LUXE

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

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HELMHOLTZ
SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

Online seminar in Bologna, Frascati and Padova, January 2021

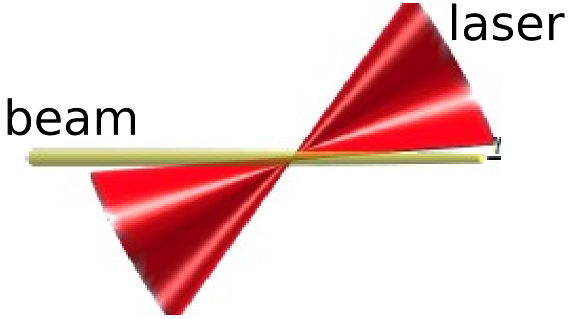
OUTLINE

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

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

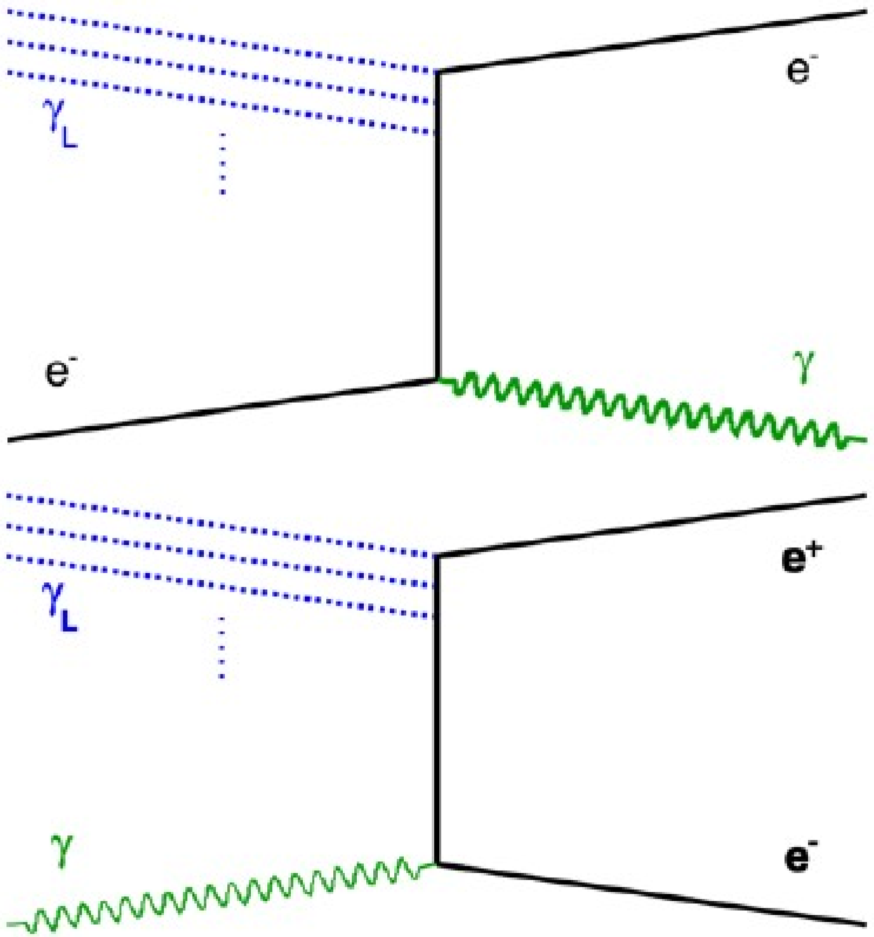
LUXE: LASER UND XFEL EXPERIMENT

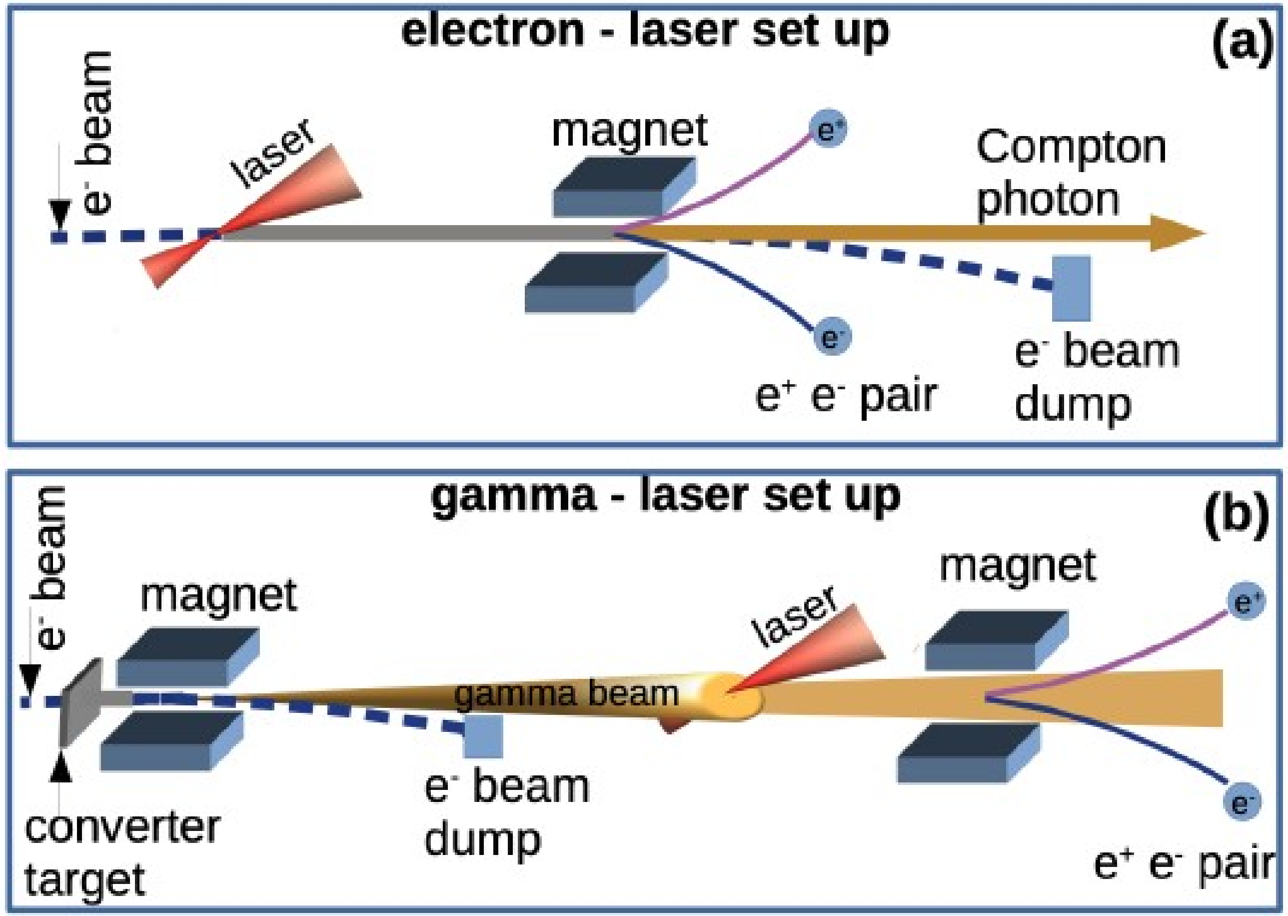
What is LUXE?



