Final report from CERN NA63

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on behalf of the collaboration

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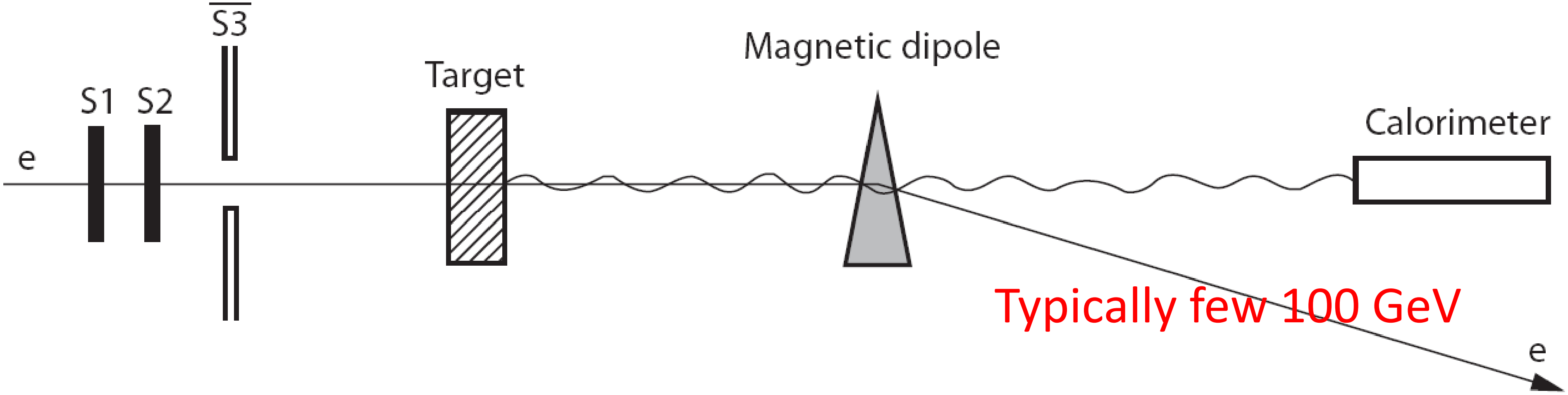
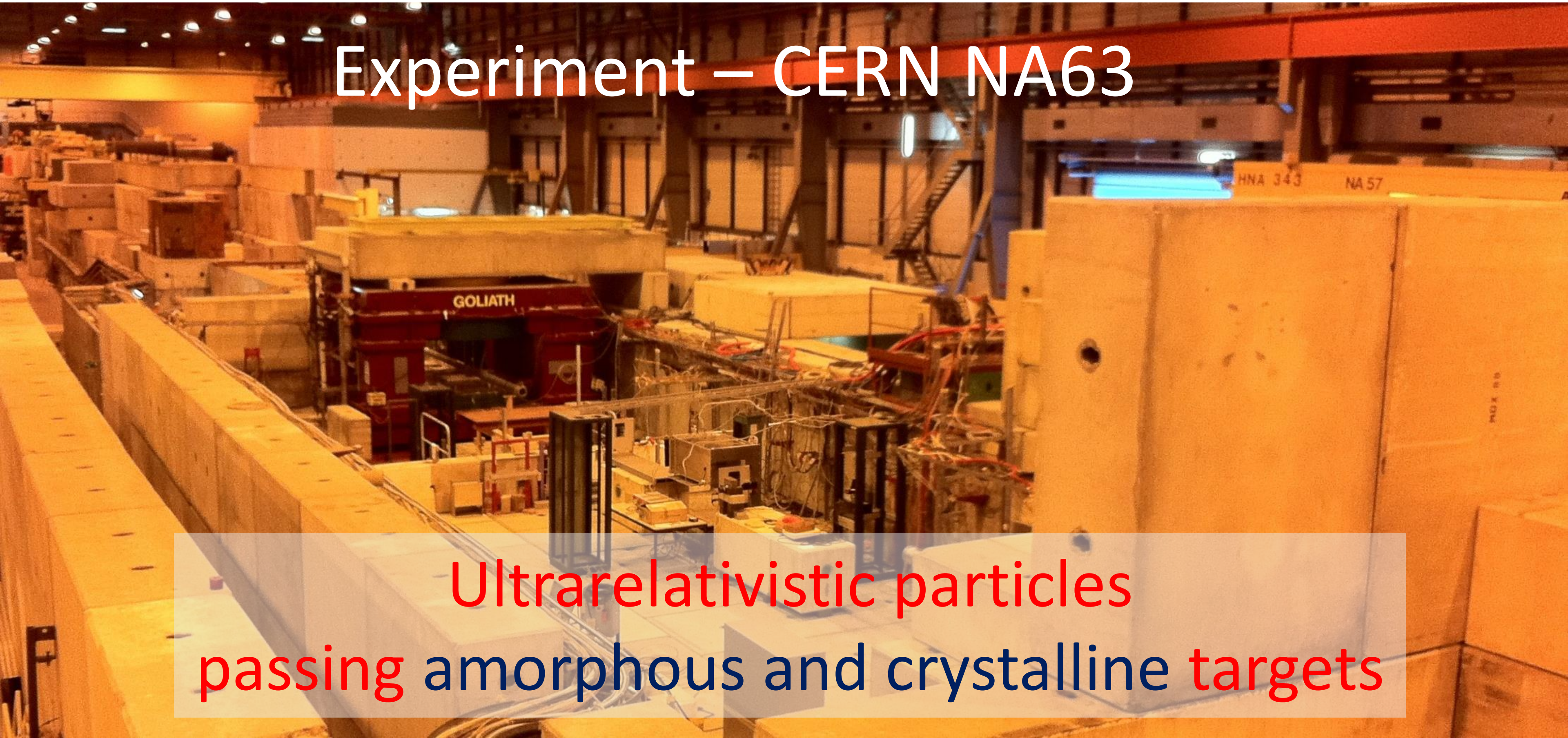
Scientific investigations in the framework of NA63

- Direct measurement of the Chudakov effect: PRL **100**, 164802 (2008); NIMB **269**, 1919 (2011)
- LPM effect: NIMB **266**, 5013 (2008); NIMB **269**, 1977 (2011); NIMB **289** 5-17 (2012); PRD **88**, 072007 (2013)
- Formation length of the photon: PLB **672**, 323 (2009); PRL **108**, 071802 (2012); NIMB **315**, 278 (2013); PLB **732**, 309-314 (2014)
- Beamstrahlung in strong fields: JPCS **198**, 012007 (2009); PRST-AB **17**, 051003 (2014)
- Strong field trident production: PRD **82**, 072002 (2010); PRL **130**, 071601 (2023); PRD **108**, 052013 (2023)
- Logarithmic thickness dep. of radiation: PRD **81**, 052003 (2010)
- Quantum synchrotron radiation: PRD **86**, 072001 (2012)
- Strong field vacuum birefringence: PRD **88**, 053009 (2013)
- Quantum/classical Radiation Reaction: PLB **765**, 1-5 (2016); Nat. Comm. **82**, art. 795 (2018); PRR **1**, 033014 (2019); PRL 124, 044801 (2020); PRD **102**, 052004 (2020)



Experiment – CERN NA63



Ultrarelativistic particles
passing amorphous and crystalline targets

LPM effect

When the formation length

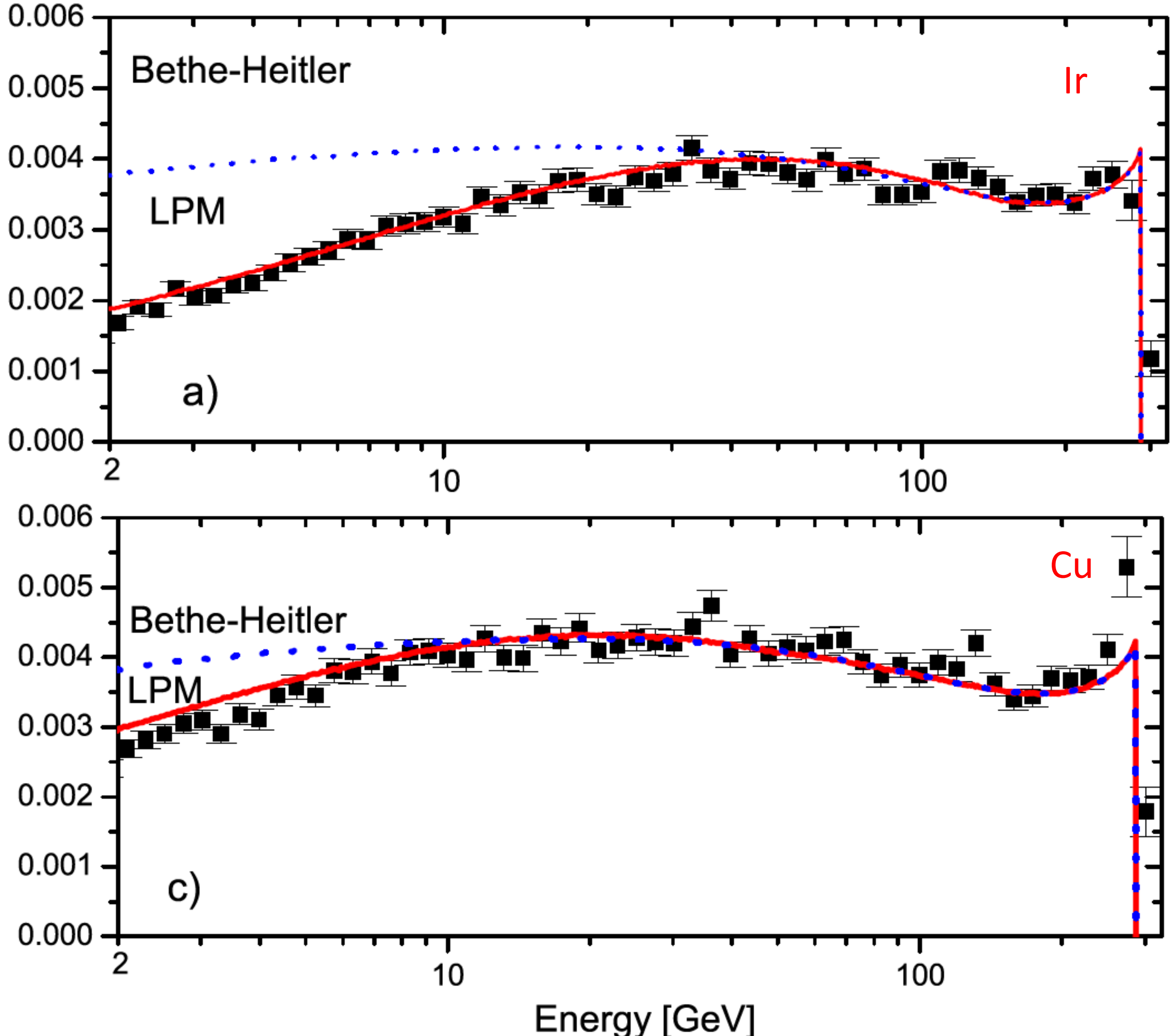
$$l_{\mathrm{f}} = \frac{2\gamma^2 c}{\omega^*}$$

exceeds the multiple-scattering length:

$$l_\gamma = \frac{\alpha}{4\pi} X_0$$

suppression arises below:

$$\hbar\omega^{\mathrm{q}}_{\mathrm{LPM}} = \frac{E^2}{E + E_{\mathrm{LPM}}}$$



$$E_{\mathrm{LPM}} = mc^2 X_0 / 4\pi a_0 = 7.684 \cdot X_0 \;\; \mathrm{TeV/cm}$$

