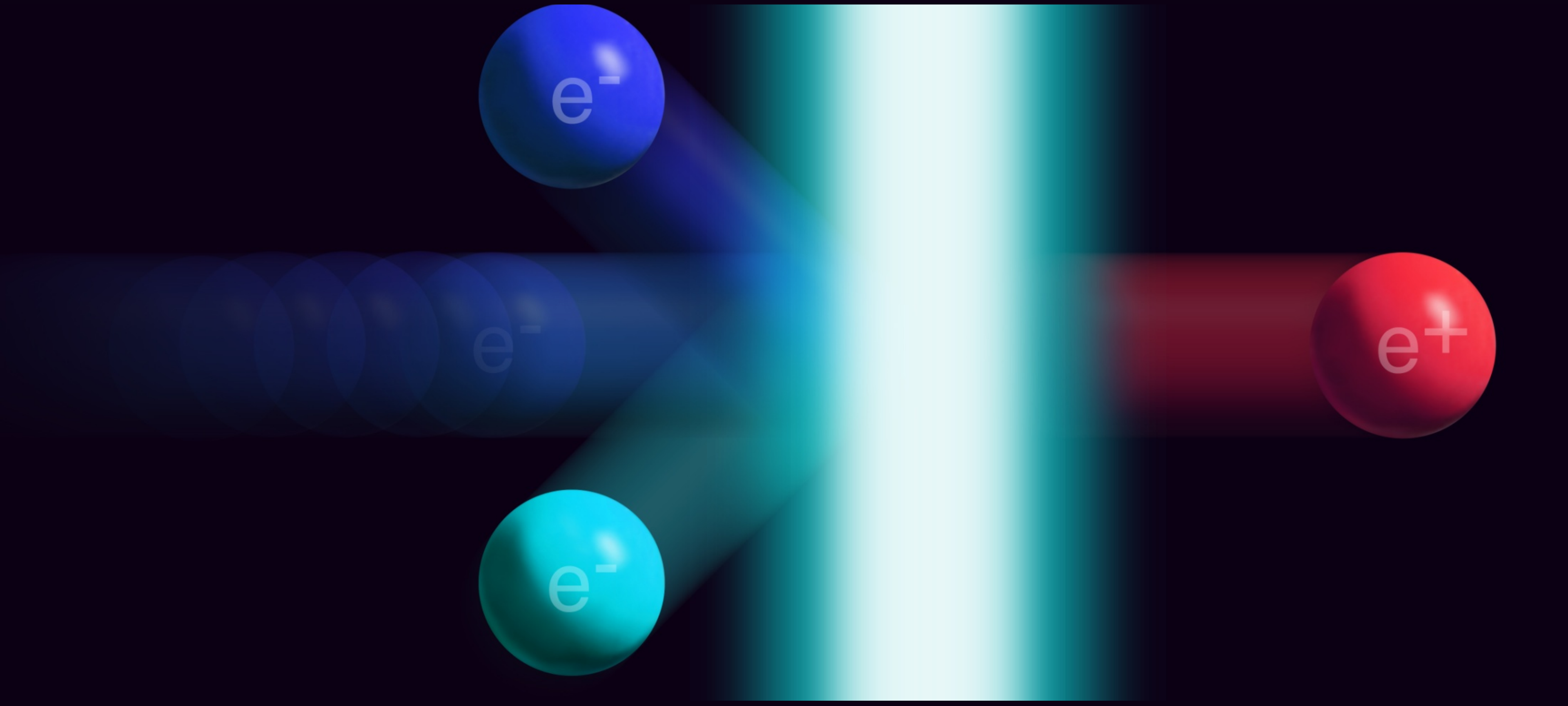
Strong-field QED and radiation-reaction effects in aligned crystals

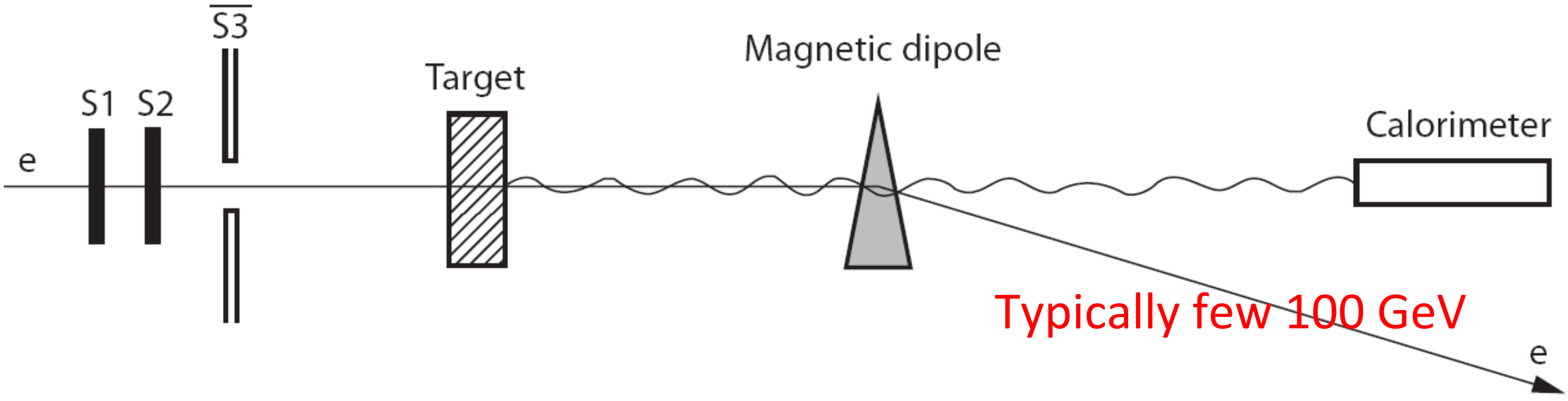


Ulrik I. Uggerhøj

Department of Physics and Astronomy, Aarhus University, Denmark

Representing the CERN NA63, SLAC T-513 and SLAC E-212 collaborations

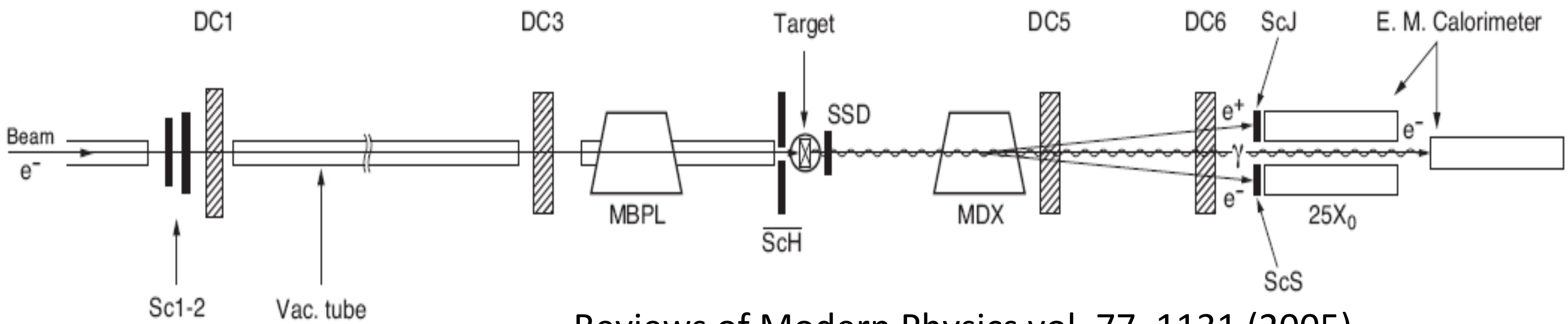
Experiments – here: CERN NA63



Ultrarelativistic particles

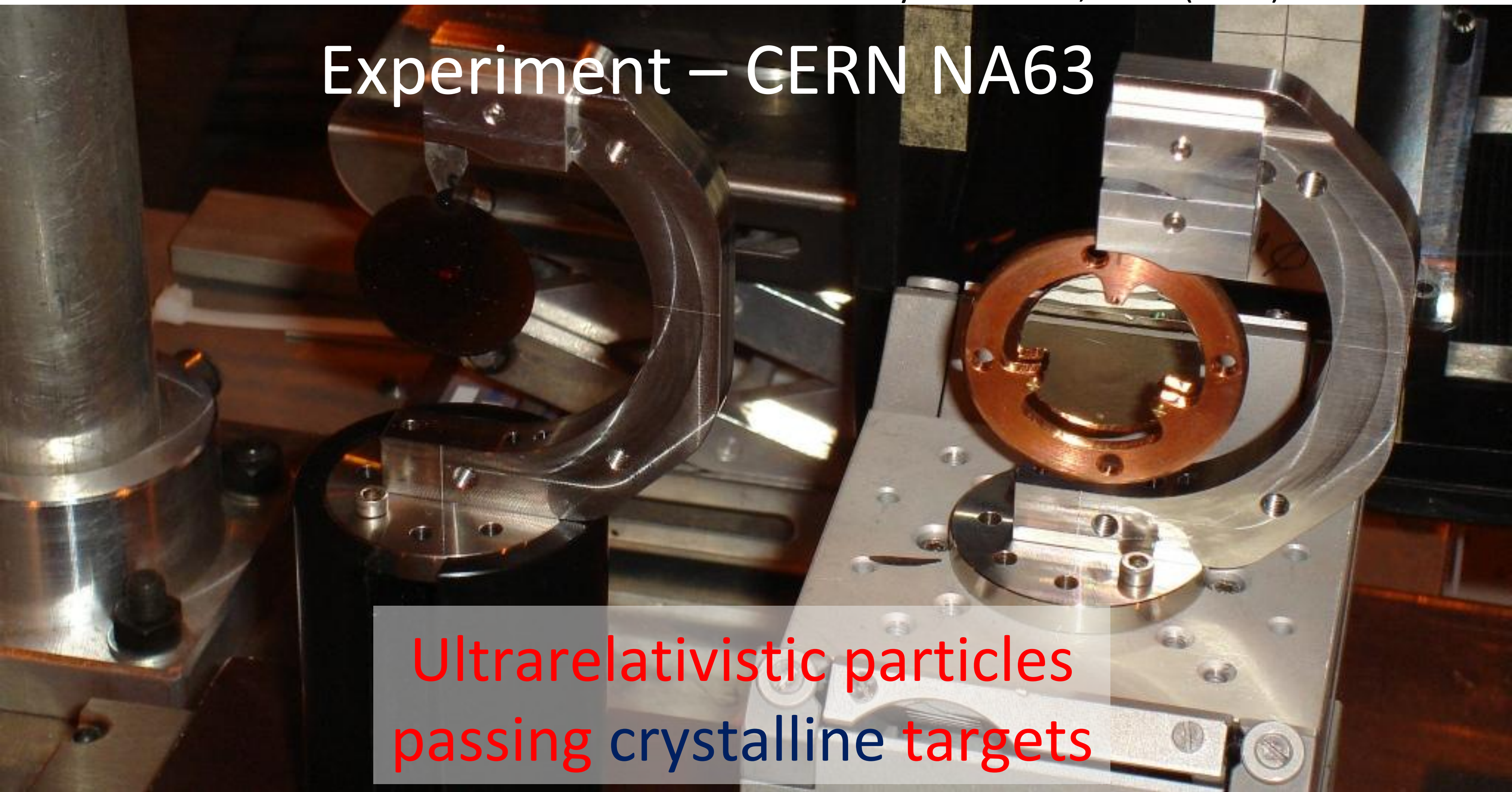
passing amorphous and crystalline targets

