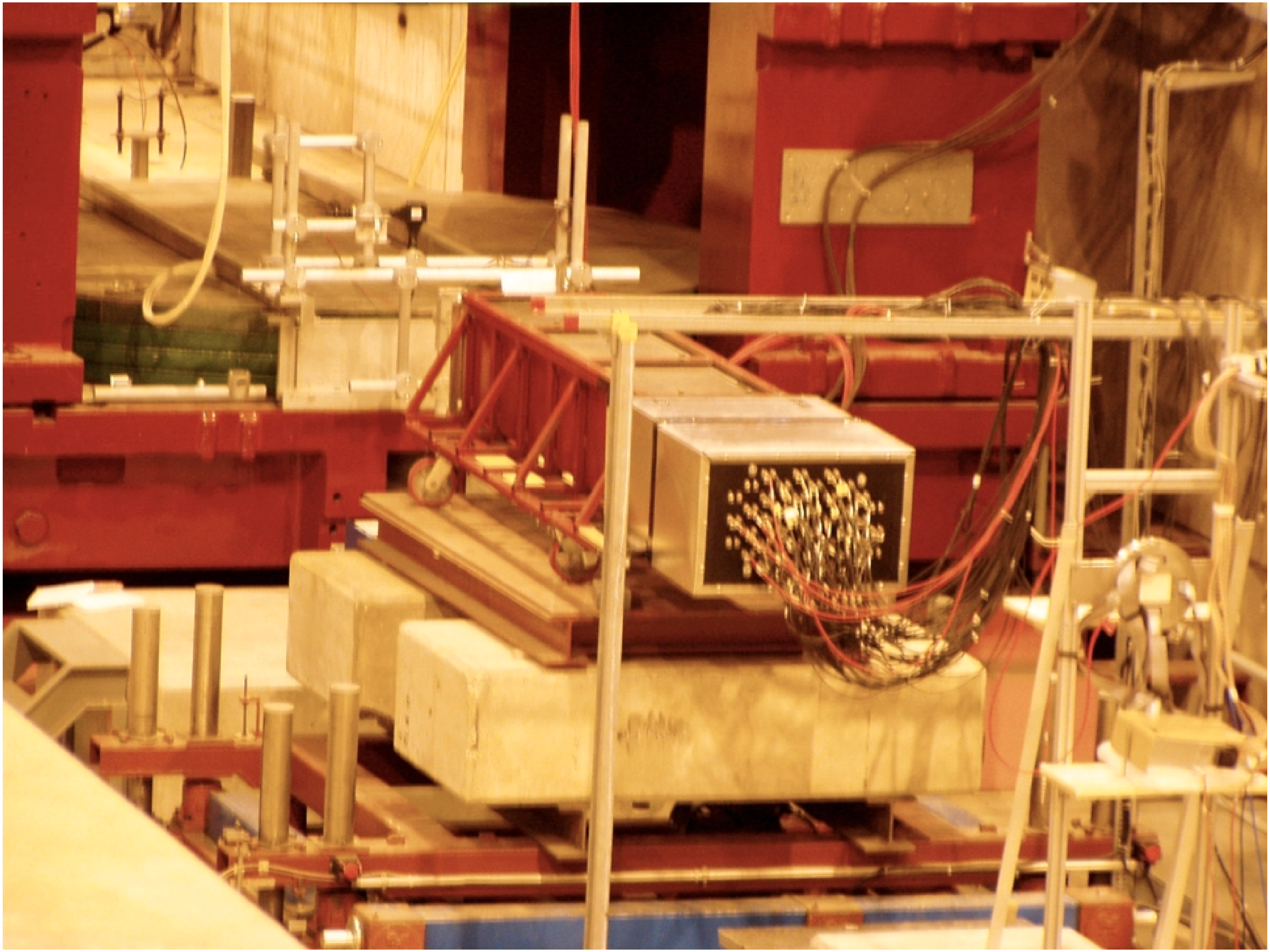


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

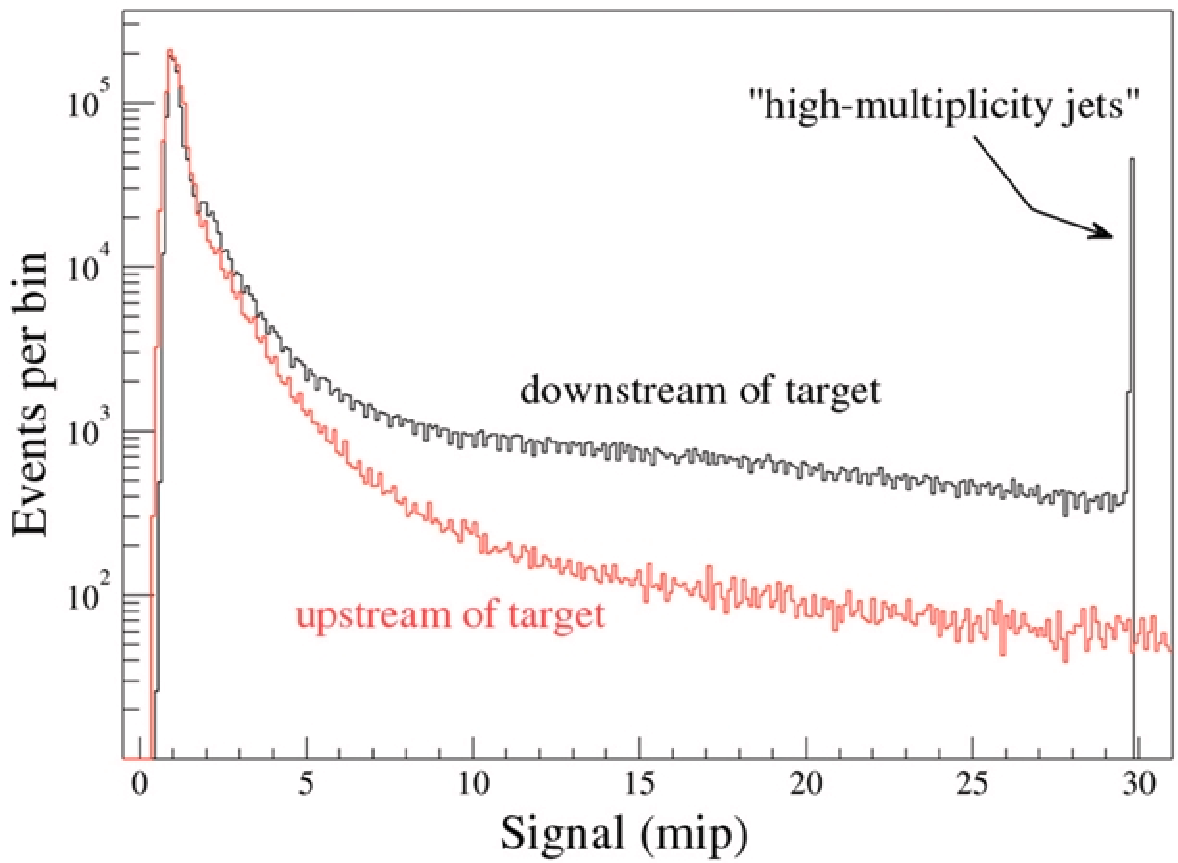
DREAM readout





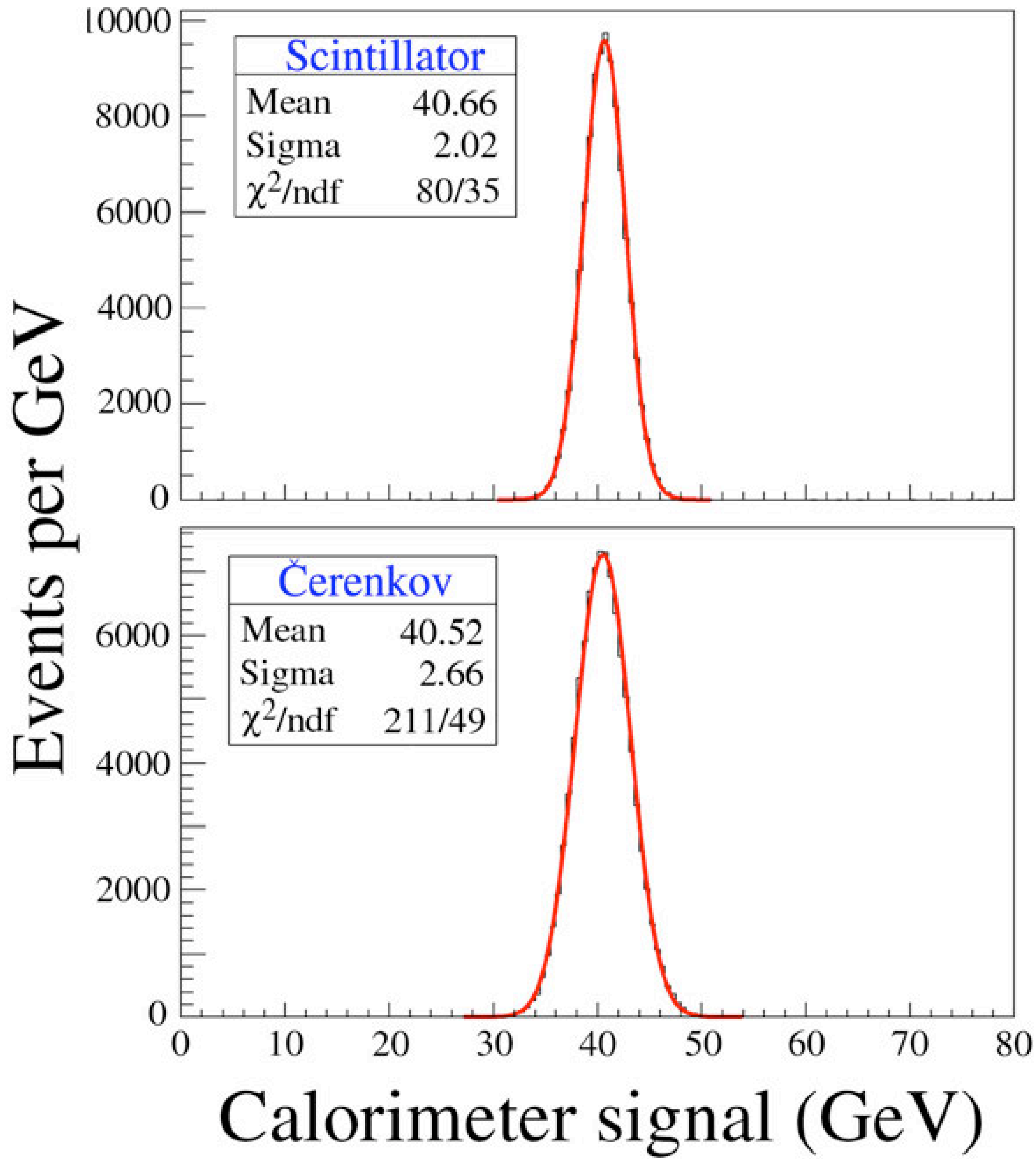


Experimental setup for DREAM beam tests

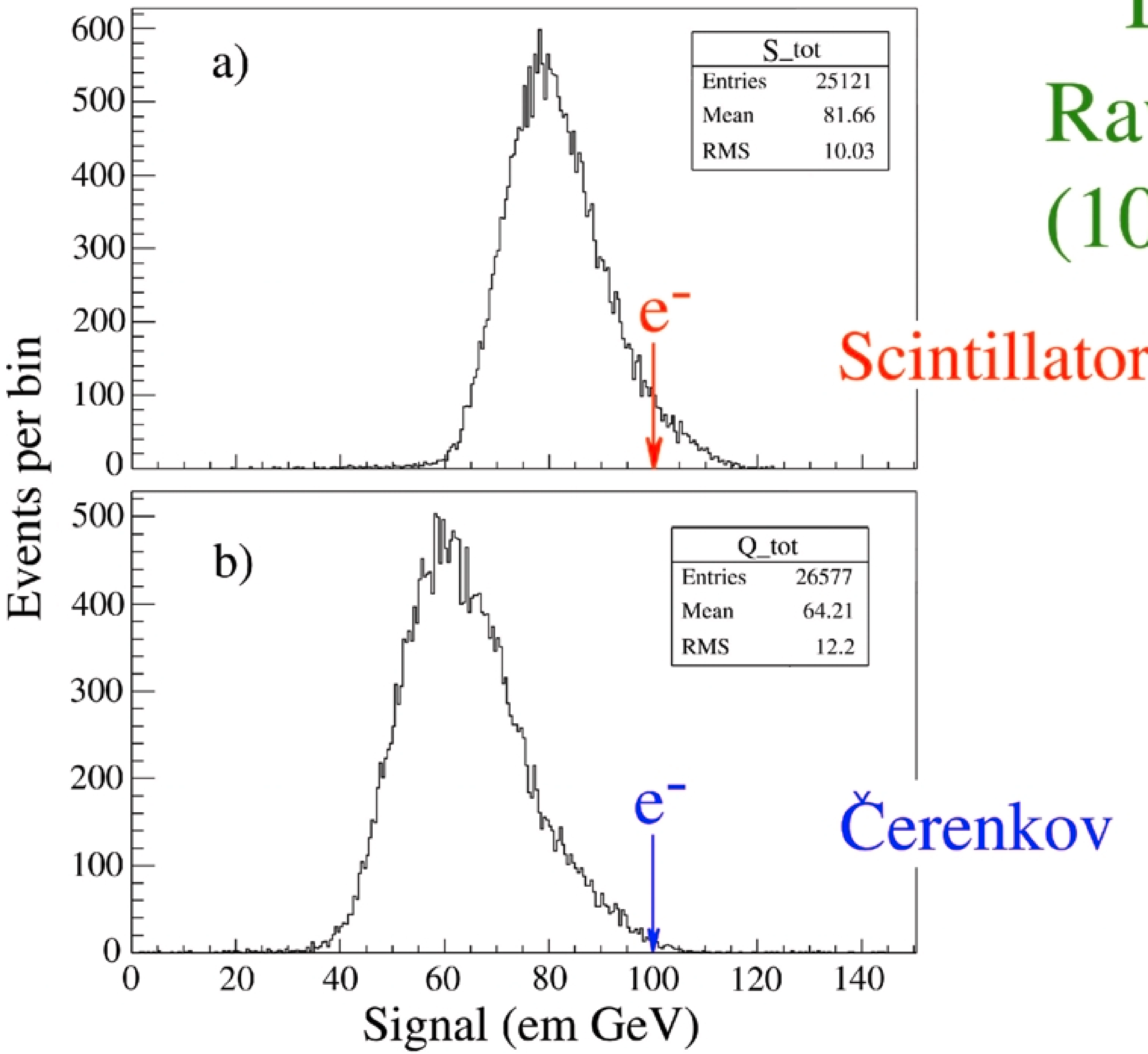


"JET" Measurements

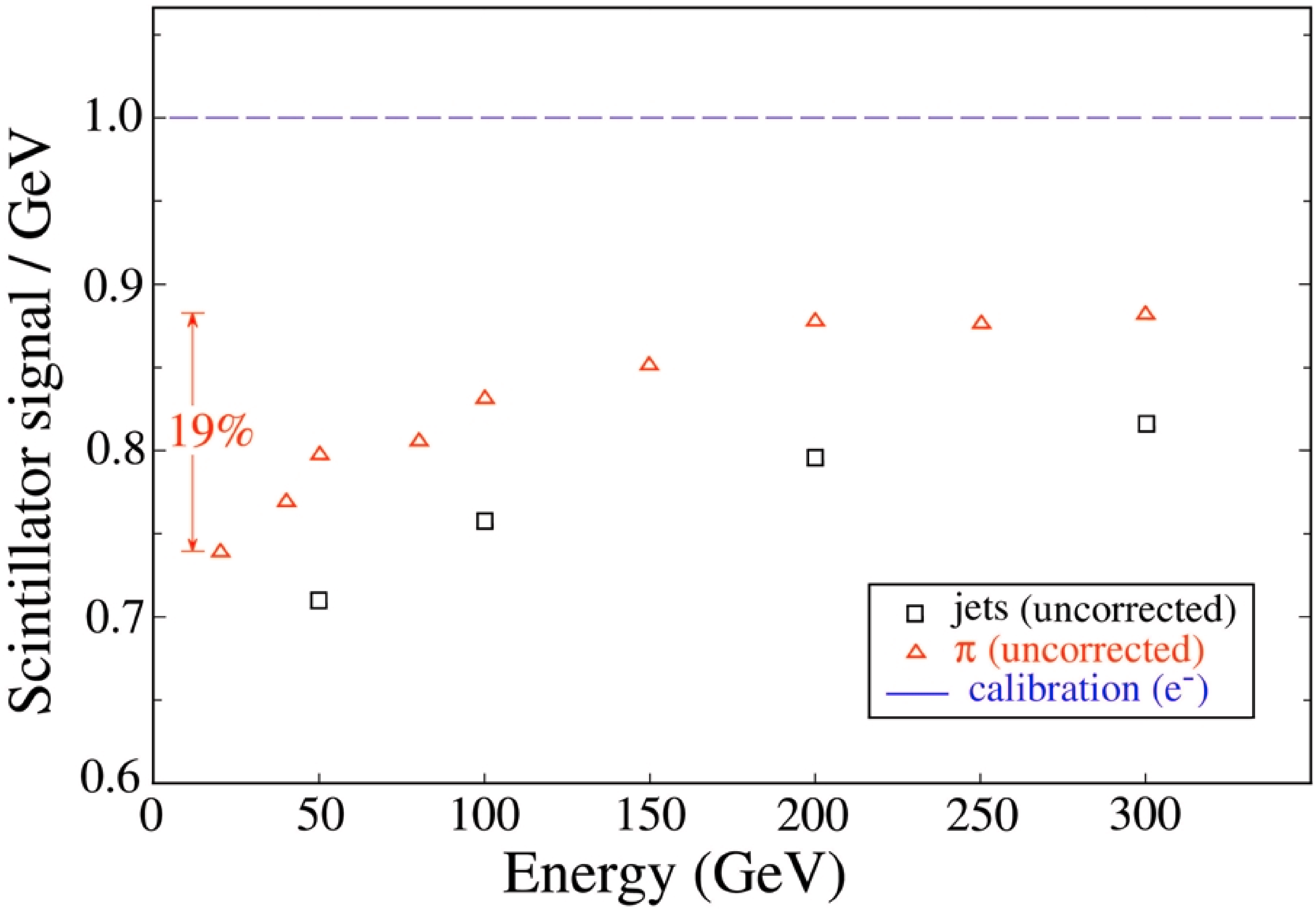
Calibration with 40 GeV electrons (tilt 2^o)



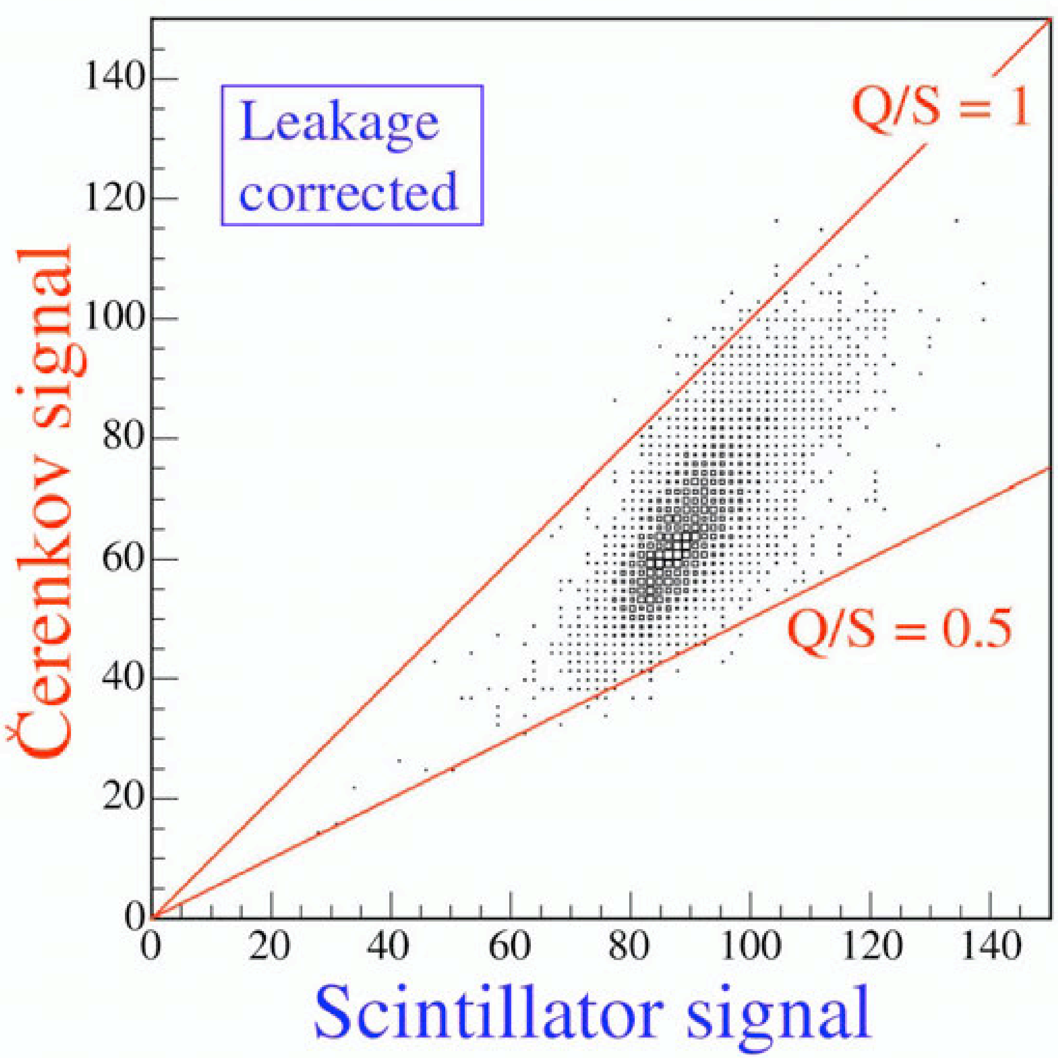
DREAM Raw signals (100 GeV π^-)



DREAM: Hadronic response (non-linearity)



DREAM: How to determine f_{em} and E ?



