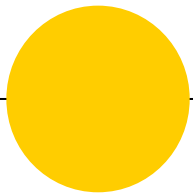




Istituto Nazionale di Fisica Nucleare

ERMES:

active TeV-class **muon** interrogation of
piezoelectric stress fields for
earthquake precursor monitoring.

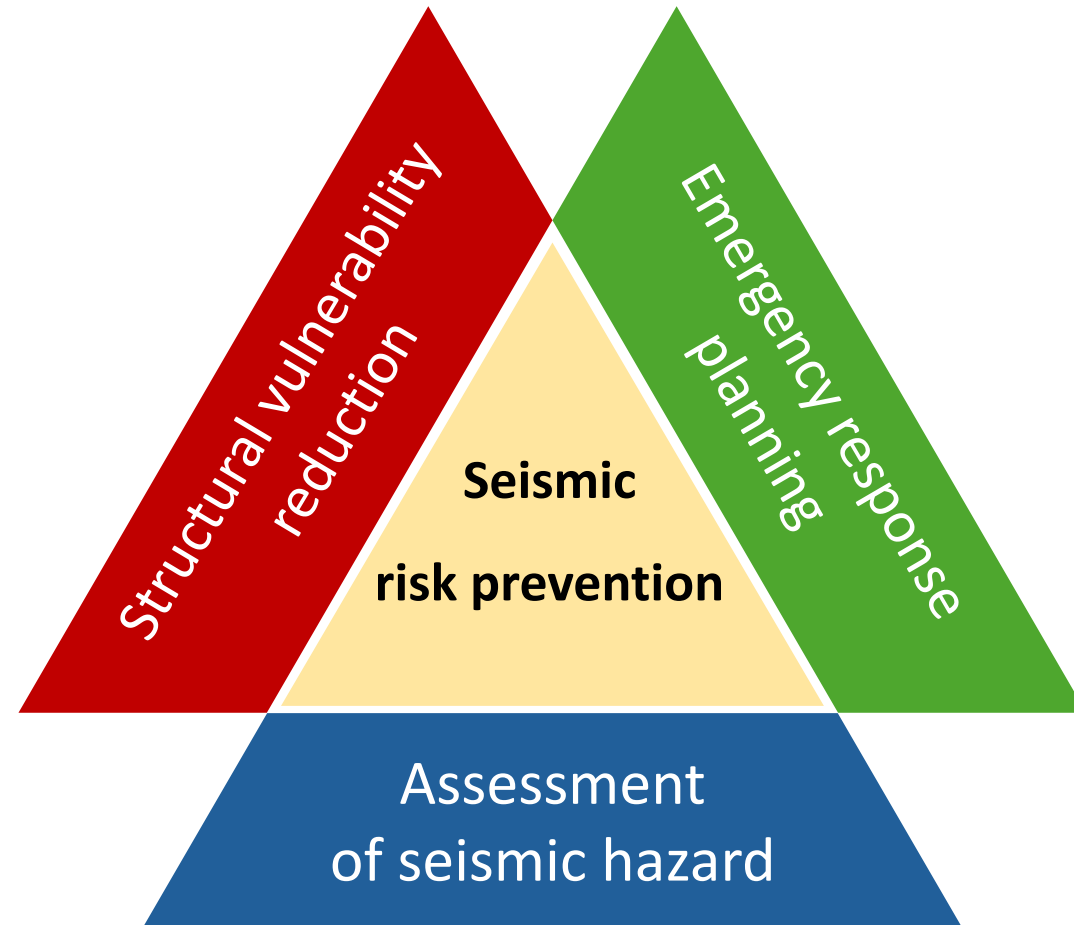


M. Rossetti Conti



Pillars of seismic risk prevention

- **Structural vulnerability reduction**
→ Safer buildings & infrastructure
- **Emergency response planning**
→ Prepared communities
- **Seismic hazard assessment**
→ Informed decisions



Integration of all three ensures *effective seismic risk prevention*.



ERMES

Earthquake **R**econnnaissance via **M**uon beam **E**volution in **S**ilicon dioxide

The goal: monitoring tectonic stress building-up across seismic faults.








ERMES

Earthquake Reconnaissance via Muon beam Evolution in Silicon dioxide

The goal: monitoring tectonic stress building-up across seismic faults.


PHYSICAL REVIEW RESEARCH 7, 043336 (2025)


Remote-sensing of tectonic-induced stress across faults using high energy muon beams

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(Received 17 June 2025; accepted 8 September 2025; published 26 December 2025)



ERMES

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- Accelerator Physics
- Geophysics



Piezoelectric Igniter – a spark

Air dielectric strength

$$E_{air} = 3 \text{ kV/mm}$$

Electrodes distance

$$d_{gap} = 1 \text{ cm}$$

Minimum voltage to spark

$$V = 30 \text{ kV}$$

Same voltage on PZT crystal faces

Piezoelectric field ($L_{crystal} = 2 \text{ cm}$)

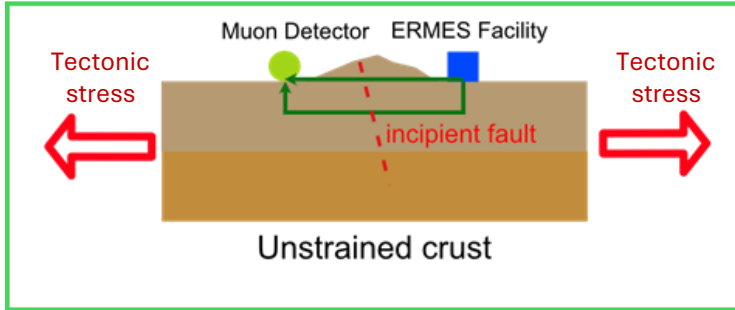
$$E_{crystal} = 1.5 \text{ MV/m}$$

(Just applying a force of few N!)





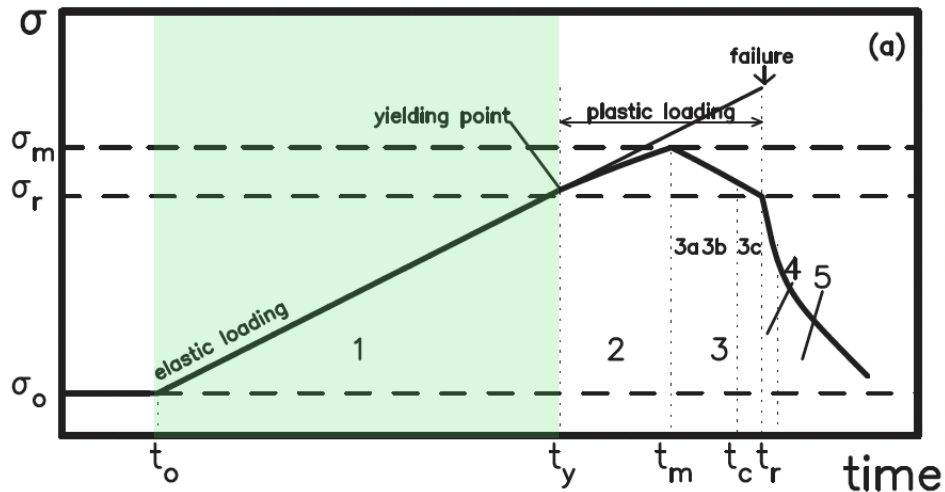
Stress evolution



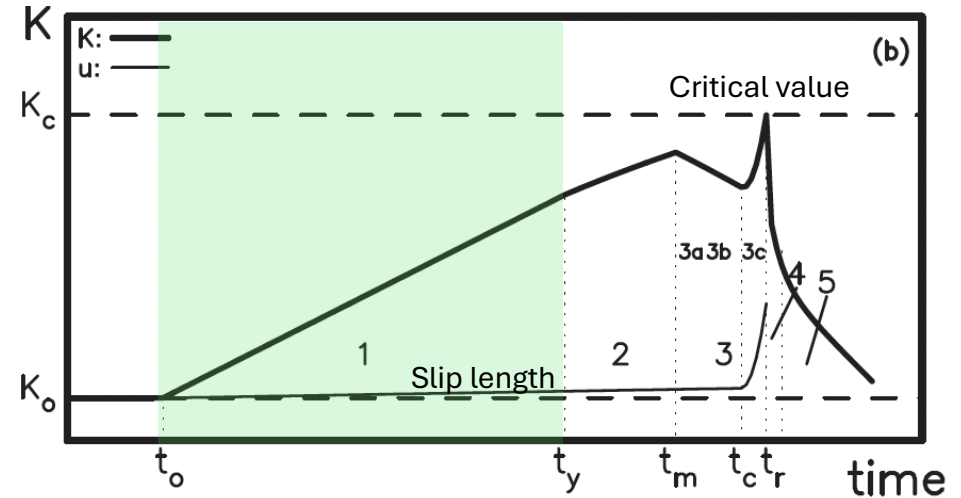
TIME

Courtesy of M. Zucali and G. Muttoni

Macroscopic Stress



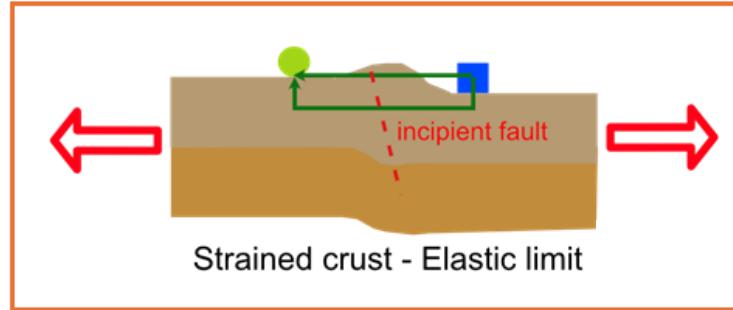
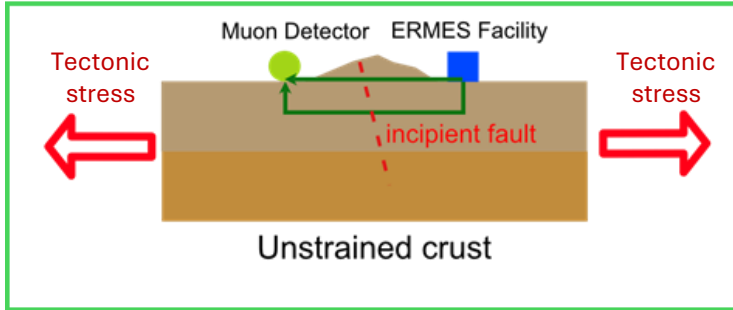
Stress Intensity Factor



Wang, J.-H. "Piezoelectricity as a mechanism on generation of electromagnetic precursors before earthquakes." *Geophysical Journal International* **224**(1), 682–700 (2021).



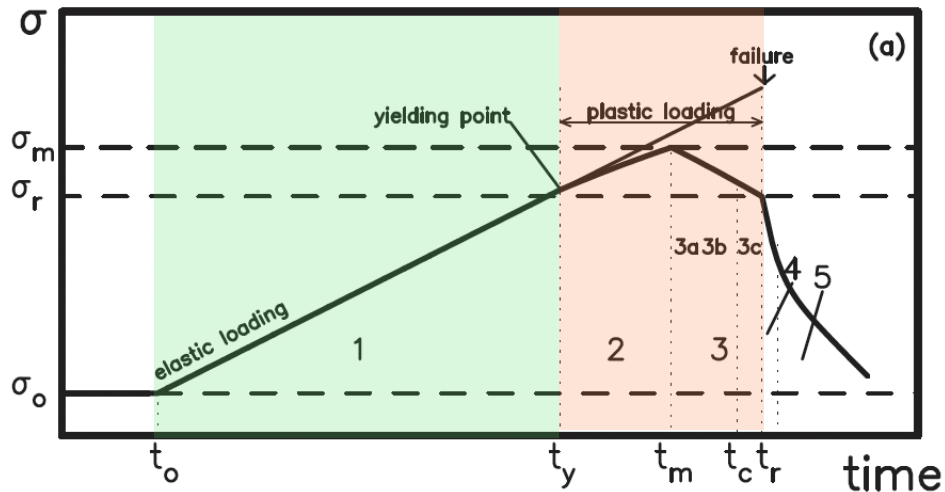
Stress evolution



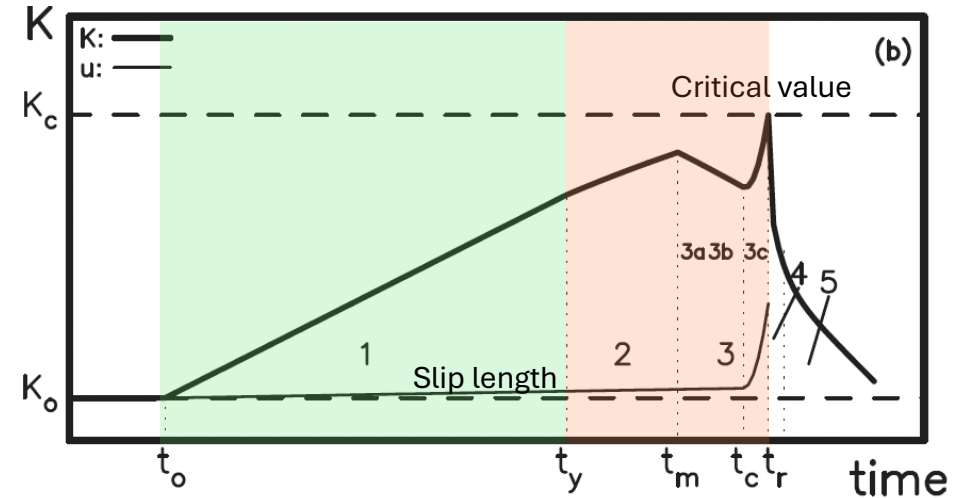
TIME

Courtesy of M. Zucali and G. Muttoni

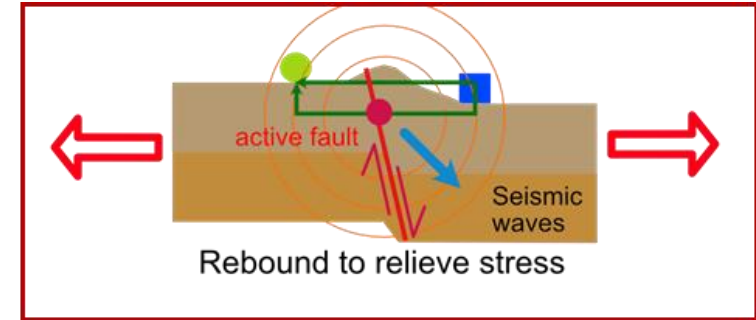
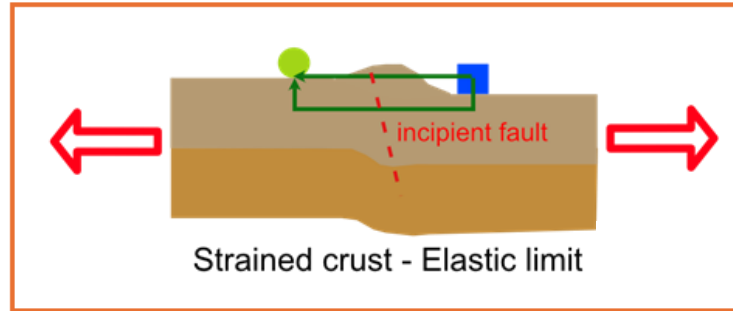
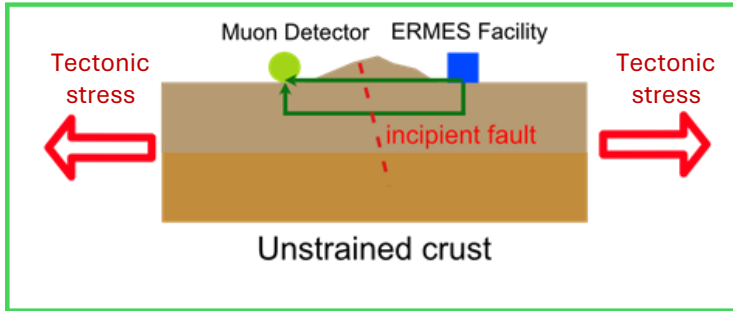
Macroscopic Stress



