ETH zürich

IPA

Predicting hadron-specific damage from fast hadrons in crystals for calorimetry

G. Dissertori, C. Martín Pérez, F. Nessi-Tedaldi*
ETH Zürich, Switzerland

** Now at Laboratoire Leprince-Ringuet, Ecole Polytechnique, Palaiseau, France*

Experimental evidence in $PbWO_4$, LYSO, CeF_3

Exposure of long (10 – 20 cm) crystals to 24 GeV protons → hadron showers

The Light Transmission is changed (LT0 → LT), quantified by the induced absorption coefficient μ_{IND}

$$\frac{\mathrm{LT}(\lambda)}{\mathrm{LT0}(\lambda)} = e^{-\mu_{\mathrm{IND}}(\lambda) L}$$

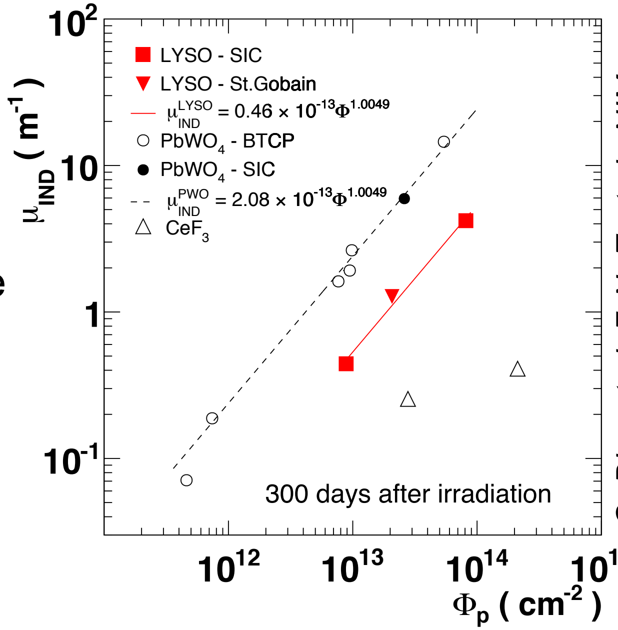
Experimental evidence in $PbWO_4$, LYSO, CeF_3

Exposure of long (10 – 20 cm) crystals to 24 GeV protons → hadron showers

The Light Transmission is changed (LT0 → LT), quantified by the induced absorption coefficient μ_{IND}

$$\frac{LT(\lambda)}{LT0(\lambda)} = e^{-\mu_{IND}(\lambda)L}$$

- Damage cumulative: μ_{IND} increases linearly with fluence



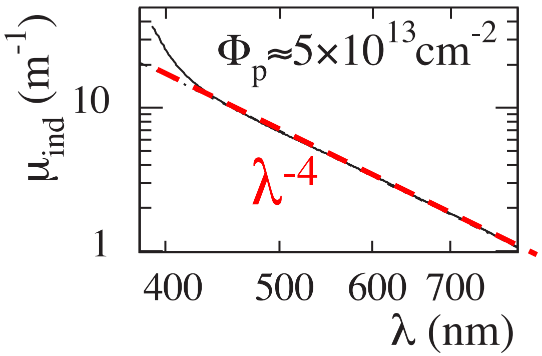
G. Dissertori, F. N.-T. et al., NIM A745 (2014) 1-6

Experimental evidence in $PbWO_4$, LYSO, CeF_3

Exposure of long (10 – 20 cm) crystals to 24 GeV protons → hadron showers

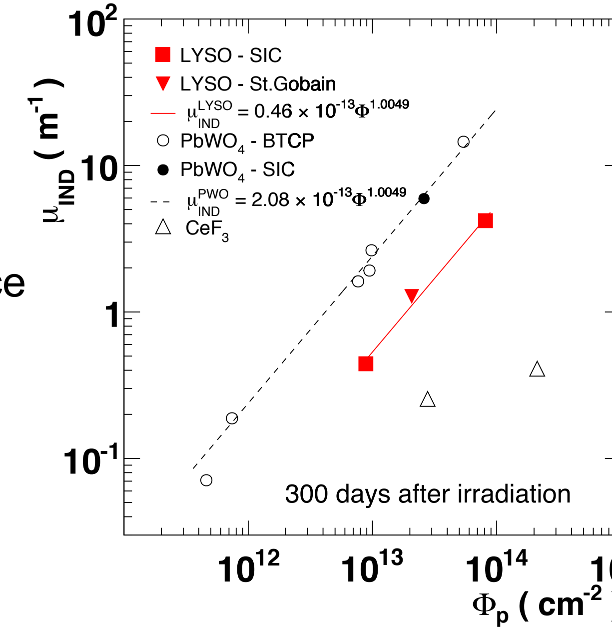
The Light Transmission is changed (LT0 → LT), quantified by the induced absorption coefficient μ_{IND}

$$\frac{\mathrm{LT}(\lambda)}{\mathrm{LT0}(\lambda)} = e^{-\mu_{\mathrm{IND}}(\lambda)L}$$



M. Huhtinen, F.-T. et al., NIM A545 (2005) 63-87

- Damage cumulative: μ_{IND} increases linearly with fluence
- λ^{-4} dependence of μ_{IND}



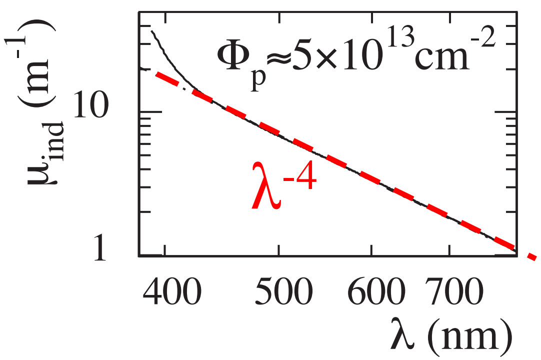
G. Dissertori, F. N.-T. et al., NIM A745 (2014) 1-6

Experimental evidence in $PbWO_4$, LYSO, CeF_3

Exposure of long (10 – 20 cm) crystals to 24 GeV protons → hadron showers

The Light Transmission is changed (LT0 → LT), quantified by the induced absorption coefficient μ_{IND}

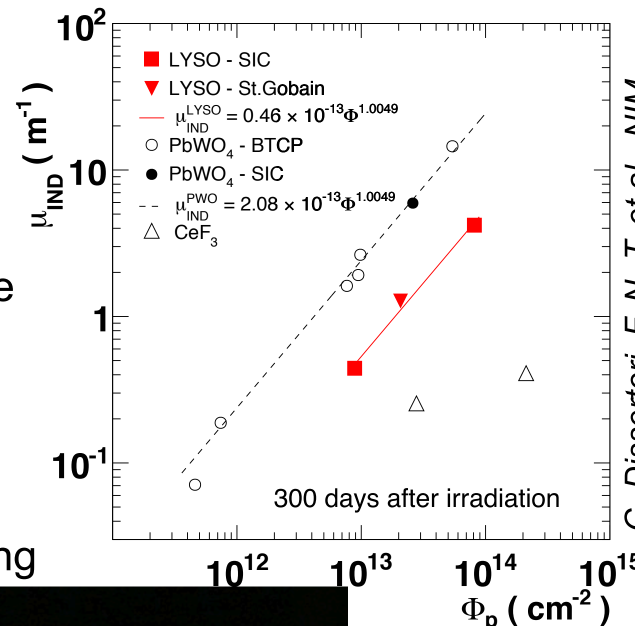
$$\frac{LT(\lambda)}{LT0(\lambda)} = e^{-\mu_{IND}(\lambda) L}$$



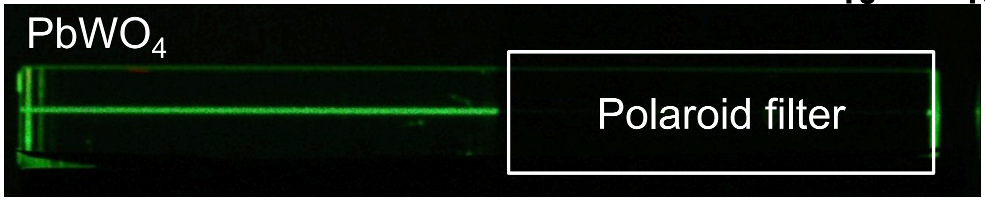
M. Huhtinen, F.-T. et al., NIM A545 (2005) 63-87

- Damage cumulative: μ_{IND} increases linearly with fluence
- λ^{-4} dependence of μ_{IND}
- Laser light is scattered, scattered light is polarized

→ evidence for Rayleigh scattering



G. Dissertori, F. N.-T. et al., NIM A745 (2014) 1-6

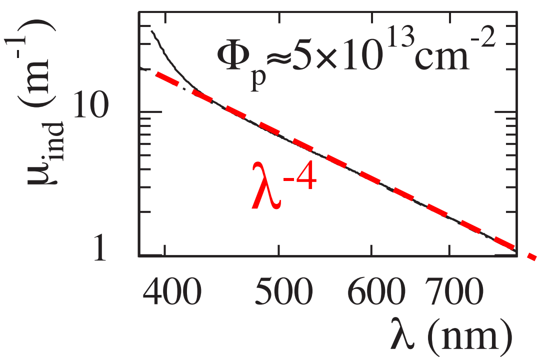


Experimental evidence in $PbWO_4$, LYSO, CeF_3

Exposure of long (10 – 20 cm) crystals to 24 GeV protons → hadron showers

The Light Transmission is changed (LT0 → LT), quantified by the induced absorption coefficient μ_{IND}

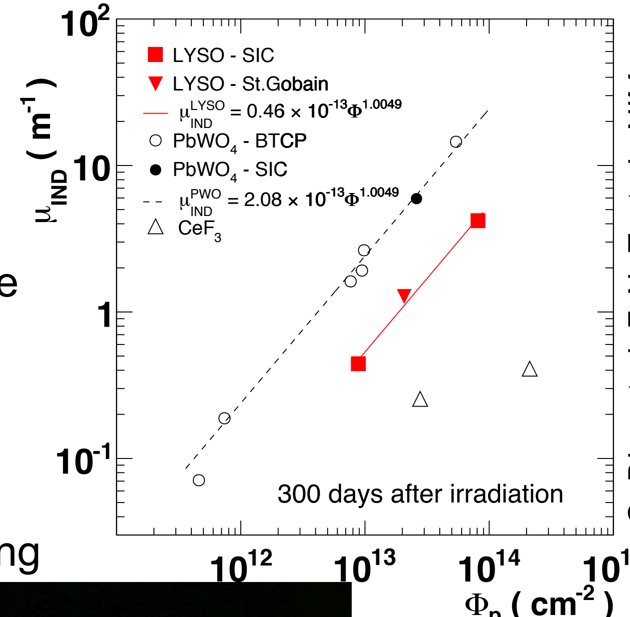
$$\frac{\mathrm{LT}(\lambda)}{\mathrm{LT0}(\lambda)} = e^{-\mu_{\mathrm{IND}}(\lambda)L}$$