- **New experiment planned in Hamburg using**
  - European XFEL accelerator
  - High-power laser
- **Documentation:**
  - Letter of Intent published in Sept. 2019: https://arxiv.org/abs/1909.00860
  - Conceptual Design Report (CDR) about to be published
- **Multi-purpose experiment**
  - It offers a range of new measurements and a variety of detector technologies is needed to accomplish the physics goals
- **Collaboration**
  - Not yet formally founded collaboration (process started)
  - CDR includes authors from 29 institutions

CONCEPTUAL IDEA OF LUXE EXPERIMENT

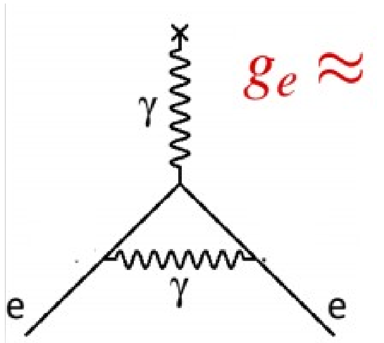




SCIENTIFIC MOTIVATION

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:
    - At leading order
    - $O(\alpha)$ correction calculated by Schwinger (1947):
    - State-of-the-art calculations includes terms $O(\alpha^5)$
    - Precision better than 10^{-9}!
  - Anomalous magnetic dipole moment of muon shows interesting tension
    - New experiment at FNAL ("Muon g-2") => ~factor 4



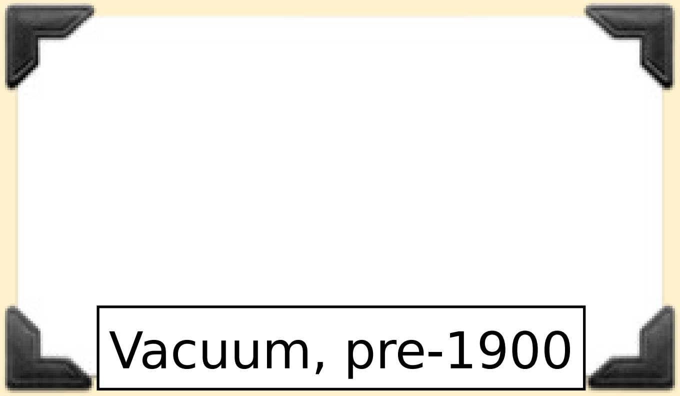
R. Feynman on QED: *"the price of gaining such an accurate theory has been the erosion of our common sense."*

THE VACUUM

The Vacuum

Classical Theory:

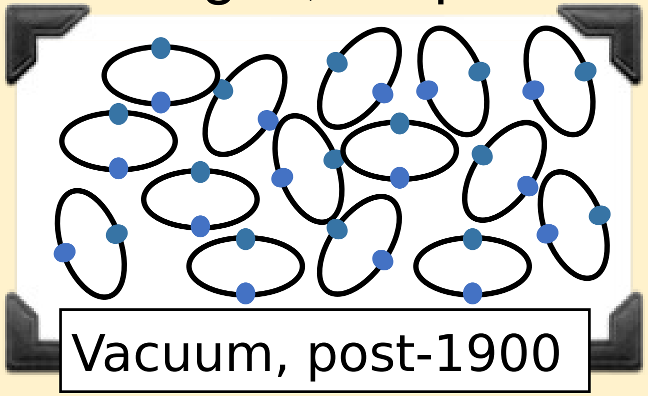
- "space devoid of matter"
- "space-time region where all elements of stress-energy tensor are zero"
  → no momentum, energy, particles or fields



Vacuum, pre-1900

Quantum (Field) Theory:

- "state with lowest energy"
- average is zero, but <u>variance non-zero</u>
- vacuum consists of virtual particles
  → can be charged, couple to fields

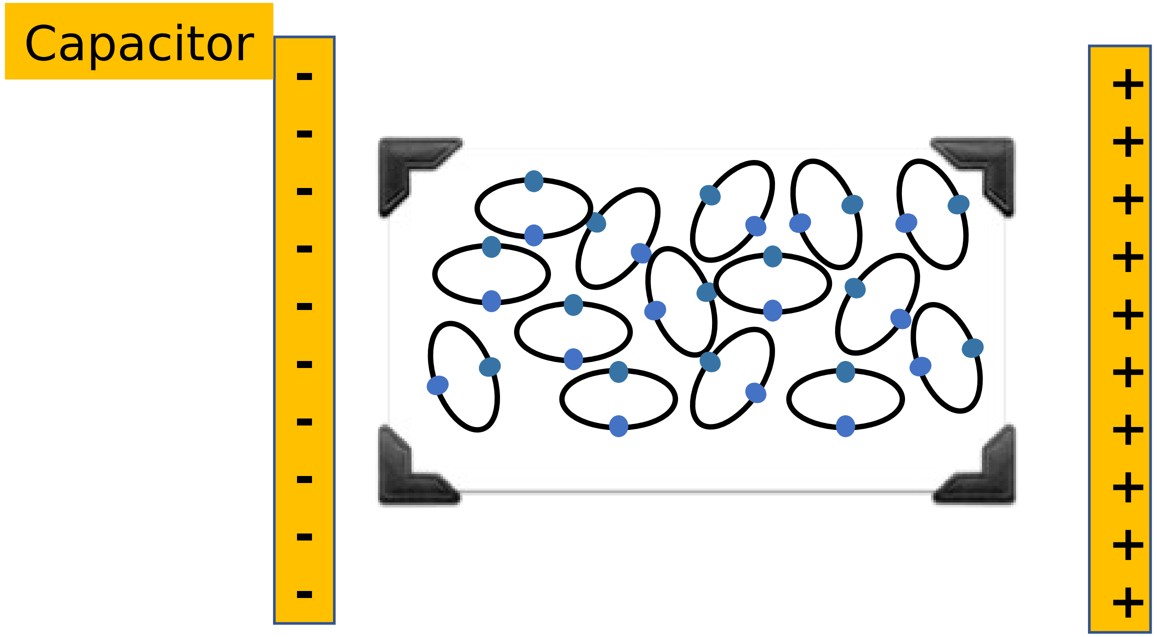


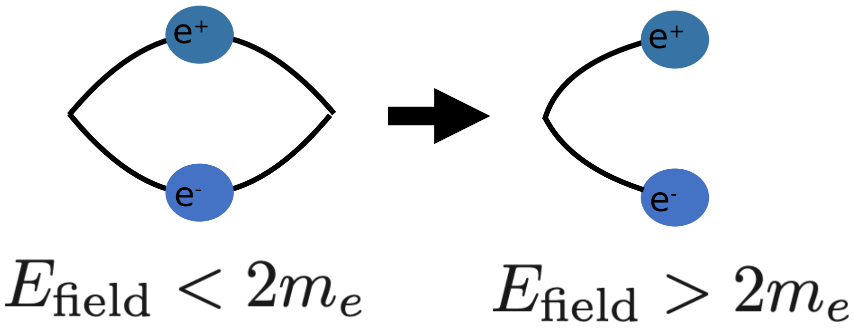
Vacuum, post-1900

With LUXE we want to boil the vacuum

VACUUM INSIDE STRONG FIELD

What happens if we now put the vacuum inside a strong field?





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

Vacuum boils if field large enough to create real pairs:
"critical field"= work by field over

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:

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

($\mathfrak{E}$, $\mathfrak{B}$ Kraft auf das Elektron.

$$|\mathfrak{E}_k| = \frac{m^2 c^3}{e\hbar} = \frac{1}{„137“}\,\frac{e}{(e^2/m c^2)^2} = \text{„Kritische Feldstärke“.}$$)

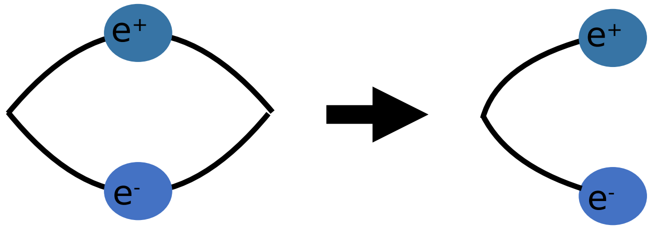
Z.Phys. 98 (1936) no.11-12, 714-732
(translation at arXiv:physics/0605038

THE CRITICAL FIELD

Presence of strong external field:

- work by field over Compton wavelength > than two rest masses of particles→ critical field (aka “Schwinger limit”)

