Electromagnetic lepton interactions in bent single crystals
(theoretical view)

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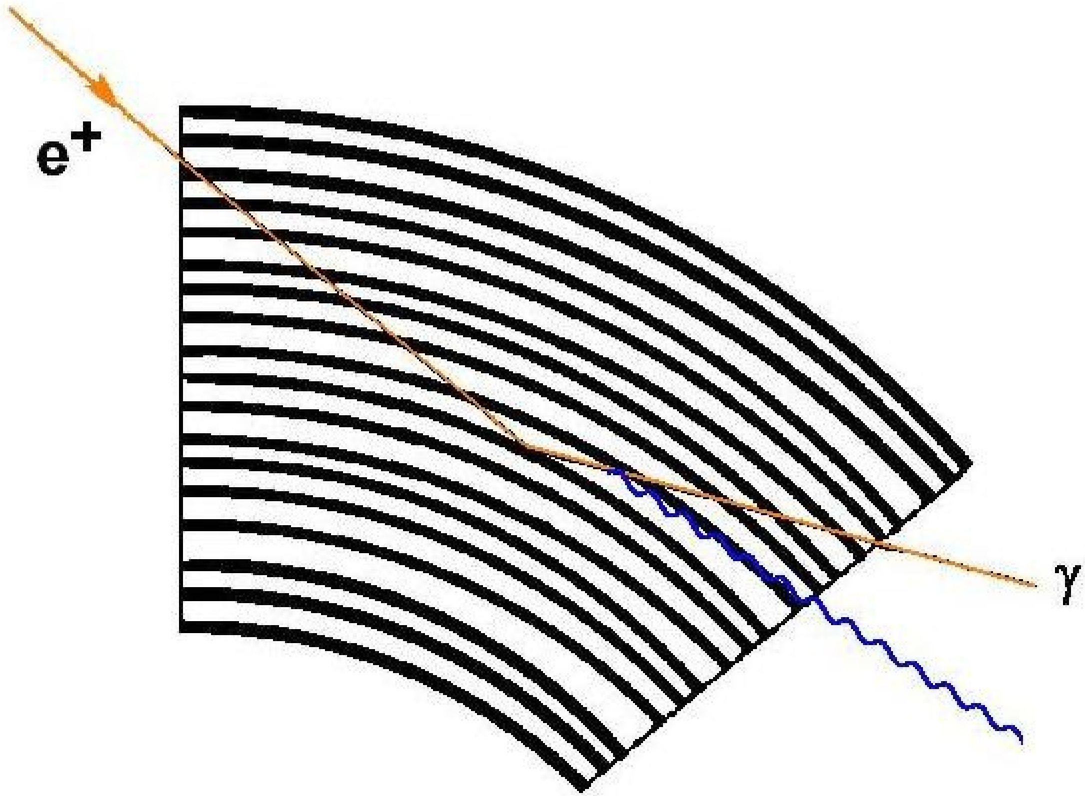
IHEP, Protvino, Russia

Electromagnetic processes in planar fields of bent single crystals

1. Photon emission of positrons (electrons) at volume reflection.
2. Photon emission of positrons (electrons) at multiple volume reflection.
3. Channeling radiation of positrons (electrons) in bent single crystals.
4. Photoproduction of electron-positrons pairs in bent single crystals.

1. Photon emission of positrons (electrons) at volume reflection.



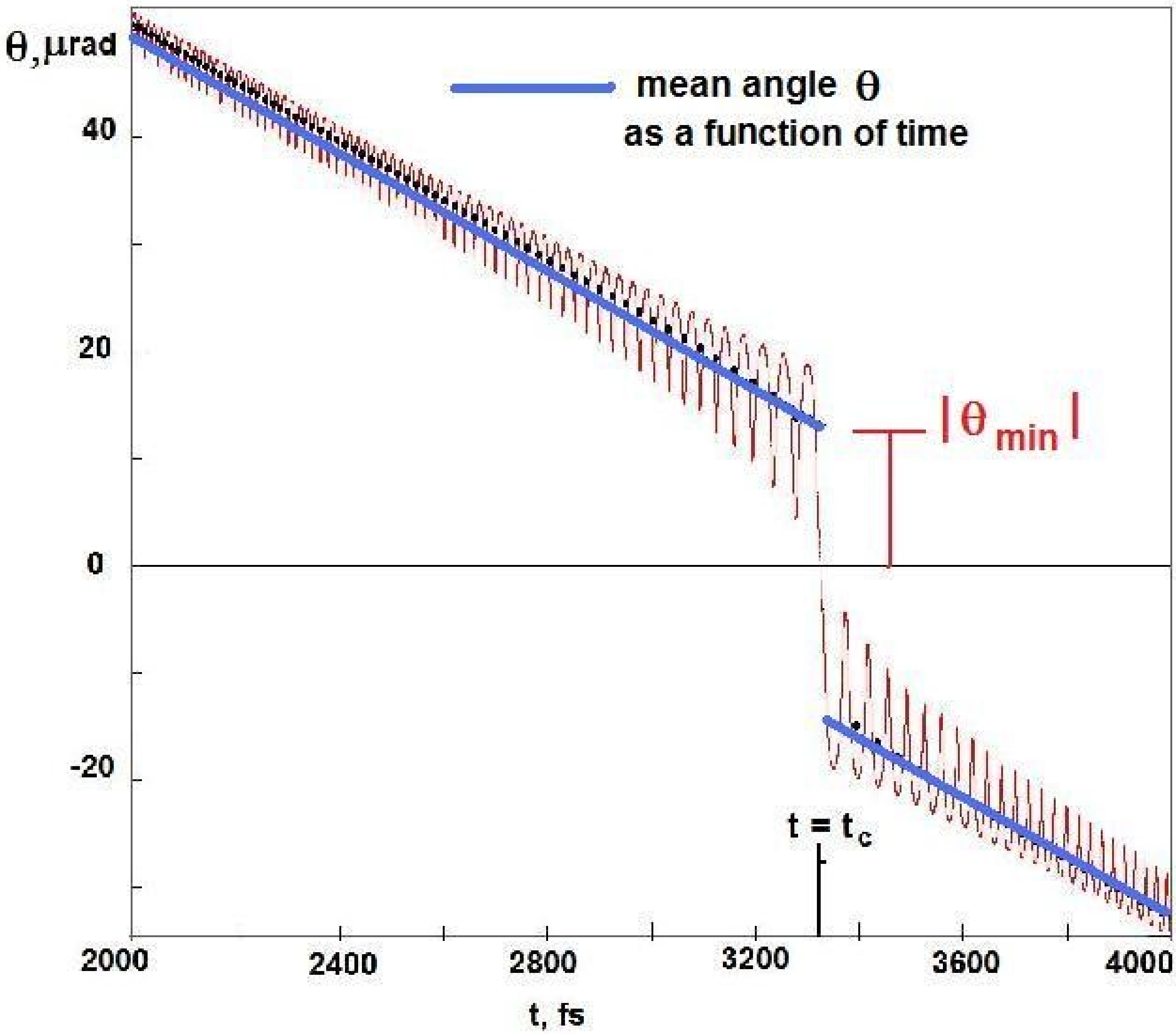
Simple description of the process was suggested in report on Channeling 2010 conference:
V. Maisheev Photon emission and photoproduction processes in bent single crystals

This description based on the almost obvious assumption: on short part of the positron trajectory a particle emission is as in a straight single crystal. It means that for energy losses we can write

$$\frac{d^2\mathcal{E}}{dE_q}(t) = \frac{dI}{dE_q}(\tilde{\theta}(t))cdt = \frac{dI}{dE\gamma}(\tilde{\theta}(t))cdt,$$

where I is the intensity of radiation is straight crystal, when particle move under angle $\tilde{\theta}$ with respect to crystallographic planes
t is time, c is the velocity of light, $E\gamma$ is the photon energy

It is important that I is well known function.


θ, μrad
40
20
0
-20
mean angle θ
as a function of time
|θ min|
t = t c
2000
2400
2800
3200
3600
4000
t, fs

As result we obtain the final equation:

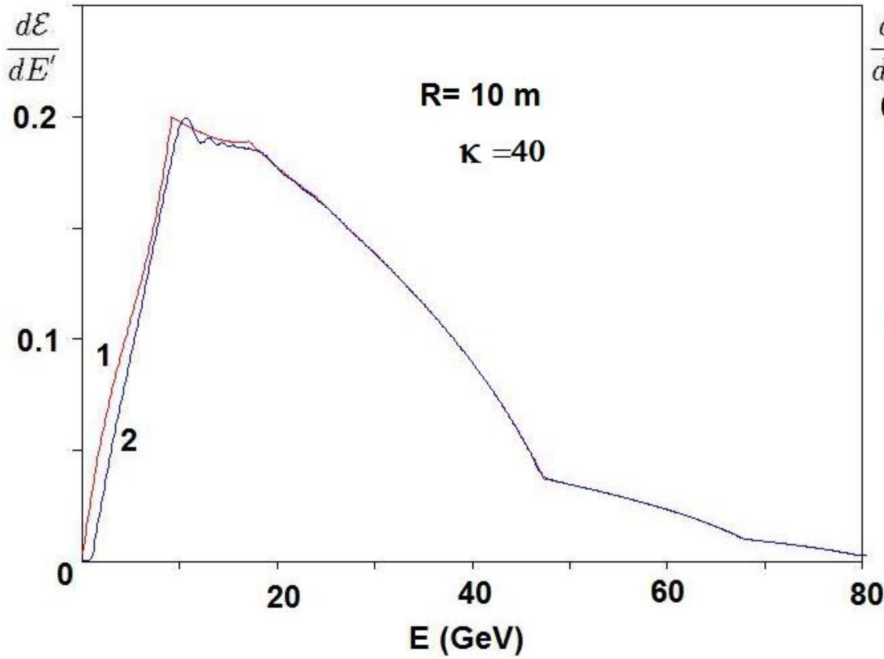
$$\frac{d\mathcal{E}}{dE_q}(E_q) = R\int_{\theta_1}^{-\theta_{min}} \frac{dI}{dE_q}(\tilde{\theta})d\tilde{\theta} + R\int_{\theta_{min}}^{\theta_2} \frac{dI}{dE_q}(\tilde{\theta})d\tilde{\theta},$$

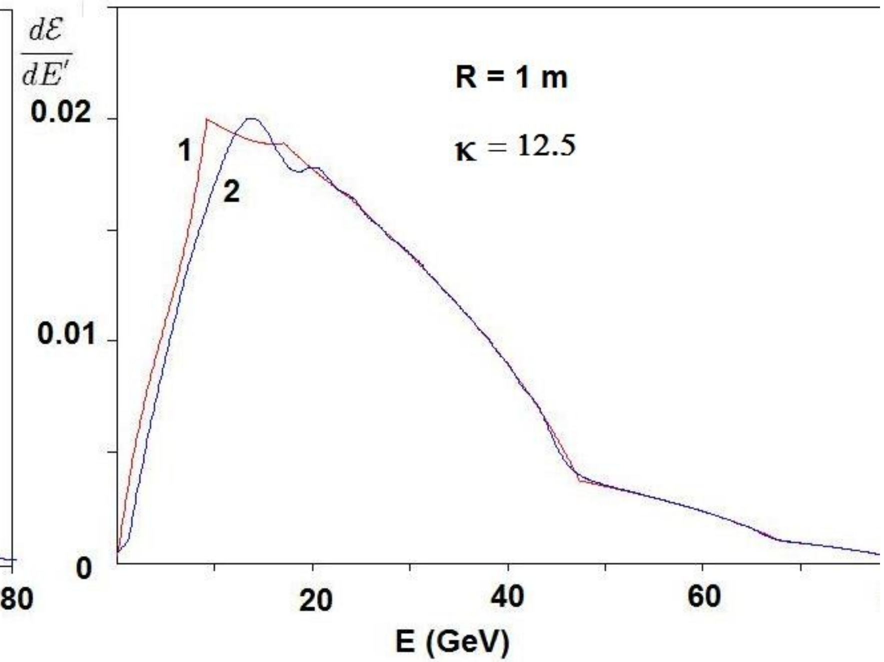
This description stands on an intuitive ideas of the process.

