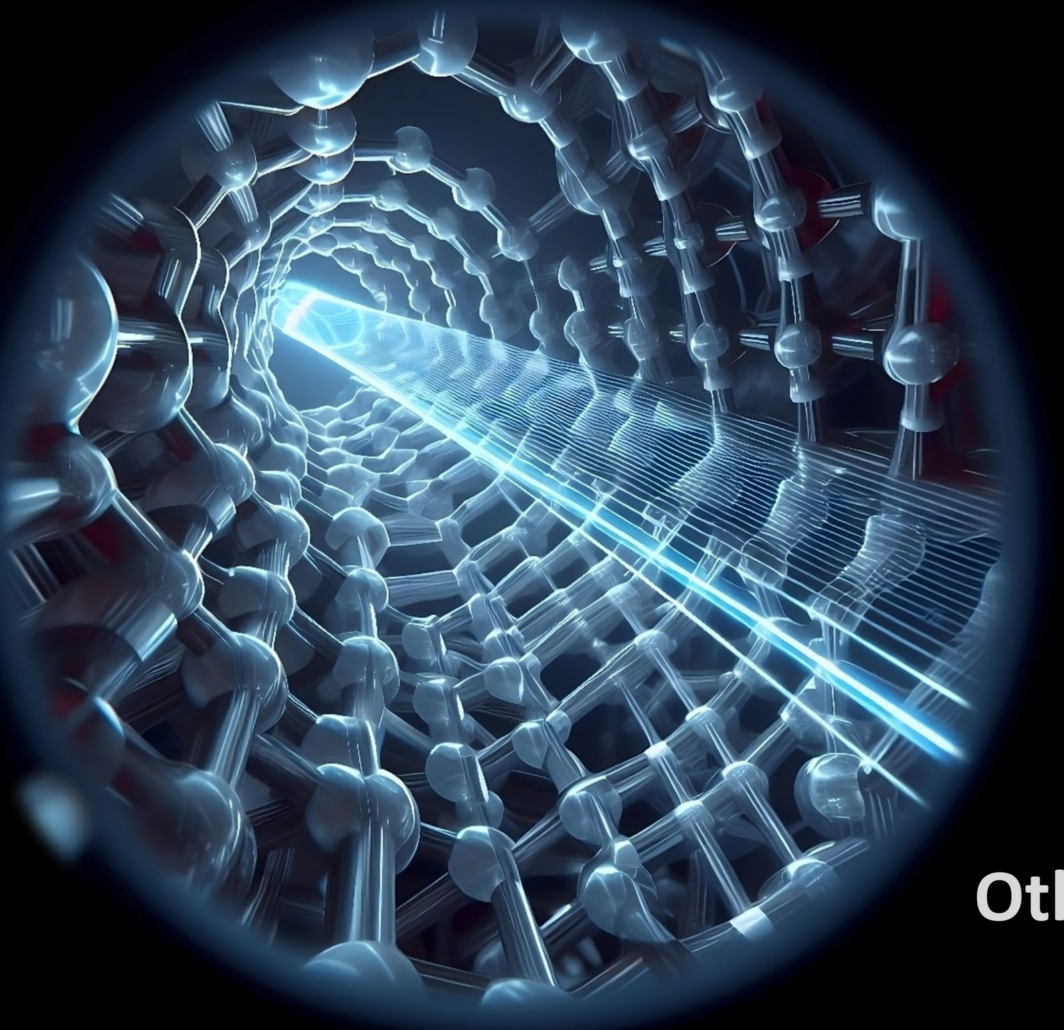
Strong Field QED in crystals



L. Bandiera

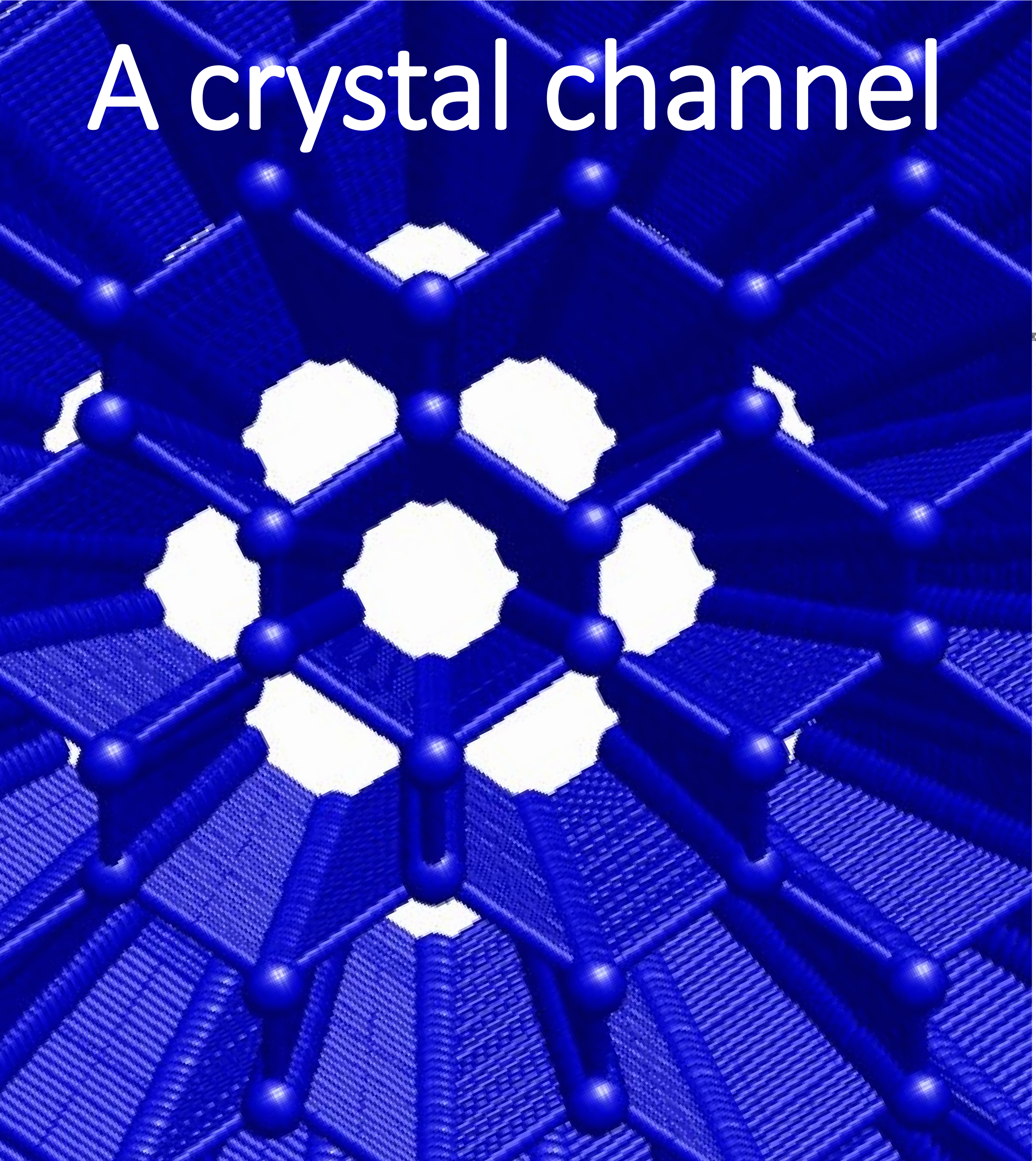
INFN FERRARA

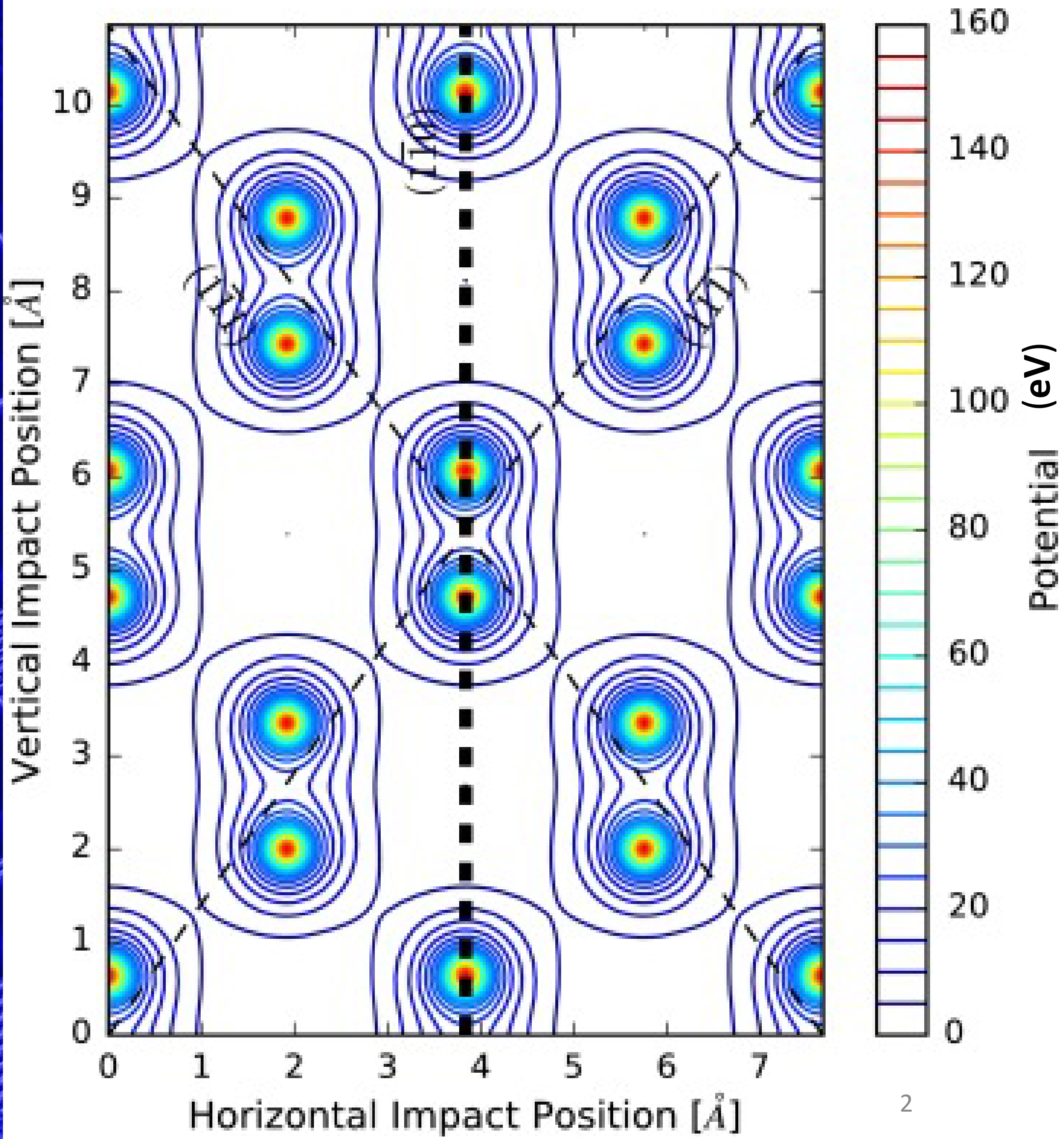
Contact: bandiera@fe.infn.it

Other Science Opportunities at the FCC-ee

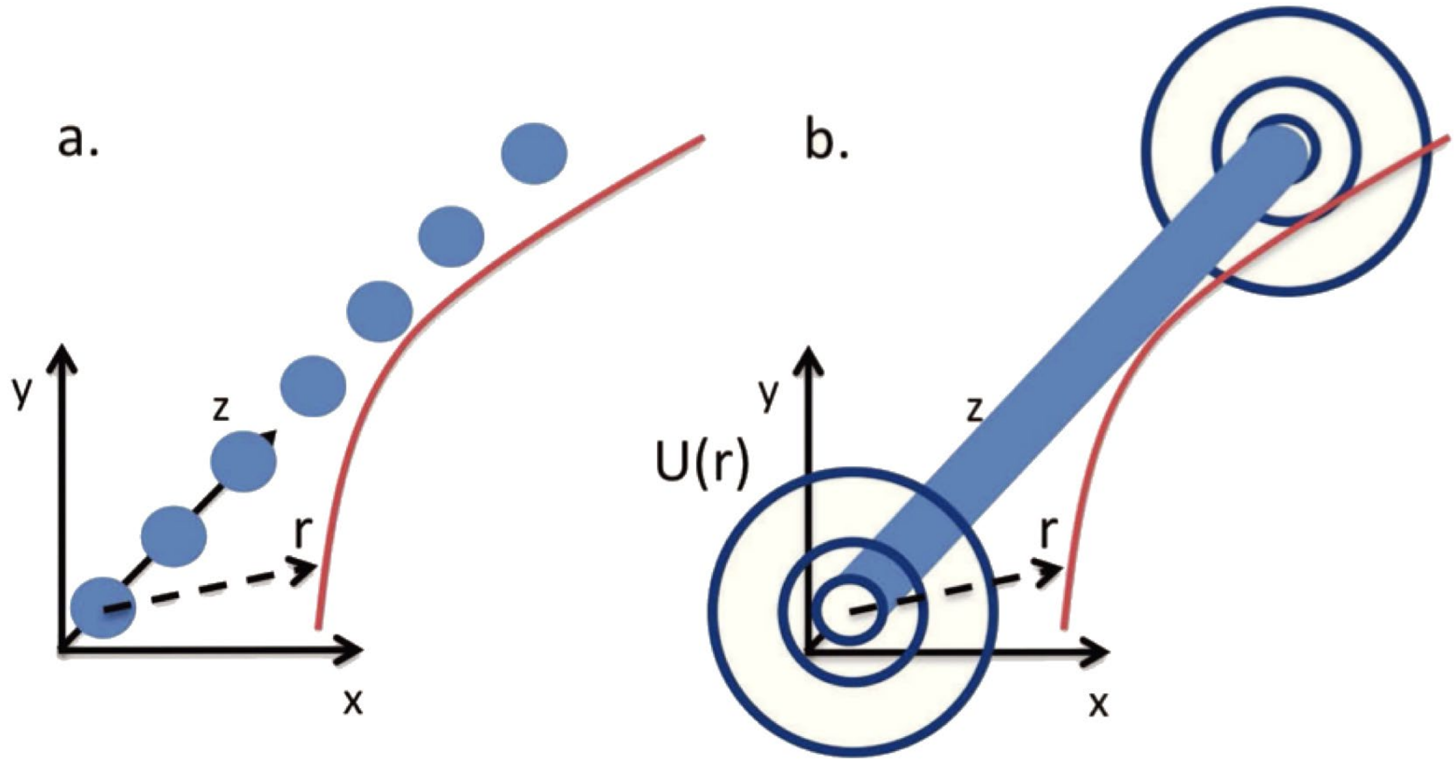
CERN, 28th November 2024

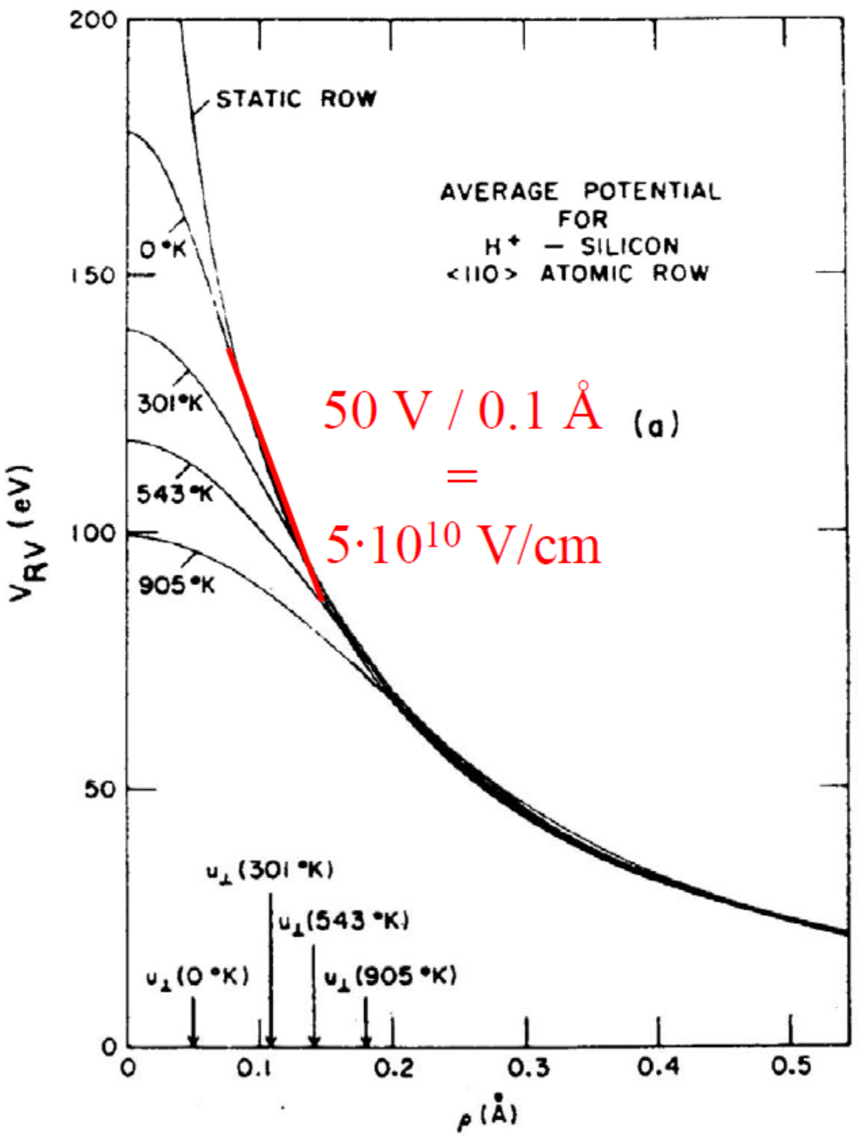
A crystal channel





Crystal extremely strong electric fields

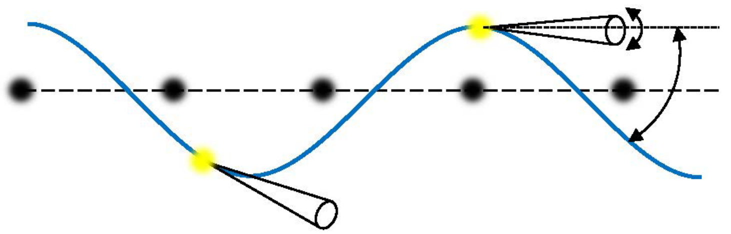


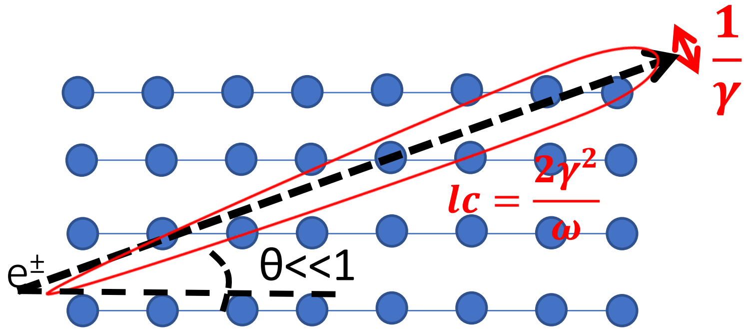


Radiation regime vs. beam energy

For beam energies < 1 GeV the radiation cone 1/γ >> channeling deflection angle ->
$\rho \ll 1$ the radiation features a dipole-like for both channeling and coherent bremsstrahlung

***2 LIMIT CASES at energies above few GeV*:**
if the incident angle θ_0 with respect to the crystal axis (or plane) is:





$$\theta_0 << \frac{V_0}{m}$$

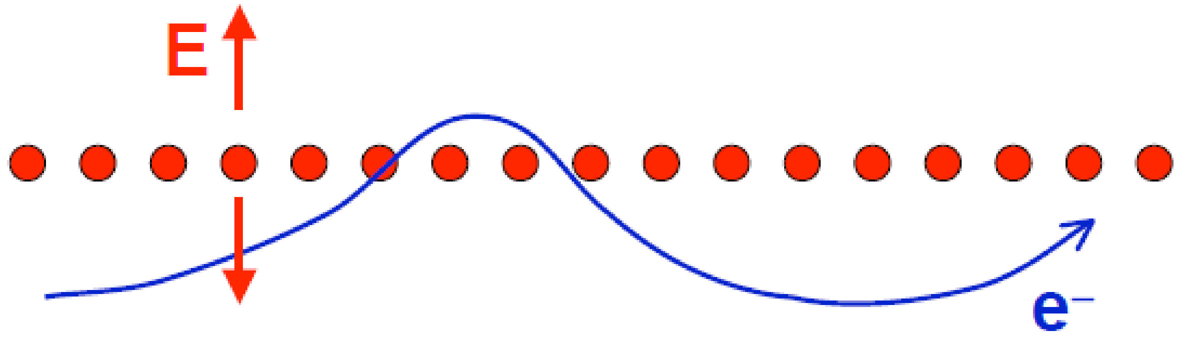
- **Synchrotrone-like radiation**

$$\theta_0 >> \frac{V_0}{m}$$

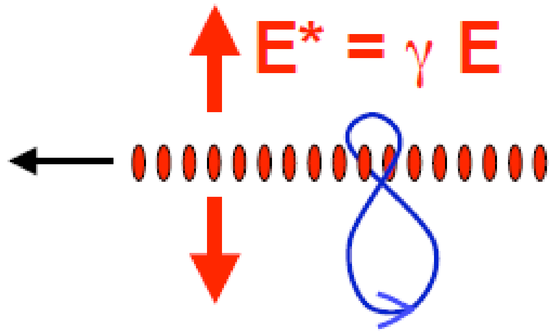
- **Coherent Bremsstrahlung**

