



Hadron damage in PbWO₄ extrapolated to SLHC



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Reminder: Approximate radiation levels and fluences, rescaled from the ECAL TDR for
3500 fb⁻¹ at 10³⁵cm⁻²s⁻¹:

in front of crystals:

$\eta=2.0$: **5x10¹³ fast** hadrons/cm²

$\eta=2.9$: **4x10¹⁴ fast** hadrons/cm²

at shower max → crystals :

$\eta=2.6$: **570 kGy, 50 Gy/h**

$\eta=2.9$: **1400 kGy, 140 Gy/h**



Expected changes in PbWO_4 at LHC and SLHC



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- Radiation and particle fluxes change the crystals **Light Output** and Light Output **Uniformity** (L.O. dependence on shower position in the crystal)
- Reduced Light Output → effect on E-resolution **stochastic** term, increased importance of **noise**
- Change in Uniformity → effect on E-resolution **constant** term, especially in the front part of crystals (Front-Non-Uniformity, **FNUF**)
- **Activation** → maintenance problems
- Higher L and Int L at SLHC will make the issue **more severe**.



Changes due to ionizing radiation



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➤ Radiation and particle fluxes change the crystals Light Output and Light Output Uniformity

➤ Measurements indicate that at LHC and SLHC, the scintillation mechanism is not affected. Instead, Light Transmission (LT) is reduced. This is quantified as an induced absorption coefficient μ_{IND} :

$$\frac{LT(\lambda)}{LT_0(\lambda)} = e^{-\mu_{IND}(\lambda)L}$$

➤ Ionizing radiation causes a damage by forming color centers: **this damage reaches an equilibrium** at a level proportional to the **dose rate**.

At SLHC, the dose rate is expected to reach ~ 140 Gy/h at $\eta = 2.9$.

Throughout the EE, the damage from **ionizing radiation** is expected to saturate with Light Output losses reaching **40%-60%** (from ^{60}Co irradiations at the **Geneva Hospital, ~ 200 Gy/h**).



Changes due to hadron fluxes



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Hadrons induce as well a reduction of Light Transmission.

- There is a **specific hadron damage**. It can probably be mostly ascribed to the high dE/dx of heavy fragments.
- It is **cumulative**, thus a **function of delivered Int L**
- It is **nearly permanent** on an LHC and SLHC time scale.
- Tested over 2 orders of magnitude in fluence, up to $5 \times 10^{13} \text{ cm}^2$, i.e. **$\eta \approx 2.0$ at SLHC**

and for fluxes between $5 \times 10^{11} / \text{cm}^2/\text{h}$ and $10^{13} / \text{cm}^2/\text{h}$.

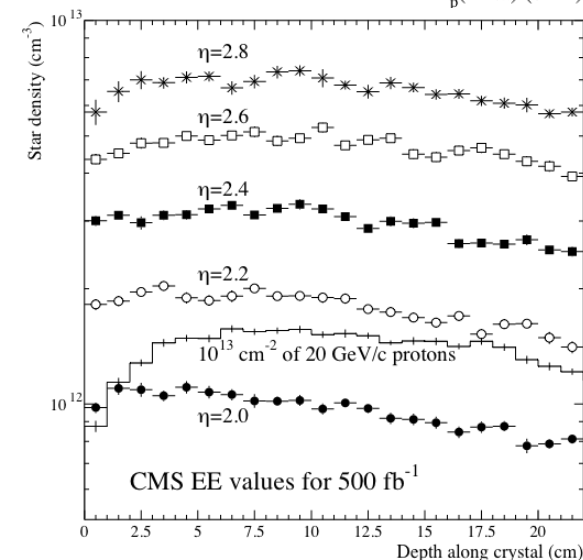
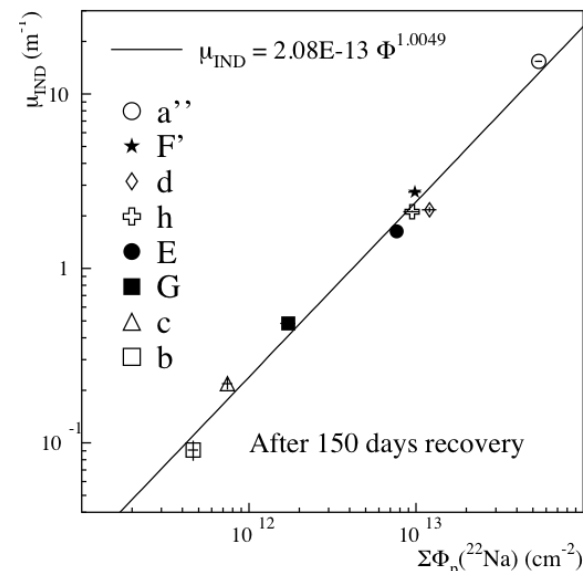
M. Huhtinen et al., Nucl. Instr. Meth. A545 (2005) 63-87

Scintillation does not appear to be affected measurably. Thus, the **damage can be monitored**.