Radiation emission



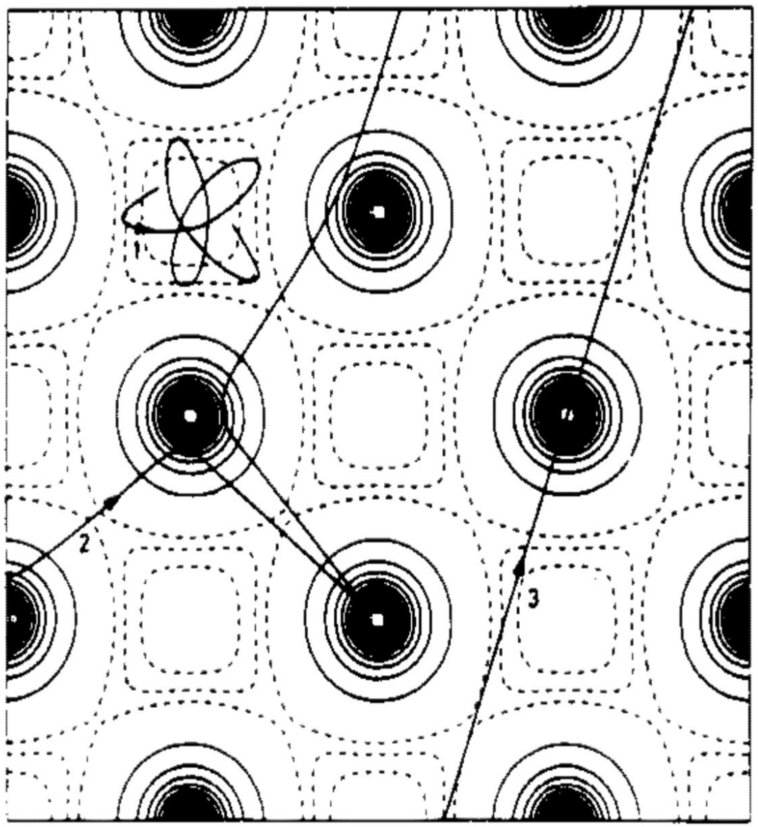
Reviews of Modern Physics vol. 77, 1131 (2005)

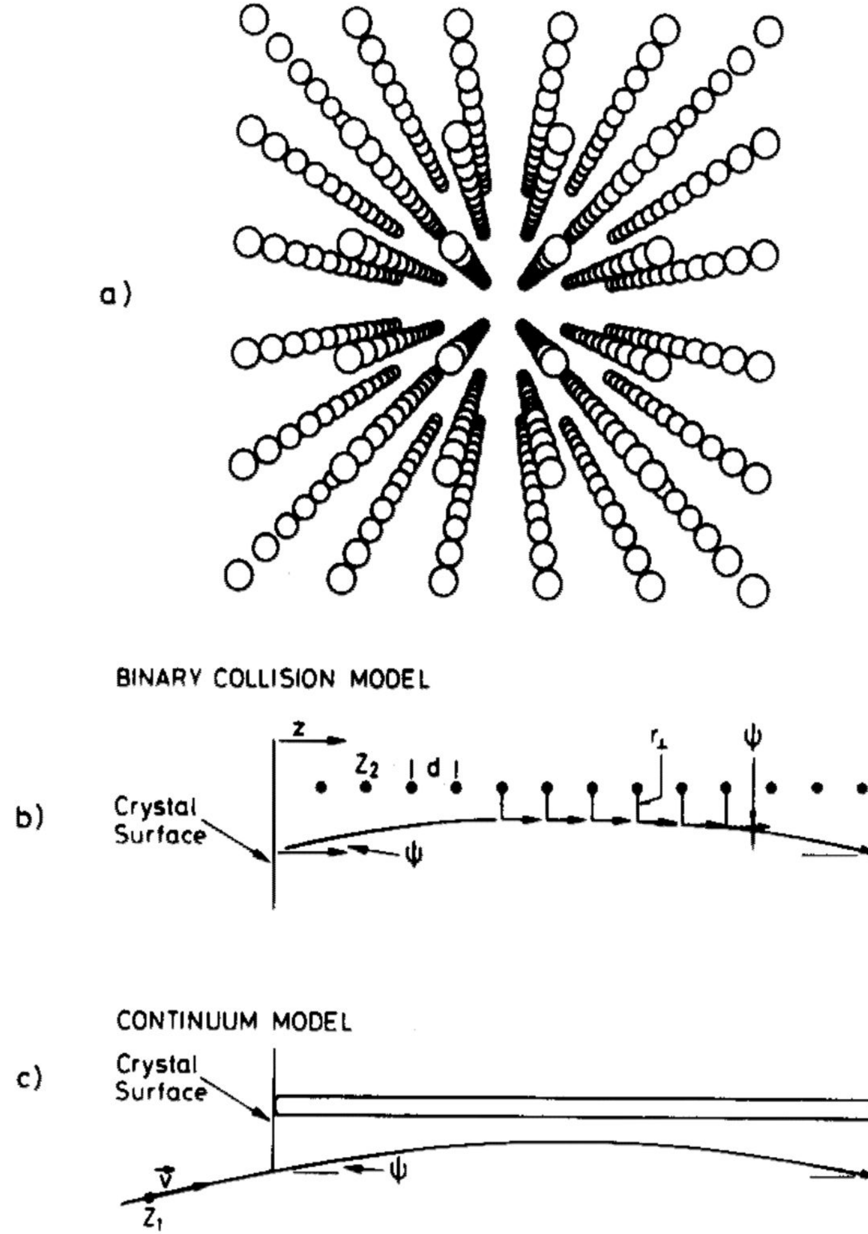
Experiment – CERN NA63



Ultrarelativistic particles passing crystalline targets

Crystals


1
2
3


a)
BINARY COLLISION MODEL
z
Z_2
d
$r_\perp$
ψ
b)
Crystal Surface
ψ
CONTINUUM MODEL
c)
Crystal Surface
$\vec{v}$
ψ
Z_1

Crystals

Extremely strong electric fields

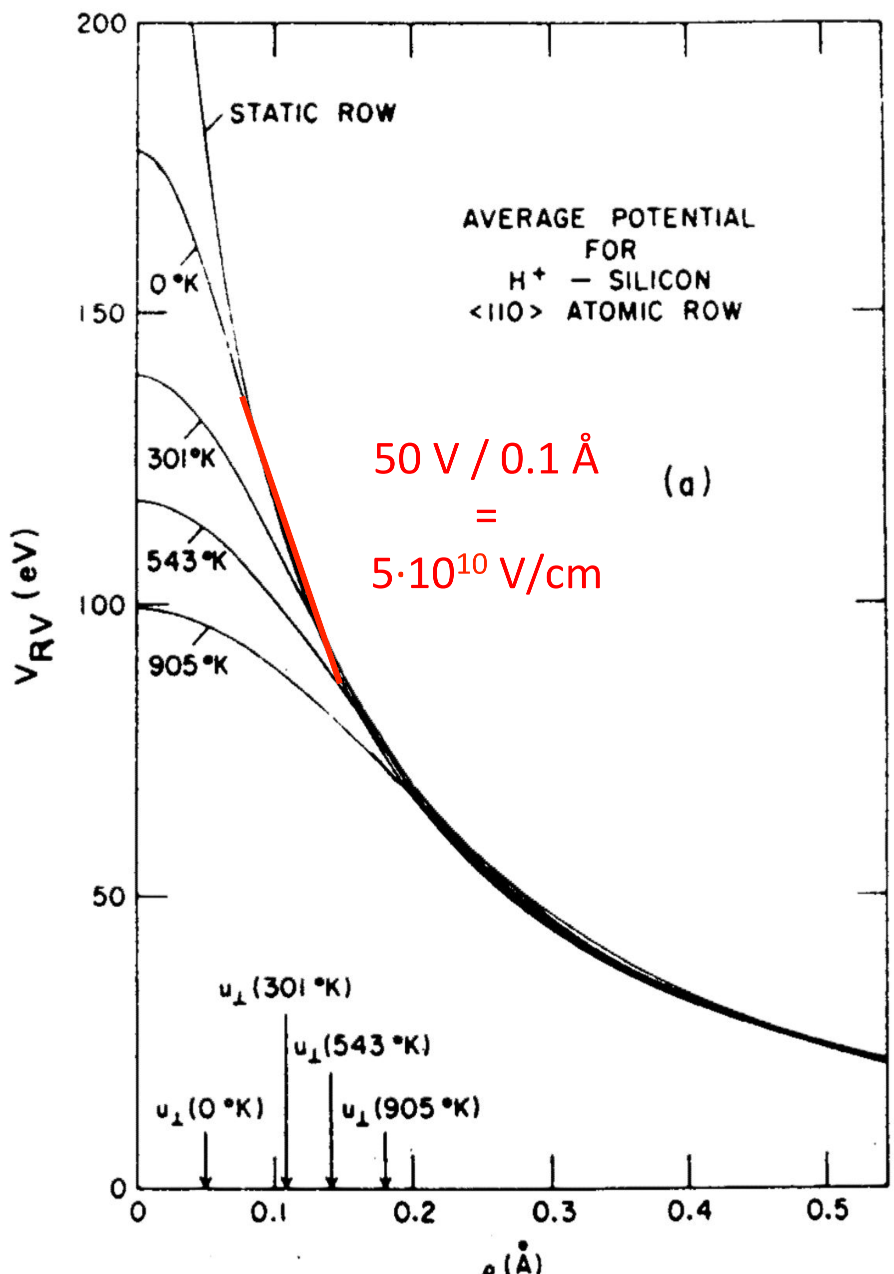
10^{10}-10^{11} V/cm

Relativistic invariant:

$$\chi = \gamma \mathcal{E} / \mathcal{E}_0$$

$$\mathcal{E}_0 = mc^2 / e\lambda\!\!\!^{-}_c$$

$=1.32\cdot 10^{16}$ V/cm



Quantum synchrotron radiation

PHYSICAL REVIEW VOLUME 75, NUMBER 12 JUNE 15, 1949

On the Classical Radiation of Accelerated Electrons

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts
(Received March 8, 1949)

$$\mathcal{E}_0 = mc^2/e\lambdabar_c$$

We shall conclude this section by briefly examining under what conditions quantum phenomena will invalidate the classical considerations we have presented. This will occur when the momentum of the emitted quantum is comparable with the electron momentum. Hence, for the validity of our classical treatment, it is required that

$$\frac{E}{mc^2} \ll \frac{mc^2}{(e\hbar/mc)H},$$

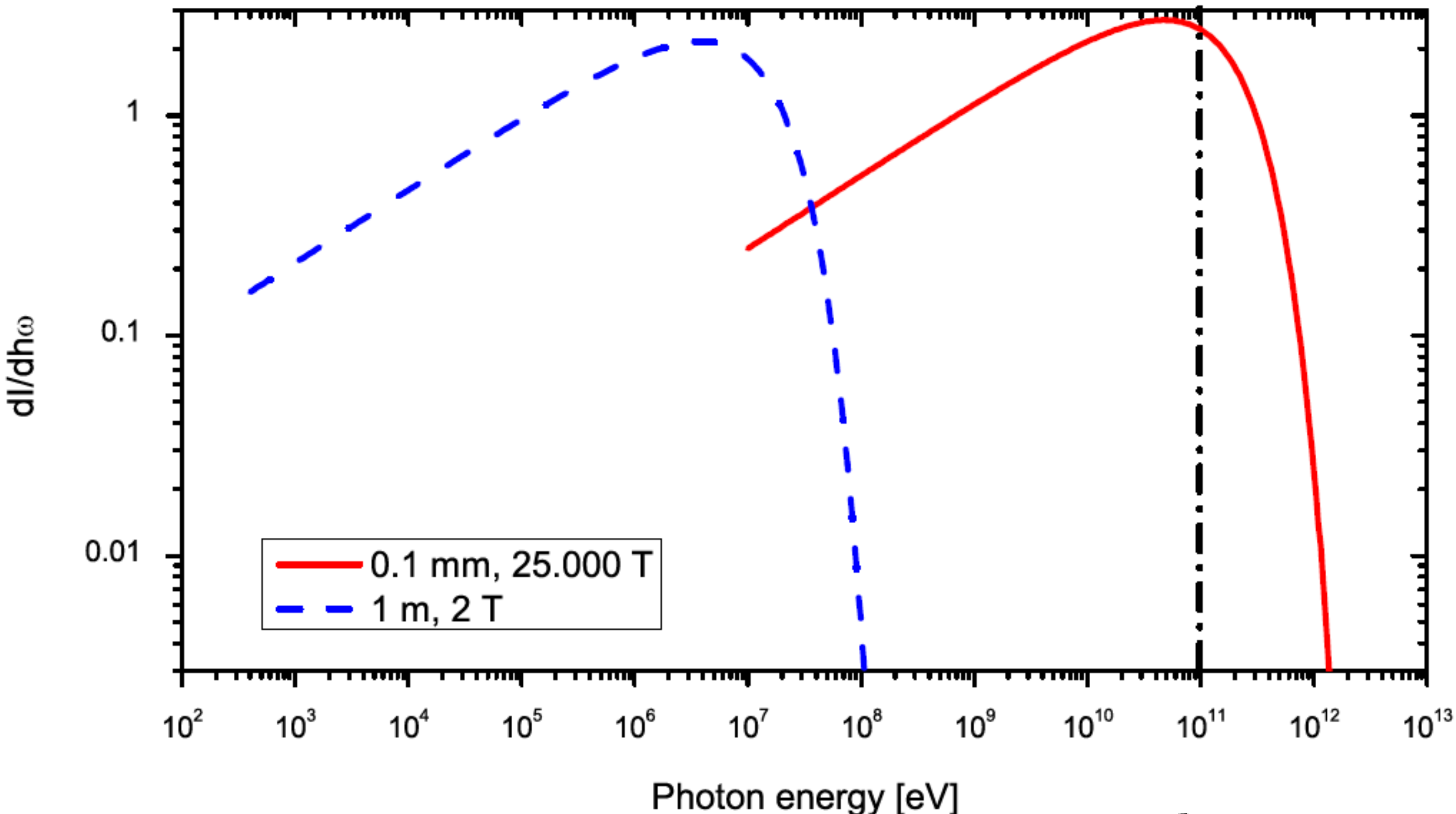
$$\chi = \frac{\gamma\mathcal{E}}{\mathcal{E}_0} << 1$$