V_0 = Axial/Planar potential well depth, with **V_0/m >> $\Theta_{crit} = (2V_0/E)^{1/2}$ for large particle energy E**

Strong electromagnetic field in oriented crystals



lab. frame



e⁻ - comoving frame

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**:

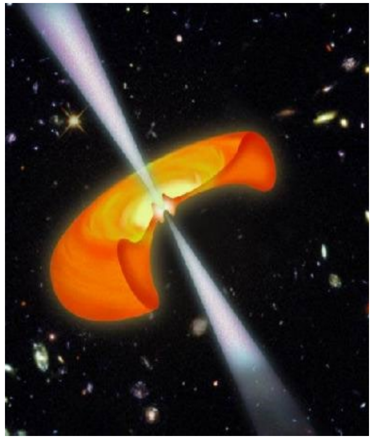
$$E_0 = m^2c^3/e\hbar \simeq 1.3 \times 10^{16} V/cm$$

above which electrodynamics becomes non linear

V. N. Baier, V. M. Katkov, V. M. Strakhovenko Electromagnetic Processes at High Energies in Oriented Single Crystals
Ulrik I. Uggerhøj, REVIEWS OF MODERN PHYSICS, VOLUME 77, OCTOBER 2005

Strong Fields in nature and labs

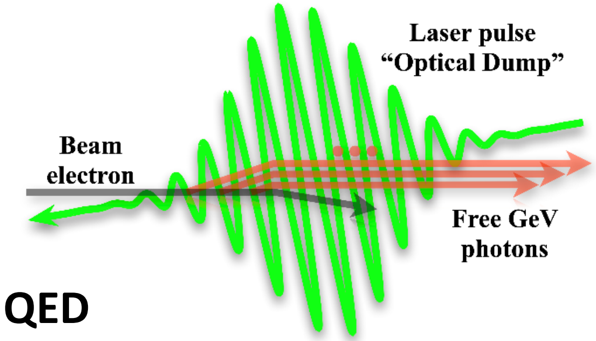
Magnetars
$B \approx 10^{10}$ T



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 (quantum and classical radiation reaction, trident production 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!!

“Quantum” synchrotron-like radiation is observable in crystals

TABLE I. Certain parameters of the averaged potentials of the principal axes and planes of a number of crystals.