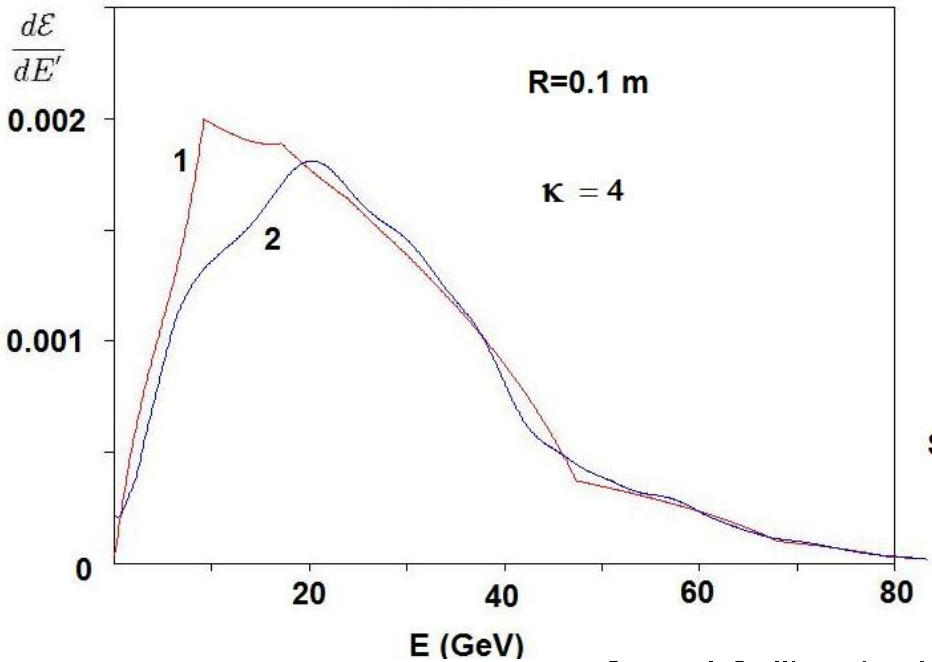
Recently we got new more strong description of the process.
We also show that new mathematical equations are reduced to old equations at condition

$$\kappa = \sqrt{\frac{\pi R}{d}}(\theta_b - \theta_c) \gg 1$$

where R is the bending radius, d interlanar distance,
$(\theta_b - \theta_c)$ **is appoximately bending angle**





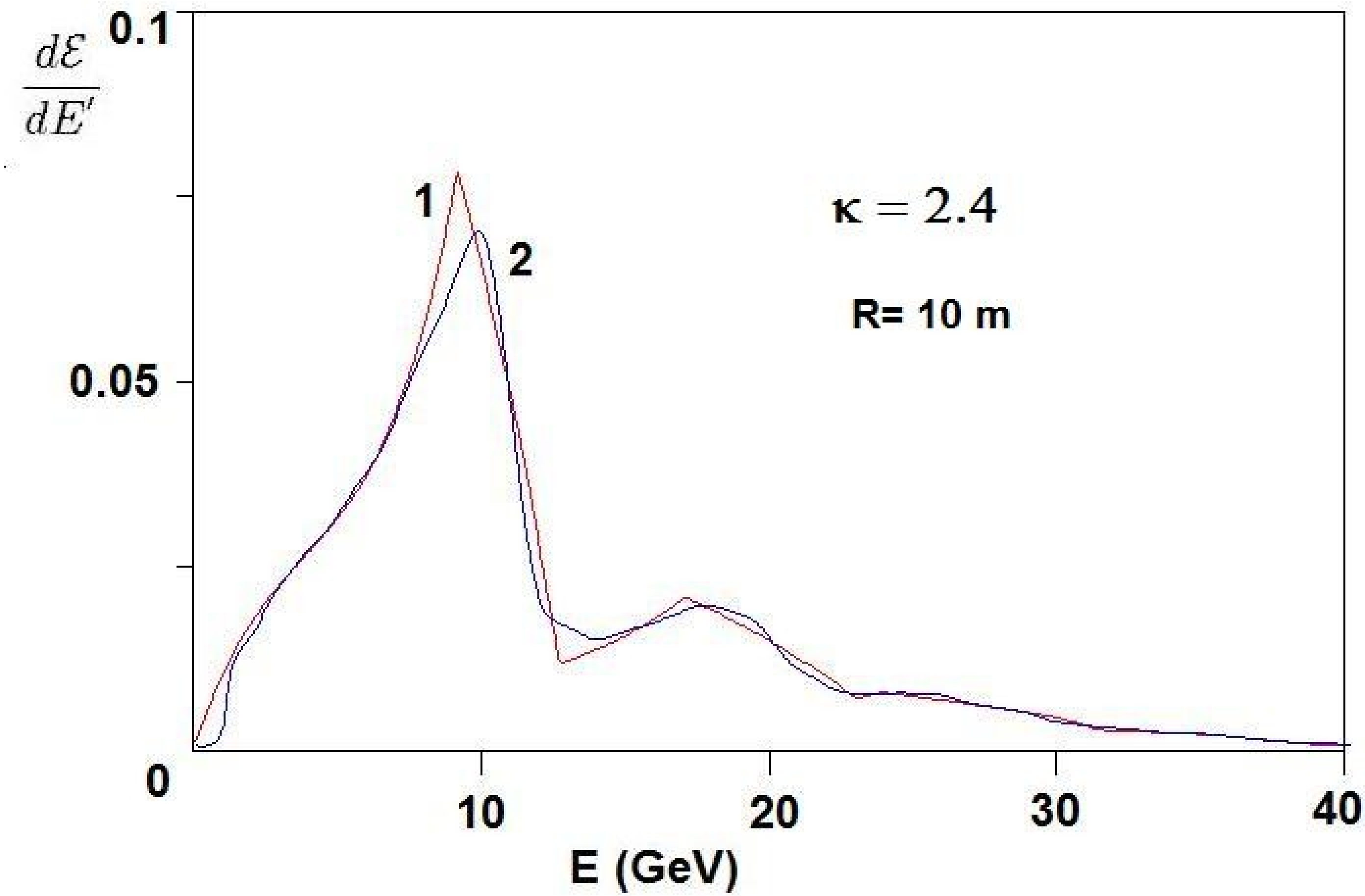


Eo = 120 GeV e+

$(\theta_b - \theta_c)$ = 100 microrad

Curves
1 - on a basic of Coh. Bremsstahlung in unbent crystals
2 - more strong description

Si (110) plane



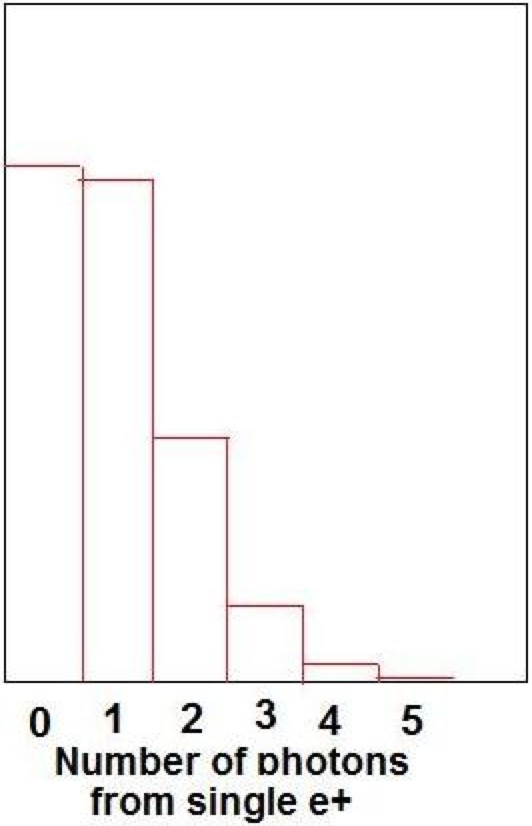
Radiation in a thin single crystal (Si (110)-plane)

Thickness = 0.006 cm

Multiple photon emiision by single positron (electron)

Analysis shows that for crystals about 1-2 mm of thickness the probability of second photon emission is large enough.
This conclusion was confirmed by Monte Carlo calculations.