'Typical' fraction of energy radiated classically

$$\hbar\omega_c/E_e \simeq 3\gamma^3\hbar eB/2pE_e = 3\gamma B/2B_0$$

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E_0} = \gamma\frac{B}{B_0}$$

Quantum synchrotron radiation



’Typical’ fraction of energy radiated classically

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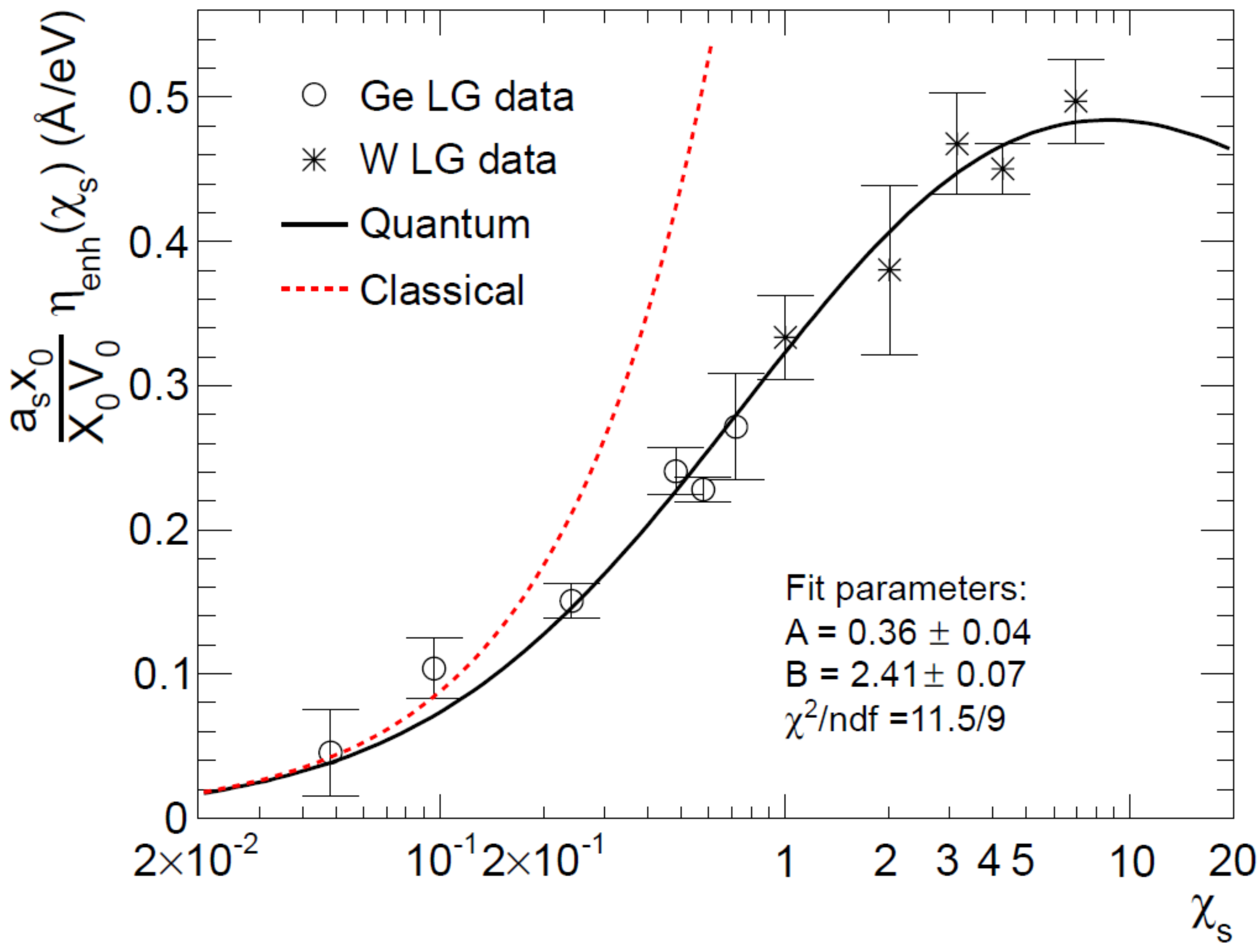
PHYSICAL REVIEW D 86, 072001 (2012)

Experimental investigations of synchrotron radiation at the onset of the quantum regime

K. K. Andersen,[1] J. Esberg,[1] H. Knudsen,[1] H. D. Thomsen,[1] U. I. Uggerhøj,[1] P. Sona,[2] A. Mangiarotti,[3] T. J. Ketel,[4] A. Dizdar,[5] and S. Ballestrero[6]

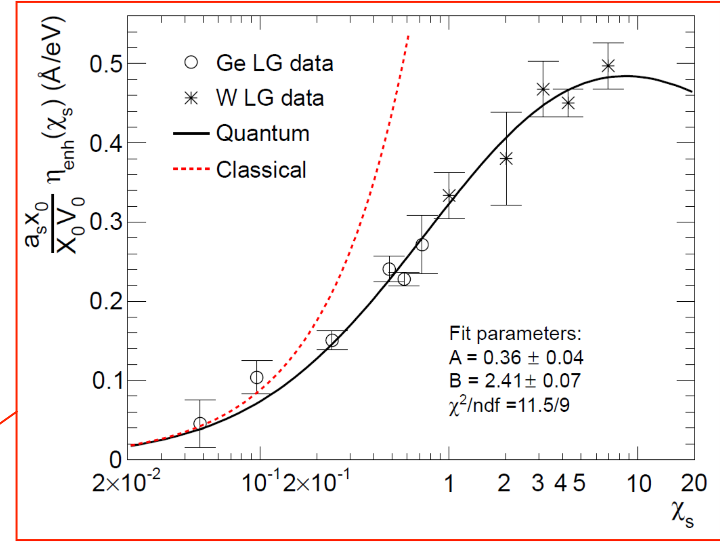
(CERN NA63)

$$\frac{I_e}{I_{\rm cl}} = (1 + 4.8(1+\chi)\ln(1+1.7\chi) + 2.44\chi^2)^{-2/3}.$$



Classical -> Quantum synchrotron

So we have verified that radiation emission works as predicted in the regime relevant for beamstrahlung at future colliders



PHYSICAL REVIEW D VOLUME 36, NUMBER 1

Quantum treatment of beamstrahlung

Richard Blankenbecler and Sidney D. Drell

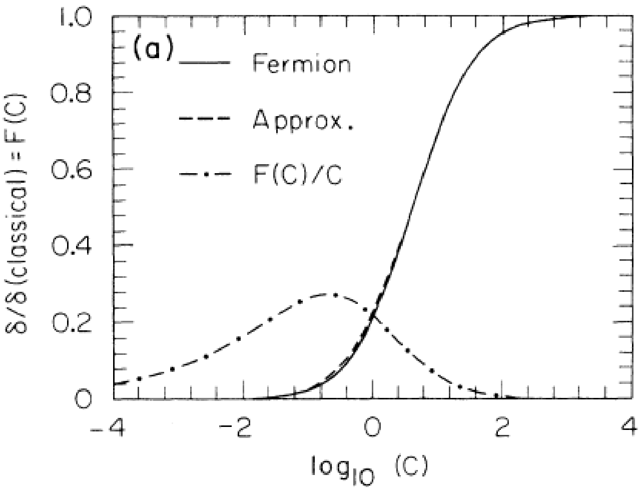
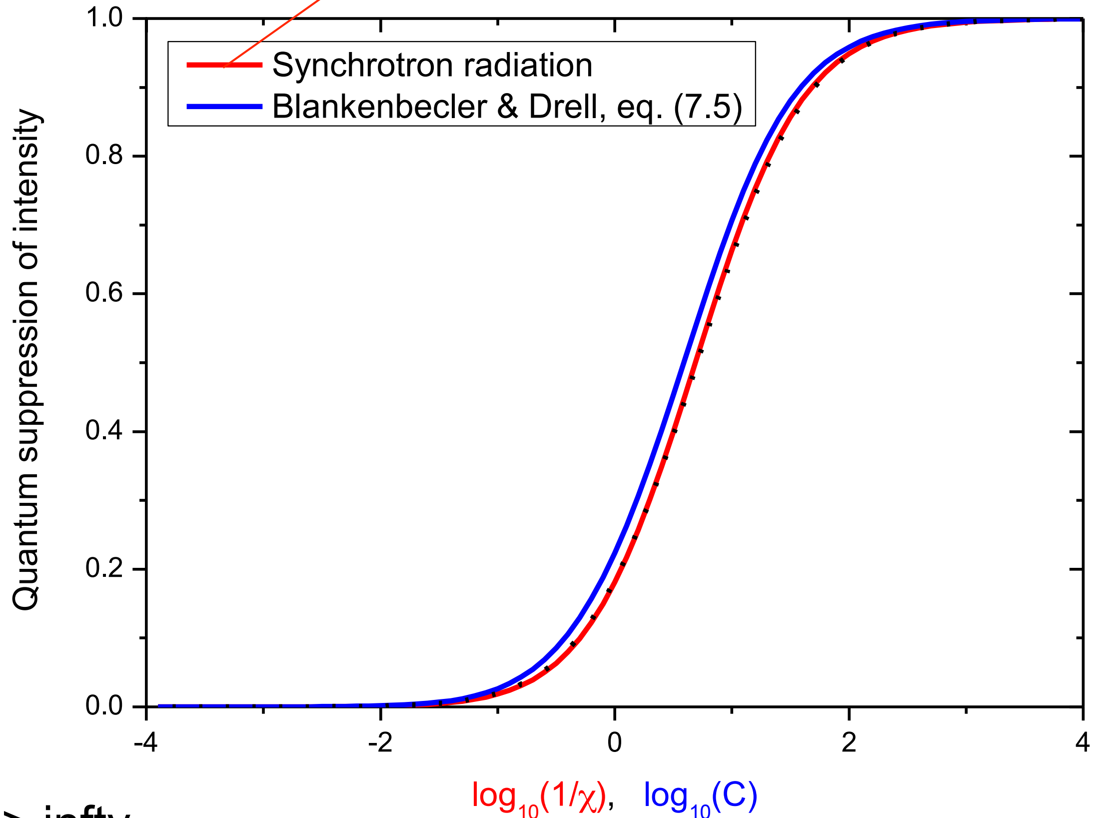


