The Strong Crystalline Field

or how to play with particle beams using tiny crystals!

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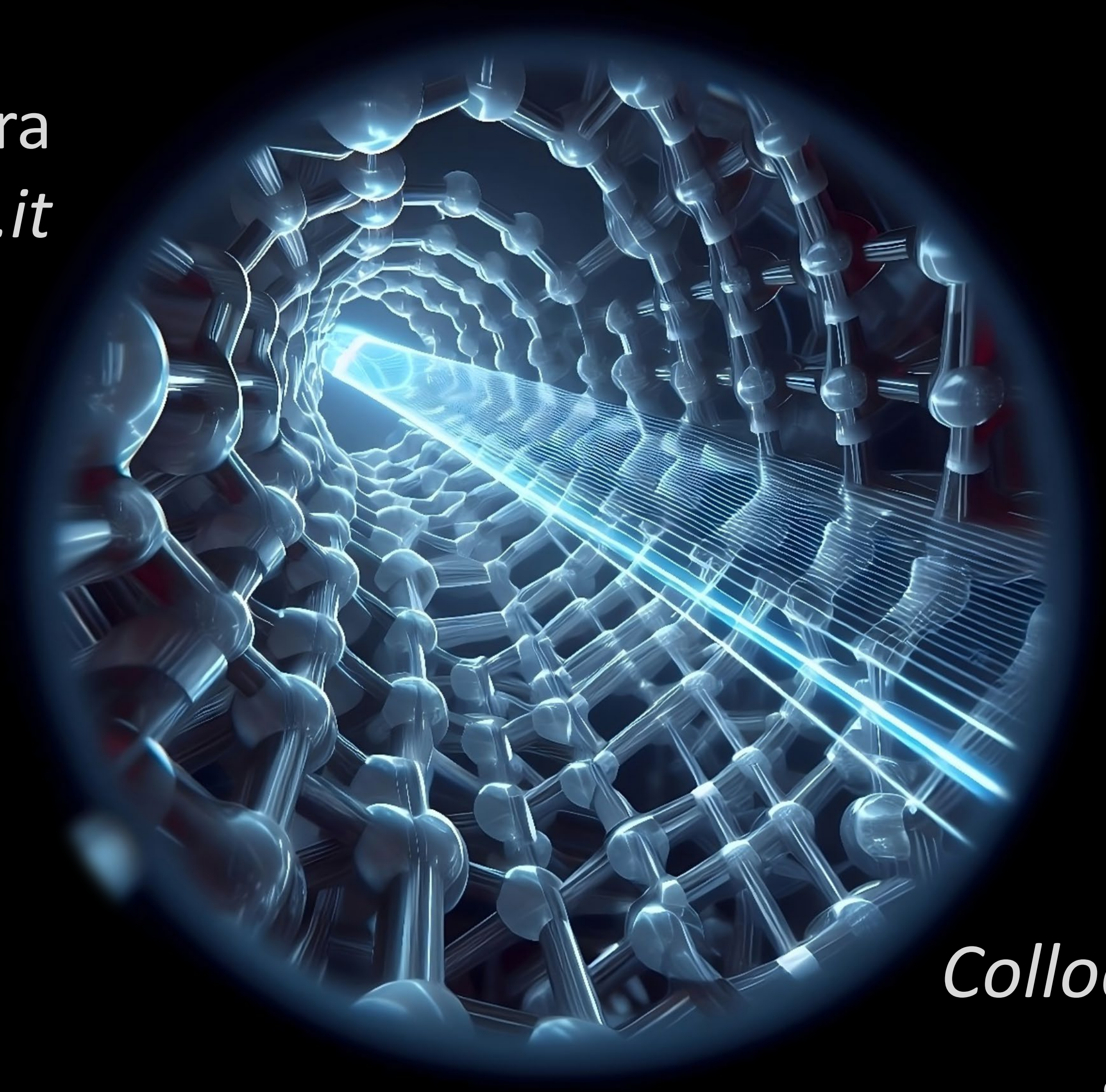

INFN
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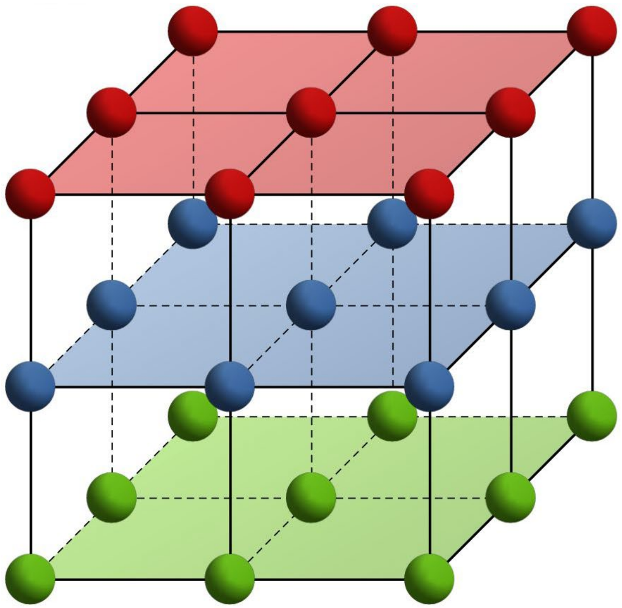
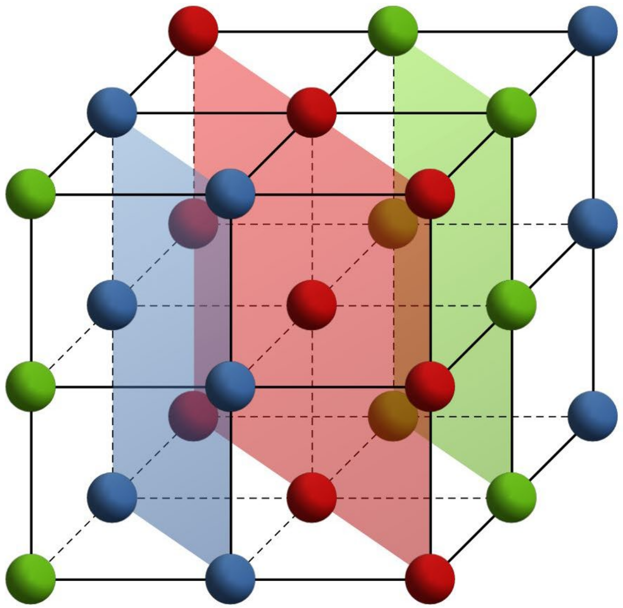
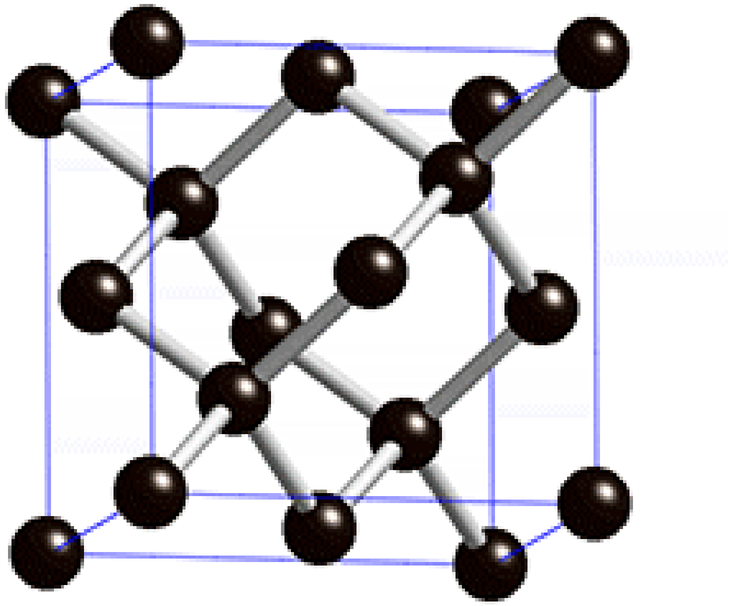
Colloquio di Dipartimento
21st November 2023

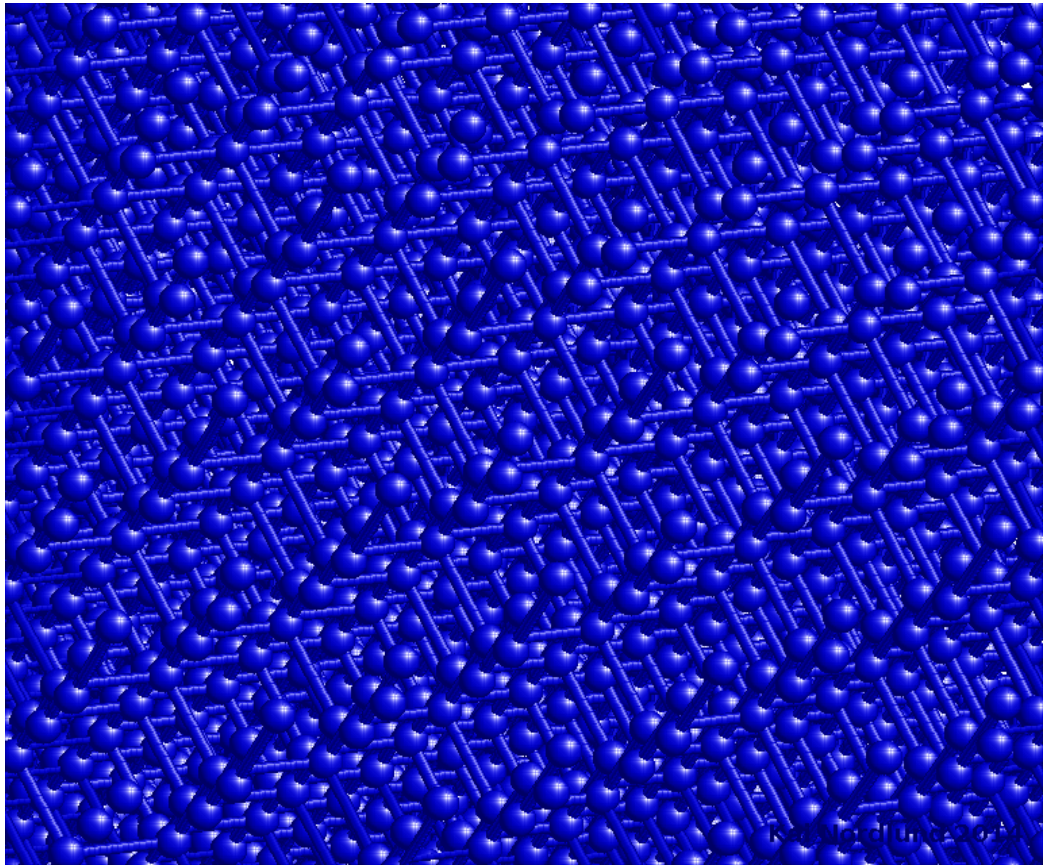
The crystal lattice

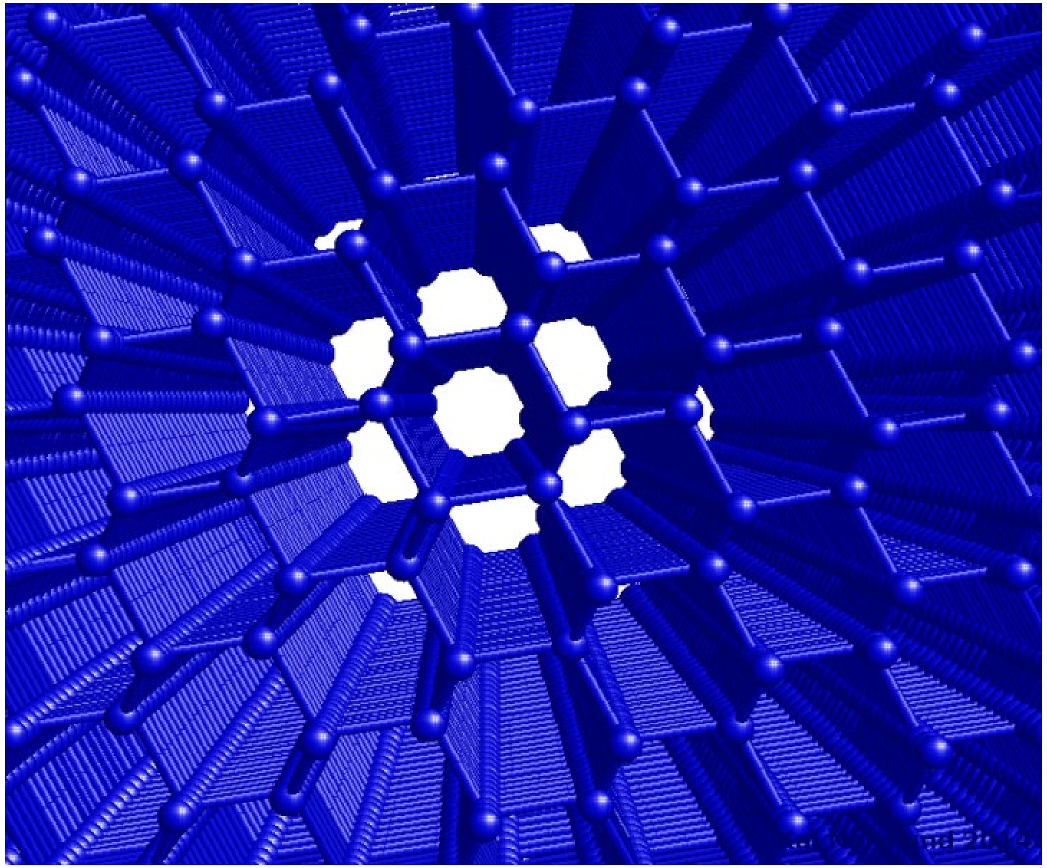






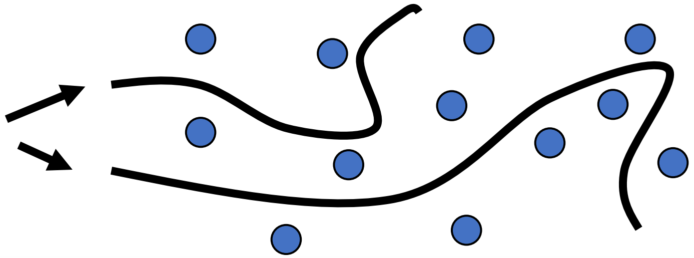
A strong electrostatic potential





Channeling: trapping of charged particles

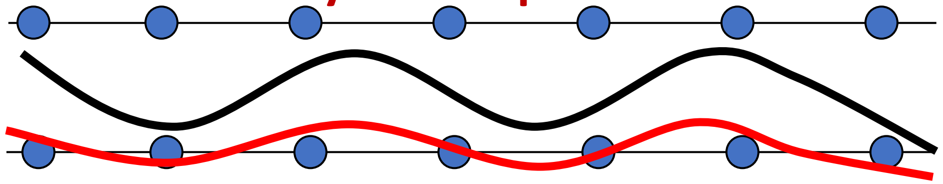
proton

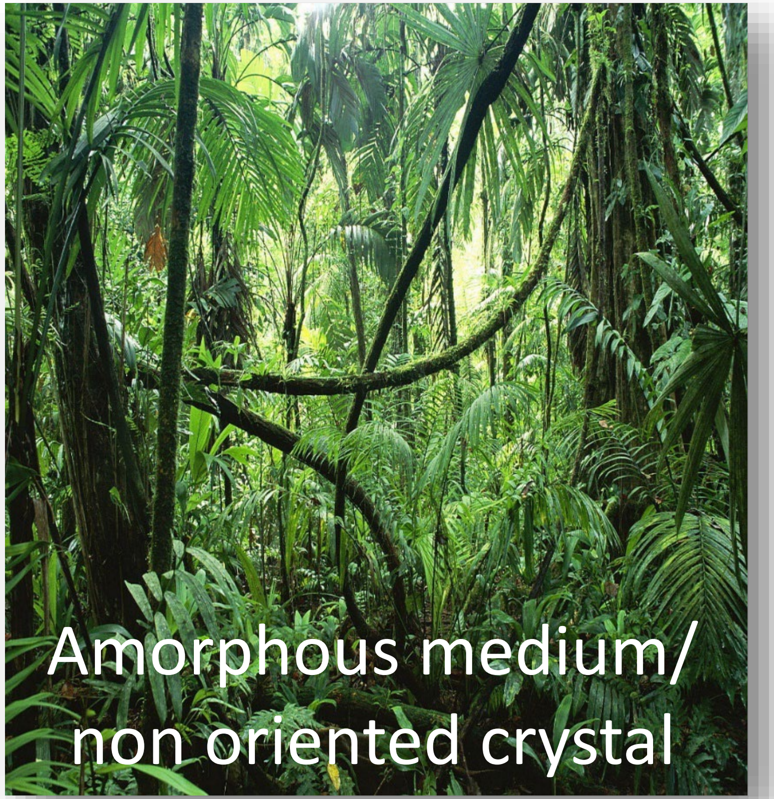


crystalline plane

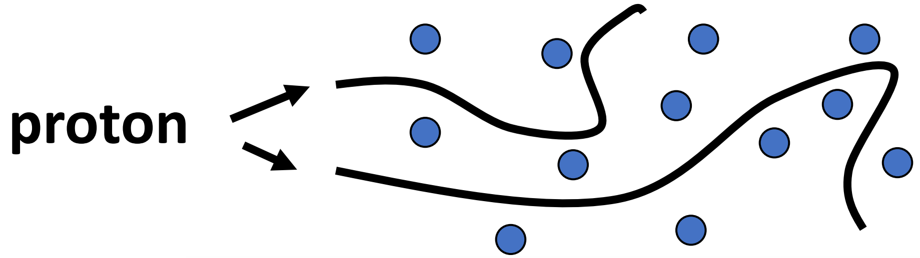
proton

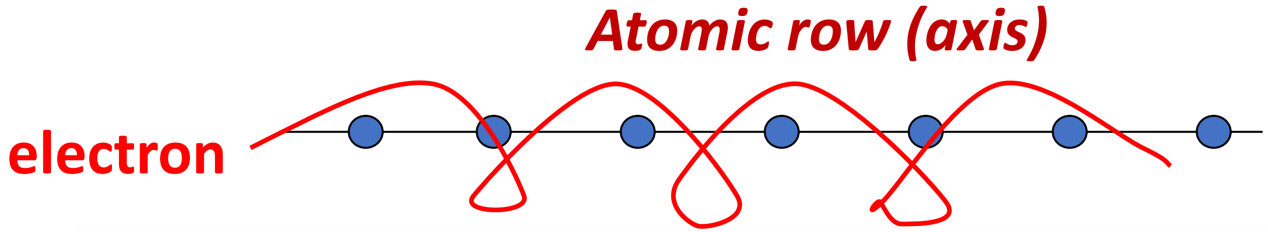
electron

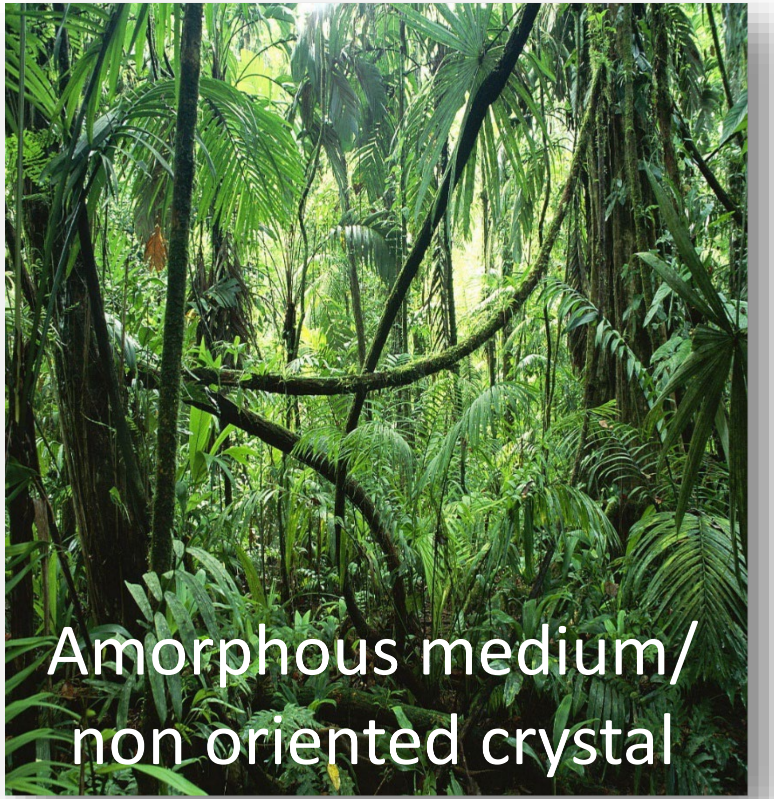




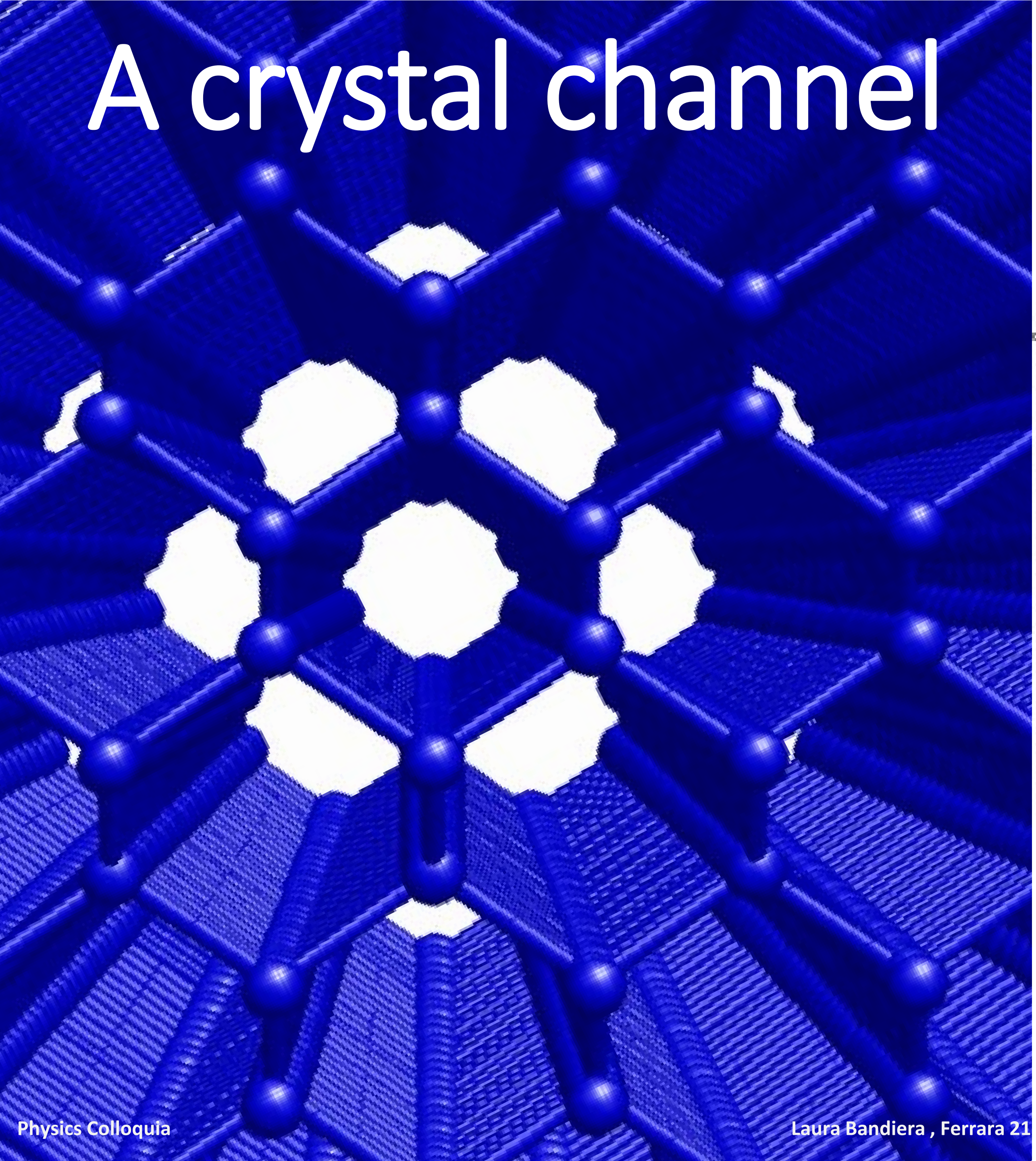
Channeling: trapping of charged particles