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



$E_{\text{field}} < 2m_e$ $E_{\text{field}} > 2m_e$

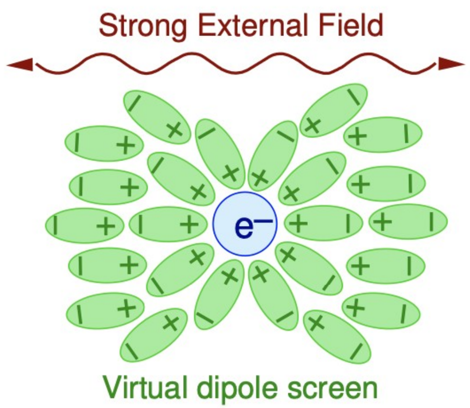
1) Field-Induced Pair Creation:

- pair production from vacuum $P \propto exp\left(-\pi \frac{\varepsilon_{crit}}{\varepsilon}\right)$

Schwinger 1951

2) Modified Compton Spectrum:

- electron becomes “dressed” => larger effective m_e



STATIC ELECTRIC FIELD VS LASER FIELD

- **Pair production in a constant static field via tunneling ("Schwinger process")**

$$\Gamma_{\text{Schwinger}} \propto \left(\frac{\mathscr{E}_S}{\mathscr{E}_{\text{cr}}}\right)^2 \exp\left[-\pi\frac{\mathscr{E}_{\text{cr}}}{\mathscr{E}_S}\right]$$

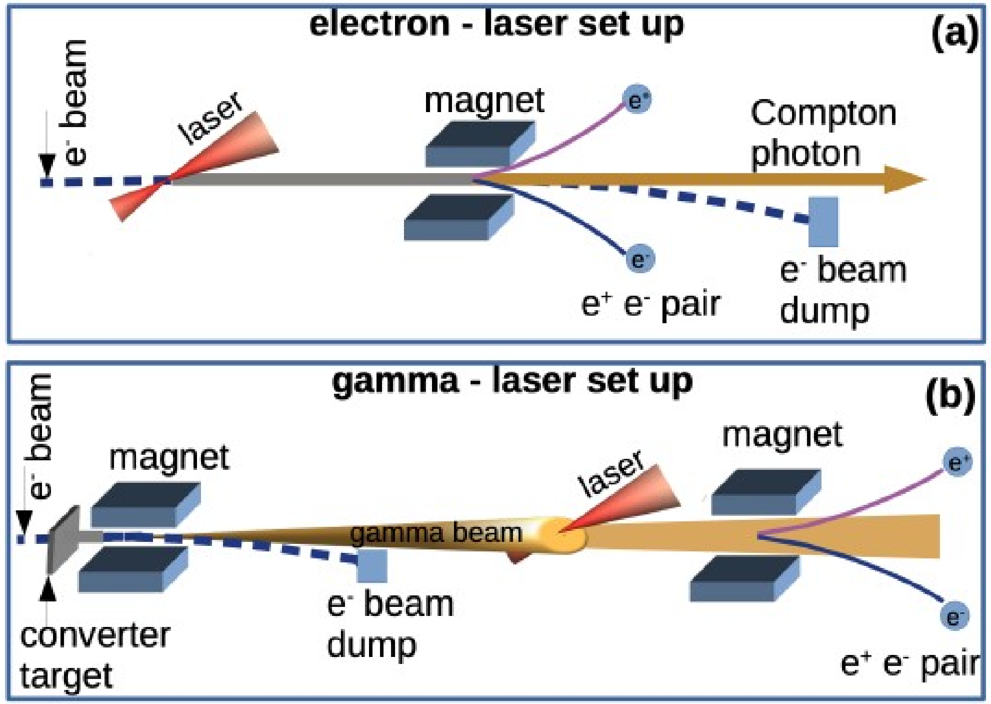
- **Pair production in plane wave laser: asymptotic result**

$$\Gamma_{\text{BW}} \propto \left(\frac{\mathscr{E}_{\text{L}}}{\mathscr{E}_{\text{cr}}}\right)^2 \exp\left[-\frac{8}{3}\frac{1}{\gamma_e(1+\cos\theta)}\frac{\mathscr{E}_{\text{cr}}}{\mathscr{E}_{\text{L}}}\right]$$

PARTICLE BEAM AND LASER

- Use laser to generate electric field
- Use high energy electron beam $\gamma = \frac{E_{beam}}{m_e}$

$$\xi = \frac{e\,\varepsilon_L}{m_e \omega_L c} \propto I_{Laser} \qquad \chi \approx \gamma \frac{\varepsilon_L}{\varepsilon_{crit}} \propto \sqrt{I_{Laser}}\, E_{beam}$$



- Laser intensity required to reach Schwinger field ():

Beam energy	I_{Laser} [W/cm2]
1 eV	2×10^{29}
1 GeV	$\sim10^{22}$
10 GeV	$\sim10^{20}$

> Much beyond currently achievable values
> State-of-the-art laser needed (~10 PW)
· Can use well-tested laser technology (~100 TW

~10 GeV beams can reach Schwinger limit in rest frame with current laser techn

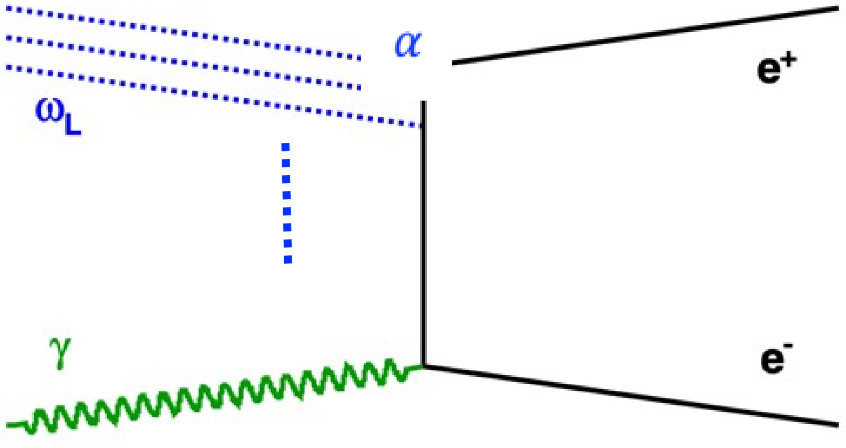
CROSS SECTION OF QED PROCESSES

- Perturbative QED valid
  - For n photons: n vertices =>
  - With it follows:

- If 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 and
  - Since cannot expand perturbatively