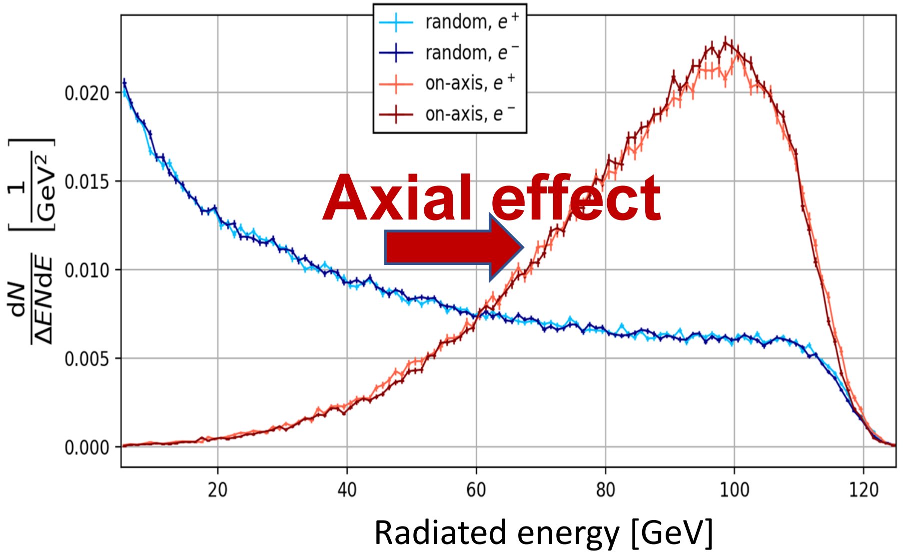
Element	Z	(Plane) ⟨Axis⟩	d_{pl} (d_{ax}), Å	T, K	u_1, Å	V_{max}, eV	$\mathscr{E}_{max}$, GV/cm	$\varepsilon_{\chi=1}$
Diamond	6	(110)	1.26	293	0.04	20.8	7.7	890
		⟨110⟩	2.52	293	0.04	137	68	100
Si	14	(110)	1.92	293	0.075	21.5	5.7	1193
		⟨110⟩	3.84	293	0.075	133	46	145
Ge	32	(110)	2.00	293	0.085	37.7	9.9	684
		(110)	2.00	0	0.036	44.0	14.9	454
		⟨110⟩	4.00	293	0.085	229	78	87
		⟨110⟩	4.00	100	0.054	309	144	47 GeV
W	74	(110)	2.24	293	0.05	127	43	158
		(110)	2.24	0	0.025	142	57	119
		⟨111⟩	2.74	293	0.05	931	500	13.6
		⟨111⟩	2.74	0	0.025	1367	1160	5.8

At $\chi = \gamma E/E_0 \geq 1$ – quantum strong field limit

Multiphoton emission, emission of hard photons with energy comparable to the primary electron/positron – cannot be treated classically
-> Strong increase in the energy lost by the primary particle.

Radiation and pair production in axial alignment

Radiative energy loss spectrum of 120 GeV e± aligned with the <001> axis of a 4 mm PWO scintillator crystal



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

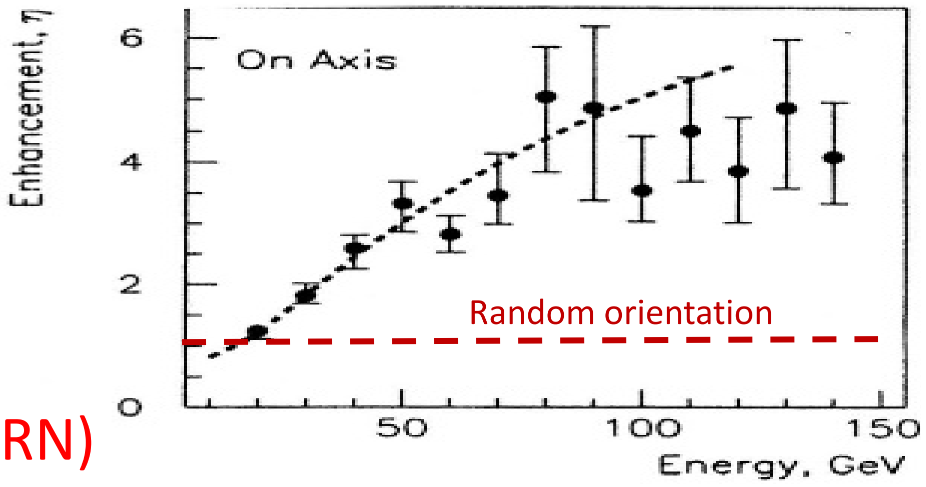
Strong Field regime

$$X = E^*/E_0 \geq 1$$

Strong increase in the energy radiated by e± with emission of hard photons and in the pair production probability by high-energy gamma-rays!

Enhancement of pair production in a 3 mm W crystal axially oriented – compared to random orientation Vs. photon energy

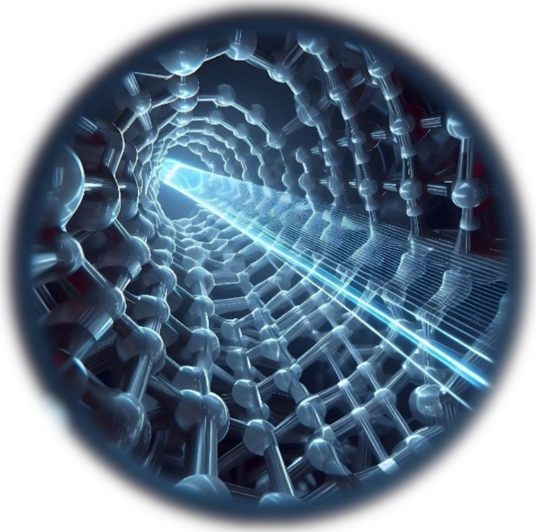
(NA48 exp. @CERN)



- ***Angular range:***
  - **$\Theta_{max} = V_0/m$ (0.1° for W, 0.05° for PWO)**
  - **few mrad up to 0.5°-1°** of misalignment between particle direction and crystal axes;
  - Depends weakly on particle energy.

$$V_0/m \gg \Theta_{crit} = (2V_0/E)^{1/2}$$

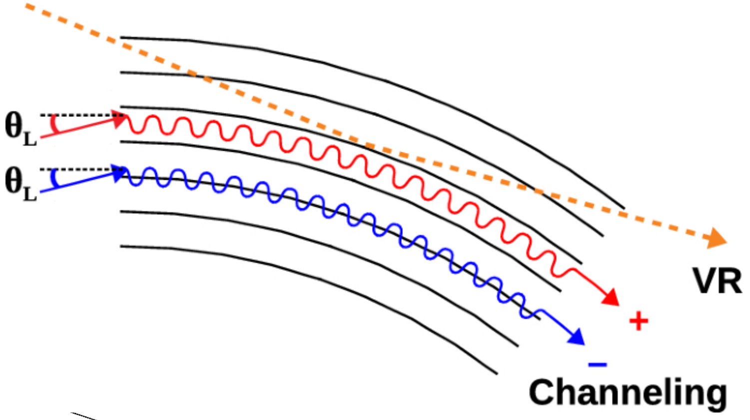
Some recent results in strong field QED in crystals:
- radiation emission in bent crystals

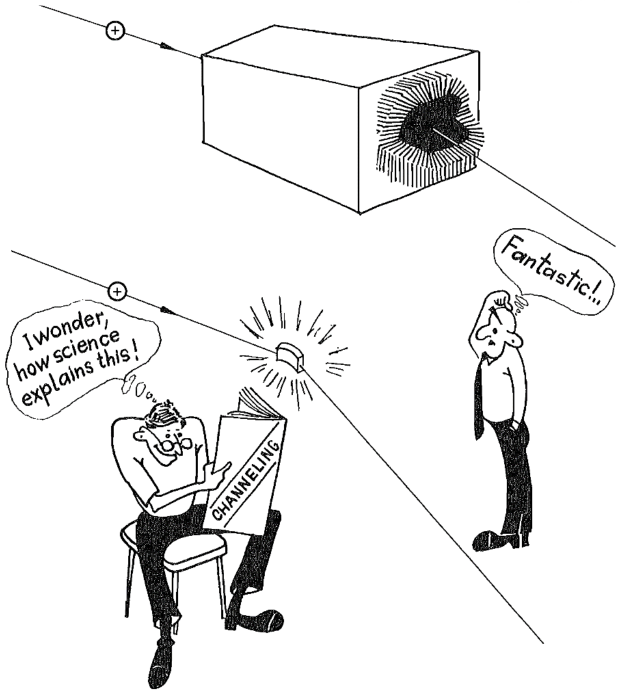


100 GeV energy range:

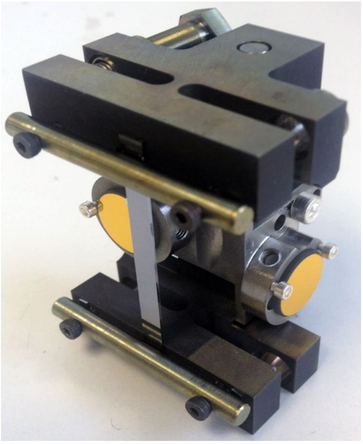
- Quantum correction;
- Multiple photon emission.

Bending a crystal:
A way to steer a particle beam





LHC crystal for colllimation



Bent Silicon crystal – 4 mm thick

Equivalent magnetic field of 100 Tesla

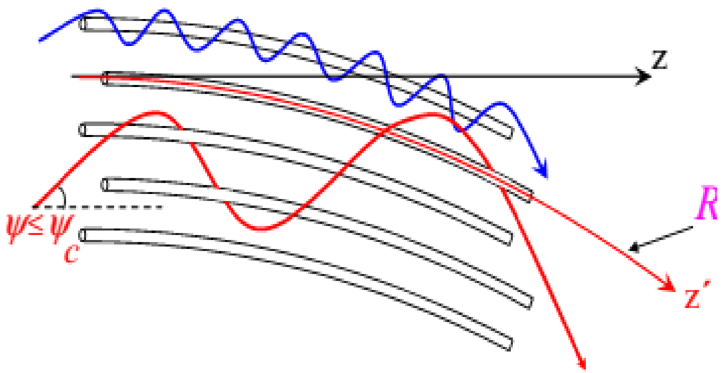
V.S.

Investigated for decates by CERN UA9 for LHC collimation and other purposes

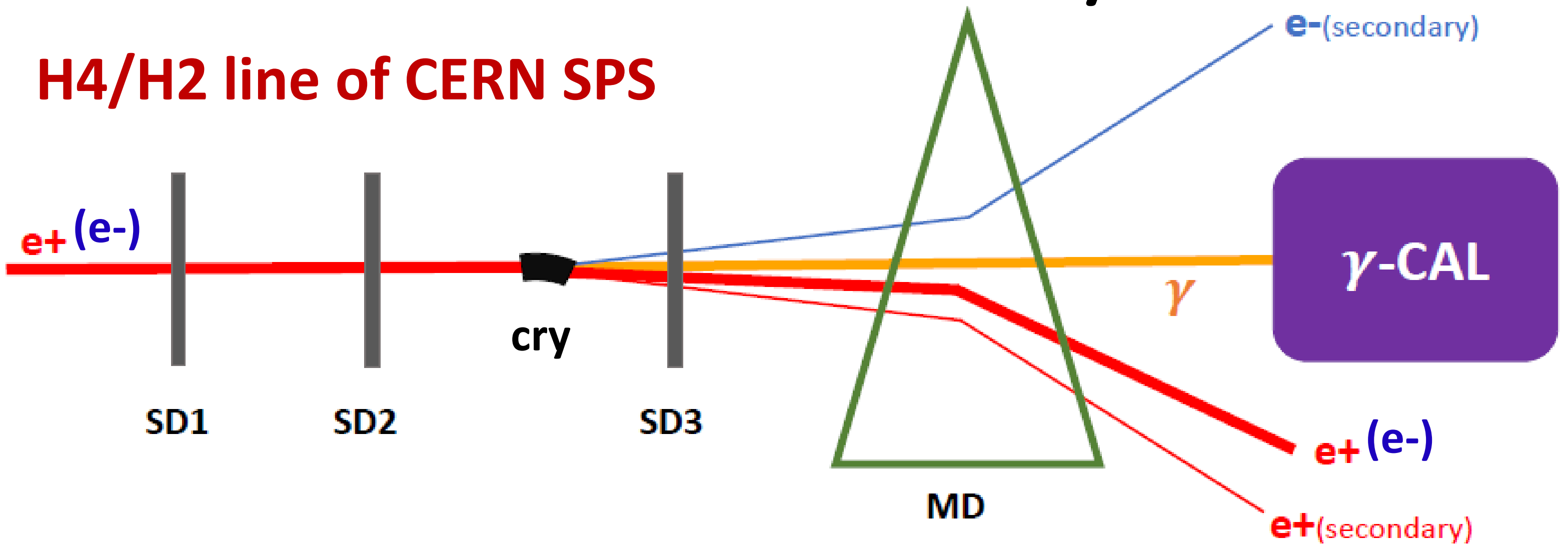
8.3 Tesla supermagnet – 15 m long

Bent crystals can be used in particle accelerators as «passive» collimating or extraction elements