FIG. 1. (a) The form factor

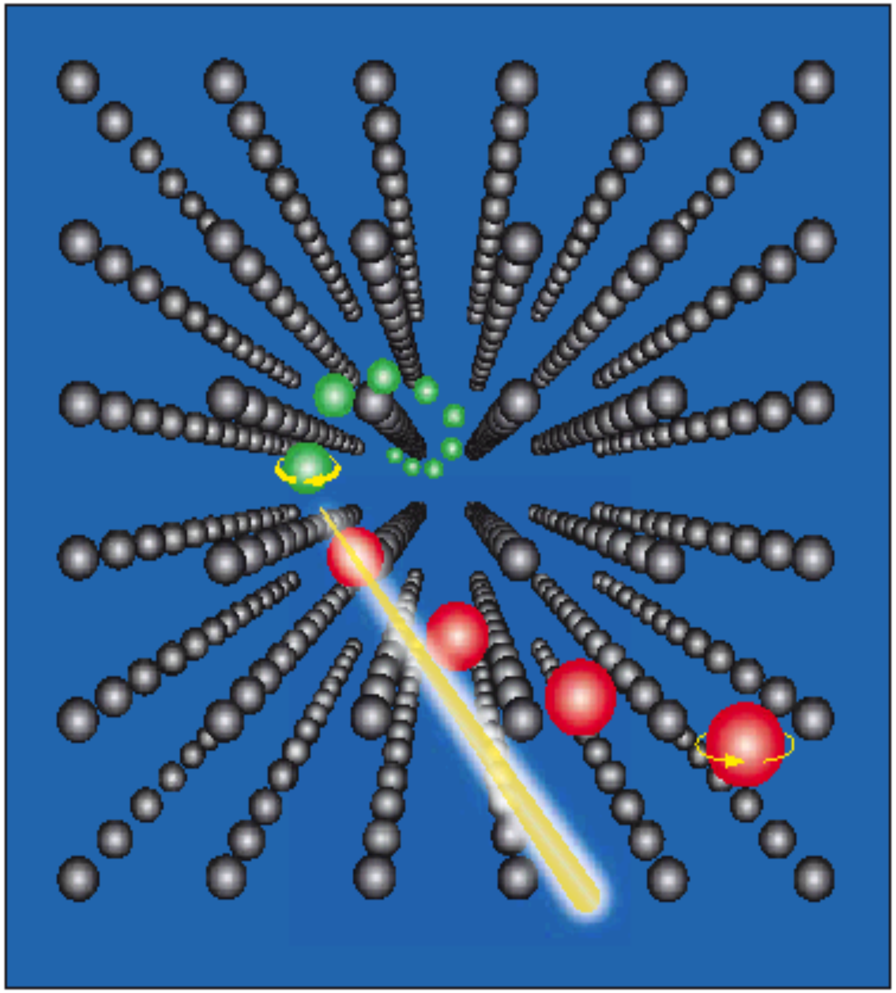
$$C_b = \frac{m^2 c^3 R L}{4 N e^2 \gamma^2 \hbar}$$



Classical: h -> 0 => C_b -> infty

Spin-flip

$$B = \gamma\beta\mathcal{E}_{\mathrm{lab}}$$



$$W_{\mathrm{mag}} = -\overline{\mu}\cdot\overline{B}$$

$$\Delta W = e\hbar B/mc$$

$$\mathcal{E}_0 = m^2c^3/e\hbar$$

$$\boxed{\Delta W = \gamma^2\beta\frac{\mathcal{E}}{\mathcal{E}_0}mc^2}$$

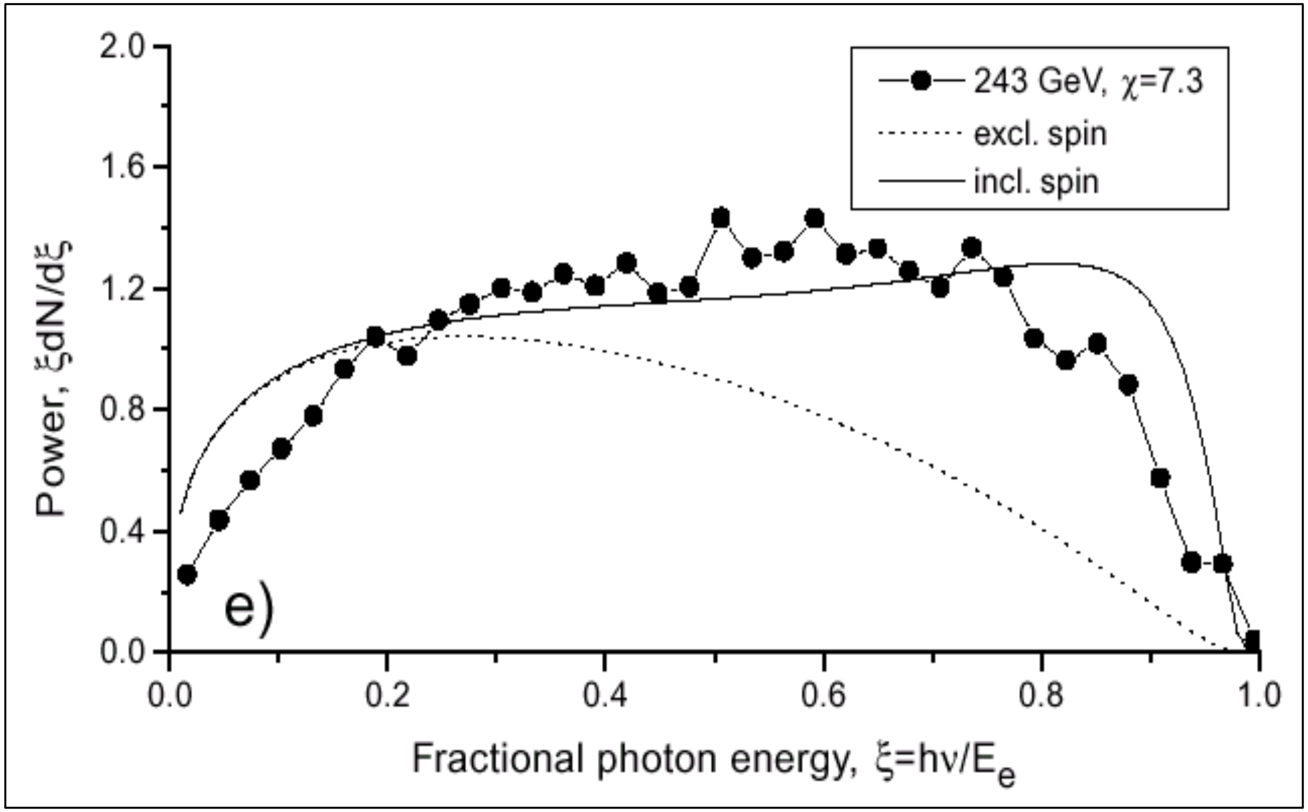
Equals incoming energy if

$$\chi = \gamma\mathcal{E}/\mathcal{E}_0$$

is one

Phys. Rev. Lett. vol. 87, 054801 (2001)

Spin-flip



$$\chi = \gamma \mathcal{E} / \mathcal{E}_0$$

$$\Delta W = \gamma^2 \beta \frac{\mathcal{E}}{\mathcal{E}_0} mc^2$$

$$\tau = \frac{8\hbar}{5\sqrt{3}\,\alpha m}\left(\frac{B_0}{B}\right)^3 \frac{1}{\gamma^2} = \frac{8\hbar}{5\sqrt{3}\,\alpha m}\frac{\gamma}{\chi^3}$$

100 GeV
$\chi = 1$
10 μm

'Polarization time/length'

1 GeV
1 T field
7.3 AU

Radiation reaction

Classical Radiation Reaction

Jackson 1975 p. 786-798

$$m\dot{\mathbf{v}} = \mathbf{F}_{\text{ext}}$$ N2

$$P(t) = \frac{2}{3}\frac{e^2}{c^3}(\dot{\mathbf{v}})^2$$ Larmor

$$m\dot{\mathbf{v}} = \mathbf{F}_{\text{ext}} + \mathbf{F}_{\text{rad}}$$

$\mathbf{F}_{\text{rad}}$ "must" vanish if $\dot{\mathbf{v}} = 0$ (no radiation)

$$m(\dot{\mathbf{v}} - \tau\ddot{\mathbf{v}}) = \mathbf{F}_{\text{ext}}$$ Lorentz-Abraham-Dirac (LAD) equation

$$\mathbf{F}_{\text{rad}} = \frac{2}{3}\frac{e^2}{c^3}\ddot{\mathbf{v}} = m\tau\ddot{\mathbf{v}} \qquad \tau = \frac{2}{3}\frac{e^2}{mc^3}$$

Step-fct. field, solution to LAD eq.: (pre-acceleration)

No field, solution to LAD eq.: (runaway)

$$a(t) = a_0 e^{t/\tau},$$

$$\tau \equiv \frac{\mu_0 q^2}{6\pi mc}.$$

$$\tau = 6 \times 10^{-24}\text{s}.$$

Classical Electrodynamics

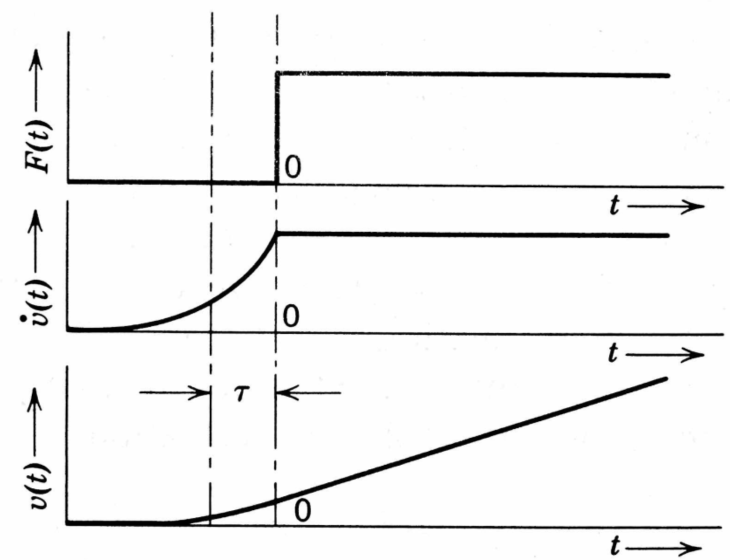
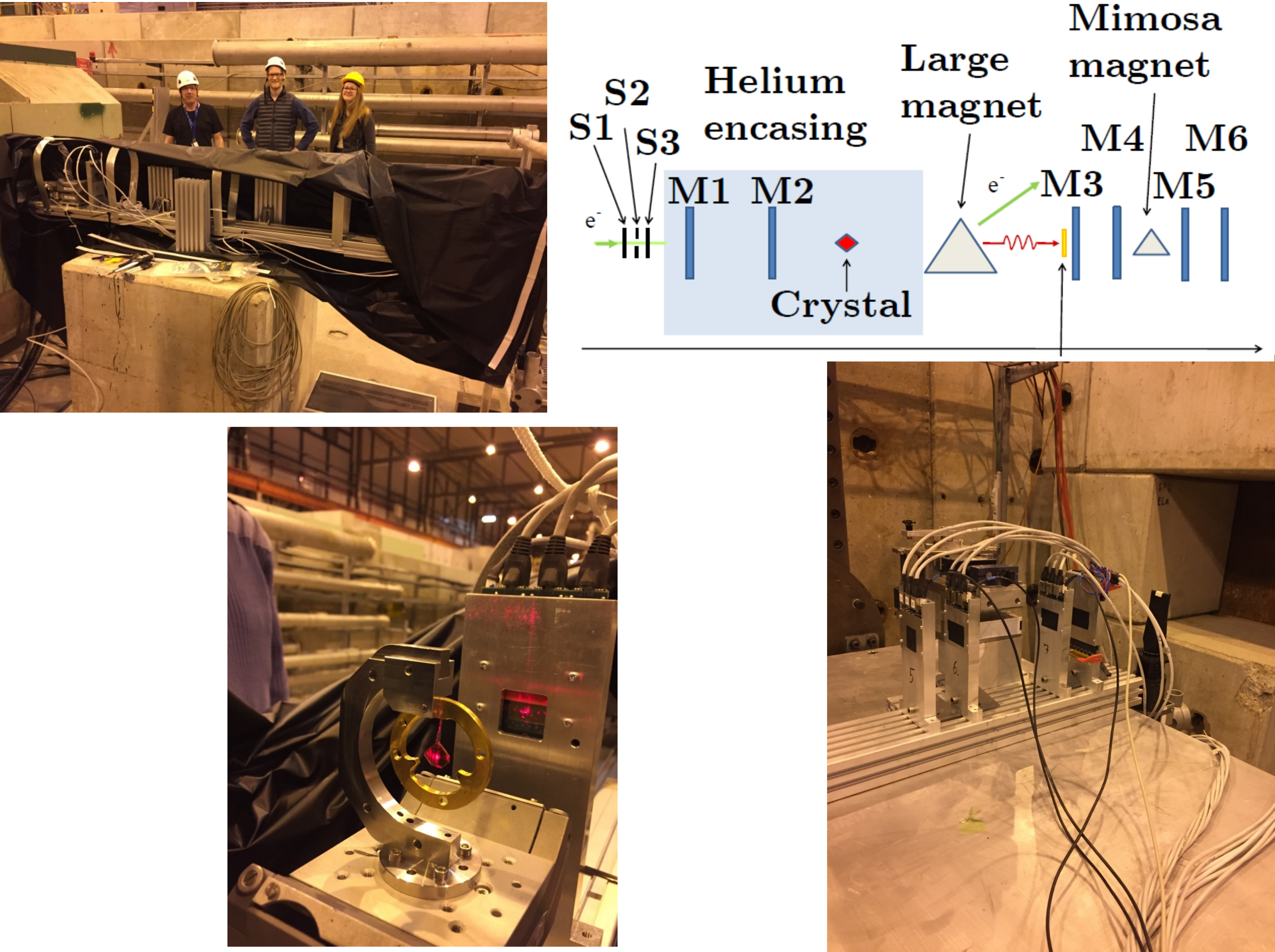
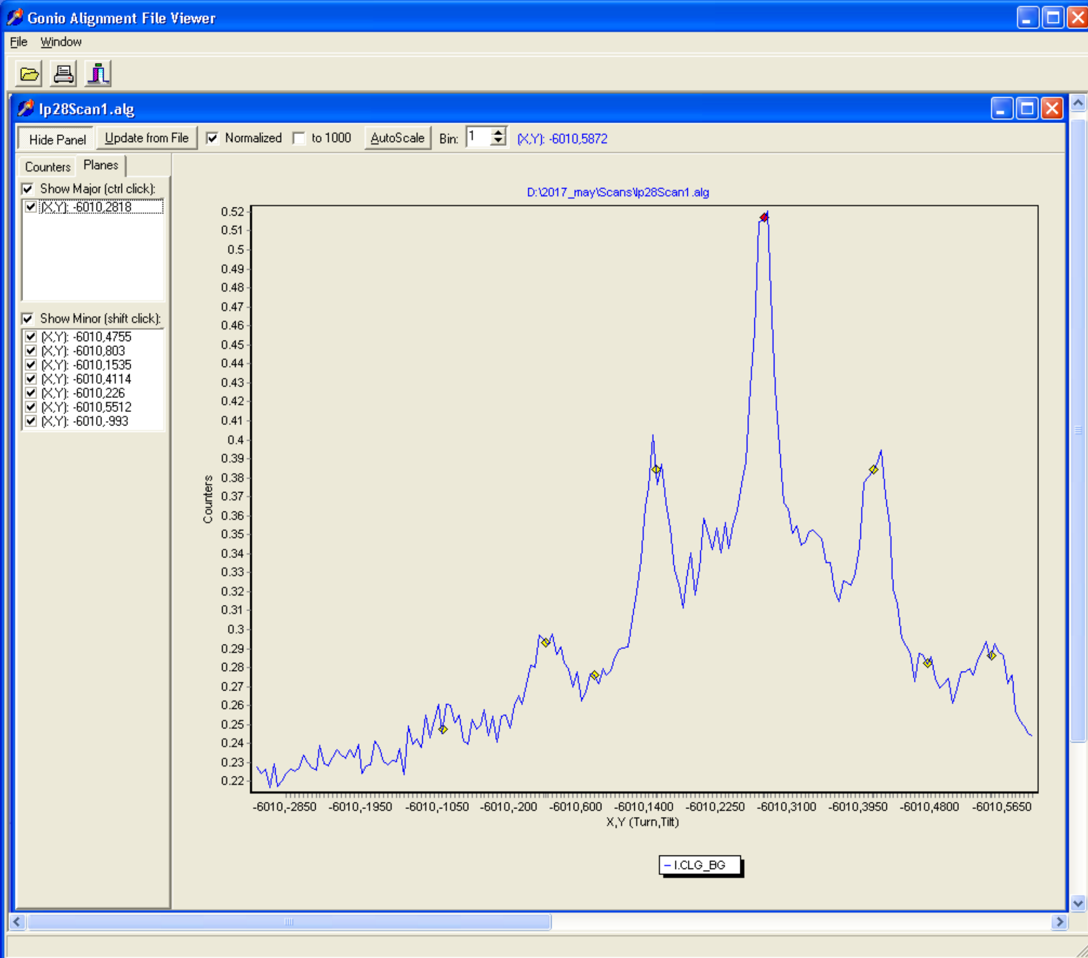


