Processes with half-bare particles at high energy

S.Fomin[1,2], M.Shul'ga[1,2], O.Fomin[1-3], A.Stocchi [3]

[1] *NSC "Kharkiv Institute of Physics & Technology" , Kharkiv, Ukraine*
[2] *V.N. Karazin Kharkiv National University , Kharkiv, Ukraine*
[3] *Laboratoire de l'Accélérateur Linéaire, CNRS–UPS, Orsay, France*

e-mail: sfomin@kipt.kharkov.ua

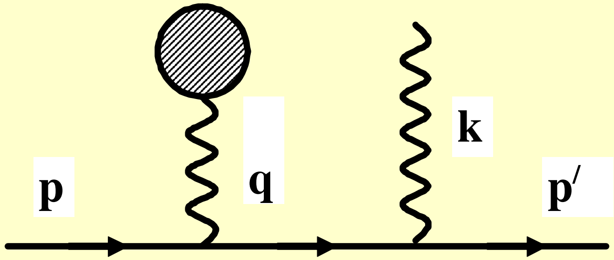
WS LIA IDEATE **6 - 8 November 2017** **LAL, Orsay, France**

Overview

- Coherence length of bremsstrahlung process
- LPM effect and Radiation length
- Suppression effects in a thin layer of substance
- CERN experiment NA63 and radiation of “half-bare” electron
- Spectral-angular distribution and polarization of γ-quanta at the non-dipole regime of radiation
- Formation zone of pair production processes
- Coherent effect at pair production in crystal and its suppression
- Conclusion and prospective

Coherence length of Bremsstrahlung

(Ter-Mikaelian, 1953)



$$\varepsilon = \varepsilon' + \omega, \qquad \mathbf{p} = \mathbf{p}' + \mathbf{k} + \mathbf{q}$$

$$r_{\|eff} \approx 1 / q_{\|eff} \approx \boxed{l_c = \frac{2\varepsilon\varepsilon'}{m^2\omega}}$$

$$q_{\|\,eff} = q_{\|\min} = \omega m^2 / 2\varepsilon\varepsilon'$$

$$\omega \ll \varepsilon: \quad l_c = \frac{2\gamma^2}{\omega} \qquad \gamma = \frac{\varepsilon}{m}$$

$$d\sigma \approx \int d^2 q_\perp \int_{q_{\min}}^{\infty} dq_{\|} \frac{q_\perp^2}{q_{\|}^2} \left| U_q \right|^2$$

$$\varepsilon = 1\,\mathrm{TeV}$$

$$\omega = 100\ \mathrm{MeV}$$

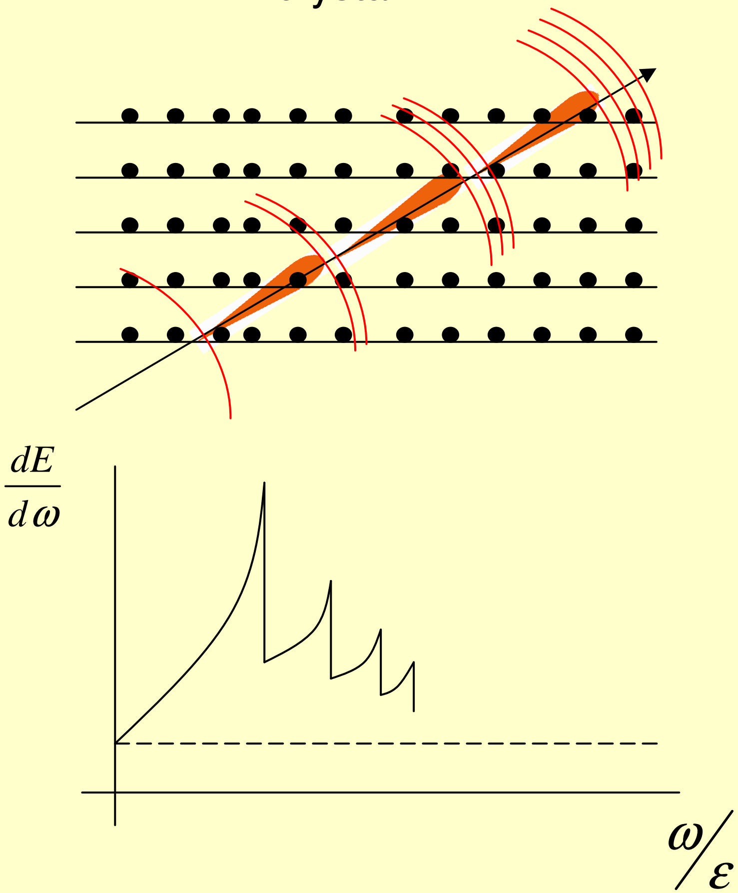
$$r_{\perp eff} \approx 1 / q_{\perp eff} \approx R \qquad U(r) = \frac{Z|e|}{r} e^{-r/R}$$

$$\underline{l_c \approx 1\,\mathrm{cm}\ !!!}$$

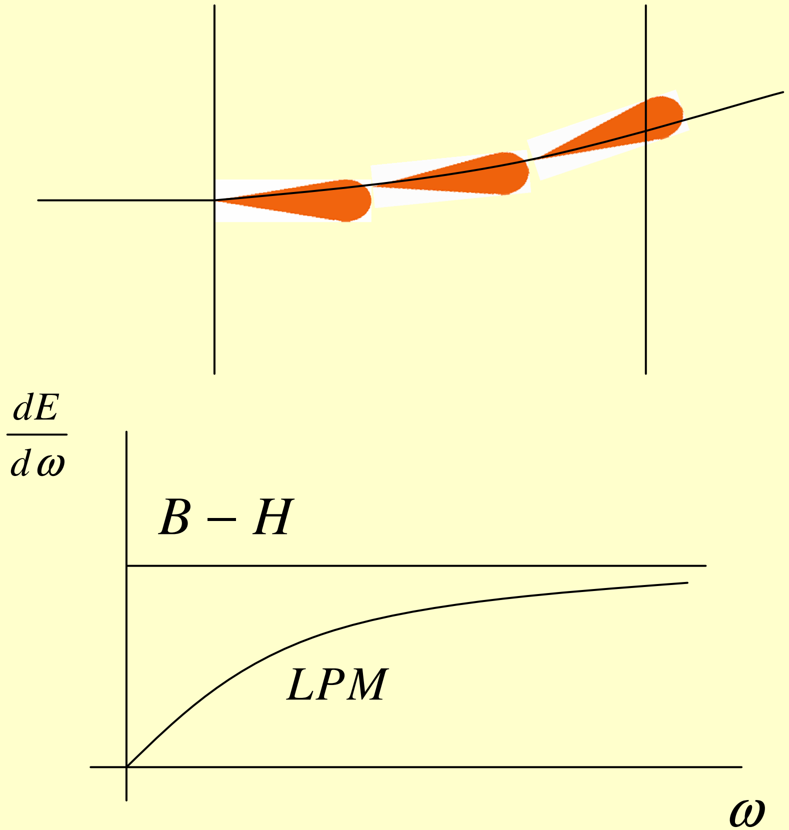
Coherence Length

$$l_c = {2\gamma^2}/{\omega}$$

crystal



amorphous media



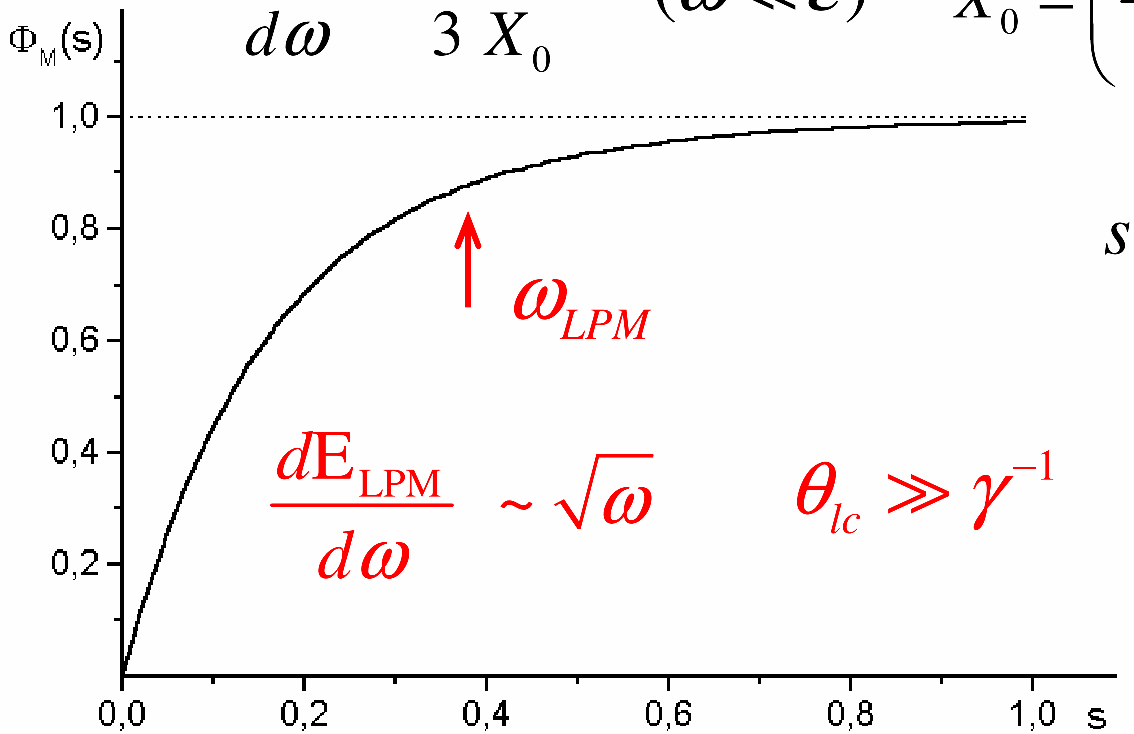
Multiple Scattering Effect on Radiation in Amorphous Medium

L. Landau and Ya. Pomeranchuk Dokl. Akad. Nauk SSSR 92 (1953) 735.

A.B. Migdal, Dokl. Akad. Nauk SSSR 96 (1954) 49; JETP 32 (1957) 633.

$$\frac{dE_{LPM}}{d\omega} = \frac{dE_{BH}}{d\omega} \cdot \Phi_M(s) \qquad \Phi_M(s) = 24 s^2 \left\{ \int_0^\infty dt\, cth\, t \quad e^{-2st} \quad \sin 2st - \frac{\pi}{4} \right\}$$

$$\frac{dE_{BH}}{d\omega} = \frac{4}{3}\frac{T}{X_0} \qquad (\omega \ll \varepsilon) \qquad X_0 = \left(\frac{4Z^2 e^6 n}{m^2} \ln mR \right)^{-1} \underline{\neq f(\varepsilon)\,!!!}$$



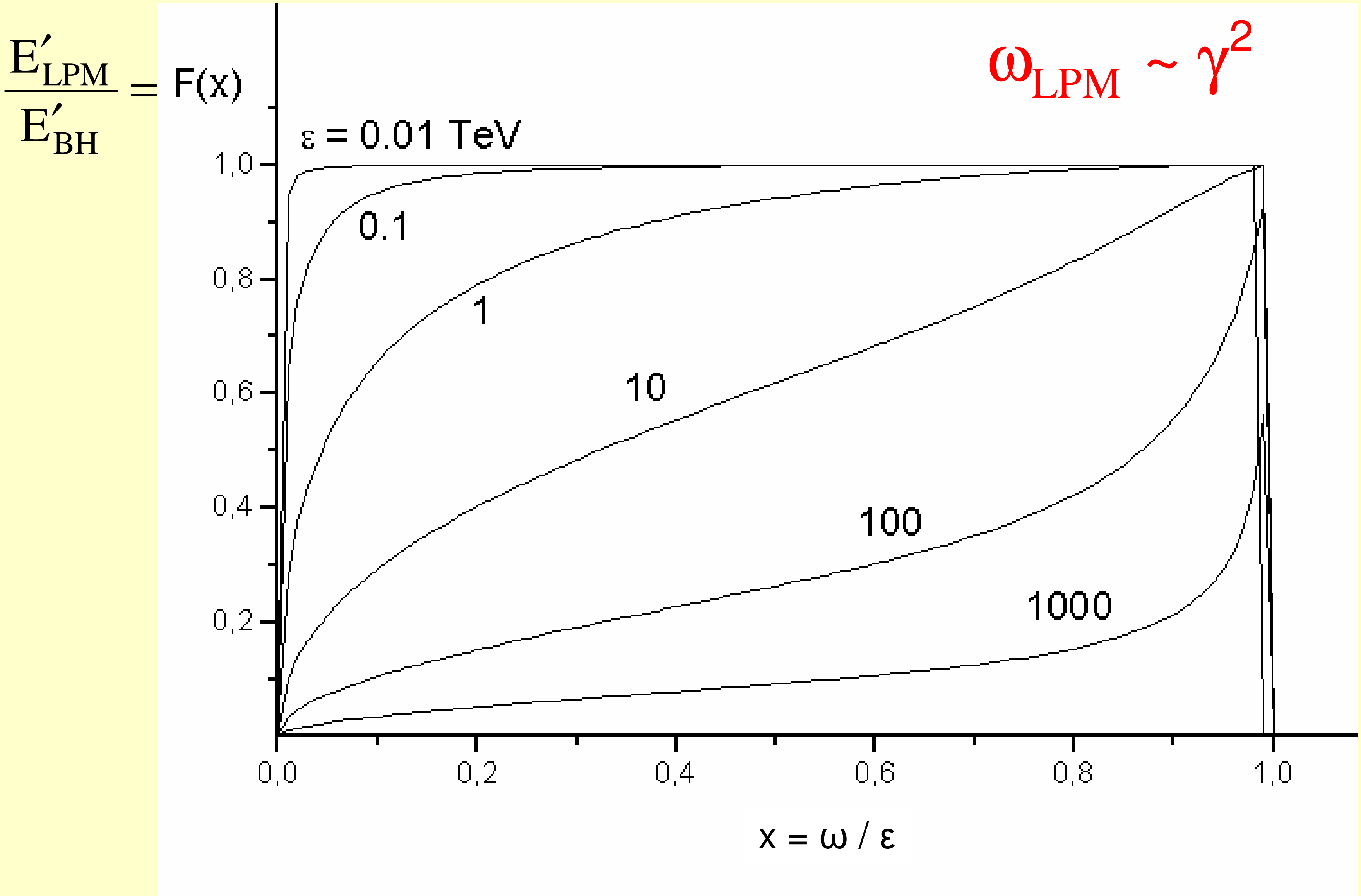
$$\frac{dE_{LPM}}{d\omega} \sim \sqrt{\omega} \qquad \theta_{lc} \gg \gamma^{-1}$$

