

Dual-readout: recent results and possible futures

John Hauptman, 4th
TILC09, 17-22 April 2009
Tsukuba, Japan

Results

- successful use of crystals with fibers
- tests of several crystals
- simulations detailed and OK with data

Possible futures

- crystal results will improve: a cubic-foot module will be tested
- fiber designs will improve: a cubic-meter module will be tested
- both SiD and ILD adopt dual-readout calorimeters

CERN beam test of BGO array with DREAM module behind, surrounded by large scintillators to catch neutrons. A beam of pions, electrons and muons enters from the lower left.



Dual-Readout Calorimetry with a Full-Size BGO Electromagnetic Section

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Submitted to
Nucl. Instrs.
Meths.

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Abstract

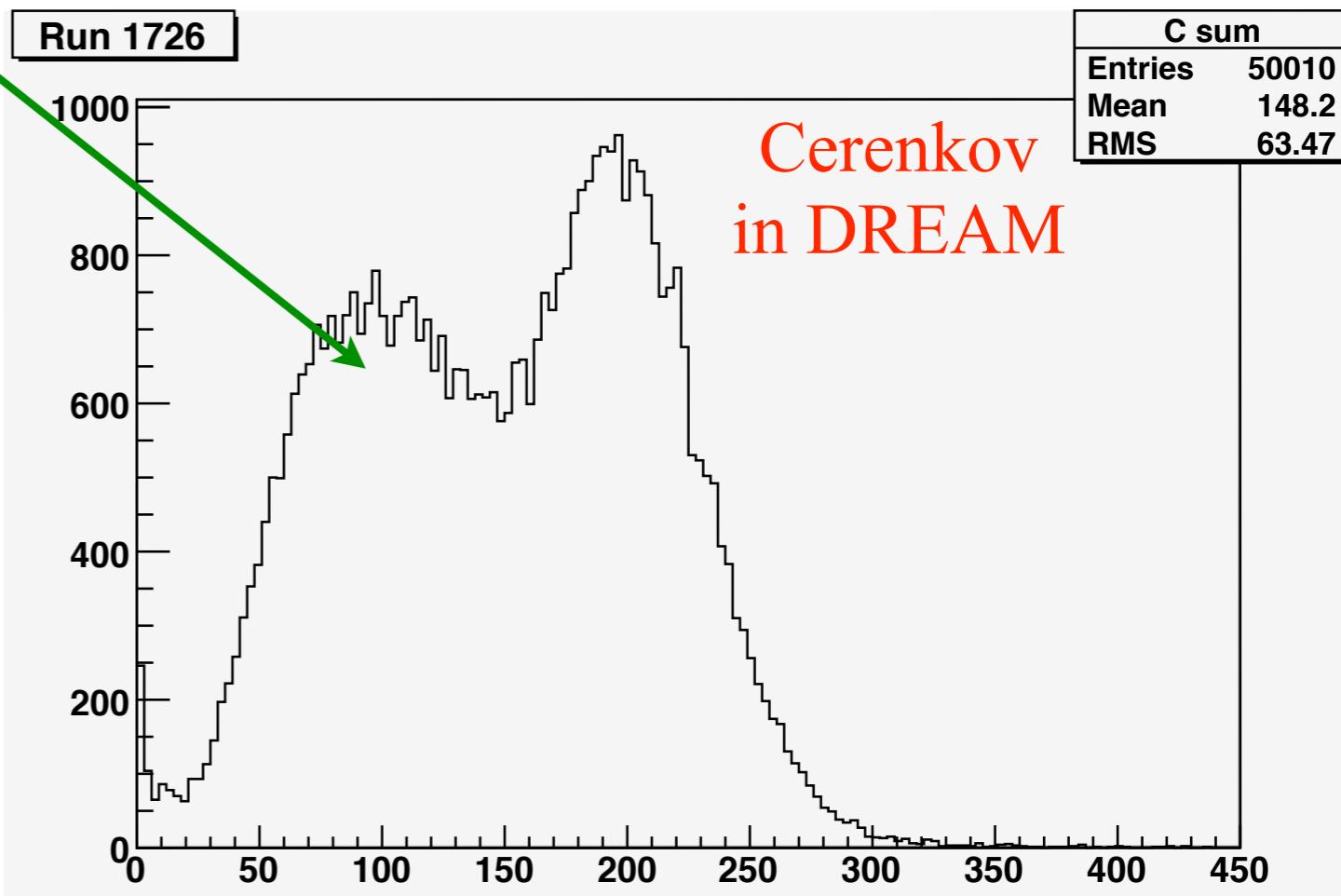
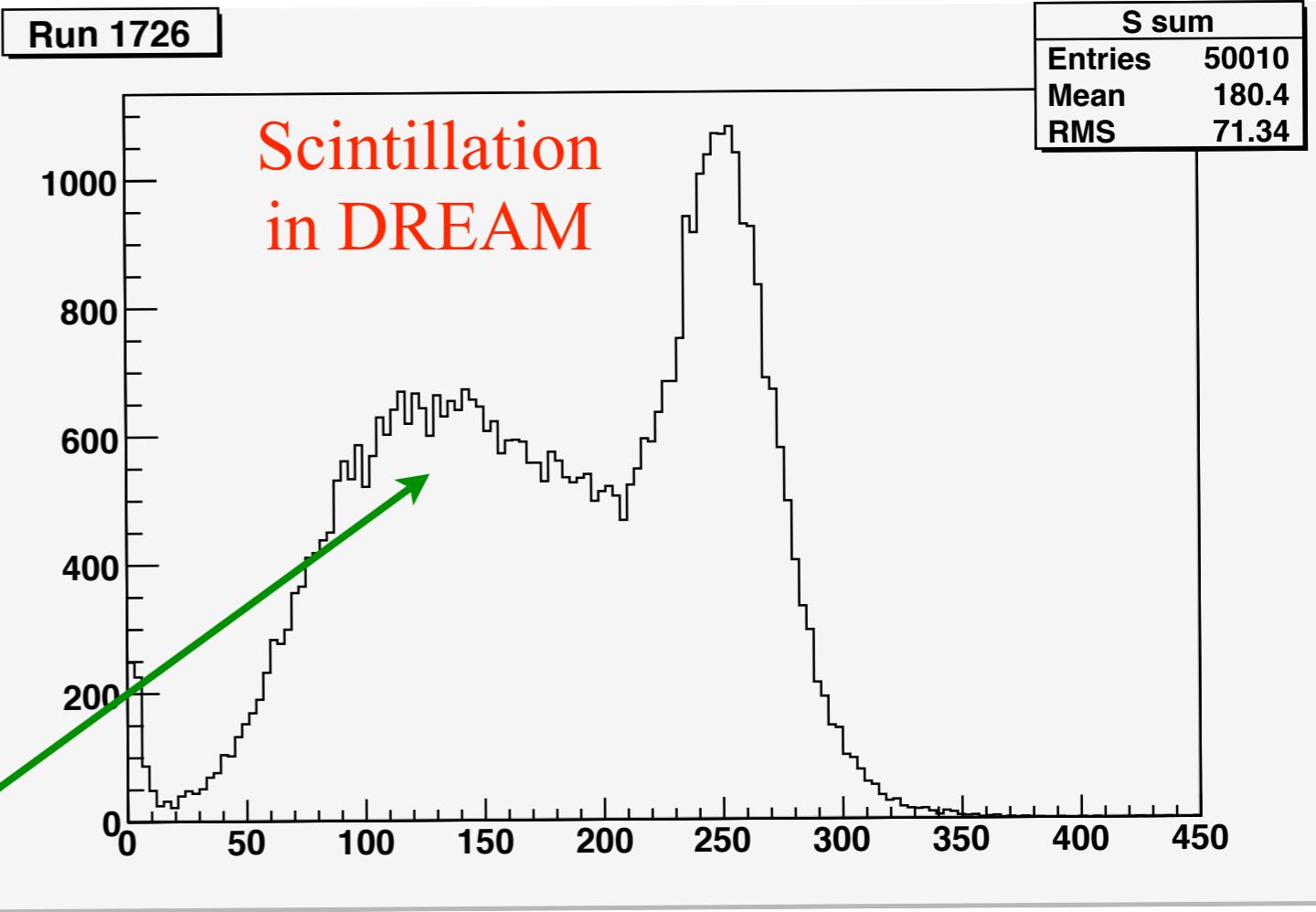
Beam tests of a hybrid dual-readout calorimeter are described. The electromagnetic section of this instrument consists of 100 BGO crystals and the hadronic section is made of copper in which two types of optical fibers are embedded. The electromagnetic fraction of hadronic showers developing in this calorimeter system is determined event by event from the relative amounts of Čerenkov light and scintillation light produced in the shower development. The benefits and limitations of this detector system for the detection of showers induced by single hadrons and by multiparticle jets are investigated. Effects of side leakage on the detector performance are also studied.

PACS: 29.40.Ka, 29.40.Mc, 29.40.Vj

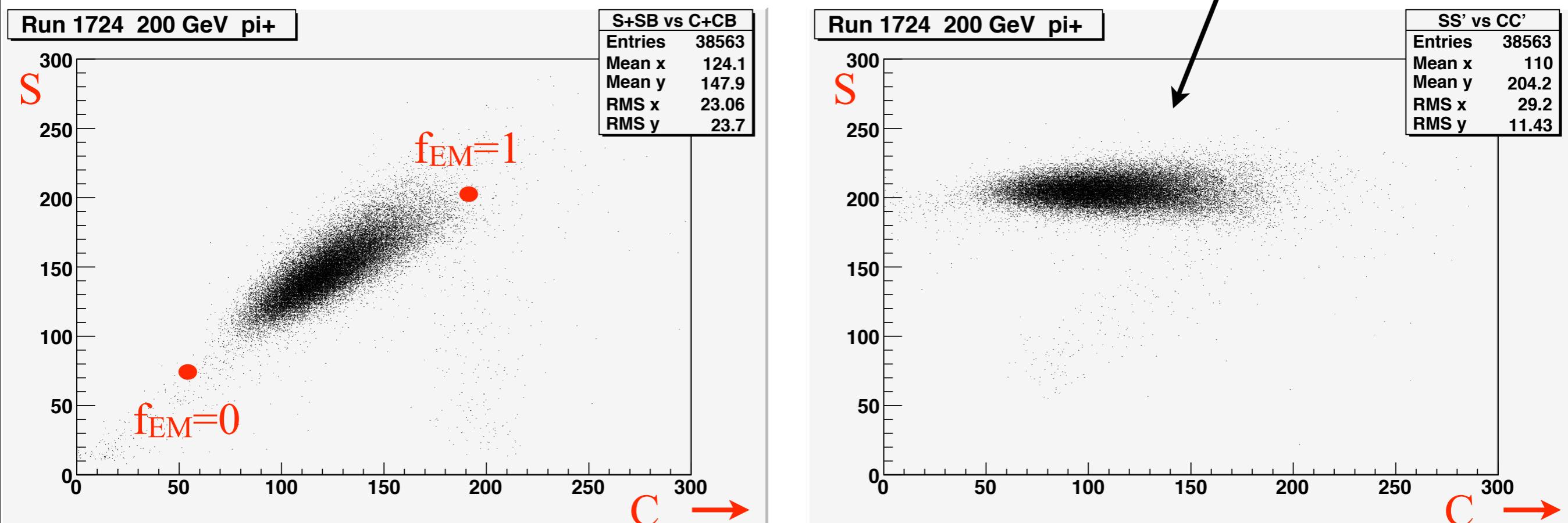
Key words: Calorimetry, Čerenkov light, crystals, optical fibers

The **BGO+DREAM** calorimeter is a complicated beast. In my opinion, we can still do better with the analysis.

