Crystals in extreme environments

ETH Institute for Particle Physics

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Focus on crystal calorimeters in HEP detector environments:

- ➪ High ionizing radiation levels
  - ♦ Thoroughly studied, mainly since used for e+e- collider experiments
  - ♦ Growth technology optimized for best performance
  - ♦ Main characteristics briefly summarized
- ➪ High hadron fluxes
  - ♦ Present concern, mainly since chosen for hadron collider experiments
  - ♦ Discussion of some new and older results

Crystal characteristics

Review of particle Properties 2004, S. Eidelman et al., Phys. Lett. B592, 1 (2004)

Parameter:	ρ	M P	X_0	R_M	dE/dx	λ_I	τ_{decay}	$\lambda_{\max}$	n^*	Relative output[†]	Hygroscopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%°C[‡]
NaI($T\ell$)	3.67	651	2.59	4.8	4.8	41.4	230	410	1.85	100	yes	~ 0
BGO	7.13	1050	1.12	2.3	9.0	21.8	300	480	2.15	9	no	-1.6
BaF$_2$	4.89	1280	2.06	3.4	6.6	29.9	630^s	300^s	1.50	21^s	no	-2^s
							0.9^f	220^f		2.7^f		$\sim 0^f$
CsI($T\ell$)	4.51	621	1.85	3.5	5.6	37.0	1300	560	1.79	45	slight	0.3
CsI(pure)	4.51	621	1.85	3.5	5.6	37.0	35^s	420^s	1.95	5.6^s	slight	-0.6
							6^f	310^f		2.3^f		
PbWO$_4$	8.3	1123	0.9	2.0	10.2	18	50^s	560^s	2.20	0.1^s	no	-1.9
							10^f	420^f		0.6^f		
LSO(Ce)	740	2070	1.14	2.3	9.6	21	40	420	1.82	75	no	-0.3
GSO(Ce)	6.71	1950	1.37	2.4	8.9	22	600^s	430	1.85	3^s	no	-0.1
							56^f			30^f		

compactness

speed

photo-statistics

T stability

[*] Refractive index at the wavelength of the emission maximum.

[†] Relative light yield measured with a bi-alkali cathode PMT.

[‡] Variation of light yield with temperature evalutated at room temperature.

f = fast component, s = slow component

Characteristics of ionizing radiation damage

R.Y. Zhu, NIM A413(1998) 297-311 & ref. therein

1) Appearance of radiation-induced absorption bands

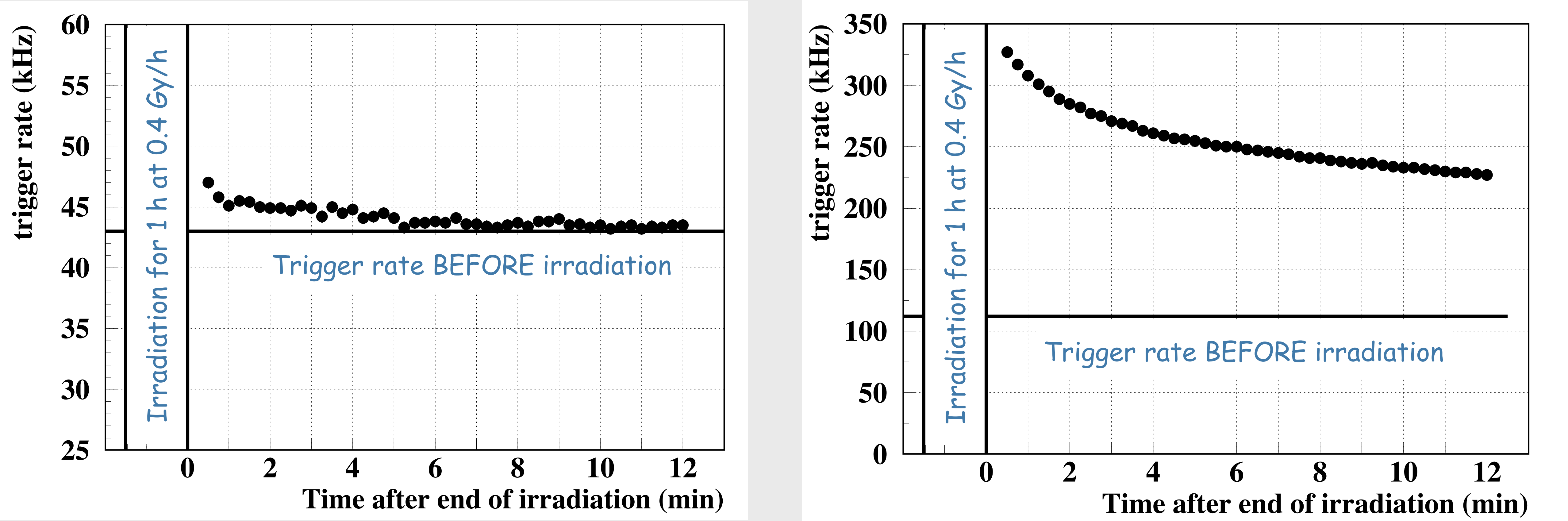
- ➪ Formation of color centers (e- in anion vacancies or holes in cation vacancies)
- ➪ Reduction of Light Transmission (LT)
- ➪ Possibly loss of uniformity in Light Output

BaF_2 CsI	alkali halides	Radiation damage related to oxygen contamination
BGO $PbWO_4$	oxides	Radiation damage related to oxygen vacancies and impurities (contaminants)

Characteristics of ionizing radiation damage

2) Phosphorescence / afterglow

H.Hofer, P.Lecomte, F.N.-T., A433 (1999) 630-636



Afterglow detected in PWO through photomultiplier single photoelectron counting rate after irradiation.
Left: crystal without afterglow, Right: crystal with afterglow

➪ Noise increase in detected Light (energy equivalent contribution negligible e.g. for $PbWO_4$ in LHC experiments, according to *R.Y. Zhu et al., NIM A376(1996) 319*)

3) No damage in scintillation mechanism (demonstrated in BGO, BaF_2, CsI(Tl), PWO)

Characteristics of ionizing radiation damage

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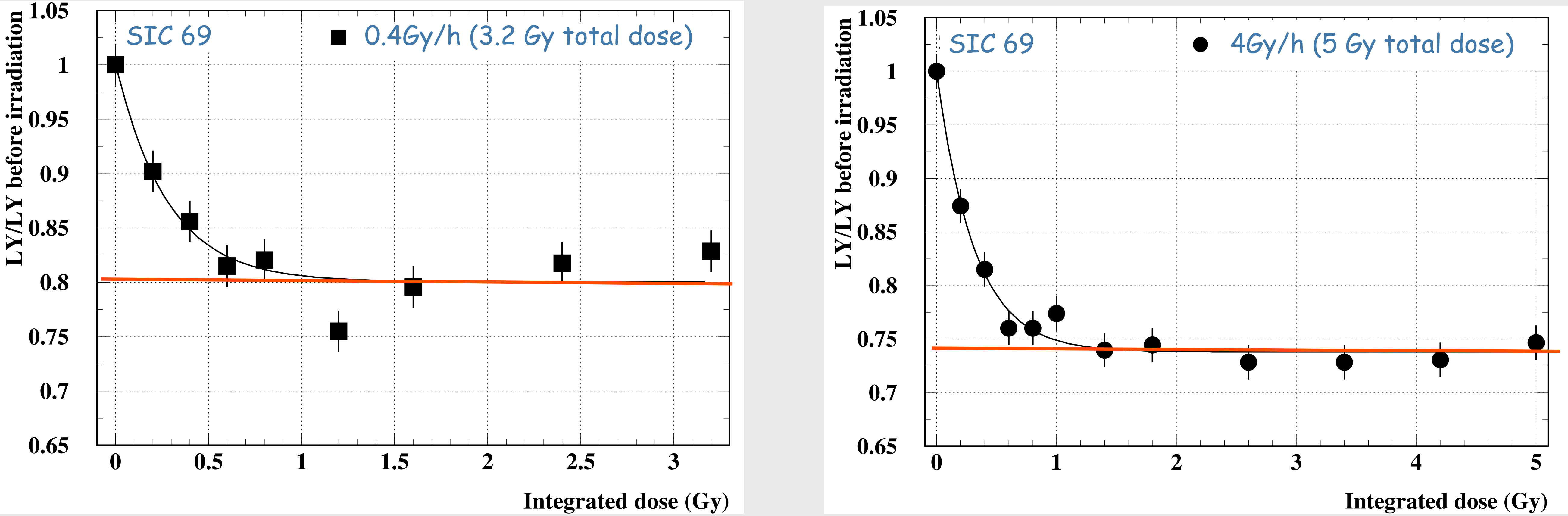
4) Recovery of damage at room temperature can occur
It depends on crystal type and, within one type, from growth parameters

➪ Dose rate dependence of damage equilibrium level
➪ Recovery speed ⇔ depth of traps

P.Lecomte, F.N-T. et al. A414 (1998) 149-155



Dose rate dependence of Light Output measured in PWO throughout irradiation.
Left: crystal irradiated at 0.4 Gy/h, Right: same crystal under 4 Gy/h

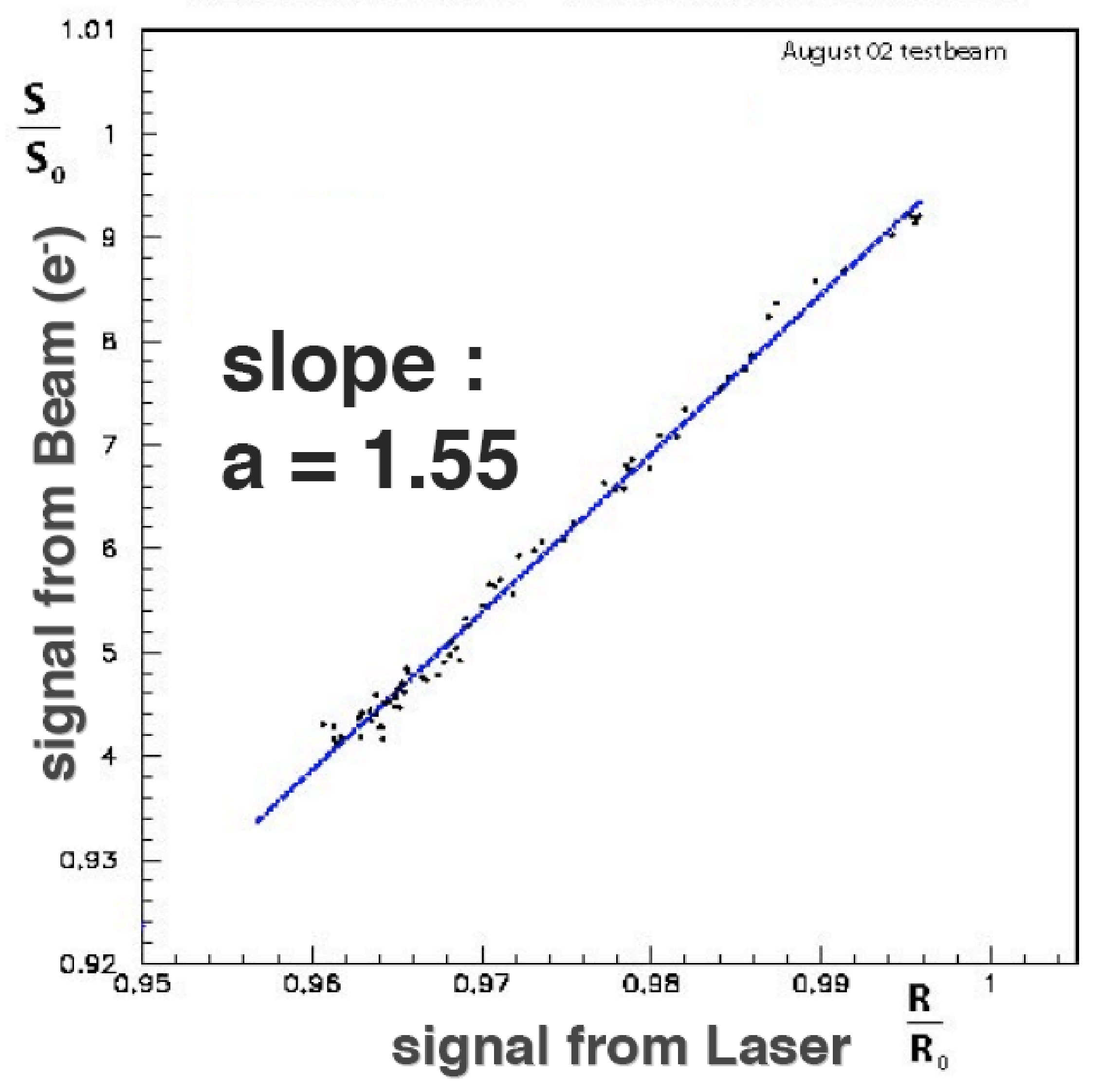
Consequences

Even some positive ones!