Stress Intensity Factor



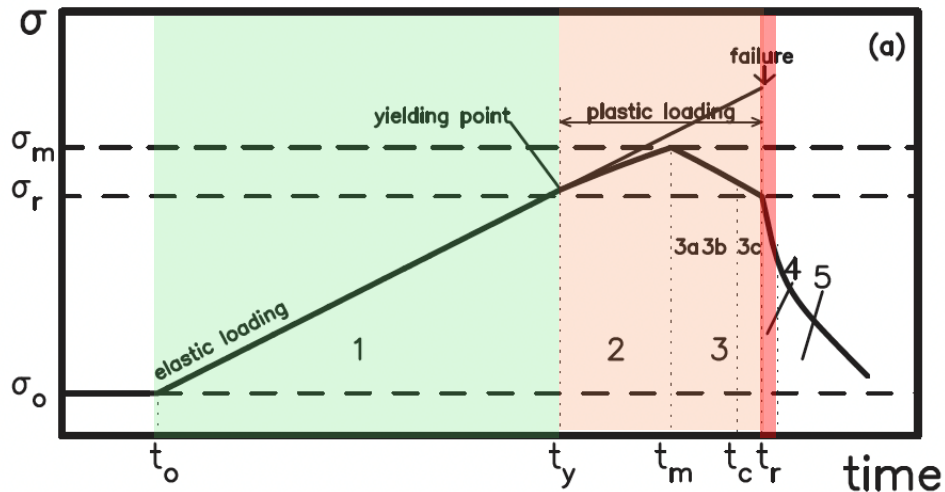
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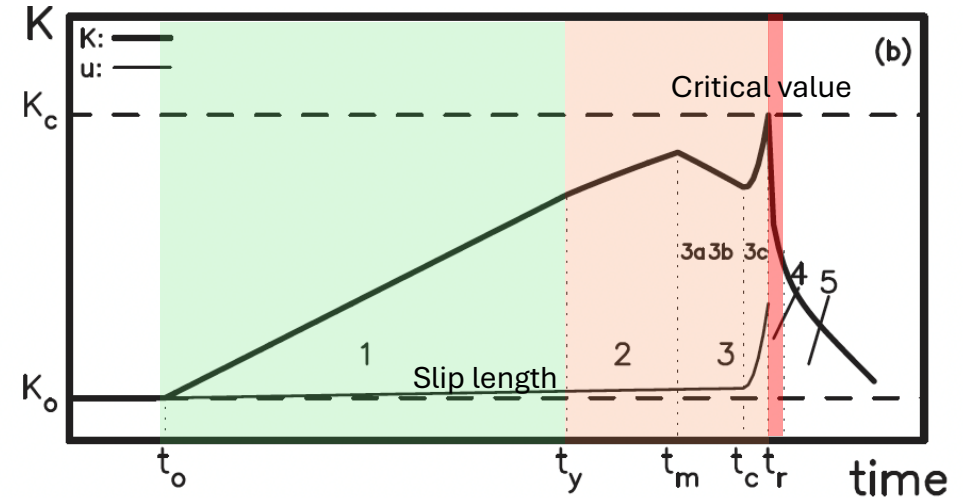
TIME

Courtesy of M. Zucali and G. Muttoni

Macroscopic Stress



Stress Intensity Factor

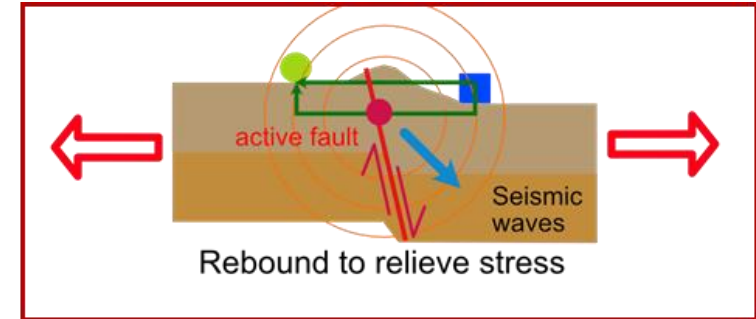
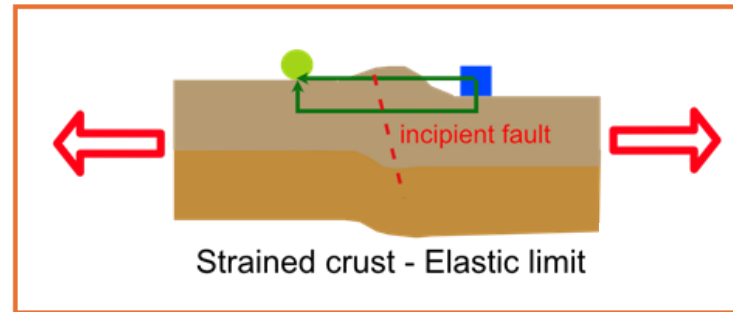
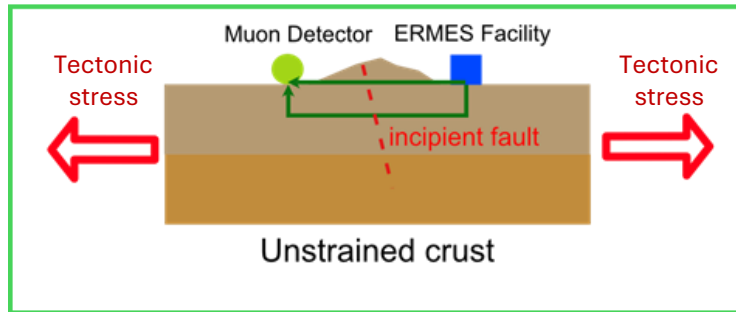


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Quartz whispers, muons listen

10



TIME

Courtesy of M. Zucali and G. Muttoni

The physics:

- **Stress** generates an **electric field** inside **piezoelectric** materials such as **quartz**.
- Charged **particles** can be **deflected** by these fields and **transport information** about pressure level.

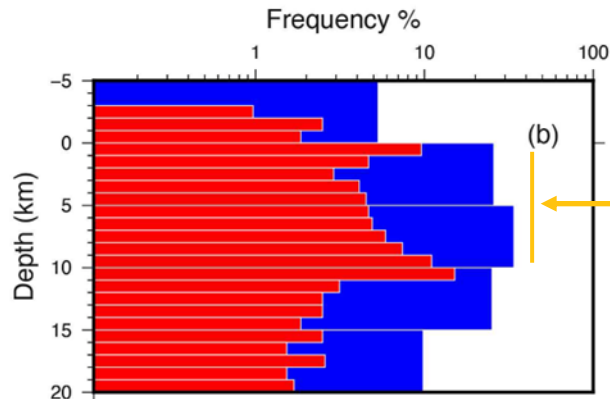
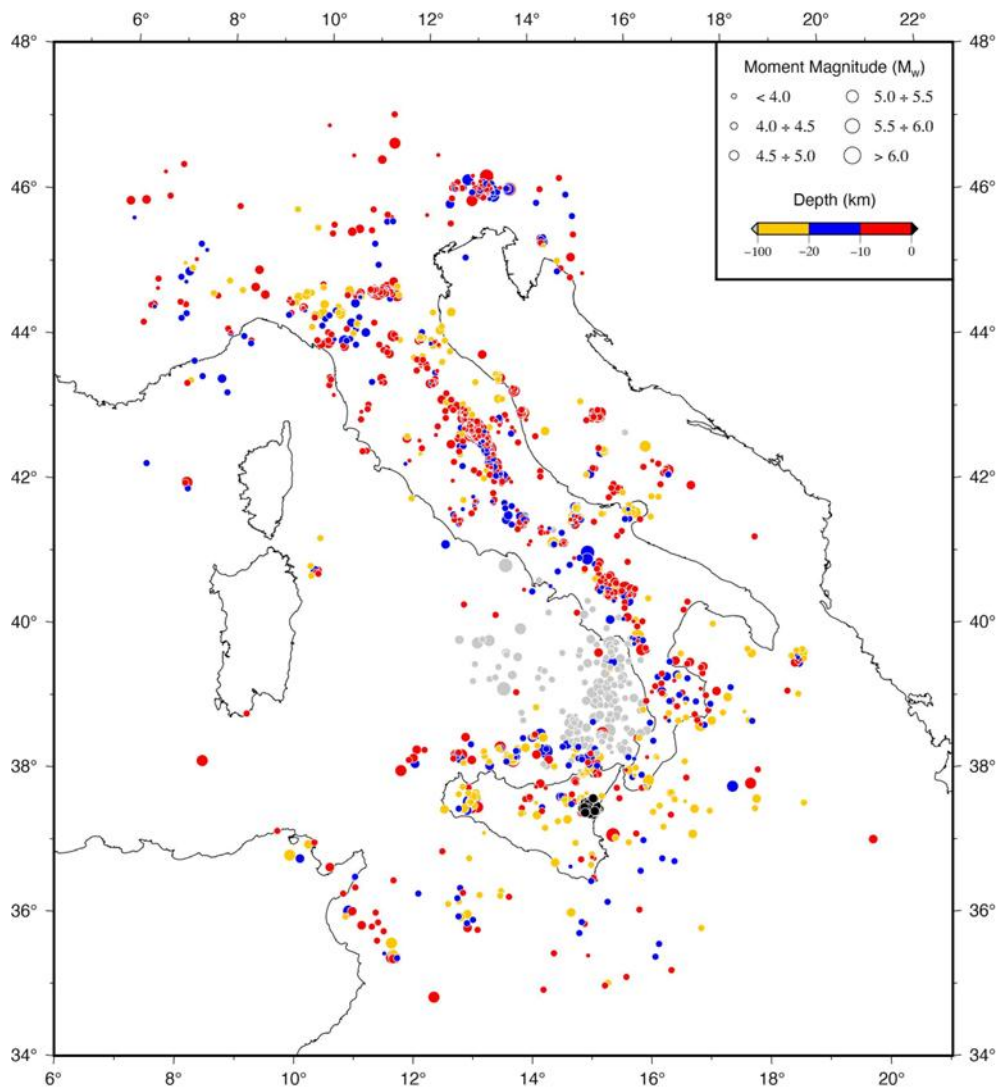
Framework:

- **Muons** are **best** candidates for this task (can be produced in accelerators and travel long distances in SiO_2)
- Technique applicable up to about **10 km dept.**

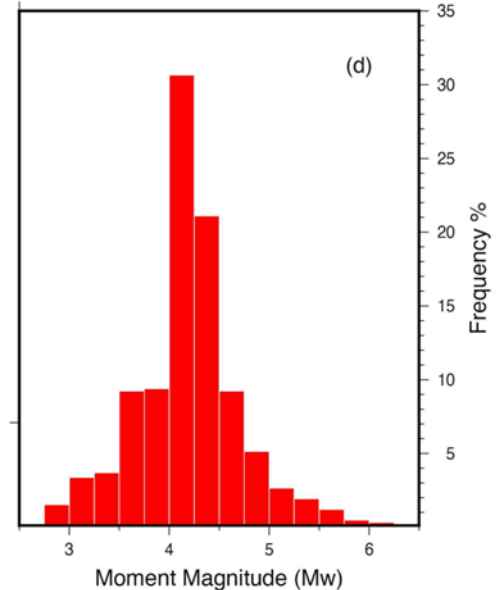


Shallow quakes are common

Italian area – earthquake data (1918-2020)



55% of the events occurred at depth below 10 km.



70% of these had momentum magnitude > 4.

Courtesy of A. M. Marotta



Simulations

Modeling muon transport and
beam dynamics in stressed
quartz-rich rocks



The code

ERMES needed a **simulator** to study charged **particle interactions** in long **crystalline rock** sections.

MonteCarlo codes for particle tracking through matter (**FLUKA, GEANT4**) **don't simulate piezoelectricity**.



ERMES needed a **simulator** to study charged **particle interactions** in long **crystalline rock** sections.

MonteCarlo codes for particle tracking through matter (**FLUKA, GEANT4**) **don't simulate piezoelectricity**.