Pion interacted in BGO



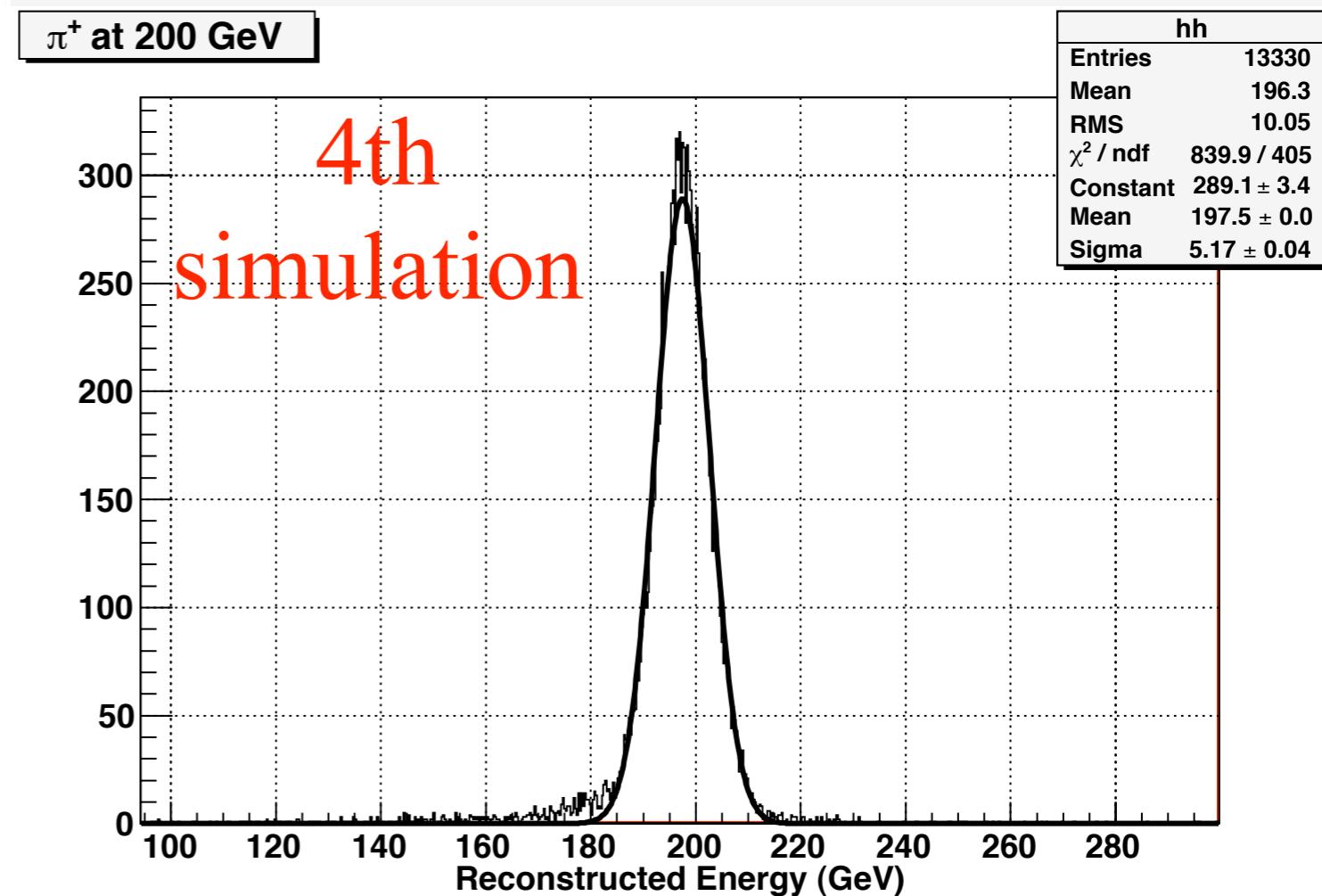
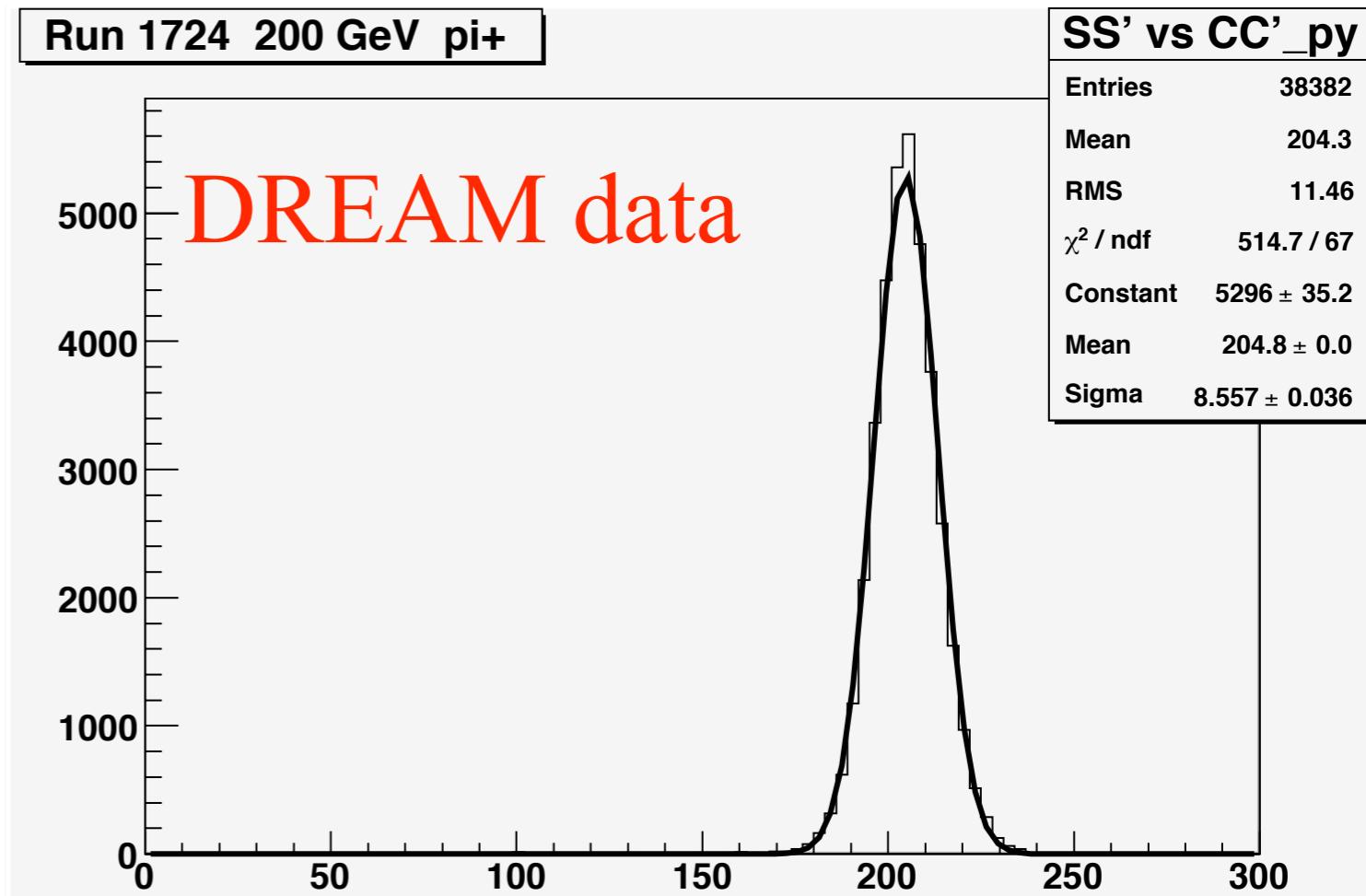
Dual-readout in the BGO+DREAM configuration for 200 GeV pi+. Measuring C allows a simple rotation of this figure, which achieves “compensation”.



This BGO+DREAM configuration caused us months of grief: to be frank, I do not understand why it works so well when we use (S+S_{BGO}) and (C+C_{BGO}). I suspect we have more to learn (and more to gain).

BGO+fiber calorimeter: DREAM data and 4th simulation

Note the rare occurrence here of the data being “cleaner” than the simulation: no tails, no background. This is because the DREAM module is simple (e.g., uniform fiber density) and we had good control of the beam quality, whereas the simulation is fiber-for-fiber exact with slight non-uniform fiber densities at the boundaries of the modules.