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

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

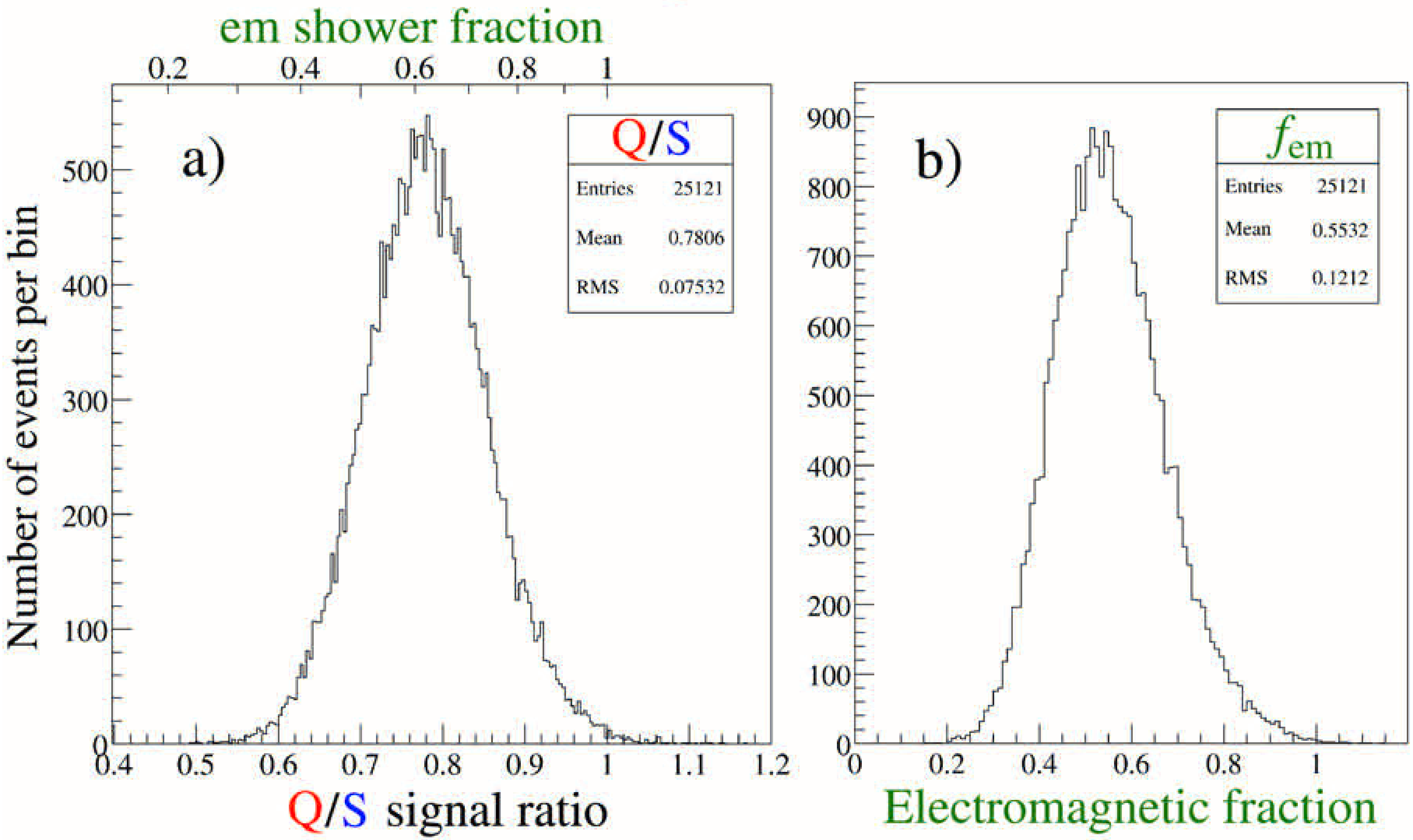
e.g. If $e/h = 1.3$ (S), 5 (Q)

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

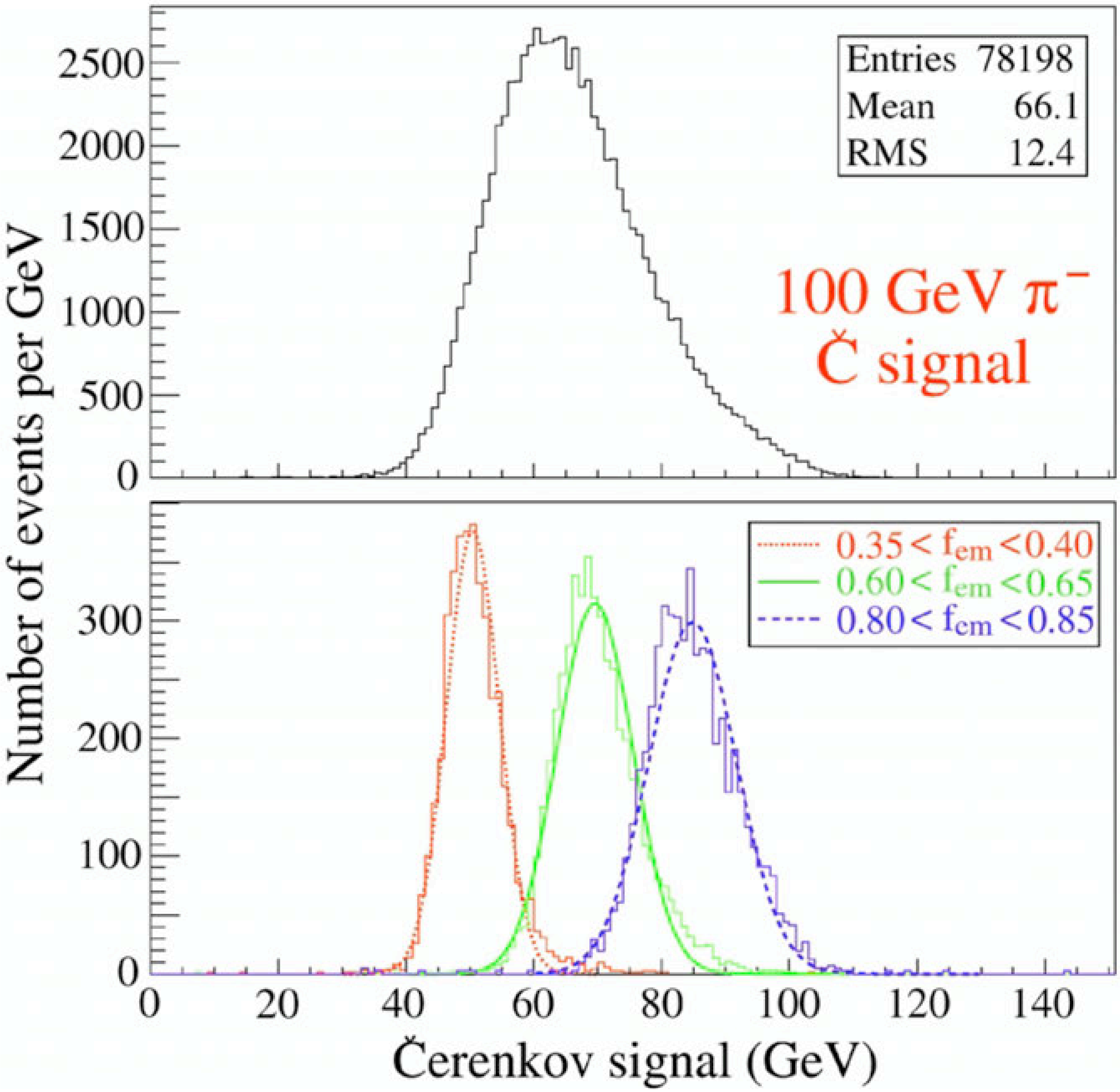
$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \dfrac{1-(h/e)_S}{1-(h/e)_Q} \sim 0.3$

DREAM: relationship between Q/S ratio and f_{em}

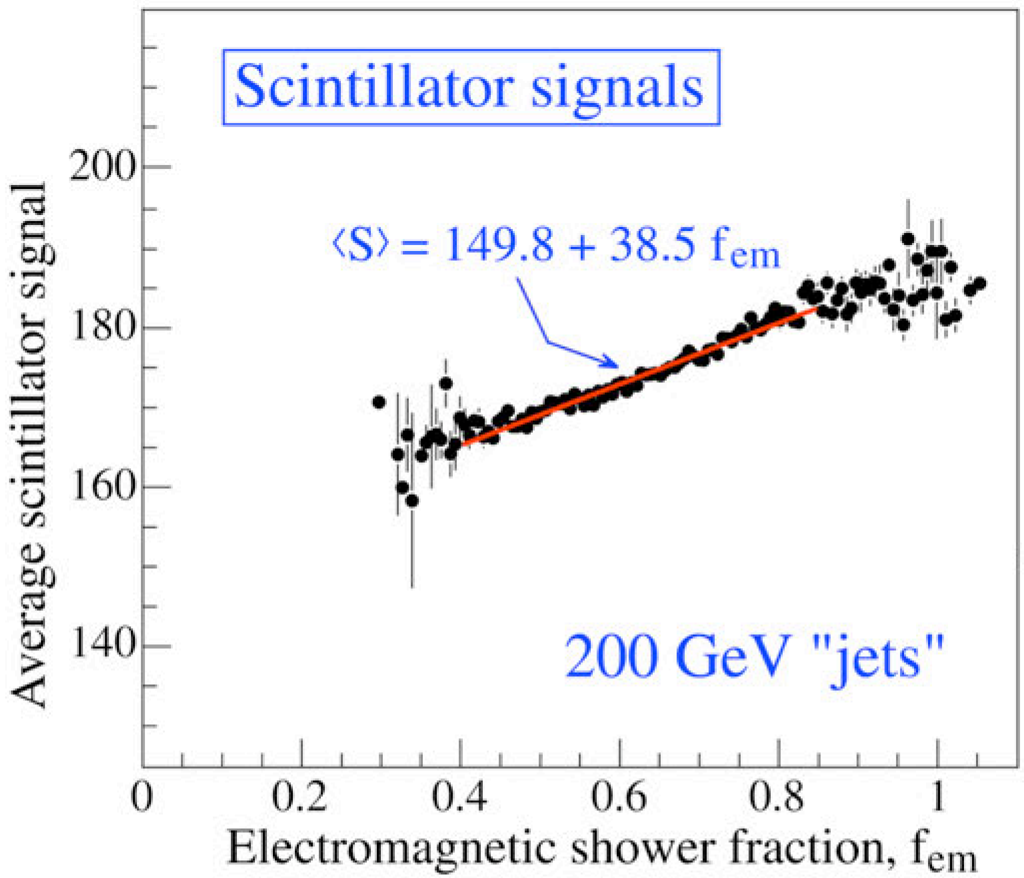


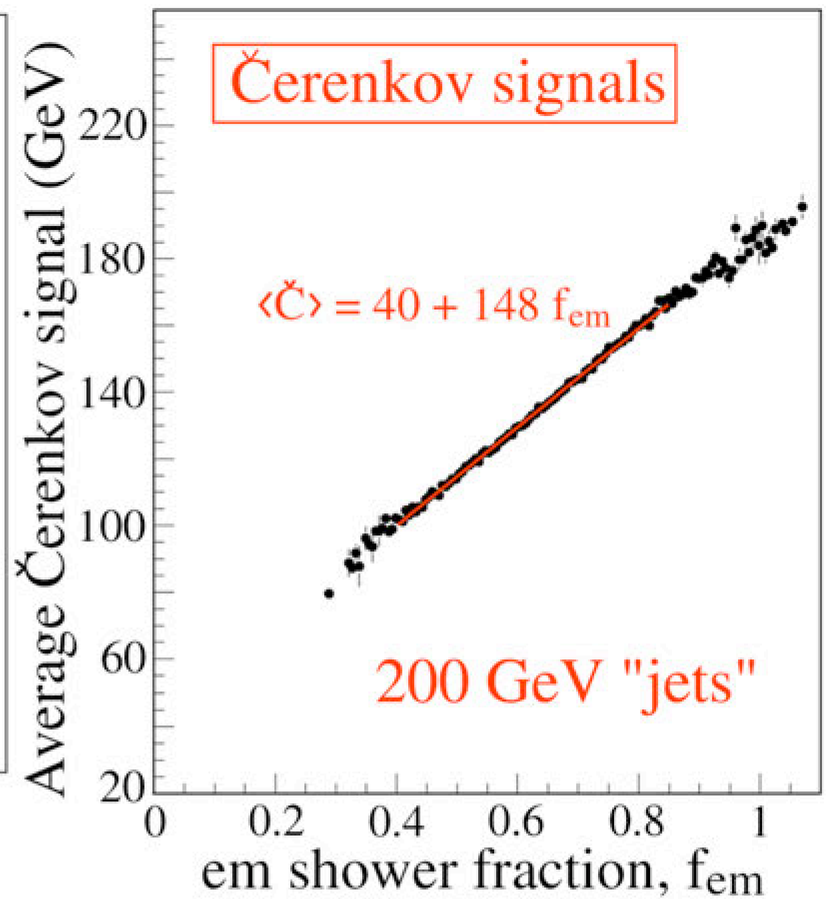
DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

DREAM: Signal dependence on f_{em}



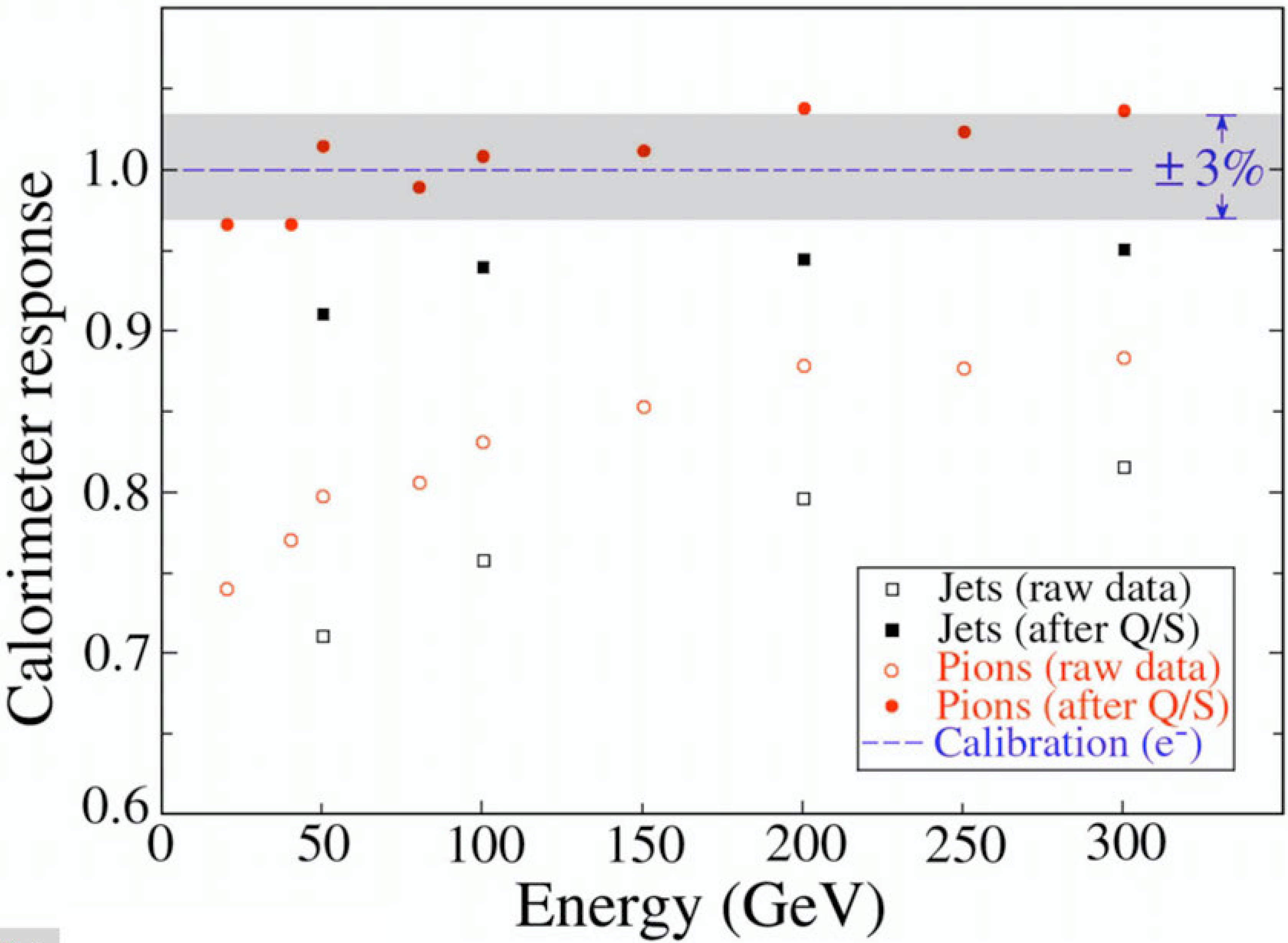


$$R(f_{em}) = p_0 + p_1 f_{em}$$ with $$\frac{p_1}{p_0} = e/h - 1$$

Cu/scintillator e/h = 1.3 Cu/quartz e/h = 4.7

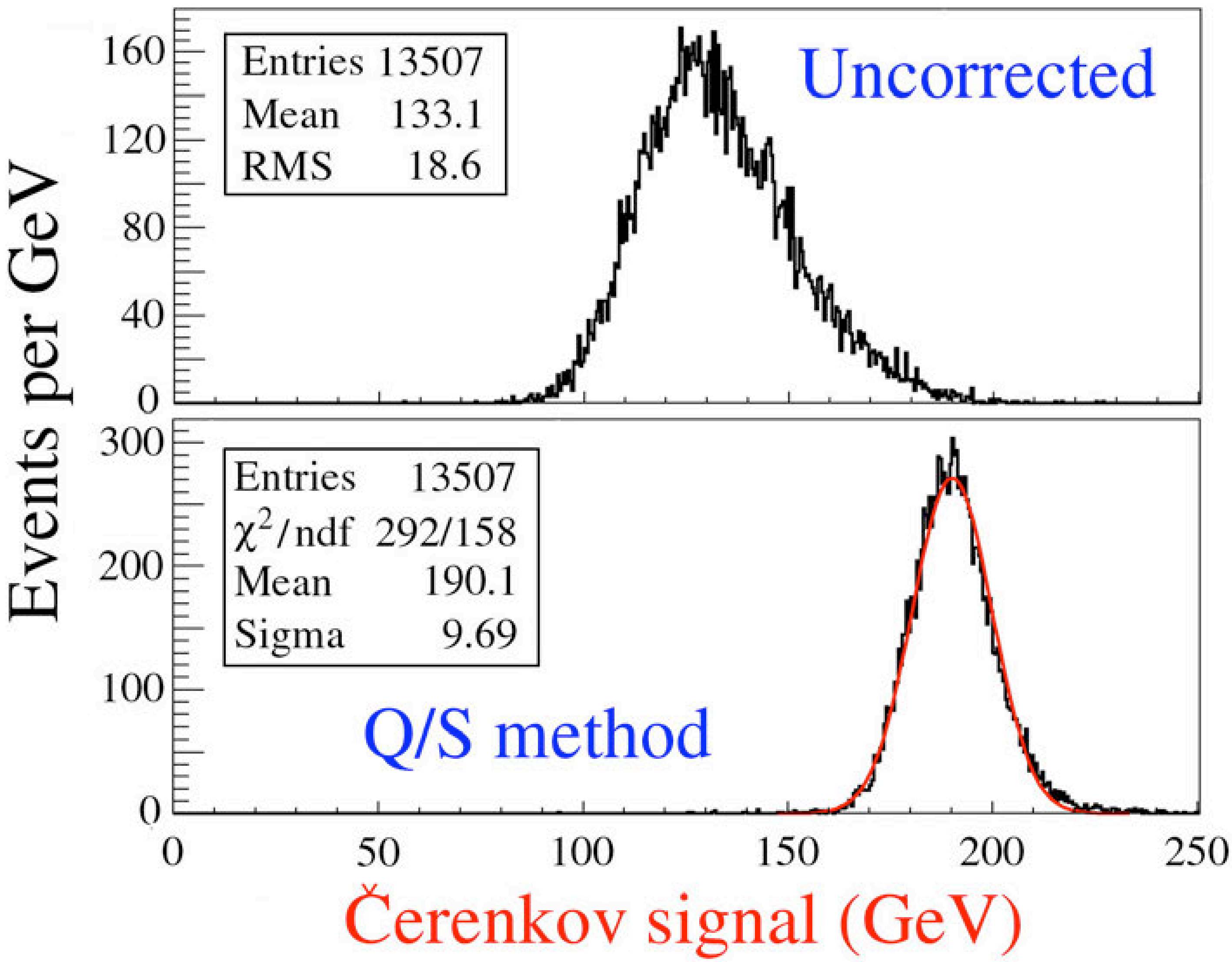
From:
NIM A537 (2005) 537

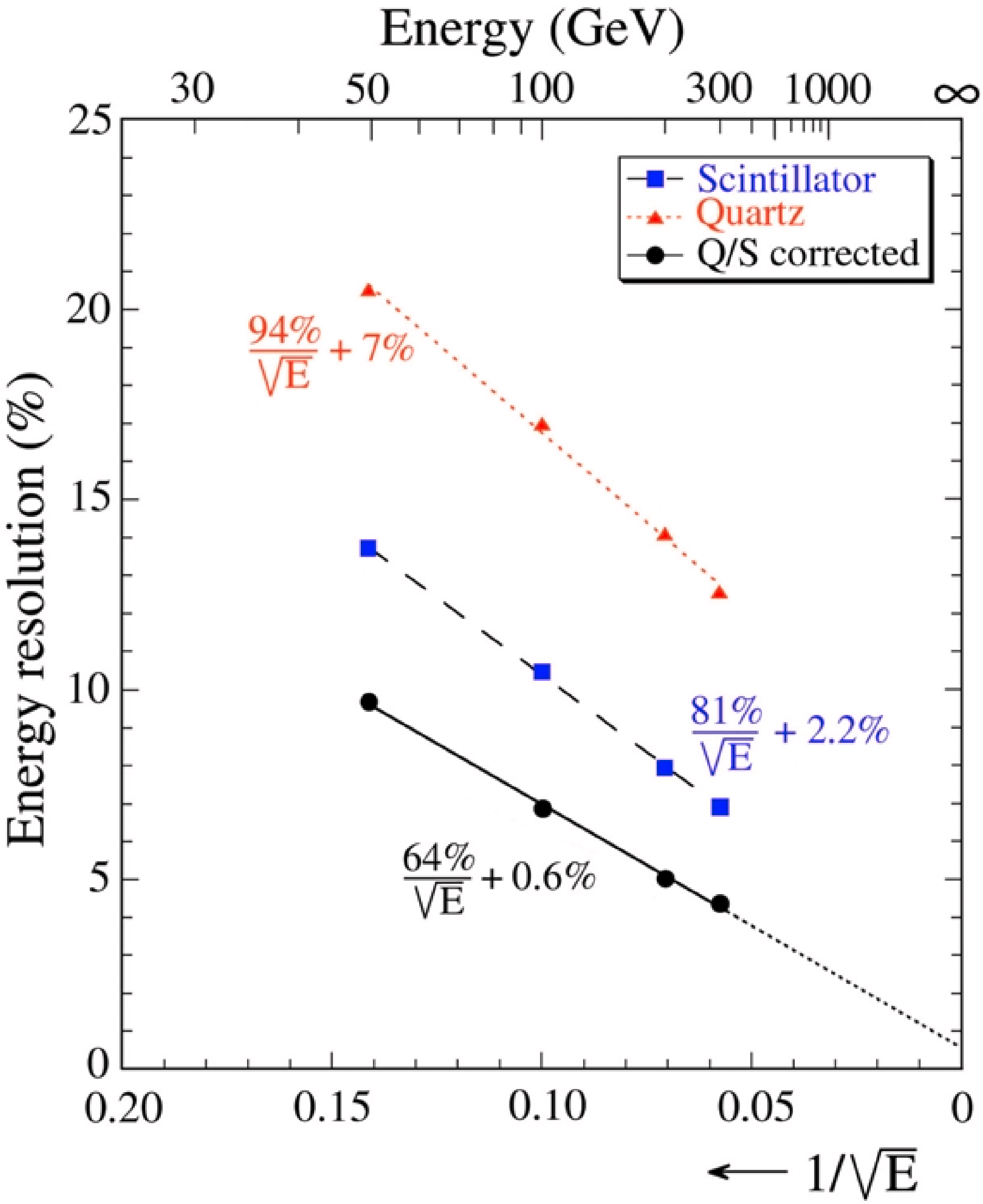
DREAM: *Reconstructed hadronic energy*



From:
NIM A537 (2005) 537

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





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

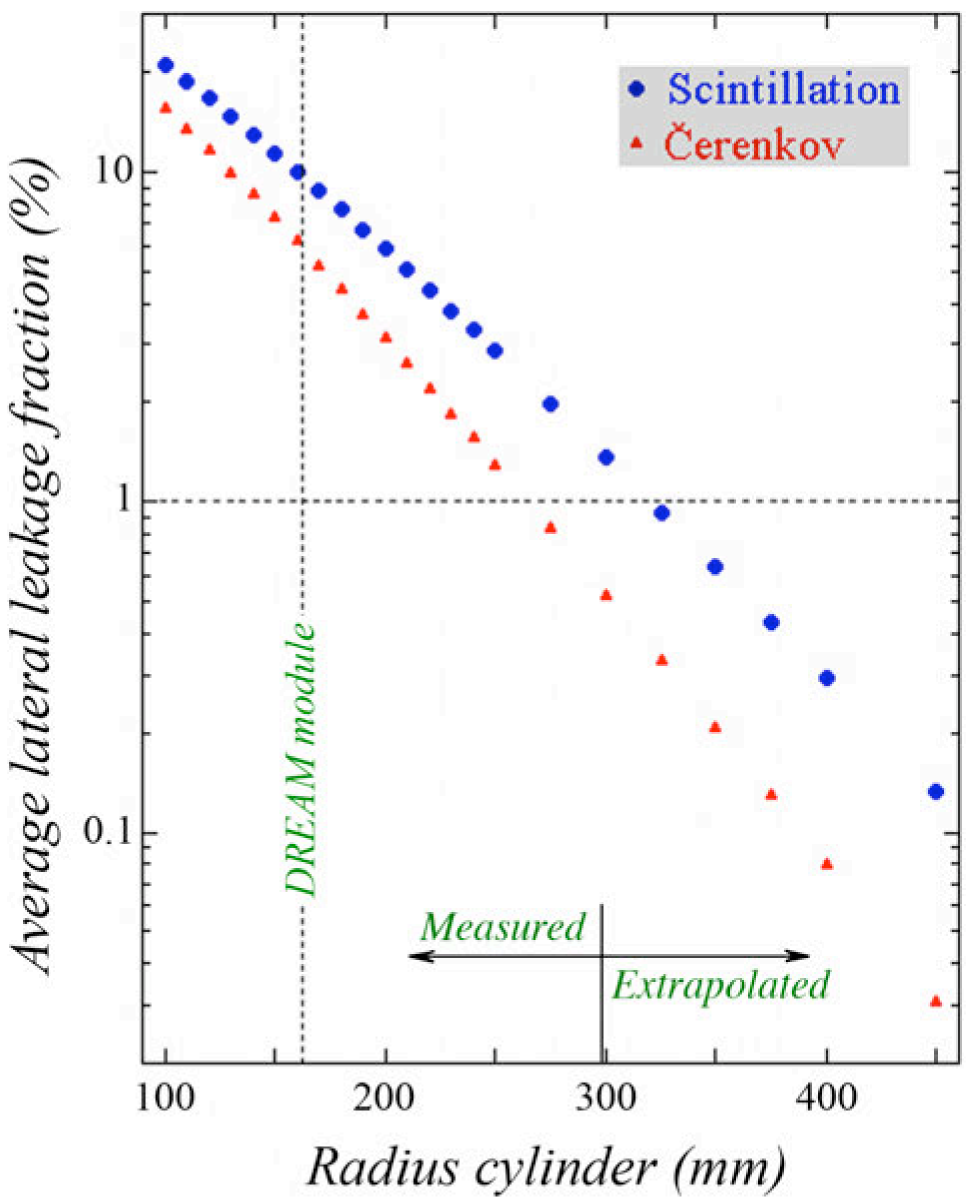
- These, and many other, experimental results are described in 3 papers:

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

How to improve DREAM performance

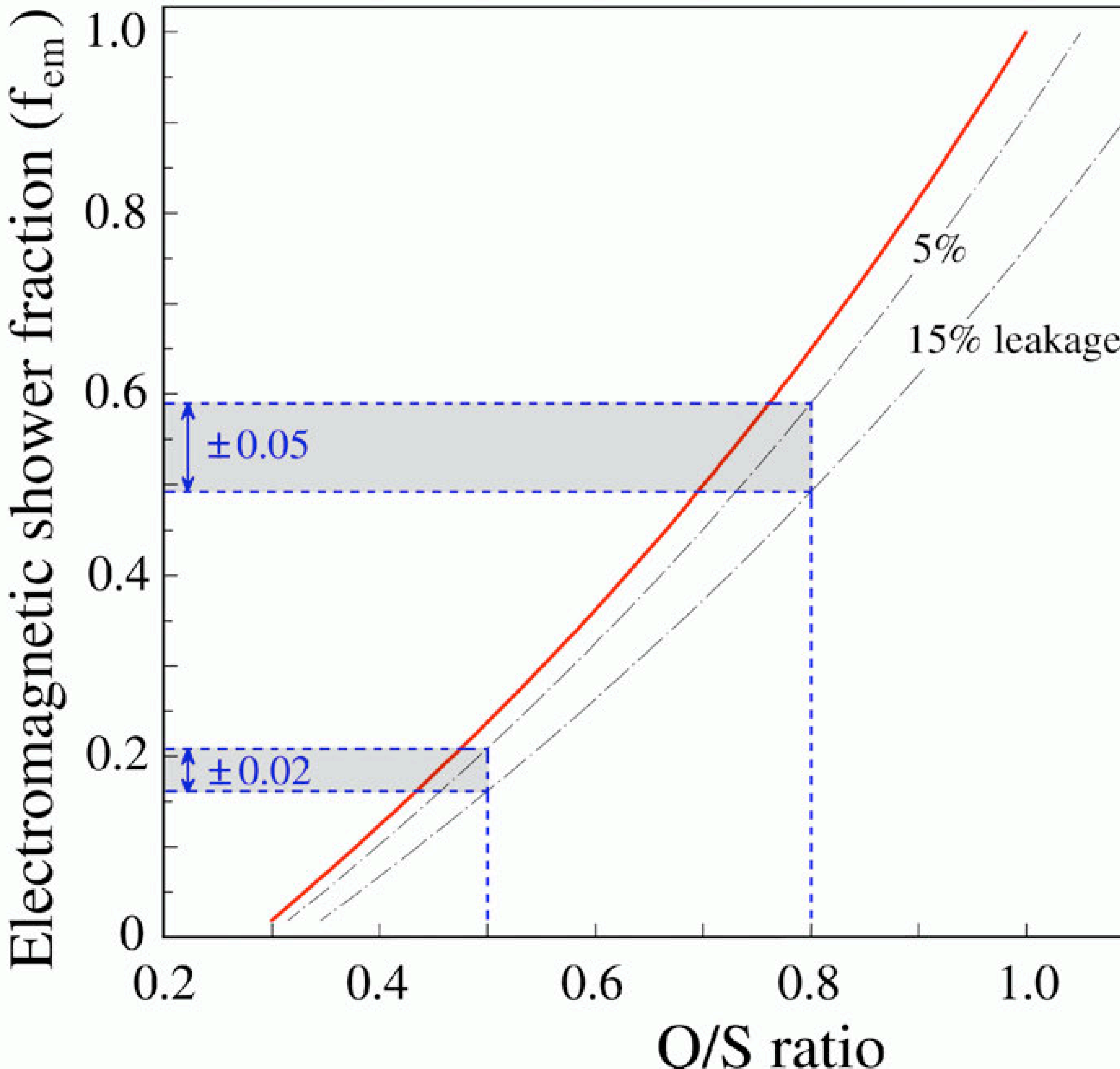
- Build a larger detector ⟶ *reduce effects side leakage*

Hadronic shower containment in the DREAM calorimeter

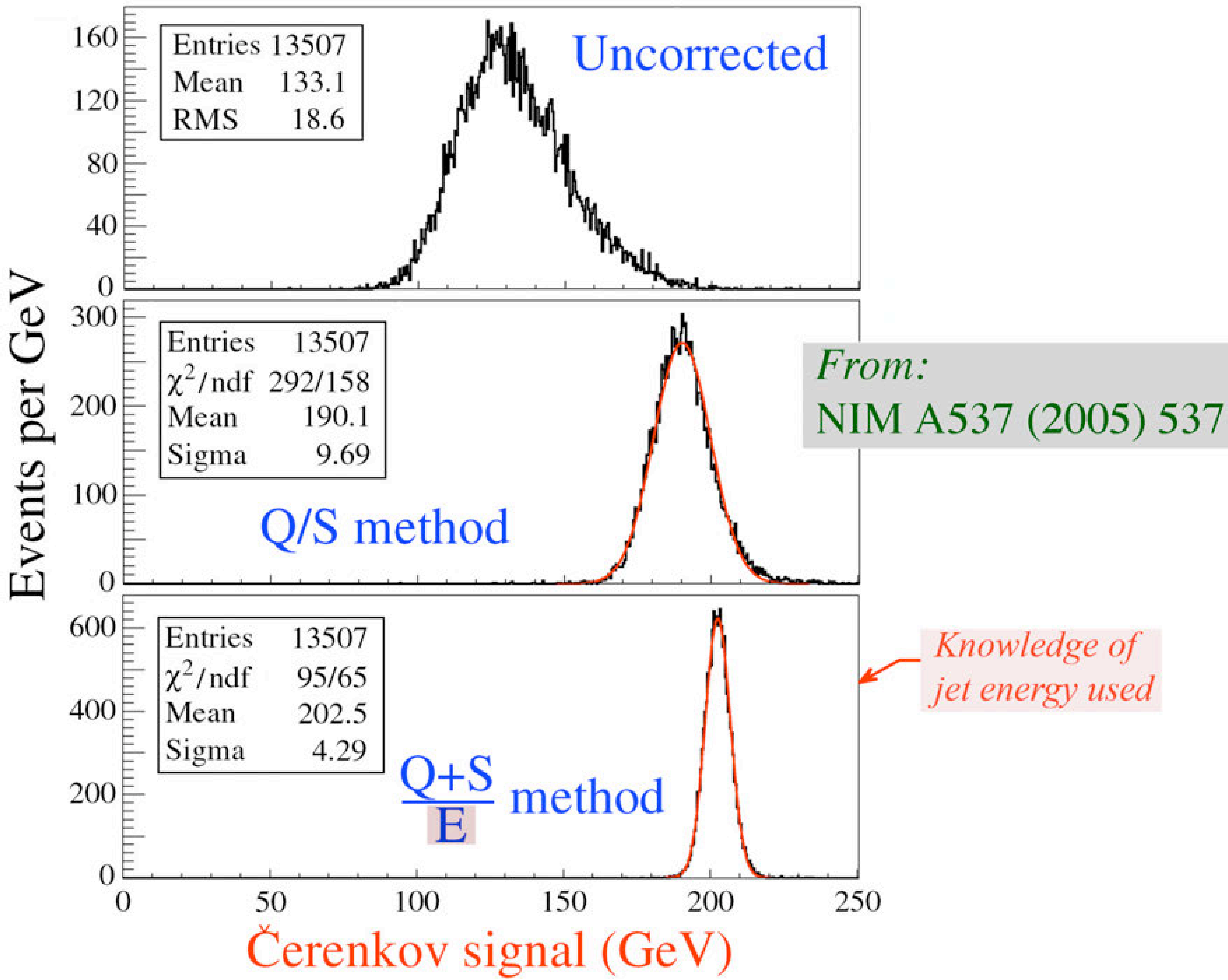


From:
NIM A584 (2008) 273

DREAM: The importance of leakage and its fluctuations



DREAM: *Reconstructed response function* (200 GeV "jets")



How to improve DREAM performance?

- Build a larger detector ⟶ *reduce effects side leakage*

- *Increase Čerenkov light yield*

  DREAM: 8 p.e./GeV ⟶ fluctuations contribute 35%/$\sqrt{E}$

  No reason why DREAM principle is limited to fiber calorimeters

Homogeneous detector ?!

⟶ *Need to separate the light into its Č, S components*

Čerenkov component in light from $PbWO_4$ crystals?

- Light yield typically ~10 p.e./MeV (dependent on T, readout)
- Lead glass: 500 - 1000 p.e./GeV from Čerenkov effect (3 - 5%/$\sqrt{E}$)

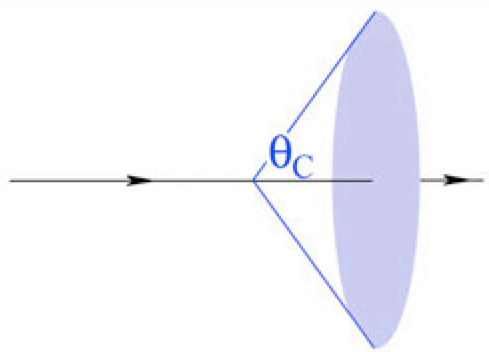
  ⟶ *Expect substantial Č component in $PbWO_4$ signals*
- *How to detect / isolate Čerenkov component?*

  - *Directionality of Čerenkov component*
  - *Time structure of the signals*
  - *Spectral differences*

We have performed dedicated beam tests with $PbWO_4$
We tested both single crystals ($22X_0$ long, $2.2X_0$ across)
and an ECAL made of 19 such crystals*

* *courtesy ALICE*

Experimental setup Čerenkov measurements
(directionality)



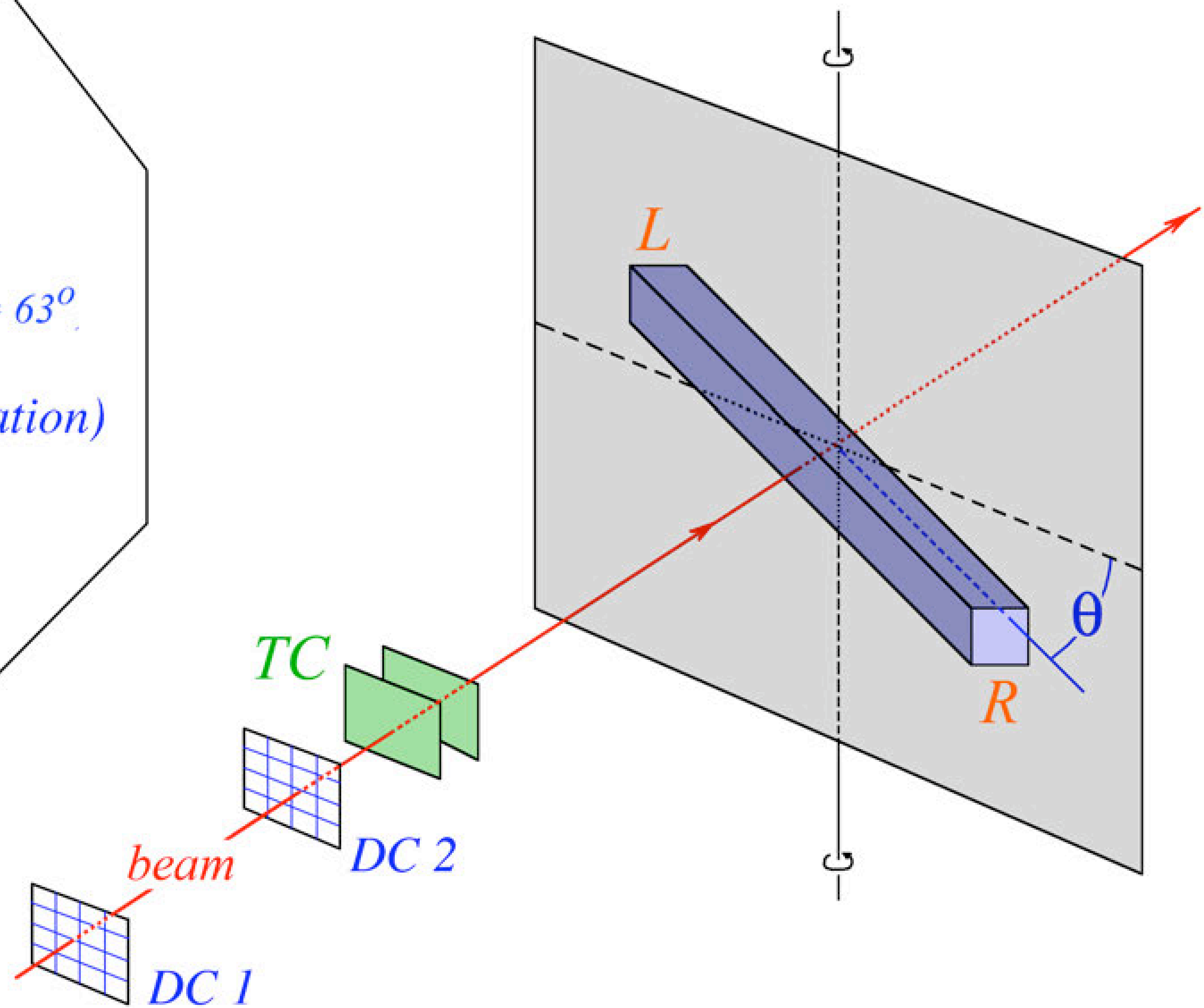
$n = 2.2$, $\cos\theta_C = 1/n \rightarrow \theta_C = 63^o$

$\theta = 0 \longrightarrow L = R$ (calibration)

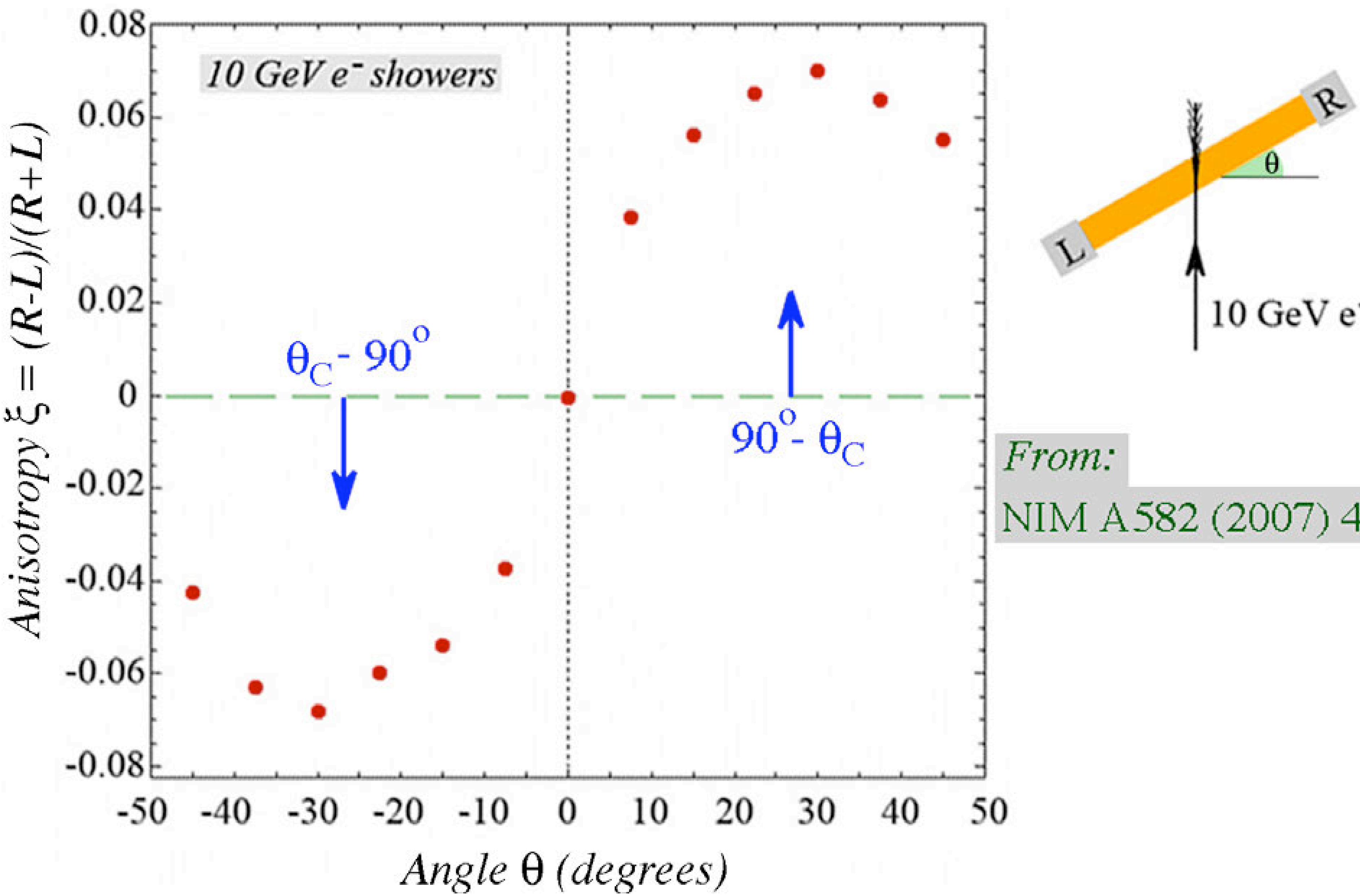
$\theta < 0 \longrightarrow L > R$

$\theta > 0 \longrightarrow L < R$

Measure $\frac{L-R}{L+R}(\theta)$



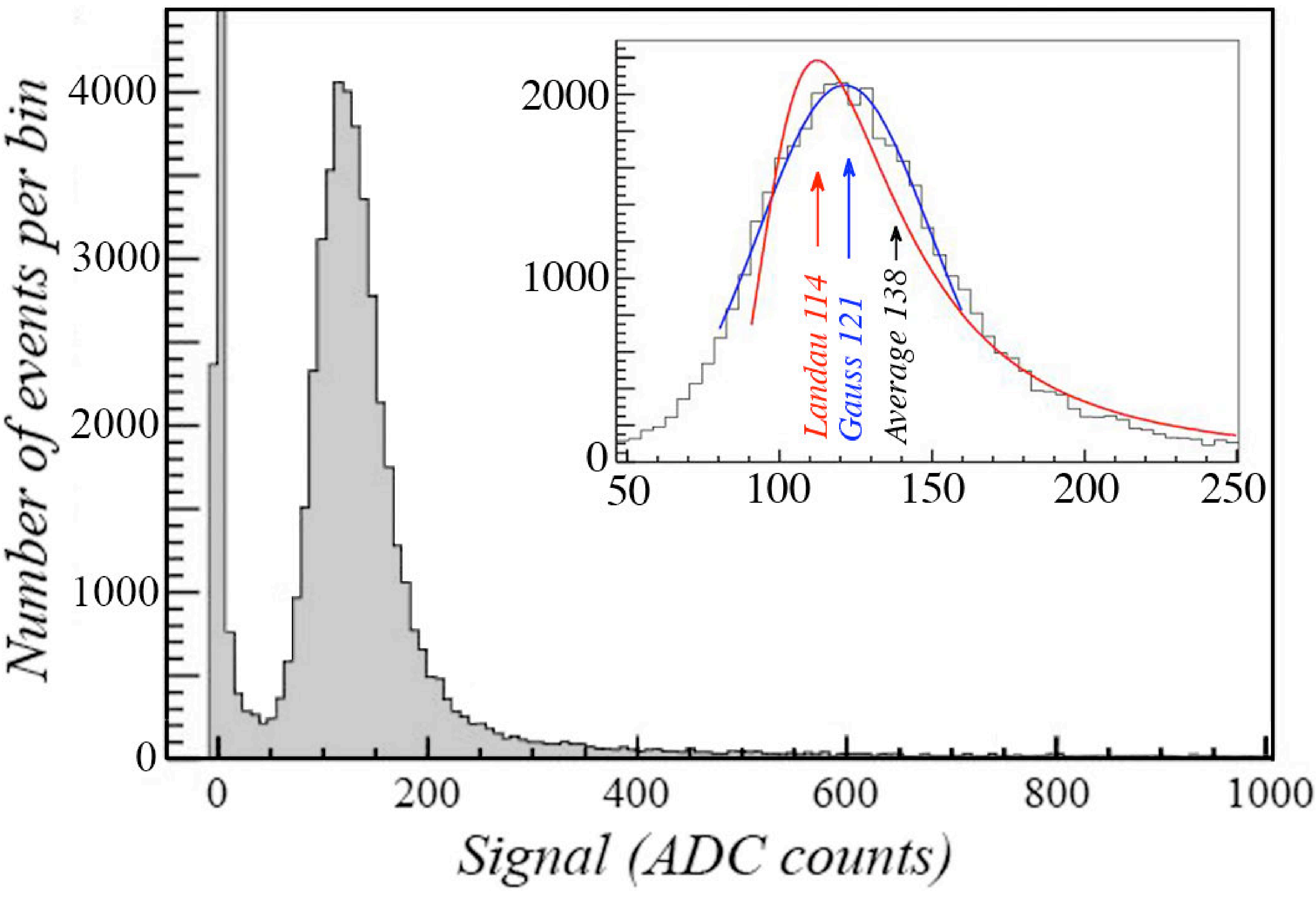
Experimental results $PbWO_4$: Directionality



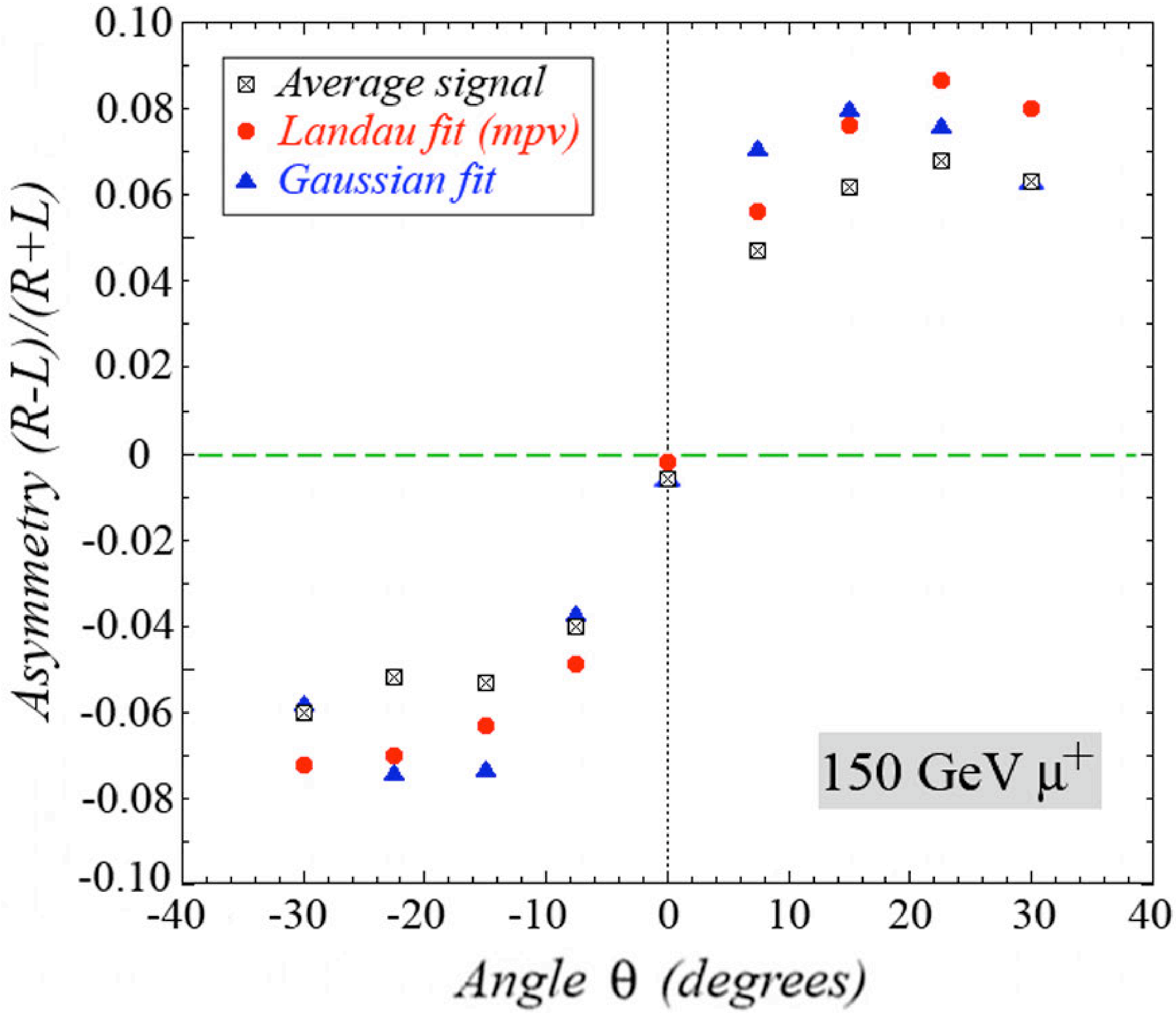
From:

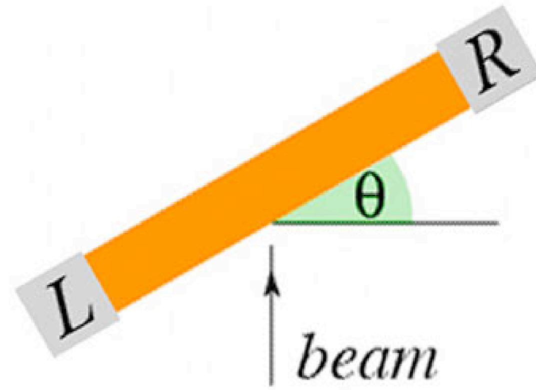
NIM A582 (2007) 474

Muon spectra in single $PbWO_4$ crystal

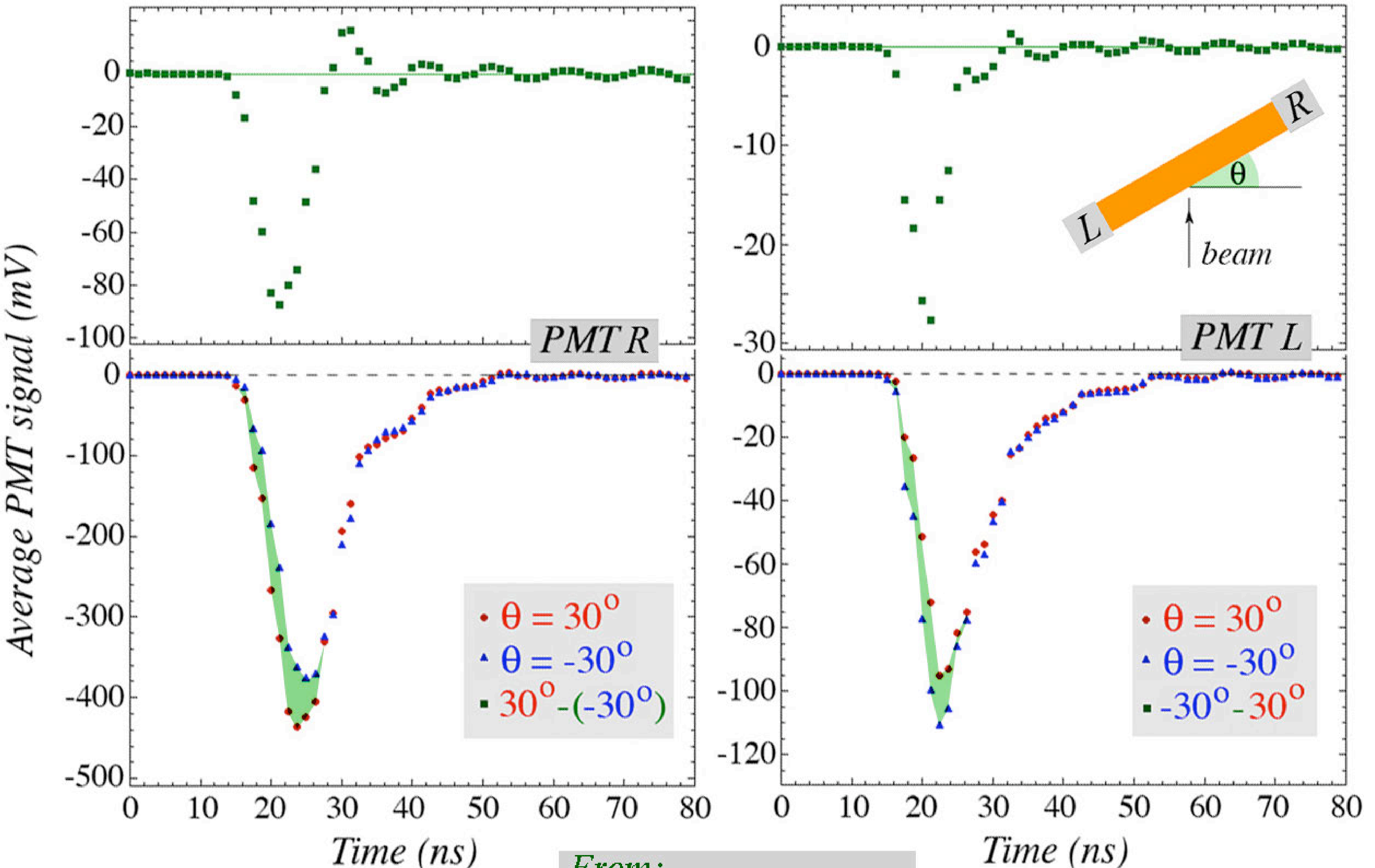


Left / Right asymmetry measured with muons



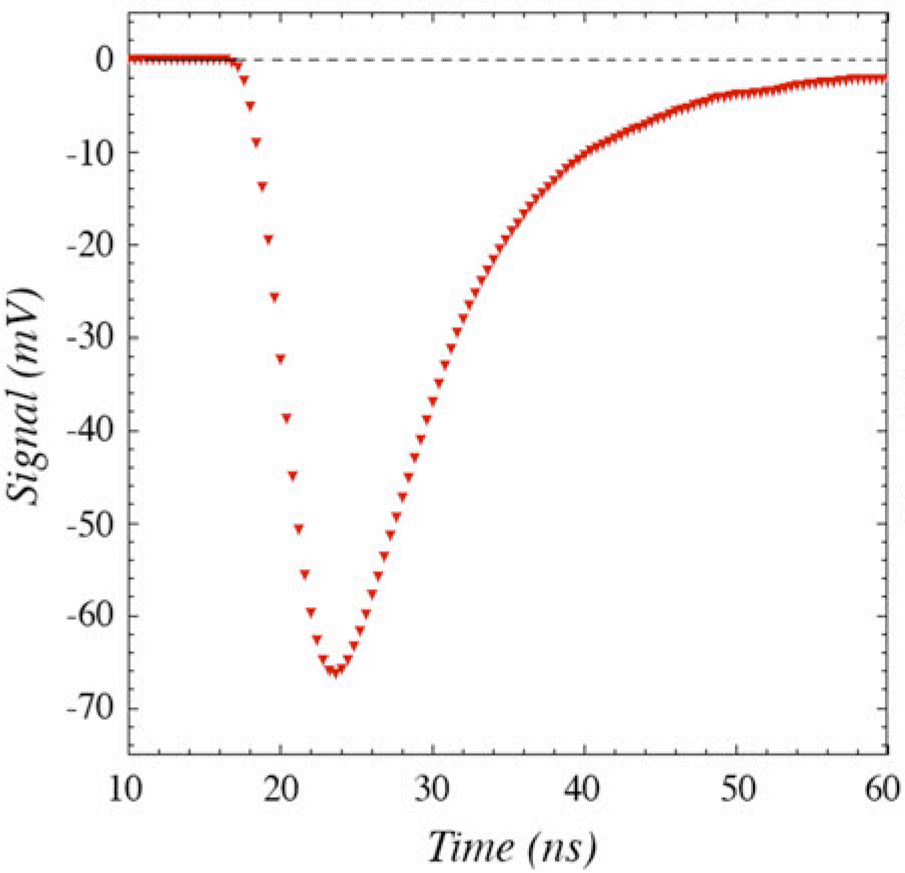


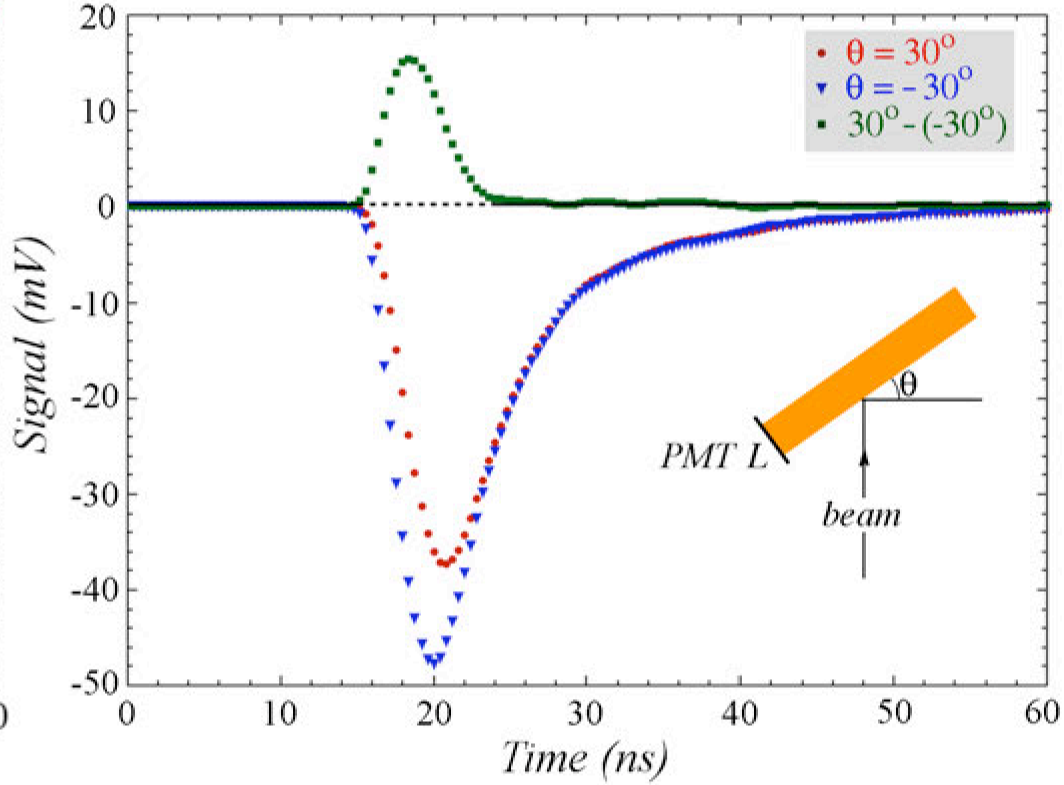
Experimental results $PbWO_4$: Time structure mip signals



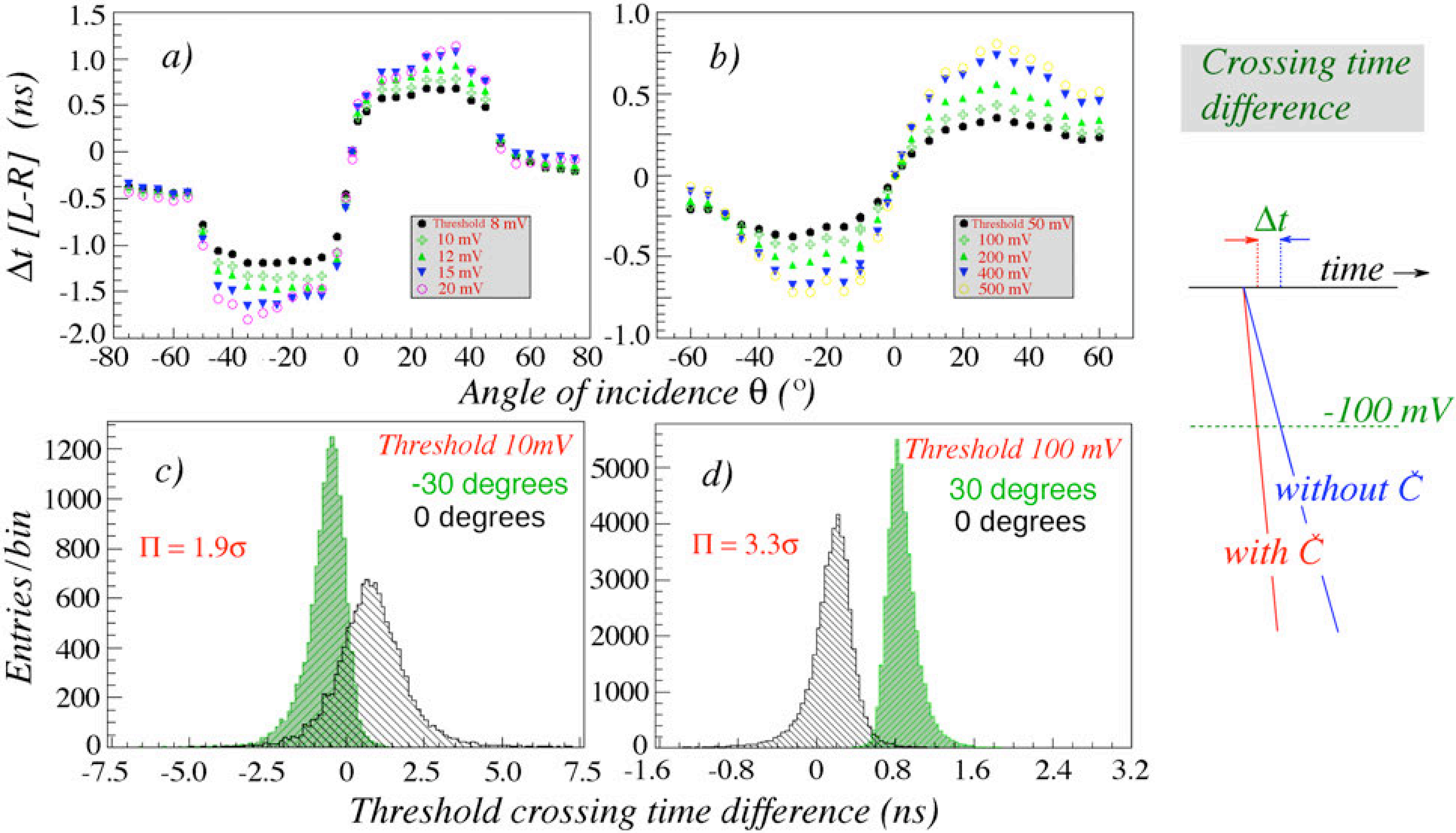
From:
NIM A582 (2007) 474

The importance of time resolution for the $PbWO_4$ signals (0.4 ns sampling oscilloscope)

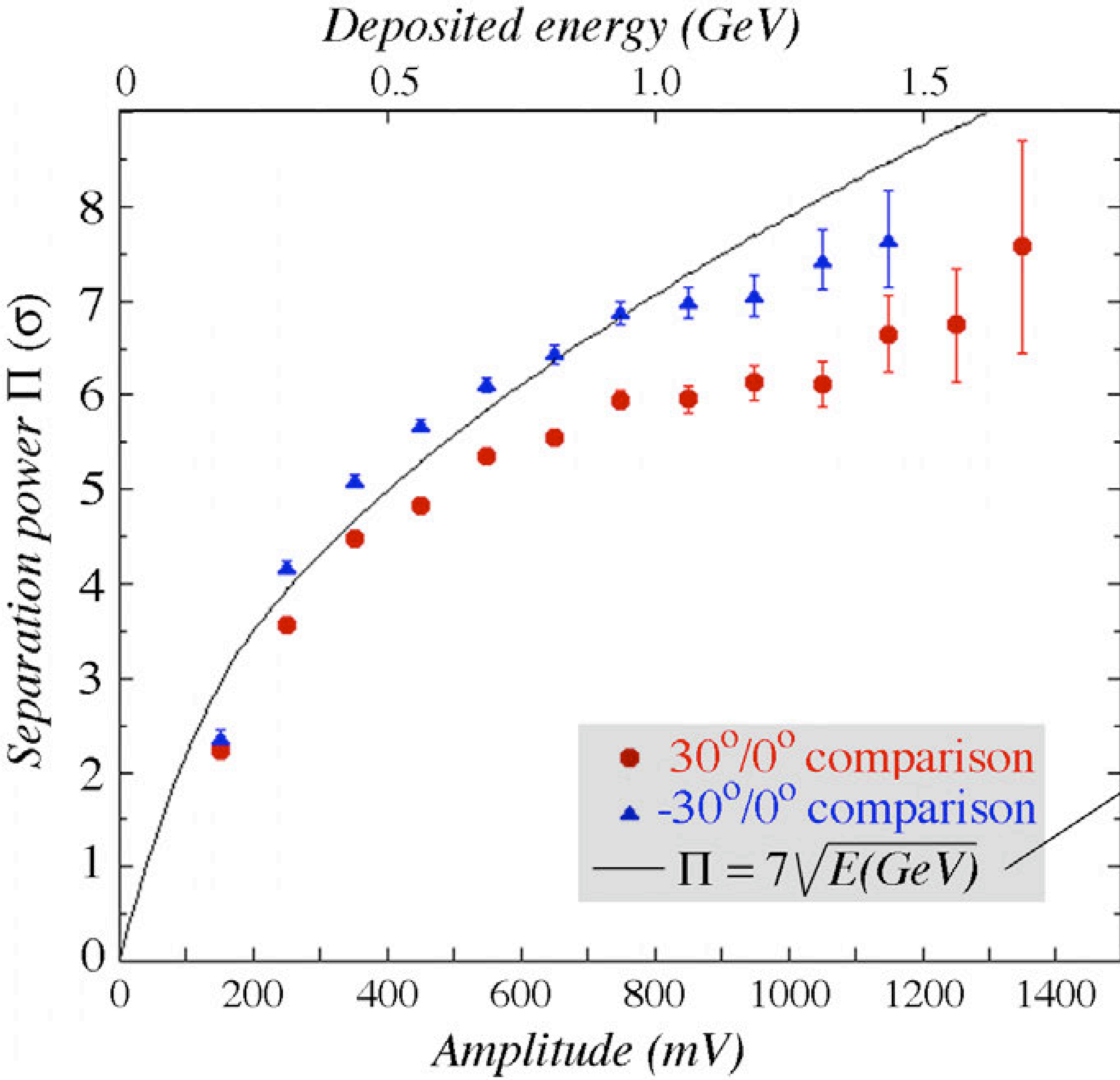




Č-fraction in $PbWO_4$ signals: Measurement precision (1)



Č-fraction in $PbWO_4$ signals: Measurement precision (2)



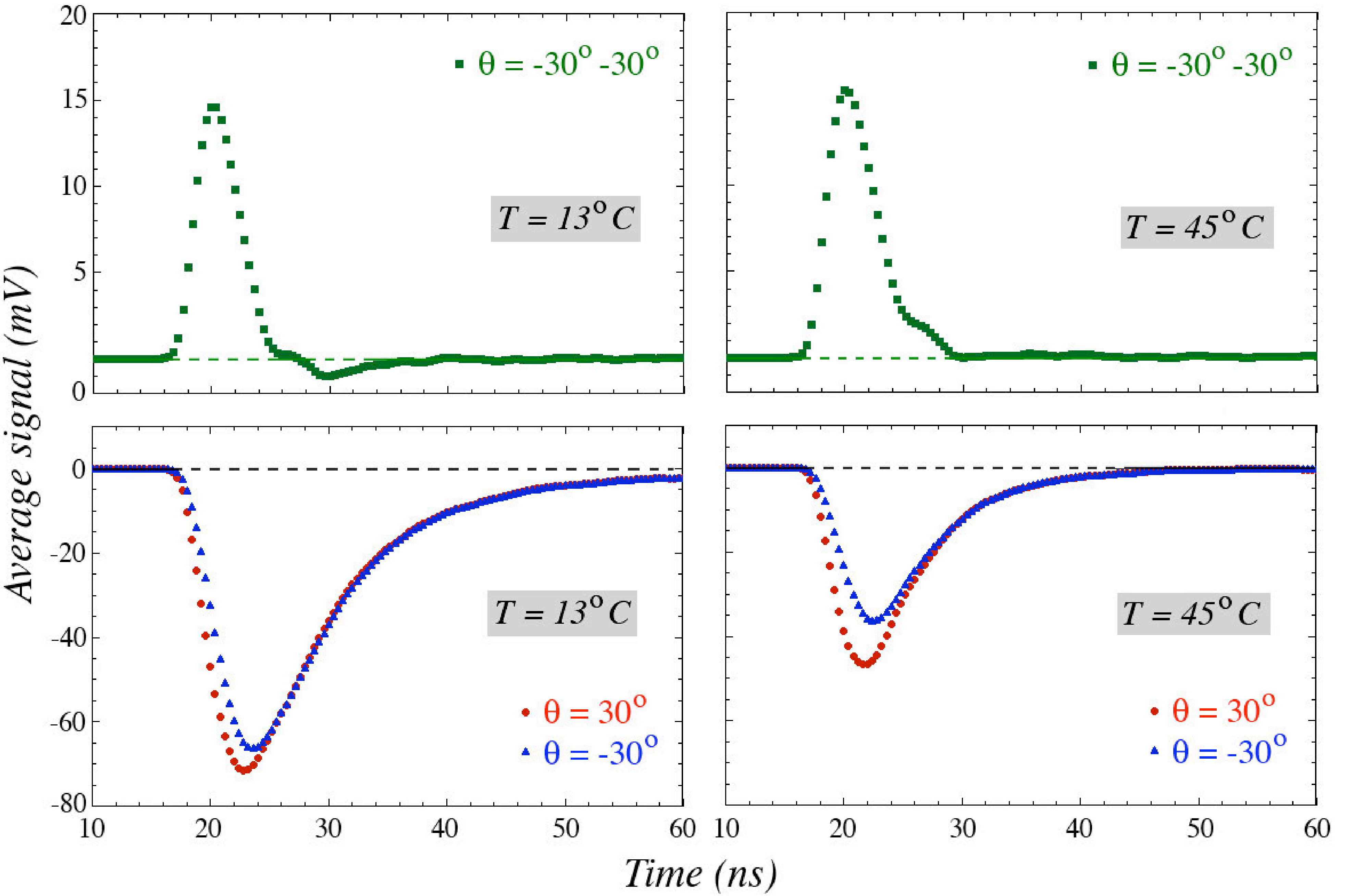
e.g.

7σ @ 1 GeV

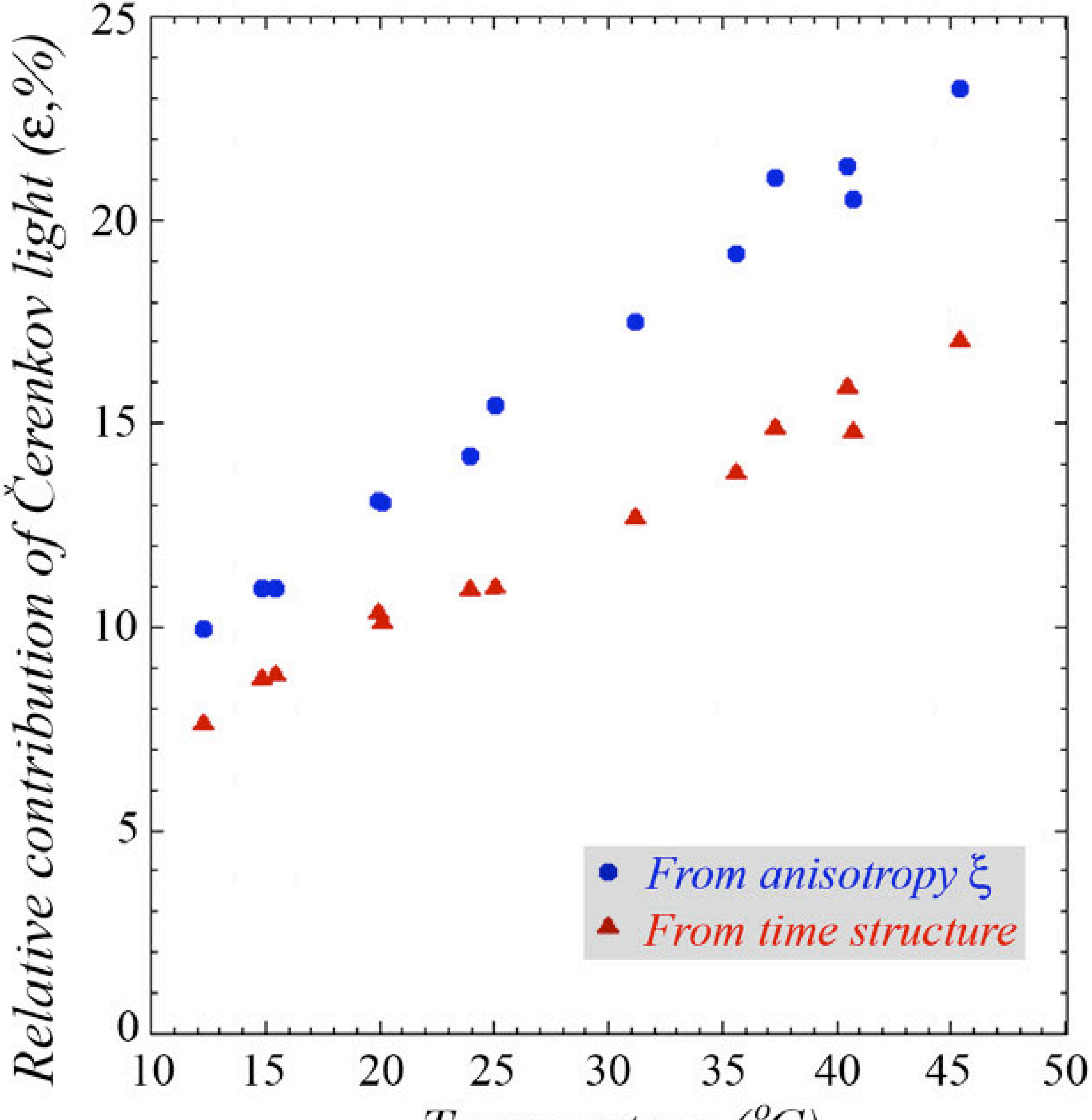
→ $\Delta f_{Č} \sim \pm 2\%$

> 50 Č.p.e./GeV

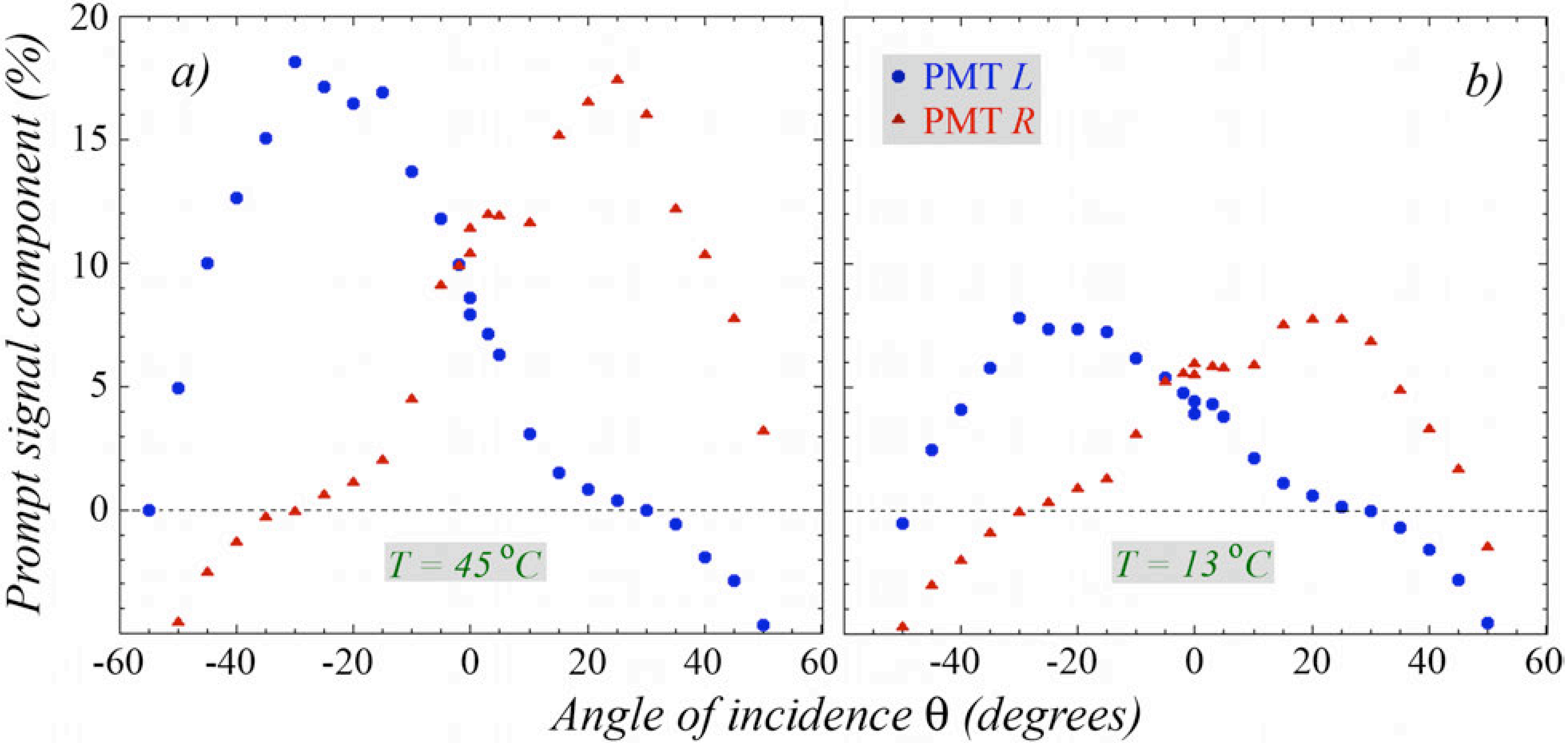
Temperature effects on the $PbWO_4$ signals