So, we developed our own:

MuAEGIS

Muon **U**nderground **A**ctive **E**arthquake **G**enesis **I**nvestigation **S**oftware

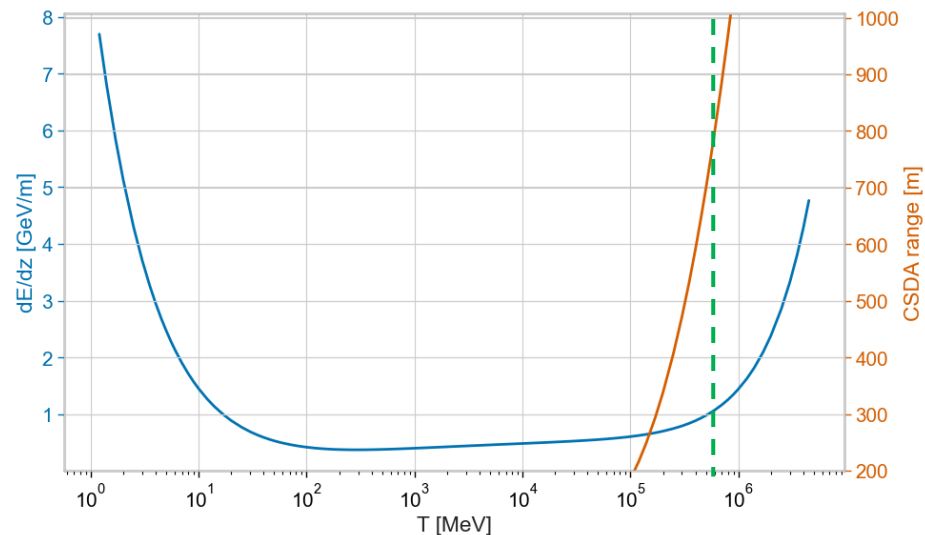
- **Objective:** quantify the modifications on muon **beam dynamics** in presence of **stress induced electric fields**.
- Developed in **python** with support for **multiprocessing**.
- MuAEGIS have an **internal** beam generator but accepts also **external beam distributions**.
- **Simulates** key effects of **beam-rock interaction**.



Energy loss

MuAEGIS considers the **average** muon energy **loss** $\frac{dE}{dz}$ given by the sum radiation losses and ionization.

- Rock and quartz approximated as pure SiO_2 .
- **500 GeV** muons propagate **~700 m**
- **1 TeV** muons: **~1 km**

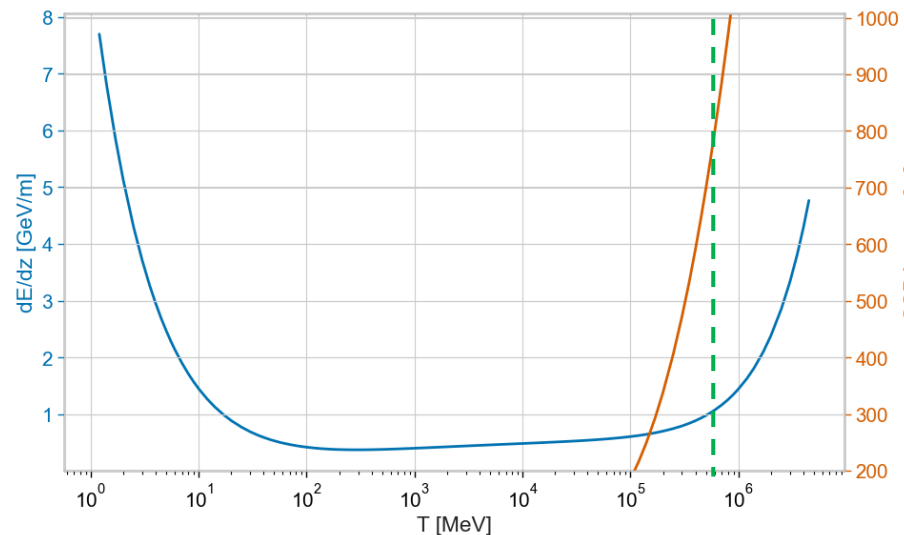




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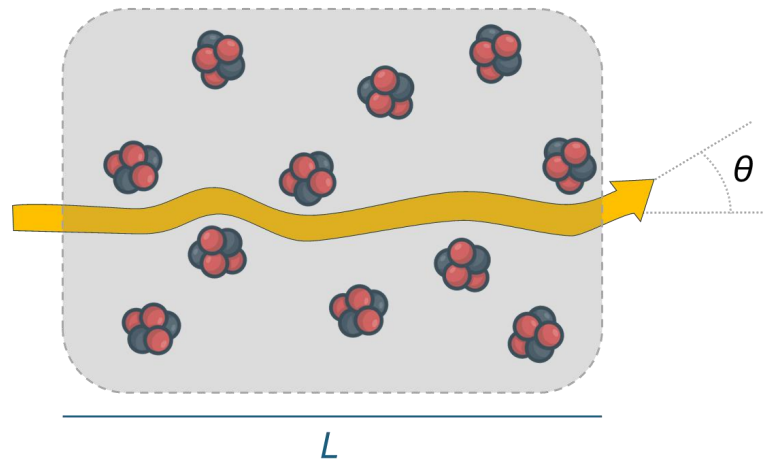
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Multiple Coulomb Scattering

The code calculates Molière angle

$$\theta_0 = \frac{13.6}{cp} \sqrt{\frac{L}{L_0}} \left[1 + 0.038 \ln \left(\frac{L}{L_0} \right) \right]$$

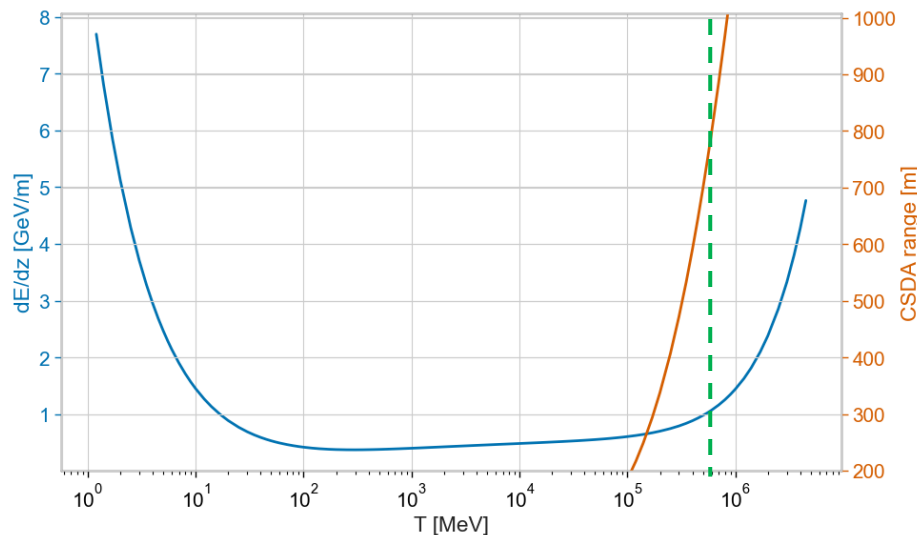




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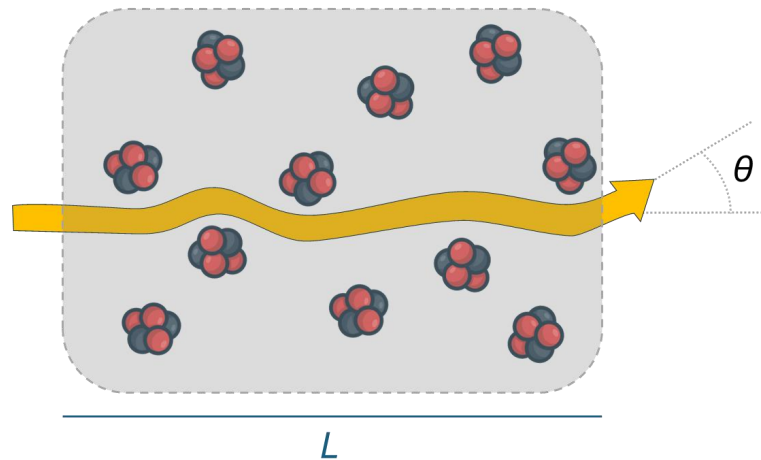
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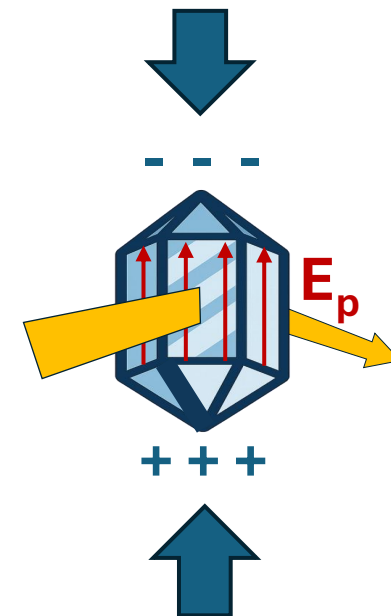
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Piezoelectric Random Walk

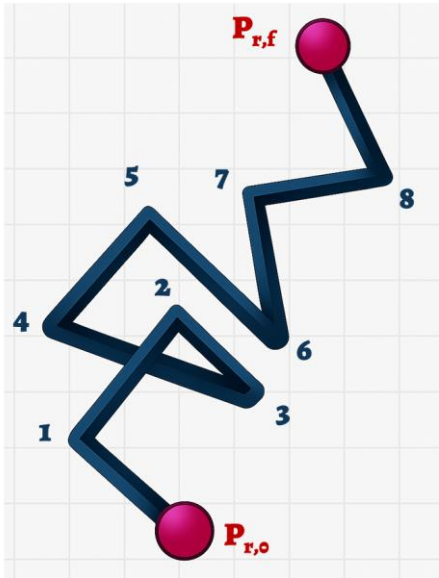
$$\Delta \vec{p} = \frac{q \vec{E}_p L_c}{c}$$

$E_p = 20 \text{ MV/m}$ for $P = 400 \text{ MPa}$ (= 4 kbar)
 L_c up to few cm





2D random walk



PRW and **MCS** affect transverse momentum like a **2D random walk**.

Each **momentum step** has a **random** direction.

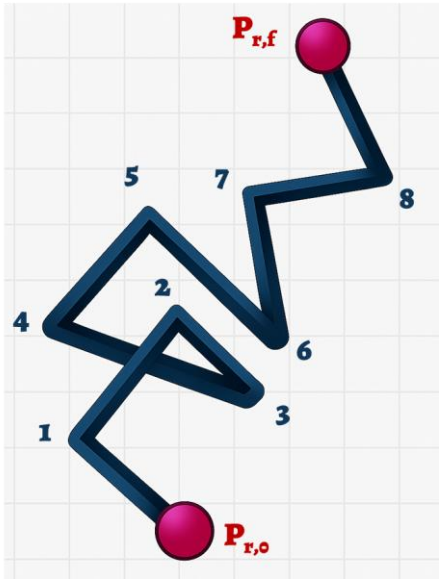
Each particle follows a unique transverse path, but the bunch evolves with averaged, ordered behavior:

$$\sqrt{\langle p_r^2 \rangle} = \sqrt{N} \langle l_i \rangle$$

N: number of steps
 l_i : step length ($\Delta p_{r,i}$)



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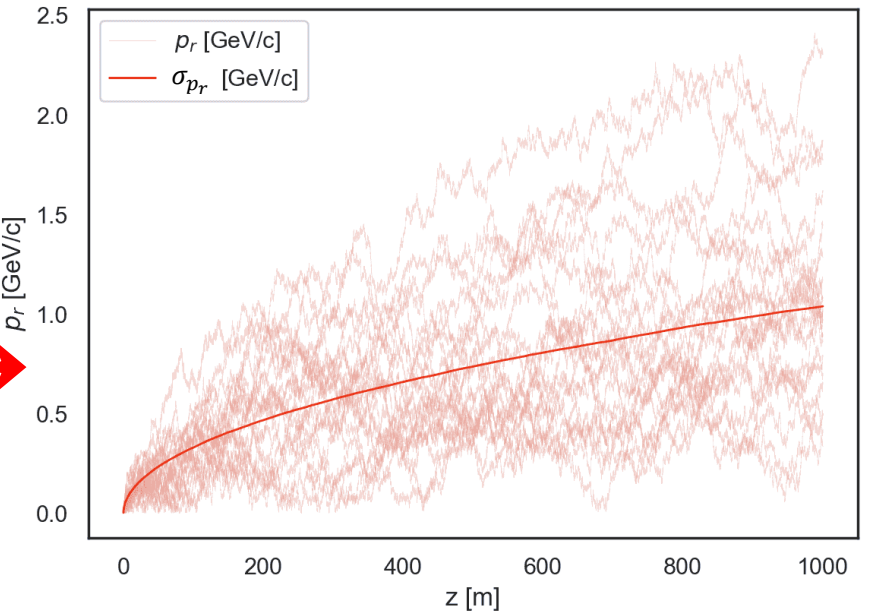
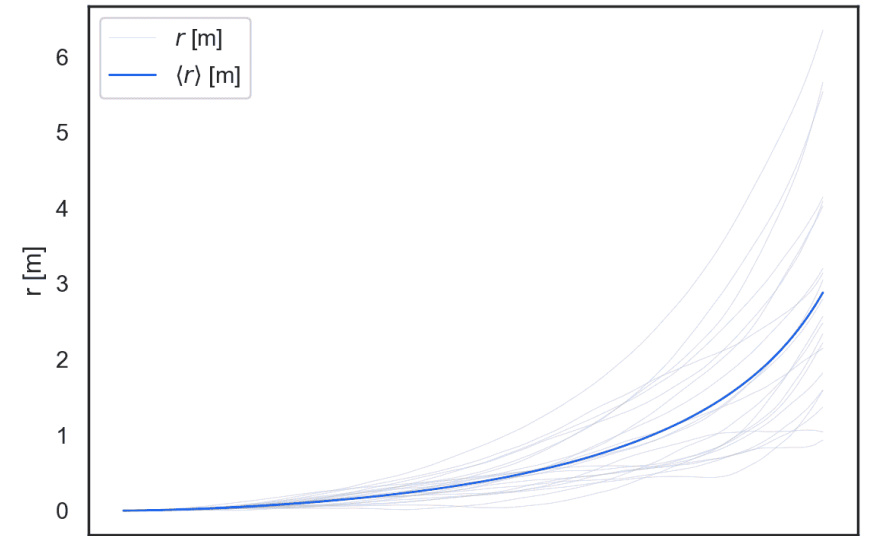
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Visual example:

20,000 muons through **1 km** of ground
 Periodic layers: **1 cm** rock / **1 cm** quartz
 (20 tracks shown)





There is a signal!