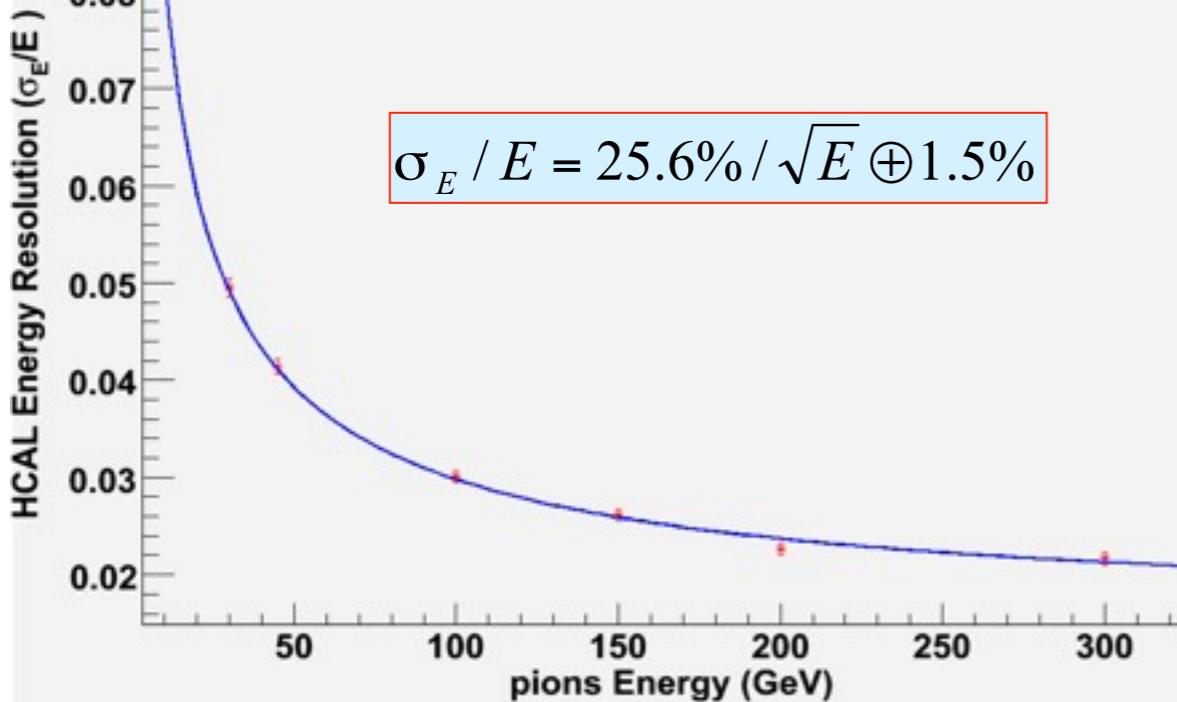


4th dual-readout simulation performance up to 1 TeV

Single π

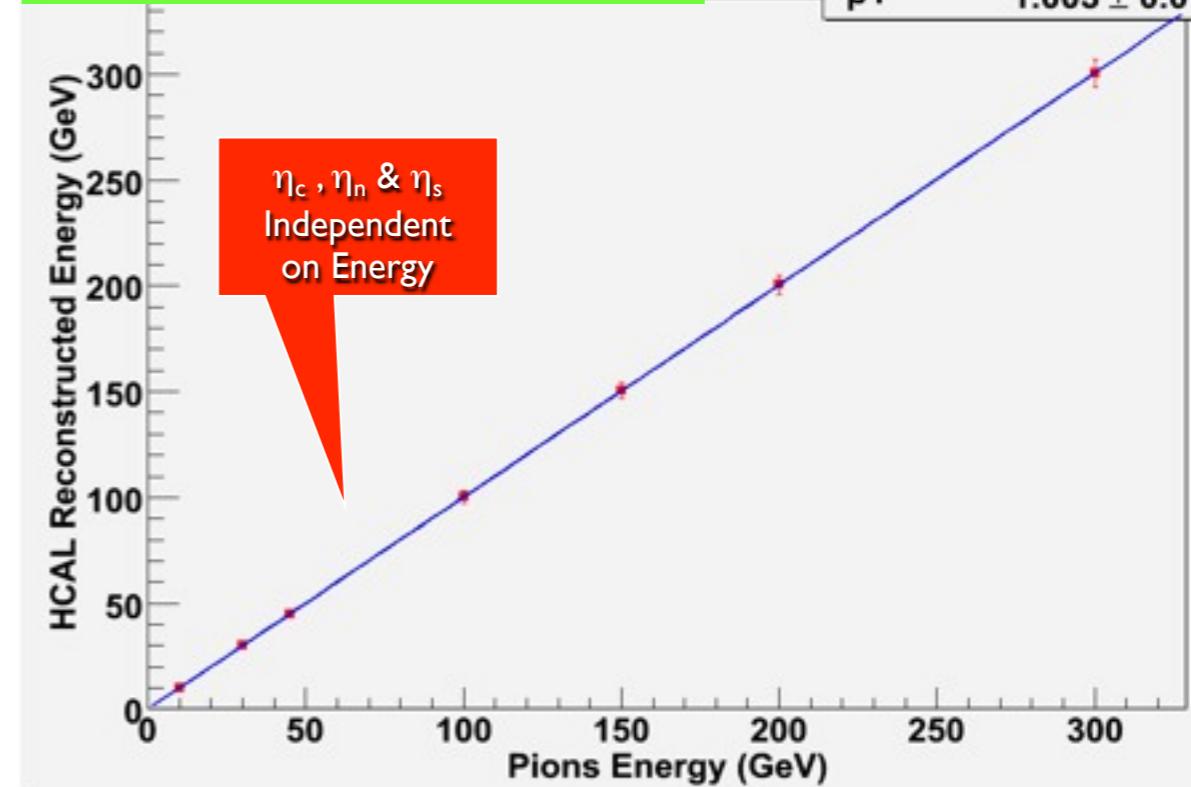
χ^2 / ndf 4.178 / 5
 p0 0.2558 ± 0.003636
 p1 0.01534 ± 0.0006835

$$\sigma_E / E = 25.6\% / \sqrt{E} \oplus 1.5\%$$



Single π

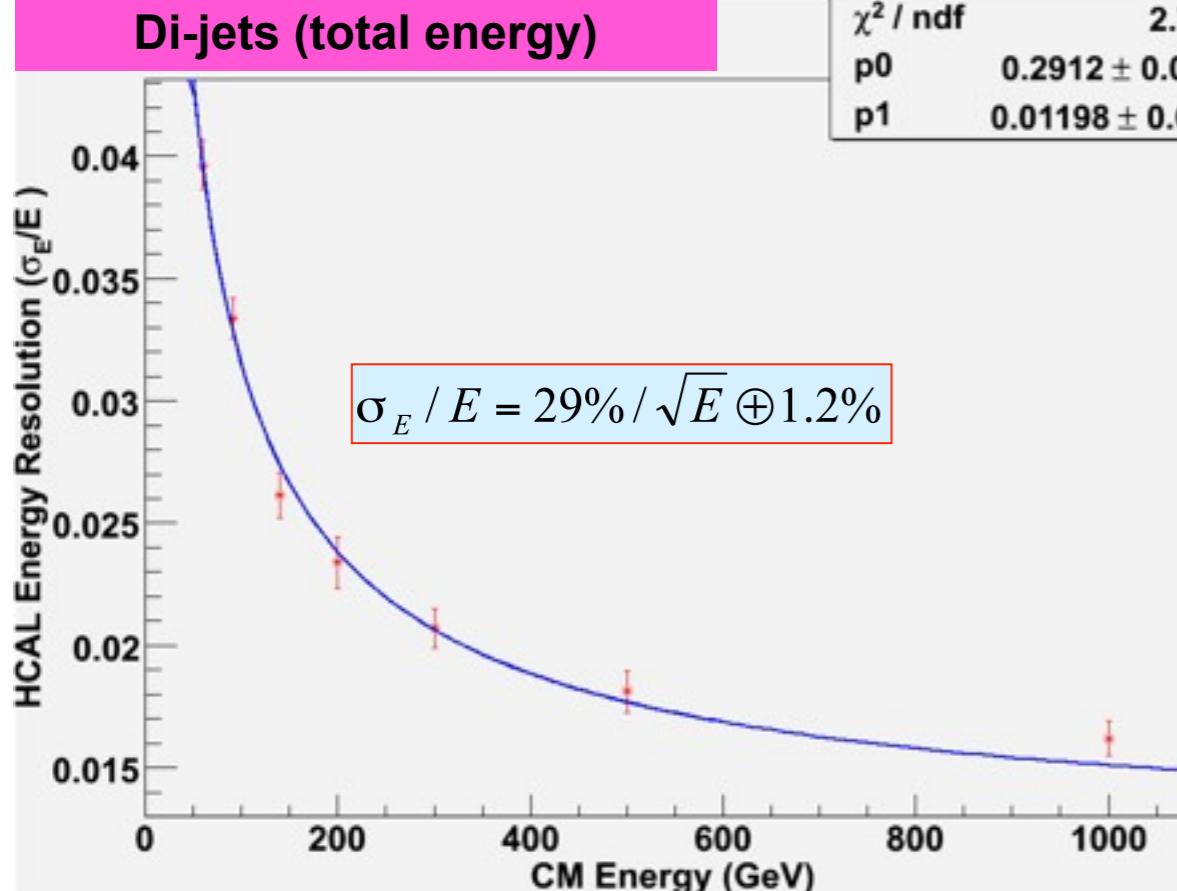
p0 -0.02298 ± 0.7674
 p1 1.003 ± 0.01377



Di-jets (total energy)

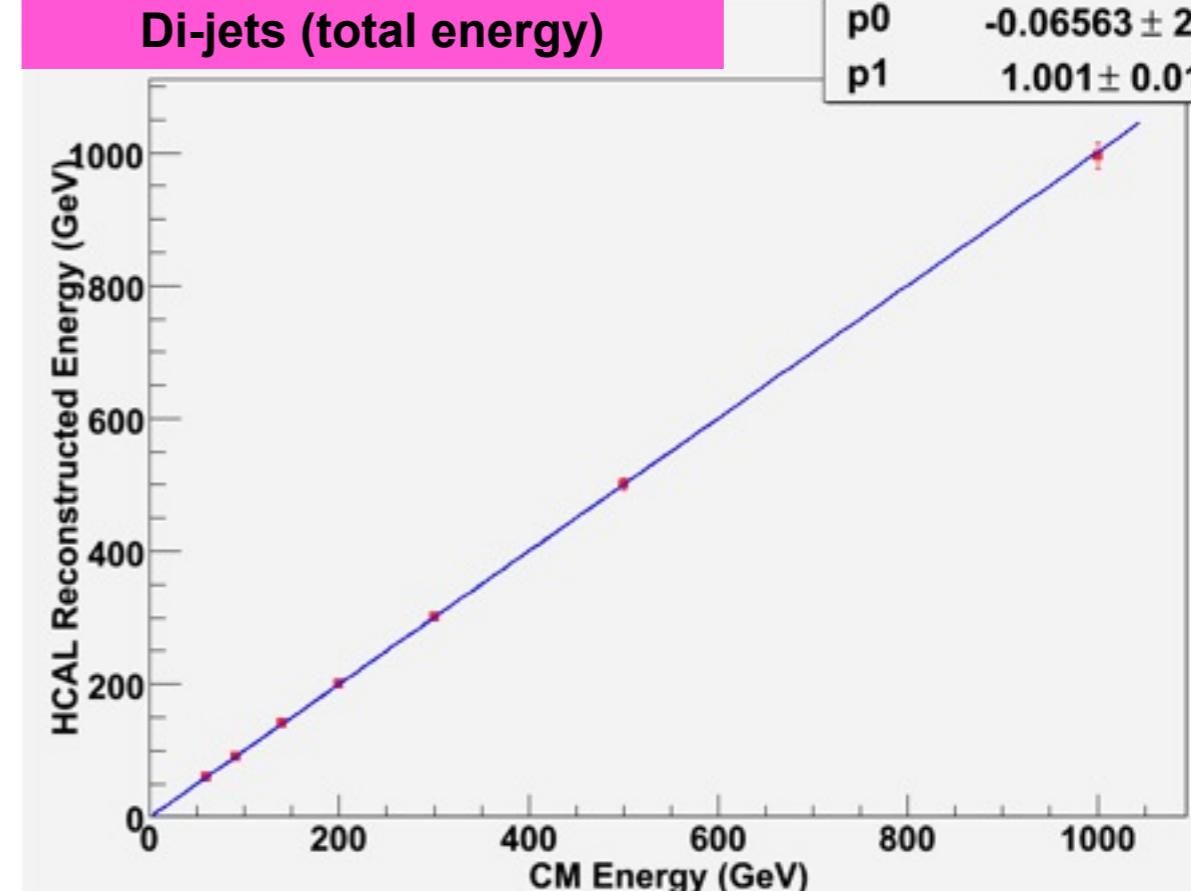
χ^2 / ndf 2.778 / 4
 p0 0.2912 ± 0.007816
 p1 0.01198 ± 0.001191

