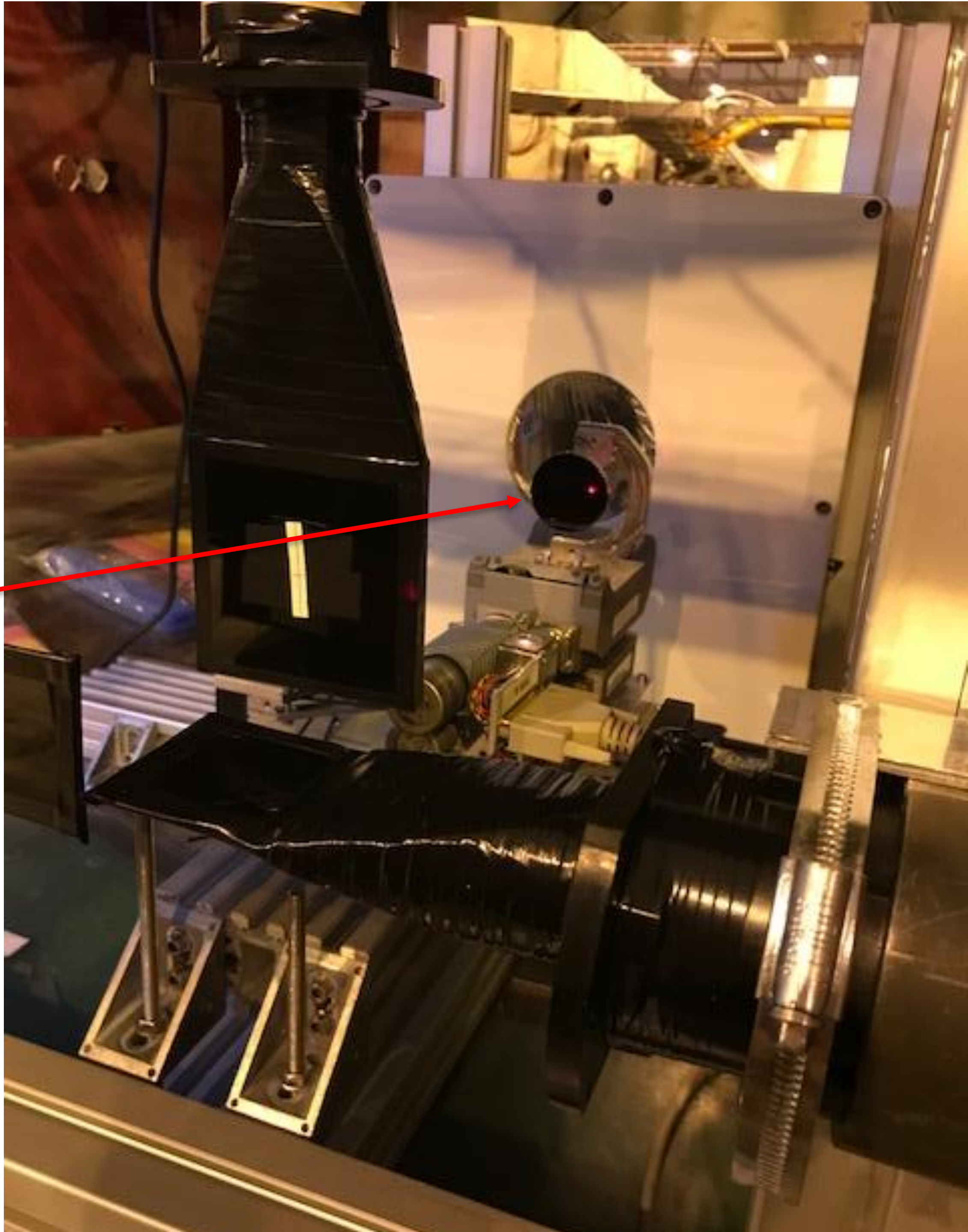
Status and plans of the NA63 experiment

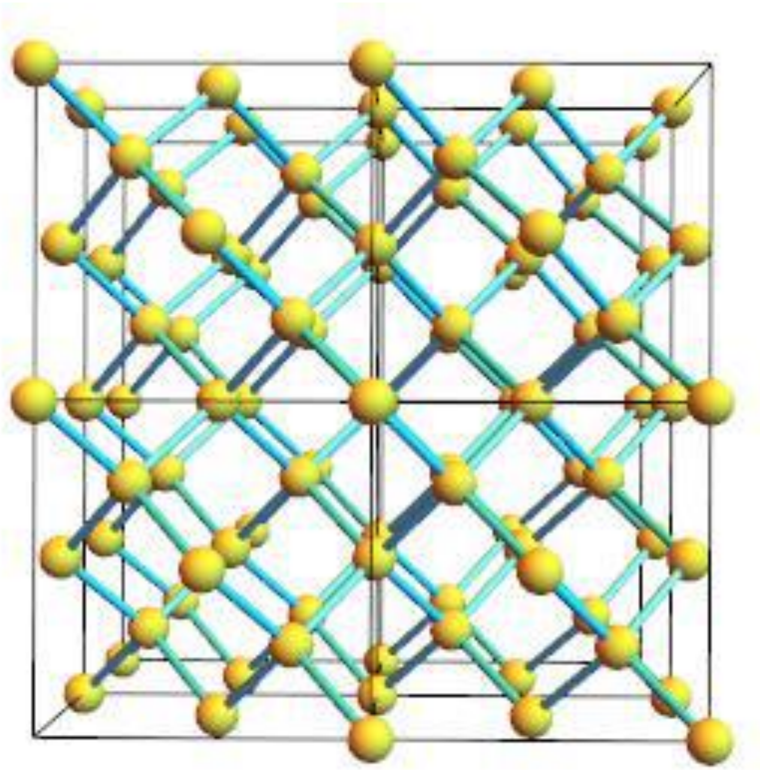
Ulrik I. Uggerhøj
on behalf of NA63

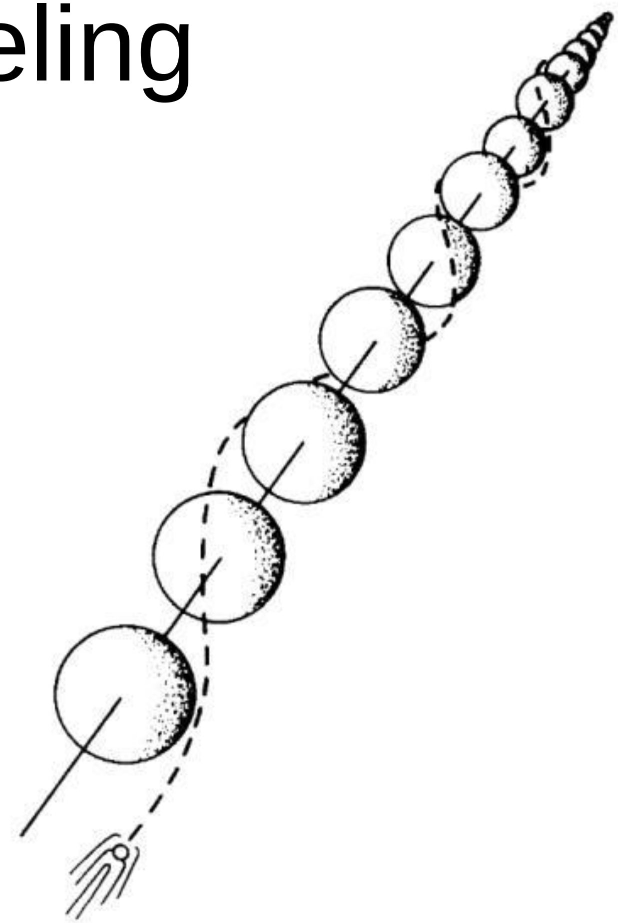
NA63

Crystals in GeV e^+/e^- beams



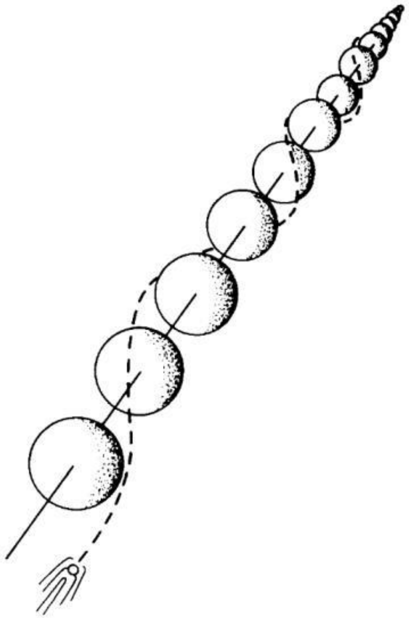
Channeling

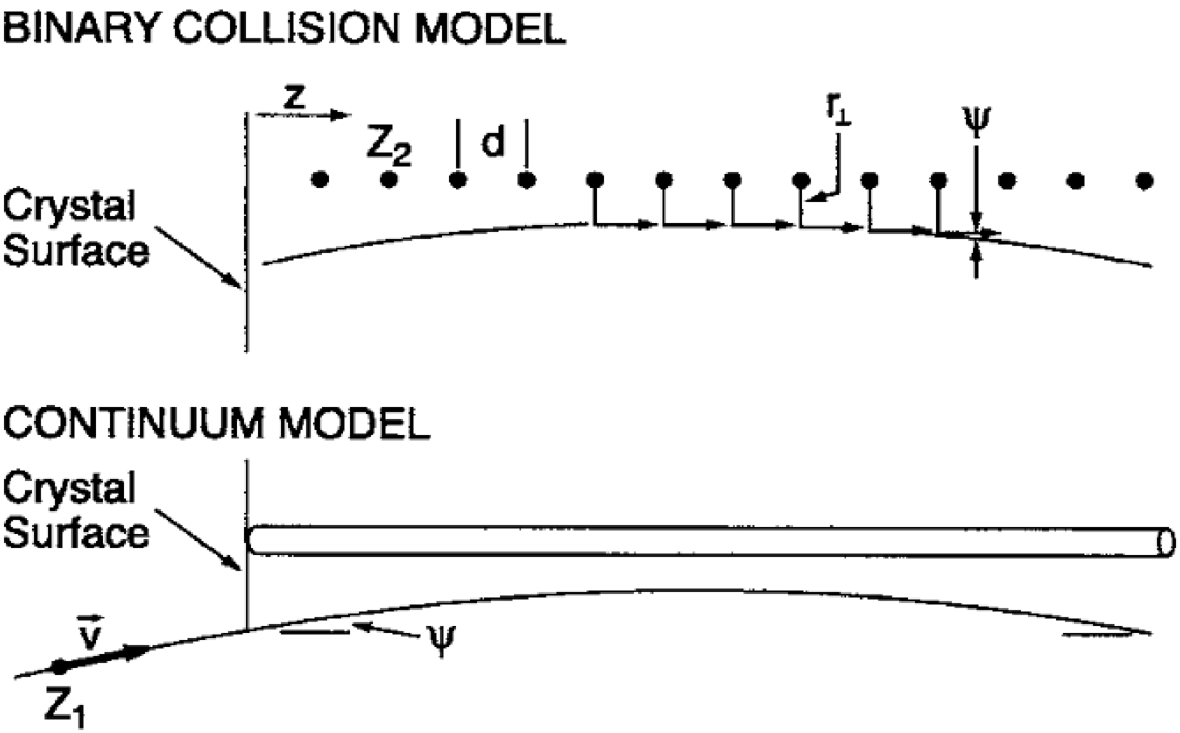




- Channeling is a phenomenon that takes places when a high energy charged particle enters the crystal close to a direction of high symmetry.