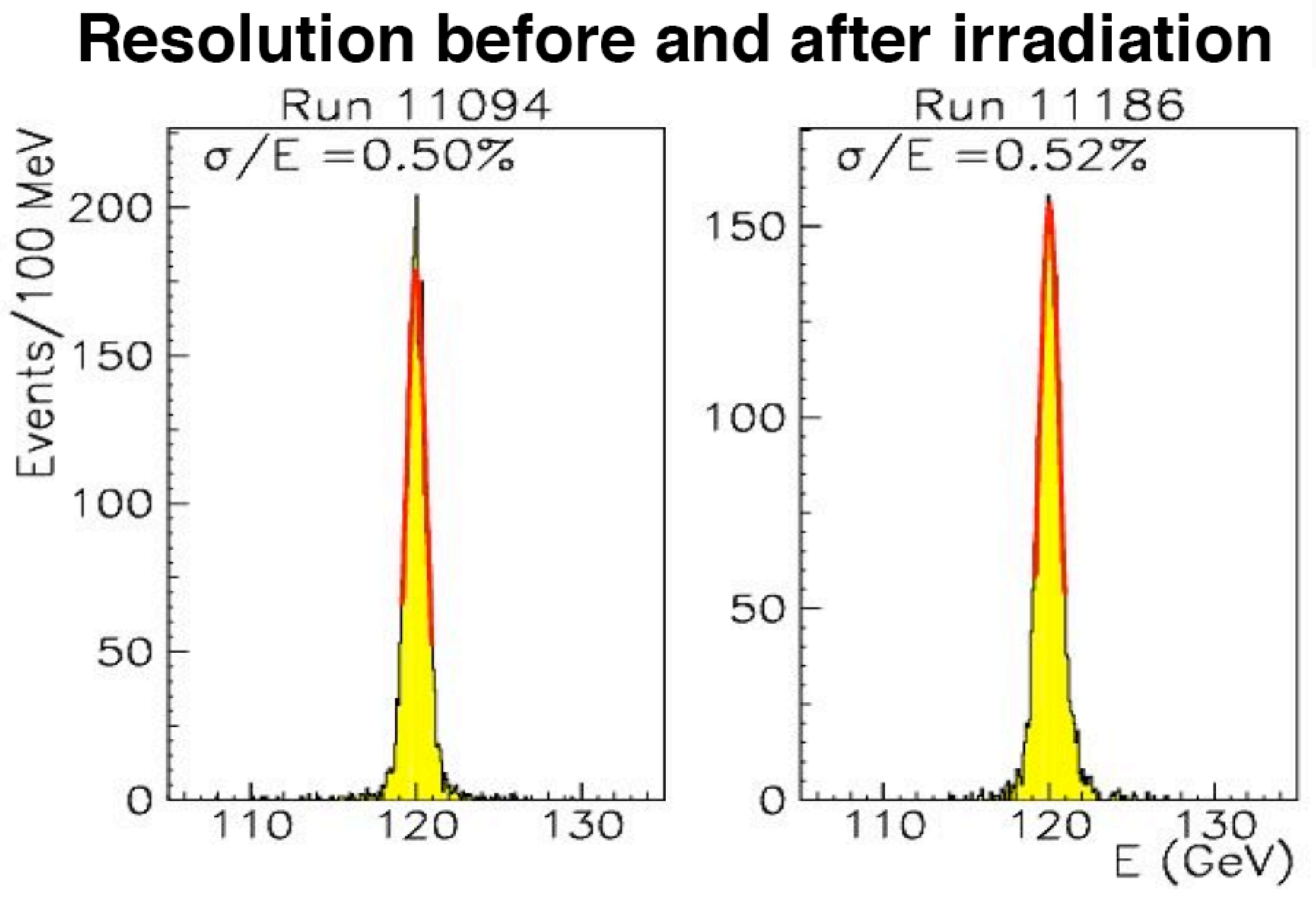
Ionizing radiation only affects transmission, thus evolution of damage can be monitored through light injection, and corrected for:

ex: CMS ECAL monitoring system of PWO through LASER light injection

A. Bornheim (CMS ECAL), Calor2004



E.Auffray et al. (CMS ECAL), NIM A 412 (1998) 223-237



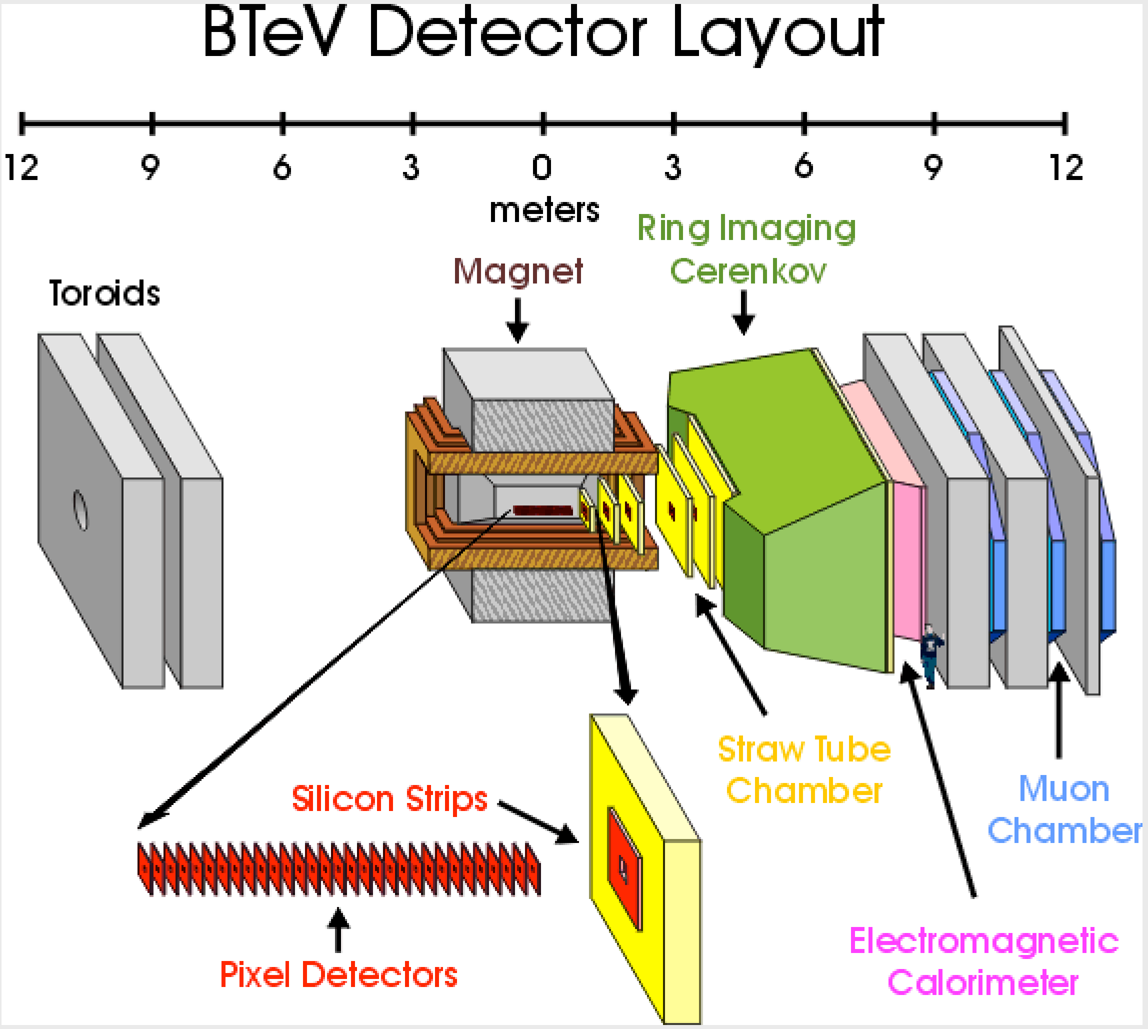
Hadron damage concerns

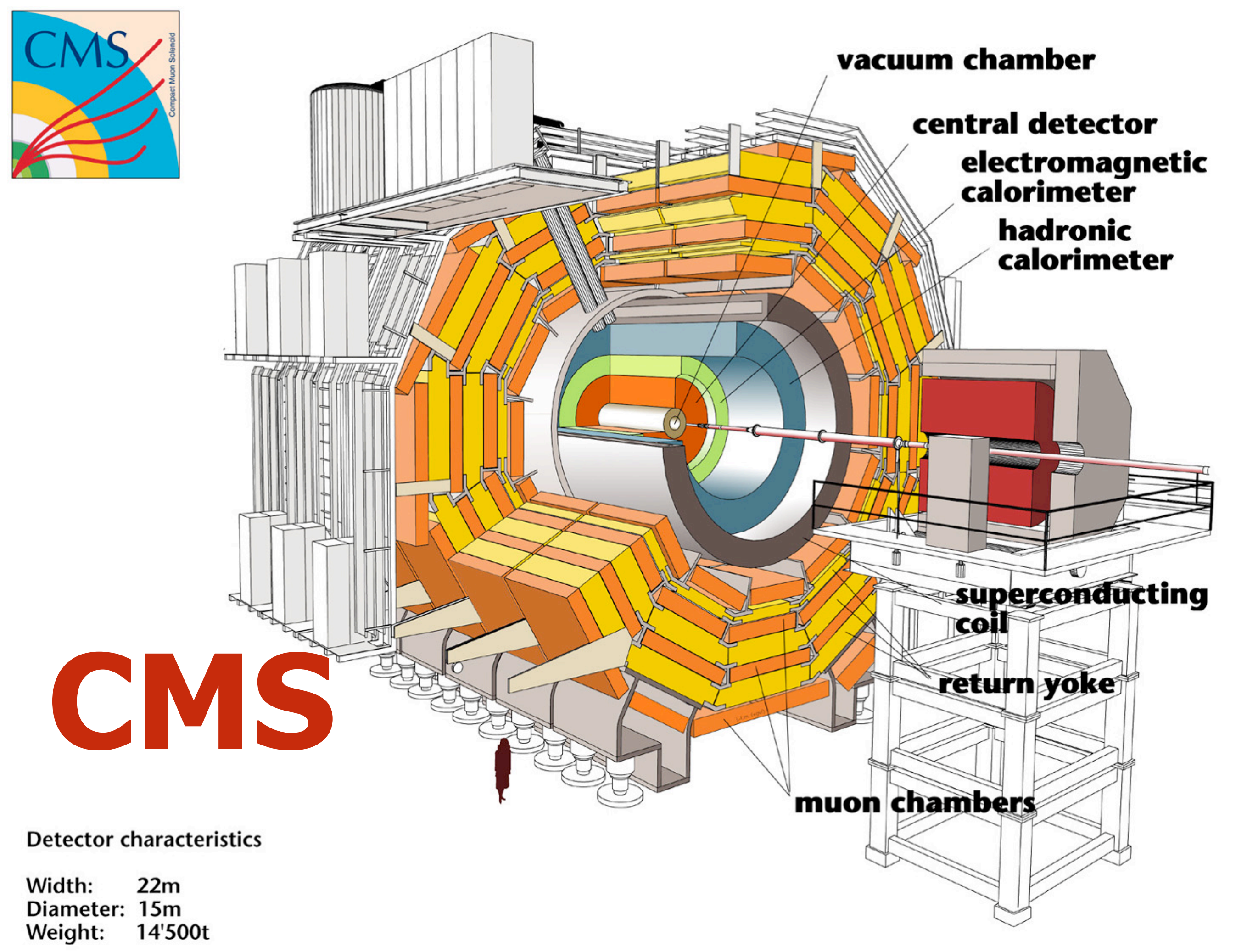
- ➪ Is there a specific, possibly cumulative damage from hadrons?
- ➪ If so, what is its quantitative importance?
- ➪ Does it affect the light transmission only, and can thus be “easily” monitored?
- ➪ Does it alter the scintillation mechanism?