Number events



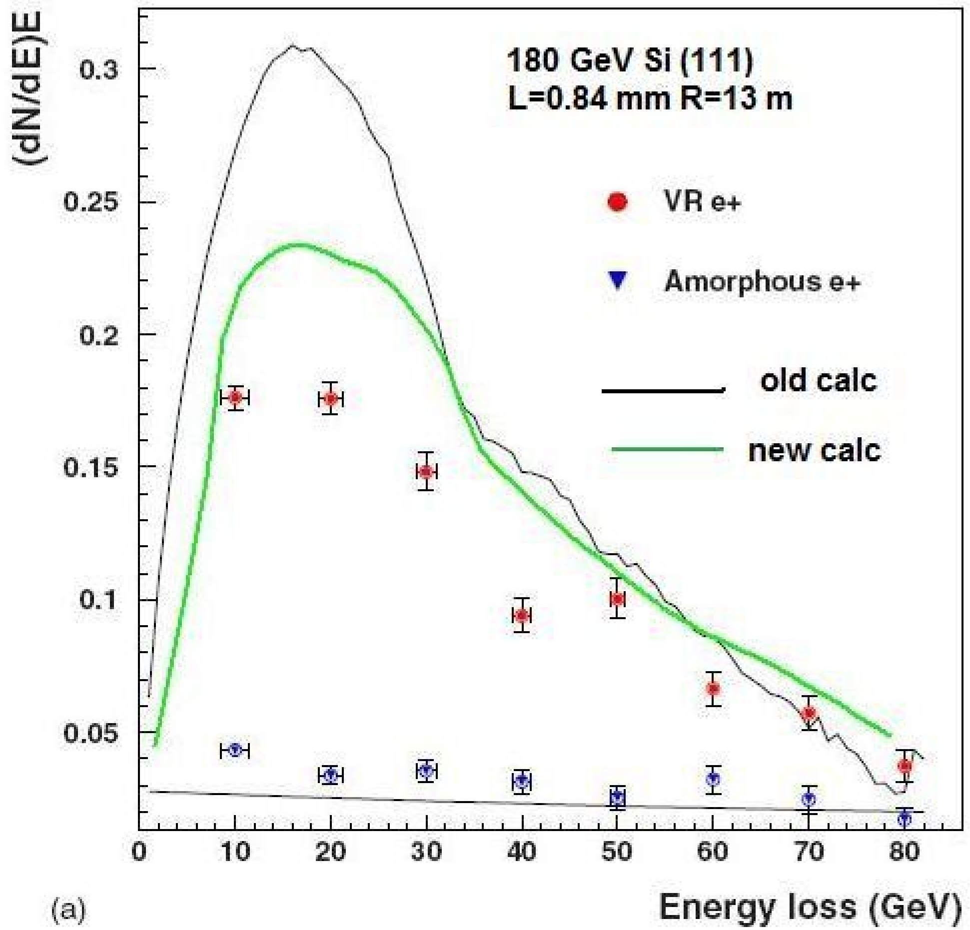
E = 120 GeV, R ~ 10 m L=2 mm
Si (110)

Photon energies in the range
1.2 GeV till 120 GeV

We got the analytical description of the process which taking into account influence of this factor.

Recalculation of CERN experiment for e+ and 180 GeV
(W. Scandale et. al. Phys. Rev. A 79, 012903 (2009).)

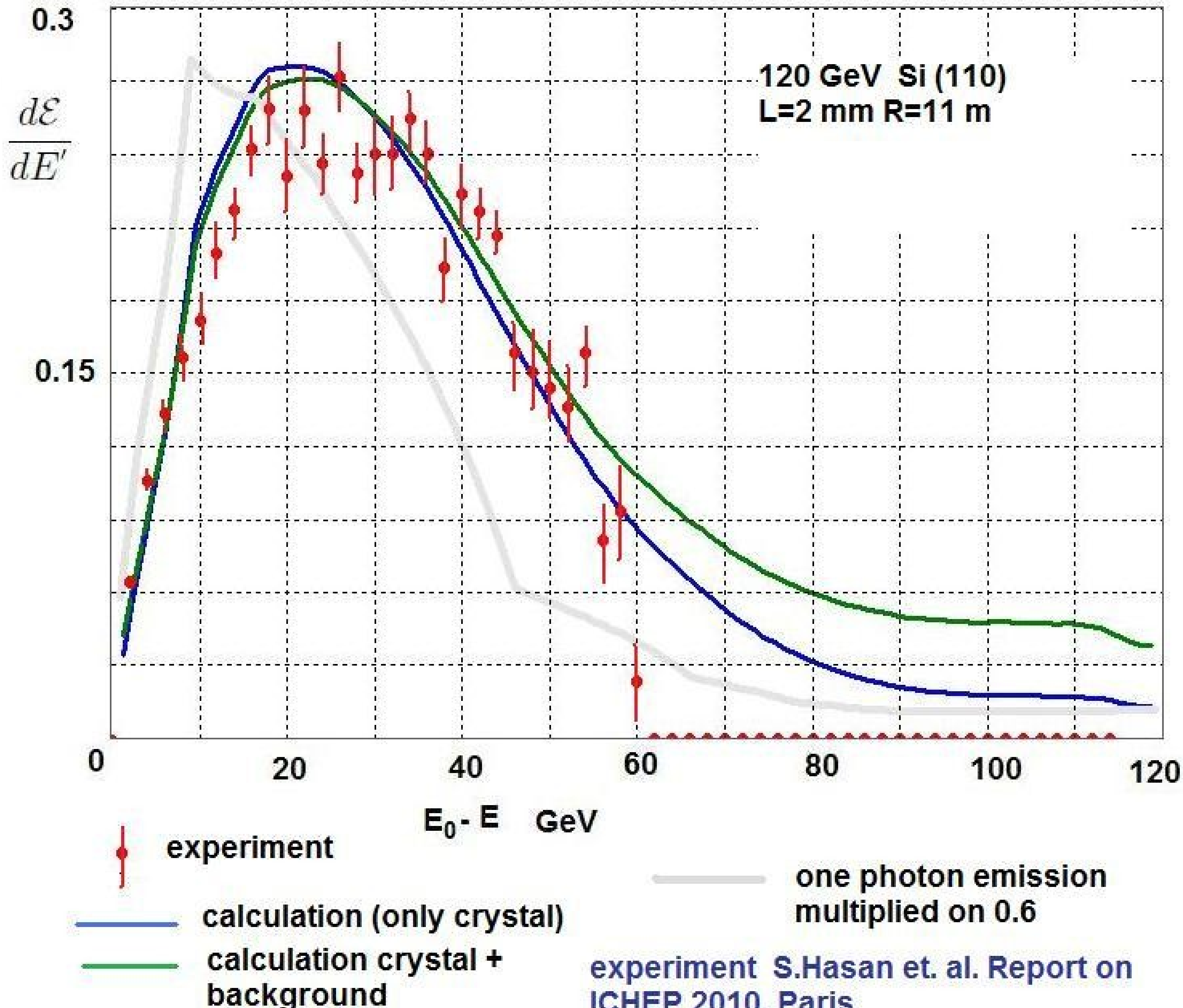
taking into account multiplicity of photon emission



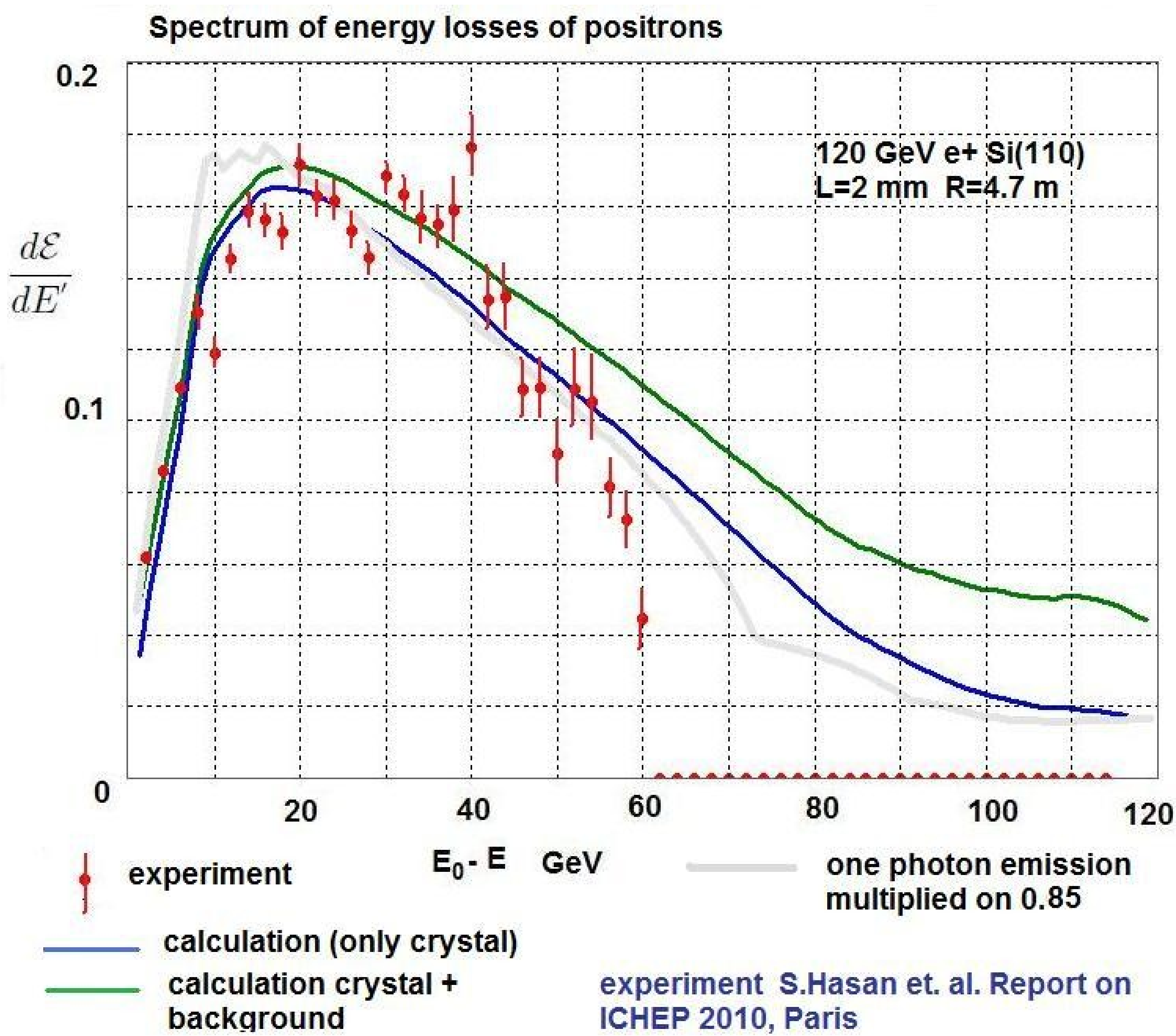
(a)