$$\sigma_E / E = 29\% / \sqrt{E} \oplus 1.2\%$$



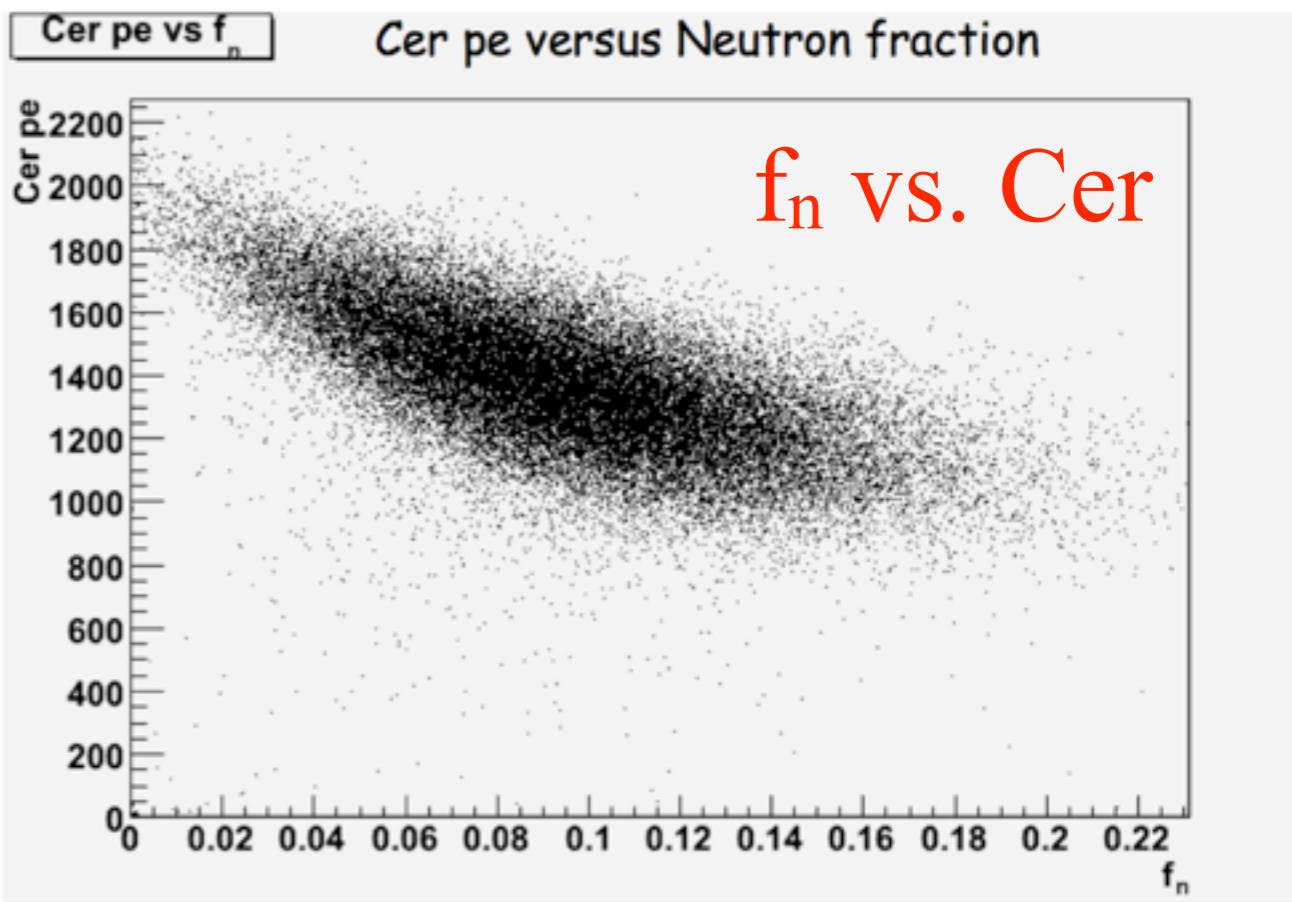
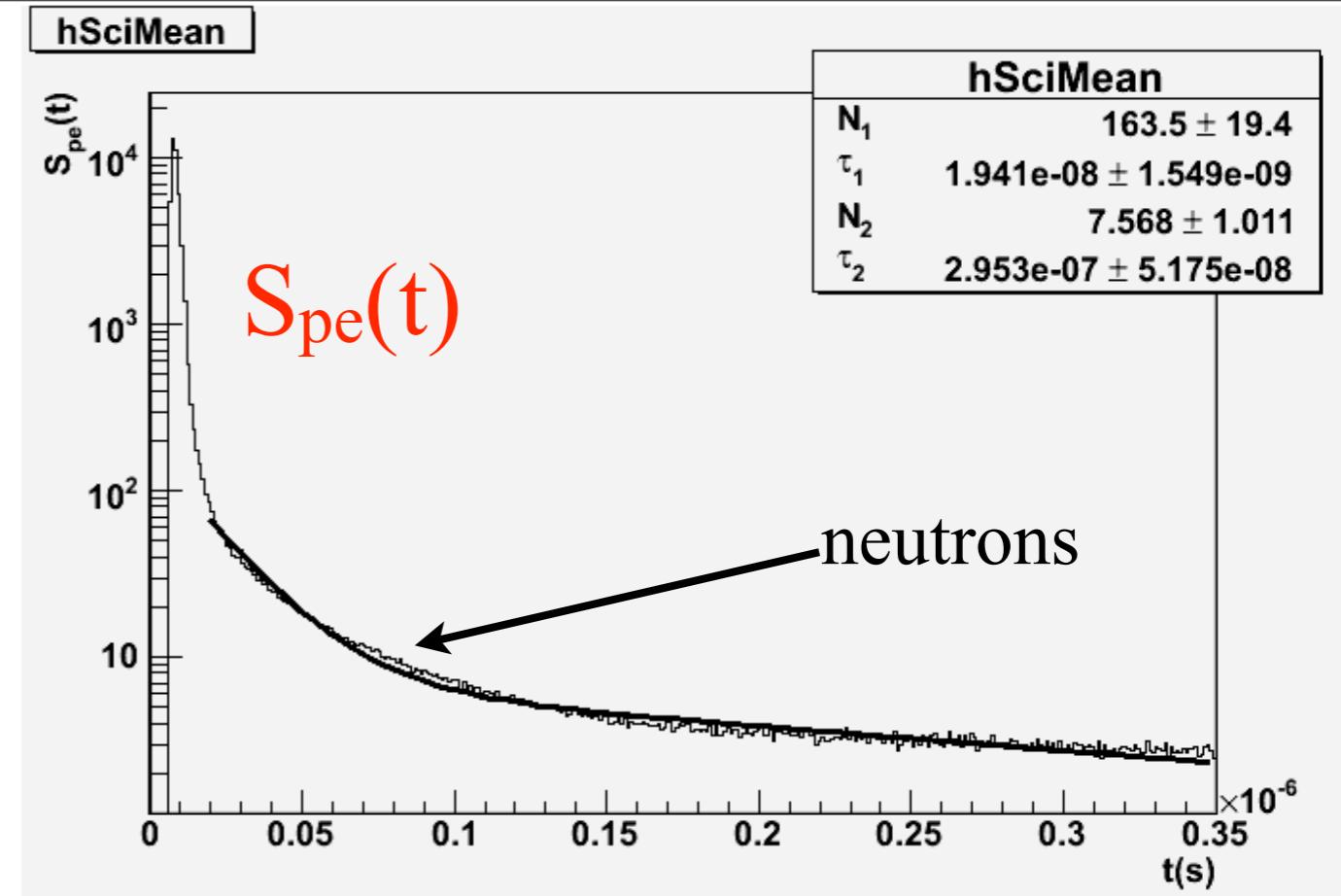
Di-jets (total energy)

p0 -0.06563 ± 2.513
 p1 1.001 ± 0.01656



Neutron detection in 4th simulation

I find good agreement,
considering wide differences
between 4th and the small
DREAM module

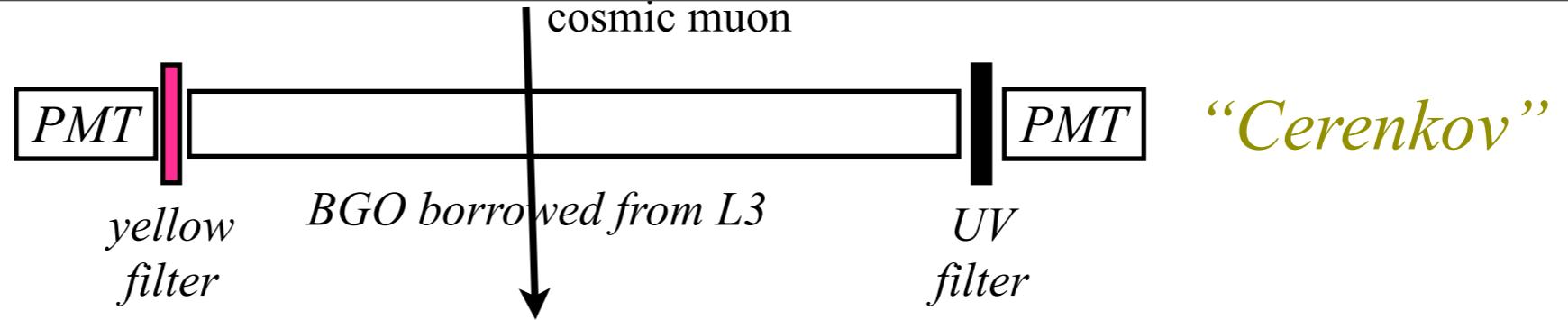


Crystals as dual-readout media

The DREAM collaboration has tested several crystals as dual-readout media, and all can be made to work (good reference: Silvia Franchino talk at TIPP09):

- PbWO₄ is hard (“too fast, too blue, and too luminous”)
- PbWO₄:Pr is OK, but too slow
- PbWO₄:Mo is OK, but too much attenuation
- BGO is easy, and it is in 4th design (although we want a less expensive replacement, e.g., BSO)
- We are thinking of many more crystals (better doped PbWO₄, doped PbF₂, etc.)

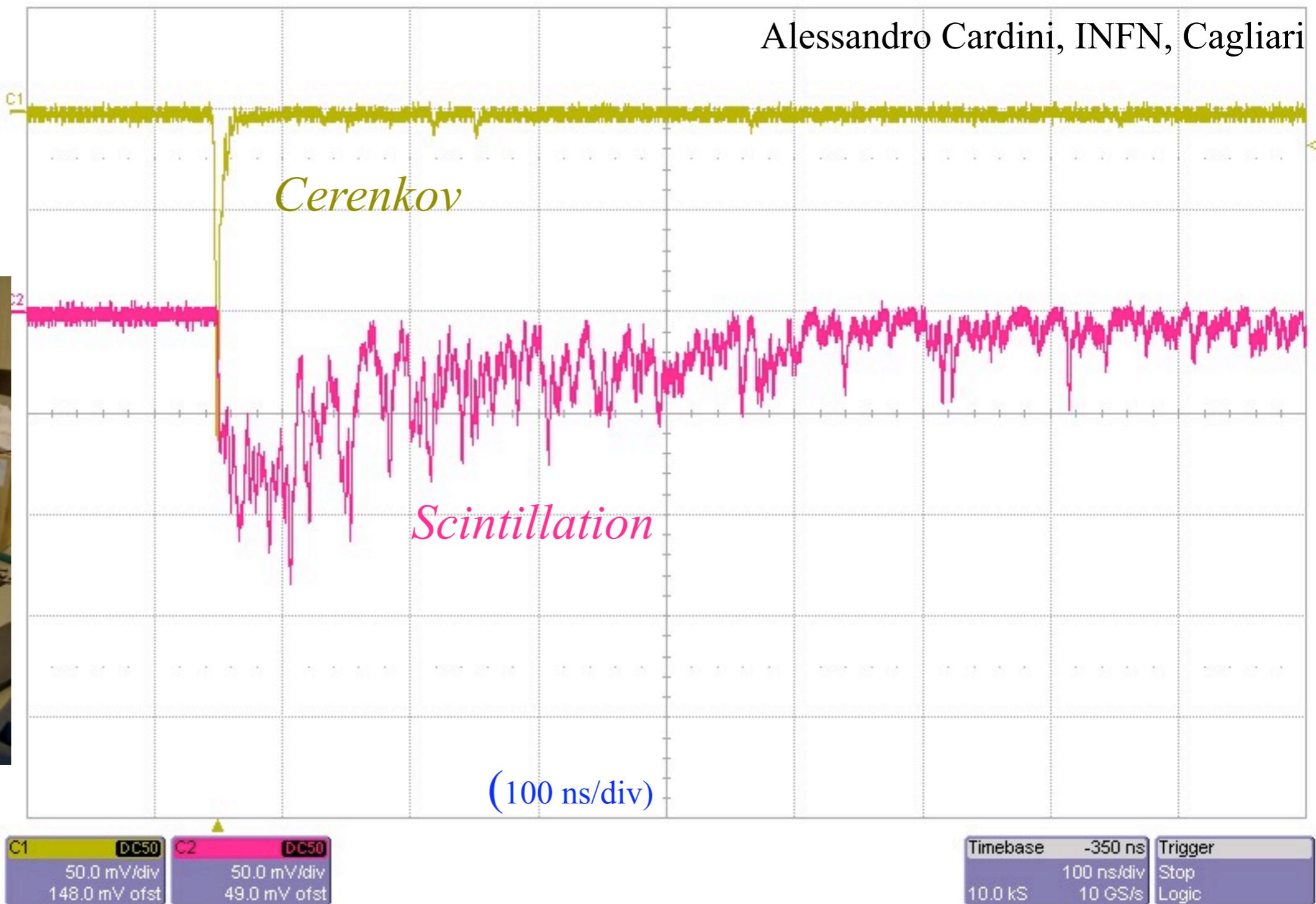
“Scintillation”