Low-energy photons from laser



High-energy (relativistic) photon

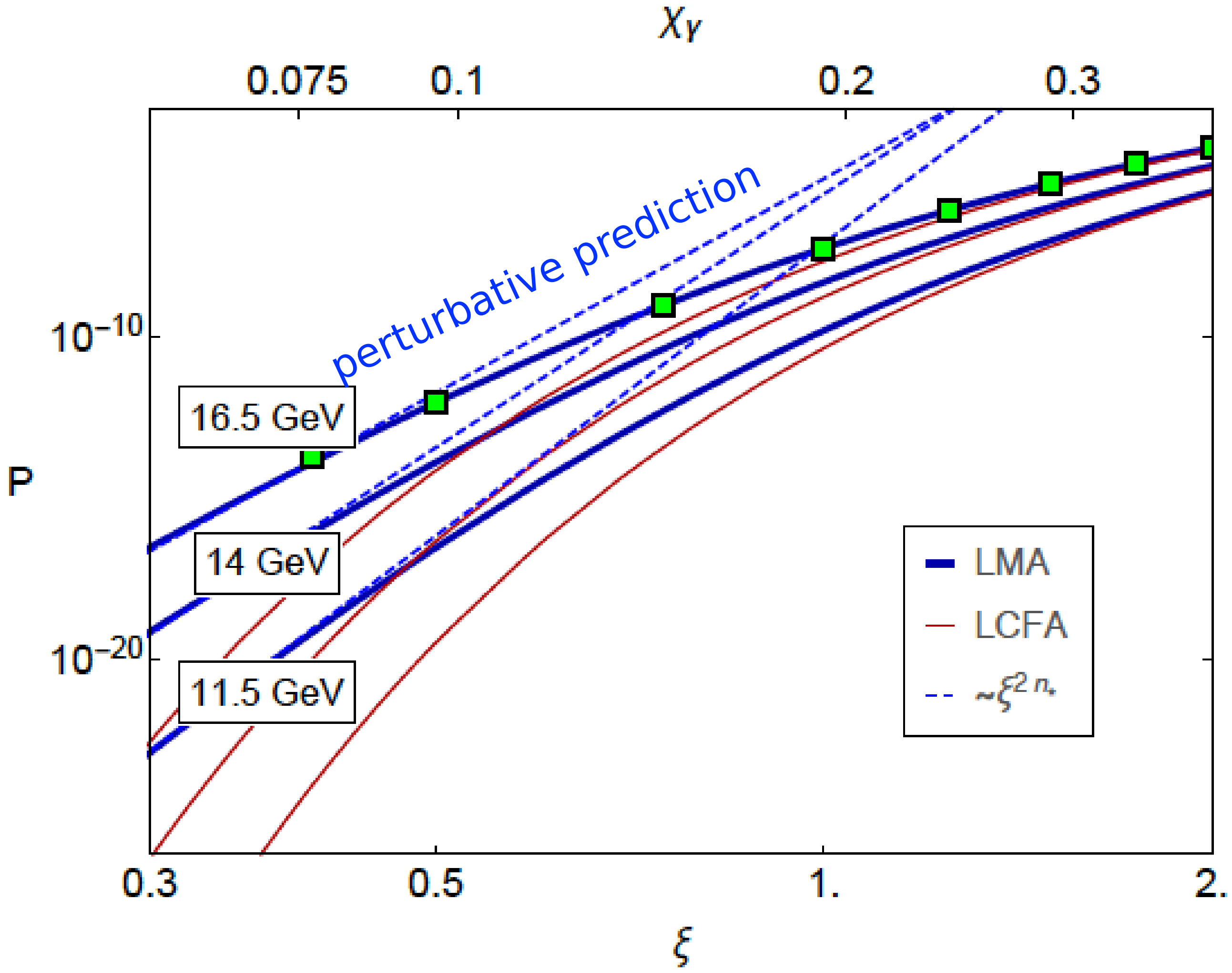
ABSORBING LIGHT WITH LIGHT

- **Prediction for rate of positrons per laser shot**
  - Perturbative regime: power-law

$$\xi \ll 1 : R_{e^{+¿}} \propto \alpha^{n} \propto \xi^{2n} ¿$$

  - Non-perturbative regime: departure from power-law

$$\xi \gg 1 : R_{e^{+¿}} \propto \chi_{\gamma} \exp\left(-\frac{8}{3\,\chi_{\gamma}}\right) ¿$$



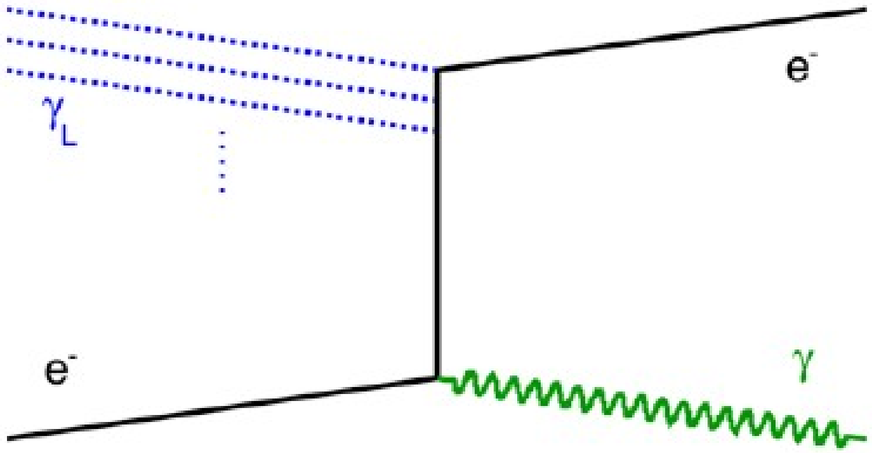
T. Blackwell, B. King

MAIN PROCESSES OF INTEREST

Low-energy photons from laser (E=1.5 eV)