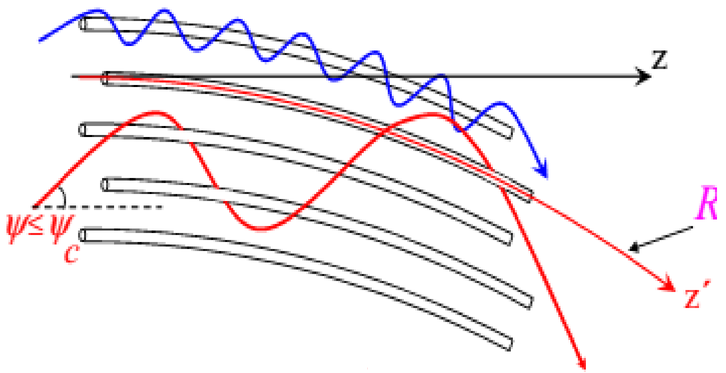
Interaction of 120 GeV electrons and positrons with the axial field of bent crystals



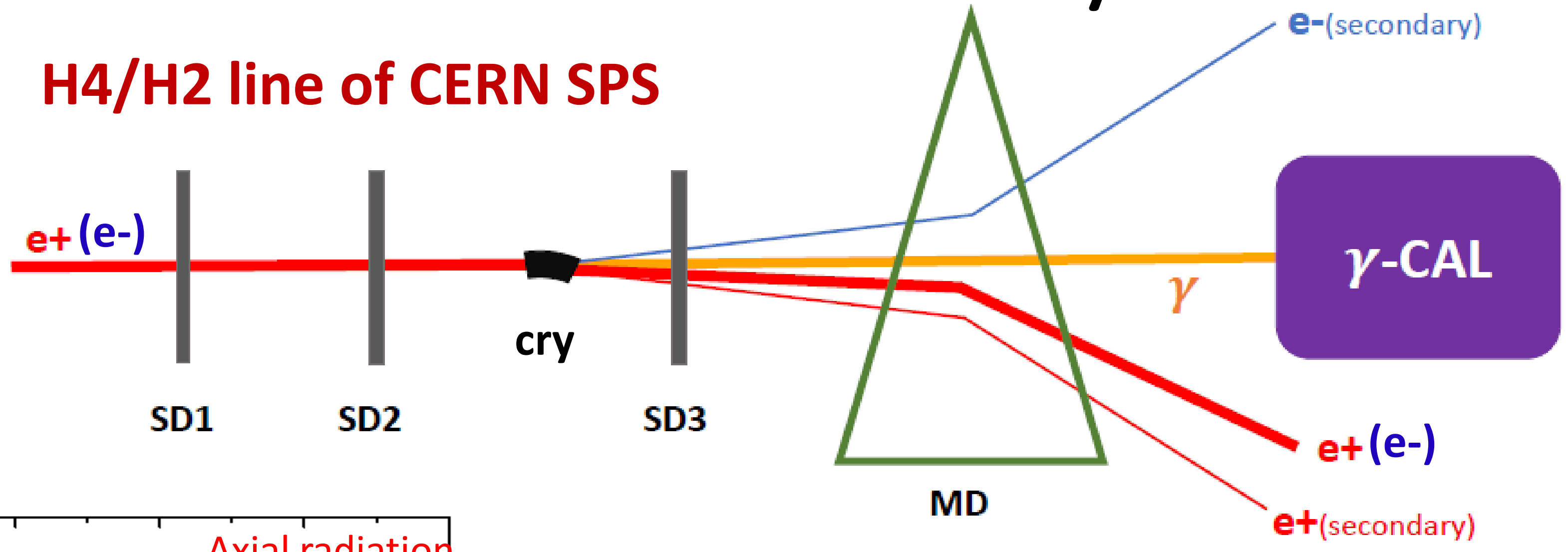
H4/H2 line of CERN SPS

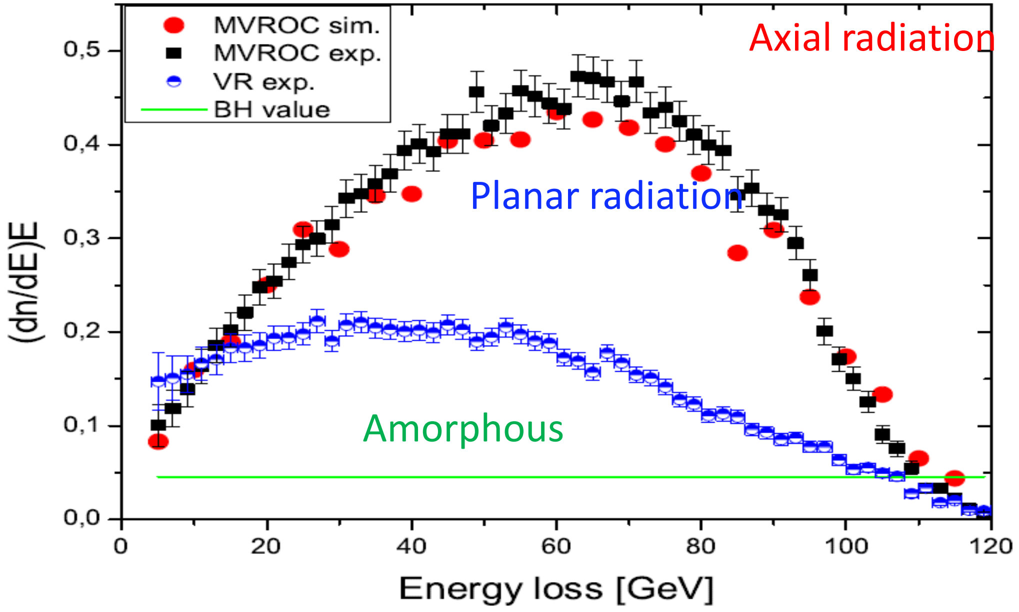


Interaction of 120 GeV electrons and positrons with the axial field of bent crystals



H4/H2 line of CERN SPS





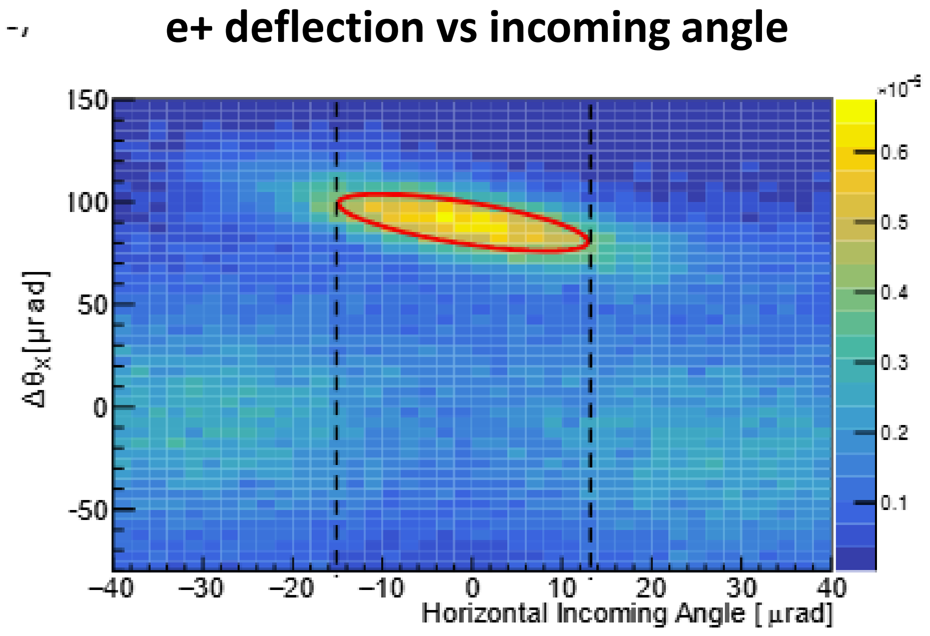
L. Bandiera et al., PRL 111(2013) 255502

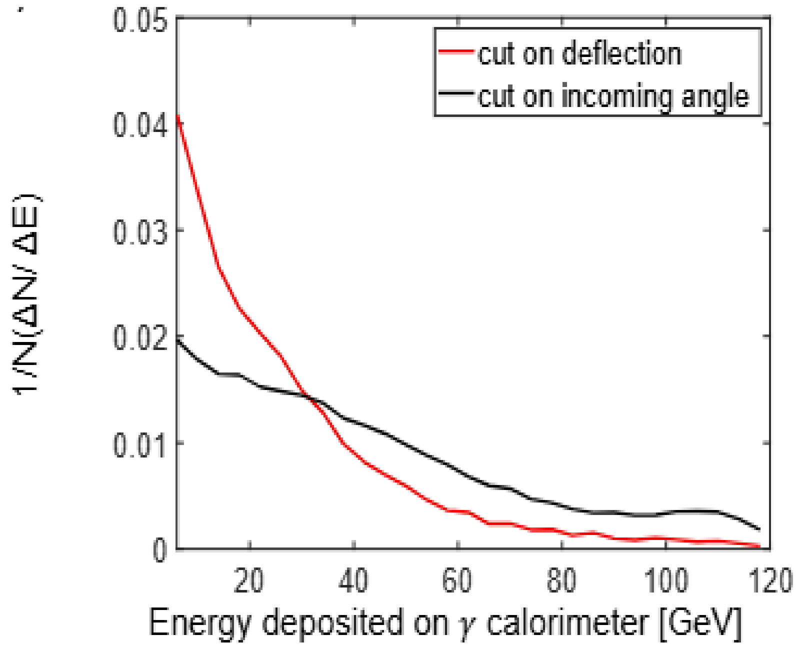
Axial Multiple Volume Reflection Radiation
2 mm Si bent crystal
<111> axes

Multi-photon emission

A mean number of photons emitted by each particles $2.2/e^{-}$ for $\hbar\omega > 1$ GeV.

Radiation vs e+ dynamics in strong field regime





e+ @120 GeV/c
Germanium
2.8 mm long
(100) planes
Deflection 100 μrad

Bent crystals permit to experimentally separate different beam dynamics -> different radiation regime:

- Useful to **test theoretical models on channeling radiation/radiation reaction in strong field** – quantum, semiclassical or classical (see for instance Phys. Rev. D 99, 11601)

Paper under preparation

An algorithm for integration of the Baier-Katkov quasiclassical formula (1967-1968)

General method for calculation of radiation generated by $e^{\pm}$ in an external field

The electromagnetic radiated energy is evaluated with the BK formula:

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[\left(E^2+E'^2\right)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1 - x_2)} \quad (1)$$

where the integration is made over the classical trajectory.

Why classical trajectory?

2 types of quantum effects :

- the quantization of particle motion $\sim \hbar\omega_0/E$

In crystals: **nearly negligible for e± energy >10-100 MeV**

- the **quantum recoil** of the particle when it radiates a photon with energy $\hbar\omega \sim E$

NOT negligible for electron/positron energy >tens GeV

How to compute multiple photon emission?

- **Separation of particle trajectory in intermediate lenghts** > coherence length and << typical distance between two sequential photon emission points.
- **Total probability of radiation on such trajectory part does not exceed 0.1**.

V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903.