To be answered in an experiment-specific context of particle fluxes and fluences.

PWO crystals in a hadron flux

Tests performed at IHEP Protvino for the BTeV experiment, which is designed to measure mixing, CP violation and rare decays in charm and beauty particle decays at the Fermilab Collider





Tests done at CERN and ETH for the running conditions of the CMS experiment, which is being constructed to study hard proton-proton collisions at the Large Hadron Collider

PWO crystals in BTeV

V.Batarin et al, NIM A512 (2003) 488-505
V.Batarin et al, IHEP preprint 2003-04, NIM A in press

Relative number (%)	Absorbed dose (krad/y)	Dose rate (rad/h)
33	0.3 - 2	0.11 - 0.72
27	2 - 5	0.72 - 1.8
12	5 - 10	1.8 - 3.6
16	10 - 50	3.6 - 18
6.2	50 - 100	18 - 36
3.2	100 - 200	36 - 72
2	200 - 500	72 - 180
0.4	500 - 1000	180 - 360
0.2	1000 - 2000	360 - 720

100 rad = 1 Gy

dose calculations performed for $\mathcal{L}=2\text{x}10^{32}$ cm^{-2} s^{-1} and 10^7 s running time

90% of crystals

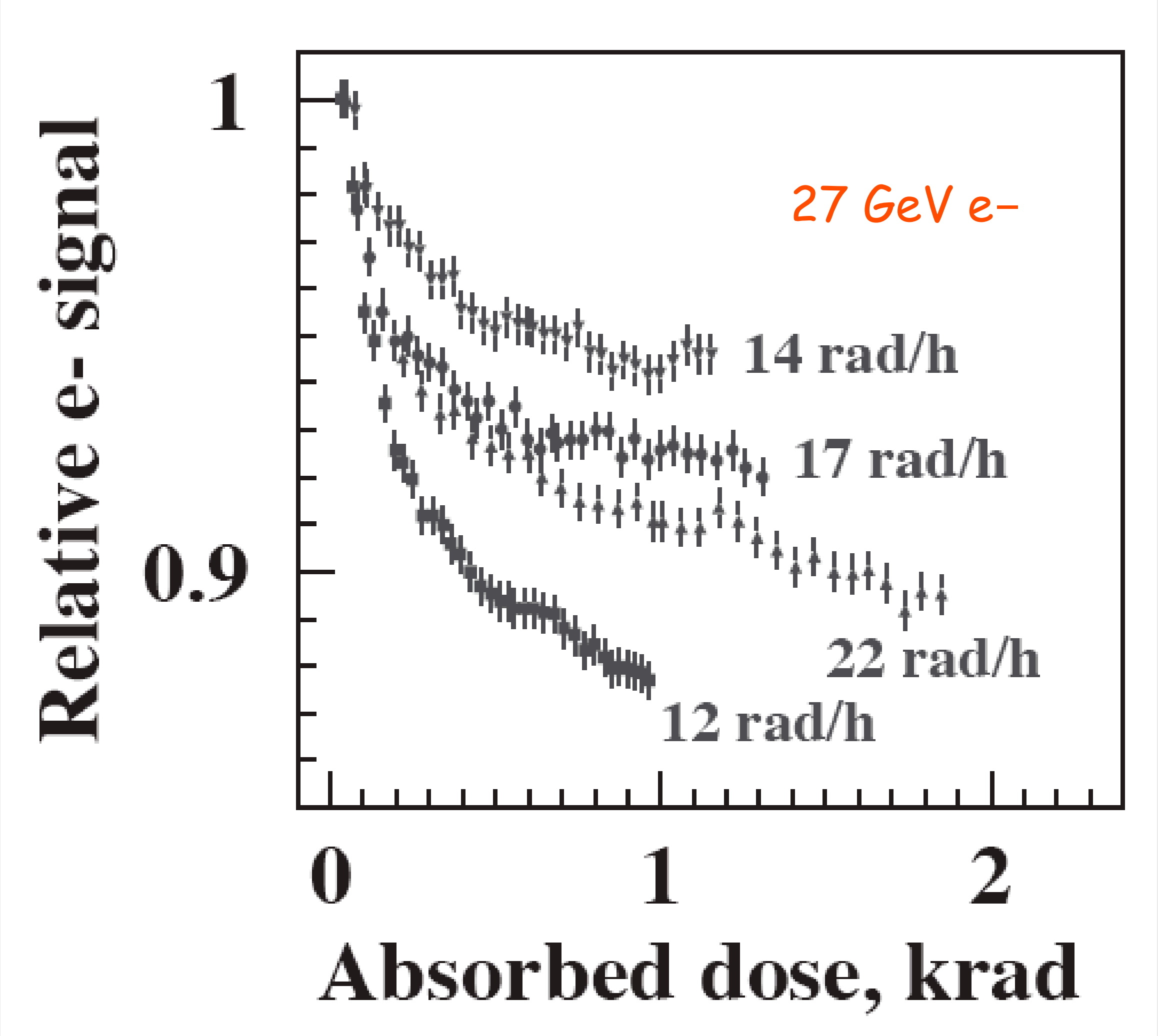
Electron + pion beams and Υ irradiation studies up to 2 krad at 1 to 60 rad/h

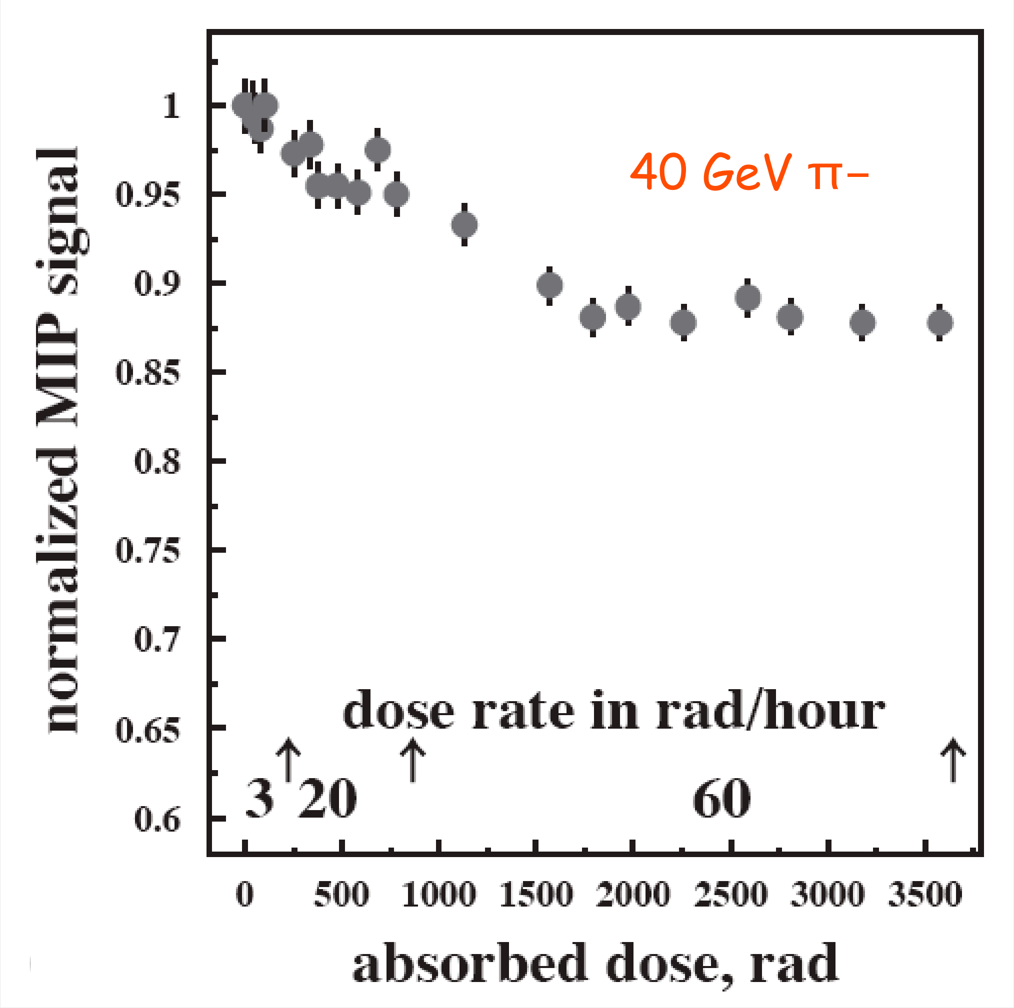
1% of crystals

Super-intensive, mixed beam (ch. hadrons, neutrons, Υ) studies up to 2500 krad at 1000 and 100000 rad/h