$$s = \frac{1}{2\sqrt{2}} \sqrt{\frac{\omega}{\omega_{LPM}}}$$

$$\omega_{LPM} = 2q\gamma^4 \, \underline{\sim \gamma^2 \,!!!}$$

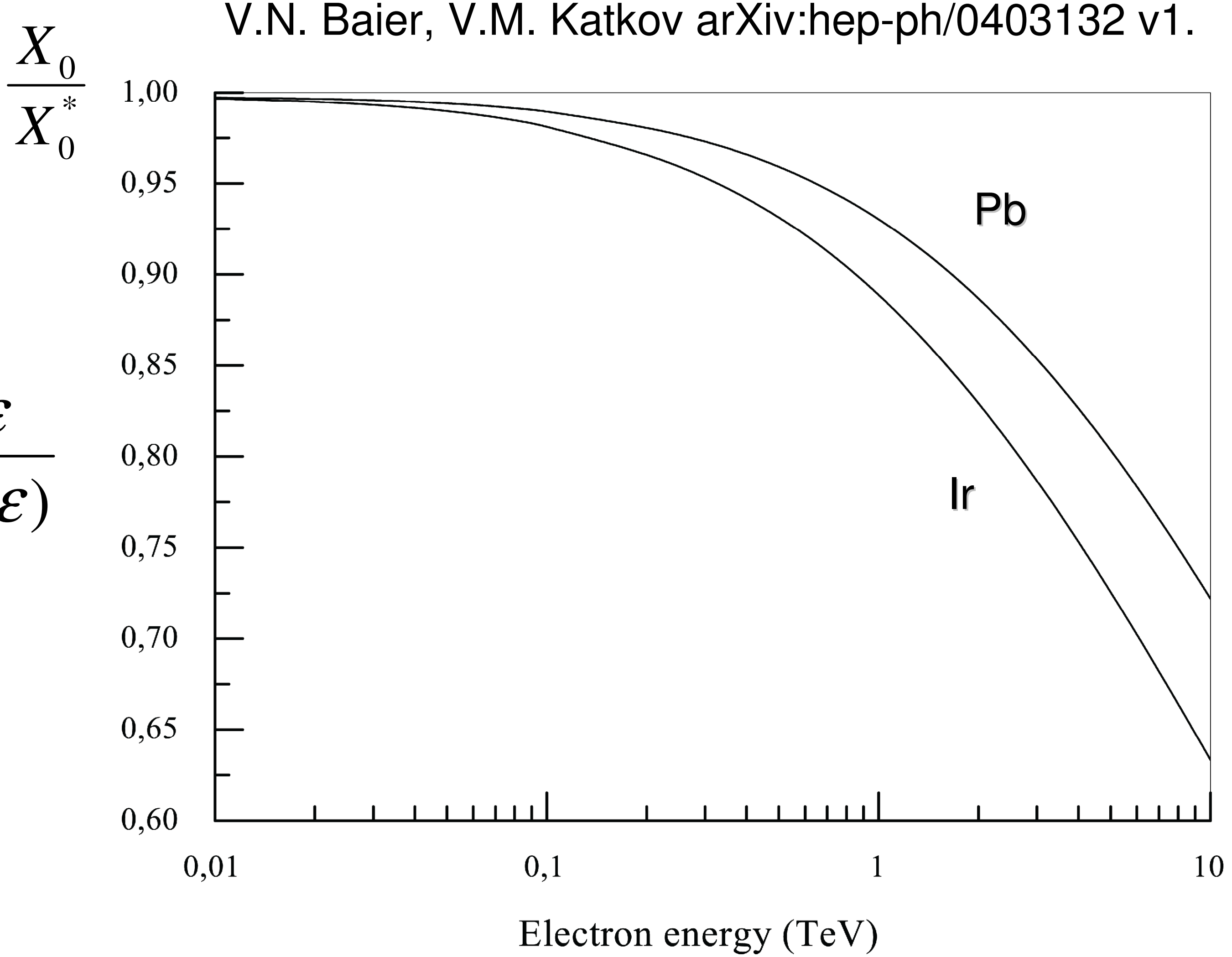
$$q = \frac{\varepsilon_s^2}{\varepsilon^2} \frac{1}{X_0}$$

LPM effect at very high energy



Radiation length depends on the particle energy !!!

V.N. Baier, V.M. Katkov arXiv:hep-ph/0403132 v1.



$$X_0^* = \frac{\varepsilon}{I(\varepsilon)}$$

Detector design and radiation shielding calculation - GEANT, …

1994: SLAC experiment E-146

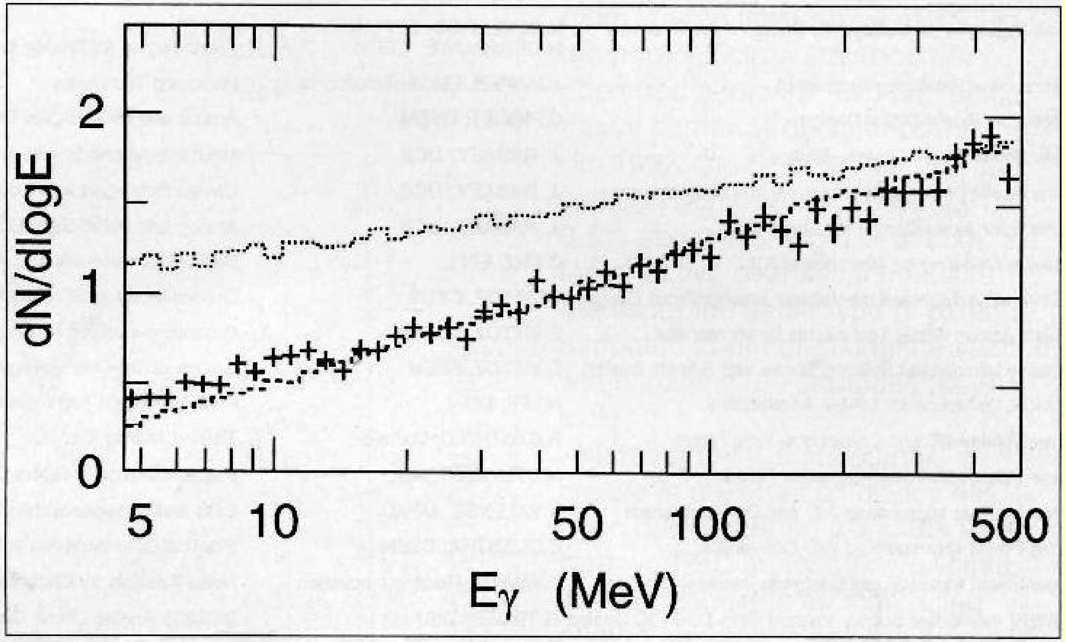
Volume 34
No. 1
January/February
1994

CERN COURIER

Covering current developments in high energy physics and related fields worldwide

STANFORD (SLAC)
Photon theory verified after 40 years

Developed by Landau, Pomeranchuk, and Migdal forty years ago, the LPM effect predicts that the production of low energy photons by high energy electrons should be suppressed in dense media.
In 1993 this was finally verified at Stanford (SLAC). The diagram compares data (crosses) with Monte Carlo simulations - one (dashed line) including LPM suppression and the other (dotted line) ignoring it - for 25 GeV electrons on uranium. Data recorded with two different targets were subtracted to remove edge effects.



A collaboration of physicists from the University of California at Santa Cruz (UCSC), the Stanford Linear Accelerator Center (SLAC), American University and Livermore has verified a theory that is almost forty years old.

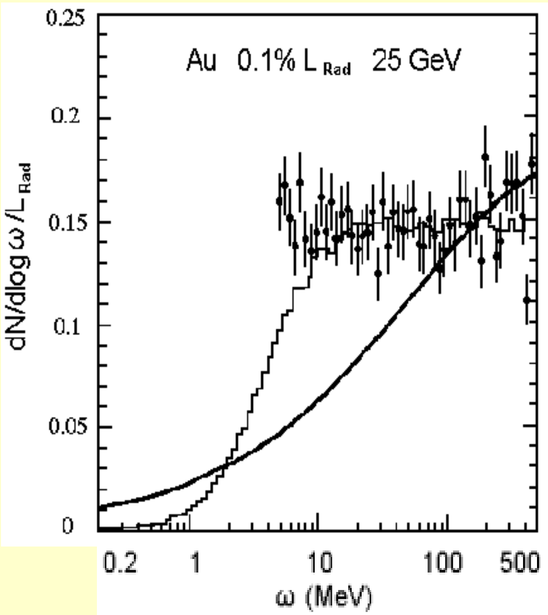
In SLAC experiment E-146, 25 GeV electrons passed through slim targets of carbon, aluminum, iron, gold, lead, tungsten and uranium — as well as a very thin gold target. After traversing the target, the electrons were de-

The E-146 data confirm that the LPM effect exists. The magnitude of the suppression in dense media such as uranium is consistent with Migdal's prediction. Lighter targets such as carbon show little suppres-

SLAC experiment E-146

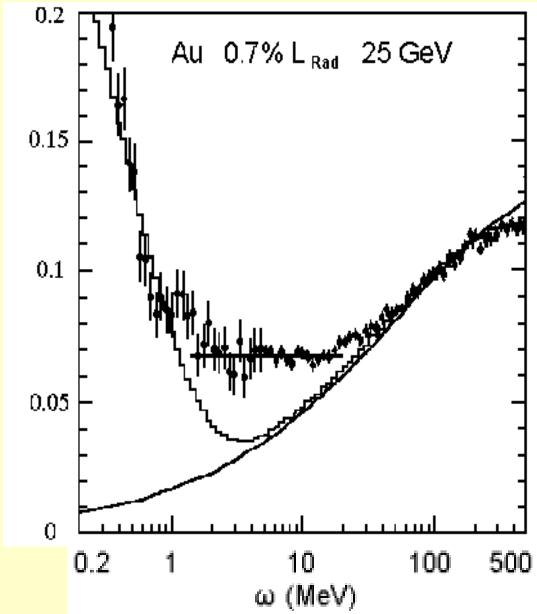
Anthony P.L. et al., Phys. Rev. Lett. **75** (1995) 1949.
Klein S., Rev. Mod. Phys. **71** (1999) 1501.

Bethe-Heitler



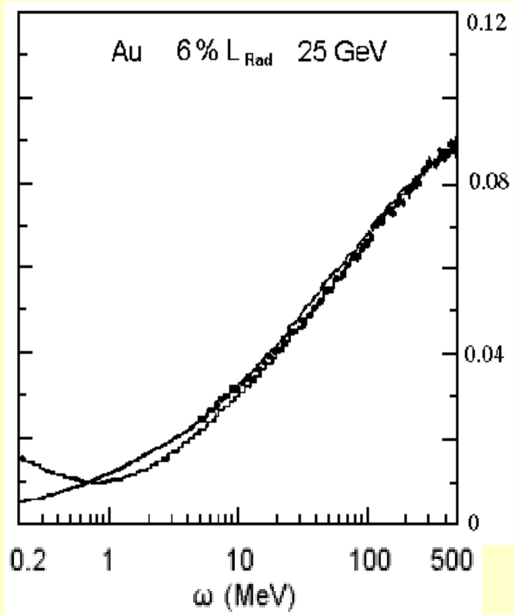
$$\gamma^2 \overline{\vartheta^2} < 1$$

? ? ?