BGO ...
by time and
wavelength



Alessandro Cardini, INFN, Cagliari

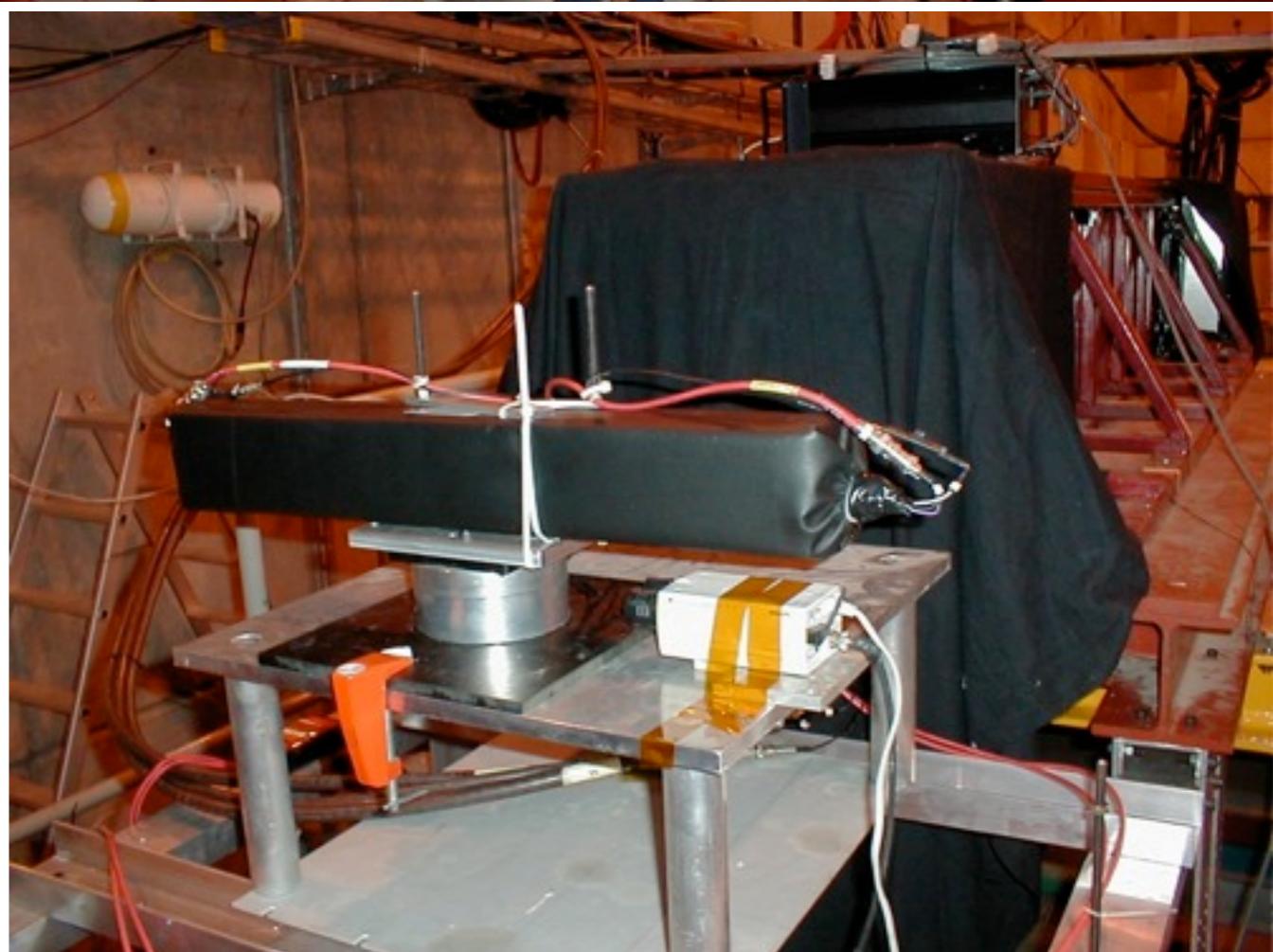
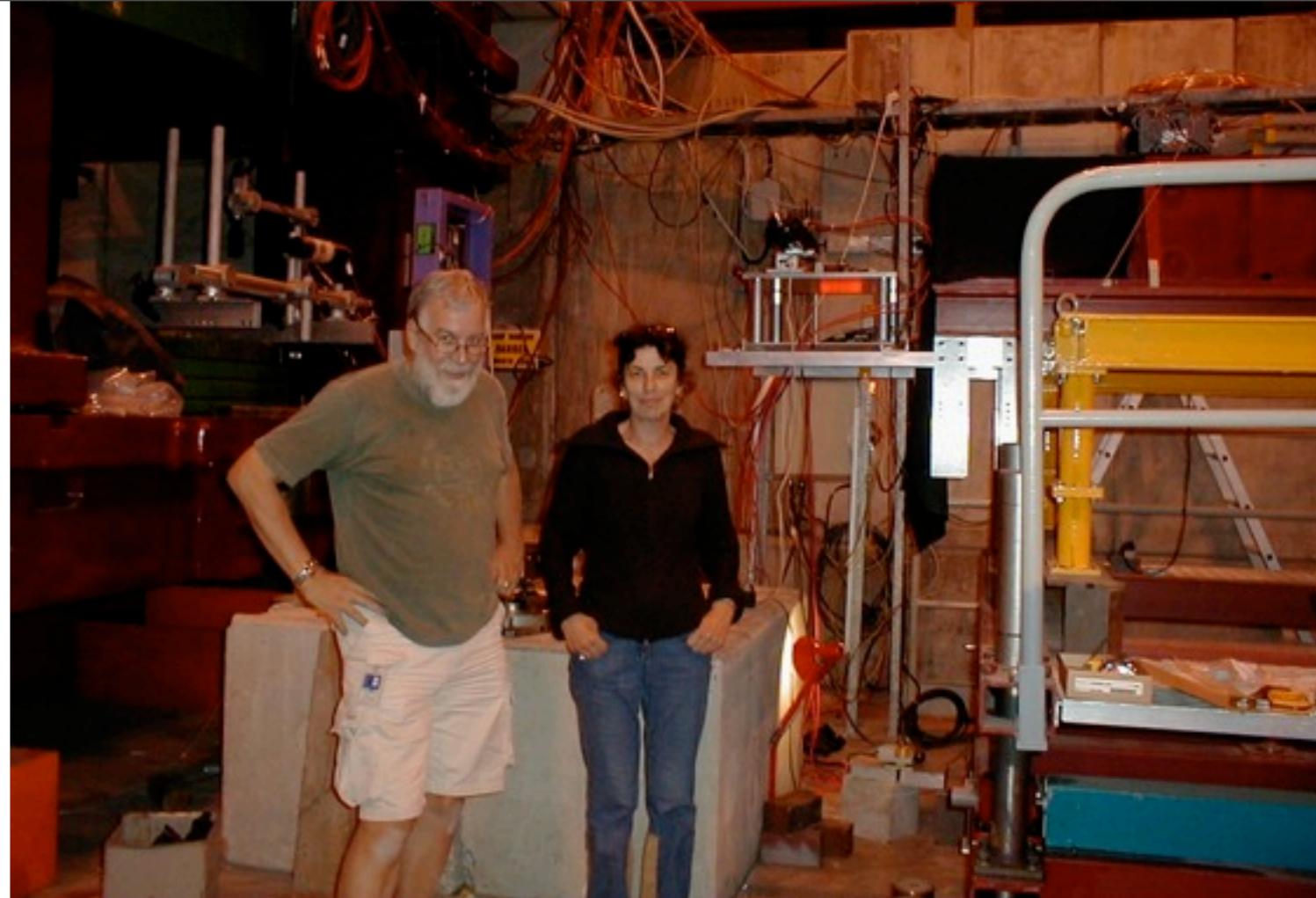