Crystal Collimation Workshop,
Roma, 2011, V. Maisheev

Spectrum of energy losses of positrons

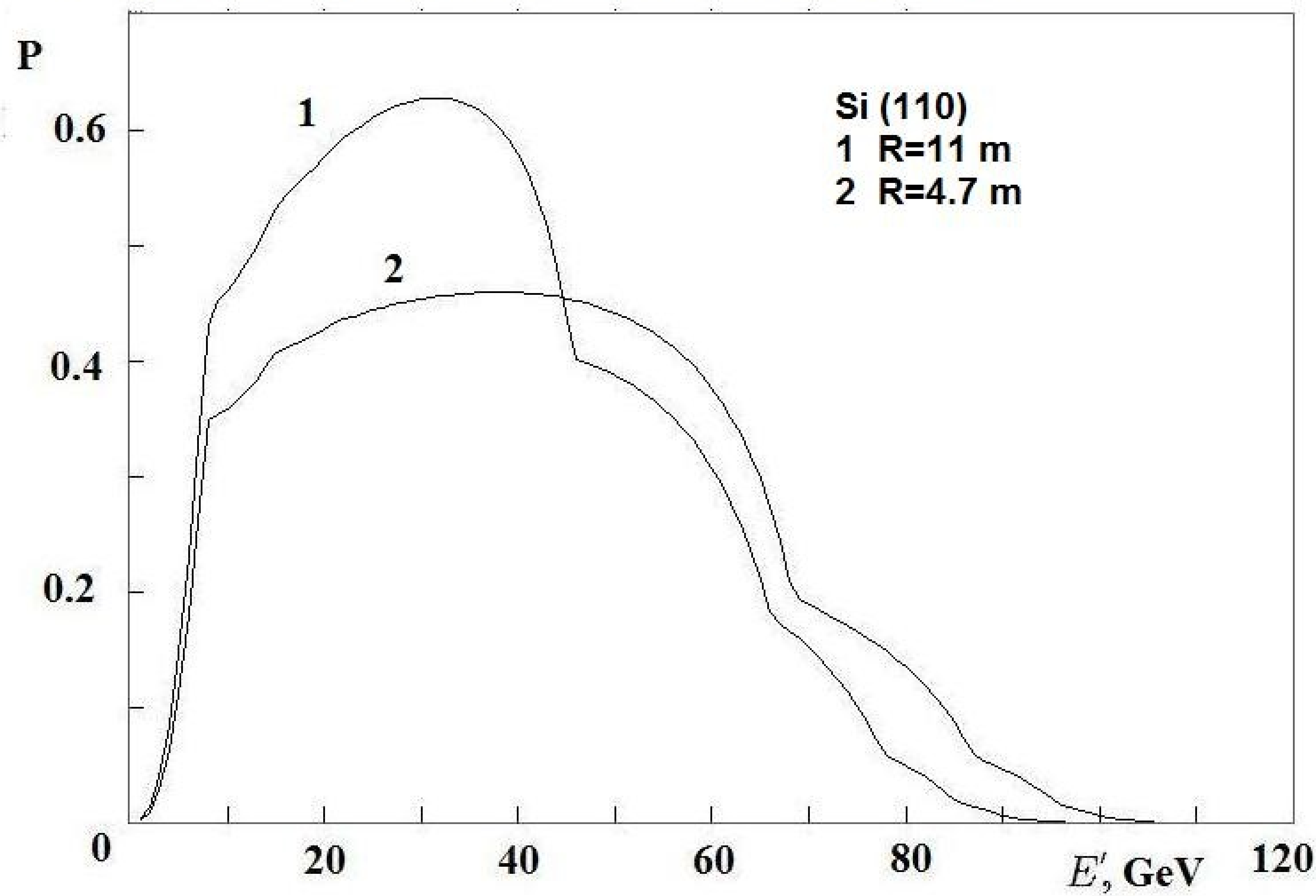


experiment S.Hasan et. al. Report on ICHEP 2010, Paris



Spectrum of energy losses of positrons
120 GeV e+ Si(110)
L=2 mm R=4.7 m
0.2
0.1
0
$\frac{d\mathcal{E}}{dE'}$
20
40
60
80
100
120
E_0 - E GeV
experiment
one photon emission multiplied on 0.85
calculation (only crystal)
calculation crystal + background
experiment S.Hasan et. al. Report on ICHEP 2010, Paris

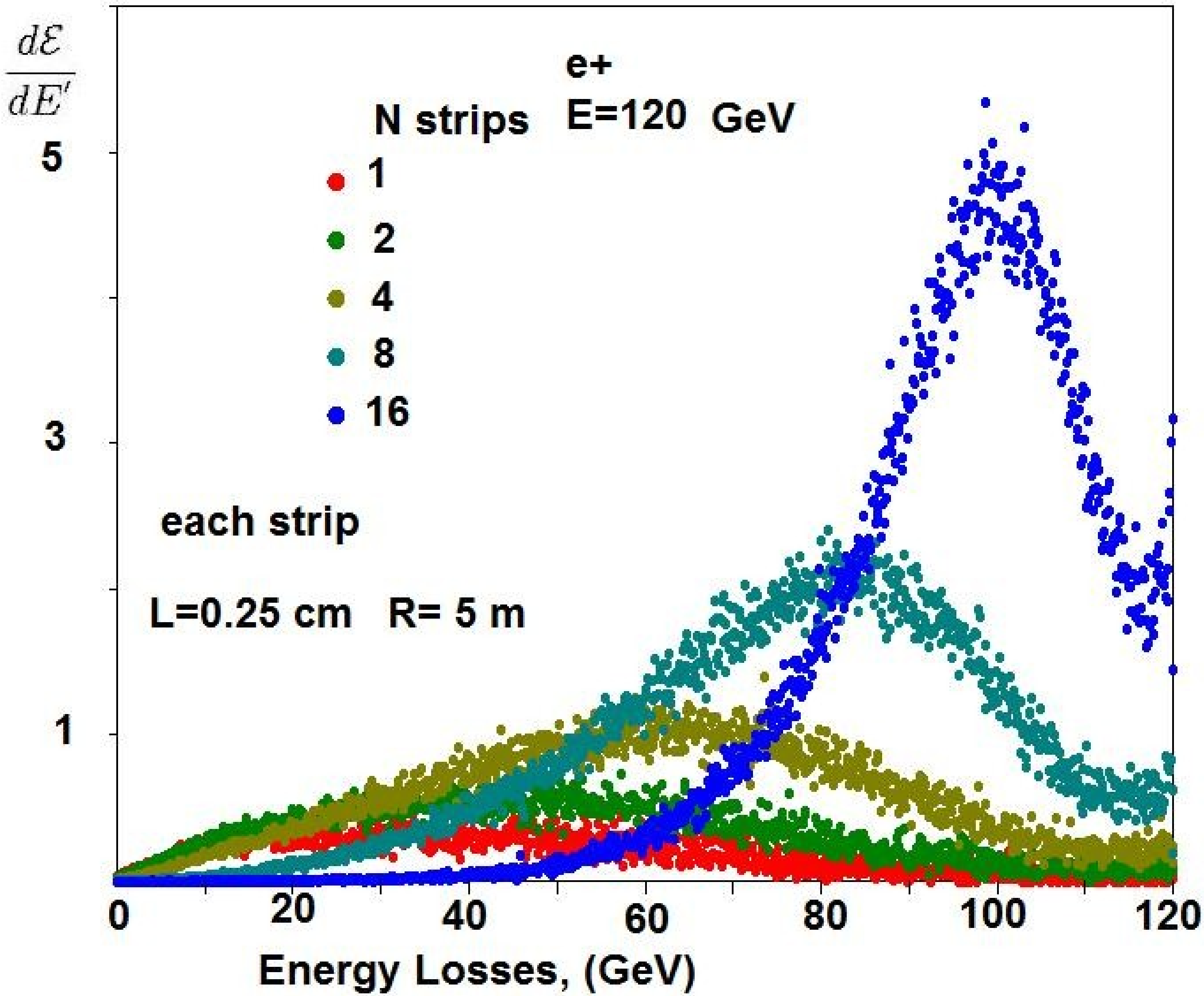
Linear polarization of emmited photons (calculation)

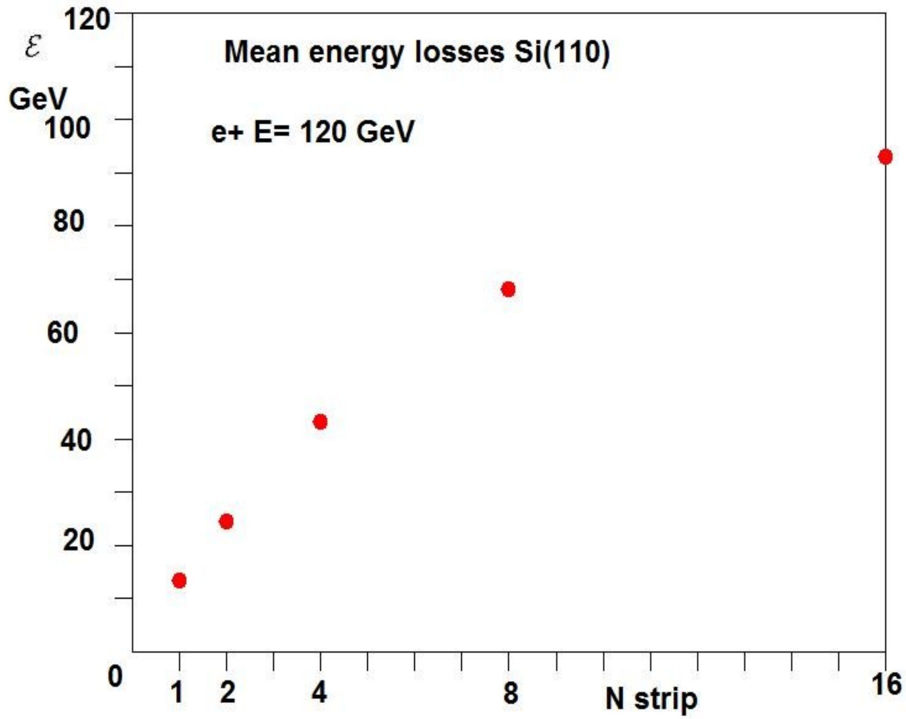


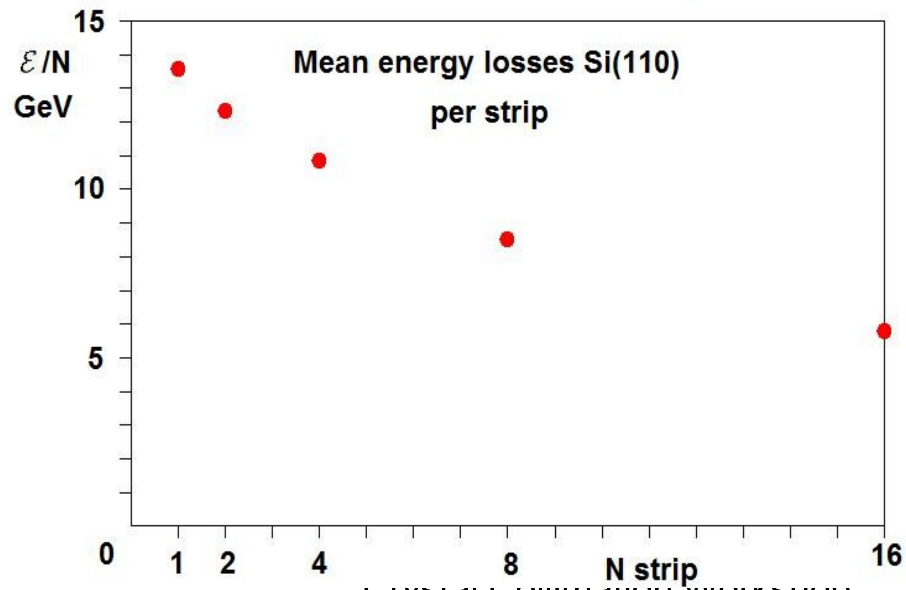
VR radiation of positrons (electrons) in multi strips.