We simulate 10^6 muons into 600 m of ground -- Periodic layers: **1 cm** rock / **2 cm** quartz

| P [kbar] | E_p [MV/m] | L [m] | E_0 [GeV] | E_f [GeV] | ϵ_{n,x_0} [mm mrad] | σ_{x_0} [m] |
|----------|--------------|-------|-------------|-------------|------------------------------|--------------------|
| 4.0 | 20.0 | 600 | 500.0 | 49.89 | 50.0 | 0.2 |

| | σ_r | σ_{Pr} | $\epsilon_{n,r}$ |
|-----------------|------------|---------------|------------------|
| | m | MeV/c | m rad |
| MCS+PRW | 2.246 | 899.3 | 5.08 |
| Pure MCS | 2.243 | 898.1 | 5.07 |
| Pure PRW | 0.305 | 46.2 | 0.09 |



Quality is not mandatory

What happens with a **higher emittance (10x)** beam?

| P [kbar] | E _p [MV/m] | L [m] | E _o [GeV] | E _f [GeV] | ε _{n,x_o} [mm mrad] | σ _{x_o} [m] |
|----------|-----------------------|-------|----------------------|----------------------|--|--------------------------------|
| 4.0 | 20.0 | 600 | 500.0 | 49.89 | 50.0 | 0.2 |



| ε _{n,x_o} [mm mrad] | σ _{x_o} [m] |
|--|--------------------------------|
| 500.0 | 0.2 |

| | σ _r | σ _{Pr} | ε _{n,r} |
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| | σ _r | σ _{Pr} | ε _{n,r} |
|-----------------|----------------|-----------------|------------------|
| | m | MeV/c | m rad |
| MCS+PRW | 2.246 | 899.6 | 5.08 |
| Pure MCS | 2.243 | 898.5 | 5.07 |
| Pure PRW | 0.305 | 46.2 | 0.09 |

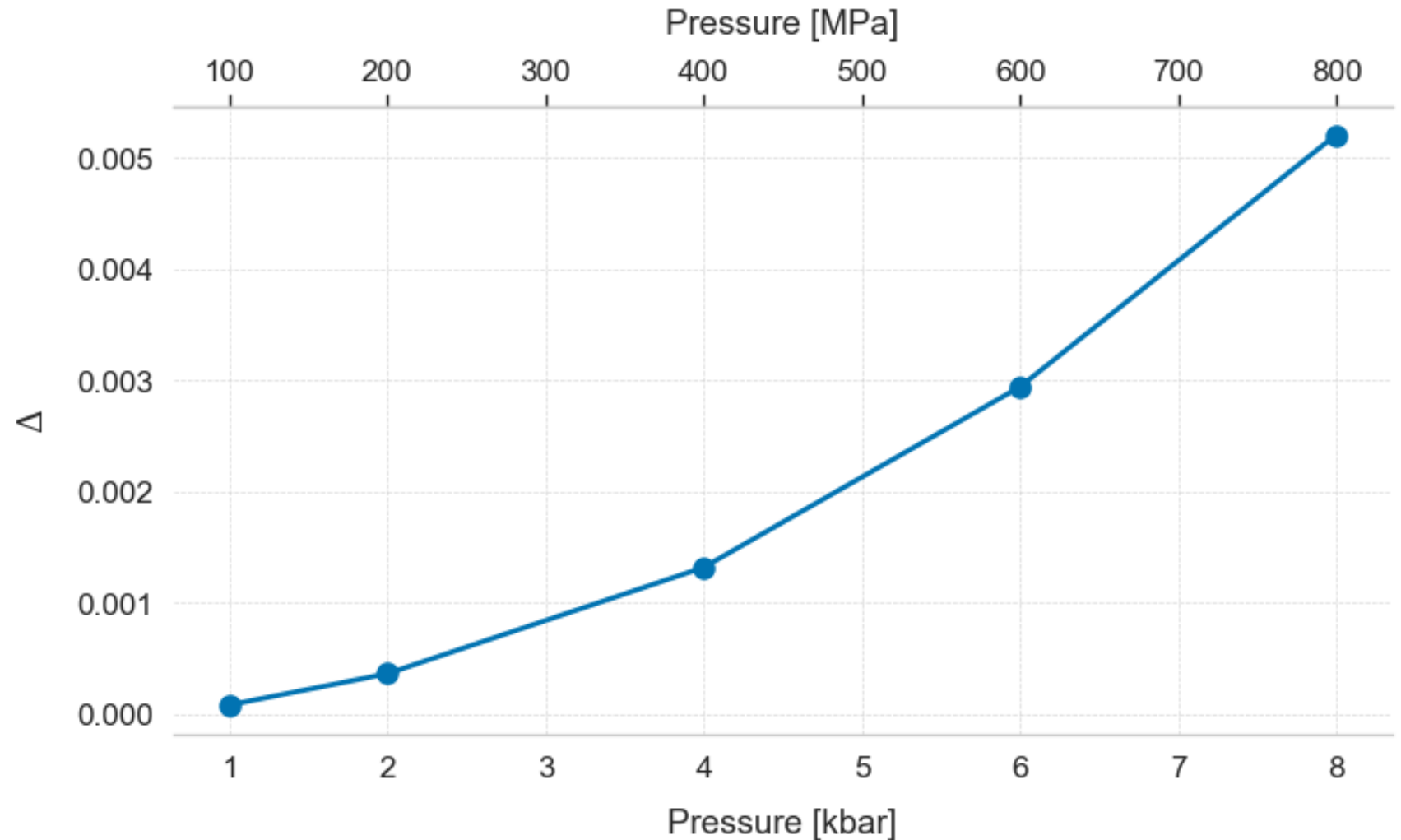
The final beam **dimension** is not impacted.
High quality muons are **not necessary!**



We can see the build-up

We simulated **beam envelope enhancement (Δ)** under varying quartz pressures observing non-linear evolution.

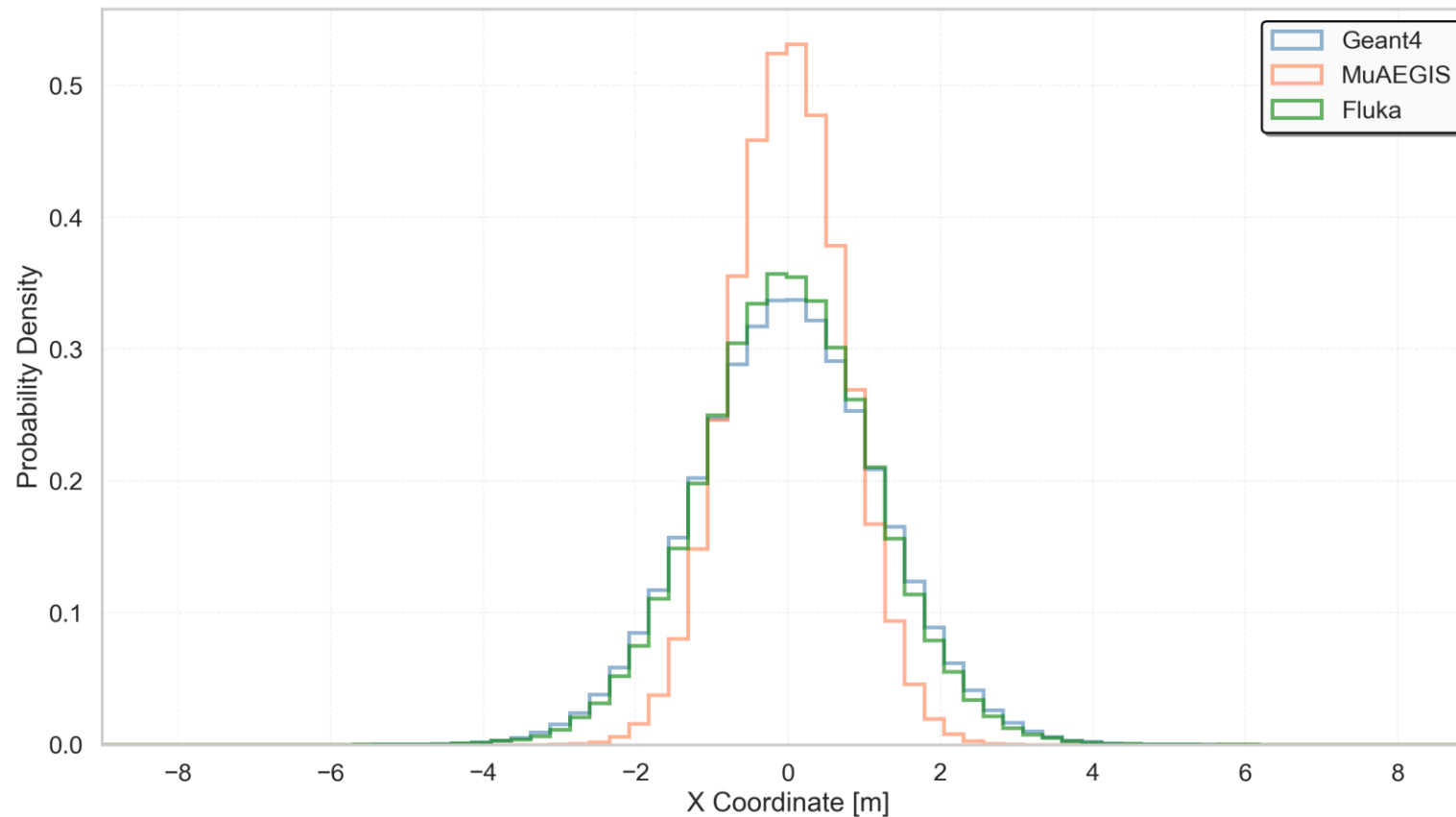
$$\Delta = \frac{\sigma_{TOT,r}}{\sigma_{MCS,r}} - 1$$





Simulation done with **Fluka** and **GEANT 4** (600 m of SiO_2) show an **acceptable accordance** with **MuAEGIS**.

MuAEGIS predictions on final transverse envelope are slightly smaller than Montecarlo codes.

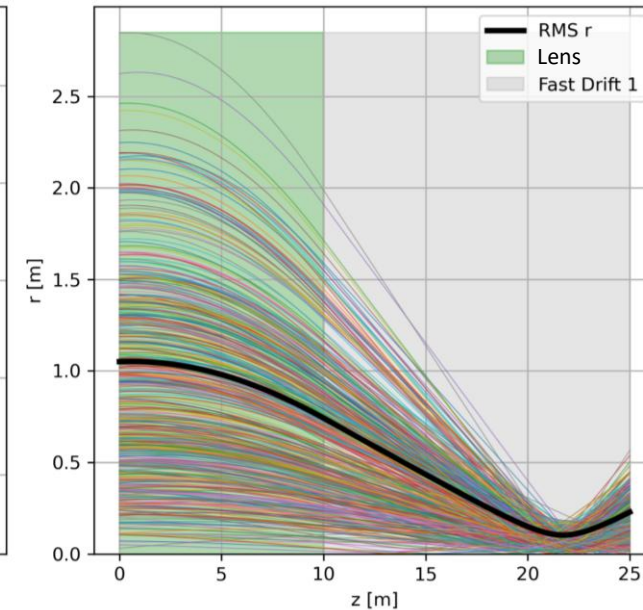
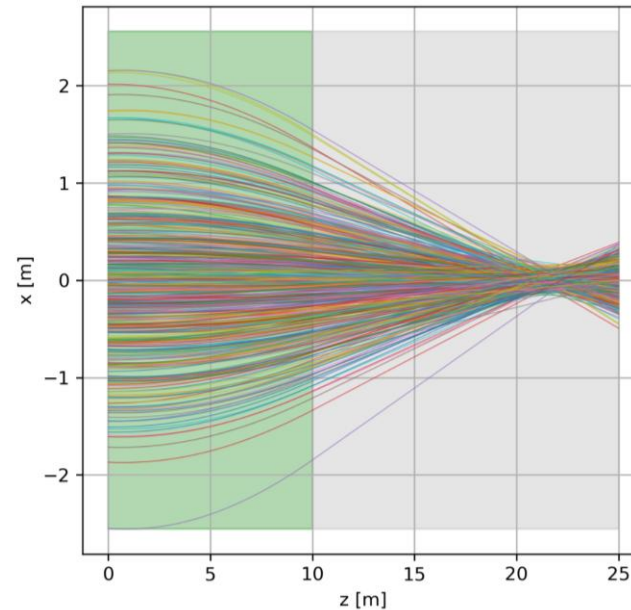
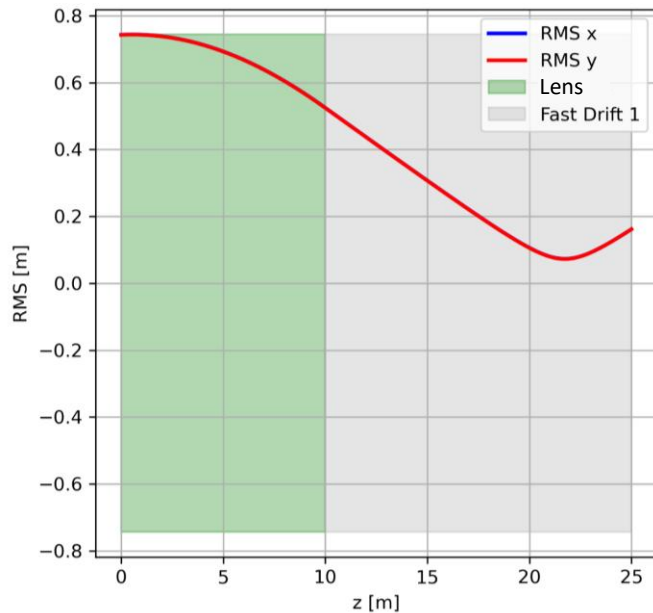
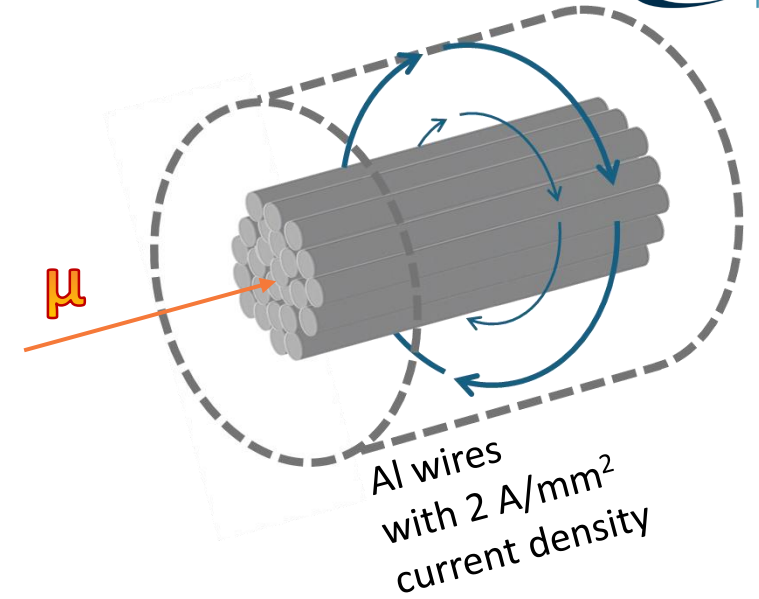




The Muonic Lens

How to focus a **large-aperture 50 GeV** muon beam?