Semi-infinite target…

Structured targets and the Landau-Pomeranchuk-Migdal effect

SLAC E-146

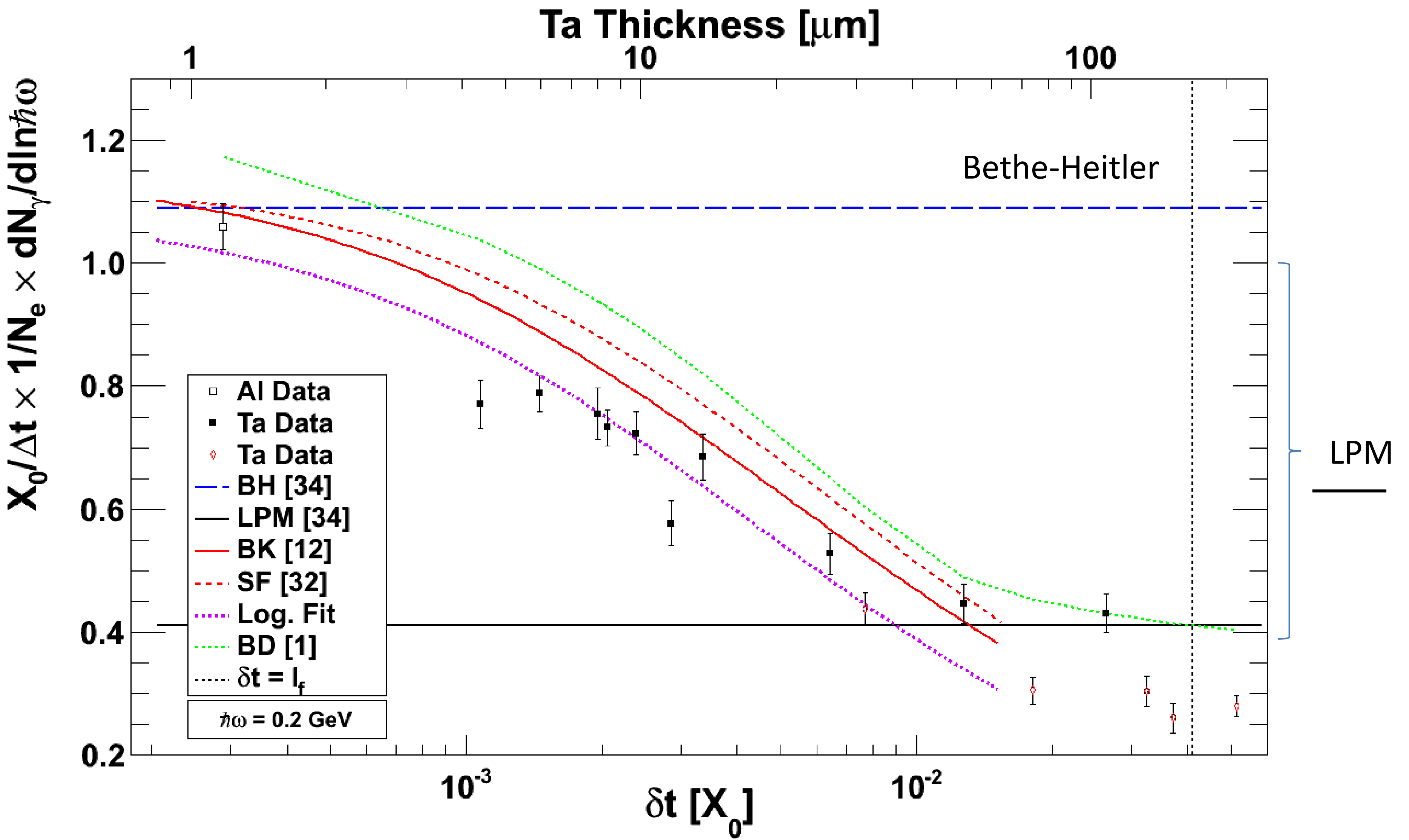
Richard Blankenbecler*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

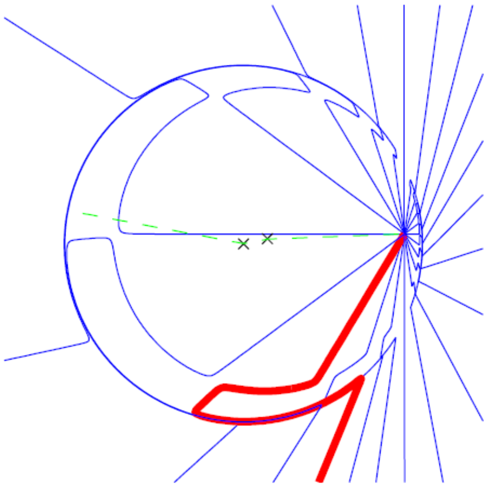
PHYSICAL REVIEW D 55 190 1997

Multiple scattering and functional integrals

PHYSICAL REVIEW D 55 2441 1997

What is the bremsstrahlung transition from single-scattering (BH) to multiple-scattering (LPM)?





Logarithmic *t* dependence

Transition between Bethe-Heitler and LPM regimes:

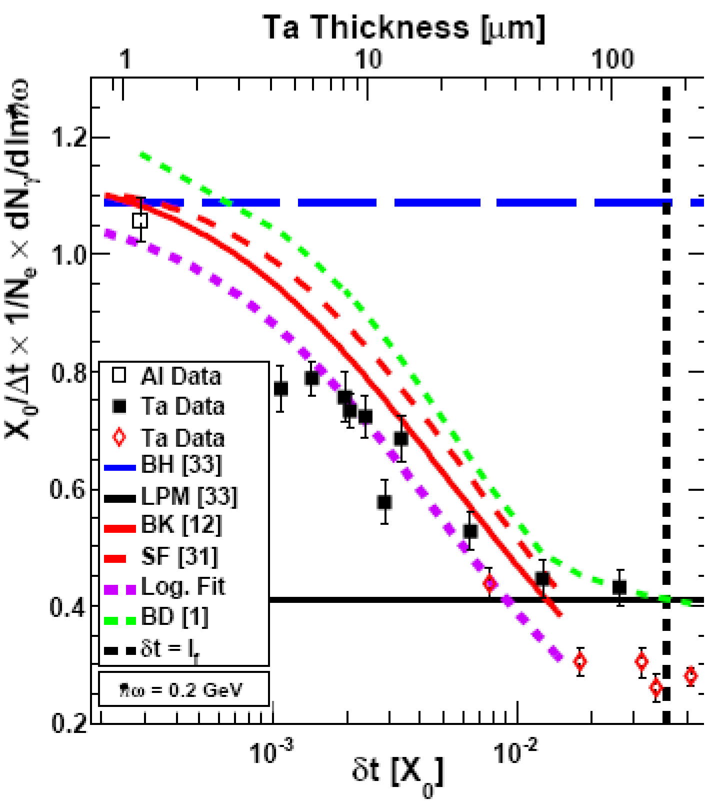
$$1/N_e \times \frac{dN_\gamma}{d\ln\hbar\omega}$$

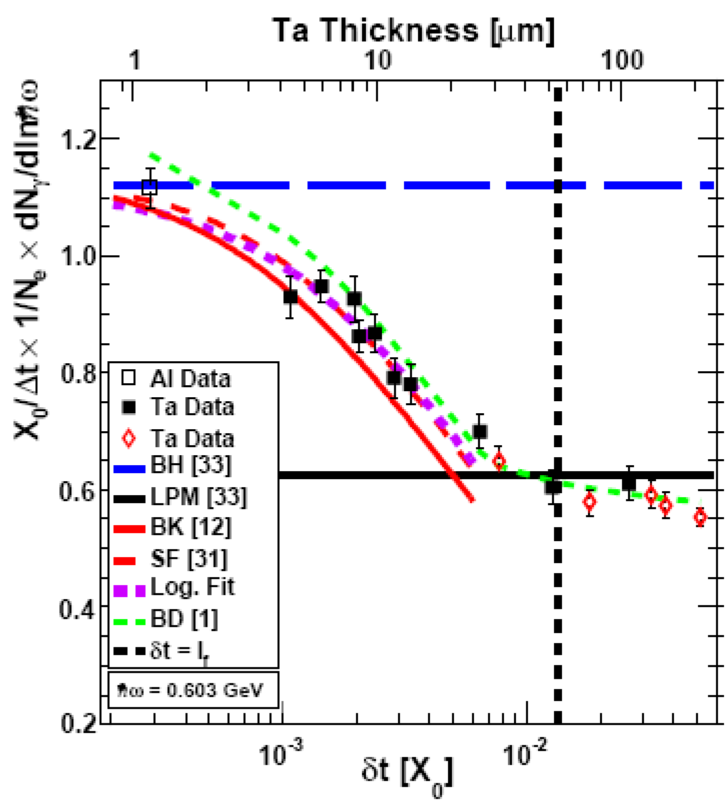
$$\simeq a \times \frac{\ln(b \times \delta t + 1)}{b \times \delta t}$$