$\gamma^2 \overline{\vartheta^2} > 1$, but T < l_c

LPM effect



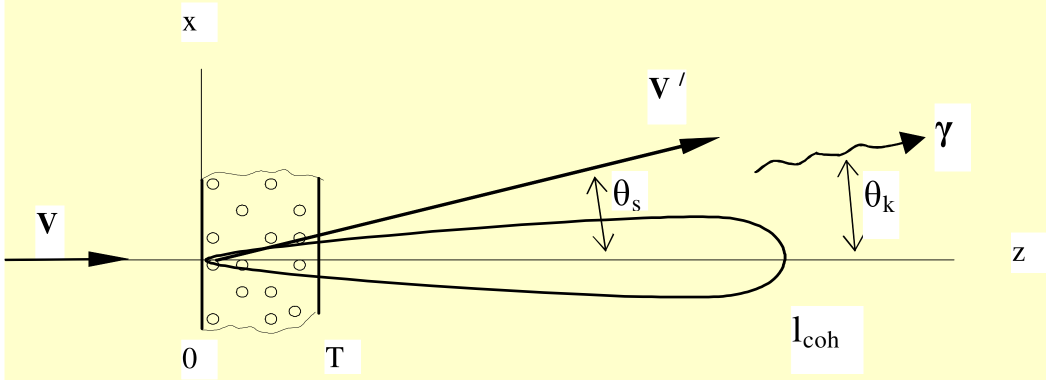
$\gamma^2 \overline{\vartheta^2} > 1$ and T > l_c

F.F. Ternovskii. *JETP* 12 (1961) 123.

$$\overline{\vartheta^2_{ms}} = \frac{\varepsilon_s^2}{\varepsilon^2}\frac{T}{X_0} \times \left(1 + 0.038 \ln \frac{T}{X_0}\right)$$

Radiation in a thin layer of matter : $l_c >> T$

Shul'ga N.F. and Fomin S.P., JETP Lett. **27** (1978)126;
Fomin S.P. and Shul'ga N.F., Phys. Lett. **A114** (1986)148.



$$\frac{d^2E}{d\omega do} = \frac{e^2\omega^2}{4\pi^2}\left[\vec{n}\times\vec{I}\right]^2$$

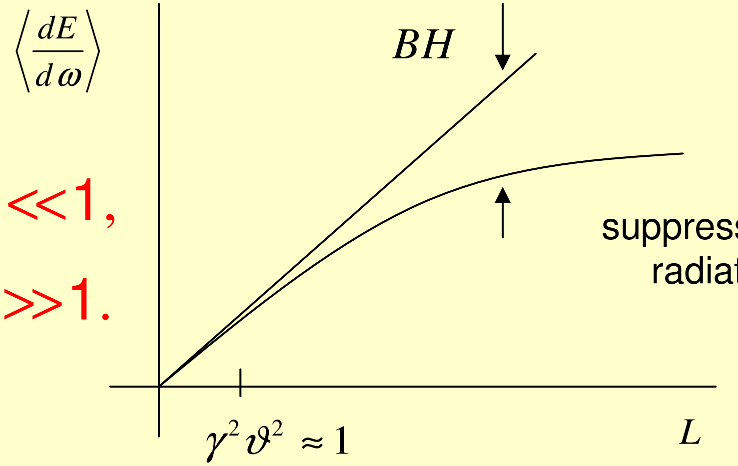
$$\vec{I} = i\int_{-\infty}^{\infty} dt\, e^{i\left(\omega t - \vec{k}\vec{r}(t)\right)} \frac{d}{dt}\frac{\vec{v}}{\omega - \vec{k}\vec{v}}$$

$$\vec{I} \approx i\left(\frac{\vec{v}'}{\omega - \vec{k}\vec{v}'} - \frac{\vec{v}}{\omega - \vec{k}\vec{v}}\right)$$

$$\frac{dE}{d\omega} = \frac{2e^2}{\pi}\left[\frac{2\xi^2+1}{\xi\sqrt{\xi^2+1}}\ln(\xi+\sqrt{\xi^2+1}) - 1\right], \quad \xi = \frac{1}{2}\gamma\vartheta$$

$$\frac{dE}{d\omega} \approx \begin{cases} \dfrac{3e^2}{\pi}\xi^2, & \xi^2 << 1, \\ \dfrac{2e^2}{\pi}\ln(4\xi^2), & \xi^2 >> 1. \end{cases}$$

$$\frac{dE}{d\omega} \approx \begin{cases} T, & \xi^2 << 1, \\ \ln T, & \xi^2 >> 1. \end{cases}$$

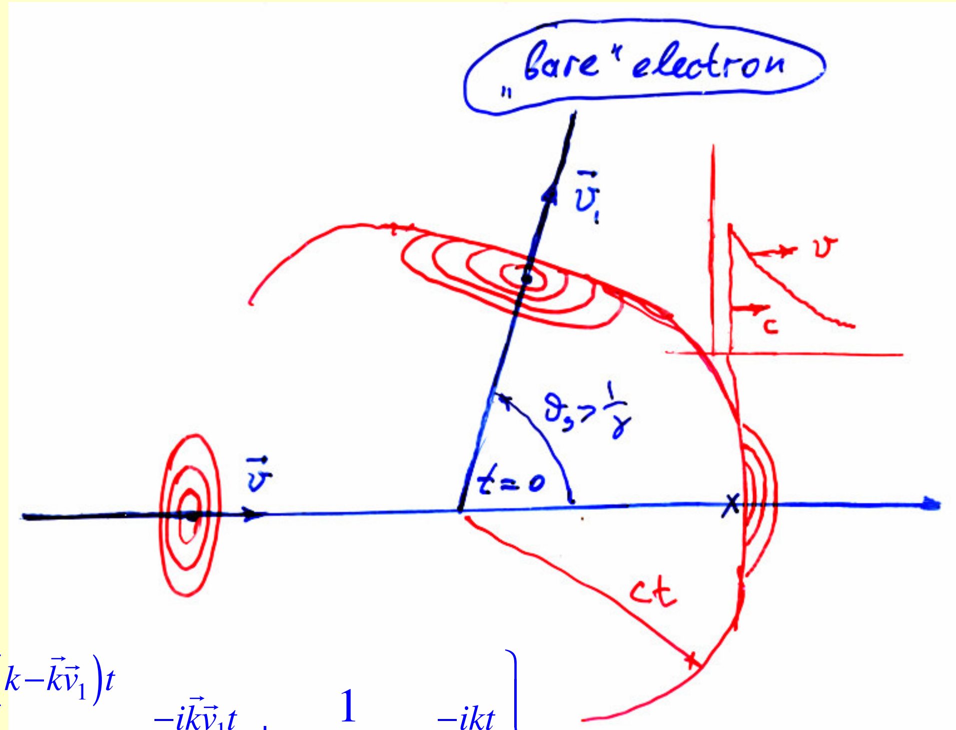


Electromagnetic field of electron at scattering

$$\left(\Delta - \frac{\partial^2}{\partial t^2}\right)\varphi = 4\pi e\delta\left(\vec{r} - \vec{r}\left(t\right)\right)$$

$$\varphi_v\left(\vec{r},t\right) = \frac{e}{\sqrt{\left(z - vt\right)^2 + \rho/\gamma^2}}, \qquad t < 0$$

- retarded Liénard–Wiechert potential



$$\varphi_{ret}\left(\vec{r},t\right)\Big|_{t>0} = \frac{e}{2\pi^2}\mathrm{Re}\int \frac{d^3k}{k} e^{i\vec{k}\vec{r}} \left\{ \frac{1 - e^{-i\left(k - \vec{k}\vec{v}_1\right)t}}{\omega - \vec{k}\vec{v}_1} e^{-i\vec{k}\vec{v}_1 t} + \frac{1}{k - \vec{k}\vec{v}} e^{-ikt} \right\} =$$

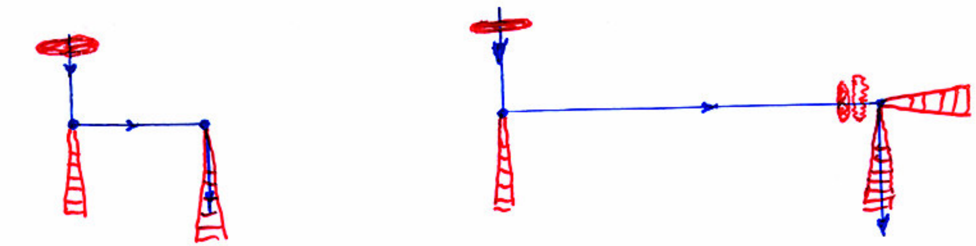
$$= \Theta\left(t - r\right)\varphi_{v_1}\left(\vec{r},t\right) + \Theta\left(r - t\right)\varphi_v\left(\vec{r},t\right)$$

$\Delta t \ll \left(k - kv_1\right)^{-1} \approx 2\gamma^2/\omega = l_c$ For $\varepsilon = 25\,\mathrm{GeV}$, $\omega = 10\,\mathrm{MeV}$, $l_c = 0.1\,\mathrm{mm}$

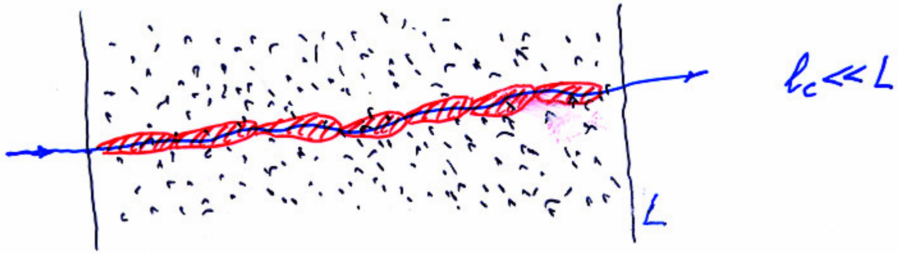
E.Feinberg, *JETP* 50 (1966) 202.

S.P. Fomin, N.F. Shul'ga, *Phys. Let. A* 114 (1986) 148
A.I. Akhiezer, N.F. Shul'ga, *Sov.Phys.Usp.* 30 (1987) 197

E. Feinberg (JETP, 1966, v. 50, 202)

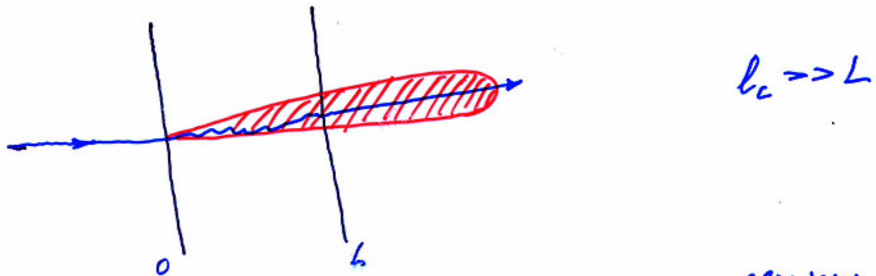


LPM case



balance = e^- is undressed + e^- is dressed

N. Shul'ga, S. Fomin (1978)

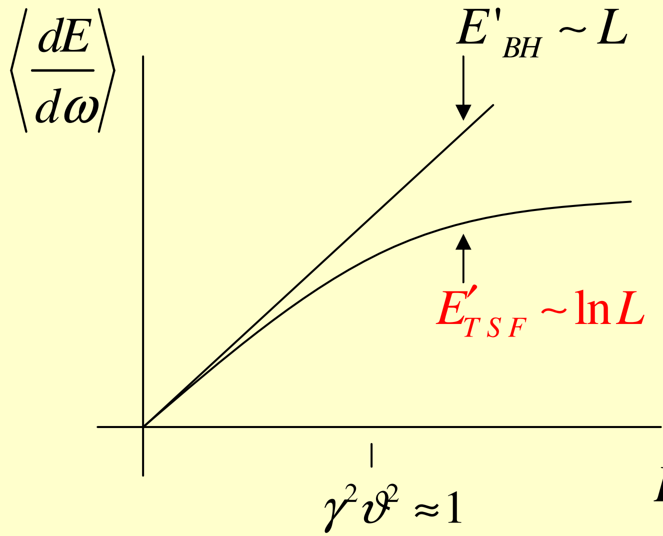


Electron is "bare" for all collisions !!!

$$\gamma^2 \overline{\vartheta^2} > 1$$

$$\sqrt{\overline{\vartheta^2}} > \gamma^{-1}$$

$$\frac{dE_{LPM}}{d\omega} \sim \frac{L}{X_0}\sqrt{\frac{\omega}{\omega_{LPM}}}$$