e- and π irradiations of PWO at IHEP for BTeV

Irradiation studies for bulk of crystals, up to 2 krad at 1 to 60 rad/h



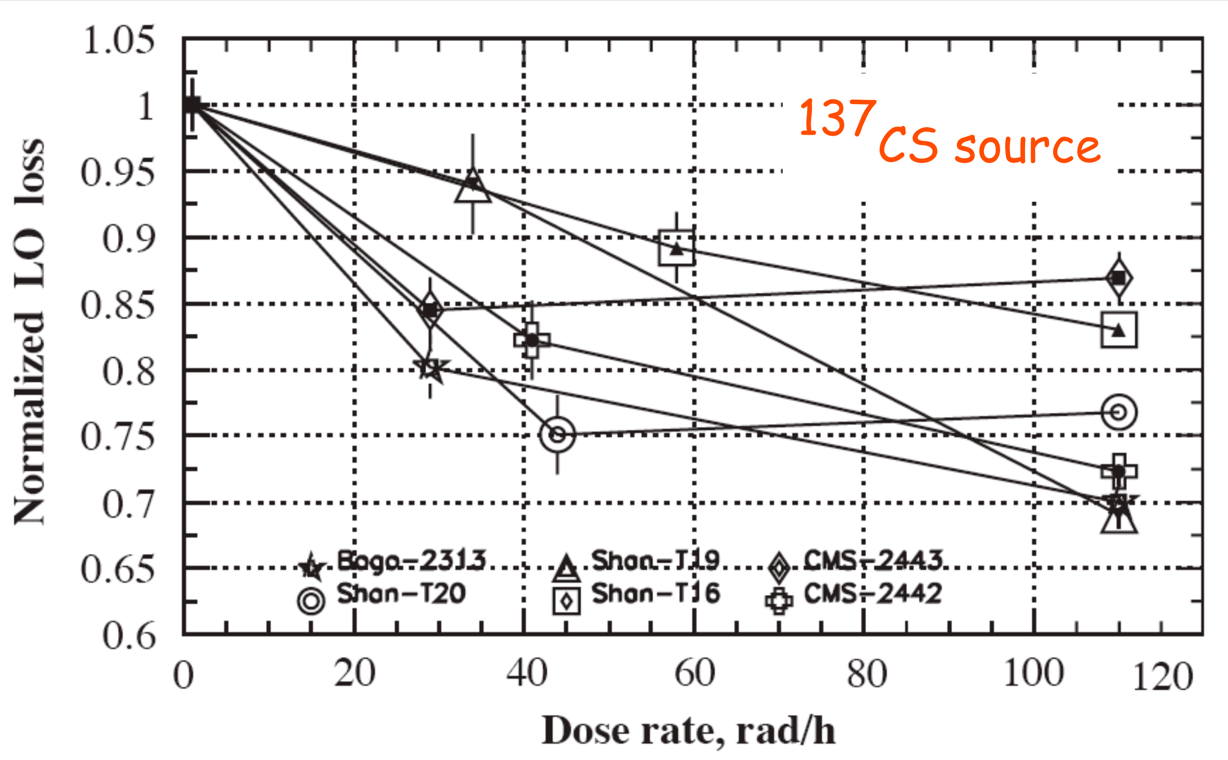


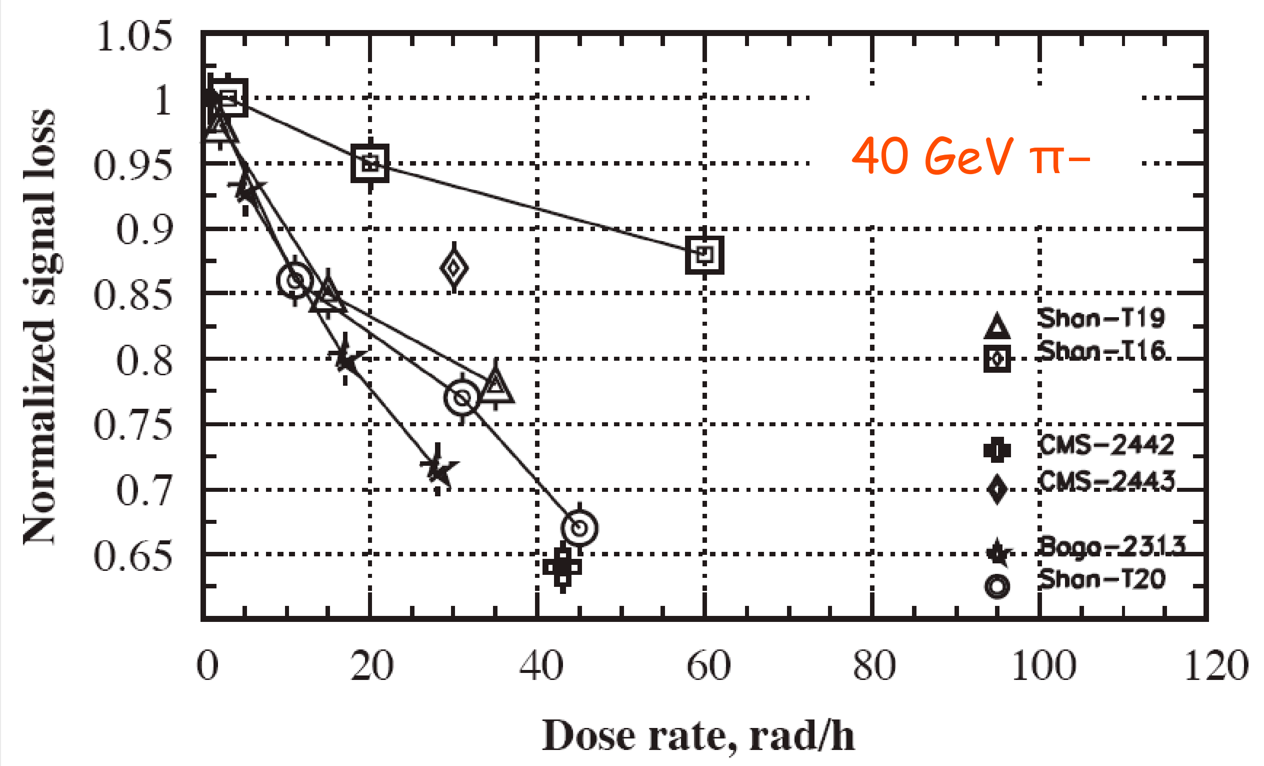
Signal loss behavior qualitatively similar between electrons and pions.
Damage appears to reach equilibrium at a dose-rate dependent level

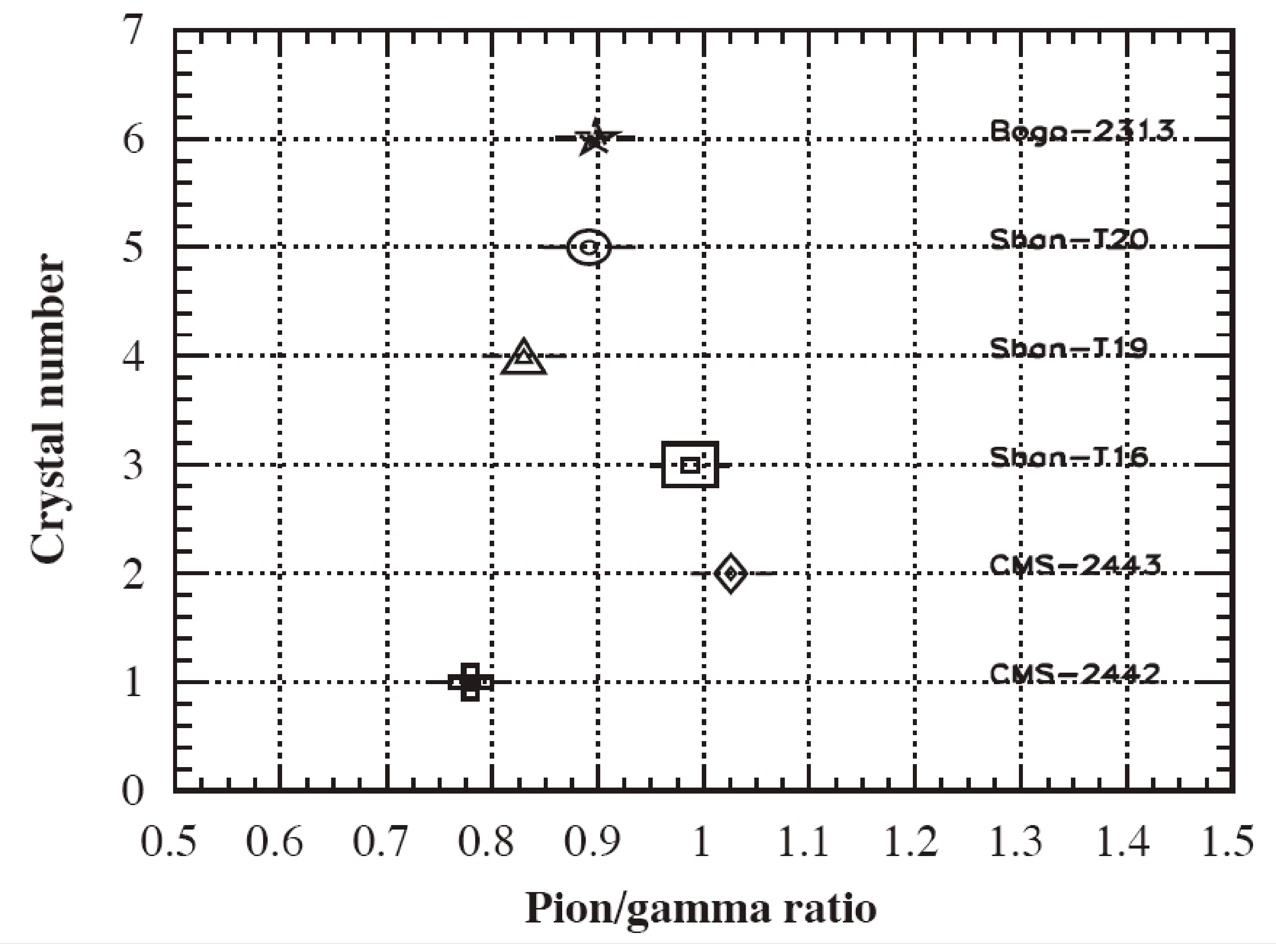
Concern: for the dose-rates used, absorbed dose expected in the experiment not explored. An additional, specific, possibly cumulative damage from hadrons cannot be excluded.

π and γ irradiations of PWO at IHEP

Apparent damage equilibrium level reached within 10 h, plotted versus dose rate:







V.Batarin et al, IHEP preprint 2003-04, Nucl. Instr. Meth. A in press

At the dose level investigated, damage level of similar importance between γ and π within the same crystal.

No indication of damage to scintillation mechanism from π irradiation in

V.A. Batarin et al., IHEP preprint 2004-7

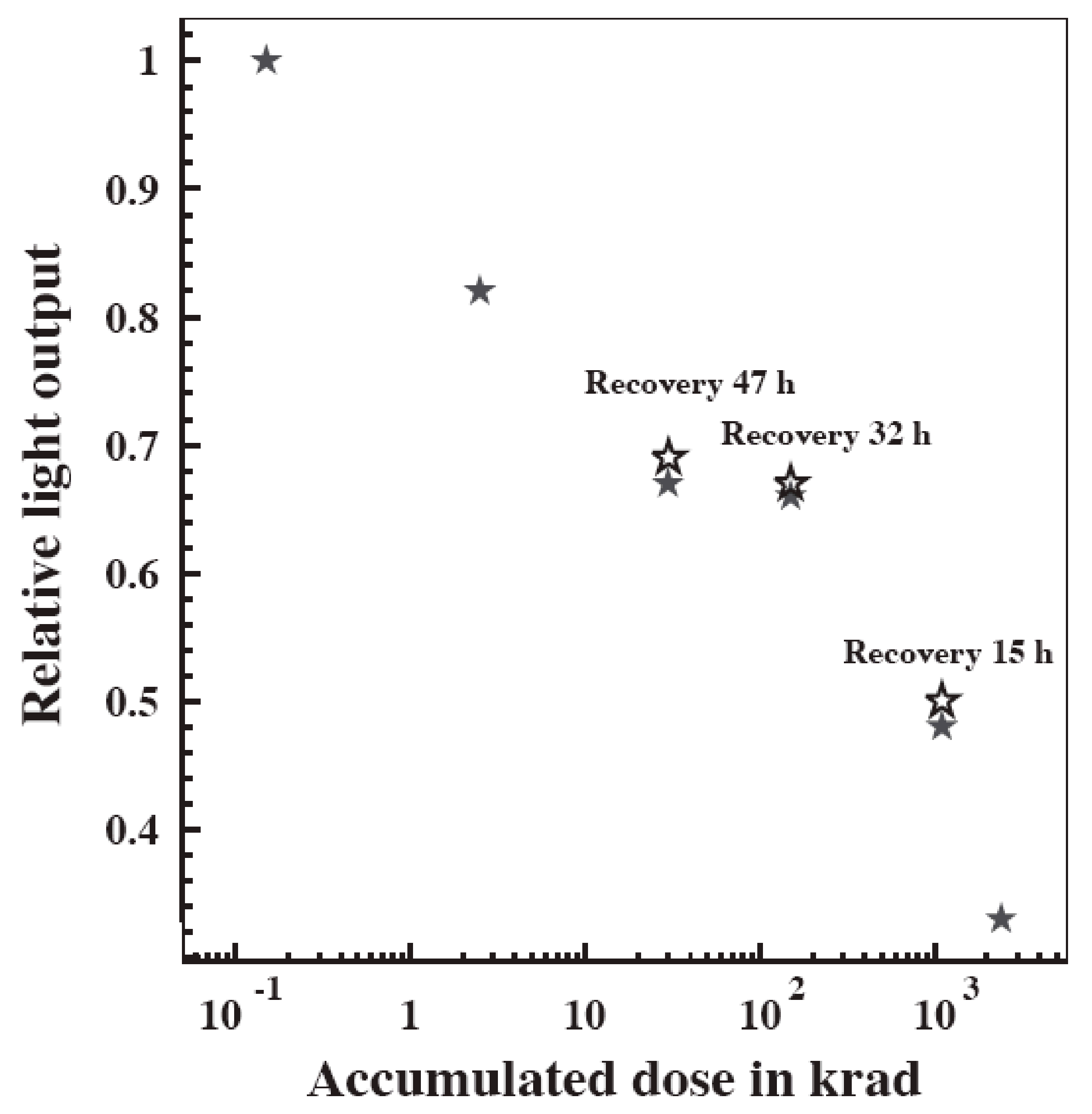
Super-intensive hadron beam tests of PWO at IHEP

Mixed beam of charged hadrons, neutrons and gammas with dose rates of 100 krad/h. Absorbed dose explored corresponds to 3 y running for the most exposed crystals, yielding thus an upper limit to the damage expected in BTeV running.