An algorithm for integration of the Baier-Katkov quasiclassical formula (1967-1968)

General method for calculation of radiation generated by $e^{\pm}$ in an external field

Included in GEANT4

In Geant4 since geant4-11.2.0 ! geant4-v11.2.0/source/parameterisations/channeling/

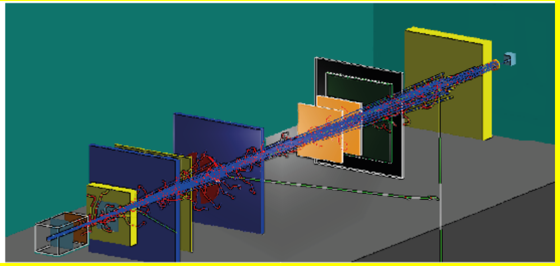
Marie Curie Individual fellow

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

European Commission

I.N.F.N

GEANT



Contacts: sytov@fe.infn.it

W … photon

2 …

- the quantization of particle motion ~$\hbar\omega_0$/E

In crystals: **nearly negligible for e± energy >10-100 MeV**

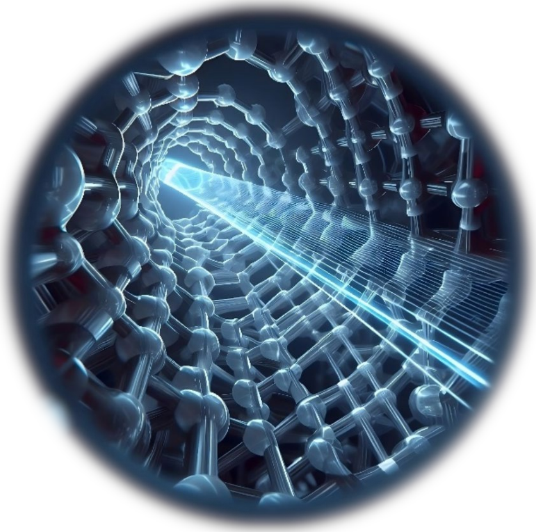
- the **quantum recoil** of the particle when it radiates a photon with energy $\hbar\omega$~E

NOT negligible for electron/positron energy >tens GeV

- **Separation of particle trajectory in intermediate lenghts** > coherence length and << typical distance between two sequential photon emission points.
- **Total probability of radiation on such trajectory part does not exceed 0.1**.

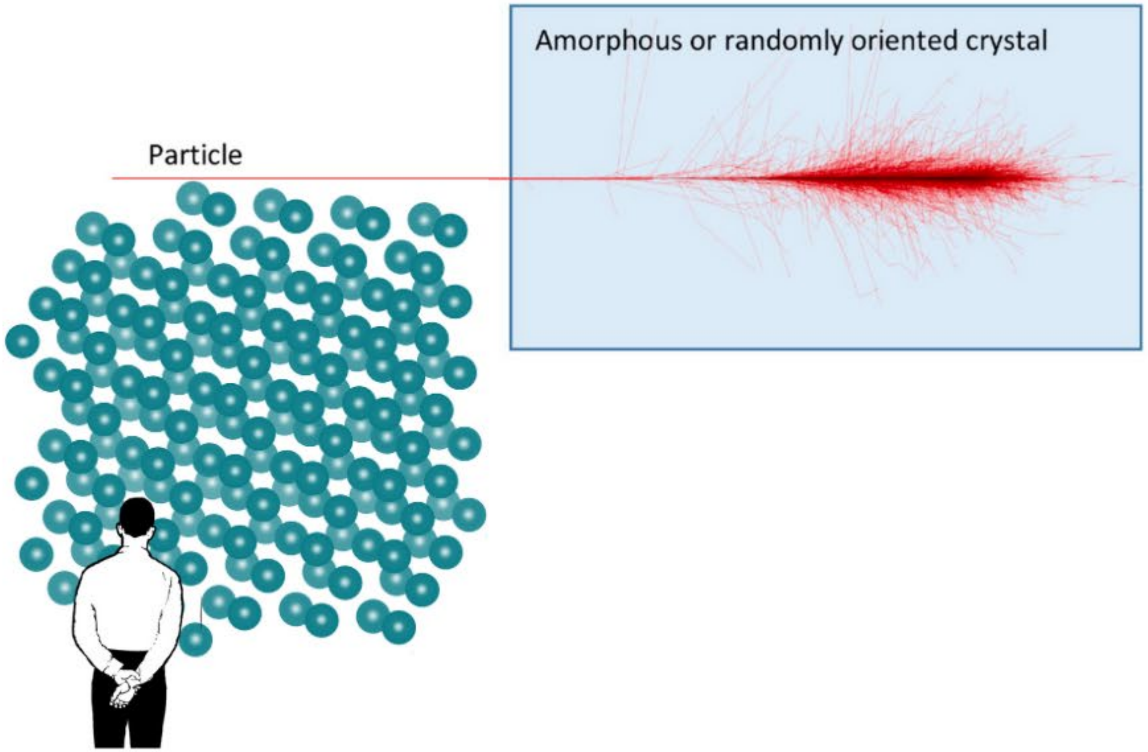
V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903.

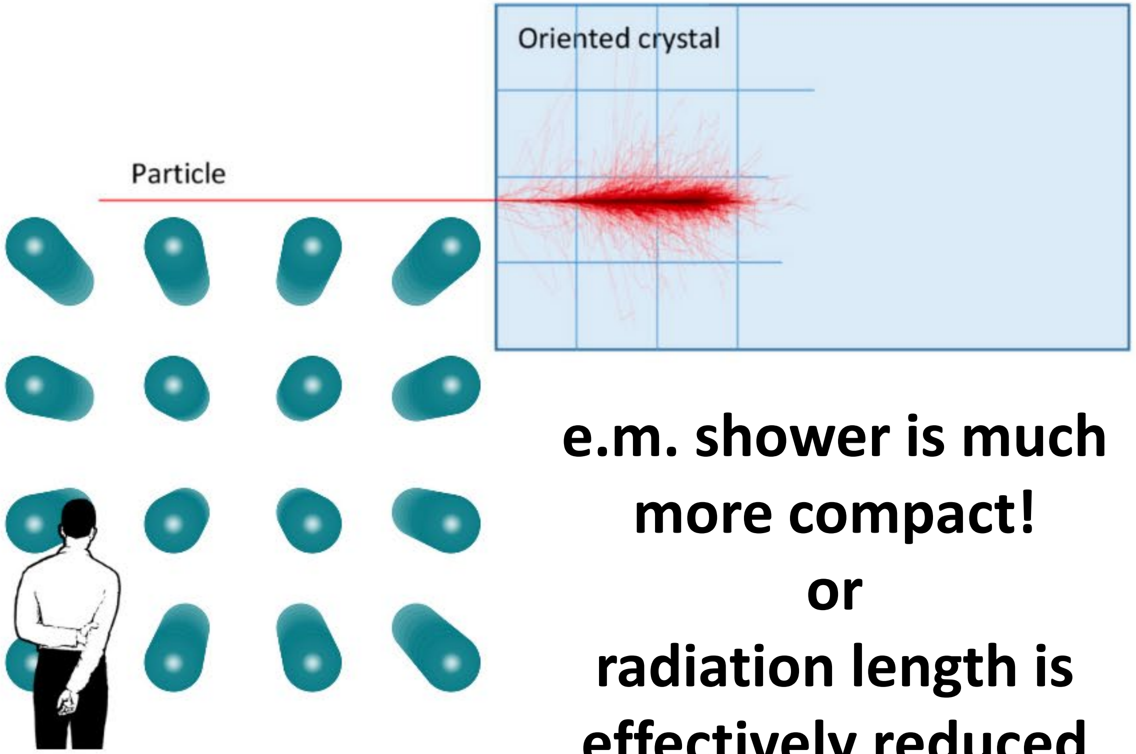
Some recent results in strong field QED in crystals:
- electromagnetic shower acceleration



- Compact calorimeter/active targets
- Compact absorbers/dump

Strong Crystal Fields:
Electromagnetic shower acceleration…..





e.m. shower is much more compact!
or
radiation length is effectively reduced

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

Novel idea: orienting an e.m. calorimeter….

Scintillators emitters commonly employed in HEP electromagnetic calorimetry: lattice effects are neglected

Em showers can develop in a much lower thickness with respect to the current state-of-the-art detectors, with the same light yield

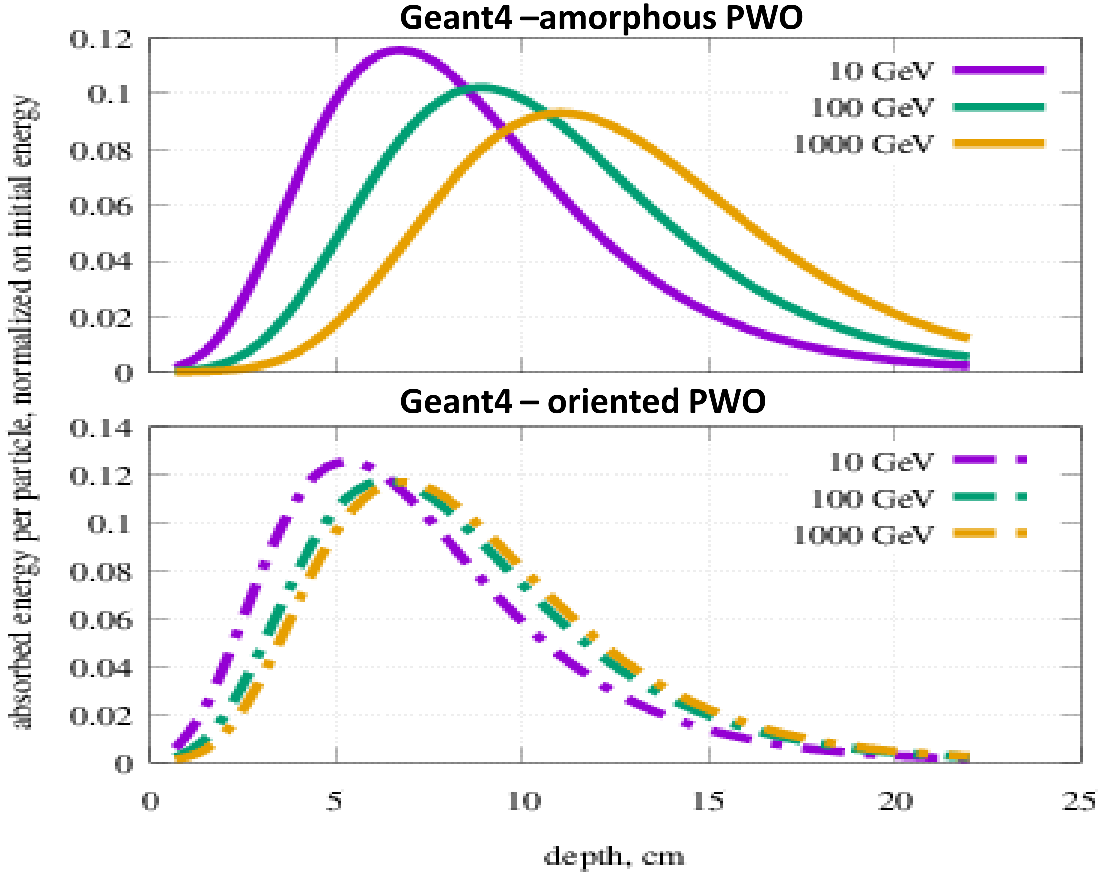
→ Enhanced compactness

→ Cost reduction

→ better n/γ discrimination

⇒ interesting for forward calorimetry, in fixed-target HEP and space-borne experiments