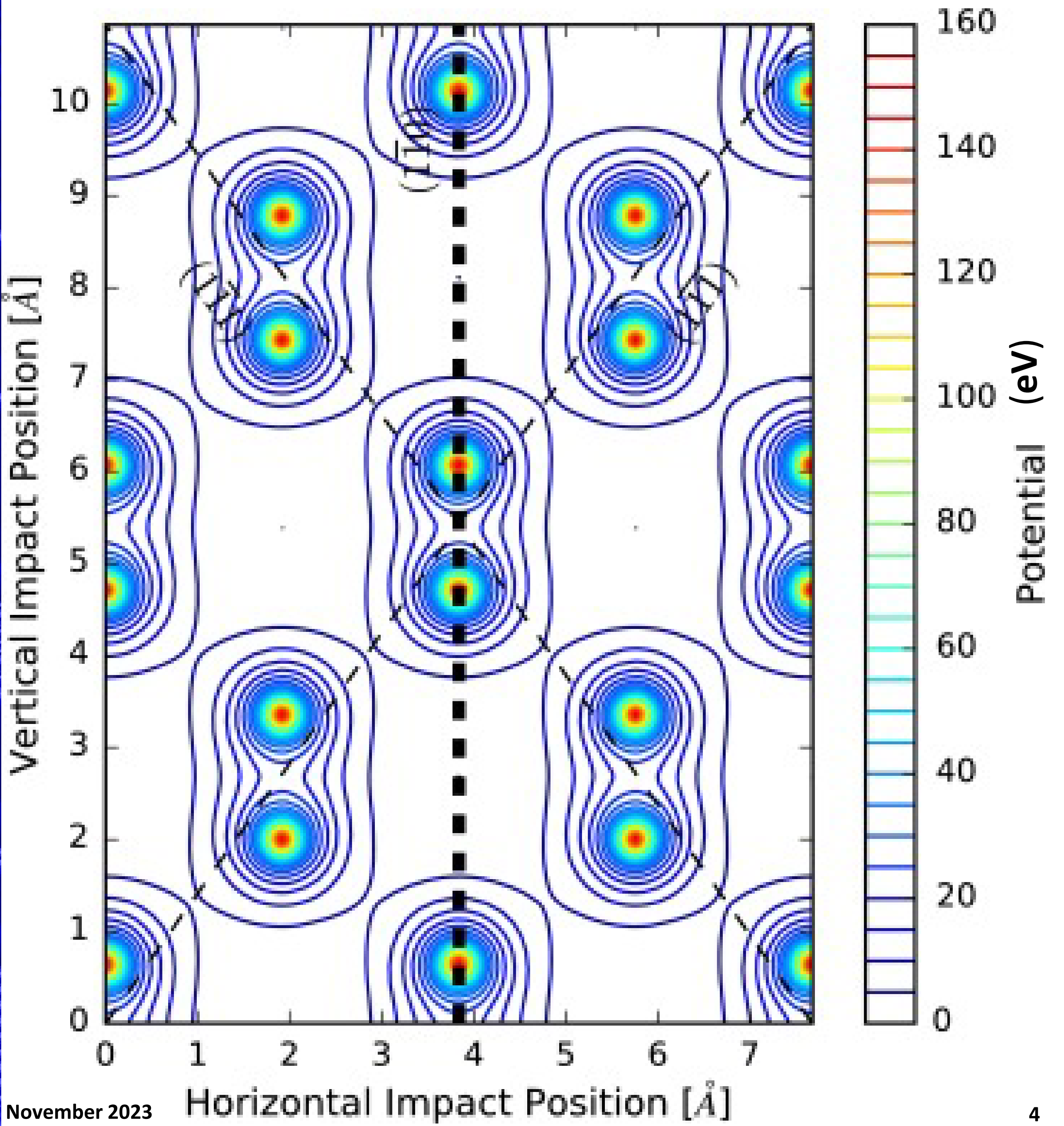




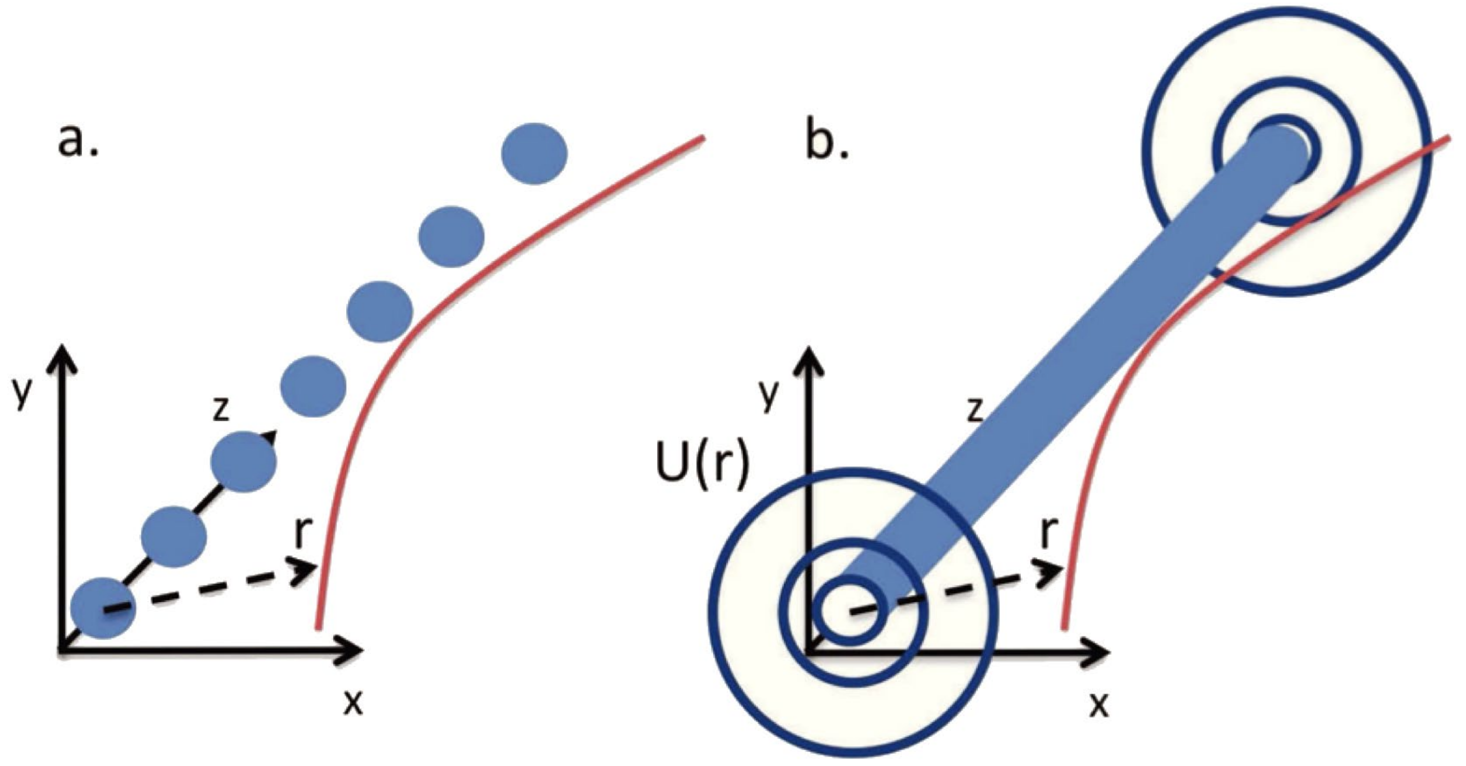


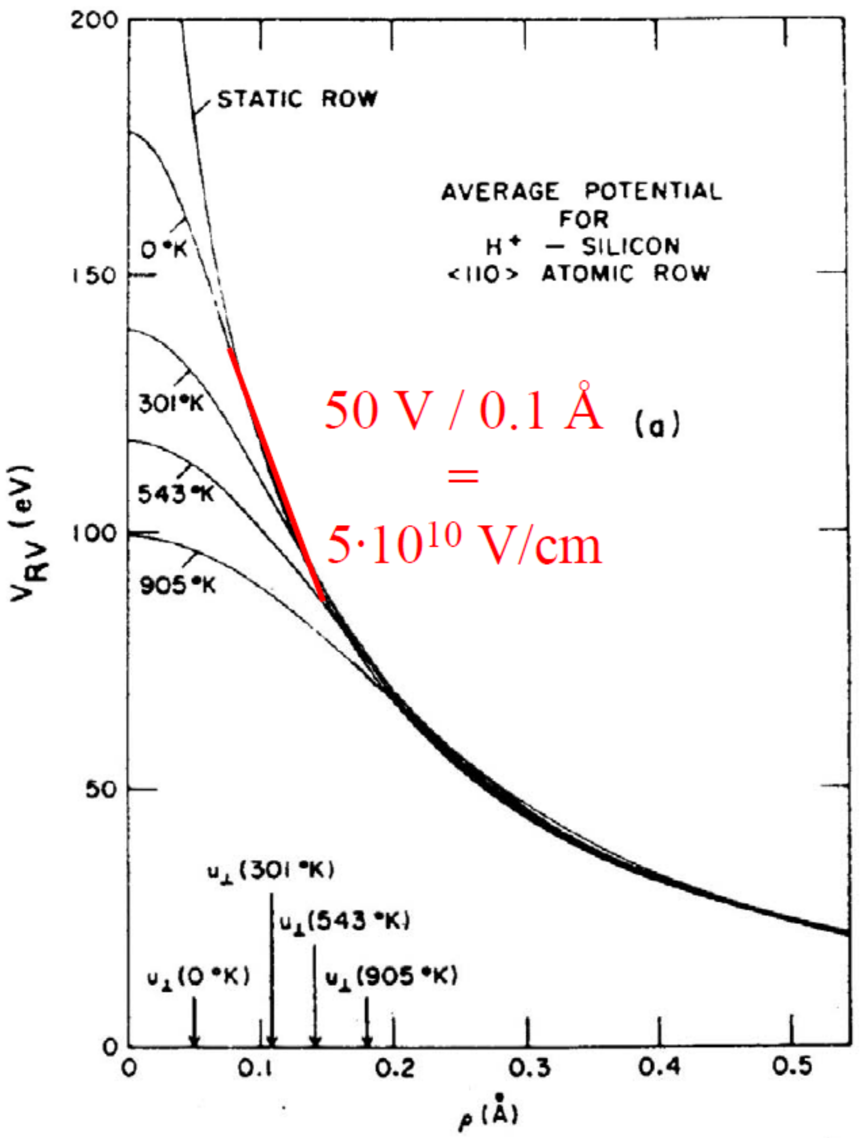
A crystal channel



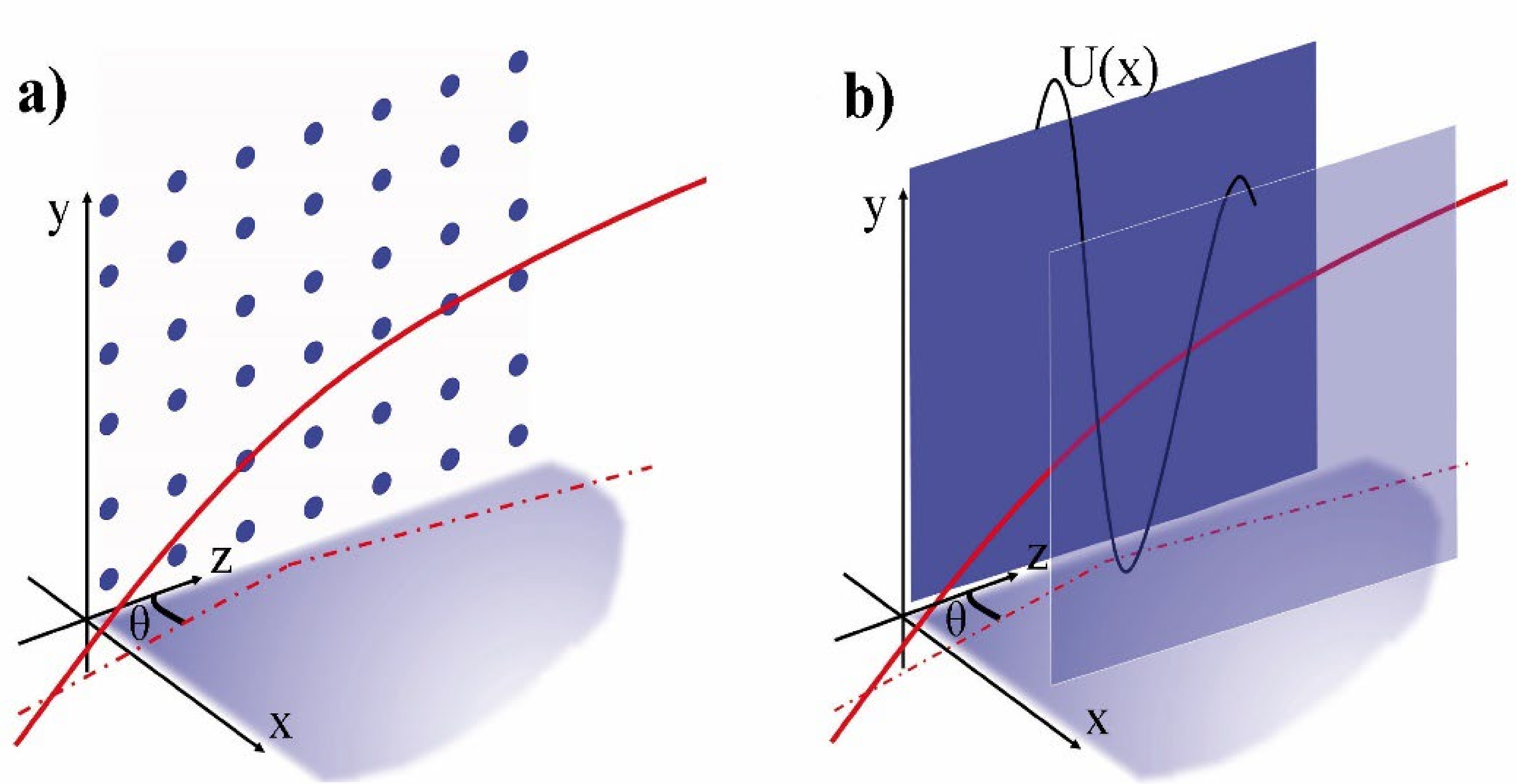


Extremely strong electric fields

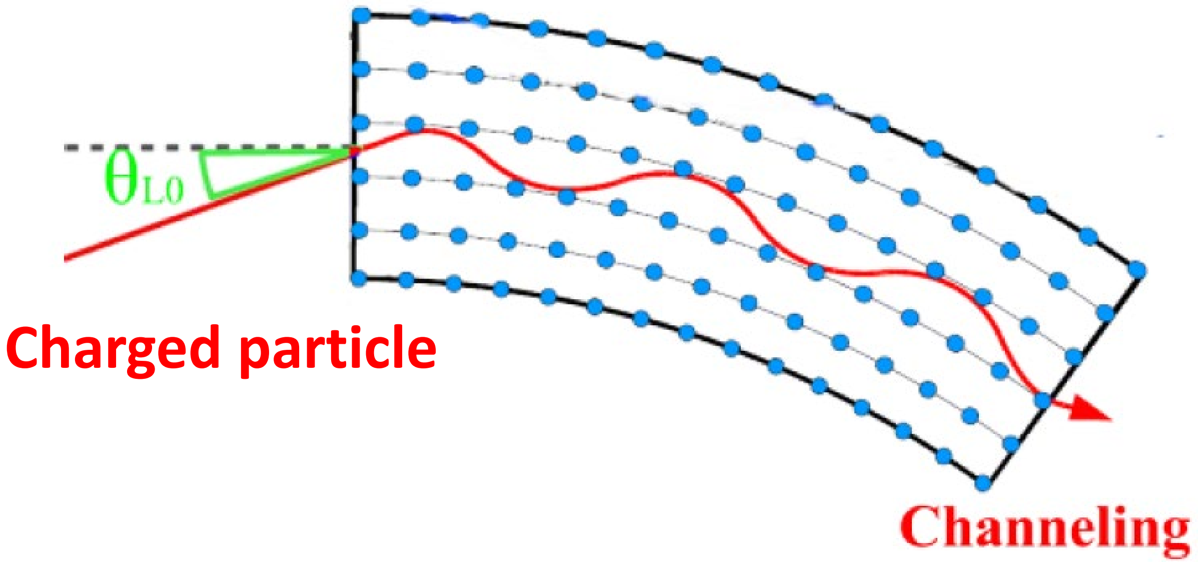




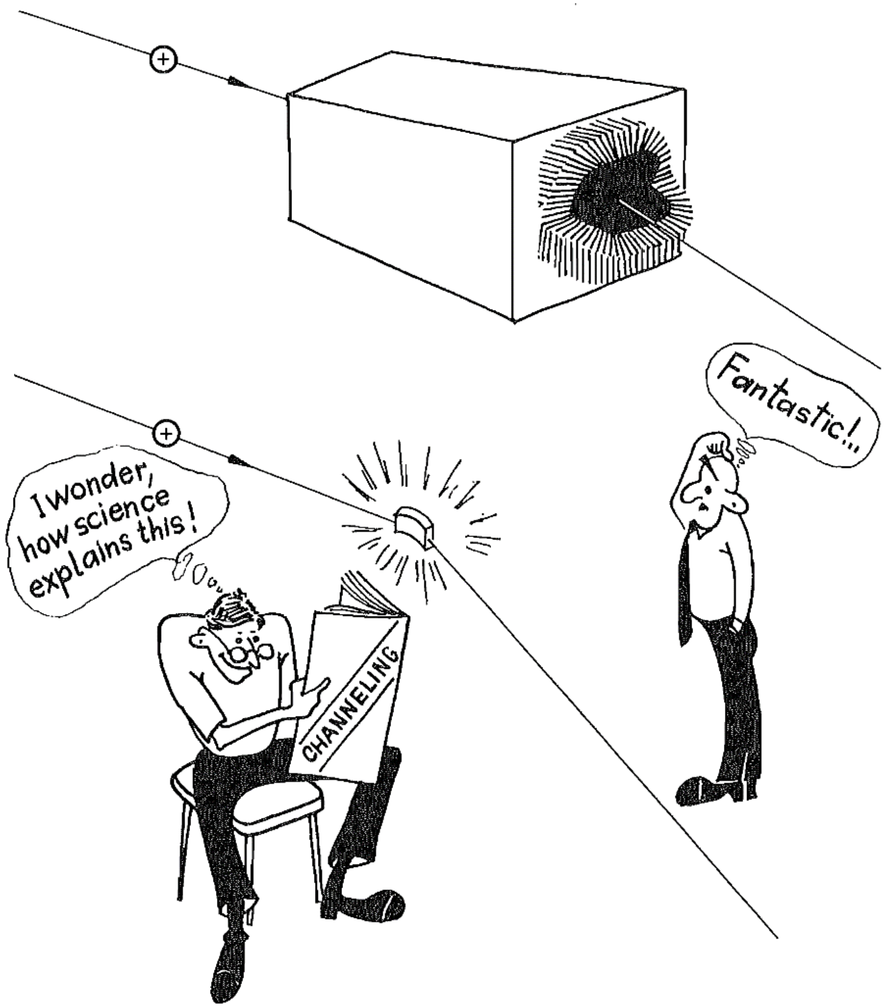
And also planar channels



Bending a crystal:
A way to steer a particle beam



E. Tsyganov, 1976



Bending a crystal:
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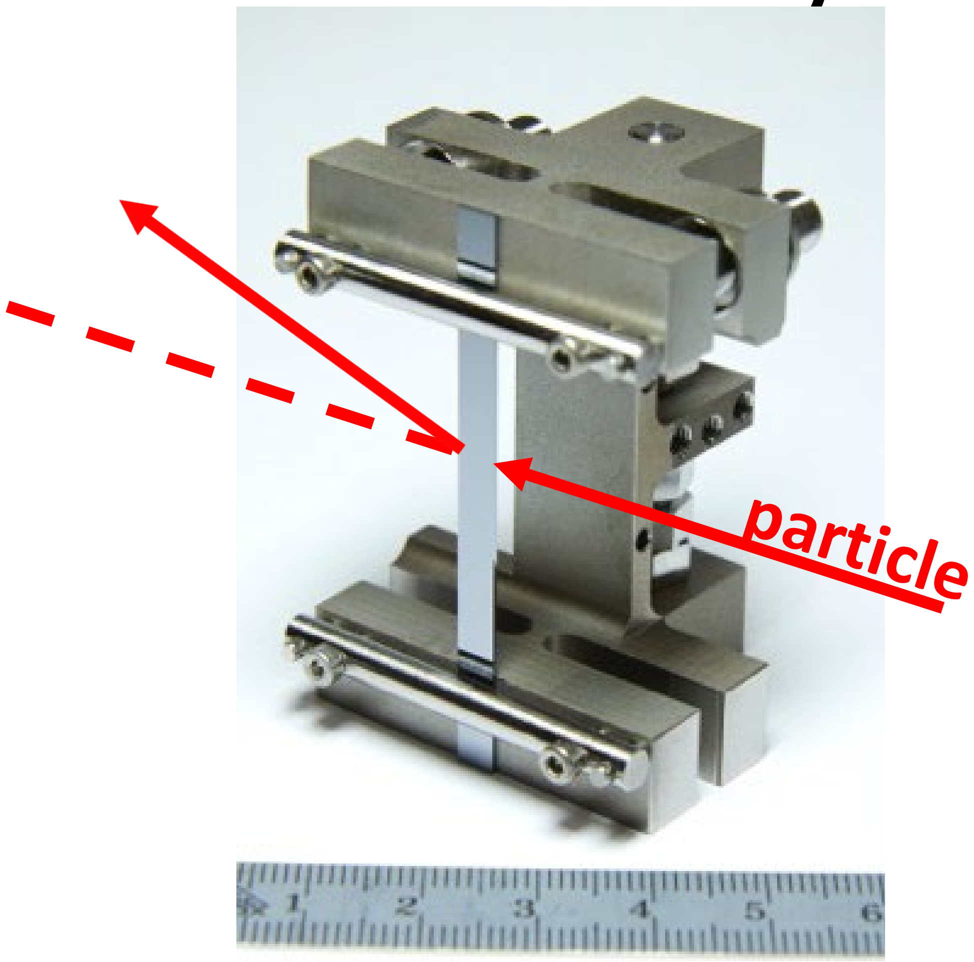
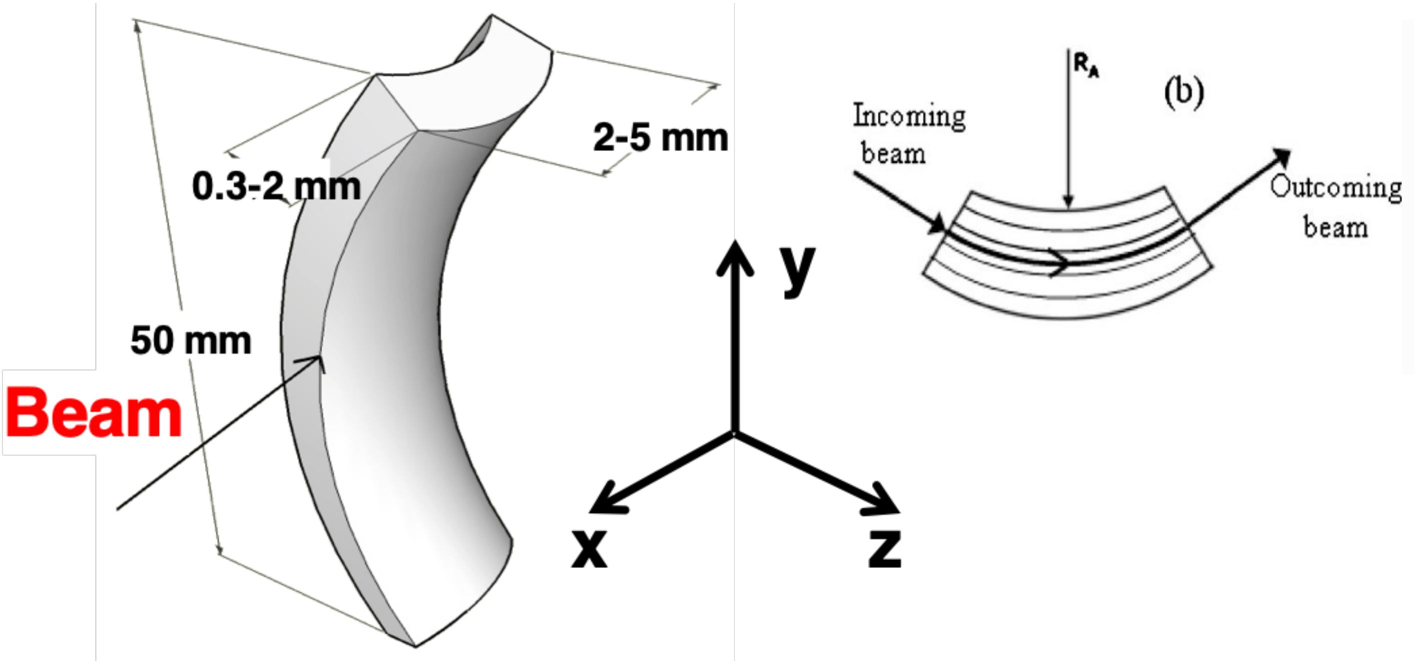
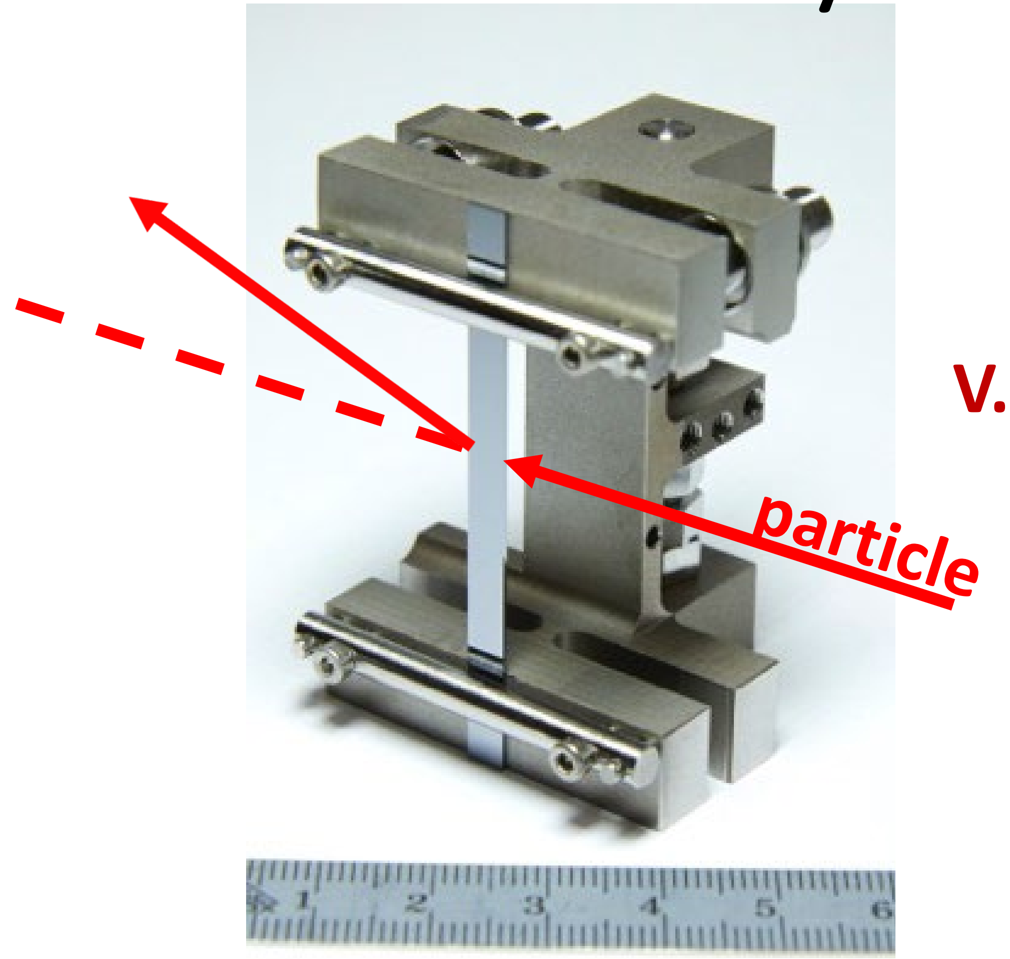




Bent Si crystal – 4 mm long

Bending a crystal:
A way to steer a particle beam



Bent Si crystal – 4 mm long

V.S.

8.3 Tesla supermagnet – 15 m long

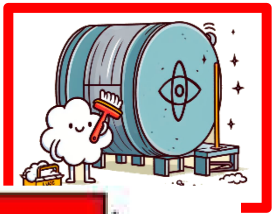
Deflection of 50 µrad at 6.5 TeV is equivalent to a 300 T dipole magnet bending!

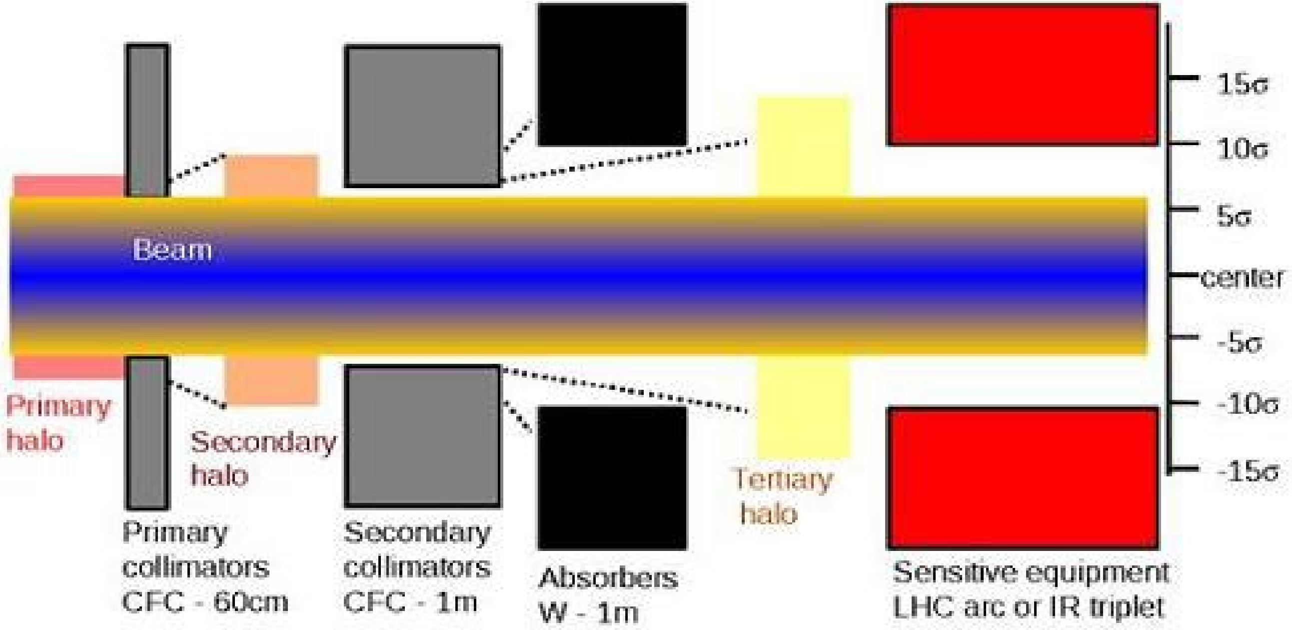
Where to use bent crystals:

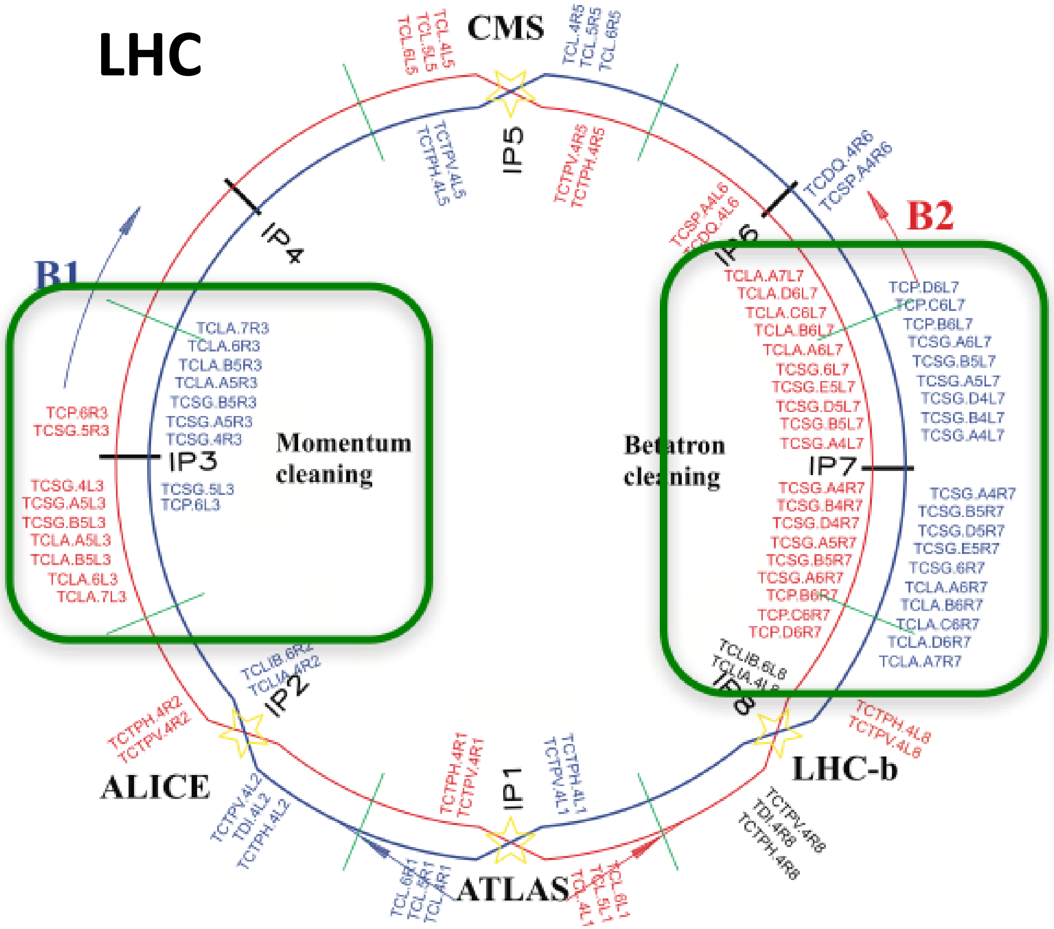
THE LARGE HADRON COLLIDER

Cleaning a multi-TeV hadron beam:

The LHC collimation system

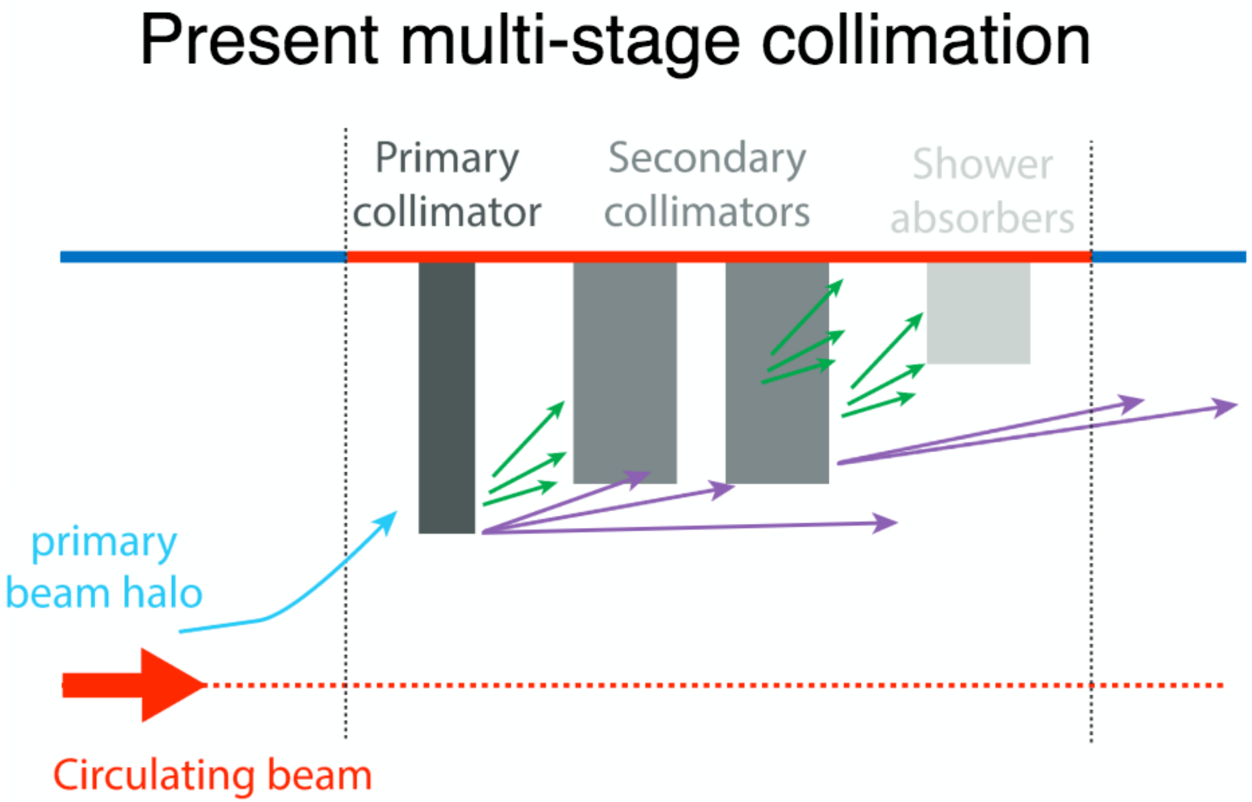


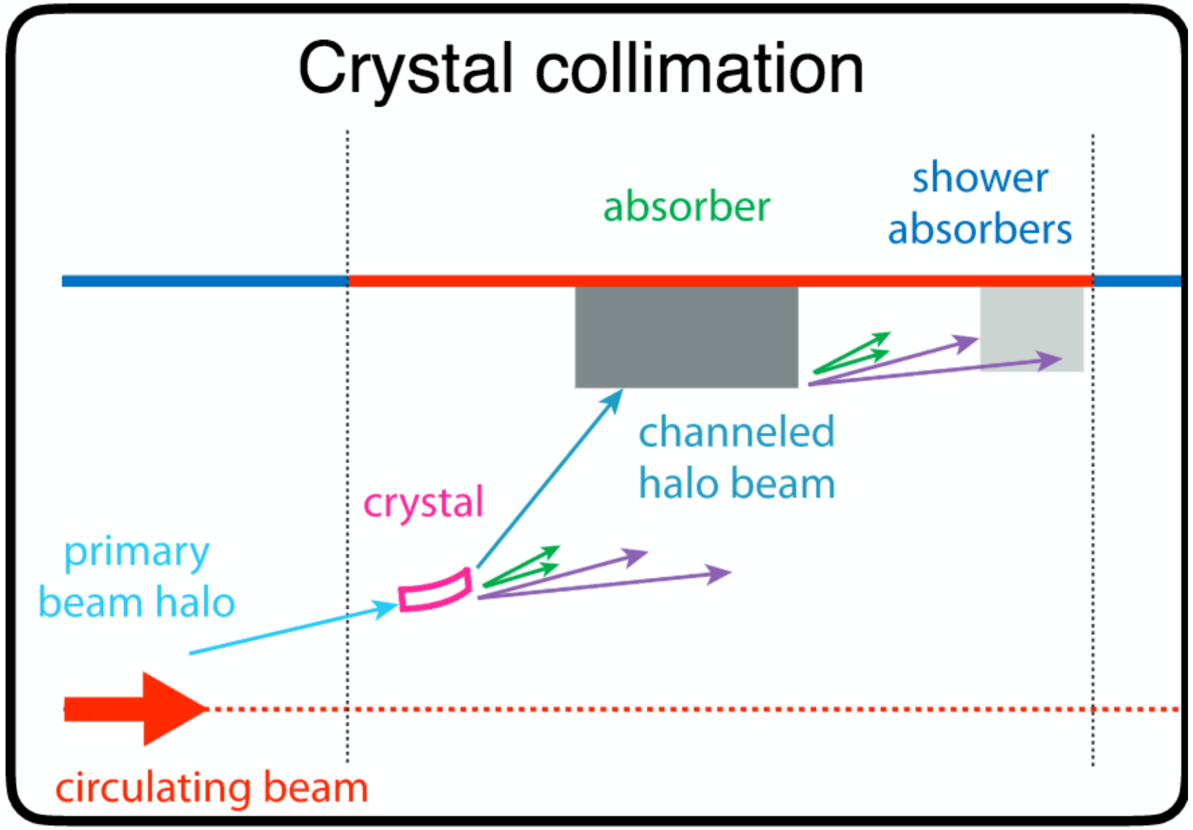




A total of ~50 collimators per beam to protect the superconducting magnets and other sensitive areas

The High Luminosity LHC:
The crystal collimation system

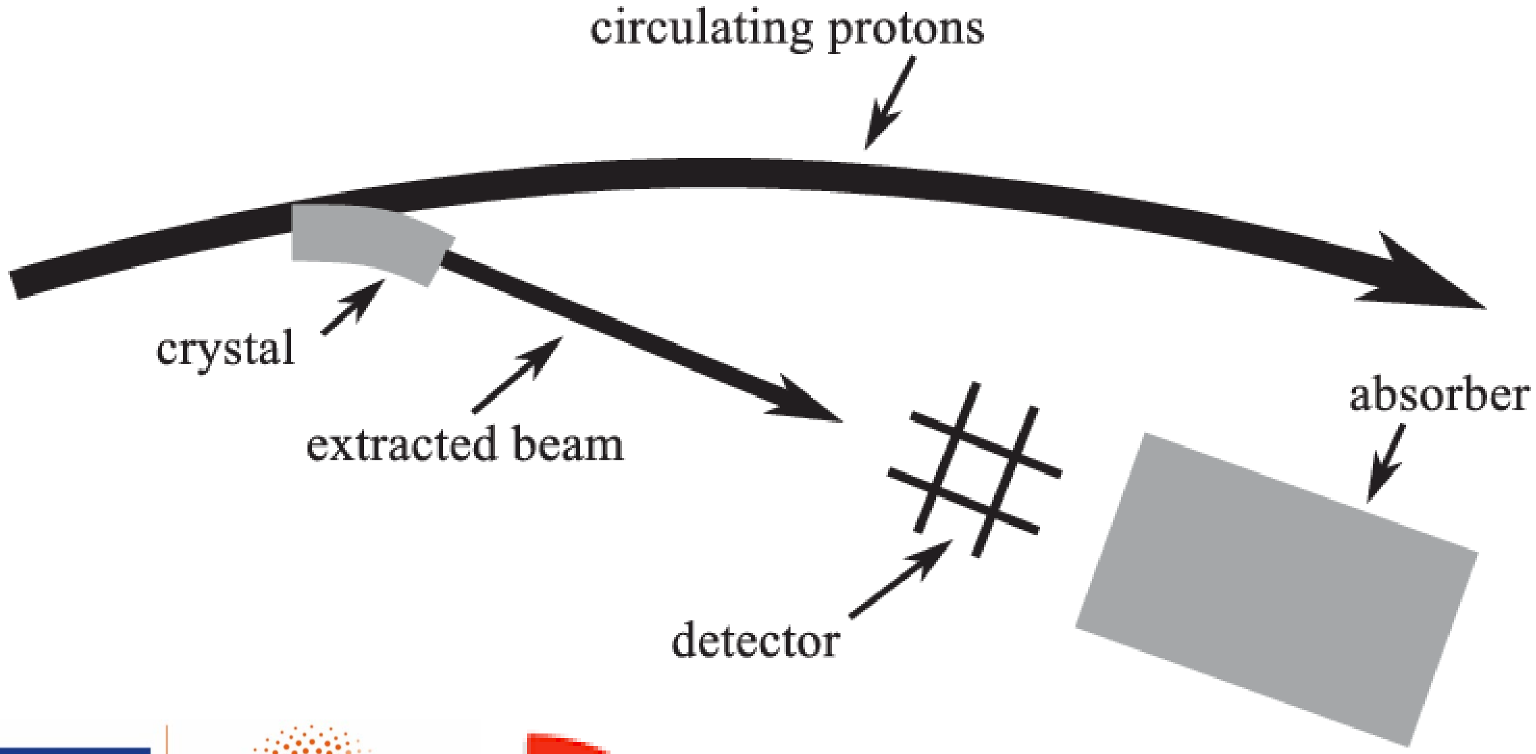




W. Scandale et al., Phys.Lett. B758 (2016) 129-133

First successful test with **6.5 TeV protons in** Nov 2015 with Ferrara crystals!

Extraction of the multi-TeV LHC beam

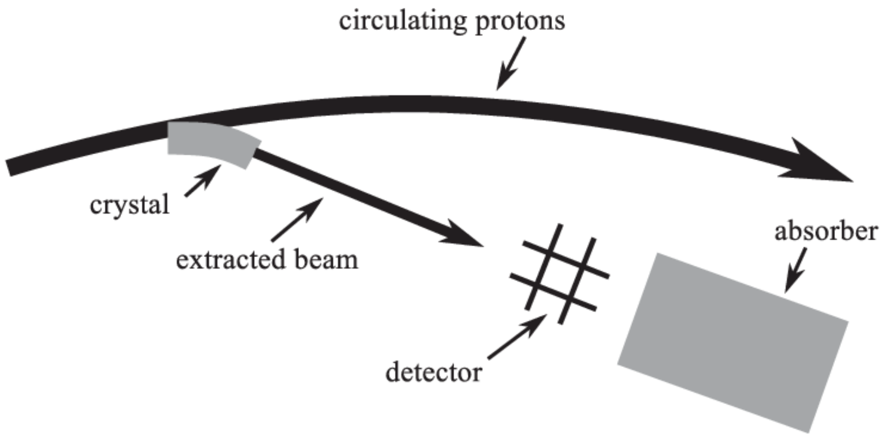


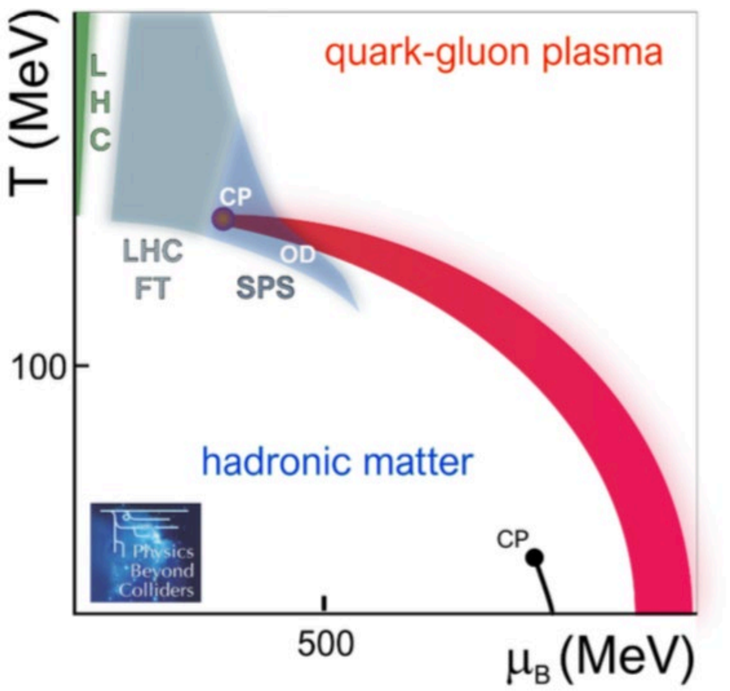
An upgraded **internal gas target** is another solution to for fixed target physics (already operational in LHC-b, **SMOG**)

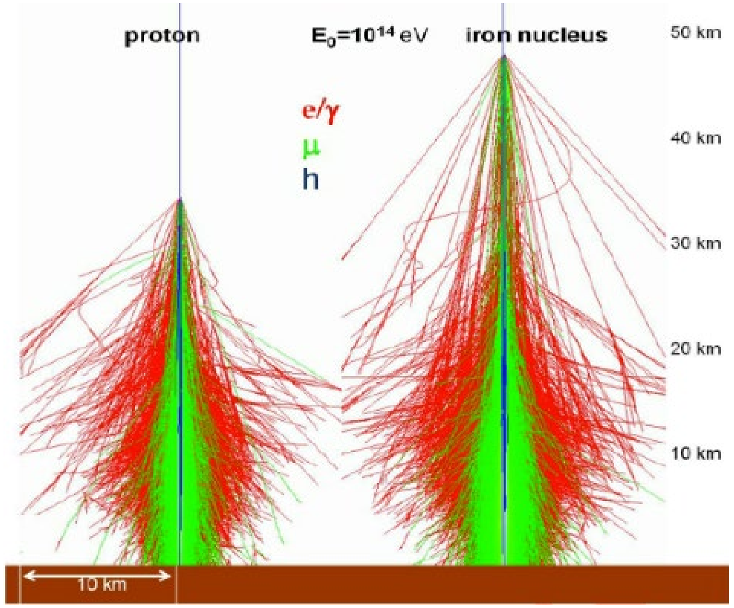
Future developments for crystals (from the Physics Beyond Colliders CERN group)

Extraction of the multi-TeV LHC beam

To address open questions in the domain of proton and neutron spins, Quark Gluon Plasma and what is the nature of cosmic rays? … at the **highest energy** ever reached in the fixed-target experiments!

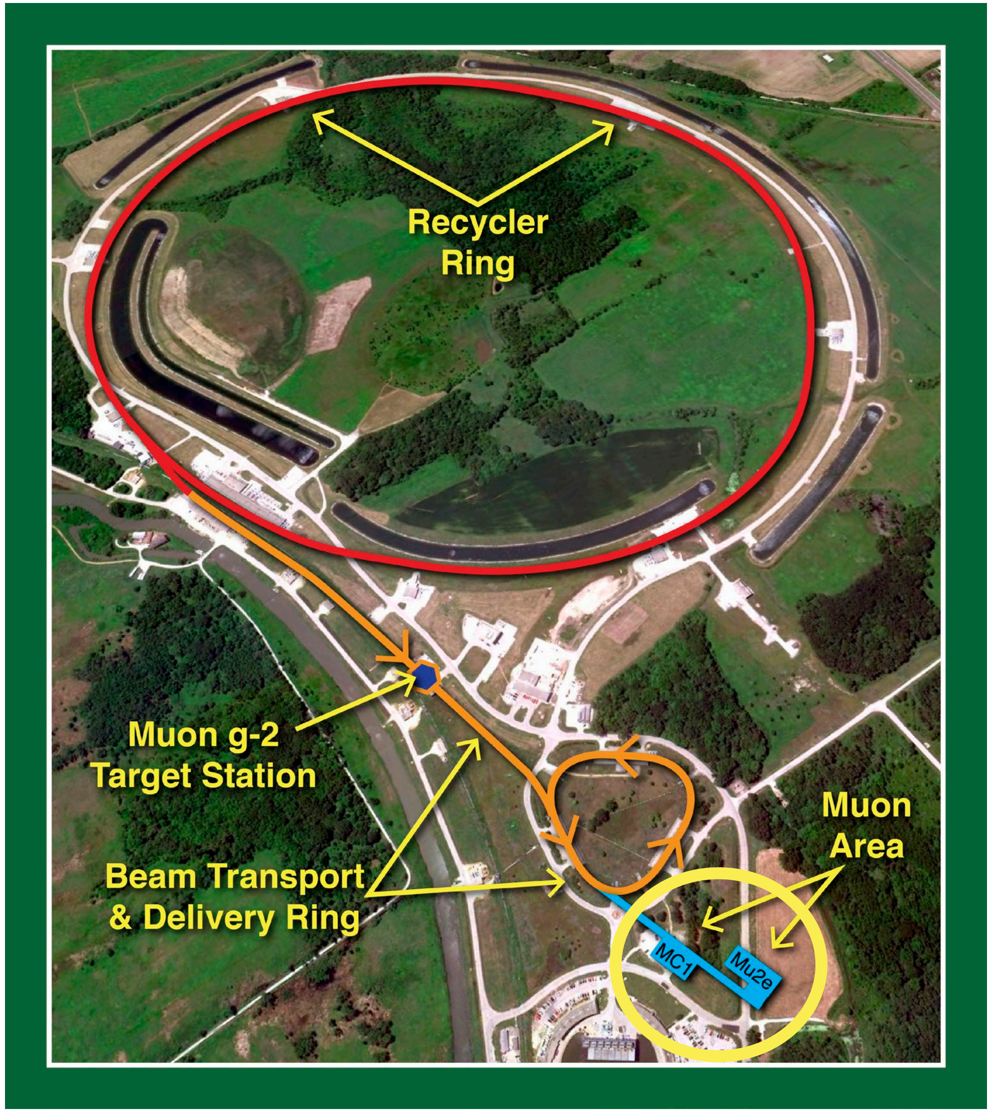


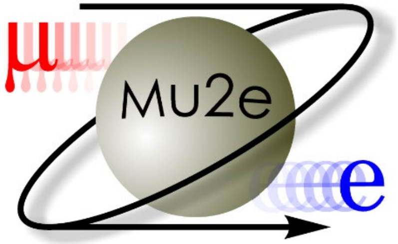




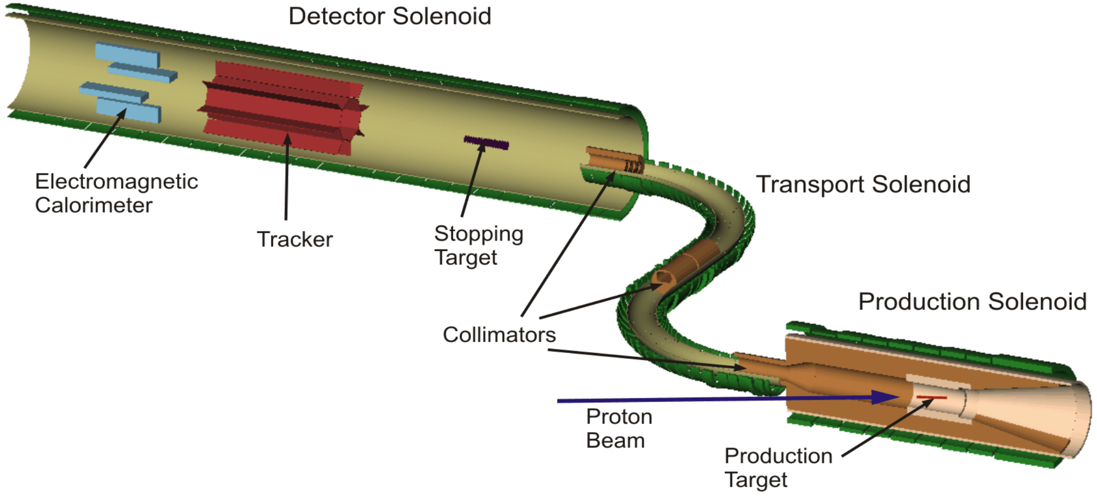
C. Hadjidakis, et al, A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies - https://arxiv.org/abs/1807.00603

Not only at LHC: Fermilab

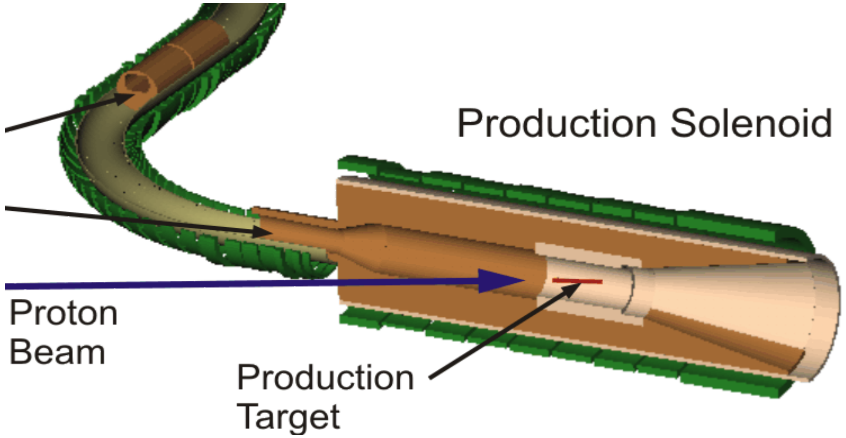




The goal of **Mu2e** is to looking for the **conversion of muons to electrons without the emission of neutrinos**, in search of New Physics



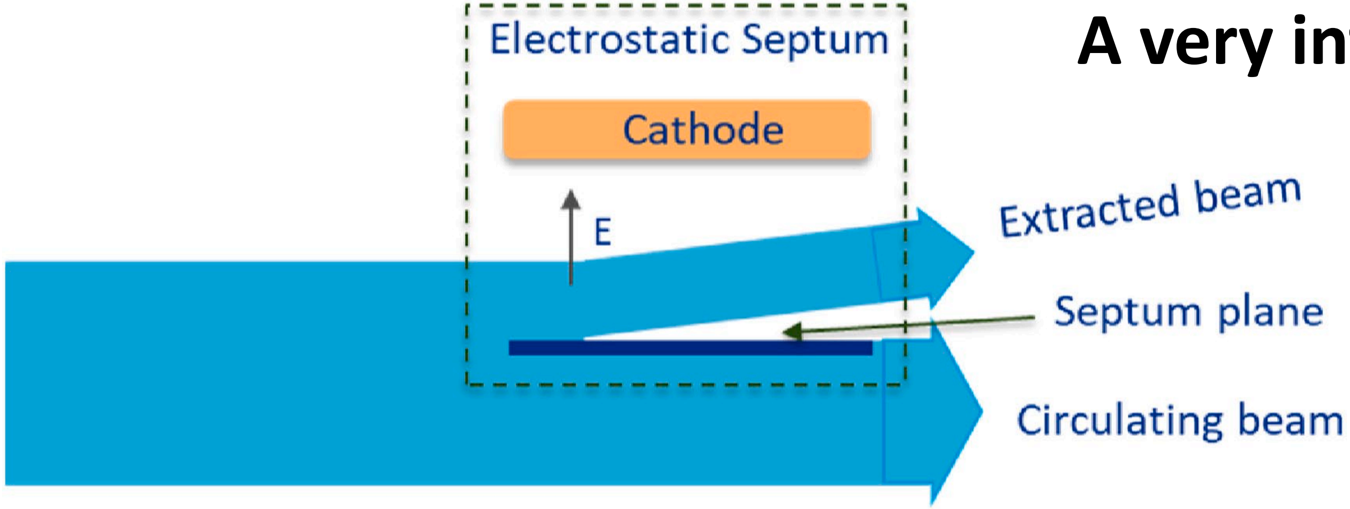
Mu2e experiment:



Branching Ratio for $\mu \rightarrow e\gamma$ is $\leq 10^{-54}$

- ❑ Unobservable low probability
- ❑ An observation means that there is new <u>Physics Beyond the Standard Model</u>

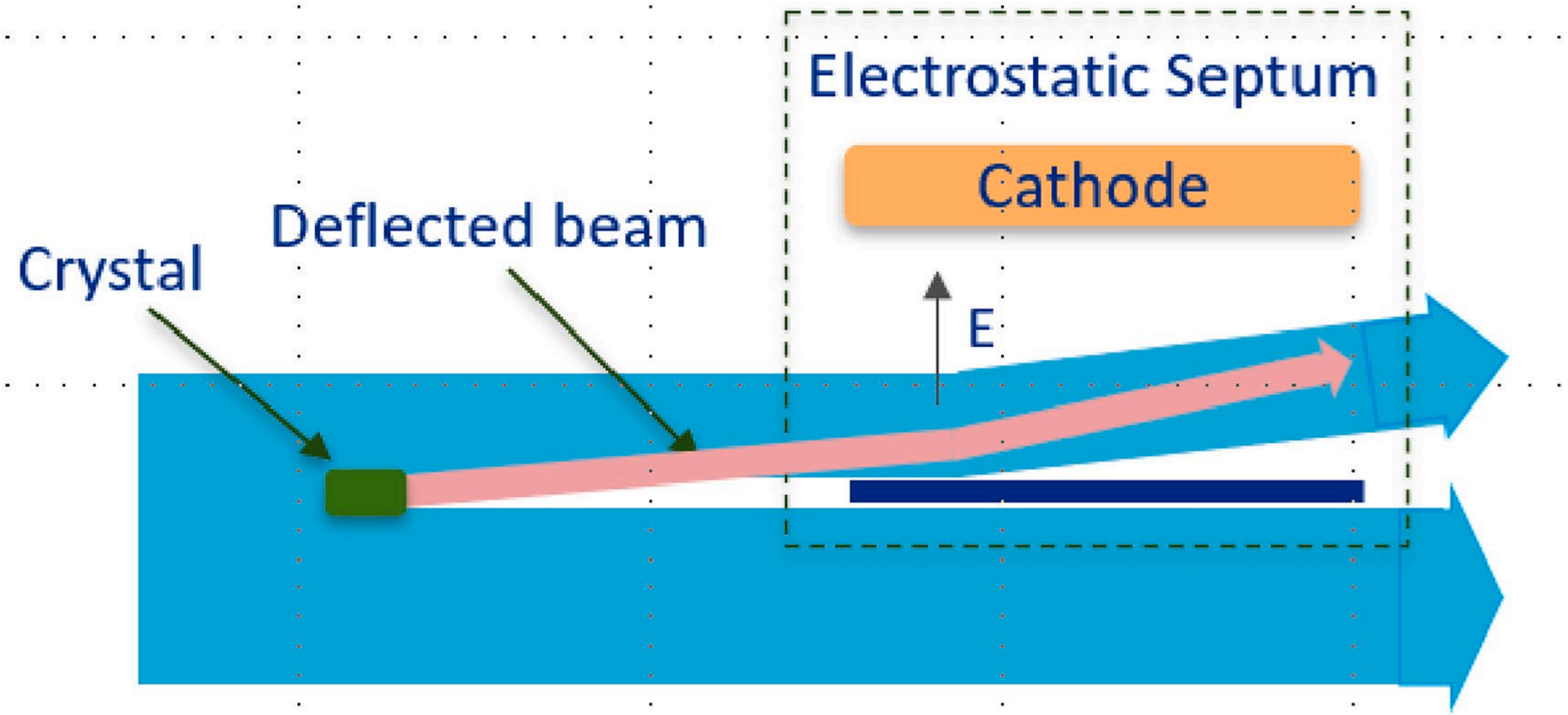
A very intense muon beam is needed!



p→Au interactions generate pions and these pions decay into muons

Mu2e experiment: Fermilab

A very intense muon beam is needed!