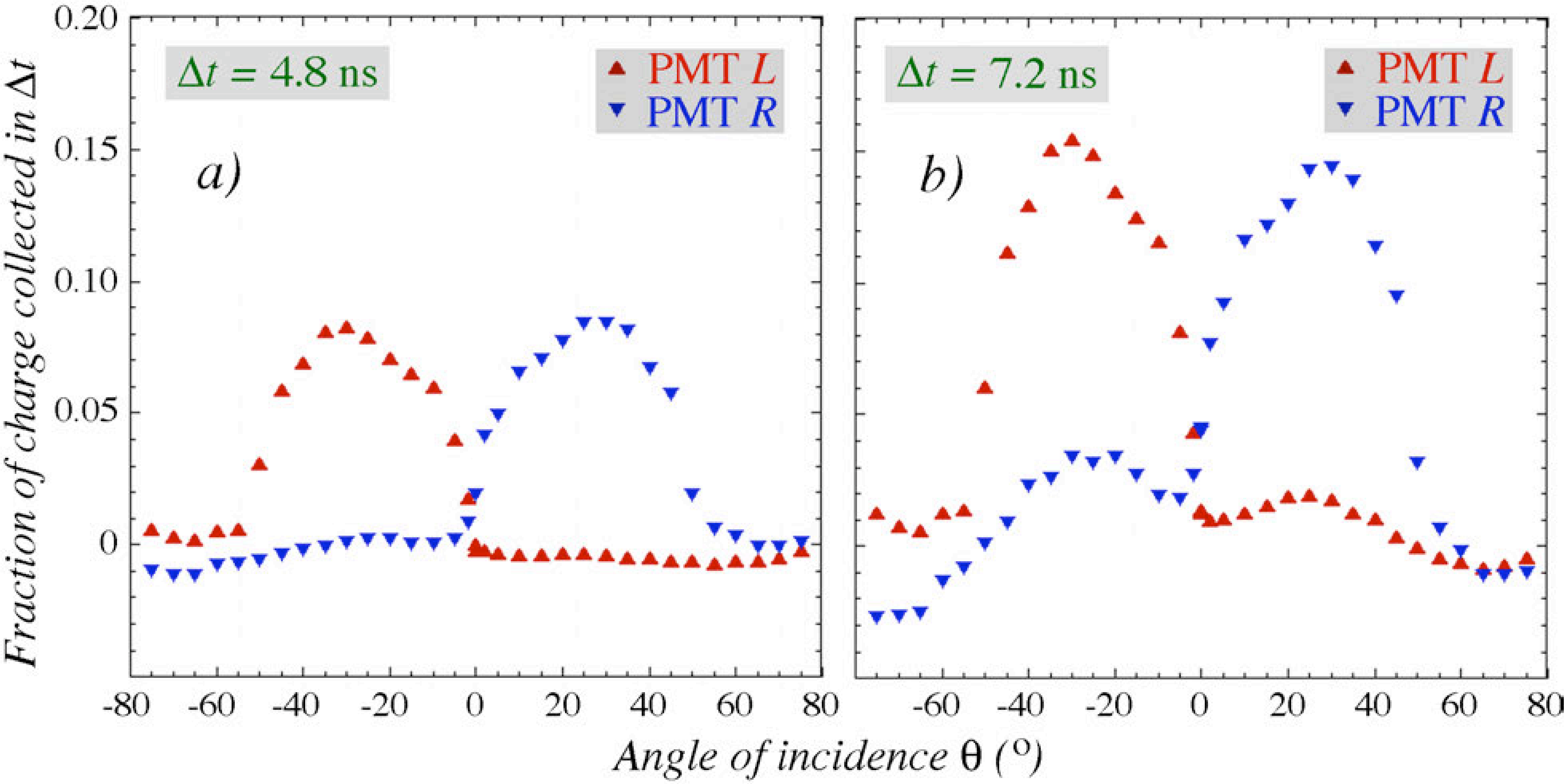
Temperature dependence of Čerenkov fraction $PbWO_4$ signals



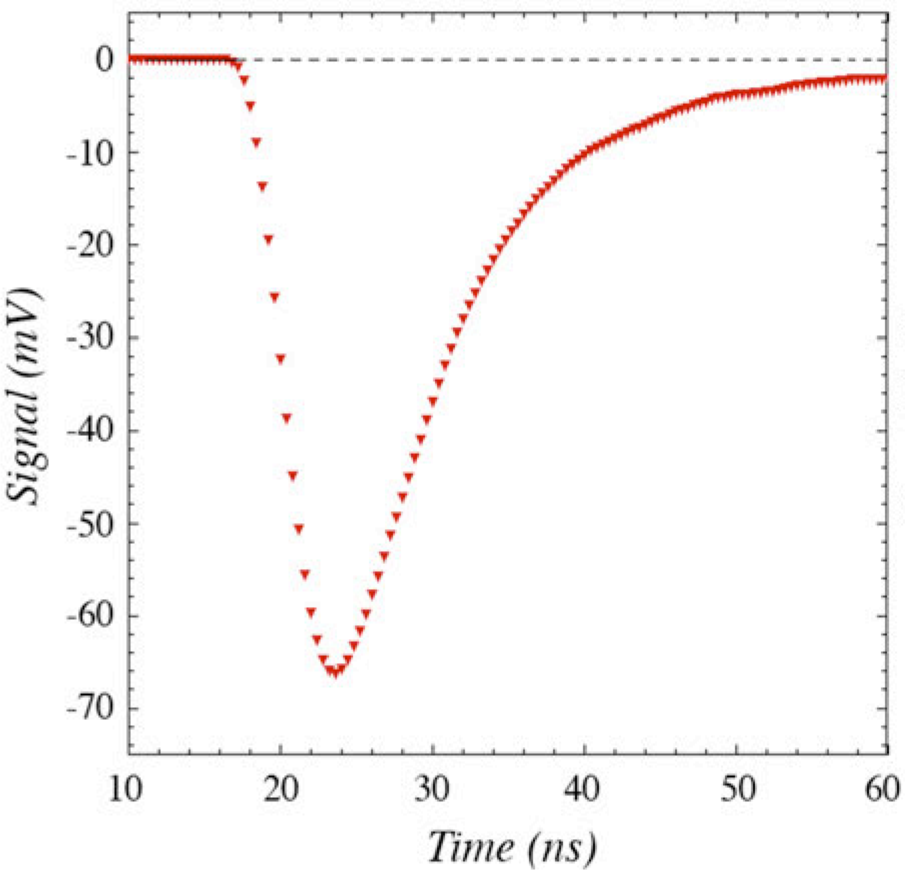
Signals at "anti-Č" angle are NOT purely from scintillation light

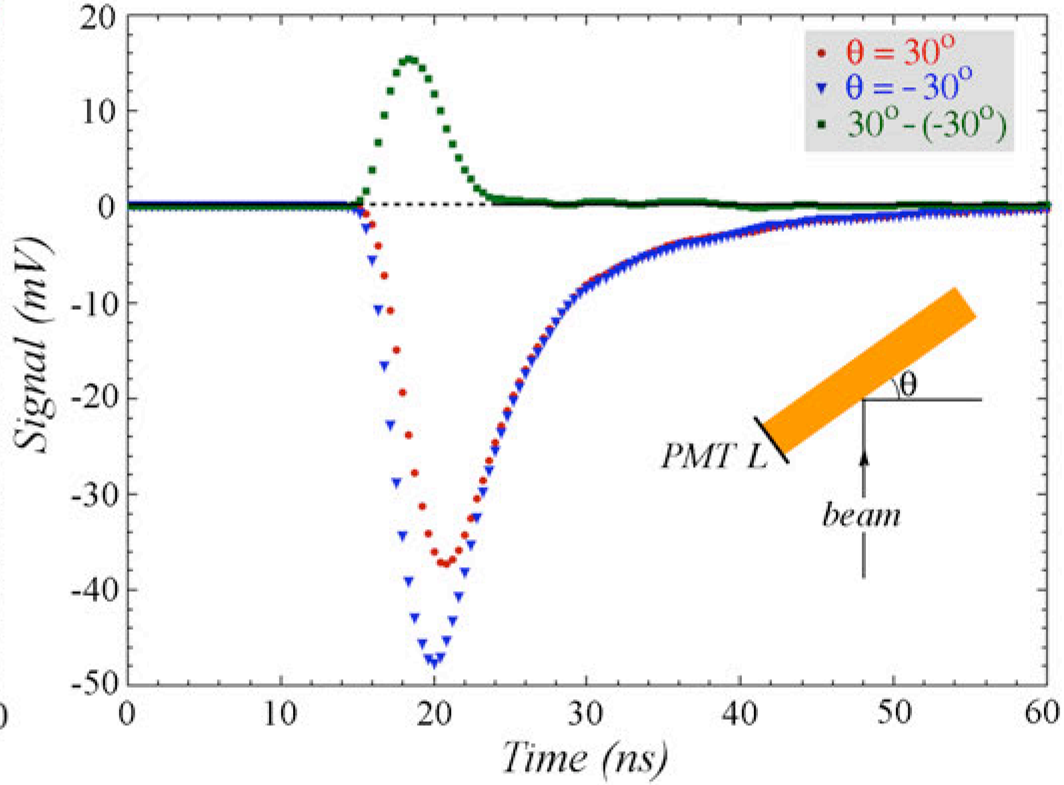


Signals at "anti-Č" angle are NOT purely from scintillation light (2)



The importance of time resolution for the $PbWO_4$ signals (0.4 ns sampling oscilloscope)



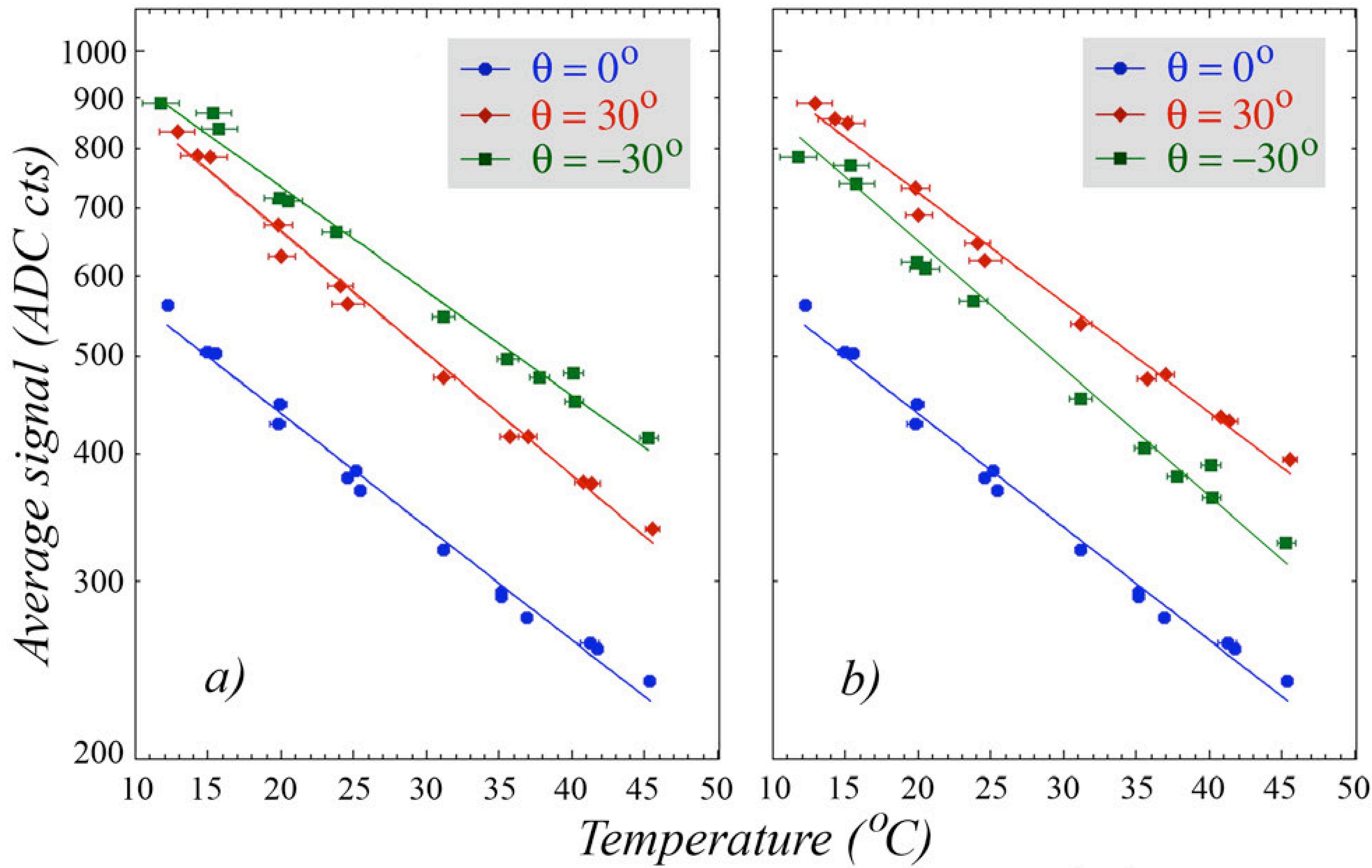


Temperature dependence of light yield $PbWO_4$ crystals

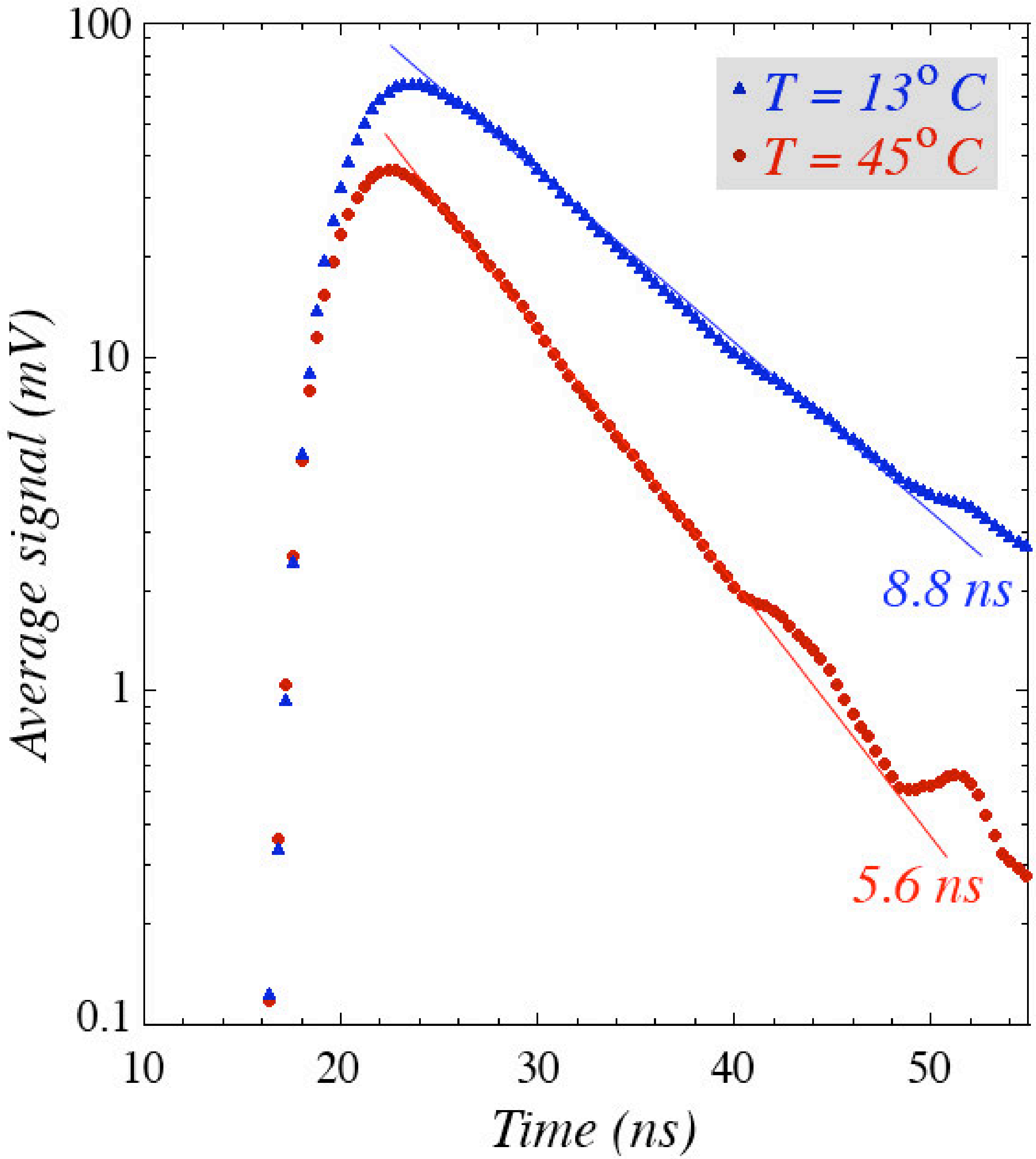
Č-angle: 2.64 ± 0.03%/°C

θ = 0: *2.81 ± 0.03%/°C*

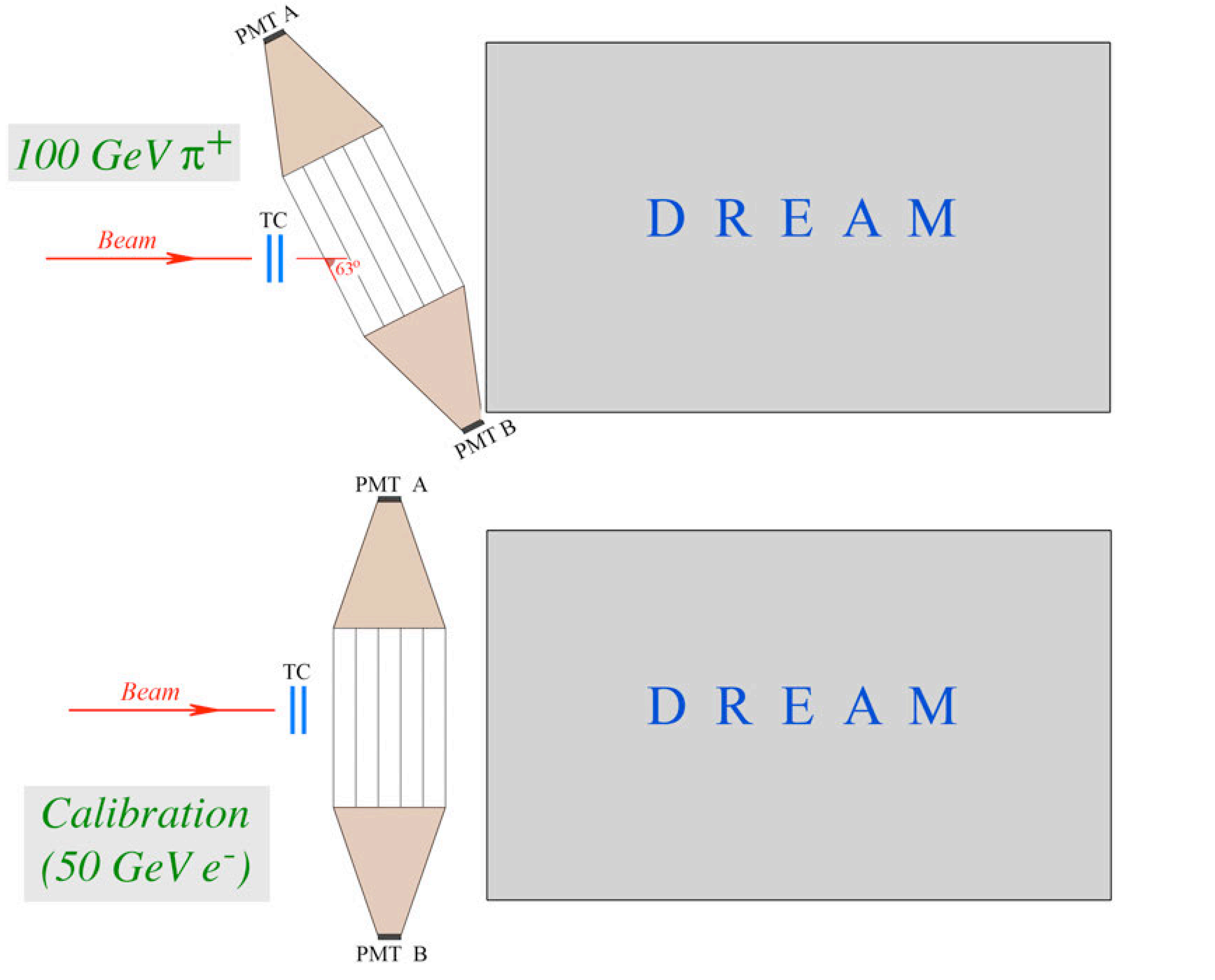
$\overline{\text{Č}}$-angle: 2.97 ± 0.03%/°C