P.Lecomte et al., Nucl. Instr. Meth. A564 (2006) 164-168

We know **how to can scale** from our 24 GeV/c proton results: we cross-checked with a 290 MeV/c π^+ irradiation (typical for EE energy spectrum). Damage ratio was measured to be consistent with star density ratios from FLUKA.

P.Lecomte et al., Nucl. Instr. Meth. A587 (2008) 266-271





Evolution of ECAL performance due to hadrons

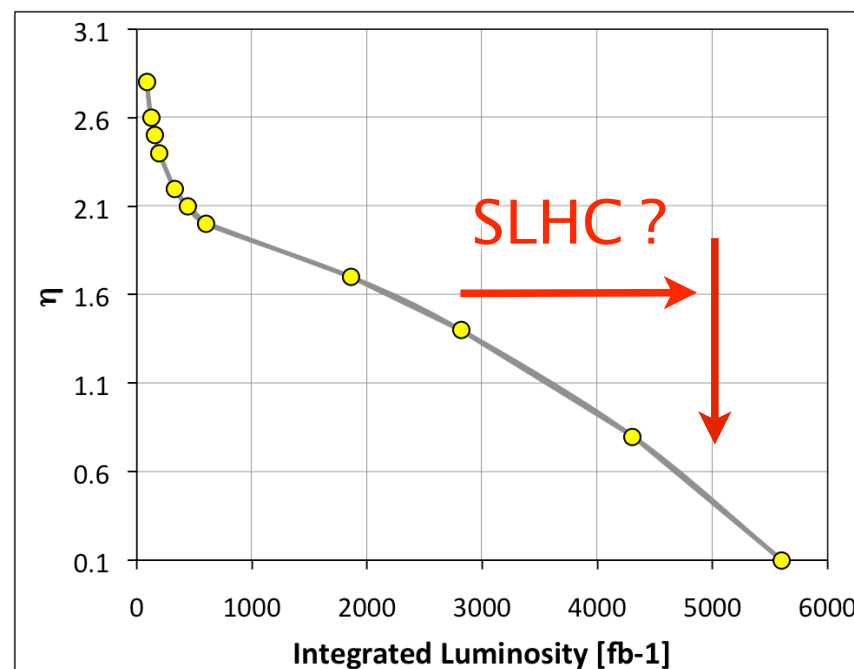
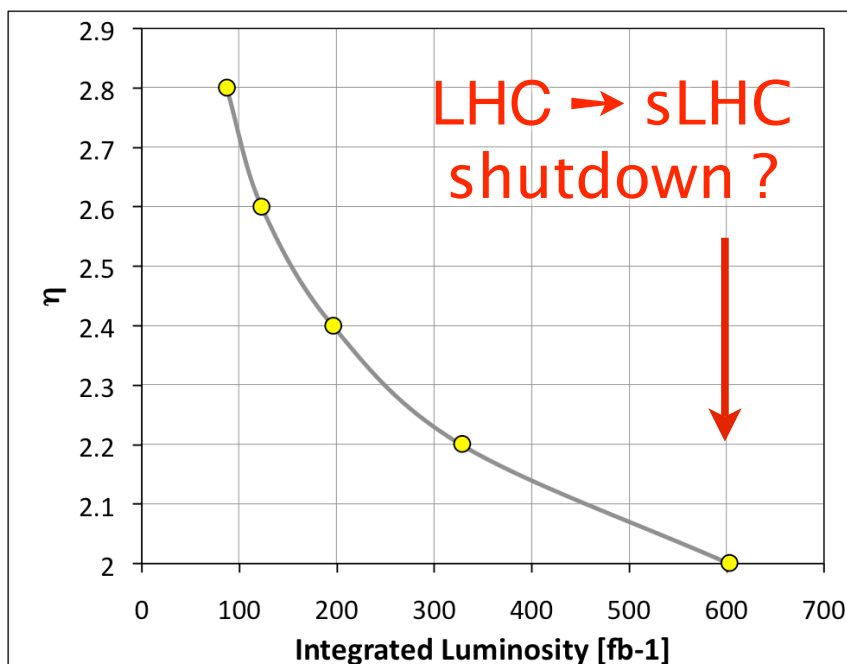


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F. N., ECAL XPG meeting, 27-FEB-08

η value vs. $\int \mathcal{L} dt$, at which $\mu_{\text{IND}}(420 \text{ nm}) = 2 \text{ m}^{-1}$ (~60% of Light Output loss) is expected to be reached in the ECAL

(LHC and SLHC scenario presented yesterday by J. Nash)



(using EB star densities from draft Radiation Hardness ECAL detector paper, Ed. I. Dafinei)

Let's attempt a very crude extrapolation to estimate the evolution of ECAL performance as a function of integrated Luminosity