- A cylindrical array of **parallel aluminum wires** (aligned with the beam) **carrying DC** is used as the lens structure.
- The lens generates an **azimuthal magnetic field** linear with radius.
- The resulting transverse force can **focus or defocus** the beam, depending on the current direction.





2 experiments

Purpose:

- **Demonstrate** core **concepts** of the ERMES technique.
- **Validate theoretical** predictions and **numerical** simulations.
- Crucial for **assessing feasibility** and future implementation.

- **PoP-1: Single Quartz Crystals**

- **Objective:** Characterize direct **piezoelectric response**.
- **Measurement:** Detectable, deterministic beam centroid deflection (e.g., mm-scale).
- **Method:** Tens-MeV to hundreds-MeV electron beams through a stressed crystal.

Simulations done

- **PoP-2: Meter-Thick Granite Slabs**

- **Objective:** Investigate Piezoelectric Random Walk (**PRW**).
- **Measurement:** Detectable enhancement of the muon beam spot size (parameter Δ).
- **Method:** GeV-class muon beams through granite under significant pressure.



- **ERMES is a novel technique for earthquake forecasting.** It aims to actively monitor the temporal evolution of tectonic stress in seismic fault zones
- **MuAEGIS:** a lightweight, stochastic simulation tool modeling relativistic muon transport through stressed piezoelectric rock.
- **Piezoelectric-induced deflections** become increasingly **significant at high pressures**, perturbing the transverse beam profile **despite MCS dominance**.
- **Final beam parameters are largely independent of initial quality** — easing ERMES design constraints.

Next Steps

- **PoP-1:** Quartz crystal **tests with electron beams** → validating pressure-field coupling. We are investigating the possibility to perform the experiment **@ STAR in south Italy**.
- **Extend MuAEGIS** to include:
 - Realistic **energy spread evolution**
 - **Stress profile** along muons path
 - **Coherent piezoelectric** effects

Thanks!

Any questions ?

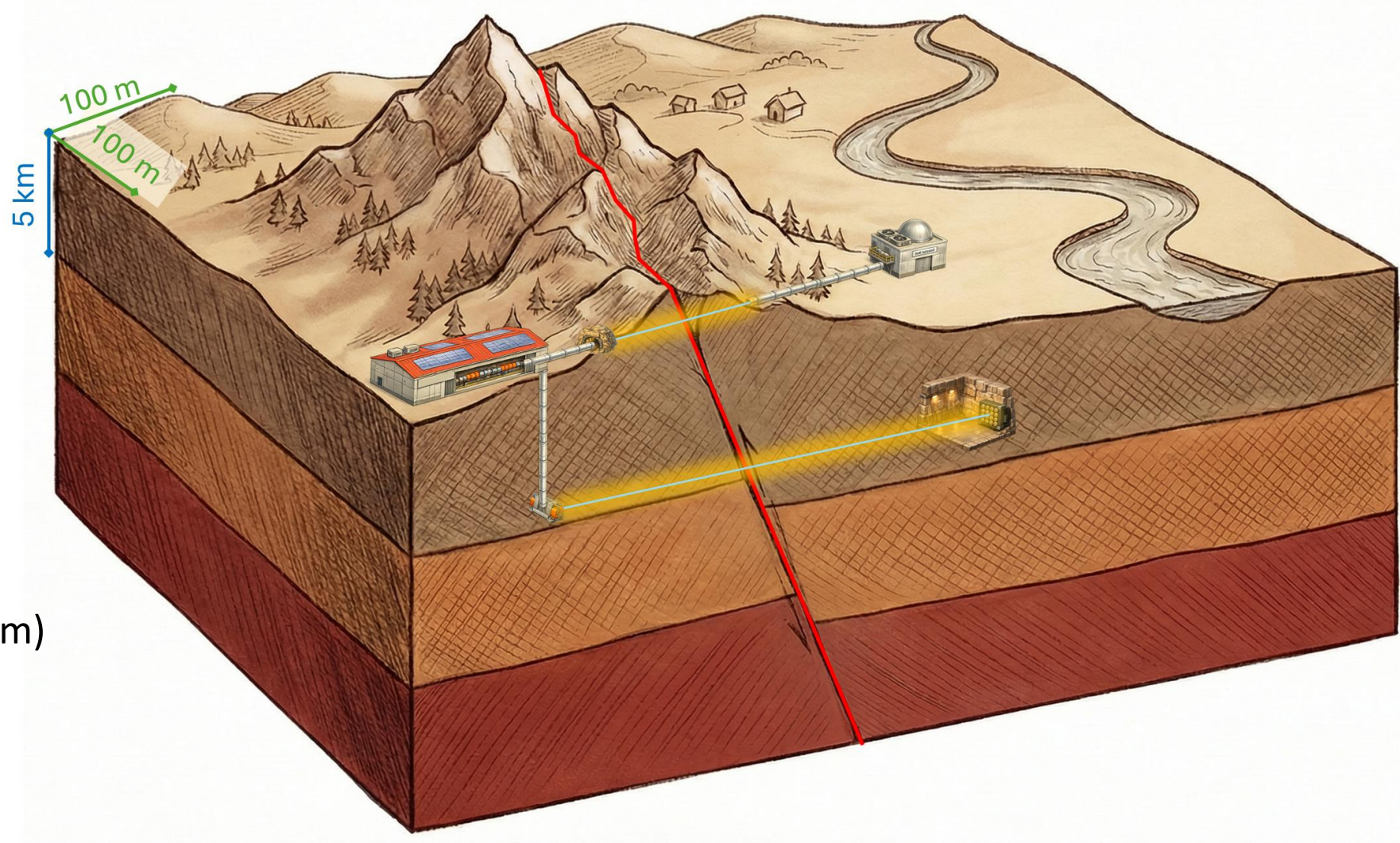


Hermes, The Messenger from the Depths.



Two possible setups

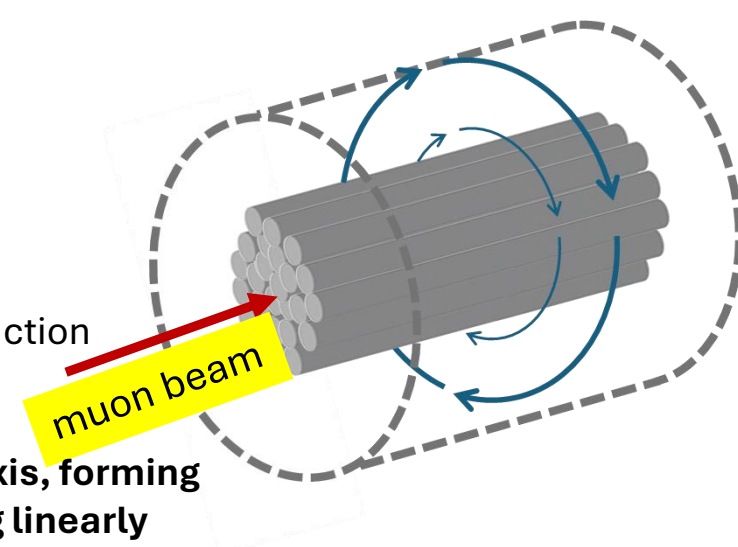
- **Ground-level beamline for subaerial faults**
- **Underground beamline for deeper active faults (< 10 km)**



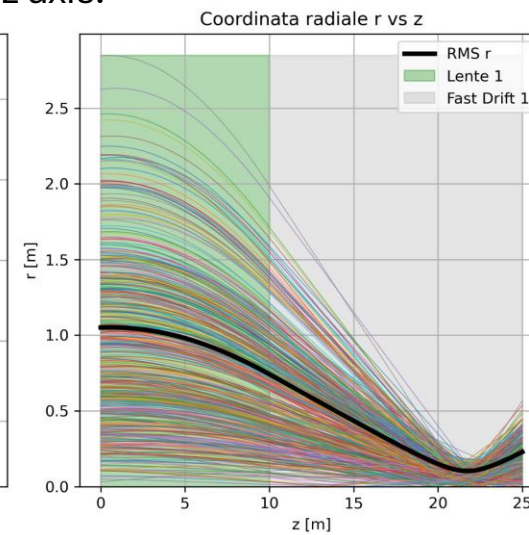
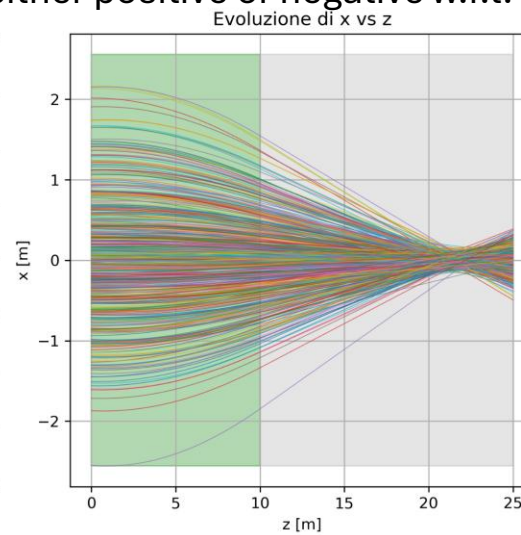
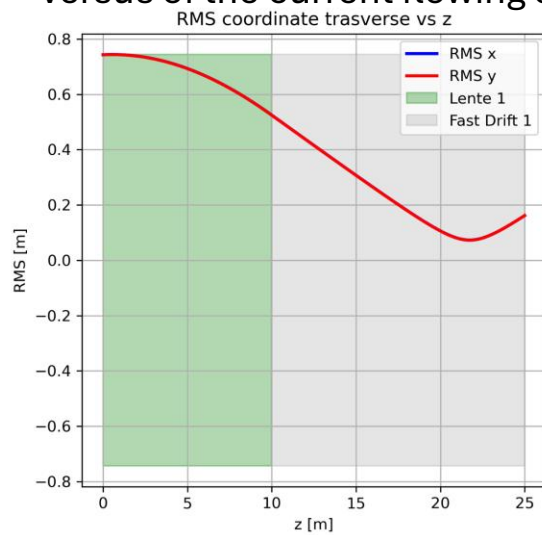
An alternative (viable) option: the muonic lens

How can we focus muon beams at 50 GeV affected by large diffraction and with meter wide transverse spot sizes?

Aluminum wires arranged parallel to the muon propagation axis, forming a big cylinder, generating an azimuthal magnetic field growing linearly with the inner radial coordinate, from 0 at the symmetry z axis toward a maximum value at the edge.



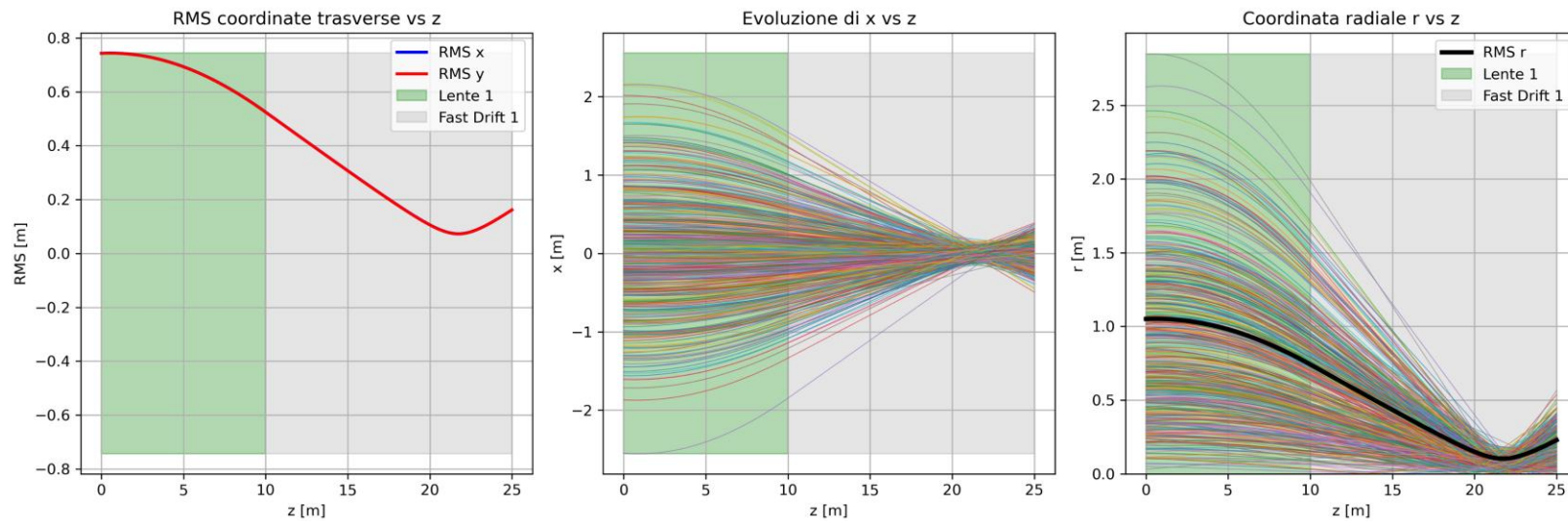
The force acting on the muon beam is focusing or defocusing depending on the
versus of the current flowing either positive or negative w.r.t. z axis.