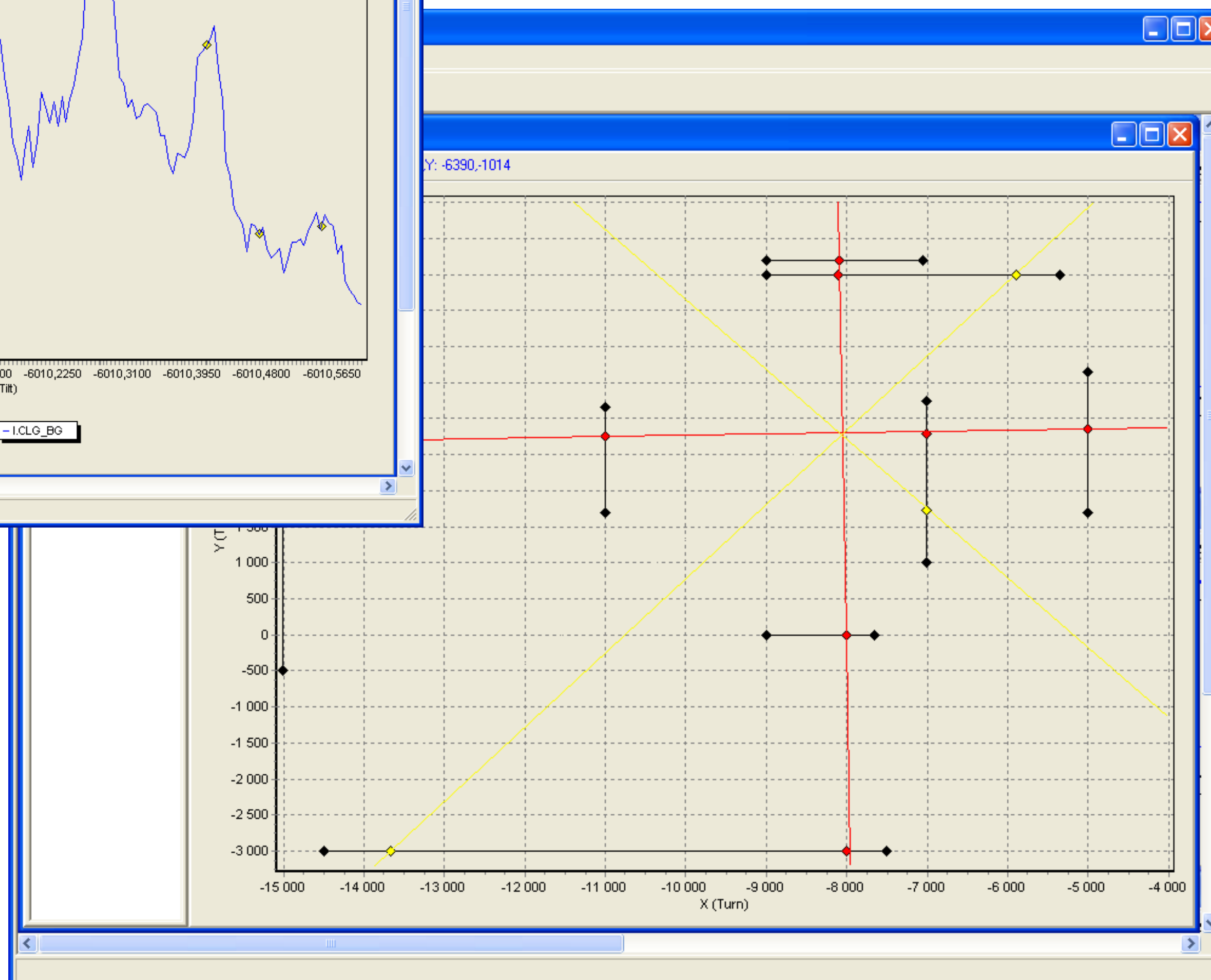
Fig. 17.1 "Preacceleration" of charged particle.


S1
S2
S3
e-
Helium
encasing
M1
M2
Crystal
Large
magnet
e-
M3
M4
Mimosa
magnet
M5
M6

Crystal planar alignment



Lindhard critical angle @ 50 GeV: 23 microrad



Crystals prealigned with x-rays

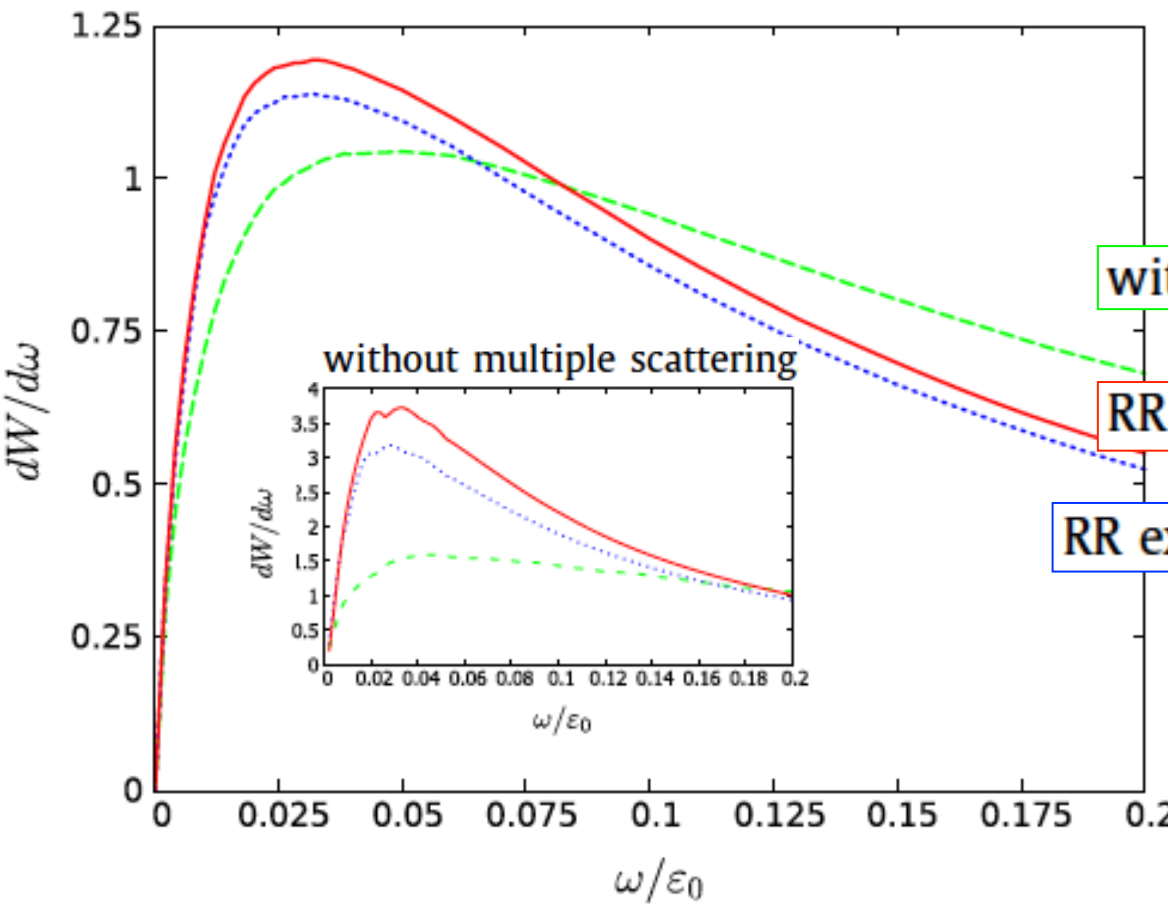
2017 data (planar case)

Investigation of classical radiation reaction with aligned crystals

A. Di Piazza [a,*], Tobias N. Wistisen [b], Ulrik I. Uggerhøj [b]

[a] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117, Germany
[b] Department of Physics and Astronomy, Aarhus University, 8000 Aarhus, Denmark