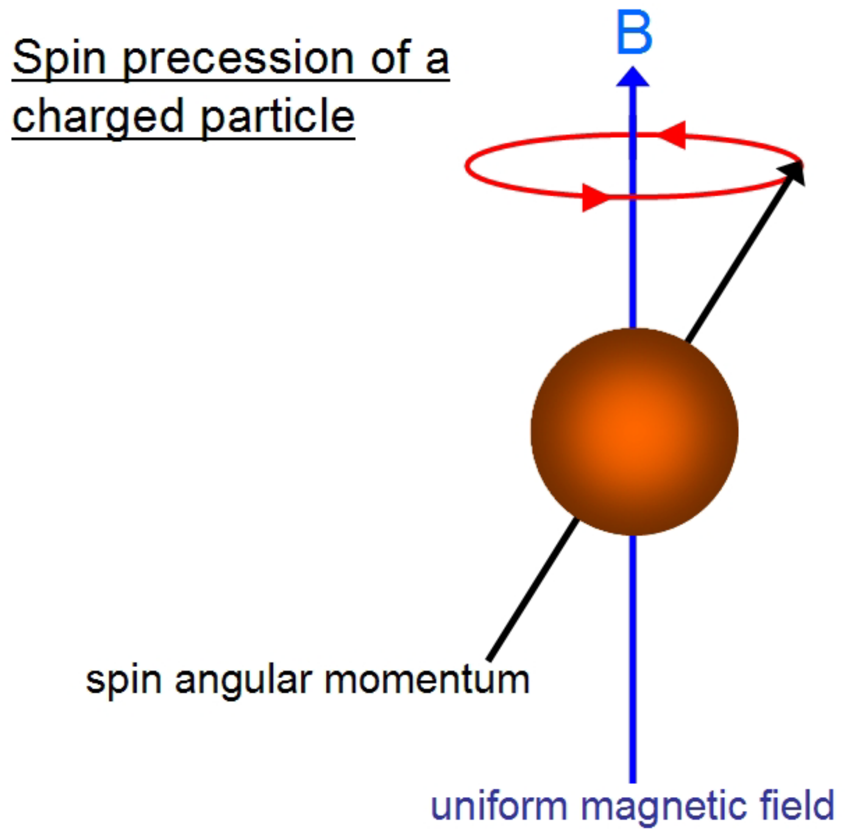


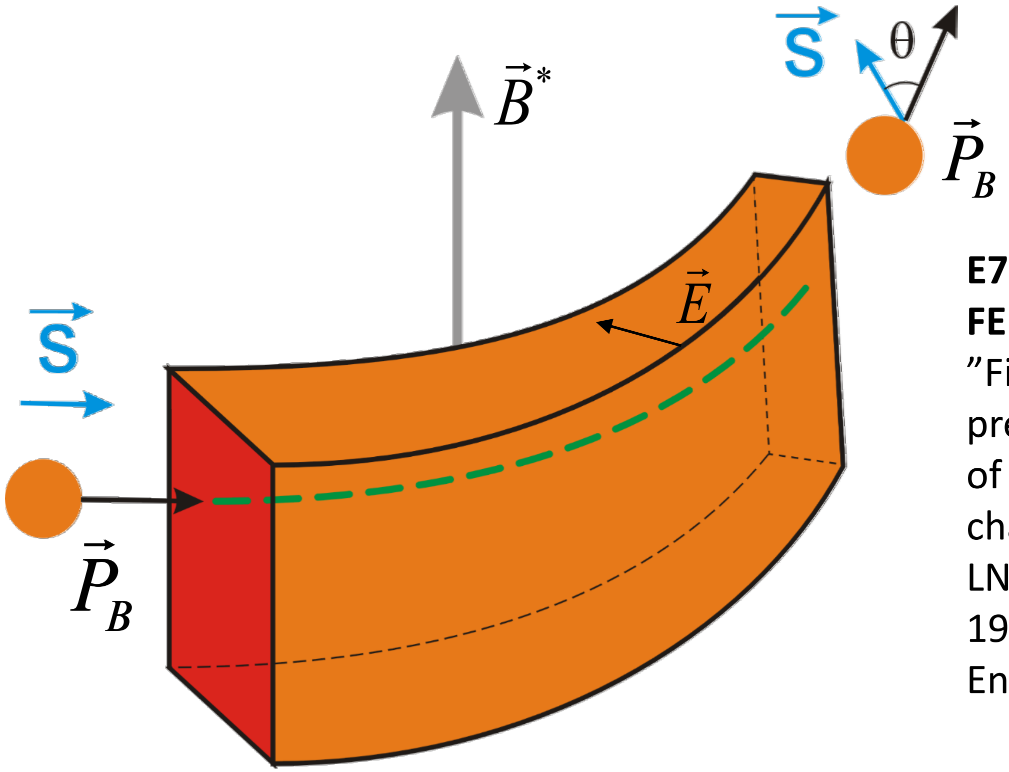
Introduction of a bent crystal:

avoid the interaction with the septum
-> decreases the beam losses
-> increases the extracted proton beam intensity
-> increases the muon beam intensity

V. Nagaslaev et al., NIM A 1058 (2024) 168892

Spin rotation of ultra-relativistic particles





E761 Collaboration, FERMILAB
"First observation of spin precession of polarized hyperons channeled in bent crystals", LNPI Research Reports (1990-1991) 129.
Energy: 200 – 300 GeV

D. Chen et all "*First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals*", Phys. Rev. Lett. 69 (1992) 3286.

A.V. Khanzadeev, V.M. Samsoov, R.A. Carrigan, D. Chen "*Experiment to observe the spin precession of channeled relativistic hyperons*" NIM 119 (1996) 266.

Electromagnetic dipole moments

Electromagnetic dipole moments are static properties of particles, never measured for **short-lived charm**, **beauty** baryons, and **τ lepton**

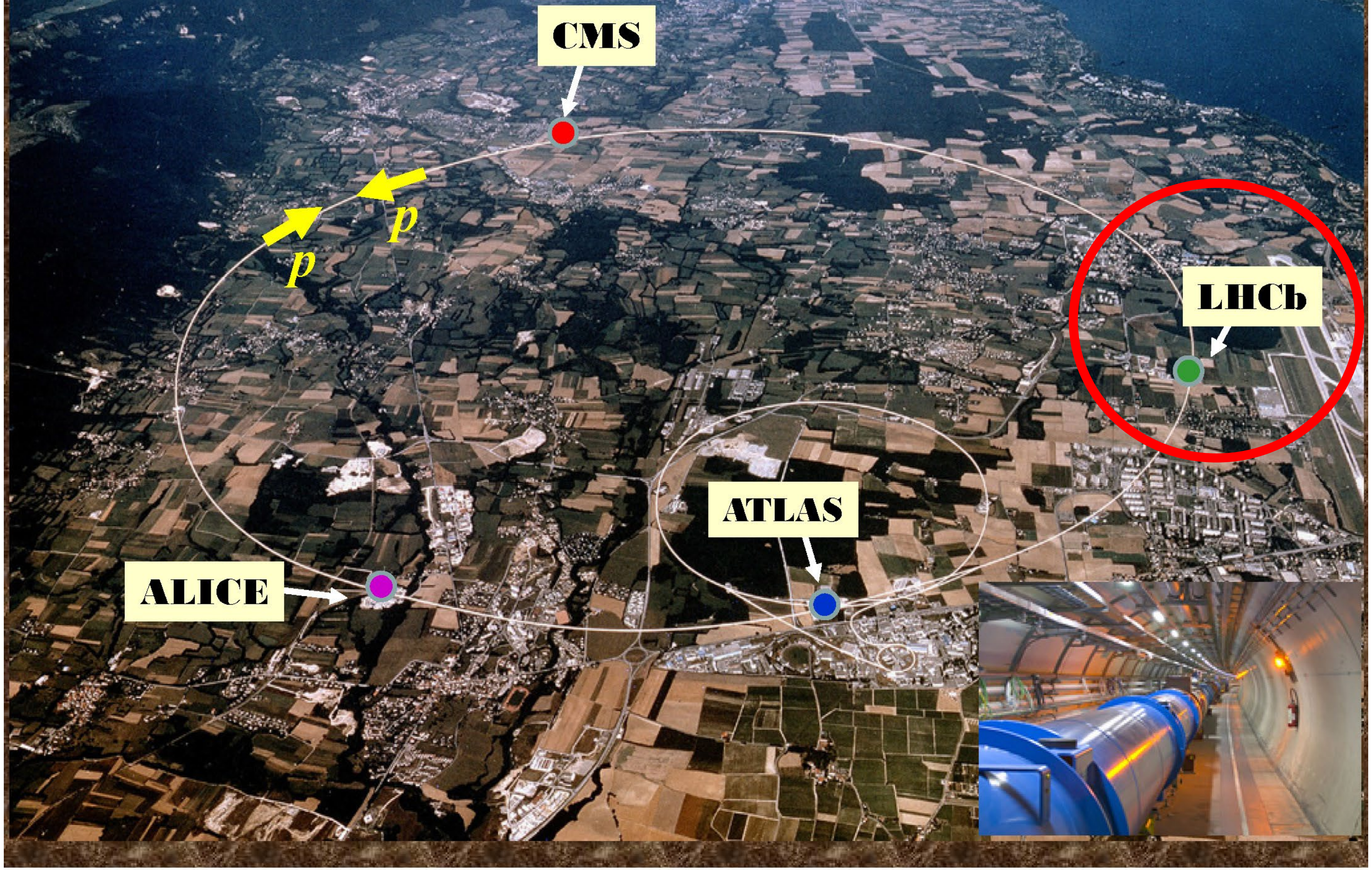
μ= magnetic dipole moment (MDM) $\boldsymbol{\mu} = g\mu_N \frac{\mathbf{S}}{2}$

- MDM provide stringent **test of the Standard Model** for leptons (e.g. anomalous muon g-2) and QCD models for baryons

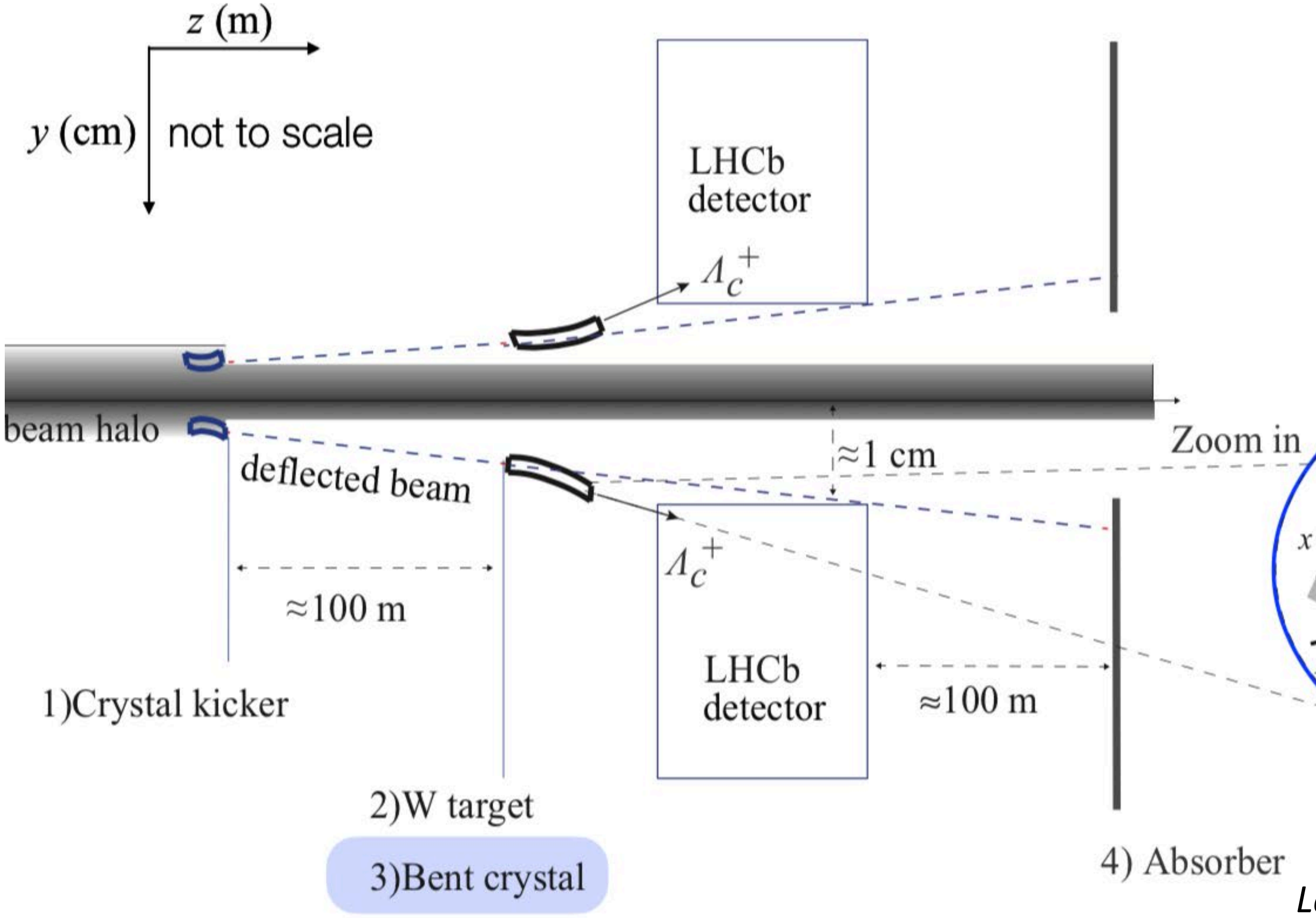
δ= electric dipole moment (EDM) $\boldsymbol{\delta} = d\mu_N \frac{\mathbf{S}}{2}$

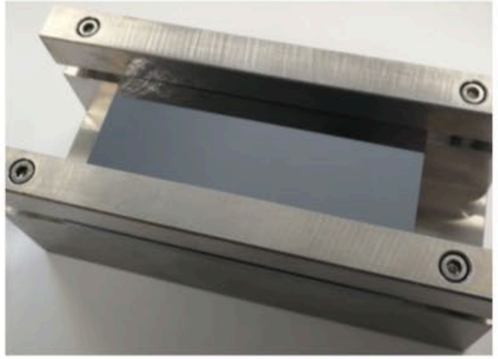
- EDM searches are sensitive to **new physics**. Violation of P, T and CP via CPT
- Standard Model CP violation → very tiny EDM (e.g. for quarks < 10^{-31} e cm)
- **EDM observation in fundamental particles is a direct evidence of New Physics**

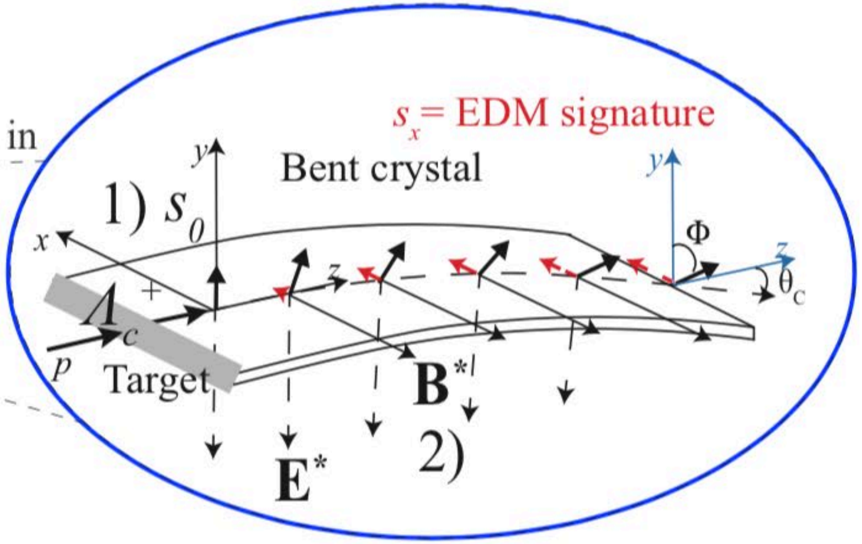
Large Hadron Collider



S. Aiola et al.,Eur. Phys. J. C (2017) 77:181







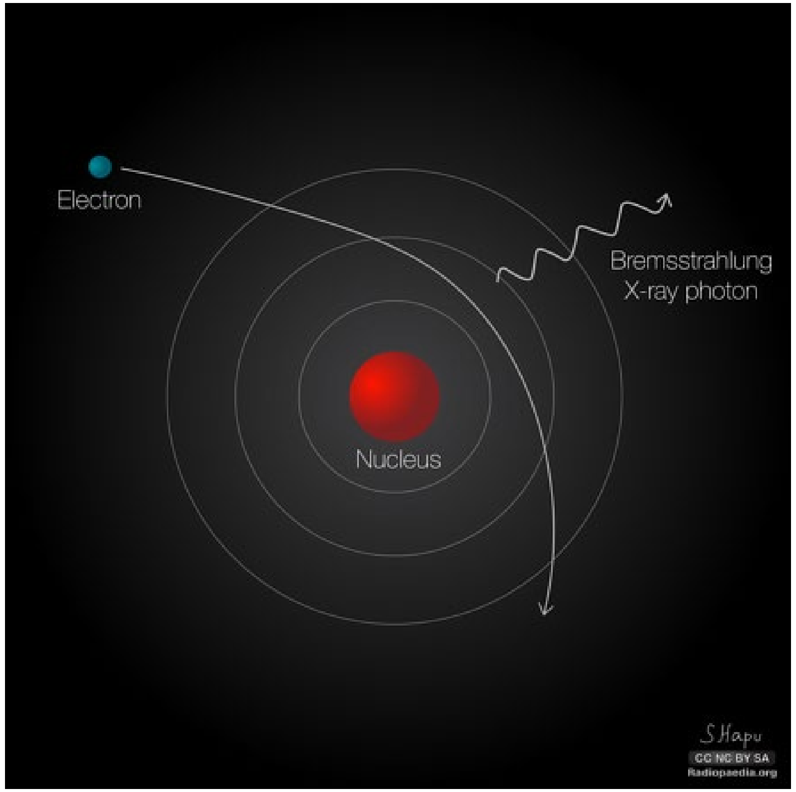
Large deflection ***(0.5°/1°)*** *to enhance the precession effect & to send particles within the LHCb acceptance*

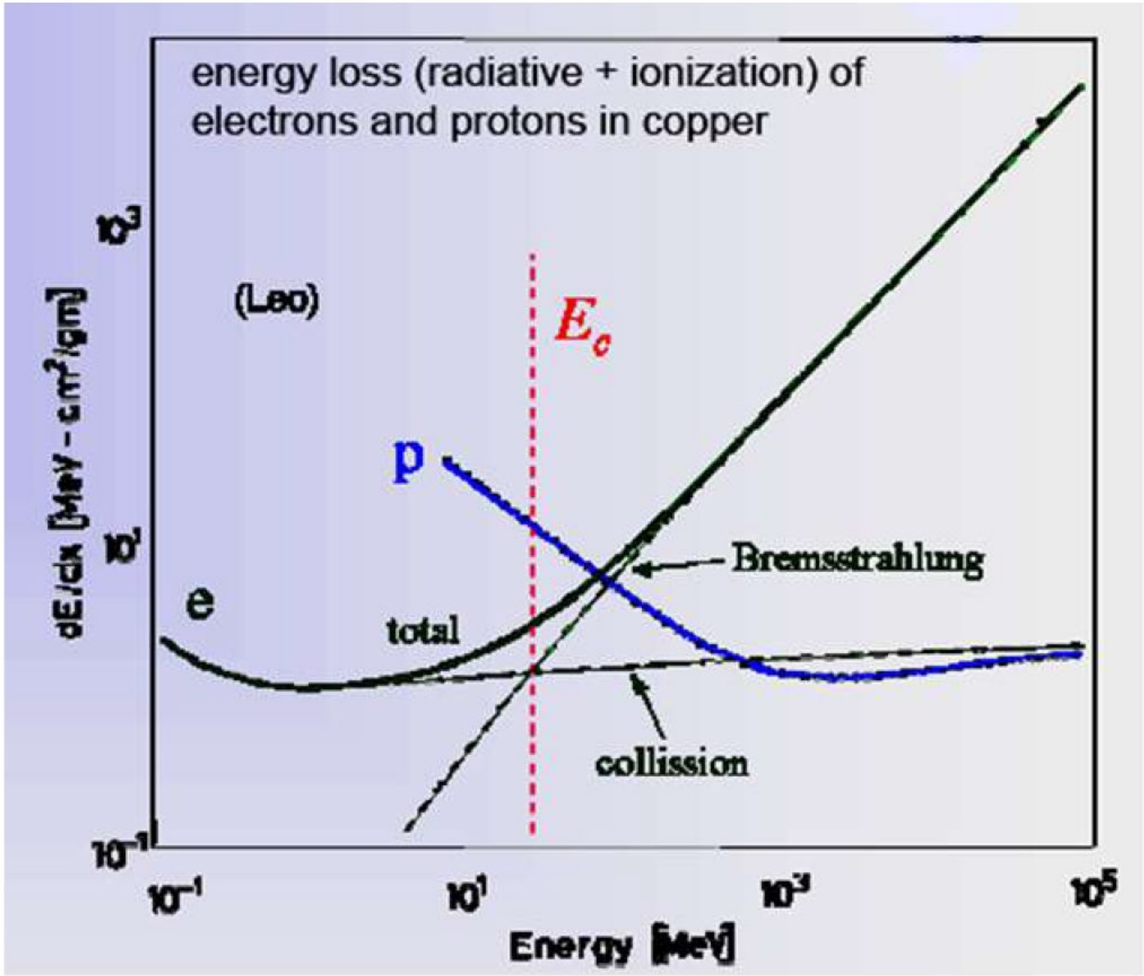
p extraction Λ_c^+ polarised production channeling spin precession

We have seen how to exploit the **Strong Crystal Field** to **deflect** and **manipulate** heavy charged particles …
(protons, ions, baryons, tau lepton)

BUT what about **lighter charged particles**?
(electrons and positrons)

BUT what about lighter charged particles?





Power radiated by an electron is $\mathbf{(m_p/m_e)^4 \sim 10^{13}}$ times more than for a proton

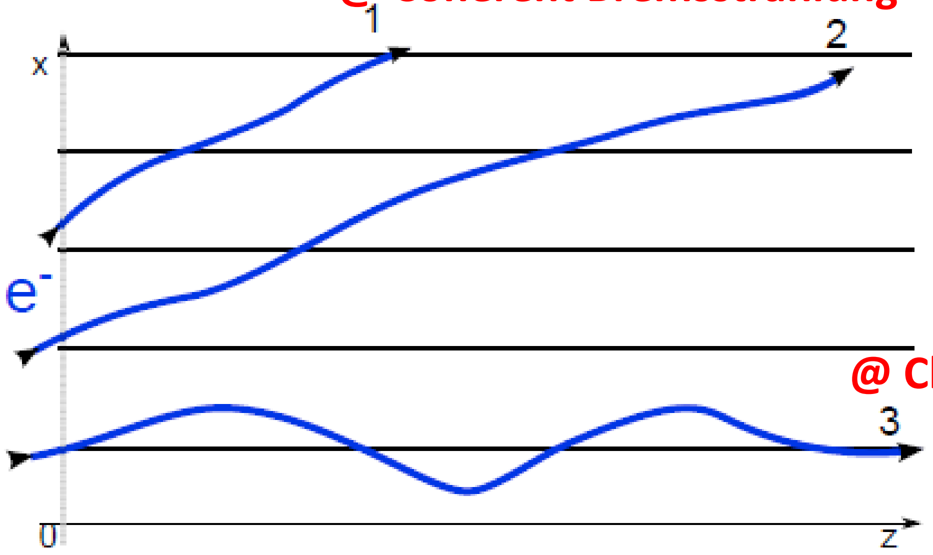
Does the crystal structure influence the process of bremsstrahlung?

Does the crystal structure influence the process of bremsstrahlung?

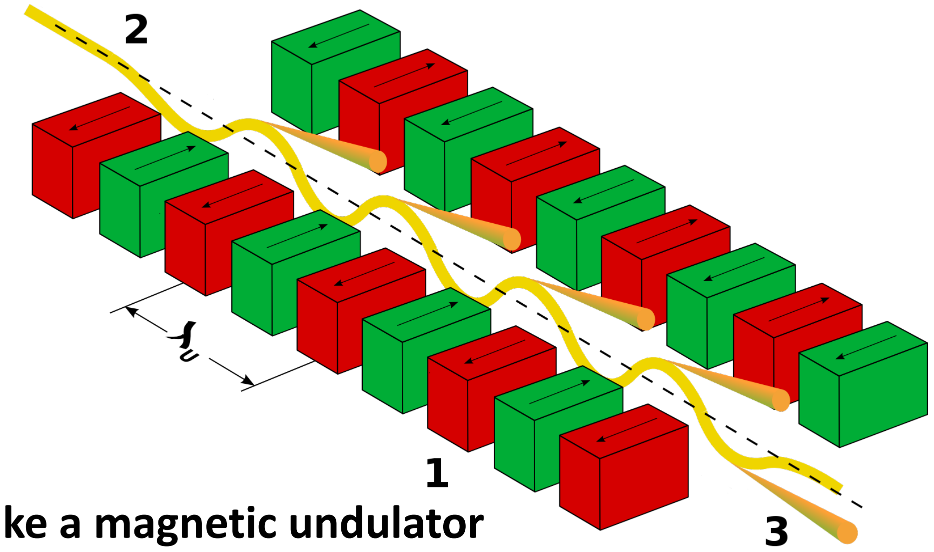
Yes!

In case of small incidence angle with some crystal lattice direction (electron periodic oscillation -> radiation emission)

@ Coherent Bremsstrahlung

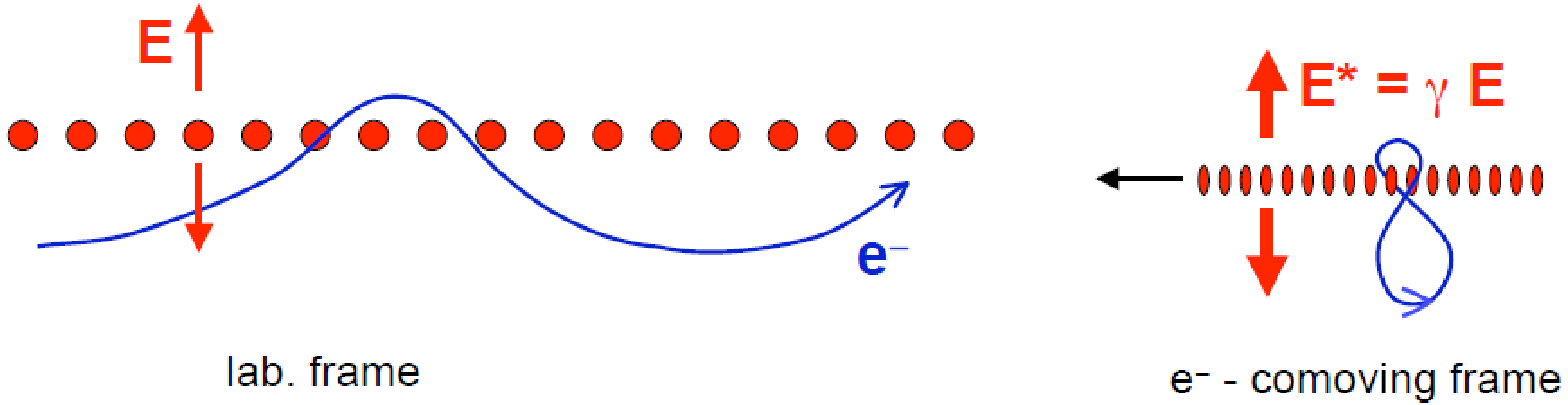


@ Channeling



Like a magnetic undulator

Strong electromagnetic field in oriented crystals

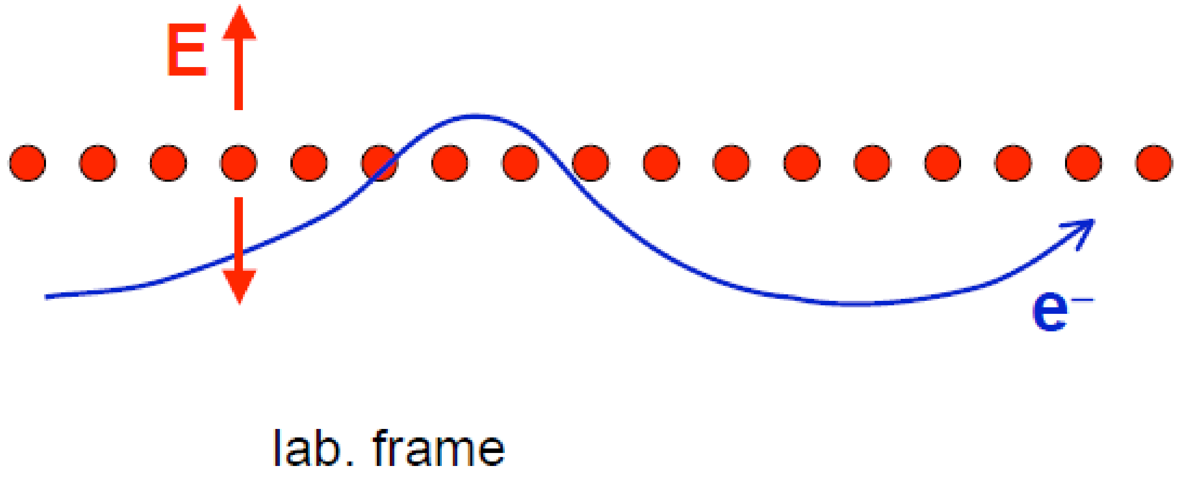


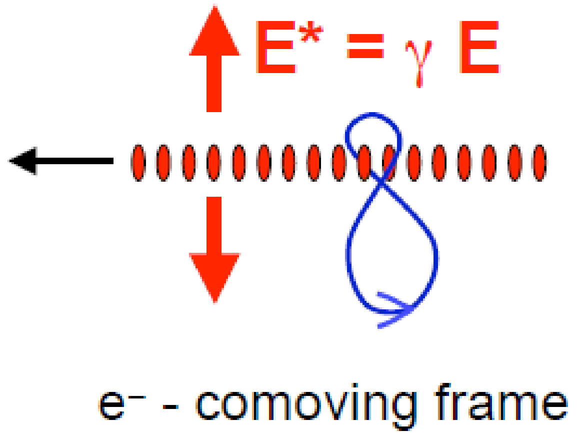
In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

$$E^* = \gamma E$$

Being the Axial field of high-Z crystals $E \approx 10^{11}$ V/cm

Strong electromagnetic field in oriented crystals





In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

$$E^* = \gamma E$$

Being the Axial field of high-Z crystals $E \approx 10^{11}$ V/cm

At beam energies > 10 GeV, E* can reach the **Critical Schwinger QED field**:

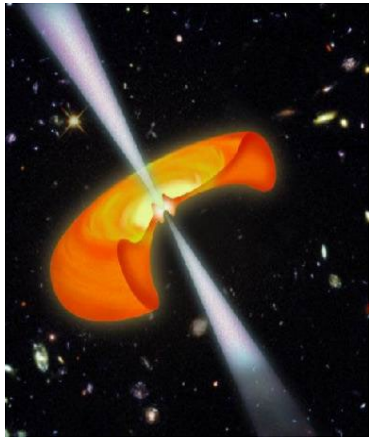
$$E_0 = m^2c^3/e\hbar \simeq 1.3 \times 10^{16} V/cm$$

above which electrodynamics becomes non linear

Ulrik I. Uggerhøj, REVIEWS OF MODERN PHYSICS, VOLUME 77, OCTOBER 2005

Strong Fields in nature and labs

Magnetars
$B \approx 10^{10}$ T



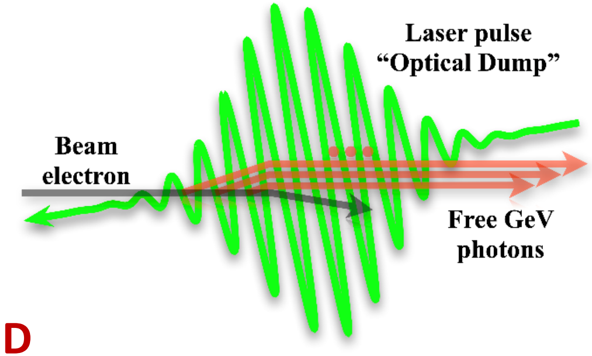
Beamstrahlung in future linear colliders

ILC/CLIC

Heavy ion collider

RHIC/LHC

Strong lasers



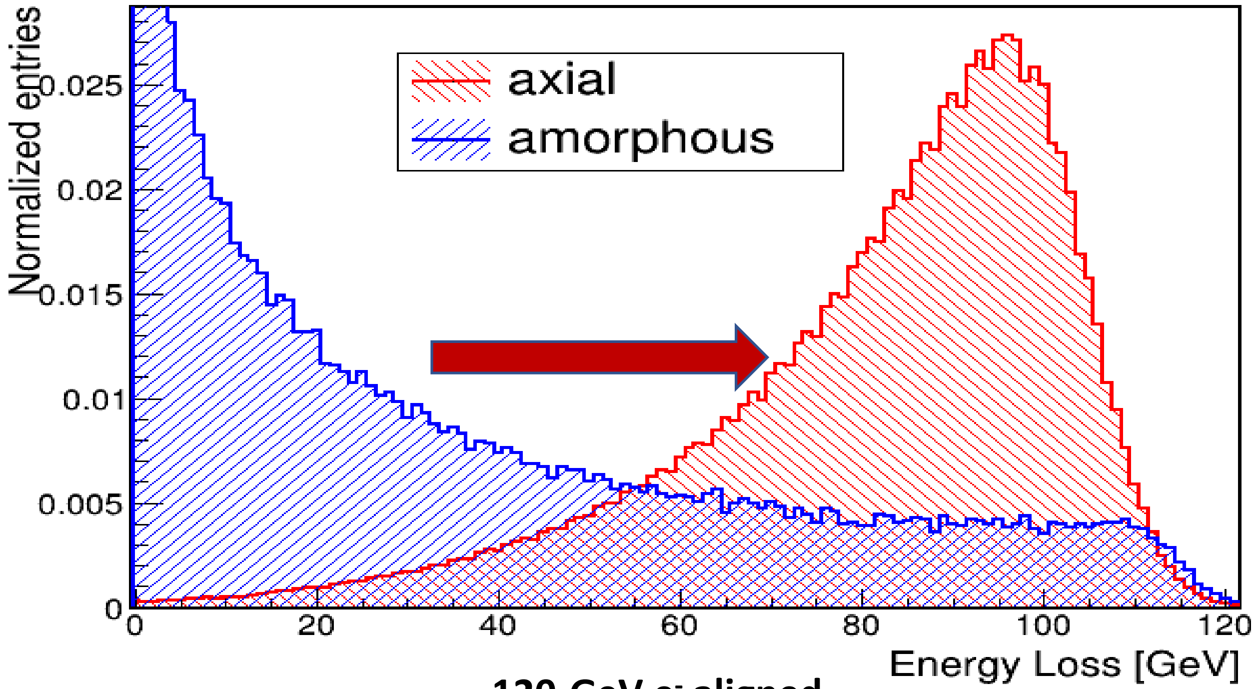
Many experiments worldwide dedicated to investigate Strong Field QED
NA63 @CERN (crystals), E-320 @SLAC (Stanford, US) and LUXE @EU XFEL/DESY (Hamburg)

With crystals, the **Critical Schwinger Field** is accessible with no need of multi-TeV beams or ultra-intense lasers

Crystals are powerful tools to test Strong Field QED!!