$$\ln(b \times \delta t + 1)$$

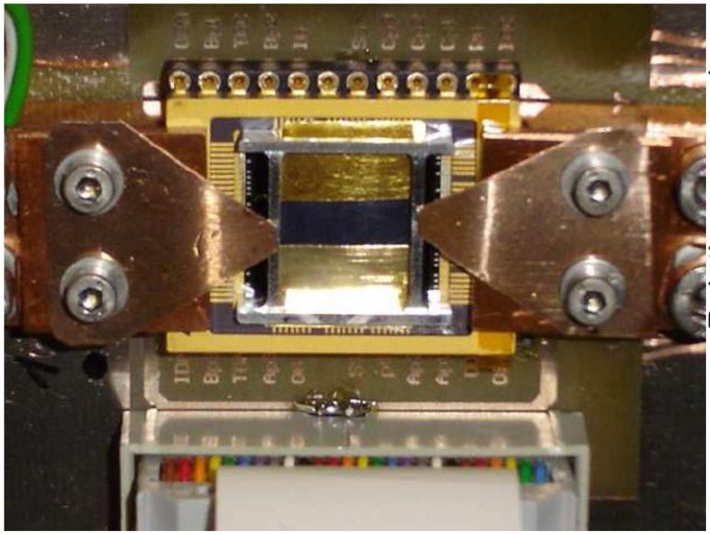
$$b = 2\pi/3\alpha X_0 \simeq 287/X_0$$

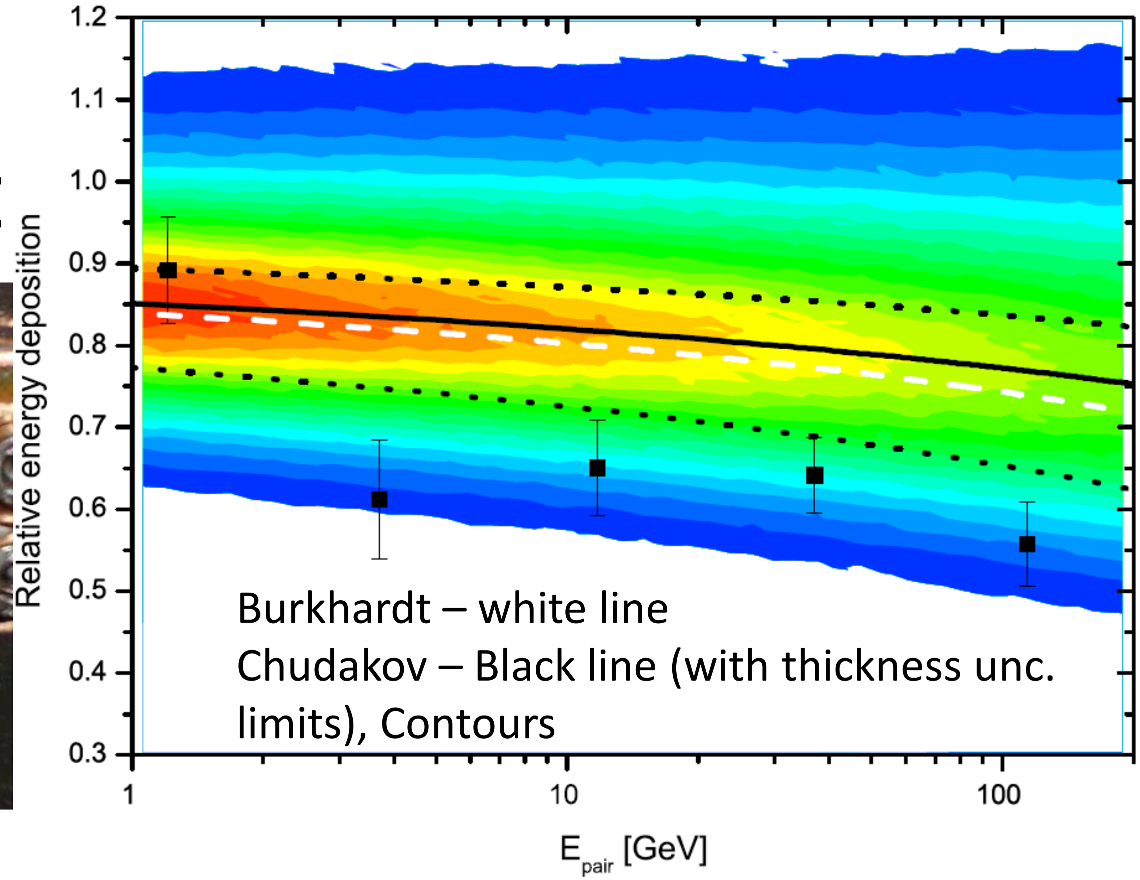
'Radiation per interaction as a function of number of scatterings'

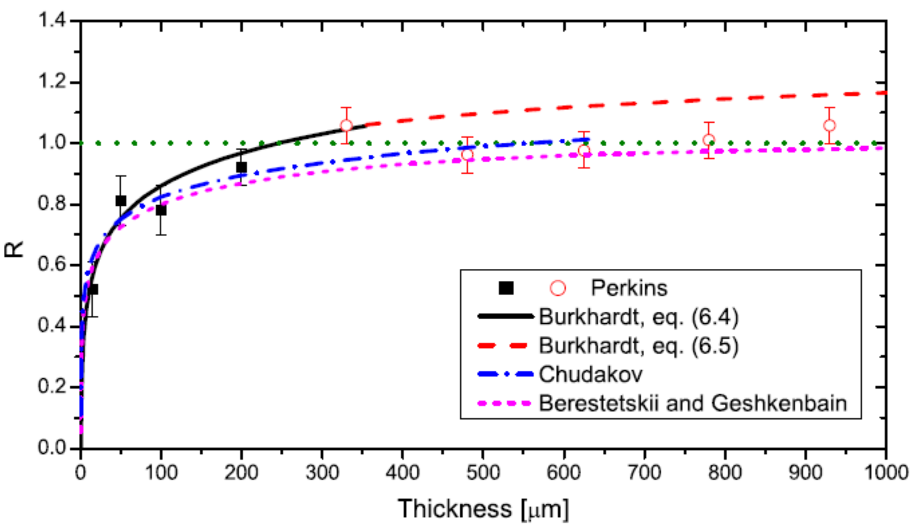


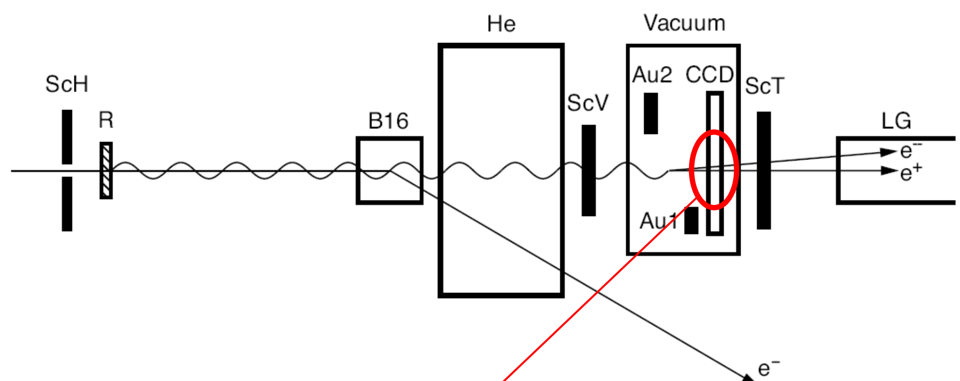


King-Perkins-Chudakov effect







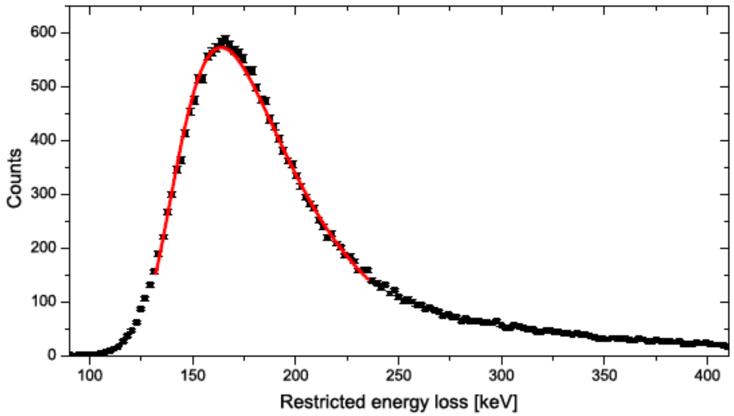


Mutual screening of charges in the pair => reduced dE/dx?