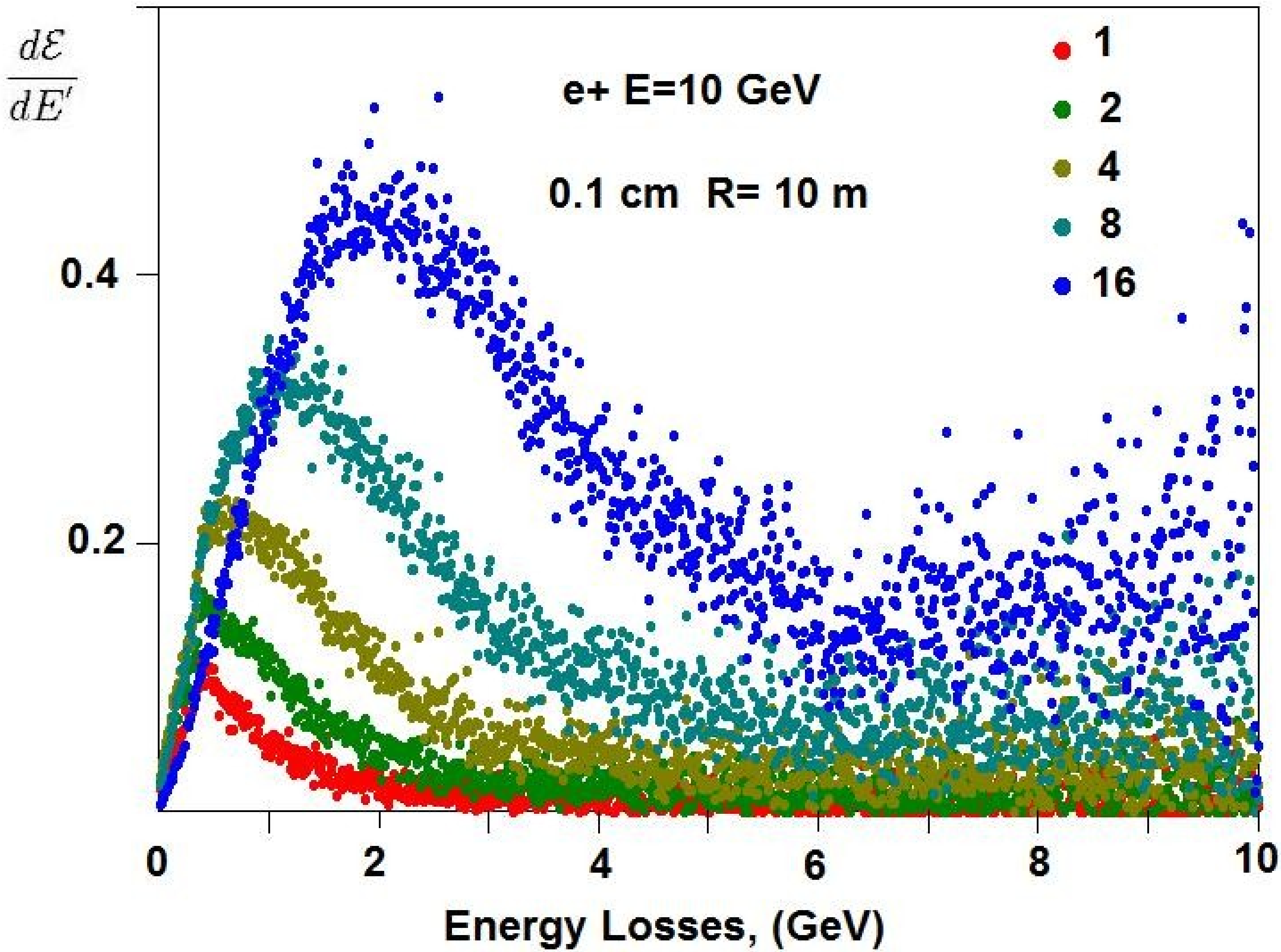
Calculations were perfomed by Monte Carlo method which was based on consideration of single photon emission on a short distance.

Results of calculation have preliminary character.


$\frac{d\mathcal{E}}{dE'}$
e+
E=120 GeV
N strips
1
2
4
8
16
each strip
L=0.25 cm R= 5 m
5
3
1
0
20
40
60
80
100
120
Energy Losses, (GeV)


Mean energy losses Si(110)
e+ E= 120 GeV
$\mathcal{E}$ GeV
N strip
0
20
40
60
80
100
120
1
2
4
8
16


Mean energy losses Si(110)
per strip
$\mathcal{E}$/N GeV
N strip
0
5
10
15
1
2
4
8
16

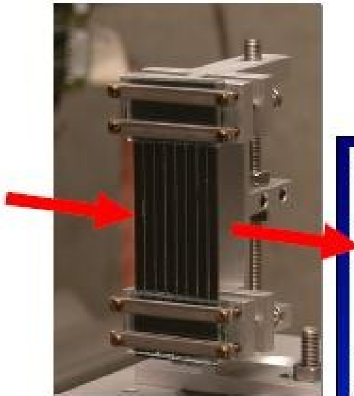


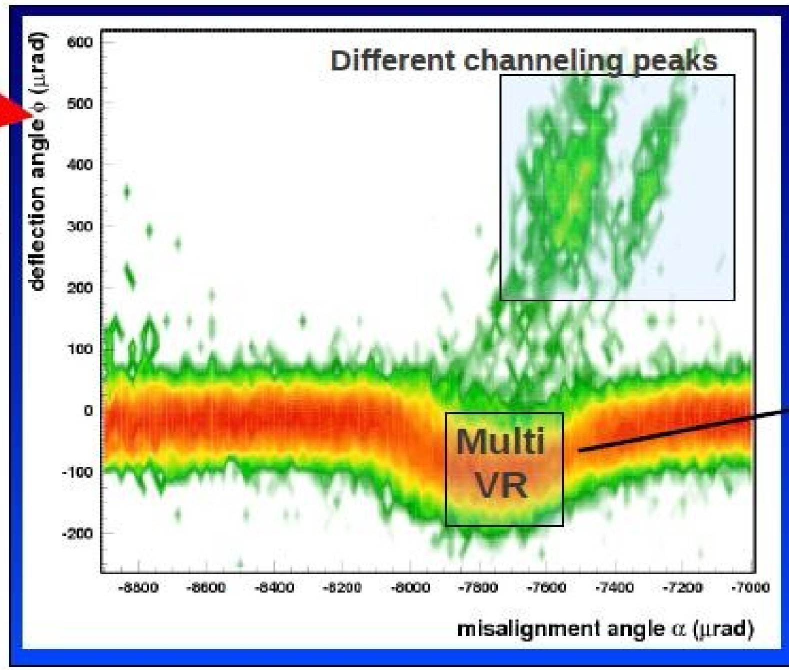
$\frac{d\mathcal{E}}{dE'}$
e+ E=10 GeV
0.1 cm R= 10 m
1
2
4
8
16
0.4
0.2
0
2
4
6
8
10
Energy Losses, (GeV)

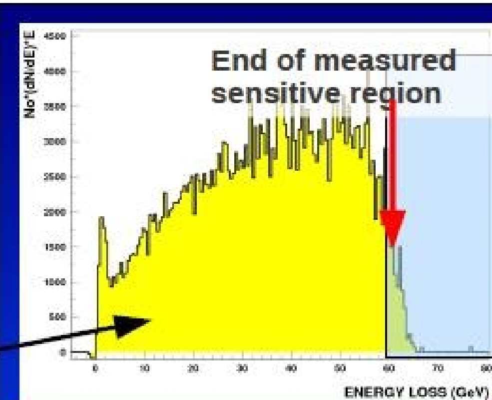
Increasing the emitted energy

Volume Reflection → larger angular acceptance

➡ *Using a series of crystals to increase deflection and radiation is possible!*







The radiation energy loss shows an amplification but it is not possible either to view all the spectrum or to normalize it as the spectrometer is sensitive until ~60GeV

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Channeling radiation of high energy positrons (E > 50 GeV) in bent single crystals

This type of radiation at high energies has synchrotron like character.

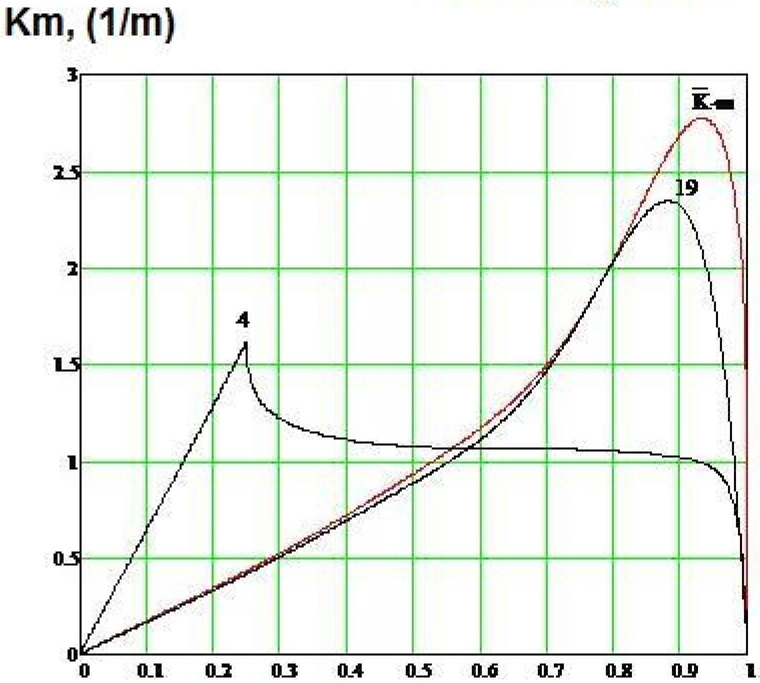
Such radiation has mainly non interference character and may be characterized by an instant (current) radius R_C of particle trajectory curvature.