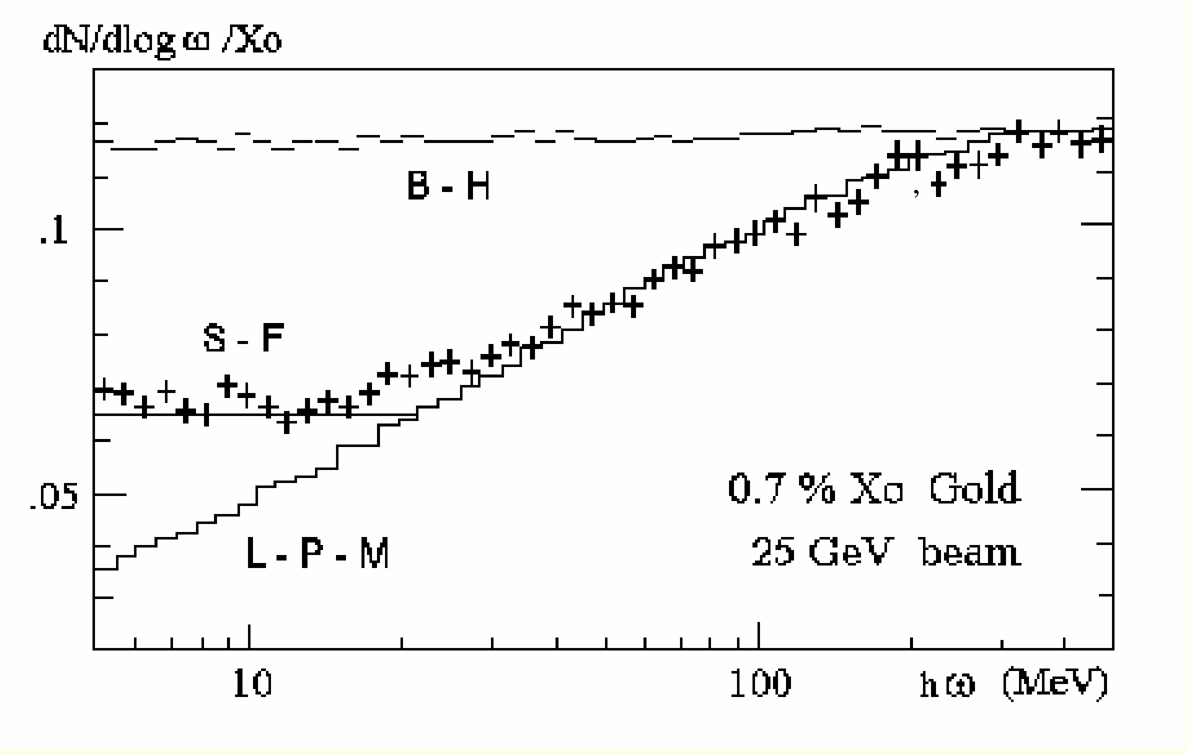


Quantitative theory of radiation in a thin layer of matter

Shul'ga N.F., Fomin S.P., JETP Lett. 63 (1996) 873; JETP 86 (1998) 32; NIM B145 (1998) 73.

$$\left\langle \frac{dE}{d\omega} \right\rangle = \int d\vec{\vartheta}_s\, f(\vec{\vartheta}_s) \frac{dE}{d\omega}, \qquad f_{B-M}(\vartheta) = \frac{1}{2\pi} \int_0^\infty \eta\, d\eta\, J_0(\eta\vartheta) \exp\left\{ -2\chi_c^2 \int_0^\infty \chi\, d\chi\, q(\chi) \chi^{-4} [1 - J_0(\eta\chi)] \right\}$$

$$\gamma^2 \overline{\vartheta^2} > 1 \qquad \frac{dE_{SF}}{d\omega} = \frac{2e^2}{\pi} \left[\left(\ln a^2 - C \right) \left(1 + \frac{2}{a^2} \right) + \frac{2}{a^2} + \frac{C}{B} - 1 \right] \qquad a^2 = \gamma^2 \overline{\vartheta^2}$$



$$\overline{\vartheta^2} = \chi_c^2 B$$

$$B - \ln B = \ln(\varepsilon^2 R^2 \chi_c^2) + 1 - 2C$$

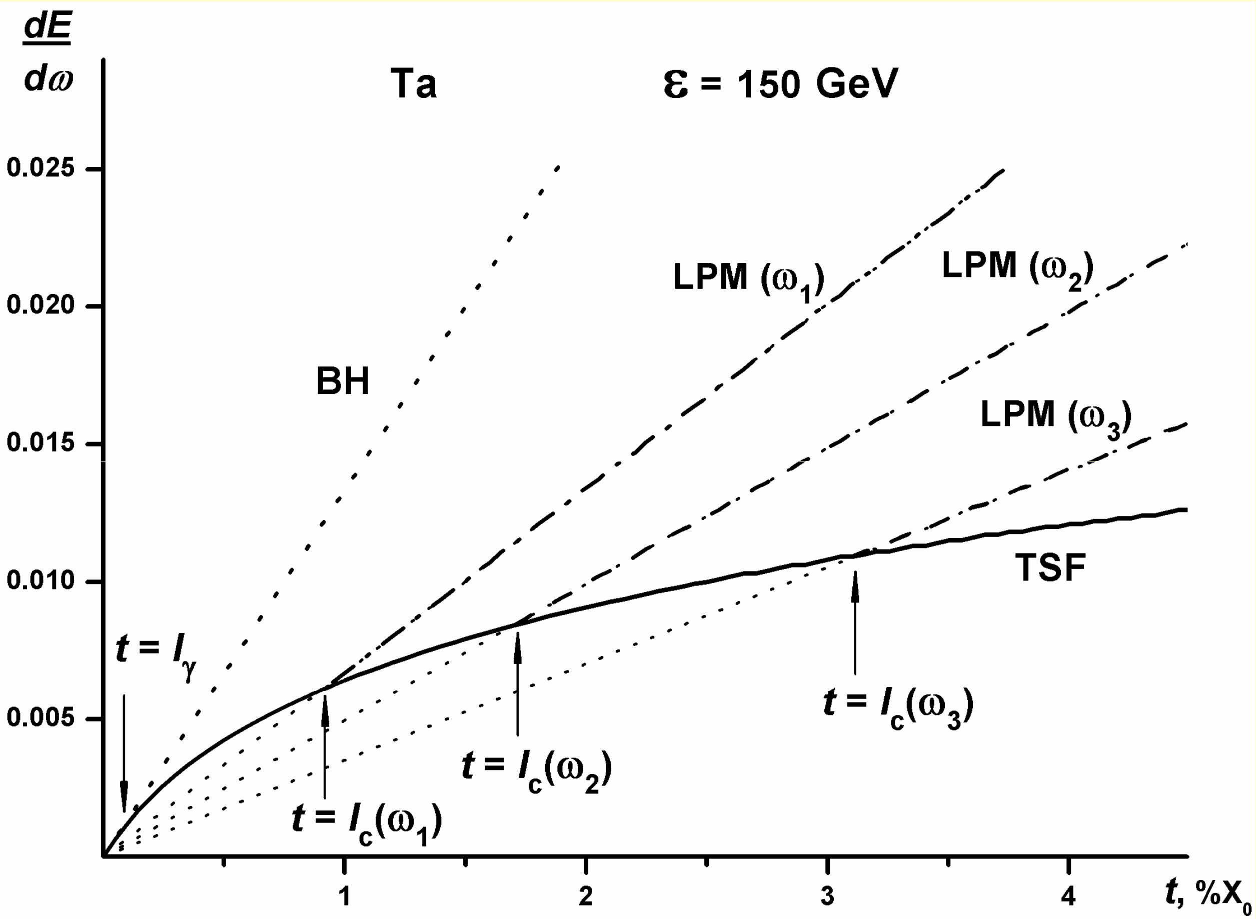
$$\chi_c^2 = 4\pi\, nLZ^2 e^4 / \varepsilon^2$$

$$C = 0{,}577$$

Thickness dependence !!!

N. Shul'ga, S. Fomin: JETP Lett. **27**(1978)126. Phys.Let.A **114**(1986)148; JETP **86**(1998)32

$$\omega_{TFS} = \frac{\varepsilon}{1+\varepsilon_{TSF}/\varepsilon} \qquad \varepsilon_{TSF} = m^2 t/2 \approx 6.6\ \mathrm{PeV}\cdot t\,(\mathrm{cm})$$



If $\varepsilon << \varepsilon_{TSF}$:

$\omega_{TSF} \approx 2\gamma^2/t$

$t \approx l_c(\omega)$

ω_1 = 800 MeV

ω_2 = 350 MeV

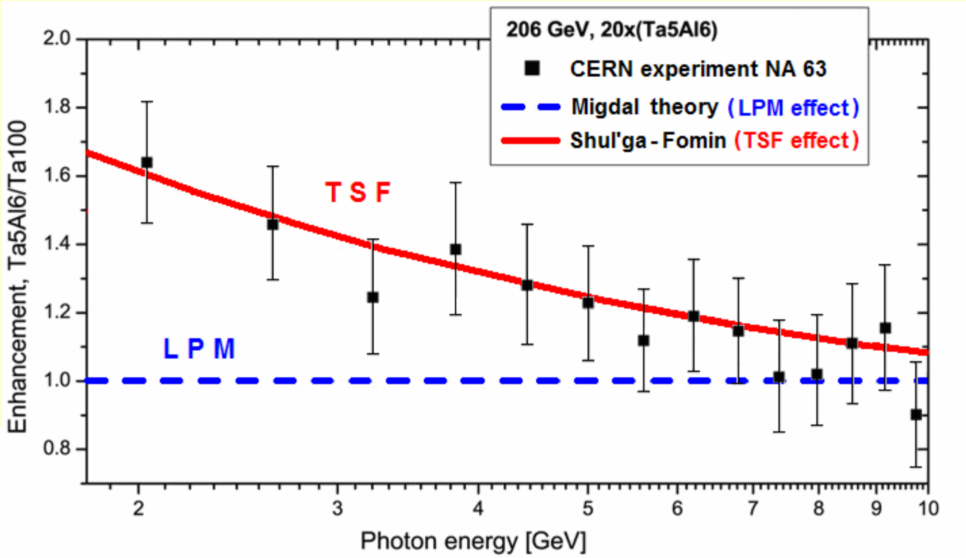
ω_3 = 150 MeV

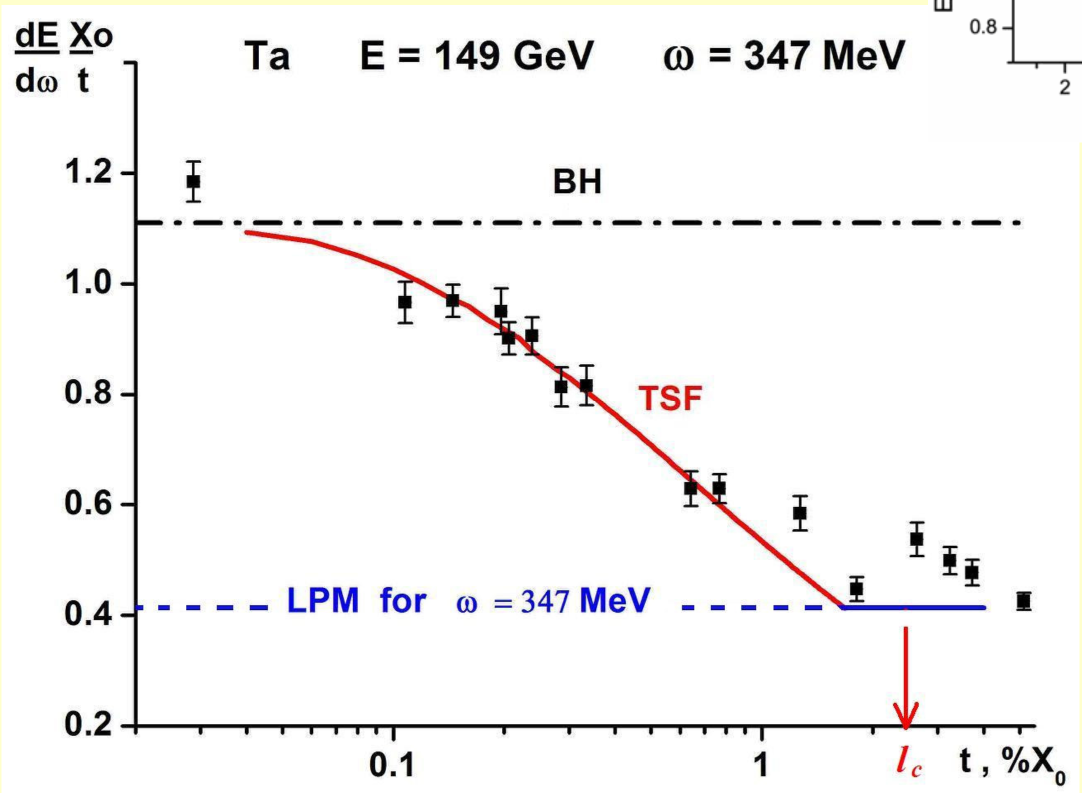
CERN NA63 experiment 2005-2010

Ulrik I.Uggerhoj et al. Phys.Rev. D 72 (2005) 112001.

H.D.Thomsen et al. Phys.Lett. B 672 (2009) 323–327.

H.D.Thomsen et al., Phys. Rev. D 81 (2010) 052003.





A.S.Fomin, S.P.Fomin, N.F.Sul'ga,

Nuovo Cimento 34C (2011) 45-53.

