Where we are with advancing the marriage between electron and photon beams: the way ahead

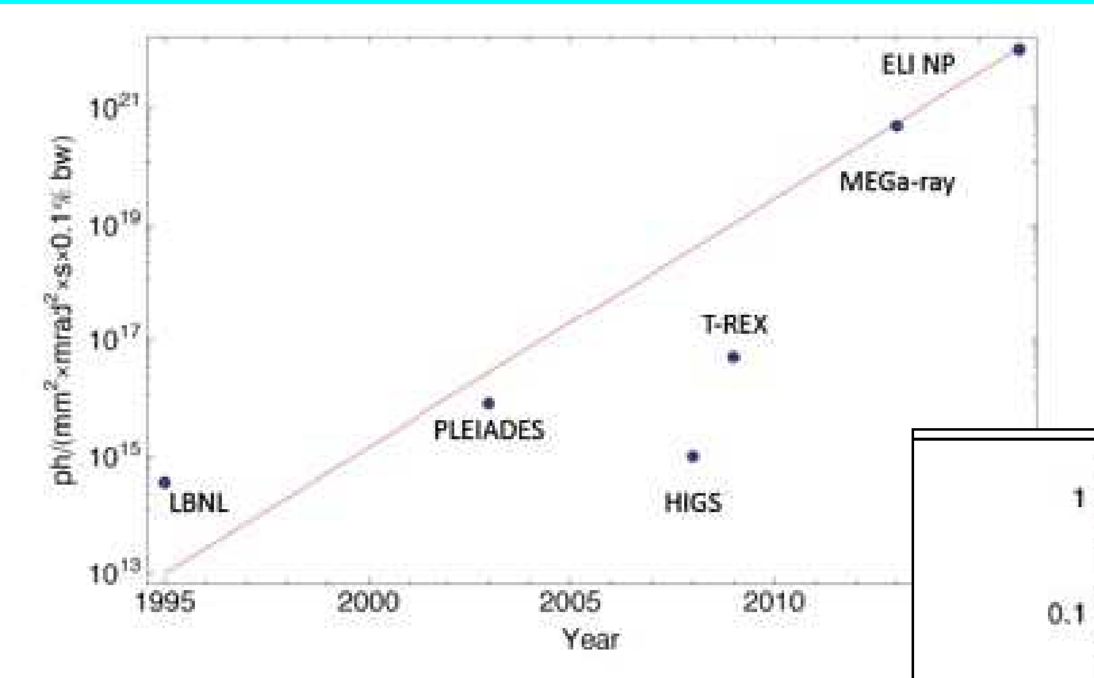
Luca Serafini – INFN Milano

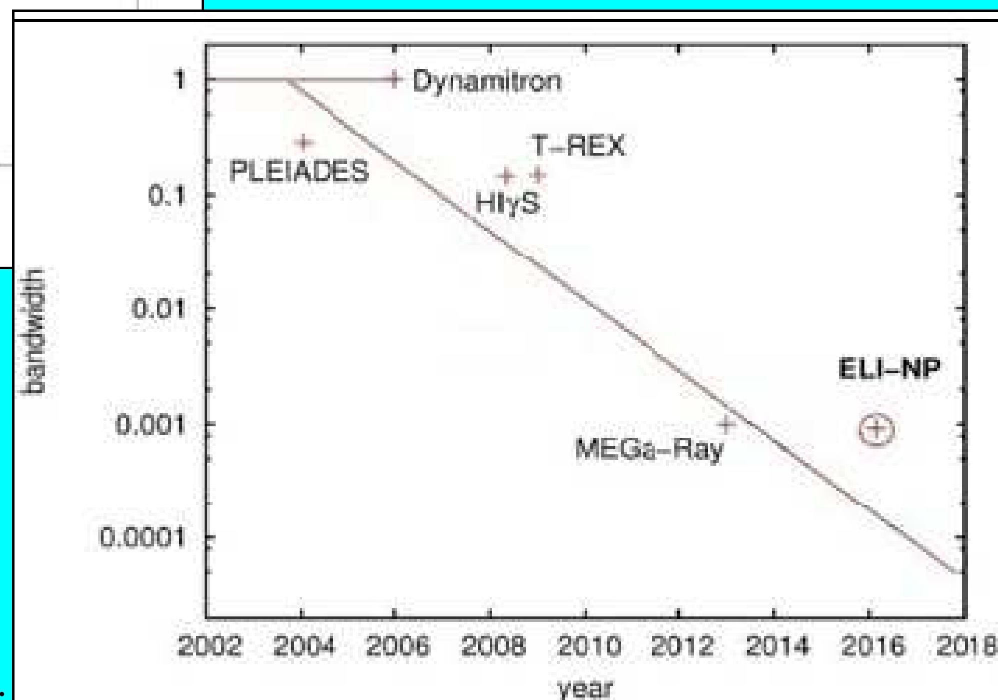
- **Advancing the Phase Space Density of Electron and Photon Beams is a key issue for the development of many machines and applications: FEL's, Inverse FEL's, Plasma Accelerators, Thomson/Compton *X/γ* Ray Sources, Photon-Photon Colliders**
- **Co or Counter-propagating, at the *μm/fs* alignment and synchronization level, beams of electrons and optical/*X/γ* photons (either in vacuum or in plasma) enables a new generation of machines capable to drive unprecedented applications and experiments in the fields of Photonics, Nuclear Physics and Nuclear Photonics, Light-to-Light QED fundam. research, etc**

- **Golden Examples of marriage between electron and photon beams are: Inverse Free Electron Lasers (in vacuum co-propagation of high brightness electron beams and high intensity laser pulses), Seeding FEL's, Plasma Acceleration with External Injection (in plasma co-propagation of high brightness electron beams and high intensity laser pulses), Thomson/Compton Back-Scattering Sources (in vacuum counter-propagation of high phase space density electron beams vs. high average power laser beams)**
- **Most of these techniques/machines aim at producing advanced radiation beams, mainly for applications. -> Light Sources**

- **We will consider here a unique example of a machine aimed at the opposite: Fundamental Physics (almost HEP) with a Light Source! i.e. Light-to-Light interaction, vs. Light-to-Matter, as typical of Light Sources**
- **Why a Photon-Photon elastic/inelastic scattering experiment? Fundamental test for QED never observed so far (elastic scattering with real photons, pure light-to-light interaction)**
- **Why now? Future availability of tunable/polarized/mono-chromatic/high-phase-space-density *MeV-class photon beams* mutuated from *Nuclear Photonics (ELI-NP-GBS, MegaRay, STAR, etc)***

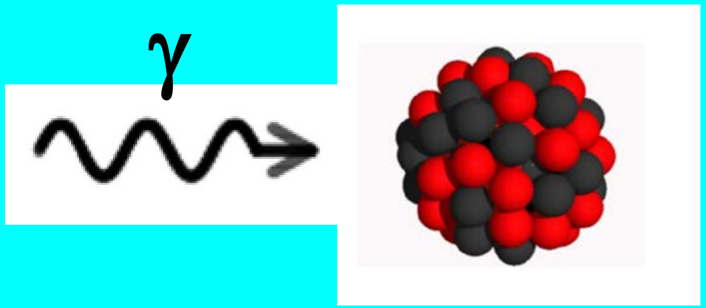
ELI-NP γ beam: the quest for narrow bandwidths (from 10^{-2} down to 10^{-3})

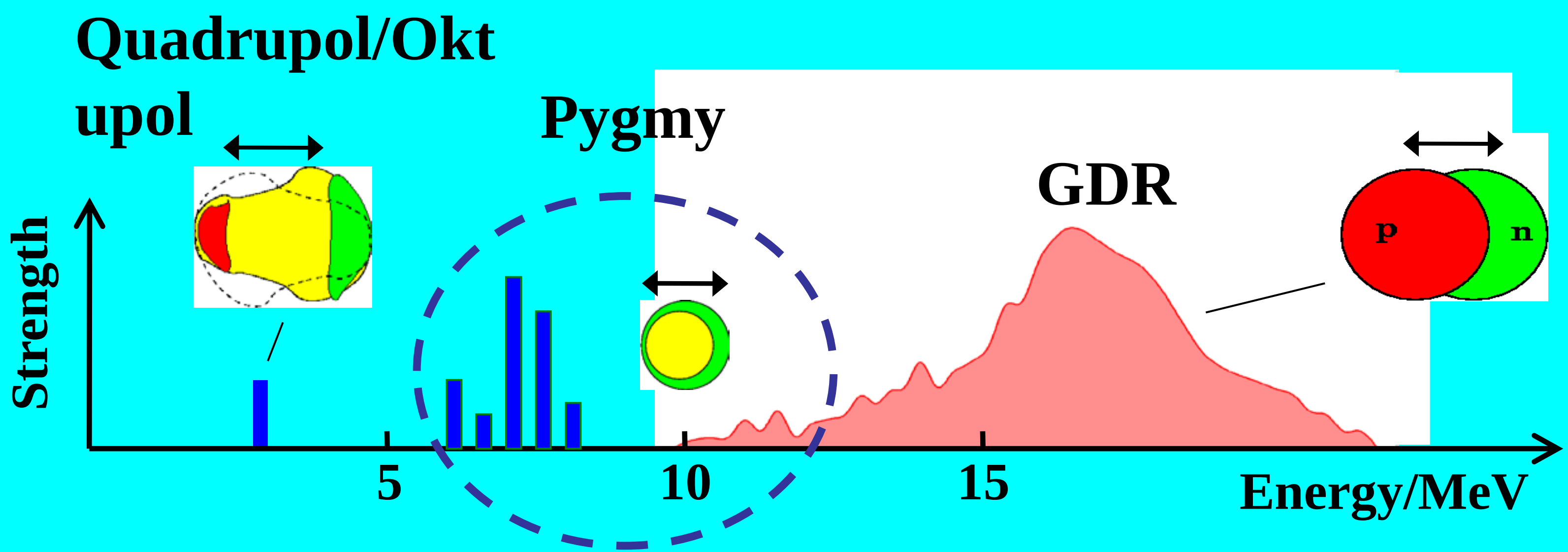




Courtesy V. Zamfir – ELI-NP

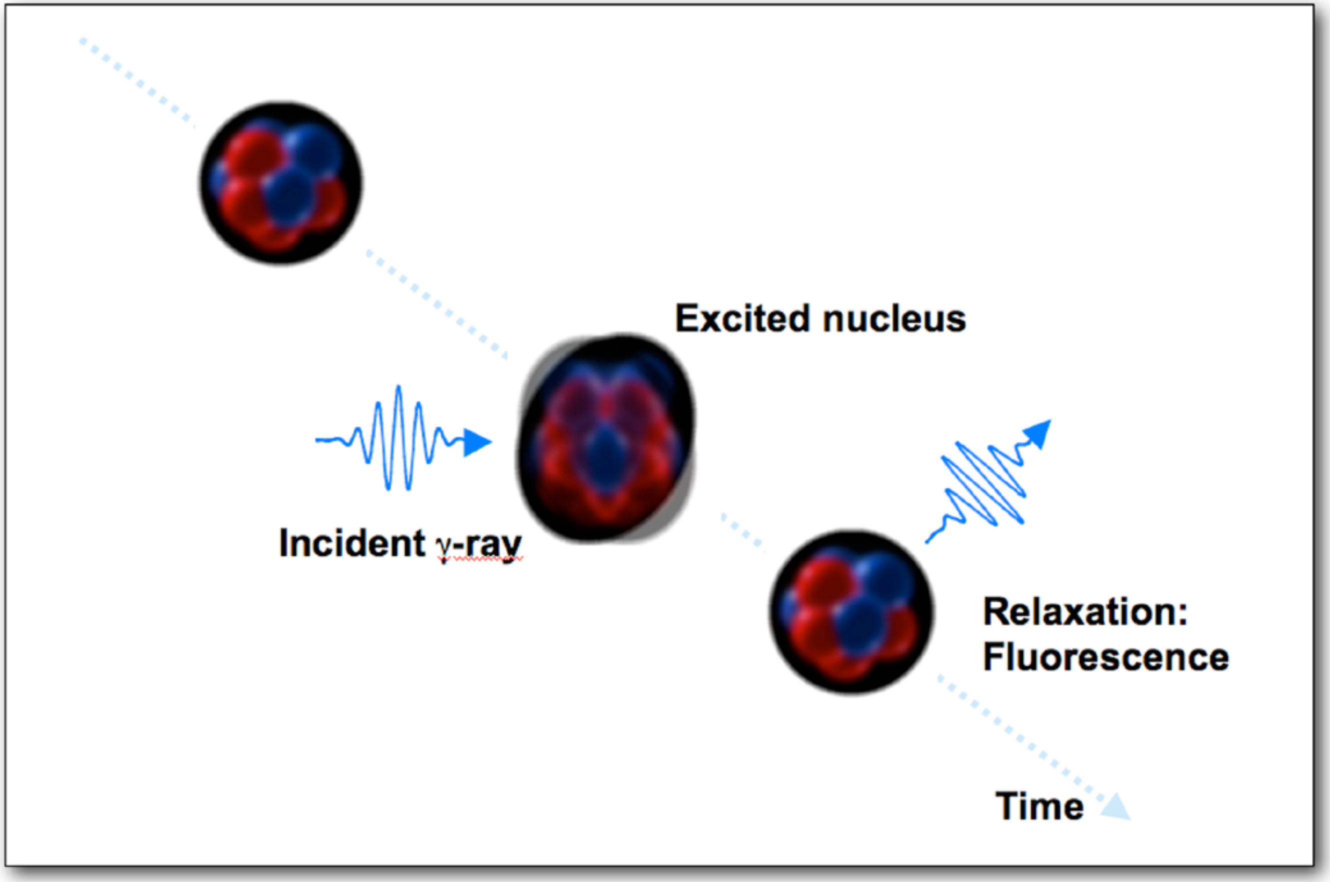
E1 Strength Distribution





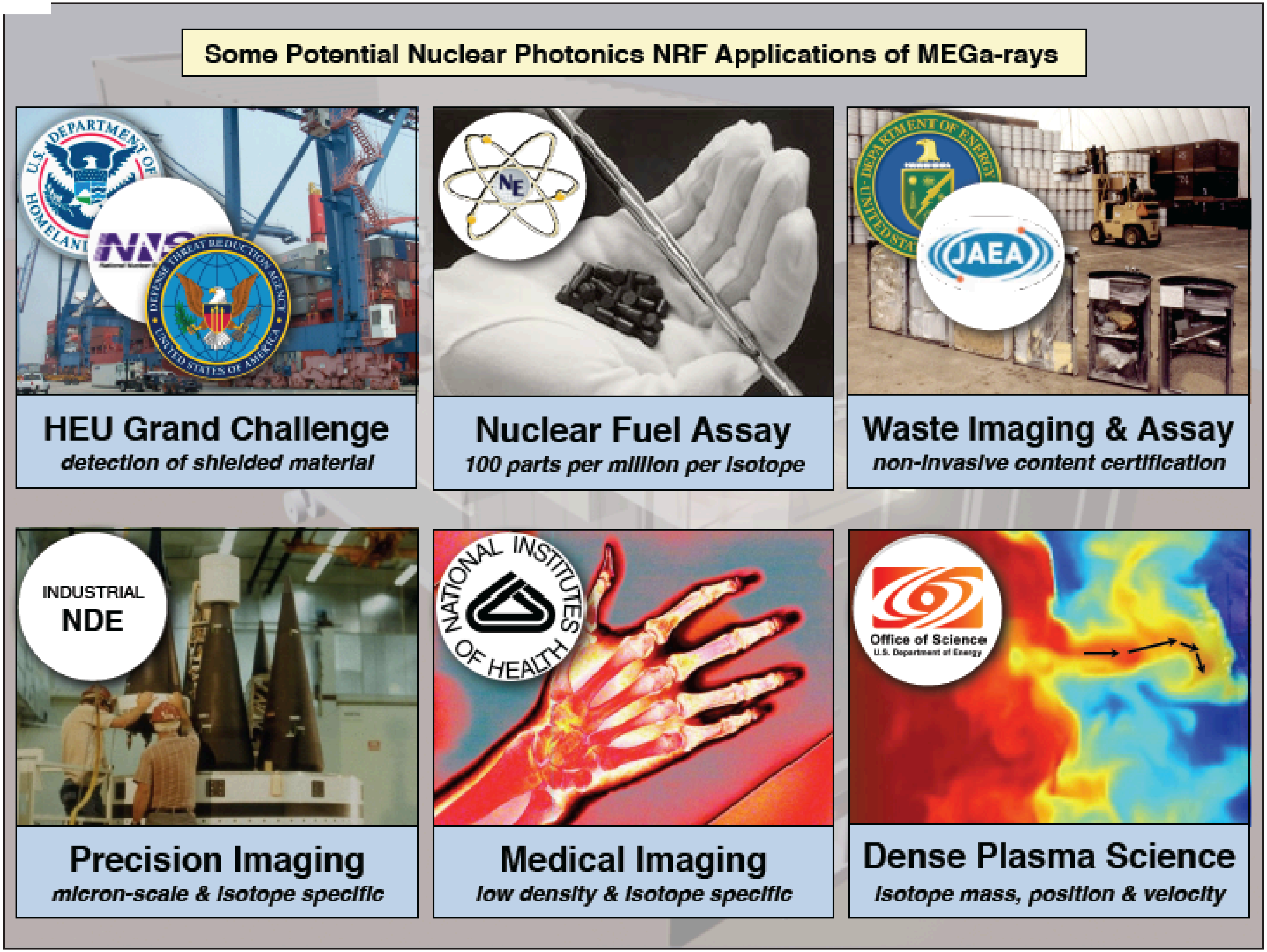
courtesy of N. Pietralla (Darmstadt)

Narrowband gamma-ray absorption and re-radiation by the nucleus is an "isotope-specific" signature



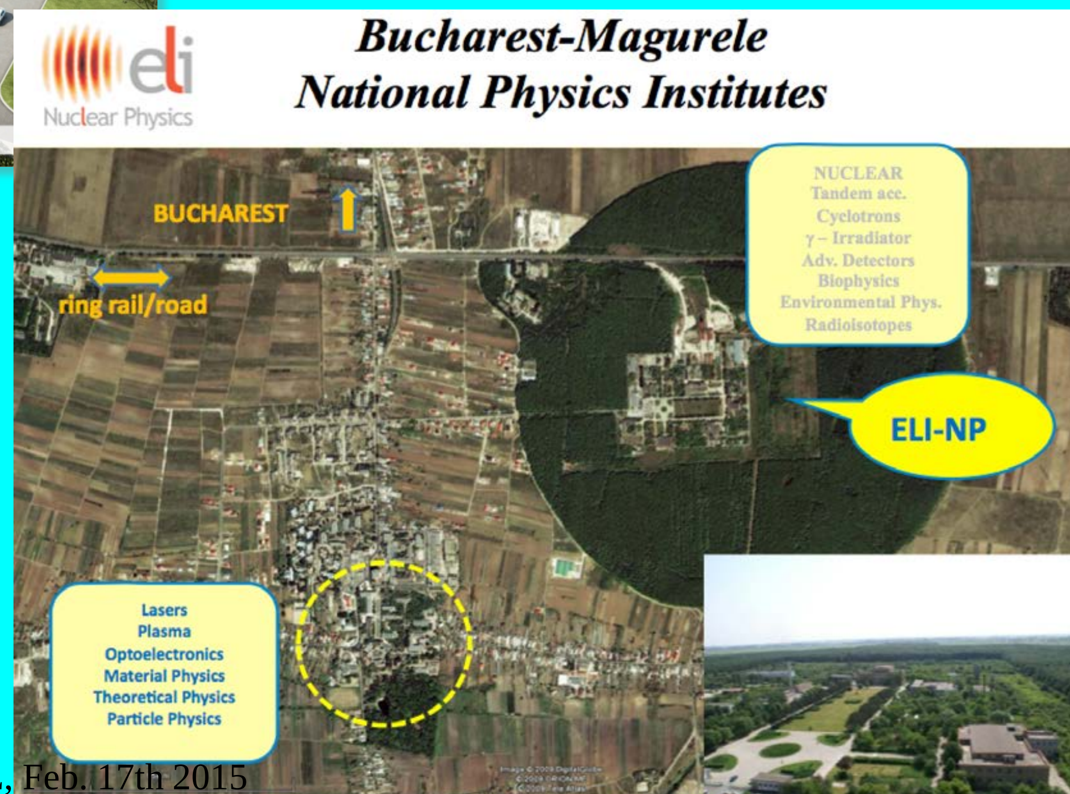
Nuclear Resonance Fluorescence (NRF) is analogous to atomic resonance fluorescence but depends upon the number of protons AND the number of neutrons in the nucleus

Courtesy C. Barty - LLNL



Courtesy C. Barty - LLNL

ELI-Nuclear Physics



ELI-NP-Gamma Beam System
designed by EuroGammaS
INFN as main coordinator

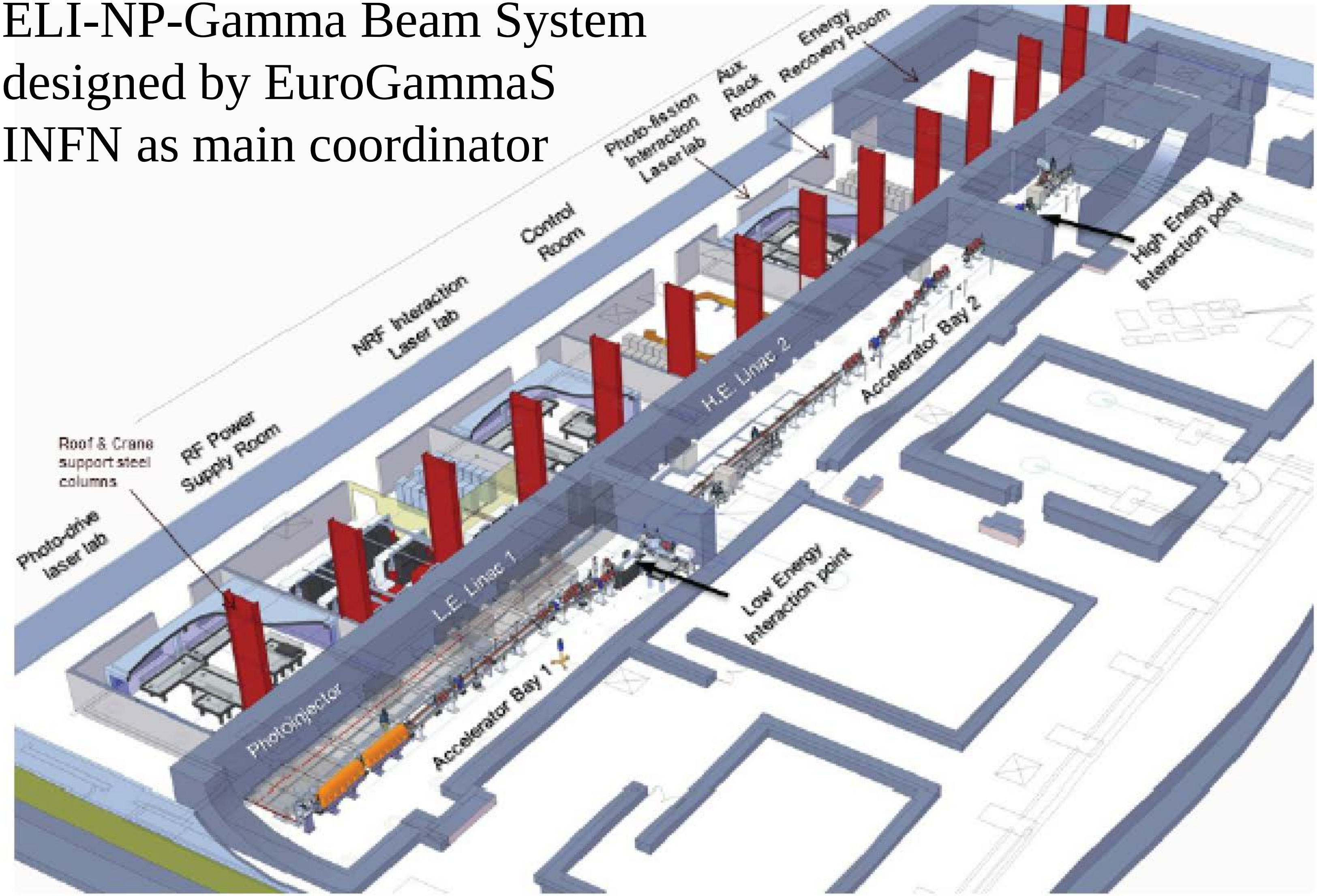


Fig. 197. Isometric 3D view of Building Layout of the Accelerator Hall & Experimental Areas

Technical Design Report

EuroGammaS proposal for the ELI-NP Gamma beam System

With 73 tables and 230 figures

O. Adriani, S. Albergo, D. Alesini, M. Anania, D. Angal-Kalinin, P. Antici, A. Bacci, R. Bedogni, M. Bellaveglia, C. Biscari, N. Bliss, R. Boni, M. Boscolo, F. Broggi, P. Cardarelli, K. Cassou, M. Castellano, L. Catani, I. Chaikovska, E. Chiadroni, R. Chiche, A. Cianchi, J. Clarke, A. Clozza, M. Coppola, A. Courjaud, C. Curatolo, O. Dadoun, N. Delerue, C. De Martinis, G. Di Domenico, E. Di Pasquale, G. Di Pirro, A. Drago, F. Druon, K. Dupraz, F. Egal, A. Esposito, F. Falcoz, B. Fell, M. Ferrario, L. Ficcadenti, P. Fichot, A. Gallo, M. Gambaccini, G. Gatti, P. Georges, A. Ghigo, A. Goulden, G. Graziani, D. Guibout, O. Guilbaud, M. Hanna, J. Herbert, T. Hovsepian, E. Iarocci, P. Iorio, S. Jamison, S. Kazamias, F. Labaye, L. Lancia, F. Marcellini, A. Martens, C. Maroli, B. Martlew, M. Marziani, G. Mazzitelli, P. McIntosh, M. Migliorati, A. Mostacci, A. Mueller, V. Nardone, E. Pace, D.T. Palmer, L. Palumbo, A. Pelorosso, F.X. Perin, G. Passaleva, L. Pellegrino, V. Petrillo, M. Pittman, G. Riboulet, R. Ricci, C. Ronsivalle, D. Ros, A. Rossi, L. Serafini, M. Serio, F. Sgam … Stocchi,
S. To … Vescovi,
F. Vil …

This new generation machines will enable photon-photon scattering high luminosity colliders

108 Authors, 327 pages

Published on ArXiv

http://arxiv.org/abs/1407.3669

SAPIENZA UNIVERSITÀ DI ROMA

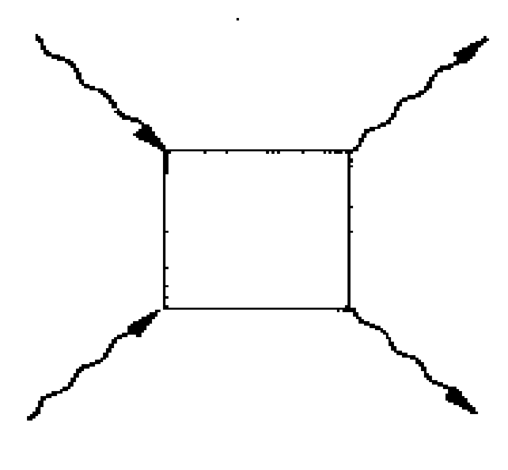
INFN Istituto Nazionale di Fisica Nucleare

Science & Technology Facilities Council

cnrs IN2P3 Les deux infinis

UNIVERSITE PARIS SUD Comprendre le monde, construire l'avenir

Photon-photon scattering is a probe into the structure of the vacuum of QFT



The QFT vacuum holds the key to the understanding of renormalization in QFTs.

Different vacua are possible, and the observation of photon-photon scattering would provide important clues on the actual structure of the QFT vacuum.

Photon-photon scattering at low energy is very difficult to observe, the total cross-section is extremely small. The total unpolarized scattering cross section predicted by QED is

$$\sigma_{\gamma\gamma}^{(QED)} = \frac{973\mu_0^2(\hbar\omega)^6}{20\pi\hbar^4c^4}A_e^2$$

Where

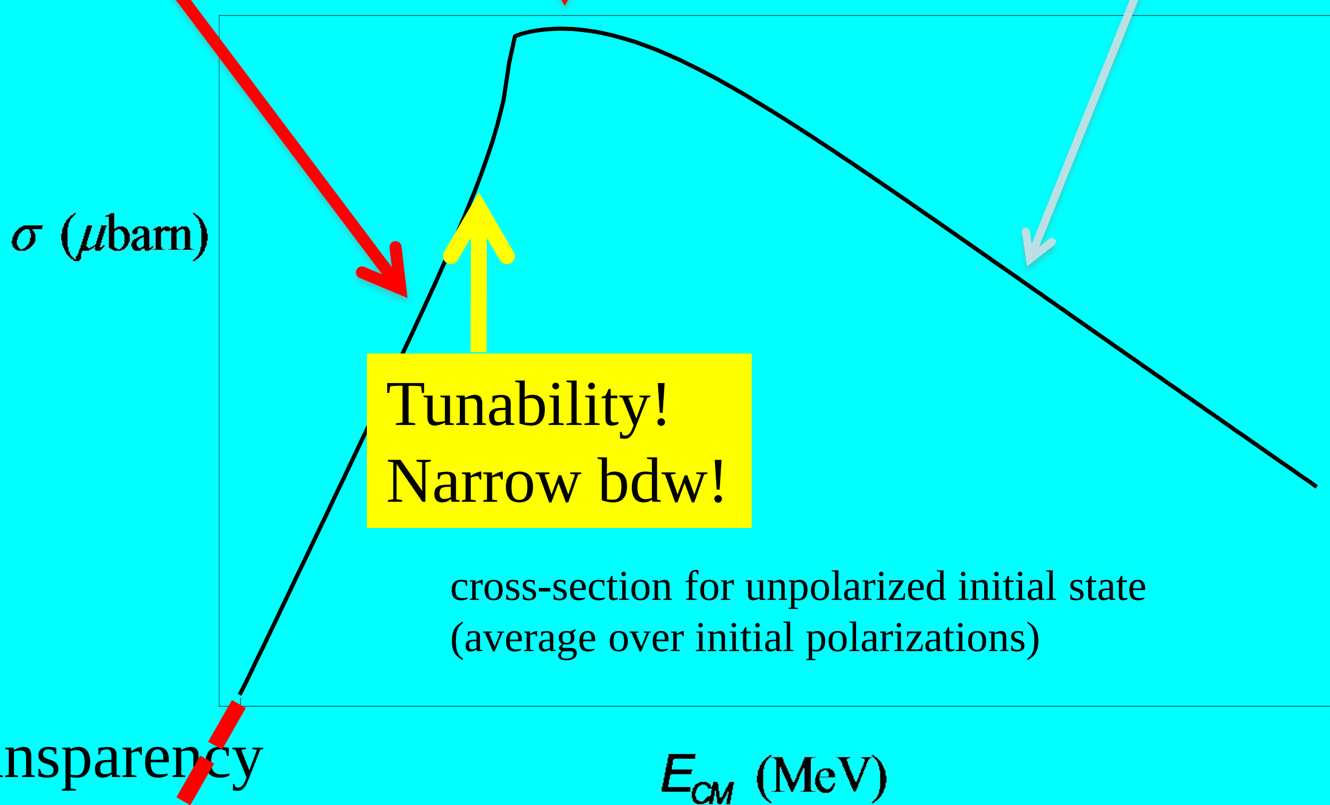
$$A_e = \frac{2\alpha^2\lambda\!\!\!^{-}{}_e^3}{45\mu_0 m_e c^2} \approx 1.32\ 10^{-24}\mathrm{T}^{-2}$$

This evaluates to a very small number with low energy (≈ 1 eV) photons, however it increases as the sixth power of photon energy.

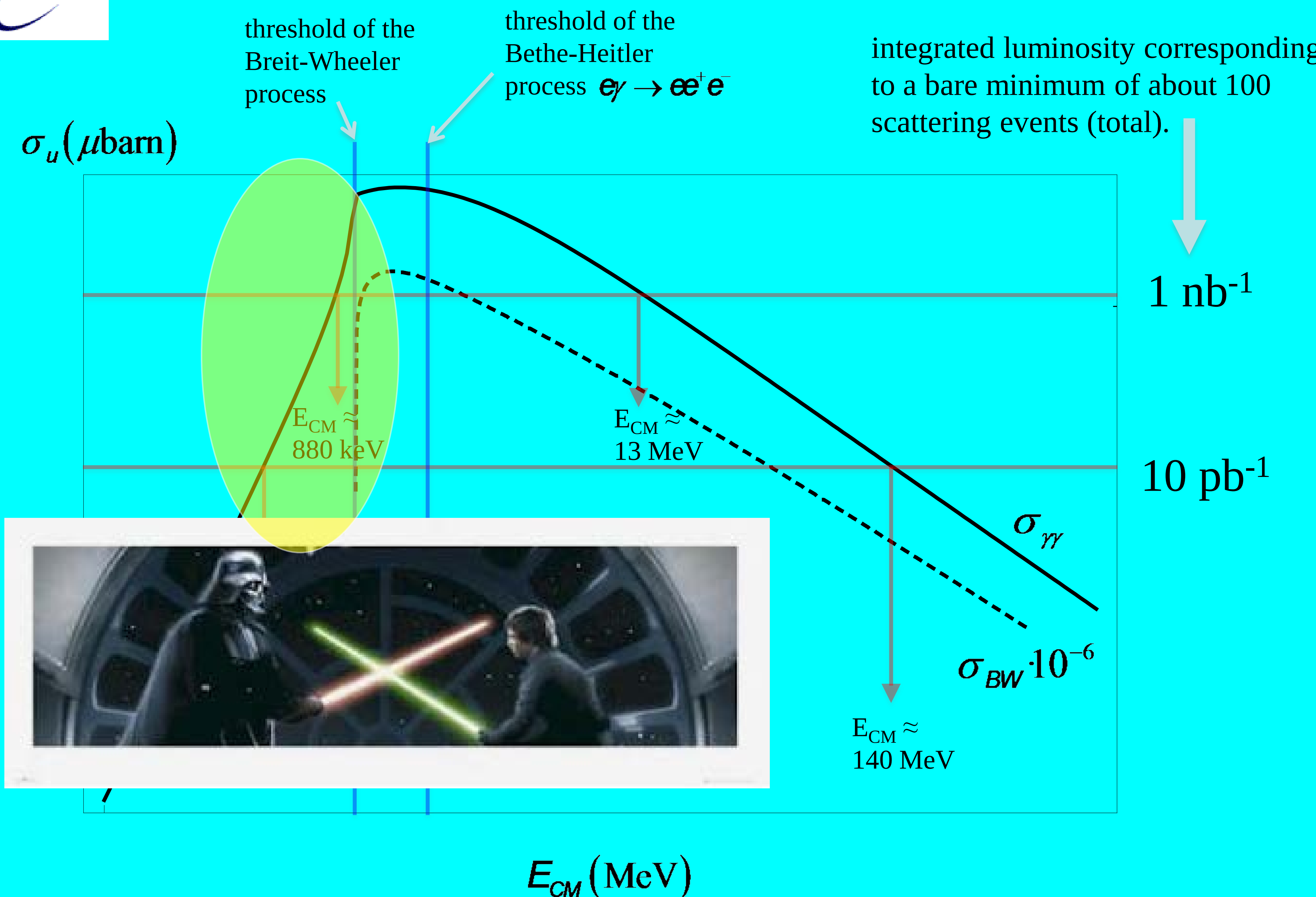
$$\sigma \approx 0.13\left(\frac{\hbar\omega}{m_e c^2}\right)^6 \mu\text{barn}$$

peak cross-section, ≈1.6 μbarn
at $\hbar\omega \approx 1.5\, m_e c^2$

$$\sigma \approx 20\left(\frac{m_e c^2}{\hbar\omega}\right)^2 \mu\text{barn}$$

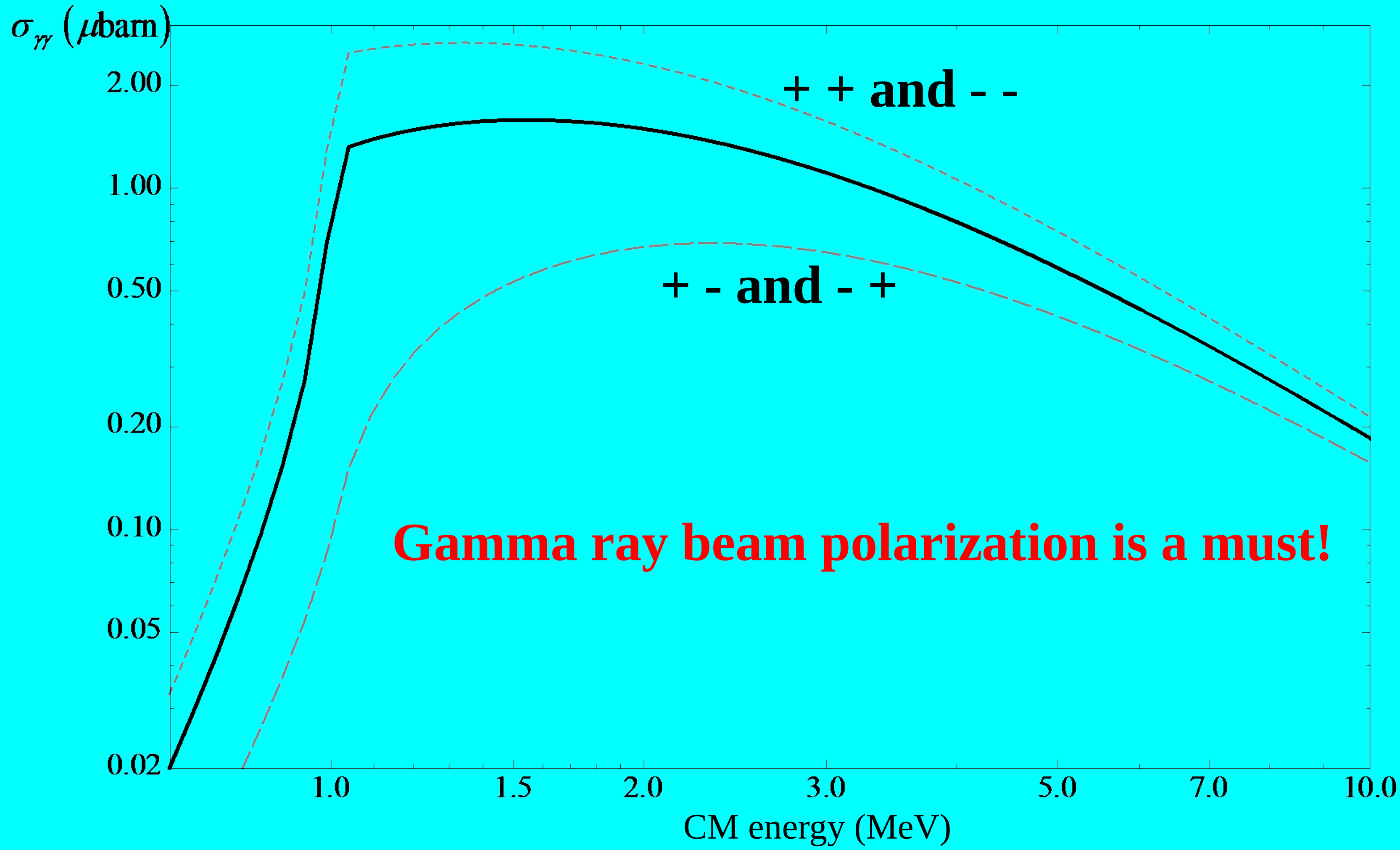


optical transparency
of the Universe

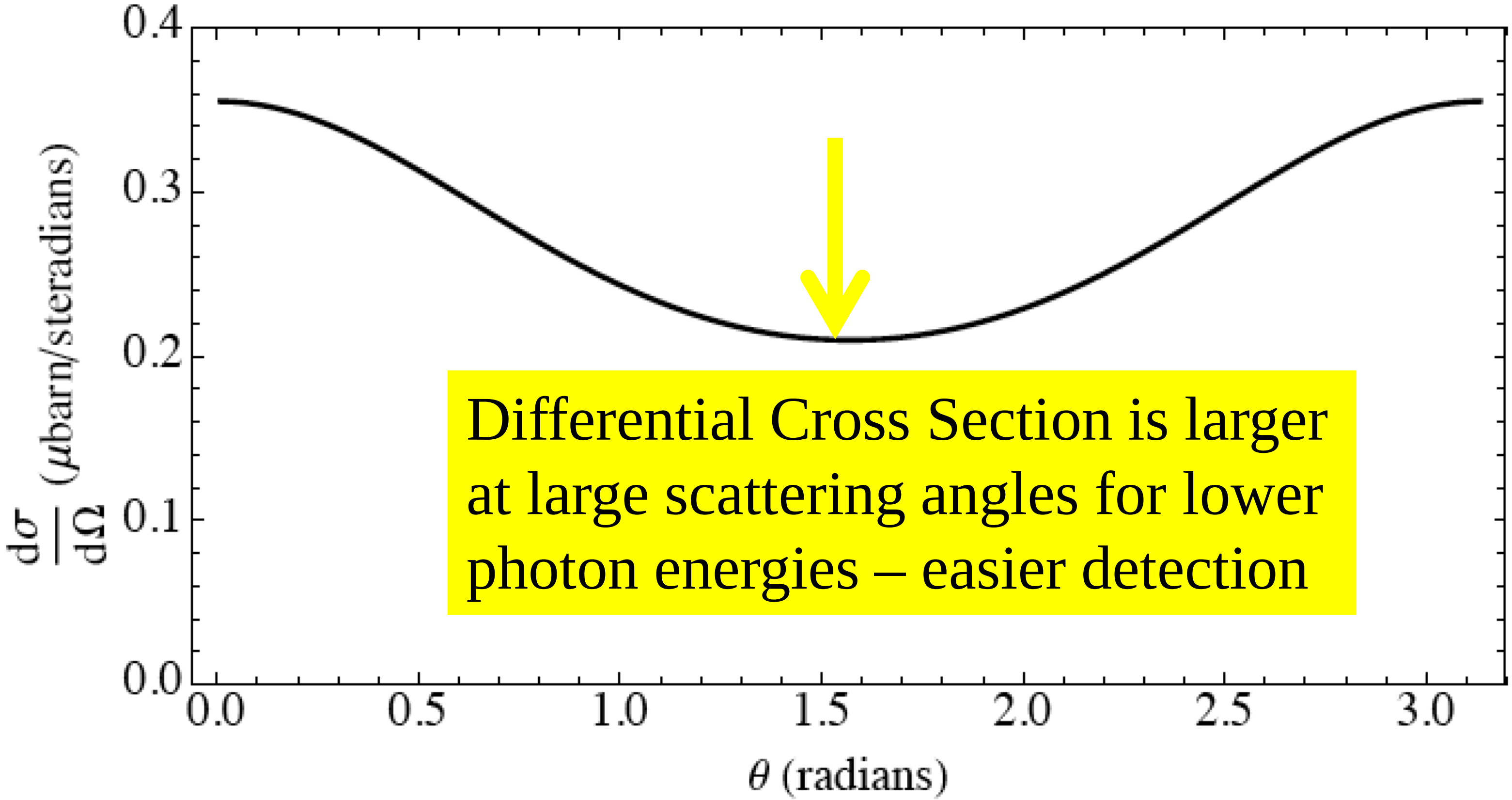

threshold of the
Breit-Wheeler
process
threshold of the
Bethe-Heitler
process $e\gamma \to ee^+e^-$
integrated luminosity corresponding
to a bare minimum of about 100
scattering events (total).
$\sigma_u(\mu\text{barn})$
1 nb^{-1}
10 pb^{-1}
$E_{CM} \approx$
880 keV
$E_{CM} \approx$
13 MeV
$E_{CM} \approx$
140 MeV
$\sigma_{\gamma\gamma}$
$\sigma_{BW} \cdot 10^{-6}$
$E_{CM}(\text{MeV})$

Unpolarized and (circularly) polarized initial photons.

The scattering of polarized photons yields additional information

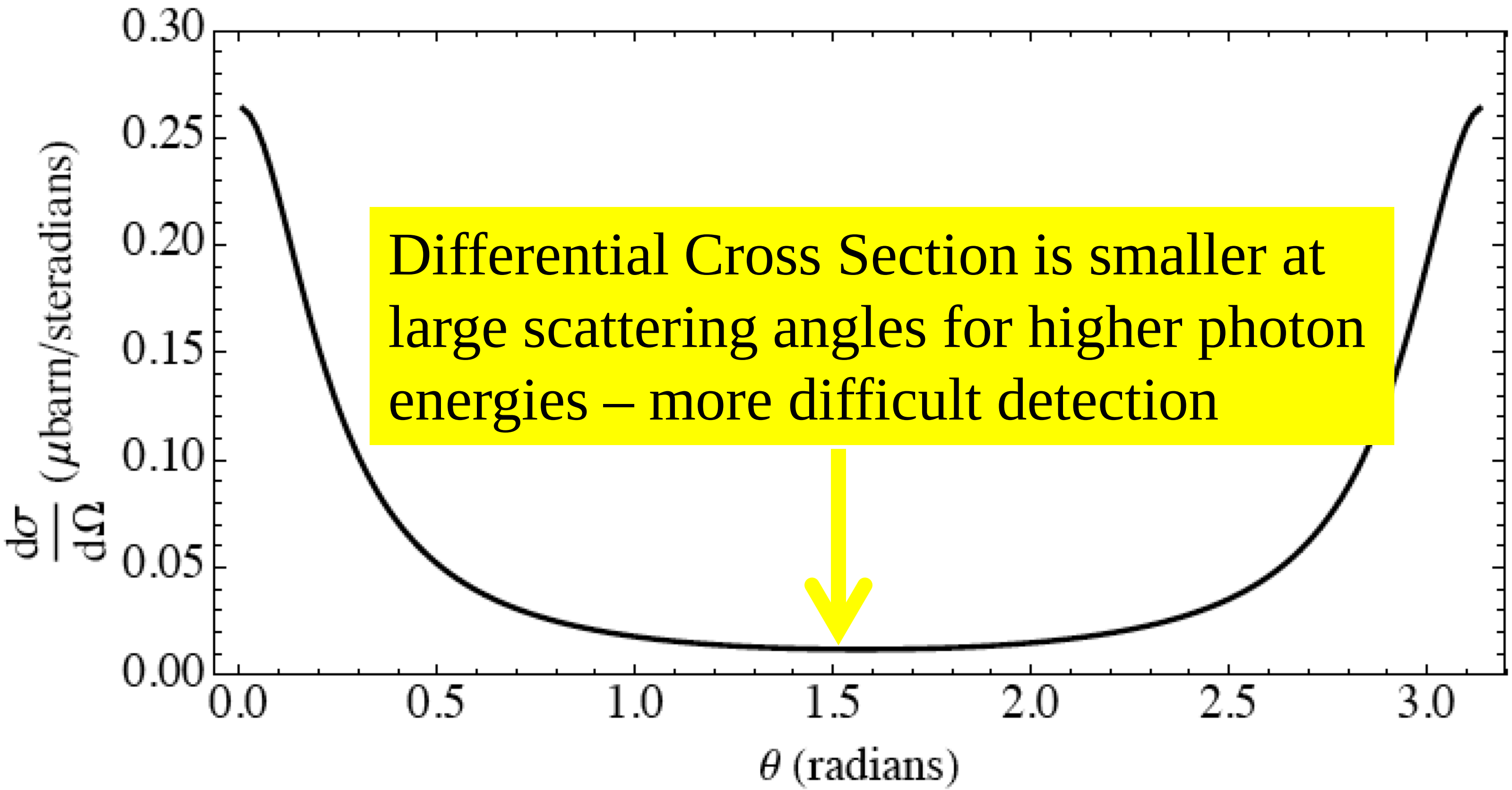


Differential cross-section at ECM = 1.6 MeV (peak)



$$\frac{d\sigma}{d\Omega} \approx \frac{139}{(180\pi)^2}\alpha^2 r_0^2\left(\frac{\hbar\omega}{mc^2}\right)^6\left(3+\cos^2\theta\right)^2$$

Differential cross-section at ECM = 10 MeV

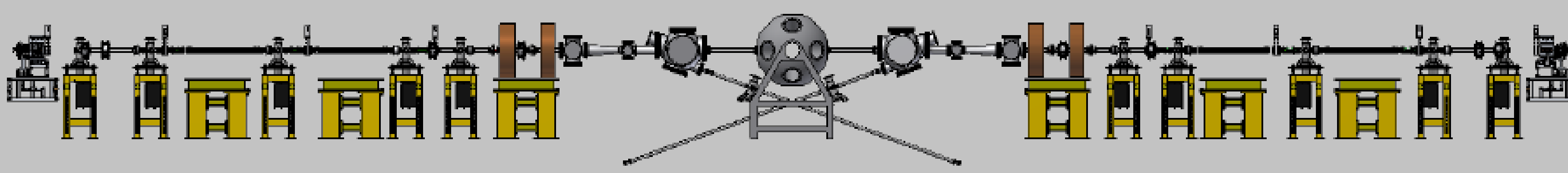


$$\left.\frac{d\sigma}{d\Omega}\right|_{\theta=0} \approx \frac{\alpha^2}{\pi^2} r_0^2 \left(\frac{\hbar\omega}{mc^2}\right)^2 \left(\ln\frac{\hbar\omega}{mc^2}\right)^4 \qquad \left.\frac{d\sigma}{d\Omega}\right|_{\theta=\pi/2} \approx \frac{\alpha^2}{\pi^2} r_0^2 \left(\frac{\hbar\omega}{mc^2}\right)^2$$

A Photon-Photon Scattering Machine based on twin Photo-Injectors and Compton Sources

- **Mono-chromatic High Brilliance micron-spot psec Gamma Ray beams are needed for pursuing Photon-Photon scattering experiments at high luminosity ⇒ scaling laws**
- **Similar to those generated by Compton (back-scattering) Sources for Nuclear Physics/Photonics**
- **(mini) Colliders similar to γ–γ colliders, but at low energy (in the 0.5-2 MeV range): issue with photon beam diffraction!**
- **Best option: twin system of X-band 200 MeV photo-injectors with Compton converters and amplified *J-class* ps lasers (ELI-NP-GBS/STAR) – single bunch no laser re-circulation**

Strawman Design of Photon-Photon Scattering machine based on X-Band SLAC RF Photo-Injector (XTA-like, C. Limborg) + SLAC new X-band (Tantawi-Dolgashev ATR / Spataro INFN-LNF Norcia INFN-SLAC MOU) RF cavities + J-class Yb:Yag 100 Hz collision laser (Amplitude/ELI-NP-GBS&EuroGammaS)



G. Diraddo

PH²SC = Photon-Photon SCattering

MiniWorkshop on Accelerators, CSN5 @ INFN-LNL, Feb. 17th 2015

We evaluated the event production rate of several schemes for photon-photon scattering, based on *ultra-intense lasers*, *brehmstralhung machines*, *Nuclear Photonics gamma-ray machines*, etc, in all possible combinations: collision of 0.5 MeV photon beams is the only viable solution to achieve 1 $nbarn^{-1}$ in a reasonable measurement time.

1)Colliding 2 ELI-NP 10 PW lasers under construction (ready in 2018), $h\nu=1.2$ *eV*, *f=1/60 Hz*, we achieve (E_{cm}=3 eV):
$L_{SC}=6.10^{45}$, cross section= 6.10^{-64}, events/sec=10^{-19}

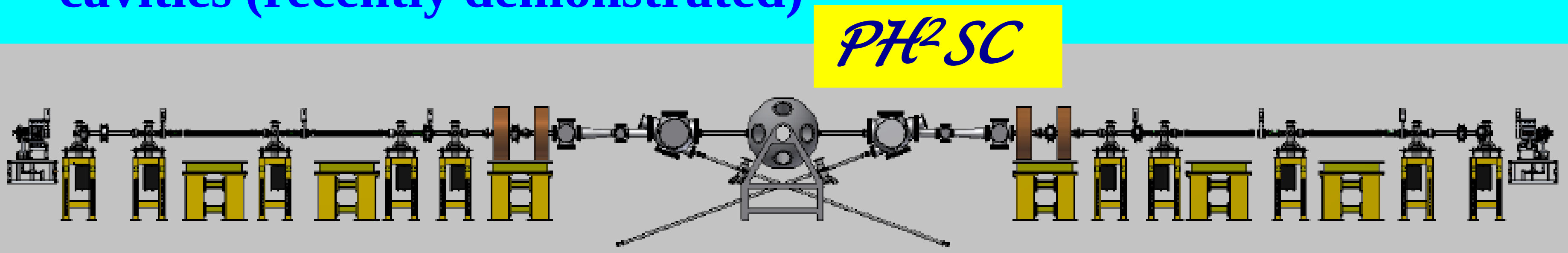
2)Colliding 1 ELI-NP 10 PW laser with the 20 MeV gamma-ray beam of ELI-NP-GBS we achieve (E_{cm}=5.5 keV): $L_{SC}=6.10^{33}$, cross section=10^{-41}, events/sec = 10^{-8}

3)Colliding a high power Brehmstralhung 50 keV X-ray beam (unpolarized, 100 kW on a mm spot size) with ELI-NP-GBS 20 MeV gamma-ray beam (E_{cm}=2 MeV) we achieve: $L_{SC}=6.10^{22}$, cross section=1 μbarn, events/s = 10^{-8}

4) **Colliding 2 gamma-ray 0.5 MeV beams, carrying 10^9 photons per pulse at 100 Hz rep rate, with focal spot size at the collision point of about 2 μm, we achieve: $L_{SC}=2.10^{26}$, cross section = 1 μbarn, events/s=2.10^{-4}, events/day=18, 1 nanobarn^{-1} accumulated after 3.2 months of 5/24 machine running.**

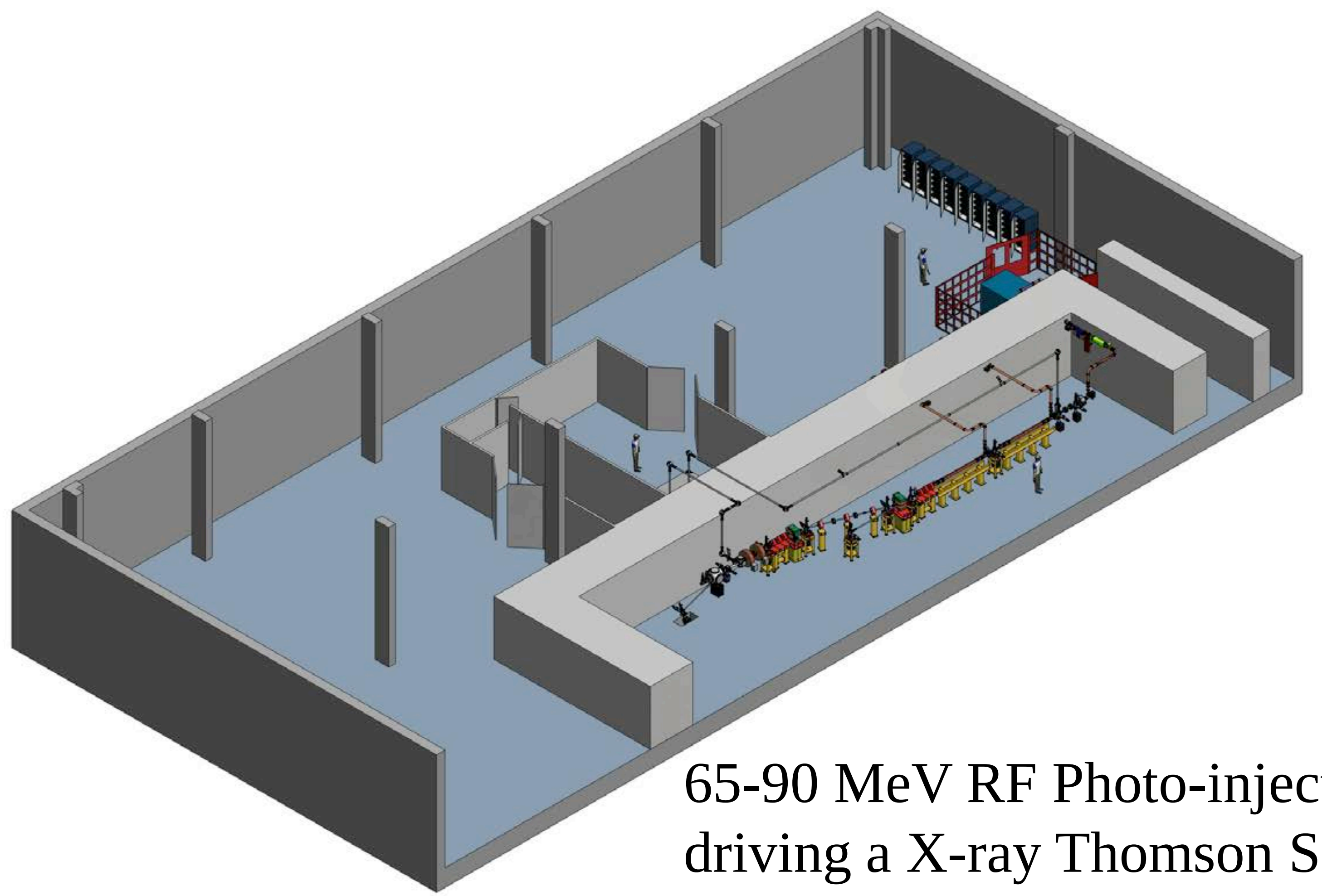
a) 200 MeV/m peak cathode field of X-Band SLAC RF Photo-Injector (recently proven)

b) 100 MeV/m SLAC (Tantawi/Dolgashev/Spataro) new X-band RF cavities (recently demonstrated)



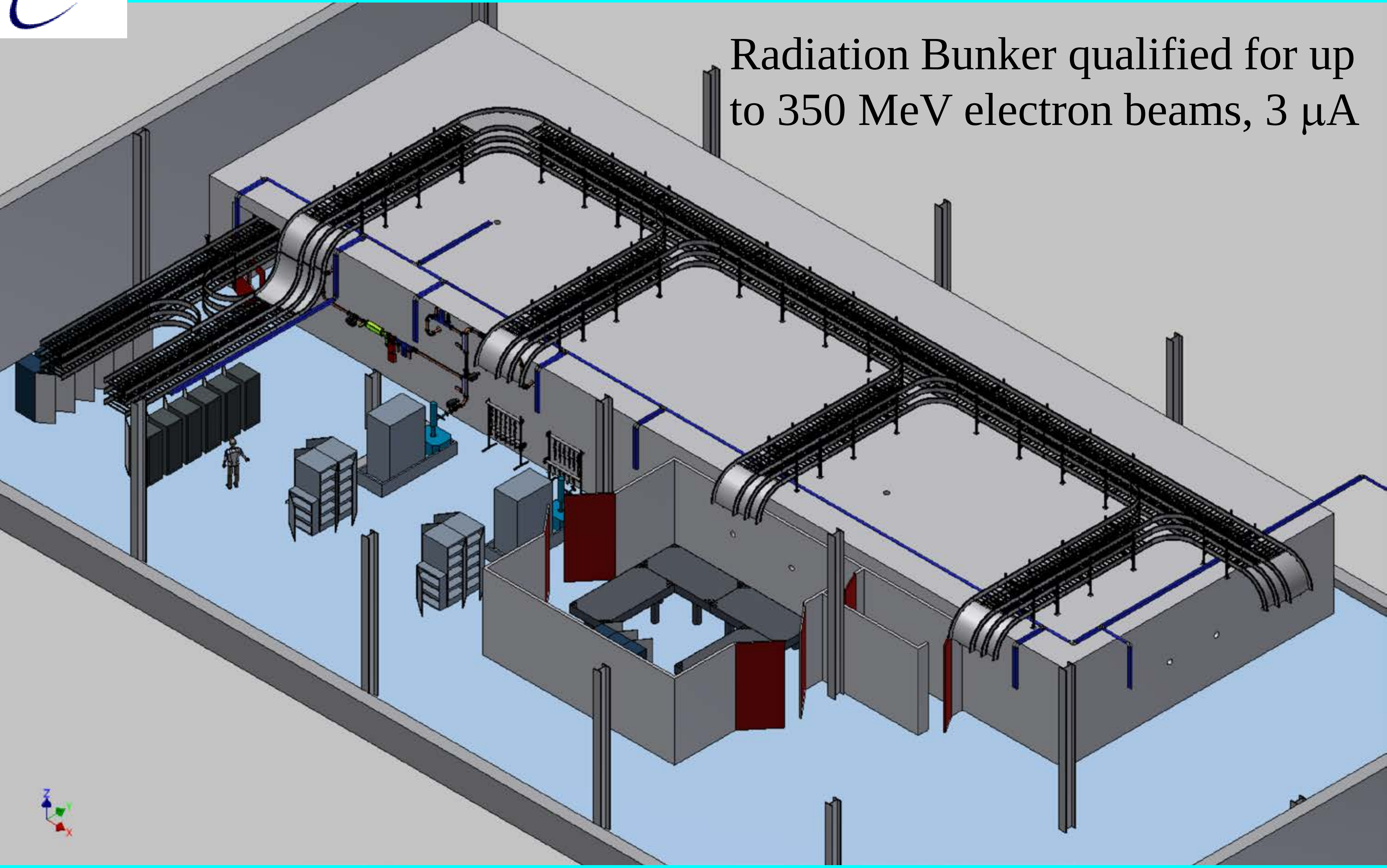
1) **Electron beam operation in single bunch – focusability to 3 micron spot size at Compton Interaction Point**
2) **Pointing stability at 2 Compton Sources**
3) **Deflection of counter-propagating electron bunches to avoid e-/e- interactions**

STAR Building – a possible site (see Poster at this Workshop)



65-90 MeV RF Photo-injector
driving a X-ray Thomson Source

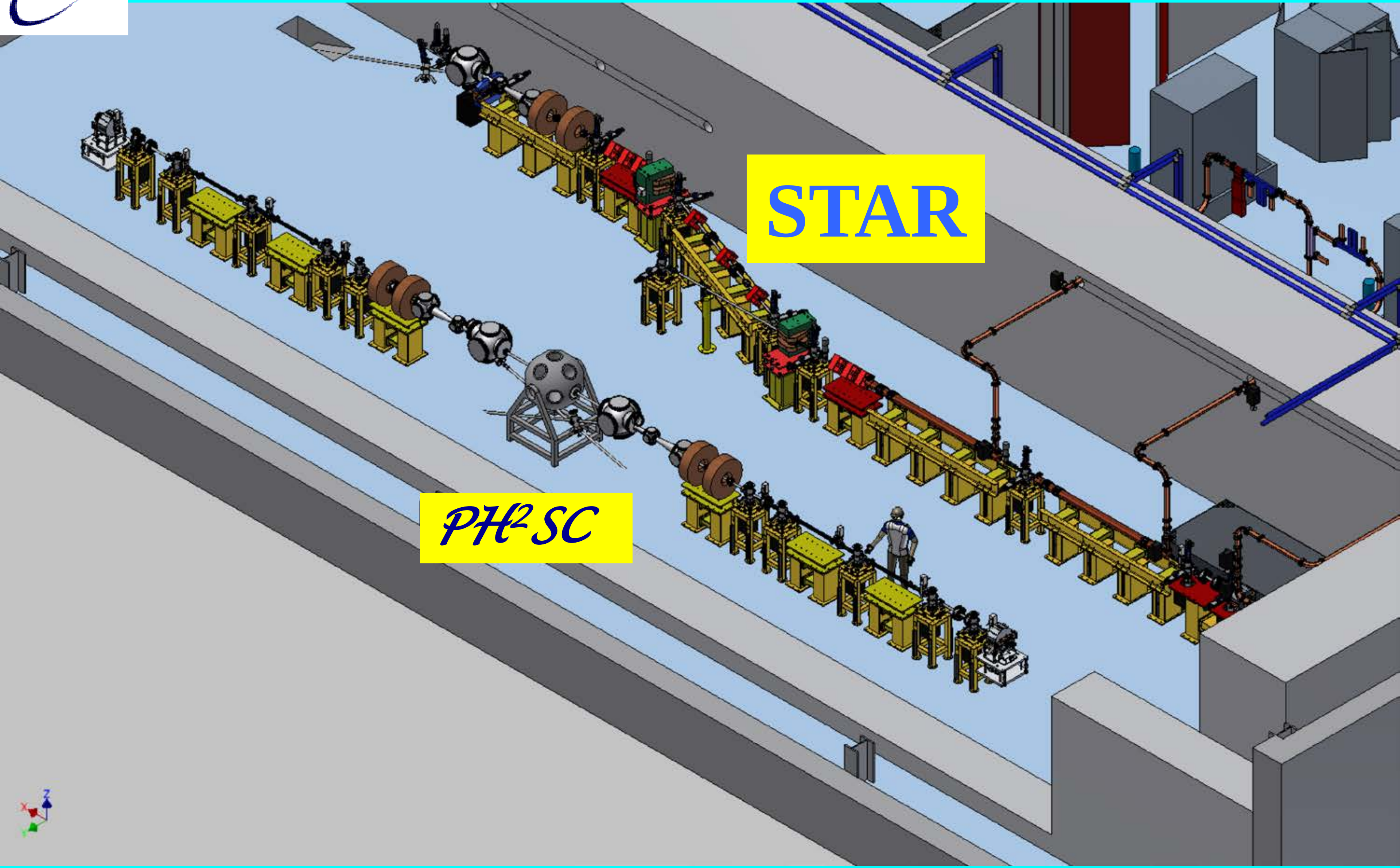
Radiation Bunker qualified for up to 350 MeV electron beams, 3 μA



STAR = Southern europe Thomson source for Applied Research

15 M€ funding 2012-2015 from PON national/european initiatives for regions of convergence (Italy: Sicily, Calabria, Puglia, Campania)


STAR
PH2SC


STAR
PH²SC

CONCLUSIONS

- **Clear Scientific Case on Fundamental QED and QFT**
- **Technical Solution for the Machine (challenging)**
- **Available Site**
- **Good opportunity for funding raising**
- **<u>Uniqueness: a HEP experiment performed with a Light Source: the paradigma for electron and photon beam marriage</u>**

Many Thanks to: E. Milotti, D. Babusci, A. Bacci, C. Curceanu, I. Drebot, M. Ferrario, D. Palmer, B. Spataro

FEL resonance condition

$$\lambda_R = \lambda_w \frac{\left(1 + a_w{}^2\right)}{2\gamma^2}$$

(magnetostatic undulator)

Example : for λ_R=1A, λ_w=2cm, E=7 GeV

$$a_w = 0.93\lambda_w\left[cm\right]B_w[T]$$

$$\lambda_R = \lambda \frac{\left(1 + a_0{}^2/2\right)}{4\gamma^2}$$

(electromagnetic undulator)

Example : for λ_R=1A, λ=0.8μm, E=25MeV

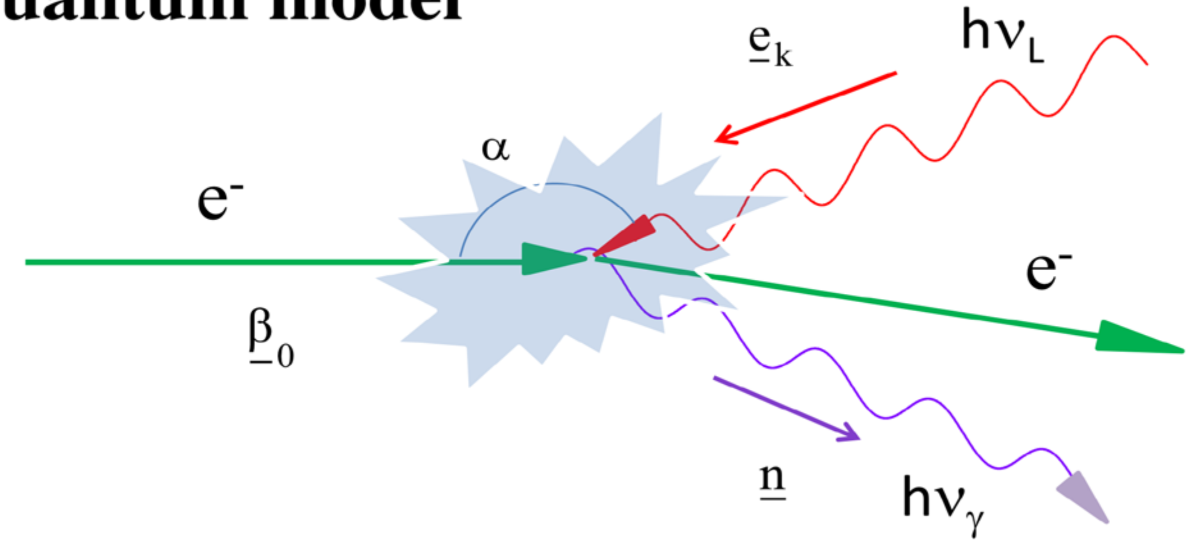
$$a_0 \propto \frac{\lambda\left[\mu m\right]\sqrt{P\left[TW\right]}}{R_0\left[\mu m\right]}$$

laser power

laser spot size

The Physics of Compton Inverse Scattering is quite straightforward

Quantum model



$$\left\{\begin{aligned} mc^2(\gamma-\gamma_0) &= -h(\nu-\nu_L) \\ mc(\underline{\beta}\gamma-\underline{\beta}_0\gamma_0) &= -h(\underline{k}-\underline{k}_L)/2\pi \end{aligned}\right.$$

Energy and momentum conservation laws

γ_0:initial Lorentz factor

$$\nu = \nu_L \frac{1-\underline{e}_k\cdot\underline{\beta}_0}{1-\underline{n}\cdot\underline{\beta}_0 + \boxed{\dfrac{h\nu_L}{mc^2\gamma_0}(1-\underline{e}_k\cdot\underline{n})}}$$

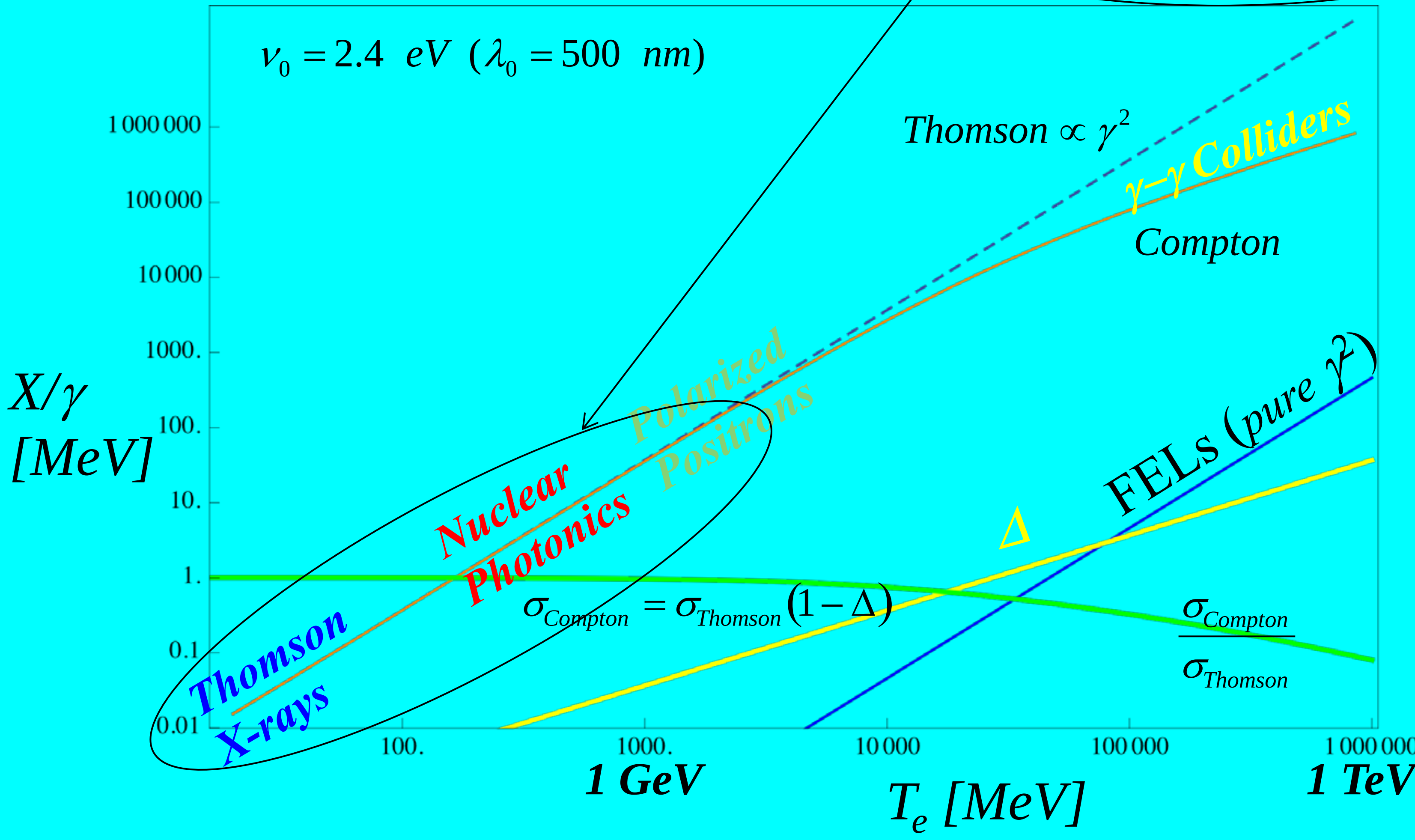
$$\lambda = \boxed{\lambda_L\frac{1-\underline{n}\cdot\underline{\beta}_0}{1-\underline{e}_k\cdot\underline{\beta}_0}} + \boxed{\frac{h}{mc\gamma_0}\,\frac{1-\underline{e}_k\cdot\underline{n}}{1-\underline{e}_k\cdot\underline{\beta}_0}}$$

3 regimes: a) Elastic, Thomson b) Quasi-Elastic, Compton with Thomson cross-section c) Inelastic, Compton, recoil dominated

$$\nu_\gamma = \nu_0 \frac{1-\underline{n}\cdot\underline{\beta}_0}{1-\underline{e}_k\cdot\underline{\beta}_0 - \frac{h\nu_0}{mc^2}(1+\cos\theta)} \Rightarrow +coll.\ eff.$$

$$\nu_\gamma = \nu_0 \frac{4\gamma^2}{1+\gamma^2\theta^2+a_0^2/2}(1-\Delta)$$

$$\Delta = \frac{4\gamma h\nu_0}{mc^2} \qquad \Delta \ll 1 \ \ Compton \ \ recoil$$



Brilliance of Lasers and X-ray sources

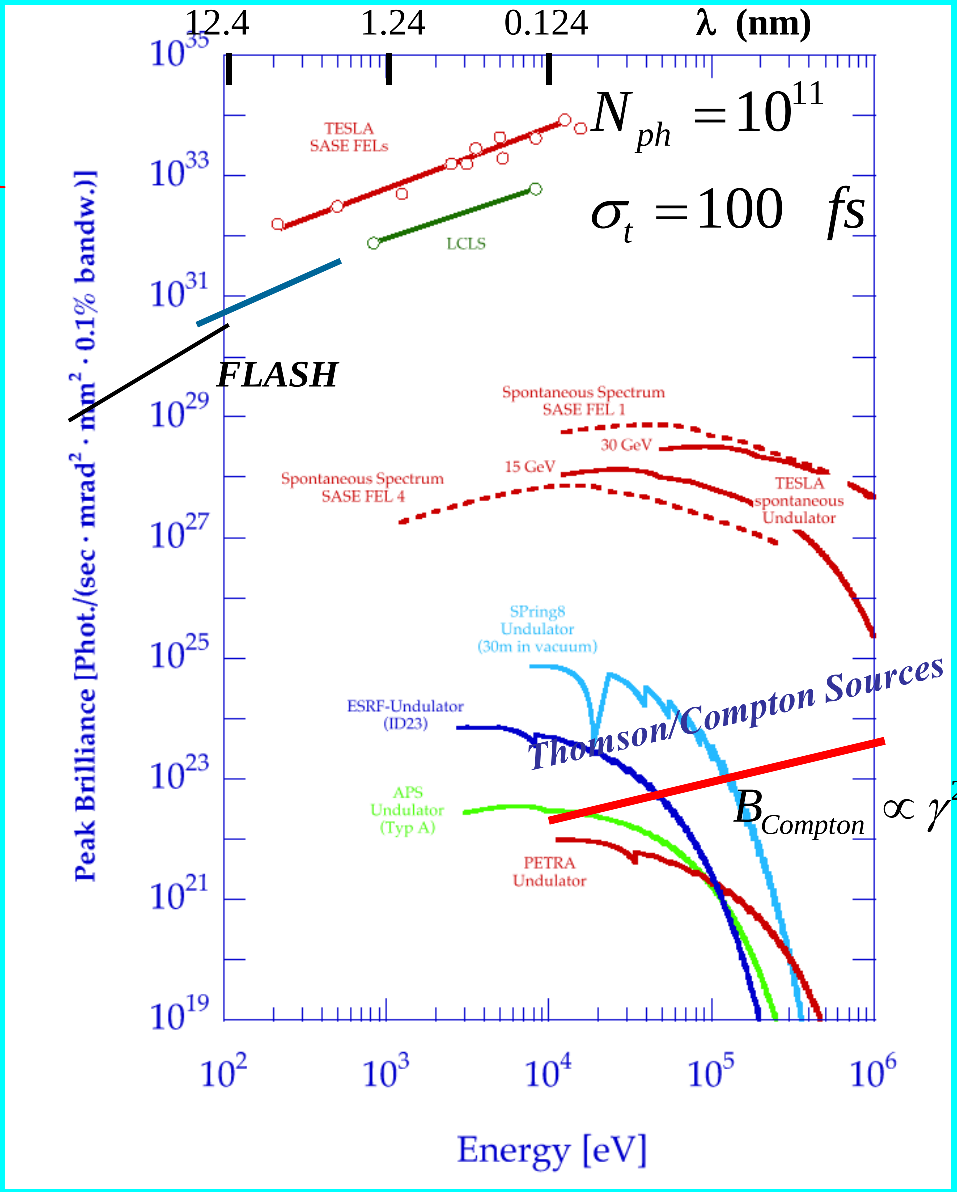
ELI

BELLA

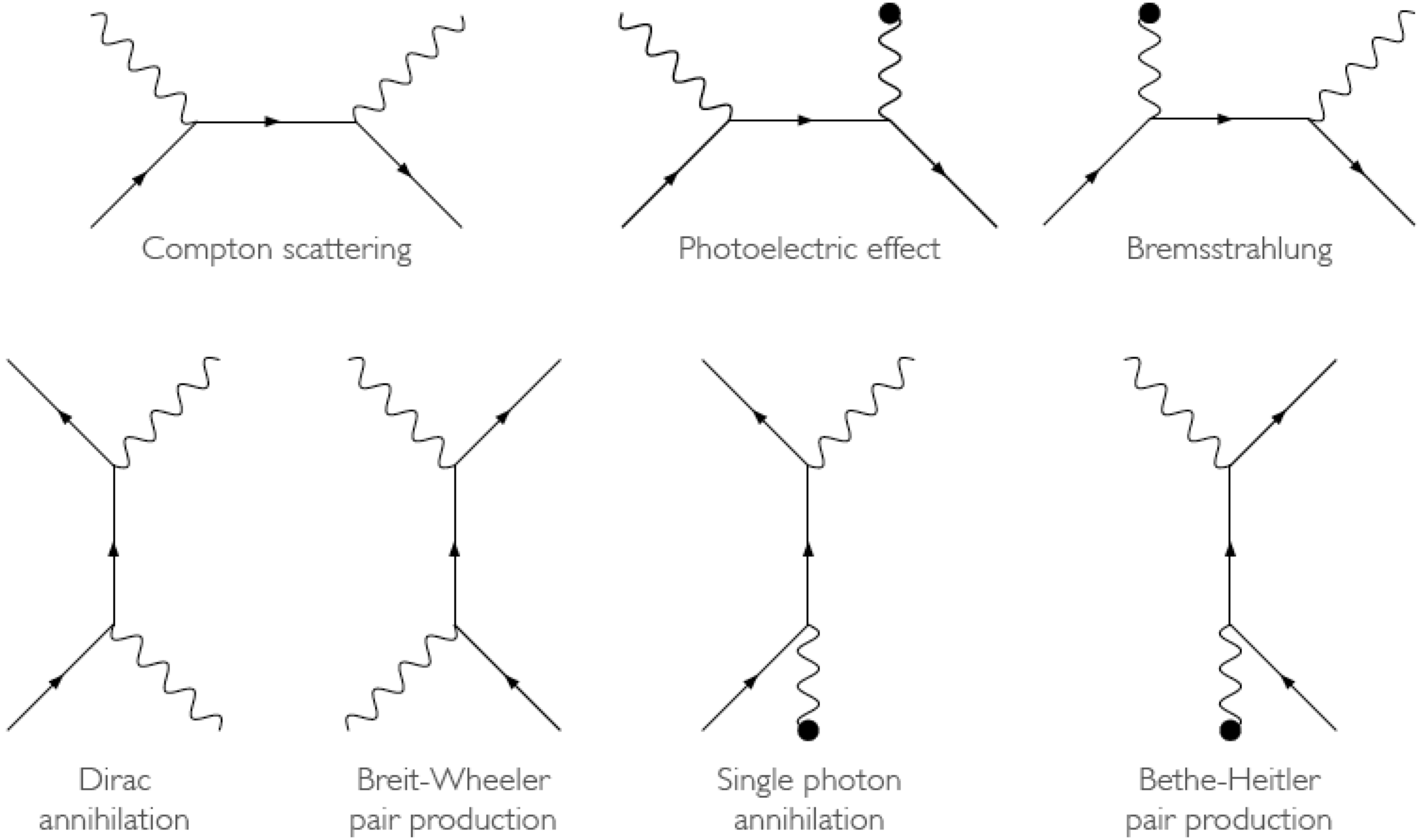
$$N_{ph} = 10^{19} - 10^{20}$$
$$\sigma_t = 10 - 20 \quad fs$$

$$B = \frac{N_{ph}}{\sqrt{2\pi}\sigma_t \left(M^2 \lambda\right)^2 \frac{\Delta\lambda}{\lambda}}$$

$$a_0 = 4.3 \frac{\lambda}{w_0} \sqrt{\frac{U[J]}{\sigma_t[ps]}}$$



The simplest interactions between light and matter: the basics of QED



Courtesy Oliver Pike

SLAC E-144 experiment:
first sign of positron production in light-by-light scattering

PHYSICAL REVIEW D, VOLUME 60, 092004

Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses

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Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

C. Bula,¶ K. T. McDonald, and E. J. Prebys
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

D. L. Burke, R. C. Field, G. Horton-Smith,** J. E. Spencer, and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

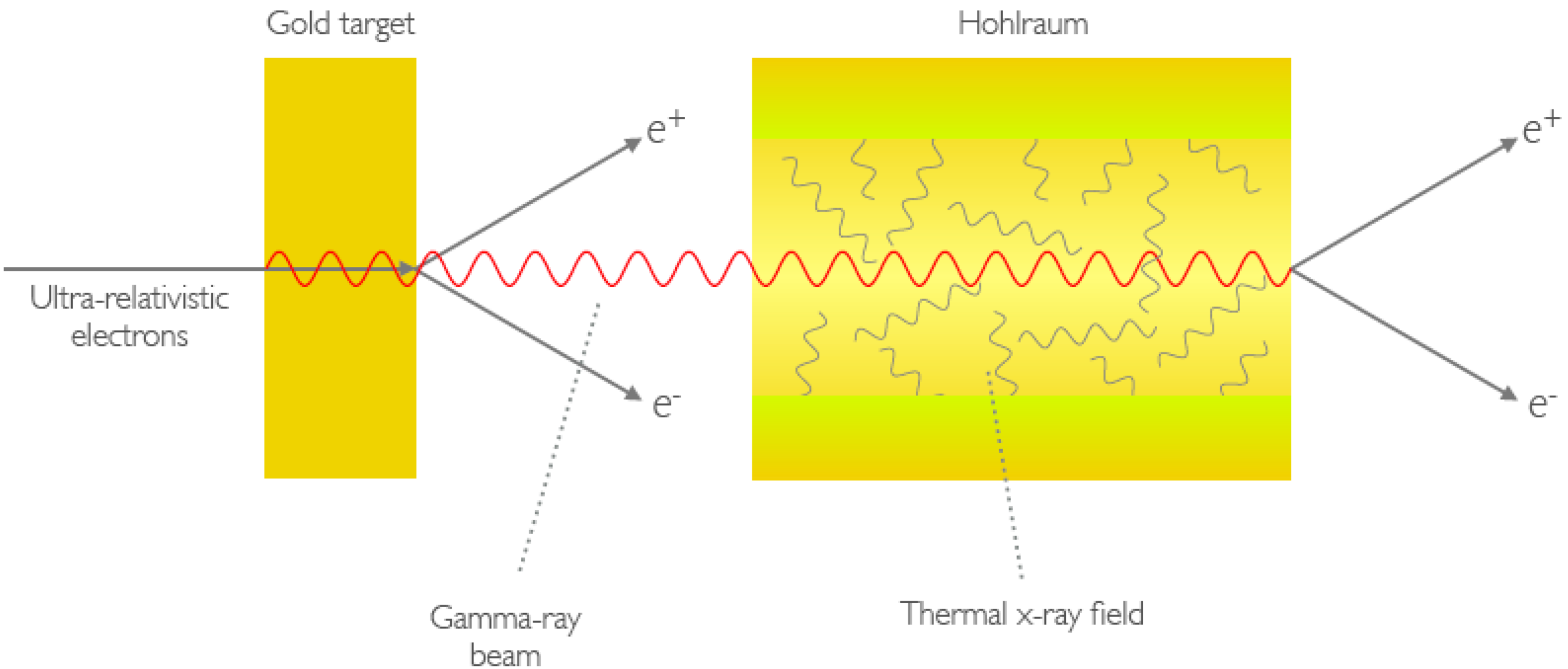
S. C. Berridge, W. M. Bugg, K. Shmakov,†† and A. W. Weidemann
Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996
(Received 1 February 1999; published 8 October 1999)

- Recently shown that, on average, n = 6.44 laser photons were absorbed.

Burke et al., *PRL* **79**, 1626 (1997)
Hu & Müller, *PRL* **107**, 090402 (2010)

Courtesy Oliver Pike

A photon-photon collider in a vacuum hohlraum: a new HEP experiment using HEDP facilities



Pike et al., *Nature Photonics* **8**, 434 (2014)

Courtesy Oliver Pike

Multiphoton Breit-Wheeler scattering was observed at SLAC. However, as clearly stated also in the paper, "The multiphoton Breit□-Wheeler reaction becomes accessible for n > 3 laser photons of wavelength 527 nm colliding with a 29.2 GeV photon□".

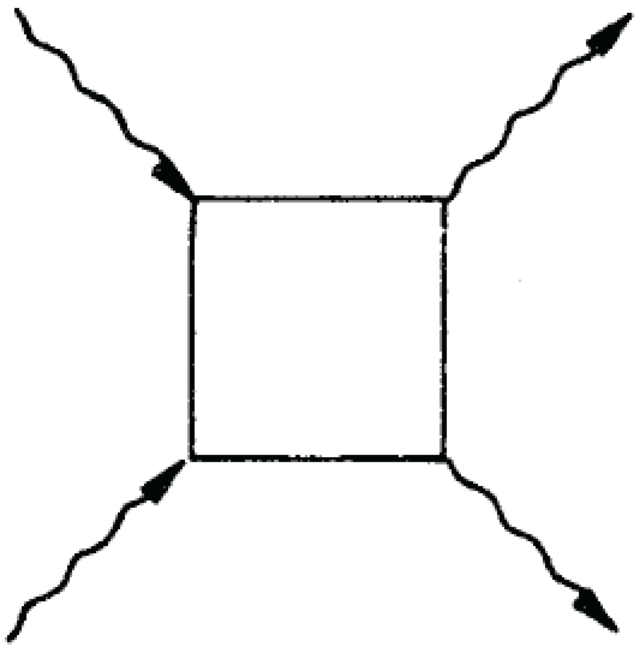
Indeed, the straghtforward two-photon Breit-Wheeler reaction has never been observed. The difference may appear minor, however it isn't. Multi photon scattering has a considerably more complex kinematics, and the dynamical calculation clearly requires more than one internal propagator in the Feynman diagram.

But more than that, Breit-Wheeler scattering — be it multi photon or not — is described by a simple tree-level diagram at the lowest perturbative order, while photon+photon —> photon+photon, needs a fermion loop at the lowest level, and thus is a true probe of the quantal nature of field theory.

Edoardo Milotti - INFN-Trieste

The cosmological constant problem is related to the zero-point energy, i.e., to the fluctuations of quantum vacuum, and therefore also to the renormalization procedure in QFT.

Photon-photon scattering directly probes the fluctuations of quantum vacuum.



This is the first nonvanishing diagram: there are no tree-level diagrams

All the involved photons are real particles

Recent references on low-energy light-magnetic field scattering (photon-photon scattering between real infrared photons and virtual magnetic field photons)

- F. Della Valle, E. Milotti, A. Ejlli, G. Messineo, L. Piemontese, G. Zavattini, U. Gastaldi, R. Pengo, G. Ruoso: "First results from the new PVLAS apparatus: A new limit on vacuum magnetic birefringence", accepted for publication in Physical Review D
- F. Della Valle, U. Gastaldi, G. Messineo, E. Milotti, R. Pengo, L. Piemontese, G. Ruoso, G. Zavattini: "Measurements of vacuum magnetic birefringence using permanent dipole magnets: the PVLAS experiment", New J. Phys. 15 (2013) 053026

Recent references on possible photon-photon scattering schemes

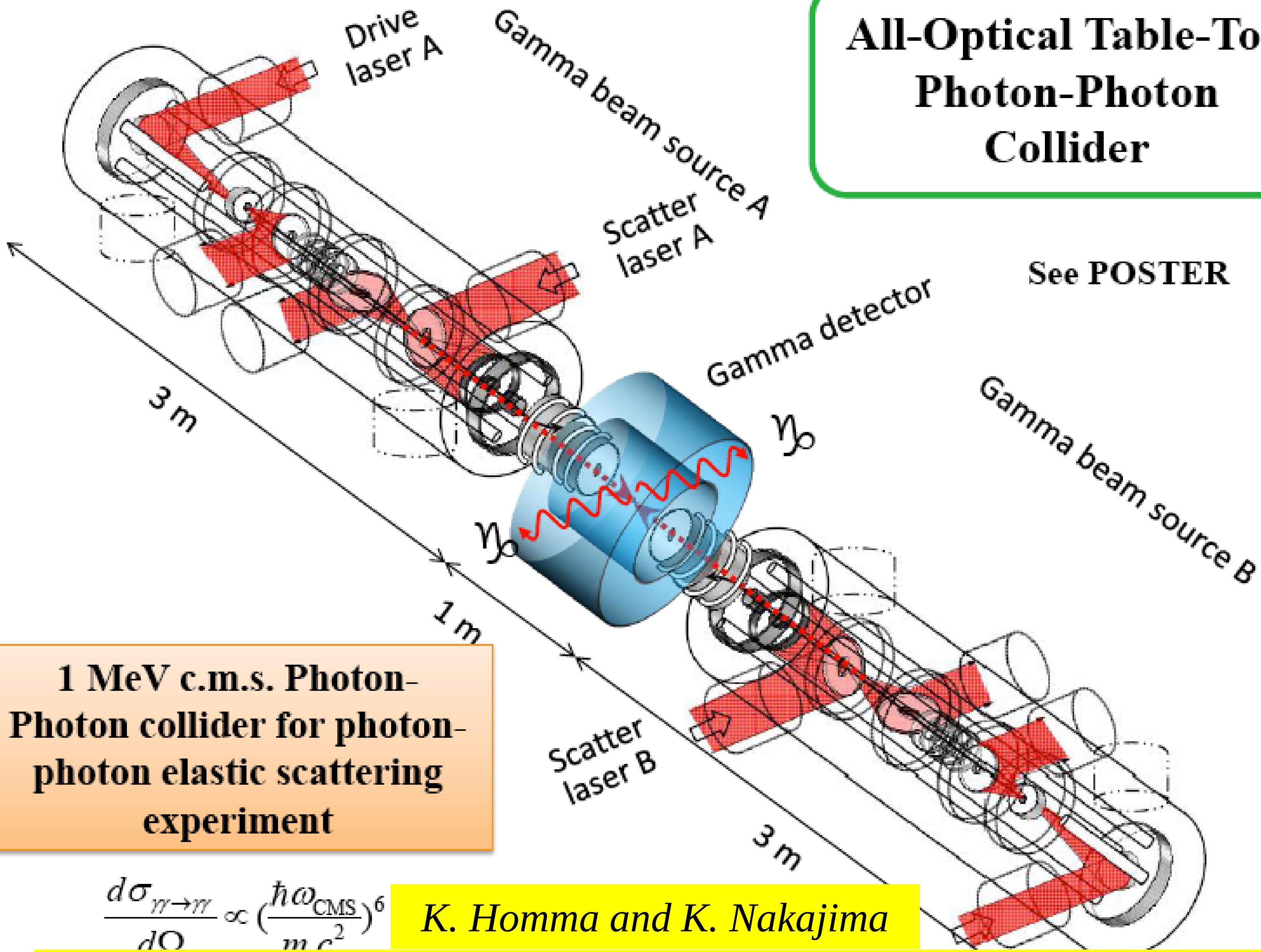
- A. Torre, G. Dattoli, I. Spassovsky, V. Surrenti, M. Ferrario, and E. Milotti: "A double FEL oscillator for photon-photon collisions", Journal of the Optical Society of America B 30 (2013) 2906-2914
- E. Milotti, F. Della Valle, G. Zavattini, G. Messineo, U. Gastaldi, R. Pengo, G. Ruoso, D. Babusci, C .Curceanu, M. Iliescu, C. Milardi: "Exploring quantum vacuum with low-energy photons", Int. J. of Quantum Information 10 (2012) 1241002

Historical reference on photon-photon scattering opportunities

- Paul L. Csonka, “Are photon-photon scattering experiments feasible?”, Phys. Lett. 24B (1967) 625

All-Optical Table-Top Photon-Photon Collider

See POSTER



1 MeV c.m.s. Photon-Photon collider for photon-photon elastic scattering experiment

$$\frac{d\sigma_{\gamma\gamma\to\gamma\gamma}}{d\Omega} \propto \left(\frac{\hbar\omega_{CMS}}{m_e c^2}\right)^6$$

K. Homma and K. Nakajima

https://www.izest.polytechnique.edu/izest-home/izest-events/09-2014-izest-eli-np-conf-extreme-light-conference-paris-france/slides/slides-317952.kjsp?RF=1412352802227

Formulas for photon scattering Luminosity extensively tested vs. ELI-NP-GBS simulations

$$L_{sc} = \frac{\left(N_{\gamma-shot}^{bw}\right)^2}{4\pi\sigma_{sc}^2} f_{RF}\delta_{\phi} \qquad \sigma_{sc} \approx \{!\} \;\; \sigma_S = \frac{\sigma_x w_0}{\sqrt{4\sigma_x^2 + w_0^2}}$$

$$N_{\gamma}^{bw} = 1.4 \cdot 10^9 \frac{U_L[J]Q[pC]f_{RF}\delta_{\phi}}{h\nu[eV]\left(\sigma_x^2[\mu m] + \frac{w_0^2[\mu m]}{4}\right)} \cdot \frac{\gamma\theta}{\sqrt{2}}$$

$$Assumptions: \;\; weak \;\; diffraction \;\; c\sigma_t < \;\; Z_0 \equiv \frac{\pi w_0^2}{\lambda}$$

$$and \;\; \sigma_{z-el} < \;\; \beta_0 \equiv \frac{\gamma\sigma_0^2}{\varepsilon_n} \quad and \;\; ideal \;\; time-space \;\; overlap$$

$$implies: \;\; \sigma_t < \;\; a \;\; few \;\; psec \quad \sigma_{z-el} < \;\; 300 \;\; \mu m$$

$$L_{sc} = 6.2 \cdot 10^{25} \frac{U_L^2[J]Q^2[pC]f_{RF}\delta_\phi^3}{h\nu^2[eV]\sigma_x^2[\mu m]w_0^2[\mu m]\left(\sigma_x^2[\mu m] + \frac{w_0^2[\mu m]}{4}\right)} \cdot \frac{\gamma^2\theta^2}{2}$$

$$Source\ \ size\ \ \sigma_S = \frac{\sigma_x w_0}{\sqrt{4\sigma_x^2 + w_0^2}}\ \ Photon\ \ emittance\ = \ \varepsilon_{\gamma 0} = \sigma_S \cdot \frac{\theta}{\sqrt{2}}$$

$$Diffraction\ \ \sigma_\gamma(z) = \sigma_S\sqrt{1 + \frac{z^2}{\beta^{*2}}}\ \ \ diffr.\ \ length\ \ \beta^* \equiv \frac{\sigma_S^2}{\varepsilon_{\gamma 0}} = \frac{\sqrt{2}\sigma_S}{\theta}$$

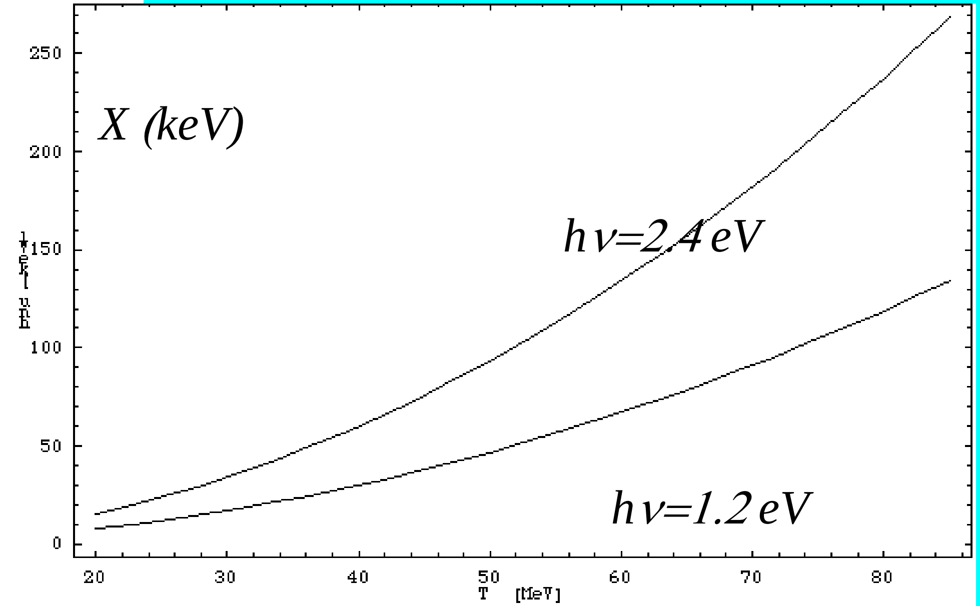
$$\beta^* \approx (ph - ph\ \ scatt) \approx 3\gamma\sigma_S$$

Formula for L_{sc} is valid if distance between 2 Compton conversion IP’s is smaller than β^*

Example γ=*300* σ_S=*3* μm β^*=*1 mm*

STAR

X-Ray Imaging



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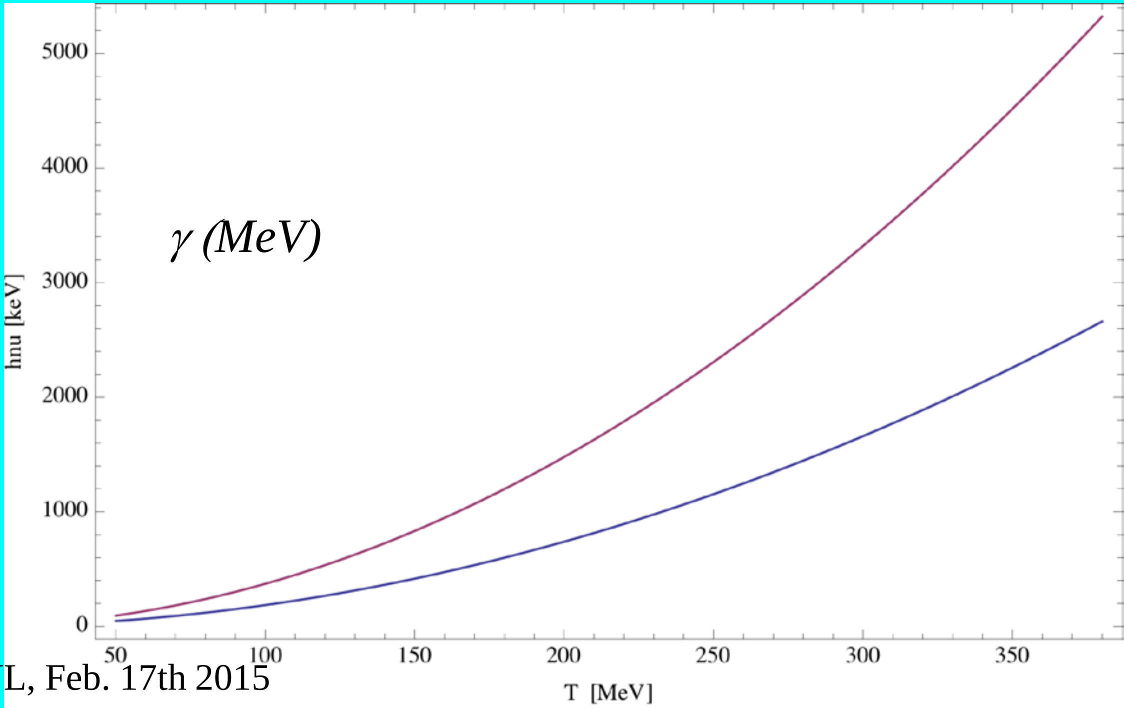
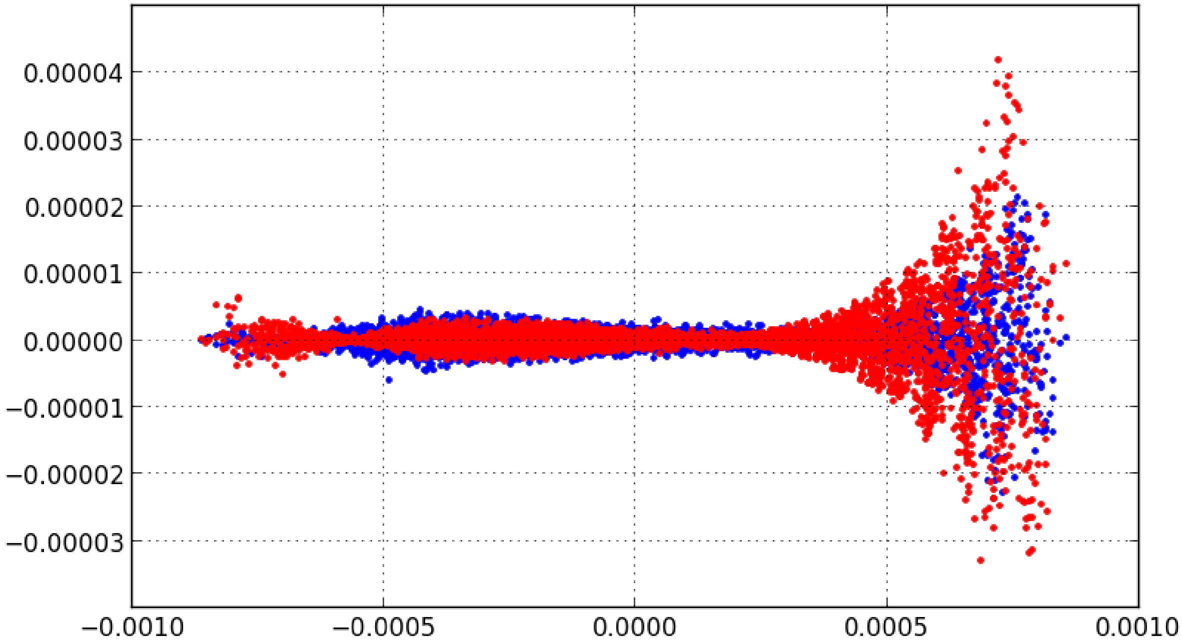
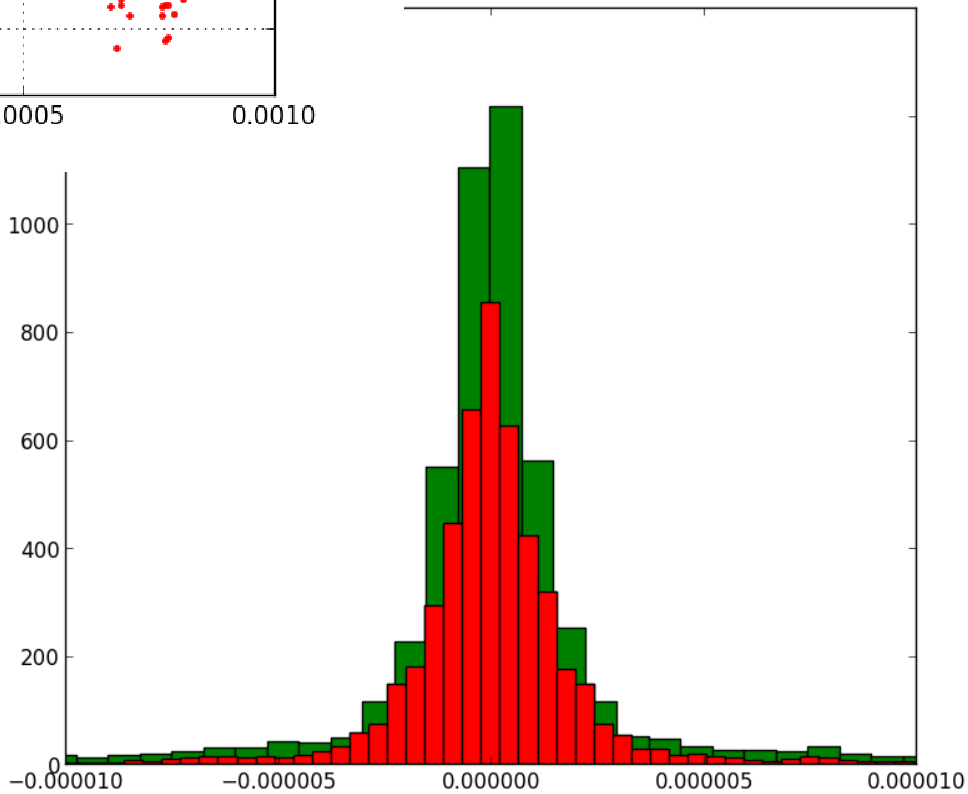
Nuclear Photonics

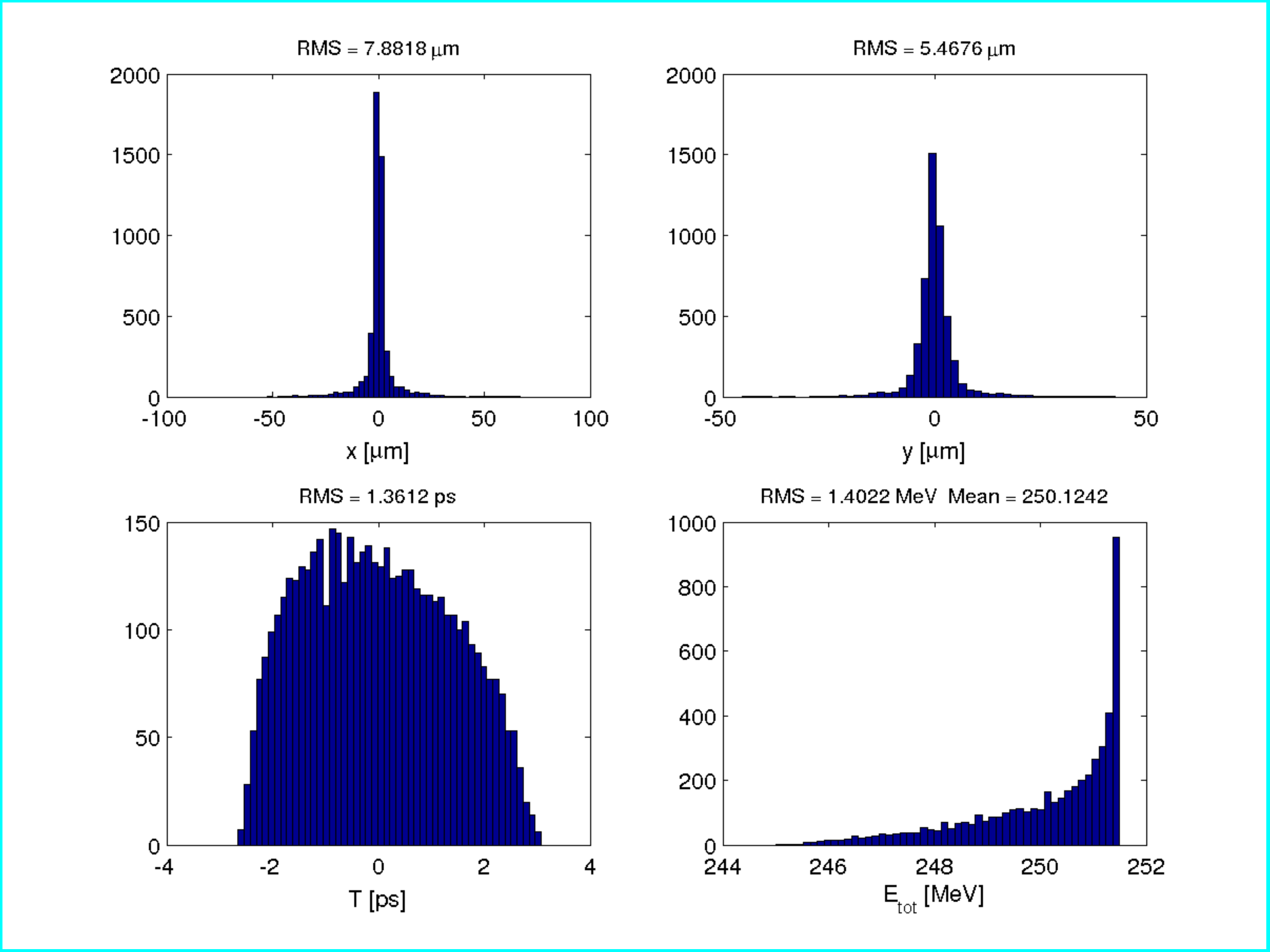


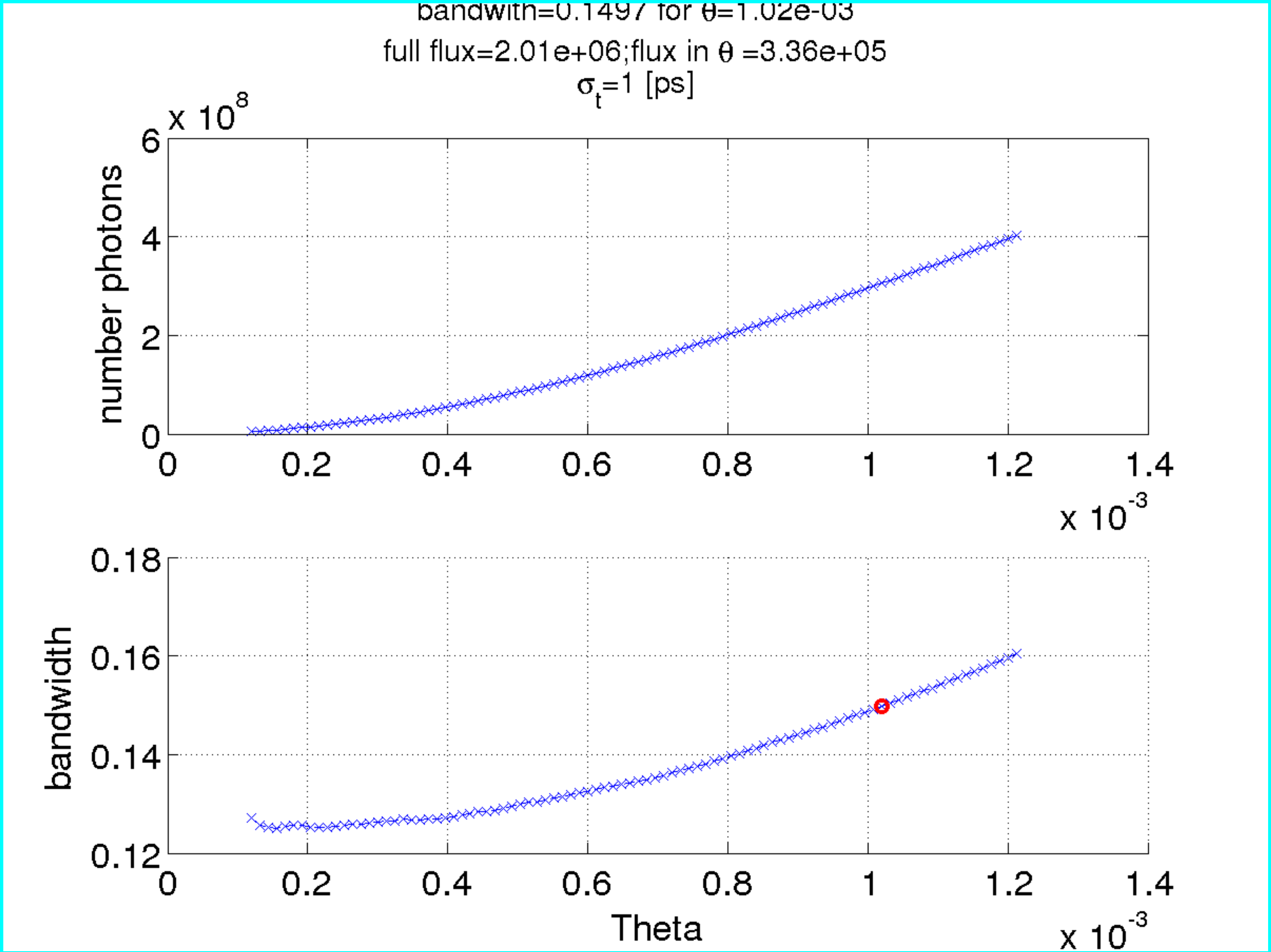


A.Bacci – first attempt, SLAC X-band RF gun and B.Spataro's X-band RF structures

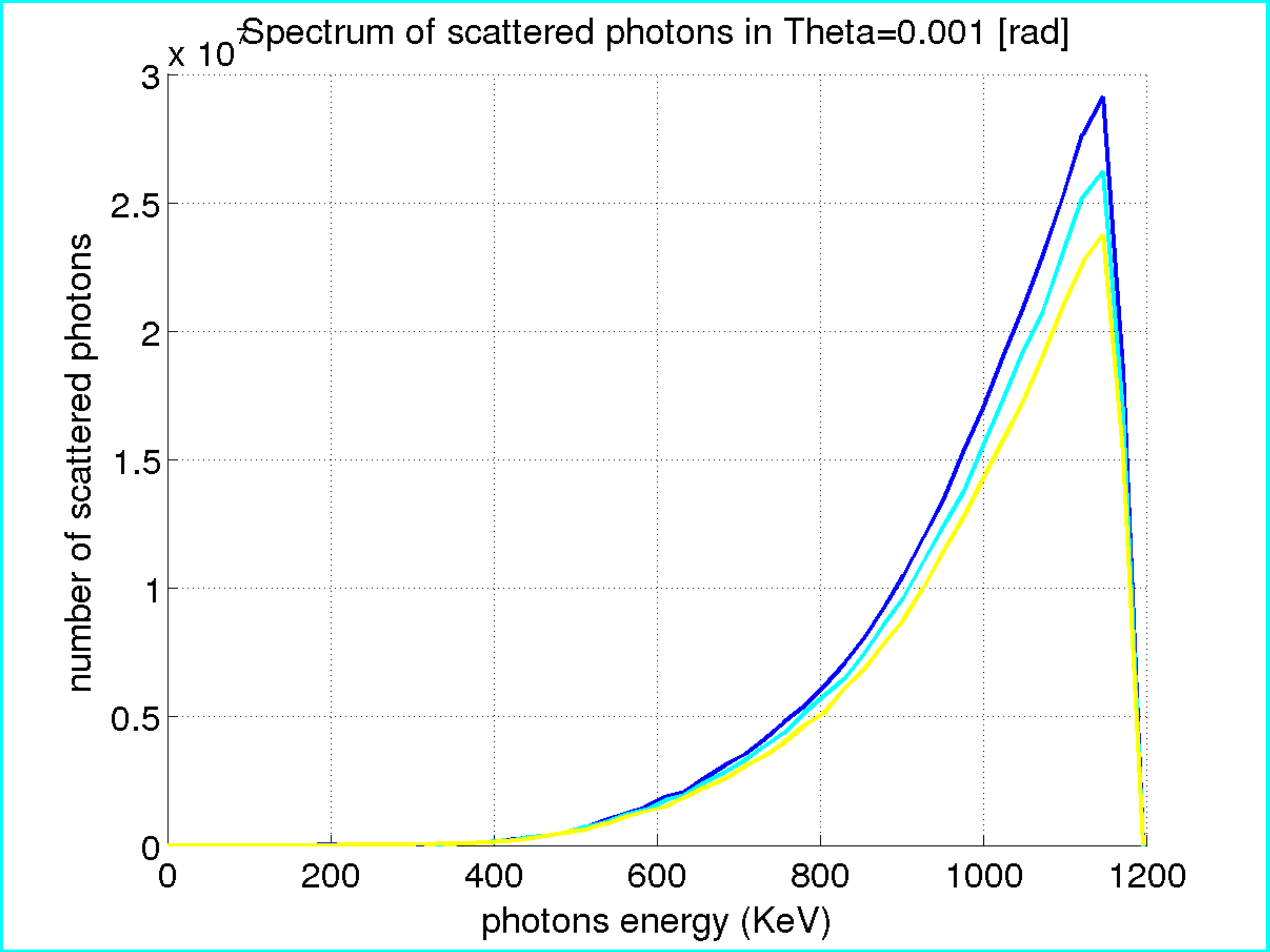
250 pC, 3 μm spot size




RMS = 7.8818 μm
x [μm]
RMS = 5.4676 μm
y [μm]
RMS = 1.3612 ps
T [ps]
RMS = 1.4022 MeV Mean = 250.1242
E_tot [MeV]

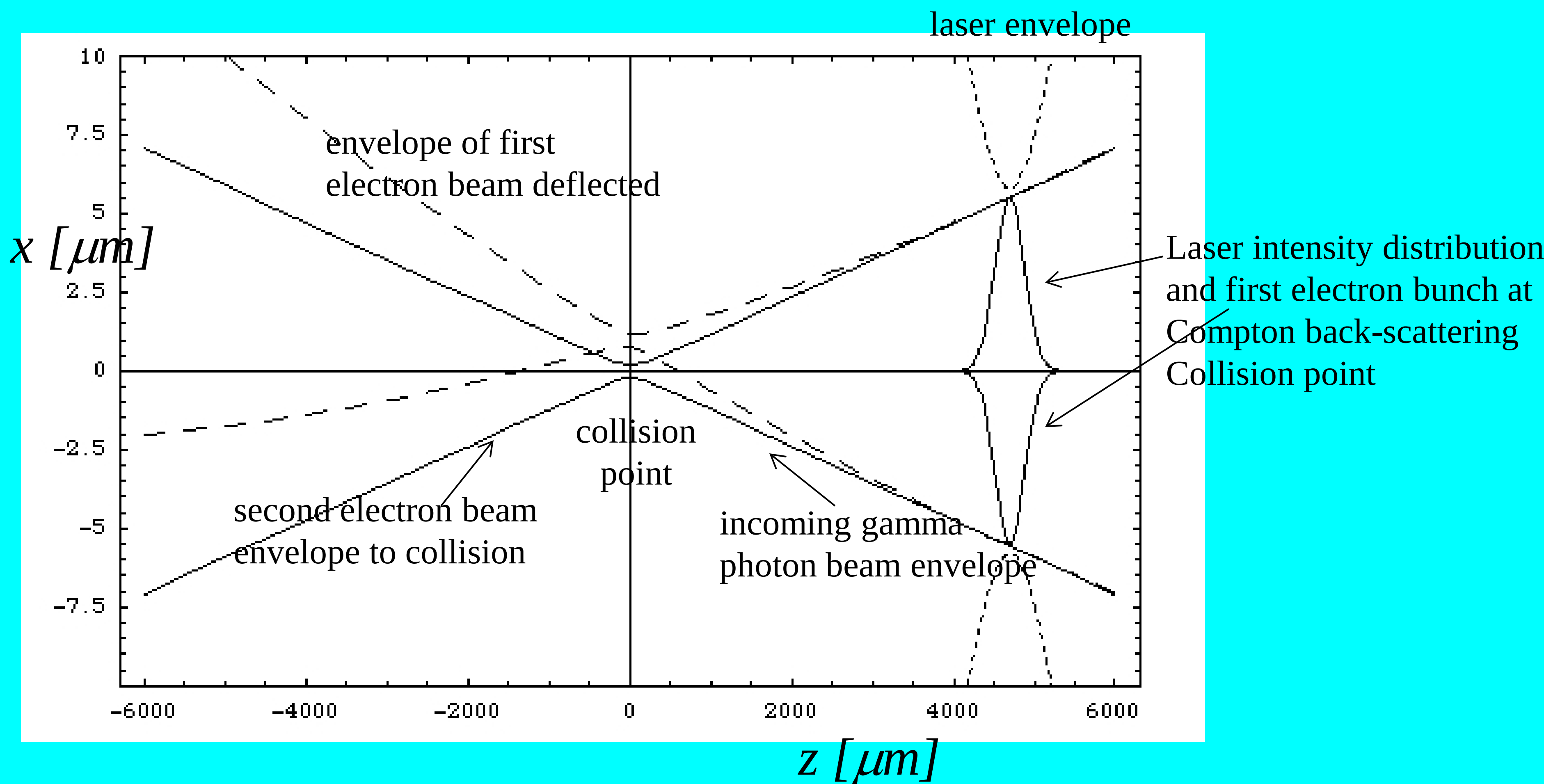


Illya Drebot with CAIN – single bunch mode 100 Hz no laser re-circul.

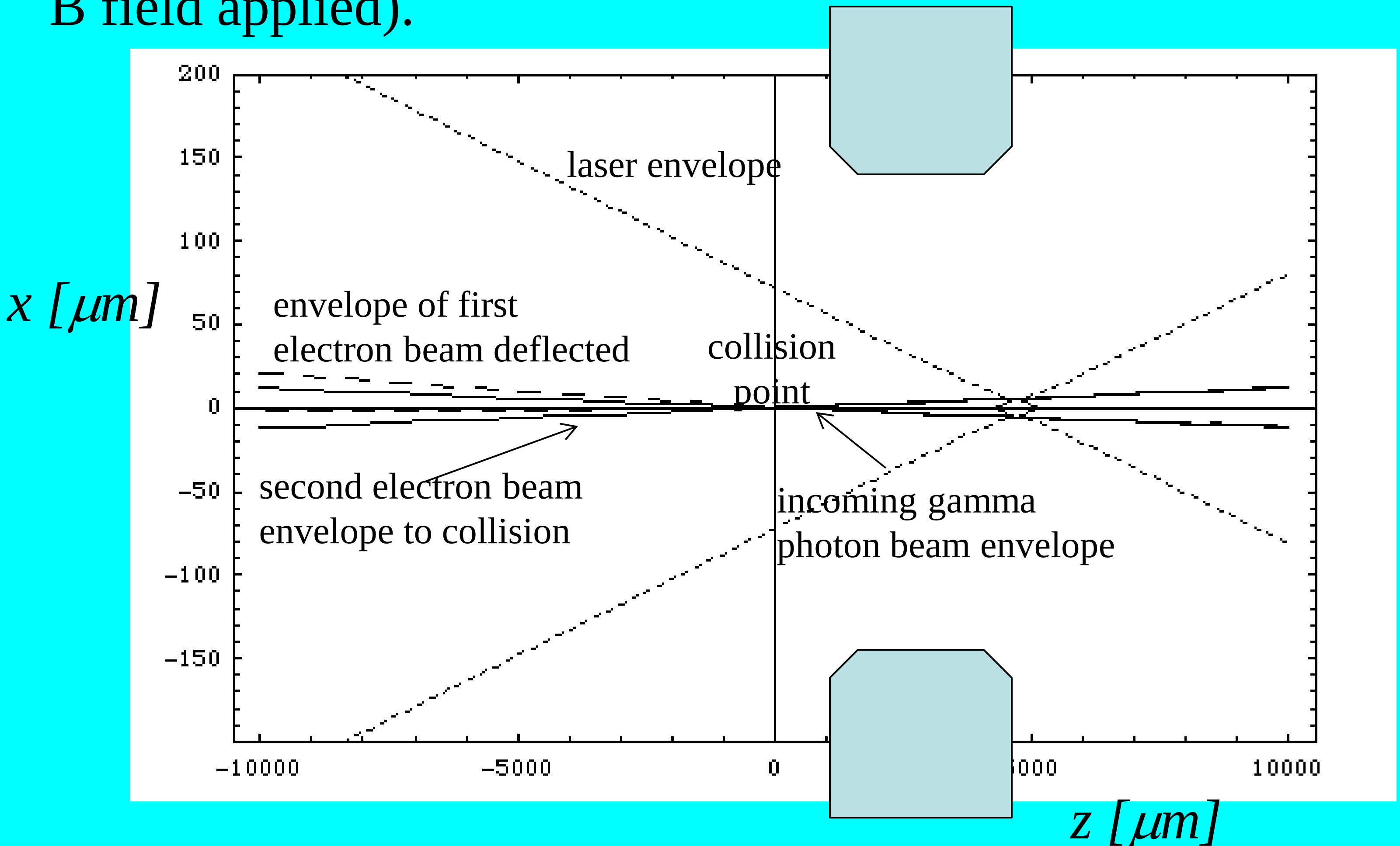


$$L_{SC} \approx 3 \cdot 10^{25} - 1 \cdot 10^{26} \quad uncollimated$$

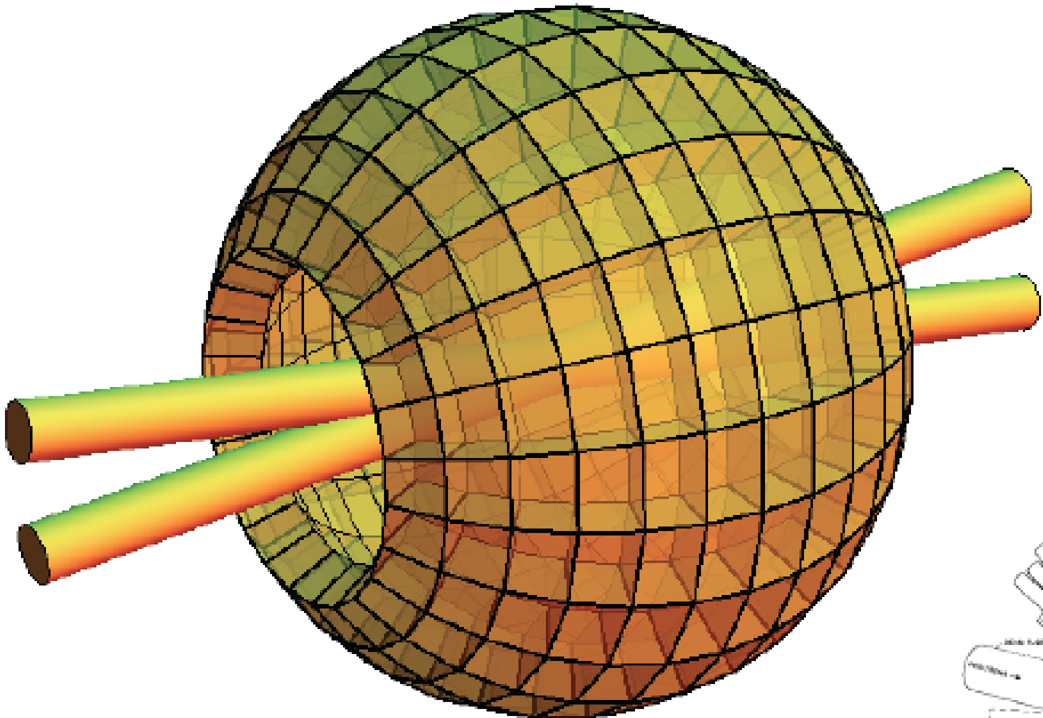
Envelopes of the laser beam (dotted line), first electron beam (for Compton back-scattering, dashed) deflected after collision with laser to clear the second electron beam (solid line).



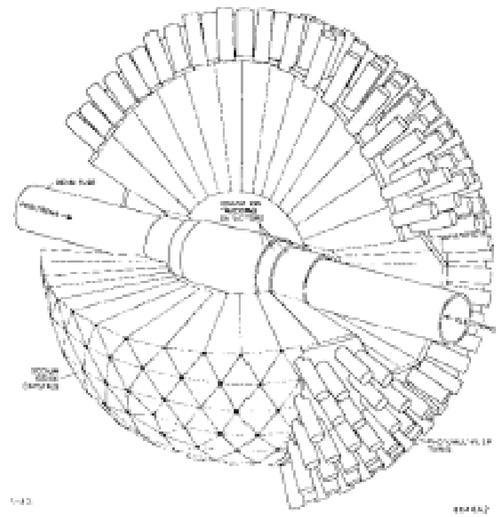
Enlarged view (zoomed out over 1 cm in z and +-200 microns in x) to show laser envelope clearance and deflecting dipole poles (0.3 T B field applied).



E. Milotti et al.



PET-like, segmented detector



... somewhat similar to Crystal Ball

For $\hbar\omega \leq 0.7 m_e c^2$, the differential photon-photon scattering cross-section is

$$\frac{d\sigma}{d\Omega} = \frac{139\alpha^4}{(180\pi)^2} \frac{\omega^6}{m^8} \left(3 + \cos^2\theta\right)^2$$

This cross-section is derived from a genuine non-linear QED effect (loop) and its value is critically dependent on the regularization procedure.

The importance of regularization has recently been emphasized by the a couple of wrong preprints, that claimed that the photon-photon cross section is actually

$$\frac{d\sigma_{\mathrm{FK}}}{d\Omega} = \frac{\alpha^4}{(12\pi)^2 \omega^2} \left(3 + 2\cos^2\theta + \cos^4\theta\right)$$

(see N. Kanda, arXiv:1106.0592, and T. Fujita and N. Kanda, arXiv:1106.0465, and the refutation by Y. Liang and A. Czarnecki, arXiv:1111.6126)