Restricted energy loss of ultrarelativistic particles in thin targets – A search for deviations from constancy

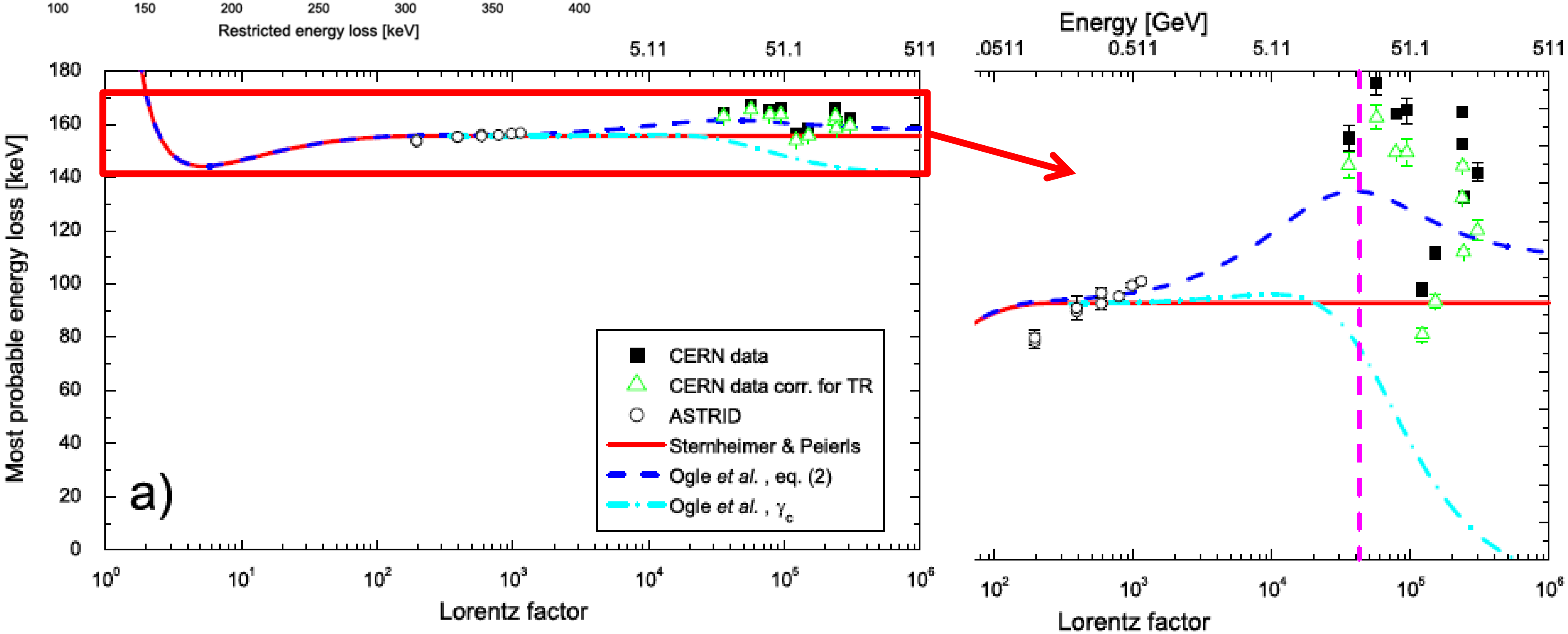
Nuclear Instruments and Methods in Physics Research B

K.K. Andersen [a], J. Esberg [a], K.R. Hansen [a], H. Knudsen [a], M. Lund [a], H.D. Thomsen [a], U.I. Uggerhøj [a,*], S.P. Møller [b], P. Sona [c], A. Mangiarotti [d], T.J. Ketel [e], A. Dizdar [f], S. Ballestrero [g], (CERN NA63)

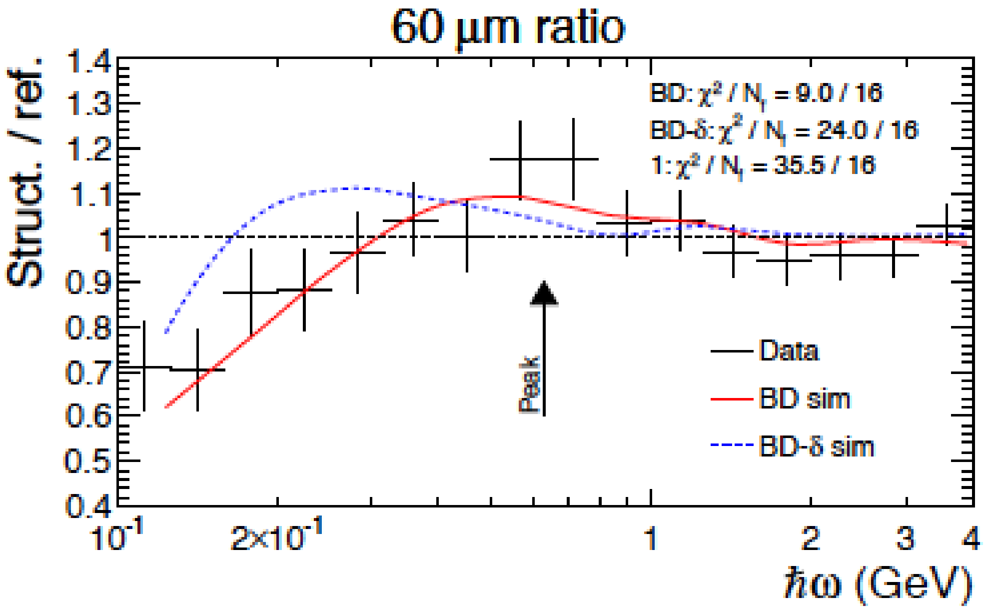


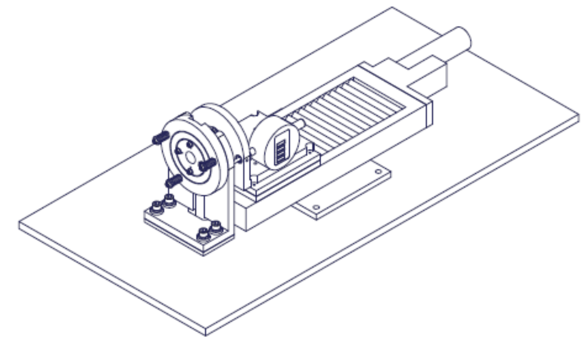
- A substantially decreased energy loss for thin targets as the Lorentz factor increases – the 'Ogle effect' - is incompatible with our measurements.
- A disappearance of the density effect, when becomes longer than the target, is possible.