CERN experiment NA63 - June 2009

June 5, 2009

Dear Nikolai and Serguei,

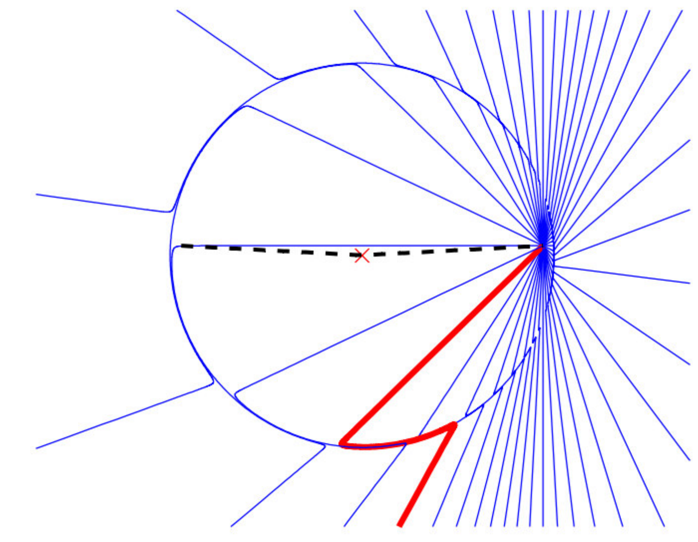
It is a pleasure for me to tell you that in the CERN experiment we are running these days, we have confirmed the logarithmic thickness dependence that your theory for thin targets has predicted, …

… we are certain that the effect is there, and we thought we would let you know that we have 'seen' the 'half-bare' electron :-)

Best regards from all of us at NA63,

Ulrik Uggerhoj

Spokesman of CERN NA63 collaboration
Professor, Aarhus University, Denmark



(a) *Single Scattering.*

BH, LPM and TSF theories applicability ranges

Thickness dependence of radiation spectral density

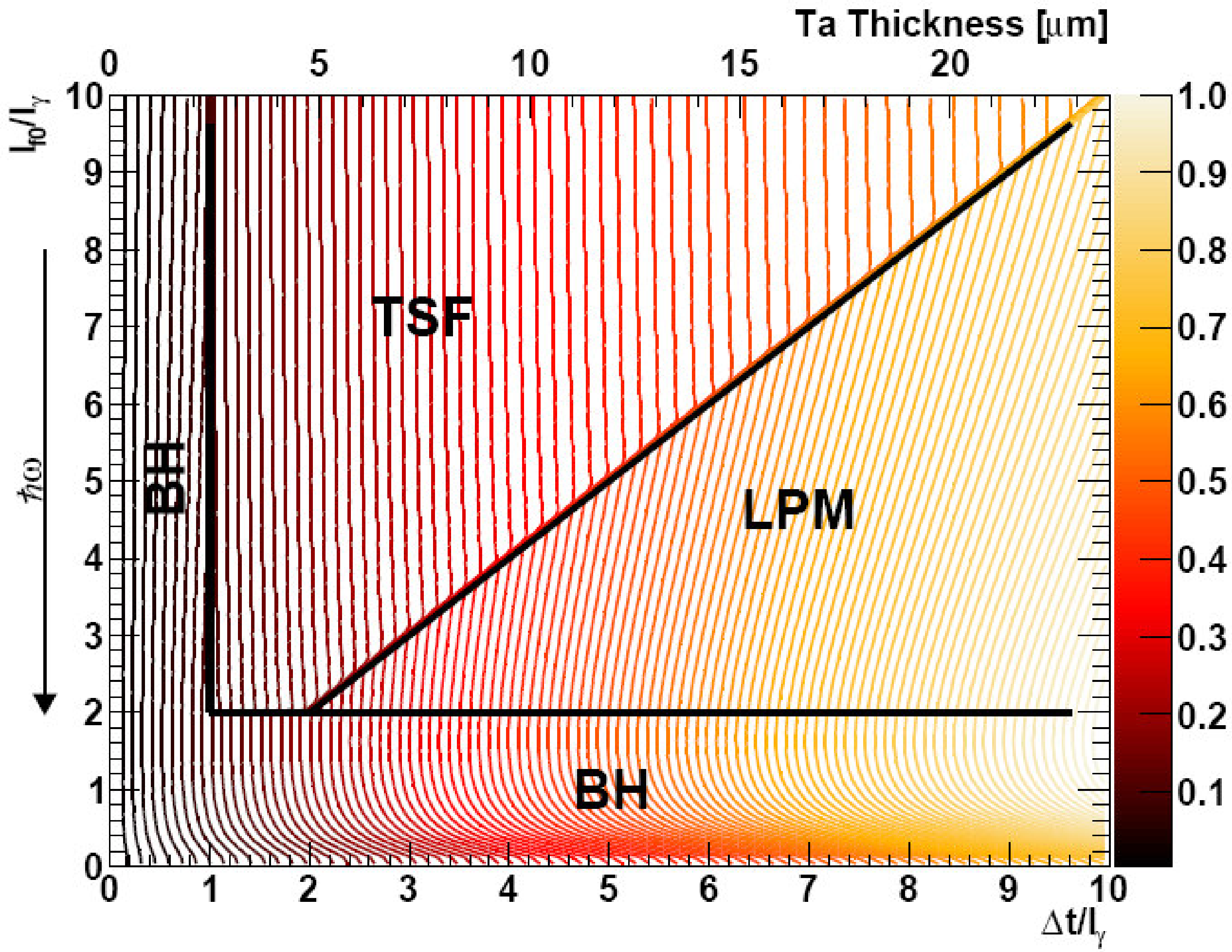


Figure 4.8: The bremsstrahlung power spectrum level (in arbitrary units) in a small part of the $(\Delta t, \ell_{f0}, \ell_\gamma)$ parameter space. The contour lines trace lines of equal bremsstrahlung yield. Upper horizontal axis shows the equivalent tantalum thickness. For the calculation, $E_0 = 200$ GeV and tantalum have been assumed.

The cover picture from H.Thomsen PhD thesises

$$\vartheta_{ms}(l_\gamma) = 1/\gamma$$

$$l_\gamma = \frac{e^2}{2\pi} X_0$$

$$l_c = \frac{2\varepsilon\varepsilon'}{m^2\omega}$$

Multiple scattering effects on the dynamics and radiation of fast charged particles in crystals. Transients in the nuclear burning wave reactor.

Alex Fomin

Laboratoire de l'Accélérateur Linéaire
Université Paris-Sud/IN2P3, Orsay, France

V.N. Karazin Kharkiv National University
Kharkiv, Ukraine

22.09.2017 / Defense of PhD thesis

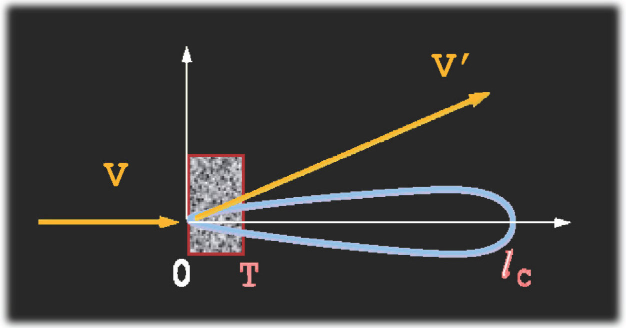
Special features of radiation in a thin target

Spectral-angular density of radiation

$$\frac{d^2E}{d\omega do} = \frac{e^2\omega}{4\pi^2}\left|\vec{n}\times\vec{I}\right|^2, \quad \vec{I} = i\int_0^T dt\, e^{i(\omega t - \vec{k}\cdot\vec{r}(t))}\frac{d}{dt}\frac{\vec{v}(t)}{\omega - \vec{k}\cdot\vec{v}(t)}$$

Coherent length

$$l_c = \frac{2\gamma^2}{\omega}$$



$$\vec{I} \approx i\left(\frac{\vec{v}'}{\omega - \vec{k}\cdot\vec{v}'} - \frac{\vec{v}}{\omega - \vec{k}\cdot\vec{v}}\right),$$

$$l_c \gg T$$

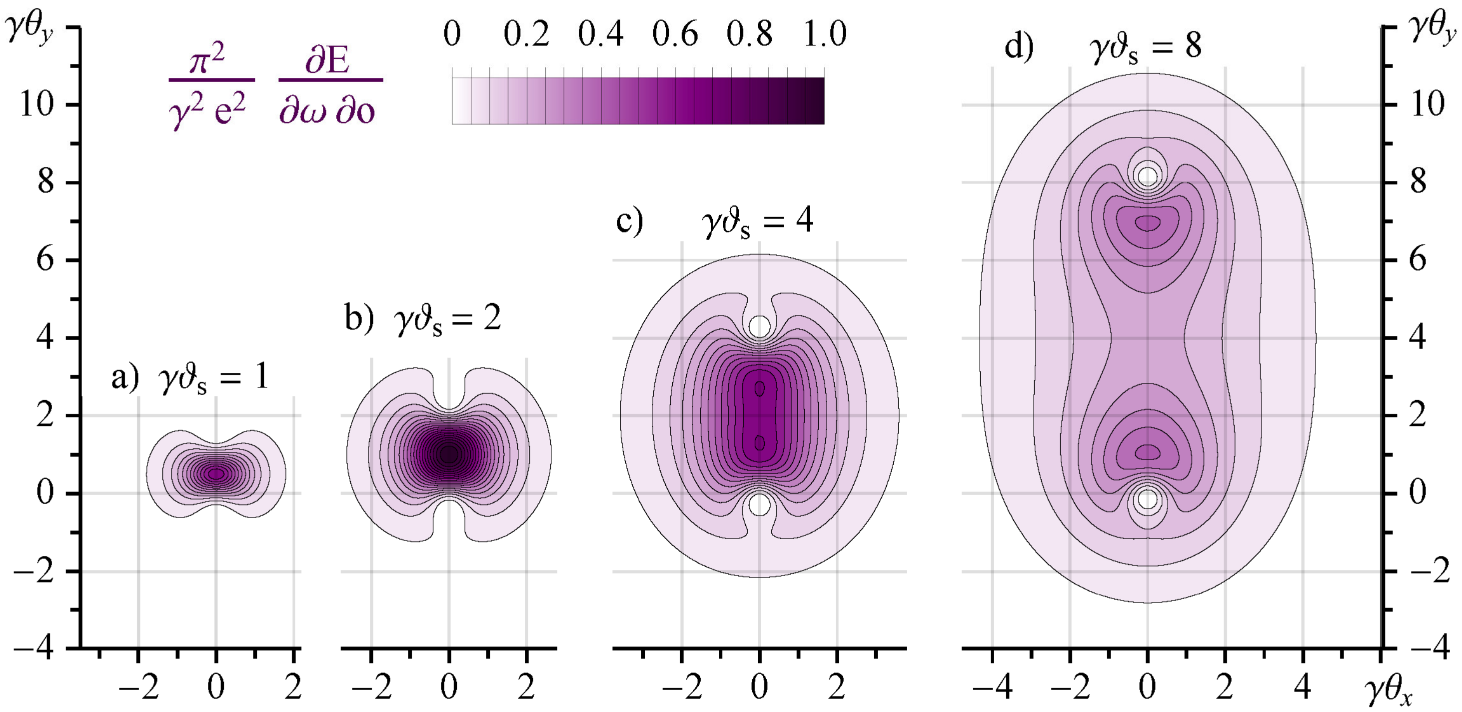
Polarization tensor

$$J_{ik} = \frac{e^2\omega^2}{4\pi^2}\left(\vec{e}_i\vec{I}\right)\left(\vec{e}_k\vec{I}^*\right)$$

$$\frac{d^2E}{d\omega do} = J_{11} + J_{22} = \frac{e^2\gamma^2}{\pi^2}\,\frac{\beta^2}{(1+\alpha^2)^2}\,\frac{\left(\left(1-\alpha^2\right)\sin\phi + \alpha\beta\right)^2 + \left(1+\alpha^2\right)^2\cos^2\phi}{\left(1+\alpha^2+\beta^2 - 2\,\alpha\beta\sin\phi\right)^2}$$

$\alpha = \gamma\,\theta$, θ and φ are the polar and azimuthal angles of emitted photon, $\beta = \gamma\,\theta_s$

Radiation in a thin target: dipole and non–dipole case



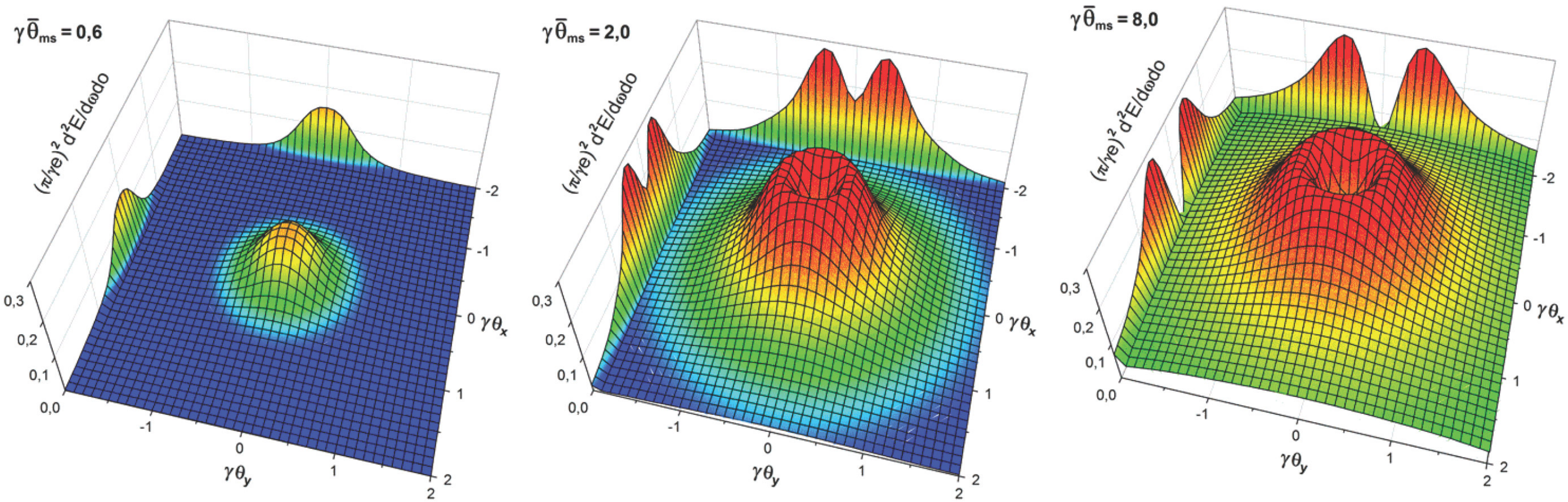
$$\frac{d^2E}{d\omega do} = \frac{e^2\gamma^2}{\pi^2}\,\frac{\beta^2}{(1+\alpha^2)^2}\,\frac{\left((1-\alpha^2)\sin\phi+\alpha\beta\right)^2+\left(1+\alpha^2\right)^2\cos^2\phi}{(1+\alpha^2+\beta^2-2\,\alpha\beta\sin\phi)^2}$$