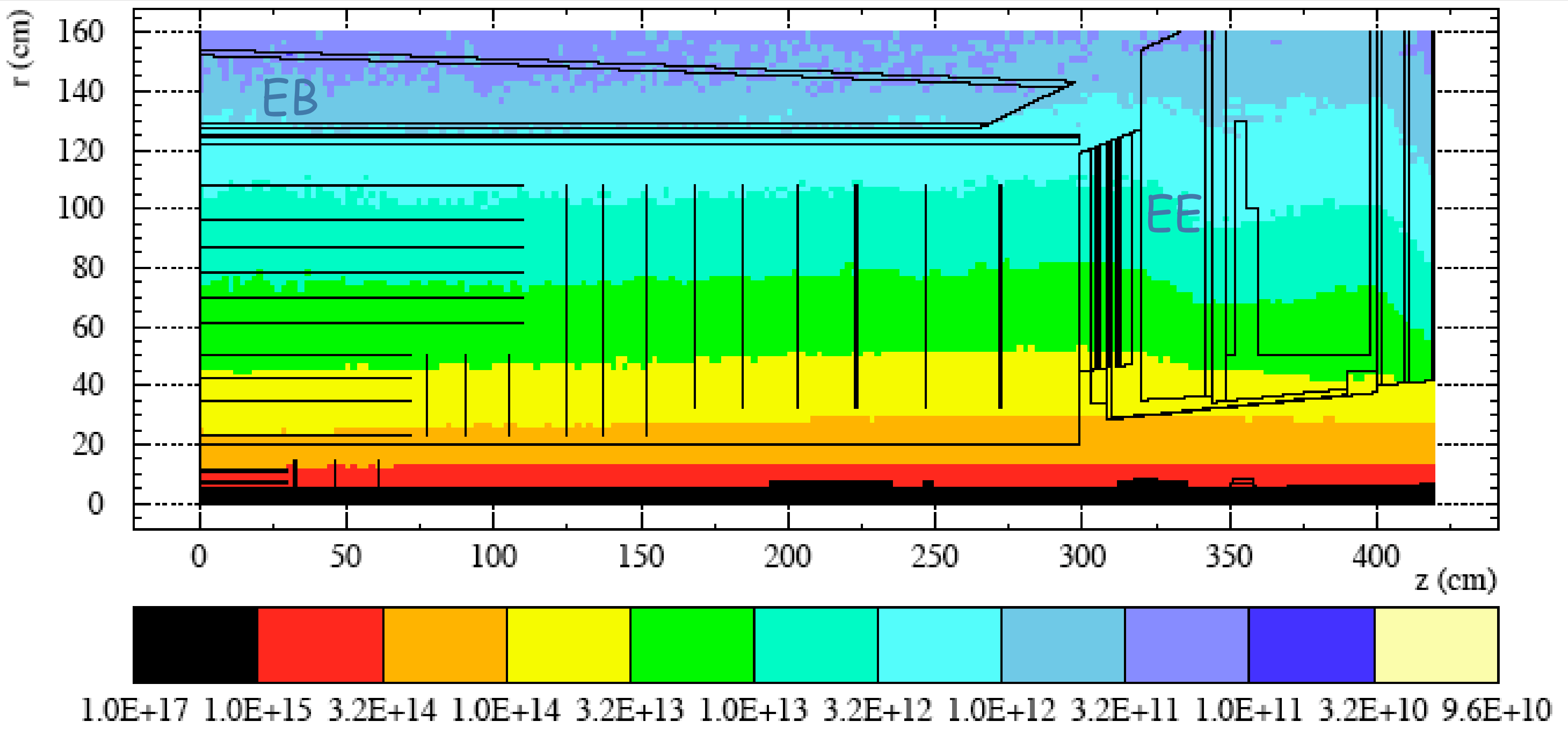
➪ At the constant flux used, the damage appears to be steadily increasing with accumulated dose

➪ This is unlike pure ionizing radiation damage, which reaches equilibrium at a level depending on dose rate, not beyond what saturation of all color centers can yield

➪ A hint for an additional, cumulative, hadron-specific contribution



Hadron fluxes in CMS



Fluence [cm^{-2}] calculated for $5x10^{5}$ pb^{-1} (10 y at LHC)

Electromagnetic calorimeter EE+EB:

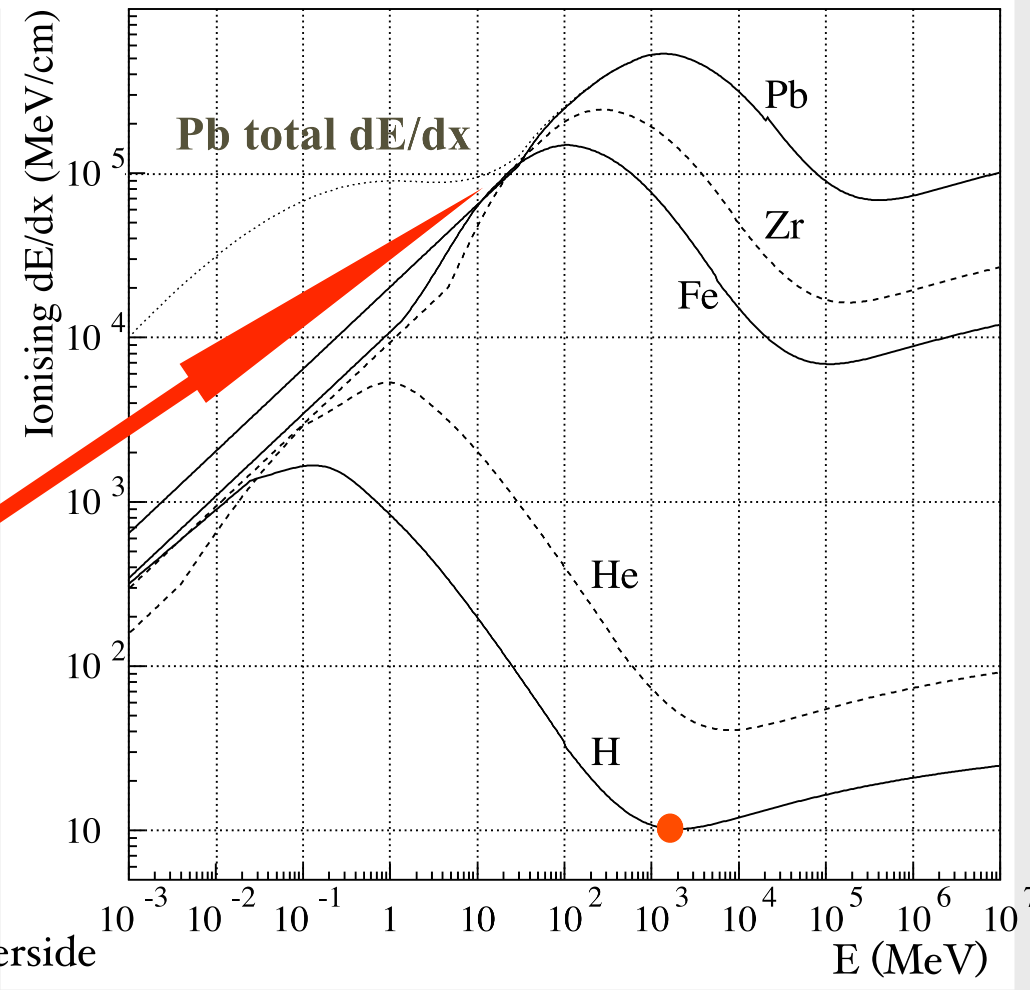
➪ Barrel: ~ 10^{12} cm^{-2} charged hadrons

➪ End Caps: up to ~ 10^{14} cm^{-2} charged hadrons

What could be the characteristics of a specific damage from hadrons:

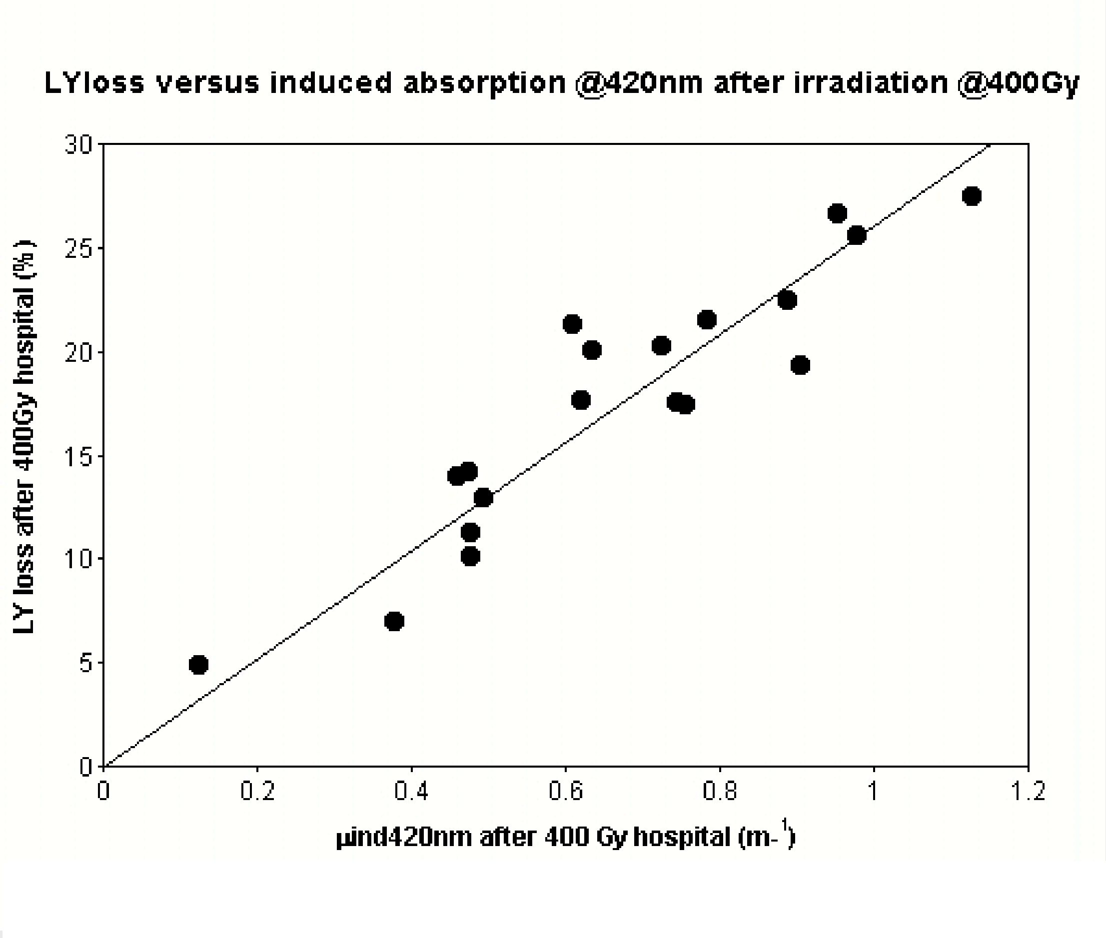
With respect to purely ionizing radiation:
Above ~20 MeV threshold, production of heavy fragments, "stars", with up to 10 μm range and E up to ~100 MeV

- ➪ displacement of lattice atoms along their path
- ➪ energy loss along their path up to 10000 x mip
- ➪ kinetics likely different from ionizing radiation damage, thus possibly cumulative



Proton beam tests of PWO at CERN

M.Huhtinen, P.Lecomte, D.Luckey, F.N.-T., 8th ICATPP Conference, Como 2003 arXiv:physics/0312056 and CMS CR 2004/021.