We can now do dual-readout in a single crystal ==> EM precision

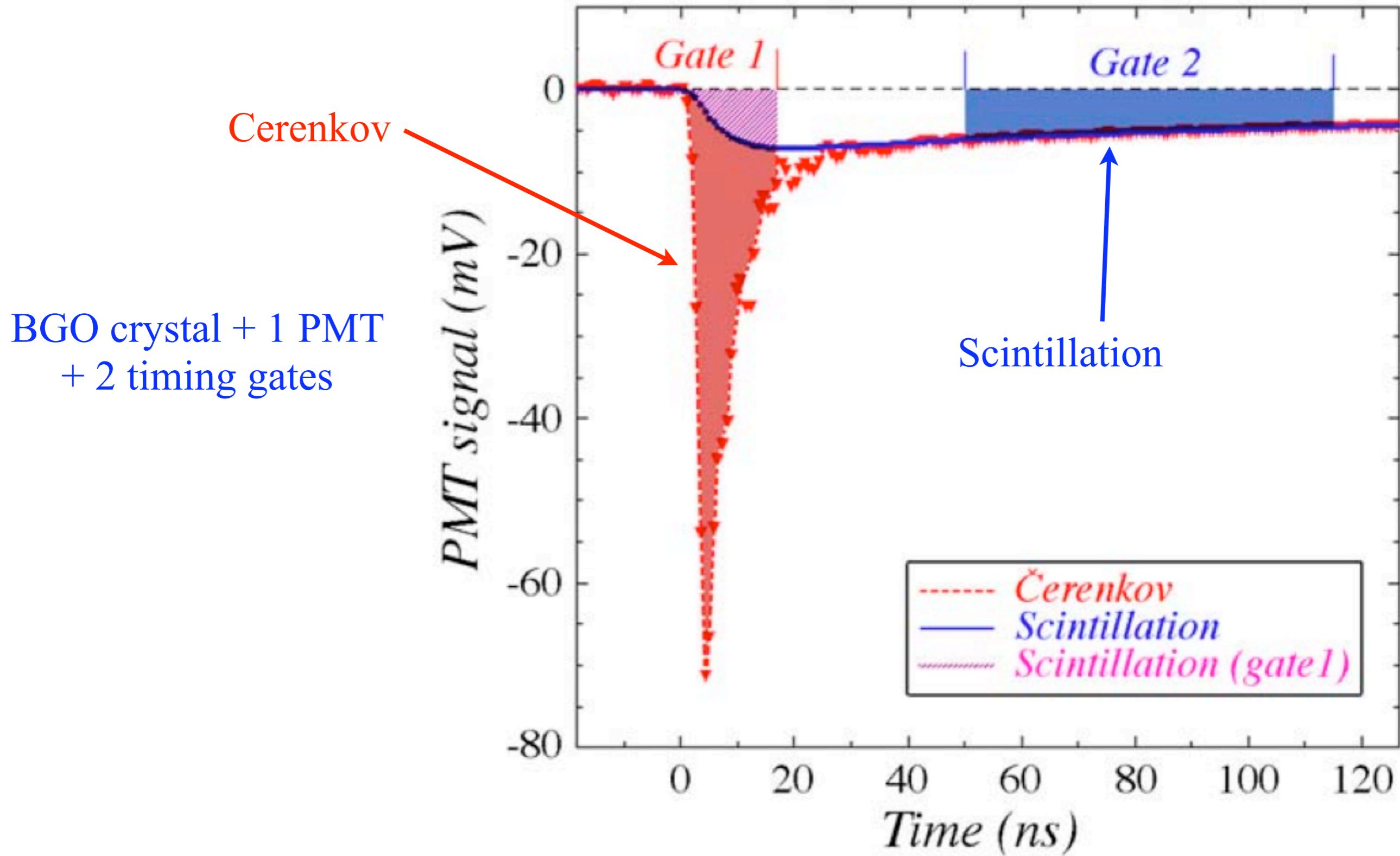
Dual-readout of BGO crystals



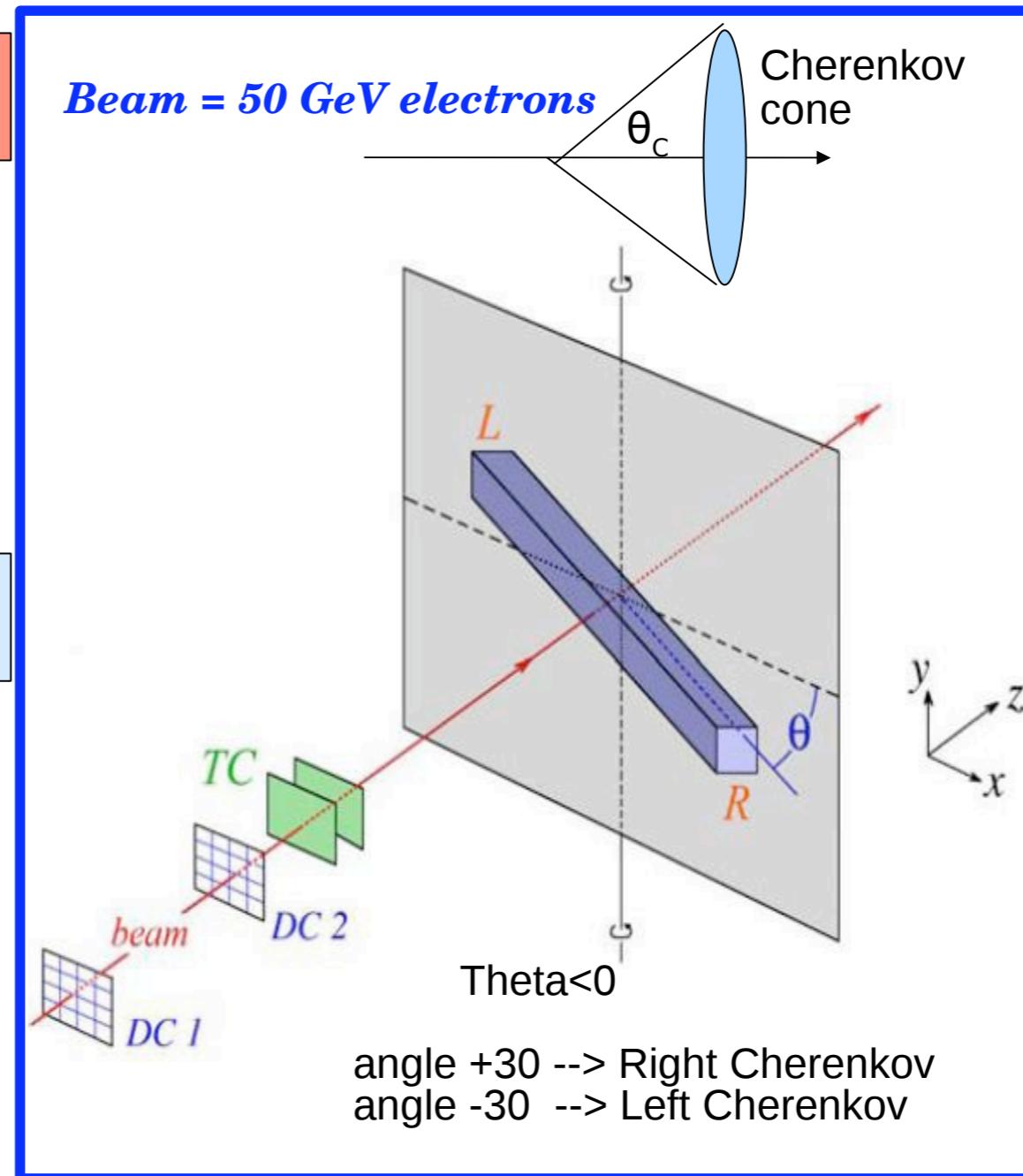
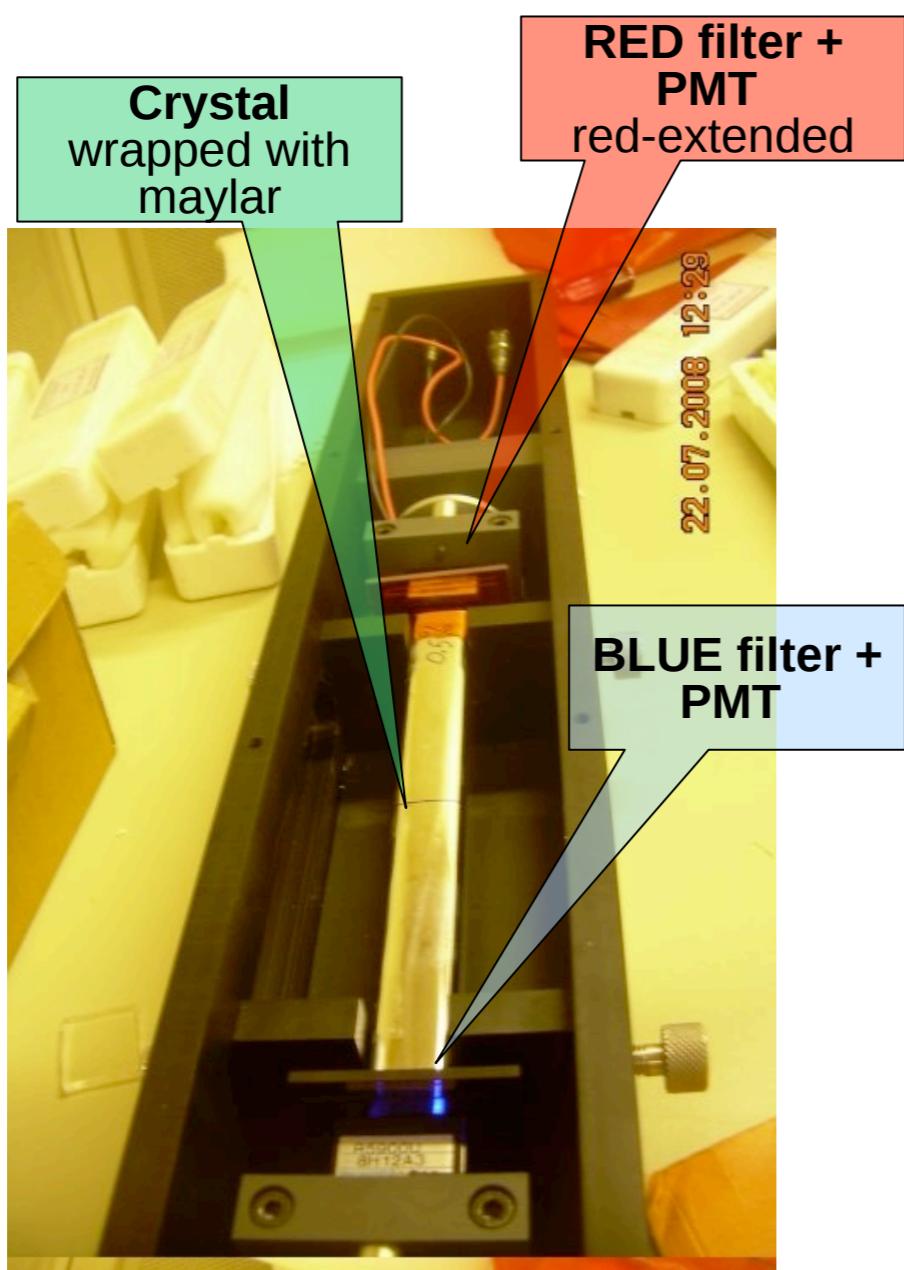
BGO crystal, its housing, and in the beam in front of DREAM module



BGO crystals are easy by two different techniques:



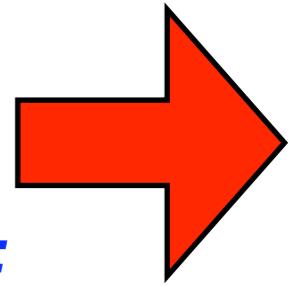
2008 Test beam, single crystal



Silvia Franchino INFN Pavia- Italy TIPPO9- March 13 2009

DREAM with homogeneous materials?

- >> Increase the number of Cherenkov photoelectrons
- >> Improve performances on em showers.



3 ways for Separation of Scintillation & Cherenkov light :

- **1) Time structure of the signal**

*Signals read by fast electronic
and separated offline
event by event*

	Cherenkov	Scintillation
Time response	Prompt	Exponential decay
Light Spectrum	$\propto 1/\lambda^2$	Peak
Directionality	Cone: $\cos \theta_c = 1/\beta n$	Isotropic

- **2) Spectral difference**

*Crystal equipped with 2 different optical filters,
high-pass frequencies for Cherenkov, low pass for scintillation*

- **3) Directionality of Cherenkov component**

(not reliable for 4π calorimeter, used just to prove the existence of C light on the crystal)

Crystal rotated wrt the beam and signals acquired in both ends

Why to dope PbWO₄ crystals?

BGO compared to PbWO₄:

Crystal	LightYield % NaI(Tl)	Decay Time (ns)	Peak wavel.(nm)	Cutoff wavel.(nm)	Refr. Index	Density (g/cm ³)
BGO	20	300	480	320	2.15	7.13
PWO	0.3	10	420	350	2.30	8.28

Disadvantages: Much brighter --> Cherenkov is a rare process --> C/S factor 100 smaller

Advantages: --> S spectrum peak at 480 nm --> allows the use of filters

--> S decay time 300 ns (very different from prompt C signal)

New Doped Crystals: to combine the advantages of BGO with the much higher C fraction of PbWO₄



- 1) **Move the scintillation wave length peak**
in order to separate C and S through **emission spectrum**
- 2) **Increase the decay time**
in order to separate C and S through the **time structure**

We have tested PbWO₄ crystals doped with*

Molybdenum (1%, 5%)
Praseodymium (0.5%, 1%, 1.5%)

(*) Thanks to our crystal experts from Milano-Bicocca University (Italy), Institute of Physics Prague (Czech Rep), Institute for Nuclear Problems Minsk Belarus

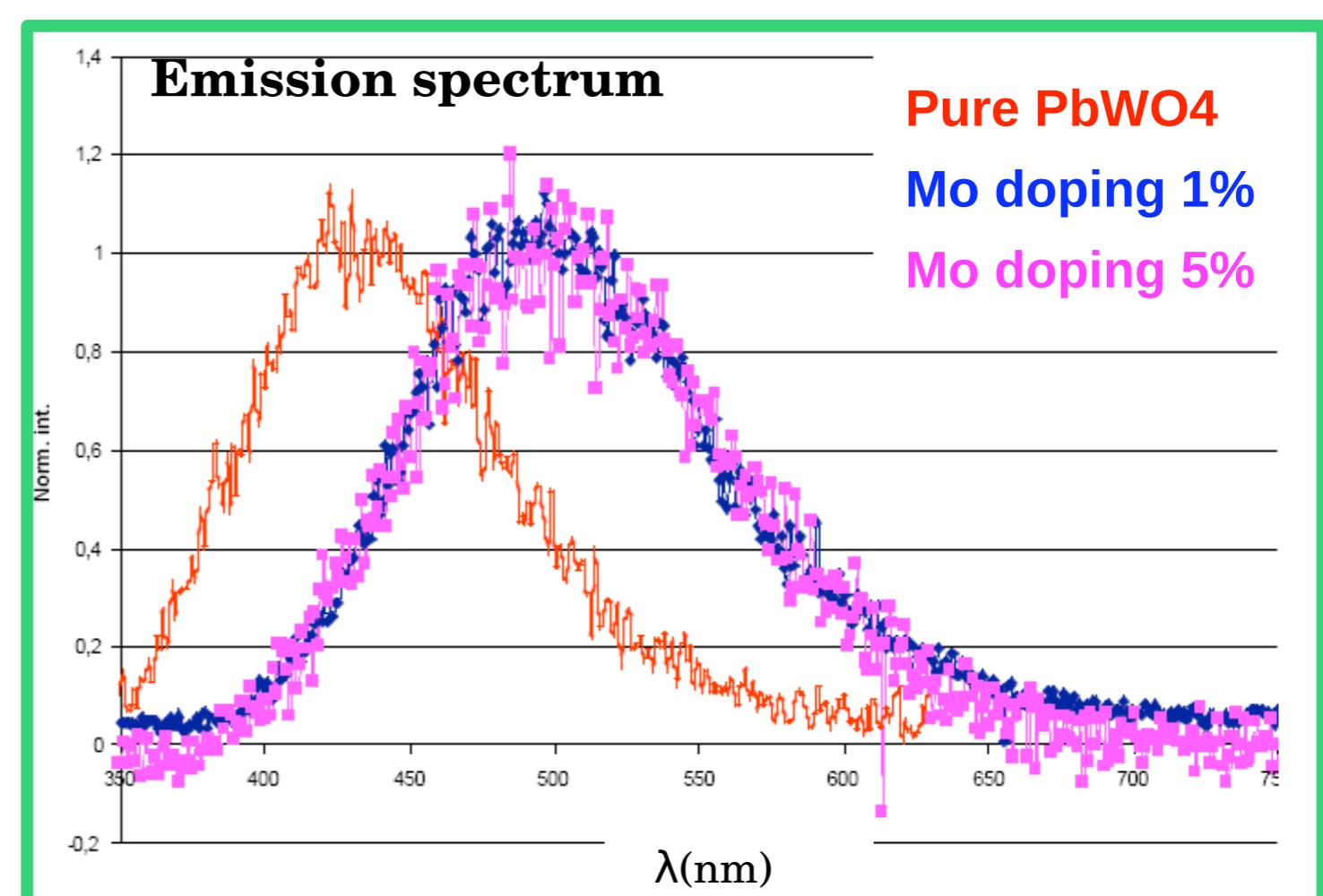
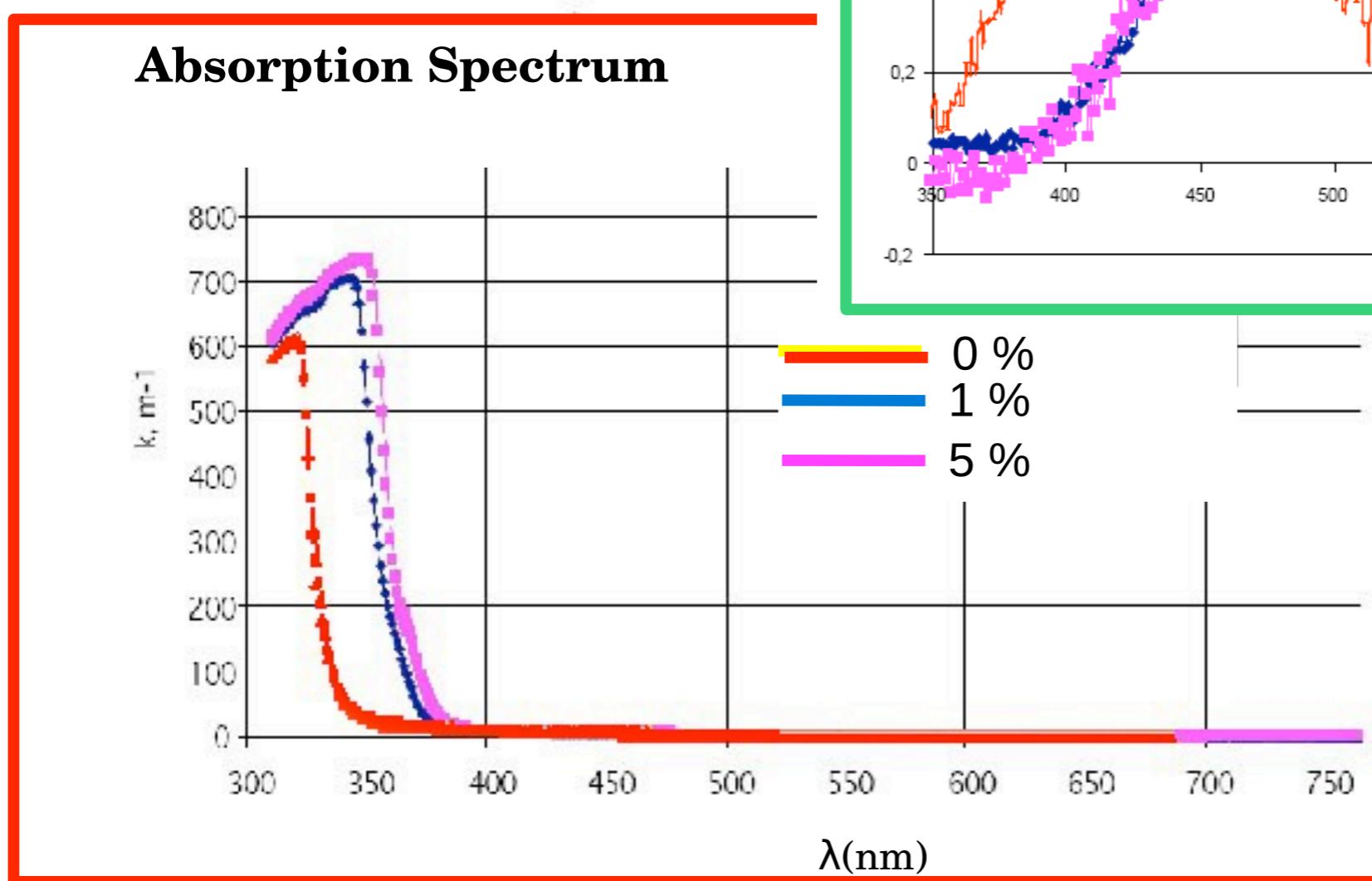
Doping with Molybdenum (1%, 5%)