$\alpha = \gamma\,\theta$, θ and φ are the polar and azimuthal angles of emitted photon, $\beta = \gamma\,\theta_{\rm s}$

Radiation of an electron beam in a thin amorphous media

$$\left\langle \frac{d^2E}{d\omega do} \right\rangle = \int d^2\vartheta_s \, f_{\mathrm{BM}}(\vartheta_s) \, \frac{d^2E}{d\omega do}$$

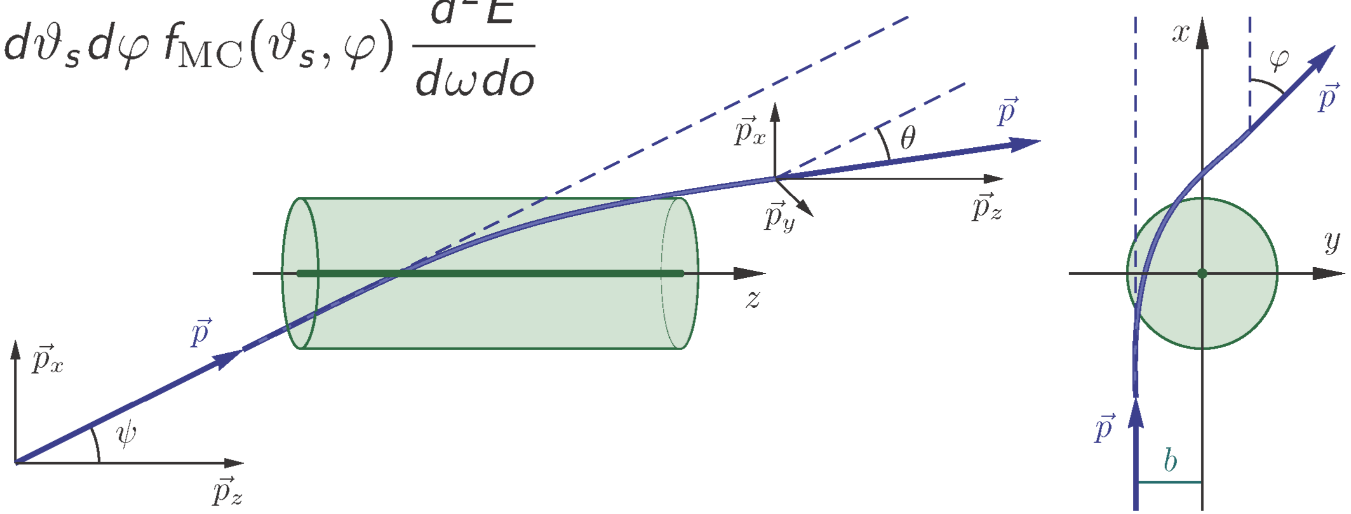
$$f_{\mathrm{BM}}(\vartheta_{\mathrm{s}}) = \frac{1}{2\pi} \int_0^T \eta \, d\eta \, J_0(\eta \, \vartheta_{\mathrm{s}}) \times \exp\left\{-n \, T \int \chi \, d\chi \, \sigma(\chi)[1 - J_0(\eta \, \chi)]\right\}$$



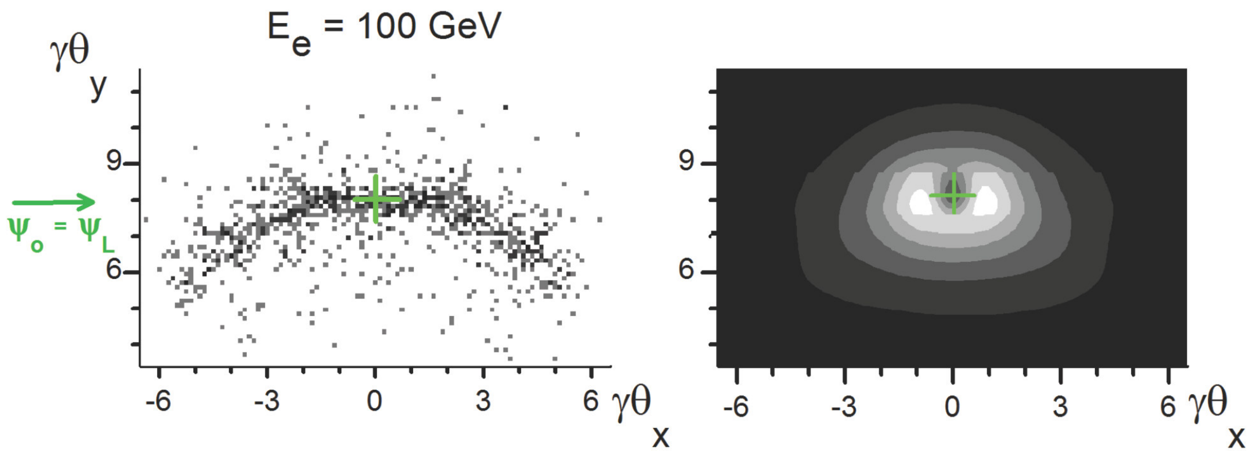
Important for future lepton colliders (ILC or CLIC)

Radiation in a thin crystal

$$\left\langle \frac{d^2E}{d\omega do} \right\rangle = \int \sin\vartheta_s d\vartheta_s d\varphi\, f_{\mathrm{MC}}(\vartheta_s,\varphi)\, \frac{d^2E}{d\omega do}$$



$f_{\mathrm{MC}}(\vartheta_s,\varphi) \leftarrow$ computation model described above



Polarization of radiation in a thin crystal

$$P_{\mathrm{L}} = \frac{J_{11} - J_{22}}{J_{11} + J_{22}}$$

$$P_{\mathrm{circ}} = \frac{J_{12} - J_{21}}{J_{11} + J_{22}}$$

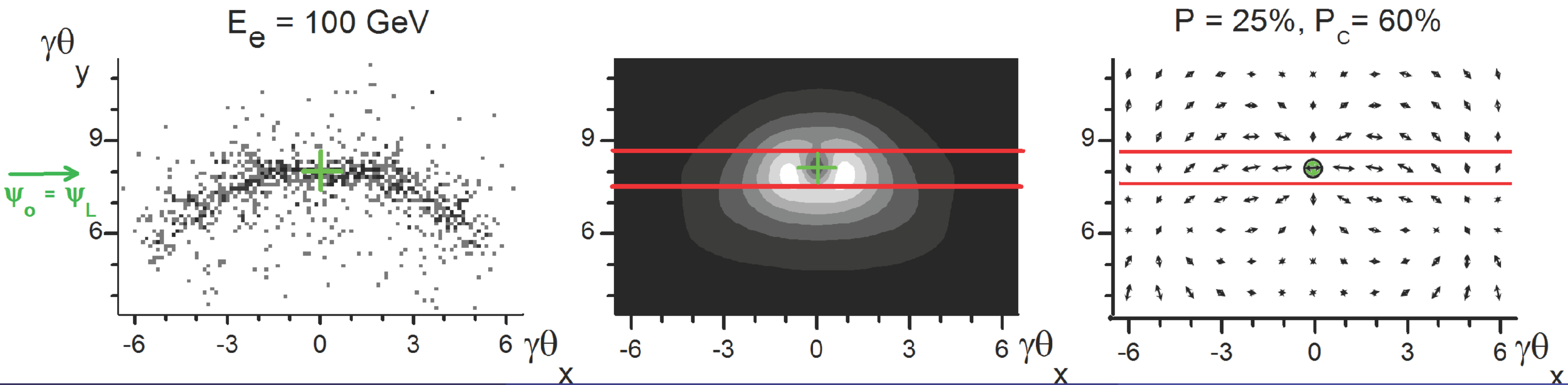
Polarization tensor

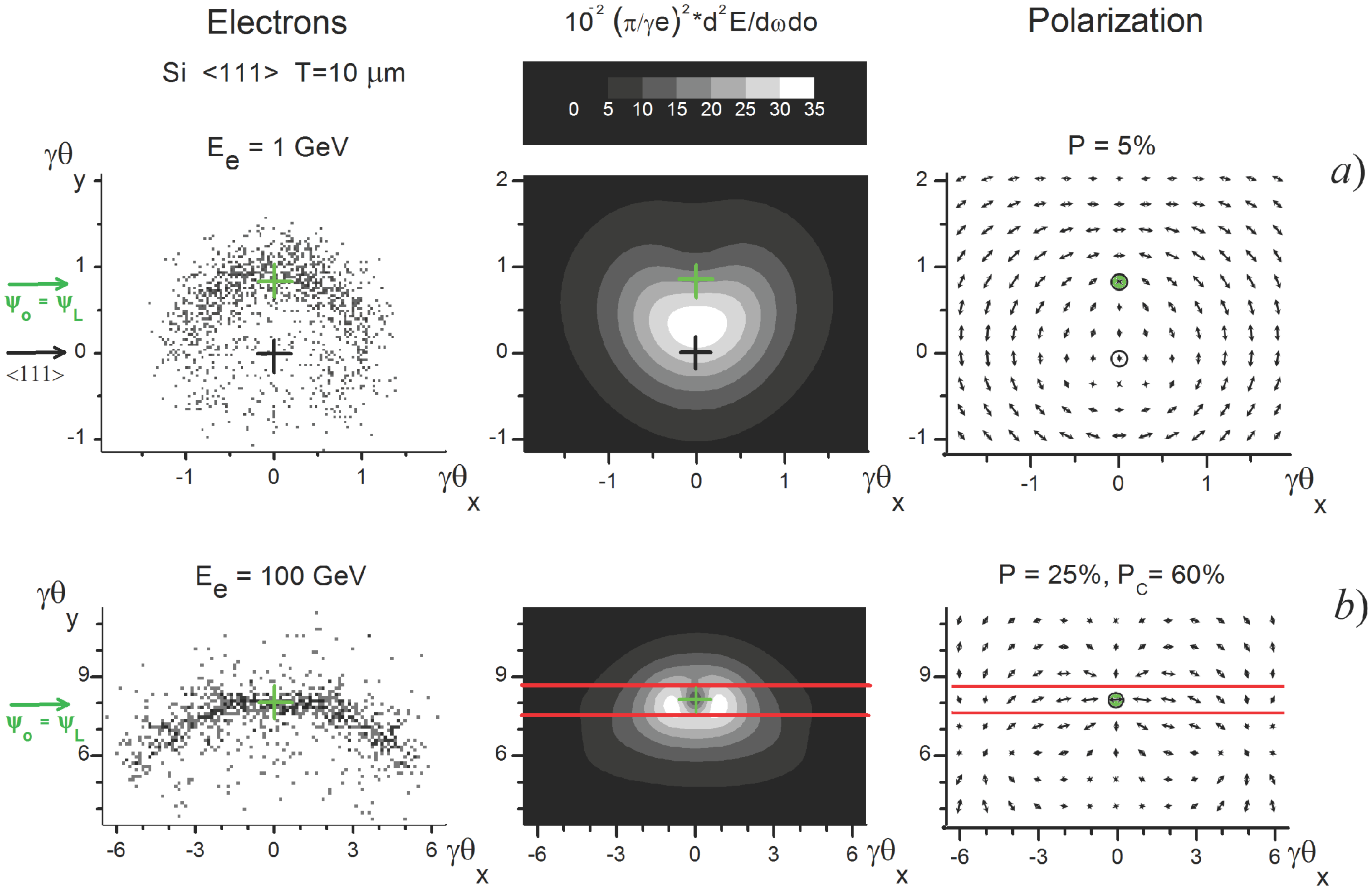
$$J_{ik} = \frac{e^2\omega^2}{4\pi^2} \left(\vec{e}_i \vec{I}\right) \left(\vec{e}_k \vec{I}^*\right)$$