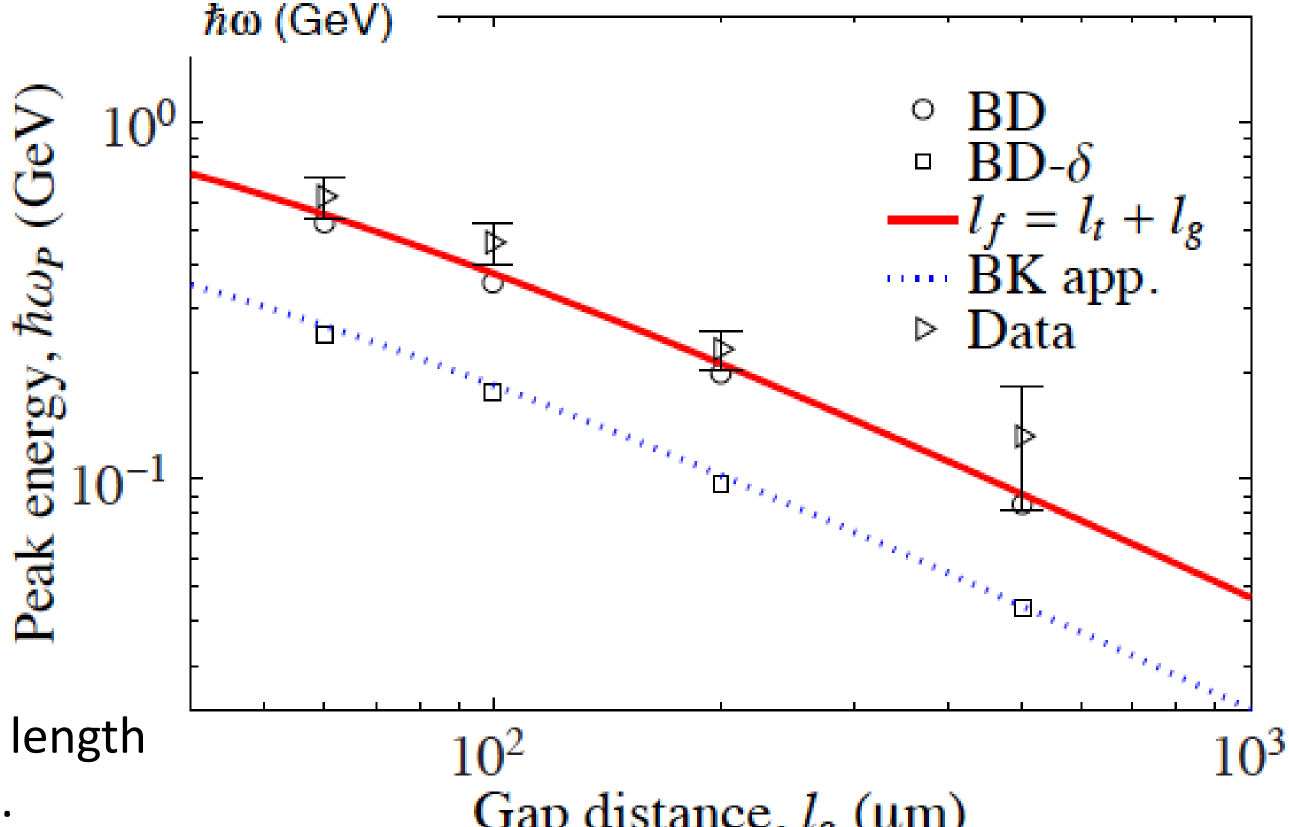
$$D = 2\gamma c/\omega_p$$



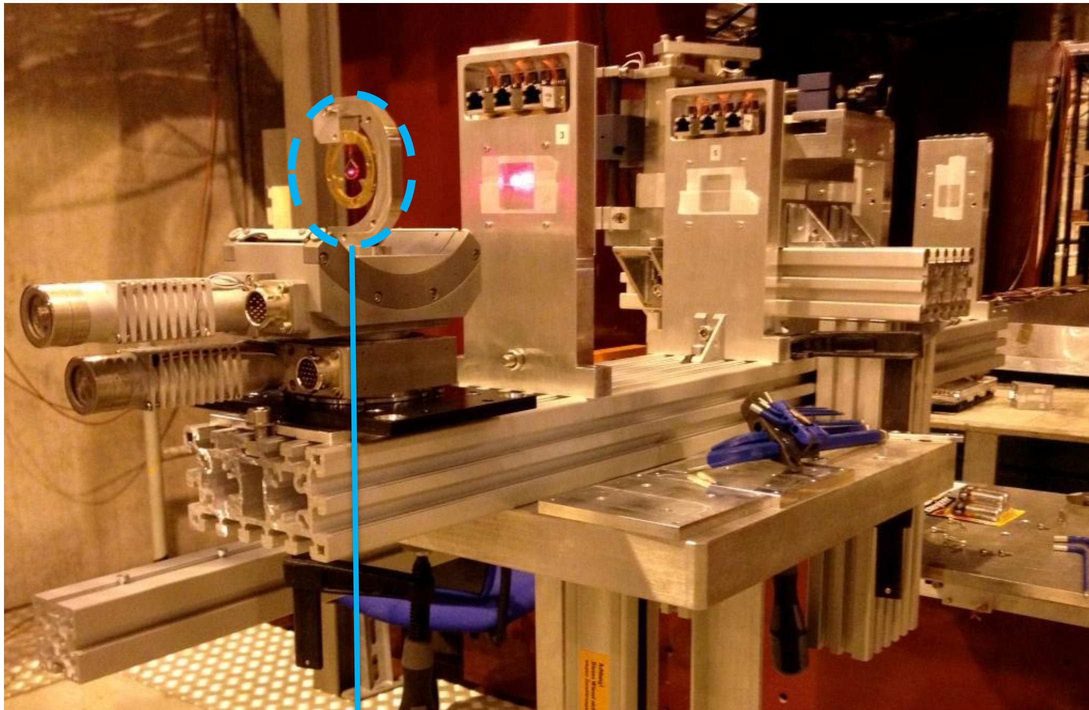
Structured targets

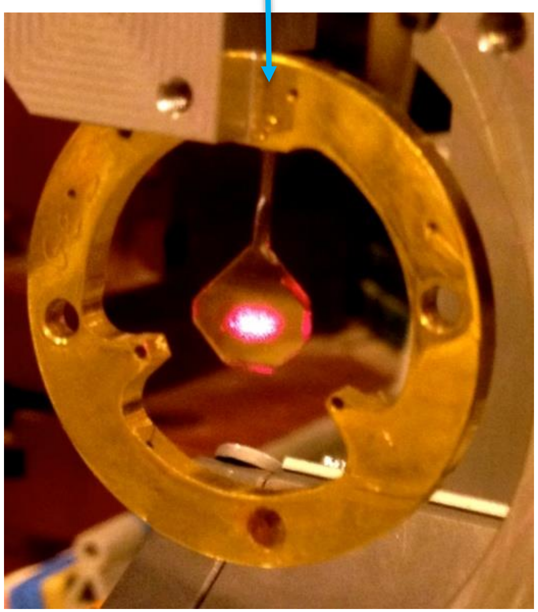




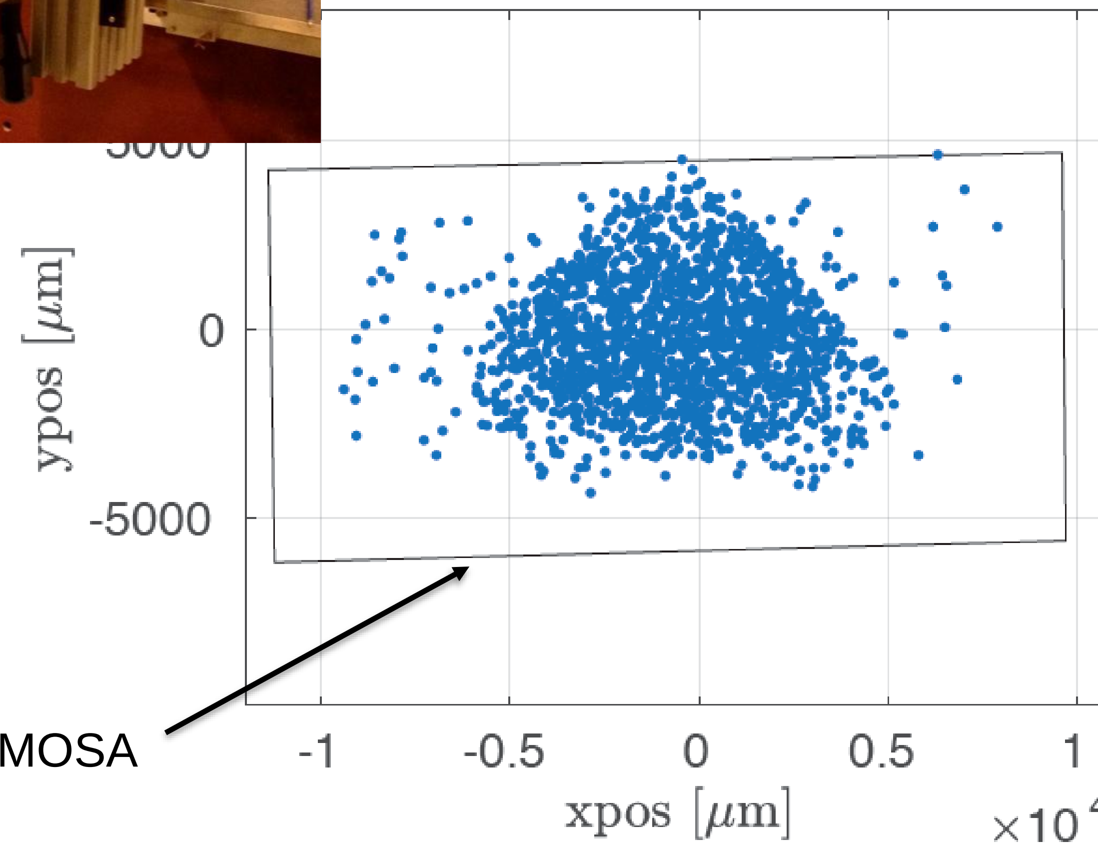


Measuring the formation length with a micrometer screw....





‘Picture’ of a 1.5 mm thick diamond, taken with tracked e+e- pairs:



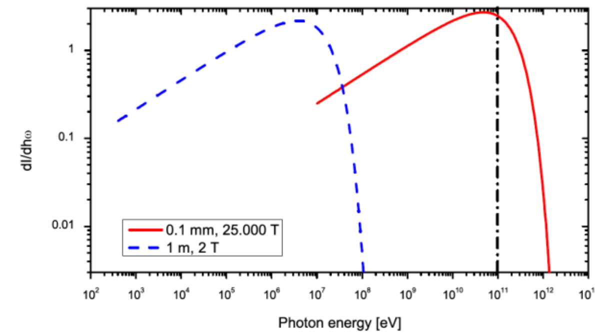
PHYSICAL REVIEW D 86, 072001 (2012)

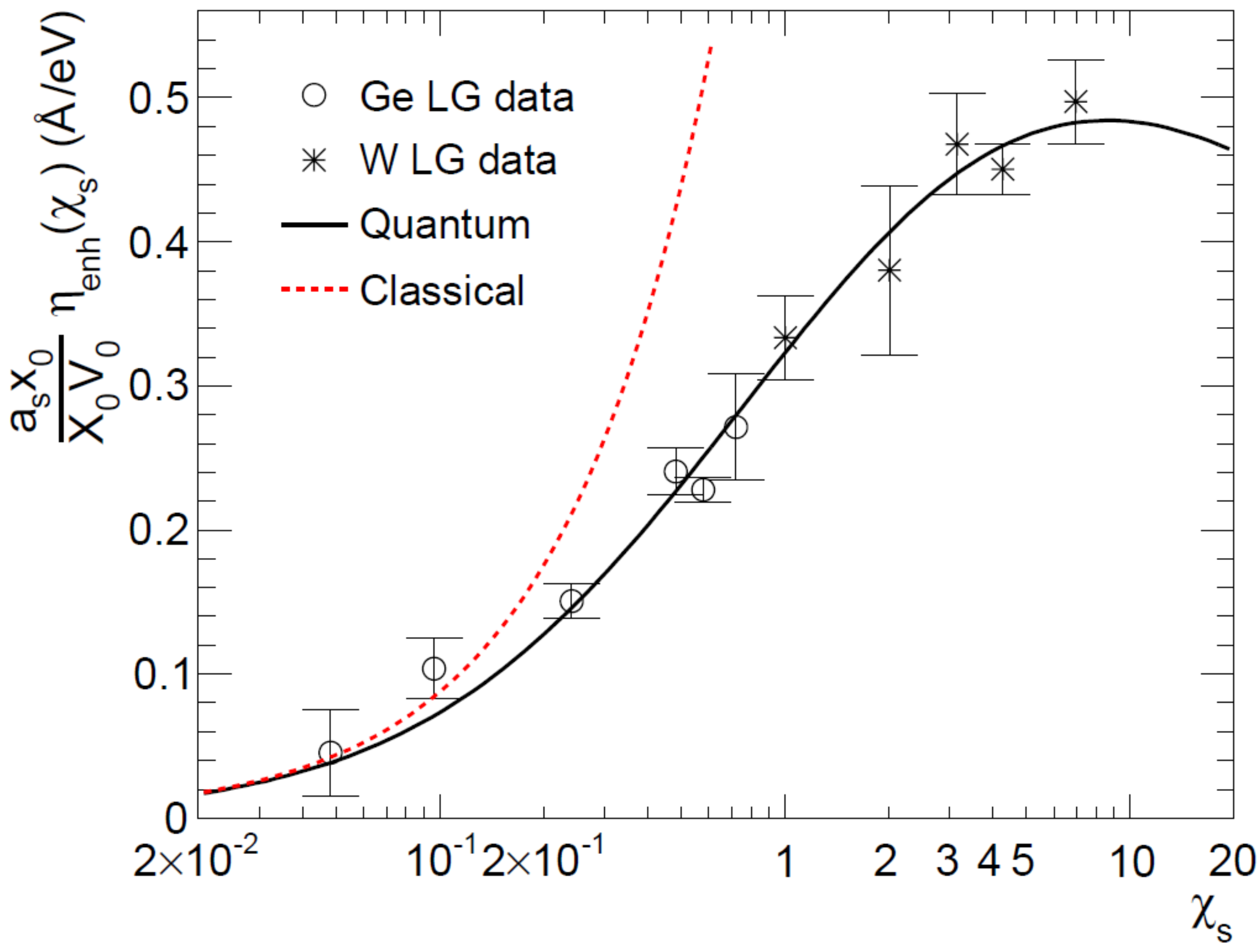
Experimental investigations of synchrotron radiation at the onset of the quantum regime

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)