Physics Letters B 765 (2017) 1–5



without RR

RR including the derivative term

RR excluding the derivative term

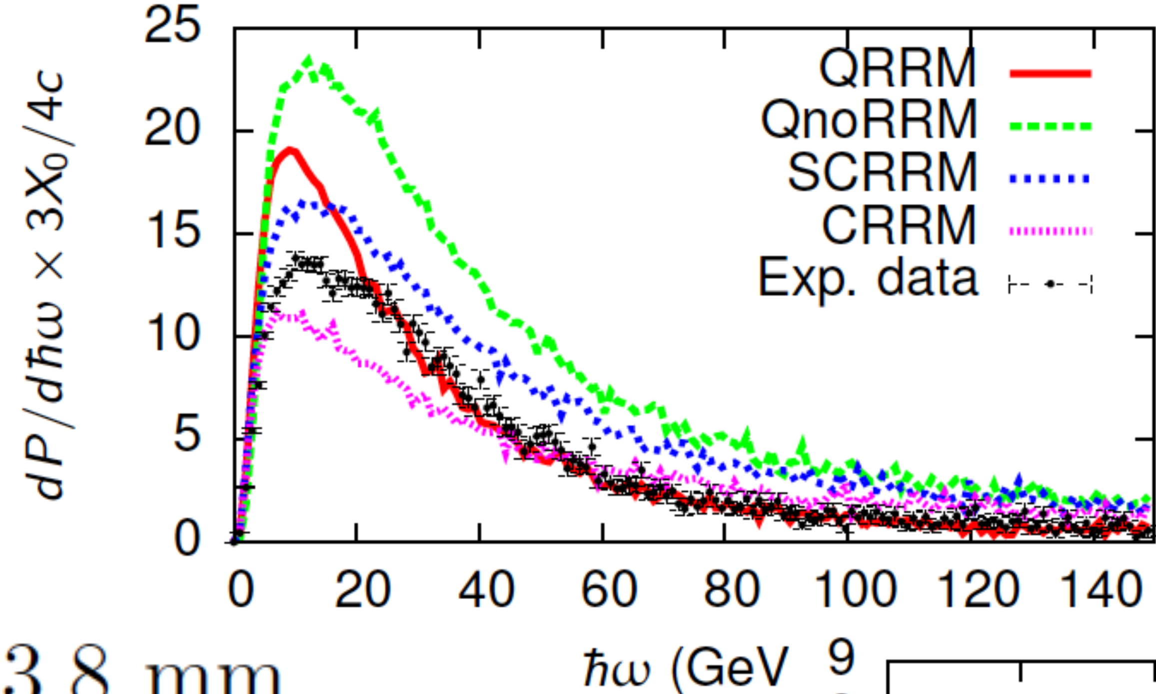
Derivative term not accessible in laser interactions

In a purely electric field (in the lab frame), 'Landau-Lifshitz' equation :

$$f = \frac{2e^3}{3m}\gamma\left\{(v\cdot\nabla)E\right\} + \frac{2e^4}{3m^2}\left\{E(v\cdot E)\right\} - \frac{2e^4}{3m^2}\gamma^2 v\left\{(E)^2 - (E\cdot v)^2\right\}$$

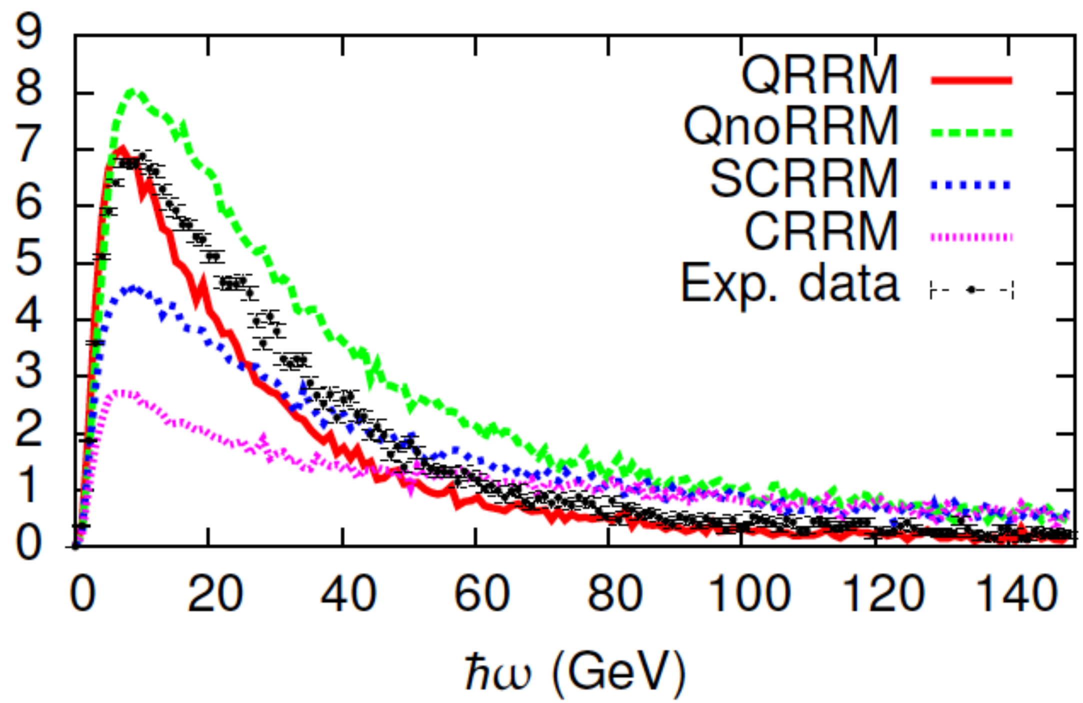
2016 data (axial case)

After propagation through analysis algorithm



3.8 mm

10.0 mm



Lindhard critical angle @ 178 GeV: 36 microrad

https://arxiv.org/abs/1704.01080, Nature Communications **9**, 795 (2018)

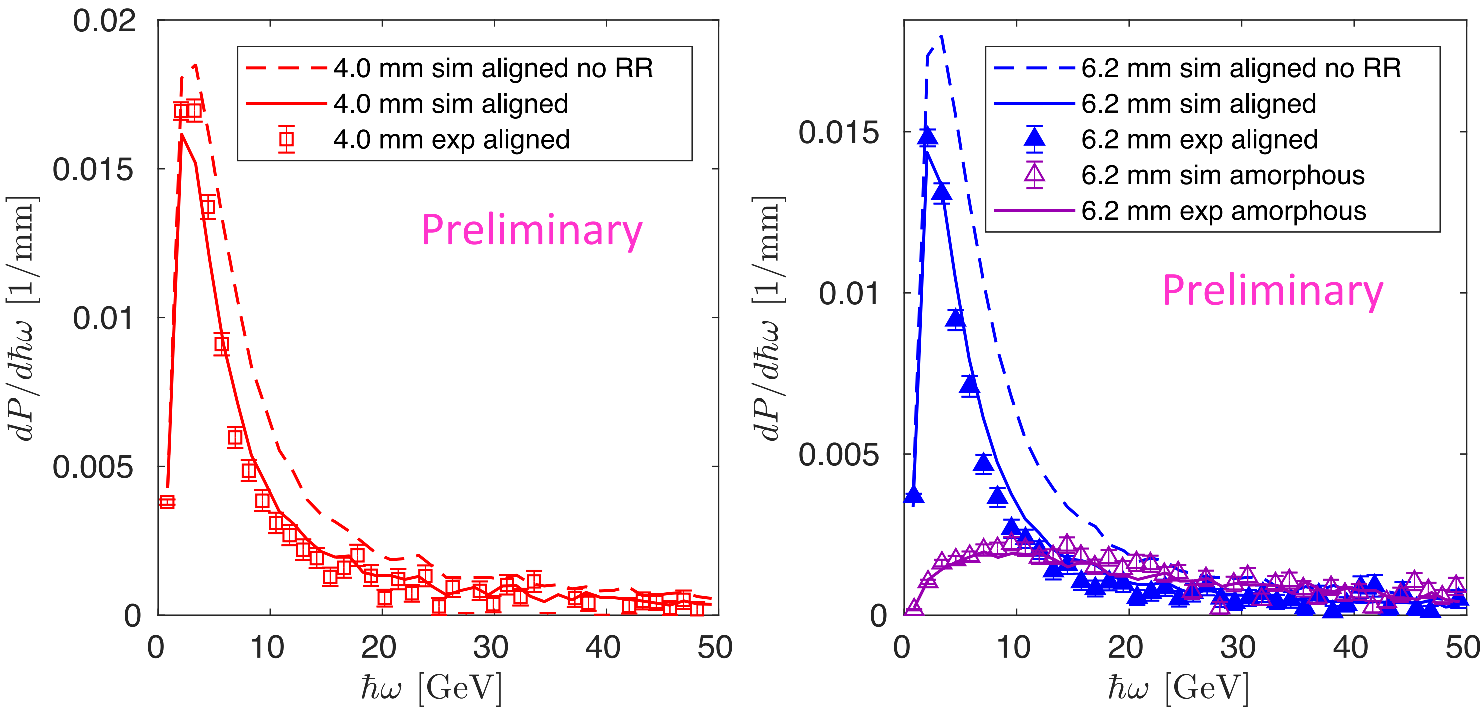
Unpublished (to be subm. soon), 50 GeV e^+ in Si (110)

2017 data (planar case)

$$m\frac{du^\mu}{ds} = eF^{\mu\nu}u_\nu + \frac{2}{3}e^2\left[\frac{e}{m}(\partial_\alpha F^{\mu\nu})u^\alpha u_\nu + \frac{e^2}{m^2}F^{\mu\nu}F_{\nu\alpha}u^\alpha + \frac{e^2}{m^2}(F^{\alpha\nu}u_\nu)(F_{\alpha\lambda}u^\lambda)u^\mu\right]$$

'Landau-Lifshitz equation'

$$\frac{d\mathcal{E}}{d\omega d\Omega} = \frac{e^2}{4\pi^2}\left|\int_{-\infty}^{\infty} dt \frac{\boldsymbol{n}\times[(\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}]}{(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^2}e^{i\omega(t-\boldsymbol{n}\cdot\boldsymbol{r})}\right|^2$$



Investigation of classical radiation reaction with aligned crystals

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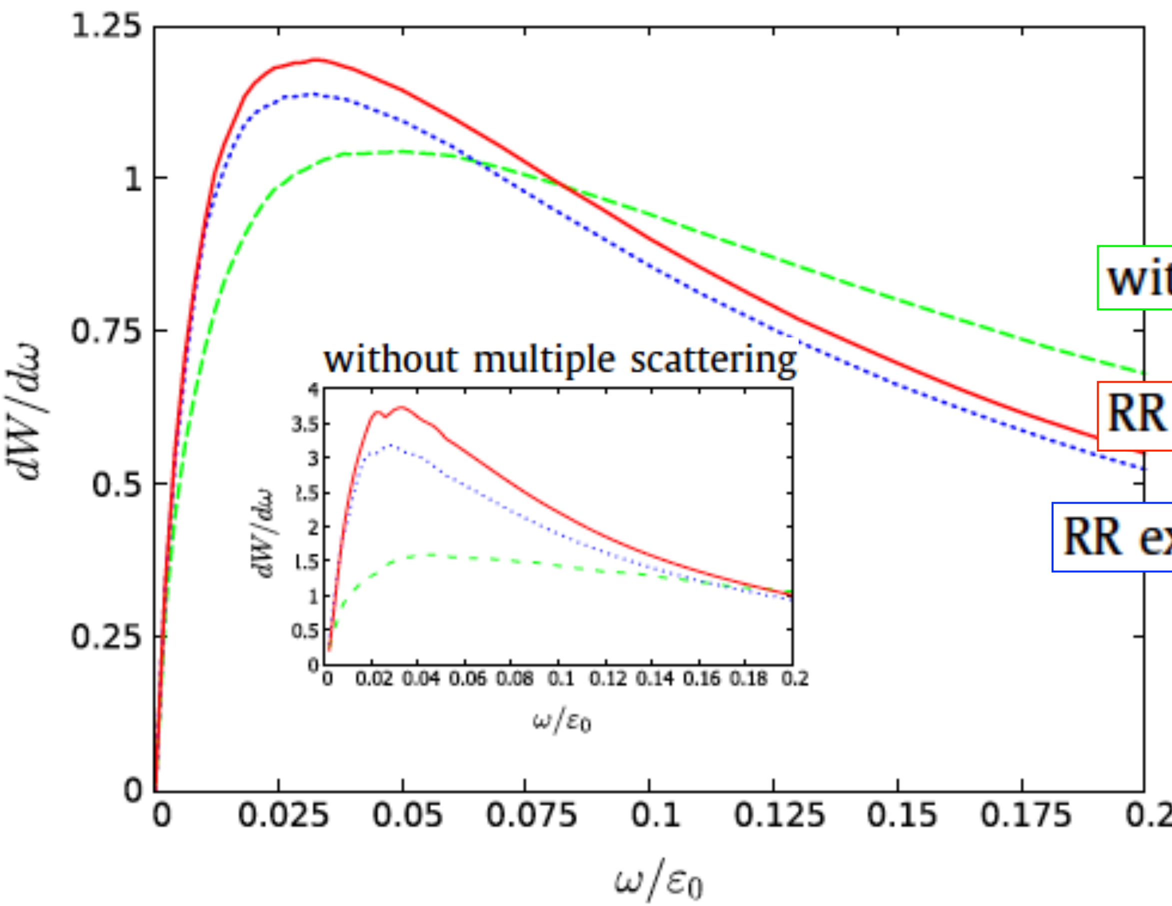
[a] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117, Germany
[b] Department of Physics and Astronomy, Aarhus University, 8000 Aarhus, Denmark

Physics Letters B 765 (2017) 1–5



aim for 2018 data

without RR

RR including the derivative term

RR excluding the derivative term

Derivative term not accessible in laser interactions

In a purely electric field (in the lab frame), 'Landau-Lifshitz' equation :

$$\boldsymbol{f} = \frac{2e^3}{3m}\gamma\left\{(\boldsymbol{v}\cdot\nabla)\boldsymbol{E}\right\} + \frac{2e^4}{3m^2}\left\{\boldsymbol{E}(\boldsymbol{v}\cdot\boldsymbol{E})\right\} - \frac{2e^4}{3m^2}\gamma^2\boldsymbol{v}\left\{(\boldsymbol{E})^2 - (\boldsymbol{E}\cdot\boldsymbol{v})^2\right\}$$

Thank you for your attention.