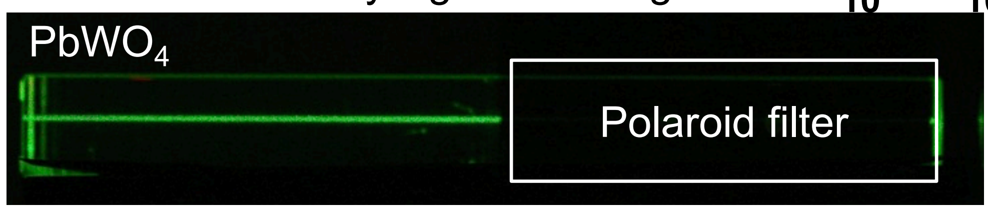
M. Huhtinen, F.-T. et al., NIM A545 (2005) 63-87

- Damage cumulative: μ_{IND} increases linearly with fluence
- λ^{-4} dependence of μ_{IND}
- Laser light is scattered, scattered light is polarized

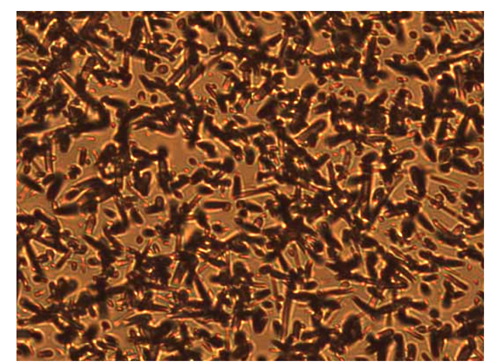
→ evidence for Rayleigh scattering



G. Dissertori, F. N.-T. et al., NIM A745 (2014) 1-6



- The scattering centers are tracks left by fission fragments
- Tracks have been visualized → *see talk today at 10h45*

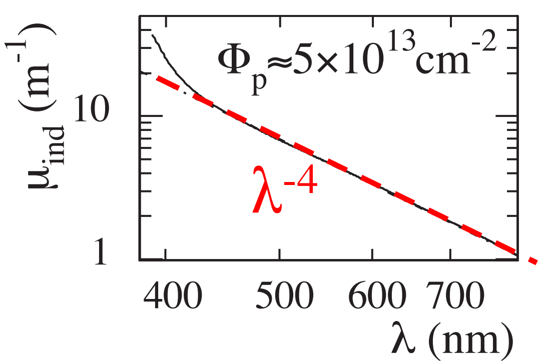


Experimental evidence in $PbWO_4$, LYSO, CeF_3

Exposure of long (10 – 20 cm) crystals to 24 GeV protons → hadron showers

The Light Transmission is changed (LT0 → LT), quantified by the induced absorption coefficient μ_{IND}

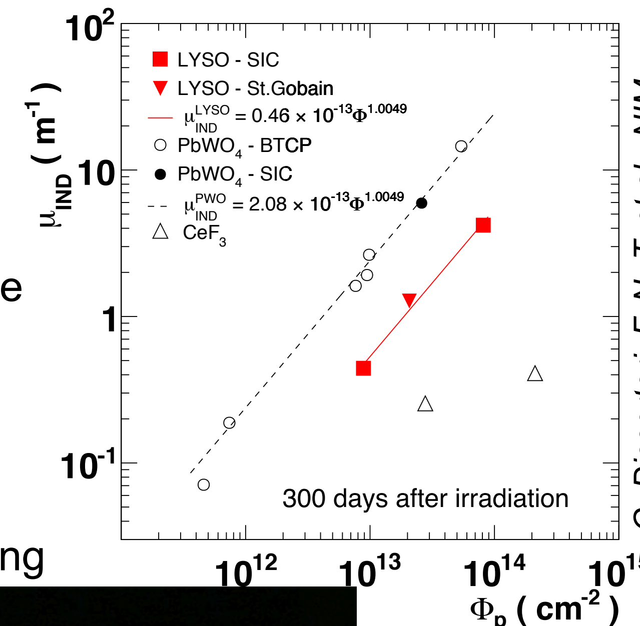
$$\frac{\mathrm{LT}(\lambda)}{\mathrm{LT0}(\lambda)} = e^{-\mu_{\mathrm{IND}}(\lambda)L}$$



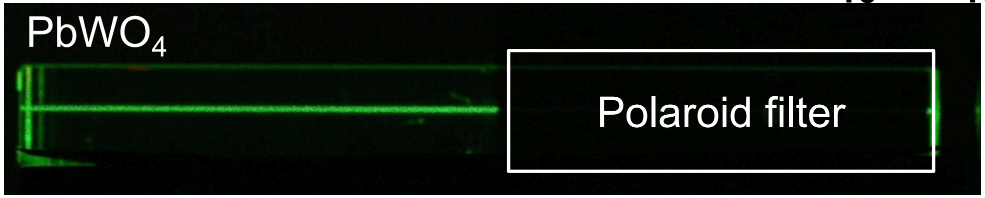
M. Huhtinen, F.-T. et al., NIM A545 (2005) 63-87

- Damage cumulative: μ_{IND} increases linearly with fluence
- λ^{-4} dependence of μ_{IND}
- Laser light is scattered, scattered light is polarized

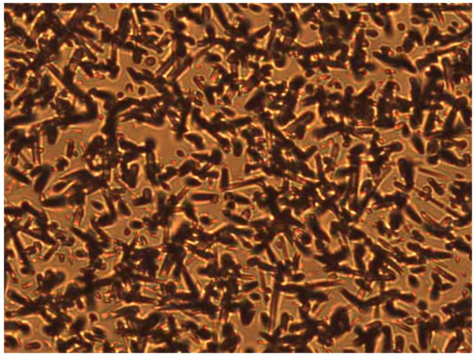
→ evidence for Rayleigh scattering



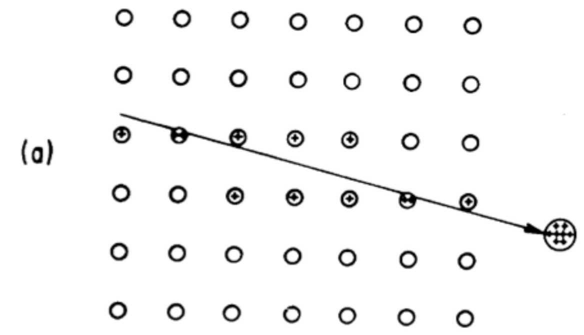
G. Dissertori, F. N.-T. et al., NIM A745 (2014) 1-6



- The scattering centers are tracks left by fission fragments
- Tracks have been visualized → *see talk today at 10h45*
- No scattering centers observed in CeF_3 *(NIM A622 (2010) 41-48)*, as expected, since made of light elements, while fission threshold Z>71 *(Iljinov et al., PR C39 (1989) 1420)*



Mechanism for track formation



Present understanding:

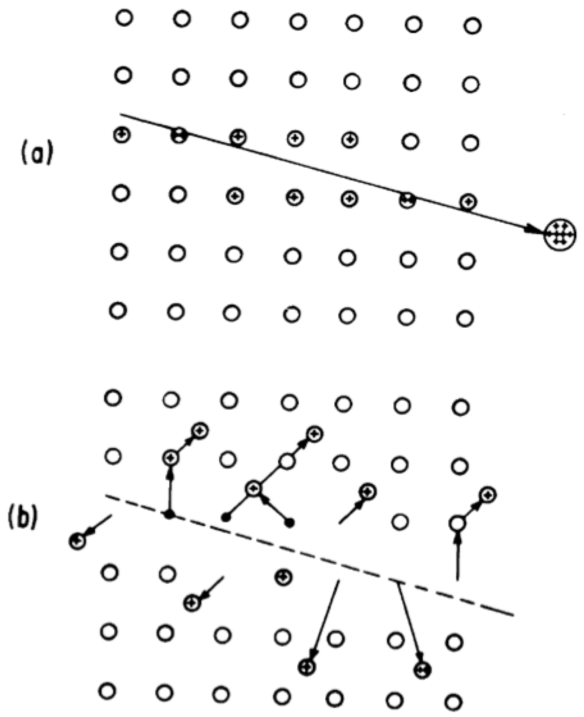
R. Fleischer, J. Mat. Sci. 39 (2004) 3901 and refs.

- Track formation is explained by the ionization spike model, a 3-stage process
  a) a charged particle passage causes ionization

Mechanism for track formation

Present understanding:

R. Fleischer, J. Mat. Sci. 39 (2004) 3901 and refs.



– Track formation is explained by the ionization spike model, a 3-stage process
  a) a charged particle passage causes ionization
  b) ions are ejected due to Coulomb repulsion

Mechanism for track formation

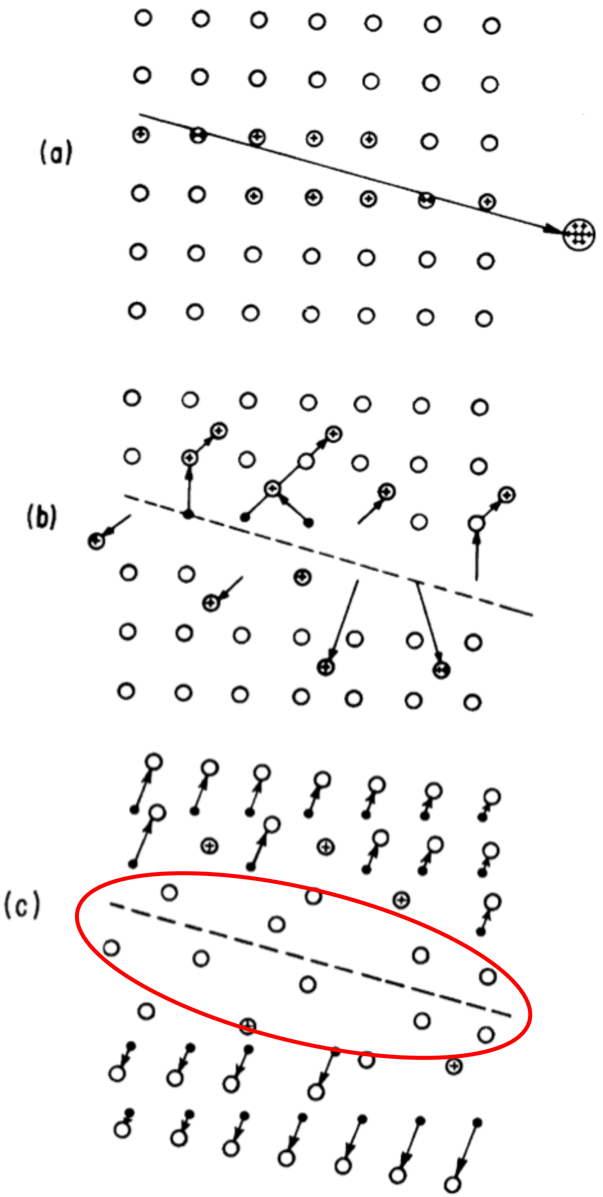
Present understanding:

R. Fleischer, J. Mat. Sci. 39 (2004) 3901 and refs.

- Track formation is explained by the ionization spike model, a 3-stage process
  - a) a charged particle passage causes ionization
  - b) ions are ejected due to Coulomb repulsion
  - c) a region of atomic disorder is left behind