Primarily investigated quantity:
Induced absorption coefficient at peak of emission wavelength:

$$\mu_{IND} = \frac{1}{L} \times \ln \frac{LT_{INIT}}{LT_{END}}$$

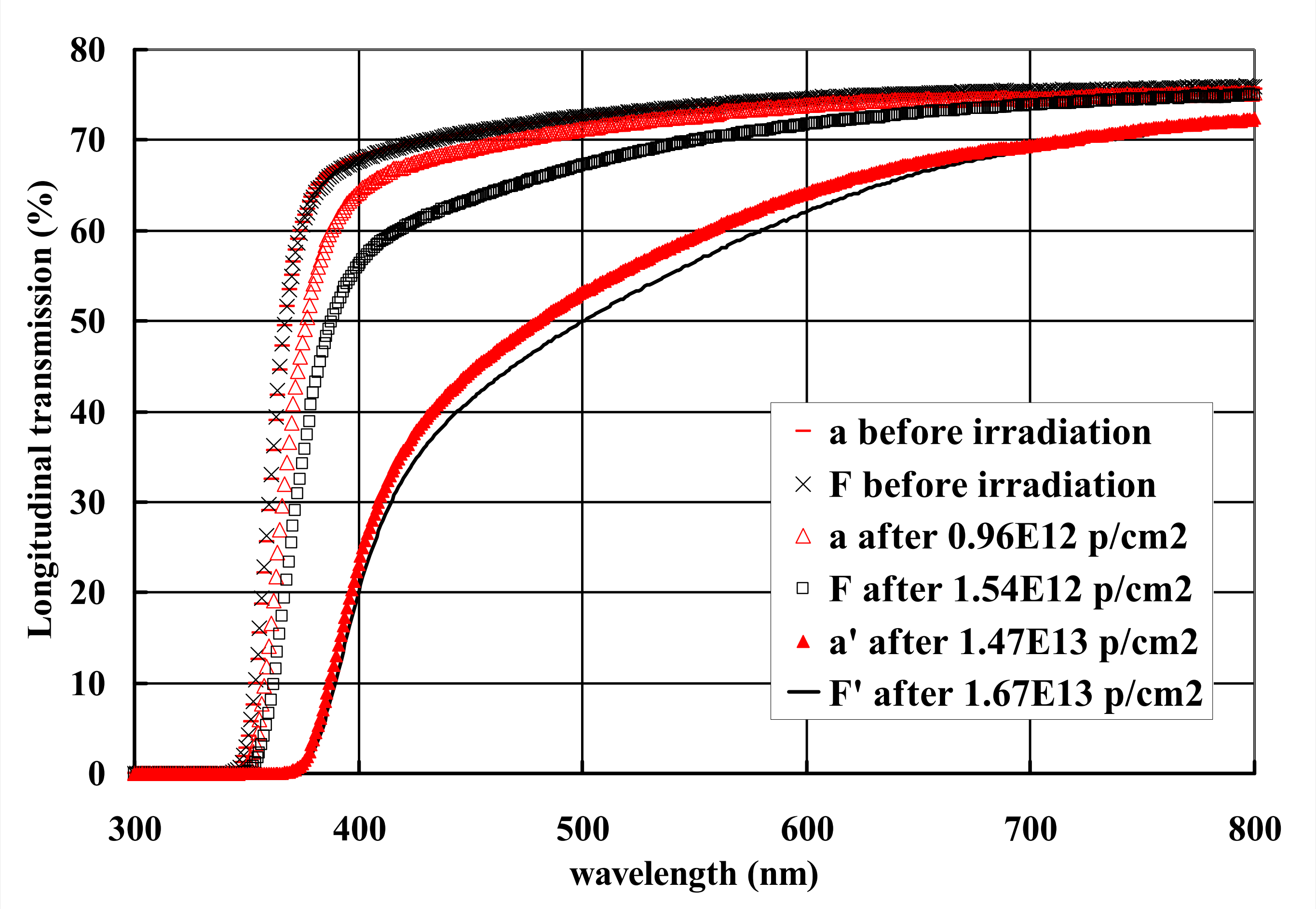
- ➪ Transmission measurements highly accurate
- ➪ Directly related to the Light Output loss (if scintillation not affected)
- ➪ For these crystals, $\mu_{IND}=1\text{m}^{-1}$ corresponds to a relative L.O. loss of ~ 25%

Several CMS production crystals of consistent quality irradiated:

a,b,c,d: crystals irradiated at a lower flux, of 10^{12} p/cm^2/h , at 20 GeV/c
E, F, G: crystals irradiated at a higher flux, of 10^{13} p/cm^2/h, at 20 GeV/c

(a', F' same crystals as a, F in a second irradiation)

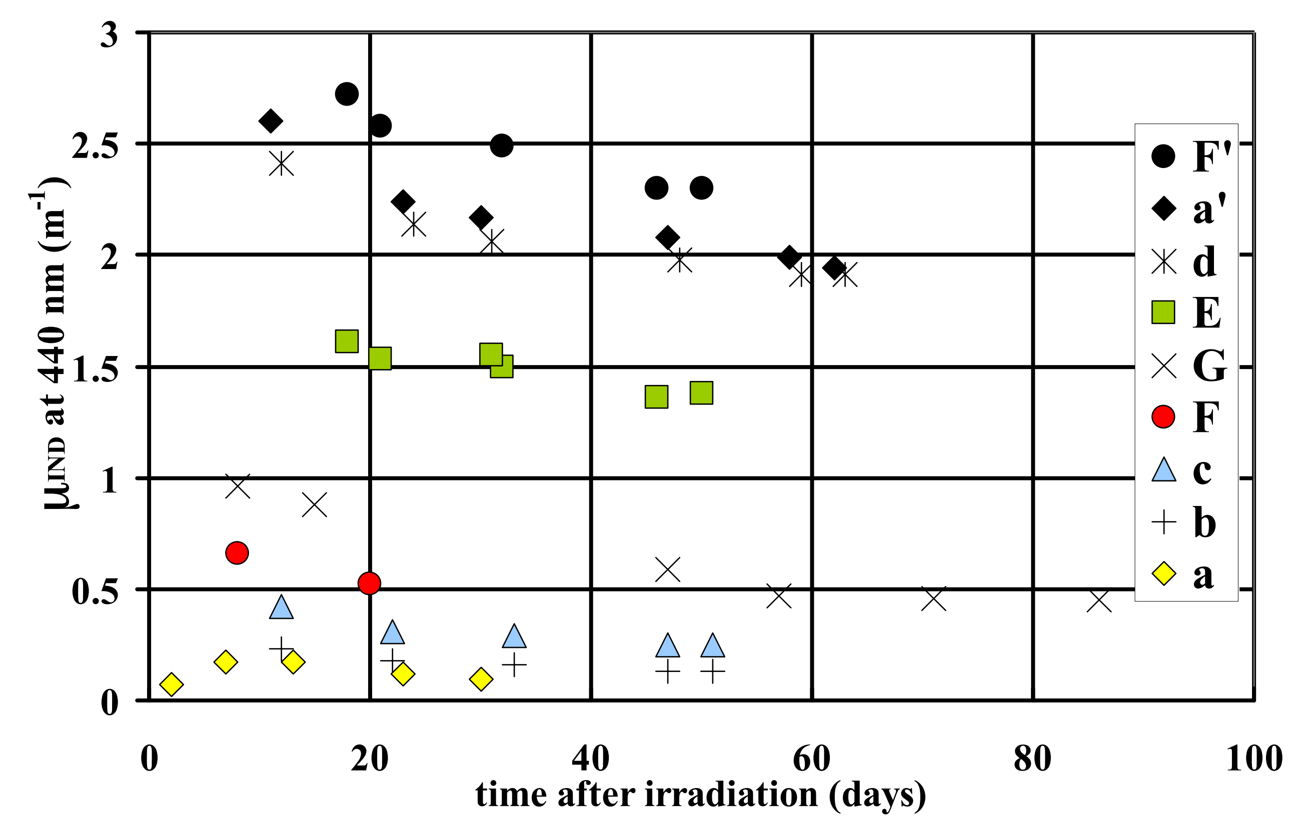
Proton test of PWO



- ➪ Possible flux dependence at low fluence
- ➪ No flux dependence at high fluence
- ➪ Transmission band-edge shifts, unlike what happens in purely ionizing radiation

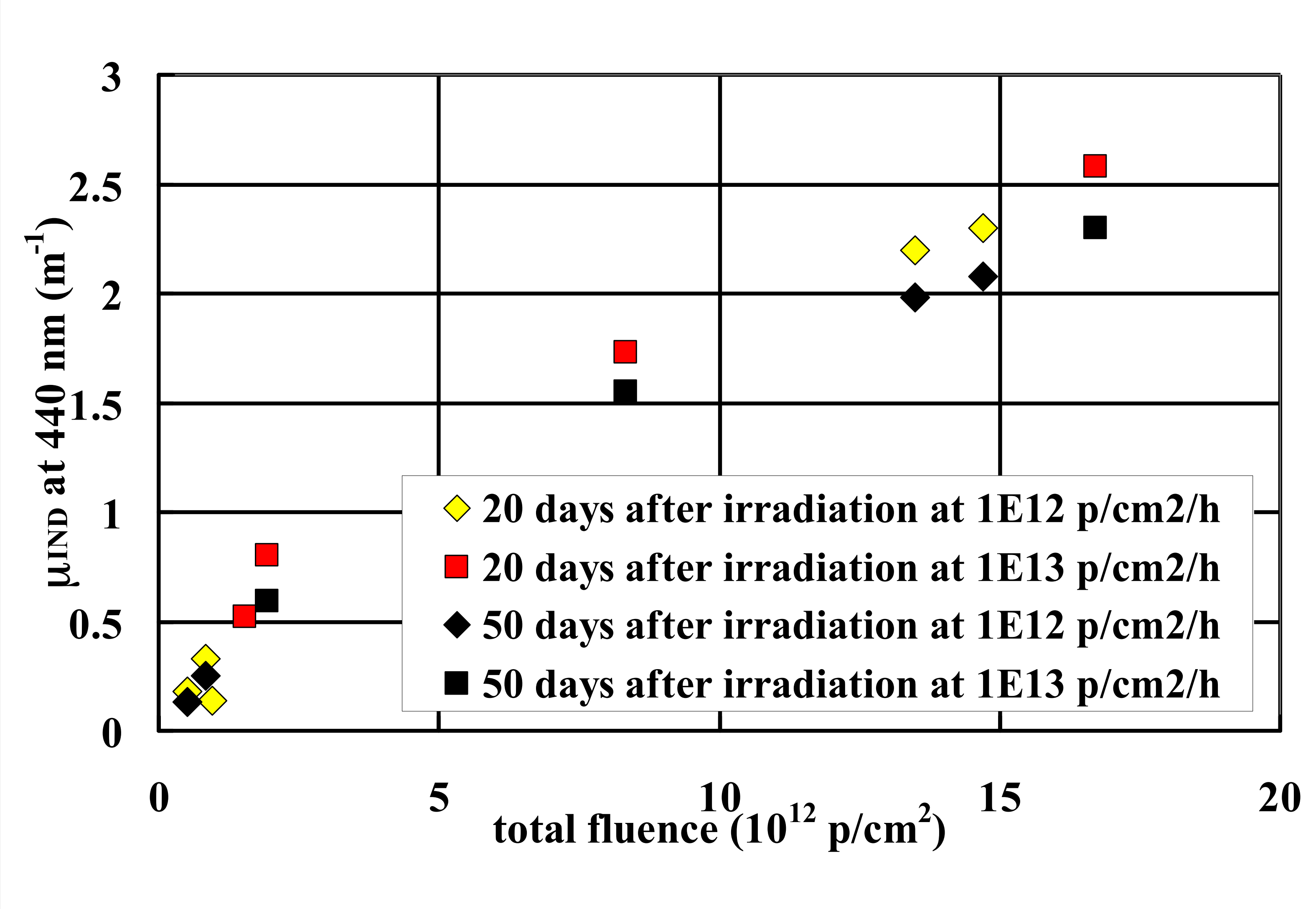
Some recovery of μ_{IND} between 10 and 60 days after irradiation.