MIMOSA-26 detectors

(M. Winter, Strasbourg)

Vertex detectors for CLIC (?)

CMOS-based position sensitive detectors

1152 columns of

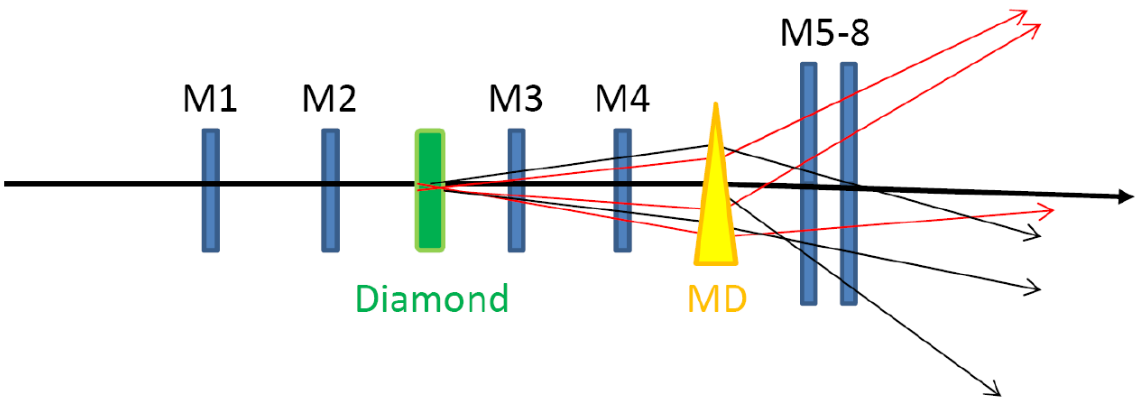
576 pixels, $\simeq$ 18.4 μm pitch

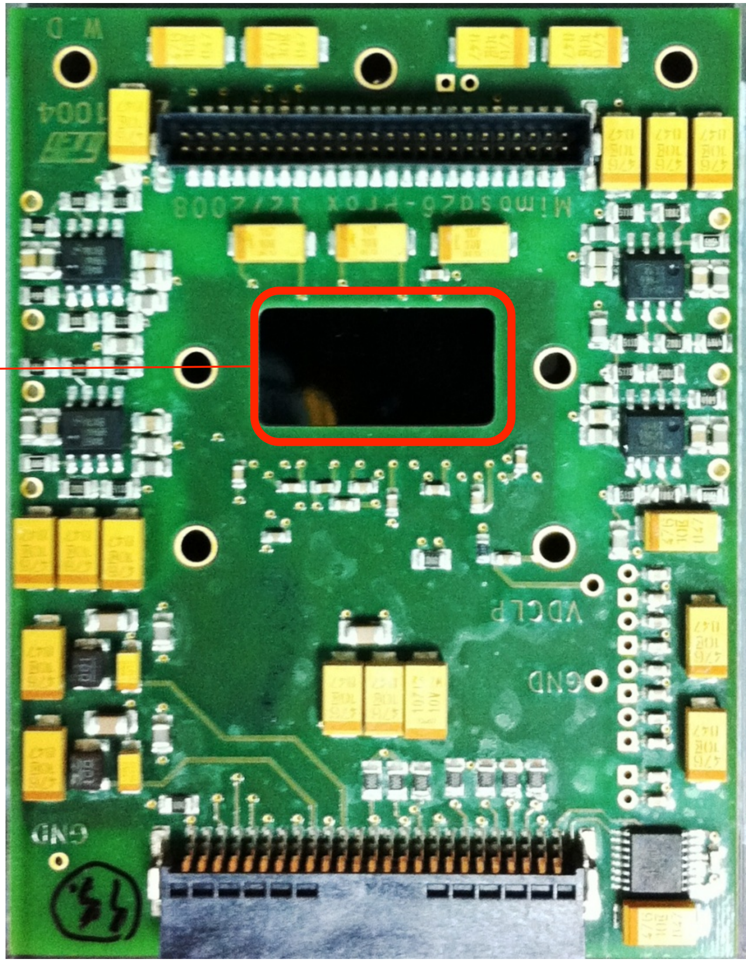
readout in 110 ms, $\simeq$ 3.5 μm resolution

true multi-hit capability

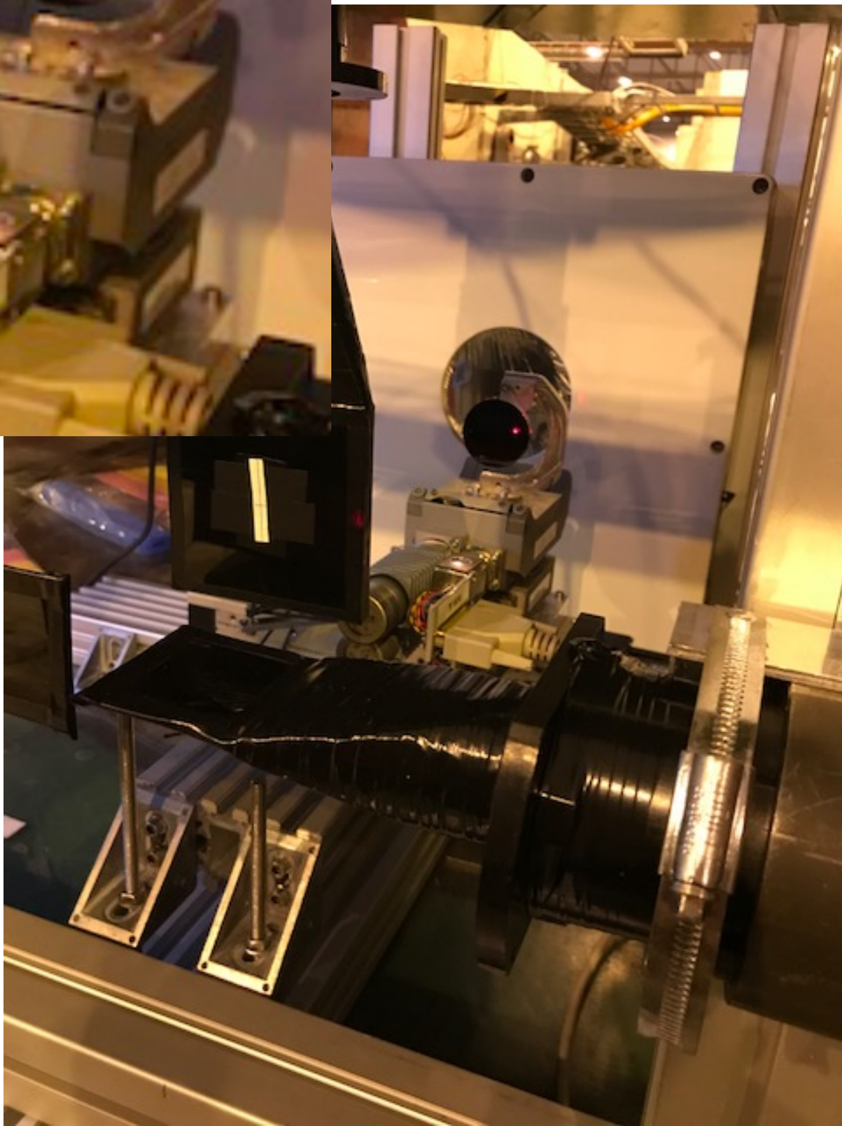
1×2 cm^2

$\Delta t / X_0 \simeq 0.05\%$

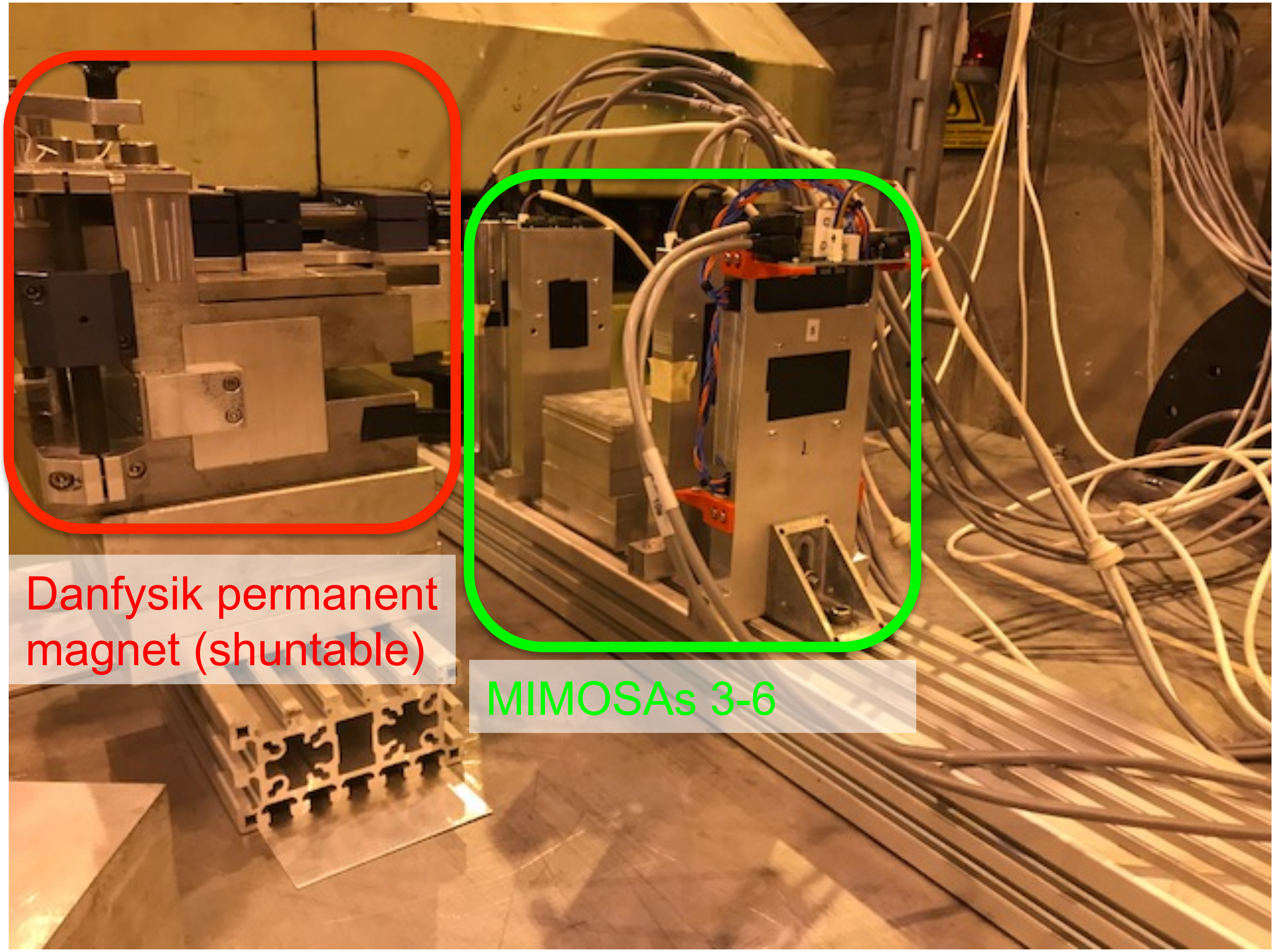




Detectors and crystal



MIMOSA spectrometer



Beamstrahlung

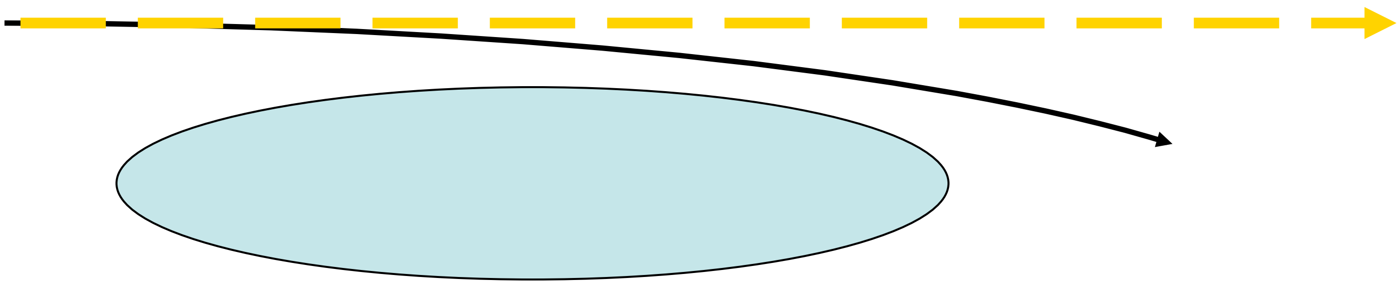
$$\mathcal{L} = H_D \frac{N^2 f_{rep} n_b}{4\pi\sigma_x\sigma_y}$$