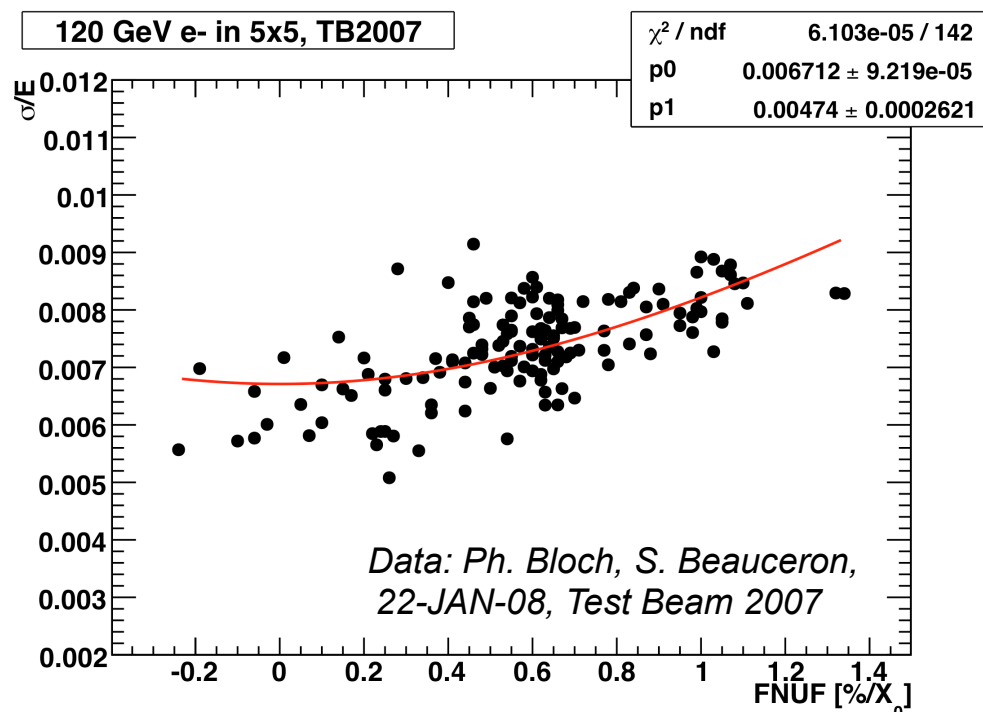
Constant term in σ/E depends on FNUF



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Notice: crystals are non-uniform to some extent from production,
but their non-uniformity changes due to radiation damage

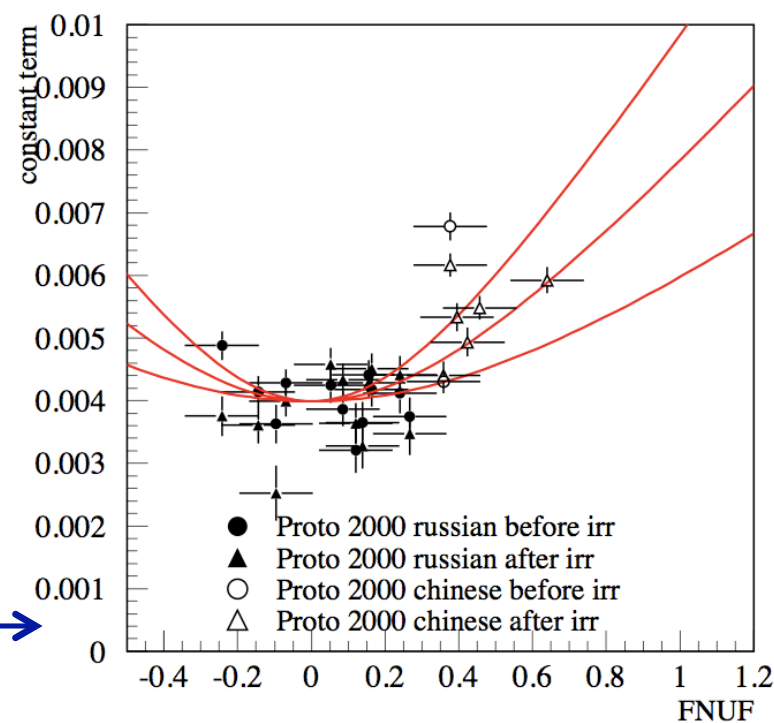
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$



Fit

yields

c1 = 0.67 % and c2 = 0.47%



C2 consistent with σ_{FNUF}/E for all previous MC and
data. See in particular F. Cavallari et al, CMS
IN 2001/033:

c1 = $(0.40 \pm 0.01)\%$ and

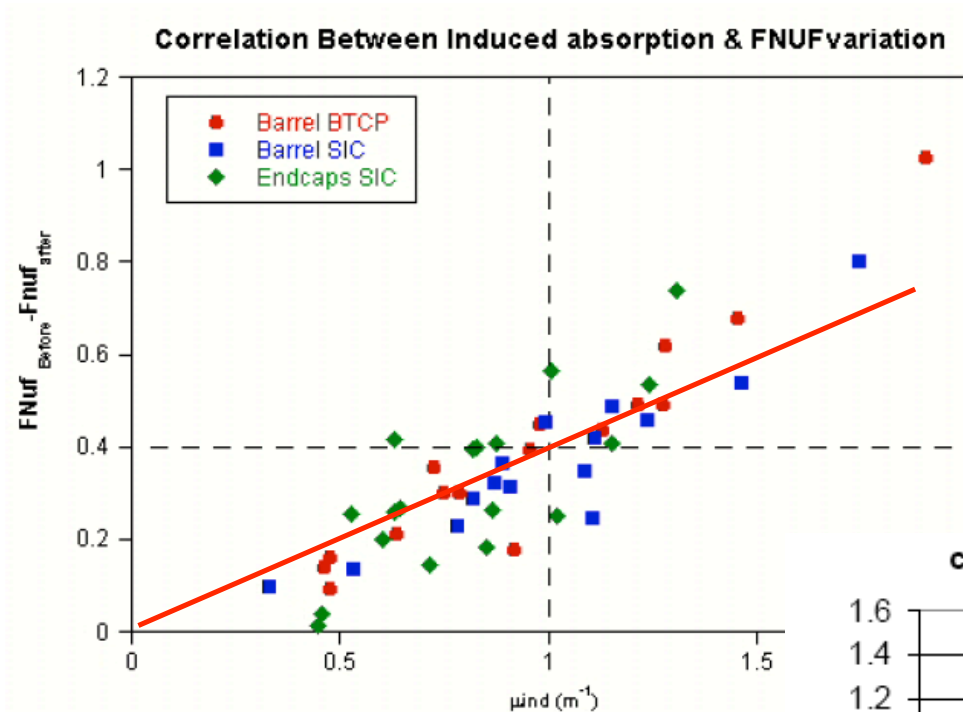
c2 = $(0.68 \pm 0.23)\%$ for $[\text{FNUF}] = \%/X_0$



Correlation FNUF vs μ_{IND}

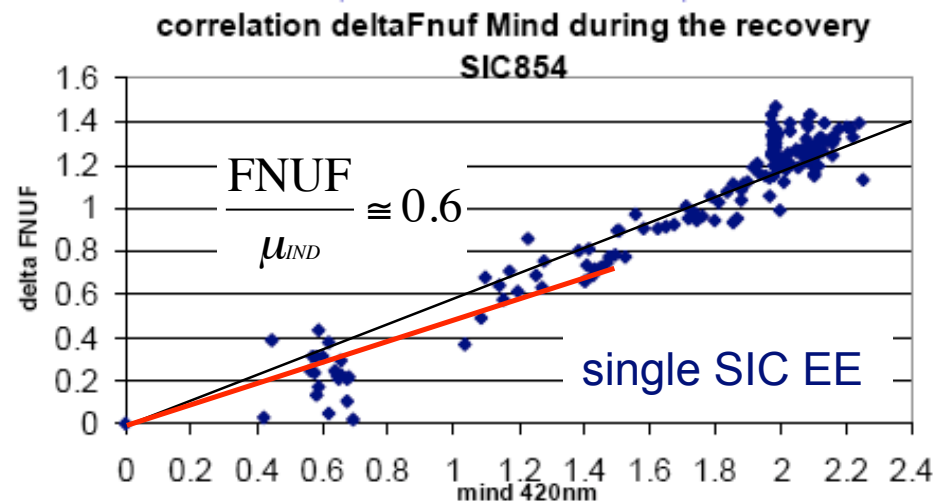


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$$FNUF \approx 0.5 \times \mu_{IND} [m^{-1}]$$