$$\vec{I} = i \int_0^T dt\, e^{i(\omega t - \vec{k}\cdot\vec{r}(t))} \frac{d}{dt} \frac{\vec{v}(t)}{\omega - \vec{k}\cdot\vec{v}(t)}$$

$$P_{\mathrm{L}} = 1 - \frac{2\,\alpha^2 \cos^2\phi\ \left(\beta - 2\,\alpha\ \sin\phi\right)^2}{\left((1-\alpha^2)\sin\phi + \alpha\beta\right)^2 + (1+\alpha^2)^2 \cos^2\phi}$$

$$P_{\mathrm{circ}} = 0$$



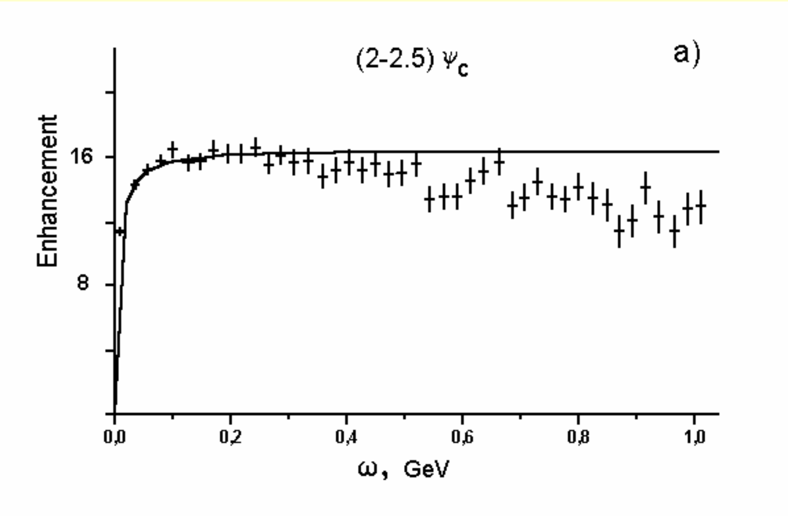


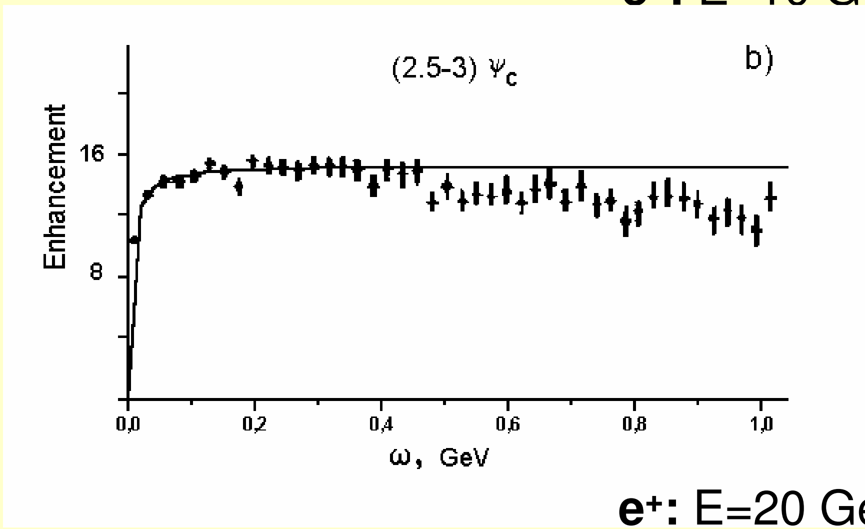
One can produce polarized beam if running in a non-dipole regime

CERN experiment: **Bak J.F. et al.** Nucl. Phys., **B302** (1988) 525.

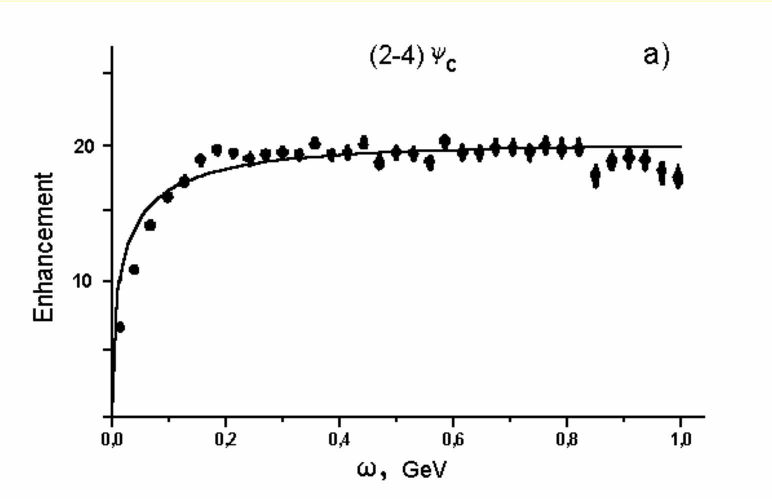
Theory: **Laskin N., Shul'ga N.,** Phys.Lett. **A135** (1989) 147.

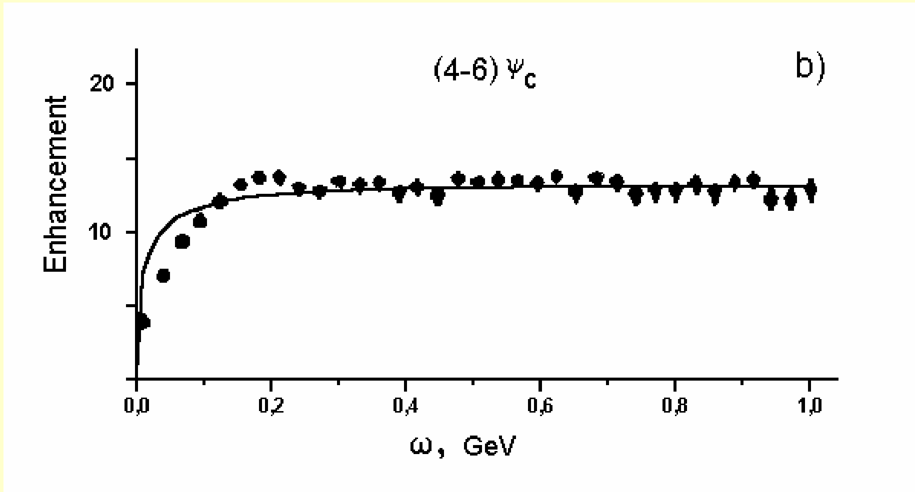
e^- : E=10 GeV





e^+: E=20 GeV





Multiple scattering on crystal atomic strings in random string approximation

$$\frac{d}{dz} f(\varphi, z) = n\, d\, \psi \int_{-\infty}^{\infty} db \left[f(\varphi + \varphi(b), z) - f(\varphi, z) \right] \qquad \int_{-\pi}^{\pi} d\varphi\; f(\varphi, z) = 1$$

$$f(\varphi, z) = \frac{1}{2\pi} \sum_{k=-\infty}^{\infty} \cos k\varphi \, \exp\left\{ -n d \psi z \int_{-\infty}^{\infty} db \left[1 - \cos(k\varphi(b)) \right] \right\}$$

$$\vartheta(b) = 2\psi \sin\frac{\varphi(b)}{2} \qquad \overline{\vartheta^2} = \int_{-\pi}^{\pi} d\varphi\, f(\varphi, z)\, 4\psi^2 \sin^2 \frac{\varphi}{2}$$

$$\overline{\vartheta^2} = 2\psi^2 \left\{ 1 - \exp\left[-2 n d \psi z \int_{-\infty}^{\infty} db \sin^2\left(\frac{\varphi(b)}{2} \right) \right] \right\}$$

Multiple scattering on crystal atomic strings in random string approximation

$$\overline{\vartheta^2} = 2\psi^2 \left\{ 1 - \exp\left[-2 n\, d\, \psi\, z \int_{-\infty}^{\infty} db \sin^2\left(\frac{\varphi(b)}{2} \right) \right] \right\}$$

For $qU(\rho) = \frac{\pi}{2}\frac{R}{\rho}U_0$ $\quad f(\varphi, z) = \frac{1}{2\pi}\frac{\operatorname{sh} B}{\operatorname{ch} B - \cos\varphi}$ $\quad B = \pi\, d\, n\, z\, \psi_c^{\;2} R / \psi$

$$\vartheta(b) = 2\psi \sin\frac{\varphi(b)}{2} \qquad \overline{\vartheta^2} = 2\psi^2 \left\{ 1 - \exp\left[-\pi n\, d\, R\, \psi_{\mathrm{c}}^{\;2}\, z / \psi \right] \right\}$$

For thick crystal ($T \sim L_0$) : $\quad \mathrm{B} >> 1$ $\quad f(\varphi, z) = \frac{1}{2\pi}$ $\quad \overline{\vartheta^2} = 2\psi^2$

L_0 – thickness of uniform distribution: $\quad \frac{1}{L_0} = nd\,\psi \int_{-\infty}^{\infty} db\left[1 - \cos(\varphi(b)) \right]$

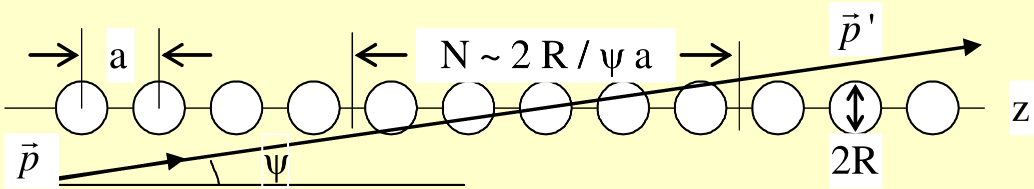
Multiple scattering on crystal atomic strings in random string approximation

$\psi \gg \psi_c$:

$$\frac{d}{dz} f = \frac{1}{2} n d \psi \left(\int_{-\infty}^{\infty} db\, \varphi^2(b) \right) \frac{\partial^2 f}{\partial \varphi^2} \qquad f(\varphi, z) = \frac{1}{\sqrt{2\pi \overline{\overline{\varphi^2}}}} \exp\left(-\frac{\varphi^2}{2\overline{\overline{\varphi^2}}} \right)$$

$$\vartheta(b) = 2\psi \sin\frac{\varphi(b)}{2} \qquad \overline{\varphi^2} \ll 1 \qquad \overline{\varphi^2} = ndz\,\psi \int_{-\infty}^{\infty} db\, \varphi^2(b)$$

$$U_L(\rho) = \frac{1}{2} U_0 \ln\left(1 + \frac{3R^2}{\rho^2} \right) \qquad \overline{\vartheta^2}(\mathrm{T}) = \sqrt{3}(4-\pi) 4\pi^2 \mathrm{Z}^2 \mathrm{e}^4 n\, R\, \mathrm{T} / (\varepsilon^2 \psi d)$$

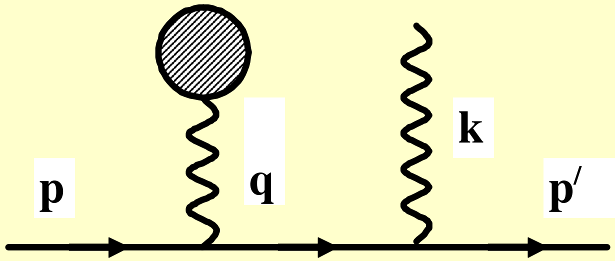


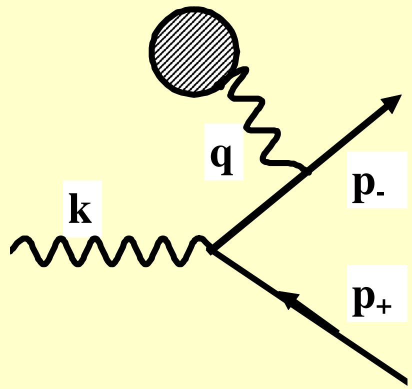
$$\overline{\vartheta^2} / \overline{\vartheta^2}_{am} \approx R / \psi d \qquad \text{!!!}$$

S.P. Fomin, N.F. Shul'ga. On the theory of fast particles scattering in a crystal. Preprint KFTI 79-42, Kharkov, 34c., 1979.

N.F. Shul'ga, V.I. Truten', S.P. Fomin, Journal of Thech. Phys., 52 (1982) 2279.