- Main parameter: primary ionization density

  N. electrons displaced / unit length



Mechanism for track formation

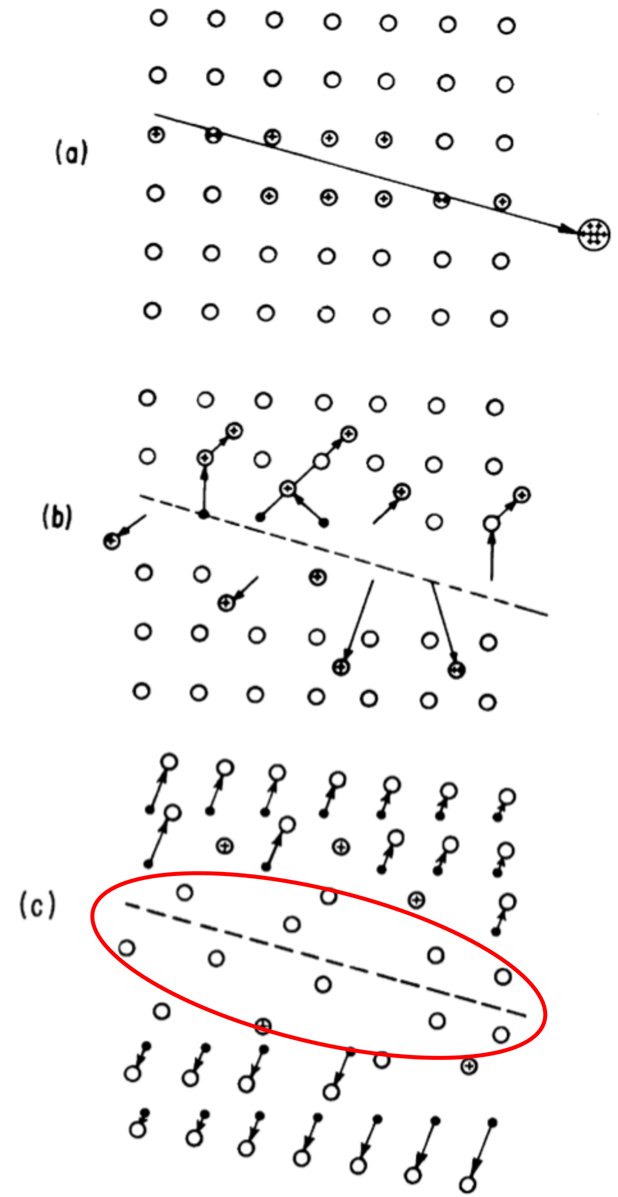
Present understanding:

R. Fleischer, J. Mat. Sci. 39 (2004) 3901 and refs.

- Track formation is explained by the ionization spike model, a 3-stage process
  - a) a charged particle passage causes ionization
  - b) ions are ejected due to Coulomb repulsion
  - c) a region of atomic disorder is left behind
- Main parameter: primary ionization density

  N. electrons displaced / unit length

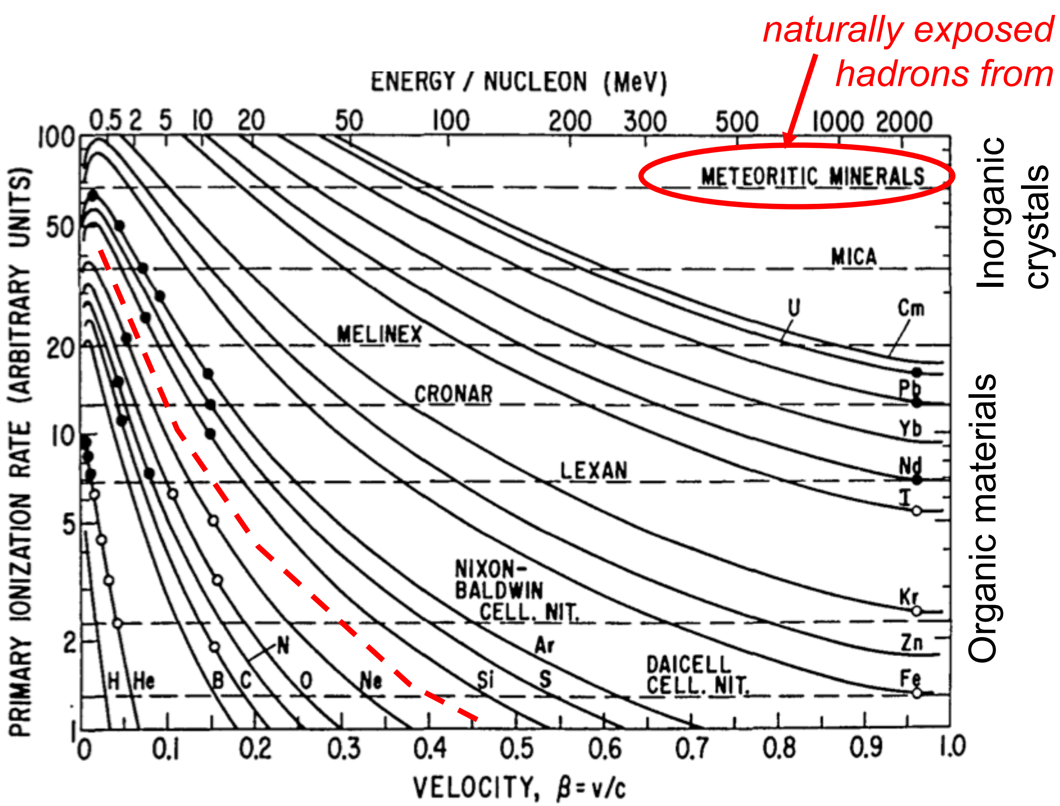
- This is bulk damage, it can be studied in simulations of track lengths and densities



Tracks are caused by heavy fragments

R. Fleischer, Intermetallic Compounds, Wiley Ed. 2002

- From experimental data
- Track formation is observed above a material-specific ionization density threshold
- Common threshold for all projectile hadrons in a given material
- Higher thresholds for inorganic crystals than for organic materials



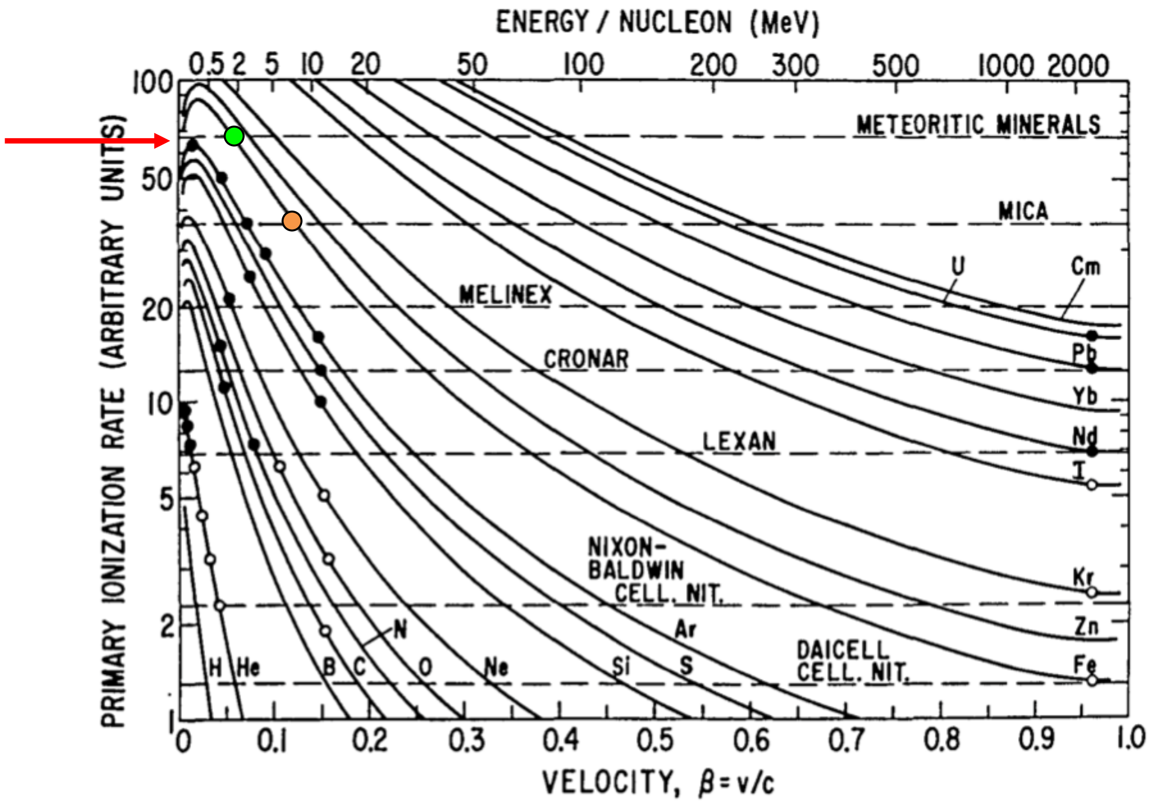
- Black dots: tracks observed
- White dots: no tracks

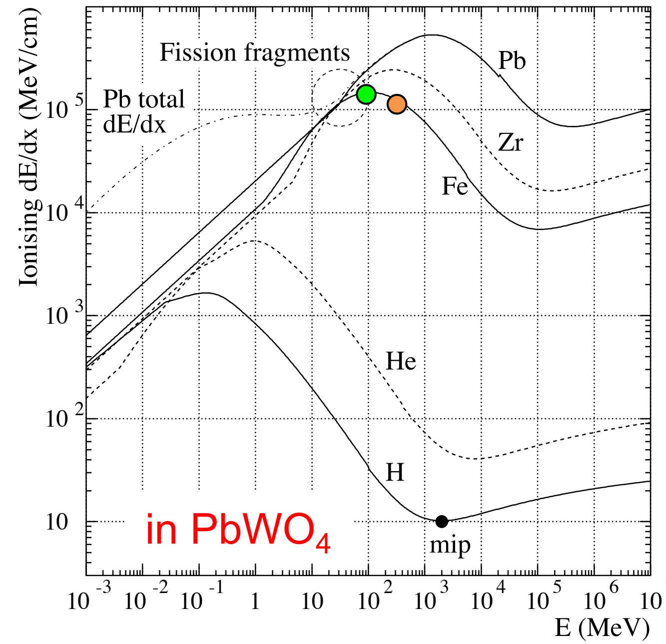
In inorganic crystals

Tracks formed for projectile A > 30

No tracks formed for projectile A < 20

Ionisation rate thresholds in minerals





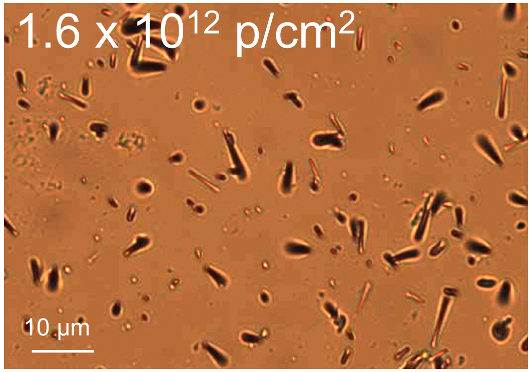
M. Huhtinen, F. N.-T. et al., NIM A545 (2005) 63 - 87

- For ^{56}Fe in meteoritic minerals, E/A ≅ 2 MeV/amu ⟷ dE/dx ≅ 1.5x10^5 MeV/cm in $PbWO_4$
- For ^{56}Fe in mica, E/A ≅ 7 MeV/amu ⟷ dE/dx ≅ 1x10^5 MeV/cm in $PbWO_4$

> 1x10^5 MeV/cm needed to create a track !