Radioluminescence measurements

---> shift of scintillation emission spectra to higher λ

--> lengthen scintillation decay time (50ns)



--> shift the absorption spectrum

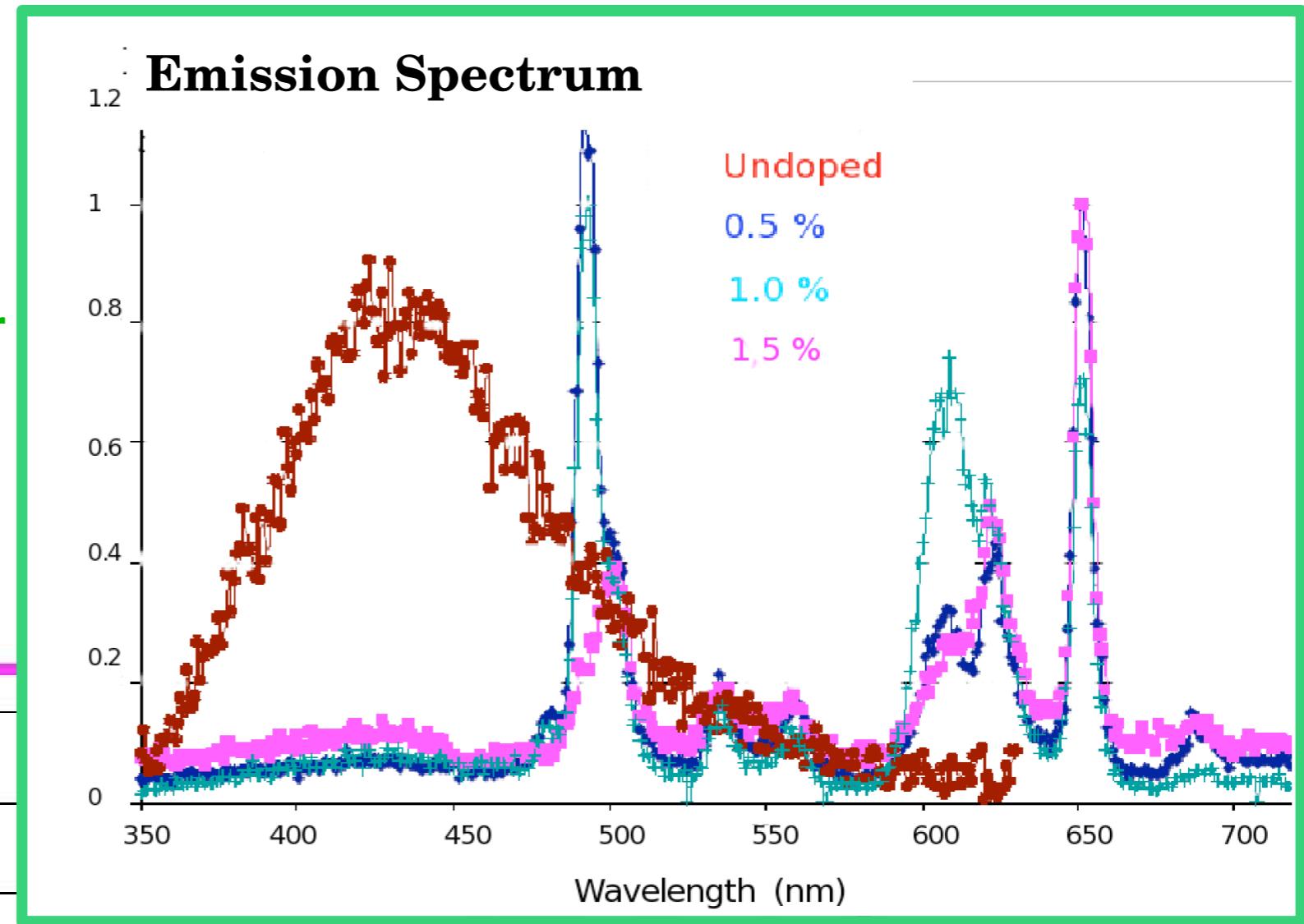
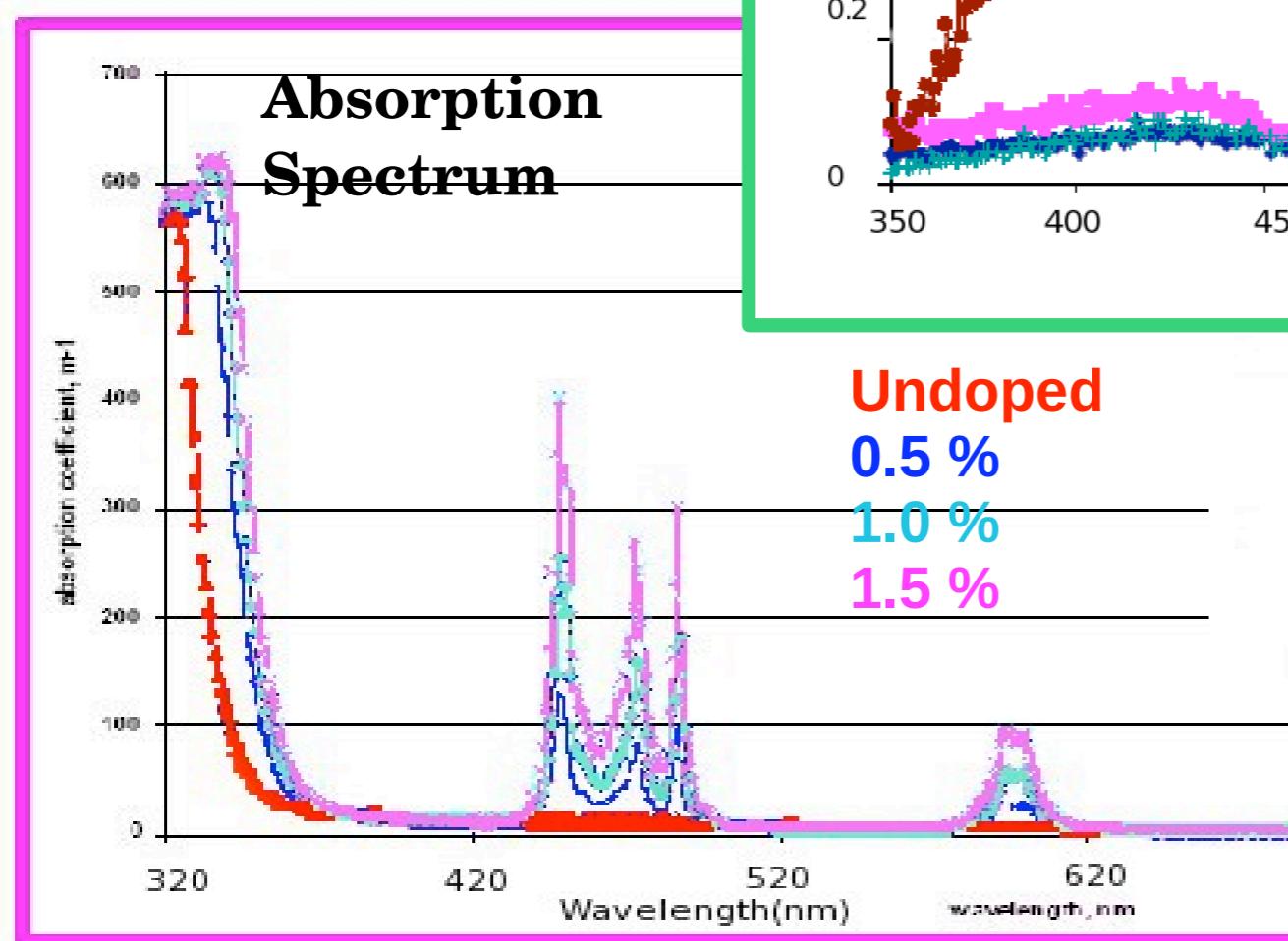
Doping with Praseodymium (0.5%, 1%, 1.5%)



Radioluminescence measurements

---> shift of scintillation emission spectra to higher (many different red-peaks)