Recovery appears to slow down asymptotically



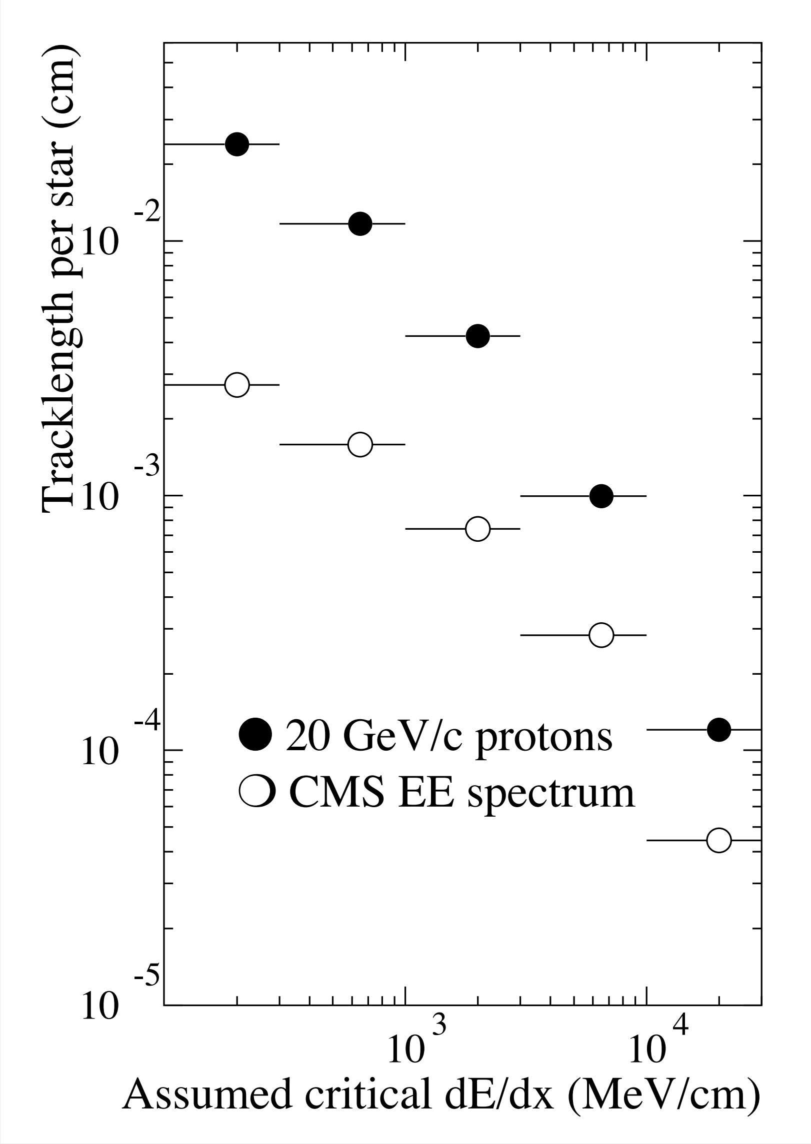
Proton damage vs. fluence in PWO

- ➪ ~ linear increase with fluence
- ➪ flux dependence negligible



Thus proton damage appears to yield a cumulative effect, with essentially no recovery, combined with a damage which anneals at room temperature with a time constant of several months or longer.

20 GeV/c p vs CMS EE



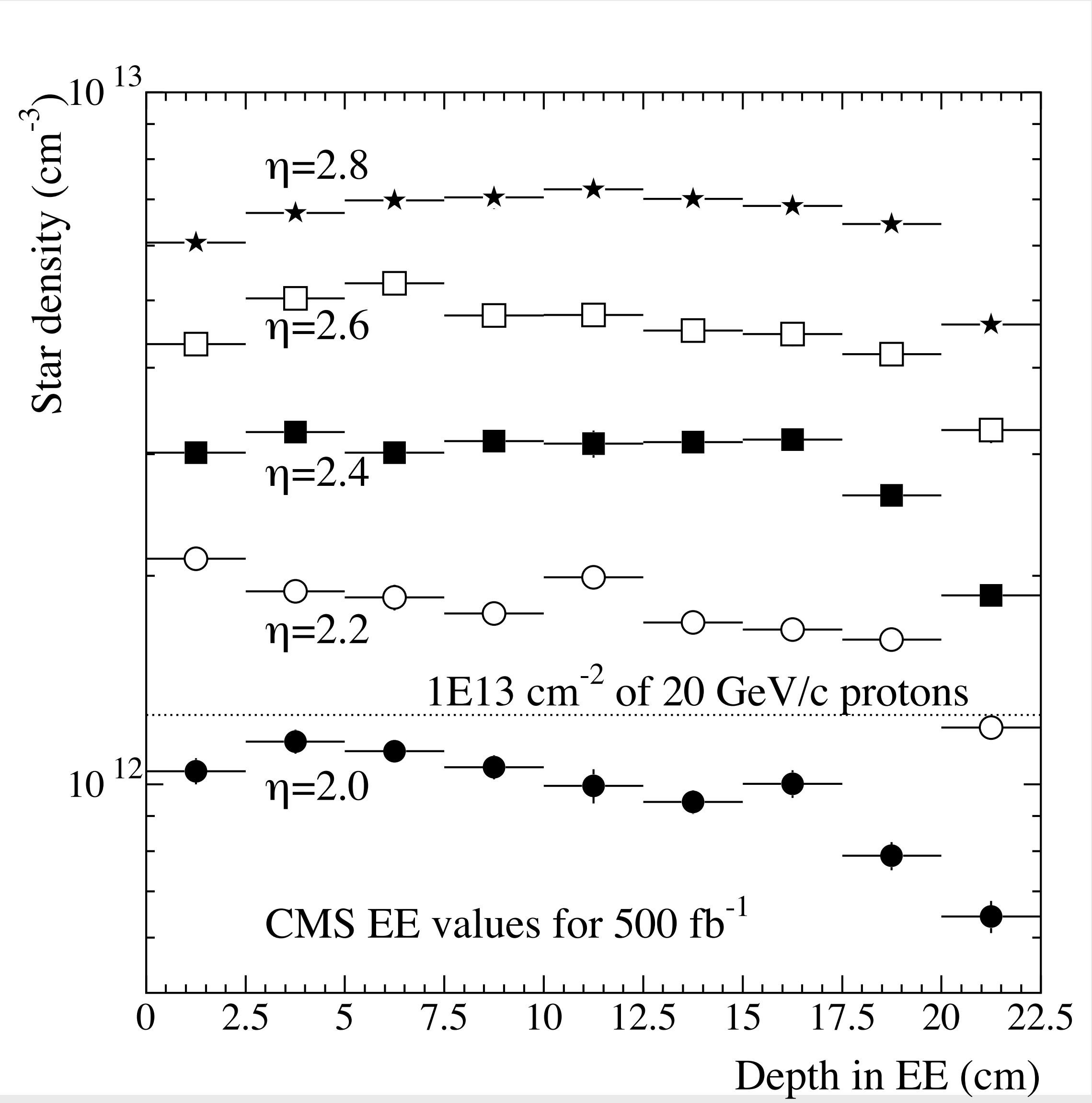
One can assume that damage occurs only when

$$\frac{dE}{dx} > \frac{dE}{dx}_{CRIT}$$

➪ expected damage in CMS EE a factor 2.7 to 8.7 smaller than the one from 20 GeV/c protons

➪ energy loss along their path up to 10000 x mip

Star densities for 10^{13} p/cm^2 at 20 GeV/c same as in CMS EE at η=2



Including factor 2.7 to 8.7, radiation test covers entire high-precision EE region, and possibly up to η=2.9

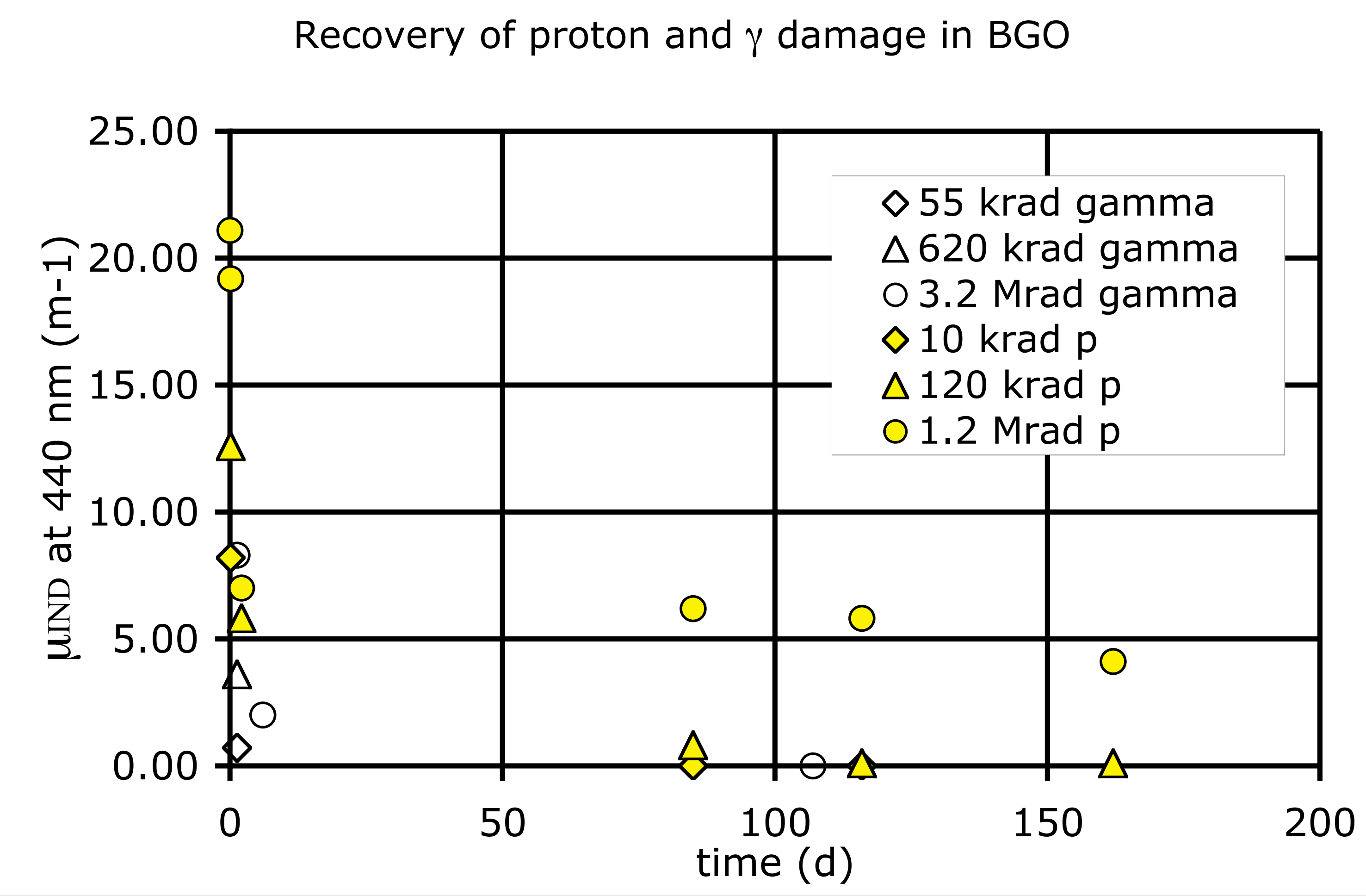
Proton damage in BGO

Data extracted from *M. Kobayashi et al., NIM 206 (1983) 107-117*

Comparison between damage from 12 GeV protons and from γ.