In this case the influence of bending radius R of crystal on the radiation process will be take place if

$$R \sim R_C \quad \text{OR} \quad R \ll R_C$$

When $R \gg R_C$ the influence is weak (insignificant)

Estimations for 120 GeV positrons channeling in (110) planes of Si crystals



$$K_{eff}(\vartheta_o) = \int_0^1 \bar{K}(\xi_m) f(\xi_m, \vartheta_o)\, d\xi_m$$

$K_{eff}(4) = 1.16\ m^{-1}$ $R_C = 0.86$ m

$K_{eff}(19) = 1.68\ m^{-1}$ $R_C = 0.6$ m

at R > 2-3 m influence is small

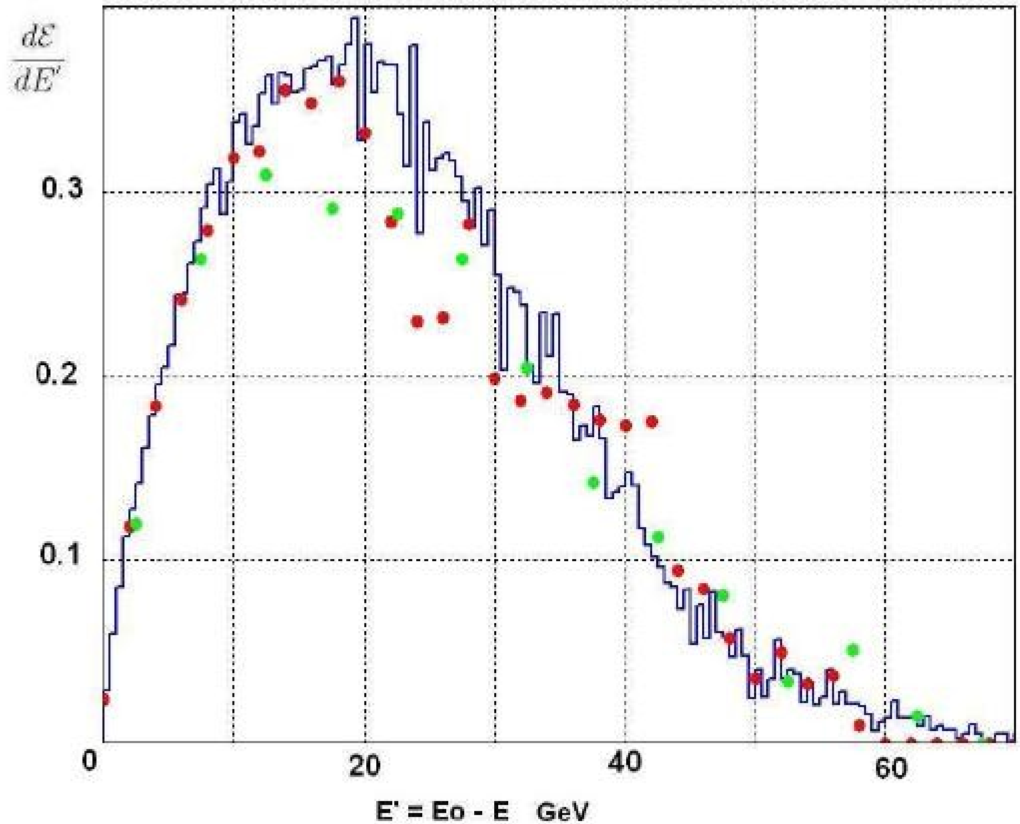
Preprint IHEP 2009- 21 ArXiv:1102.3778.

V.A. Maisheev, Yu. A. Chesnokov, P.N. Chirkov, I. A. Yazynin, D. Bolognini, S. Hasan, M. Prest, E. Vallazza

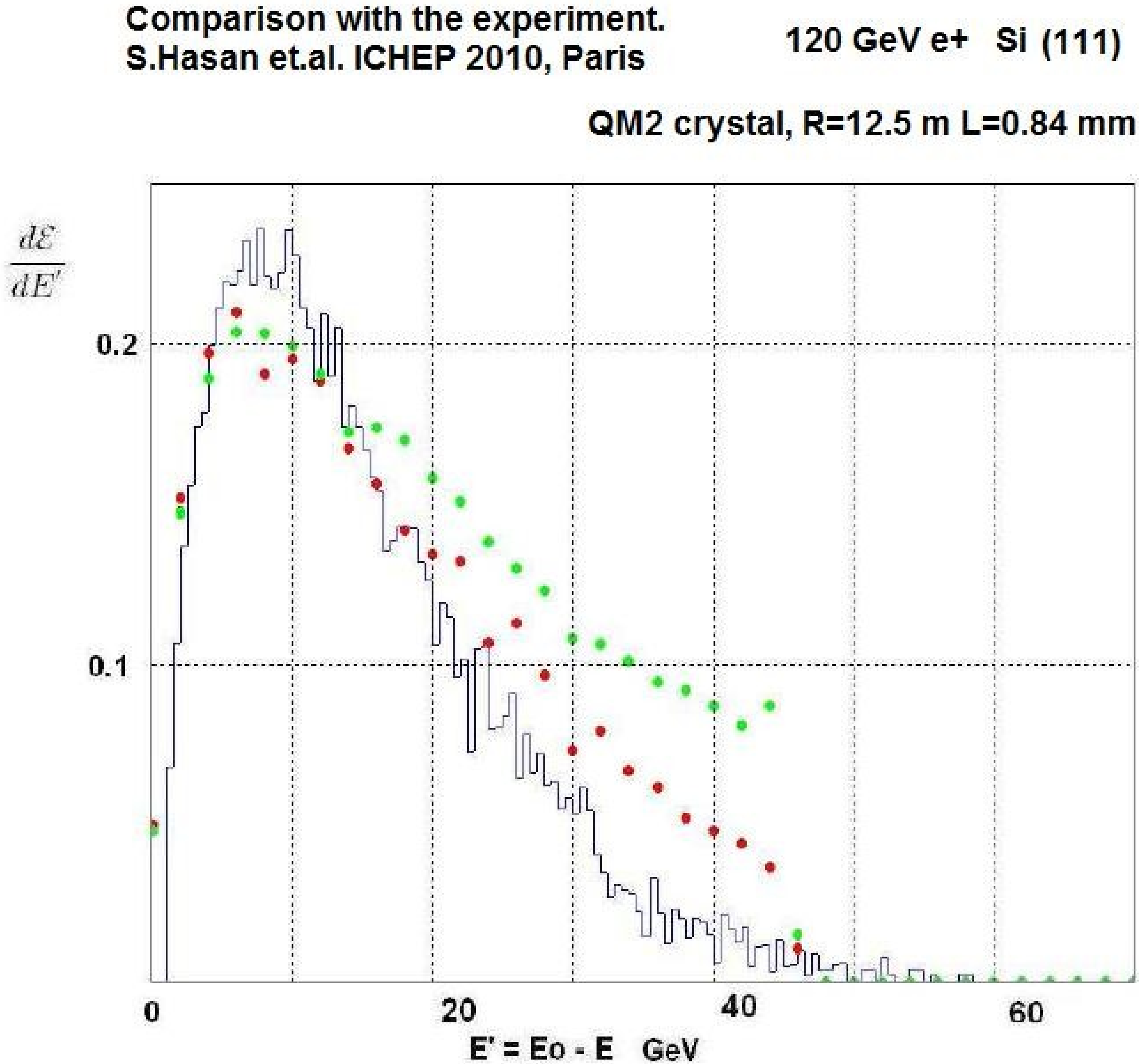
contains solution of problem of radiation of positrons with the energies in hundreds GeV

Comparison with the experiment.
S.Hasan et.al. ICHEP 2010, Paris

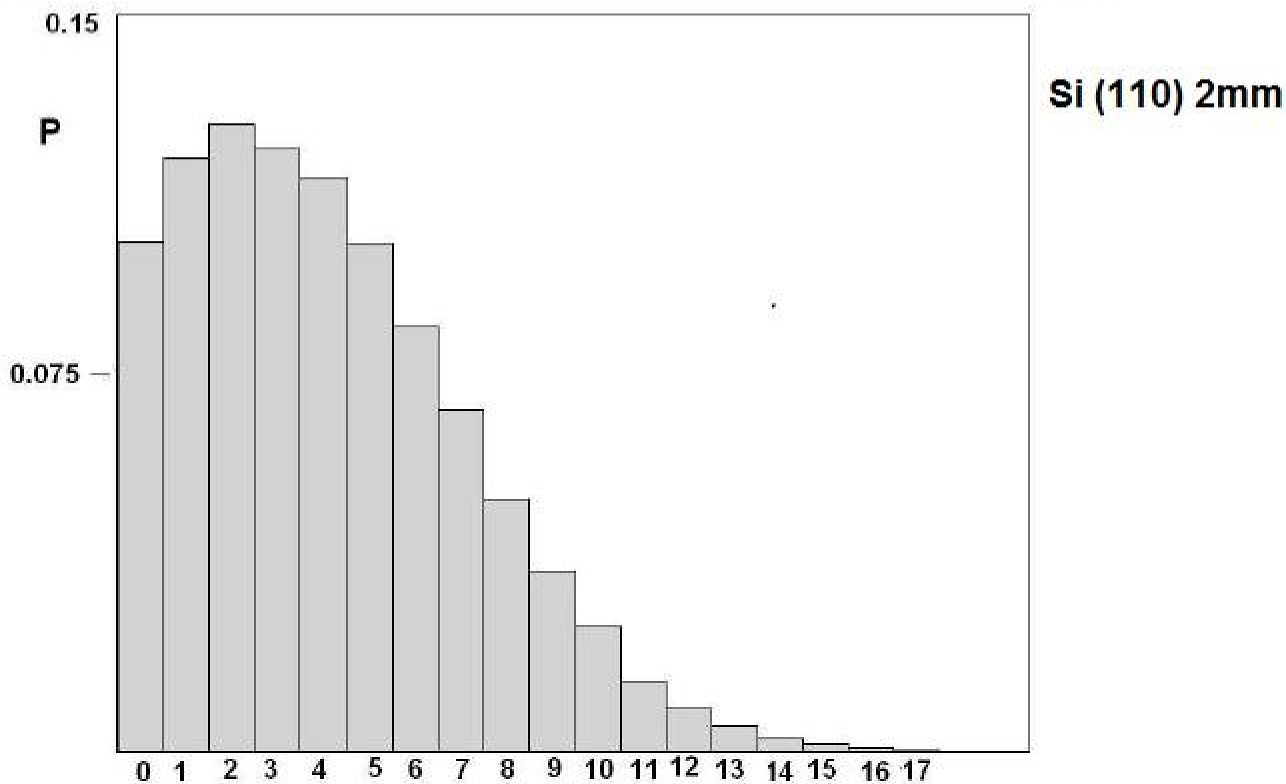
120 GeV e+ Si (110)



Comparison experimental and calculated data for (110) plane of the 2mm silicon single crystal. The red points are the results of measurement for radius 11 m and green ones for radius 4.74 m. (in the last case $\langle E \rangle = 10.7$ GeV) The curve is Monte Carko calculation by Monte Carlo method with the help of the first method for photon emission