Simulation of the e.m. shower of HE electrons in a PWO crystal



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

L. Bandiera, et al. NIM A 936 (2019) p.124-126

L. Bandiera et al., Front. Phys. 2023 11:1254020.

CSN5 Ricerca Tecnologica

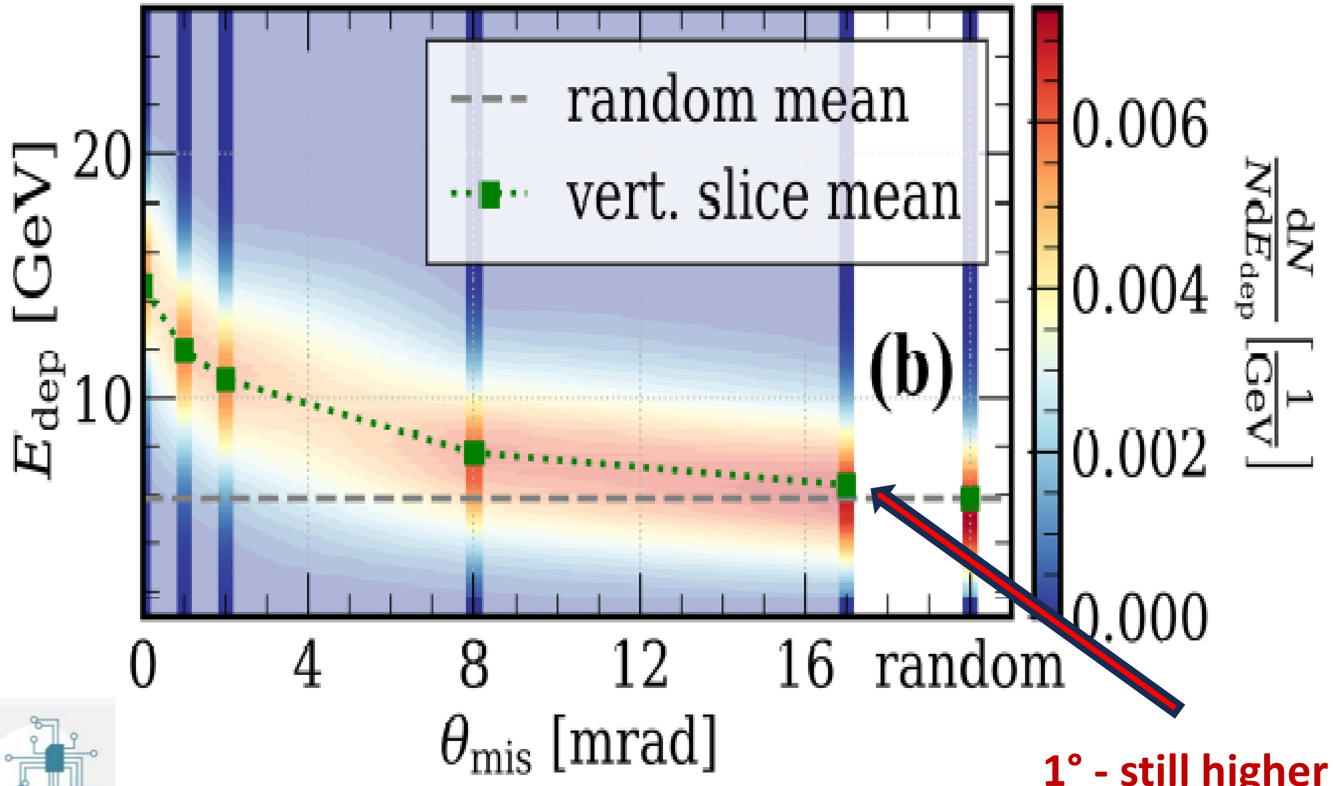
DRD6 WP3 substask 3.1.4 OREO

Energy deposited by electrons in an axially oriented PWO crystal

CERN SPS NA H2 beamline

Beam: **e^- @120 GeV**

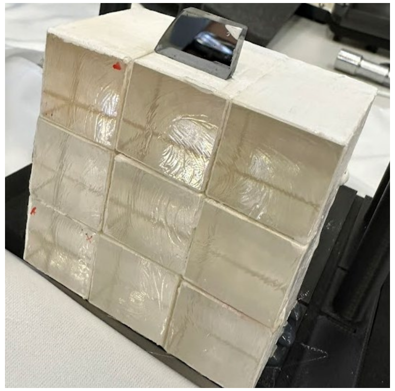
Crystal: PWO , 4.6 X_0 (from CMS ECAL)

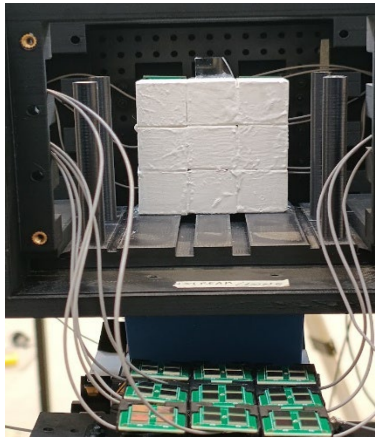


1° - still higher than
in random orientation

2024: First prototype construction and test at CERN

3x3 matrix of axially oriented PWO





CSN5 Ricerca Tecnologica

DRD6 WP3 substask 3.1.4 OREO

M. Soldani et al., arXiv:2404.12016v1

A compact active target to increase the sensitivity in light dark matter search

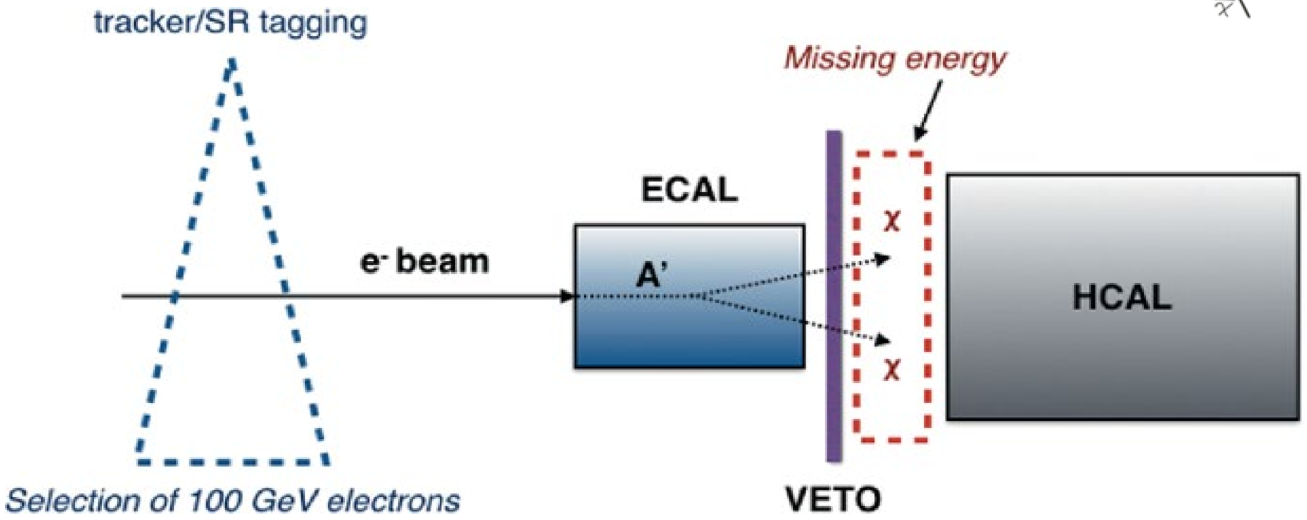
OREO technology to realize **compact active beam dump or target** with an **increased sensitivity to light dark matter**.

If a dark photon is created in a shower initiated by an $e^{\pm}$, it can be detected only if it survives for the remaining dump or target length. **The shorter the length, the higher the sensitivity.**

Interest by the POKER collaboration within NA64 @SPS, where the PWO calorimeter is either the target and the missing energy detector

L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603
L. Bandiera et al., Front. Phys. 2023 11:1254020.

NA64 experiment



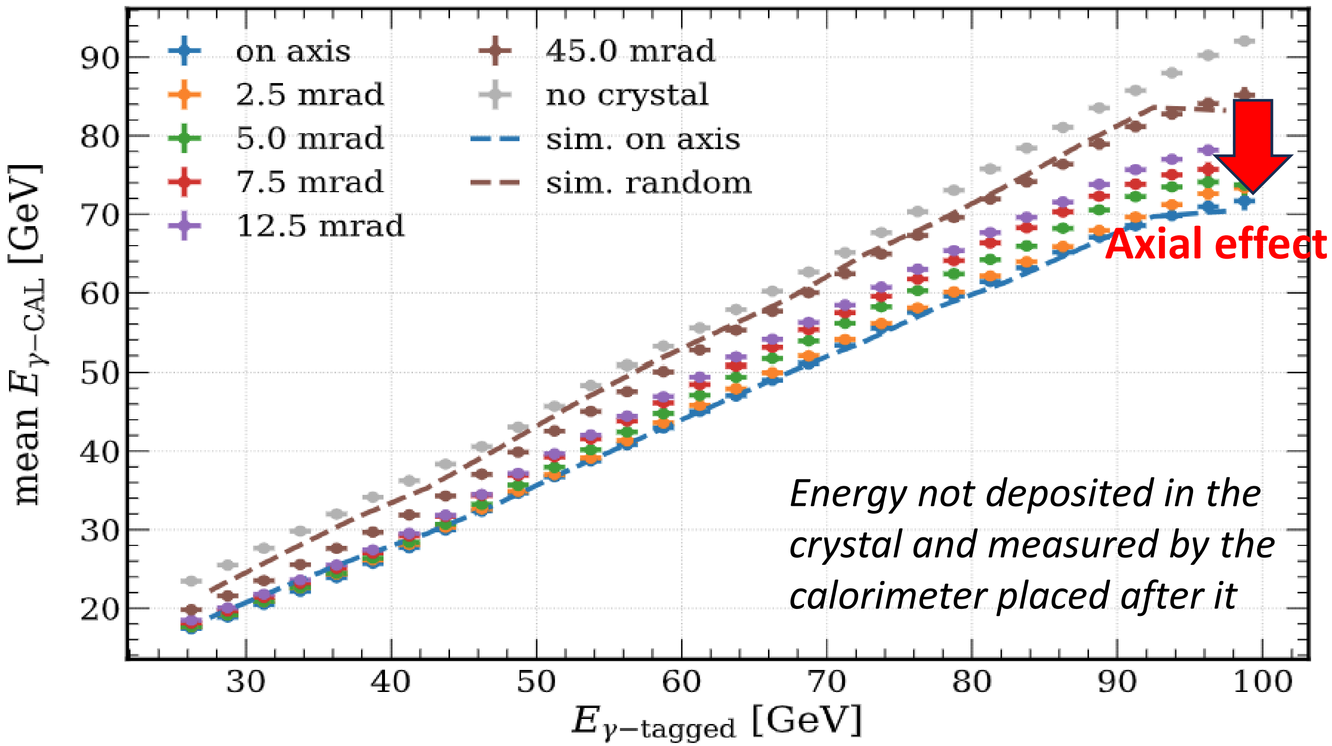
A' = dark photon

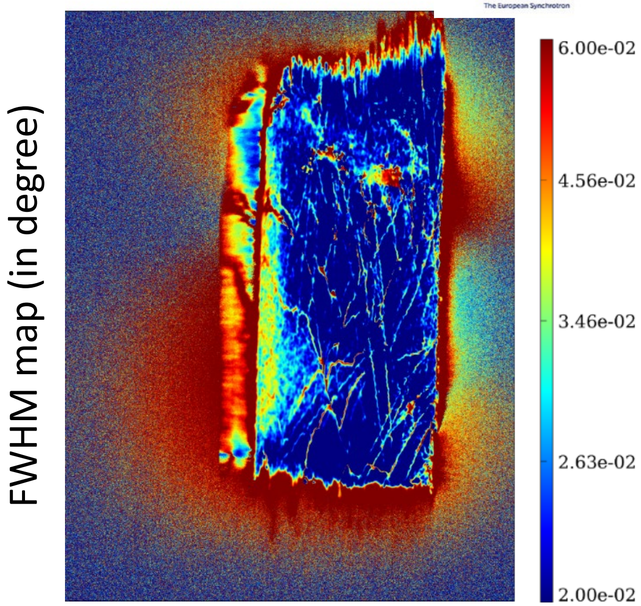
Credits to:
L. Marsicano and A. Celentano
INFN Genova

Acknowledgment of initial discussions with M. Raggi.

Absorption power of an axially oriented tungtesn

In collaboration with NA62&HIKE/KLEVER teams





W crystal X-ray topography @BM05
Courtesy of Thu Nhi Tran CALISTE

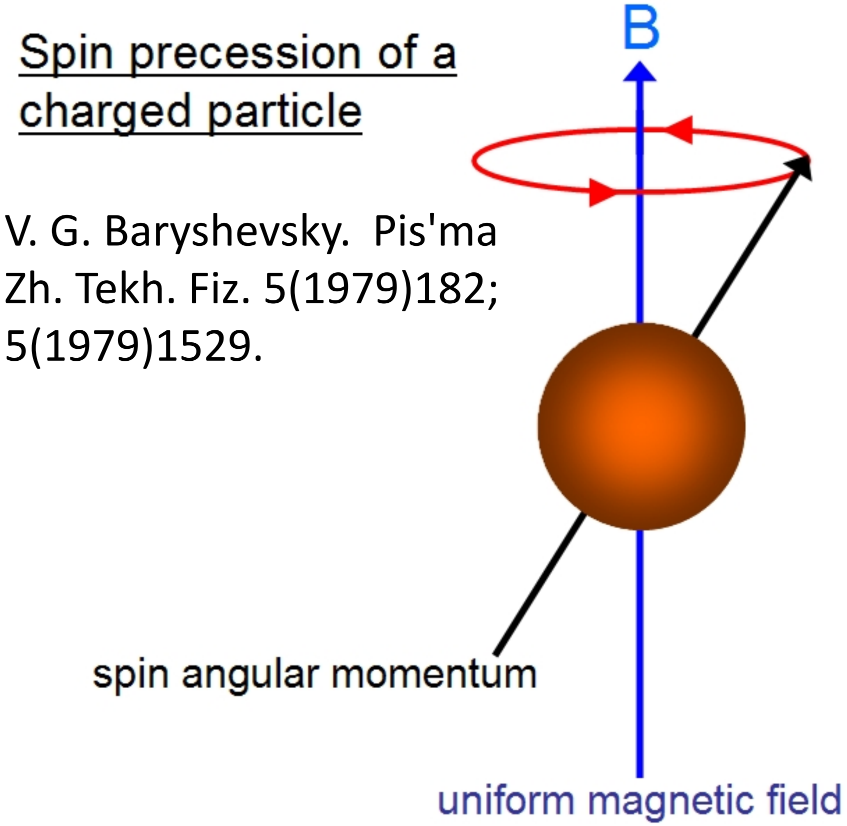
For photons @100 GeV the energy not absorbed in the crystal (and measured by the gamma-CAL) is 70 GeV in axial orientation, while for random orientation is about 85 GeV!