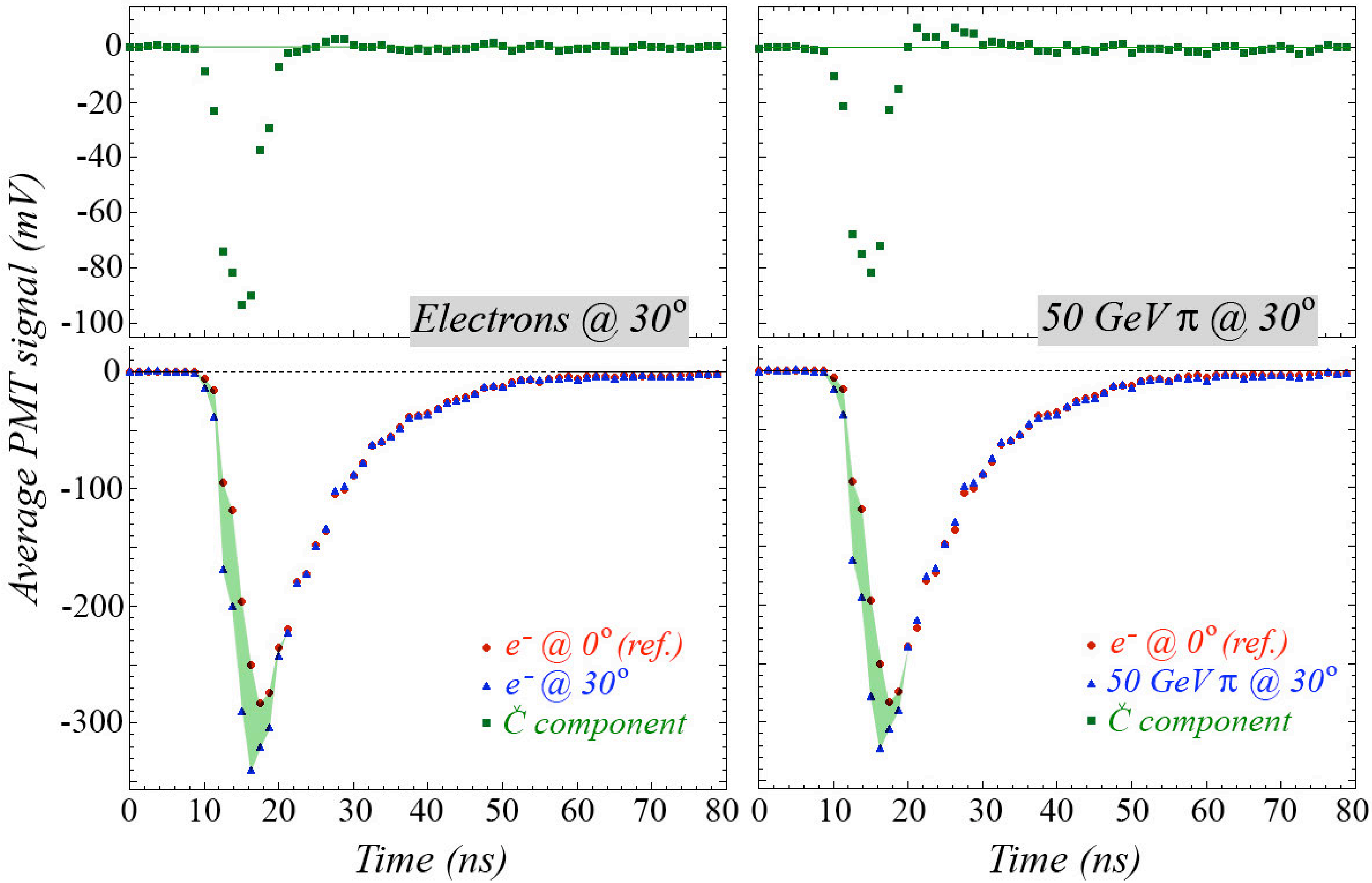
Also the decay time of $PbWO_4$ is temperature dependent



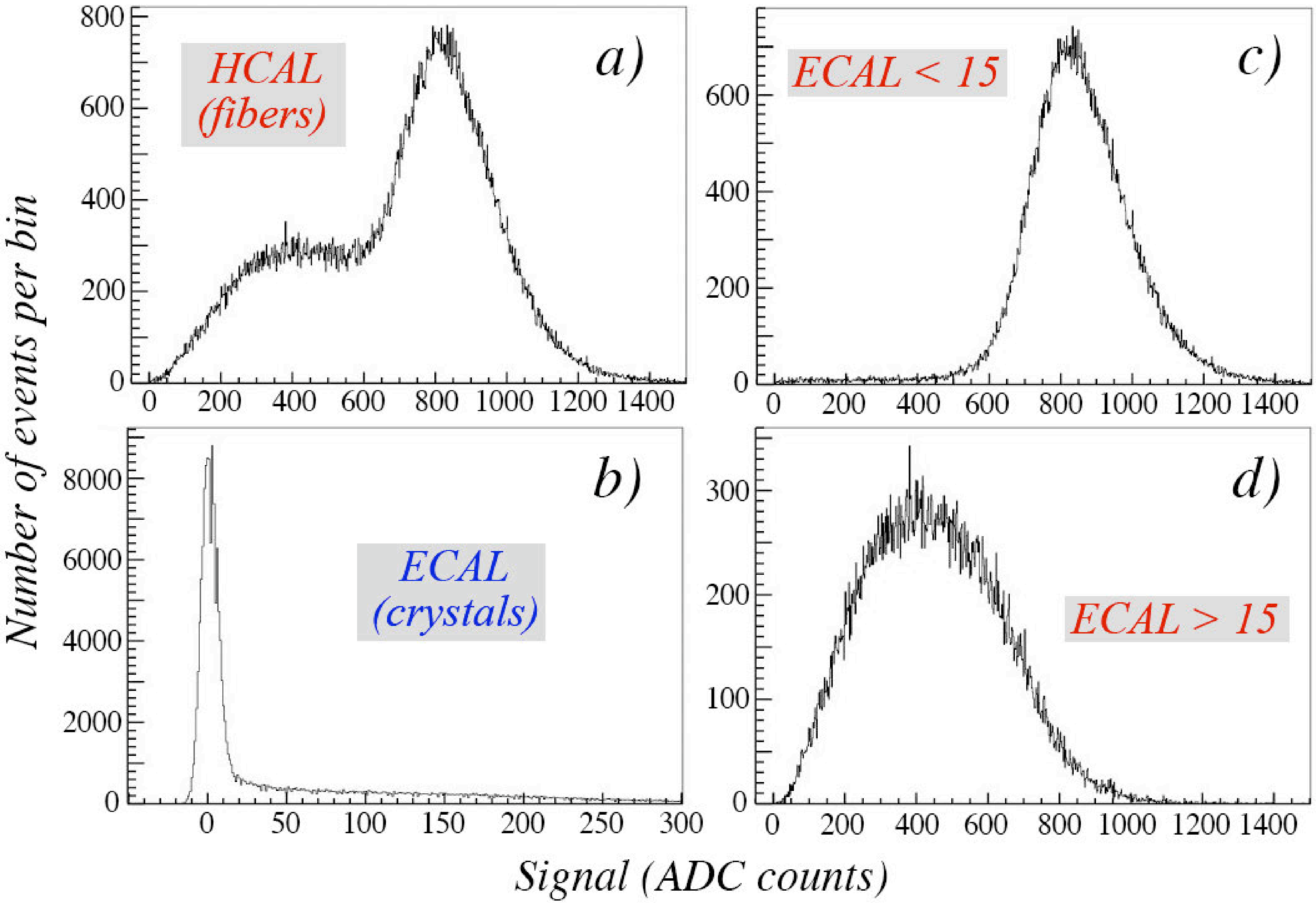
Dual-Readout Calorimetry with $PbWO_4$ crystals



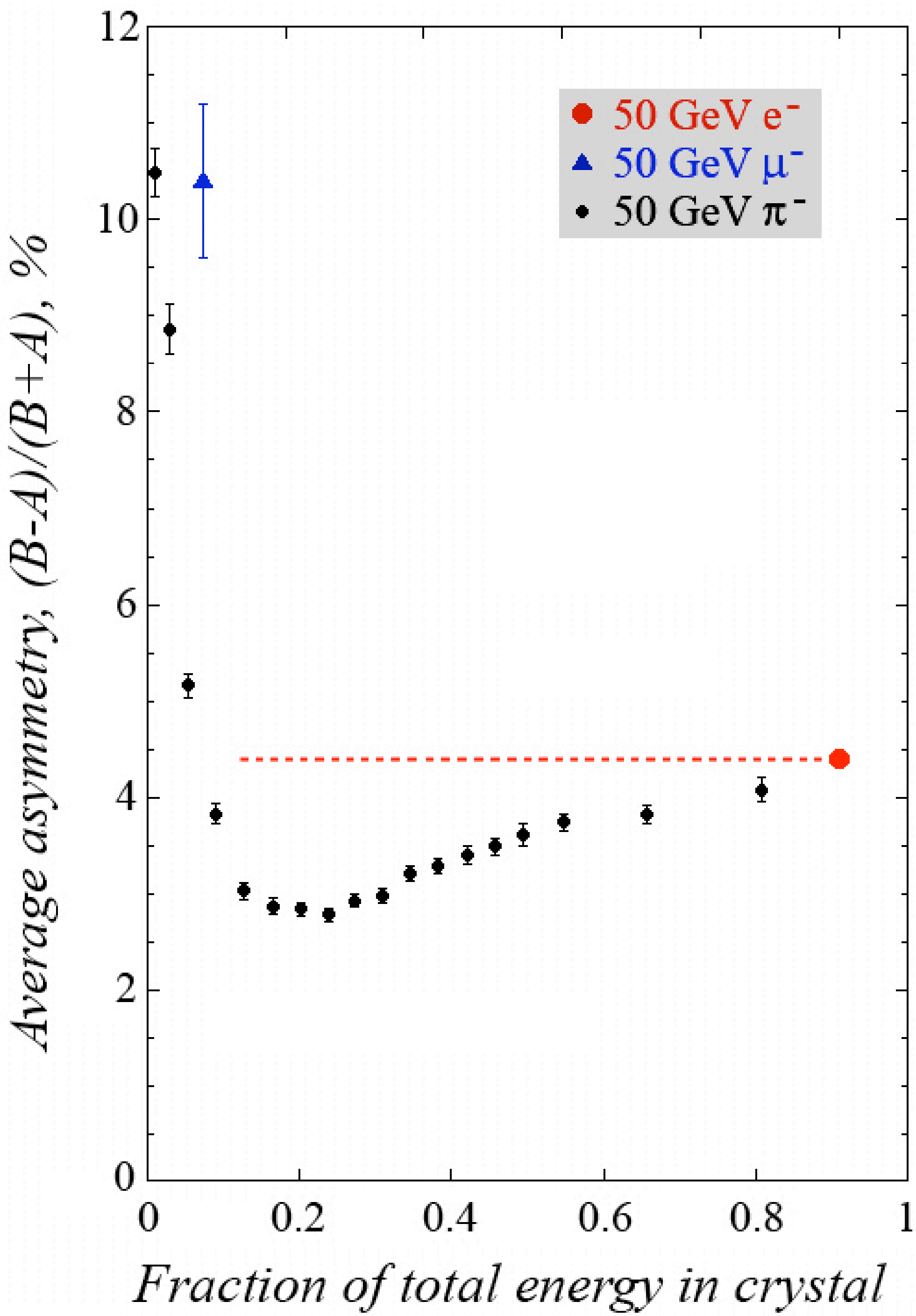
Experimental results $PbWO_4$: Time structure shower signals



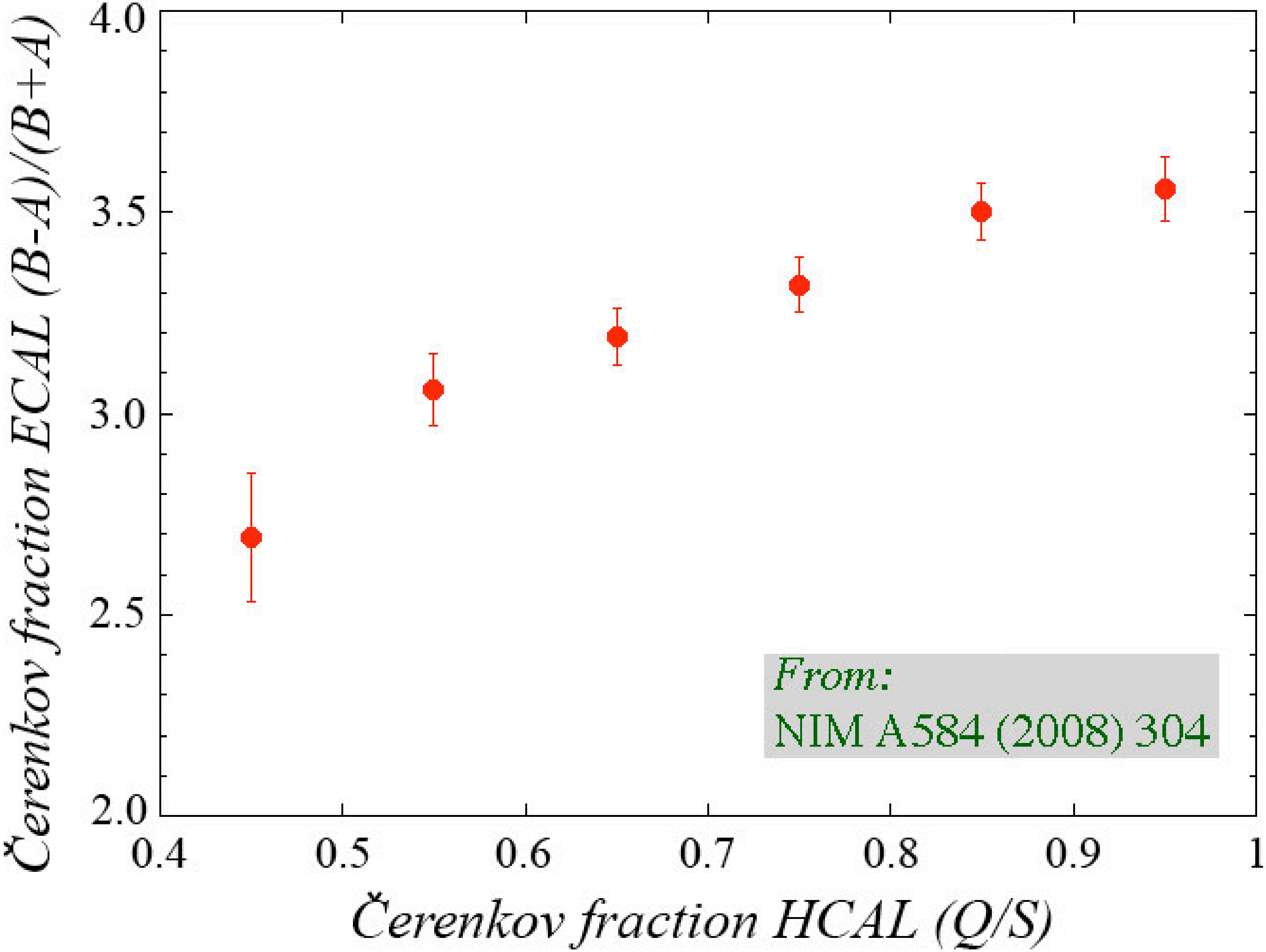
Signal Distributions for Pions



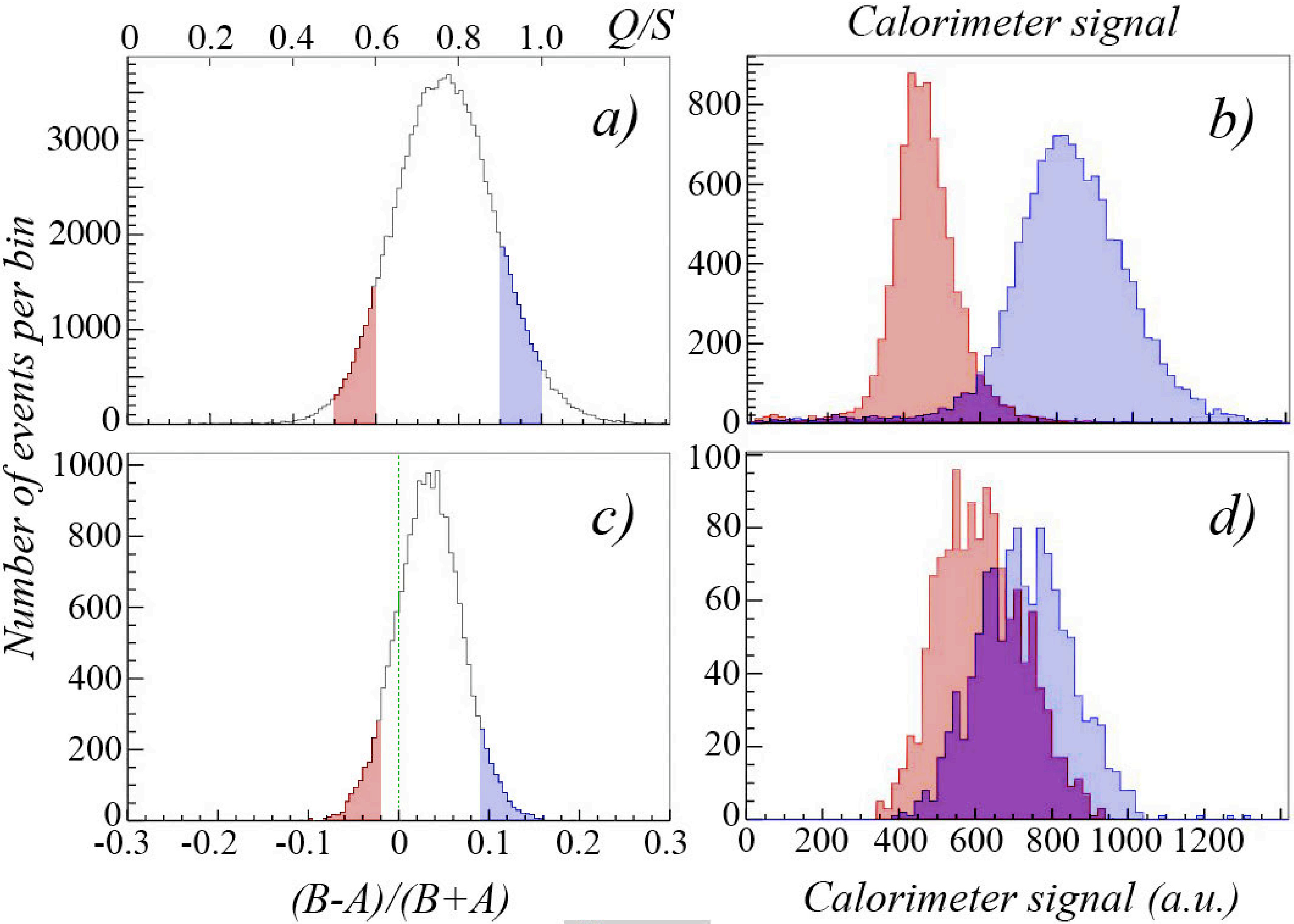
Asymmetry measurement Pion Showers



Čerenkov signals in crystals and in fiber calorimeter



Čerenkov content & total calorimeter signal



From:
NIM A584 (2008) 304

A new crystal: BGO!!

Disadvantage compared to $PbWO_4$:

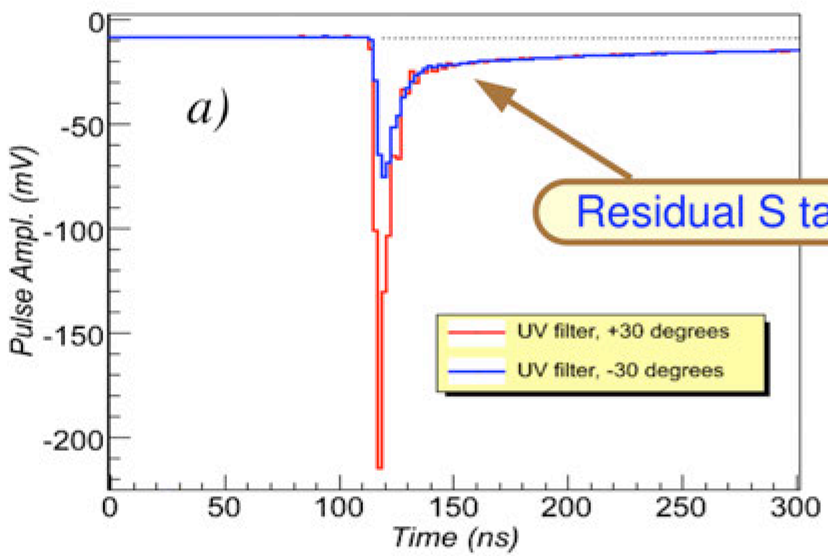
A much brighter scintillator, Č/S factor 100 smaller

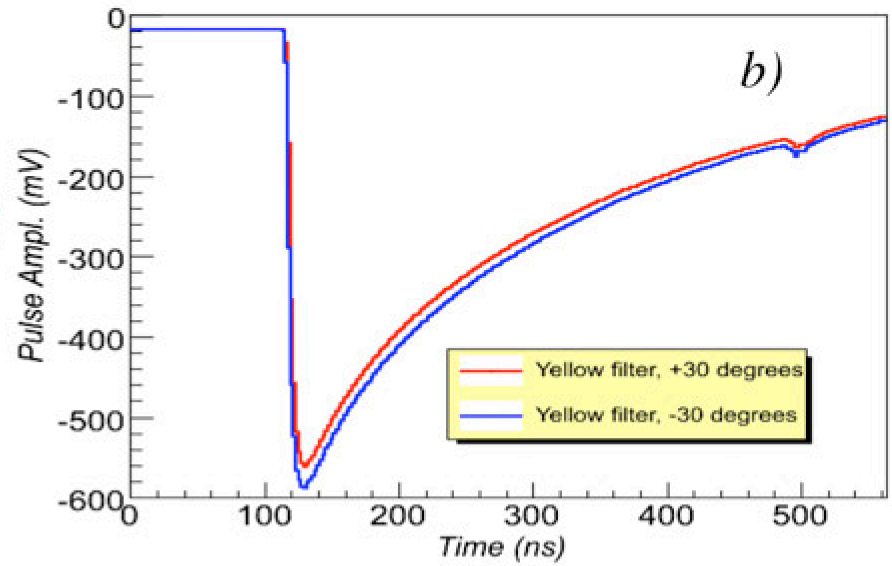
Advantages:

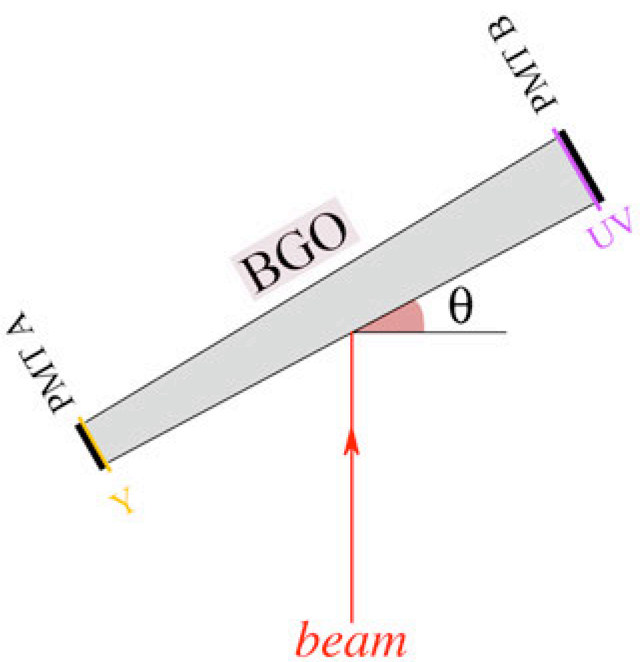
- *Scintillation spectrum peaks at 480 nm ⟶ use filters*
- *Decay time scintillaton 300 ns (very different from prompt)*

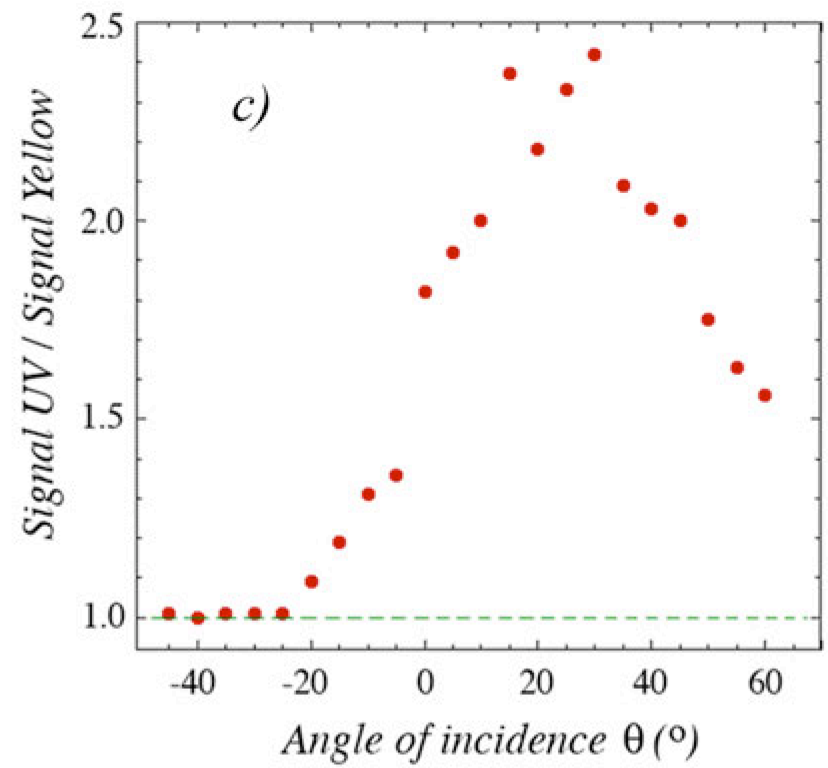
⟶ More (and better) options to isolate Čerenkov signal