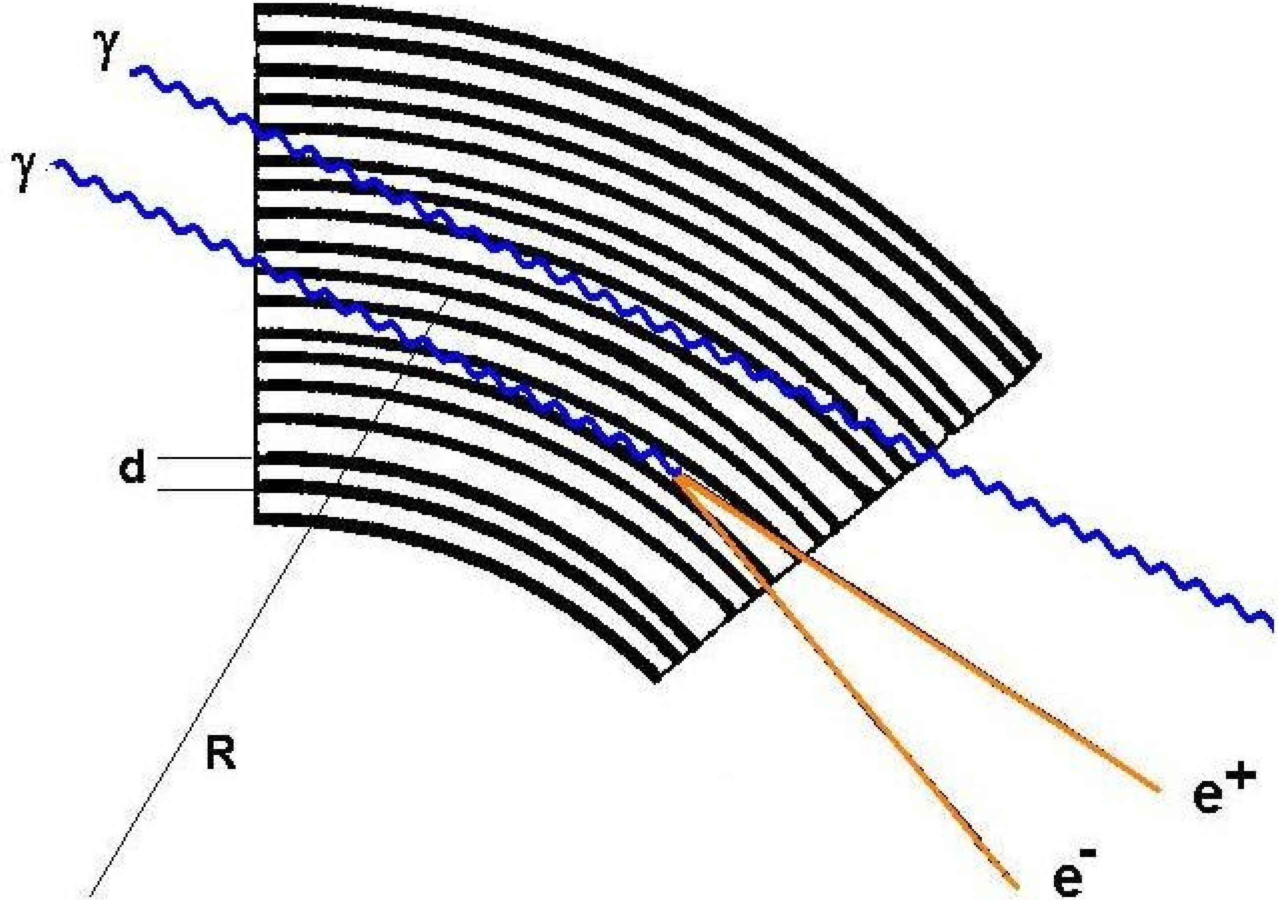

Comparison with the experiment.
S.Hasan et.al. ICHEP 2010, Paris
120 GeV e+ Si (111)
QM2 crystal, R=12.5 m L=0.84 mm
$\frac{d\mathcal{E}}{dE'}$
0.2
0.1
0
20
40
60
E' = Eo - E GeV

Calculations were performed by Monter Carlo method. which was based on one photon spectra and taking account the nuclear dechanneling.

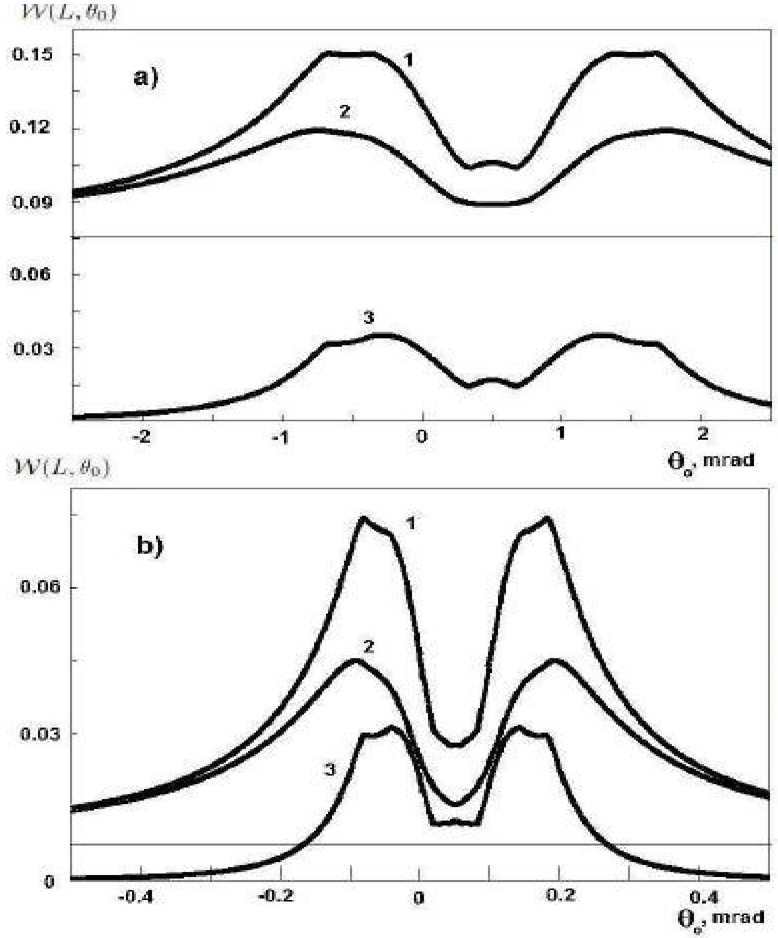


Distribution of multiplicity of emitted photons (with the energy > 50 MeV

Photoproduction of $e^{\pm}$ pairs in bent single crystals



Yu.A. Chesnokov, V.A. Maisheev, D. Bolognini, S. Hasan, M. Prest, E. Vallazza Phys. Rev. AB ST, 13, 070706, (2010)



E =120 GeV

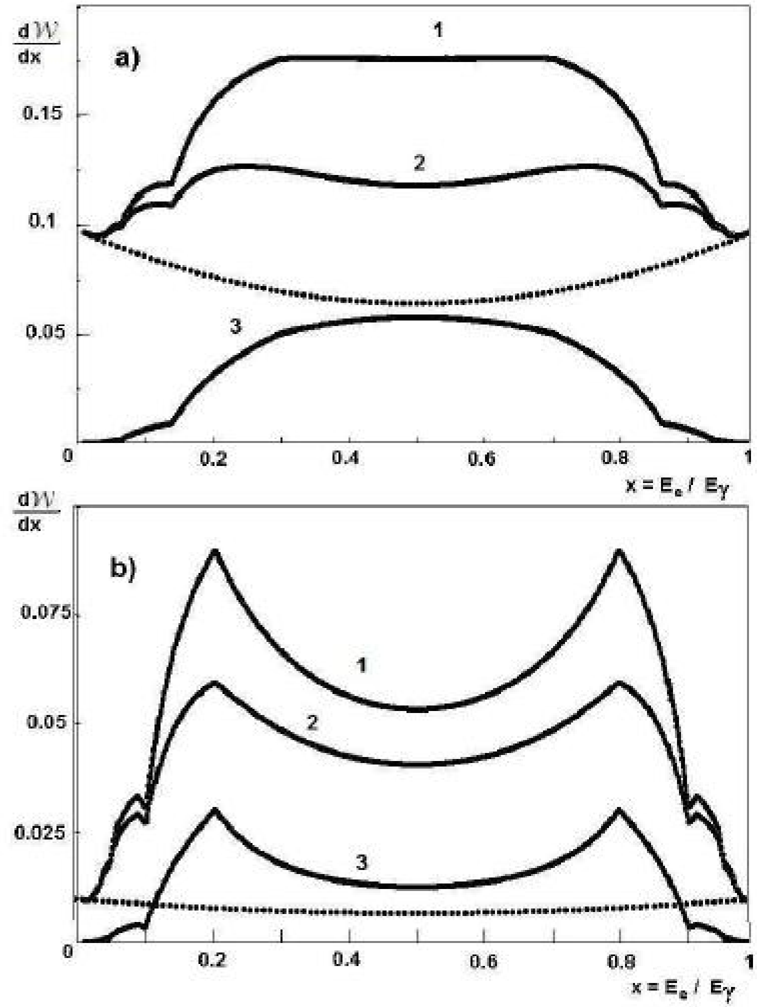
R=10 m
L=1cm

Si (110)

E=1000 GeV

R=10 m
L=0.1cm

The probabilities of pair production in the (110) bent planes of silicon single crystals as a function of the entrance angle θ_0. The curves 1 and 2 are the $\mathcal{W}_{||}$ and $\mathcal{W}_{\perp}$-probabilities and the curve 3 is their difference. The thin straight line is probability in nonoriented single crystal. The bending radius is 10 m Photon energies and thickness of crystal are 120 GeV and 1 cm (a) and 1000 GeV and 0.1 cm (b), correspondingly.



: Spectral distributions of electrons (positrons) at pair production in bent silicon single crystal at conditions as in Fig.2, for the two cases (a) and (b), correspondingly. The entrance angle θ_0= +1.5 mrad (a) and +0.2 mrad (b). The numbers near curves correspond probabilities as in Fig. 2. The black point curves are for nonoriented single crystals.

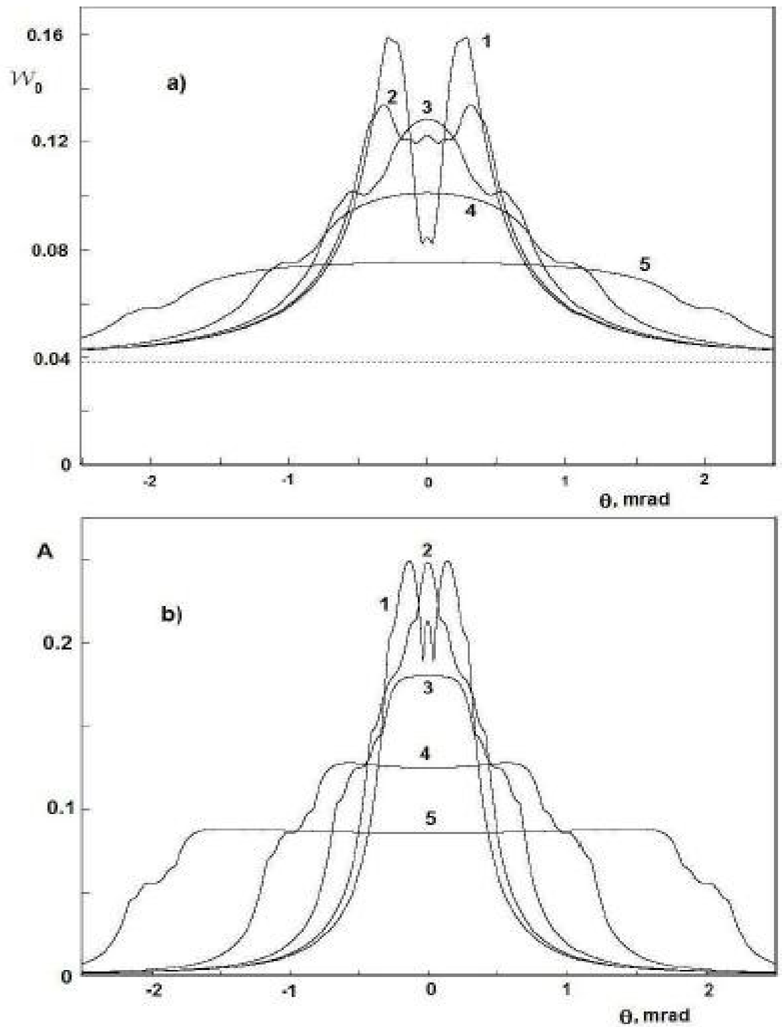


Figure 4: The probability $\mathcal{W}_0$ (a) and assymmetry A (b) for the 0.5 cm silicon single crystal at diiferent bending radii as functions of orientation angle θ. The curves 1, 2, 3, 4, 5 correspond to $R = 20, 10, 5, 2.5$ and 1.25 meters ($\theta = 0$ for symmetric orientation of a single crystal). The point curves correspond to nonoriented crystal. The photon energy is equal to 500 GeV.