$$\Upsilon \propto \frac{N\gamma}{(\sigma_x + \sigma_y)\sigma_z}$$

$\Upsilon \ll 1$: classical regime

$\Upsilon \gg 1$: quantum regime

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E_0}$$



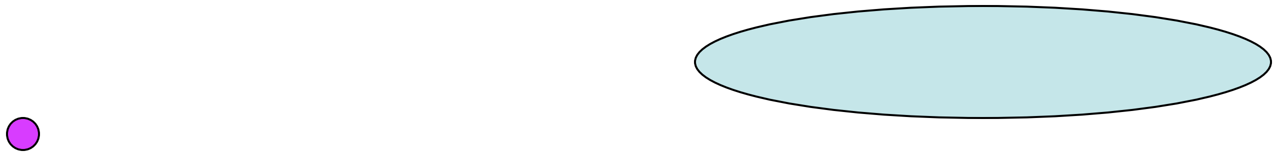
Journal of Physics Conference Series, vol. 198, 012007 (2009)

Phys. Rev. Spec. Top. Acc. Beams vol. 17, 051003 (2014)

Similar situations ?

Blankenbecler, Drell (PRD **36**, 277 (1987), Quantum treatment of beamstrahlung:
"Pulse transforms into a very long narrow 'string' of *N* charges."

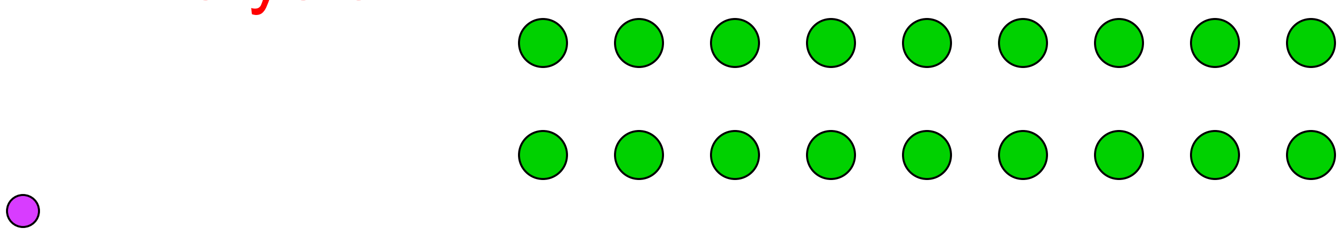
ILC / CLIC



Bunch-size: 300×0.6×0.006 μm^3, 2·10^{10} particles

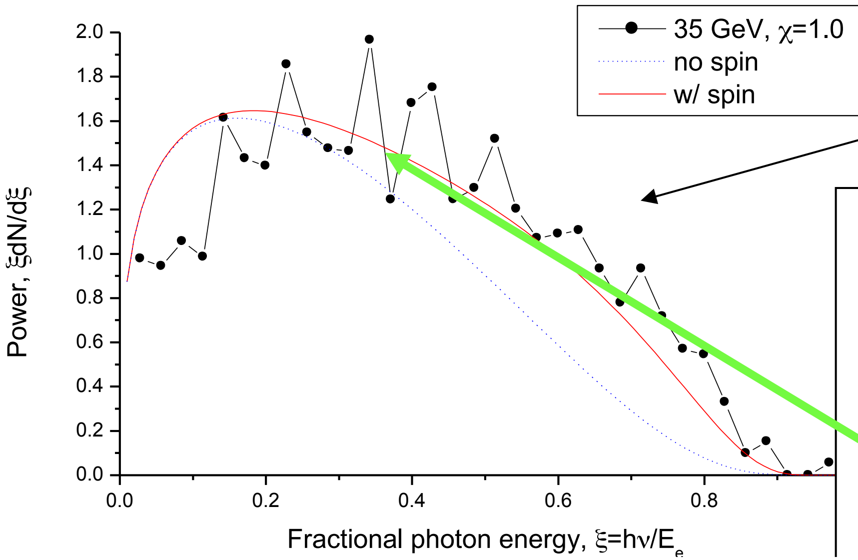
Density: 0.005 Å^{-3}, 0.6 Å^{-3} (at IP)

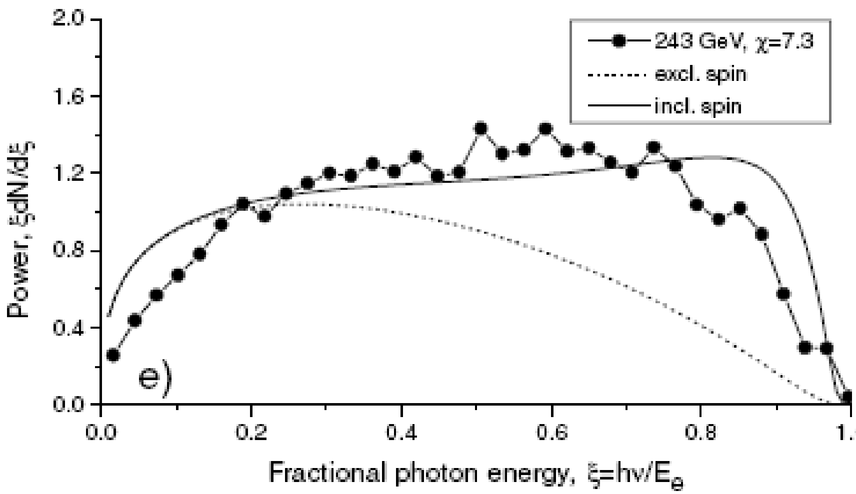
Si crystal



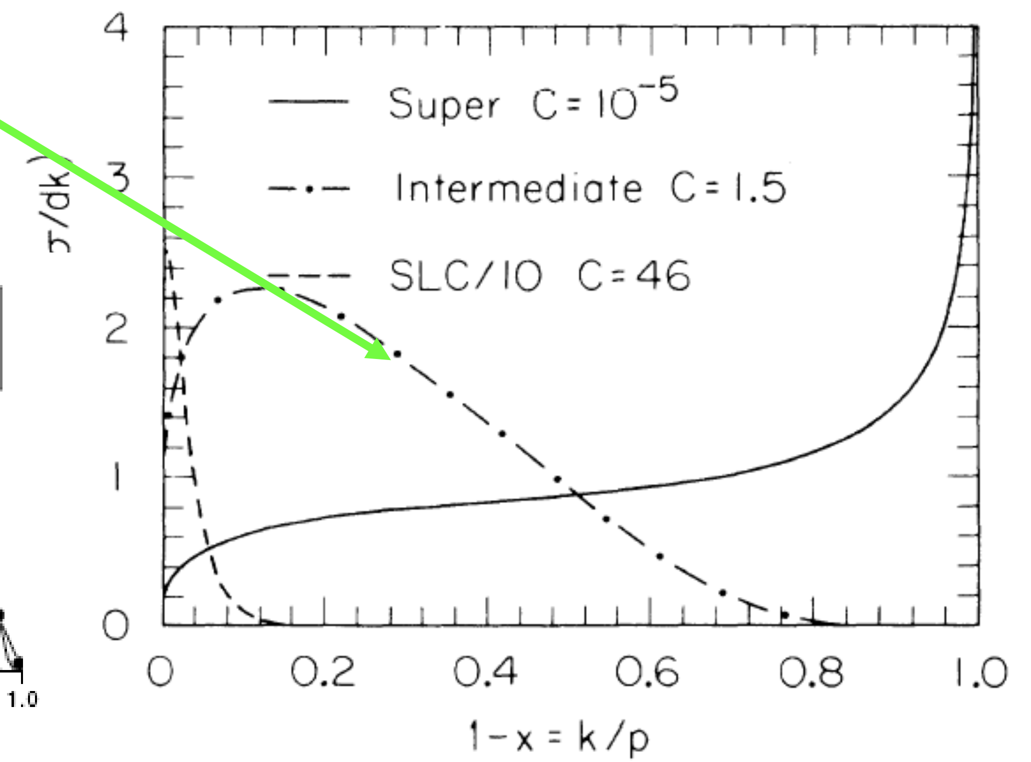
Density: 0.05 Å^{-3}, of Z = 14

Spin contr. to beamstrahlung





Blankenbecler and Drell, "Quantum treatment of beamstrahlung", PRD **36**, 277 (1987)



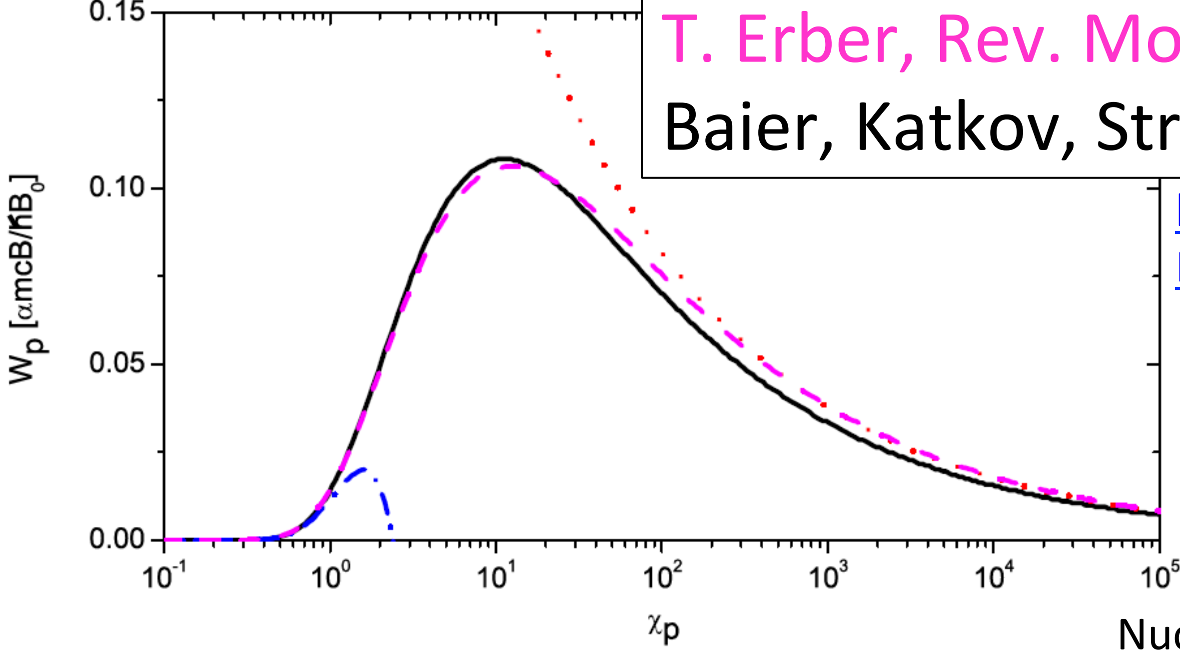
Phys. Rev. Lett. vol. 87, 054801 (2001)

Pair production

T. Erber, Rev. Mod. Phys. 1969

Baier, Katkov, Strakhovenko

http://www.phys.au.dk/~ulrik/Doct_dis_UIU.pdf



Pair production

Nucl. Instr. Meth. B vol. 135, 143 (1998)