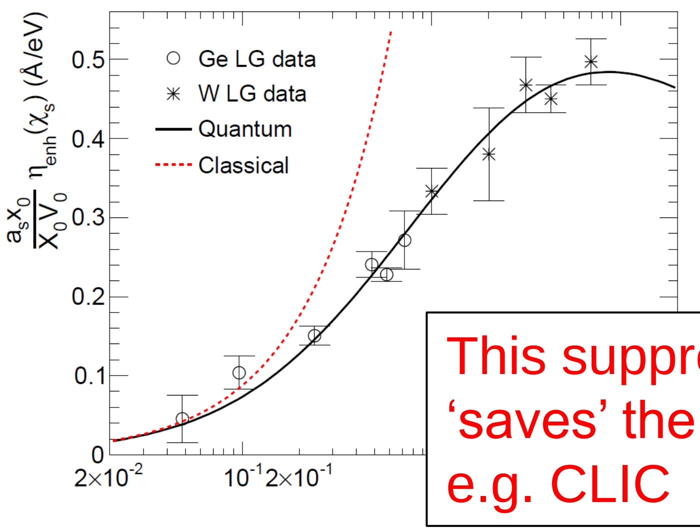
$$\frac{I_e}{I_{\rm cl}} = (1 + 4.8(1+\chi)\ln(1+1.7\chi) + 2.44\chi^2)^{-2/3}.$$





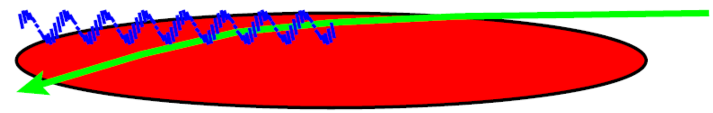
Classical -> Quantum synchrotron in strong fields

Quantum suppression



This suppression 'saves' the luminosity at e.g. CLIC

Beam-Beam Interaction



beamstrahlung ⇒ luminosity spectrum

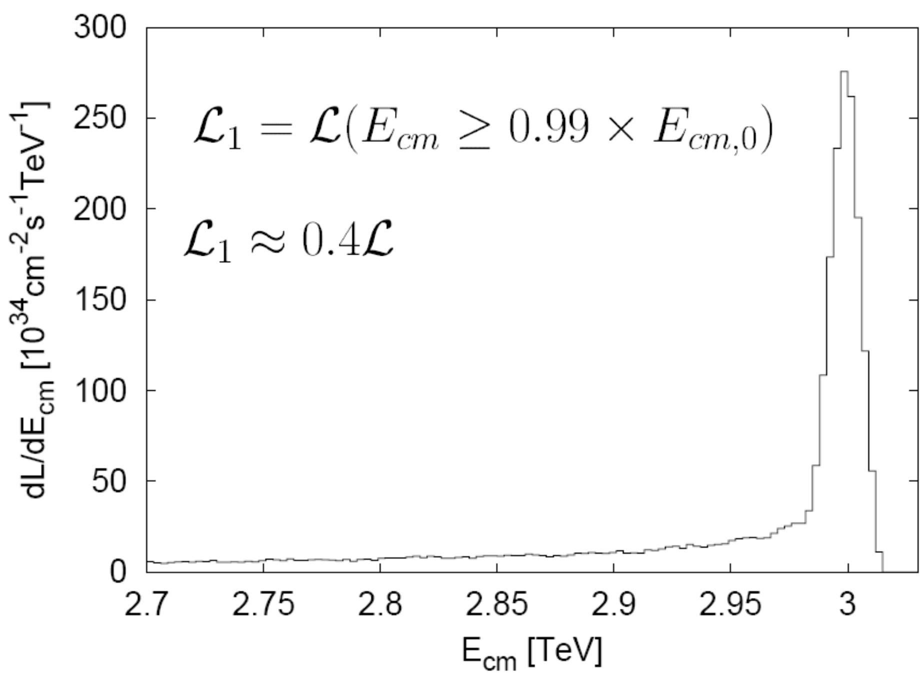
$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E_0}$$

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

$\Upsilon \ll 1$: classical regime

$\Upsilon \gg 1$: quantum regime

in CLIC $\langle\Upsilon\rangle \approx 4$



From: CLIC: Beam Dynamics and Limitations on Main Parameters

J. Esberg (NA63) – CTF3, GUINEA-PIG implementation

PHYSICAL REVIEW D **88,** 053009 (2013)

Vacuum birefringence by Compton backscattering through a strong field

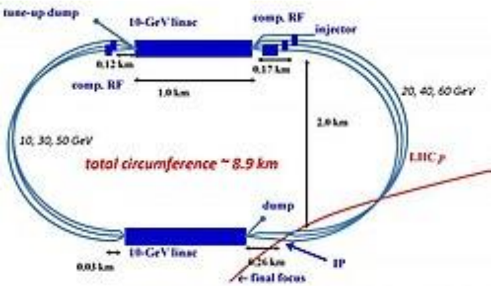
Tobias N. Wistisen and Ulrik I. Uggerhøj

Department of Physics and Astronomy, Aarhus University, Aarhus 8000, Denmark

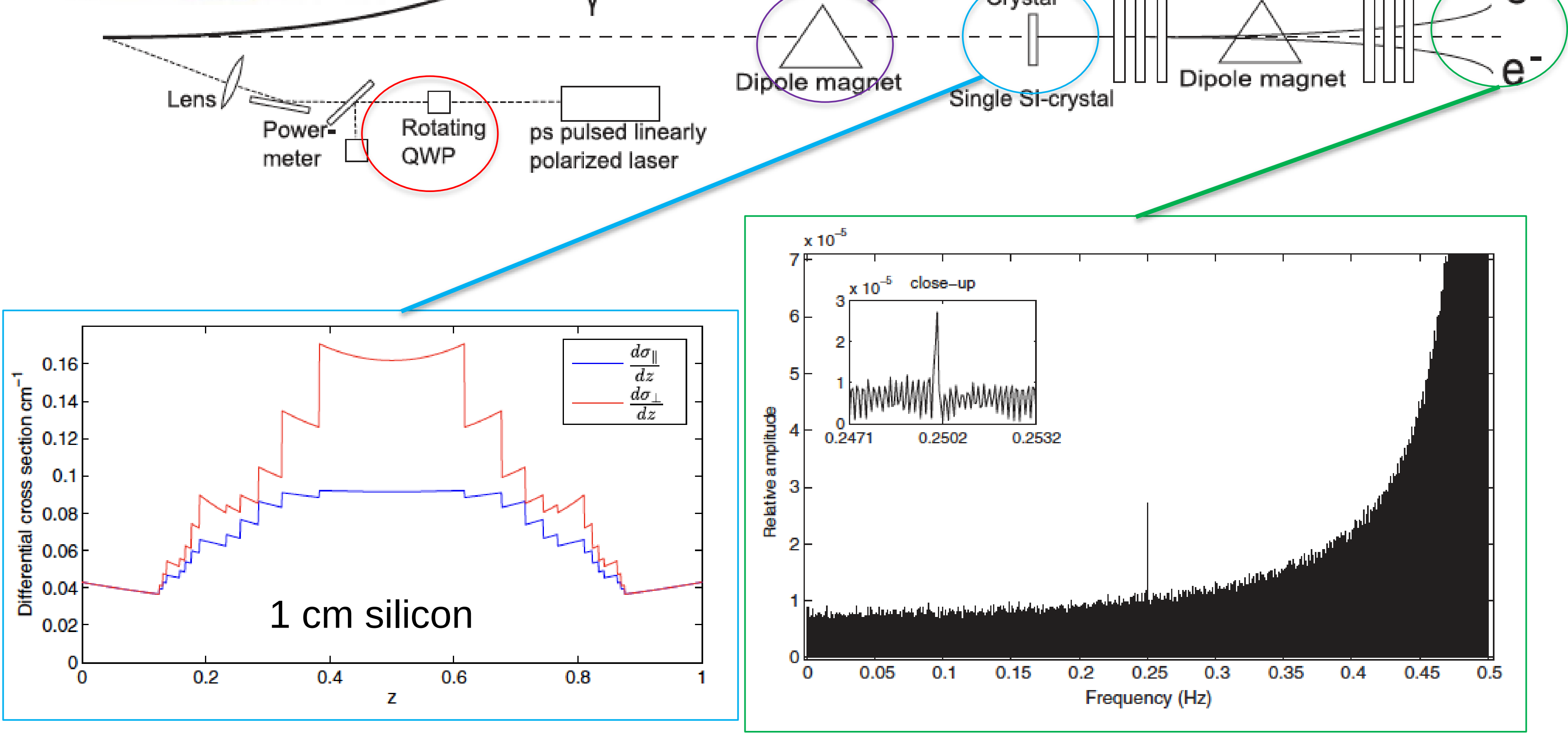
(Received 18 July 2013; published 17 September 2013)