Channeling



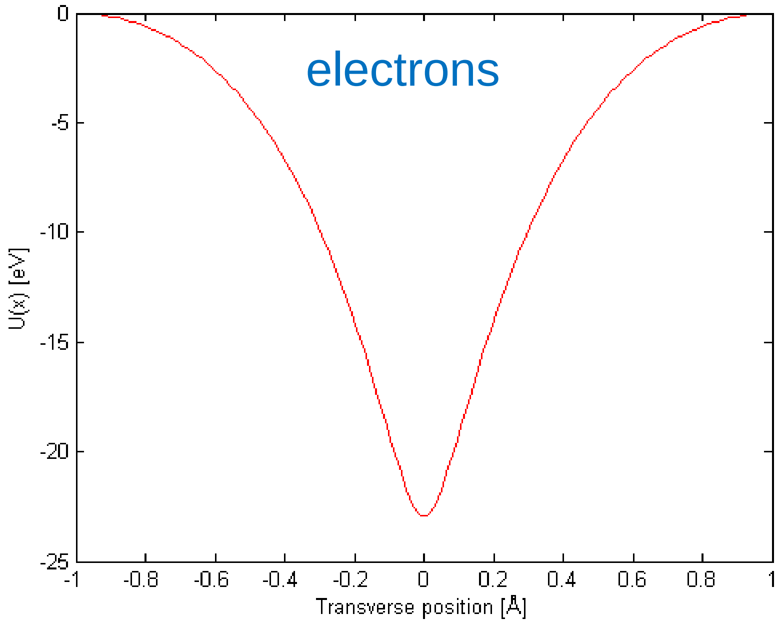


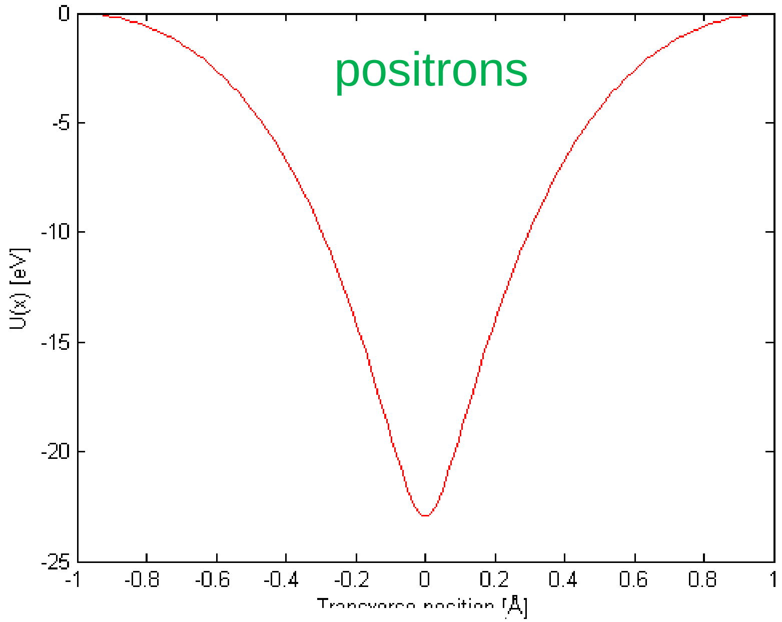
- Often employed is the continuum model of the potential.

Channeling

- Model of the (110) planar potential for Si

$$U(x) = V[\cosh(\delta(\sqrt{1+\eta^2} - \sqrt{y^2+\eta^2})) - 1],$$



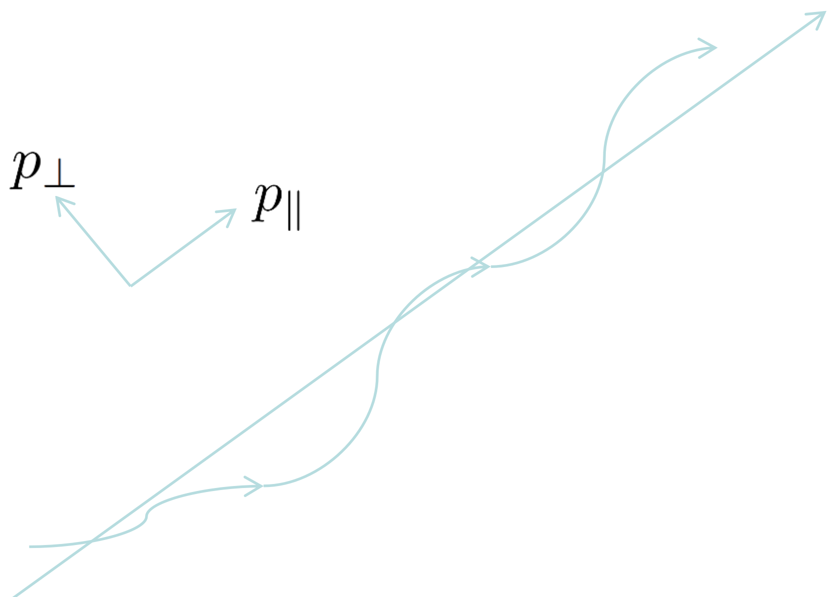


- Important dynamics is transverse

$$E_\perp = \frac{\boldsymbol{p}_\perp^2}{2\gamma m} + U(\boldsymbol{x}_\perp),$$

Classical radiation emission

- Two extreme cases of classical radiation emission



Electron/positron trajectory

Longitudinal is average velocity motion.

Transverse the remainder

Radiation characteristics decided by parameter

$$\xi = \frac{p_{\perp,\mathrm{max}}}{m}$$

$$\xi \ll 1$$

- Dipole-regime
- Undulator

$$\xi \gg 1$$

- Local constant field regime
- Synchrotron

Classical Radiation Reaction

Jackson 1975 p. 786-798

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

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

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

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

$$m(\dot{\mathbf{v}} - \tau\ddot{\mathbf{v}}) = \mathbf{F}_{ext}$$

Lorentz-Abraham-Dirac (LAD) equation

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

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

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

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

Possible remedy: 'Landau-Lifshitz equation'

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

Classical Electrodynamics

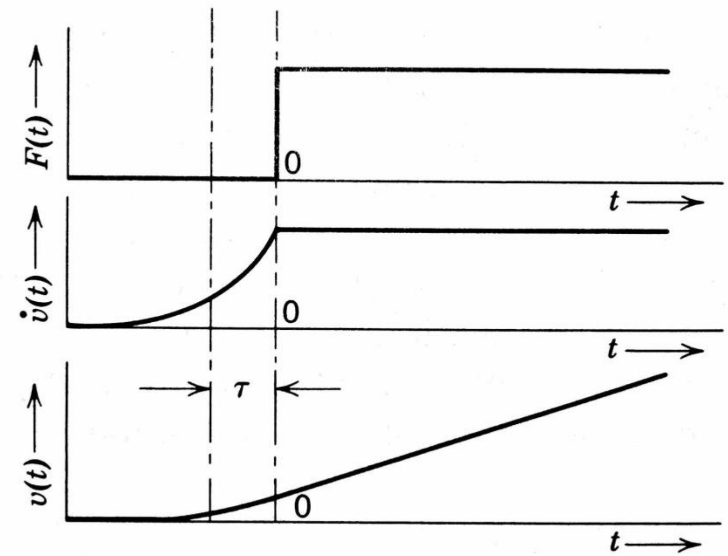


Fig. 17.1 "Preacceleration" of charged particle.

Significant damping in strong fields

quantum nonlinearity/strong field parameter χ

$$\chi^2 = (mF_{\mu\nu}u^\nu)^2/\mathcal{E}_0^2$$

A ‘specialty’ of NA63 to address strong field phenomena

$$\chi \simeq \gamma\mathcal{E}_\perp/\mathcal{E}_0$$

ratio of damping force to external force

$$\boxed{\eta = \alpha\gamma\chi = \alpha\gamma^2\mathcal{E}_\perp/\mathcal{E}_0}$$

$$\alpha = e^2/\hbar c \simeq 1/137$$

classical for:

$\chi \ll 1$ which means: $\gamma \gg 1$

for significant damping

- Landau-Lifshitz equation, “Reduction of order”, valid when $\chi\alpha \ll 1$

experiment: $\chi < 0.1$

What is classical radiation reaction?

- Landau-Lifshitz equation, "Reduction of order": $\chi\alpha \ll 1$

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

or in 3-vector notation:

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

In the case of a time-independent electric field as found in a crystal this reduces to

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

Schott

Investigation of classical radiation reaction with aligned crystals

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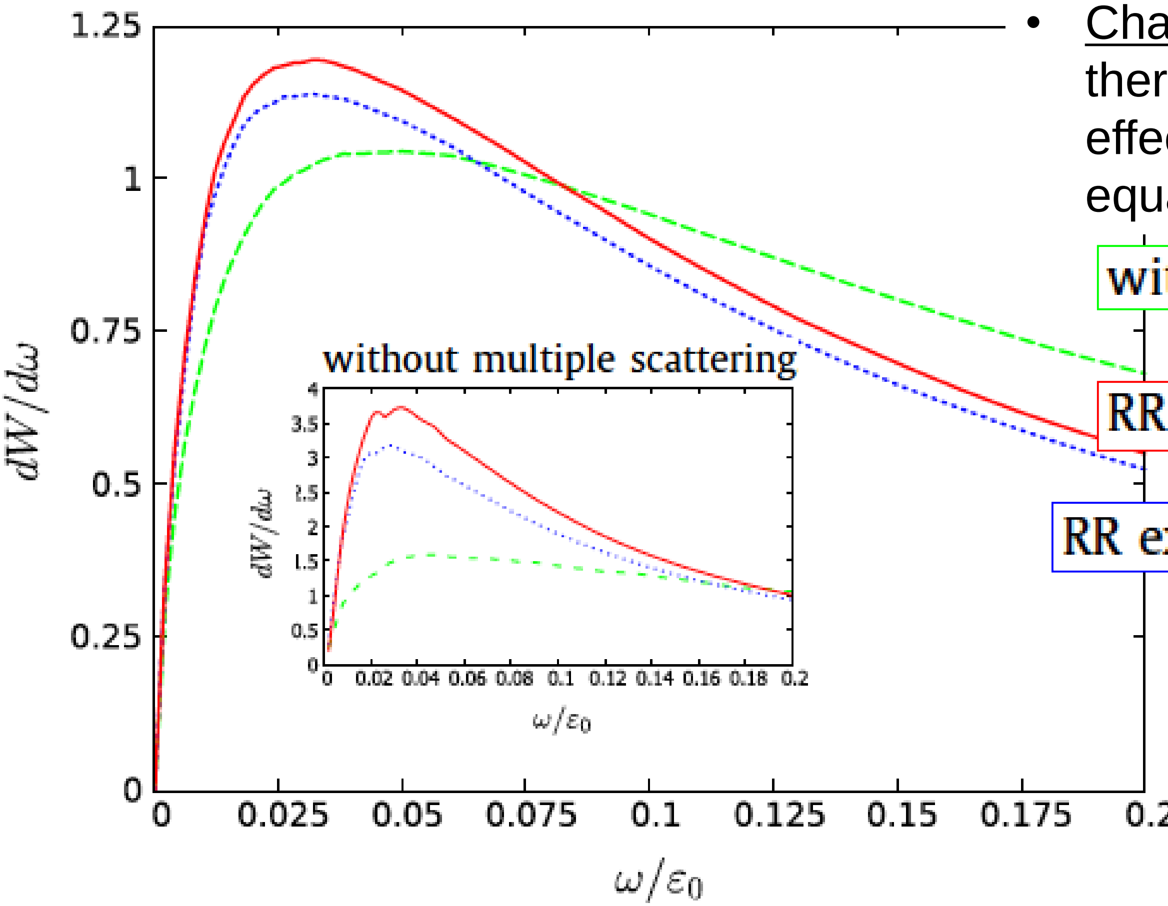
Physics Letters B 765 (2017) 1–5

- Challenging, but the only place where there would be a chance to see the effect of the derivative term in the LL equation.