-> **compact absorber of em particles**

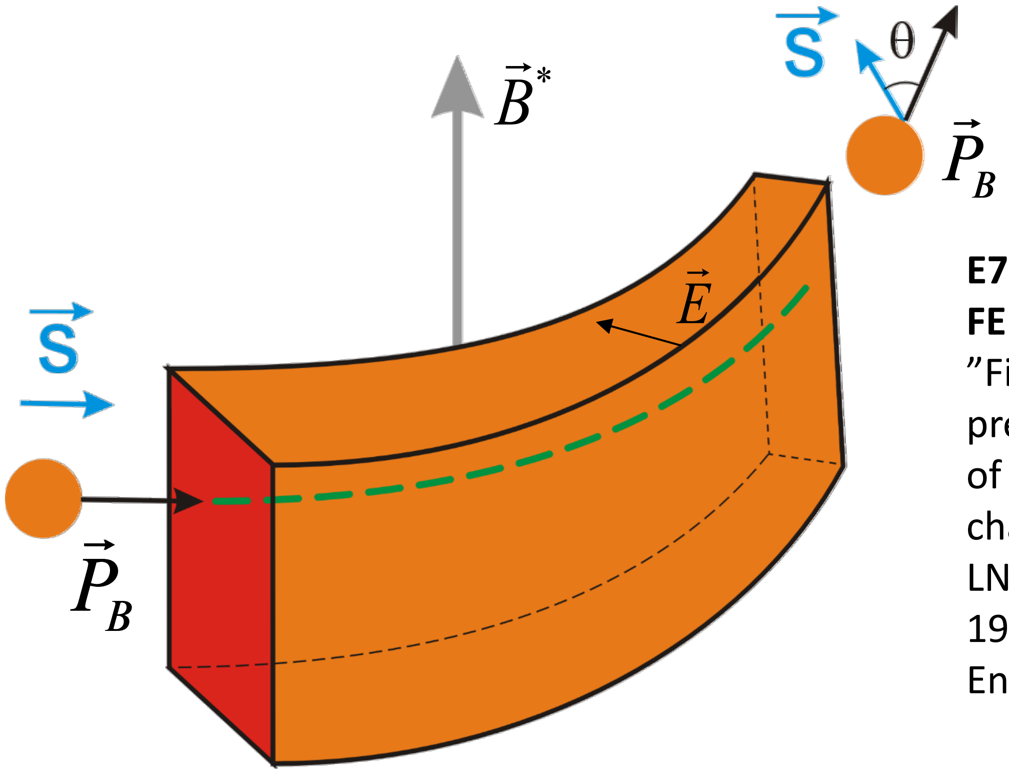
CERN SPS H2
Bremsstrahlung photons: 25-100 GeV
Crystal: W <111>, 10 mm long (~2.85 X_0)

M. Soldani, L. Bandiera*, M. Moulson et al., Eur. Phys. J. C 83, 101 (2023)**

Spin rotation of ultra-relativistic particles



V. G. Baryshevsky. Pis'ma Zh. Tekh. Fiz. 5(1979)182; 5(1979)1529.

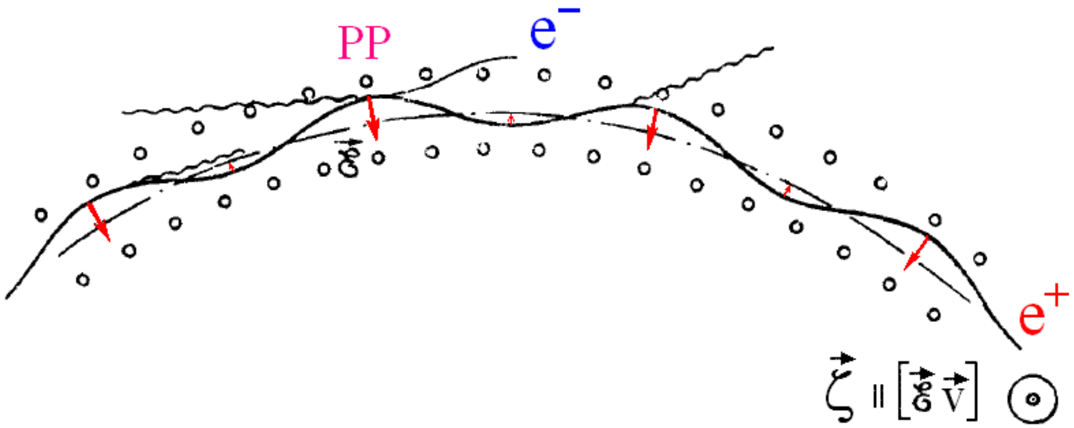


E761 Collaboration, FERMILAB
"First observation of spin precession of polarized hyperons channeled in bent crystals", LNPI Research Reports (1990-1991) 129.
Energy: 200 – 300 GeV

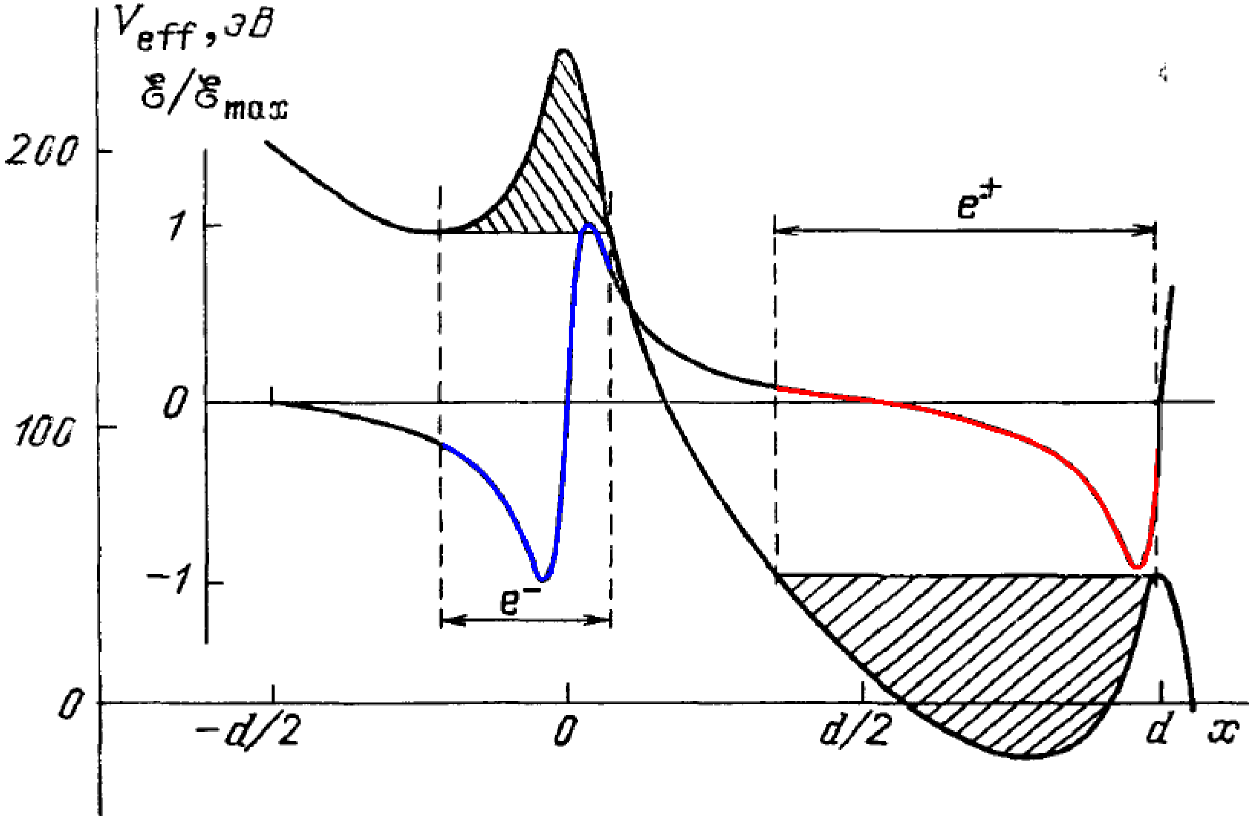
D. Chen et all "*First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals*", Phys. Rev. Lett. 69 (1992) 3286.

Currently under investigation by CERN TWOCRYST for proof of principle
MDM and EDM measurements in short living charmed baryons in search of New Physics

But what about Spin effects of electrons and positrons in bent crystal in strong field regime?



Channeled e^+ and e^- move or are produced by gamma-quanta in bent crystals in the regions with **dominating direction** of the planar electric field, which represents itself the origin of different **spin effects**.



V. G. Baryshevsky. Pis'ma Zh. Tekh. Fiz. 5(1979)182; 5(1979)1529.

Courtesy of V. Tikhomirov

Positron magnetic moment modification in strong crystal field

“Let us note that for electrons and positrons, the experiments on spin rotation in bent crystals provide **a unique possibility for studying the effects of quantum electrodynamics of a strong field**, namely, **the dependence of the anomalous magnetic moment, i.e., (g − 2)/2, on the crystal electric field intensity and the particle energy**”

V. Baryshevsky
https://doi.org/10.48550/arXiv.1504.06702 (2015)

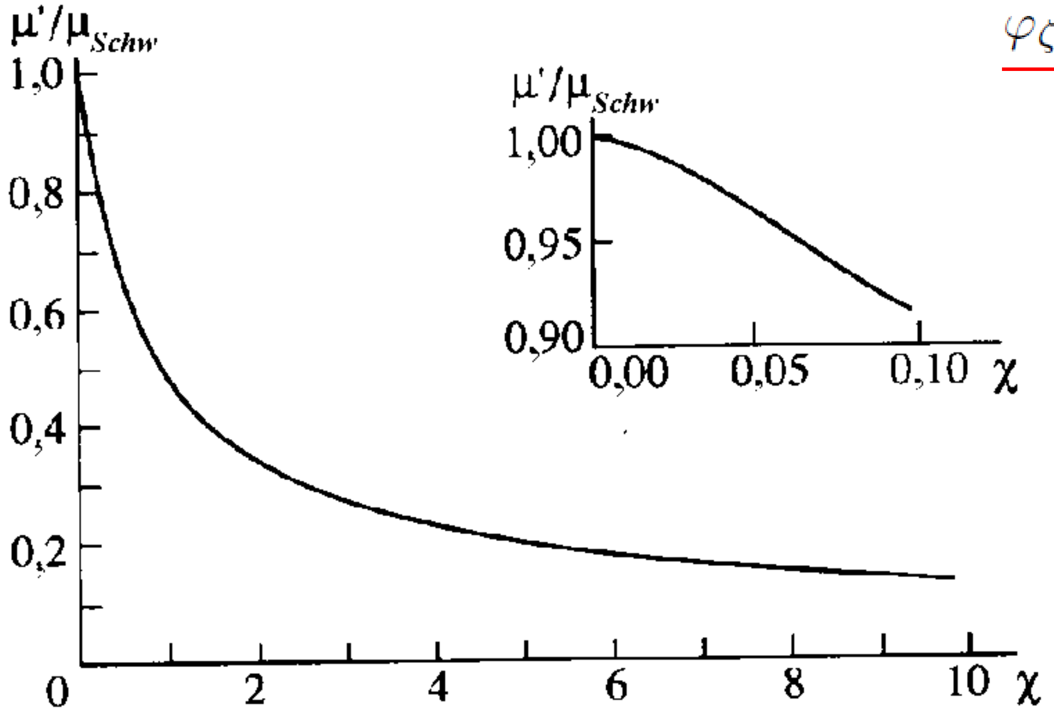
Baryshevsky V.G., High-Energy Nuclear Optics of Polarized Particles, World Scientific Publishing, Singapore, 2012

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

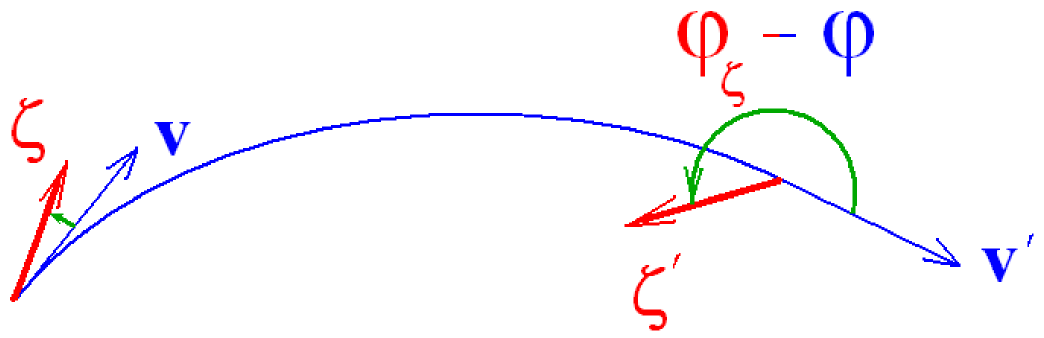
Baryshevsky, V. G. and Grubich, A. O. (1986). Possibility of measuring the dependence of the anomalous magnetic moment of ultrarelativistic e−(e+) on the particle energy and external field strength, Sov. J. Nucl. Phys. 44, 4, p. 721.