Electromagnetic processes in axial fields of bent single crystals

This is a new field of investagation.
Quantitative experimental data and theoretical considerations are practically absent.
However, one can ponit out on preliminary calculations of photon emission by 120 GeV positrotns at axial volume reflection.

Electromagnetic Radiation Accompanying Multiple Volume Reflection in One Crystal,

V. Guidi, **A. Mazzolari**, and V. Tikhomirov

Poster report on Channeling 2010, Ferrara

Qualitative experimental data for this process contains the report

High energy photon production in bent crystals: the latest measurements,
S.Hasan, A.G. Afonin, E. Bagli, S. Baricordi, D. Bolognini, Yu.A. Chesnokov, P.N. Chirkov, P. Dalpiaz, G. Della Mea, V. Guidi, V. A. Maisheev, A. Mazzolari, M.Prest, E.Vallazza, D. Vincenzi, and I.A. Yazynin

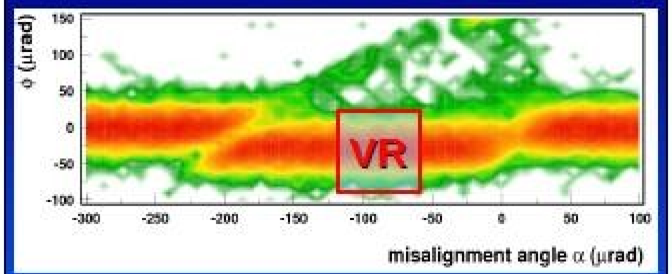
Report on ICHEP, 2010, Paris and Channeling 2010, Ferrara.

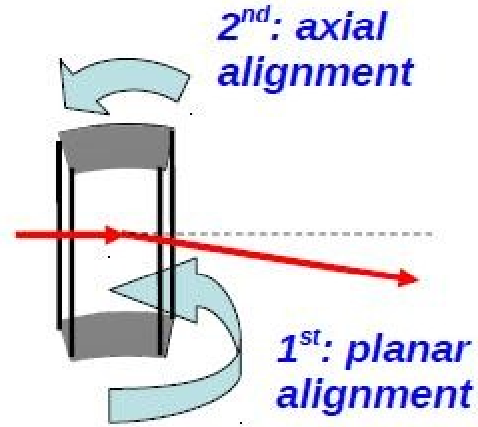
ICHEP 201

Increasing emitted energy

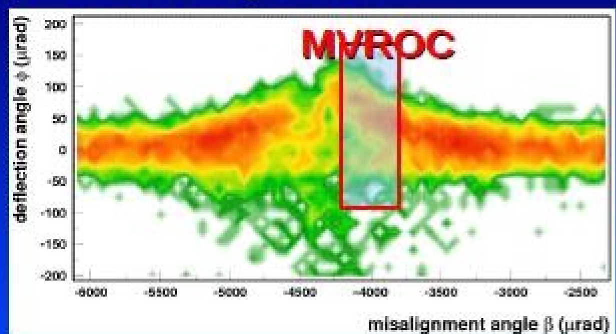
Axial alignment → Multivolume reflection in one crystal

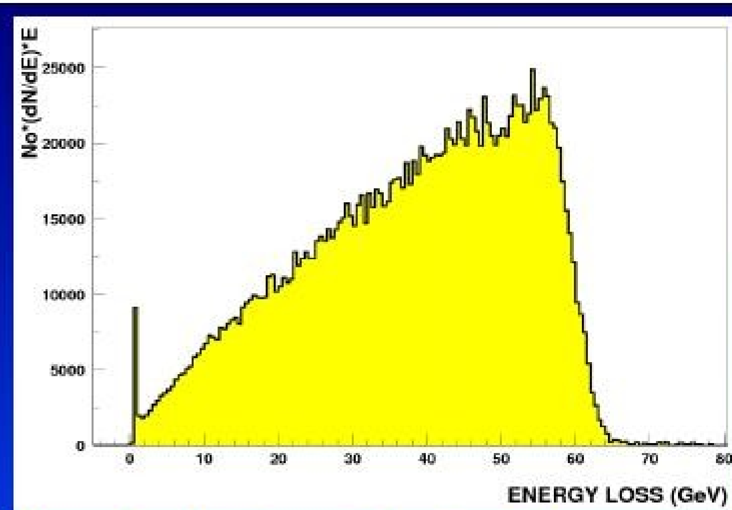
1^{st}: planar alignment





2^{nd}: axial alignment





As well as for the "crystal series" the measurement is limited by the spectrometer acceptance thus it provides only a qualitative result

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Calculation of radiation in axial fields of bent single crystals (proposal)

In the case when on a shor part of trajectory the angles with respect to axes is changed weakly then we can suggest that

$$\frac{d^2\mathcal{E}}{dE_q}(t) = \frac{dI}{dE_q}(\tilde{\theta}_h(t), \tilde{\theta}_v(t))cdt$$

where $d\mathcal{E}/dE_e$ is the differential energy losses of positrons in the moment of time t, $E_q = E_0 - E_e = E_\gamma$, E_0 and E_e are the positron energies before and after radiation, $\tilde{\theta}_h$ and $\tilde{\theta}_v$ are the averaged (may be, or may be not) angles with respect to selected orthogonal crystallographic planes. These angles are the functions of time and they should be found from calculations of particle trajectories.

The function I is an intensity of radiation. We think that for calculations we can use for this function the corresponding intensity for a straight crystal (as a function of the both angles). In particular, the intensity of coherent bremsstrahlung.

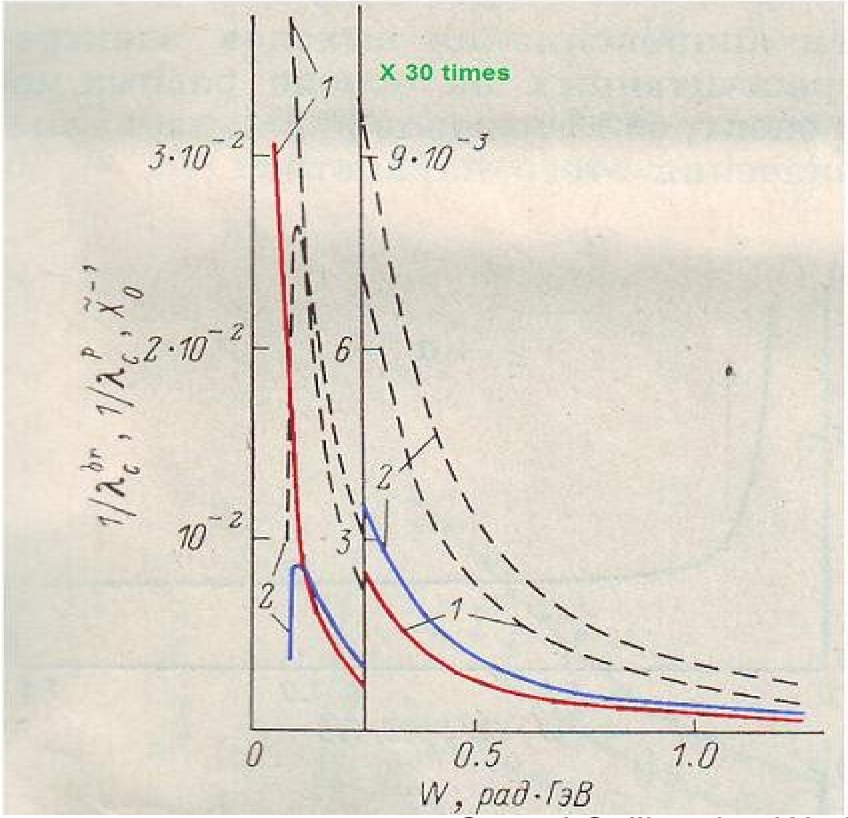
In similar manner one can consider and process of $e^{\pm}$ pair production by γ-quanta moving in axial fields of bent crystals. This problem is simplifaed because only one angle is changed (in bending plane).

Problem. Comparison radiation in bent and straight single crystals.

We know that energy losses due to radiation in straight crystal more high but more narrow than in bent ones. However the quantitative comparison is very desirable. For the planar case it may be obtained
1) by simulations and 2) by experimental measurements.

As result the function losses F(θ , L) should be found. (for bent and unbent crystals) where F is the mean value of energy losses for very small divergence of the beam.
As expected for small L these functions should be close in between.

It is interesting that maximums of intensity radiation and probability of e+= productions take place at different orientation angles, while for bent ones take place for the same angles.



Coherent. part
radiation
e+- production

Si (110) straight

Reaction probabilities as fumctions of angle (in rel. units)

The list of some another electromagnetic processes in single crystals which may be interested (in principle)

e+ or e-

1) Electron cooling
2) Spin rotation
3) Radiation with spin flip
4) Ondulator like photon emission

γ – quanta

5) Birefringence
6) Photon splitting: gamma to gamma_1 + gamma_2
7) Delbruck scattering
8) Creation of axion like (hypotetical) particles.

Conclusions

1. At the present time there ia a good understanding of the planar electromagnetic processes in bent single crystals (for energies up to approximately 150 GeV). Calculations and measurements are in a good agreement in between. It is desirable to consider theoretically the photon emission process at energies in 200 and more GeV.
2. Calculations show the opportunity of the usage of multi strip system for increasing of radiation energy losses and effective generation of electromagnetic cascades.
3. The electromagnetic processes in axial fields of bent crystals is practically not investigated area but we made some proposals for description of this case.
4. In the report we point out on on different electromagnetic processes in bent single crystals. For example, linear polarization, enhansment of energy losses in multy strips, processes in axial fields and etc. Experimental measurements of their have scientific meaning.
5. We also think that program for lepton interactions for collaboration should be stand on its first aims (collimation?), experimental possibilities, agreement of participants and others.

Thank you for the attention