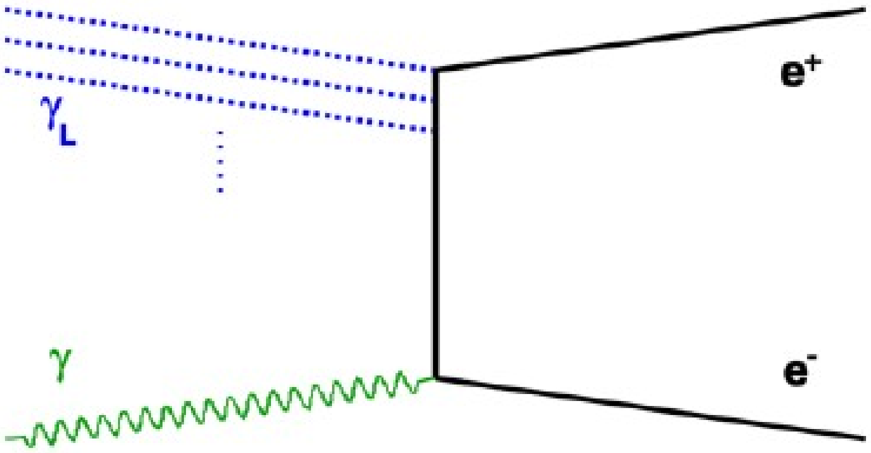
Compton

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



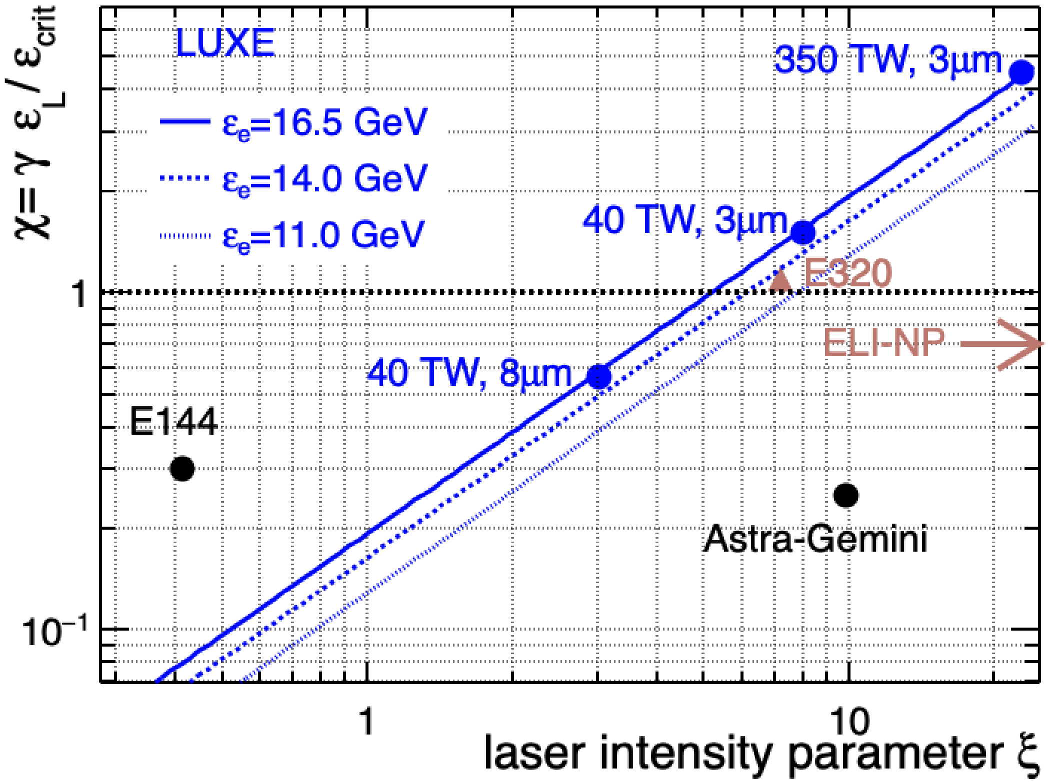
Breit-Wheeler: pair production

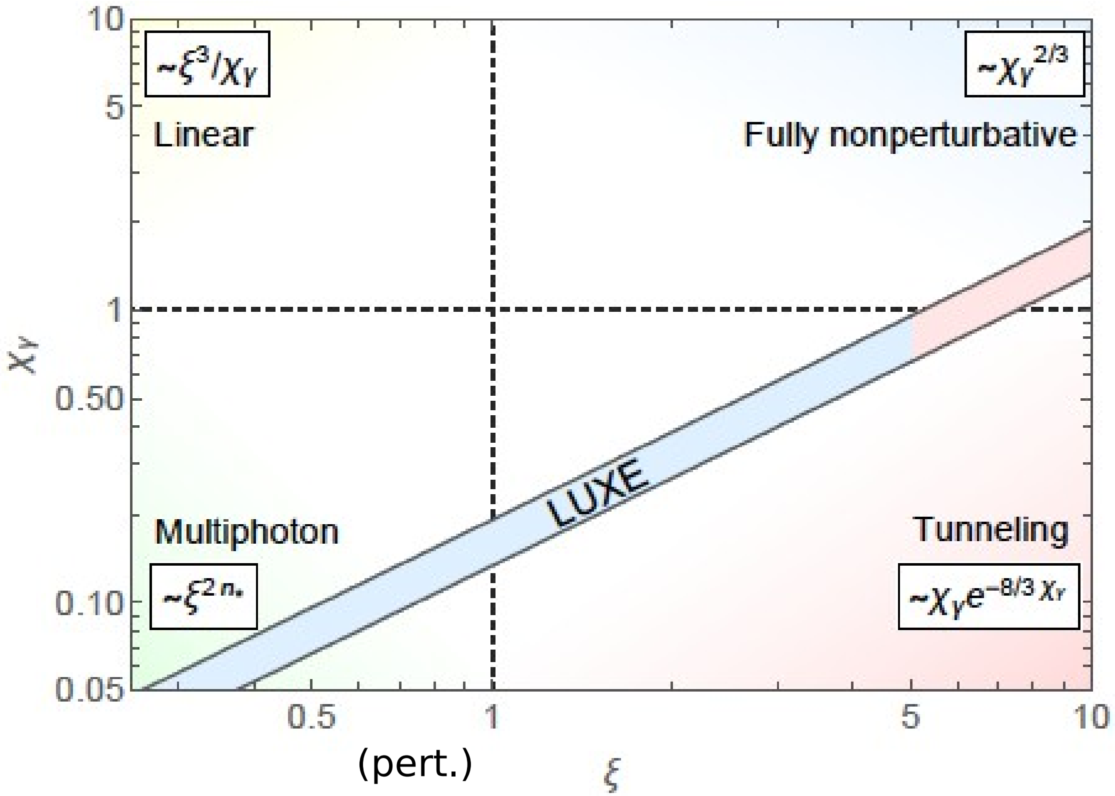
$$\gamma + n\gamma_L \rightarrow e^+ e^-$$



- **High energy electron or photon interacts with laser**
  - Also higher order process "trident": $e^- + n\gamma_L \rightarrow e^- e^+ e^-$
  - E144 experiment probed $e^- + n\gamma_L$ process in perturbative regime
  - LUXE first to directly probe $\gamma + n\gamma_L \rightarrow e^+ e^-$

LUXE IN CONTEXT



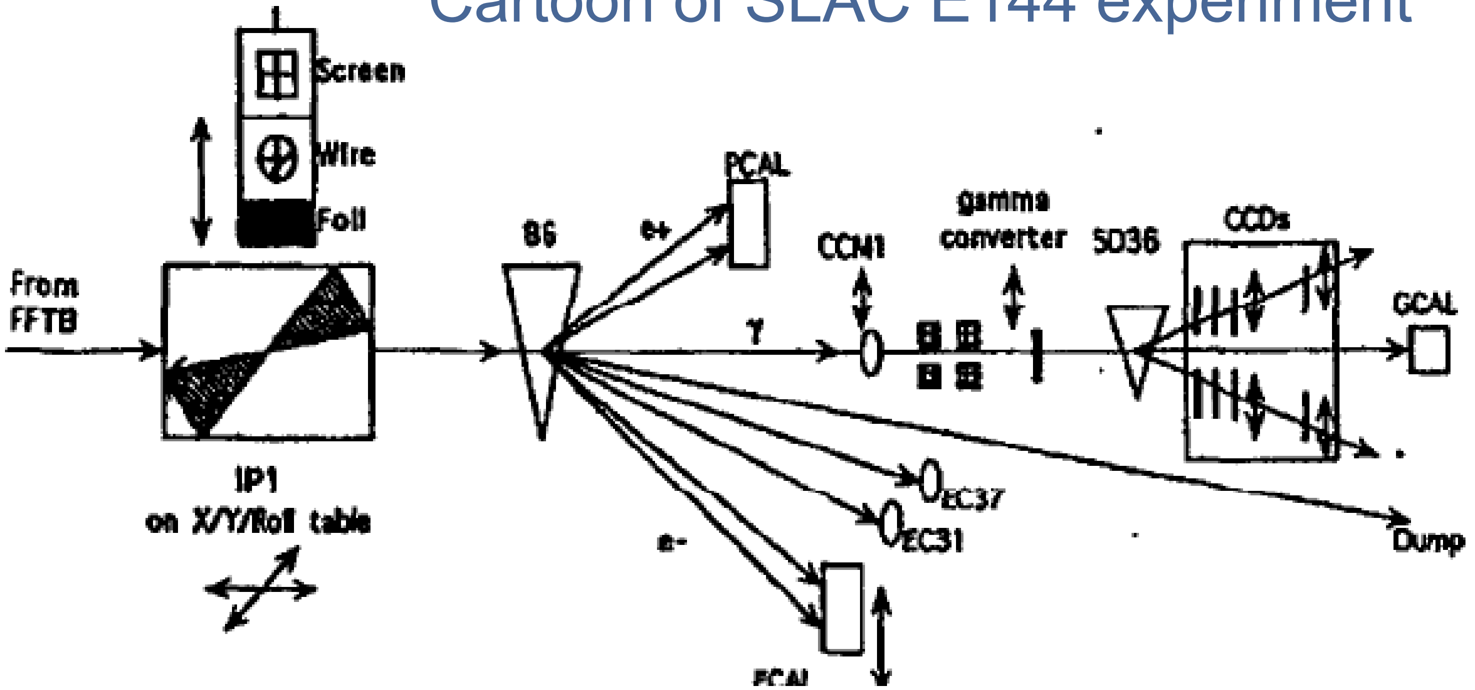


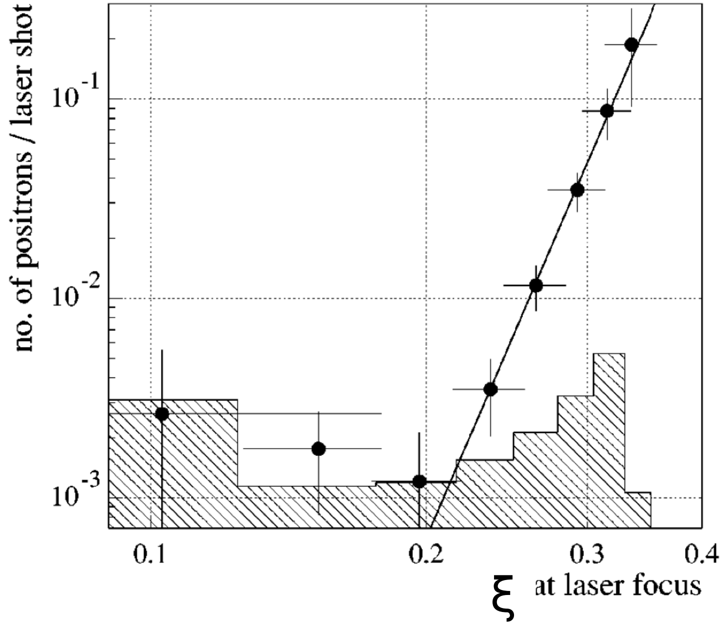
- LUXE has good chance to be first to actually break into regime
- And only experiment proposed to directly explore photon-laser interactions

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 power-law increase 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 specks 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 thou... most powerful.