A proposal

Pair spectrometer

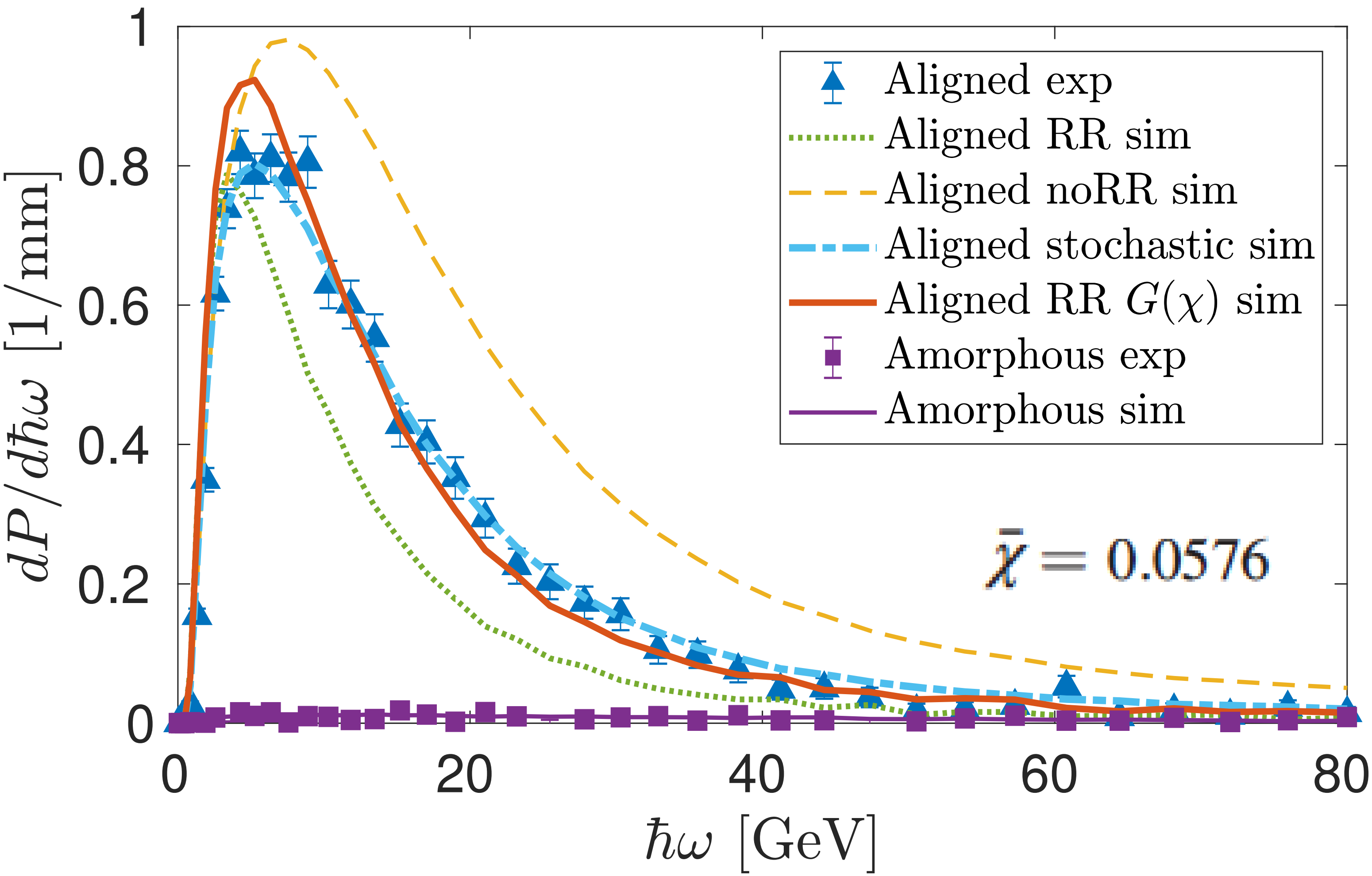


LHeC



Radiation reaction

PHYSICAL REVIEW D **102**, 052004 (2020)

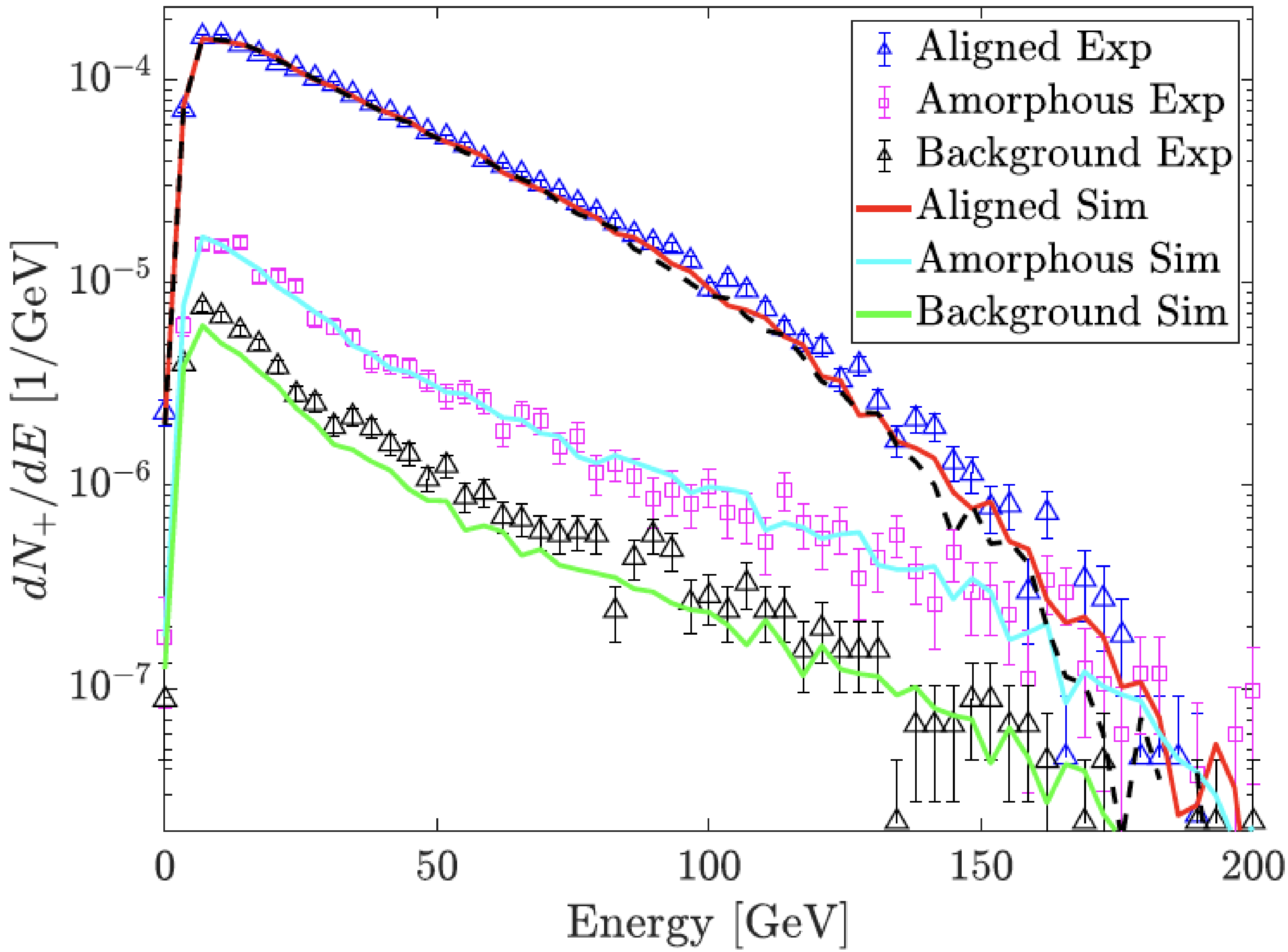


An example from a total of 22 experimental comparisons with theory.

Figure 2: Radiation power spectra obtained for 80 GeV (right) electrons traversing a 1.5 mm (top) thick diamond crystal aligned to the ⟨100⟩ axis, and the corresponding amorphous spectra. This spectrum 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 $\psi_1 \approx 35 \times 10^{-6}$ for 80 GeV electrons.

PHYSICAL REVIEW LETTERS 130, 071601 (2023)
PHYSICAL REVIEW D 108, 052013 (2023)

Tridents



Difference

hints at direct virtual contribution at high energies

Advances in QED with intense background fields

arXiv:2203.00019v1

A. Fedotov[a], A. Ilderton[b], F. Karbstein[c,d,e], B. King[f], D. Seipt[c,d], H. Taya[g], G. Torgrimsson[h,i]

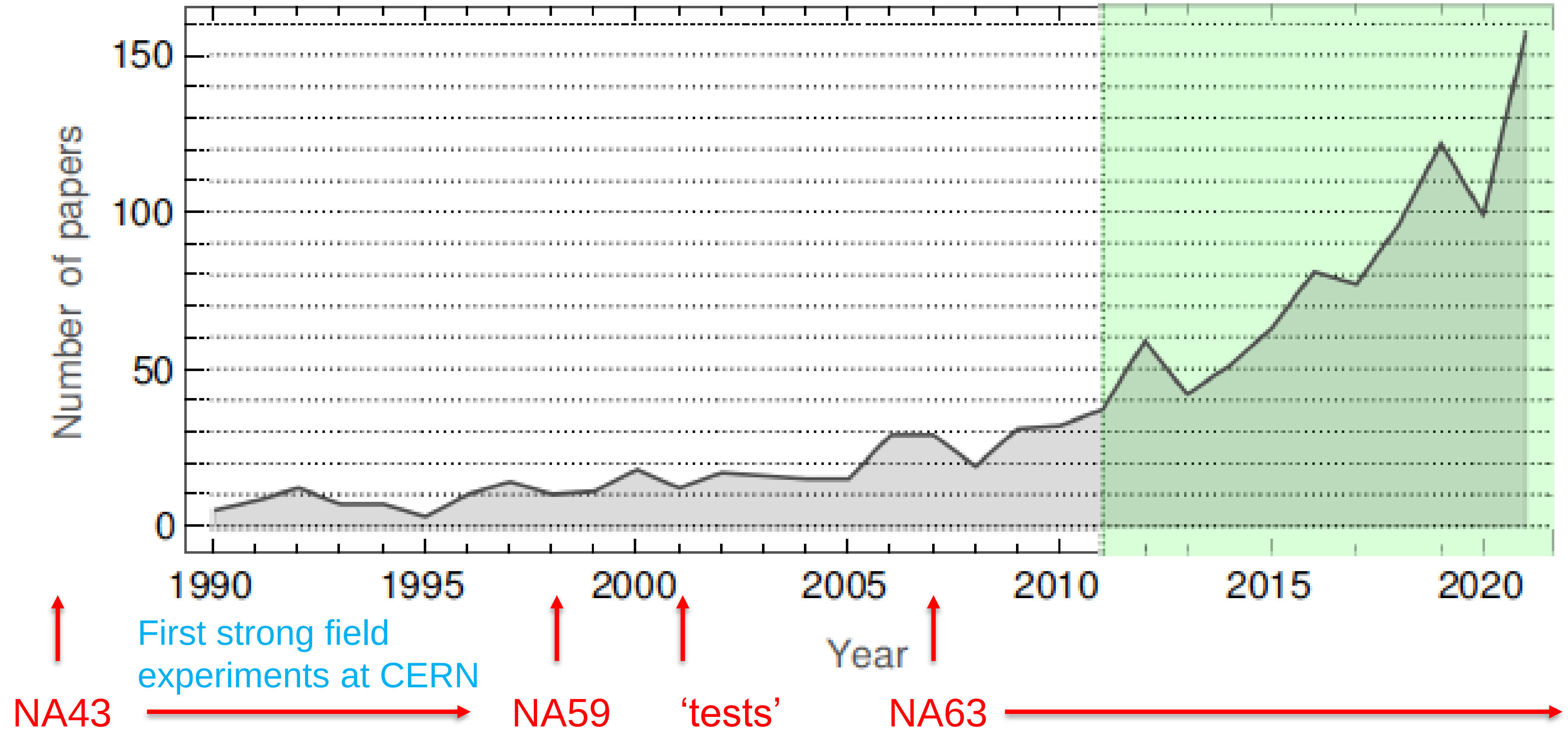


Figure 1: Indicative bibliometric search using NASA-ADS, for at least one of the following terms occurring in the abstract: "strong field QED", "nonlinear QED", "nonlinear Compton", "nonlinear Breit-Wheeler", "locally constant field", "Schwinger effect", "Schwinger pair". The shaded region is the last decade, on which the current review is focussed.