Tikhomirov V.V. To the possibility to observe positron magnetic moment variation under the propagation through crystals. Sov. Yad. Phys. 57 (1994) 2302.

Positron anomalous magnetic moment modification in strong crystal field



$$\varphi_\zeta = \varphi_\zeta(\varphi) = \left(\frac{\mu'}{\mu_B}\frac{\gamma^2-1}{\gamma} + \frac{\gamma-1}{\gamma}\right)\varphi \approx \gamma(\mu'/\mu_B)\varphi$$

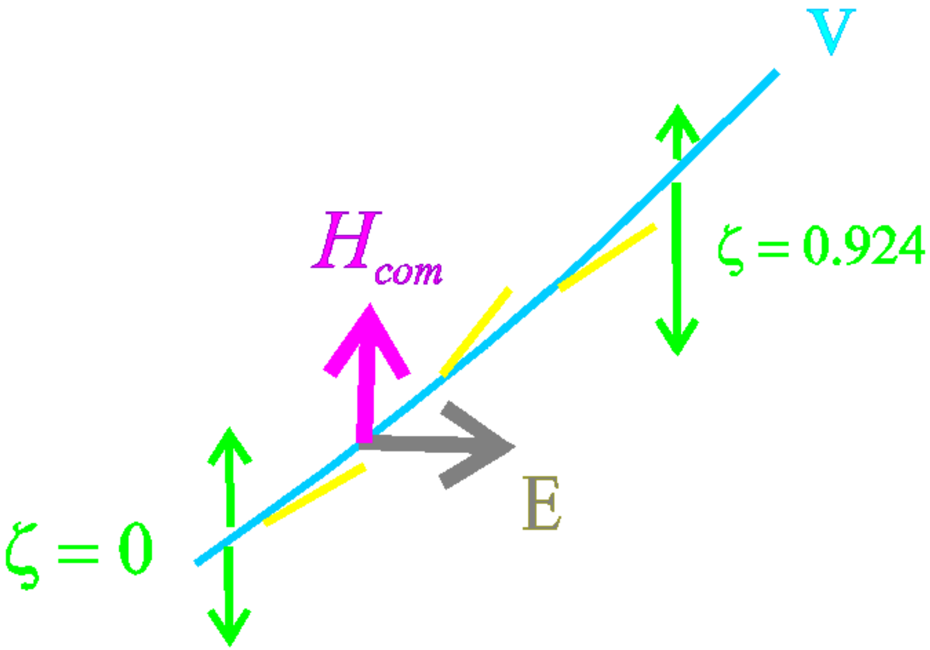


Anomalous magnetic moment dependence on $\chi = E'/E_0$

in the uniform field in Schwinger units $\mu_{Schw} = (\alpha/2\pi)\mu_B$ **Courtesy of V. Tikhomirov**

Sokolov–Ternov (self-polarization) effect

Electron/positron radiative self-polarization in bent crystals

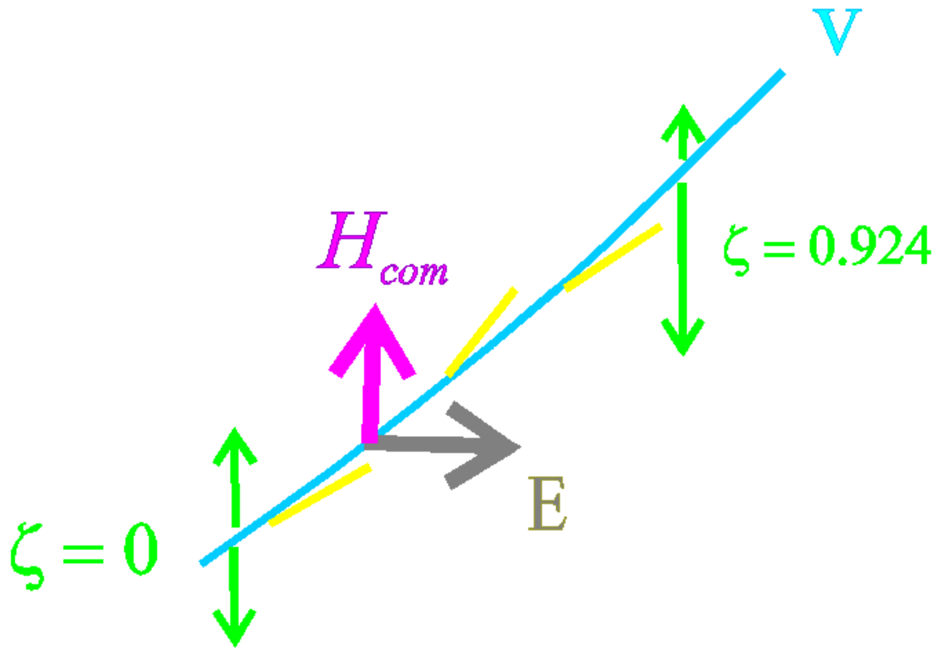


Baryshevsky V.G. and Grubich A.O. Radiative self-polarization of fast particles in bent crystals, Pis'ma. Zh. Tekh. Fiz. 5, 24, (1979) 1527–1530.
Tikhomirov V. V. Possibility of observing radiative self-polarization and the production of polarized e+e- pairs in crystal at accessible energies. JETP Lett. 58(3)(1993)166-170.

Courtesy of V. Tikhomirov

Sokolov–Ternov (self-polarization) effect

Electron/positron radiative self-polarization in bent crystals



But also..

- Production of transversely polarized electron-positron pairs in thin and bent crystals
- Circularly polarized radiation of positrons moving at small angles w.r.t. crystal axes.
- …..

Baryshevsky V.G. and Grubich A.O. Radiative self-polarization of fast particles in bent crystals, Pis’ma. Zh. Tekh. Fiz. 5, 24, (1979) 1527–1530.
Tikhomirov V. V. Possibility of observing radiative self-polarization and the production of polarized e+e- pairs in crystal at accessible energies. JETP Lett. 58(3)(1993)166-170.

Courtesy of V. Tikhomirov

Conclusions?

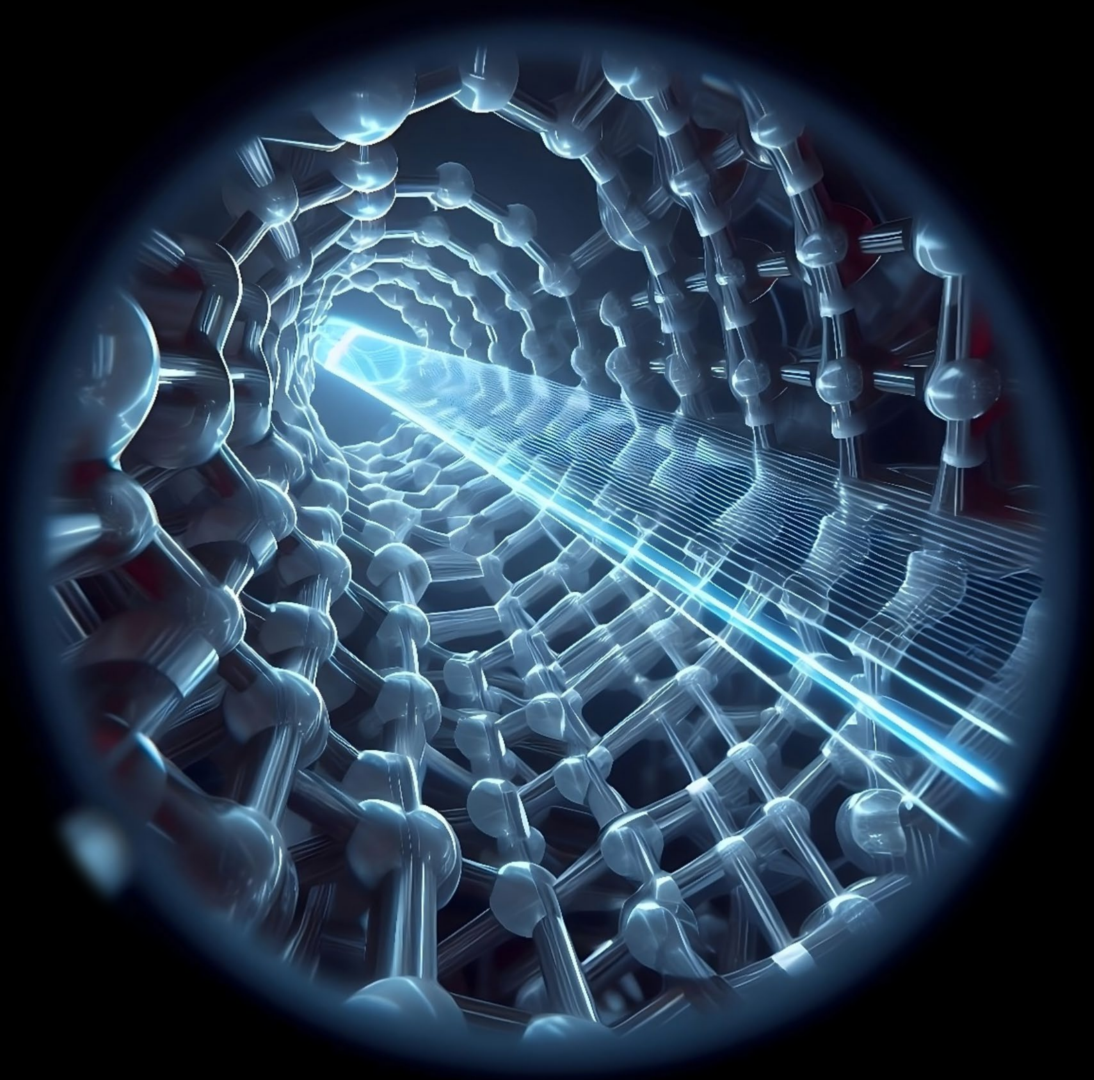
What can be done at FCC-ee injector (20 GeV) or, maybe, at the booster for higher energies…

With high intensity, high quality beam (small divergence – important for crystal studies) one can:

- continue the studies already initiated, maybe in a regime with smaller χ (>1 for W; < 1 for Si/Ge @20 GeV) with higher statistics;
- New opportunities to use ultracompact target/dump for light dark matter search with electrons/positrons (interest by POKER);
- New opportunities to do polarization studies that need statistics: electron/positron anomalous magnetic moment modification or self polarization in strong field QED;
- ……..

And just to mention.. We are currently investigating the usage of intense radiation in crystals for the FCC-ee pre-injector to be exploited for the realization of intense crystal-based positron source in collaboration with IJCLab (I. Chaikovska)

Thank you for the attention!



I welcome discussions with experts in this field and am always open to new ideas and feedback.

contact me at
bandiera@fe.infn.it !