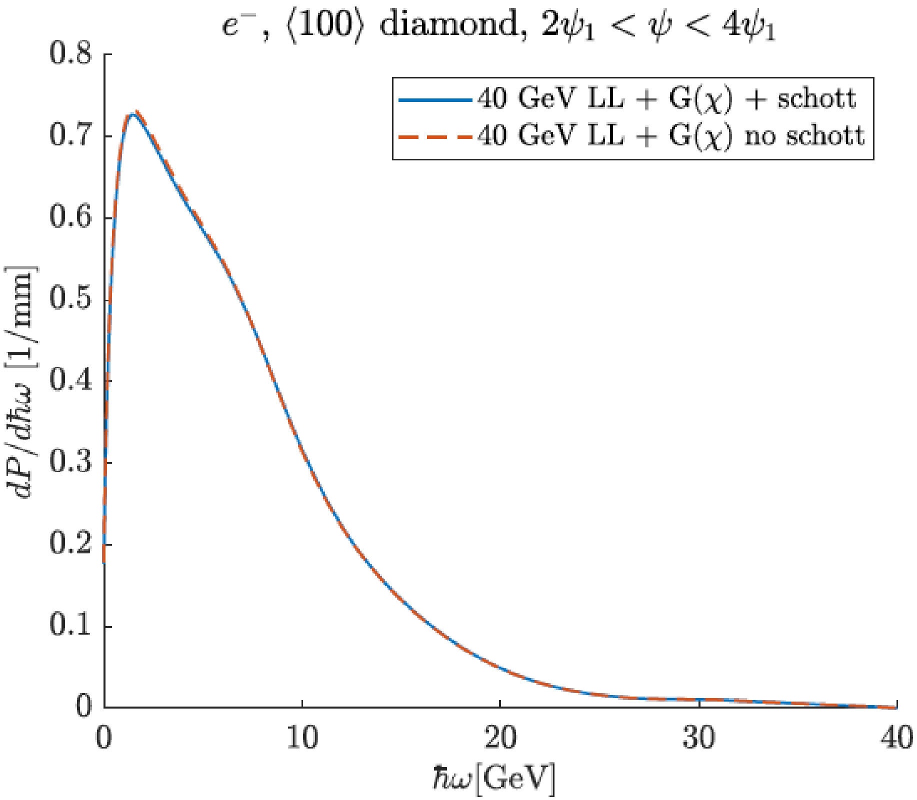


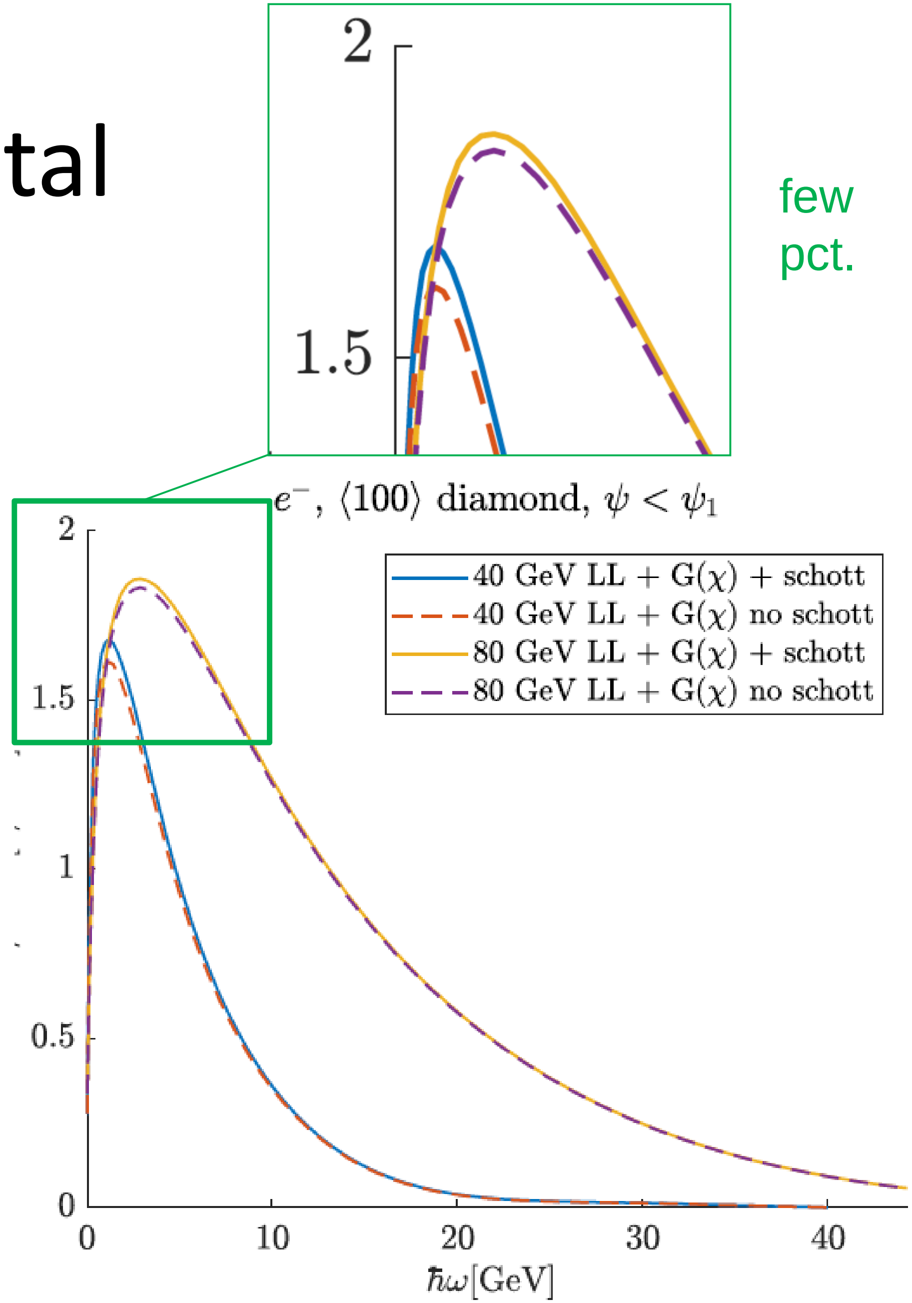
Derivative term not accessible in laser interactions

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

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

For our experimental conditions…





… the Schott term is however too small.

MIMOSA-26 detectors

(M. Winter, Strasbourg)

Vertex detectors for CLIC (?)

CMOS-based position sensitive detectors

1152 columns of

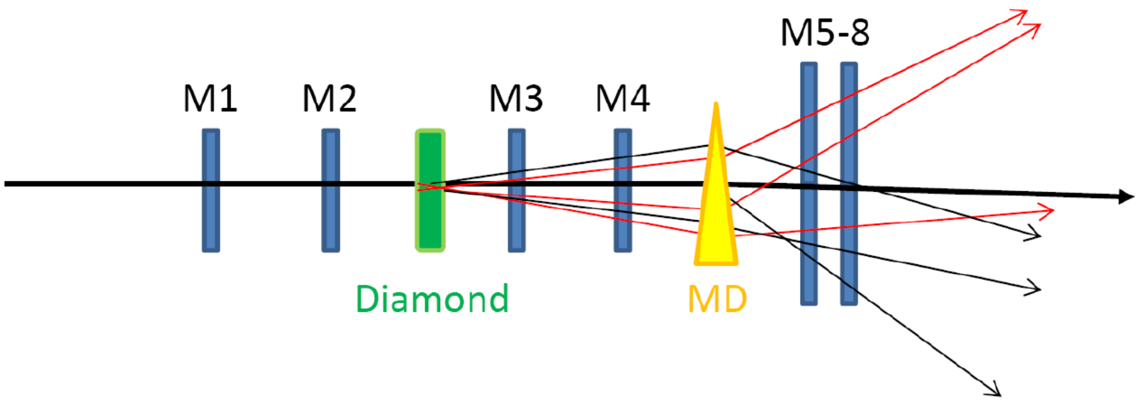
576 pixels, $\simeq$ 18.4 μm pitch

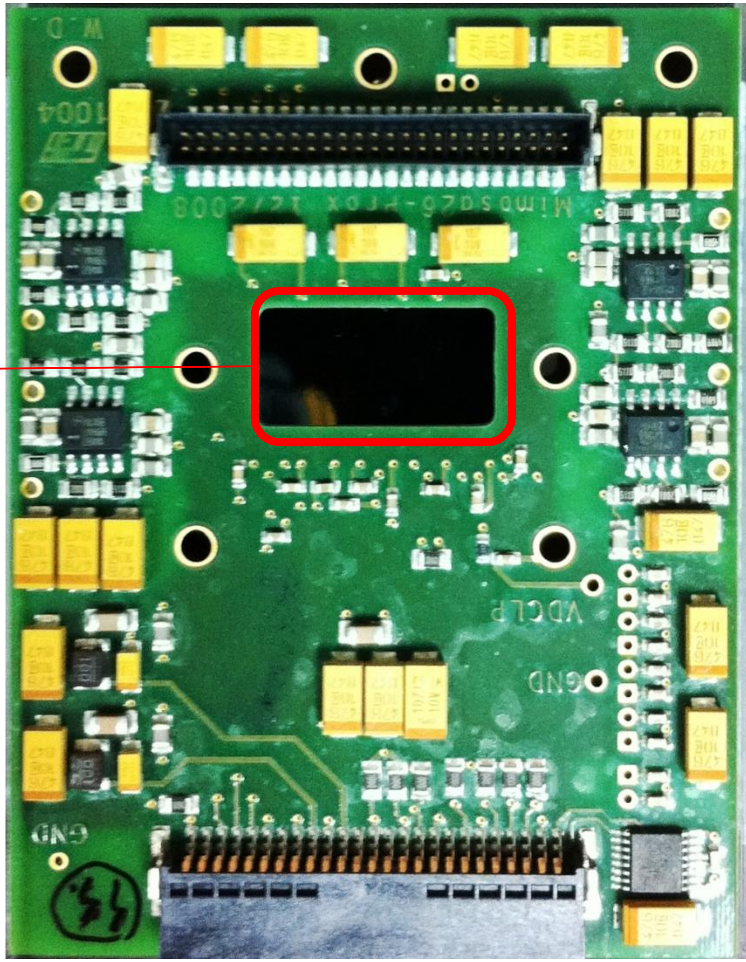
readout in 110 ms, $\simeq$ 3.5 μm resolution