The structure of tracks

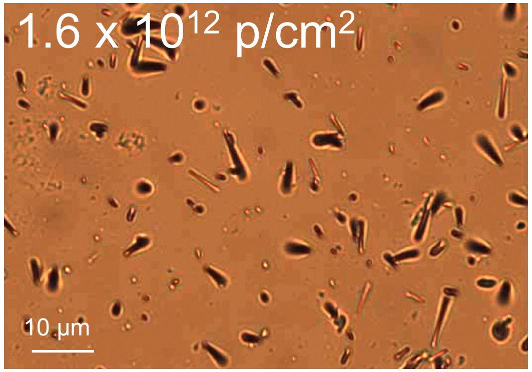
- Fission tracks are usually revealed through etching, that removes the disordered regions and makes them visible under the microscope



The structure of tracks

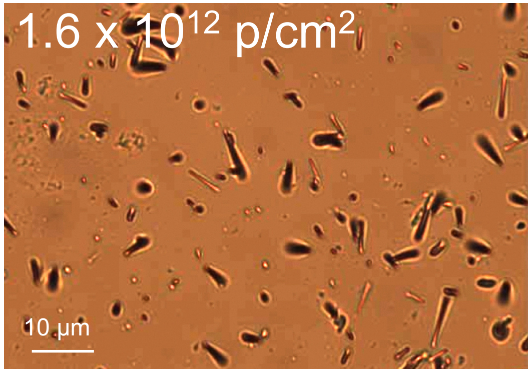
- Fission tracks are usually revealed through etching, that removes the disordered regions and makes them visible under the microscope

- However: calorimeter light is scattered by tracks which are latent



The structure of tracks

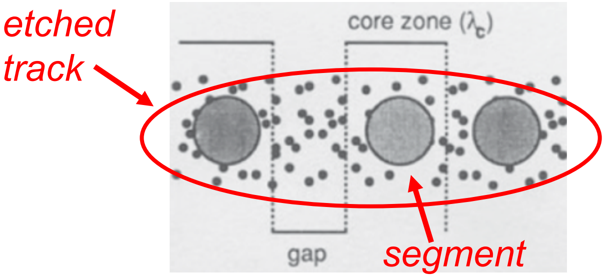
- Fission tracks are usually revealed through etching, that removes the disordered regions and makes them visible under the microscope



- However: calorimeter light is scattered by tracks which are latent

- Track studies tell us that :
  - Tracks can be composed by regions of extended defects (core zones, "segments"), with gaps of limited damage in between[1,2)]
  - The gaps are etched more slowly
  - Core diameters a few nm[3)] and lengths depending on projectile dE/dx
  - Light in calorimeter material scatters against segments
  - We follow a pragmatic approach:

$$dE/dx \gtrsim 1\times10^{5}\ \mathrm{MeV/cm}$$



1) E. Dartyge et al., Phys. Rev. B23 (1981) 5213
2) L.T. Chadderton, Nature 195 (1962) 987
3) K. Yada et al., Phys. Chem. Minerals 7 (1981) 47-52

Rayleigh scattering

- Rayleigh scattering (RS) cross section:

$$\sigma_{RS}\ \alpha\ \frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$$

d = dimension of scatterers
λ_{PWO} = 420 nm, λ_{LYSO} = 425 nm
n_{PWO}= 2.2, n_{LYSO}=1.82 , indexes of refraction

Rayleigh scattering

- Rayleigh scattering (RS) cross section:

$$\sigma_{RS} \; \alpha \; \frac{d^6}{\lambda^4} \left(\frac{n^2 - 1}{n^2 + 2} \right)^2$$

d = dimension of scatterers
λ_{PWO} = 420 nm, λ_{LYSO} = 425 nm
n_{PWO}= 2.2, n_{LYSO}=1.82 , indexes of refraction

- Fraction of Rayleigh scattered light:
(N = density of scatterers)

$$F_{RS} = N \times \sigma_{RS}$$

Rayleigh scattering

- Rayleigh scattering (RS) cross section:

$$\sigma_{RS} \; \alpha \; \frac{d^6}{\lambda^4} \left(\frac{n^2 - 1}{n^2 + 2} \right)^2$$

d = dimension of scatterers
λ_{PWO} = 420 nm, λ_{LYSO} = 425 nm
n_{PWO}= 2.2, n_{LYSO}=1.82 , indexes of refraction

- Fraction of Rayleigh scattered light:
(N = density of scatterers)

$$F_{RS} = N \times \sigma_{RS}$$

- Intensity of transmitted light:

$$I = I_0 e^{-\mu L}$$

$$\Rightarrow \; F_{RS} = \frac{I_0 - I}{I_0} \simeq \mu L$$

Rayleigh scattering

- Rayleigh scattering (RS) cross section:

$$\sigma_{RS} \; \alpha \; \frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$$

d = dimension of scatterers
λ_{PWO} = 420 nm, λ_{LYSO} = 425 nm
n_{PWO}= 2.2, n_{LYSO}=1.82 , indexes of refraction

- Fraction of Rayleigh scattered light:
(N = density of scatterers)

$$F_{RS} = N \times \sigma_{RS}$$

- Intensity of transmitted light:

$$I = I_0 e^{-\mu L} \quad \Rightarrow \quad F_{RS} = \frac{I_0 - I}{I_0} \simeq \mu L$$

- Induced absorption ratio between $PbWO_4$ and LYSO:

$$R_\mu = \frac{\mu^{PWO}}{\mu^{LYSO}} = 1.8 \times \frac{N^{PWO}}{N^{LYSO}} \times \left(\frac{d^{PWO}}{d^{LYSO}}\right)^6$$

measured: R_μ = 4.5 ± 0.2*

→ Can simulations reproduce this ratio?

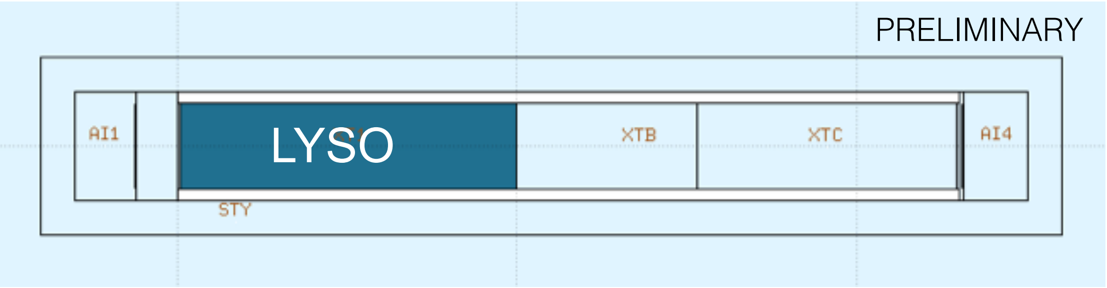
* *uncertainty inferred from publication*

FLUKA simulations

A. Ferrari, P.R. Sala, A. Fassò, J. Ranft, "FLUKA: a multi-particle transport code", CERN-2005-10 (2005)

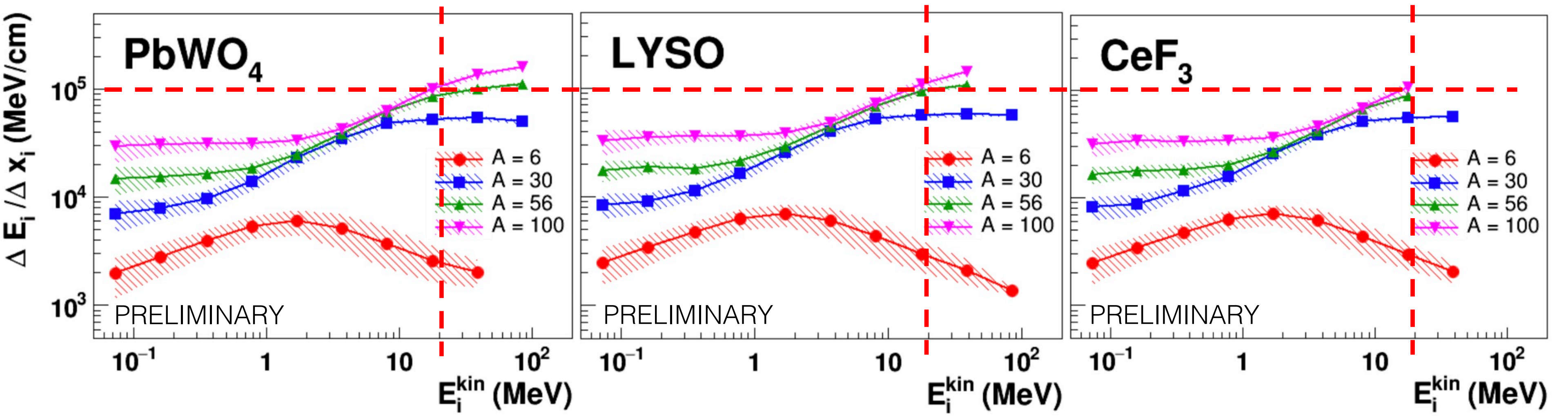
Experimental irradiation setups reproduced

- Irradiation facility IRRAD1 of the CERN PS T7 beam line
- Proton beam of 20, resp. 24 GeV, 700000 events generated
- Crystal shapes and compositions: $PbWO_4$ 24x24x230 mm^3, Ce:LYSO 25x25x100 mm^3
- Scoring of quantities of interest inside the crystal performed according to experimental measurement conditions



Features of infinitesimal steps

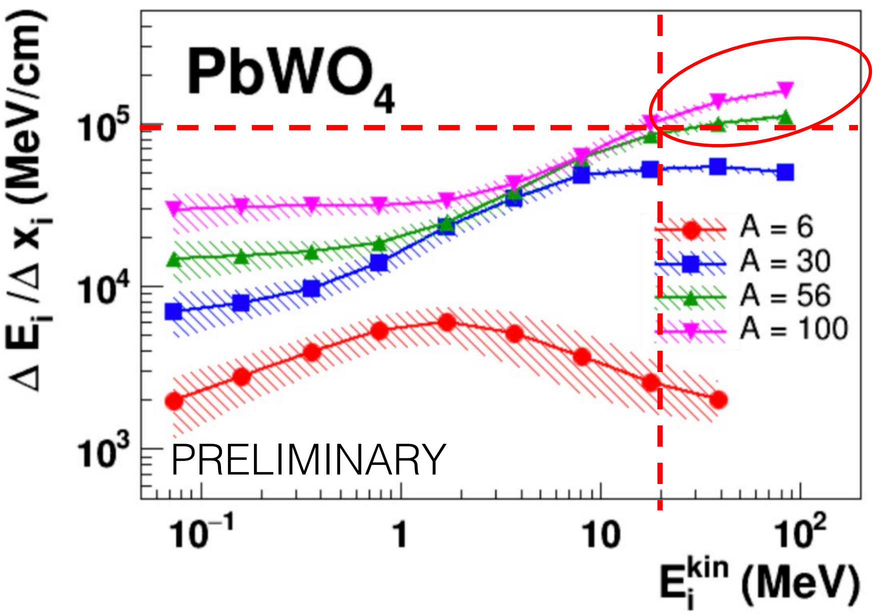
- In FLUKA, at every infinitesimal step Δx_i of a particle, calculate $dE/dx \cong \Delta E_i/\Delta x_i$
- Plot $<\Delta E_i/\Delta x_i>$, averaged over all steps, for each bin of E^{kin}
- Band = RMS