E. Auffray, XPG 21-APR-06, tests at CERN/Hospital



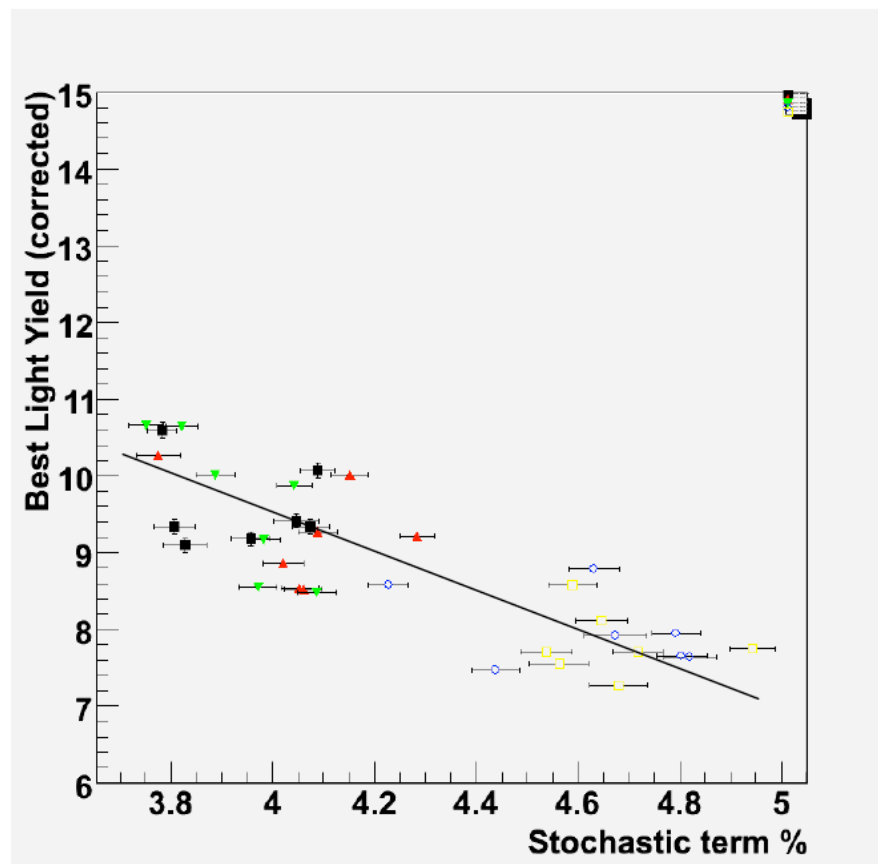
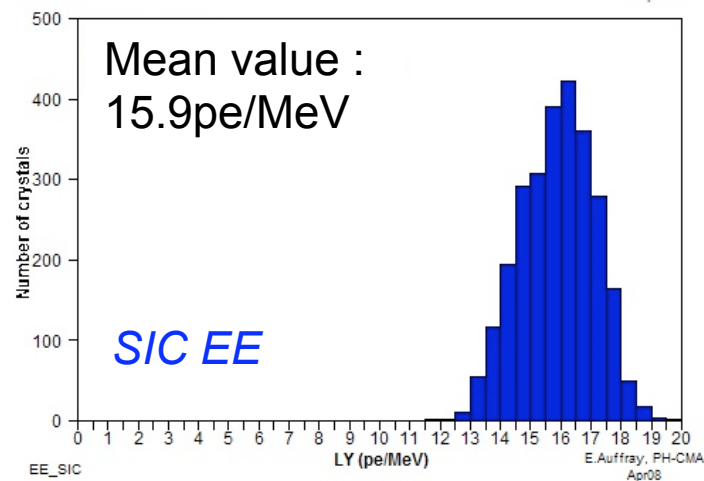
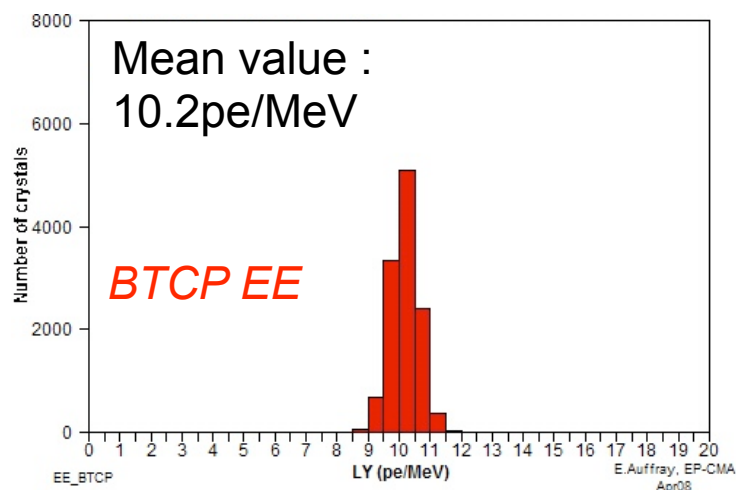


Stochastic term depends on Light Output



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Notice: crystals Light Output varies at production from crystal to crystal, but it changes also due to radiation damage