Radiation emission by an electron/positron aligned with the crystal axes

Effect of axial orientation in the radiation spectrum

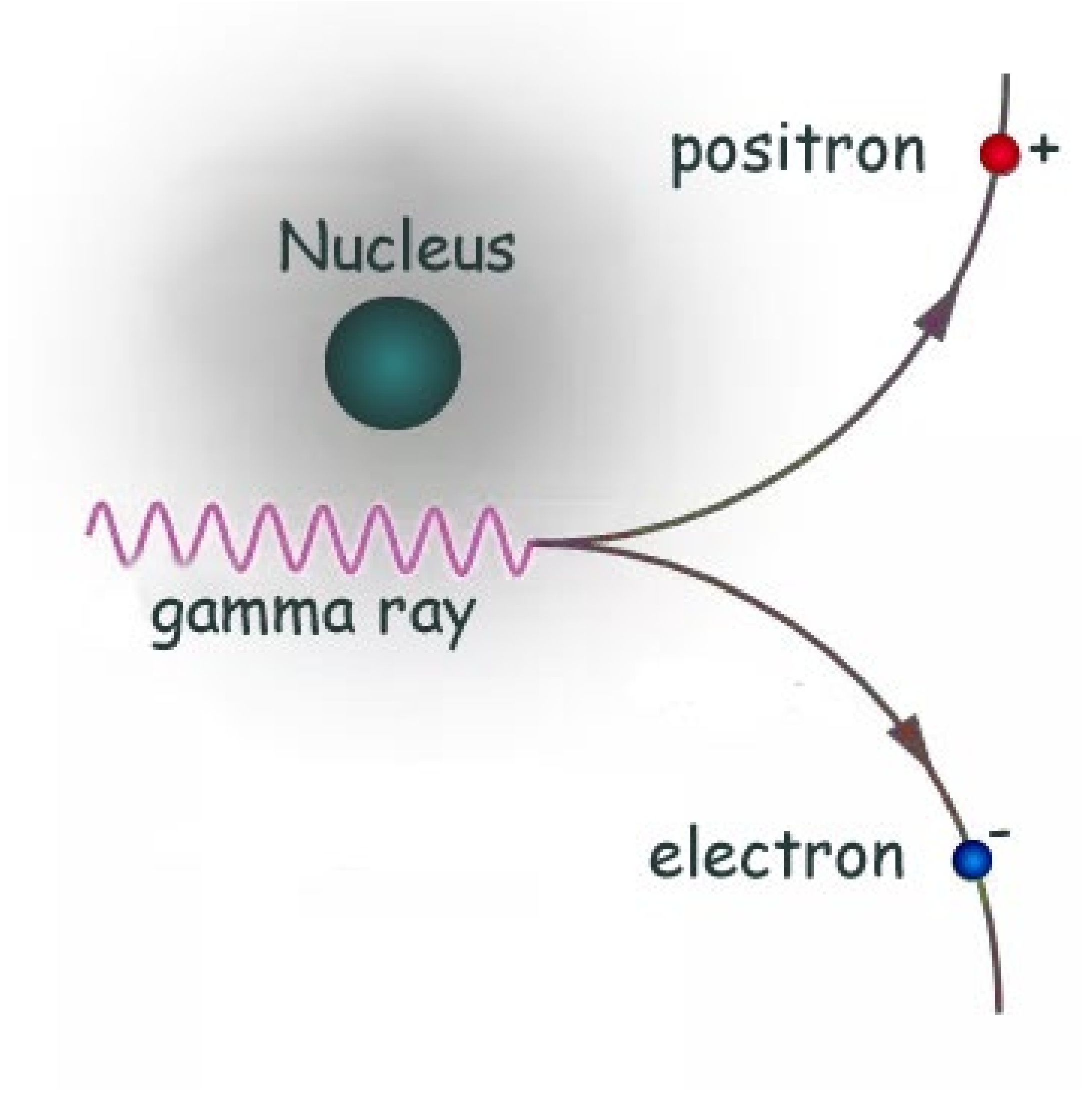


120-GeV e^- aligned
with the <110> axis of a 2.8 mm long Ge crystal

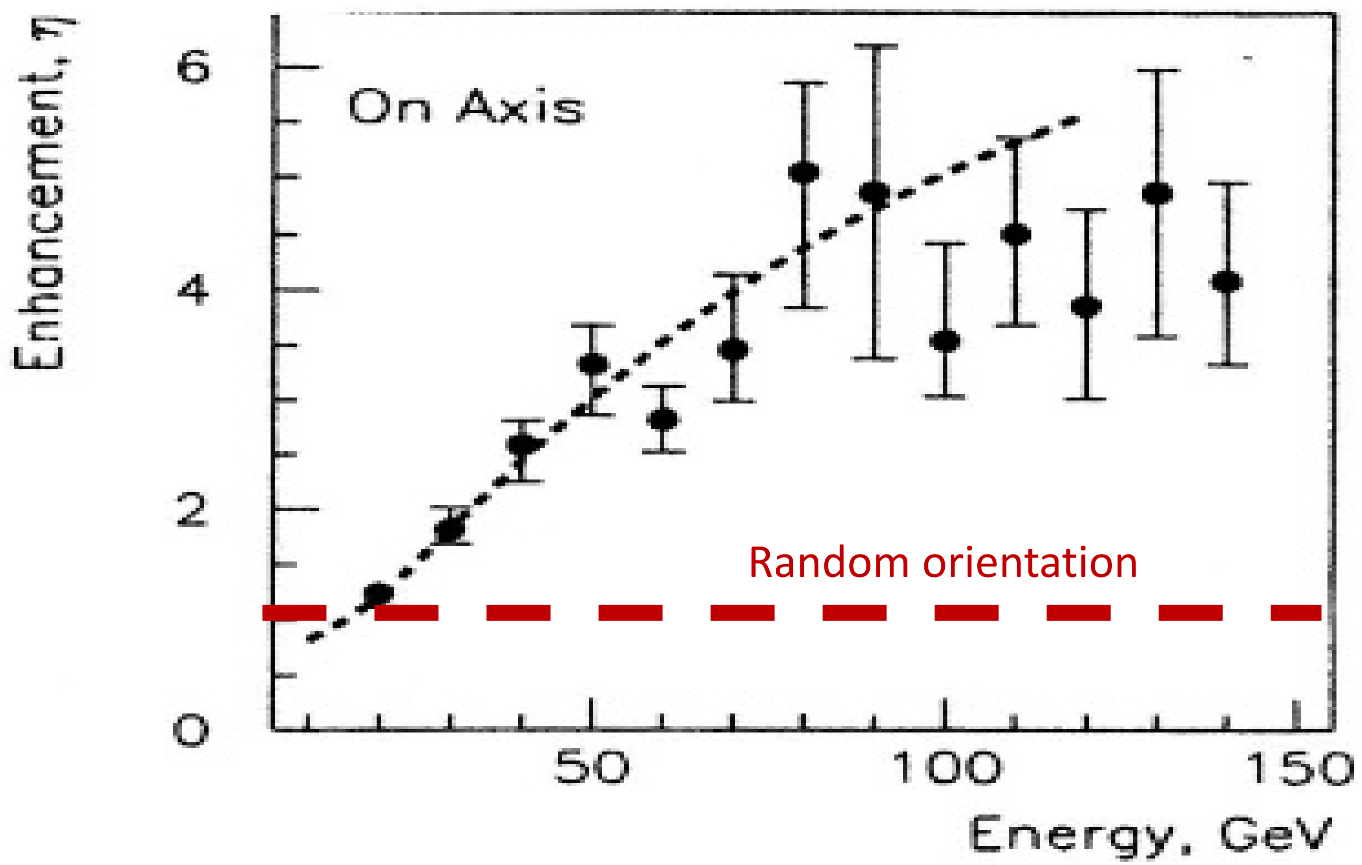
- ❖ **The Strong Field effect increase with initial particle energy**
- ❖ **Angular range*:***
  - ❖ up to 1° of misalignment between particle direction and crystal axes

Strong increase in the energy radiated by the electrons!

And what about photons



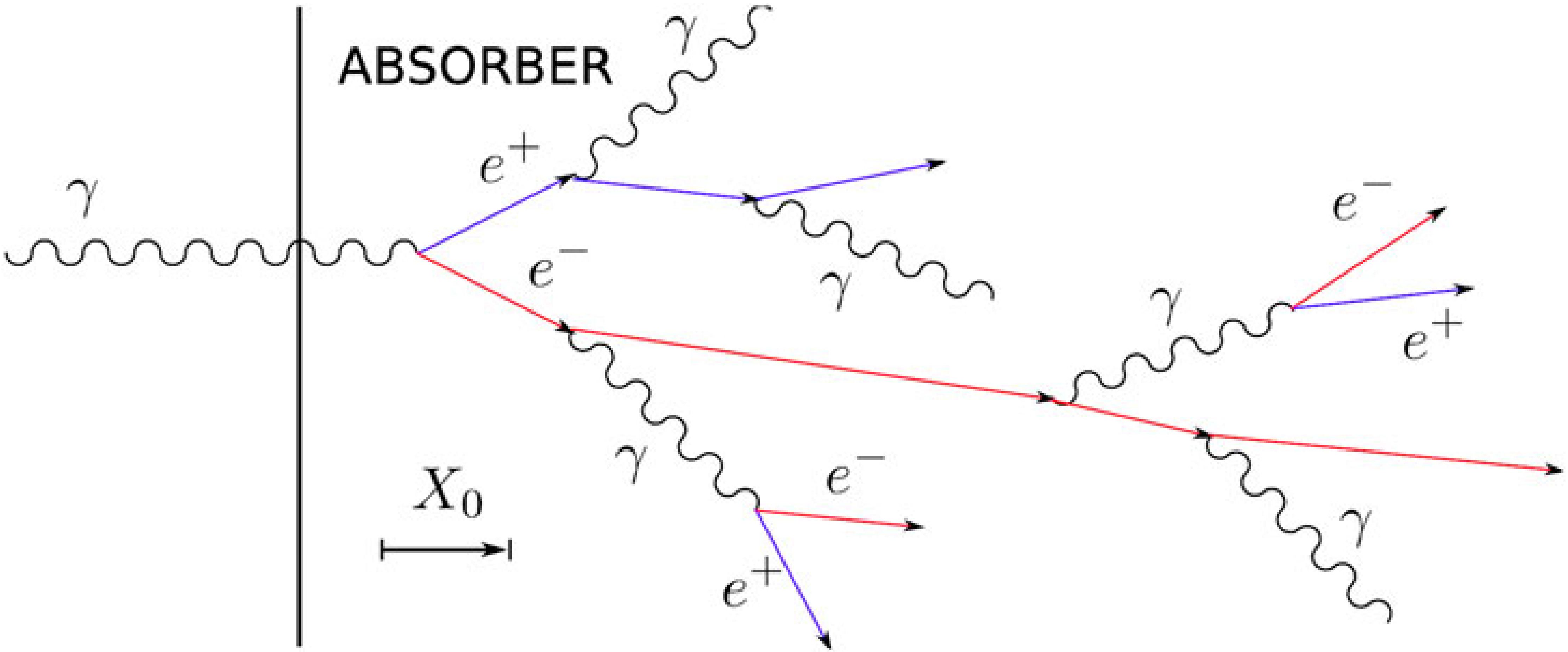
Increased e^+e^- pair production by high-energy photons



Enhancement of e+e- pair production in a Tungsten crystal axially oriented – compared to random orientation Vs. photon energy

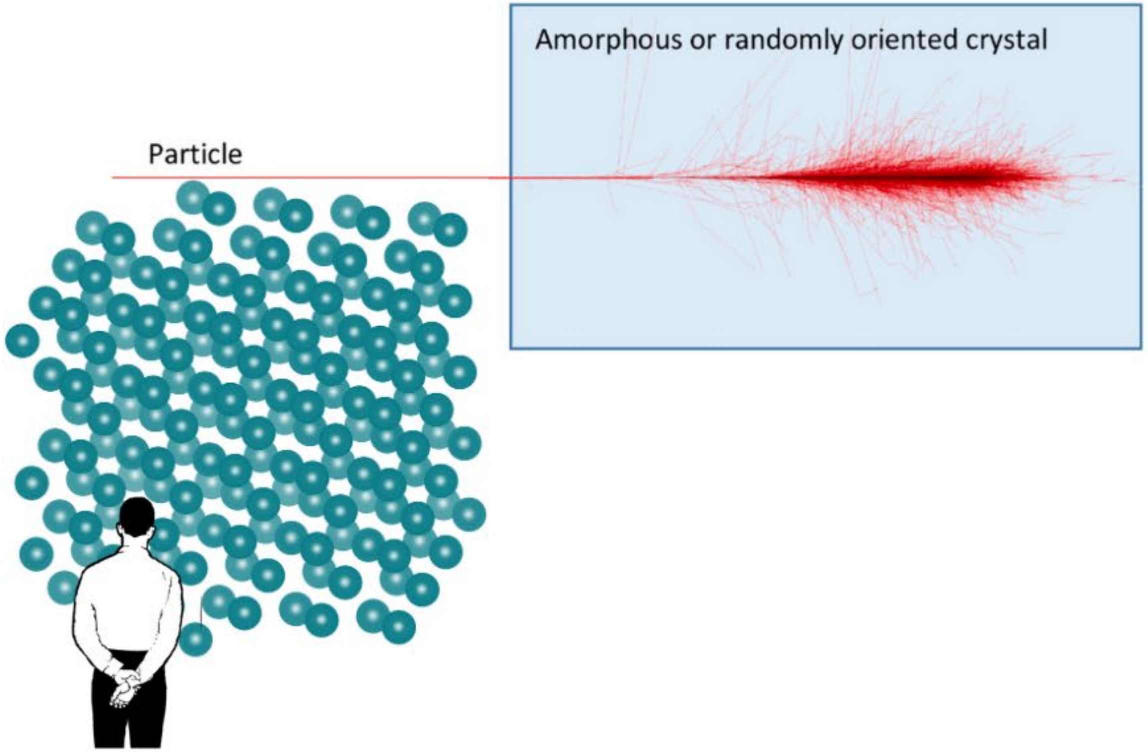
Strong increase of the pair production probability by High-energy photons in an oriented crystal

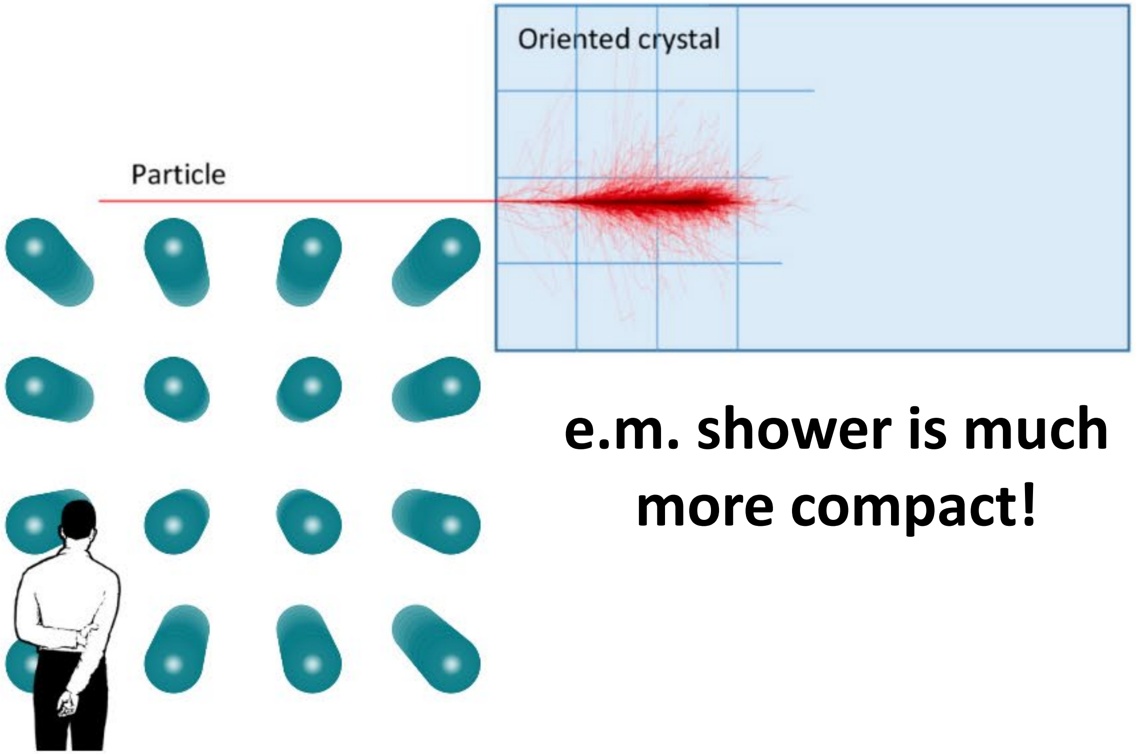
Electromagnetic shower



Radiation Length X_0 of a medium is defined as: distance over which electron energy reduced to *e* times. Characterizes the shower depth.

Strong Crystal Fields:
Electromagnetic shower acceleration.....

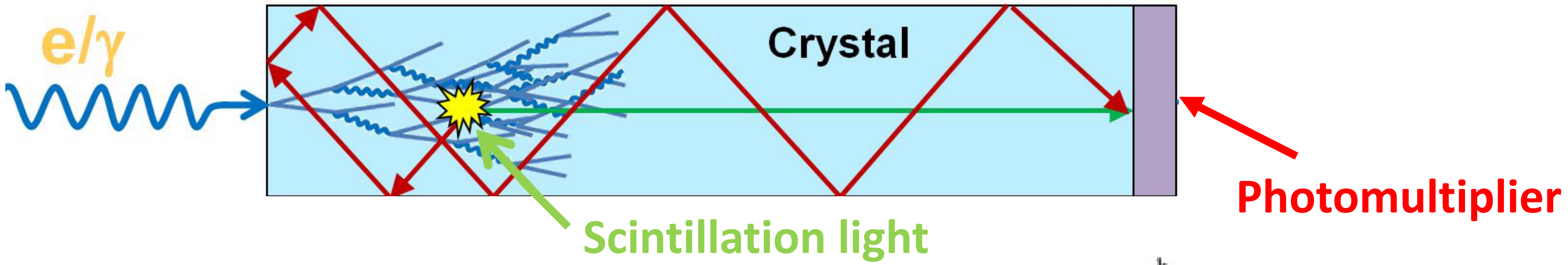


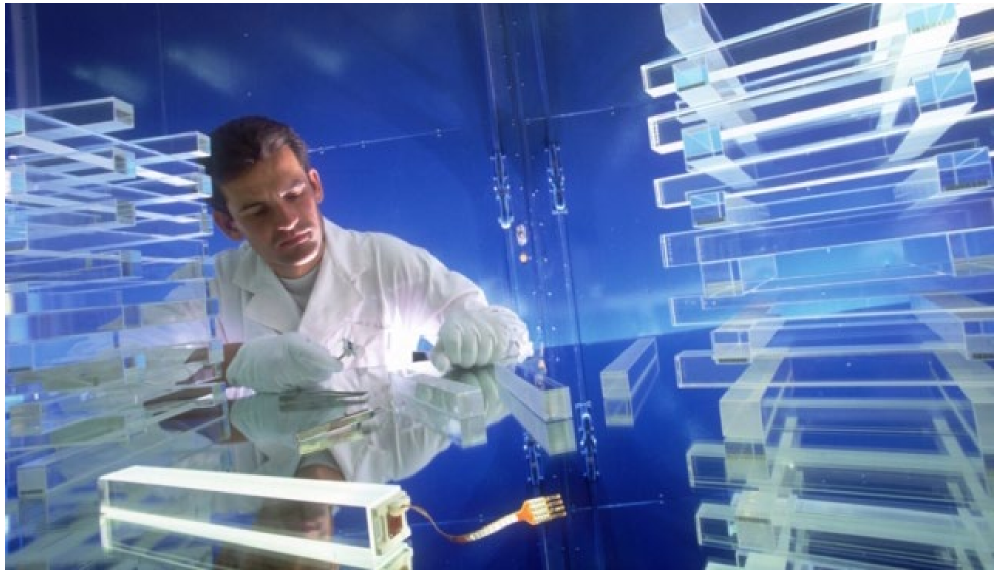


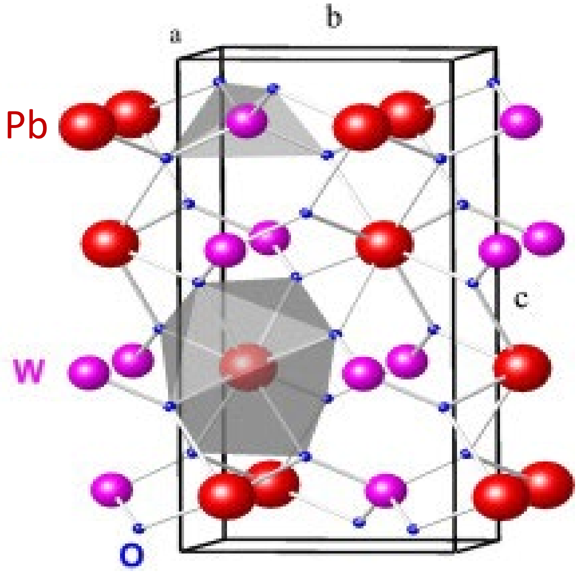
e.m. shower is much more compact!