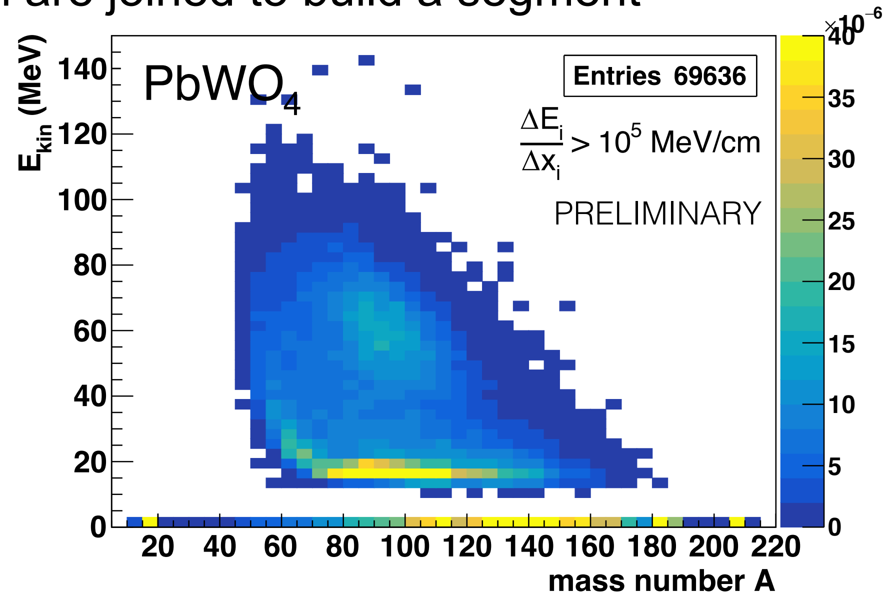


- In $PbWO_4$ and LYSO, $dE/dx > 10^5$ MeV/cm reached for heavy fragments only
- In $PbWO_4$, heavy fragments populate higher dE/dx region than in LYSO
- In CeF_3, $dE/dx > 10^5$ MeV/cm region is not populated → in agreement with experimental evidence of no hadron-specific damage

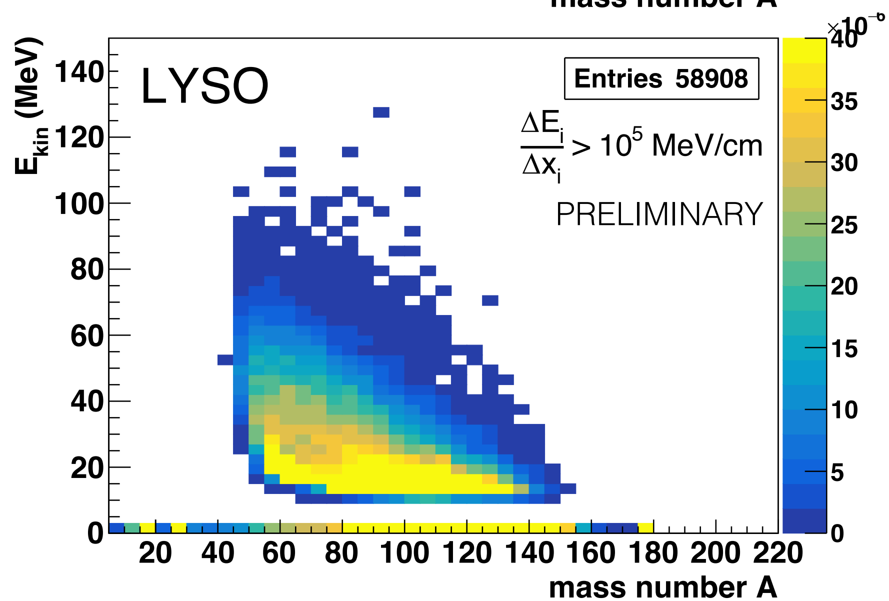
Features of segments

- Contiguous steps with dE/dx > 10^5 MeV/cm are joined to build a segment



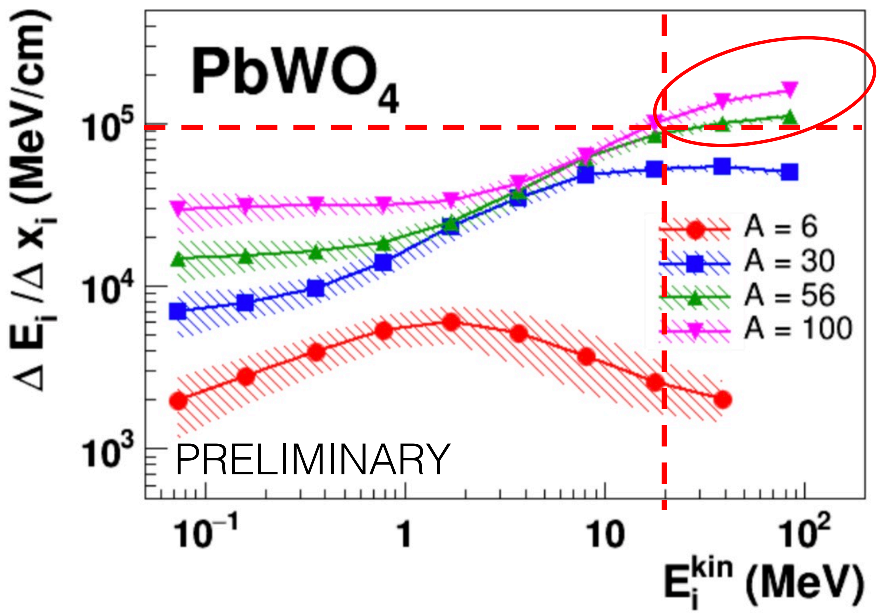


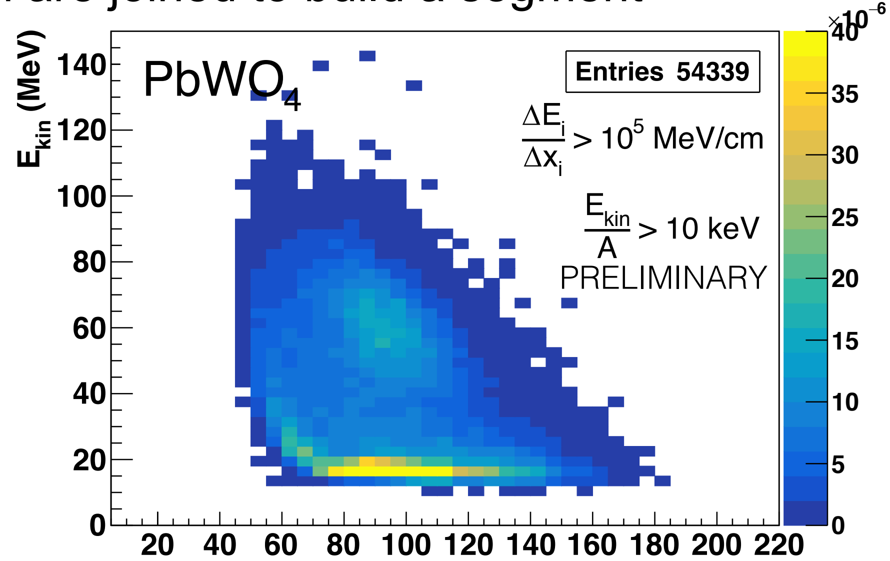
- Low-A fragments exhibit dE/dx below the threshold for track creation
- Fragments with A > 40 and highest E_{kin} are the ones that reach a sufficient dE/dx
- Entries at $E_{kin} \sim 0$?