But the opposing beam of ra... 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

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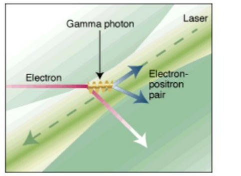
Science 29 Aug 1997:
Vol. 277, Issue 5330, pp. 1202
DOI: 10.1126/science.277.5330.1202

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 inverse 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).

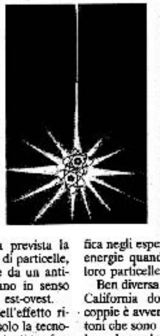


Corriere della Sera DOMENICA 21 SETTEMBRE 1997 19

L'importante risultato ottenuto a Stanford

Dalla luce è nata la materia Come predisse Einstein

di LANFRANCO BELLONI



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

FORSCHUNG UND TECHNIK

Materie aus Licht erschaffen

Amerikanischen Physikern gelingt technischer Durchbruch

Wie 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.

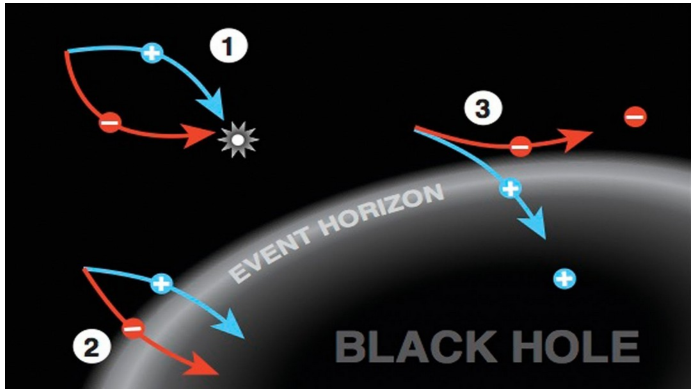
WHY IS STRONG-FIELD QED INTERESTING?

- **Relevant to numerous phenomena in our Universe**
  - Astrophysics: Hawking radiation, surface of neutron stars (magnetars), cosmic ray propagation
  - Condensed matter and atomic physics (Z>137)
  - Accelerator physics: high energy e^+e^- colliders
  - Transition from perturbative to non-perturbative regime
    - could teach us about other non-perturbative regimes, e.g. understanding confinement [Gribov, hep-ph/9902279]

- **And ….. what could be more exciting than probing quantum physics in a new regime!?**
  - M. Peskin at Snowmass 20/21: ”*…the motivation of exploring the regime is very strong”*

ANALOGY TO HAWKING RADIATION

- **Energy needed to create on-shell e^+e^- pair:**
- **Grav. Field near the event horizon:**
- **Schwarzschild radius . =>**
- **Energy to separate pair:**



H. Murayama

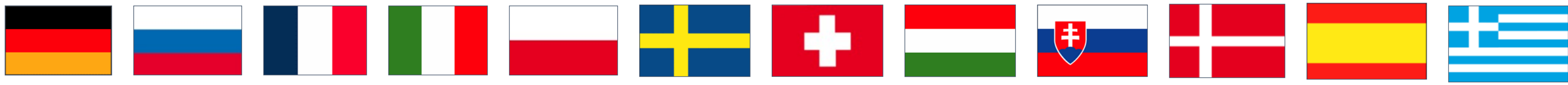
Hawking radiation possible if virtual pair becomes real, i.e.

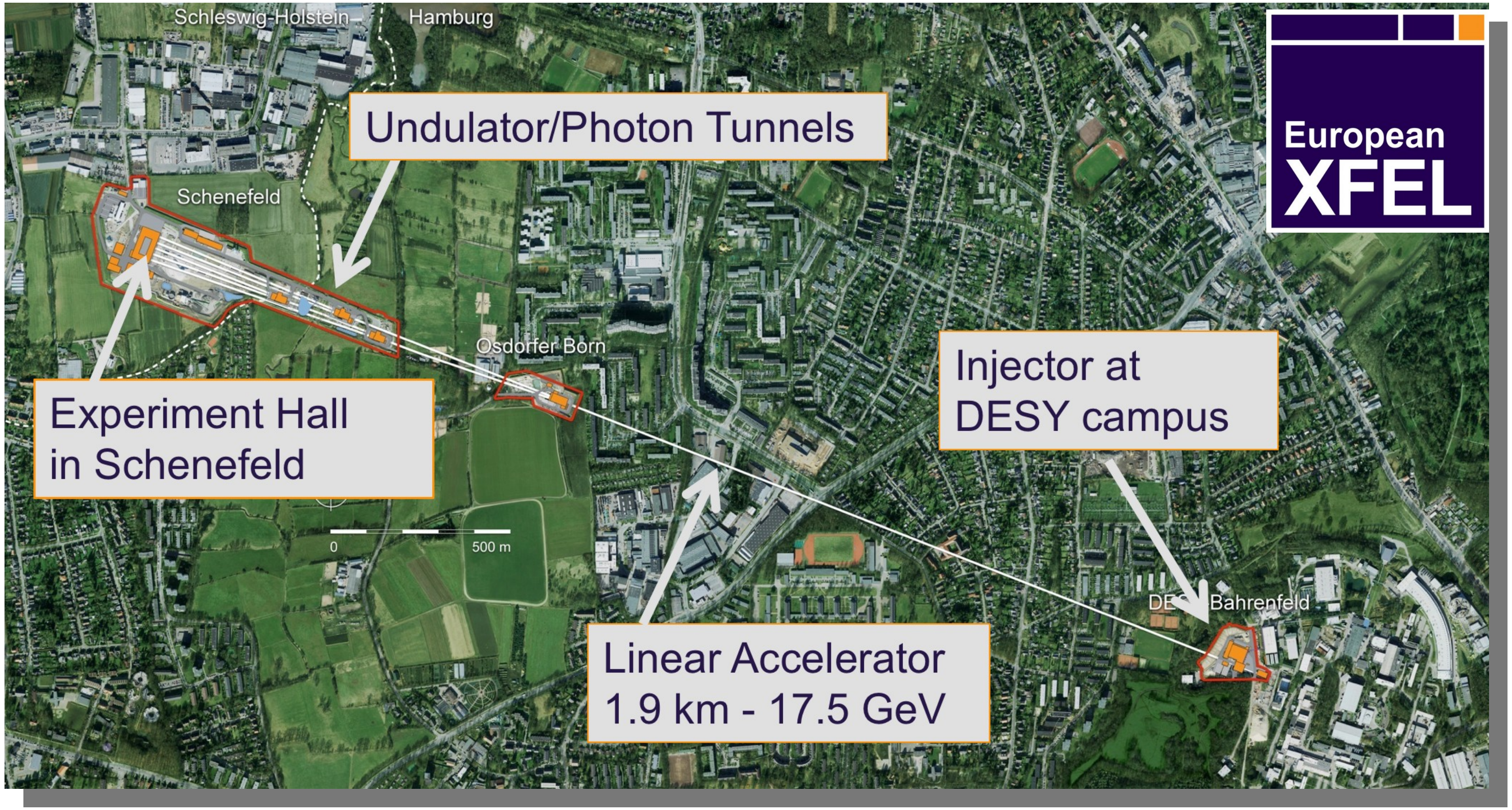
ACCELERATOR AND LASER

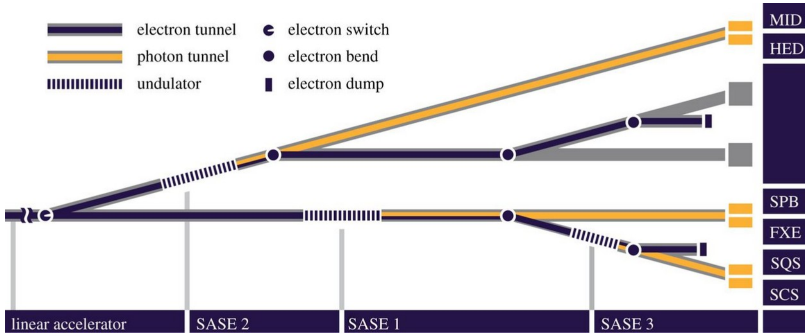
THE EUROPEAN XFEL

Electron accelerator:

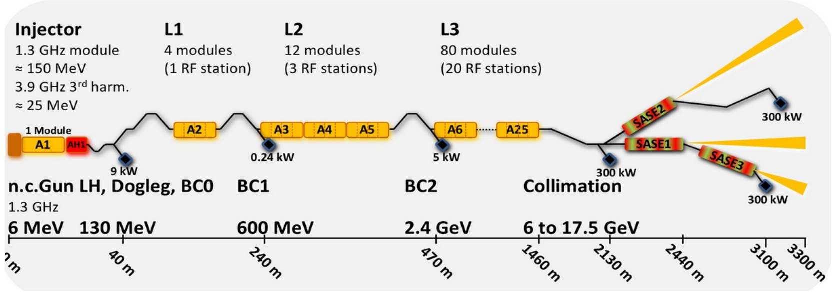
- 2.1 km 17.5 GeV SCRF linear accelerator
- 2700 electron bunches at rate of 10 Hz
- X-ray photons produced in undulators
- Experiments for physics, material science, chemistry, biology, …

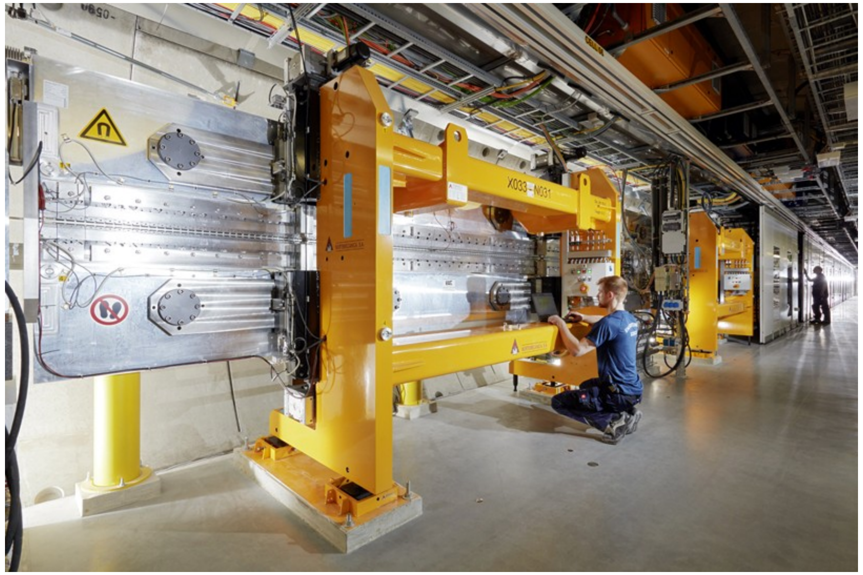


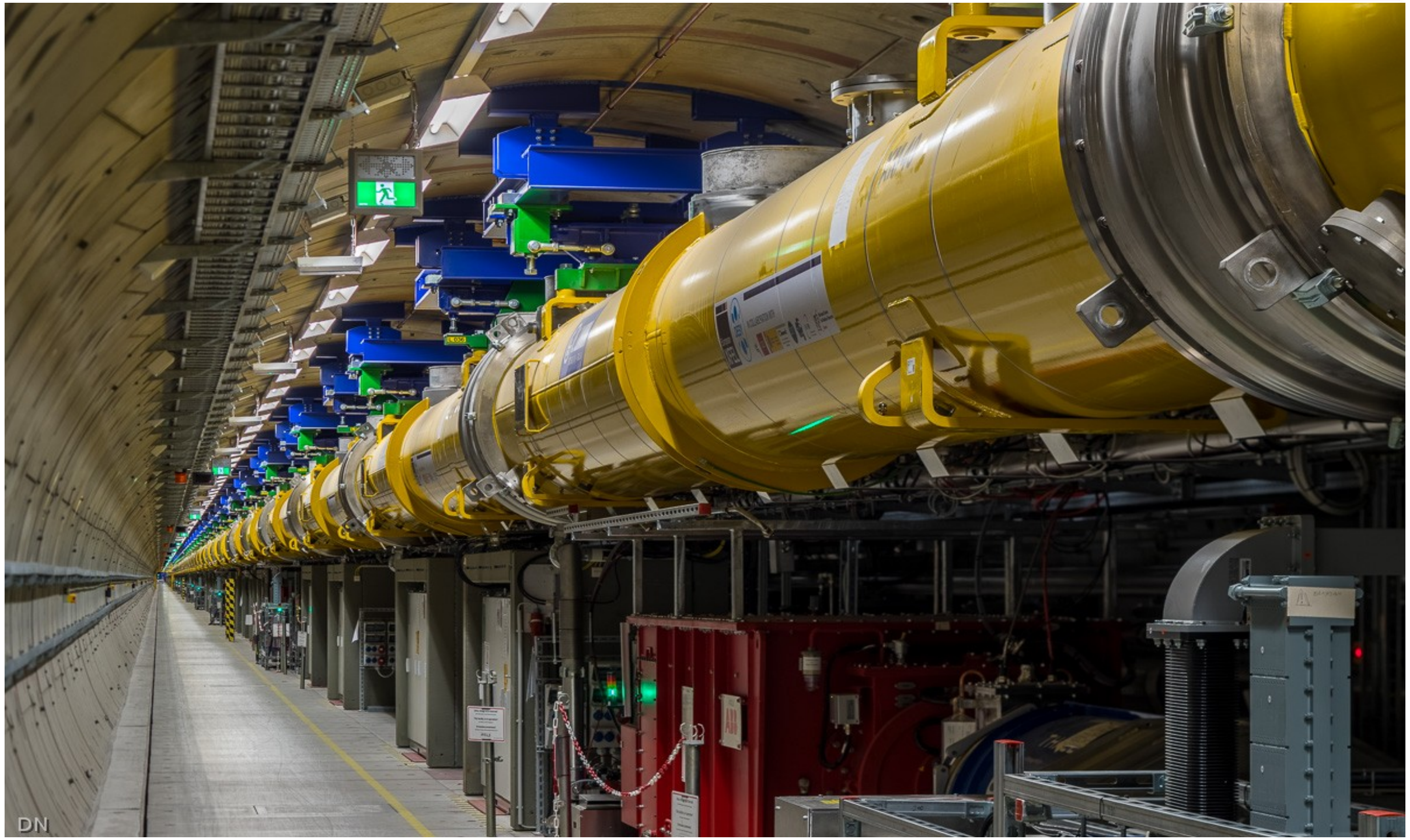




View along L3 accelerator section and undulator







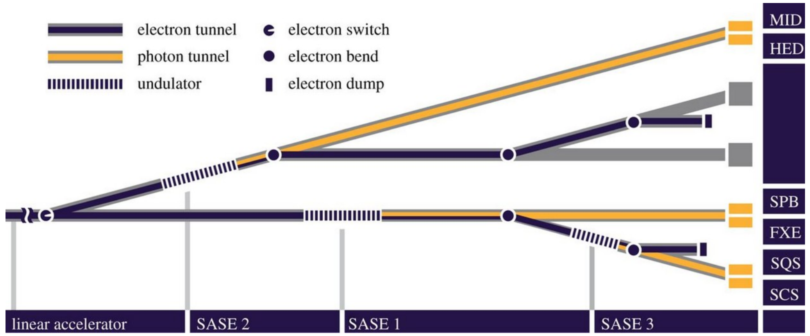