Bremsstrahlung and e^+e^- - pair production



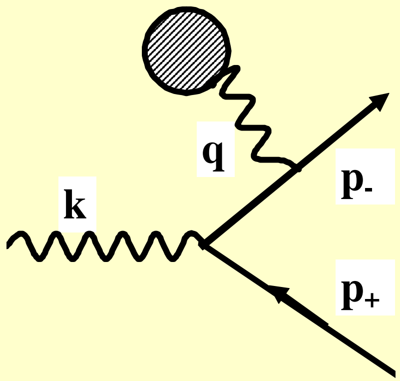


$$\varepsilon \to -\varepsilon_+ , \quad \varepsilon' \to \varepsilon_- , \quad \omega \to -\omega , \quad d\omega \to \varepsilon_+^2 \, d\varepsilon_+ / \omega$$

$$d\sigma_{BH} = 4e^2 \left(\frac{Ze^2}{m} \right)^2 \left\{ \left[1 - \frac{2}{3} \frac{\varepsilon'}{\varepsilon} + \left(\frac{\varepsilon'}{\varepsilon} \right)^2 \right] \ln\left(183 \cdot Z^{-1/3} \right) + \frac{1}{9} \frac{\varepsilon'}{\varepsilon} \right\} \frac{d\omega}{\omega}$$

$$d\sigma_{BH}^{\pm} = 4e^2 \left(\frac{Ze^2}{m} \right)^2 \left\{ \left(1 - \frac{4\varepsilon_+ \varepsilon_-}{3\omega^2} \right) \ln\left(183 Z^{-1/3} \right) - \frac{\varepsilon_+ \varepsilon_-}{9\omega^2} \right\} \frac{d\varepsilon_+}{\omega}$$

Coherence length of e$^+$e$^-$ - pair production



$$\omega = \varepsilon_+ + \varepsilon_-, \quad \mathbf{k} = \mathbf{p}_+ + \mathbf{p}_- + \mathbf{q}$$

$$r_{\|eff} \approx q_{\|eff}^{-1} \approx \boxed{l_c = \frac{2\varepsilon_+\varepsilon_-}{m^2\omega}}$$

$$q_{\|\,eff} = q_{\|\min} = \omega m^2 / 2\varepsilon_+\varepsilon_-$$

$$!!\ \omega \geq \varepsilon_\pm :\ l_c^\pm \sim \omega$$

$$d\sigma \approx \int d^2 q_\perp \int_{q_{\min}}^{\infty} dq_\| \frac{q_\perp^2}{q_\|^2} \left| U_q \right|^2$$

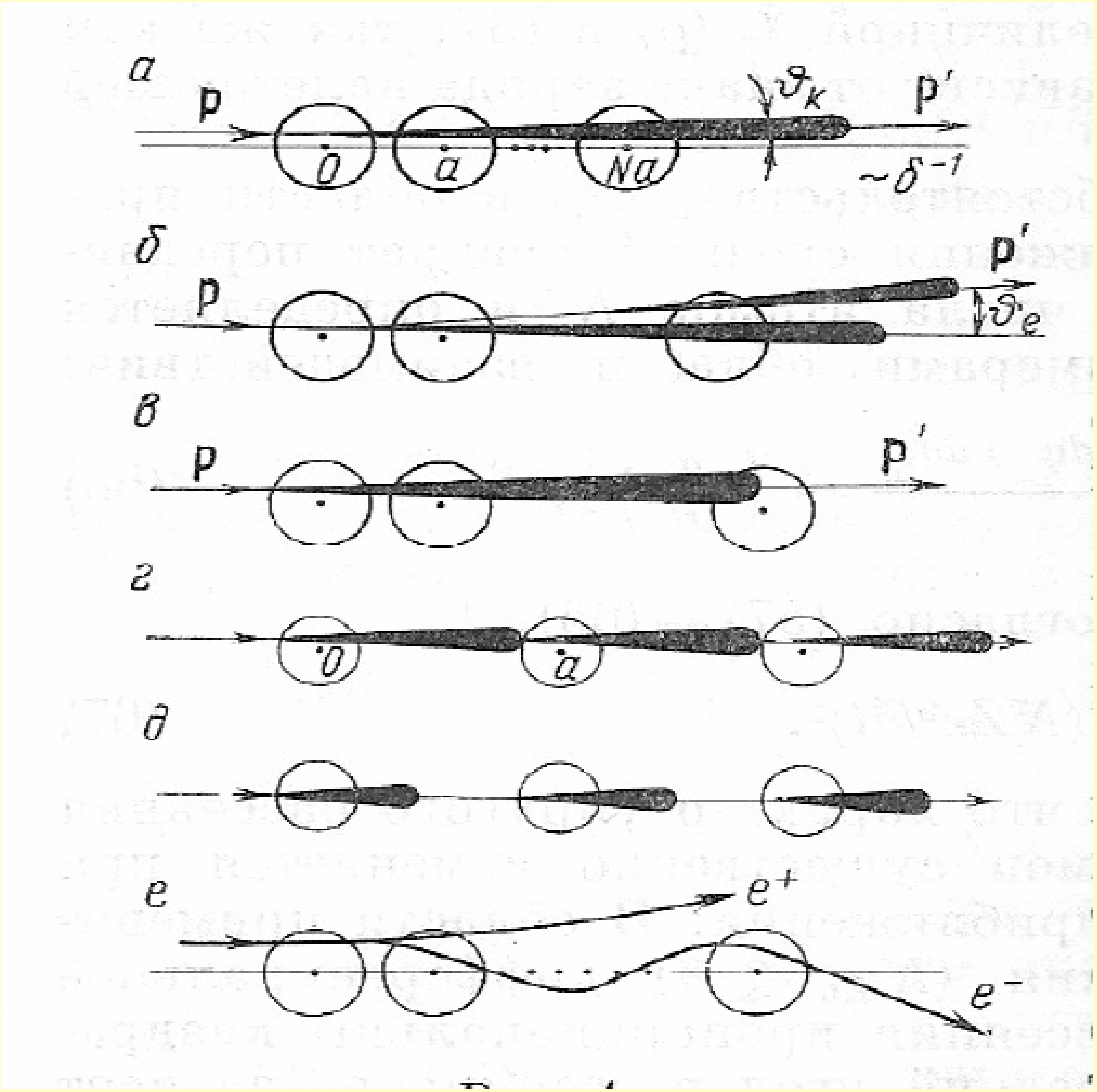
$$\omega = 1\,\text{TeV}$$

$$\varepsilon_\pm \approx 500\ \text{GeV}$$

$$r_{\perp eff} \approx 1/q_{\perp eff} \approx R \qquad U(r) = \frac{Z|e|}{r} e^{-r/R}$$

$$\underline{l_c^\pm \approx 0.5\ \mu\text{m}\ !!!}$$

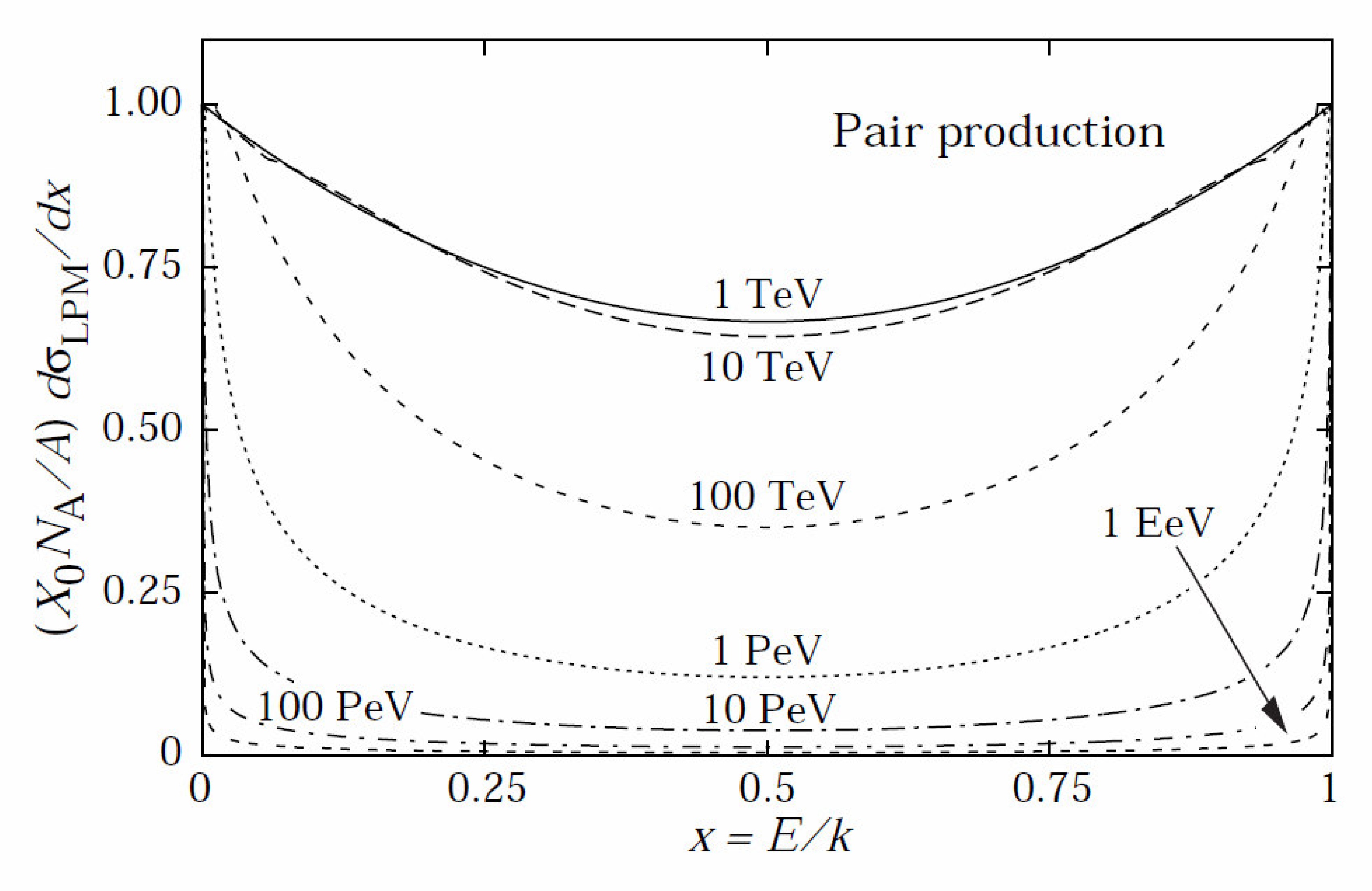
Interaction with atomic string of a crystal



Akhieser A.I., Truten' V.I., Fomin S.P., Shul'ga N.F., "Coherent effect in e^+e^--pair production in crystal" Sov. Phys. Doklady, 249 (1979) 338.

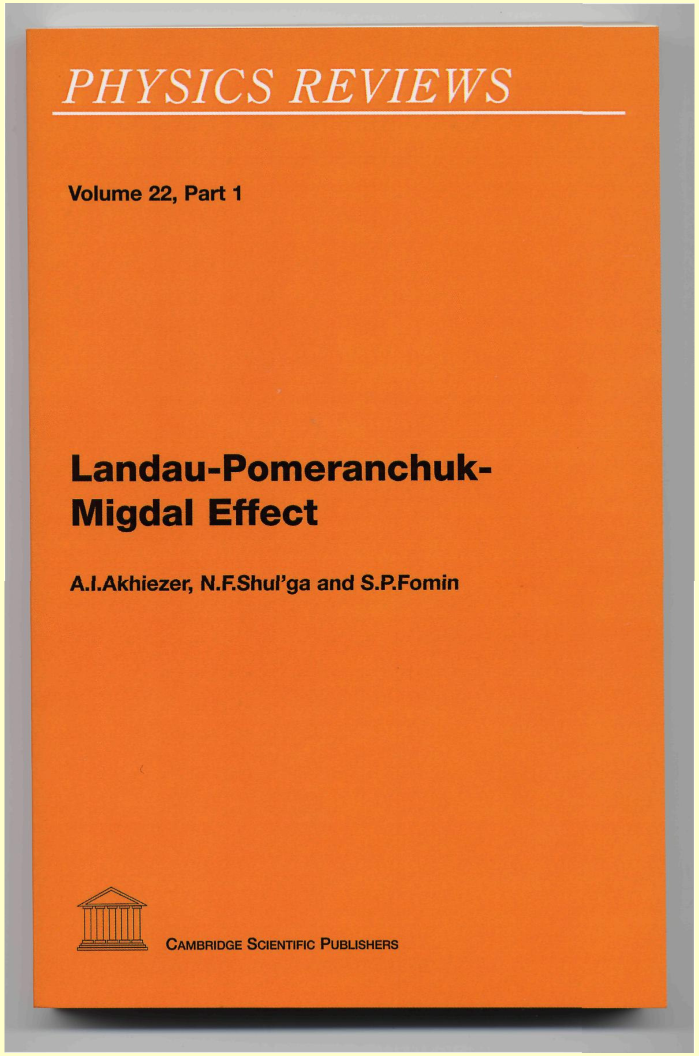
LPM effect at e^+e^--pair production ($\gamma\theta_{\pm} > 1$)

S. Eidelman et al. (PDG) Physics Letters B592 (2004) 1.



Conclusion and prospective

1. The electrodynamics processes, such as bremsstrahlug, pair production, transition radiation and some others at ultra relativistic charged particles interaction with amorphous and crystalline matter have a specific behavior connected with non-equilibrium own Coulomb field of the particle (half-bare particle).
2. The corresponding effects have to be studied in details including angular distributions and polarization characteristics both theoretically and experimentally using existing accelerators, i.e. SPS CERN, to be included in computer codes, like GEANT and others, which are using at designing detectors and other systems for a new generation of lepton colliers of TeV energy diapason (ILC, CLIC, NLC, …) as well as for cosmic rays detectors.
3. The analogous of the LPM and TSF effects have to take place in QCD at quark-gluon interactions.



2005

A.I. Akhiezer, N.F. Shul'ga, S.P. Fomin.
***The Landau-Pomeranchuk-Migdal Effect*.**
Cambridge Scientific Publishers,
Cambridge, UK, 2005, 215 p.

Thank you for attention!