*P. Jarry, 15-JAN-07, Results from EB Test
Beam campaign 2006*

*E. Auffray, XPG 15-APR-08, Status of
endcap production*

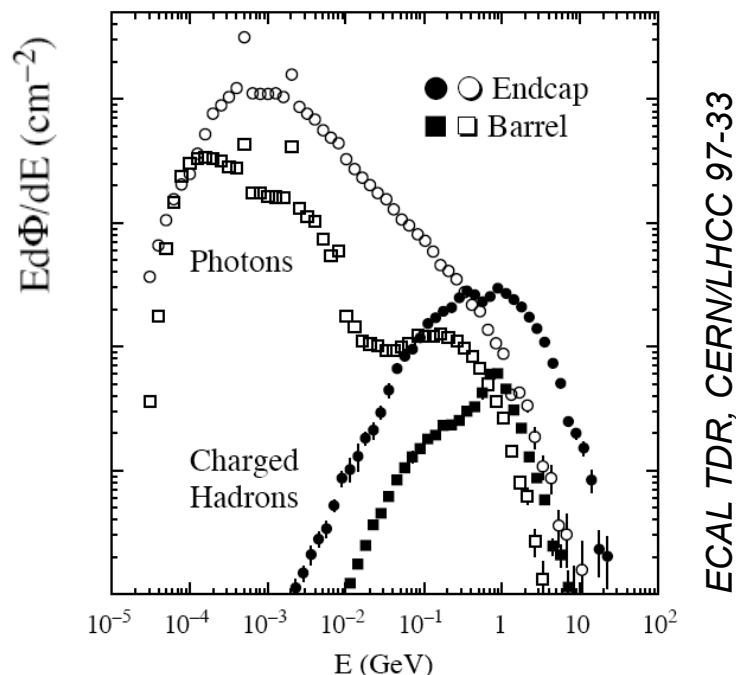


Light Output loss vs μ_{IND}



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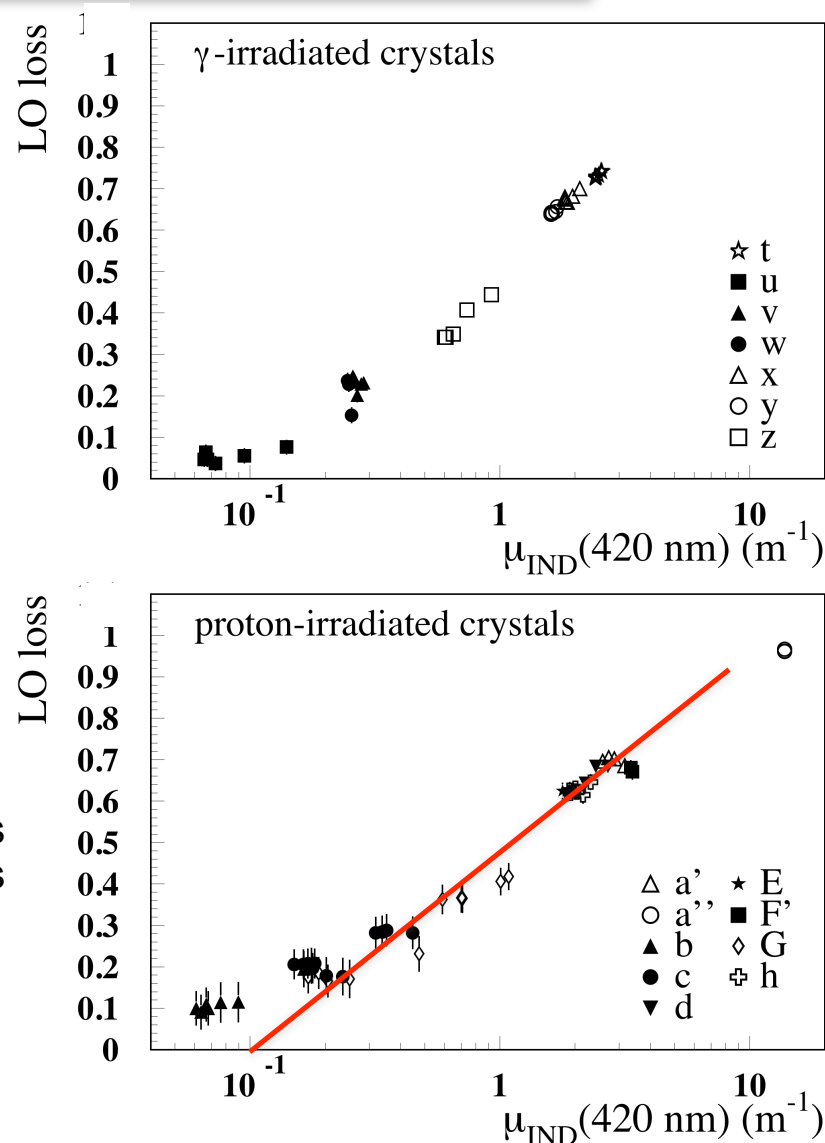
Caveat: ^{60}Co used for most γ tests, but
ECAL spectrum goes to high energies.



Remark: abscissa logarithmic! Light Output loss
flattens for high μ_{IND} values

Very approximative parametrization
VALID ONLY for $0.1 \text{ m}^{-1} \mu_{\text{IND}} < 10 \text{ m}^{-1}$:

$$\text{LO loss} \approx 0.5 \times \log_{10}(\mu_{\text{IND}}) + 0.5$$



P. Lecomte et al., NIM A 564 (2006) 164



Extrapolated evolution of σ/E due to hadron damage



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Typically,

- FNUF [%/X₀] $\approx 0.5 \times \mu_{IND}$ [m⁻¹]
- The contribution [%] to the constant term from FNUF is $\approx 0.6 \times \text{FNUF} [\%/X_0]$ i.e., when FNUF is due to an induced absorption μ_{IND} , it is $\approx 0.3 \times \mu_{IND}$ [m⁻¹]

- The stochastic term contribution due to LO losses increases by a factor
- for $0.1 \text{ m}^{-1} < \mu_{IND} < 10 \text{ m}^{-1}$

$$\frac{1}{0.7 \times \sqrt{1 - \log_{10} \mu_{IND}}}$$

- The noise term contribution due to LO losses increases in the same range by a factor