Al wires
with 2 A/mm²
current density

Focusing muon beams with muonic lens

Exit muon beam average energy **50 GeV**. Selecting $\pm 5\%$ around the average energy (12% of total muons) the beam is focused by the muonic lens ($L = 10$ m, $r = 3$ m, $B_{\max} = 3.5$ T) down to $\sigma_r = 121$ mm focal rms spot size, at a focal distance located 16.4 m from muonic lens exit

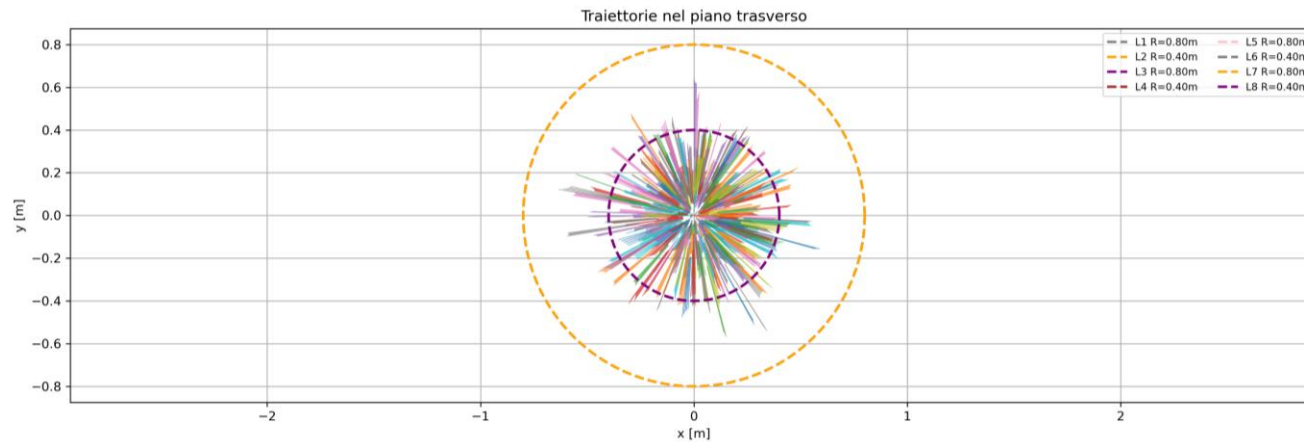
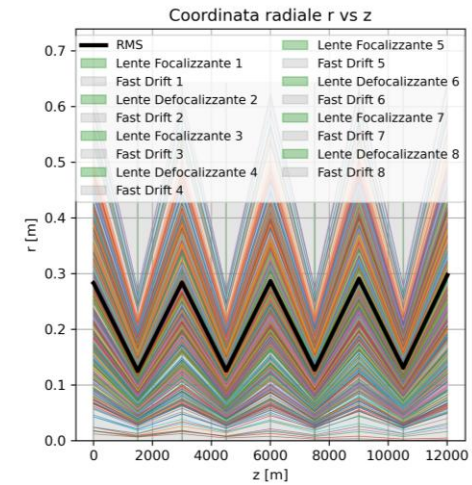
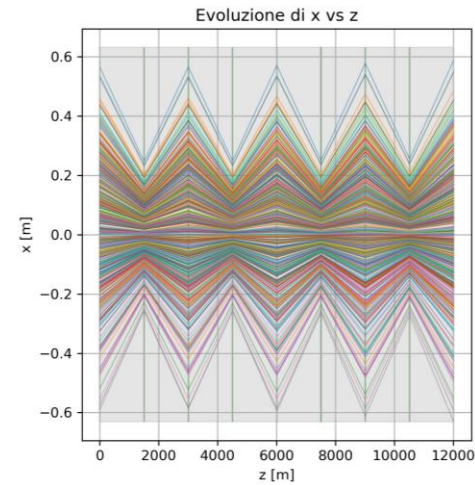


Energy loss by 50 GeV muons in 10 meters Al = 7 GeV

12 km long FODO channel based on thin muonic lenses

A lattice for a 500 GeV muon beam transport with $\varepsilon_{n,x} = 5000$ mm mrad ($\sigma_{x-y} = 20$ cm)

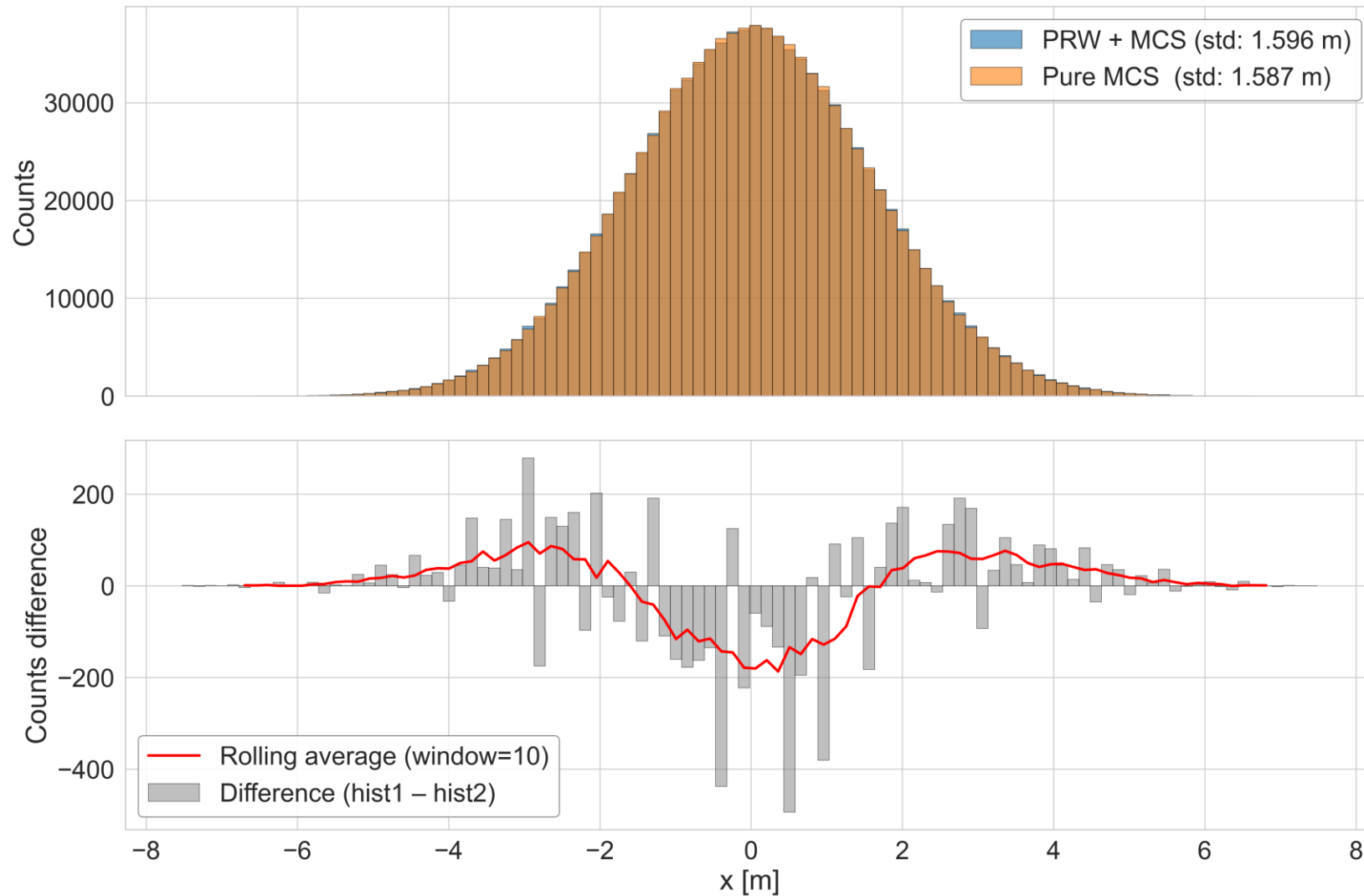
| | L1 (F) | L2 (D) | L3 (F) | L4 (D) | L5 (F) | L6 (D) | L7 (F) | L8 (D) |
|----------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| r [m] | 0.8 | 0.4 | 0.8 | 0.4 | 0.8 | 0.4 | 0.8 | 0.4 |
| L [m] | 1 | 2.3 | 2 | 2.3 | 2 | 2.3 | 2 | 2.3 |
| B _{max} [T] | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

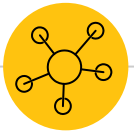




How to see the effect

Effect observed by **comparing** muon **distribution on detector plane** with ideal case (no pressure/quartz).





Muon beam maximum penetrability in SiO_2 : 3 km with 10 TeV muons

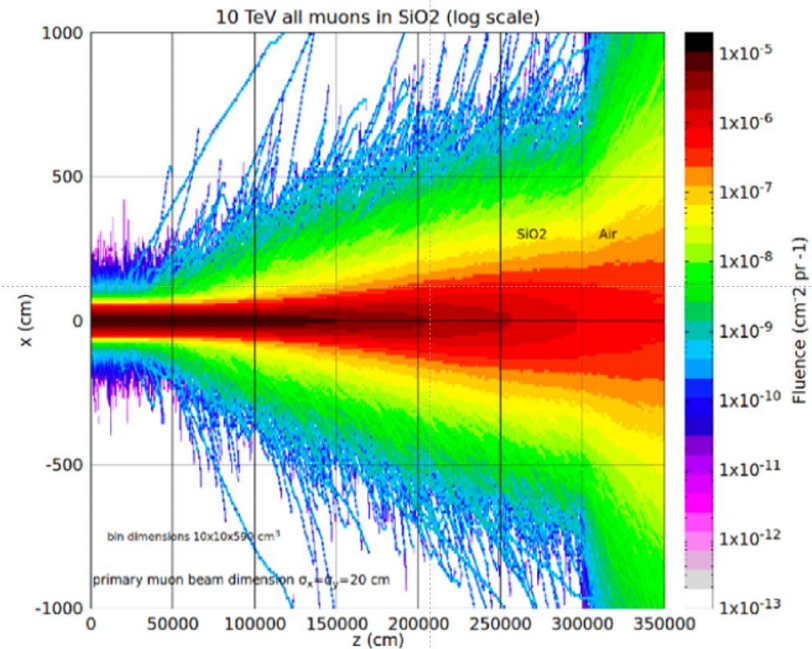
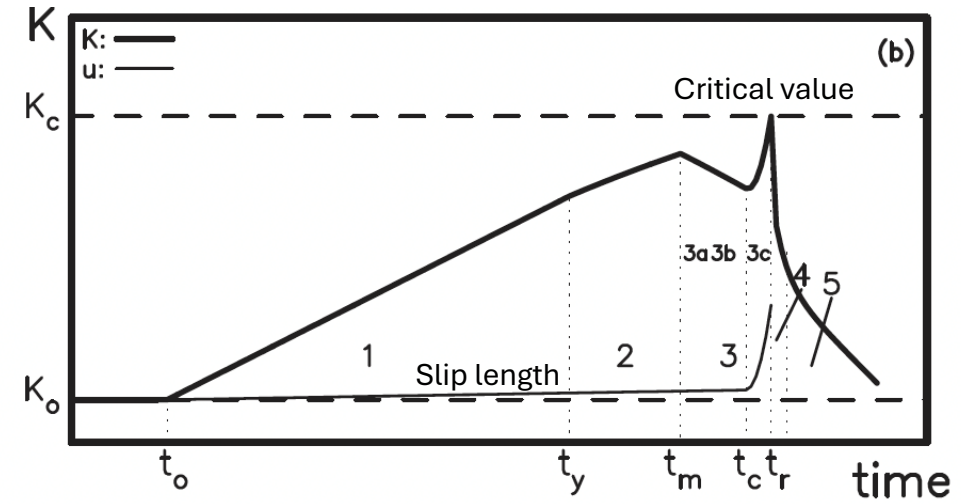
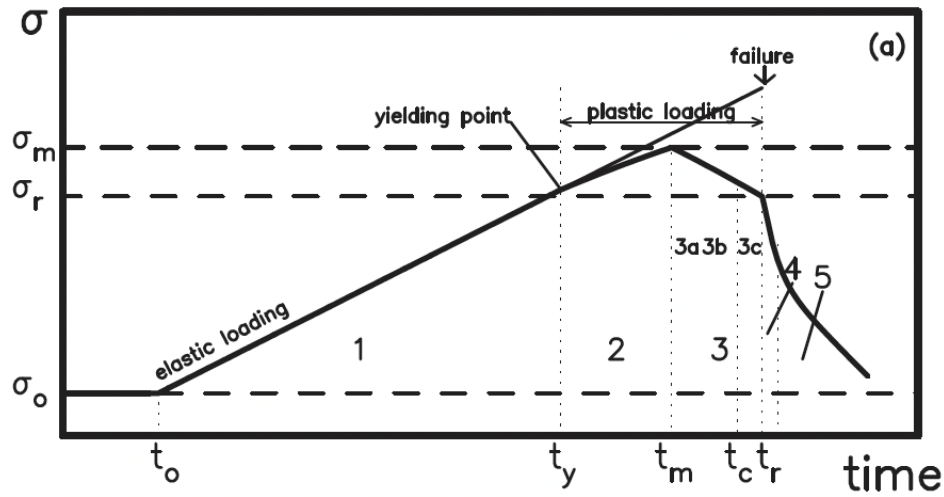


FIGURE 2: Muon fluence for an initial 10 TeV muon beam, shown on a logarithmic color scale, as a function of propagation distance through a composite medium. The muons propagate first through 3 km of silicon dioxide (SiO_2) and subsequently through 500 m of air.

L. Serafini et al. “Active interrogation of underground piezoelectric fabrics using high energy muon beams propagating across seismogenic faults.” *arXiv preprint* arXiv:2601.10430 (2026).