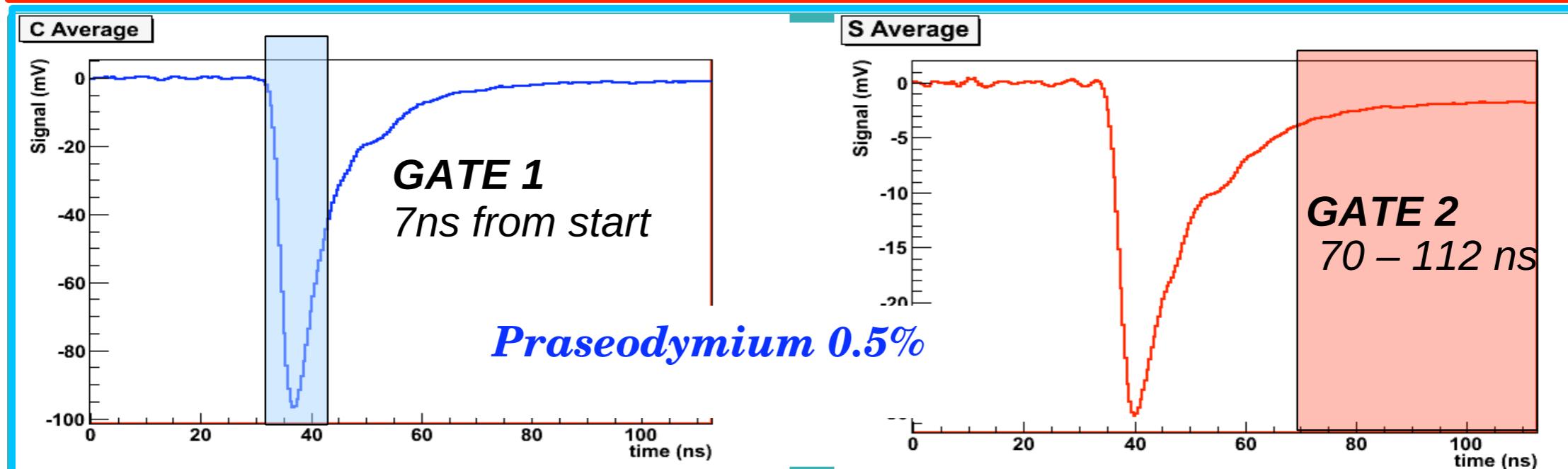
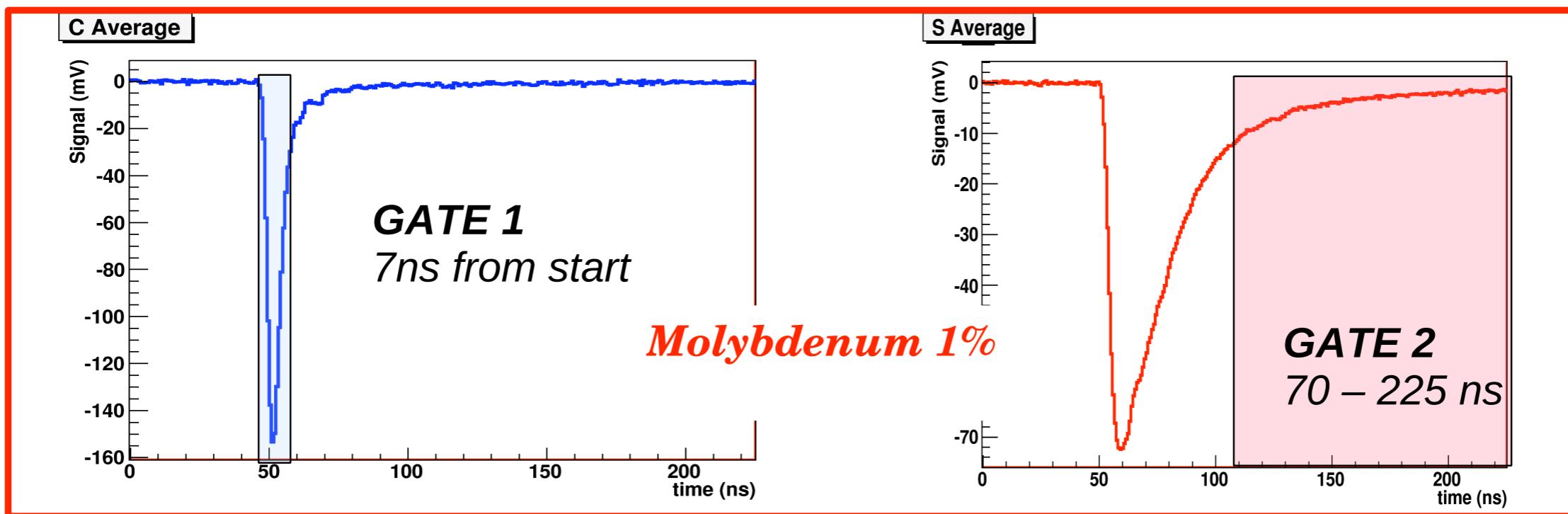
--> shift the absorption spectrum



--> lengthen scintillation decay time
(too much for our purposes... μ s)

Time windows for C, S

The C and S signals are calculated from the integral of time spectra over proper windows:
Gate1 for **Cherenkov prompt spectrum** and **Gate2** for **Scintillation slow component**



Conclusions from Test beam 2008

Investigated properties of PbWO_4 crystals doped with small amounts of Mo, Pr to improve the suitability of **Dual Readout Calorimetry** with crystals.

4 aspects are important:

<i>Dual Readout requests</i>	<i>Mo 1%</i>	<i>Pr 0.5%</i>
Separability of C and S components	OK	OK
Time characteristics of S	OK	no
C Self-absorption	no	OK
C Light Yield	no	OK

- 1) **Separability of C and S components:** both Mo, Pr-doped are a large improvement thanks to the shift of emission and hence the use of filters
- 2) **Time Structure of scintillation light:** big difference between 2 dopings.
Mo doped have an ideal decay time (26, 59 ns); Pr-doped have too long component (μs)
- 3) **Self-absorption of C light:** too hight for Mo, OK for Pr doped
- 4) **Light Yield of C light:** small for Mo (8 p.e./GeV as DREAM fib-cal); ok for Pr (44 p.e/ GeV)

- Tested crystals represent an **improvement wrt undoped PbWO_4** ;
- To use them in a real experiment further improvement is needed: **self absorption of Mo decay time Pr**

New Ideas for 2009

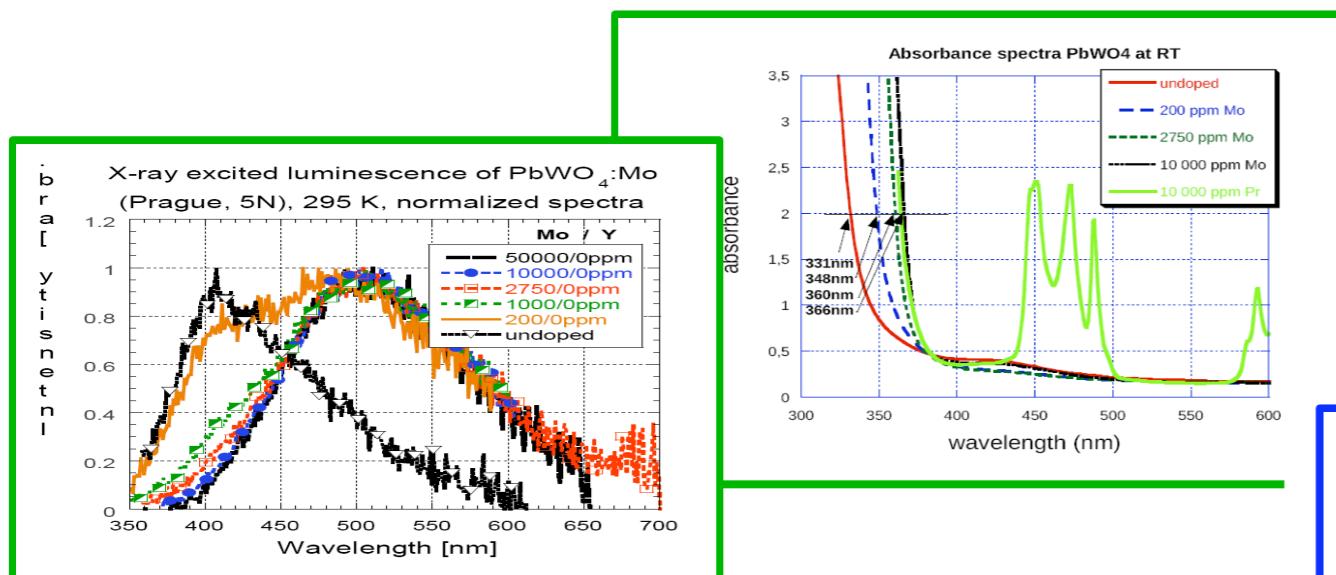
1) **Lowering the concentration of Mo doping** should lower also the absorption wavelength and allow more Cherenkov light through the UV filter and QE of PMT.

2) **Change Cherenkov filter**

(UG11: UV used on 2008,
U330, UG5 seems to be promising)

New Ideas for 2009

1) **Lowering the concentration of Mo doping** should lower also the absorption wavelength and allow more Cherenkov light through the UV filter and QE of PMT.



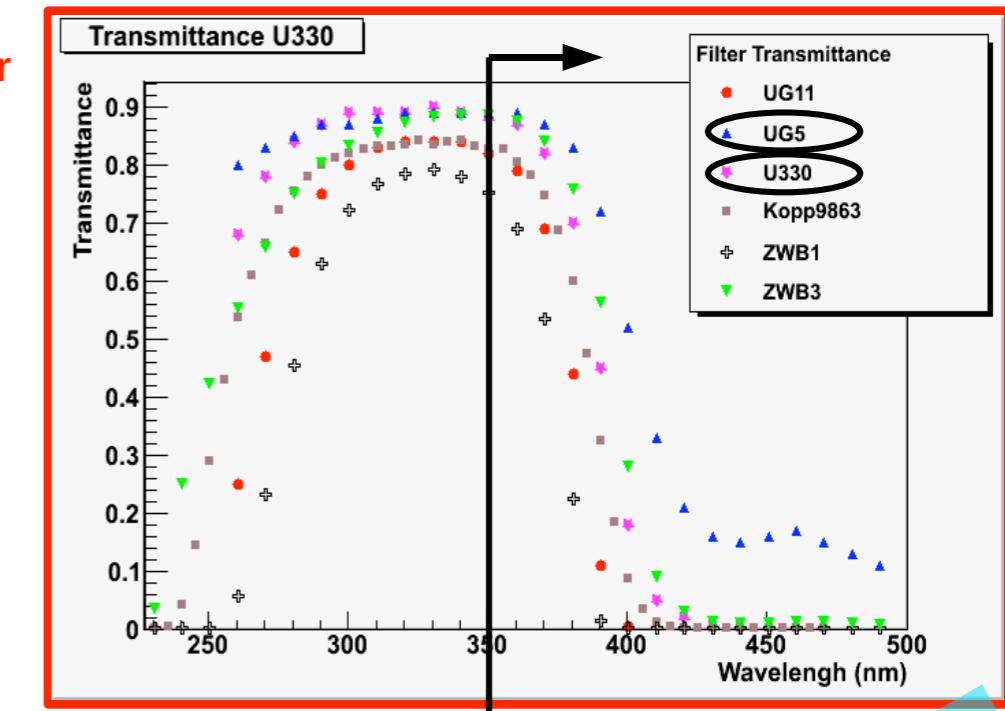
We are now measuring in Milano the absorption and emission spectra of PbWO₄ doped with:

Molybdenum 0.1%, 0.2%, 0.3%
1% Mo + 50 ppm Y

Prelimi
nary

29/32

Silvia Franchino INFN Pavia- Italy TIPP09- 1



New Crystals for Dual-Readout Calorimetry

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Accepted for publication by NIM

THE END !!!

Possible futures

1. Very little funding has gone into dual-readout calorimetry, but that is OK since it is simple to do; now is the time for a large module **now that the fundamentals are understood.**
2. The main parameters of several crystals are now known, although some “tweaking” is needed.
3. **New crystals will be developed**, this is clear, although not predictable in details.
4. A suitably inexpensive dual-readout crystal may be developed, in which case a cubic-meter crystal calorimeter may be built, although **it will not be a good idea.**