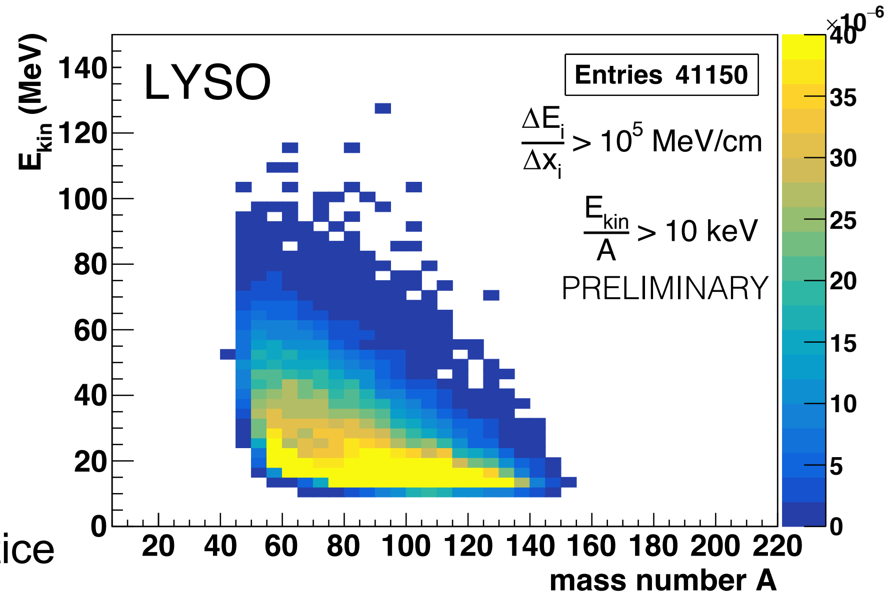


Features of segments

- Contiguous steps with dE/dx > 10^5 MeV/cm are joined to build a segment



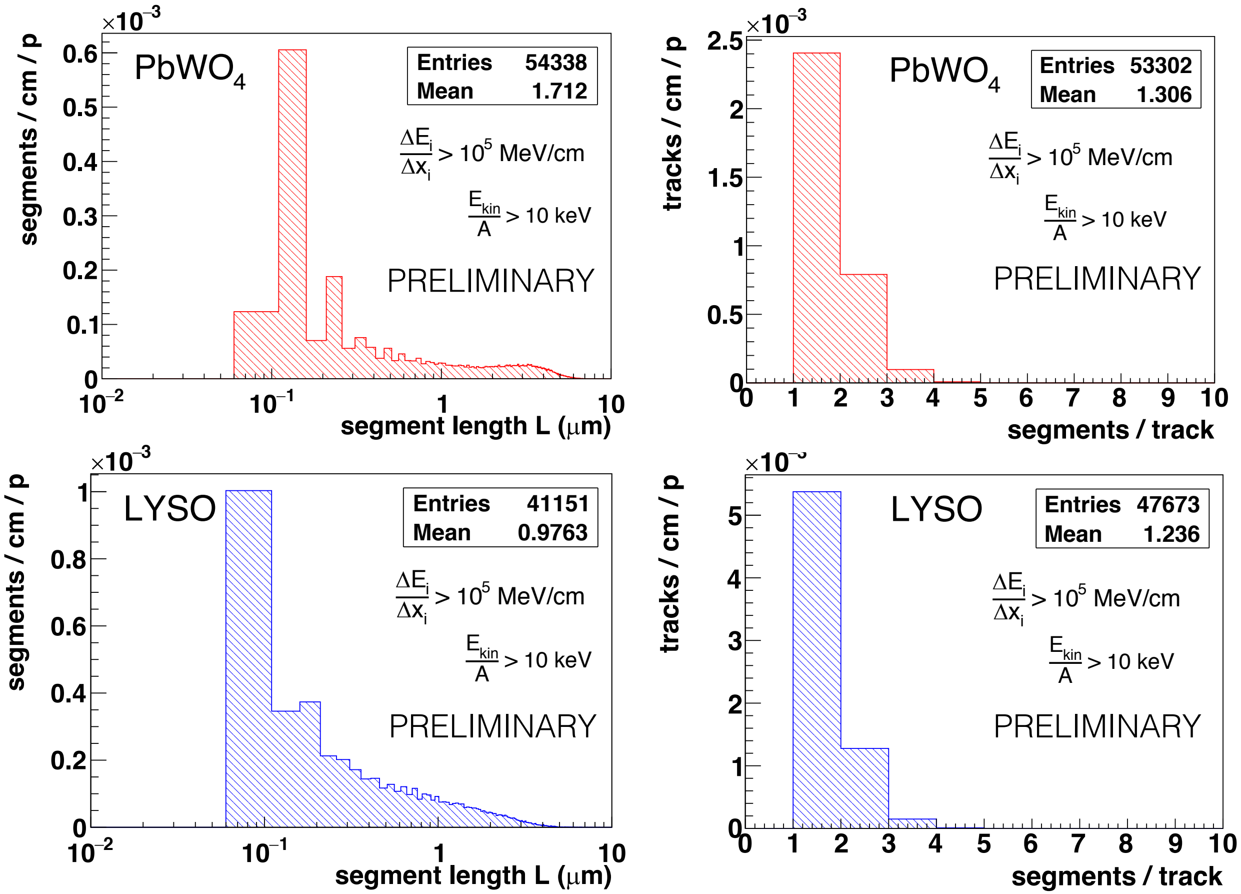




- Low-A fragments exhibit dE/dx below the threshold for track creation
- Fragments with A > 40 and highest E_{kin} are the ones that reach a sufficient dE/dx
- Entries at $E_{kin} \sim 0$ disappear by requiring $E_{kin}/A > 10$ keV
  - They are fragments that do not move from their location in the lattice
  - Δx_{max} = 10 keV / (10^5 MeV/cm) = 10 Å ~lattice cell size

Segment and track length distributions

- Track = one or more track segments separated by gaps where dE/dx falls below threshold
- Densities and average track length for comparison with observed ones



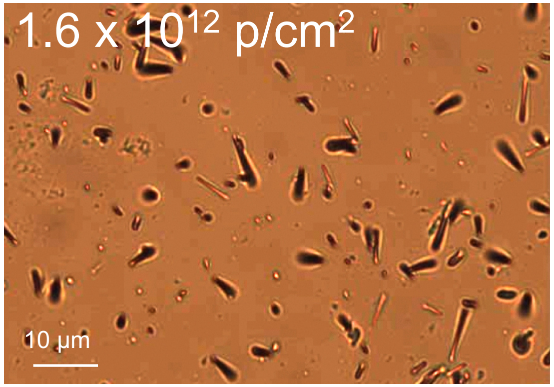
700000 events generated

- In average, 1.3 segments per track, in qualitative agreement with experimental observations[4,5)]

4) E. Dartyge et al., Phys. Rev. B23 (1981) 5213
5) L.T. Chadderton, Nature 195 (1962) 987

Compare observed and simulated densities

Tracks visualised in $PbWO_4$ (→ see talk today at 10h45): Fission tracks are usually revealed through etching. The etching process dissolves also gaps between segments and joins segments into tracks.



Measurement: the density of etched tracks crossing a surface is

$$\varphi = 1.8 \times 10^{-6} \text{ tracks/p}$$

FLUKA: the density ρ_{seg} of segments produced in the crystal is

$$\rho_{seg} = 3.4 \times 10^{-3} \text{ seg cm}^{-3} / (\text{p cm}^{-2})$$

With 1.3 segments/track, the density ρ_{track} of tracks produced in the crystal is :

$$\rho_{track} = 2.6 \times 10^{-3} \text{ tracks cm}^{-3} / (\text{p cm}^{-2})$$

- The average track length <L> is given by: $\rho_{track} \langle L \rangle = \varphi$

→ <L> = 7 µm , ~ as observed

→ the simulated track densities agree with the observed ones

Can we predict the Rayleigh Scattering ratio?

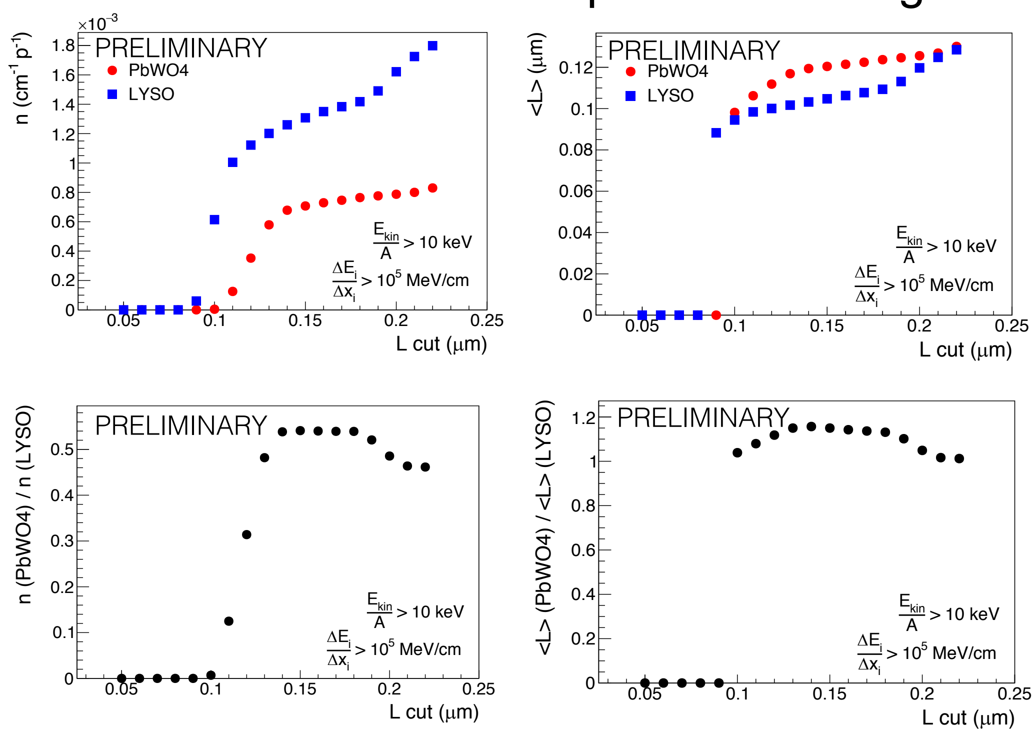
- Induced absorption ratio between $PbWO_4$ and LYSO:

$$R_\mu = \frac{\mu^{PWO}}{\mu^{LYSO}} = 1.8 \times \underbrace{\frac{N^{PWO}}{N^{LYSO}}}_{R_N} \times \underbrace{\left(\frac{d^{PWO}}{d^{LYSO}}\right)^6}_{R_d}$$

measured ratio: $R_\mu = 4.5 \pm 0.2$

Caveats:

- RS assumes spheres. Here: dipole-shaped tracks, randomly oriented
- RS occurs if scatterer dimension ≲ (λ/10)
- Cannot determine a sharp maximum segment length L_{cut}



→ Look at quantities as a function of $L_{cut} \sim \mathcal{O}$ (λ/10)

Can we predict the Rayleigh Scattering ratio?

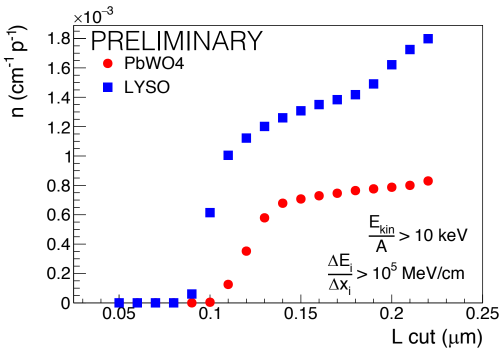
- Induced absorption ratio between $PbWO_4$ and LYSO:

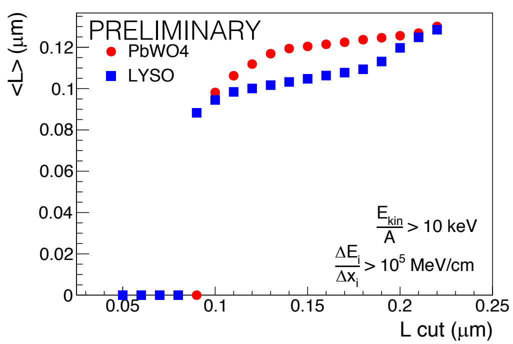
$$R_\mu = \frac{\mu^{PWO}}{\mu^{LYSO}} = 1.8 \times \underbrace{\frac{N^{PWO}}{N^{LYSO}}}_{R_N} \times \underbrace{\left(\frac{d^{PWO}}{d^{LYSO}}\right)^6}_{R_d}$$

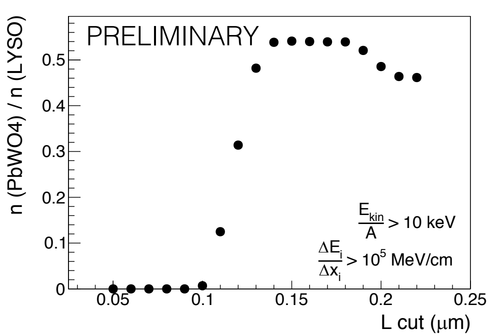
measured ratio: $R_\mu = 4.5 \pm 0.2$

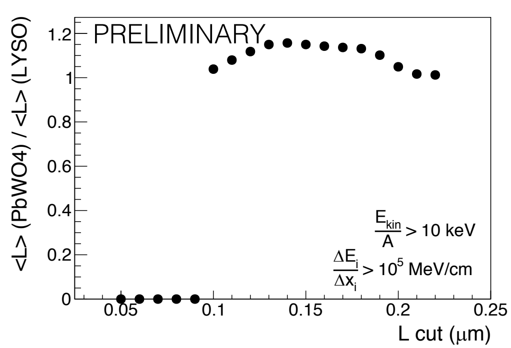
Caveats:

- RS assumes spheres. Here: dipole-shaped tracks, randomly oriented
- RS occurs if scatterer dimension ≲ (λ/10)
- Cannot determine a sharp maximum segment length L_{cut}

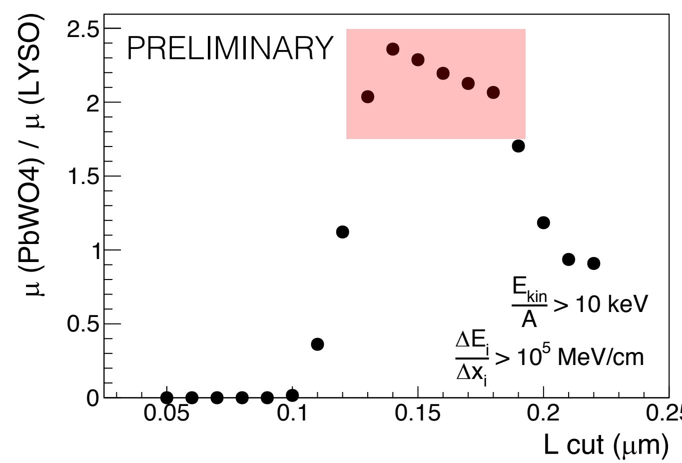








→ Look at quantities as a function of $L_{cut} \sim \mathcal{O}$ (λ/10)