true multi-hit capability

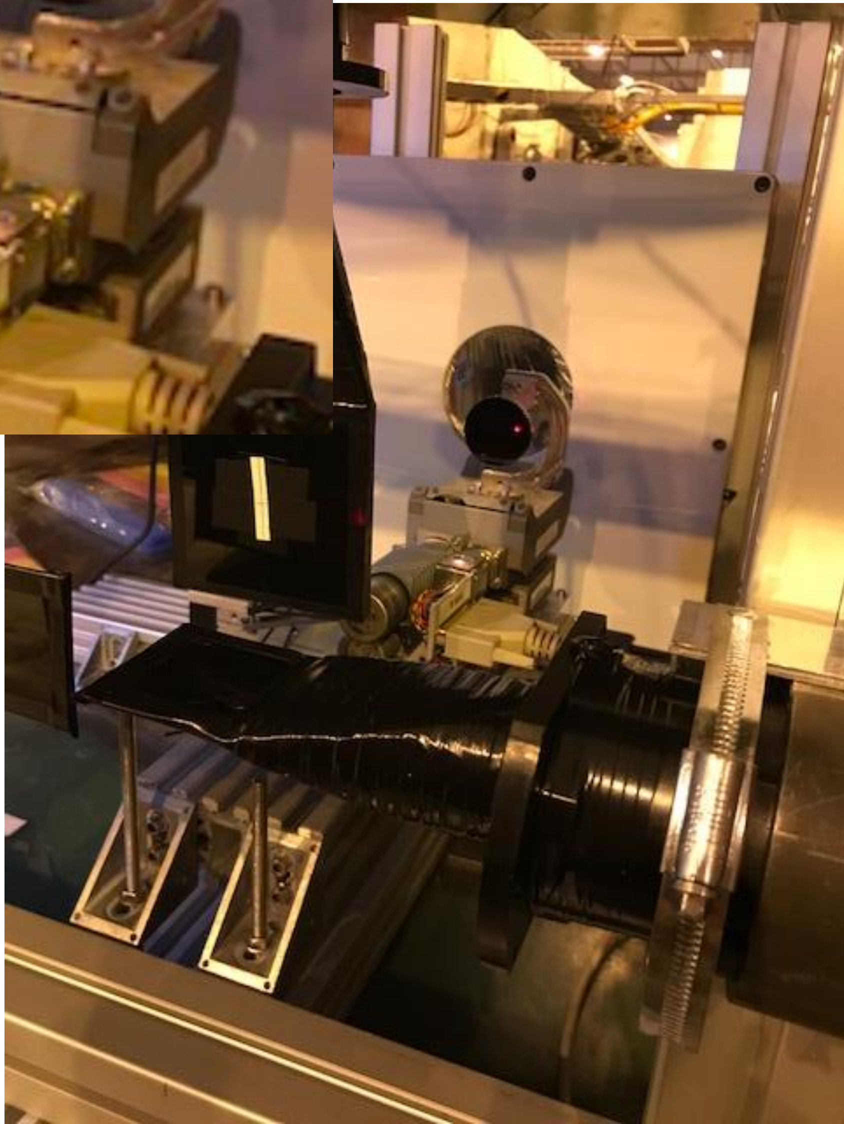
1×2 cm^2

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

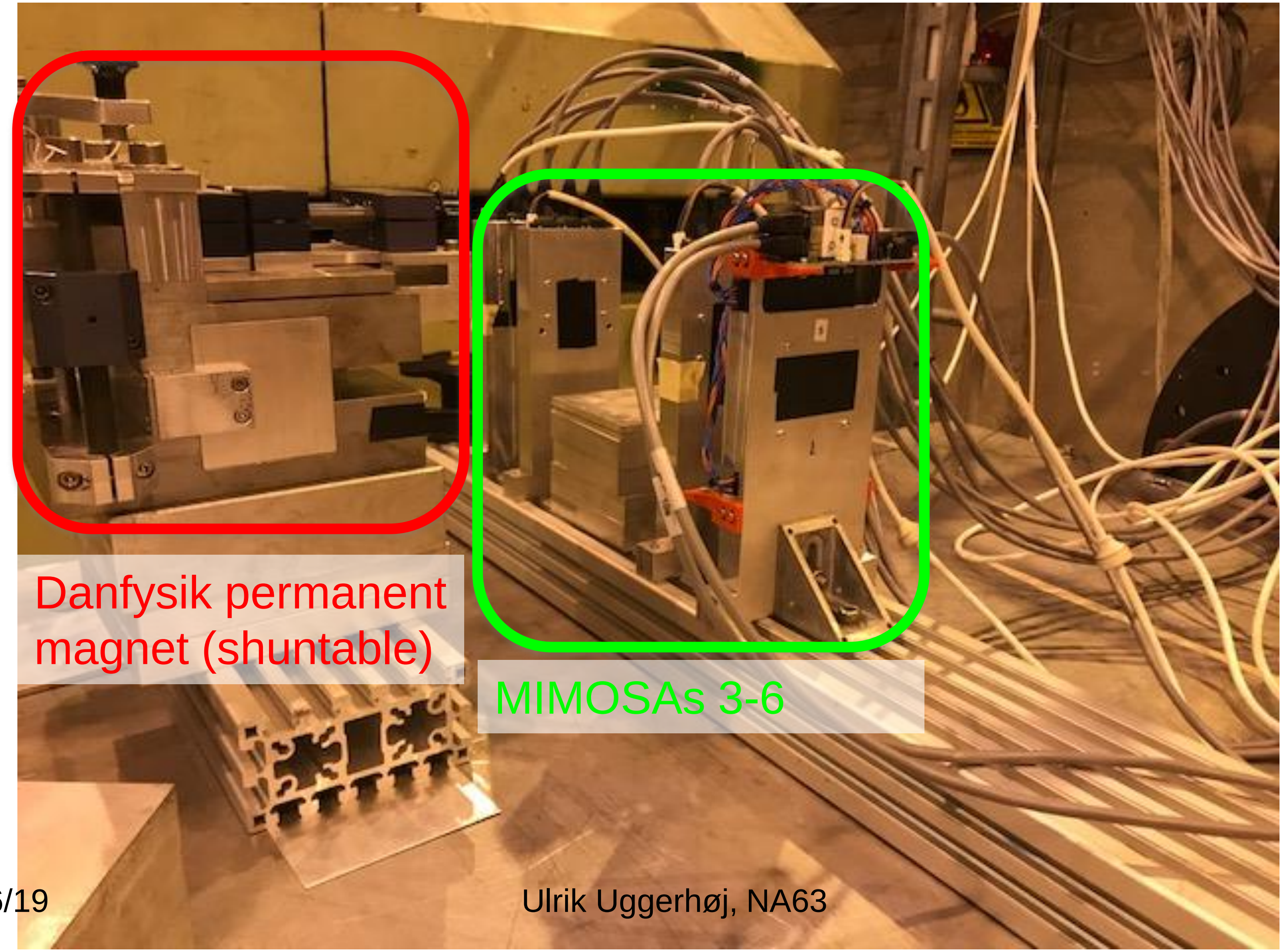




Detectors and crystal

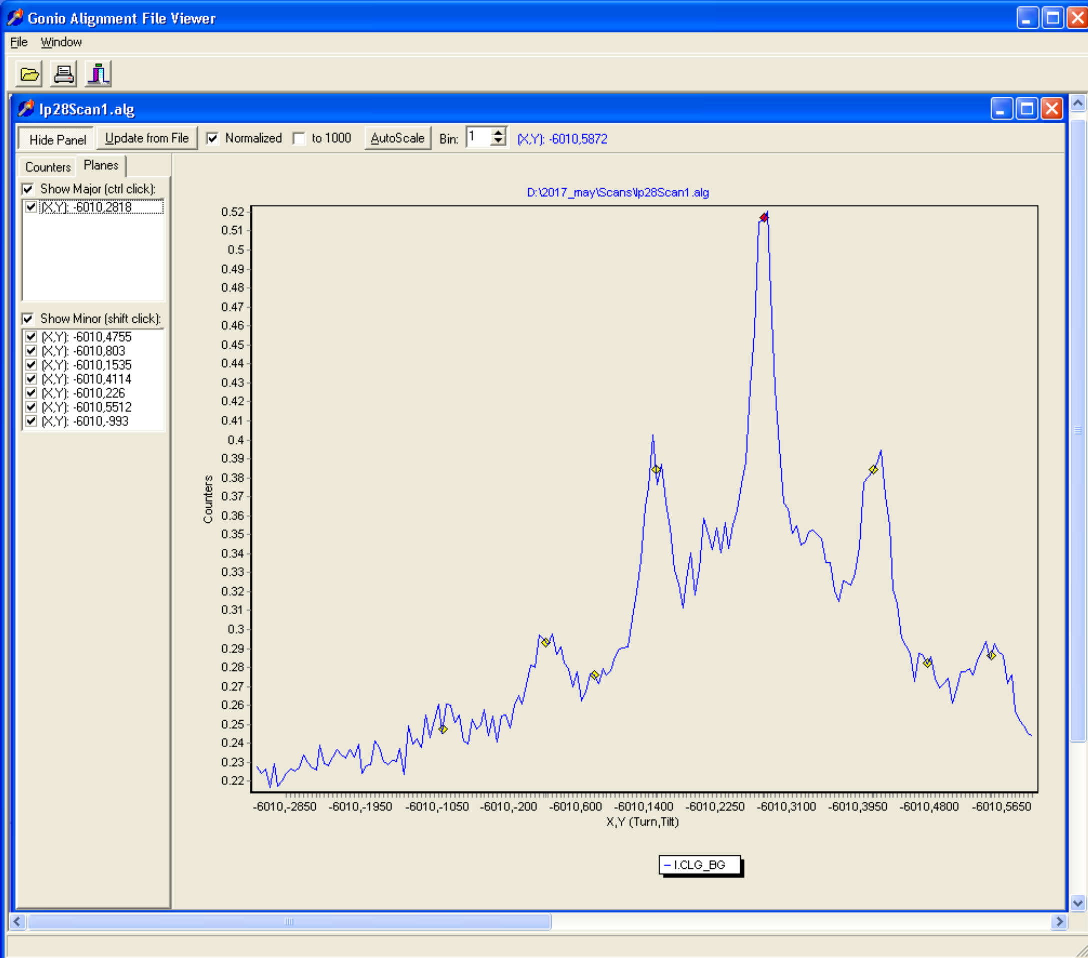


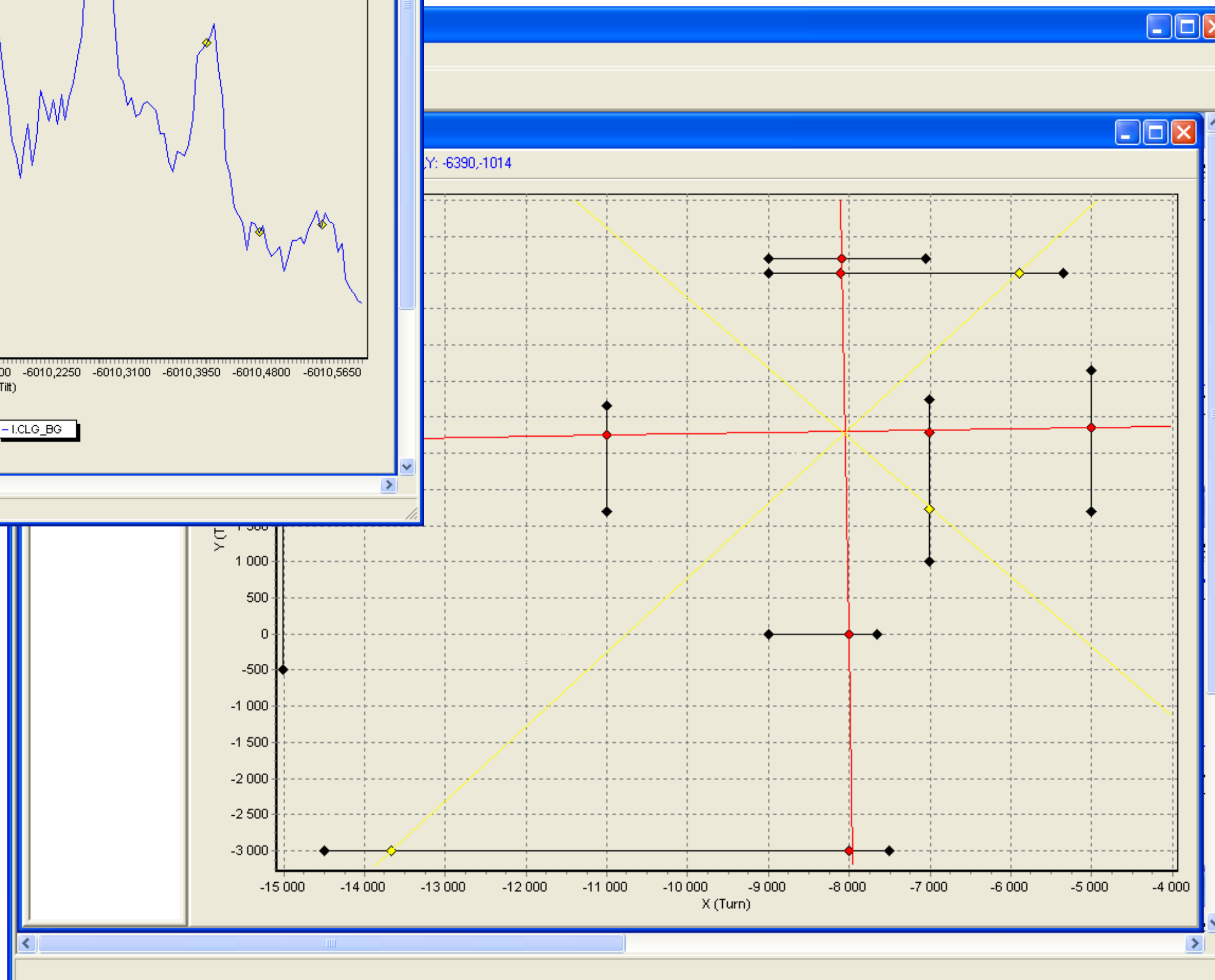
MIMOSA spectrometer



Crystal planar alignment

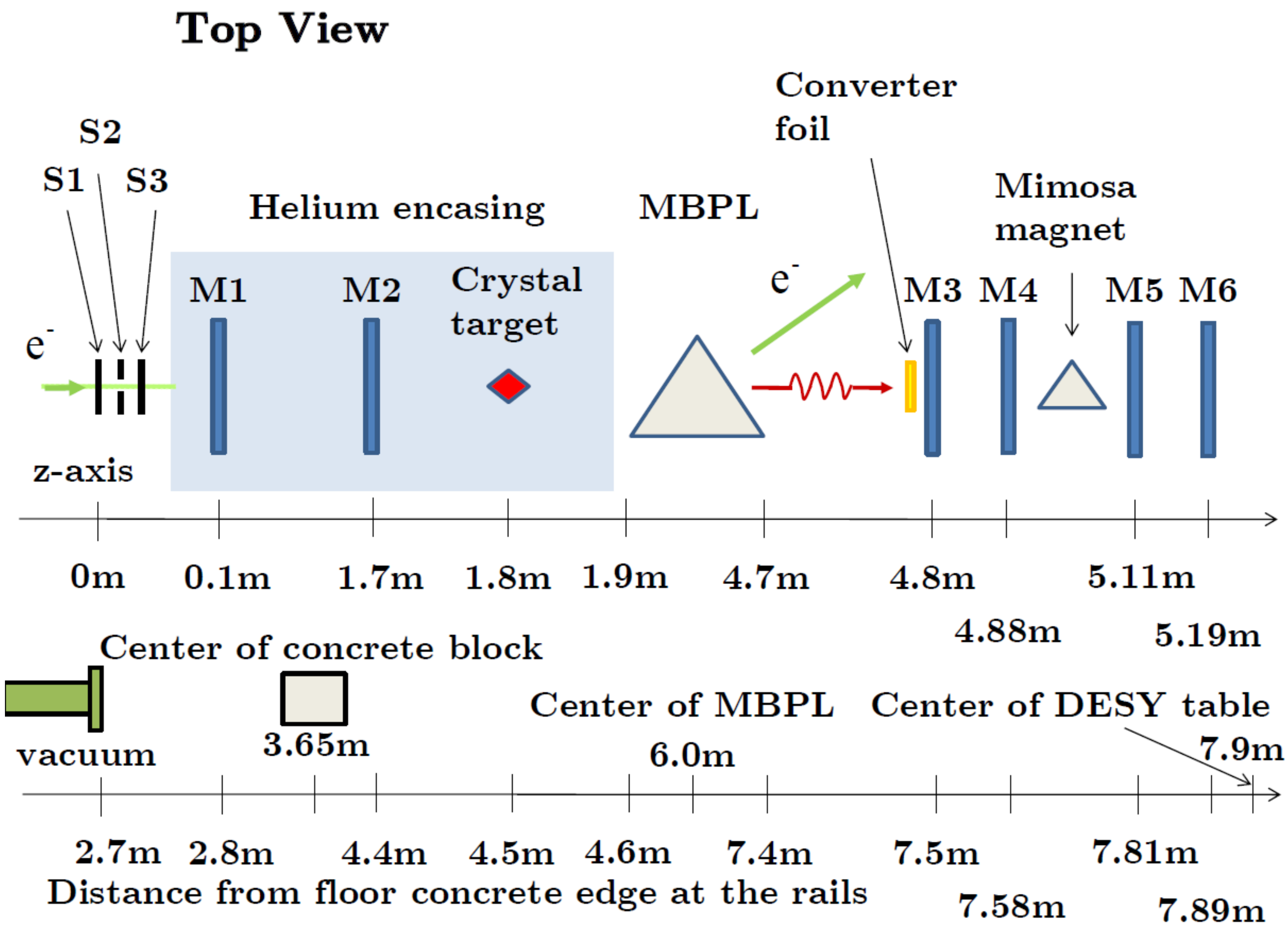
Lindhard critical angle @ 50 GeV:
23 microrad