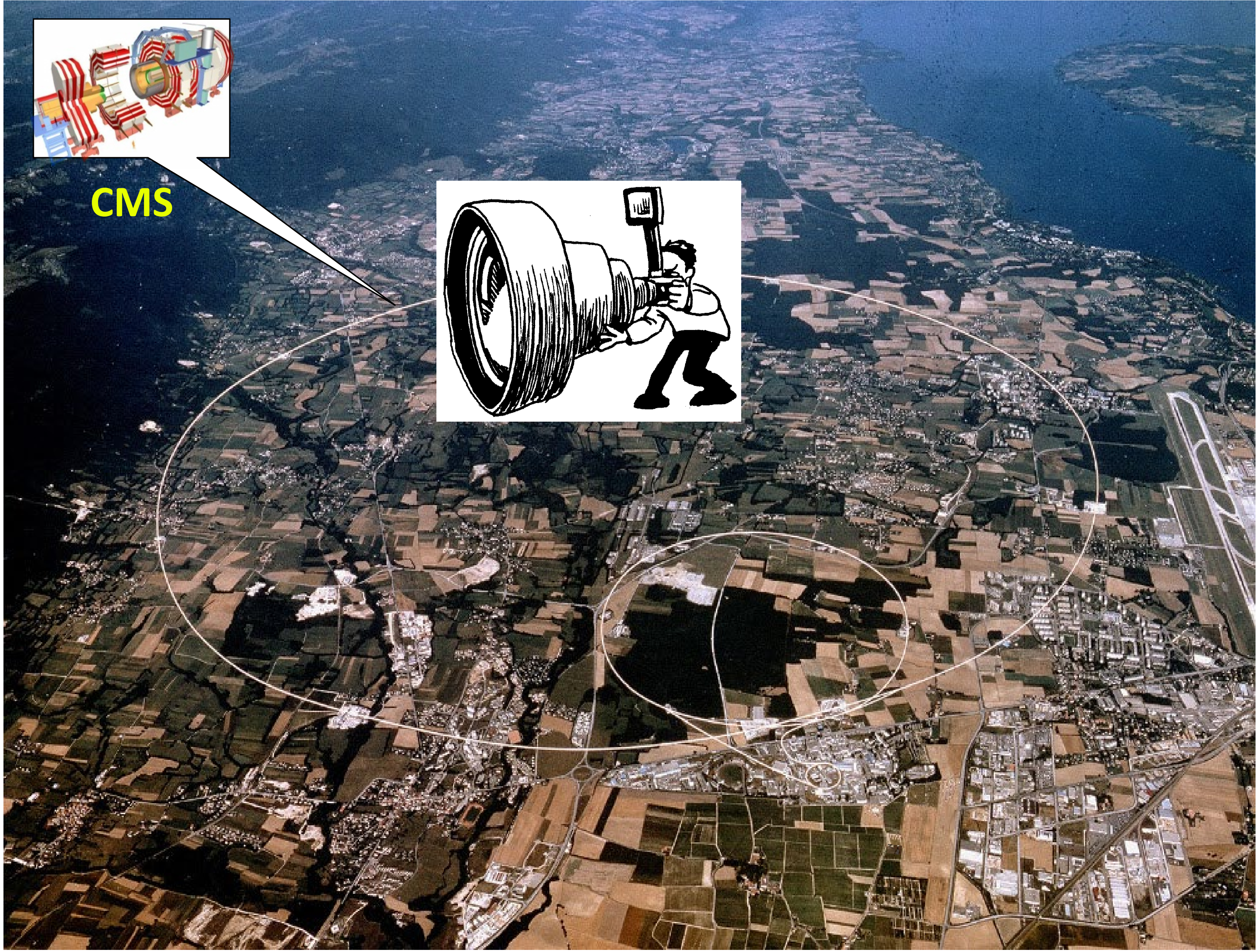
L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603

Exploiting the Strong Crystalline Field in inorganic crystal scintillators used in electromagnetic calorimeters to measure the energy of electrons/photons



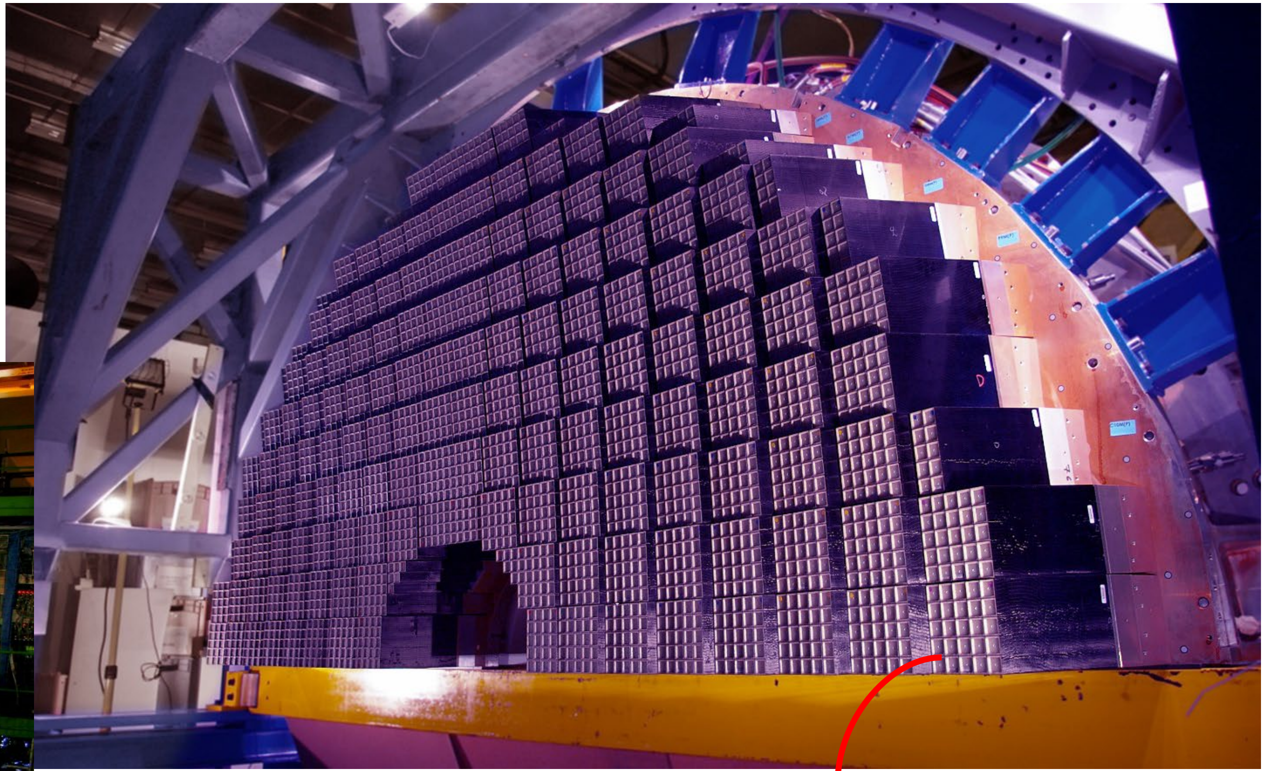


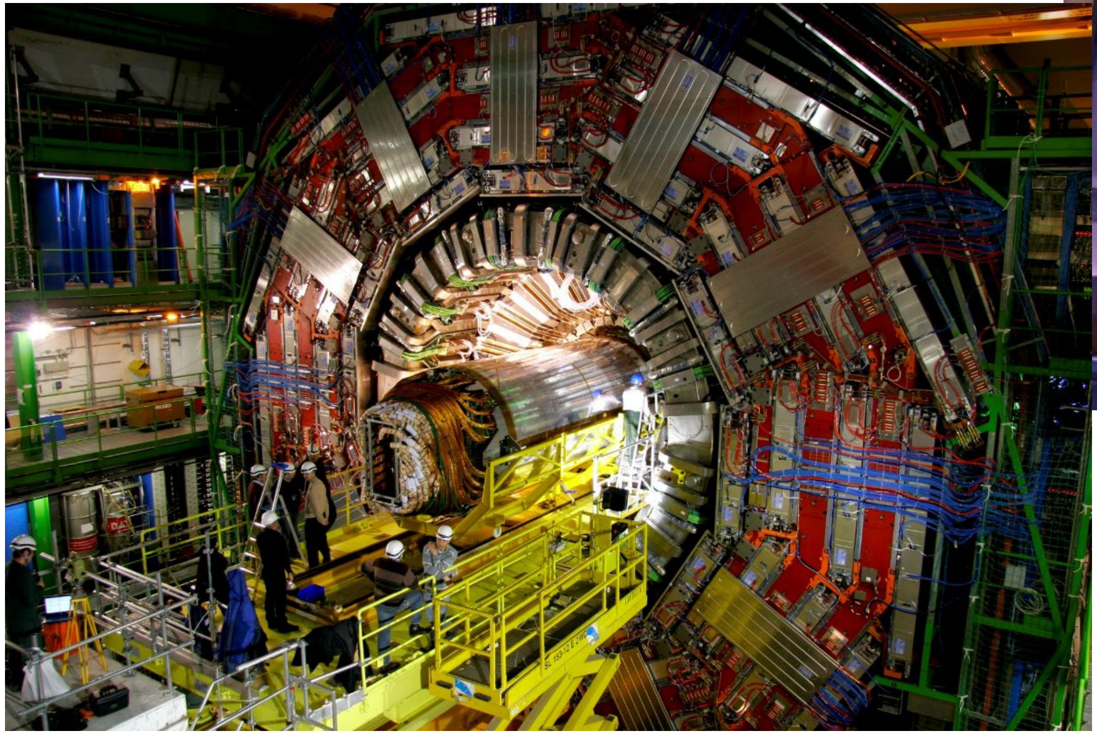


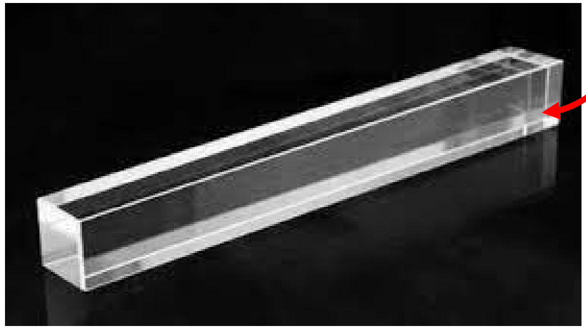

CMS

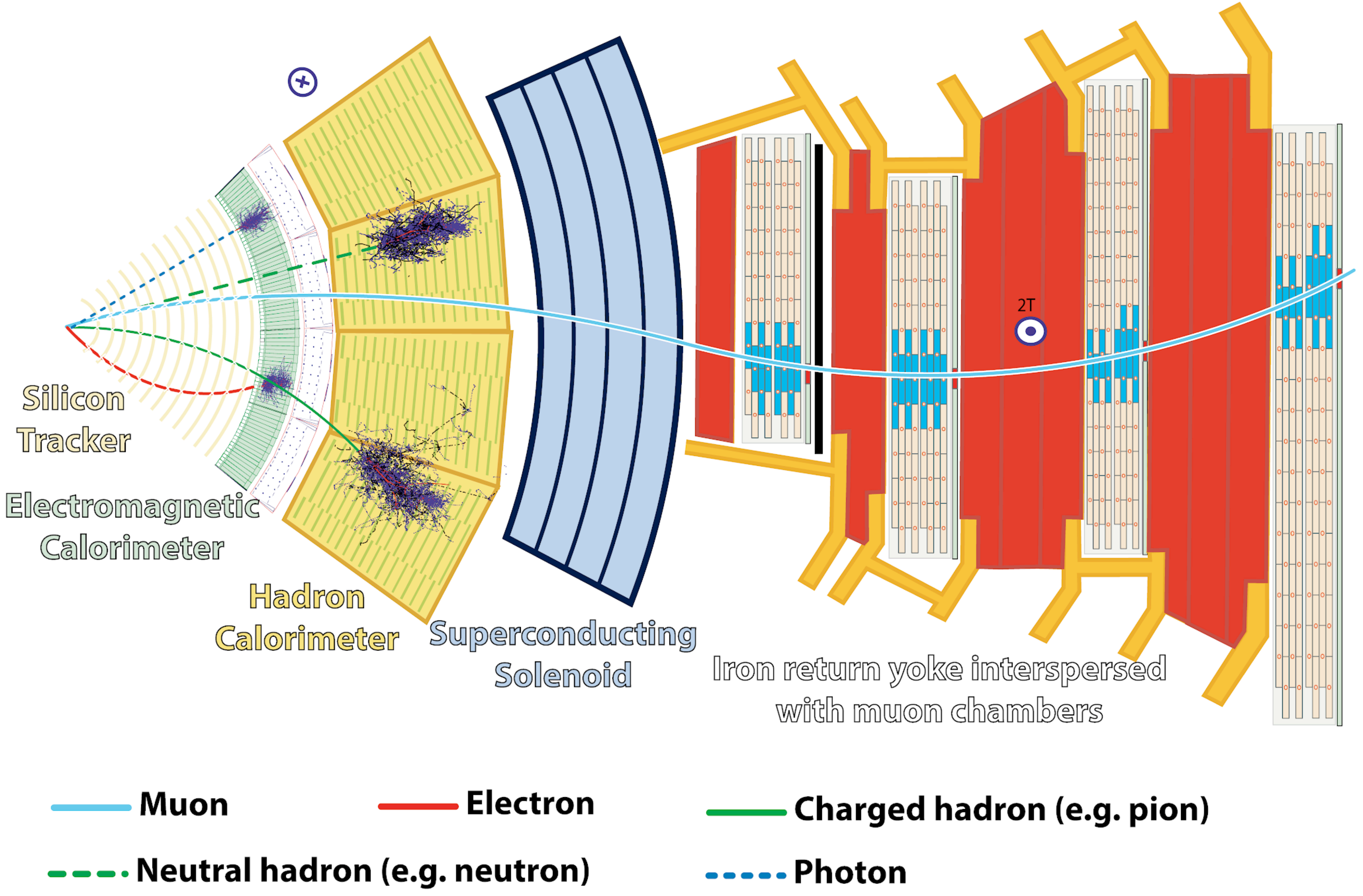
The CMS Electromagnetic Calorimeter

The CMS Electromagnetic Calorimeter at CERN LHC is composed of 77200 lead tungstate (PbWO4 or PWO) scintillator crystals

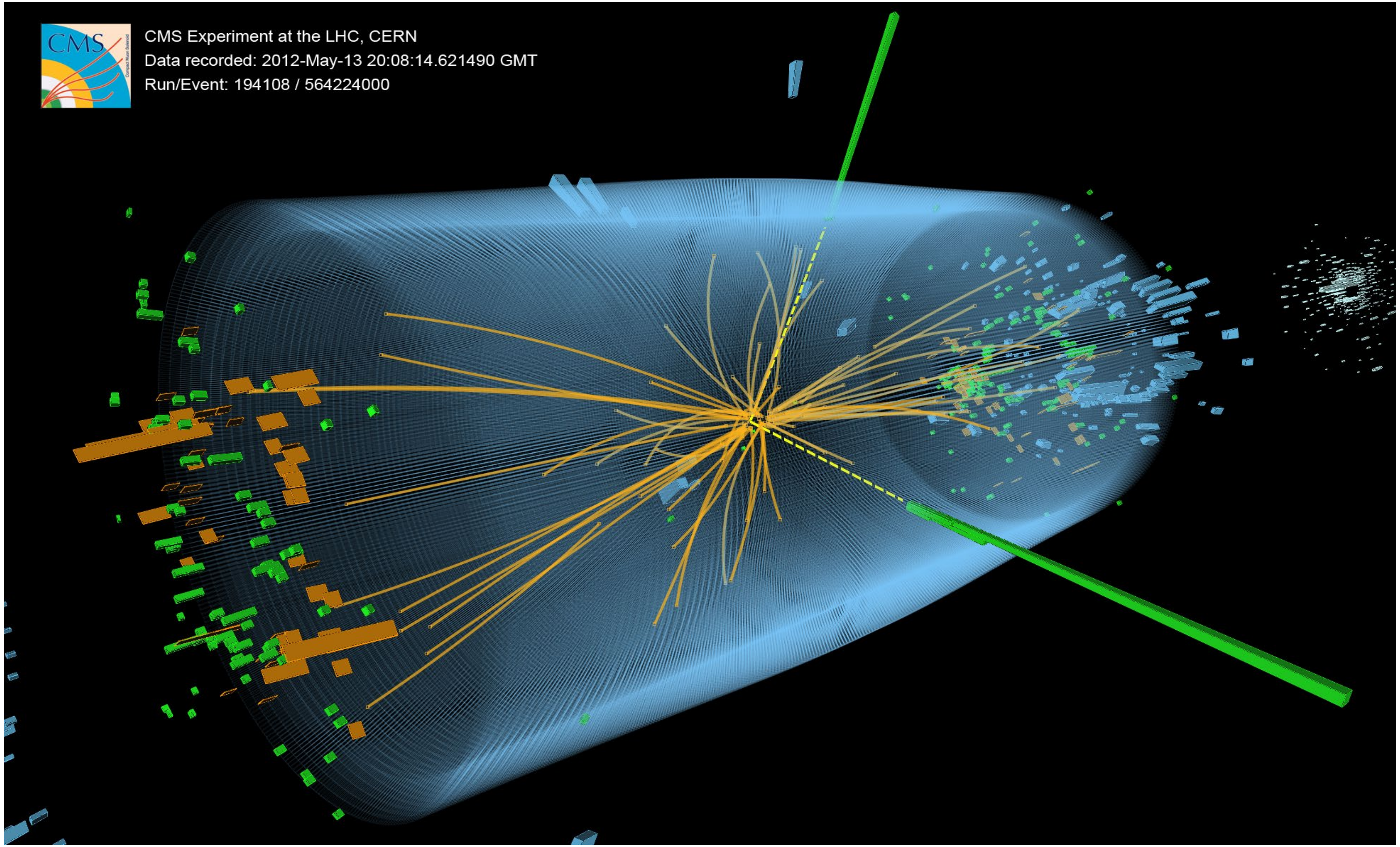




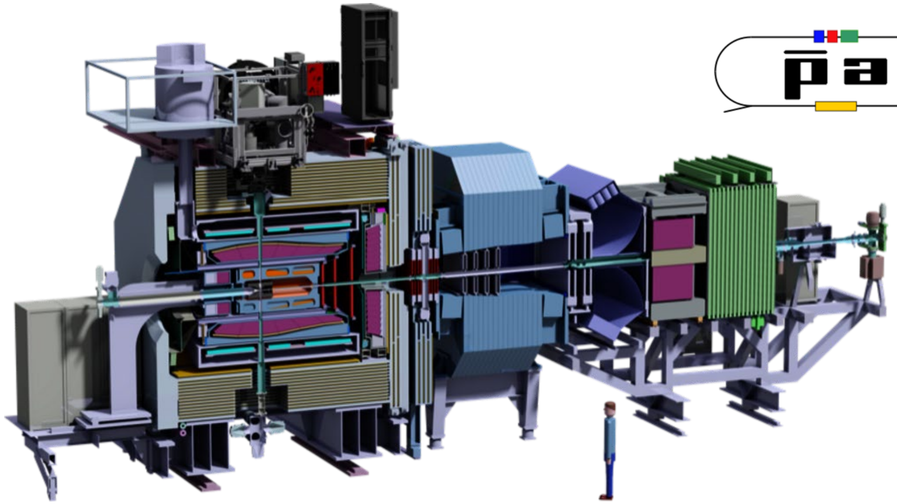



2T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
Iron return yoke interspersed
with muon chambers
Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

Higgs boson decay in two photons

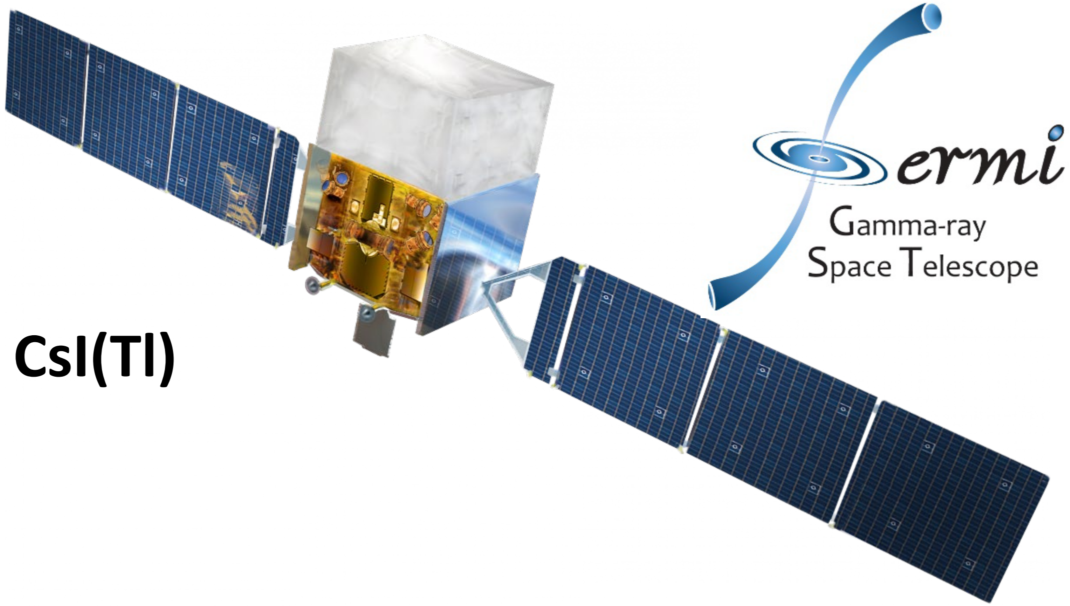


panda

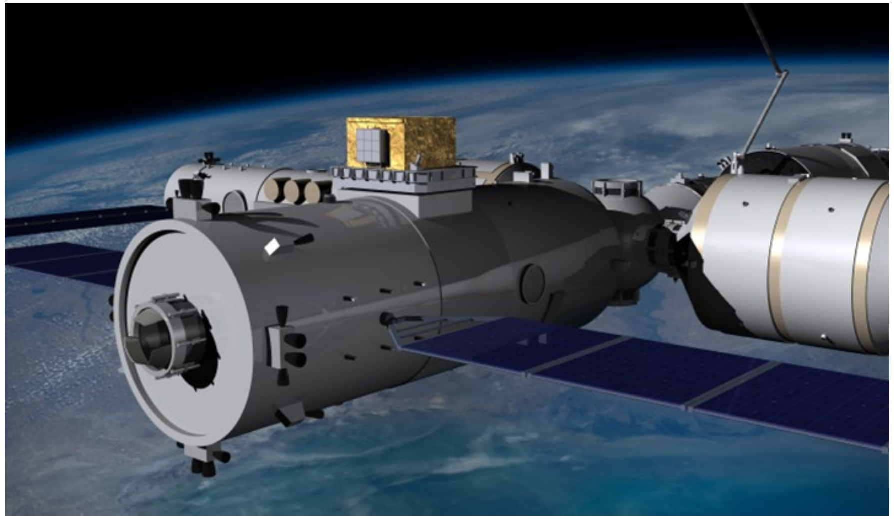


PWO

CsI(Tl)



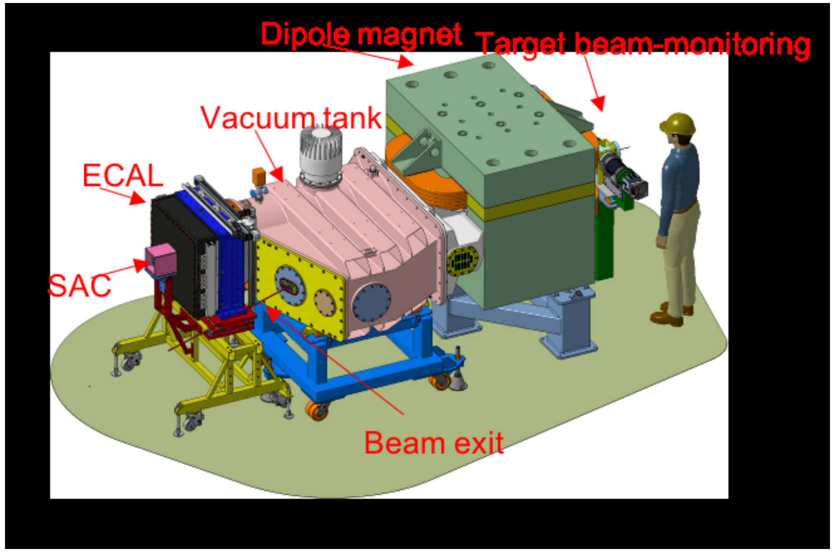
HERD



LYSO

BGO

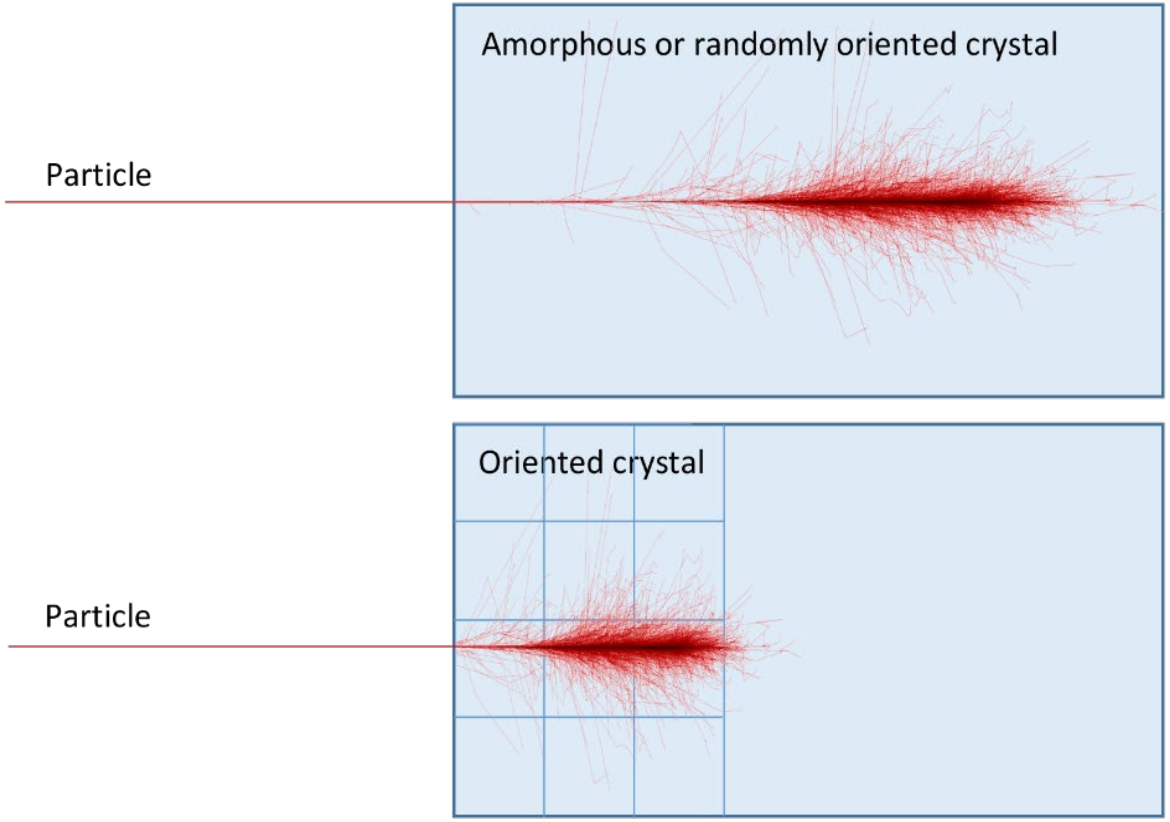
PADME



Orienting the e.m. calorimeter

The input photon or e^-/e^+ showers can fully develop in a much lower thickness with respect to the current state-of-the-art detectors

- ➢ enhanced compactness
- ➢ budget-saver
- ➢ n/γ discrimination



OREO - ORiEnted calOrimeter

2023-2024 project financed by INFN

L. Bandiera, V.V.Haurylavets, V. Tikhomirov NIM A 936 (2019) p.124-126

L. Bandiera et al., Front. Phys., doi.org/10.3389/fphy.2023.1254020

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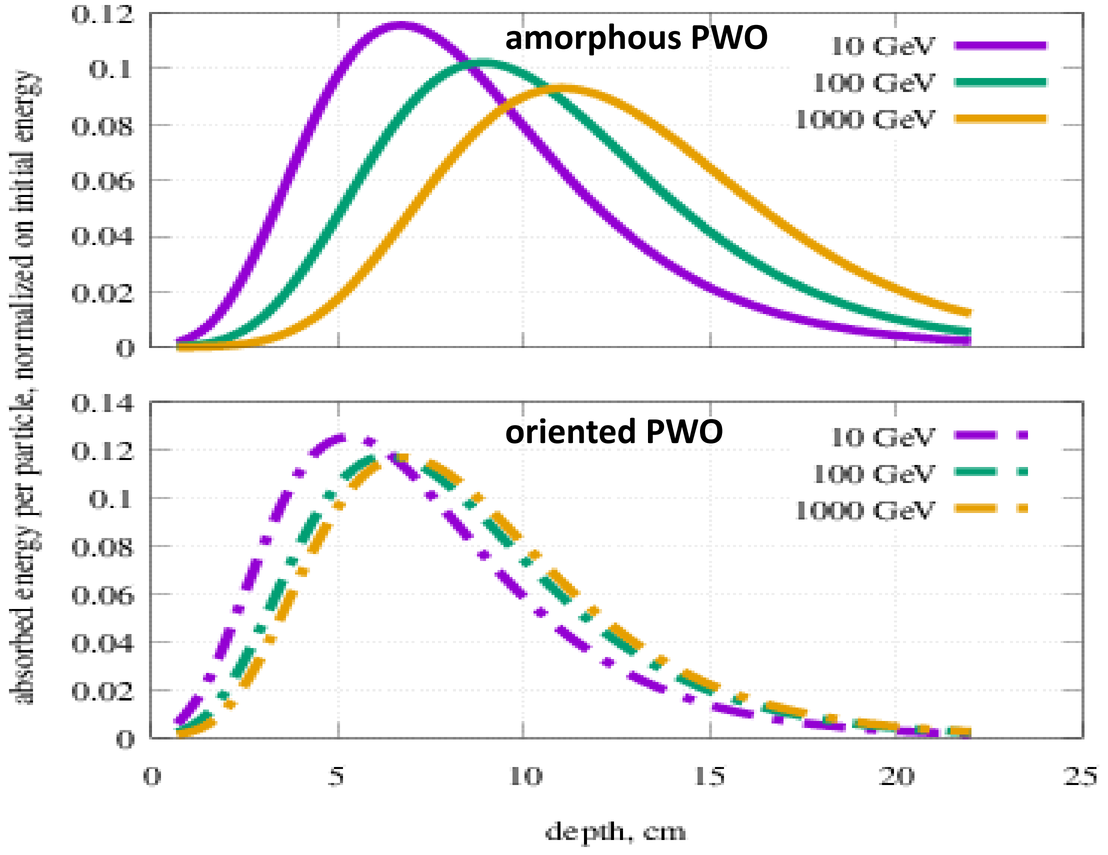
Electromagnetic shower development of HE electrons in a PWO crystal

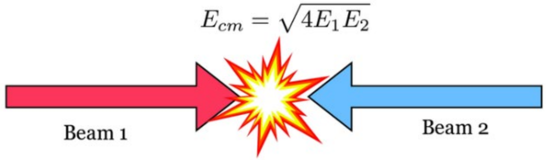


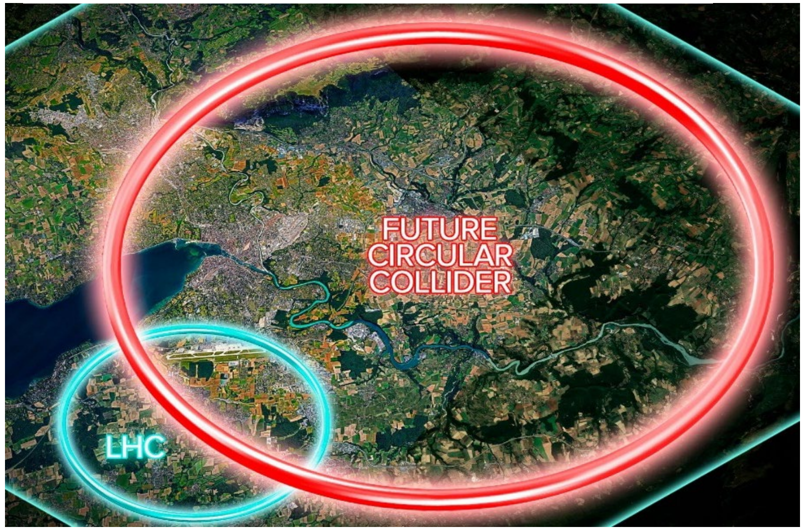
L. Bandiera, V.V.Haurylavets, V. Tikhomirov NIM A 936 (2019) p.124-126

L. Bandiera et al., Front. Phys., doi.org/10.3389/fphy.2023.1254020

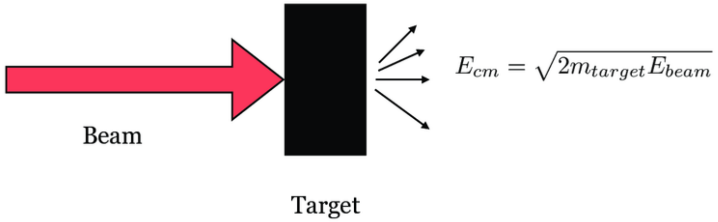
Ultra-Compact oriented crystal calorimeters

At the highest energies in future colliders (FCC, CEPC, Muon Collider…)