From FLUKA: $R_\mu \simeq 2.5$

Uncertainties

Uncertainties are mainly due to simplified assumptions:

1) A common L_{cut} has been used on both, $PbWO_4$ and LYSO → ΔRμ = ± 0.4
2) Uncertainty on lenght ratio $\Delta R_L = \pm 5\%$ → $\Delta R_\mu = \pm 0.8$
3) Uncertainty on the dE/dx threshold → $\Delta R_\mu = \pm 0.2$
4) A common dE/dx has been used on both, $PbWO_4$ and LYSO → ΔRμ = ± 0.3
5) Total estimated uncertainty ΔRμ = 1.0

FLUKA result:
$R_\mu = 2.5 \pm 1.0$

Uncertainties

Uncertainties are mainly due to simplified assumptions:

1) A common L_{cut} has been used on both, $PbWO_4$ and LYSO → ΔRμ = ± 0.4
2) Uncertainty on lenght ratio ΔR_L= ± 5%→ ΔR_μ = ± 0.8
3) Uncertainty on the dE/dx threshold → ΔR_μ = ± 0.2
4) A common dE/dx has been used on both, $PbWO_4$ and LYSO →ΔRμ = ± 0.3
5) Total estimated uncertainty ΔRμ = 1.0

FLUKA result:
$R_\mu = 2.5 \pm 1.0$

Measured ratio:
$R_\mu = 4.5 \pm 0.2$

FLUKA simulations yield a Rayleigh Scattering amplitude ratio between $PbWO_4$ and LYSO that is consistent, within the uncertainties, with the measured one

Conclusions

From a simulation study of long crystals irradiated by 24 GeV protons producing hadron showers we have learned that:

1) FLUKA simulations yield no heavy, highly ionizing fragments in CeF_3, as would be needed for track creation, in agreement with the absence of hadron specific damage

2) FLUKA simulations yield heavy, highly ionizing fragments in $PbWO_4$ and LYSO, as needed for track creation, in agreement with the observed hadron specific damage

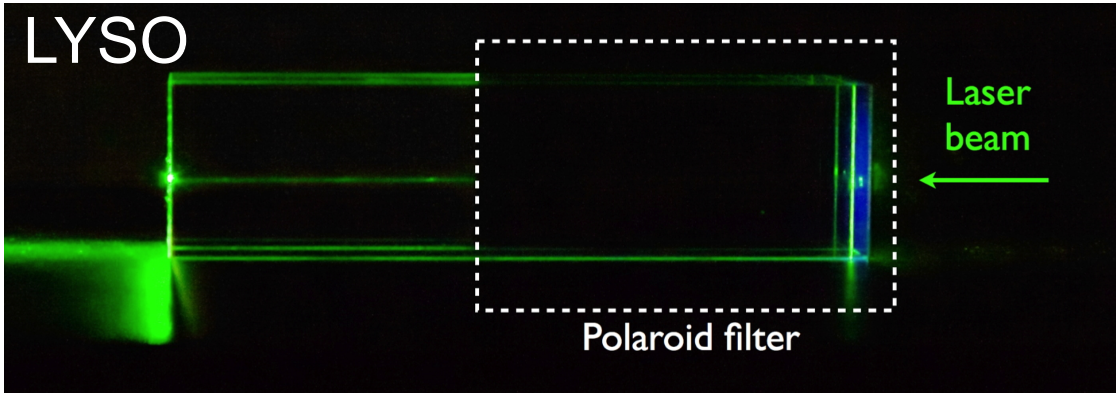
3) FLUKA simulations in $PbWO_4$ yield track densities in agreement with experimentally observed ones

4) FLUKA simulations yield a Rayleigh Scattering amplitude ratio between $PbWO_4$ and LYSO that is consistent, within the uncertainties, with the measured one

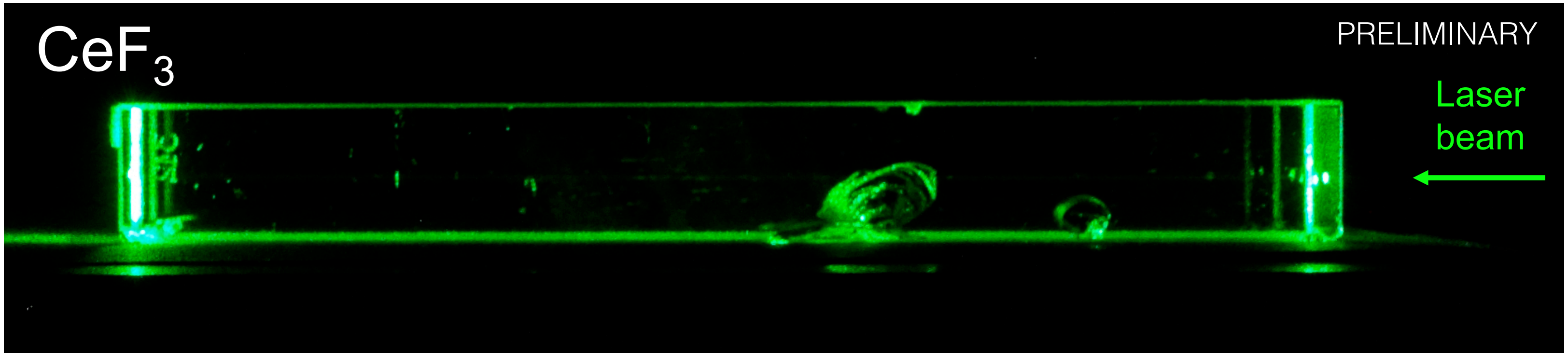
5) FLUKA simulations can be used to estimate the order of magnitude of damage amplitude to be expected from hadrons in inorganic crystals

Backup slides

Laser light in p-irradiated LYSO and CeF_3



G. Dissertori, F..N.-T. et al., NIM A745 (2014) 1-6



- In LYSO, Laser light is scattered. The scattered light is polarised
- In CeF_3, no scattering is visible (aside reflections on chipped edges)

Track segments reconstruction

- A track might be composed by several track segments which are separated by gaps where dE/dx falls below the required threshold for track formation

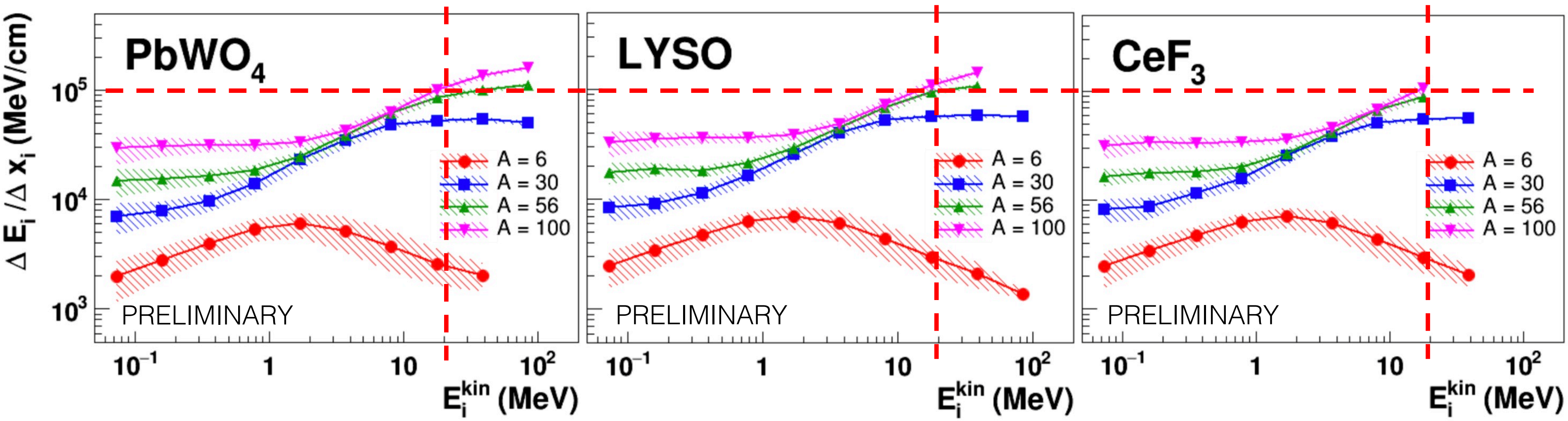
- Segments are the “objects” against which light can scatter (“core zones” in literature)

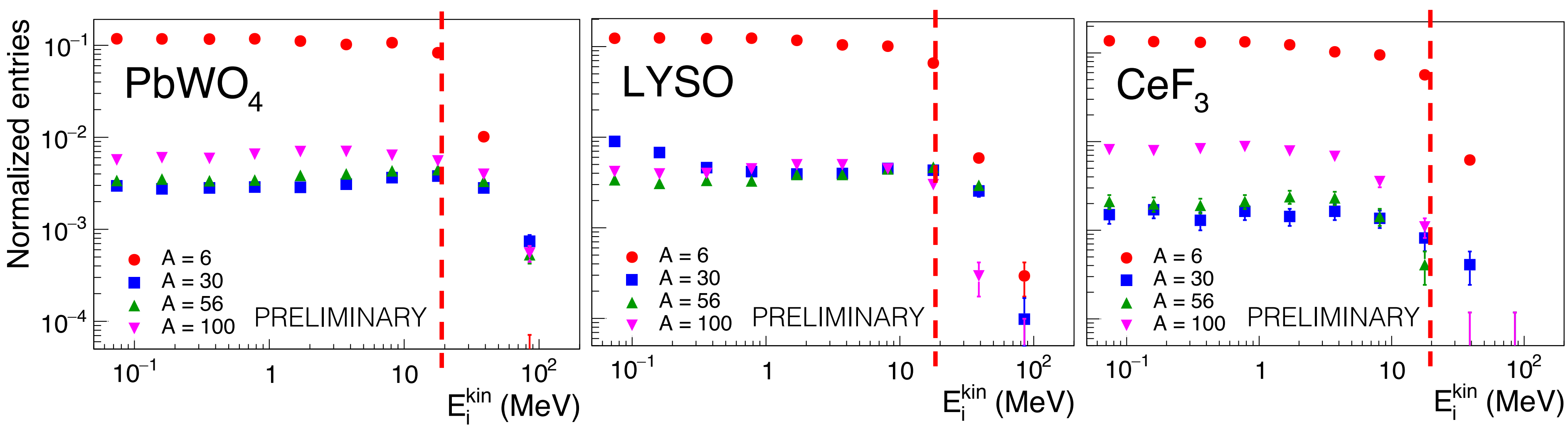
    - Merge consecutive steps into one track segment if requirement on dE/dx is satisfied in all of them

    - Determine the length of each segment, number of segments in a track, number of segments per incoming proton