Crystals prealigned
with x-rays

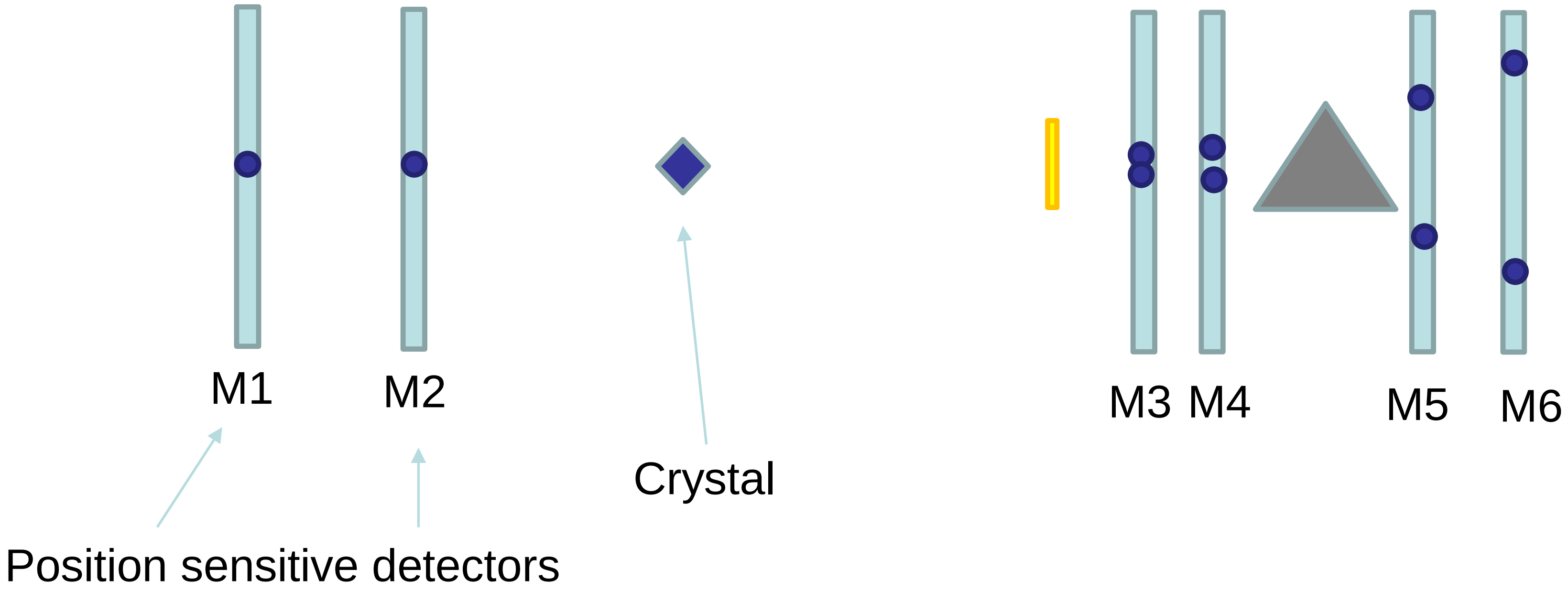
2017 data (planar case)



- In RR regime, naturally many photons are emitted per incoming charge..
- Sufficiently thin converter foil to convert single photon

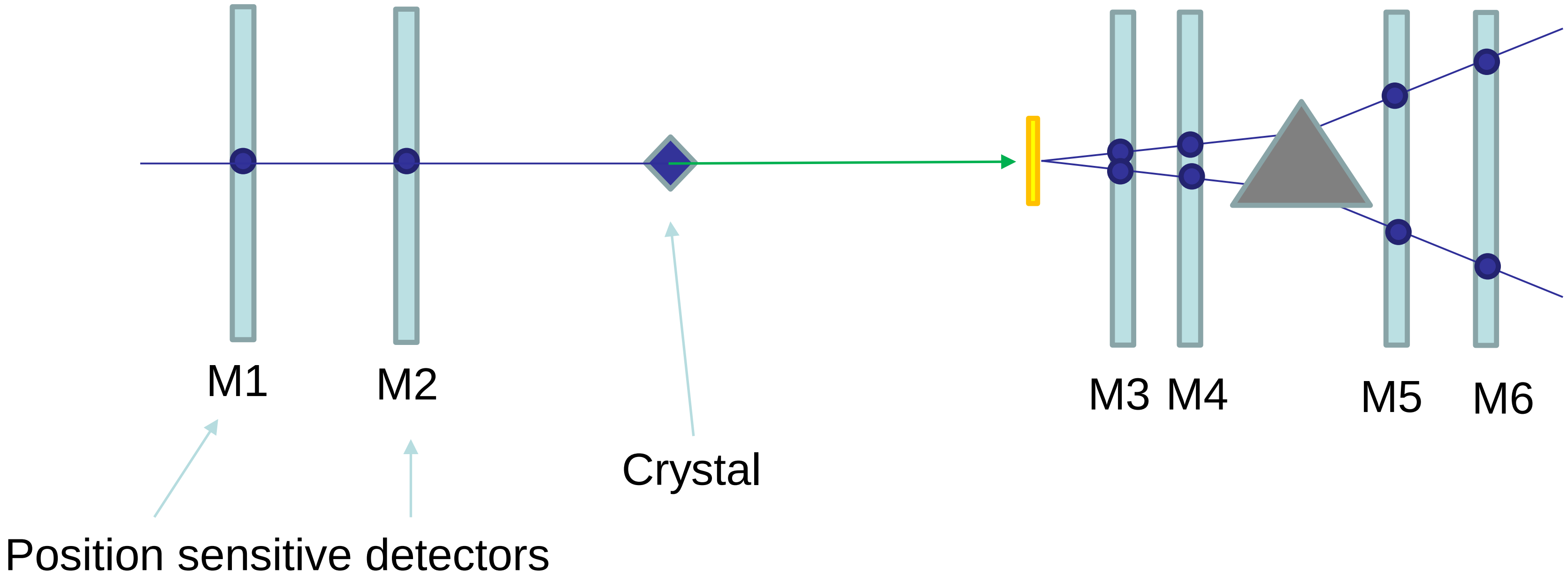
The experimental setup

- How does this setup measure photon energies?
- All you know is the position where some charged particles hit the detector



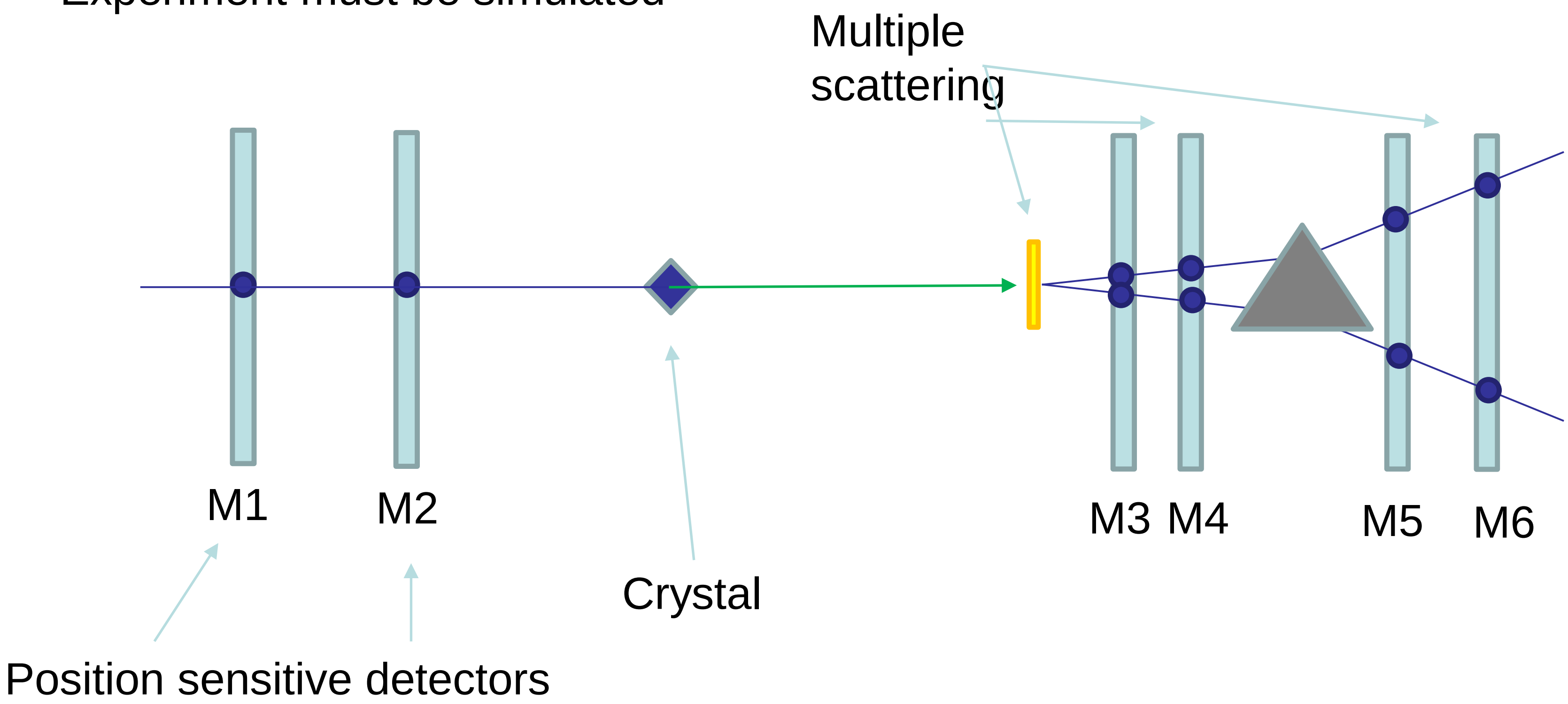
Designing the experiment.

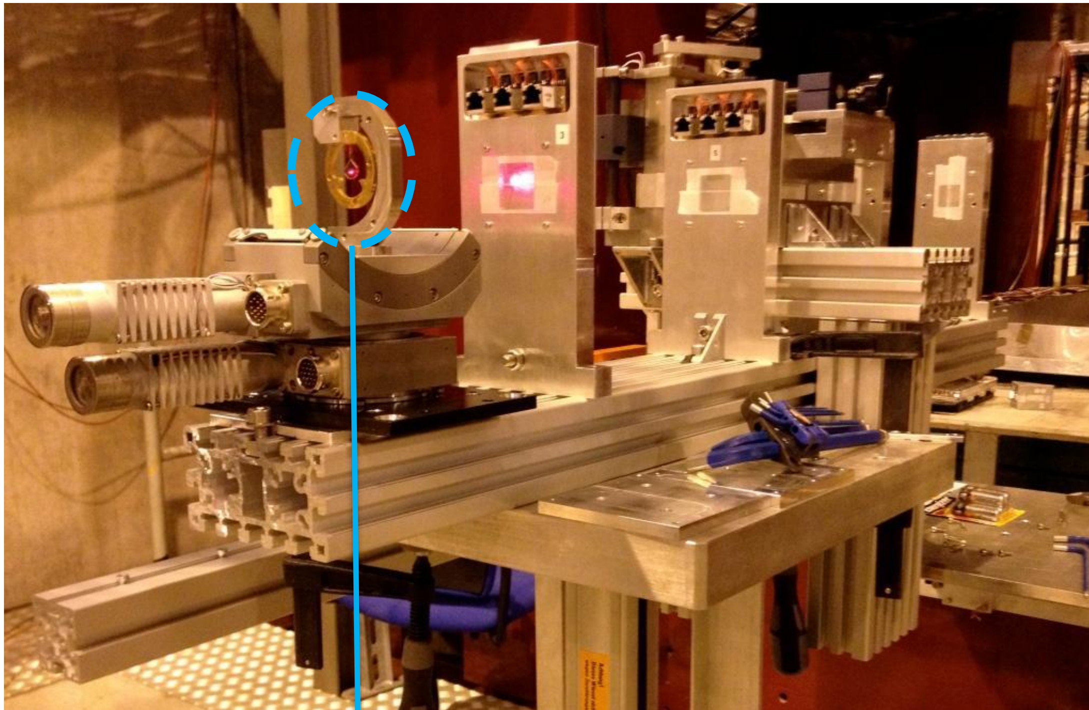
- How does this setup measure photon energies?
- All you know is the position where some charged particles hit the detector

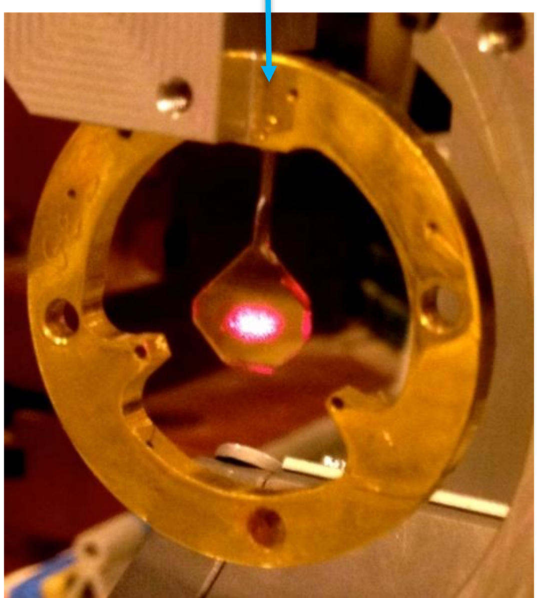


Designing the experiment.