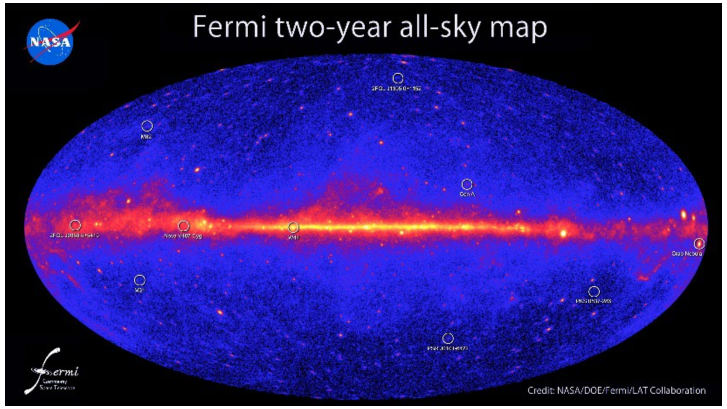




At the precision frontiers in fixed target experiments and for light dark matter search in Beam Dump

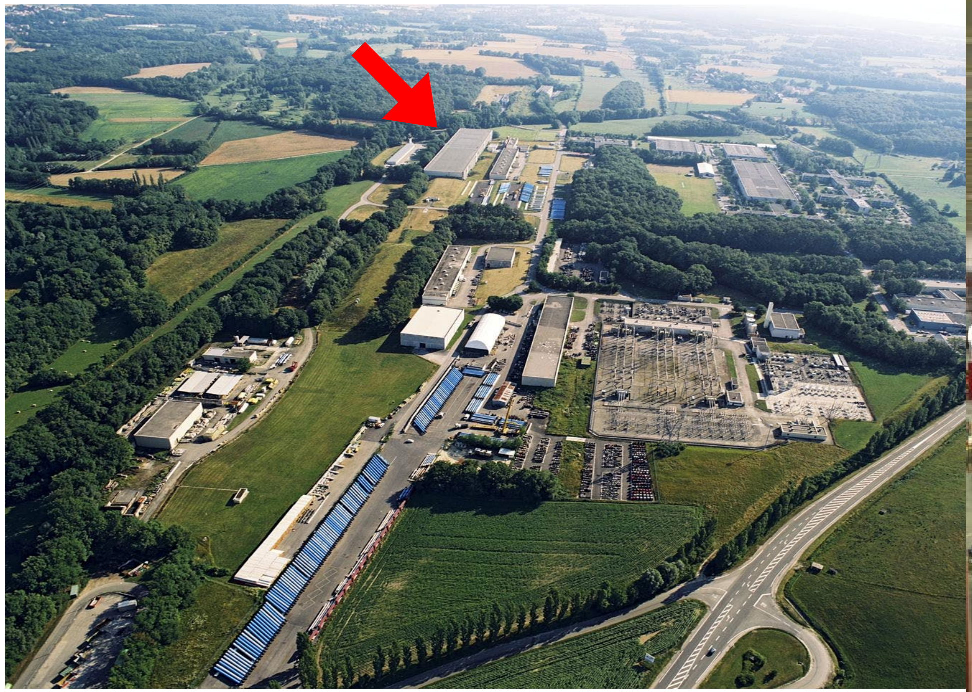


In space-borne telescope for VHE and UHE gamma-ray observation



The precision frontier
Search for New Physics beyond the Standard Model

North Area @ CERN



The precision frontier
Study of rare kaon decays at CERN

Rare kaon decays allow for the search of New Physics without the need to push the energy scale above the TeV

Running up to 2025

Exceptionally rare processes

- BR($K^+ \rightarrow \pi^+\nu\nu$) ~ 1.7×10^{-11}
- BR($K_L \rightarrow \pi^0\nu\nu$) ~ $<3 \times 10^{-9}$

→ very complex precision measurements, which require bringing the **HEP technology to its finest**

Difference from the theoretical BRs (pure Standard Model) might hint the presence of New Physics → e.g. in the weak interactions of the quarks

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Start in 2028

High Intensity Kaon Experiments

→ very complex precision measurements, which require bringing the **HEP technology to its finest**

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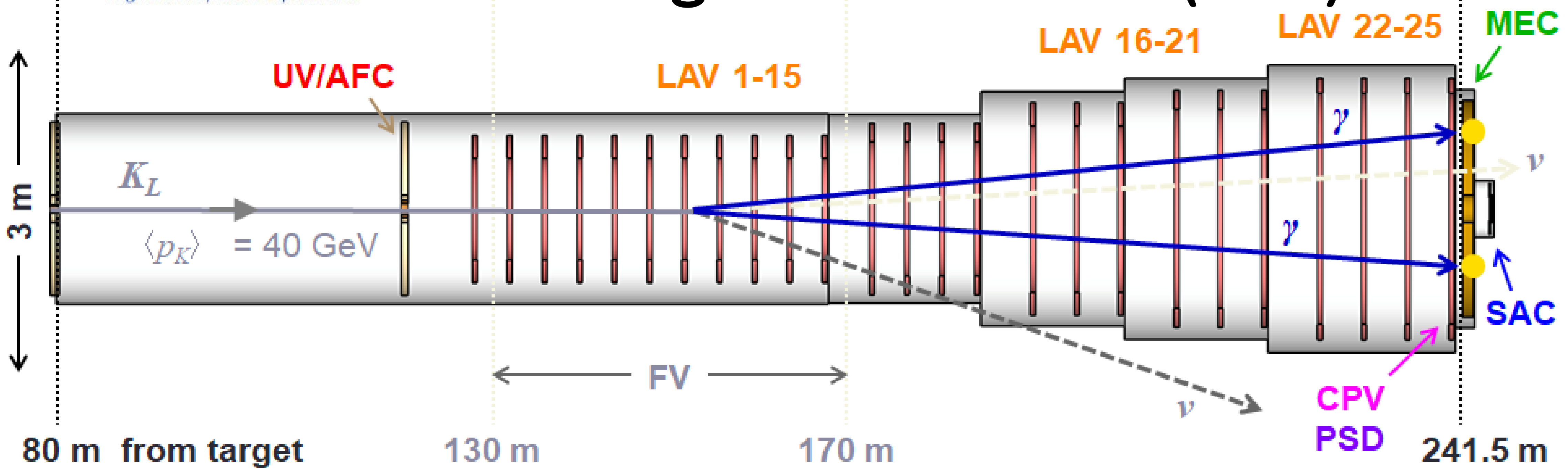
The HIKE Small Angle Calorimeter (SAC)



- Signature of $K_L \rightarrow \pi^0 \nu\bar{\nu}$: 2 γs coming from π^0
- A most probable decays is $K_L \rightarrow \pi^0 \pi^0$ (signature 4 γs)
- **The SAC has to see the 2 γs of K_L decay,** while any <u>extra photons must be vetoed with very high efficiency</u> **maintaining insensitivity to more than 500 MHz of neutral hadrons** in the beam

The HIKE Small Angle Calorimeter (SAC)

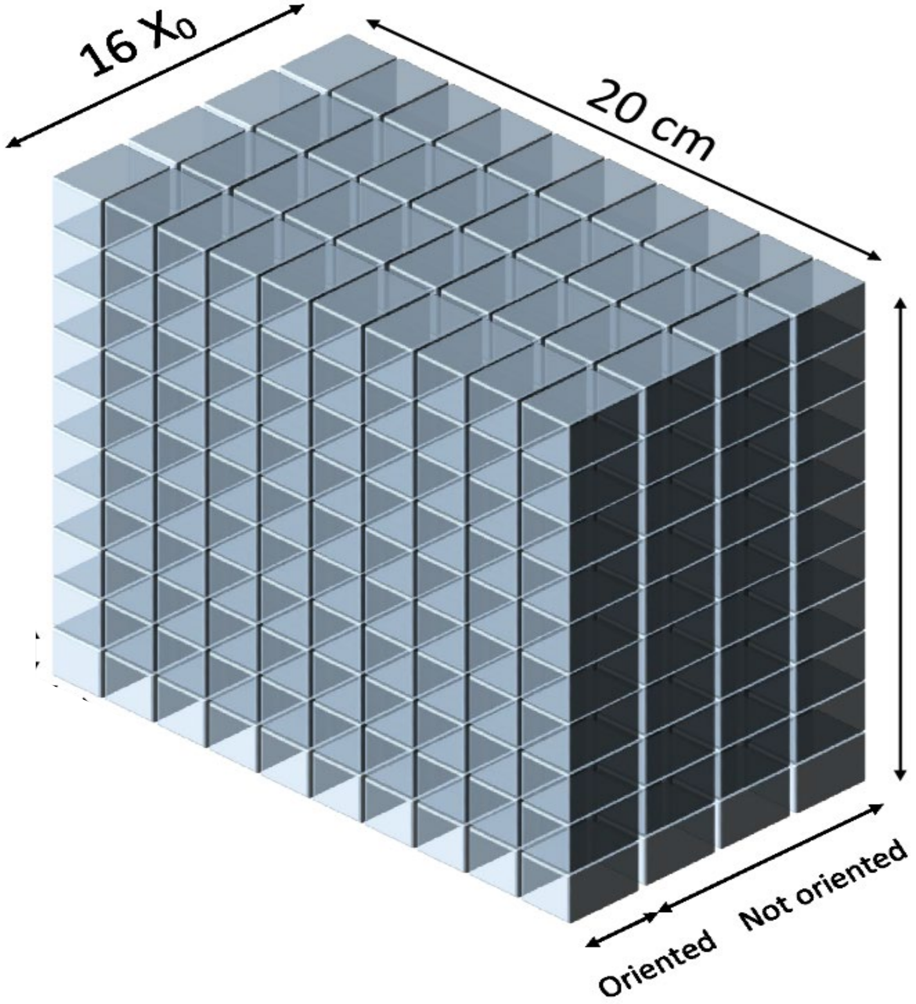
Requirements:

As compact as possible to provide maximum transparency to hadrons, while maintaining high photon-conversion efficiency

Solution:

Axially oriented PWO crystals providing

- **a higher photon-conversion** probability
- shorter electromagnetic shower -> possibility to **decrease the calorimeter length**, thus increasing its **transparency to hadrons**



Transverse and longitudinal segmentation for a better n/γ discrimination

The HIKE Small Angle Calorimeter (SAC)

Requirements:

As compact as possible to provide maximum transparency to hadrons, while maintaining high photon-conversion efficiency

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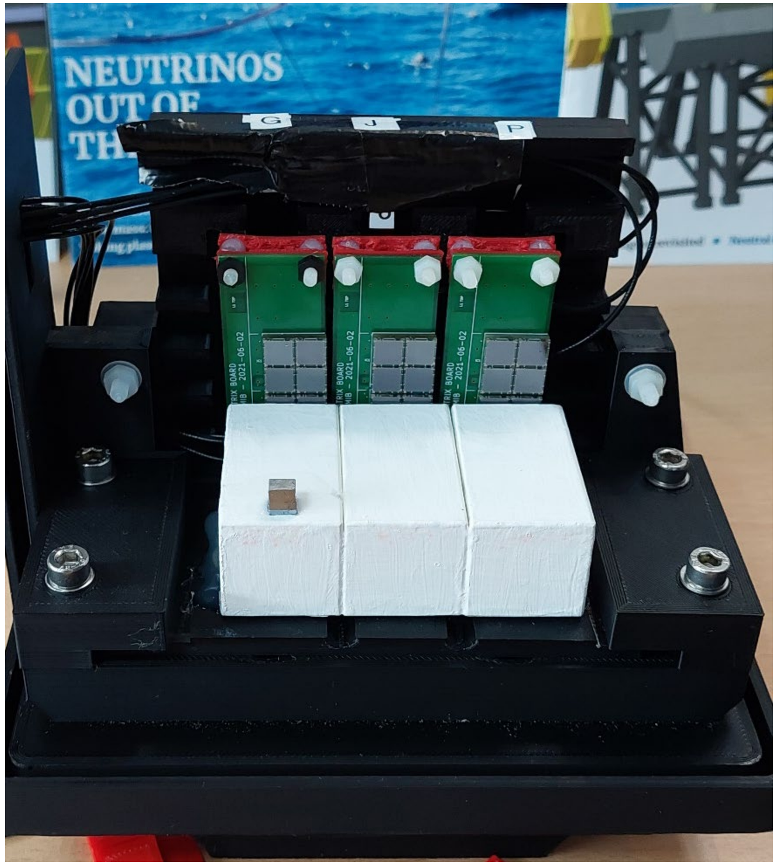
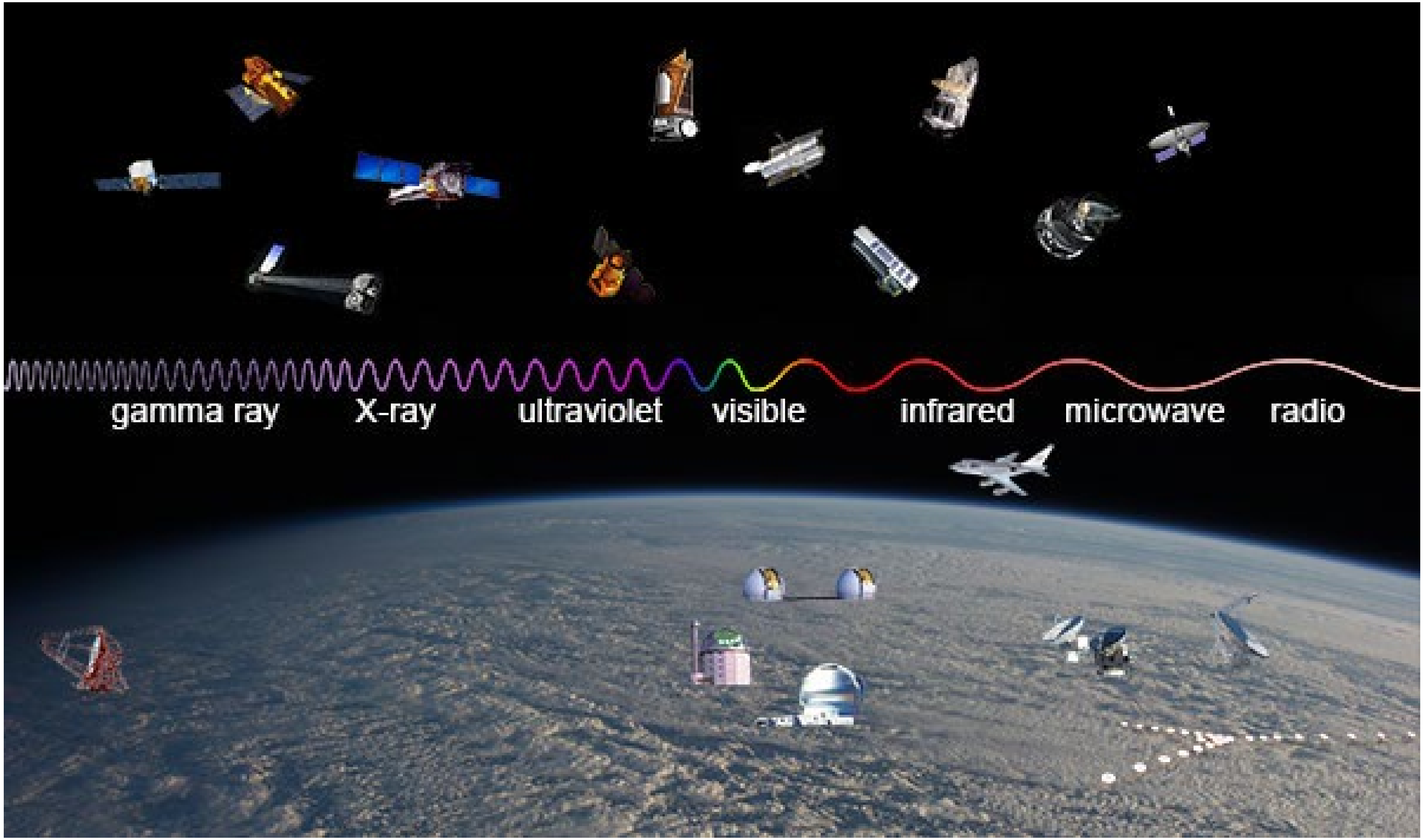


First prototype made of three axially oriented PWO
Tested in August 2023 at CERN

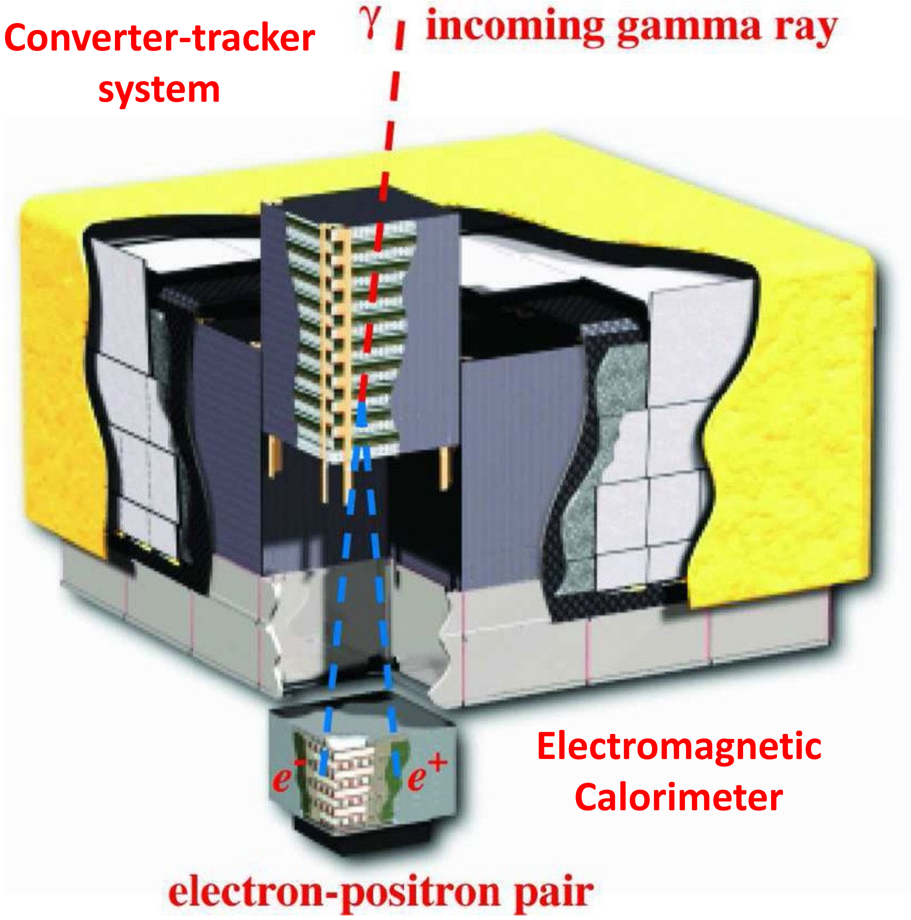
VHE/UHE gamma-ray observation from Space

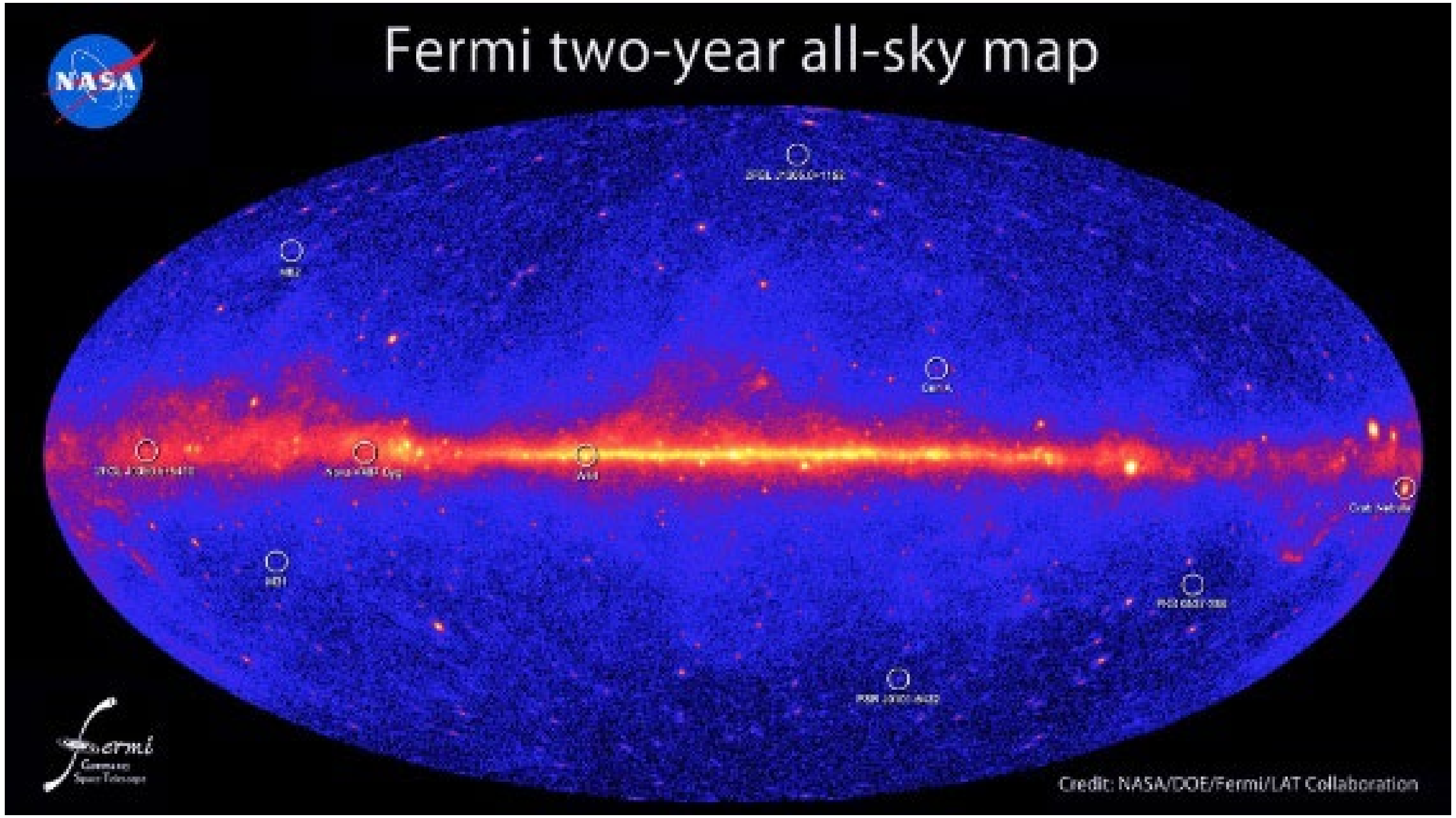


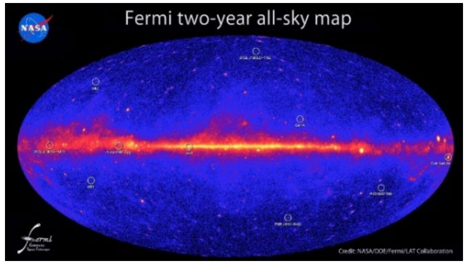
VHE/UHE gamma detectors in space

Take the FERMI-Large Area Telescope..

Converter-tracker system

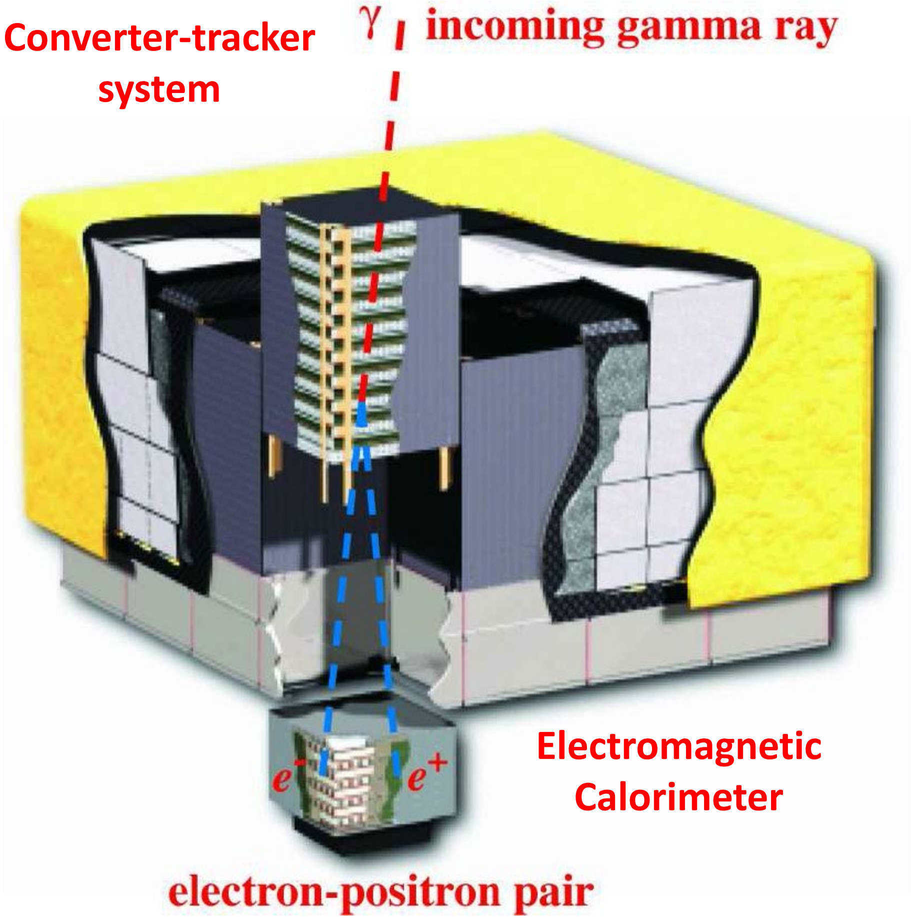






VHE/UHE gamma detectors in space

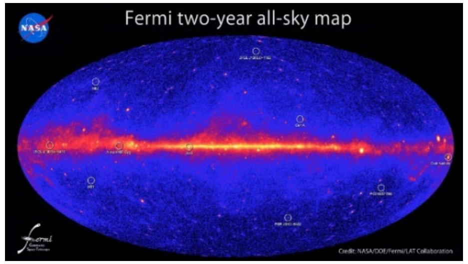
Take the FERMI-Large Area Telescope..



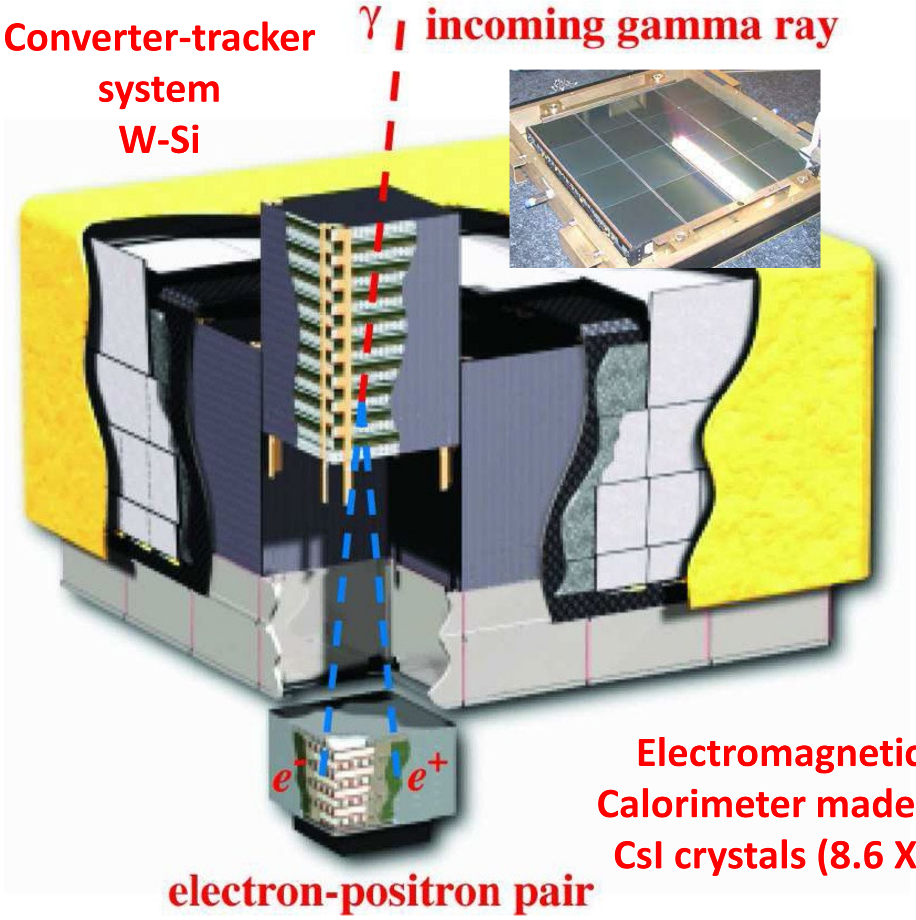
Fermi-LAT is currently doing a great job and will continue for the next years.

Nevertheless, it has its own limitations in effective area, energy and angular resolution, which have **left open several important questions** (e.g, **the nature of the few GeV γ excess from the Galactic Center**).