Stress evolution



Wang, J.-H. "Piezoelectricity as a mechanism on generation of electromagnetic precursors before earthquakes." *Geophysical Journal International* **224**(1), 682–700 (2021).

| Stage | Physical Process | Duration |
|---------|------------------------|------------------------|
| Stage 1 | Elastic Loading | 10s to 100s of years |
| Stage 2 | Plastic Hardening | Several years |
| Stage 3 | Precursory Stress Drop | Several months |
| Step 3c | Pre-seismic Slip | 10 mins to a few hours |
| Stage 4 | Earthquake Rupture | ~10s of seconds |
| Stage 5 | Aftershocks | Months or more |



1 - Energy loss

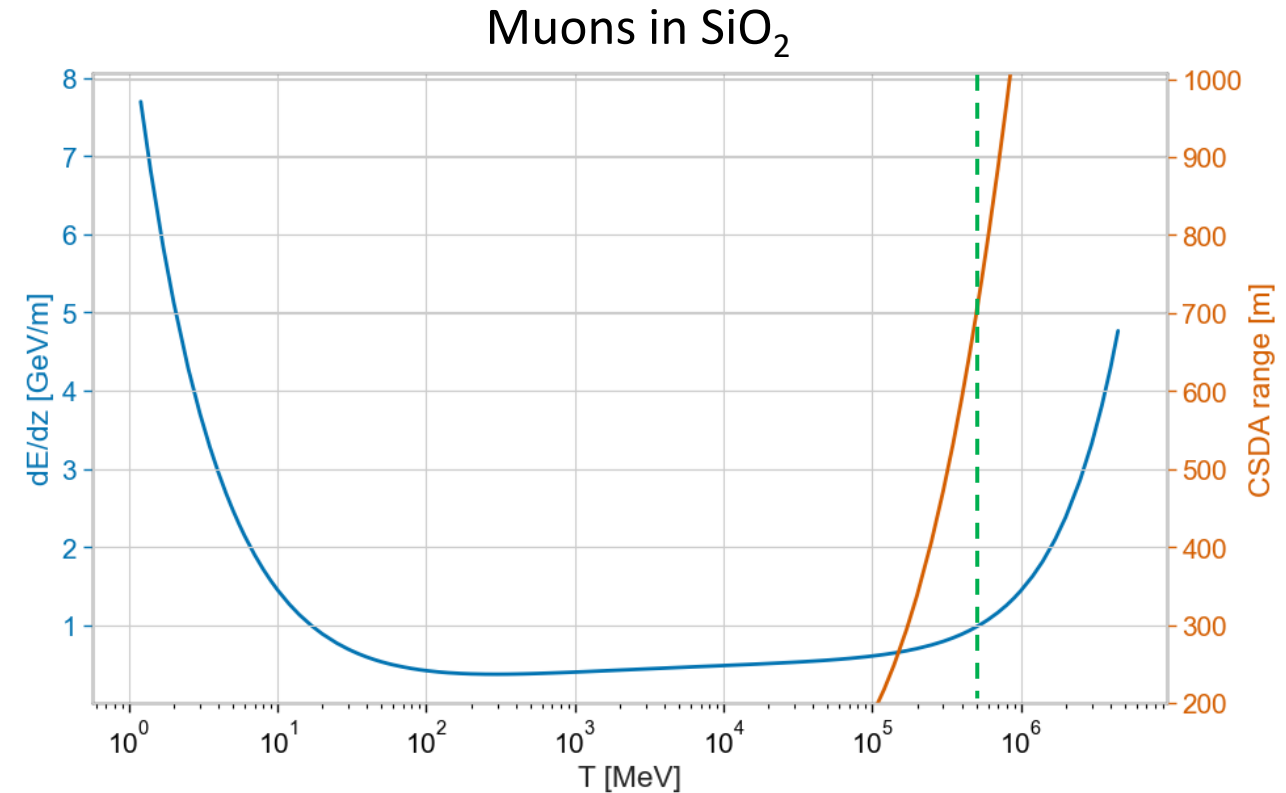
More mechanisms play a role in the **muon energy loss**:

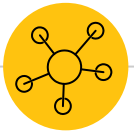
- **Ionization.**
- **Radiation losses:**
 1. Bremsstrahlung.
 2. Pair production.
 3. Photonuclear excitation.

MuAEGIS considers the **average** muon energy loss $\frac{dE}{dz}$ given by the sum of these effect.

Reference case:

- **500 GeV** muon beam propagates **~700 m** in SiO₂ rock.
- Rock and quartz approximated as pure SiO₂.





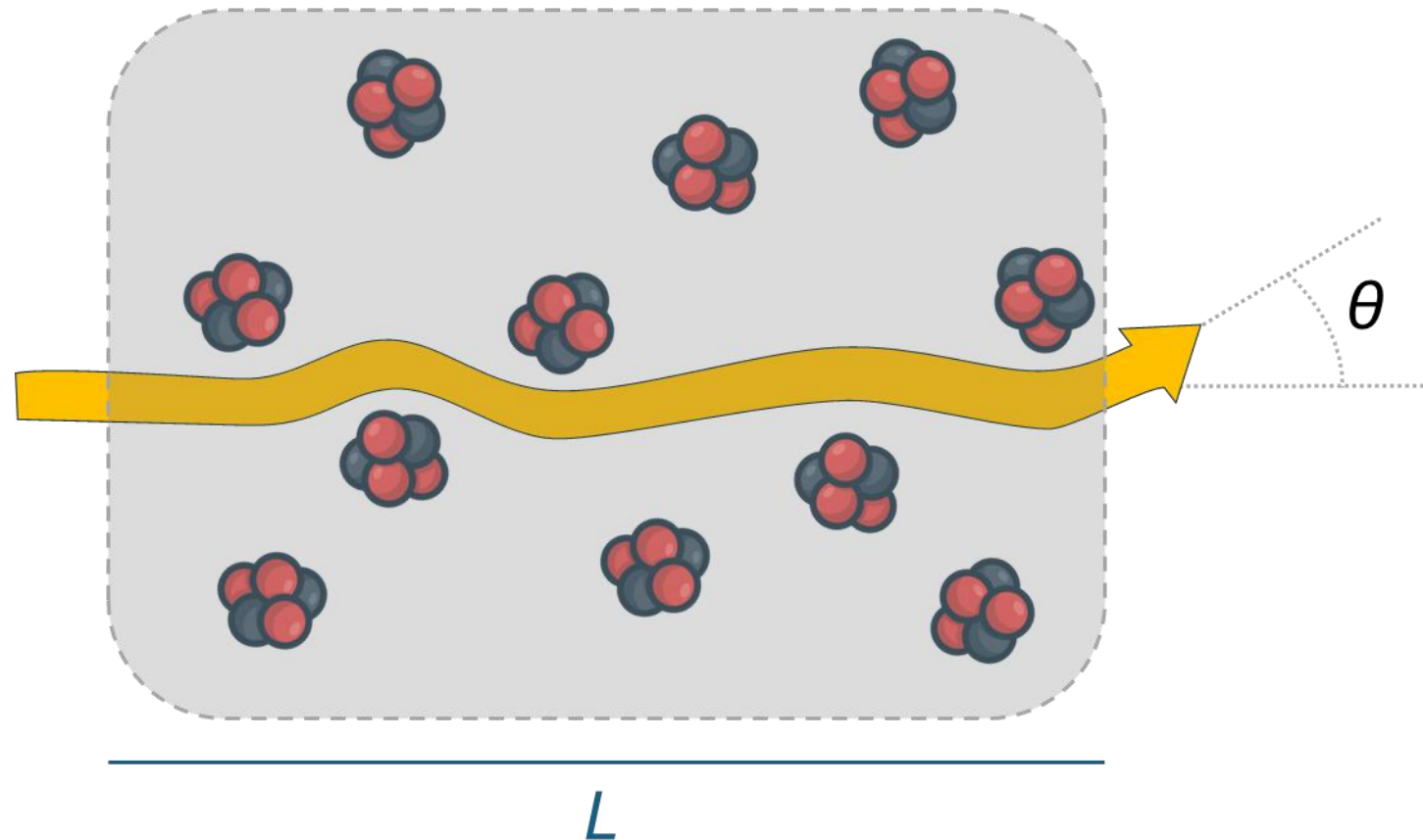
Multiple Coulomb Scattering (MCS) is the main transverse effect causing stochastic deflection by an angle θ .

Molière theory: for relativistic particles, angle θ follows a normal distribution with $\sigma = \theta_0$.

$$\theta_0 = \frac{13.6}{cp} \sqrt{\frac{L}{L_0}} \left[1 + 0.038 \ln \left(\frac{L}{L_0} \right) \right]$$

The radiation length for SiO_2 is $L_0 = 12.3$ cm

The particle momentum p is updated step by step considering $\frac{dE}{dz}$.





3 - PRW

Piezoelectric Random Walk (PRW): second effect on beam transverse plane.

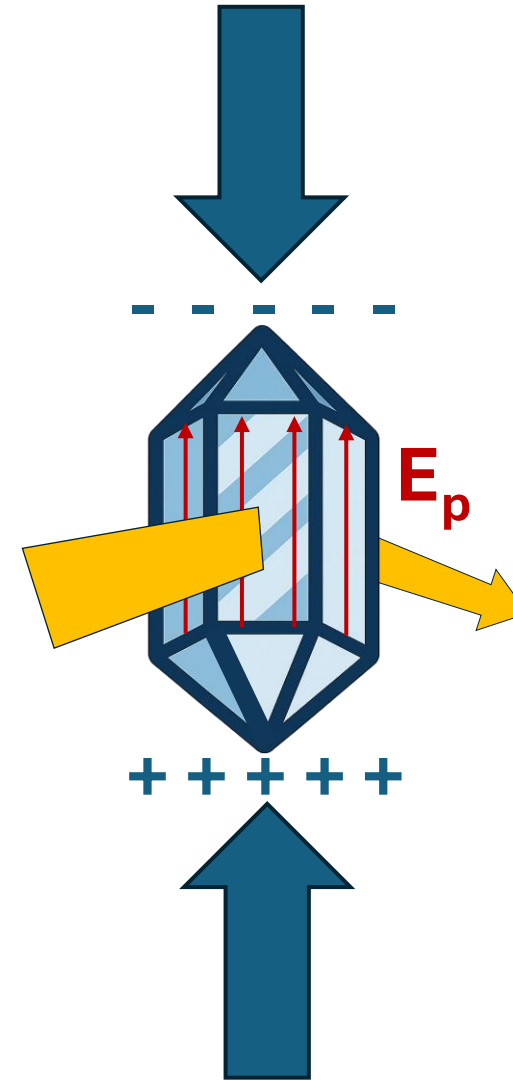
$$\Delta \vec{p} = \frac{q \vec{E}_p L_c}{c}$$

$E_p = 20 \text{ MV/m}$ for $P = 400 \text{ MPa}$ (= 4 kbar)
 L_c up to few cm

Crystals and E_p are **randomly oriented** over 4π .



Transverse momentum evolves as **2D random walk**



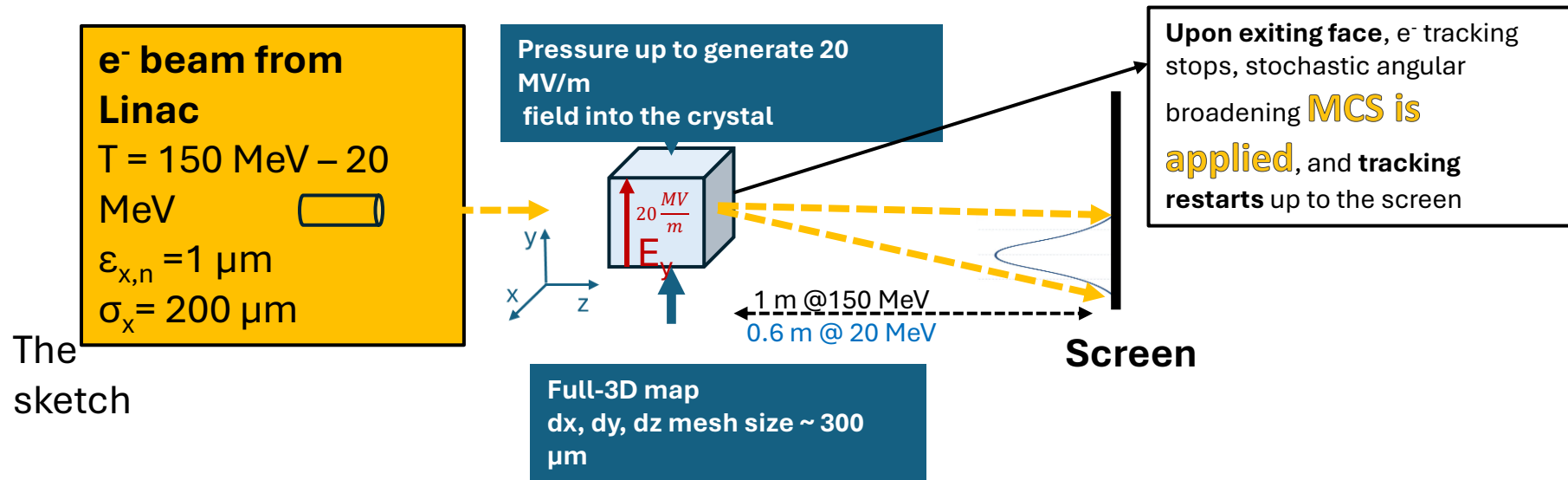
ASTRA particle tracking code is an ad hoc tool for this kind of test

1) It has a **very smart** way to **import full 3D maps** user defined (**5 & 20 MV/m** meshed “**piezo volumes**”).

2) It is **perfect for realistic Start-to-End simulations**, from the Gun up to the final screen.

We considered **electron beams** (generated by ASTRA generator @ **20 & 150 MeV**):

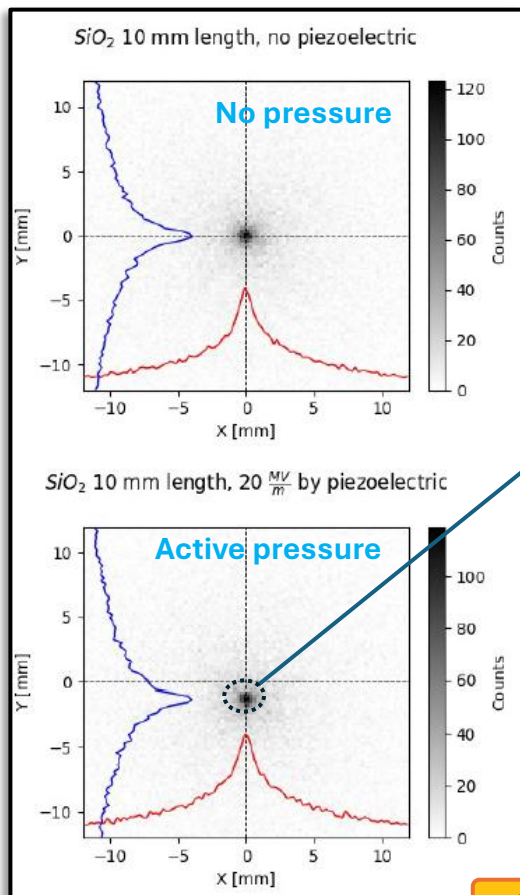
- I) a quartz crystal (1 cm x 1 cm x 1 cm) with 150 MeV – **5 & 20 MV/m** of piezo
- II) a quartz crystal (1 cm x 1 cm x 0.5 cm) with 20 MeV – **5 & 20 MV/m** of piezo





20 & 150 MeV e⁻ beam @ screen

60 kpart @ 150 MeV

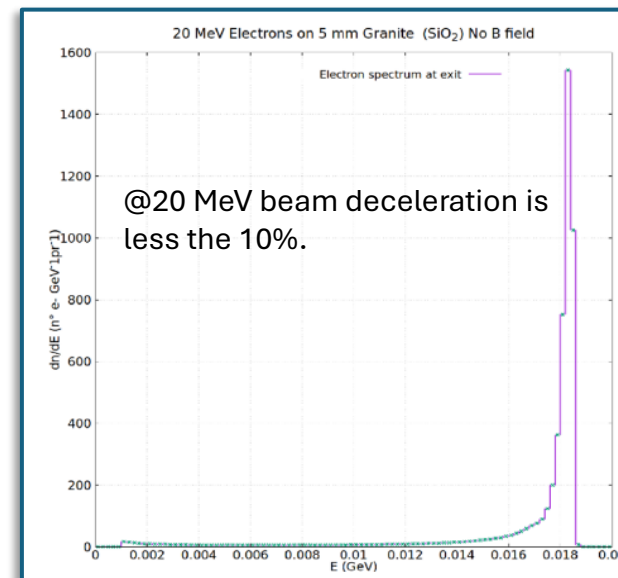


The beam shows a significant visible shift on the target!