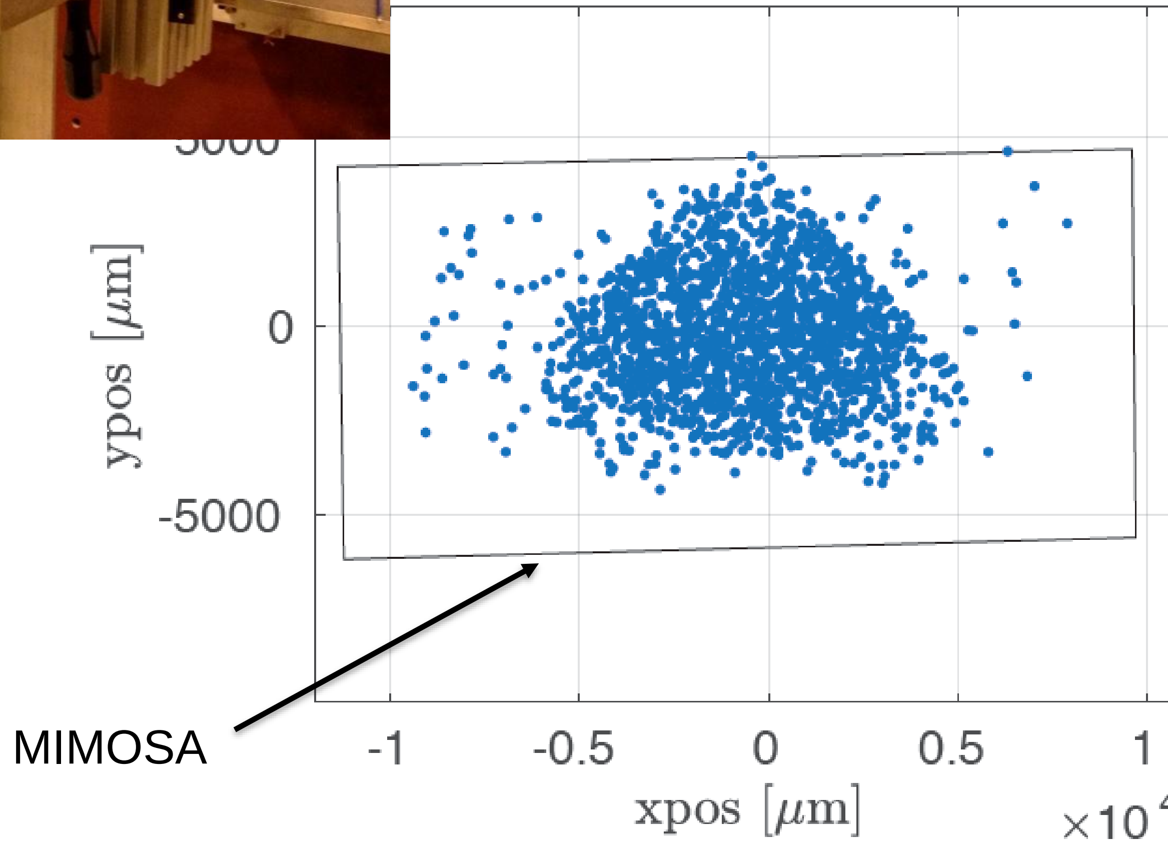
- How does this setup measure photon energies?
- All you know is the position where some charged particles hit the detector
- Experiment must be simulated







‘picture’ with tracked e+e- pairs:



Crystal	Energy	ψ_1	Θ_B
C $\langle 100 \rangle$	40 GeV	50 μrad	175 μrad
	80 GeV	35 μrad	
Si (110)	50 GeV	23 μrad	45 μrad

Substitution method takes account of quantum recoil:

$$\omega \rightarrow \omega^* = \omega / (1 - \hbar\omega / E)$$

Correction for quantum suppression of synchrotron radiation:

$$G(\chi) = \left[1 + 4.8(1+\chi)\ln(1+1.7\chi) + 2.44\chi^2\right]^{-2/3}$$

confirmed by:

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)

Crystal	d_c	E	Cut	$\overline{\chi}$	$\%E_{\mathrm{LL}}$	$\%E_{\mathrm{LL,G}(\chi)}$
C ⟨100⟩	1.0 mm	40 GeV	No cut	0.0285	47.7%	20.2%
			$2\psi_1 < \psi < 5\psi_1$	0.0274	50.0%	24.0%
			$\psi_1 > \psi$	0.0311	40.8%	8.8%
		80 GeV	No cut	0.0479	59.7%	25.1%
			$2\psi_1 < \psi < 4\psi_1$	0.0470	58.3%	22.3%
			$\psi_1 > \psi$	0.0537	50.6%	6.9%
	1.5 mm	40 GeV	No cut	0.0258	46.4%	20.1%
			$2\psi_1 < \psi < 4\psi_1$	0.0253	48.1%	22.8%
			$\psi_1 > \psi$	0.0278	39.7%	8.9%
		80 GeV	No cut	0.0418	58.3%	25.1%
			$2\psi_1 < \psi < 4\psi_1$	0.0415	56.9%	22.6%
			$\psi_1 > \psi$	0.0576	49.2%	7.0%
Si (110)	1.1 mm	50 GeV	No cut	0.0155	33.5%	25.9%
			$\psi < 30\mu$rad	0.0140	16.1%	5.7%
	2.0 mm		No cut	0.0154	32.8%	24.7%
			$\psi < 30\mu$rad	0.0130	16.2%	6.38%
	4.2 mm		No cut	0.0141	31.8%	24.9%
			$\psi < 30\mu$rad	0.0123	16.7%	7.4%
	6.2 mm		No cut	0.0139	28.9%	21.5%
			$\psi < 30\mu$rad	0.0113	16.3%	7.1%

ratio of damping force to external force

$$\eta = \alpha\gamma\chi = \alpha\gamma^2\mathcal{E}_\perp/\mathcal{E}_0$$

This number shows a compromise: with increase of chi the damping becomes more significant, but the validity of the LL becomes more questionable: the fractional difference between energy lost according to the (Lorentz-force with LL damping) trajectory and energy lost according to the full spectrum increases.

Example of results, silicon (2017 data)

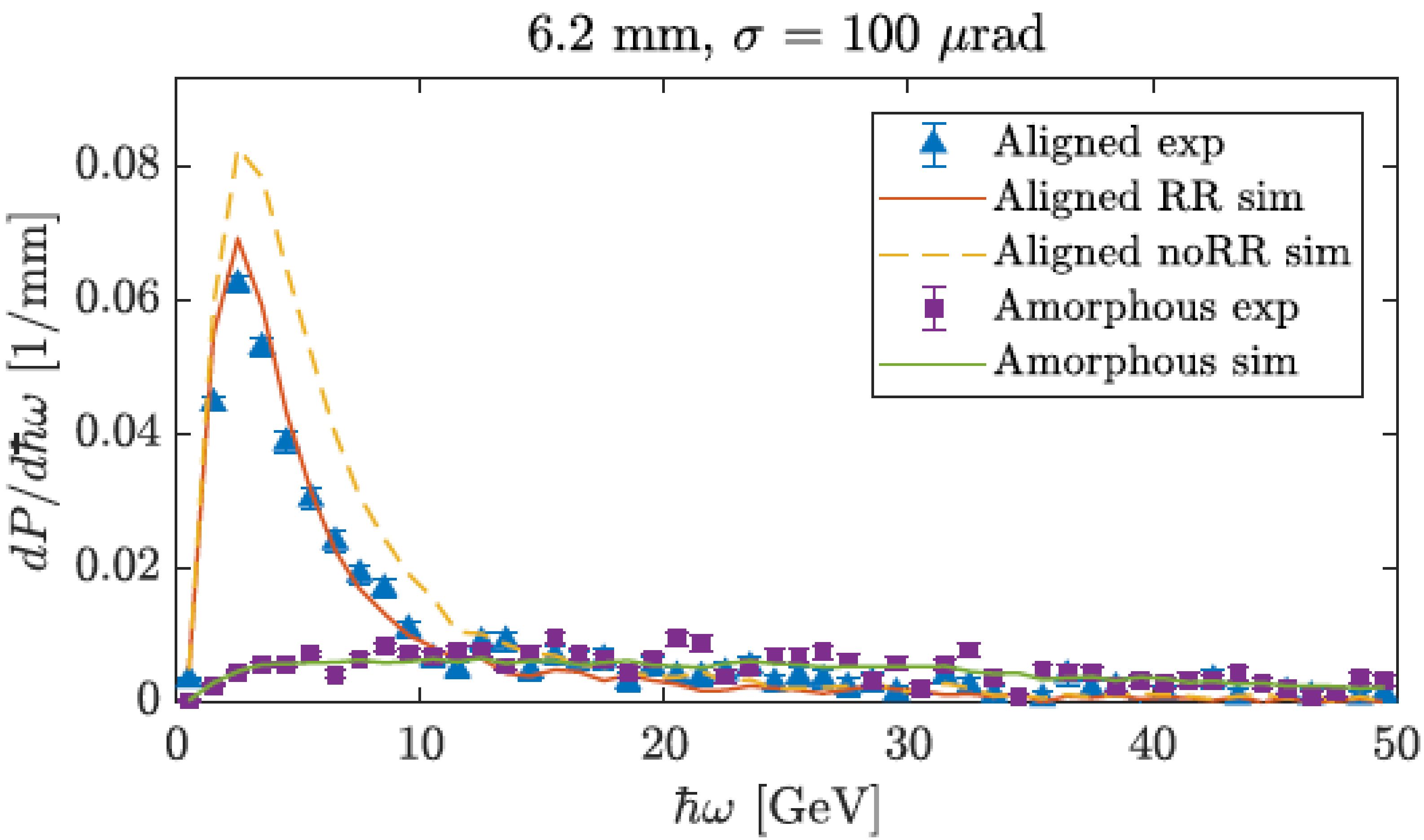


Figure 4: Radiation power spectra obtained for 50 GeV positrons passing 1.1, 2.0, 4.2 and 6.2 mm thick silicon crystals aligned to the (110) plane, and the corresponding amorphous spectra. These spectra has angular cuts, meaning that only particles with entry angle between $\pm$ 30 μrad with respect to the crystal planes are included.

Example of results, silicon (2017 data)

The agreement between experiment and theory where we include the LL equation *could* be due to a fortuitous selection of effects in the theory-based simulation, which is propagated through the same analysis algorithm as the experimental data. However, as fig. 9 and fig. 10 shows, the agreement is not a coincidence: The theoretical curves there do *not* rely on an intricate analysis algorithm. In addition, the experimental data are directly based on data obtained from the aligned crystal divided by data obtained in the amorphous orientation (Bethe-Heitler), and are thus – at least to first order – independent of selection criteria for the pairs, detection efficiencies etc, the agreement between data and simulations for the LL equation is convincing. Due to poor