The Čerenkov component in BGO signals

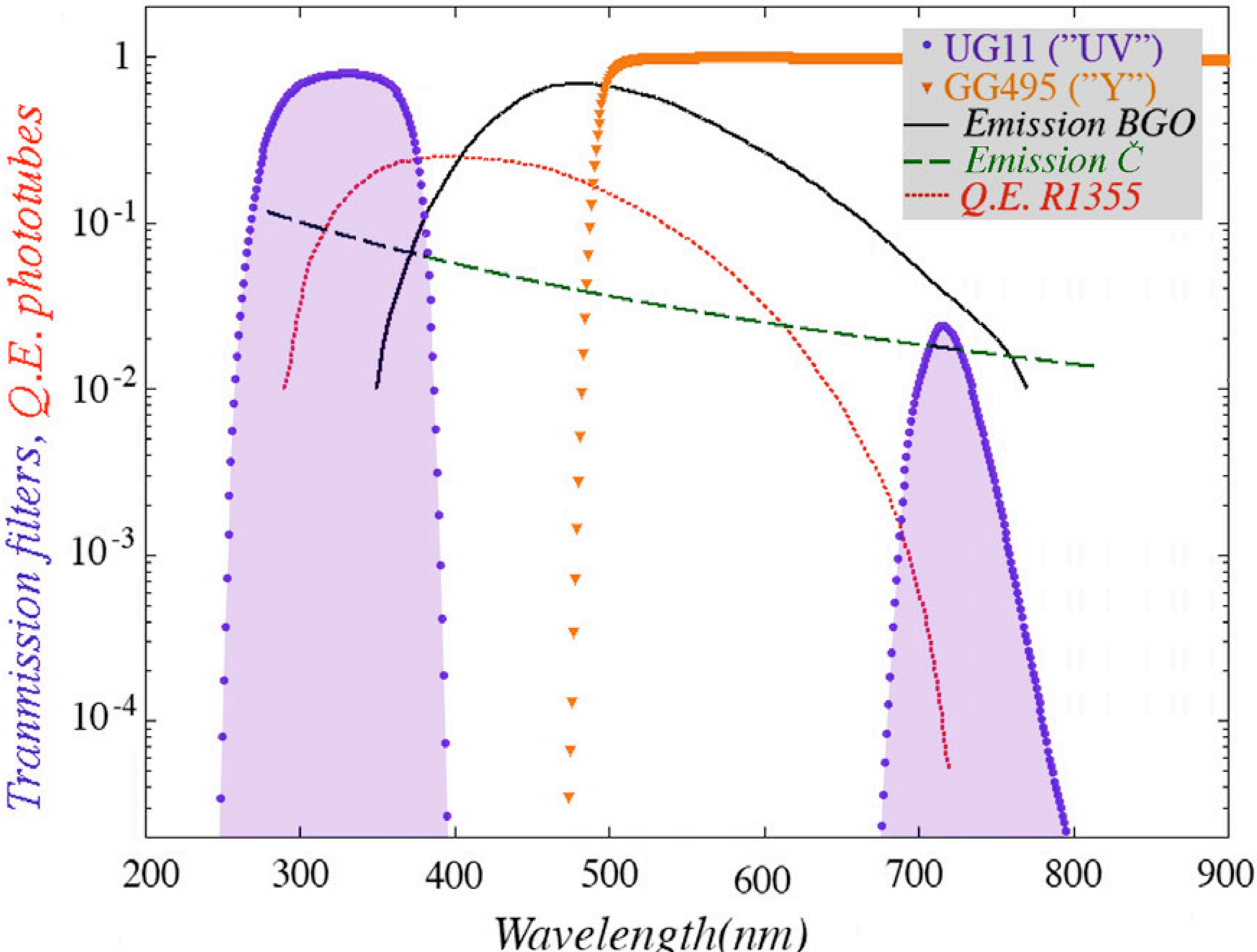




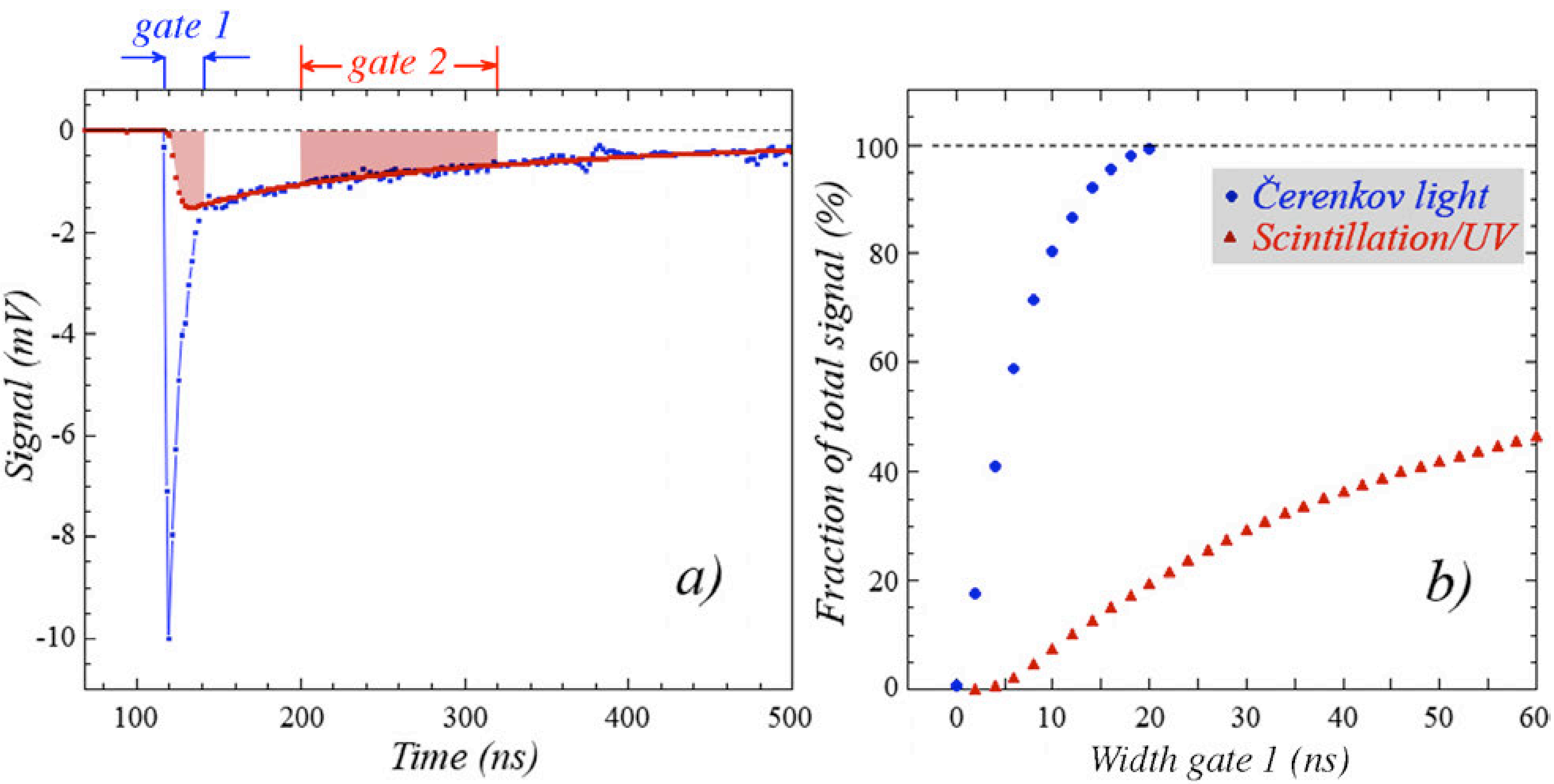




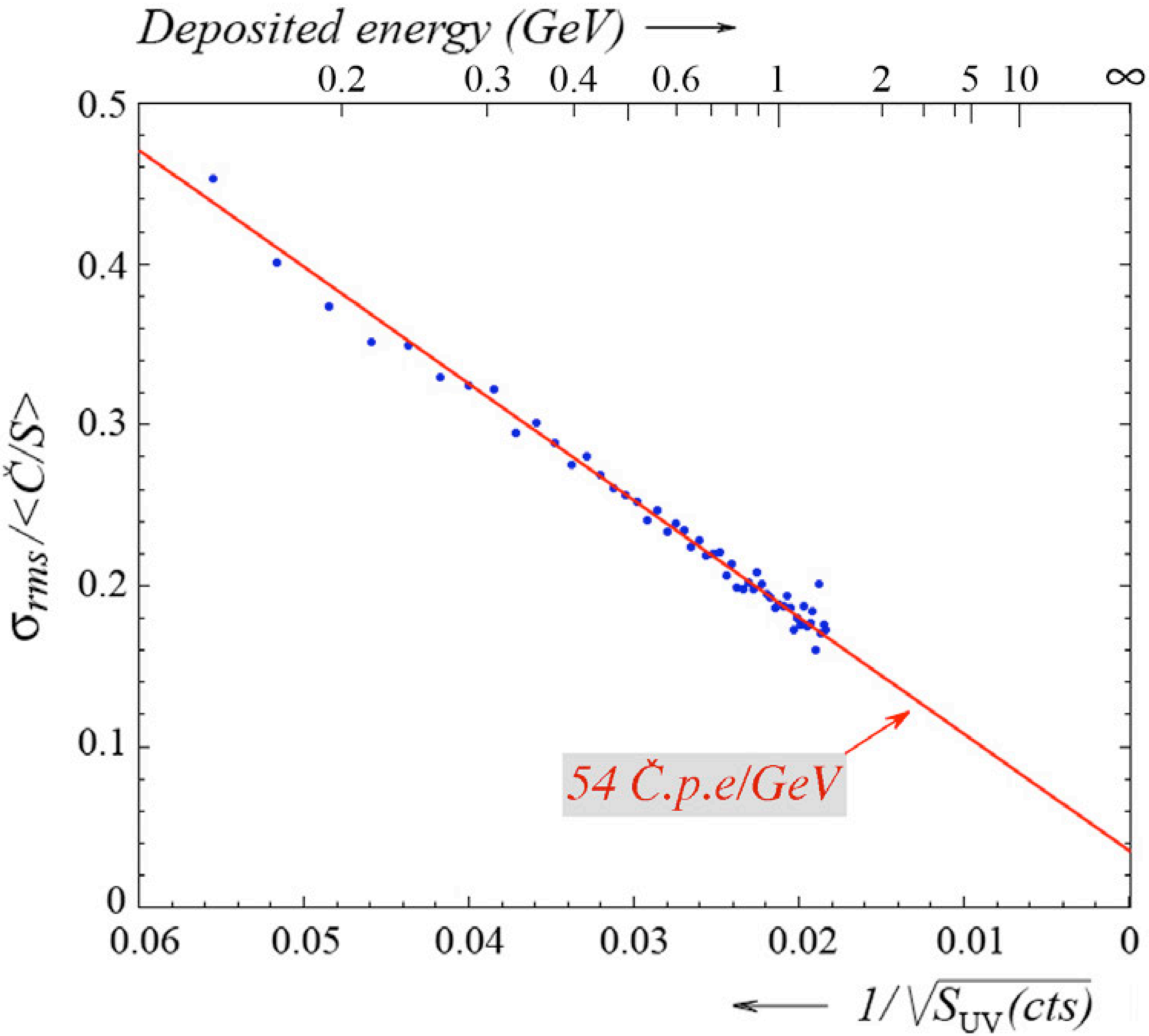
Light yield, filter transmission and quantum efficiency



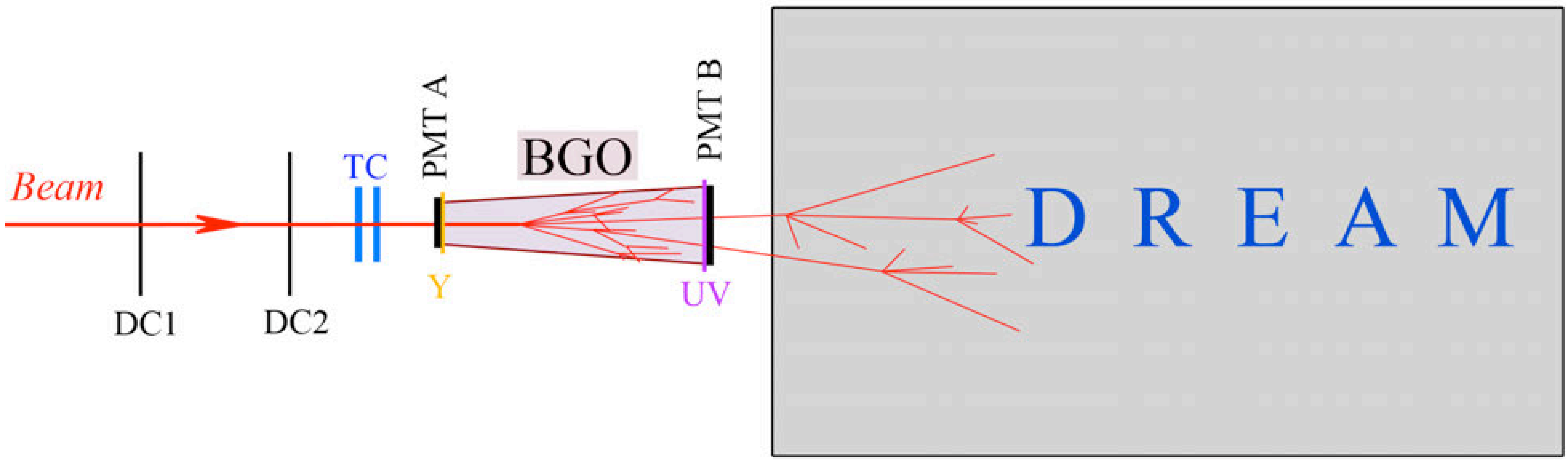
Čerenkov and Scintillator information from one signal !



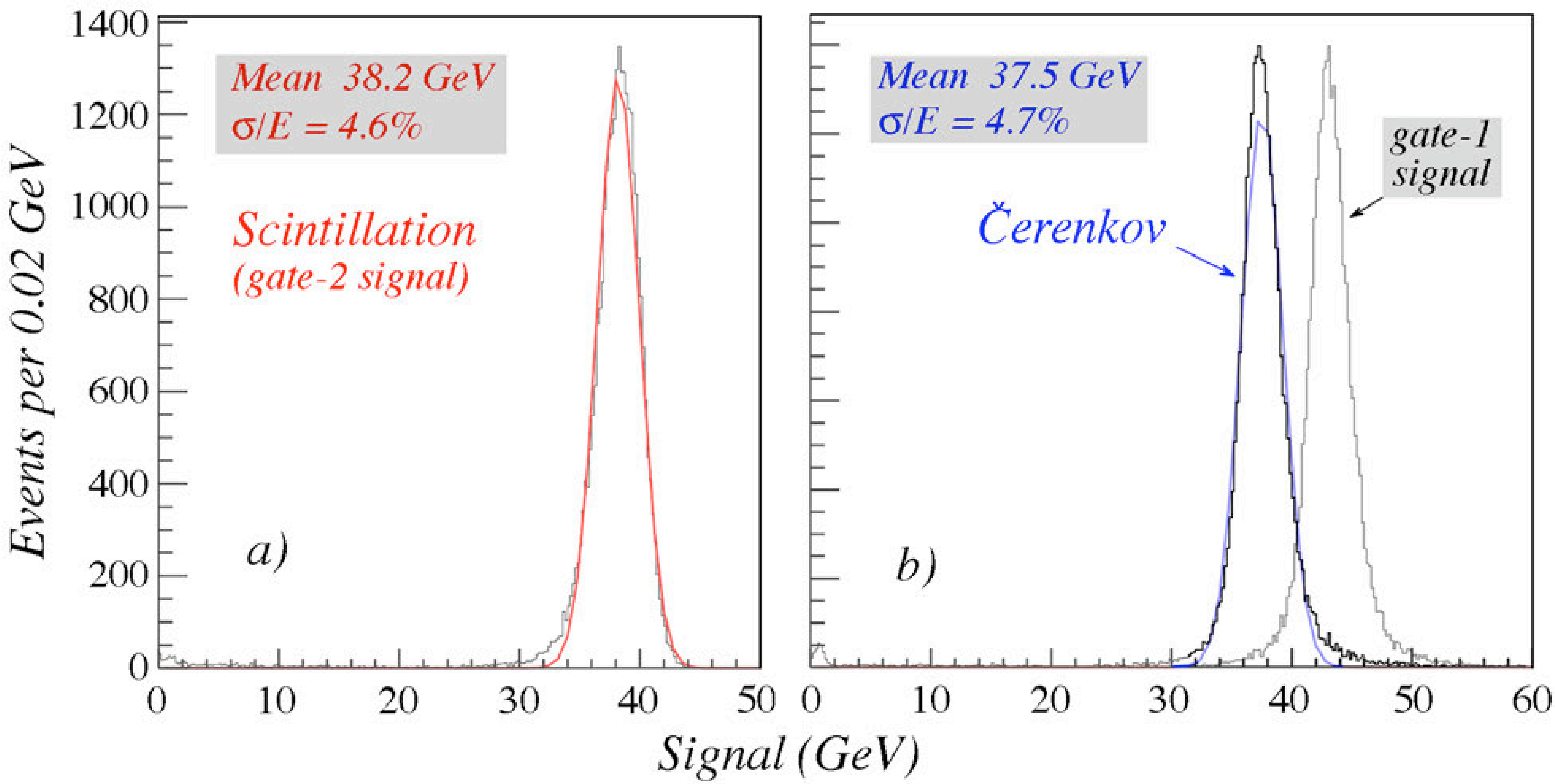
Measuring the Čerenkov light yield in BGO



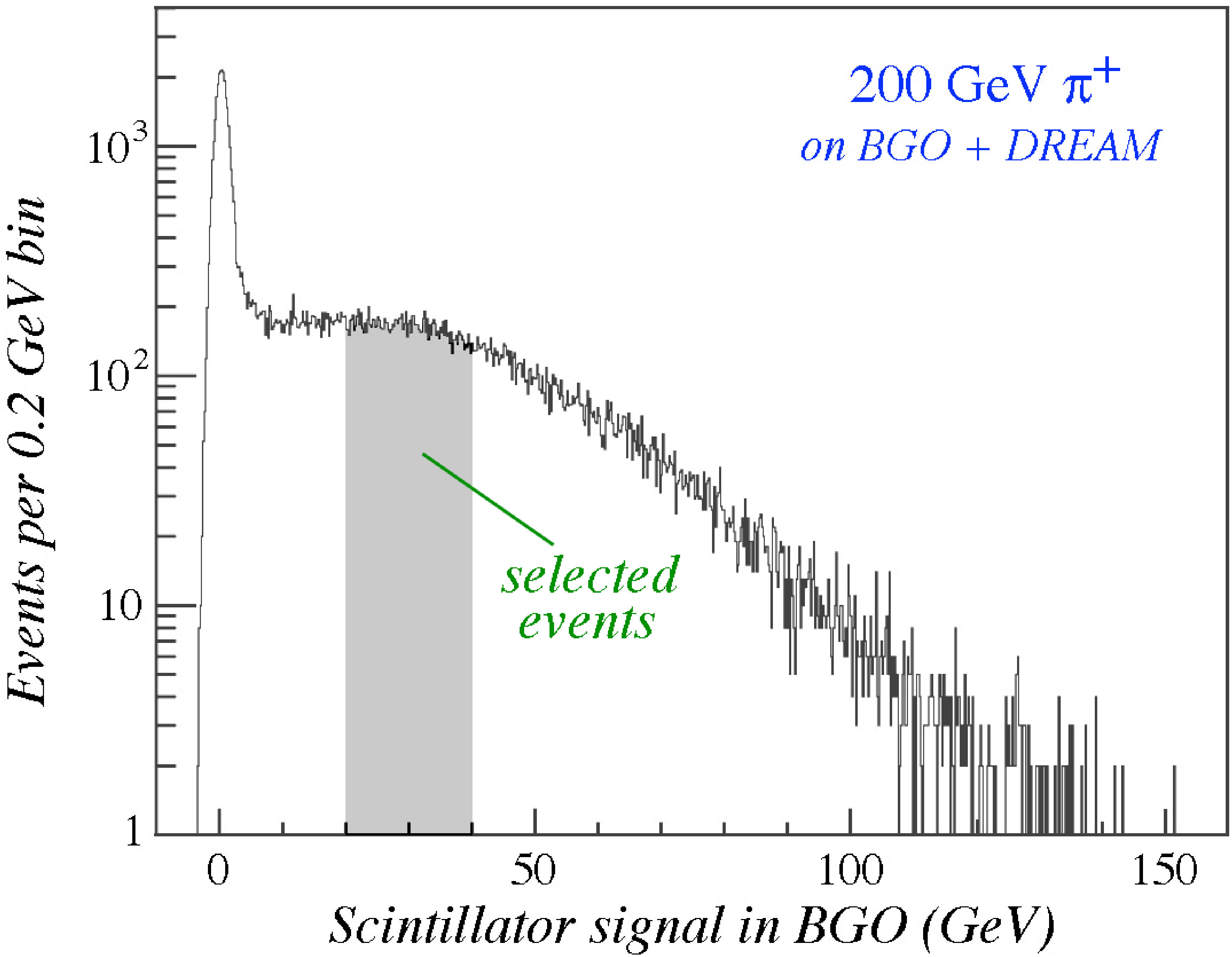
Experimental setup for the BGO + DREAM tests



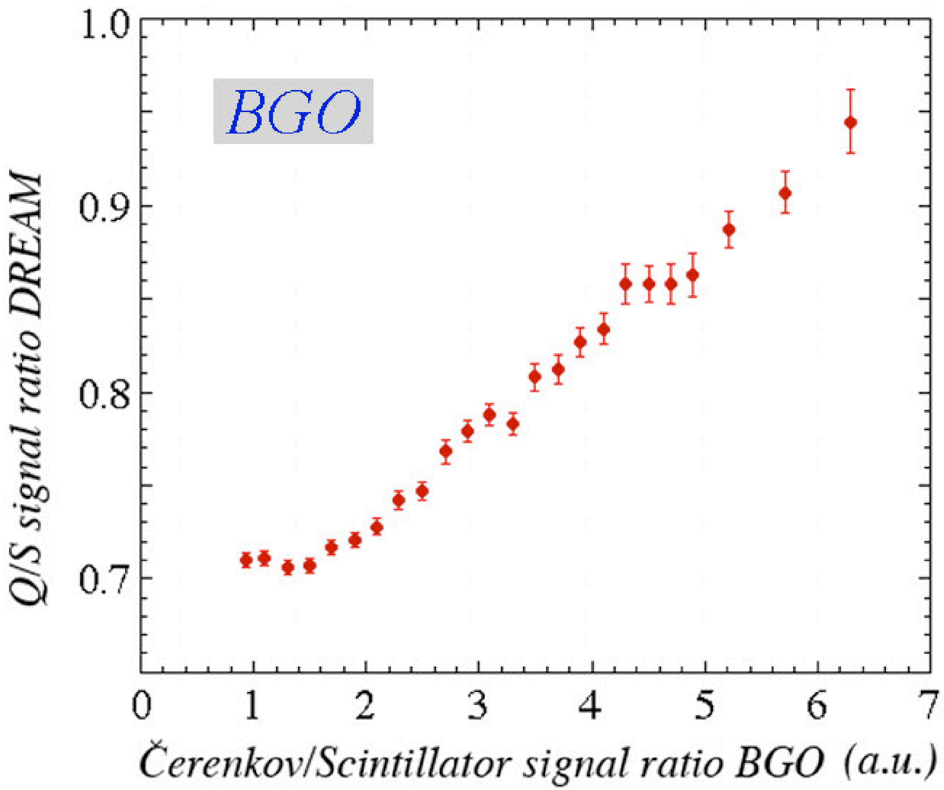
Calibration of the BGO UV signals (50 GeV electrons)