Proton flux given through its corresponding ionizing dose.

Determined μ_{IND}(440nm) for ease of comparison with PWO data, since transmissions only considered.


Recovery of proton and γ damage in BGO

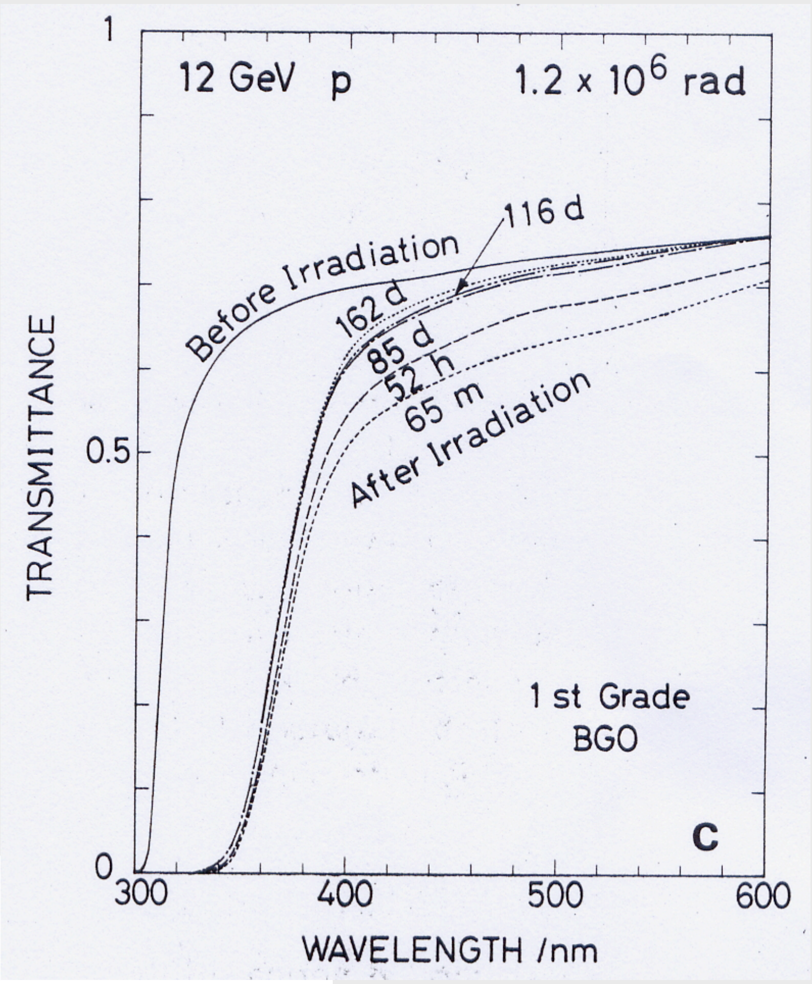
Plot damage vs absorbed dose at 85 days

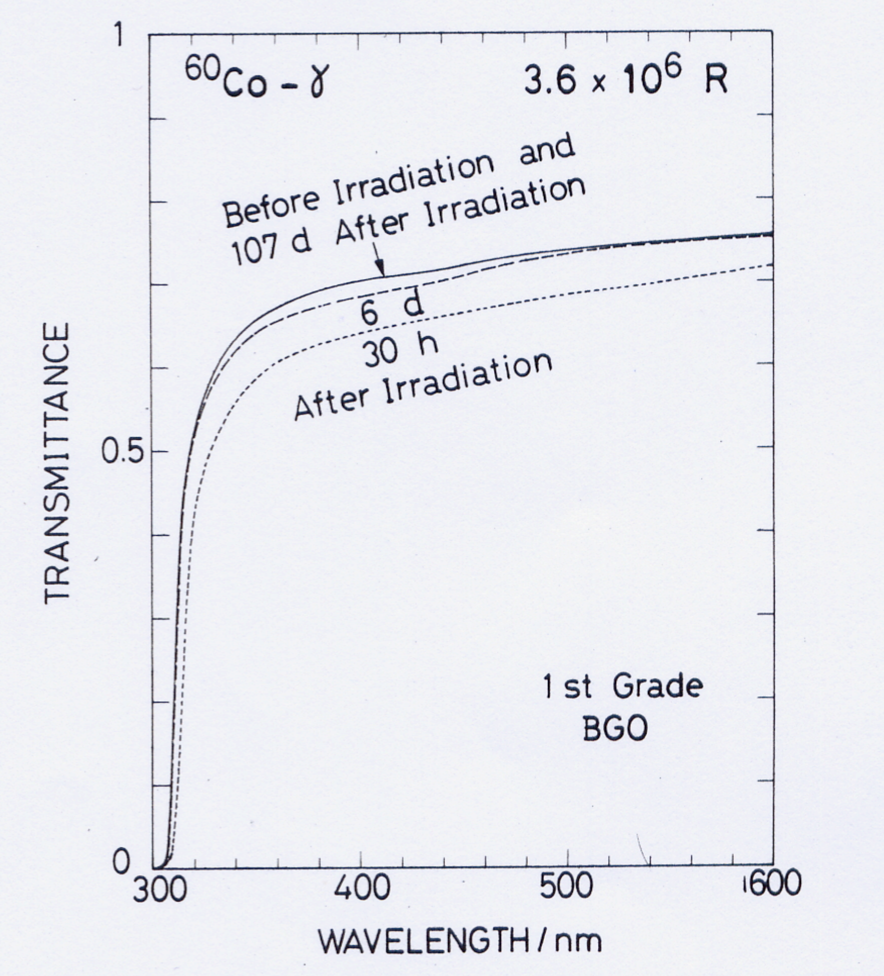
For comparable dose levels, contribution from ionizing radiation small, negligible beyond 80 days. Thus "ionizing dose" for protons meaningful only since proportional to flux, thus to number of stars: damage has clearly a different origin.

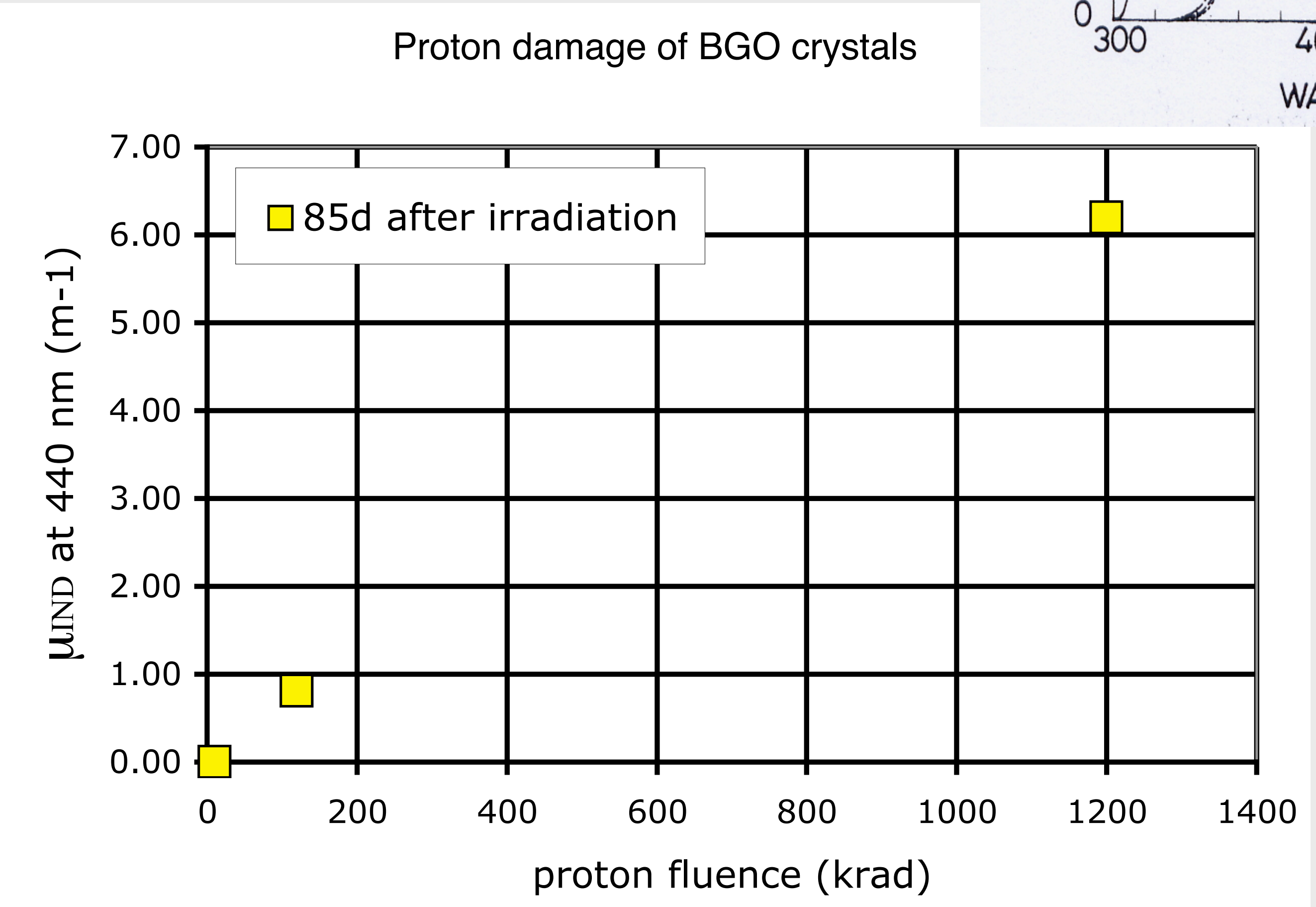
Proton damage in BGO

Data extracted from *M. Kobayashi et al., NIM 206 (1983) 107-117*

Qualitative behavior of proton damage similar to the one in PWO







- ➪ Band-edge shift which does not recover with time
- ➪ Amplitude of damage compatible with a linear dependence on proton fluence

Proton damage in pure CsI

Kobayashi et al., NIM A328 (1993) 501-505

Determined μ_{IND}(440nm) for ease of comparison with PWO data:

Υ damage:

dose (rad)	μ_{IND} (440 nm)	t
10k	5.4	60 h
100k	11.3	33 h
1M	22.3	34 h
10M	62.9	58 h
100M	137.0	21 d and 55 d

proton damage:

dose (rad)	μ_{IND} (440 nm)	t
20k	2.6	25 h
180k	8.2	25 h
1.6M	27.0	5 h and 52 h
24M	47.5	89 h to 50 d
290M	174.0	15 d and 99 d

➪ Damage from γ is larger than the one from 12 GeV protons.

➪ Furthermore, damage recovers very little for both, thus even waiting for a long time into recovery does not allow to see the "remaining hadron damage"...

Thus, no statements can be made about the behavior of the hadron-specific part of the damage.

Conclusions

- ➪ For all crystals commonly used in calorimetry, the damage from ionizing radiation has been extensively studied, and experiments have established means of monitoring and correcting for it

- ➪ The understanding of additional contributions to the damage when crystals experience a substantial hadron flux has become important since experiments are being built having to cope with that.

- ➪ A hadron-specific, cumulative contribution, likely due to the intense local energy deposition from heavy fragments, has been observed in tests on PWO and BGO.
  Within the explored flux and fluence ranges, this contribution only seems to affect Light Transmission, and thus can be monitored.

- ➪ Additional studies, taking into account the range of operation of the envisaged experiments, are expected to consolidate the present understanding of hadron damage