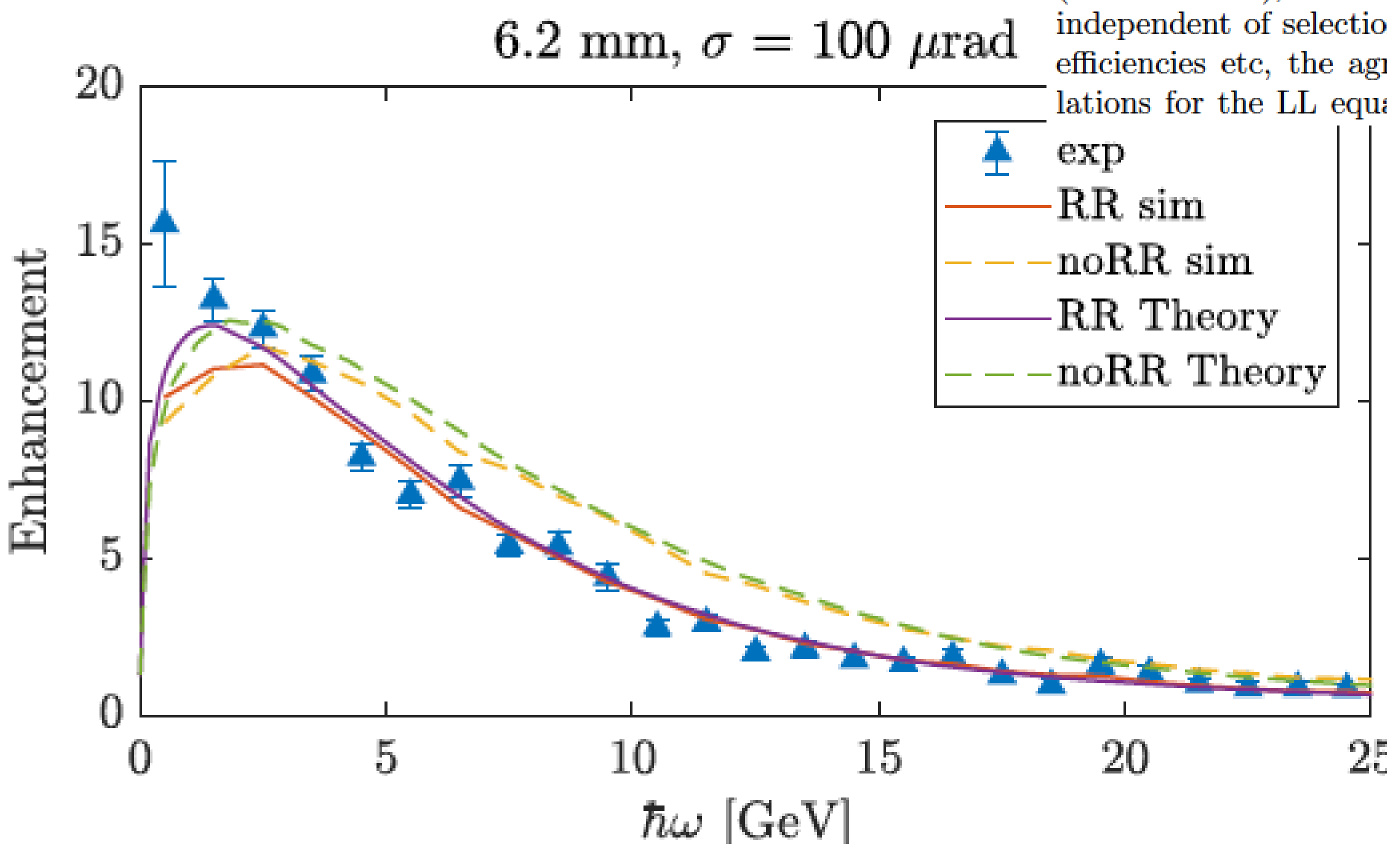
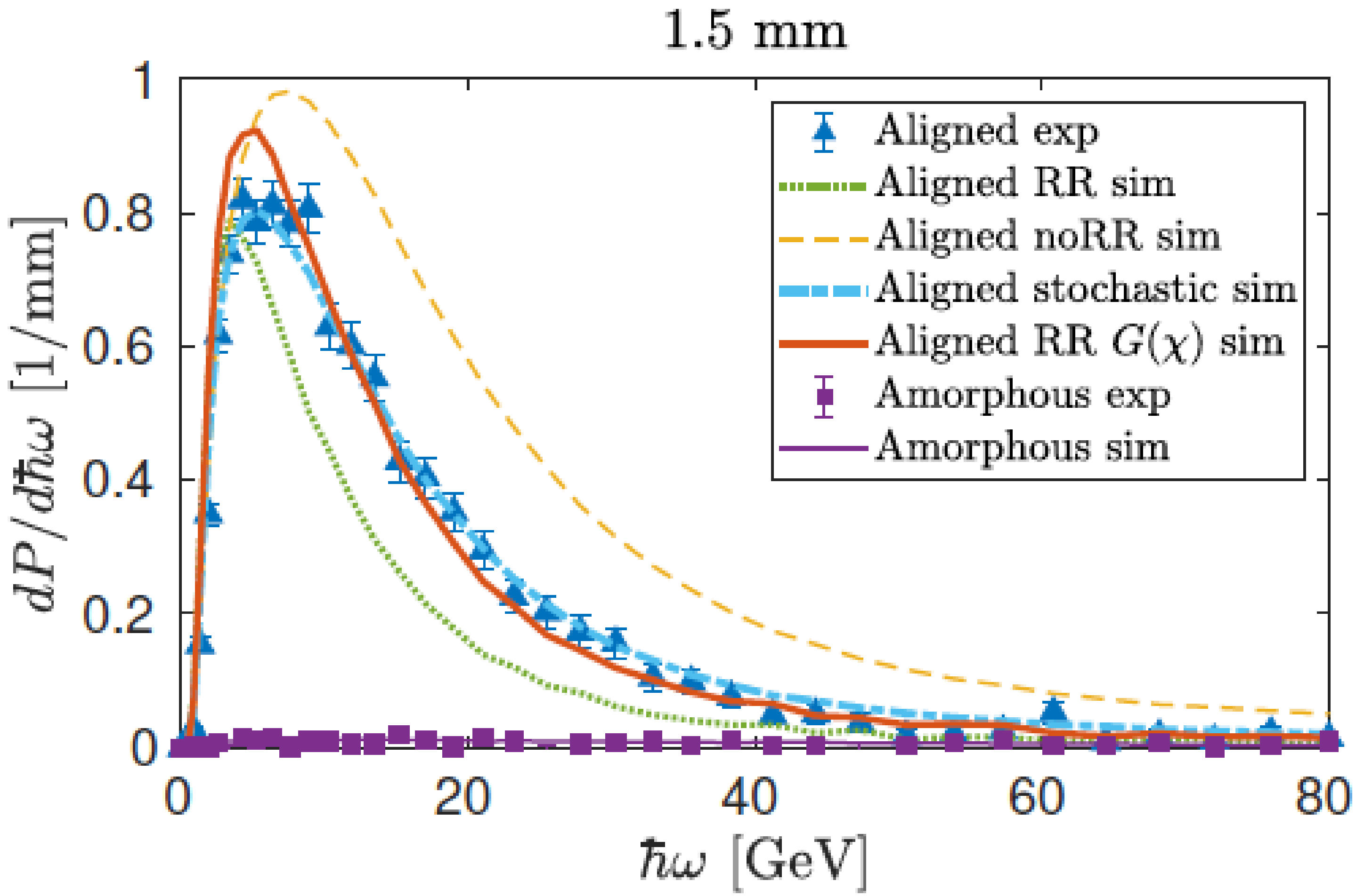


Figure 10: Enhancement spectra, i.e. the radiation obtained for 50 GeV positrons passing 1.1, 2.0, 4.2 and 6.2 mm thick silicon crystals aligned to the (110) plane, divided by the corresponding amorphous yield. These spectra has no angular cuts and all particles in the beam are included. Theoretical curves and data points are labeled as in fig. 9

Example of results, diamond (2018 data)



Another example from a total of 22 experimental comparisons with theory reported in the draft for a paper.

Figure 7: Radiation power spectra obtained for 40 GeV (left) and 80 GeV (right) electrons traversing 1.0 mm (bottom) and 1.5 mm (top) thick carbon crystals aligned to the ⟨100⟩ axis, and the corresponding amorphous spectra. These spectra has angular cuts, meaning that only particles with entry angle less than ψ_1 with respect to the crystal axis are included, where ψ_1 is the Lindhard critical angle with $\psi_1 \approx 50 \times 10^{-6}$ rad for 40 GeV electrons and $\psi_1 \approx 35 \times 10^{-6}$ for 80 GeV electrons. Theoretical curves and data points are labeled as in fig. 6.

2 papers ready for submission

(23 NA63 papers published since 2008)

To be submitted to PRX:

2018 data:

Applicability of the Landau-Lifshitz equation for Radiation Reaction based on Aligned Crystals

C. F. Nielsen,[1] J. B. Justesen,[1] A. H. Sørensen,[1] U. I. Uggerhøj,[1] and R. Holtzapple[2]

(CERN NA63)

[1] *Department of Physics and Astronomy, Aarhus University, 8000 Aarhus, Denmark*

[2] *Department of Physics, California Polytechnic State University, San Luis Obispo, California 93407, USA*

To be submitted to PRL:

2017 data:

Quantum radiation reaction in aligned crystals beyond the local constant field approximation

C. F. Nielsen[1], T. N. Wistisen[2], A. Di Piazza[2], A. H. Sørensen[1] and U. I. Uggerhøj[1]

[1] *Department of Physics and Astronomy, Aarhus University, 8000 Aarhus, Denmark and*

[2] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117, Germany*

(CERN NA63)

Thank you for listening.