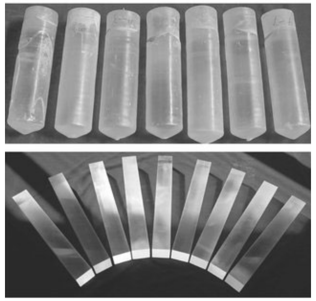
… that can be oriented along lattice directions



Converter-tracker system W-Si

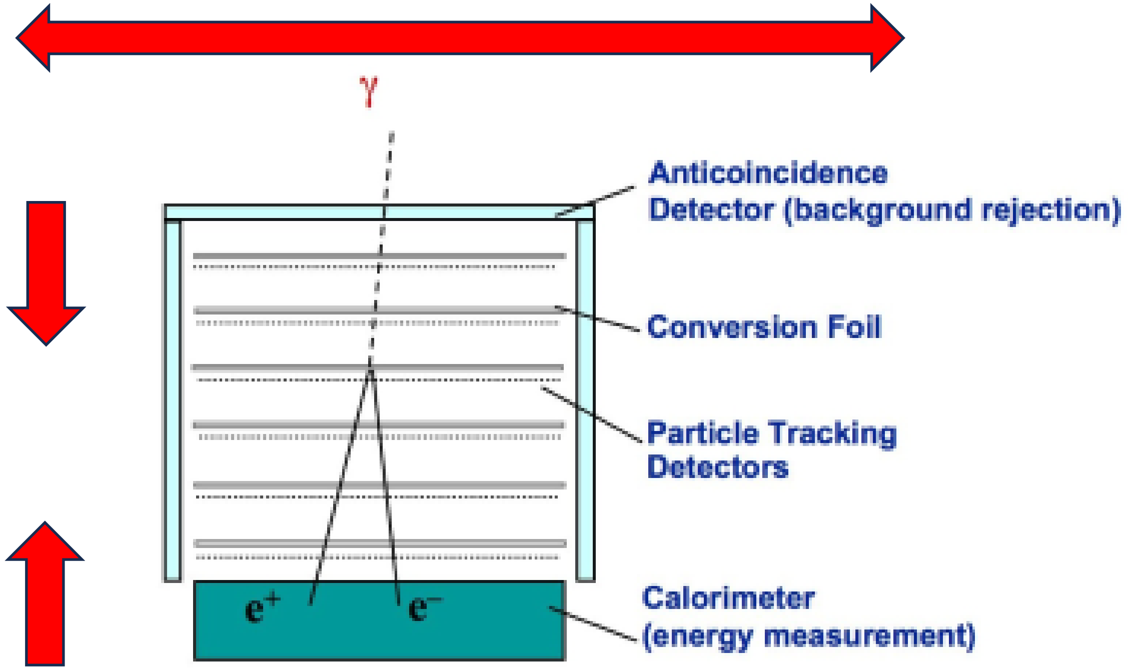


Electromagnetic Calorimeter made of CsI crystals (8.6 X_0)



All of these materials have a crystalline structure and can be oriented along some preferred lattice direction

Novel idea: ultra-compact space-borne satellite to detect VHE gamma-rays

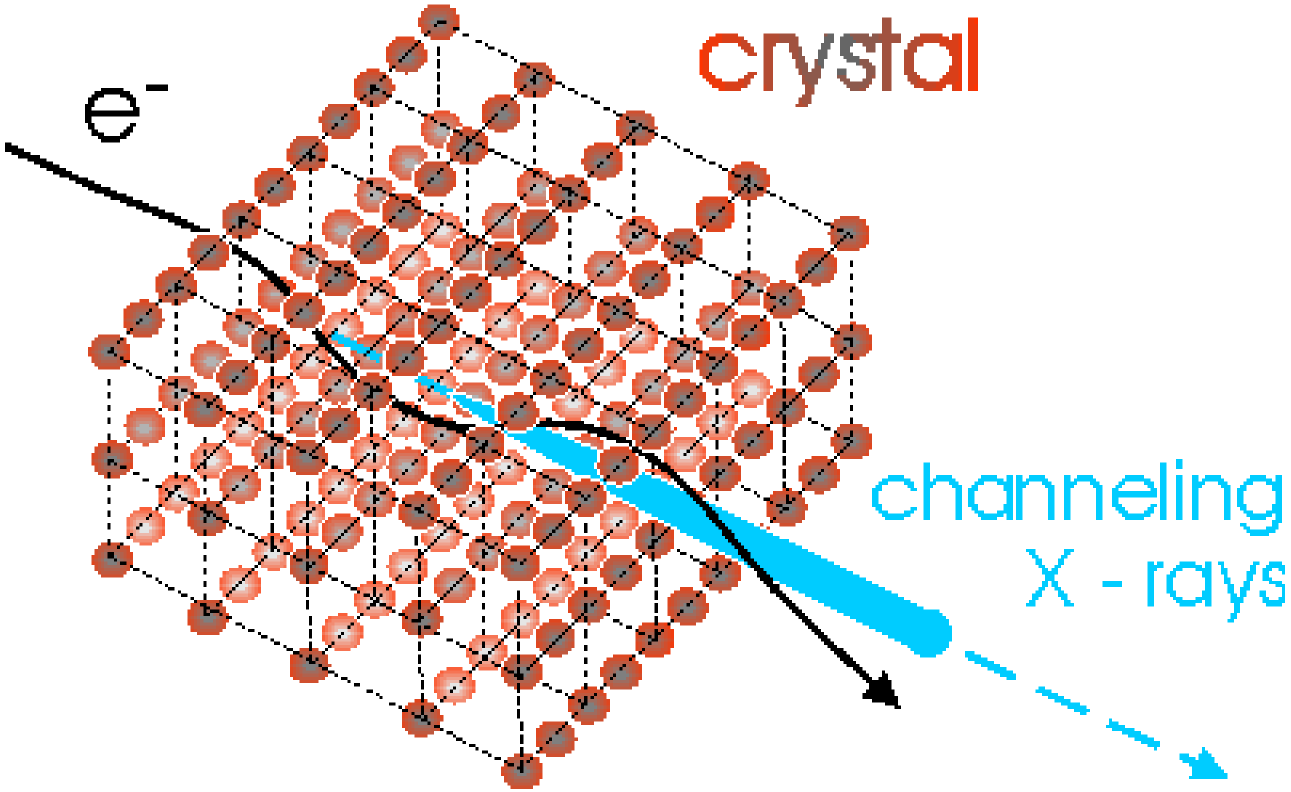


- **Above 1 GeV**, the primary challenge is the **very limited photon flux**. Reducing the longitudinal dimension of the calorimeter would enable **the increase of the detector area** (to **see more photons**!) at no net cost in weight
- Improved energy and angular resolution to **investigate the GeV gamma-ray sky open questions**!

We started a collaboration with **Fermi-LAT, Italian Space Agency** and **Brown University** researchers

L. Bandiera https://indico.cern.ch/event/1208314/contributions/5342894/

Other applications…

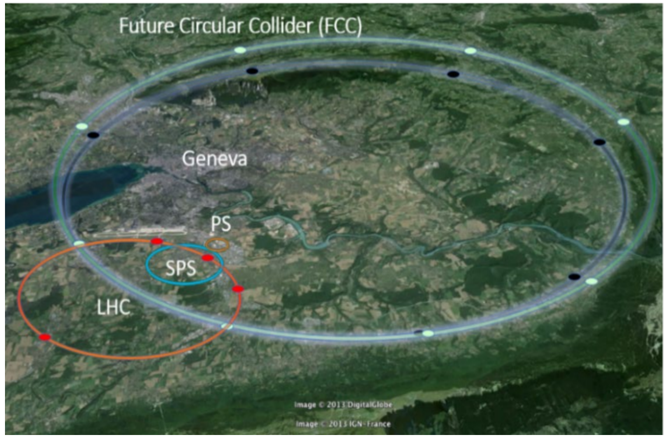


G.A. 101046458

Intense gamma-ray sources

application in base science and nuclear medicine

Korol, A.V., Solov'yov, A.V. Eur. Phys. J. D 74, 201 (2020).



Intense positron sources

for Future Circular Collider

L. Bandiera et al., Eur. Phys. J. C 82 (2022) 699

e+BOOST (PI L. Bandiera)
PRIN2022-2022Y87K7X

Bando PRIN 2022

Experiments with Crystals

INFN FERRARA

CERN

Collimation & beam steering
Innovative radiation & positron sources
Pair production studies
Innovative detectors

MAMI – MAINZER MIKROTRON

Beam steering
Innovative radiation sources

DESY.

Innovative radiation sources
Innovative detectors
Beam extraction

Fermilab

Beam steering

SLAC

Innovative radiation sources
Beam steering

erc – European Research Council – Established by the European Commission

ERC-CoG CRYSBEAM (LHC beam extraction)
ERC-CoG SELDOM (Studies of MDM and EDM of charmed baryons)
MCA-IRSES CUTE (crystalline undulators)
MSCA-RISE PEARL (crystalline undulators)
MSCA-RISE N-LIGHT (crystalline radiation sources)
INFRAIA AIDAInnova (crystal calorimeters)
EIC-PATHFINDER-OPEN TECHNO-CLS (crystalline radiation sources)

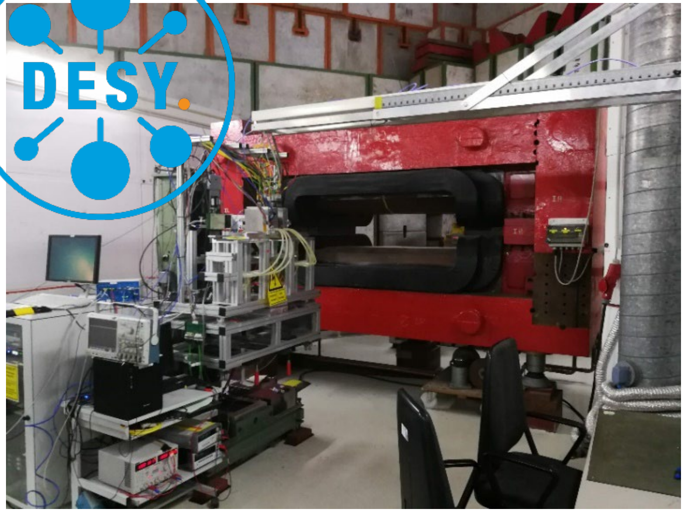
Involved in Channeling activities for about 20 years

International labs

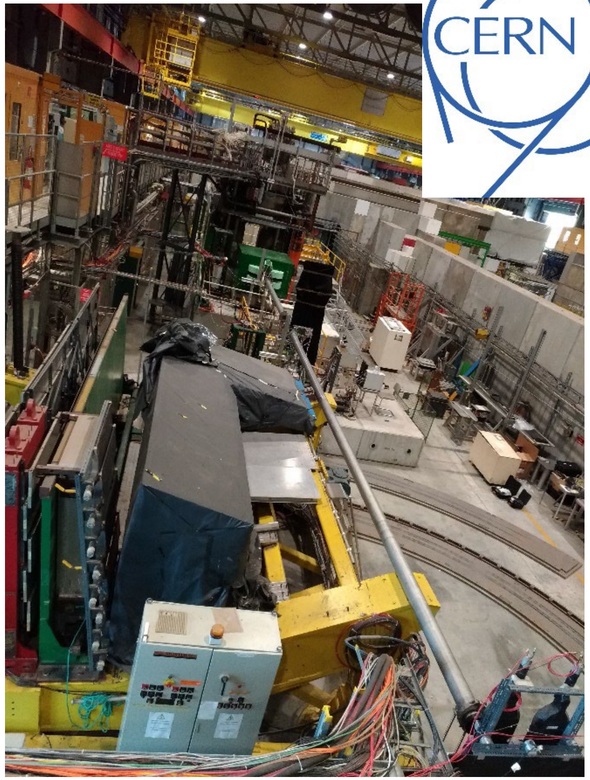
e$^-$ @ subGeV
MAMI (Mainz, Germany)

e$^\pm$ @multi-GeV
SLAC (Stanford, USA)

Hard X-ray
ESRF (Grenoble, France)

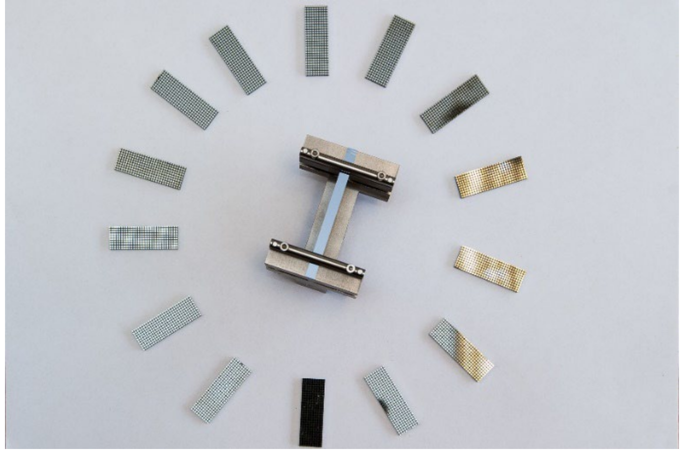


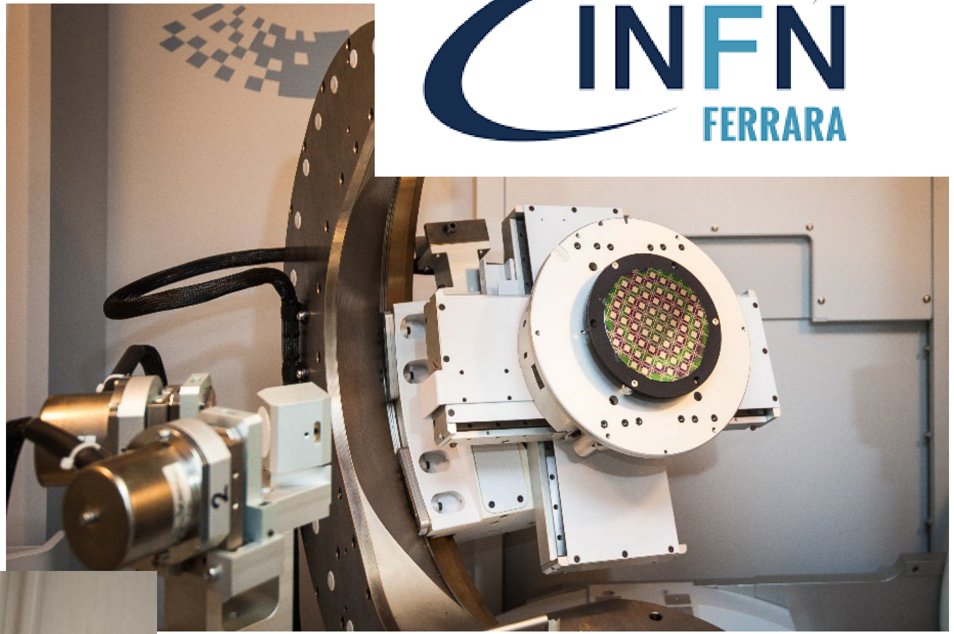
e$^\pm$ @6 GeV
DESY (Hamburg, Germany)



p, e$^\pm$, π$^\pm$ @ (20-400) GeV
CERN (Geneve, Switzerland)

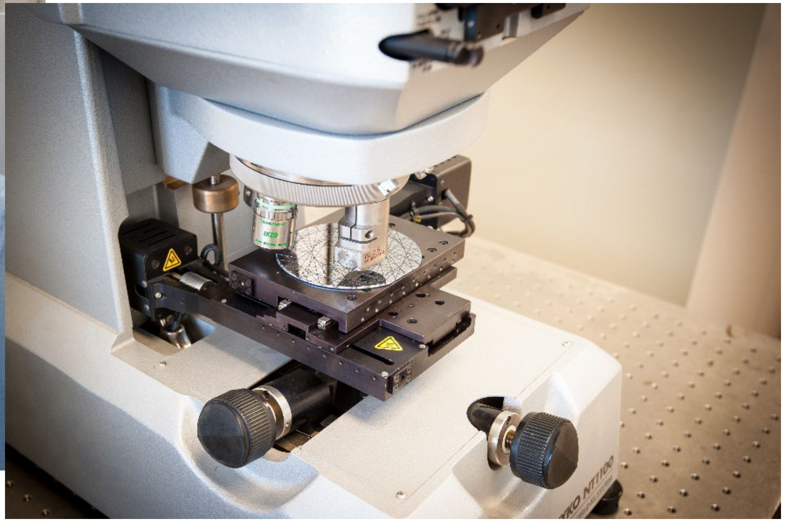
Crystal preparation and characterization





Laboratory fully equipped & Clean room (130 m^2)

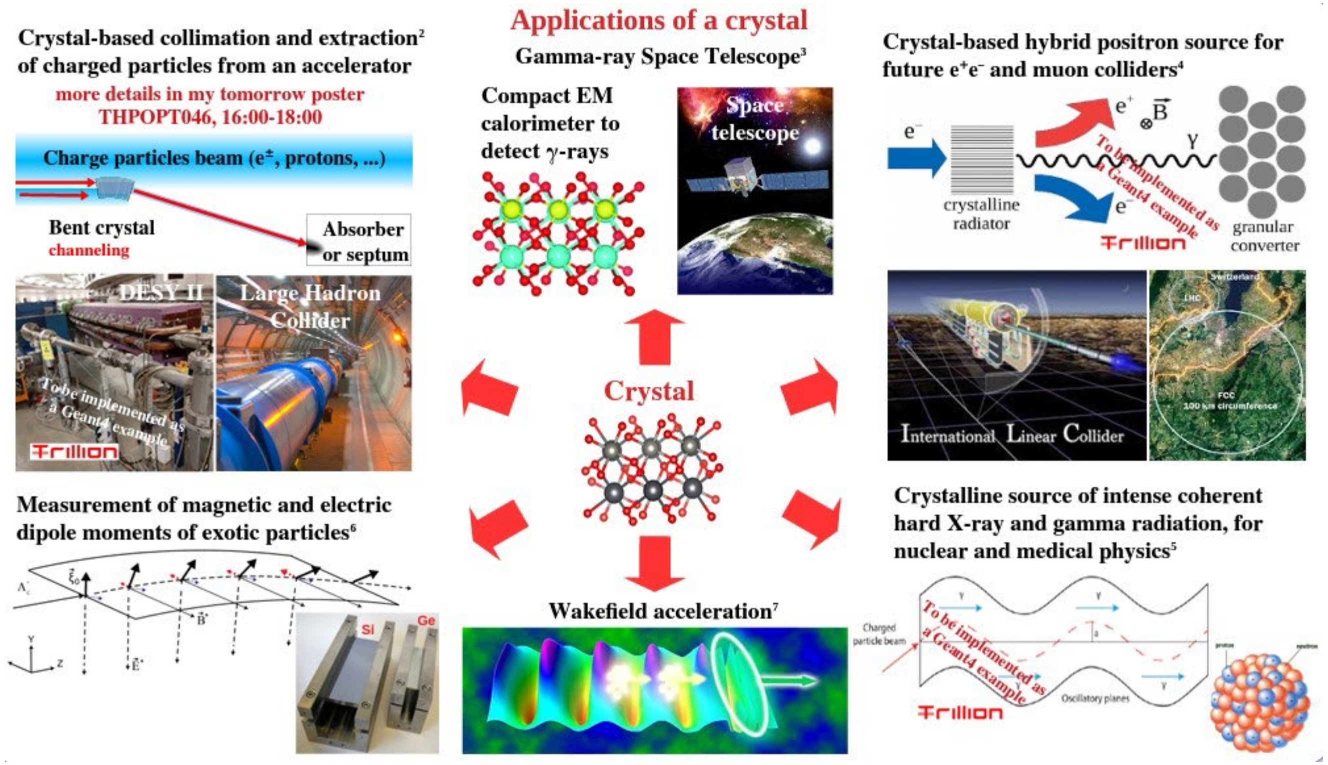
Coord: A. Mazzolari, M. Romagnoni

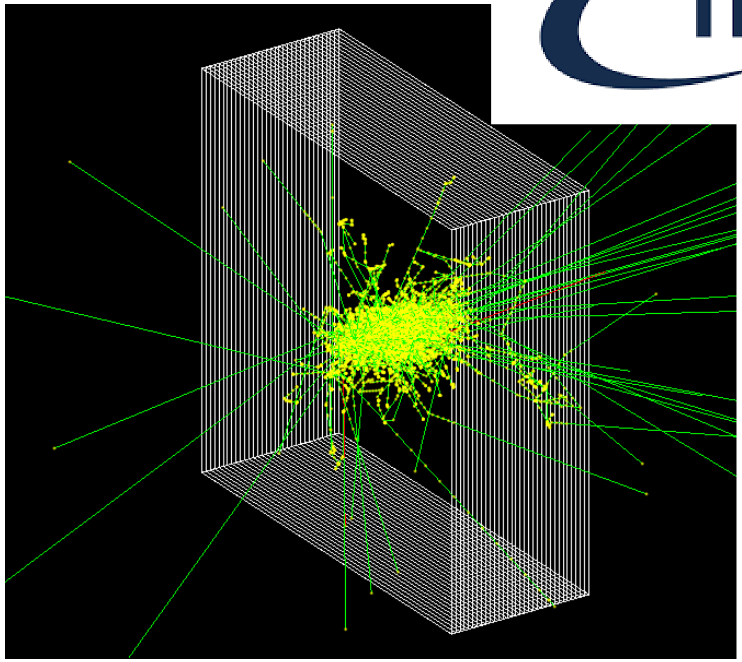


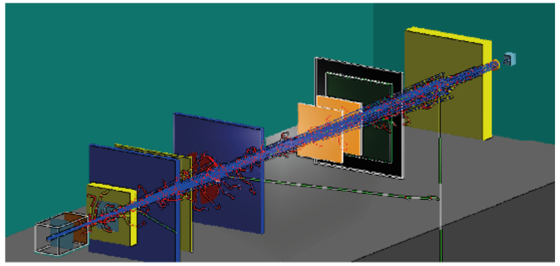
Monte Carlo simulation

Coord: G. Paternò, A. Sytov

Implementing the "crystal physics" in Geant4





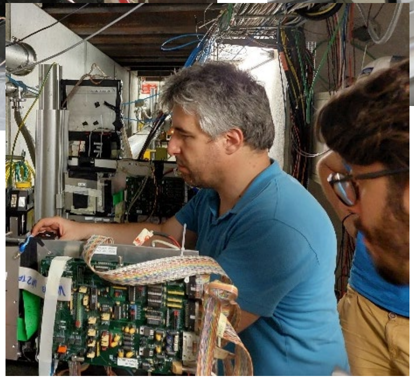


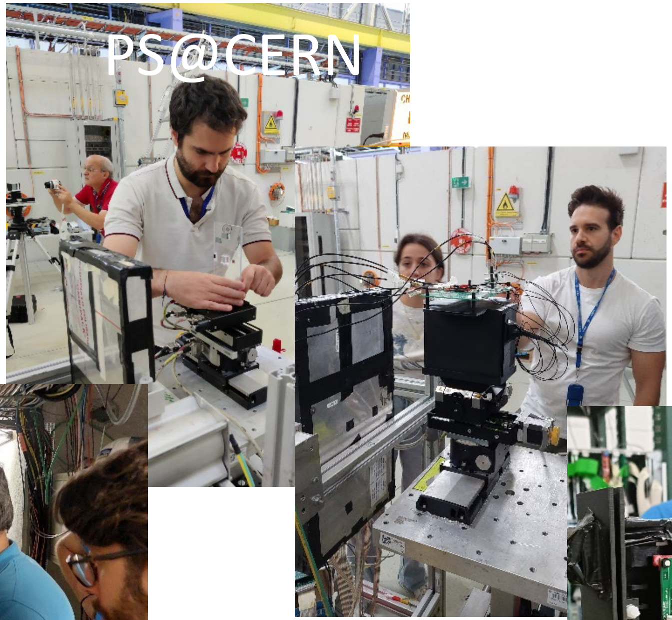
Marie Curie Individual fellow

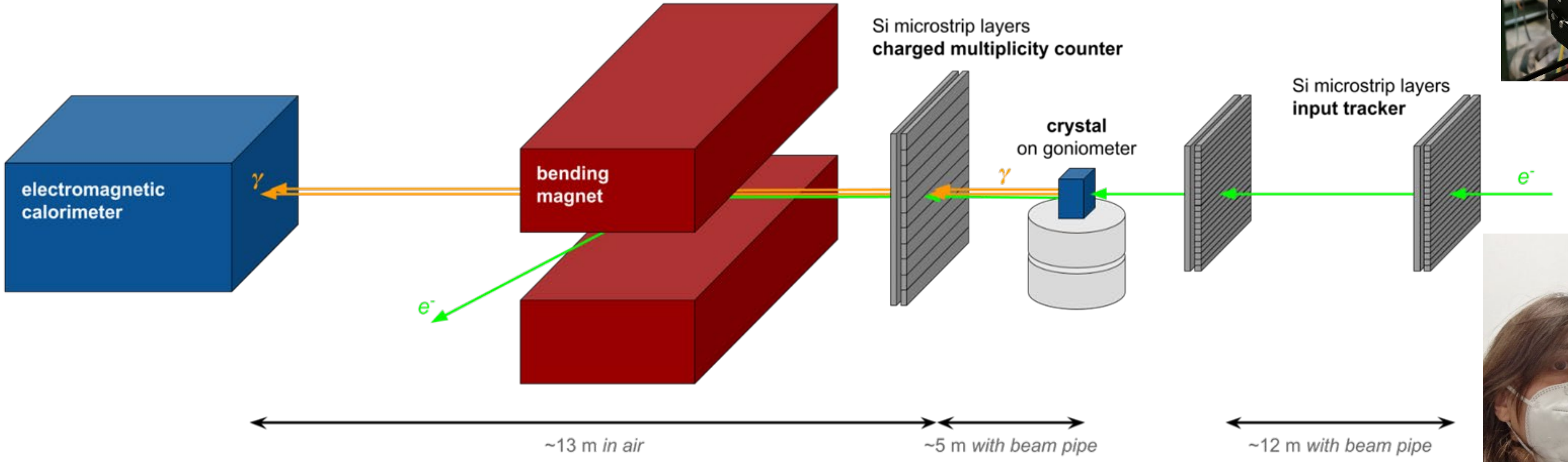
https://www.fe.infn.it/trillion/

Experiments on beam

Coord: L. Bandiera







Ferrara’s Team

Laura Bandiera
INFN researcher

Nicola Canale
post Doc

Vincenzo Guidi
UNIFE full professor

Lorenzo Malagutti
post Doc

Andrea Mazzolari
UNIFE researcher

Riccardo Negrello
PhD Student

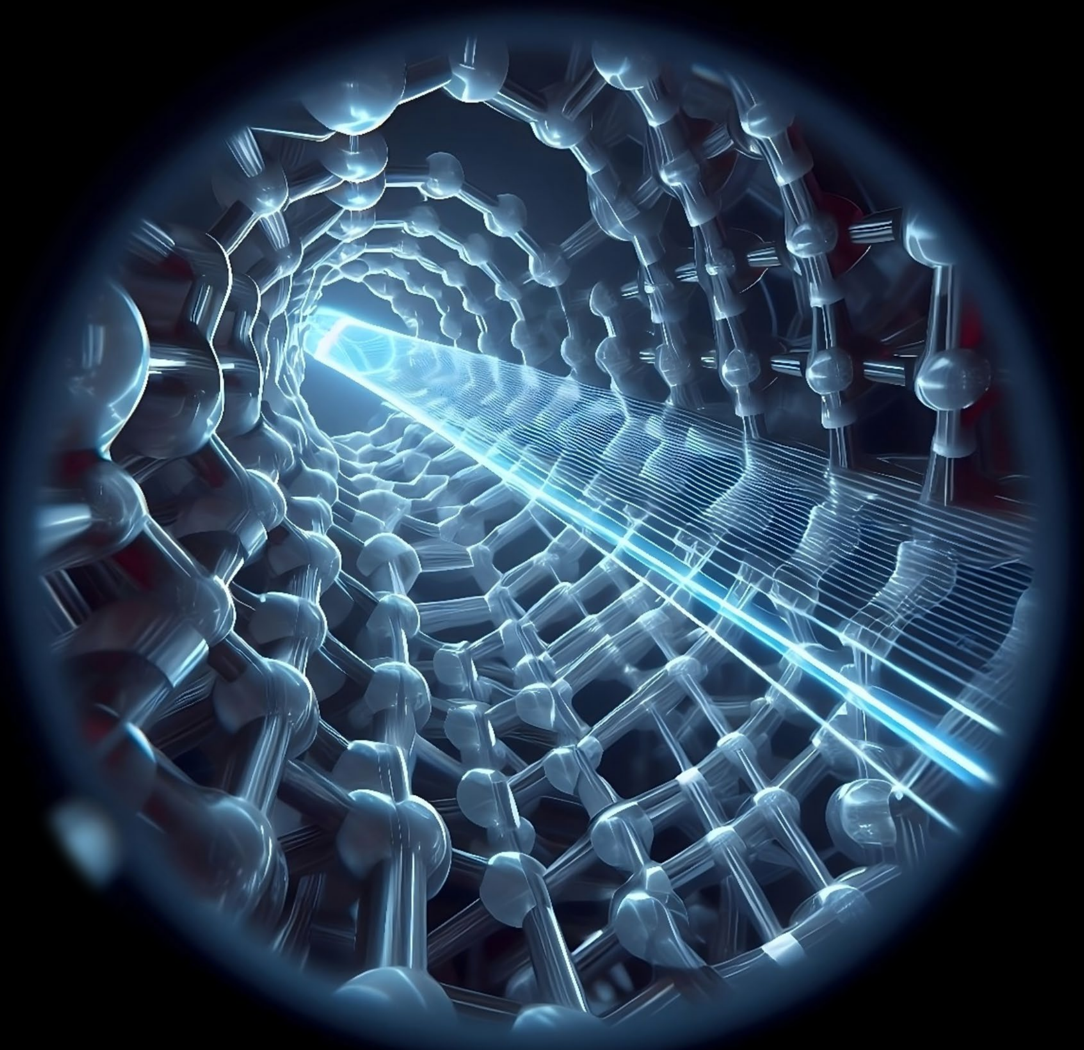
Gianfranco Paternò
INFN technologist

Marco Romagnoni
UNIFE researcher

Alexei Sytov
Marie Curie fellow

Melissa Tamisari
UNIFE researcher

Thank you for the attention!



Any comments or questions?
contact me at
bandiera@fe.infn.it !