Features of infinitesimal steps

- Complementary information: bin populations

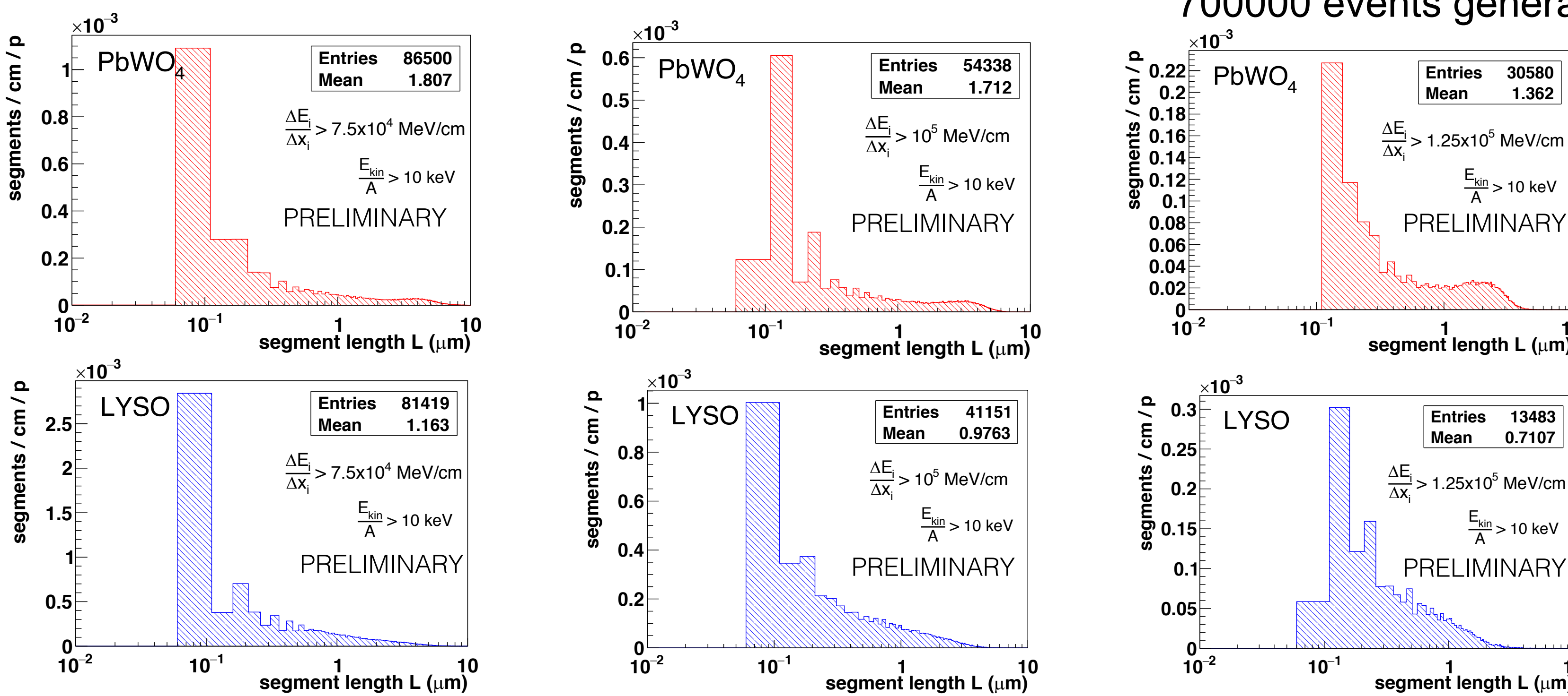




Segment length distributions

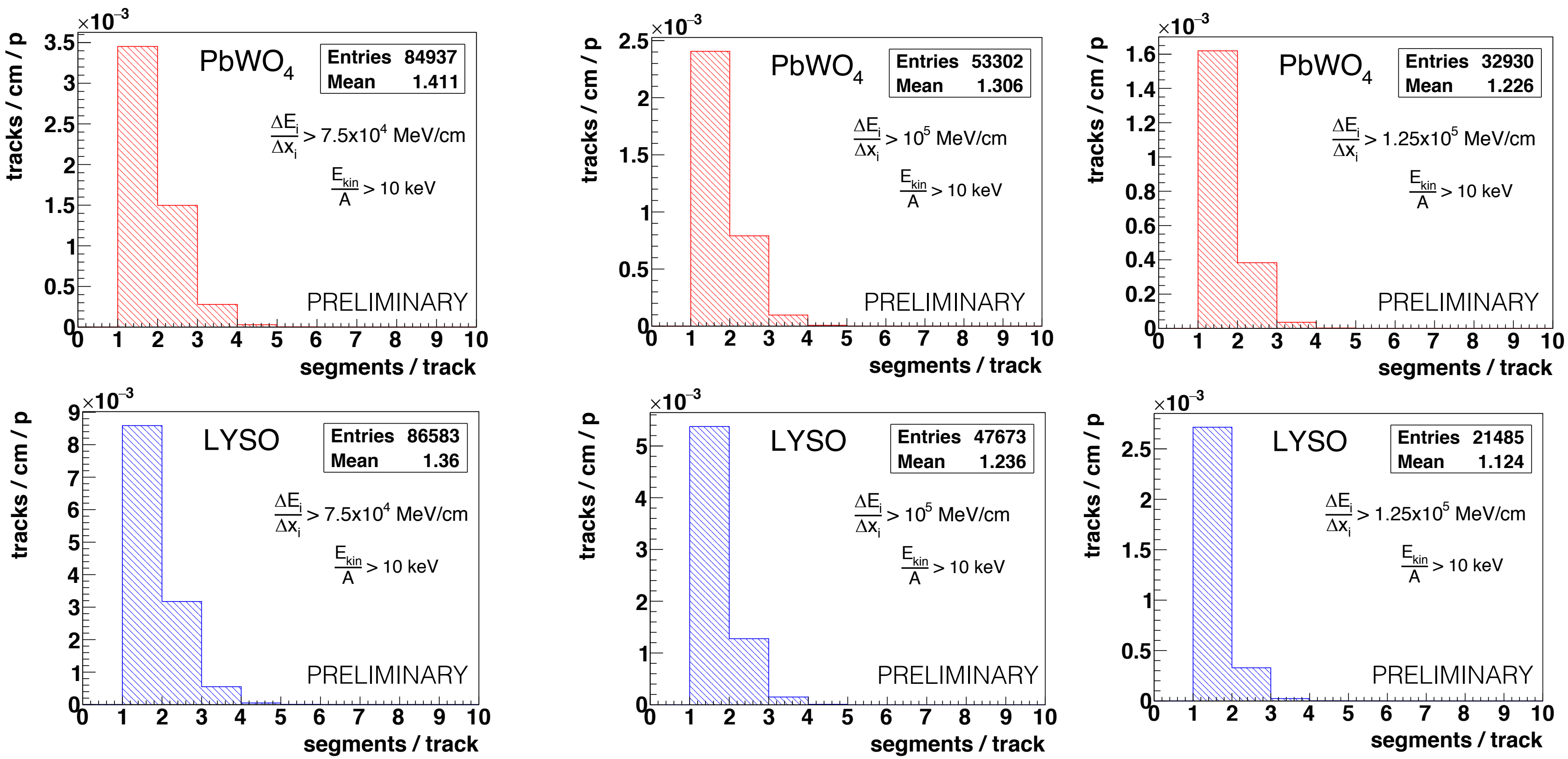
- Densities and average track length are plotted here also for different dE/dx threshold values

700000 events generated



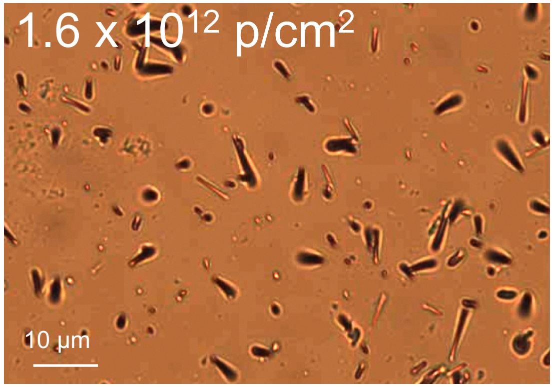
Number of segments per track

700000 events generated



Observed and simulated densities - details

Tracks visualised in $PbWO_4$ (→ see talk today at 10h45): Fission tracks are usually revealed through etching. The etching process dissolves also gaps between segments and joins segments into tracks.



Measurement: For a fluence of 1.6×10^{12} p cm^{-2}, the density of etched tracks crossing a surface is $\varphi = 2.8 \times 10^6$ cm^{-2} , i.e. $\varphi = 1.8\times10^{-6}$ tracks/p

FLUKA: 700000 protons simulated

→ fluence $\Phi_p = 1.22\times10^5$ p cm^{-2}

The density ρ_{seg} of segments produced by Φ_p in the crystal is:

ρ_{seg} = 54338/(2.4 x 2.4 x 23 cm^3) = 410 seg cm^{-3} = 3.4 x 10^{-3} seg cm^{-3} /(p cm^{-2})

With 1.3 segments/track:

ρ_{track} = 2.6 x 10^{-3} tracks cm^{-3} /(p cm^{-2})

- The average track length <L> is given by: $\rho_{track} \langle L \rangle = \varphi$

→ <L> = 7 µm , ~ as observed

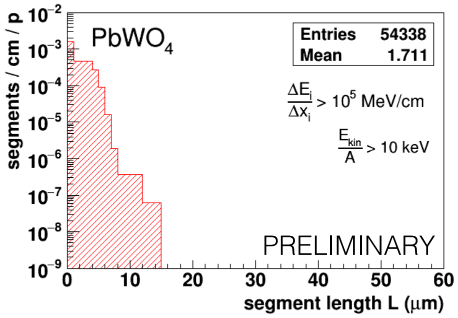
→ the simulated track densities agree with the observed ones

About observed and simulated tracks

Caveats:

- Observed etched tracks can be longer than latent ones
- The length from FLUKA in $PbWO_4$ is 2 μm, compatible with the above for the shorter, latent tracks

satisfactory agreement in order of magnitude



Observed track length in literature:
From observation in meteorites, tracks up to ~10 μm, peaked at short lengths if due to spallation recoils[6], with a tail of very long tracks due to VERY high energy heavy projectiles

Consistent shape of track length distributions

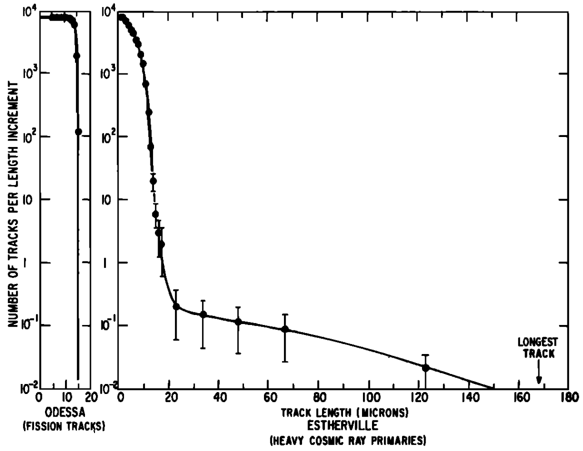


Fig. 5. Track length distribution in Estherville compared to the typical fission track length distribution observed in the iron meteorite Odessa. The existence of tracks of up to 160 μ in length implies the presence of cosmic-ray nuclei of charge considerably greater than 26.

6) R. L. Fleischer et al., J. Geophys. Res. 72 (1967) 331-366

Details about uncertainties