Xtras

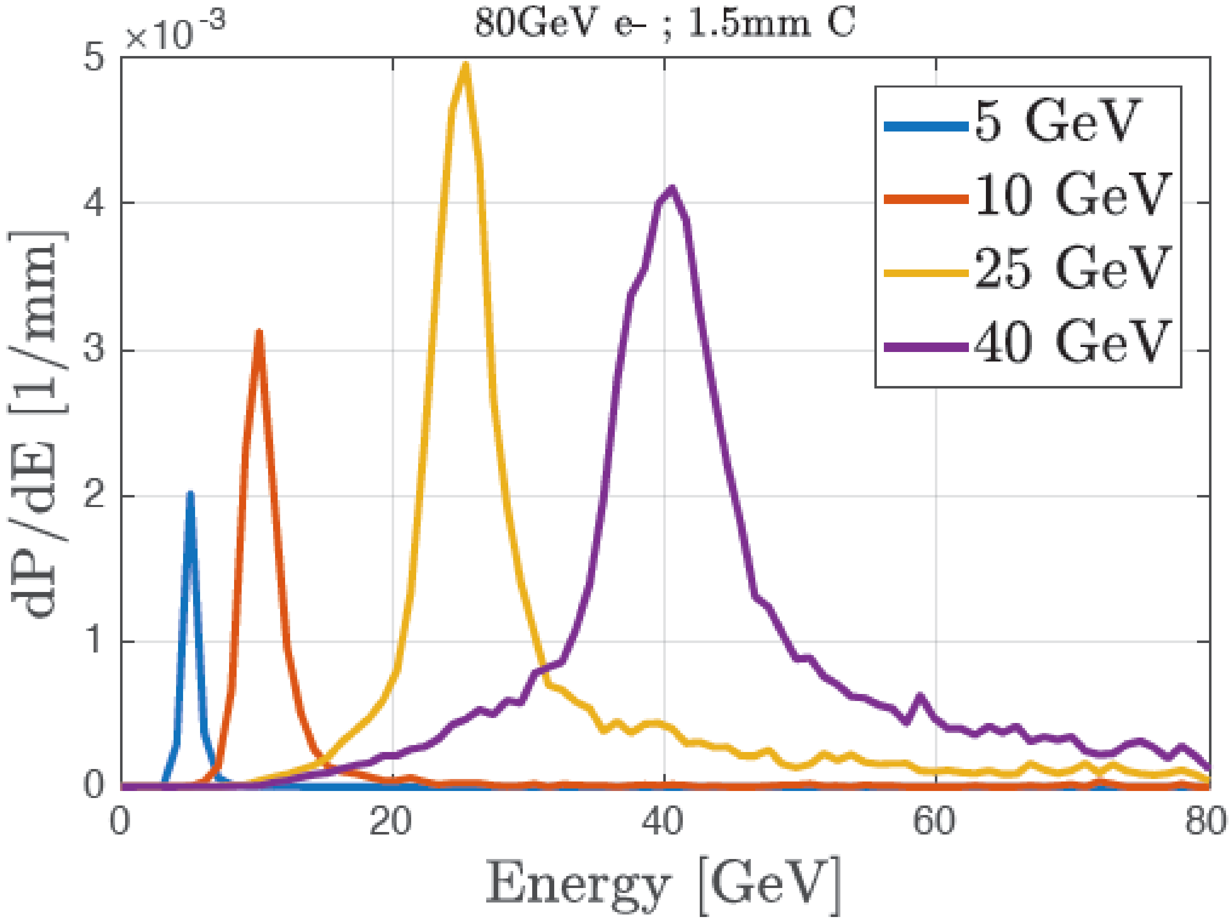
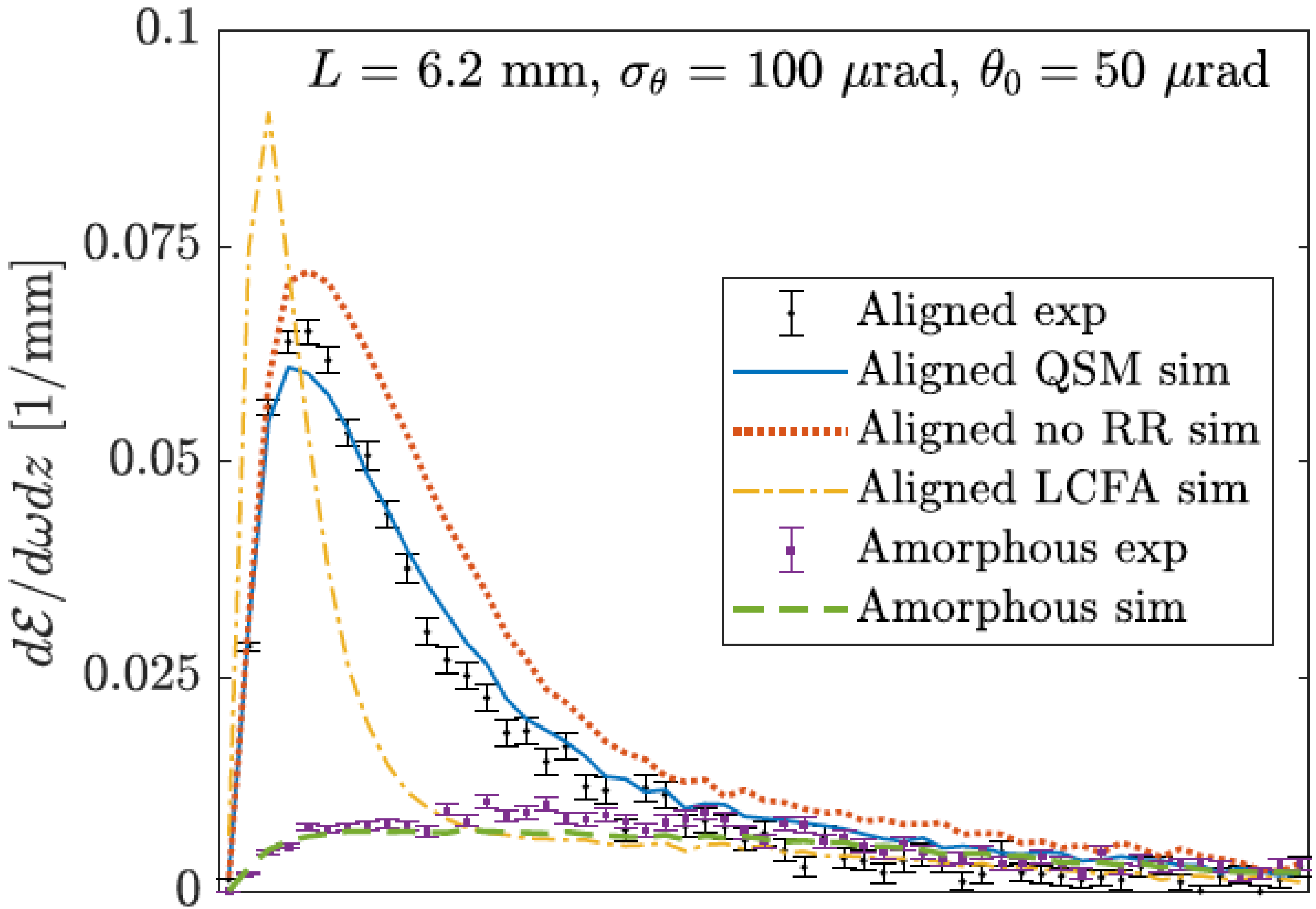
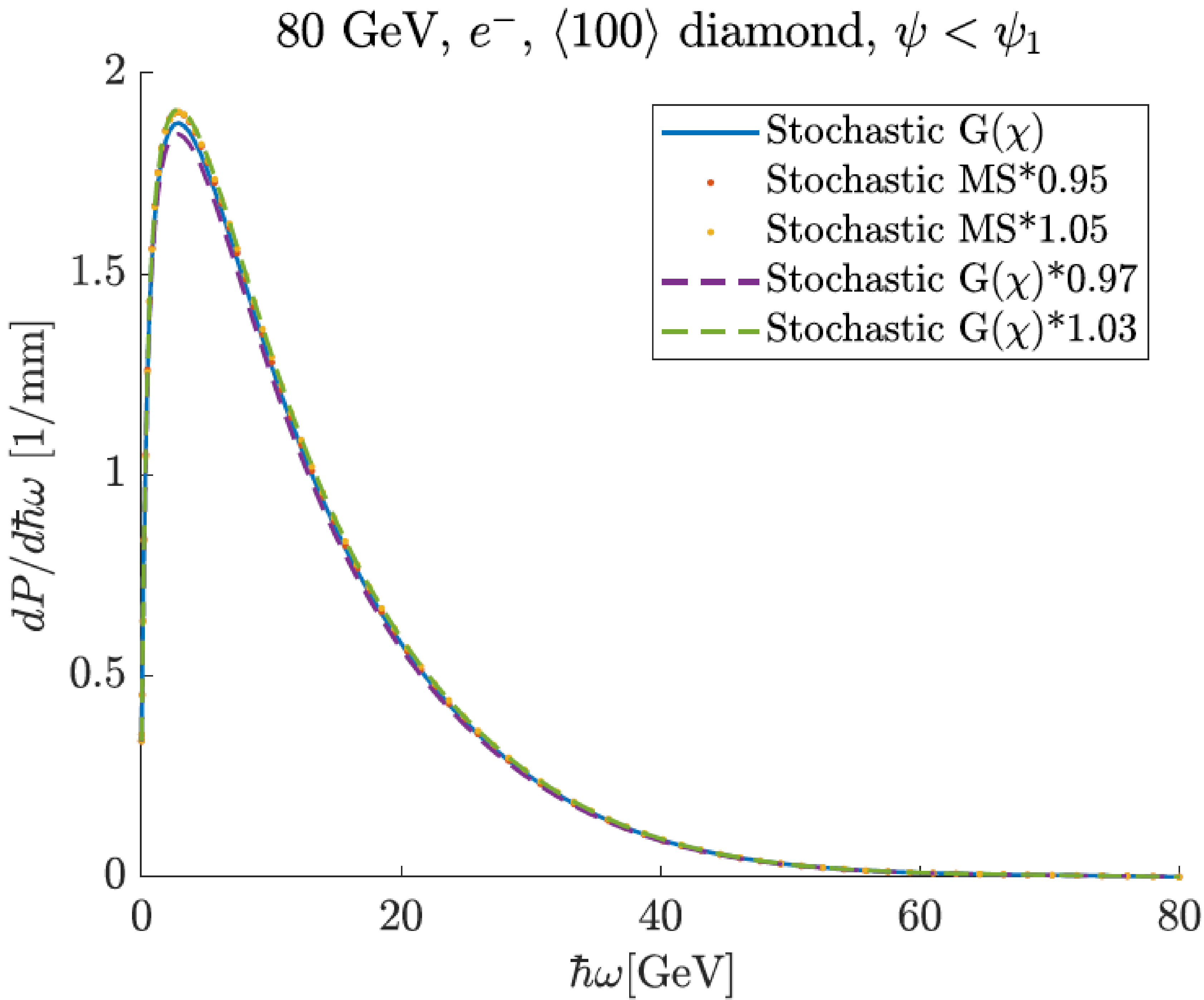


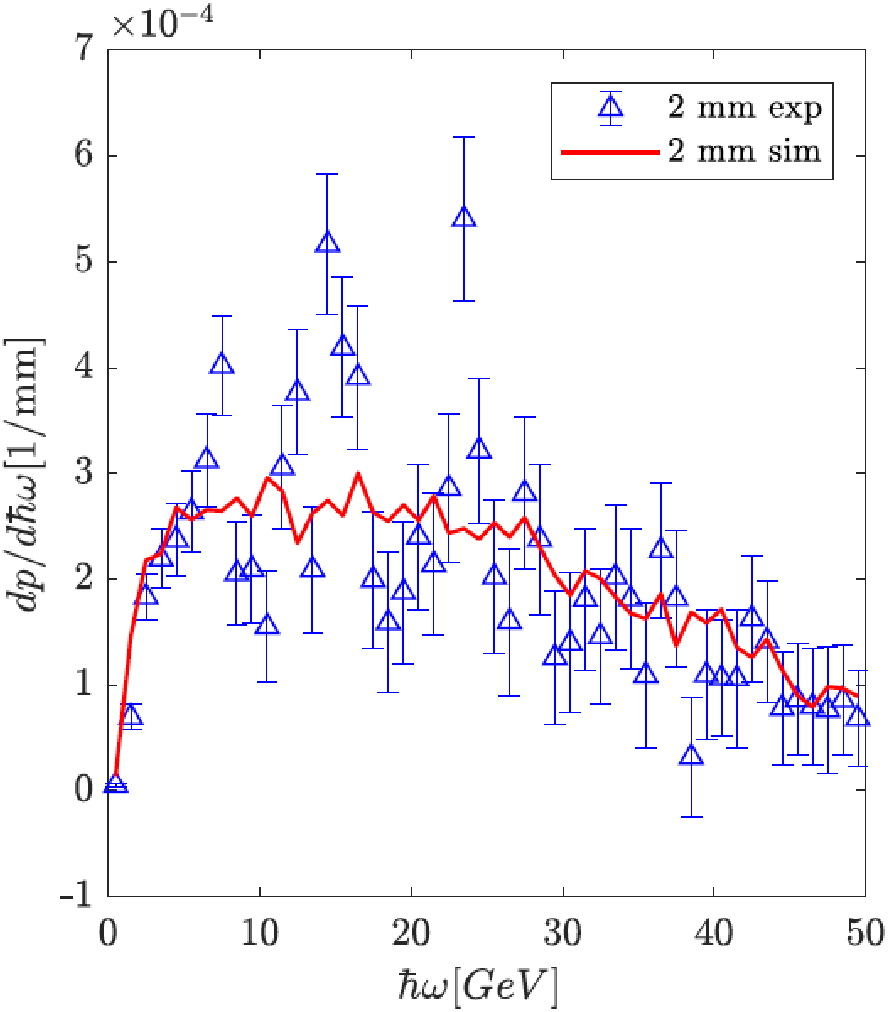
Figure 4.8: Simulations of the experiment assuming a monochromatic light source at 5 GeV (blue), 10 GeV (orange), 25 GeV (yellow) and 40 GeV (purple).



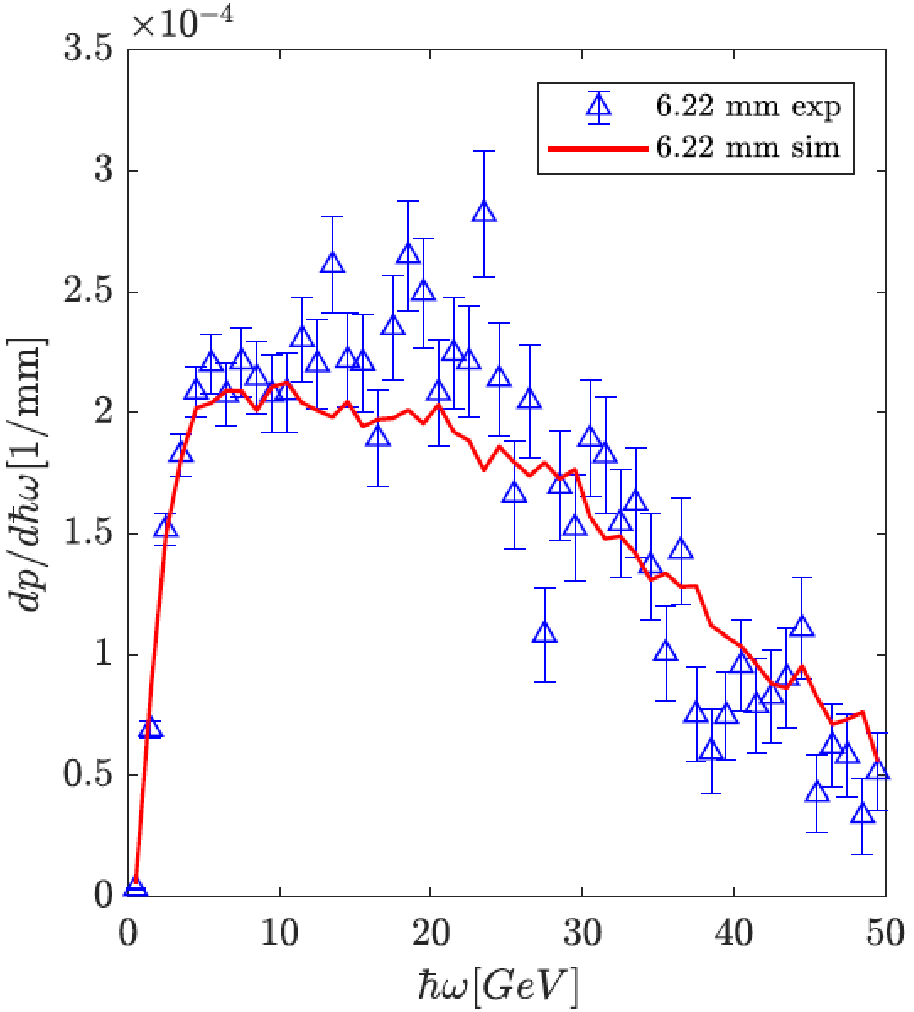
$L = 6.2$ mm, $\sigma_\theta = 100$ μrad, $\theta_0 = 50$ μrad
$d\mathcal{E}/d\omega dz$ [1/mm]
0.1
0.075
0.05
0.025
0
Aligned exp
Aligned QSM sim
Aligned no RR sim
Aligned LCFA sim
Amorphous exp
Amorphous sim



80 GeV, e^-, $\langle 100 \rangle$ diamond, $\psi < \psi_1$
Stochastic G(χ)
Stochastic MS*0.95
Stochastic MS*1.05
Stochastic G(χ)*0.97
Stochastic G(χ)*1.03
$dP/d\hbar\omega$ [1/mm]
$\hbar\omega$[GeV]
0
0.5
1
1.5
2
0
20
40
60
80



×10^-4
2 mm exp
2 mm sim
dp/dħω[1/mm]
ħω[GeV]



×10^-4
6.22 mm exp
6.22 mm sim
dp/dħω[1/mm]
ħω[GeV]