Considering other value as in the following Tab:

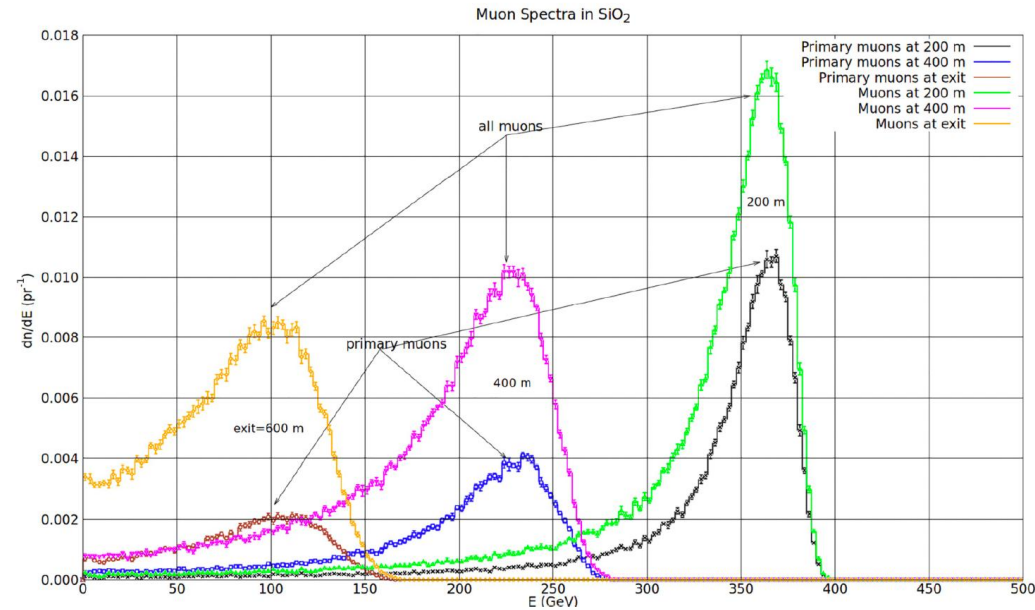
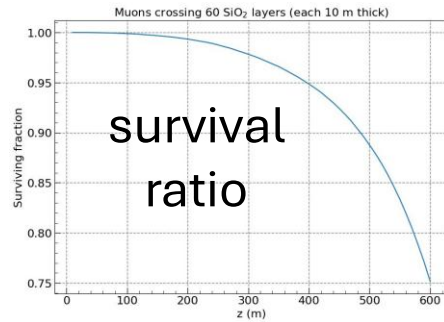
| En [MeV] | Drift [m] | SiO ₂ -length [mm] | Piezo [MV/m] | $E_{sy} \langle y \rangle$ [mm] | Deflect. [mm] |
|----------|-----------|-------------------------------|--------------|---------------------------------|---------------|
| 150 | 1 | 10 | 20 | 1.5 | 0.4 |
| 150 | 1 | 10 | 5 | 0.4 | 3.0 |
| 20 | 0.6 | 5 | 20 | 3.0 | 0.77 |
| 20 | 0.6 | 5 | 5 | 0.77 | |

Shifts are amplified at lower energy and reduced with lower field.



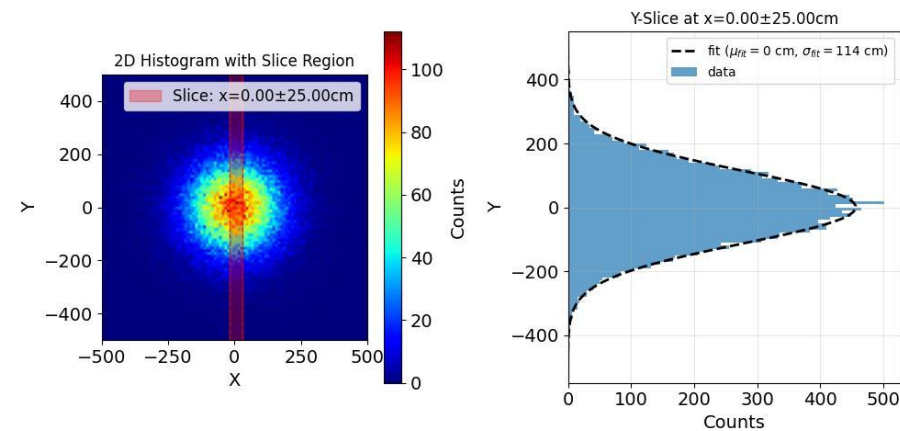
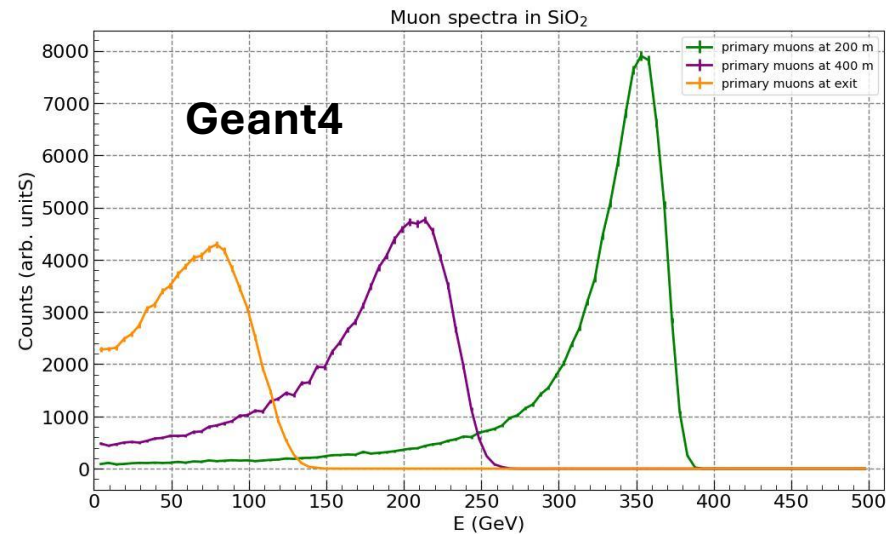
Courtesy of A. Bacci

500 GeV muons
in 600 m SiO₂



Fluka
F. Broggi
(INFN-Mi)

FIG. 15. Energy spectra of primary and all muons at various locations through the rock traversal, i.e., after 200 m, 400 m, and at the rock layer exit at 600 m.



G. Paternò, L. Bandiera (INFN-Fe)

A muon accelerator in a hangar

10^9 - 10^{10} muons on detector in 100 seconds for ERMES (see later) needs 10^7 - 10^8 muons per second in the beam (cmp. 10^{12} of muon collider), hence 10^{11} - 10^{12} primary electrons @ 10 GeV on W target for muon pair photo-production, as done at ELI-NP, (compatible with state of the art of laser-plasma driven accelerators, 1 nC @ 100 Hz). Ultra-short GeV-class muon bunches generation demonstrated with laser-plasma accelerator cm-size long inside a hangar hosting the PW laser system.

A. Rossi strawman design for 500 GeV μ - booster

the plasma stages can reach an accelerating field of 10 GV/m, allowing to increase muons energy of 5 GeV each. Overall, an ≈ 50 m active acceleration length is required, totaling an overall ≈ 100 m accelerator length. Due to a q/m ratio 200 times smaller than electrons, the muons bunch could be safely U-turned by 10 T superconducting bending magnets in an ≈ 80 m radius (at 250 GeV or less) or in about half that value by curved discharge capillaries [32,33], allowing the accelerator to be folded and reduce its overall length to dimensions of a big hangar.

A muon accelerator in a hangar, a detailed simulation of the first 40 GeV stage

PHYSICAL REVIEW ACCELERATORS AND BEAMS **29**, 021302 (2026)


Muon injection and acceleration via ultraintense electron beam-driven plasma wakefield

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 (Received 24 September 2025; accepted 14 January 2026; published 18 February 2026)

High-flux, high-energy muon beams hold transformative potential for particle physics, yet rapid acceleration to relativistic energies in plasma wakefields is limited by dephasing arising from their larger mass and lower velocity. Here, we propose a method for longitudinal injection and stable acceleration of low-energy muons using a plasma density up-ramp to separate the deceleration and acceleration regions. The nonlinear wakefield configuration required for muon injection was obtained analytically using Hamiltonian dynamics, and particle-in-cell (PIC) simulations showed that the initial energy and emittance conditions of injectable muons can be tuned. Driven by an ultraintense 23 GeV electron beam, muons with an initial energy of 300 MeV attain a final energy of 40 GeV, with an 18.85% energy spread and a normalized emittance of 8.86 mm mrad. These findings provide a feasible pathway toward the development of compact muon colliders, with potential to advance particle physics and enable the exploration of phenomena beyond the Standard Model.

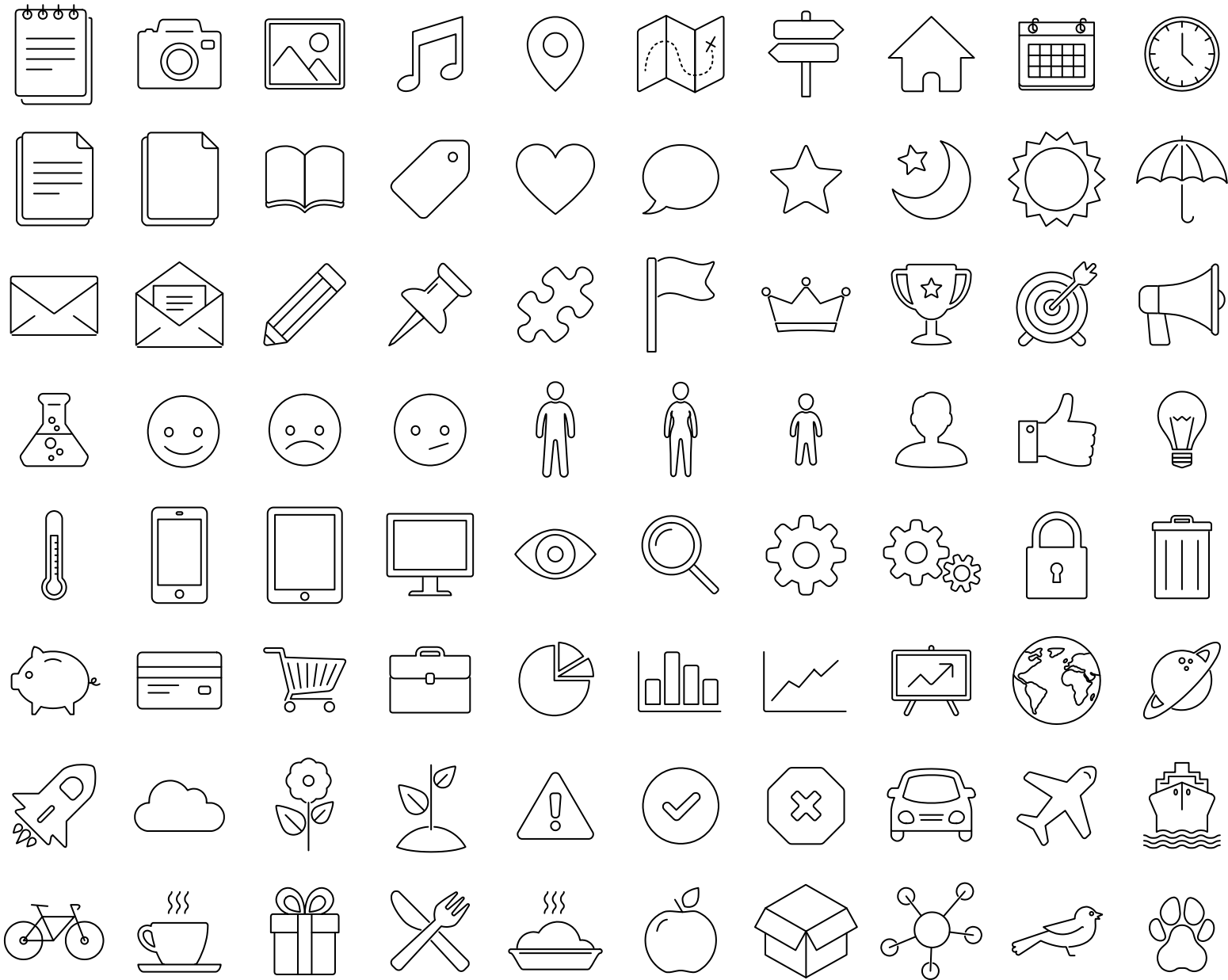
DOI: [10.1103/wq5g-mtjq](https://doi.org/10.1103/wq5g-mtjq)



Credits

Special thanks to all the people who made and released these resources for free:

- Presentation template inspired by [SlidesCarnival](#)
- Icons from [Flaticon](#)



SlidesCarnival icons are **editable shapes**.

This means that you can:

- Resize them without losing quality.
- Change line color, width and style.

Isn't that nice? :)

Examples:

