Proposal for a new experiment using a Laser and XFEL to test quantum physics in the strong-field regime

Beate Heinemann (DESY and University of Freiburg)

on behalf of LUXE Collaborators

DESY Colloquium, August 27th and 28th 2019

OUTLINE

LUXE = “Laser **U**nd **X**FEL **E**xperiment”

- Scientific Motivation
- Accelerator and Laser
- Particle Detection and Simulation Results
- Conclusions

Letter of Intent for the LUXE Experiment

H. Abramowicz[1], M. Altarelli[2], R. Assmann[3], T. Behnke[3], Y. Benhammou[1], A. Borysov[3], M. Borysova[4], R. Brinkmann[3], F. Burkart[3], O. Davidi[8], W. Decking[3], N. Elkina[5], H. Harsh[5], A. Hartin[6], I. Hartl[3], B. Heinemann[3,7], T. Heinzl[9], N. Tal Hod[8], M. Hoffmann[3], A. Ilderton[9], B. King[9], A. Levy[1], J. List[3], A. R. Maier[10], E. Negodin[3], G. Perez[8], I. Pomerantz[1], A. Ringwald[3], C. Rödel[5], M. Saimpert[3], F. Salgado[5], G. Sarri[11], I. Savoray[8], T. Teter[5], M. Wing[6], and M. Zepf[5,11,12]

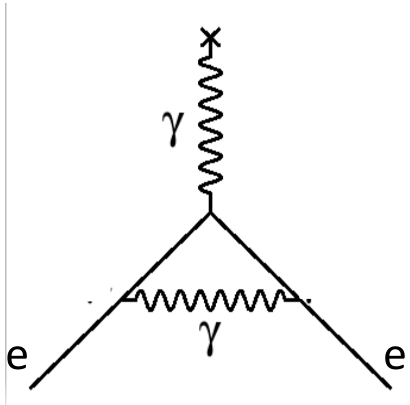
[1]Tel Aviv University, Tel Aviv, Israel
[2]Max Planck Institute for Structure and Dynamics of Matter, Hamburg, 22761, Germany
[3]Deutsches Elektronen-Synchrotron (DESY), Hamburg, 22607, Germany
[4]Institute for Nuclear Research NANU (KINR), Kiew, 03680, Ukraine
[5]Helmholtz Institut Jena, Jena, Germany
[6]University College London, London, UK
[7]Albert-Ludwigs-Universität Freiburg, Freiburg, 79104, Germany
[8]Weizmann Institute of Science, Rehovot, Israel
[9]University of Plymouth, Plymouth, UK
[10]Universität Hamburg, Hamburg, Germany
[11]Queens University Belfast, Belfast, UK
[12]Friedrich Schiller Universität Jena, Jena, Germany

from draft document, to be released end of this week

SCIENTIFIC MOTIVATION

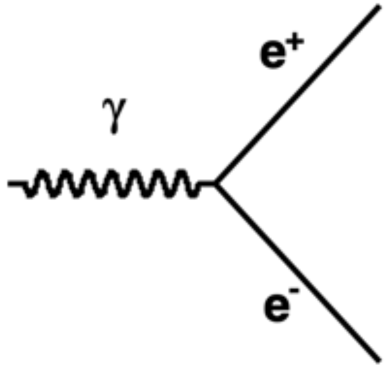
REMINDER: QUANTUM ELECTRODYNAMICS

- **Relativistic field theory of electrodynamics**
- **Perturbation theory in terms of coupling constant α**
- **World's most precisely tested theory**
  - Anomalous magnetic dipole moment (g-2) of electron:
    - Zero at leading order => first corrections calculated by Schwinger (1947)
    - Based on precise measured and calculated (includes terms of 5th order: α^5) values, extract 1/α=137.035 999 070 (98)
    - Precision better than 10^{-9}, consistent with other measurements
  - Anomalous magnetic dipole moment of muon shows interesting tension
    - New experiment at FNAL ("Muon g-2") will improve precision by factor 4



QED: WHAT DO WE NOT KNOW?

- **What happens if electrons or photons propagate in a very strong field?**
  - QED expects that vacuum becomes unstable e.g. for nucleus with Z>137. Spontaneous creation of e^+e^- pairs ("boiling of vacuum")



- **Historical developments:**
  - **1930**s: Initial discussions of EM in strong field in literature (Sauter, Euler, Heisenberg) => introduction of "critical field"
  - **1951**: First no-perturbative calculations by Julian Schwinger
  - **1990**s: E144 experiment at SLAC

$$\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \mathrm{V/m}$$

HEISENBERG AND EULER: THE CRITICAL FIELD

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwellschen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2 - \mathfrak{B}^2) + \frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B}) \cdot \frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i(\mathfrak{E}\mathfrak{B})}\right) + \text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i(\mathfrak{E}\mathfrak{B})}\right) - \text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2 - \mathfrak{E}^2)\right\}.$$

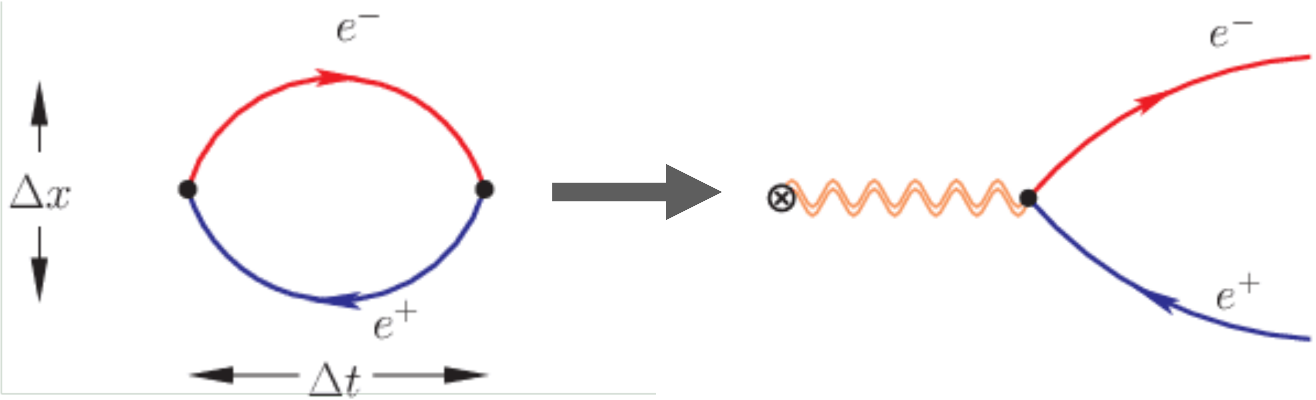
$$\left(\begin{array}{l}\mathfrak{E}, \mathfrak{B} \quad \text{Kraft auf das Elektron.} \\ |\mathfrak{E}_k| = \frac{m^2 c^3}{e\hbar} = \frac{1}{\text{„}137\text{“}} \frac{e}{(e^2/mc^2)^2} = \text{„Kritische Feldstärke“.}\end{array}\right)$$

WHY EXPLORE STRONG-FIELD QED?

- **Relevant to numerous phenomena in our Universe**
  - Astrophysics:
    - Hawking radiation, surface of neutron stars (magnetars), early Universe
  - Condensed matter and atomic physics (nuclei with Z>137)
  - Accelerator physics: high energy e^+e^- colliders
- **Main goals:**
  - Testing theoretical predictions in novel regime
    - gain deeper understanding of quantum physics
  - Measure transition from perturbative to non-perturbative regime
    - could teach us about other non-perturbative regimes, e.g. understanding confinement [Gribov, hep-ph/9902279]
- **Schwinger field has never been reached experimentally in clean environment**
  - Exciting to be the first to explore this … we might be surprised what we find!

THE SCHWINGER PROCESS

J. Schwinger: *On Gauge Invariance and Vacuum Polarization*, Phys. Rev. 82 (1951) 664



Photon in electric field: simplified

- The EM force is $F = e\varepsilon$
- Energy needed to separate e^+e^- pair: $E = Fd_{min}$
- Heisenberg: $\Delta t \geq \frac{\hbar}{\Delta E}$ => $\Delta t_{min} = \frac{\hbar}{2mc^2}$ => minimum distance: $d_{min} = 2c\Delta t_{min} = \frac{\hbar}{mc} = \lambda_c$
- Virtual pair becomes real if $E = Fd_{min} = \frac{\hbar e\varepsilon}{mc} > 2mc^2$

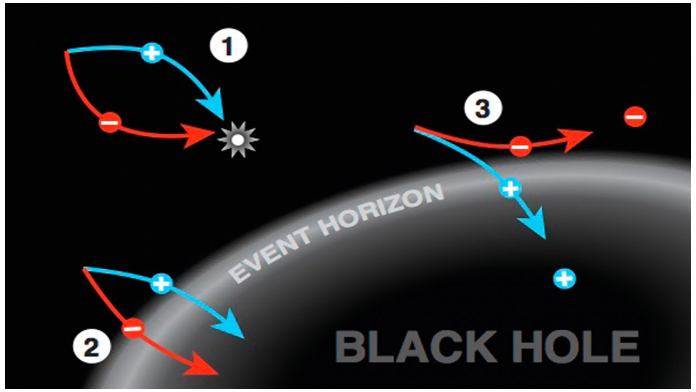
⇒Possible if $\varepsilon > \frac{2m^2c^3}{\hbar e} = 2\varepsilon_{crit}$

$$P \propto \exp\left(-\frac{d}{\lambda_C}\right) = \exp\left(-2\frac{m_e^2c^3}{\hbar e\varepsilon}\right) = \exp\left(-2\frac{\varepsilon_{crit}}{\varepsilon}\right)$$

NB: full calculation gives π instead of 2

ANALOGY TO HAWKING RADIATION

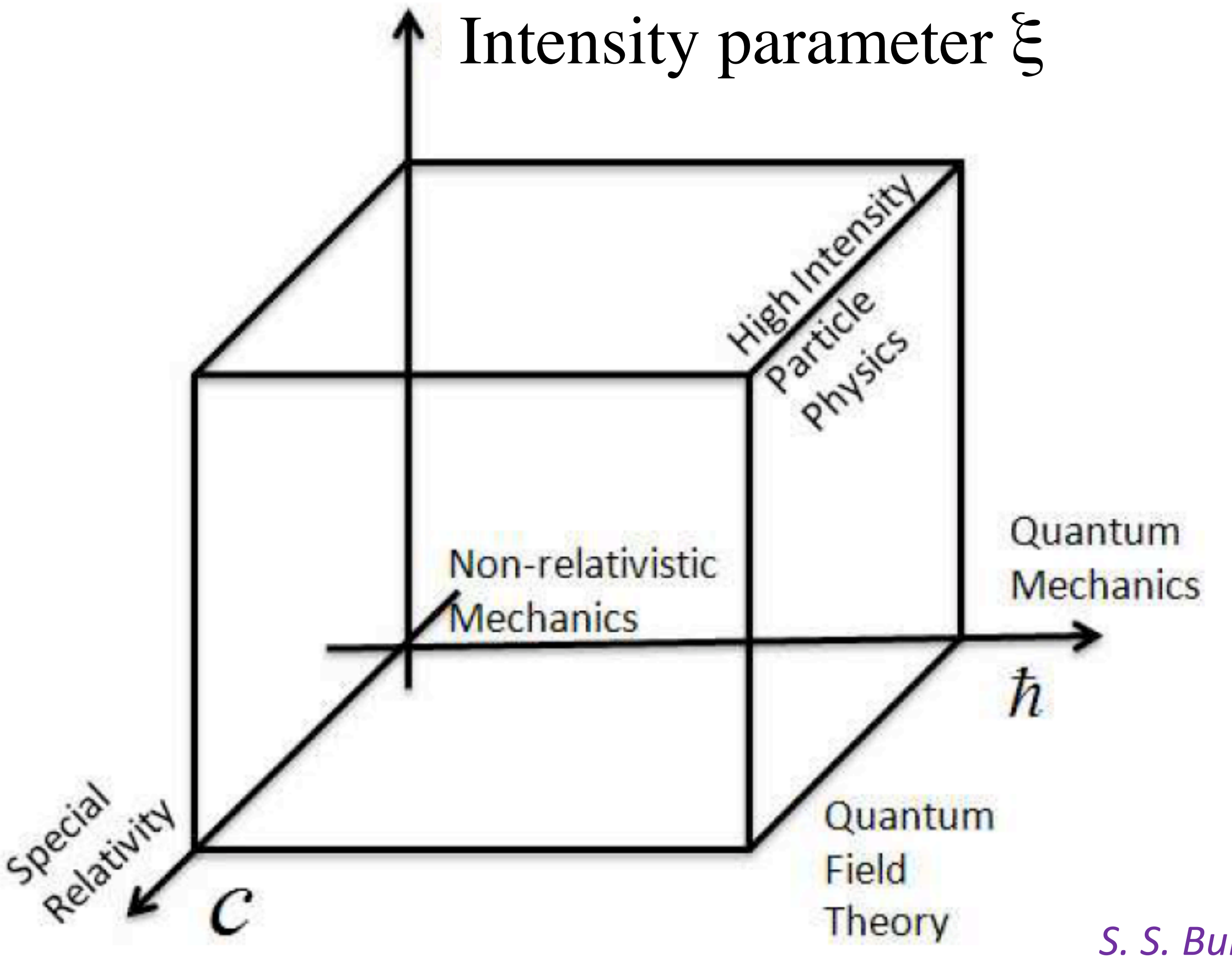
- **Energy needed to create on-shell e⁺e⁻ pair:** $\Delta E = 2mc^2$
- **Grav. Field near the event horizon:** $F = \frac{G_N M m}{r_s^2}$
- **Schwarzschild radius** $r_s = \frac{2G_N M}{c^2}$. **=>** $F = \frac{mc^4}{4G_N M}$
- **Energy to separate pair:** $E = Fd_{min} = \frac{mc^4}{4G_N M} \times \frac{\hbar}{mc} = \frac{\hbar c^3}{4G_N M}$



H. Murayama

Hawking radiation possible if virtual pair becomes real, i.e. $\frac{\hbar c^3}{4G_N M} > 2mc^2$

THEORIES ON A CUBE



S. S. Bulanov, W. Leemans et al.

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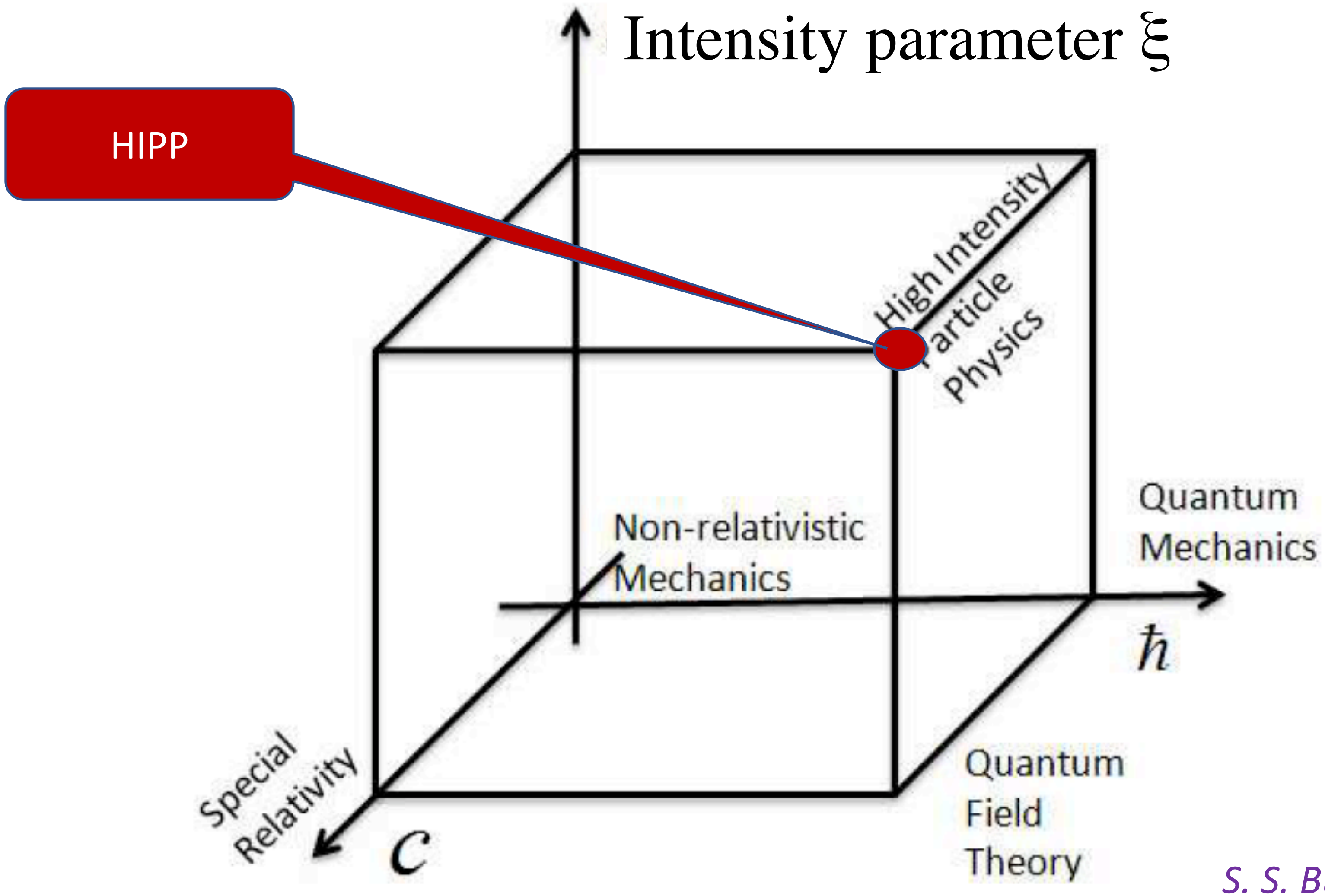
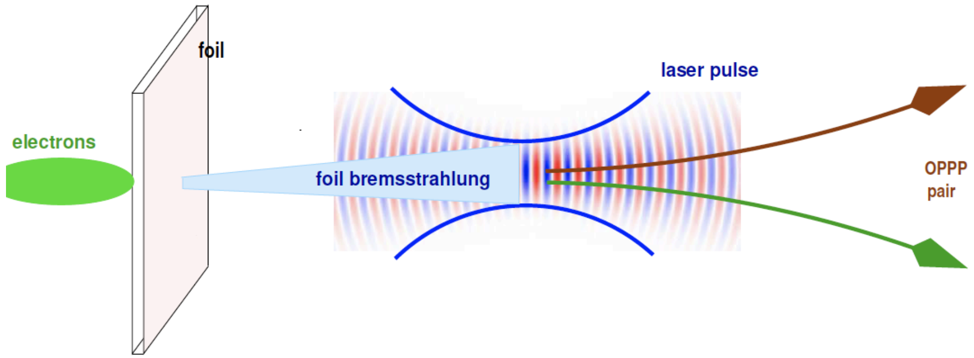


S. S. Bulanov, W. Leemans et al.

LASER AND PHOTON BEAM

- **Use Laser to generate electric field**
- **Use high energy electron beam**

$$\xi = \frac{e\varepsilon_L}{m_e\omega_L c} \qquad \chi \approx \gamma\frac{\varepsilon_L}{\varepsilon_{crit}}$$



- **Laser power required to reach Schwinger field (χ_γ~1):**
  - Non-relativistic photons: I=2x10^{29} W/cm^2
  - EU.XFEL, E_γ≈10 GeV: I≈10^{20} W/cm^2
  - ELI-NP, E_γ≈ 1 GeV: I≈10^{22} W/cm^2

=> Much beyond currently achievable values

=> Can use well-tested laser technology

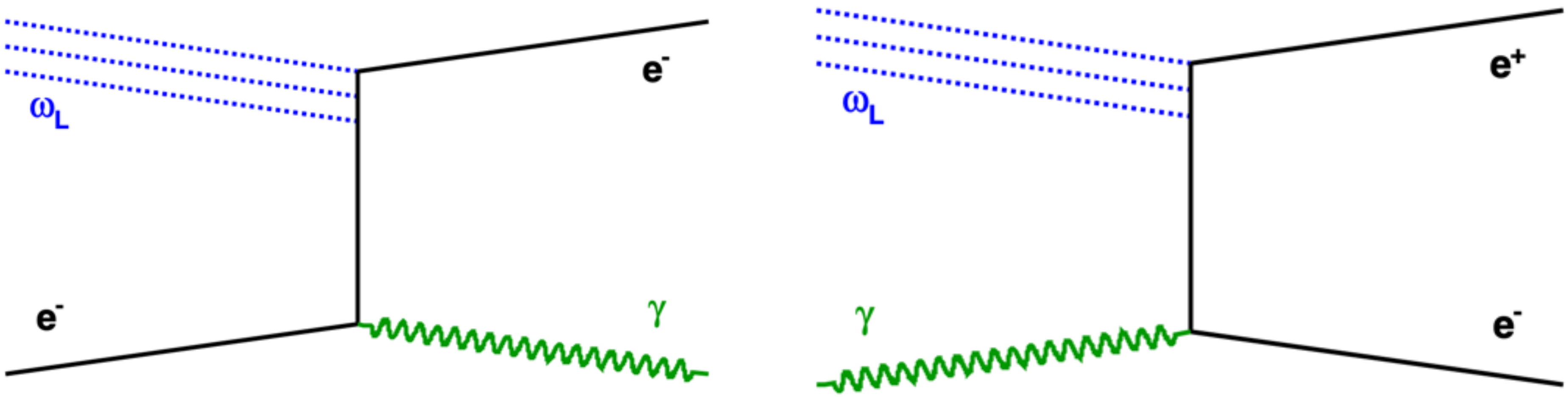
=> State-of-the-art laser needed

MAIN PROCESSES OF INTEREST

$e^- + n\omega_L \rightarrow e^- + \gamma$

$\gamma + n\omega_L \rightarrow e^+ e^-$

Low-energy photons from laser

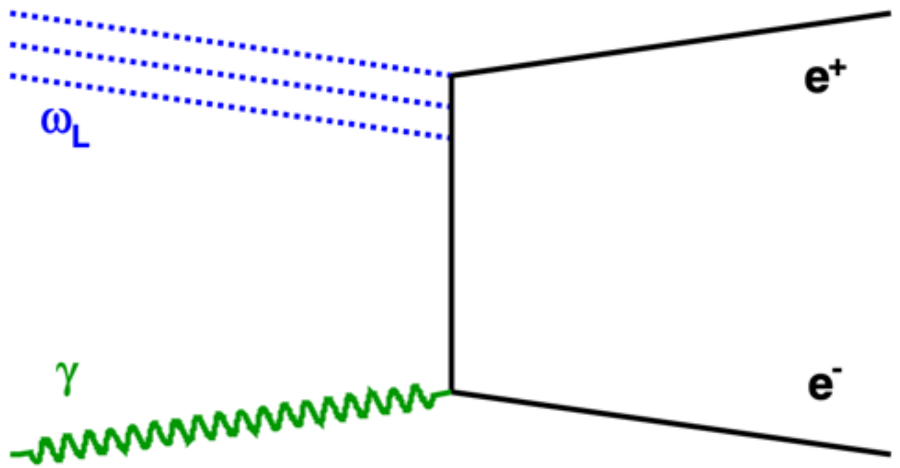


High energy electron or photon interacts with laser

- Also higher order process $e^- + n\omega_L \rightarrow e^- e^+ e^-$
- Via two steps ($e^- + n\omega_L \rightarrow e^- + \gamma$ and then $\gamma + n\omega_L \rightarrow e^+ e^-$) or one step

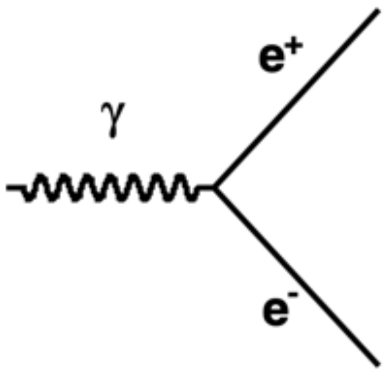
CROSS SECTION OF QED PROCESSES

- Perturbative QED valid
  - For n photons $\sigma \propto \alpha^n$
  - With $\boldsymbol{\alpha} \propto \boldsymbol{e}^2 \propto \xi^2$ it follows: $\sigma \propto \boldsymbol{\xi}^{2n}$
- If $\xi \gtrsim 1$ all orders can contribute ~equally => cannot truncate series any more
  - All-order calculation needs to be performed (which is hard)
- Example for asymptotic result for $\xi \gg 1$ and $\chi < 1$: $\sigma \propto \chi e^{-8/(3\chi)}$
  - Since $\chi \propto \sqrt{\alpha}$ cannot expand perturbatively
  - Result not proportional to powers of $\boldsymbol{\alpha}$



Observation of deviation from power-law is the experimental signature of strong QED

PAIR PRODUCTION PROCESS



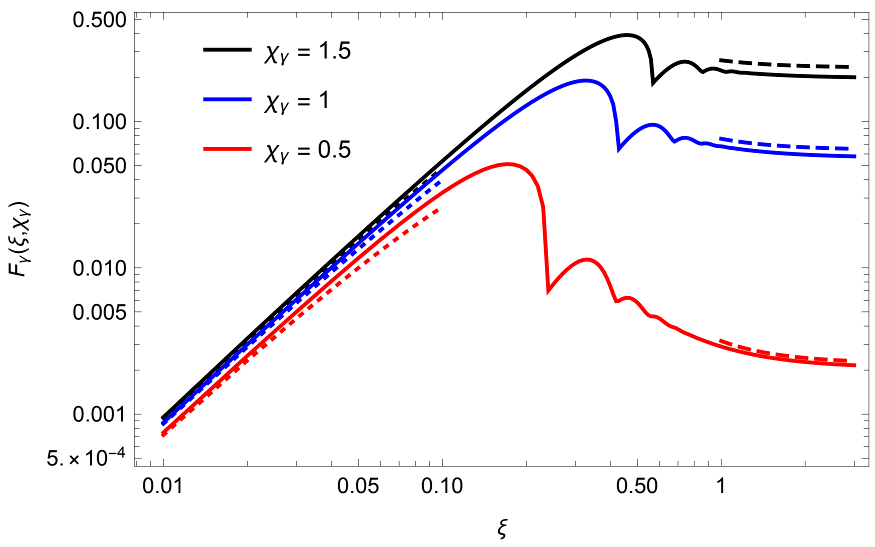
- **Process not possible in vacuum in classical electrodynamics**
- **Pair production in a constant static field (Schwinger process)**

$$\frac{\Gamma_{\mathrm{SPP}}}{V} = \frac{m_e^4}{(2\pi)^3}\left(\frac{|\mathbf{E}|}{\mathrm{E_c}}\right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{\mathrm{E_c}}{|\mathbf{E}|}\right) \qquad \propto \exp\left(-\pi \frac{E_c}{|\boldsymbol{E}|}\right)$$

- **Pair production in plane wave laser: asymptotic result**

$$\Gamma_{\mathrm{OPPP}} \to \frac{3}{16}\sqrt{\frac{3}{2}}\,\alpha\, m_e\,(1+\cos\theta)\;\; \frac{|\mathbf{E}|}{\mathrm{E}_c}\exp\left[-\frac{8}{3}\frac{1}{1+\cos\theta}\frac{m_e}{\omega_i}\frac{\mathrm{E}_c}{|\mathbf{E}|}\right]$$

- **Good agreement between full calculation and asymptotic result for $\xi \ll 1$ and $\xi > 1$**



A. Hartin, A. Ringwald, N. Tapia: arXiv:1807.10670,

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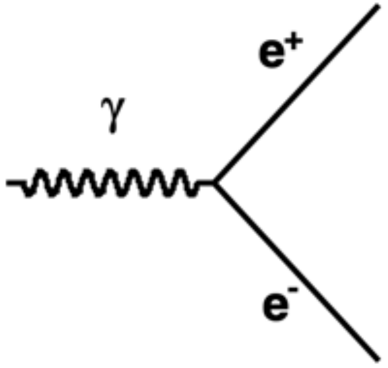
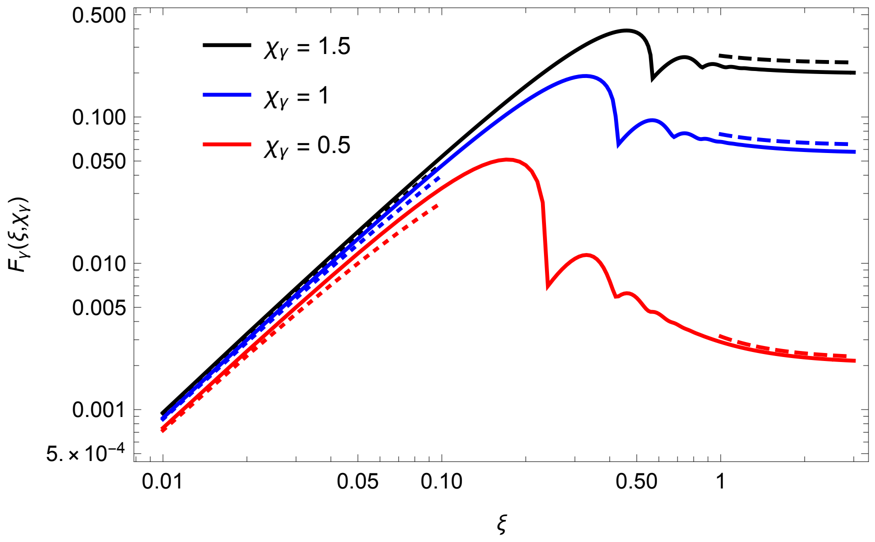


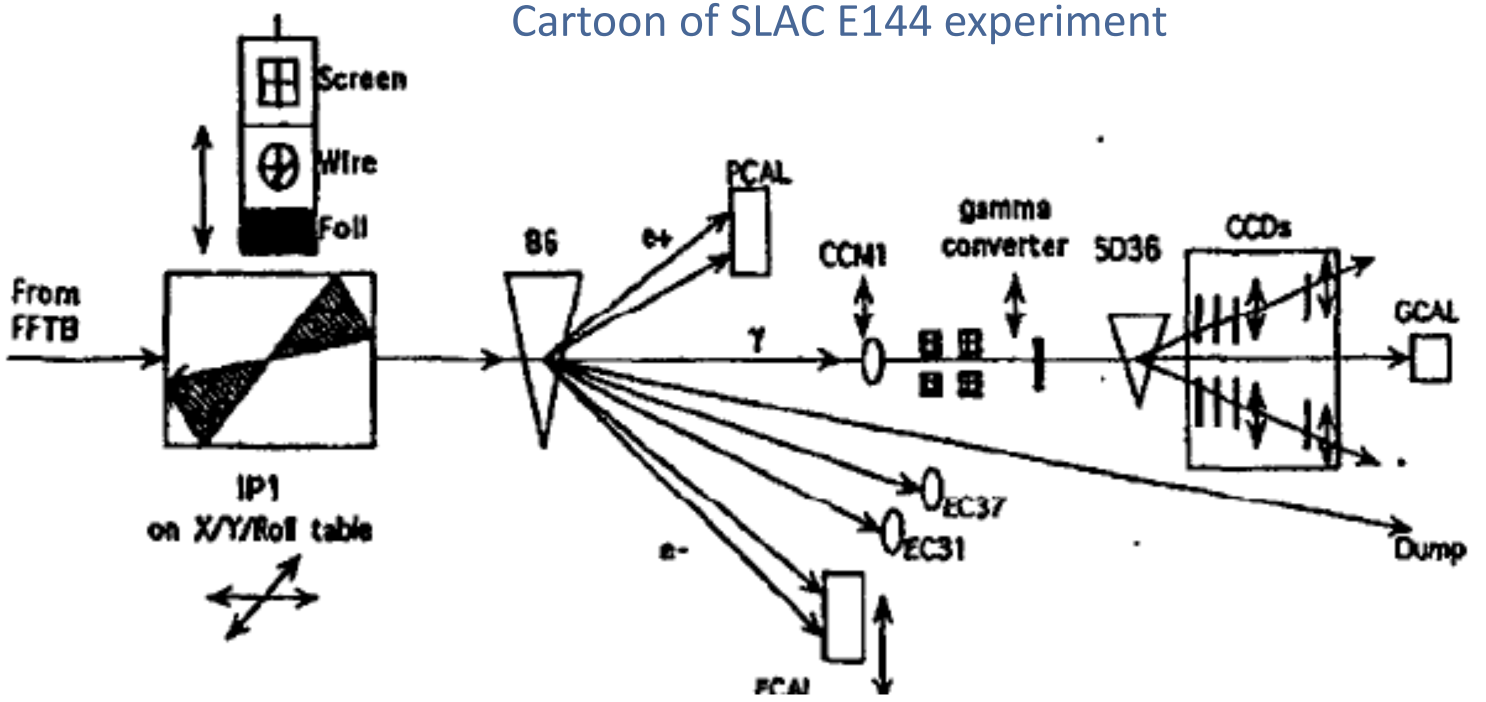


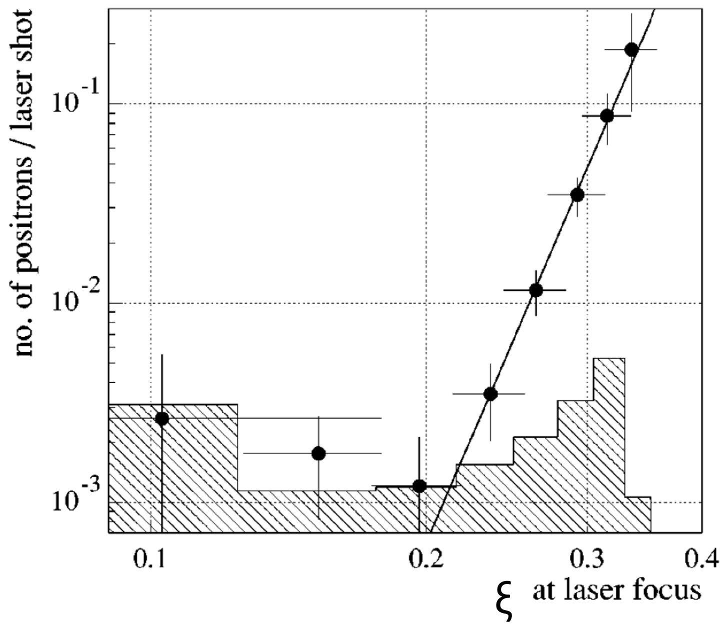
A. Hartin, A. Ringwald, N. Tapia: arXiv:1807.10670,

EXPERIMENT E144 AT SLAC

- **Experiment at SLAC in 1990s with E_{beam}=46.6 GeV achieved $\chi \leq 0.25$**
  - Did observe two-step process $e^- + n\omega_L \rightarrow e^- e^+ e^-$
  - Saw the expected strong rise with ξ^{2n} but did not reach the critical field

Cartoon of SLAC E144 experiment





[Bamber et al. (SLAC 144) '99]

E144 IN THE NEWS…

DIE ZEIT WISSEN
Nr. 42 17. Oktober 1997. Seite 17

Das Sein und das Nichts, früher das angestammte Thema der Philosophen, wird heute in Teilchenbeschleunigern näher untersucht

Warum ist etwas?

Amerikanische Physiker schufen erstmals Materie aus reinem Licht

Von Ulrich Schnabel

The New York Times

ARCHIVES | 1997

Scientists Use Light To Create Particles

By MALCOLM W. BROWNE SEPT. 16, 1997

A TRAILBLAZING experiment at the Stanford Linear Accelerator Center in California has confirmed a longstanding prediction by theorists that light beams colliding with each other can goad the empty vacuum into creating something out of nothing.

In a report published this month by the journal Physical Review Letters, 20 physicists from four research institutions disclosed that they had created two tiny specks of matter -- an electron and its antimatter counterpart, a positron -- by colliding two ultrapowerful beams of light.

The possibility of doing something like this was suggested in 1934 by two American physicists, Dr. Gregory Breit and Dr. John A. Wheeler. But more than six decades passed before any laboratory could pump enough power into colliding beams of radiation to conjure up matter from nothingness. The Stanford accelerator finally provided enou…

Dr. Adrian C. Melissinos of … group, said in an interview that … experiment was produced by a t… of the needed energy, even thoug… most powerful.

But the opposing beam of r… drawn from electrons whizzing … second beam of radiation was so… beam.

The paths of colliding electrons … complicated as those choreograp…

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RESEARCH NEWS PHYSICS

Conjuring Matter From Light

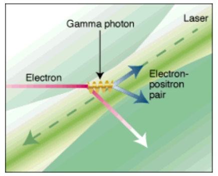
David Ehrenstein

+ See all authors and affiliations

Science 29 Aug 1997:
Vol. 277, Issue 5330, pp. 1202
DOI: 10.1126/science.277.5330.1202

Article Figures & Data Info & Metrics eLetters

Turning matter into light, heat, and other forms of energy is nothing new, as nuclear bombs spectacularly demonstrate. Now a team of physicists at the Stanford Linear Accelerator Center (SLAC) has demonstrated the reverse process—what University of Rochester physicist Adrian Melissinos, a spokesperson for the group, calls "the first creation of matter out of light." In the 1 September *Physical Review Letters*, the researchers describe how they collided large crowds of photons together so violently that the interactions spawned particles of matter and antimatter: electrons and positrons (antielectrons).



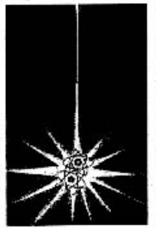
Corriere della Sera DOMENICA 21 SETTEMBRE 1997 19

L'importante risultato ottenuto a Stanford

Dalla luce è nata la materia Come predisse Einstein

di LANFRANCO BELLONI

A Stanford hanno festeggiato la nascita in laboratorio della prima materia generata da incontri ravvicinati di fasci di luce. …



Neue Zürcher Zeitung Mittwoch, 1. Oktober 1997 · Nr. 227 69

FORSCHUNG UND TECHNIK

Materie aus Licht erschaffen

Amerikanischen Physikern gelingt technischer Durchbruch

Was bisher nur theoretisch vorausgesagt wurde, hat ein Team von 20 Physikern erstmals im Experiment direkt beobachtet: die Erschaffung von Materie aus echten Lichtteilchen. Das Experiment gelang am Stanford-Teilchenbeschleuniger in Kalifornien.

DISCOVER MAGAZINE - DECEMBER 1997

Discover SCIENCE FOR THE CURIOUS

Let There Be Matter

by Jeffrey Winters

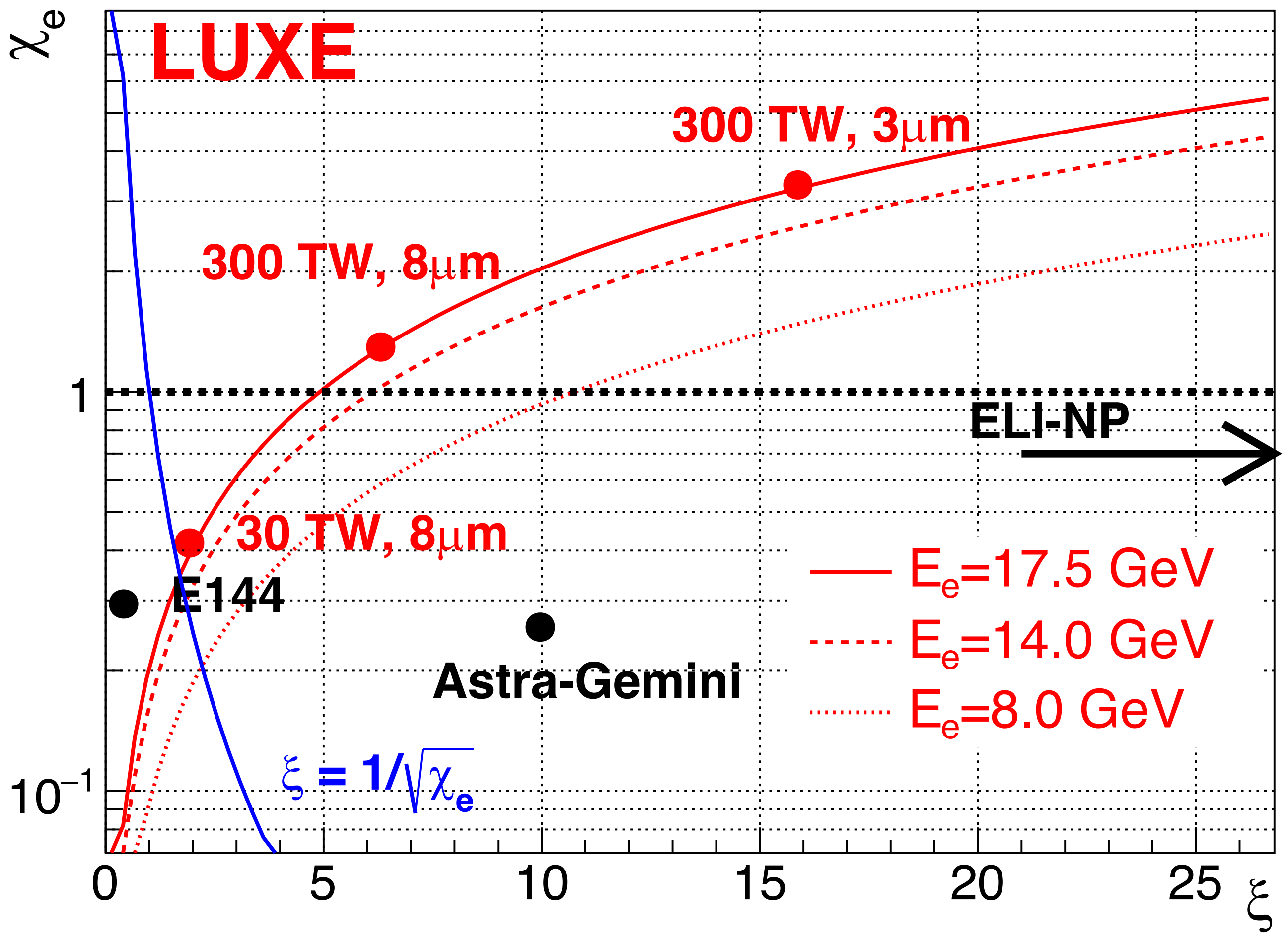
Albert Einstein's epochal insight into the equivalence of matter and energy, elegantly expressed as E=mc2, has been confirmed countless times, most dramatically whenever a nuclear weapon detonates. The process also occurs naturally--a sta… shines because atoms in its core fuse, transforming a sliver of matter into light. And when particles of matter and antimatter meet, they annihilate each other in a blaze of energy.

But like any equation, E=mc2 works in both directions, at least theoretically. That is, it should be possible to convert energy into matter. Now a team of physicists has accomplished just that: they have transmuted light into matter. "We're able to turn optical photons into matter," says Princeton physicist Kirk McDonald, coleader of the team. "That is quite a technological leap."

Of course, physicists would have been shocked if they couldn't get energy to convert into matter. After all, the entire univers… began with an explosion of energy--the Big Bang. And physicists who smash atoms together have witnessed the conversion of energy into matter--"virtual" photons that flit in and out of existence just long enough to spawn the particles of exotic matter routinely observed in particle accelerators. But such virtual photons aren't under the direct control of physicists; these photons arise as part of a complex chain of events starting with a collision of two particles of matter. Until now, no one had directly created matter from light. "Back in 1934 physicists realized that it would be possible to do this in principle," says McDonald, "But it just wasn't technically feasible."

By the early 1990s, McDonald and his colleagues had all the technological pieces in place to conduct such an experiment. The key piece was a laser capable of packing a tremendous amount of energy into a small space. The laser that McDonald and his collaborators use at Stanford generates a trillion watts of power, enough to light every home in North America. But rather than drain the national electric grid, the laser takes a rather ordinary amount of energy and compresses it into a pulse for about a trillionth of a second. By focusing this pulse on an area of just 16- millionths of a square inch, the physicists bathe a spot with an incredibly intense electromagnetic field. But even with this crowd of high-power photons squeezed together, the energy is still only about a millionth of what's needed to make matter.

PARAMETER SPACE



Intensity parameter:

$$\xi = \sqrt{4\pi\alpha}\left(\frac{\mathcal{E}_L}{\omega_L m_e}\right) = \frac{m_e \mathcal{E}_L}{\omega_L \mathcal{E}_{cr}}$$

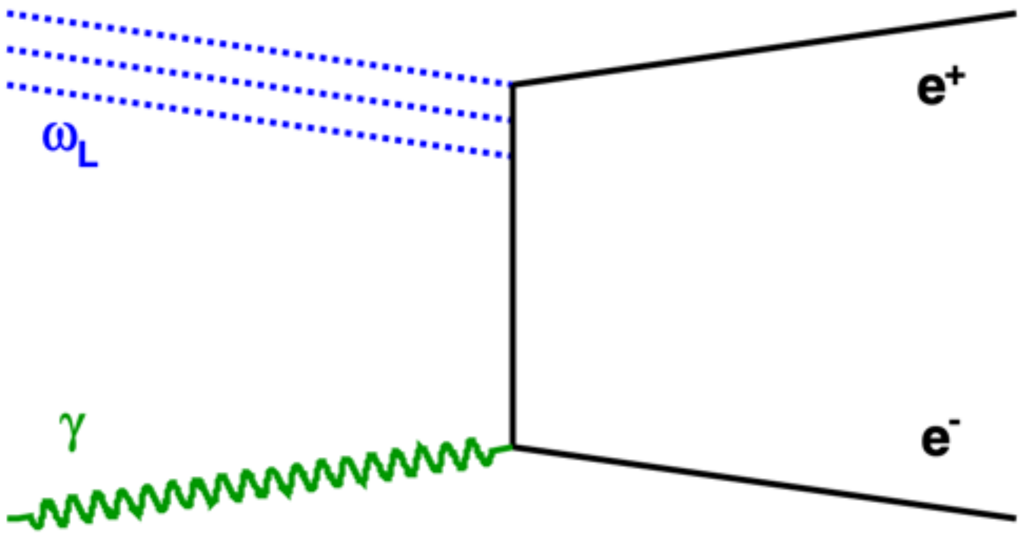
Quantum parameters:

$$\chi_e = (1 + \cos\theta)\frac{E_e}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

$$\chi_\gamma = (1 + \cos\theta)\frac{E_\gamma}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

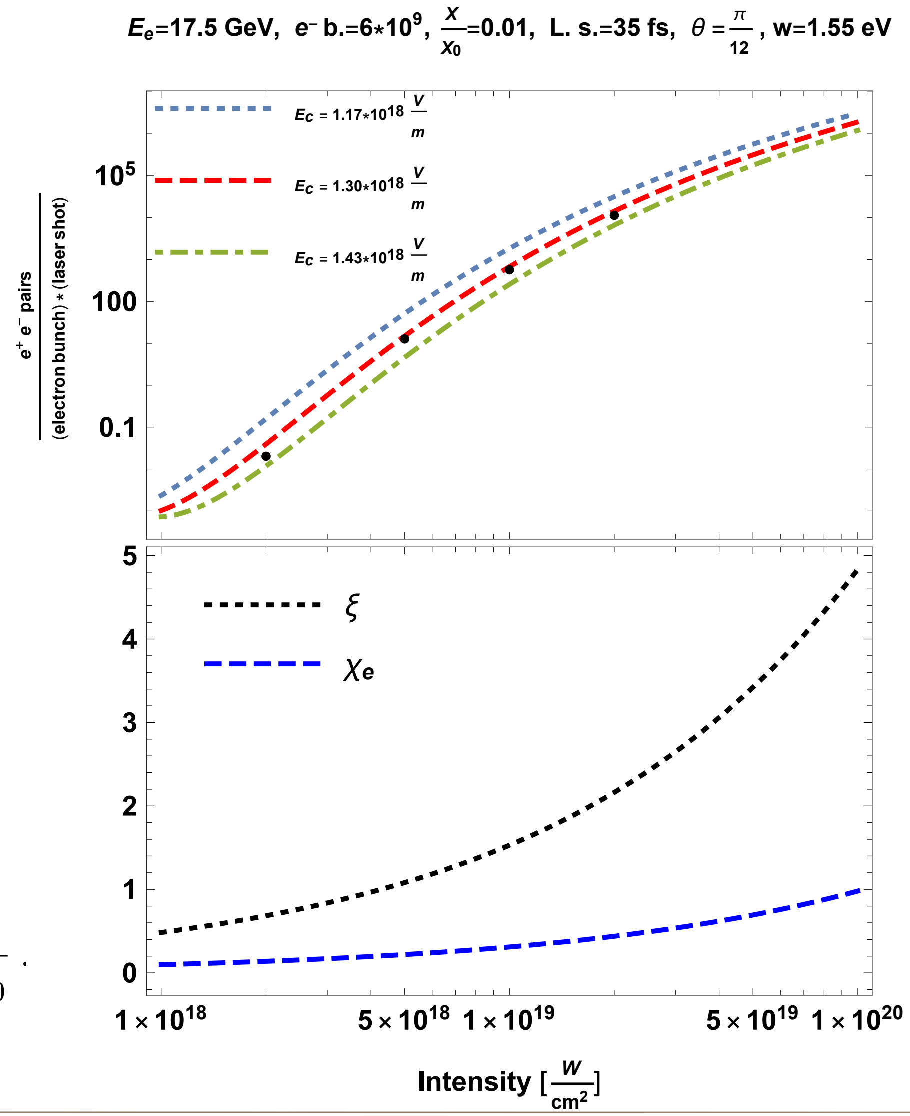
ABSORBING LIGHT WITH LIGHT

Low-energy photons from laser



High-energy (relativistic) photon

$$\Gamma_{\mathrm{BPPP}} \to \frac{9}{128}\sqrt{\frac{3}{2}}\,\alpha\,E_e\,(1+\cos\theta)^2\left(\frac{|\mathbf{E}|}{\mathrm{E}_c}\right)^2 \exp\left[-\frac{8}{3}\,\frac{1}{1+\cos\theta}\,\frac{m_e}{E_e}\,\frac{\mathrm{E}_c}{|\mathbf{E}|}\right]\frac{X}{X_0}\,.$$



A. Hartin, A. Ringwald, N. Tapia: arXiv:1807.10670,

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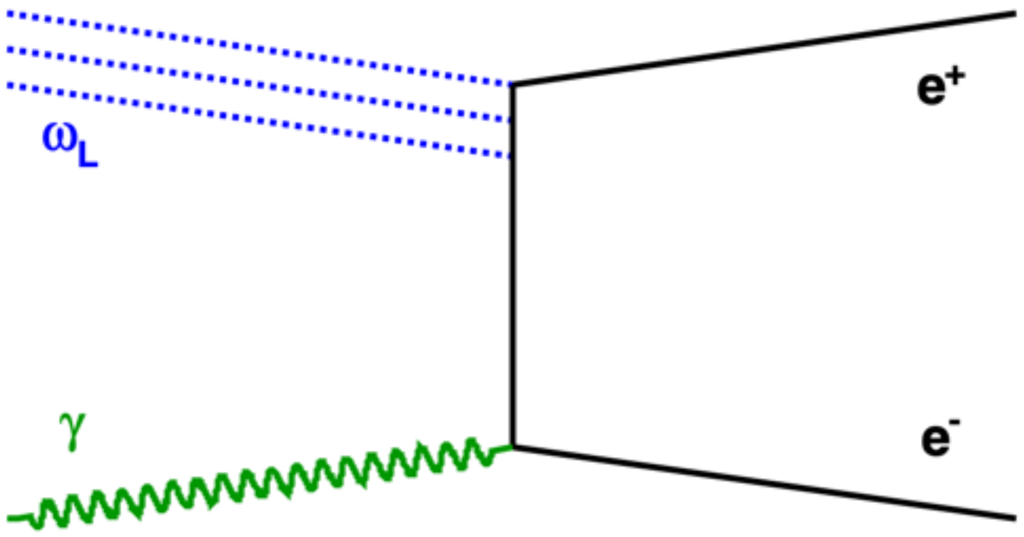

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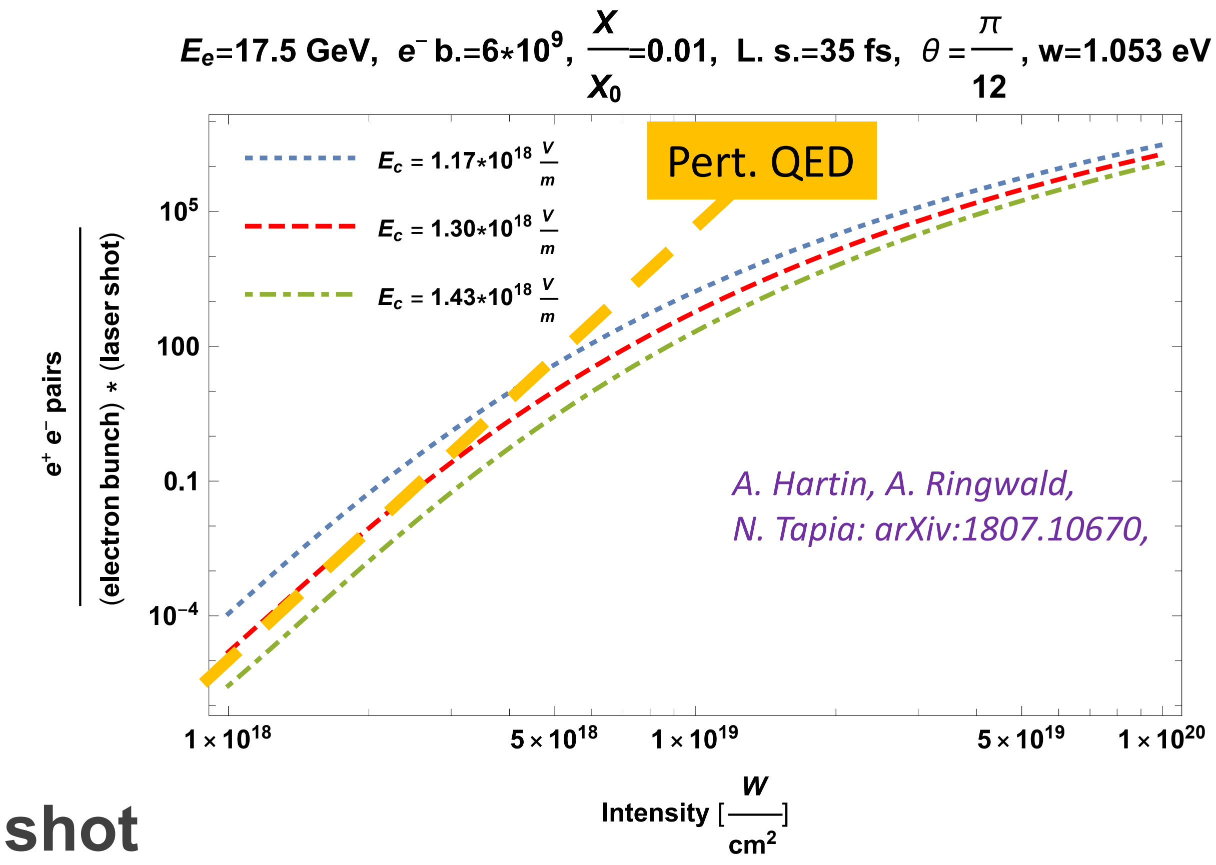


- **Prediction for rate of positrons per laser shot**

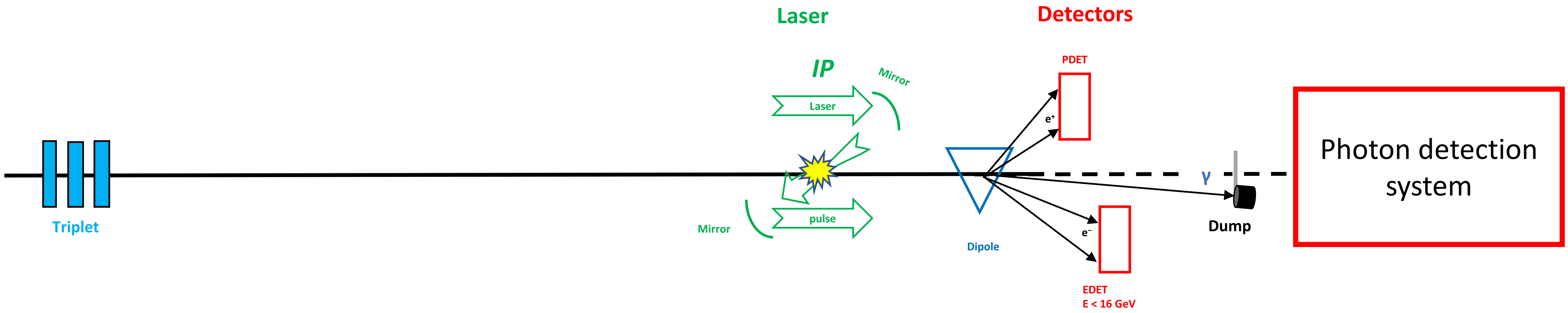
$\xi \ll 1$: $R_{e^+} \propto \xi^{2n} \propto I^n$ — Perturbative regime: strong rise, follows power-law

$\xi \gg 1$: $R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$ — Non-perturbative regime: departure from power-law

ACCELERATOR AND LASER

ELECTRON LASER COLLISIONS

Compton and trident processes: $e^- + n\omega \rightarrow e^- + \gamma$ **and** $e^- + n\omega \rightarrow e^- e^+ e^-$



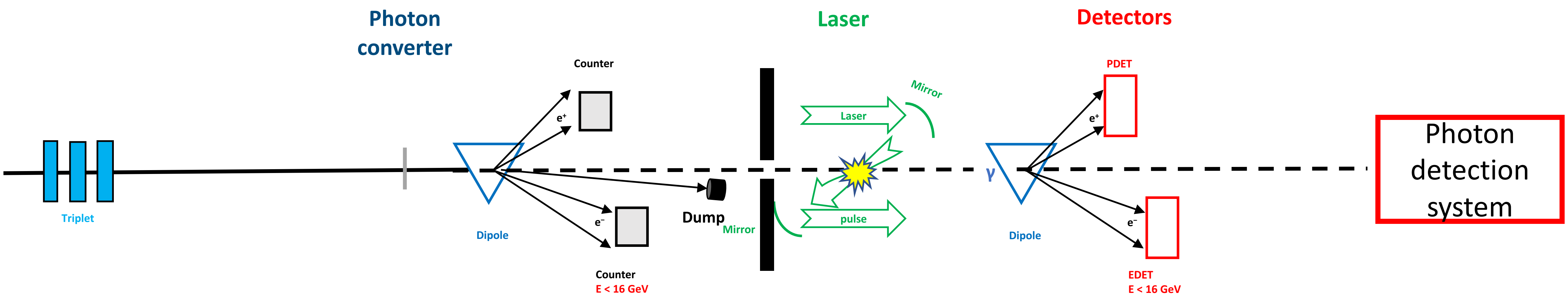
Kicker and triplet to select single bunch and focus it

Electron- Laser interaction area

Dipole and detectors to observe e+e- pairs

PHOTON LASER COLLISIONS

Pair production (Breit-Wheeler) process: $\gamma + n\omega \rightarrow e^- + e^+$



Kicker and triplet to select single bunch and focus it

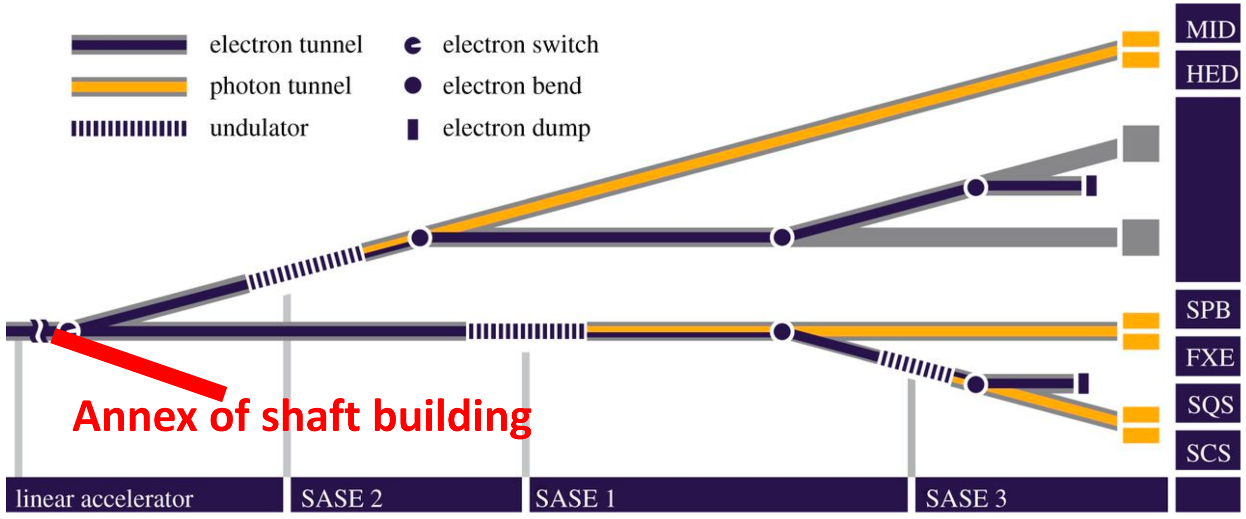
Dipole and detectors to remove e+e- pairs and monitor photon flux

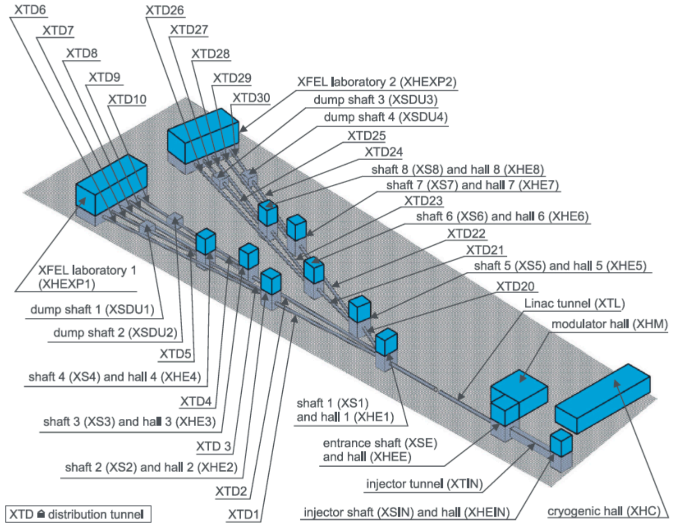
Photon- Laser interaction area

Dipole and detectors to observe e+e- pairs

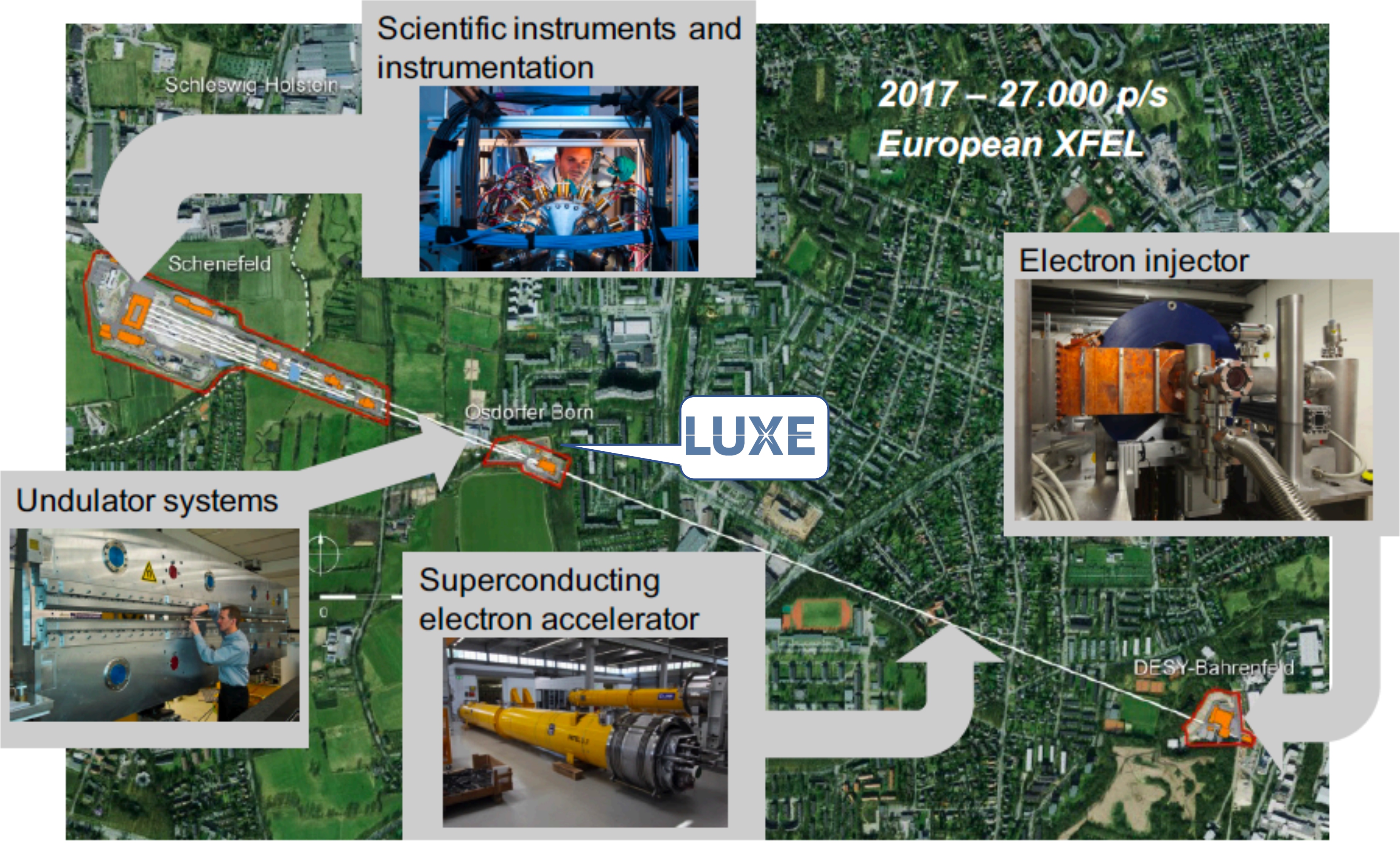
LOCATIONS IN EU.XFEL TUNNEL

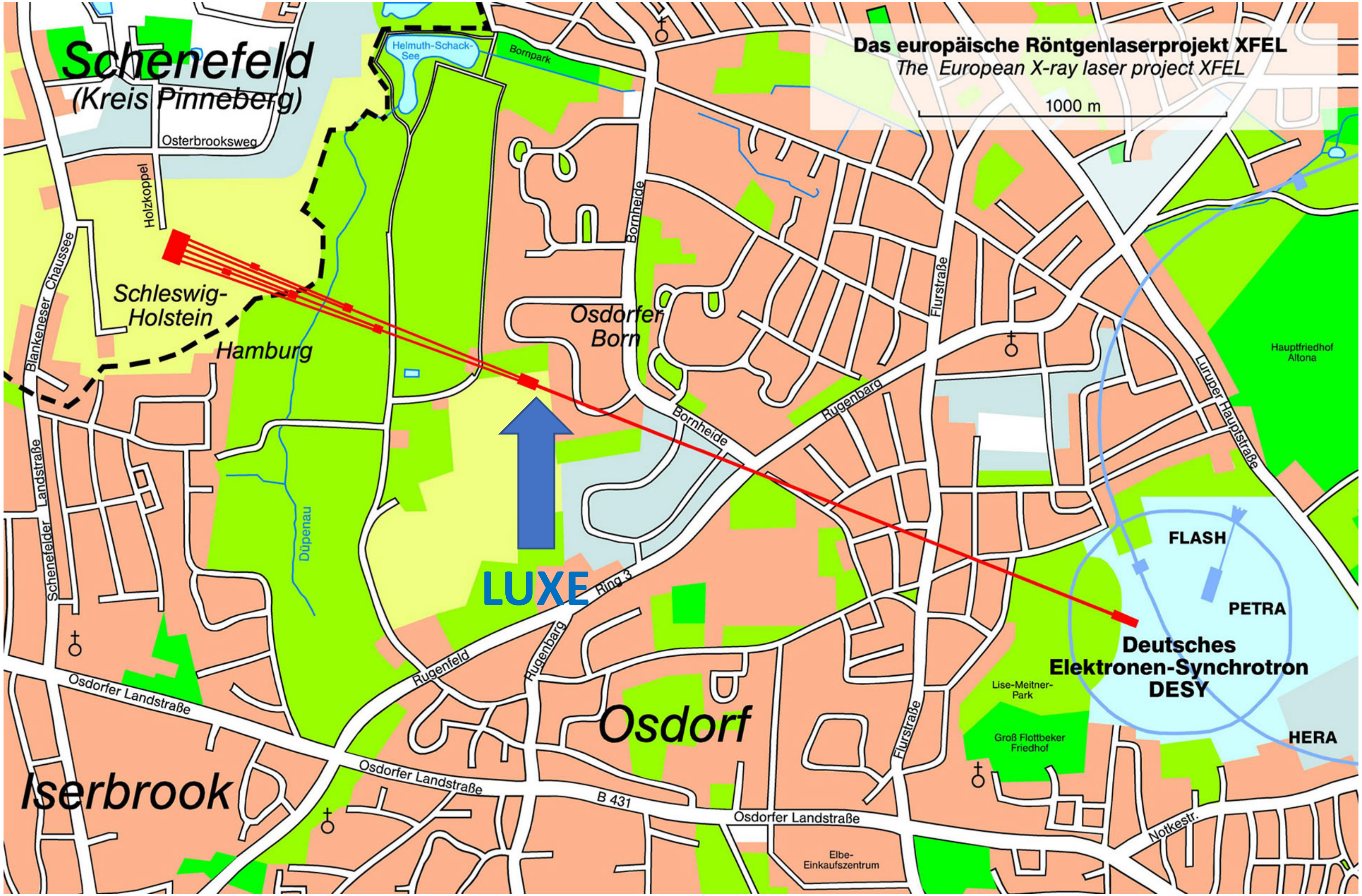
- **Location at EU.XFEL:**
  - Annex of shaft building XS1: at end of electron accelerator
  - Was build for 2nd EU.XFEL fan foreseen for later (late 2020s)
- **Design aims to have no impact on photon science programme**
  - Use only 1 of the 2700 bunches in bunch train (kicked out by fast kicker magnet)

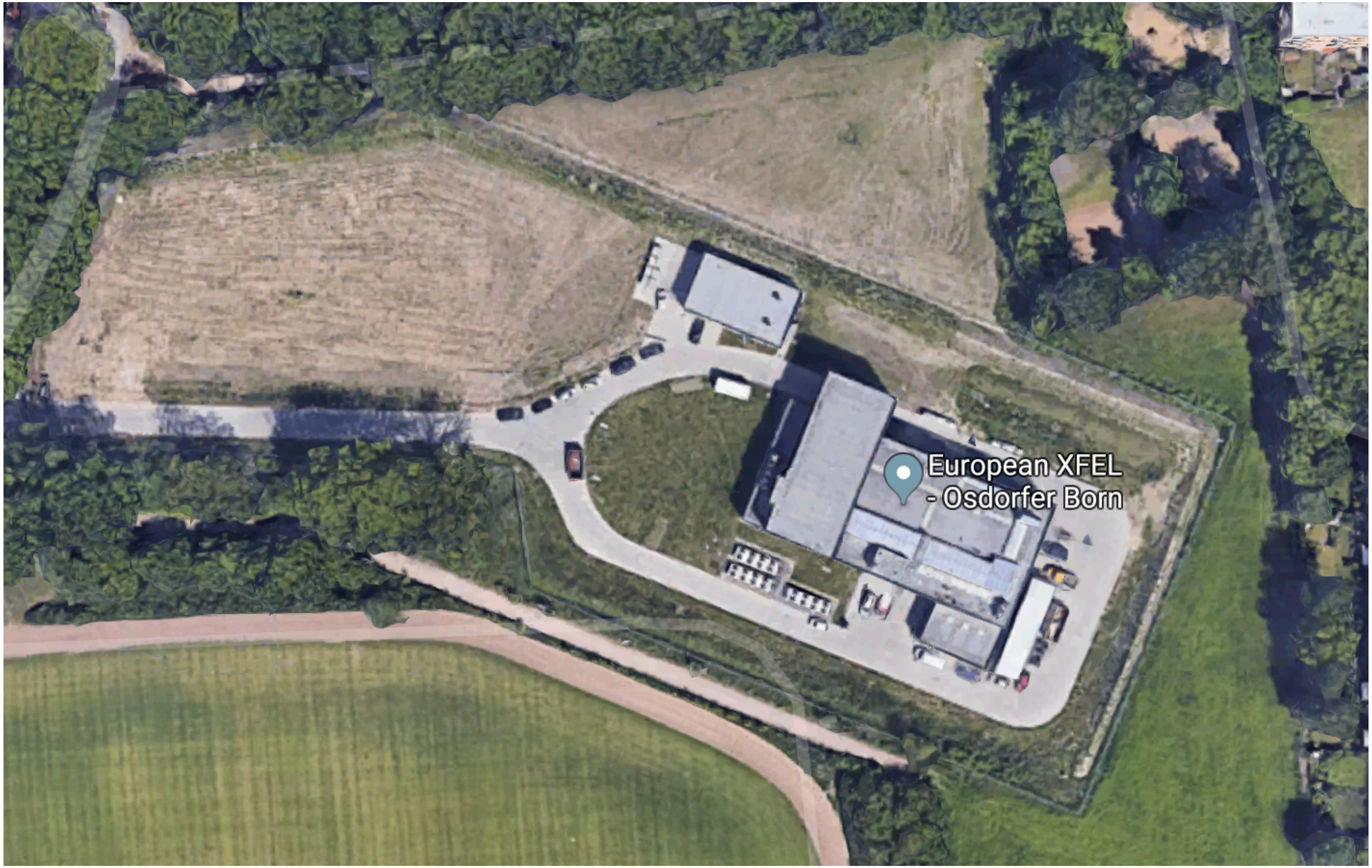




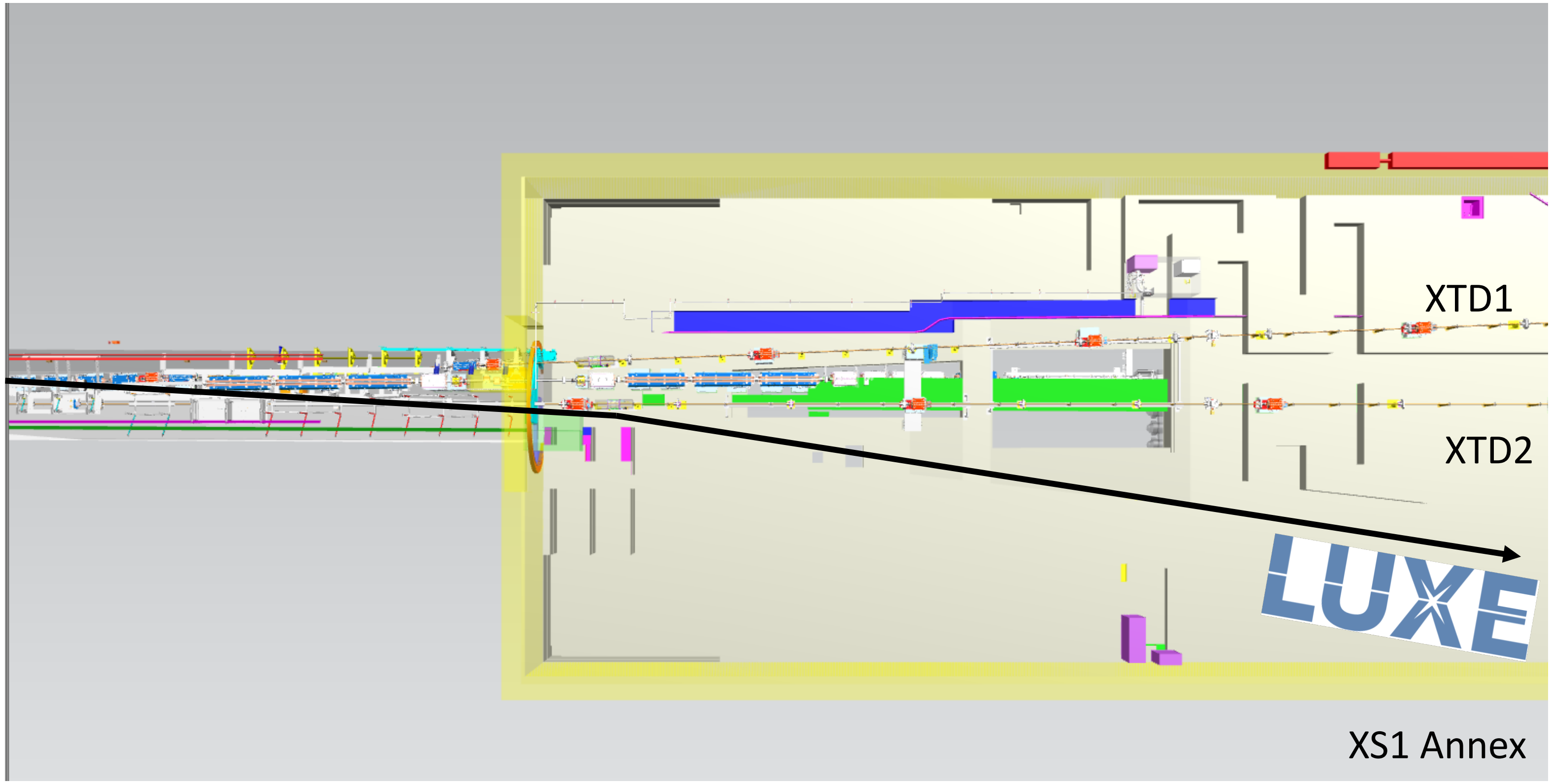
LOCATION

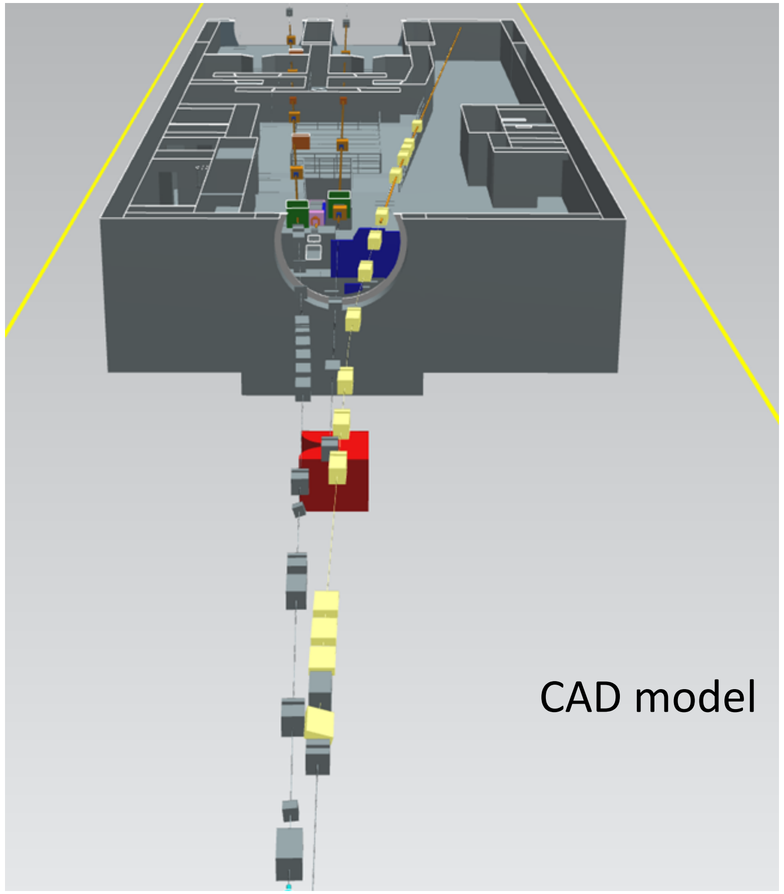

Scientific instruments and instrumentation
Schleswig-Holstein
2017 – 27.000 p/s
European XFEL
Schenefeld
Electron injector
Osdorfer Born
LUXE
Undulator systems
Superconducting electron accelerator
DESY-Bahrenfeld


Das europäische Röntgenlaserprojekt XFEL
The European X-ray laser project XFEL
1000 m
Schenefeld
(Kreis Pinneberg)
Osterbrooksweg
Helmuth-Schack-See
Bornpark
Holzkoppel
Blankeneser Chaussee
Schleswig-Holstein
Hamburg
Osdorfer Born
Bornheide
Flurstraße
Rugenbarg
Luruper Hauptstraße
Hauptfriedhof Altona
Schenefelder Landstraße
Düpenau
LUXE
Ring 3
FLASH
PETRA
Deutsches Elektronen-Synchrotron DESY
HERA
Rugenfeld
Osdorfer Landstraße
Lise-Meitner-Park
Groß Flottbeker Friedhof
Osdorf
Iserbrook
B 431
Notkestr.
Elbe-Einkaufszentrum


European XFEL
- Osdorfer Born

SCHEMATIC VIEW: BEAM EXTRACTION AND TRANSFER





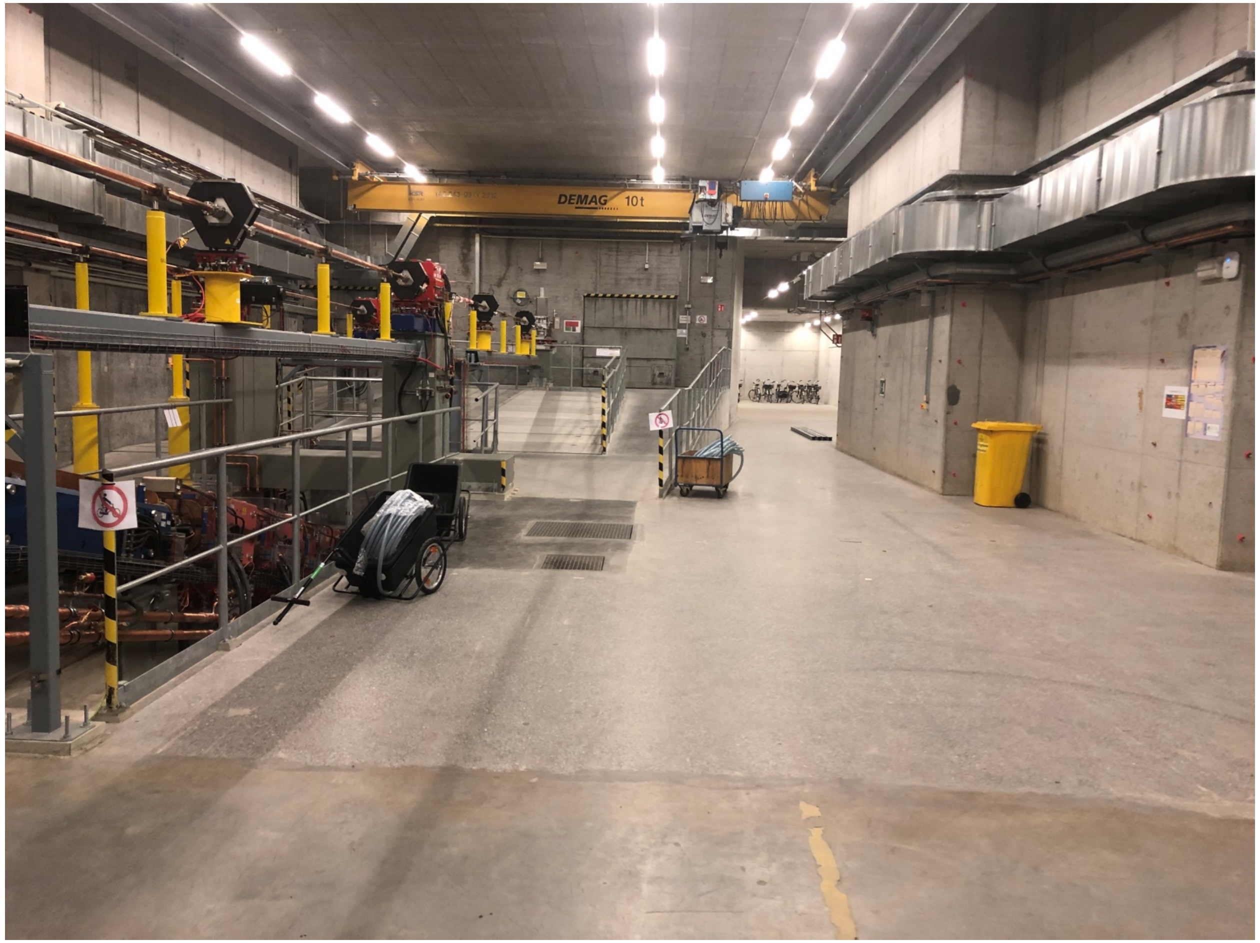
M. Huening, M. Scheer, F. Burkart, W. Decking

PICTURE OF TUNNEL AT XS1 ANNEX

Shaft located at end of linear accelerator of European XFEL

Dimensions of annex

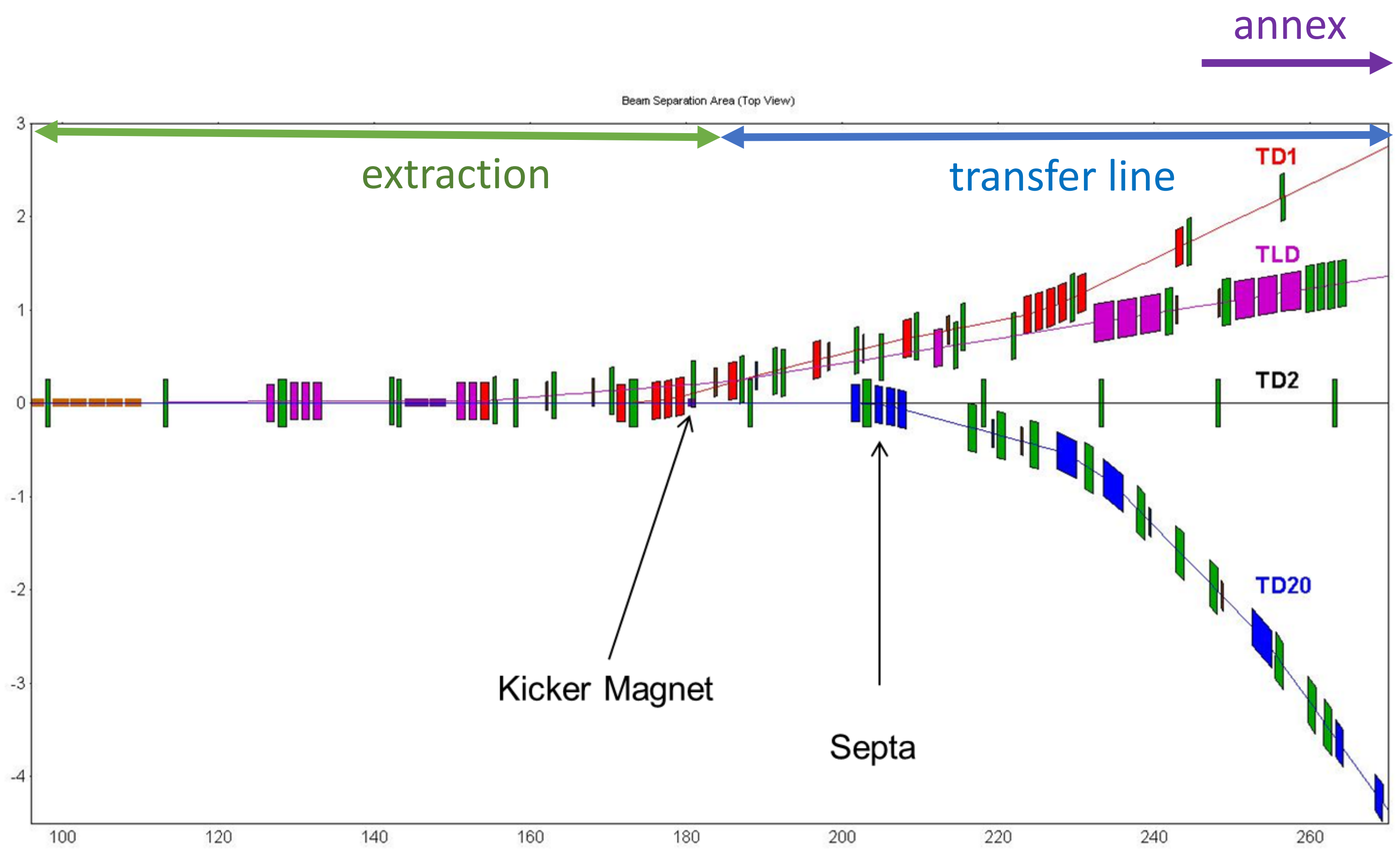
- 60m long, 5.4m wide, 5m high



BEAMLINE LAYOUT

Design of magnets for beam extraction and then beam transfer to LUXE

- Most magnets use design already operating today in XFEL.EU
- New fast kicker magnets



Installation requires

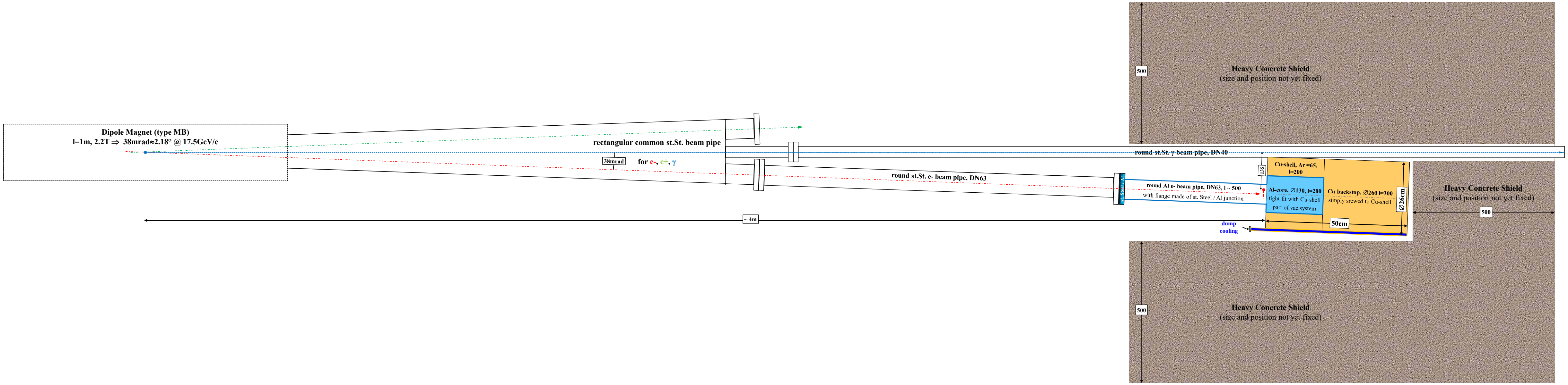
- 5 weeks for extraction
- 7 weeks for transfer line

F. Burkart, W. Decking

BEAM DUMP

Beam needs to be safely dumped, design (with radioprotection group) well advanced

F. Burkart, M. Schmitz (DESY)



BEAM DUMP

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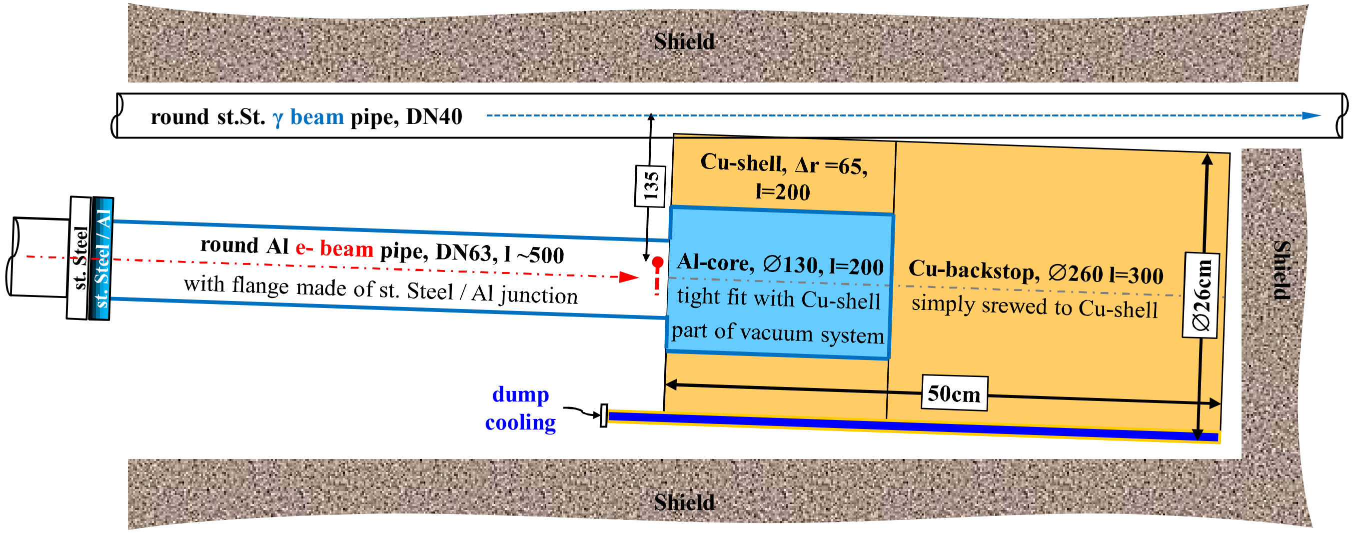
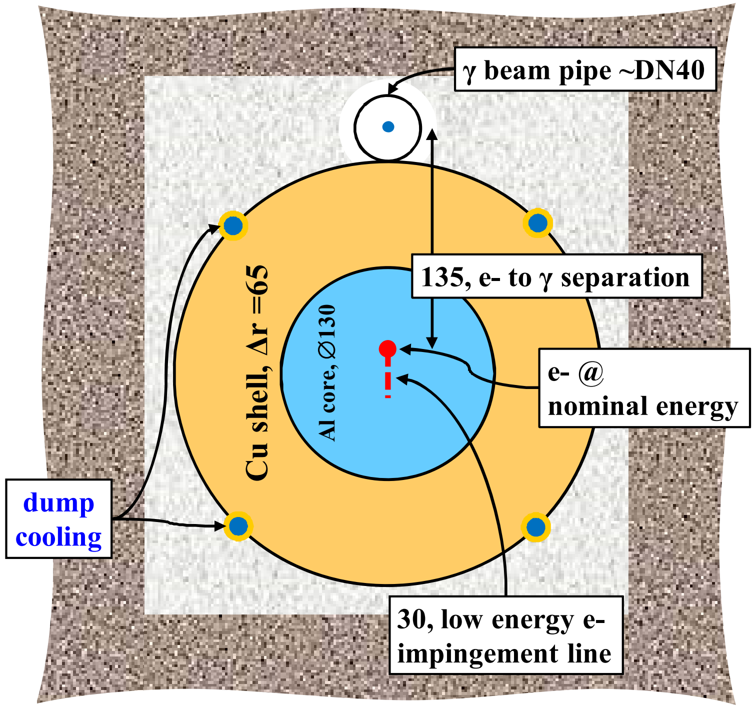


Longitudinal Cut

lenghts without units are in mm

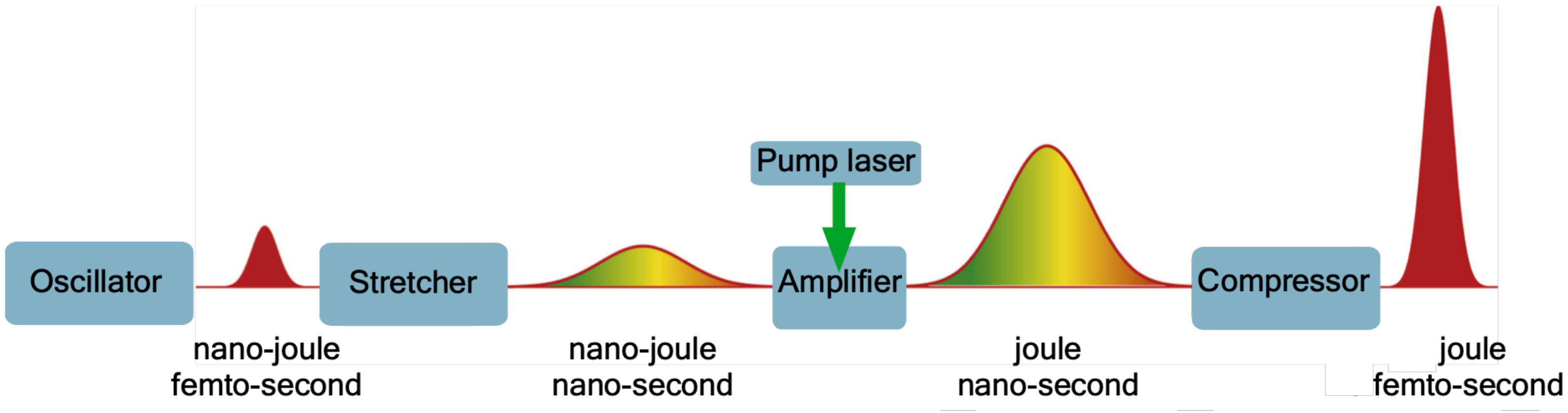


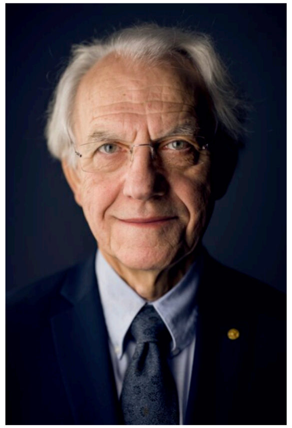
Front View

lenghts without units are in mm

F. Burkart, M. Schmitz (DESY)

LASER TECHNOLOGY





Gérard Mourou

Prize share: 1/4

Donna Strickland

Prize share: 1/4

- **Use Chirped Pulse Amplification (CPA) technique**
  - Half of the NP 2018 shared by Gerard Mourou and Donna Strickland for "for their method of generating high-intensity, ultra-short optical pulses."
- **Ti:Sa laser with 800 nm wavelength**
- **Energy focussed strongly in both time and space => high intensity**

LASER PARAMETERS

Parameter	Initial stage	Stage 1	Stage 2
Laser energy after compression [J]	0.9	9	
Percentage of laser in focus [%]	40	40	
Laser energy on focus [J]	0.36	3.6	
Laser pulse duration [fs]	30	30	
Laser repetition rate [Hz]	1	1	
Laser-beam crossing angle [degrees]	17	17	
Laser focal spot FWHM [μm]	8	8	3
Peak intensity [10^{19} W/cm^2]	**1.6**	**16**	**110**
Peak intensity parameter ξ	**2**	**6.2**	**16**
Peak quantum parameter χ: **Ebeam=17.5 GeV** **Ebeam=14.0 GeV**	 **0.41** **0.32**	 **1.3** **1.0**	 **3.3** **2.6**

Laser intensity:

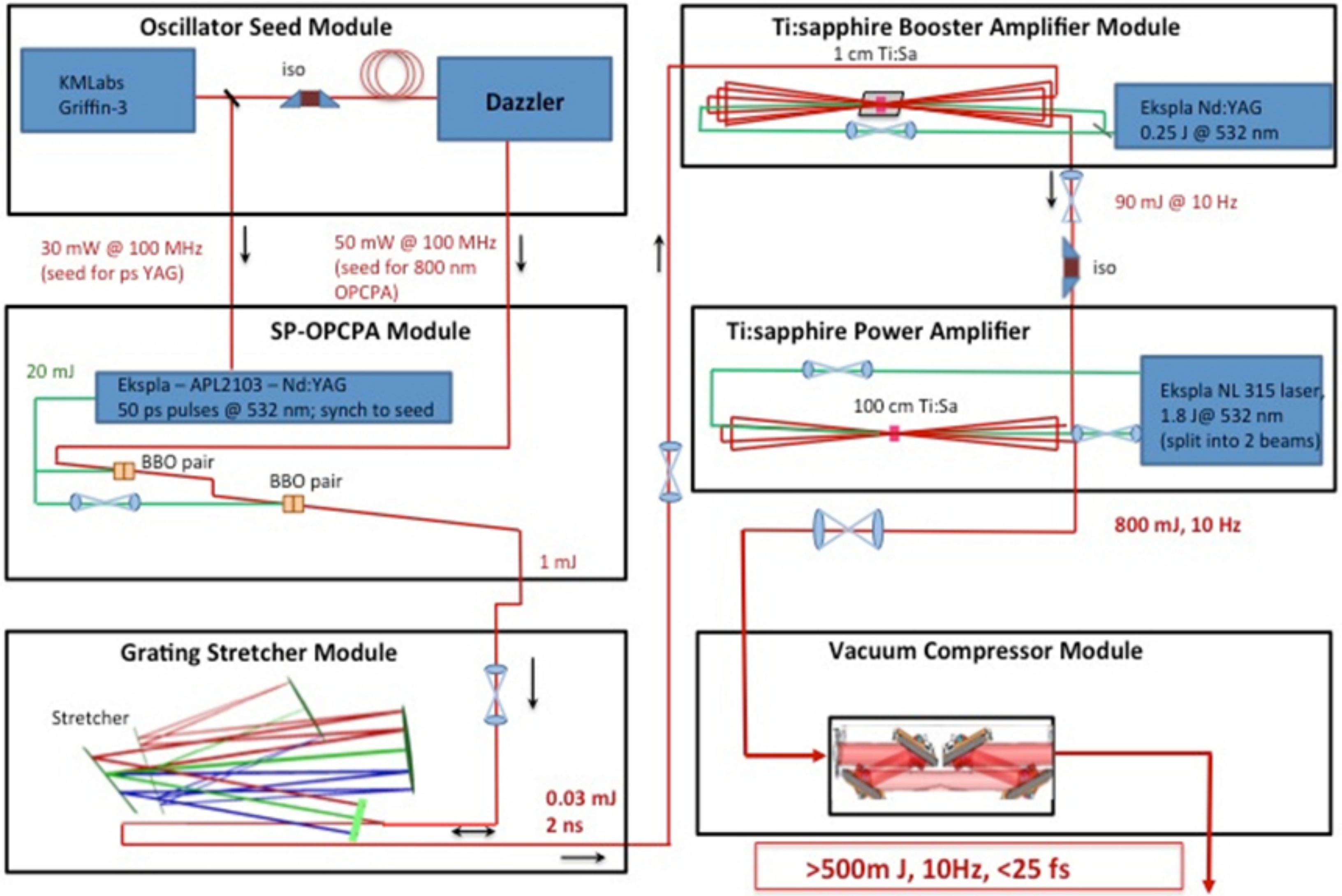
$$I = \frac{E_L}{\Delta t \pi d^2}$$

with

E_L: energy (J)
Δt: pulse length (s)
πd^2: focus area (m^2)

Lower intensities achieved by de-focussing laser or stretching pulse

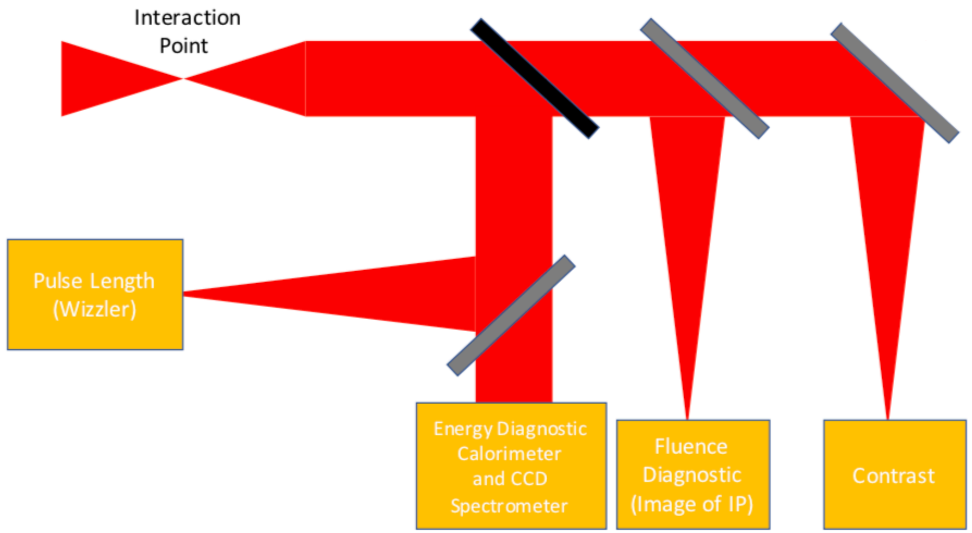
LASER DESIGN



I. Pomerantz (Tel Aviv), G. Sarre (Belfast), M. Zepf (HZI Jena, Jena, Belfast) and others

LASER DIAGNOSTICS

- **Aim to control intensity at level of 5-10%**
  - Cannot measure it directly
- **Several diagnostics measurements planned to measure parameters**
  - Energy
  - Fluence (Energy/area)
  - Pulse length
- **Laser shots can vary by ~15% for stable laser at this power**
  - System can be used to tag intensity of individual shots



PARTICLE DETECTION AND SIMULATION RESULTS

RATES OF PARTICLES

e+laser

Location	particle type	rate for $\xi = 2.6$	rate for $\xi = 0.26$
e^- detector	e^-, $E_e < 16$ GeV	1.5×10^9	6×10^6
e^+ detector	e^+	15.3	< 0.01
Photon detector	γ	6×10^{10}	1×10^7
Photon detector (W foil)	e^+ and e^-	6×10^6	1×10^4
Photon detector (W wire)	e^+ and e^-	1.5×10^5	1×10^2

γ+laser

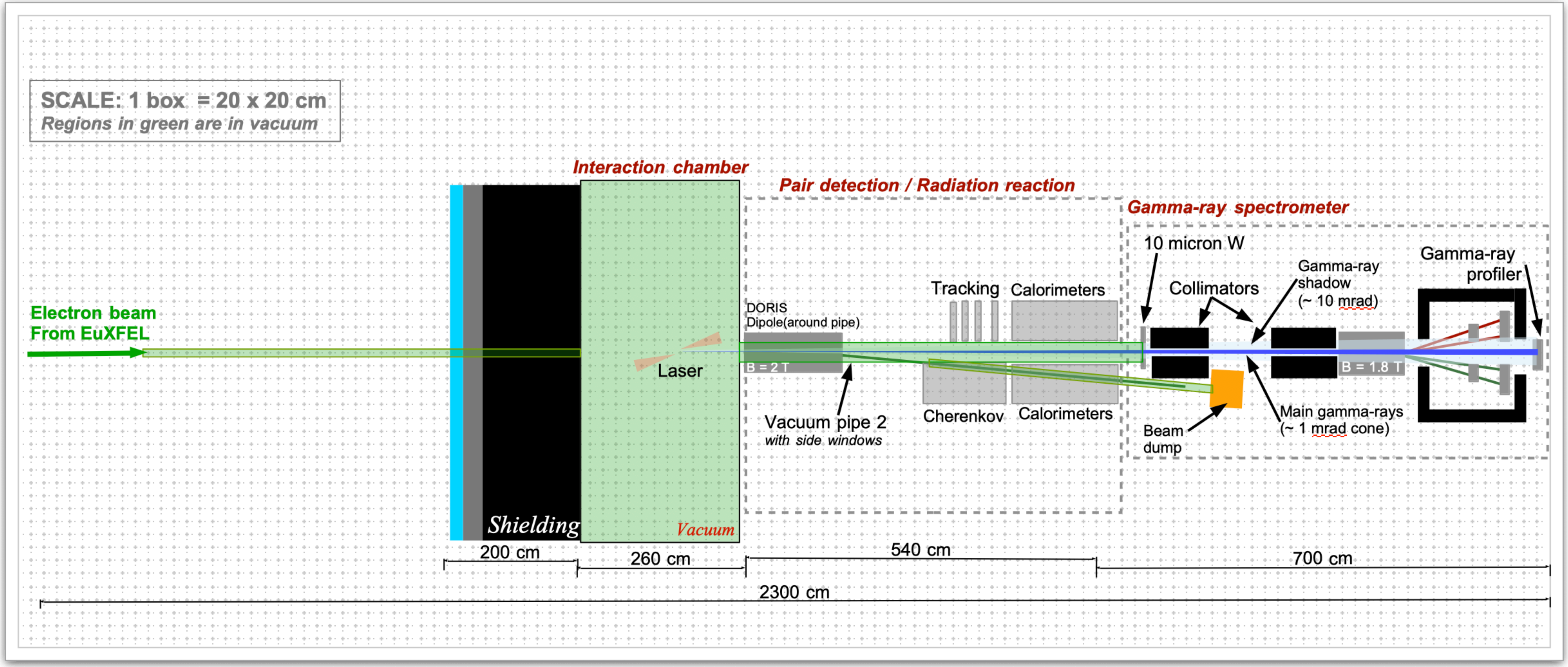
<table>
<tr><th>Location</th><th>particle type</th><th>rate for $\xi = 2.6$</th><th>rate for $\xi = 1.2$</th></tr>
<tr><td>e^- detector behind converter</td><td>e^-, $E_e < 13$ GeV</td><td colspan="2">2×10^7</td></tr>
<tr><td>e^+ detector behind converter</td><td>e^+</td><td colspan="2">9×10^4</td></tr>
<tr><td>photons after converter</td><td>γ</td><td colspan="2">1.3×10^8</td></tr>
<tr><td>$e^\pm$ detector behind IP</td><td>e^-/e^+</td><td>5</td><td>1×10^{-2}</td></tr>
<tr><td>Photon detector</td><td>γ</td><td colspan="2">1.3×10^8</td></tr>
<tr><td>Photon detector</td><td>e^+ and e^-</td><td colspan="2">160</td></tr>
</table>

M. Borysova, O. Borysov

=> Very different rates of particles => need different technologies

ELECTRON LASER COLLISIONS

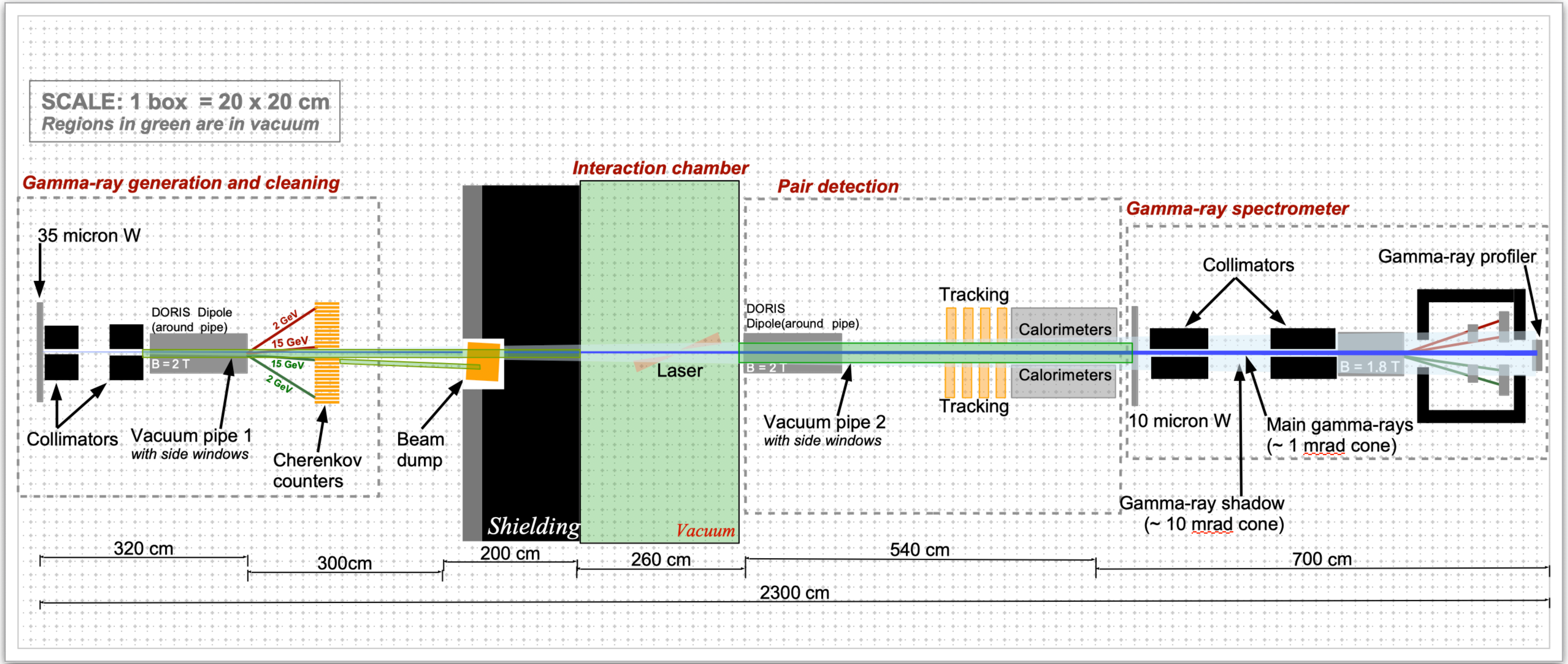
Compton and trident processes: $e^- + n\omega \rightarrow e^- + \gamma$ and $e^- + n\omega \rightarrow e^- e^+ e^-$



G. Sarre, Belfast

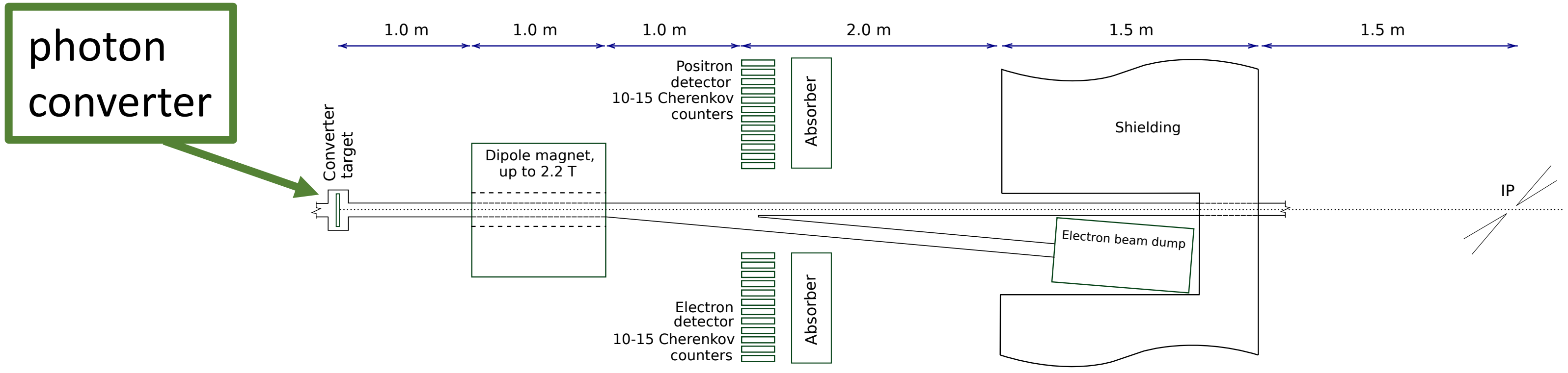
PHOTON LASER COLLISIONS

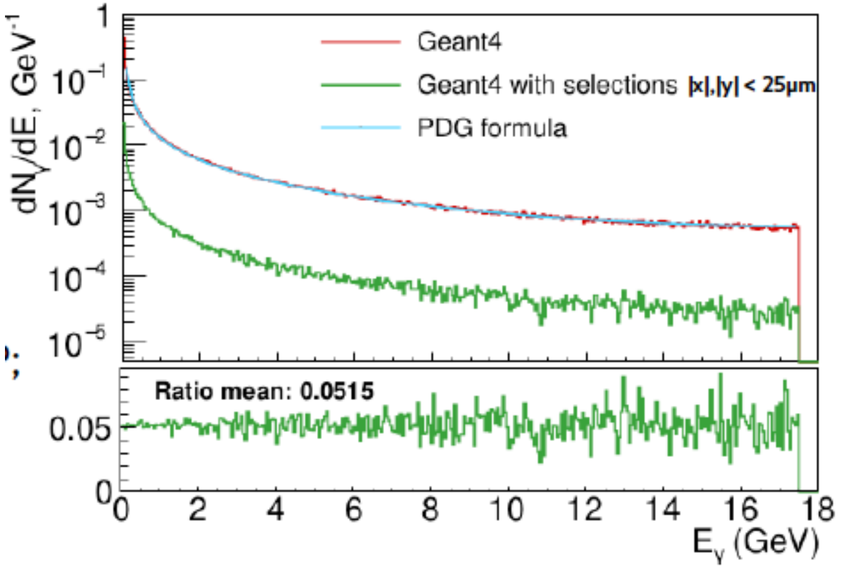
Pair production (Breit-Wheeler) process: $\gamma + n\omega \rightarrow e^- + e^+$



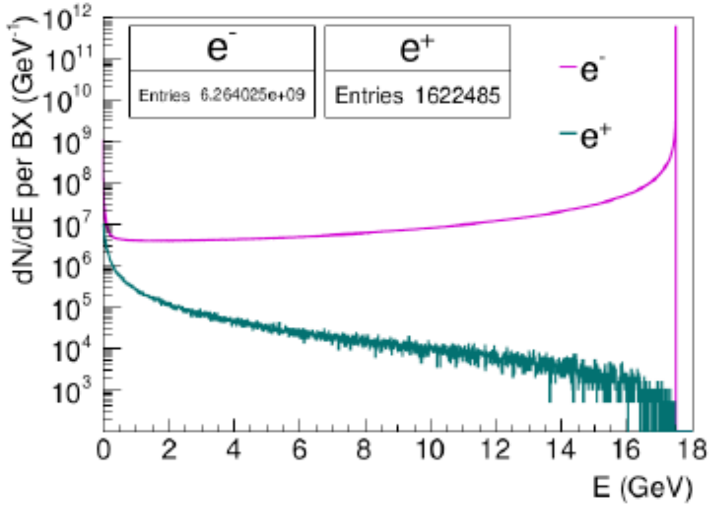
G. Sarre, Belfast

HIGH-ENERGY PHOTON FLUX



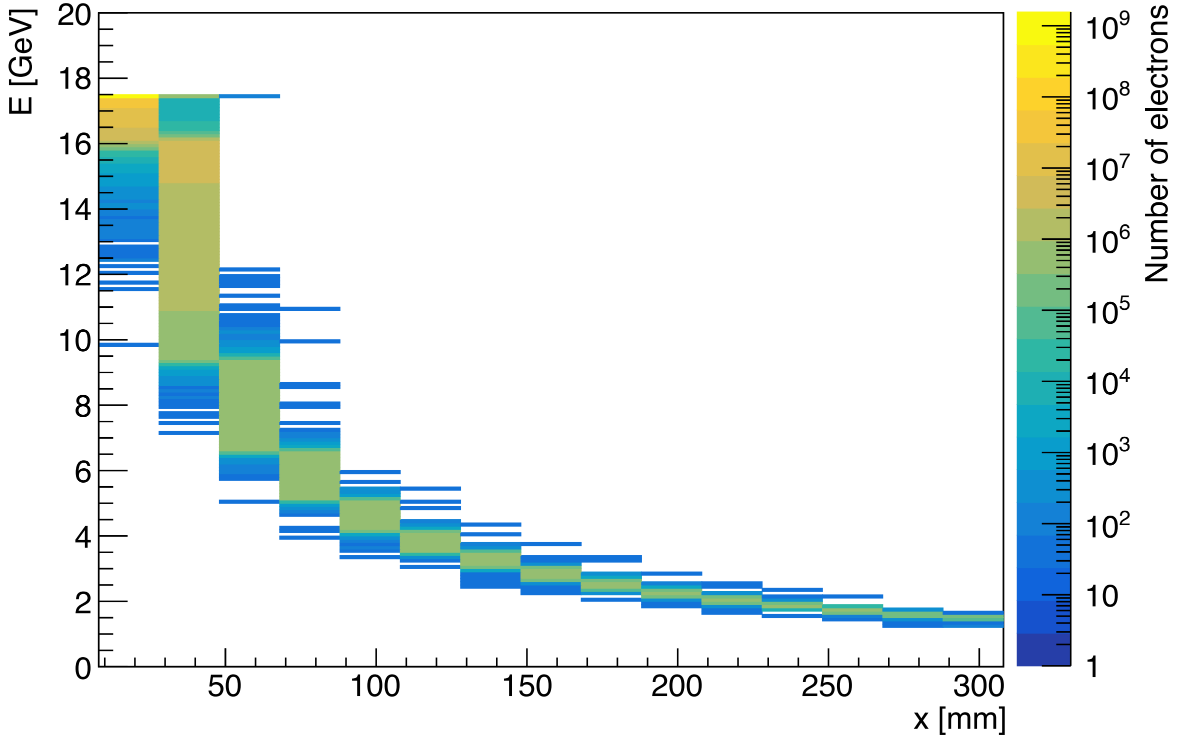


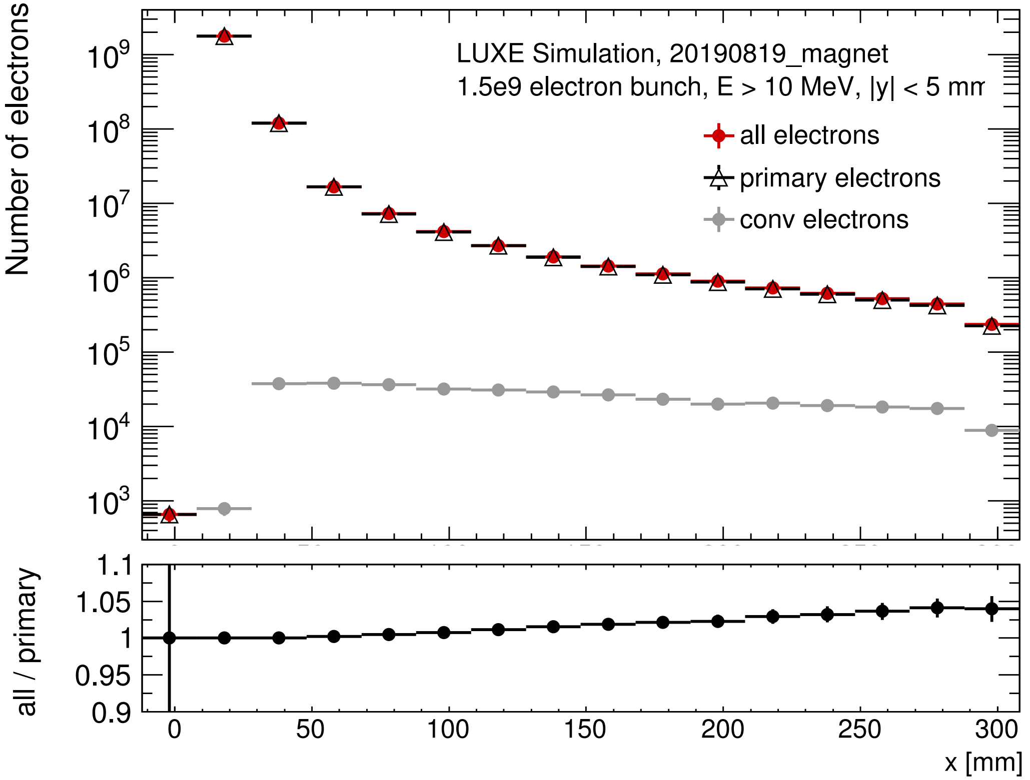
- **Simulation of converter using Geant4**
  - Tungsten Target with 0.01 X_0 (35 μm) => 1% at IP
- **Spectrum of photon energies important to know**
  - Measure by observing electrons and positrons right after dipole magnet
- **Particle detection**
  - 2T magnet followed by array of Cherenkov detectors measures flux vs impact position => energy spectrum



O. Borysov, DESY

PHOTON FLUX MEASUREMENT: ELECTRONS

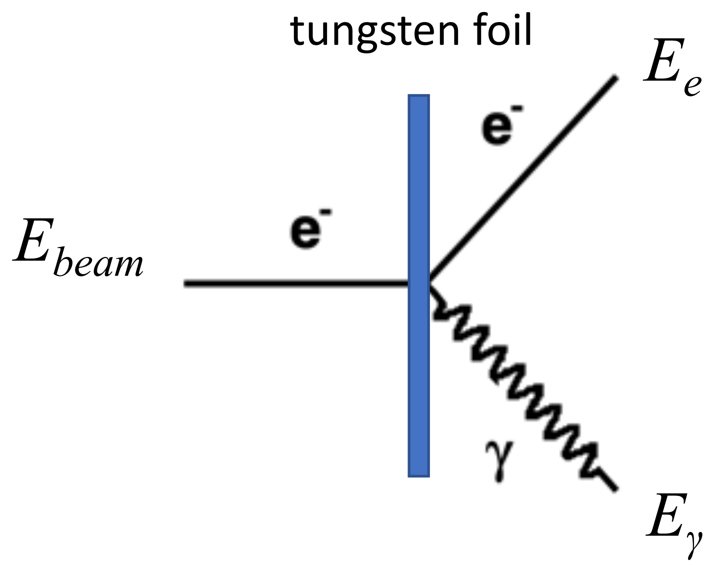


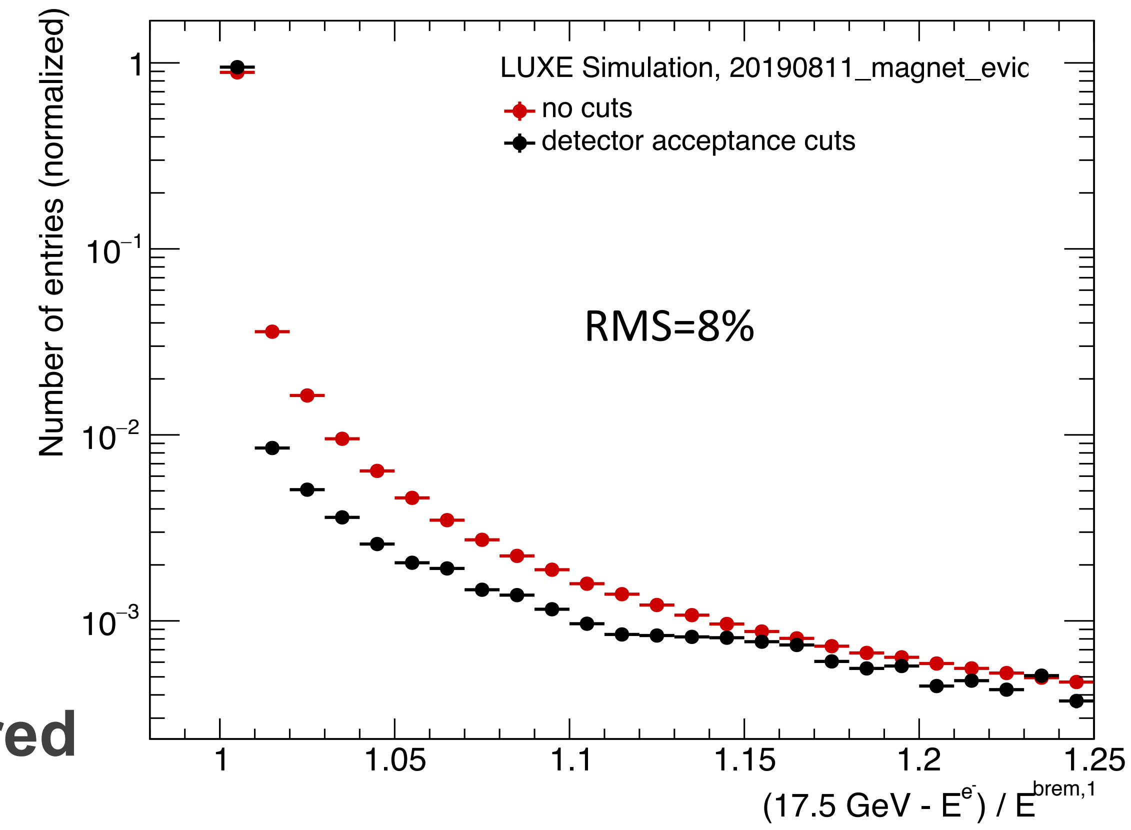


M. Saimpert, DESY

- **Electron energy measured based on position behind dipole magnet**
- **Dominated by primary electrons**
  - Contamination of converted electrons small (can estimate based on positron flux)

PHOTON ENERGY MEASUREMENT





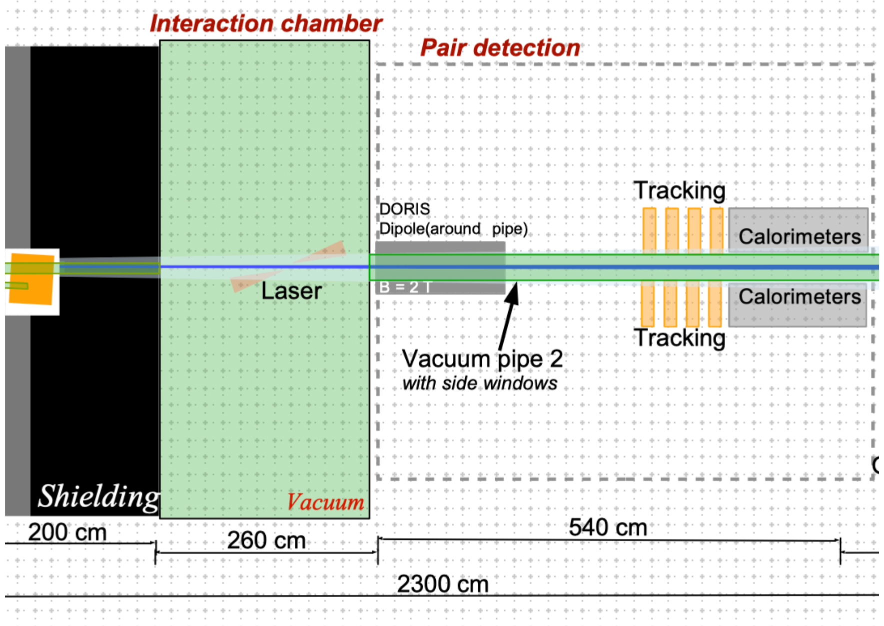
M. Saimpert, DESY

Photon energy determined from measured electron energy to within ~10%:

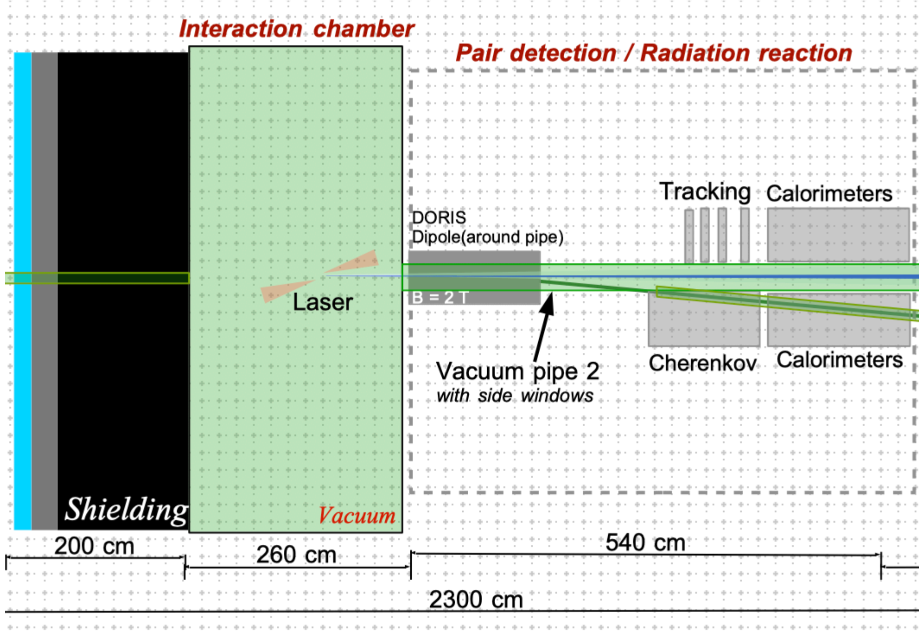
$$E_\gamma = E_{beam} - E_e$$

ELECTRON AND POSITRON DETECTORS

$$\gamma + n\omega \rightarrow e^+e^-$$



$$e^- + n\omega \rightarrow e^-e^+e^-$$

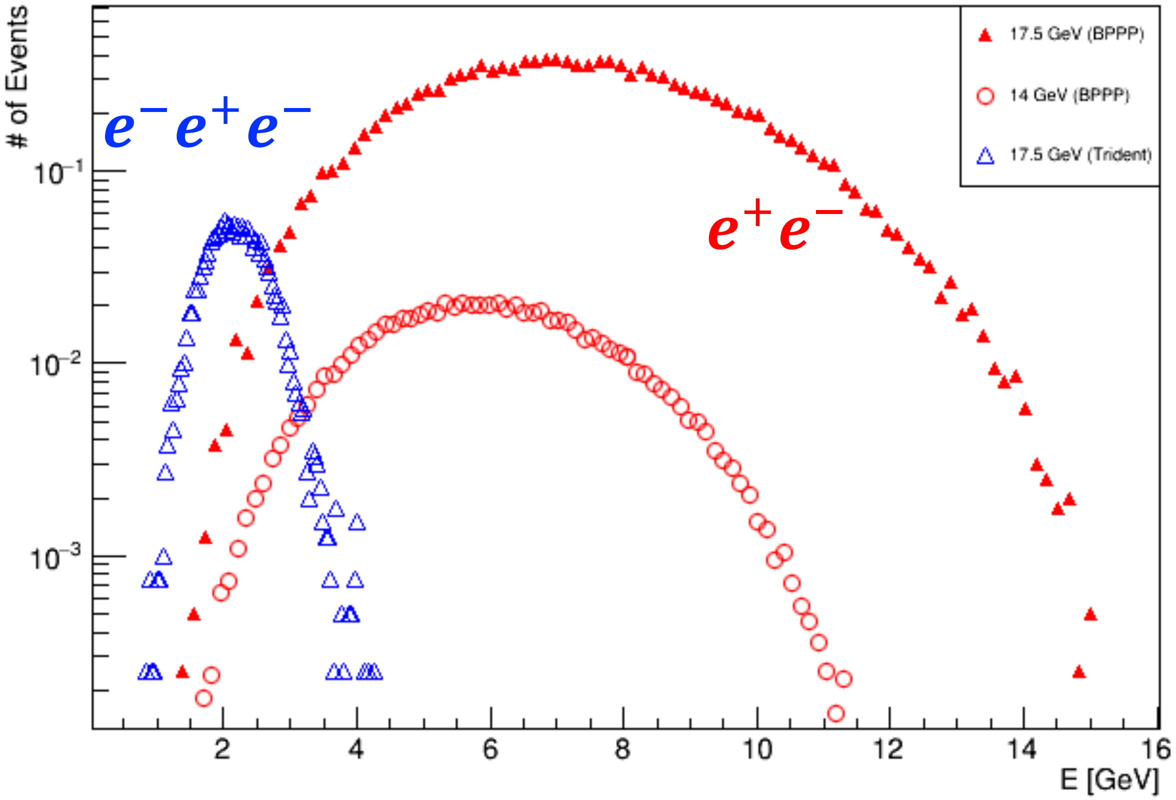


- **Pair production:**
  - e^+ and e^- rate ~0.01-100 => silicon pixel detectors and calorimeters
- **Trident:**
  - e^+ rate ~0.01-100 => silicon pixel detectors and calorimeters
  - e^- rate ~10^6-10^9 => Cerenkov counters and calorimeter/absorber

SIMULATION RESULTS

- ***Monte Carlo simulation of expected signatures used***
  - *By A. Hartin, UCL*
- ***Energy spectrum ranges between 1 and 15 GeV***
  - *Energies significantly lower for trident process*
- ***For trident process uses "two-step" process only***
  - *Calculation of one-step trident ongoing*

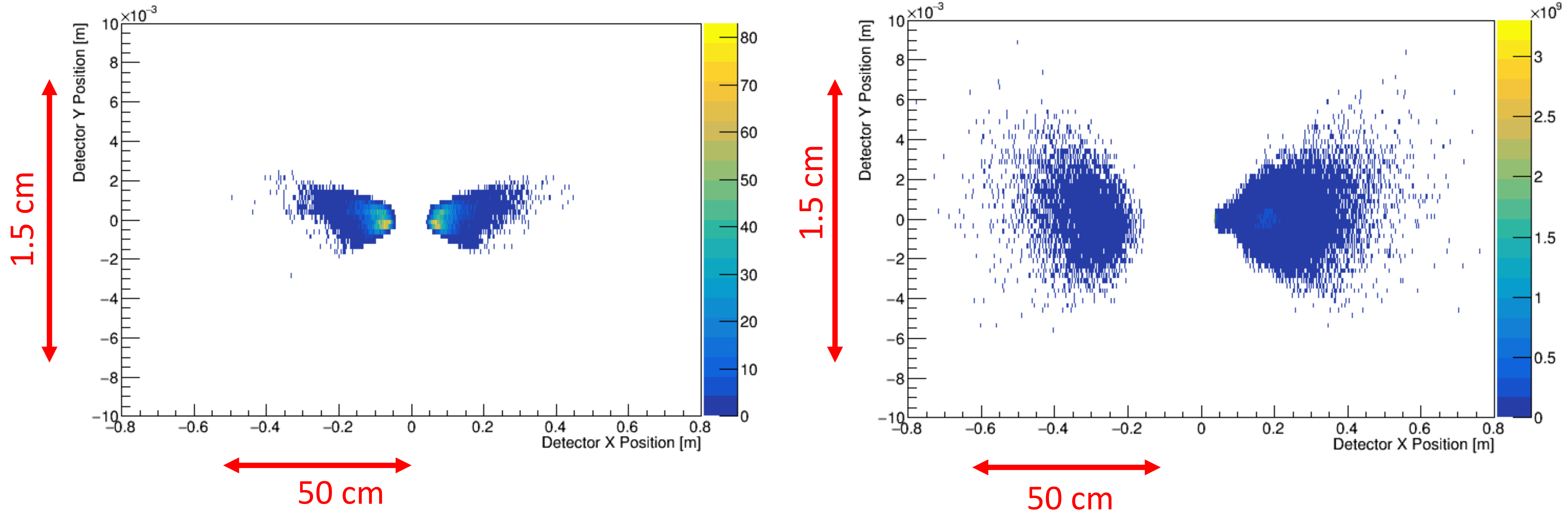
Positron Energy Spectrum



A, Hartin (UCL), M. Hoffmann (DESY)

DETECTOR OCCUPANCIES AFTER INTERACTION POINT

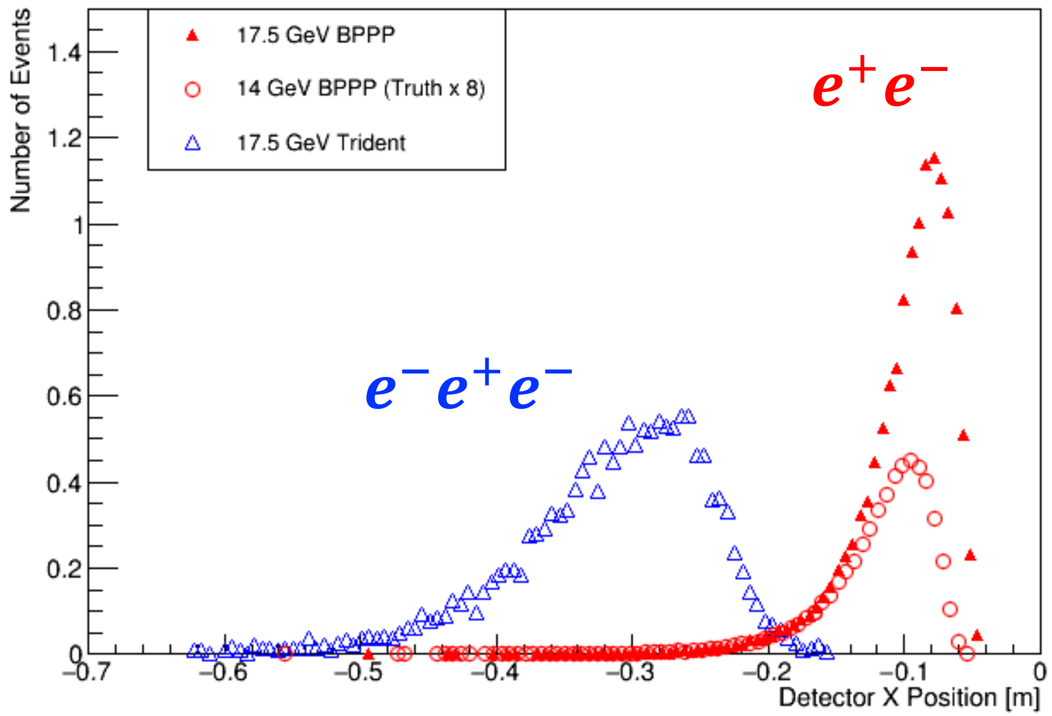
$\gamma + n\omega \rightarrow e^+e^-$ $\qquad$ $e^- + n\omega \rightarrow e^-e^+e^-$



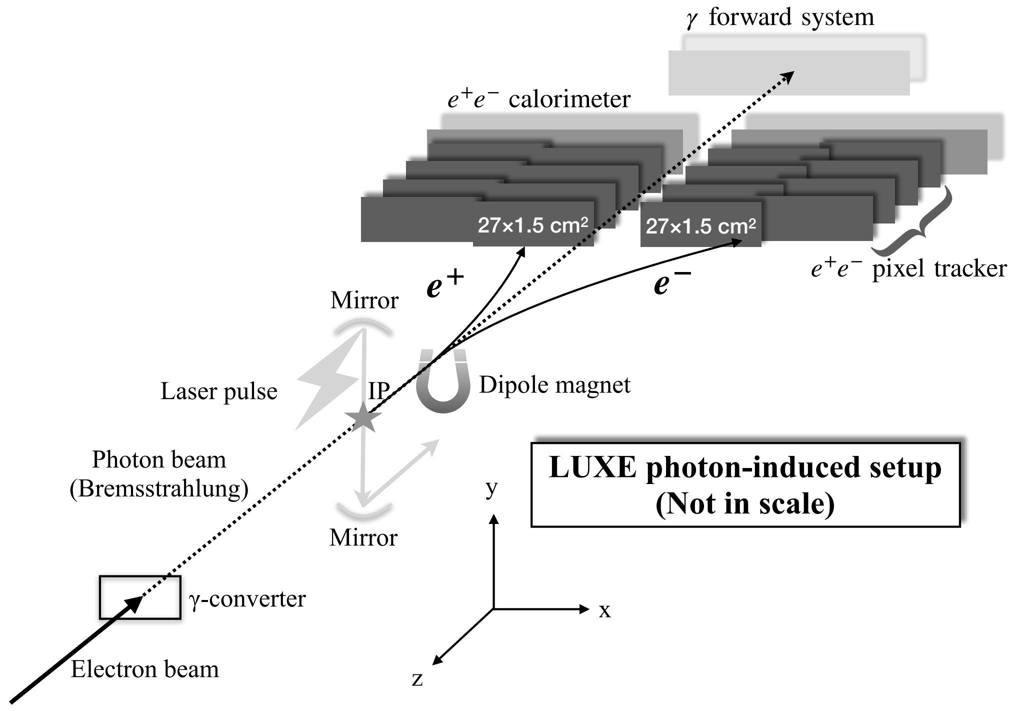
A, Hartin (UCL), N. Hod (Weizmann), M. Hoffmann (DESY)

- Vertical direction: very small spread for both processes
- Horizontal direction: particles contained within ~50 cm

HIT POSITION AT FIRST DETECTOR PLANE



A, Hartin (UCL), M. Hoffmann (DESY)

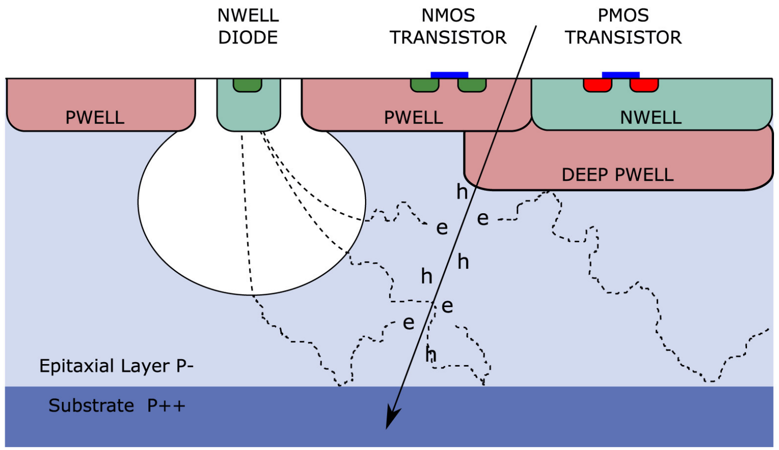


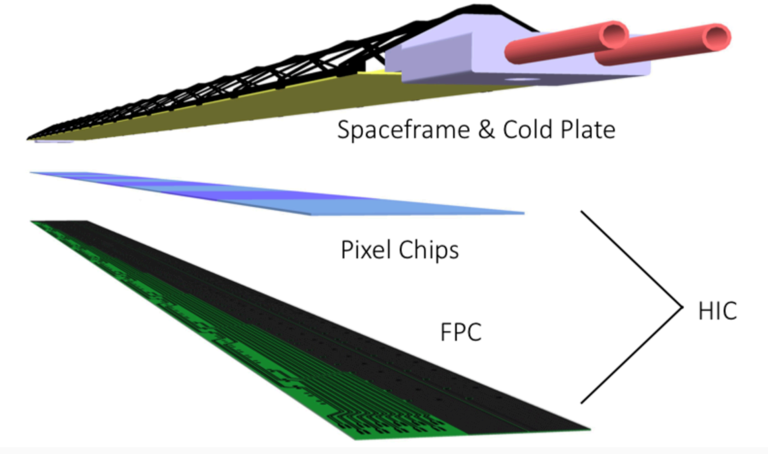
N. Hod (Weizmann Inst.)

Detectors need to span about ~50 cm to have acceptance >95%:

- $e^- + n\omega \rightarrow e^-e^+e^-$ **process: acceptance ~95%**
- $\gamma + n\omega \rightarrow e^+e^-$ **process: acceptance >99%**

SILICON DETECTORS





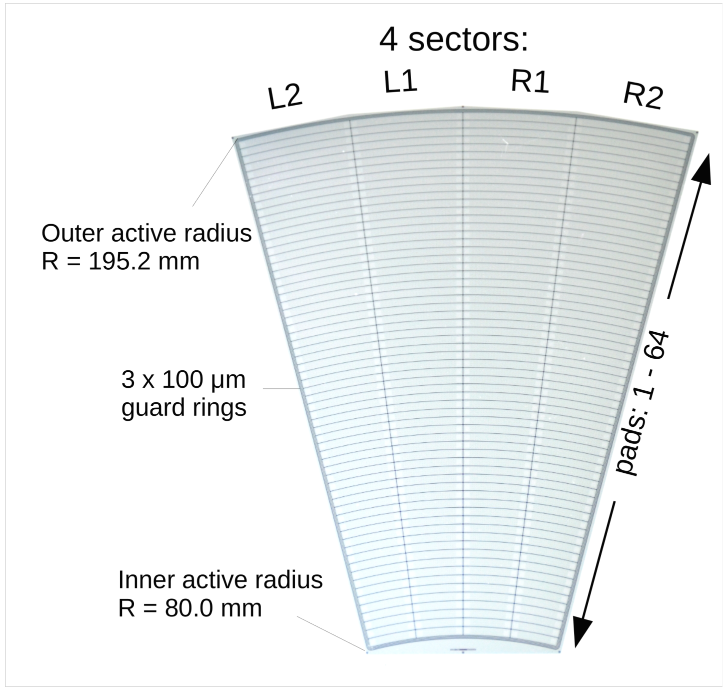
N. Hod (Weizmann Inst.)

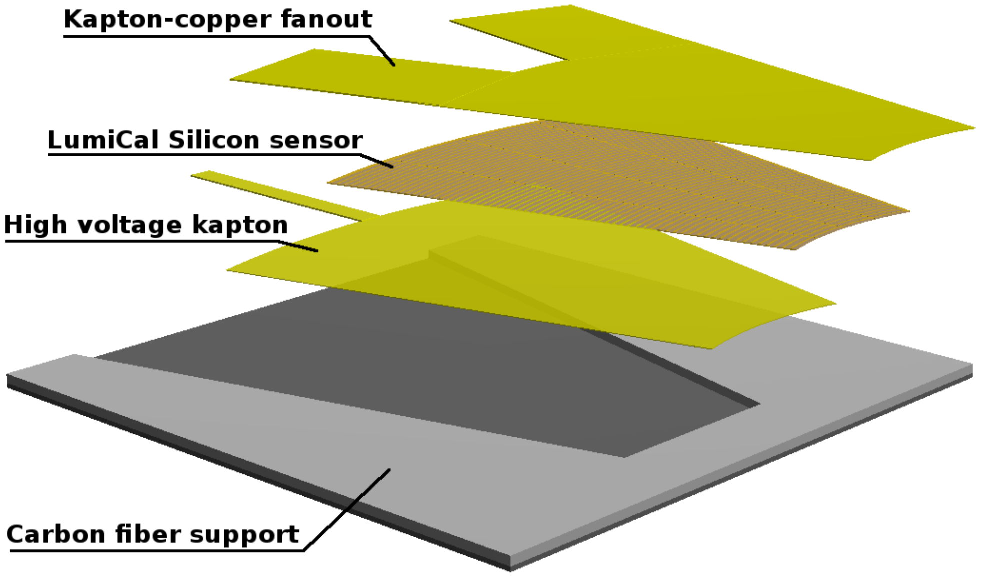
ALPIDE pixel detectors

- Developed by ALICE collaboration
- Staves of 27 cm length; sensor size 1.5x1.5 cm^2
  - Achieve full coverage with two staves placed next to each other
- Pixel size: 27 x 29 μm^2 => Spatial resolution ~5 µm
- Plan to use four layers staggered behind each other

Redundant tracking possible, important for beam background rejection

CALORIMETERS



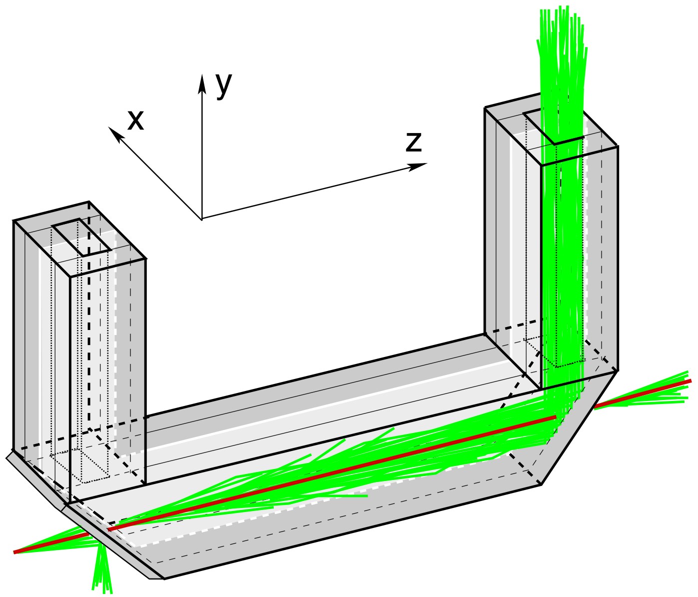


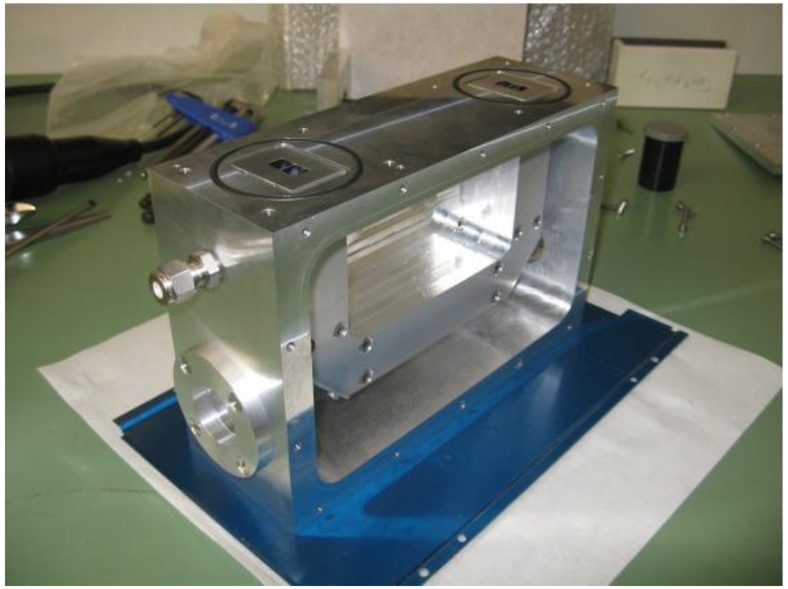
Y. Benhammou, H. Abramowicz, A. Levy (Tel Aviv U)

High granularity silicon Tungsten calorimeter

- Developed for luminosity measurement at linear colliders (LUMICAL)
- 20 tungsten absorber plates (3.5mm), Si layers in gaps (320 µm)
- Geometry adapted to fit needs of LUXE (~50cm long, vertical spread <1mm)
- Moliere radius 8 mm, Prototyped and test beam measurements available

CHERENKOV COUNTERS





J. List (DESY)

Use Cherenkov detectors in high-flux regions

- Use design developed for ILC polarimeters
- Linearity better than 0.1% over dynamic range spanning 10^3
- Threshold of ~10 MeV => robust against background from low energy radiation
- Plan to use array of 15 detectors with cross section of 2x2 cm^2

POSITRON RATE VS LASER INTENSITY

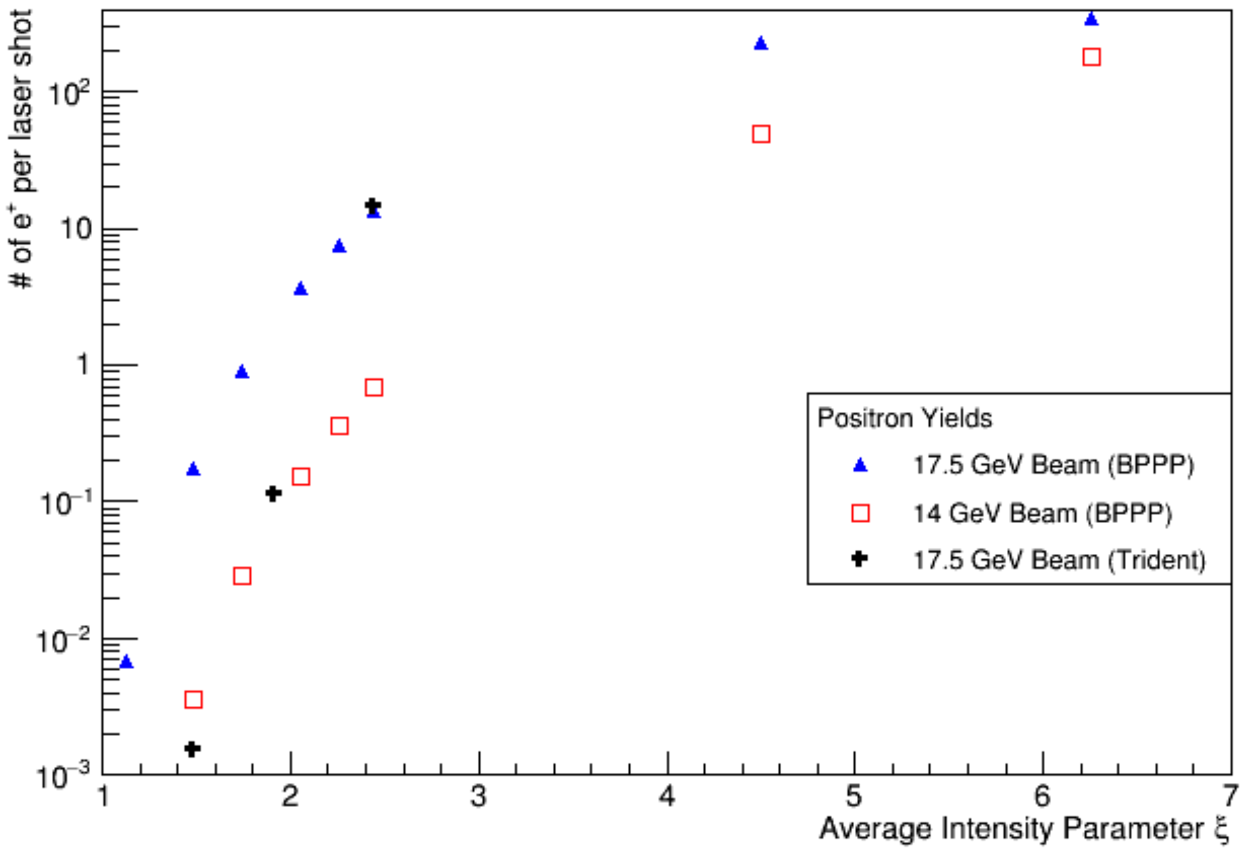
Main result of experiment

Low laser intensity

- Encounter power-law behaviour

High intensity

- Should observe deviation from power-law behaviour
- Aim to quantify by extracting coefficient



A, Hartin (UCL), M. Hoffmann (DESY)

POSITRON RATE VS LASER INTENSITY

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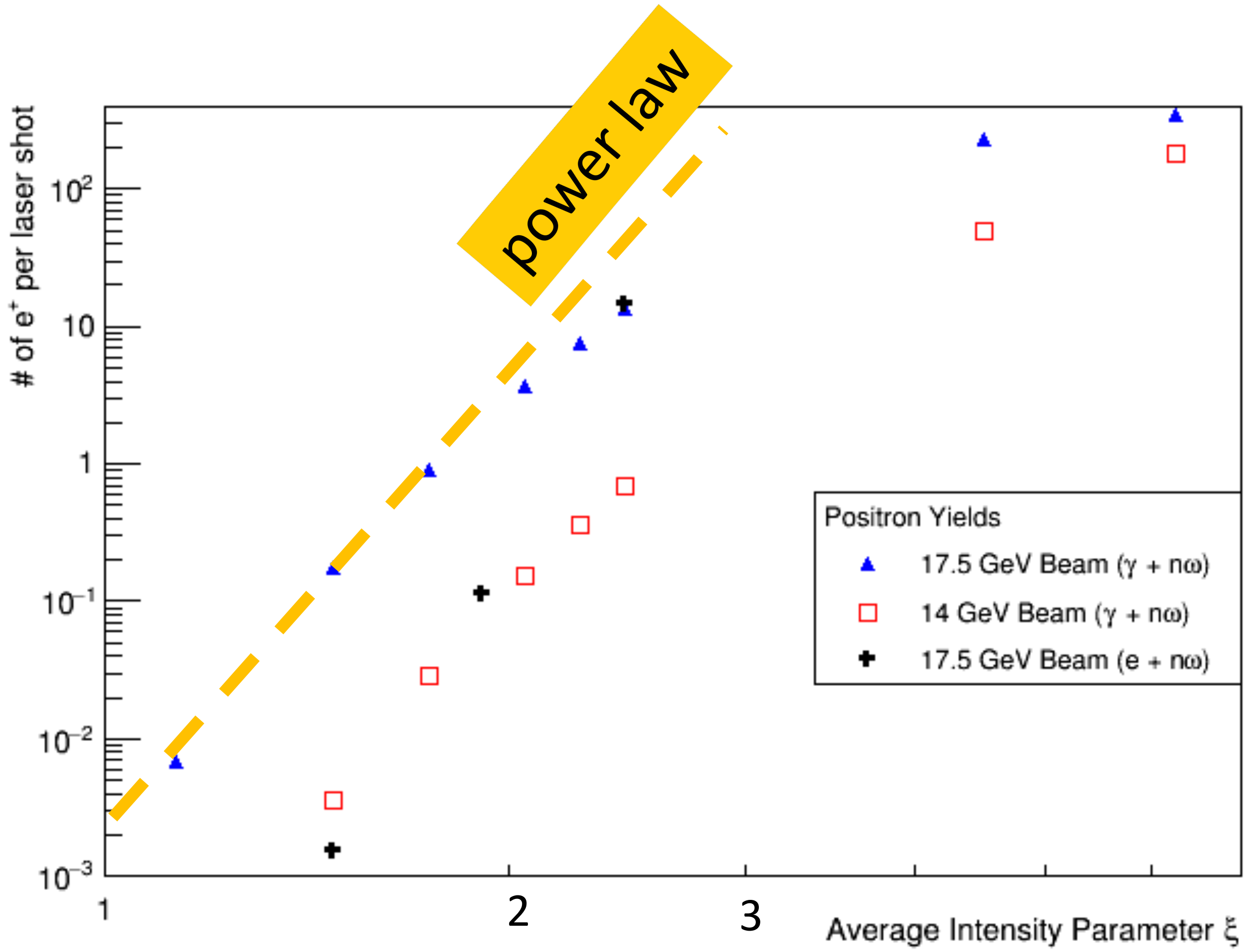
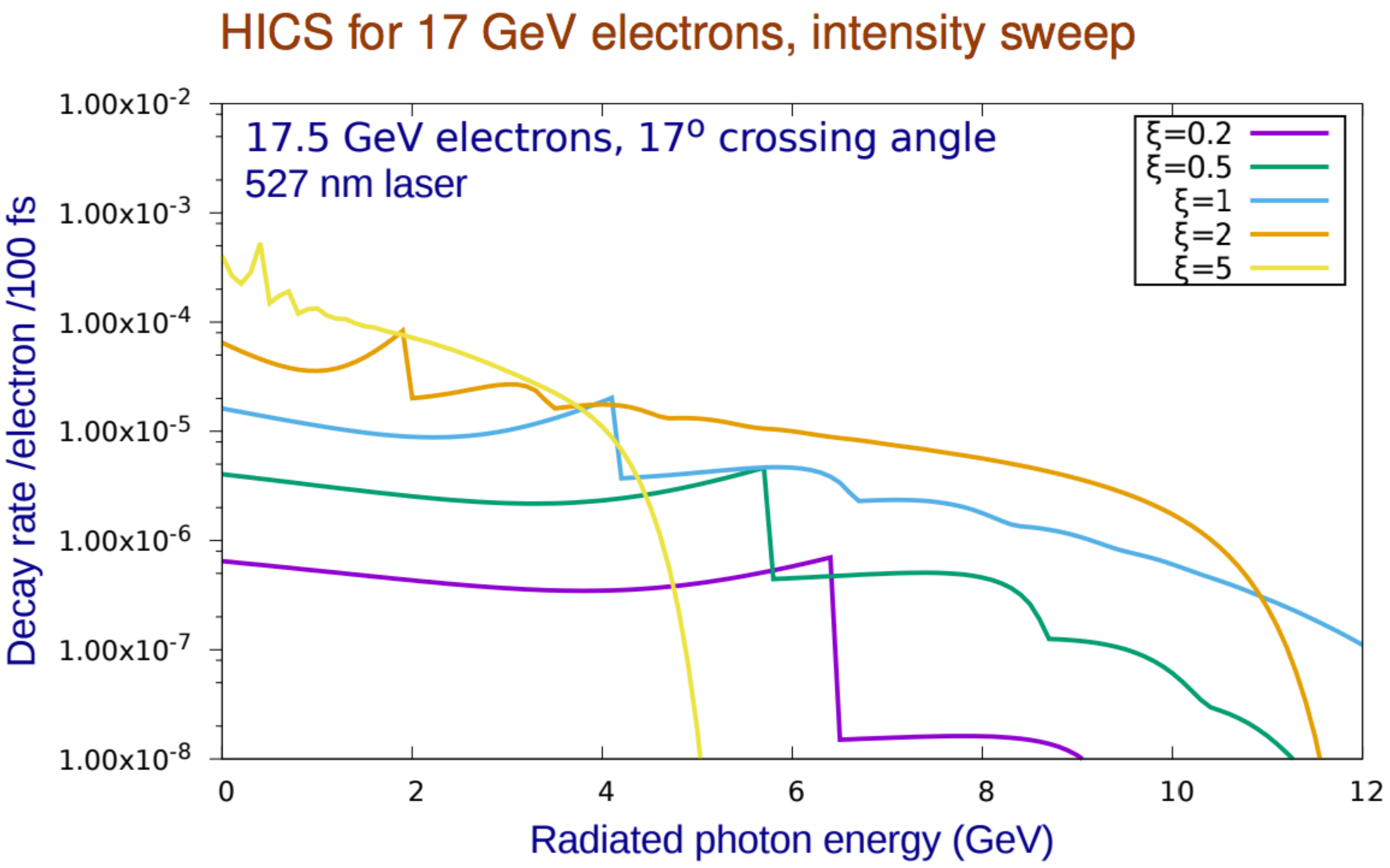
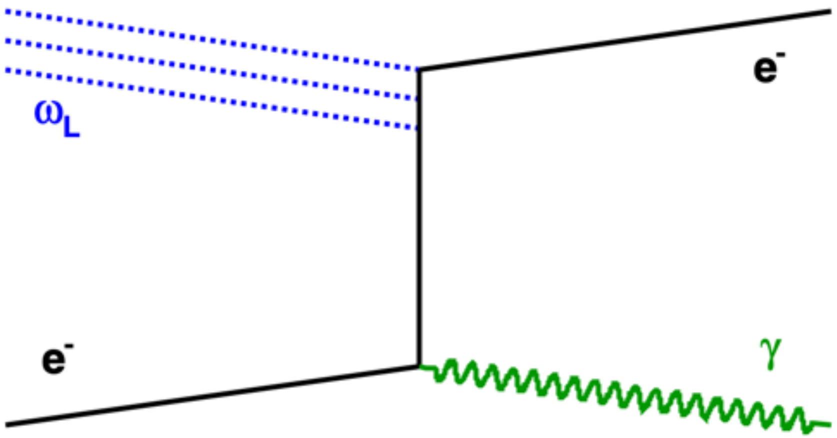


A, Hartin (UCL), M. Hoffmann (DESY)

NON-LINEAR COMPTON SCATTERING: $e^- + n\omega_L \rightarrow e^- + \gamma$

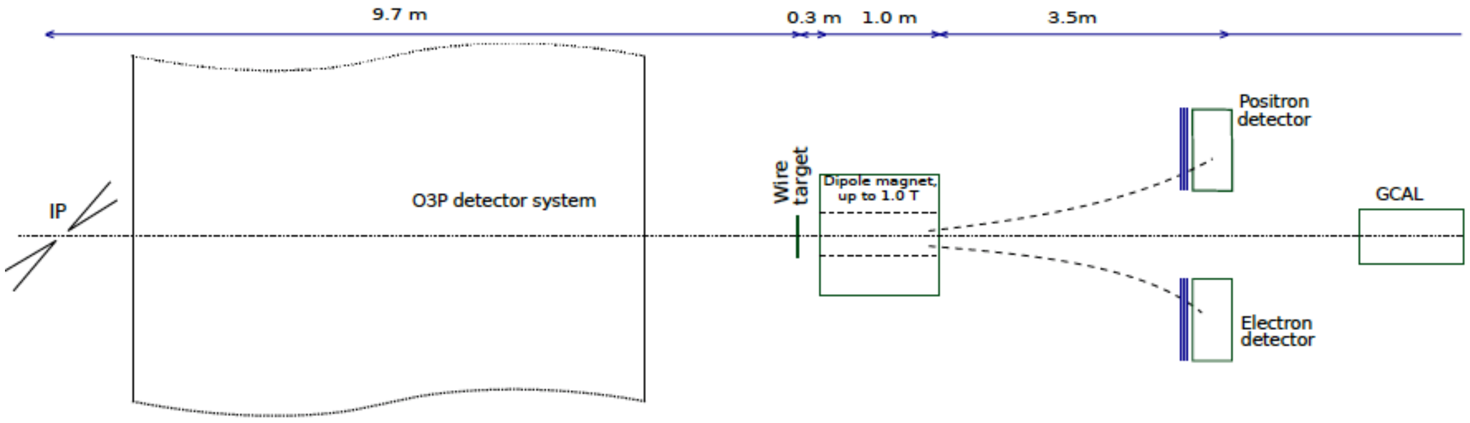




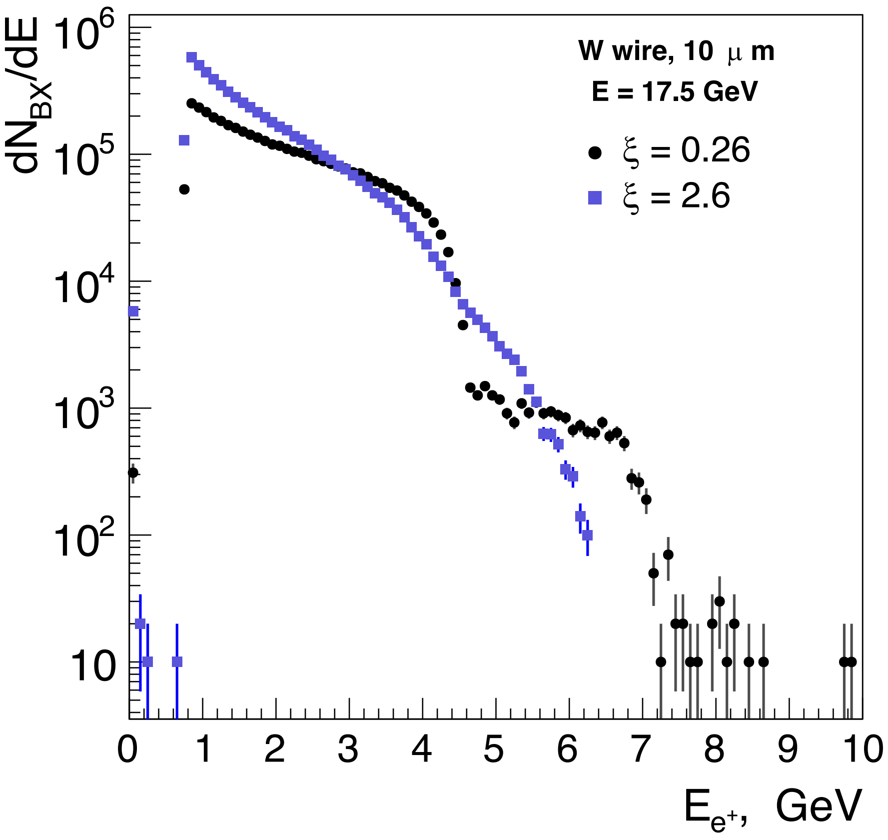
$$p_i + k\frac{\xi^3}{2\chi_i} \rightarrow p_i^2 = m^2(1+\xi^2)$$

A, Hartin (UCL)

NON-LINEAR COMPTON PROCESS



M. Borysova (Kiev KINR)



Measure photon flux and energy in "photon detection system"

- Photon flux very high (>10^7 per laser shot)
- Thin wire to convert photons to e+e- pairs

Compton edges observable in $e^{\pm}$ energy spectra at low ξ

TENTATIVE TIME SCALES: 2020 AND BEYOND

- **Summer 2020**
  - CDR for LUXE experiment (TDR a year later?)
- **Nov/Dec 2020**
  - Start preparatory work for installation; main installation following year
- **2022-2023: prototype experiment (stage-0)**
  - 1st year: electron-laser running
  - 2nd year: photon-laser running
- **2024:**
  - Install more powerful laser (~1 PW) and improved laser diagnostics
  - Publish results of stage-0 experiment
- **2025-2027: Data taking with high-power laser (stage-1)**
  - Interesting to run at different energies, currents,… configurations
  - Plan to benefit from requirements of other experiments

CONCLUSIONS

- **LUXE is an experiment to test what happens when high energy electrons or photons observe an intense laser field**
- **LUXE will probe quantum physics in new regime of high intensity QED using a minute fraction of European XFEL electron beam**
  - Measure several phenomena predicted more than 60 years ago
  - Test quantum field theory in a new regime
- **International collaboration of 36 scientists (12 institutions from 4 countries) performed feasibility study**
  - Will release a “Letter of Intent” later this week

CONCLUSIONS

- **LUXE is an experiment to test what happens when high energy electrons or photons observe an intense laser field**
- **LUXE will probe quantum physics in new regime of high intensity QED using a minute fraction of European XFEL electron beam**
  - Measure several phenomena predicted more than 60 years ago
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S. Weinberg: *“My advice is to try crazy ideas and innovative experiments. Something will come up.”*

THANKS!!

DESY directorate:

- DESY Strategy Fund funded many of studies presented here

DESY technical groups:

- MVS (Vacuum Modification)
- MIN (Kicker, Beam Dump)
- D3 (radio protection advice)
- MEA (installation and Magnets)
- ZM1 (Construction Input)
- MKK (Power/Water)
- IPP (CAD integration)

DESY divisions

- MXL, MPY, MPY1 (from M), FLC (from FH)

BACKUP SLIDES

STEVEN WEINBERG

Steven Weinberg (03/2019, interview at APS):

Do you think the problems faced by particle physicists today are different from those that you faced as a young scientist?

I do. It was a different situation 50 years ago. Back then, we had experimental data coming out of our ears, and a lot of it didn't seem to fit any pattern. The problems seemed formidable, but there were so many ways to go with new theories. It really was a thrilling time to be a physicist.

Nowadays, it's very hard to think of a challenge that we can get our teeth into. The current puzzles don't offer theorists many opportunities to propose solutions that can be tested experimentally.

Do you have any advice to offer the next generation?

Winston Churchill had a motto at the beginning of World War II: "Keep buggering on." In that spirit, I think it's better to do something than to do nothing. My advice is to try crazy ideas and innovative experiments. Something will come up.

Steven Weinberg,
NP 1979

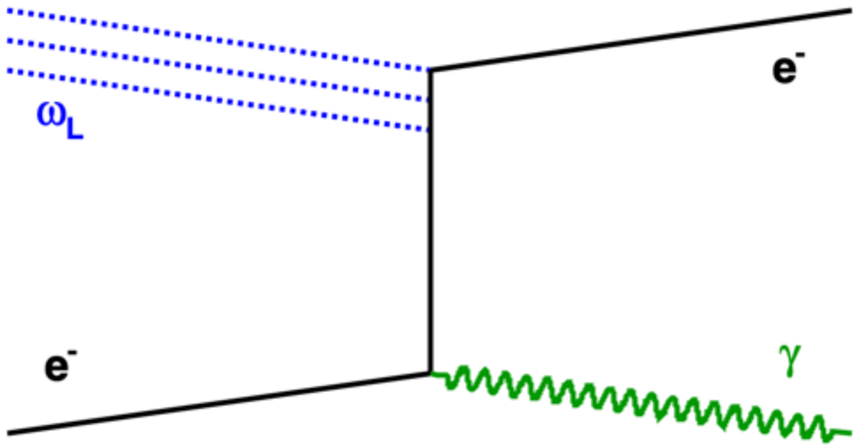
NON-LINEAR COMPTON SCATTERING: $e^- + n\omega \rightarrow e^- + \gamma$

- Rate of high-intensity Compton scattering proportional to

$$\sum_n \delta^{(4)}\left[p_i + k\frac{\xi^3}{2\chi_i} + nk - p_f - k\frac{\xi^3}{2\chi_f} - k_f\right]$$

- Even for small n expect shift of Compton edge due to effective increase of electron rest mass

$$p_i + k\frac{\xi^3}{2\chi_i} \rightarrow p_i^2 = m^2(1+\xi^2)$$

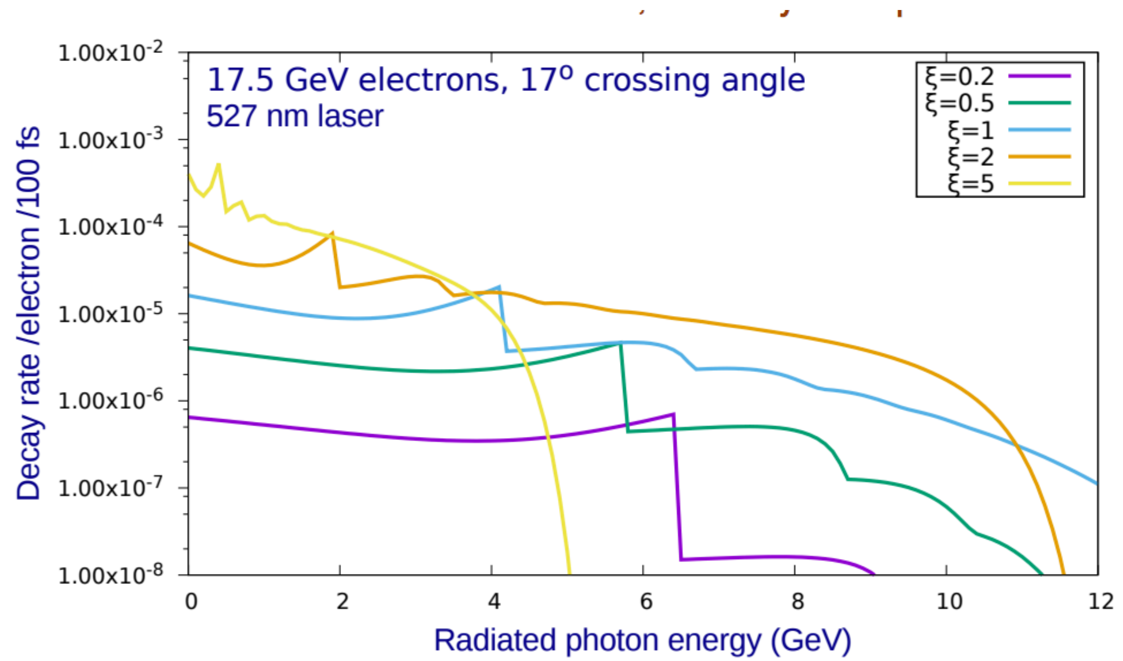


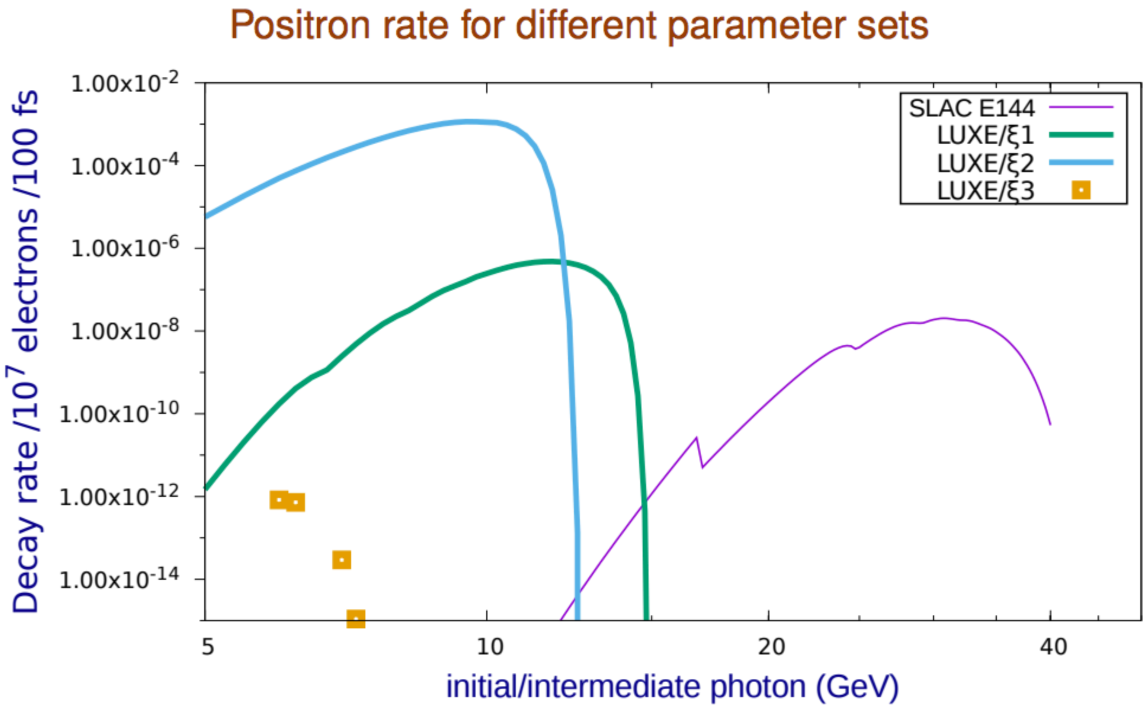
- Has never been observed

MEASUREMENTS OF MASS SHIFT AND TRIDENTS

$$e^- + n\omega \rightarrow e^- + \gamma$$

$$e^- + n\omega \rightarrow e^- e^+ e^-$$

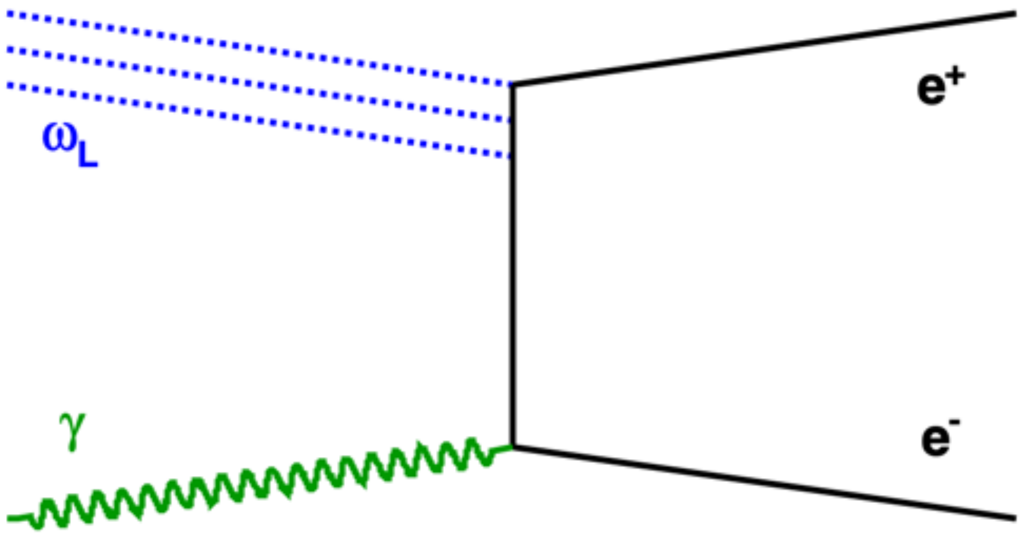




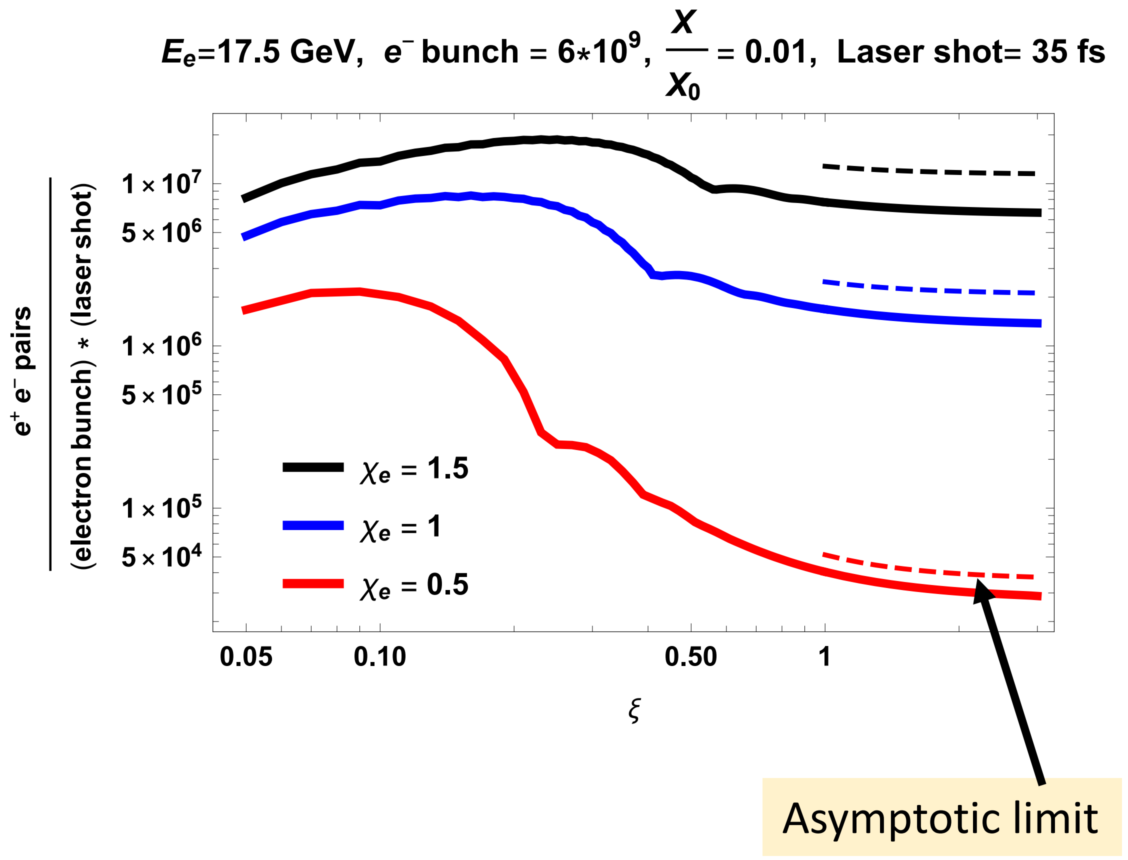
Plots from A. Hartin, IJMPA 33, 1830011 (2018)

ABSORBING LIGHT WITH LIGHT

Low-energy photons from laser



High-energy (relativistic) photon



A. Hartin, A. Ringwald, N. Tapia: arXiv:1807.10670,

- **Use spectrum of high energy photons created via Bremsstrahlung**
  - Full calculation agrees with asymptotic limit for $\xi > 1$ and $\chi \lesssim 1$