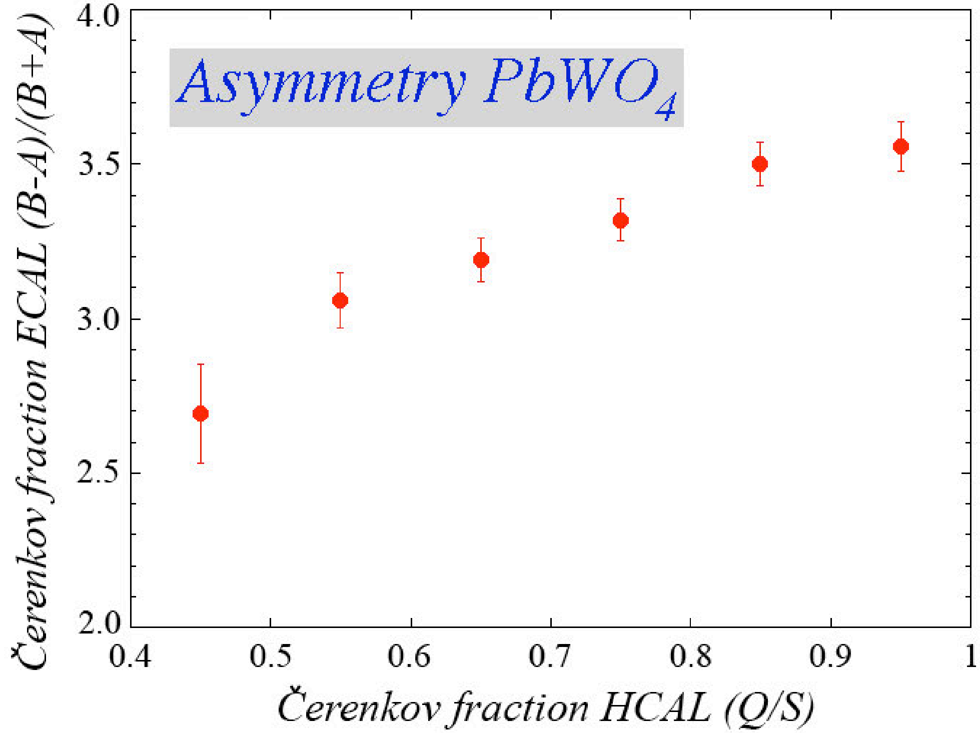


The (UV) scintillator spectrum of 200 GeV pions

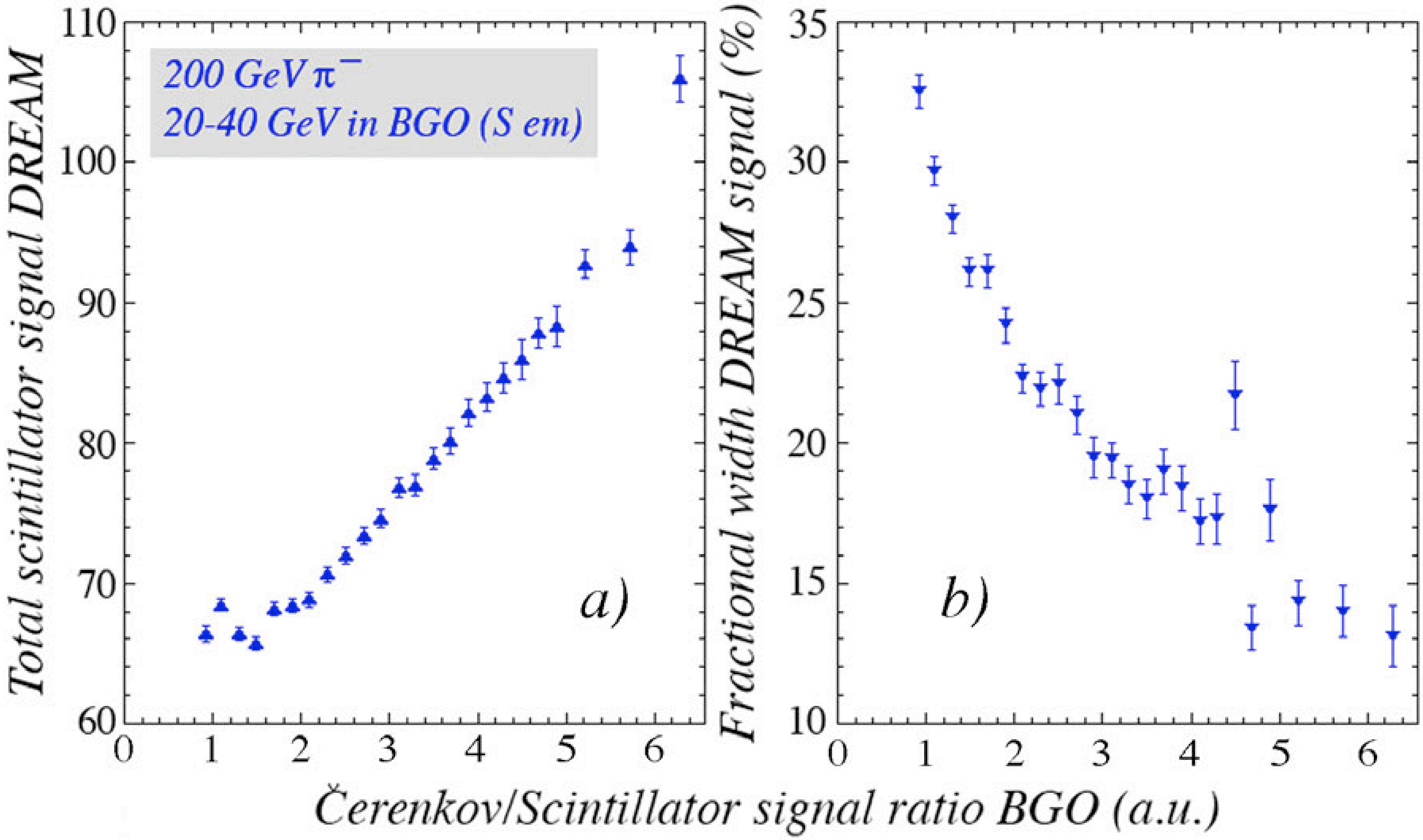


Correlation between the Čerenkov fractions in ECAL and DREAM

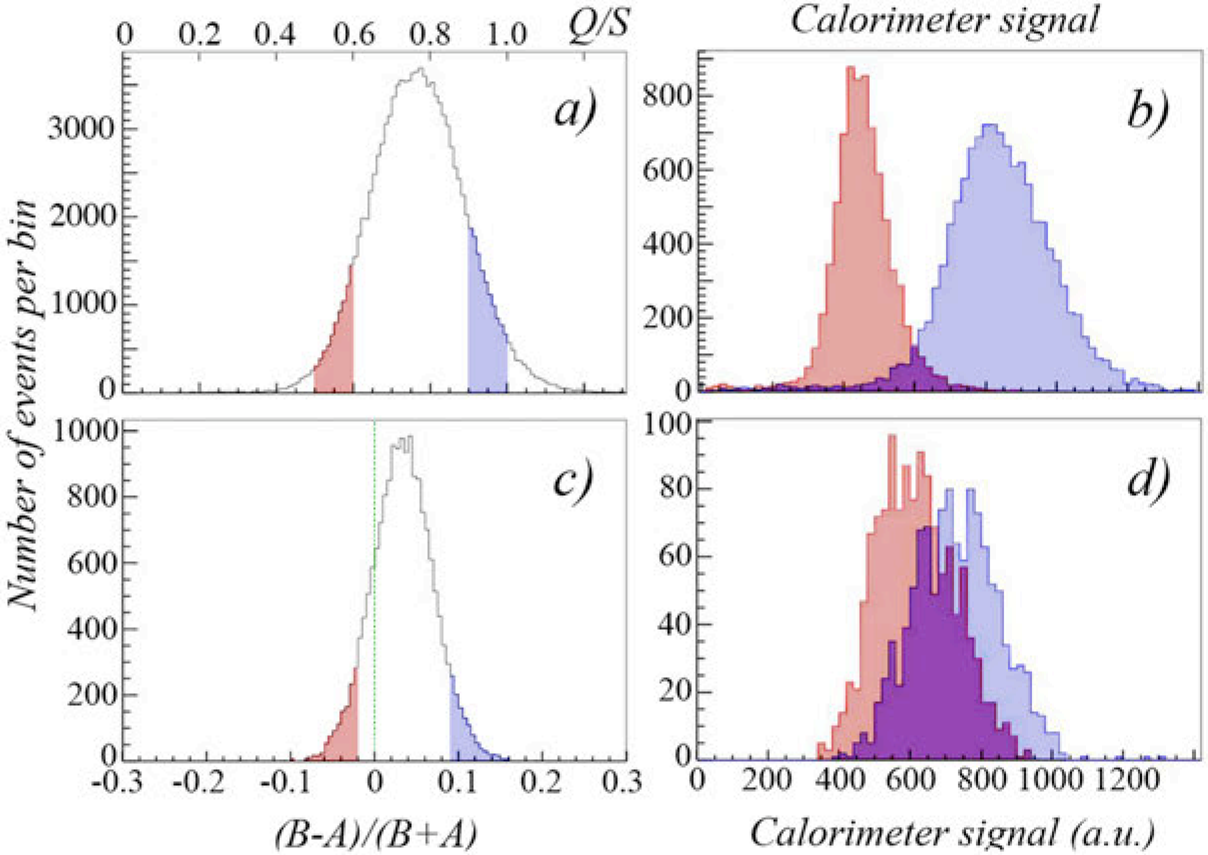




The DREAM signals as a function of the BGO Čerenkov fraction

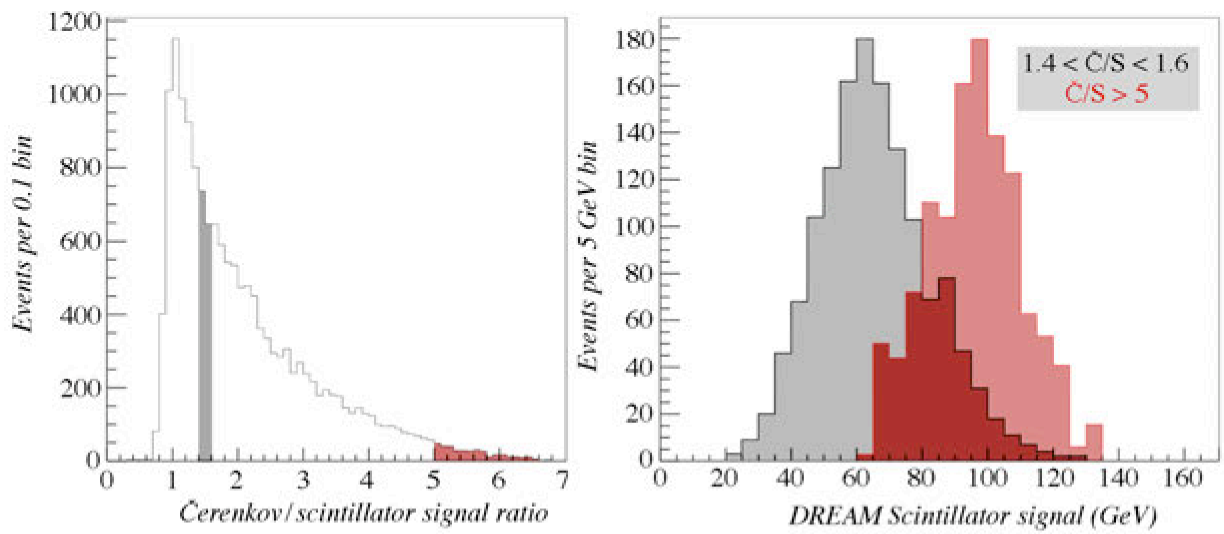


Selective power of the measured Cerenkov component



DREAM
stand-alone
(2 separate media)

$PbWO_4$ matrix
(directionality)



BGO_{UV} (1 crystal)

(time structure
+ spectrum)

How to improve DREAM performance

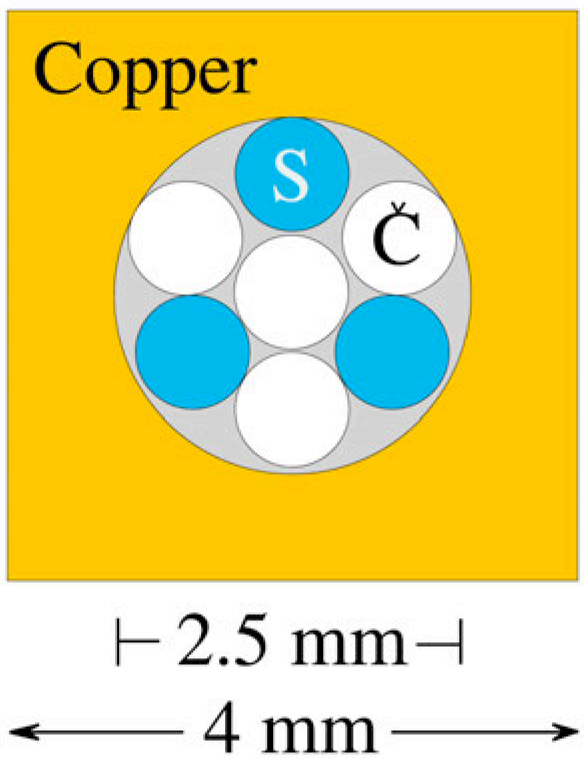
- Build a larger detector ⟶ *reduce effects side leakage*

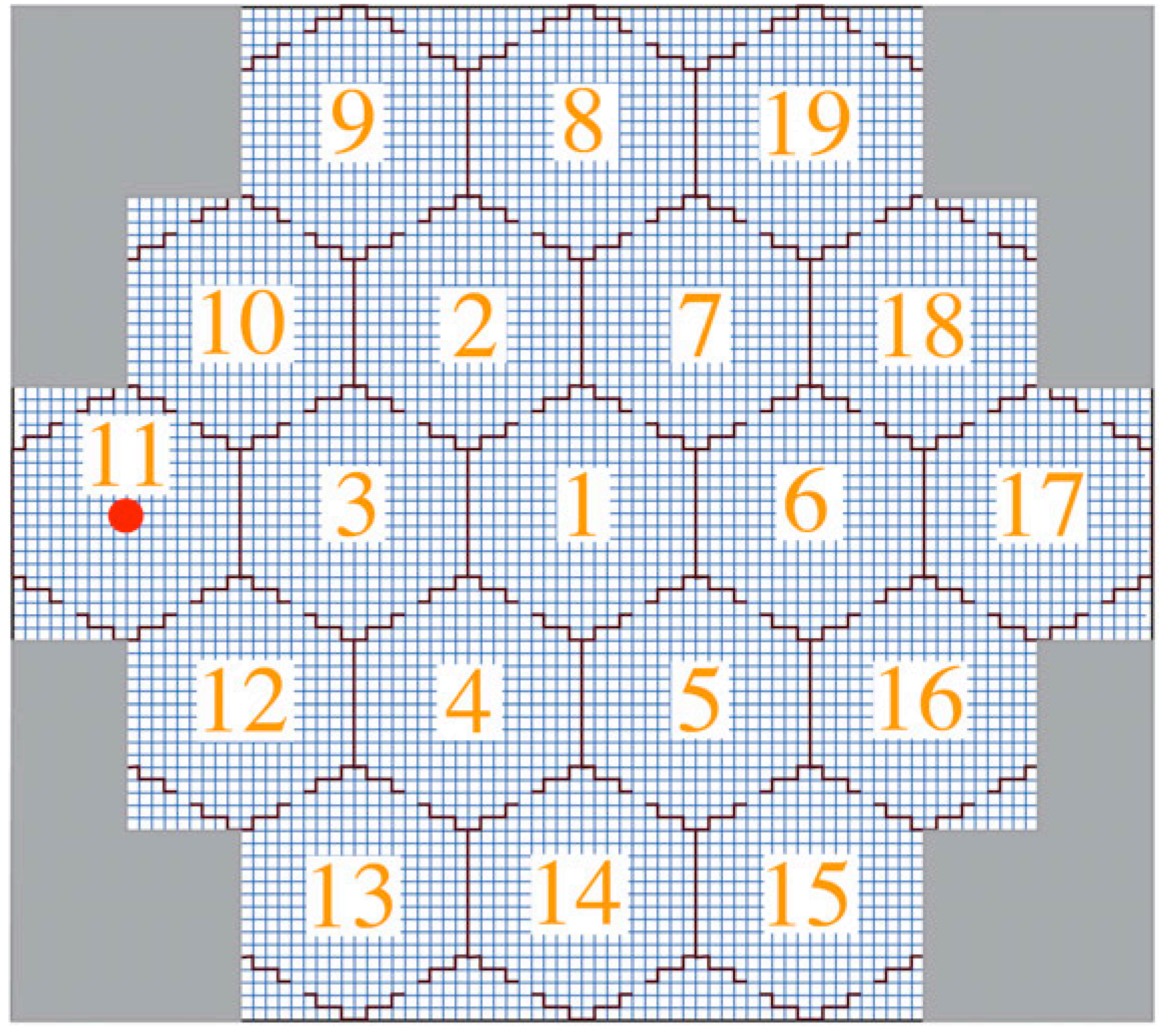
- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV ⟶ fluctuations contribute 35%/$\sqrt{E}$
  No reason why DREAM principle is limited to fiber calorimeters
  Homogeneous detector ?!
  ⟶ *Need to separate the light into its Č, S components*

- For ultimate hadron calorimetry (15%/$\sqrt{E}$): *Measure E_{kin} (neutrons)*
  Is correlated to nuclear binding energy loss (invisible energy)
  Can be measured with third type of fiber : TREAM

Or inferred from the time structure of the signals

Searching for neutrons





100 GeV pions in Tower 11

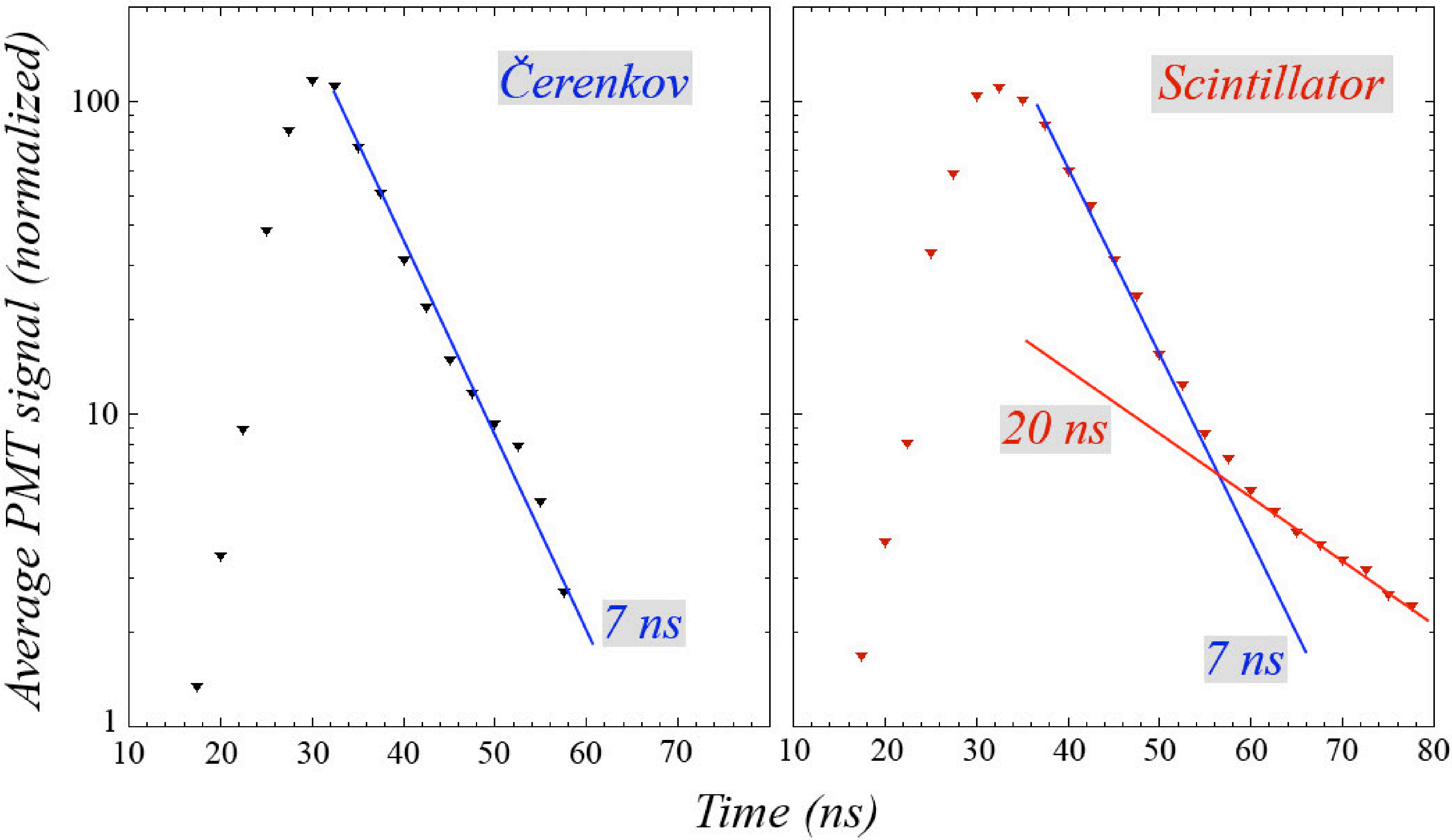
Measure time structure Q,S signals 11/3/1/6

Neutron contribution to calorimeter signals

What to expect?

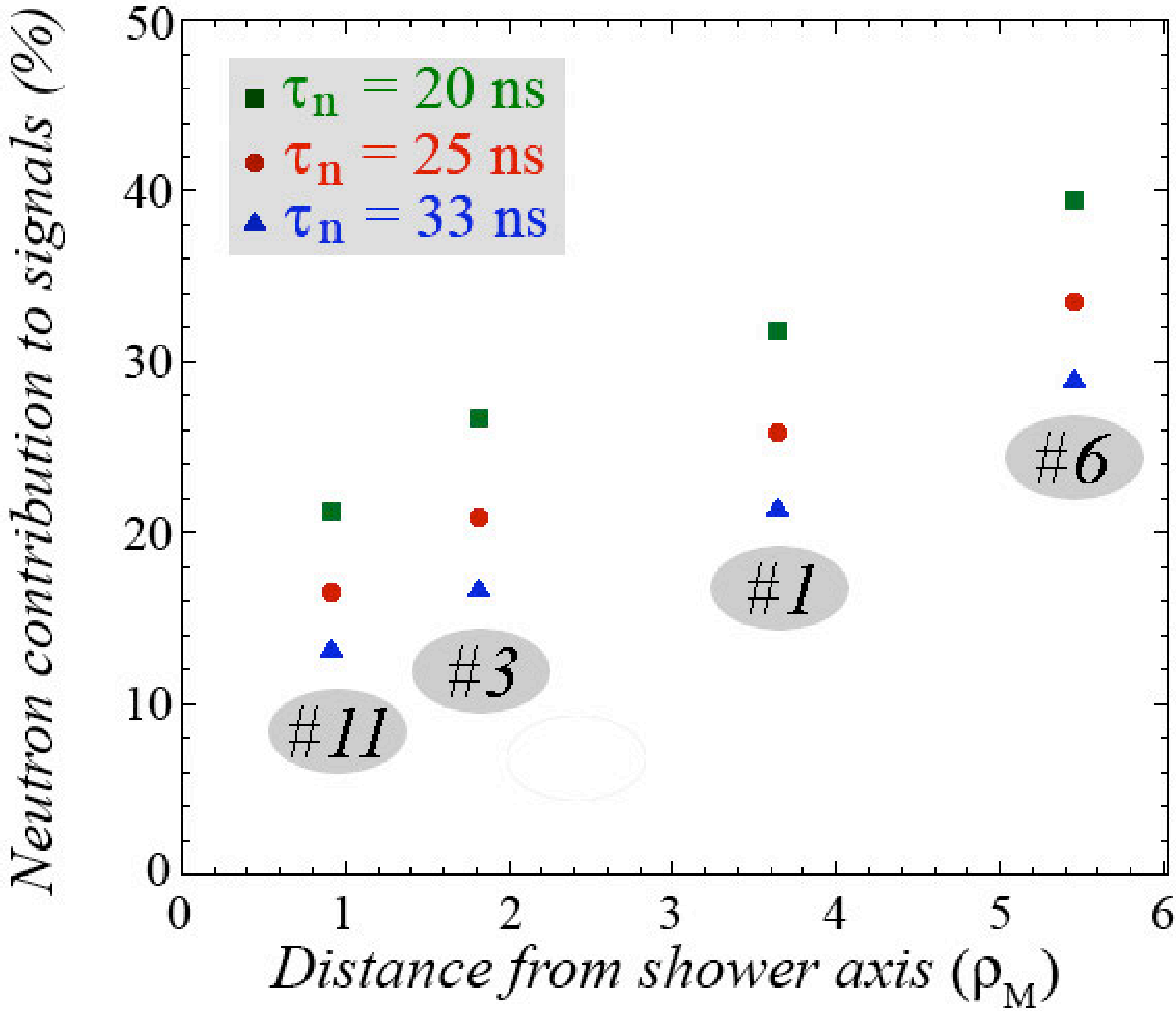
- > 95% of neutrons produced in *nuclear deexcitation*: $\langle E_n \rangle \sim 3$ MeV
- These neutrons lose their energy predominantly through *elastic scattering*
- Energy loss in elastic scattering $\sim A^{-1} \longrightarrow$ *free protons dominate this process*
- Density of free protons in DREAM (plastic fibers): $8 \cdot 10^{21}$ p/cm^3
- Cross section for elastic *n-p* scattering: 2.2 b (3 MeV) $\longrightarrow$ 12 b (0.1 MeV)
- Mean free path between elastic *n-p* scattering events: 56 cm $\longrightarrow$ 10 cm
- Average *time* between subsequent *n-p* scattering events: 23 ns
  (independent of E_n $\longrightarrow$ expect exponential tail in time structure signals)
- Neutrons lose on average *50%* of their kinetic energy in elastic *n-p* scattering
  $\longrightarrow$ *E_{kin} (n) reduced to e^{-1} in 33 ns* if other processes are negligible
- Other processes through which neutrons may lose energy:
  Elastic scattering off C,Si,Cu, inelastic scattering $\longrightarrow$ *expect $\tau_n \sim 25$ ns*

Time structure of the DREAM signals



From:
NIM A581 (2007) 643

Position dependence of the neutron component



Plans for the Future

DREAM road map:

Eliminate the dominating sources of fluctuations one after the other

- Fluctuations in the em shower fraction
- Fluctuations in Čerenkov light yield
- Sampling fluctuations
- Fluctuations in invisible energy

} *Develop dedicated crystal(s)* (applies to: Fluctuations in Čerenkov light yield; Sampling fluctuations)

Then build a full-scale prototype calorimeter

Conclusions

- The DREAM approach combines the advantages of compensating calorimetry with a reasonable amount of design flexibility

- The dominating factors that limited the hadronic resolution of compensating calorimeters (ZEUS, SPACAL) to 30 - 35%/$\sqrt{E}$ can be eliminated

- The theoretical resolution limit for hadron calorimeters (15%/$\sqrt{E}$) seems within reach

- The DREAM project holds the promise of high-quality calorimetry for *all* types of particles, with an instrument that can be calibrated with electrons