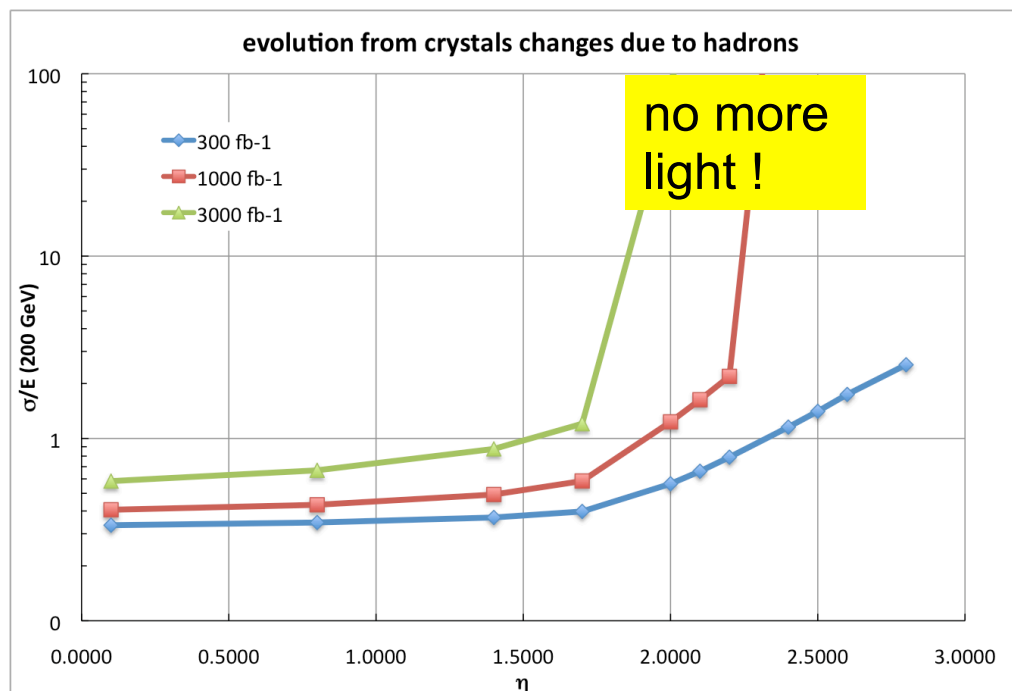
$$\frac{1}{0.5 \times (1 - \log_{10} \mu_{IND})}$$

Example for 200 GeV:

Assume stochastic term 4.5%

Neglect further contributions from

- losses from γ -damage
- damage to VPT glass
- noise from VPT current induced by activated crystals
- Preshower (*E. Auffray et al., NIM A412 (1998) 223*)
- Constant term from other sources



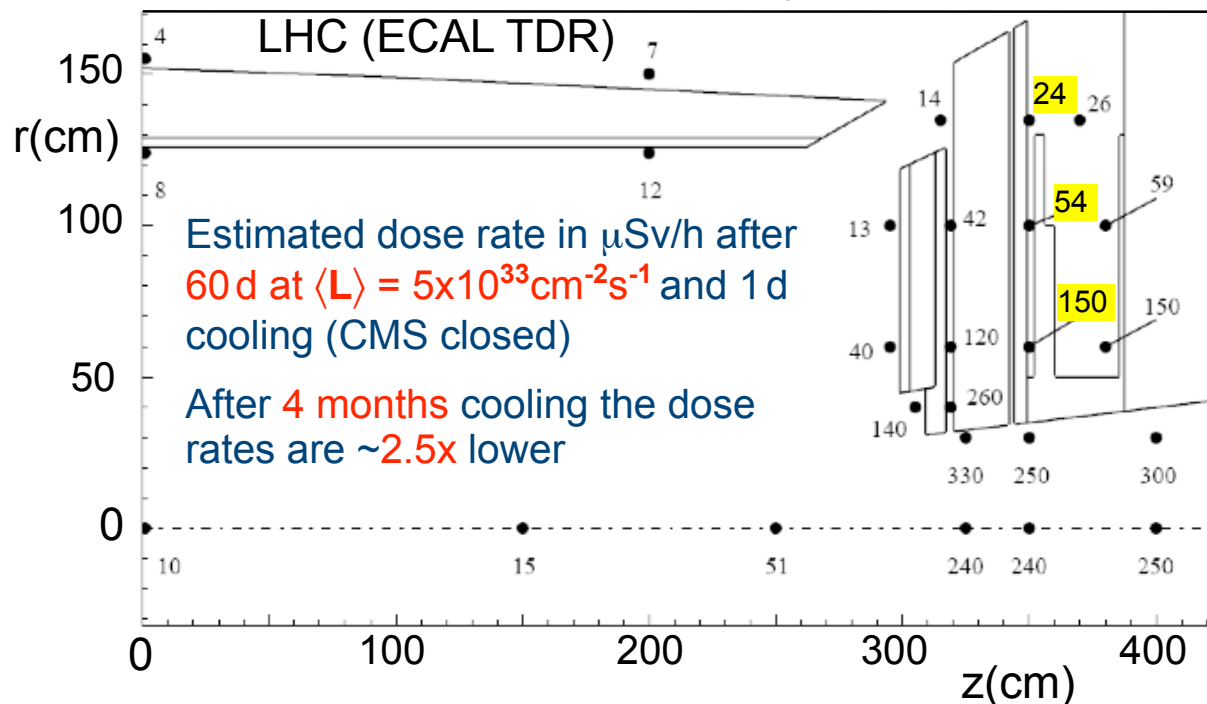


Caveat: EE activation at LHC



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R.M. Brown, EE at SLHC miniworkshop, 15-APR-08



Occupational dose limits:

- 1 mSv/wk
- 15 mSv/yr

Assume induced activity
levels at SLHC $\sim 10 \times$ LHC

The time for a worker
to reach the annual
exposure limit around
the central part of the
EE is ~ 10 h after
CMS has run for 60
days with high L at
SLHC

M. Huhtinen, SLHC electronics workshop, 26-FEB-04:

Dose at short cooling (maintenance) \propto rate

Dose at long cooling (waste) \propto integral

Activity saturates: after 10 y LHC, not much higher than above.

No linear scaling! Maintenance already prohibitive after early high-Luminosity running



Quality of radiation level simulations

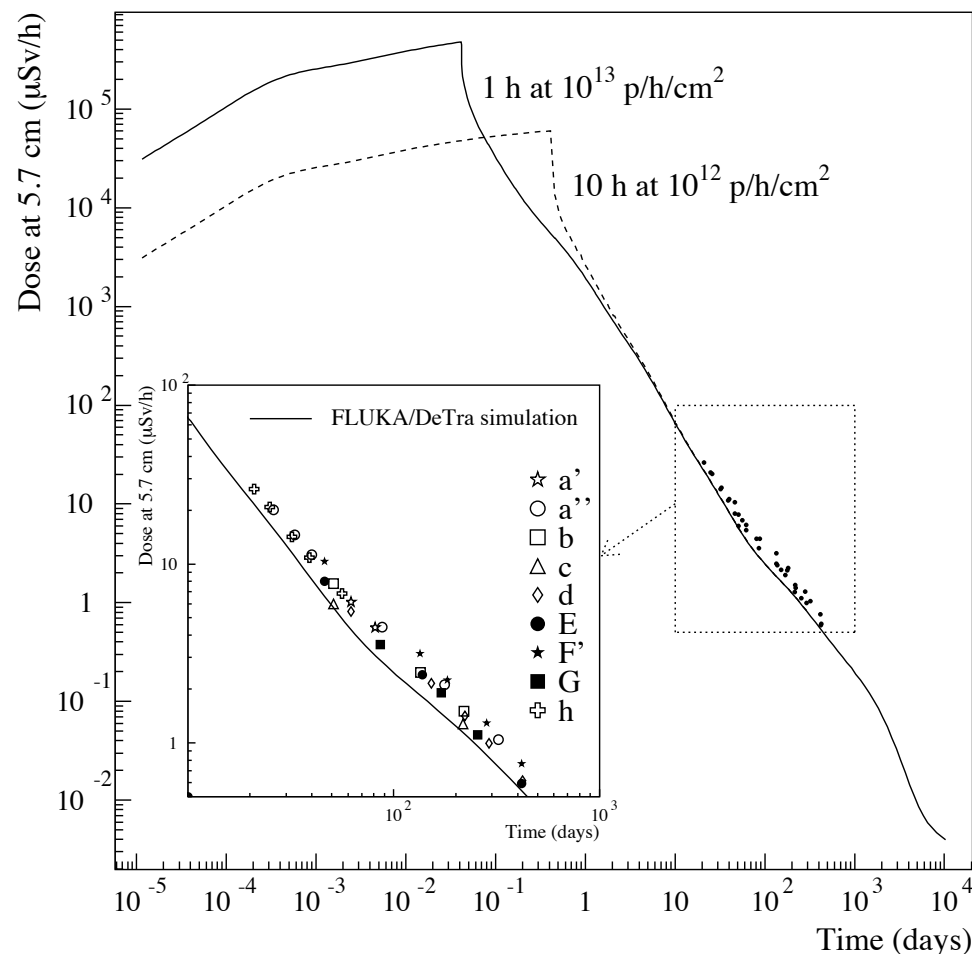


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Comparison between Lead
Tungstate activation measured
after p-irradiation as a function of
cooling time, and the simulated
values (lines).

*M. Huhtinen et al., Nucl. Instr.
Meth. A545 (2005) 63-87*

*Excellent agreement in
magnitude and in cooling over
time.*





Conclusions



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If we trust the hadron irradiation results:

➤ **Crystals:** hadron damage is likely to considerably affect all terms in the energy resolution, starting from large η values inwards, already during LHC running.

Less and less signal from EE over time

In the most extreme scenario, the replacement of PbWO_4 with something else might be necessary.

The anticipated evolution of ECAL performance has to be folded into **physics performance studies at SLHC**.

Physics requirements studies are mandatory to define the work which is necessary for a sufficiently performing ECAL at SLHC

➤ **Activation:** Not to be forgotten, maintenance problems will be prohibitive. No work around high- η region unless robot.