Students and tech.s, NA63 (2007-2023)

Students

- Henrik Dahl Hansen, MSc
- Thomas Virkus, MSc
- Alper Dizdar, PhD
- Mark Dalton, MSc
- Jacob Esberg, PhD
- Kristoffer K. Andersen, PhD
- Heine D. Thomsen, PhD
- Mikkel Lund, MSc
- Kim R. Hansen, MSc
- Søren L. Andersen, PhD
- Rune E. Mikkelsen, PhD
- Tobias N. Wistisen, PhD
- Trine M. Poulsen, MSc
- Serdar Yilmaz, MSc
- Christian F. Nielsen, PhD
- Jens B. Justesen, MSc
- Jeppe H. Surrow, MSc

9 MSc

8 PhD

Technicians

- Poul Aggerholm
- Per B. Christensen
- Frank Mikkelsen
- Erik Loft Larsen
- Frank Daugaard
- Peter Lange
- Anders Petersen

… with a big 'thank you!'

Publications NA63 (2007-2023)

1. T. Virkus, U.I. Uggerhøj, H. Knudsen, S. Ballestrero, A. Mangiarotti, P. Sona, T.J. Ketel, A. Dizdar, S. Kartal and C. Pagliarone (CERN NA63): *Direct measurement of the Chudakov effect*, Phys. Rev. Lett. **100**, 164802 (2008)
2. A. Mangiarotti, S. Ballestrero, P. Sona and U.I. Uggerhøj: *Implementation of the LPM effect in the discrete-bremsstrahlung simulation of GEANT 3 and GEANT 4*, Nucl. Instr. Meth. B **266**, 5013 (2008)
3. H.D. Thomsen, K. Kirsebom, H. Knudsen, E. Uggerhøj, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar, M. Dalton, S. Ballestrero and S. Connell (CERN NA63): *On the macroscopic formation length for GeV photons*, Phys. Lett. B **672**, 323 (2009)
4. J. Esberg and U.I. Uggerhøj: *Does experiment show that beamstrahlung theory - strong field QED - can be trusted?*, Journal of Physics Conference Series, **198**, 012007 (2009)
5. J. Esberg, K. Kirsebom, H. Knudsen, H.D. Thomsen, E. Uggerhøj, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar, M. Dalton, S. Ballestrero, S. Connell (CERN NA63): *Experimental investigation of strong field trident production*, Phys. Rev. D **82**, 072002 (2010)
6. K.K. Andersen, J. Esberg, K.R. Hansen, H. Knudsen, M. Lund, H.D. Thomsen, U.I. Uggerhøj, S.P. Møller, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar and S. Ballestrero (CERN NA63): *Restricted energy loss of ultrarelativistic particles in thin targets - a search for deviations from constancy*, Nucl. Instr. Meth. B **268**, 1412 (2010)
7. H.D. Thomsen, J. Esberg, K.K. Andersen, M. Lund, H. Knudsen, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar, S. Ballestrero and S.H. Connell (CERN NA63): *Distorted Coulomb field of the scattered electron*, Phys. Rev. D, **81**, 052003 (2010)
8. H.D. Thomsen and U.I. Uggerhøj: *Measurements and theories of the King-Perkins-Chudakov effect*, Nucl. Instr. Meth. B **269**, 1919 (2011)
9. A. Mangiarotti, P. Sona, S. Ballestrero and U.I. Uggerhøj: *A general semi-analytic method to simulate discrete bremsstrahlung at very low radiated photon energies by the Monte Carlo method*, Nucl. Instr. Meth. B **269**, 1977 (2011)
10. A. Mangiarotti, P. Sona, S. Ballestrero, K.K. Andersen and U. I. Uggerhøj: *Comparison of analytical and Monte Carlo calculations of multi-photon effects in bremsstrahlung emission by high-energy electrons*, Nucl. Instr. Meth. B **289** 5-17 (2012)
11. K.K. Andersen, S.L. Andersen, J. Esberg, H. Knudsen, R. Mikkelsen, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel and S. Ballestrero (CERN NA63): *Direct measurement of the formation length of photons*, Phys. Rev. Lett. **108**, 071802 (2012); see also accompanying Physics Synopsis and Science Daily.
12. K.K. Andersen, J. Esberg, H. Knudsen, H.D. Thomsen, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar and S. Ballestrero (CERN NA63): *Experimental investigations of synchrotron radiation at the onset of the quantum regime*, Phys. Rev. D **86**, 072001 (2012)
13. K.K. Andersen, J. Esberg, H.D. Thomsen, U.I. Uggerhøj and S. Brock: *Radiation emission as a virtually exact realization of Heisenbergs microscope*, Nucl. Instr. Meth. B **315**, 278 (2013)
14. U.I. Uggerhøj: *Crystals, critical fields, collision points and a QED analogue of Hawking radiation*, in W. Greiner (ed.): Exciting Interdisciplinary Physics, Springer Verlag (2013)
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17. K.K. Andersen, S.L. Andersen, J. Esberg, H. Knudsen, R. Mikkelsen, U.I. Uggerhøj, T.N. Wistisen, A. Mangiarotti, P. Sona and T.J. Ketel (CERN NA63): *Measurements of the spectral location of the structured target resonance for ultrarelativistic electrons*, Phys. Lett. B **732**, 309-314 (2014)
18. J. Esberg, U.I. Uggerhøj, B. Dalena and D. Schulte: *Strong field processes in beam-beam interactions at the Compact Linear Collider*, Phys. Rev. Spec. Top. Acc. Beams **17**, 051003 (2014)
19. T.N. Wistisen, K.K. Andersen, S. Yilmaz, R. Mikkelsen, J.L. Hansen, U.I. Uggerhøj, W. Lauth and H. Backe: *Experimental realization of a new type of crystalline undulator*, Phys. Rev. Lett. **112**, 254801 (2014)
20. R.E. Mikkelsen, A.H. Sørensen and U.I. Uggerhøj: *Bremsstrahlung from relativistic heavy ions in a fixed target experiment at the LHC*, Advances in High Energy Physics **2015**, 625473 (2015)
21. R.E. Mikkelsen, A.H. Sørensen and U.I. Uggerhøj: *Elastic photonuclear cross sections for bremsstrahl from relativistic heavy ions*, Nucl. Instr. Meth. B **372**, 58-66 (2016)
22. A. Di Piazza, T.N. Wistisen and U.I. Uggerhøj: *Investigation of classical radiation reaction with aligned crystals*, Phys. Lett. B **765**, 1-5 (2016)
23. T.N. Wistisen, A. Di Piazza, H.V. Knudsen and U.I. Uggerhøj: *Experimental Evidence for Quantum Radiation Reaction in Aligned Crystals*, Nature Communications **82**, art. 795 (2018)
24. T. N. Wistisen, A. Di Piazza, C. F. Nielsen, A. H. Sørensen and U. I. Uggerhøj (CERN NA63): *Quantum radiation reaction in aligned crystals beyond the local constant field approximation*, Phys. Rev. Research **1**, 033014 (2019)
25. A. Di Piazza, T.N. Wistisen, M. Tamburini and U. I. Uggerhøj: *Testing strong-field QED close to the fully nonperturbative regime using aligned crystals*, Phys. Rev. Lett. **124**, 044801 (2020)
26. C. F. Nielsen, J.B. Justesen, A. H. Sørensen, U. I. Uggerhøj and R. Holtzapple (CERN NA63): *Radiation reaction near the classical limit in aligned crystals*, Phys. Rev. D **102**, 052004 (2020)
27. C. F. Nielsen, J.B. Justesen, A. H. Sørensen, U. I. Uggerhøj and R. Holtzapple (CERN NA63): *Experimental verification of the Landau-Lifshitz equation*, New J. Phys. **23**, 085001 (2021)
28. A. Mangiarotti, P. Sona and U. I. Uggerhøj: *Comparison with experimental data of different theoretical approaches to high-energy electron bremsstrahlung including quantum coherence effects,*, Phys. Rev. D **104**, 096018 (2021)
29. R. Holtzapple, C.F. Nielsen, A. H. Sørensen, U. I. Uggerhøj (CERN NA63): *On the significance of radiation reaction*, Eur. Phys. J. D **76**, 167 (2022)
30. C.F. Nielsen, R. Holtzapple, M.M. Lund, J.H. Surrow, A. H. Sørensen, M.B. Sørensen and U. I. Uggerhøj (CERN NA63): *Precision measurement of trident production in strong electric fields*, Phys. Rev. Lett. **130**, 071601 (2023)
31. C.F. Nielsen, R. Holtzapple, M.M. Lund, J.H. Surrow, A. H. Sørensen, M.B. Sørensen and U. I. Uggerhøj (CERN NA63): *Differential measurement of trident production in strong electric fields*, Phys. Rev. D **108**, 052013 (2023)

approx. 2 per year

– 5 Phys. Rev. Lett.
– 3 Phys. Lett. B
– 8 Phys. Rev. D
– 7 Nucl. Instr. Meth. B
– 1 Nature Communications
– 1 New J. Phys.
– 1 Eur. Phys. J. D
– 1 Phys. Rev. Research
– 1 Phys. Rev. Spec. Top. Acc. Beams
– 3 Conference journals

… it has been fun!