EUROPEAN XFEL INAUGURATION

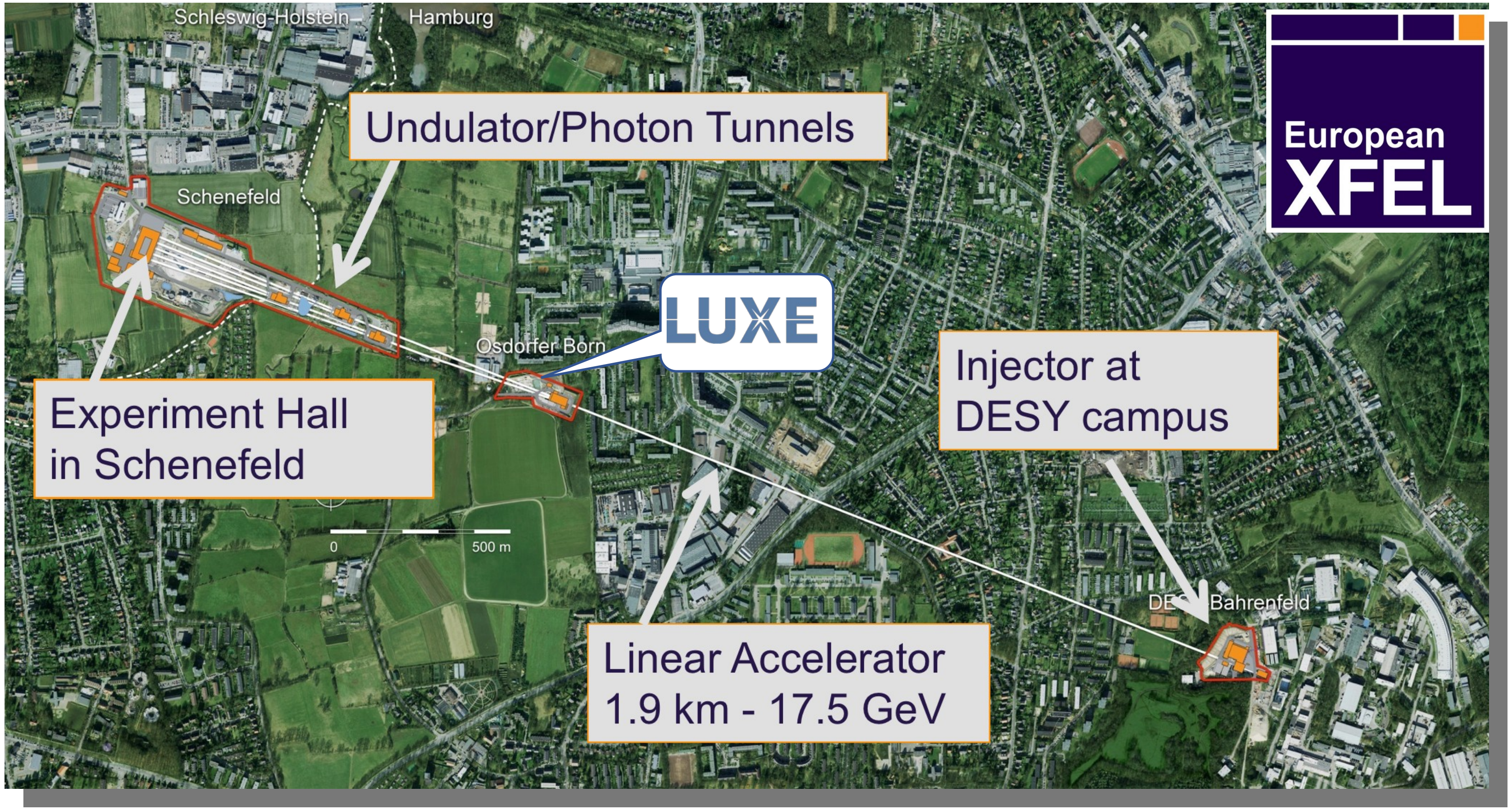
Operating since September 2016

THE EUROPEAN XFEL

Electron accelerator:

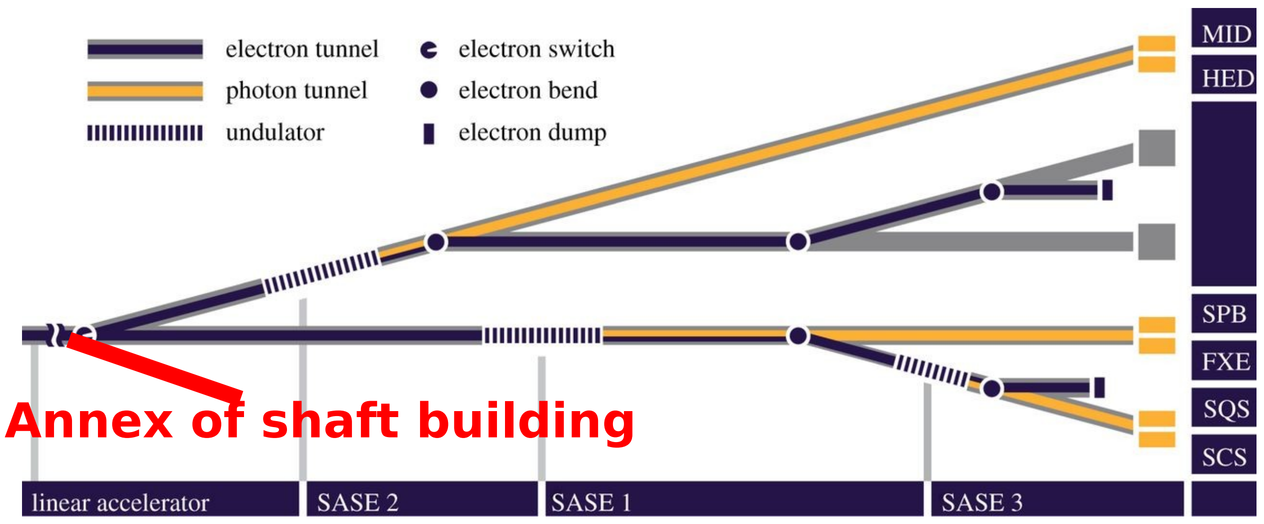
- 2.1 km 17.5 GeV SCRF linear accelerator
- 2700 electron bunches at rate of 10 Hz
- X-ray photons produced in undulators
- Experiments for physics, material science, chemistry, biology, …

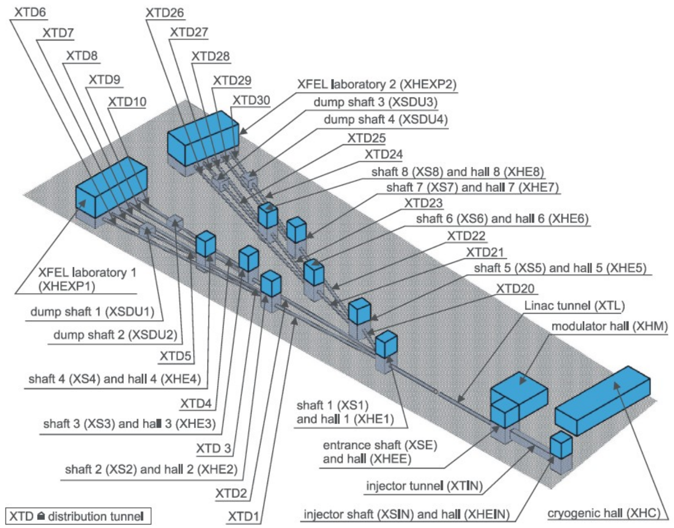




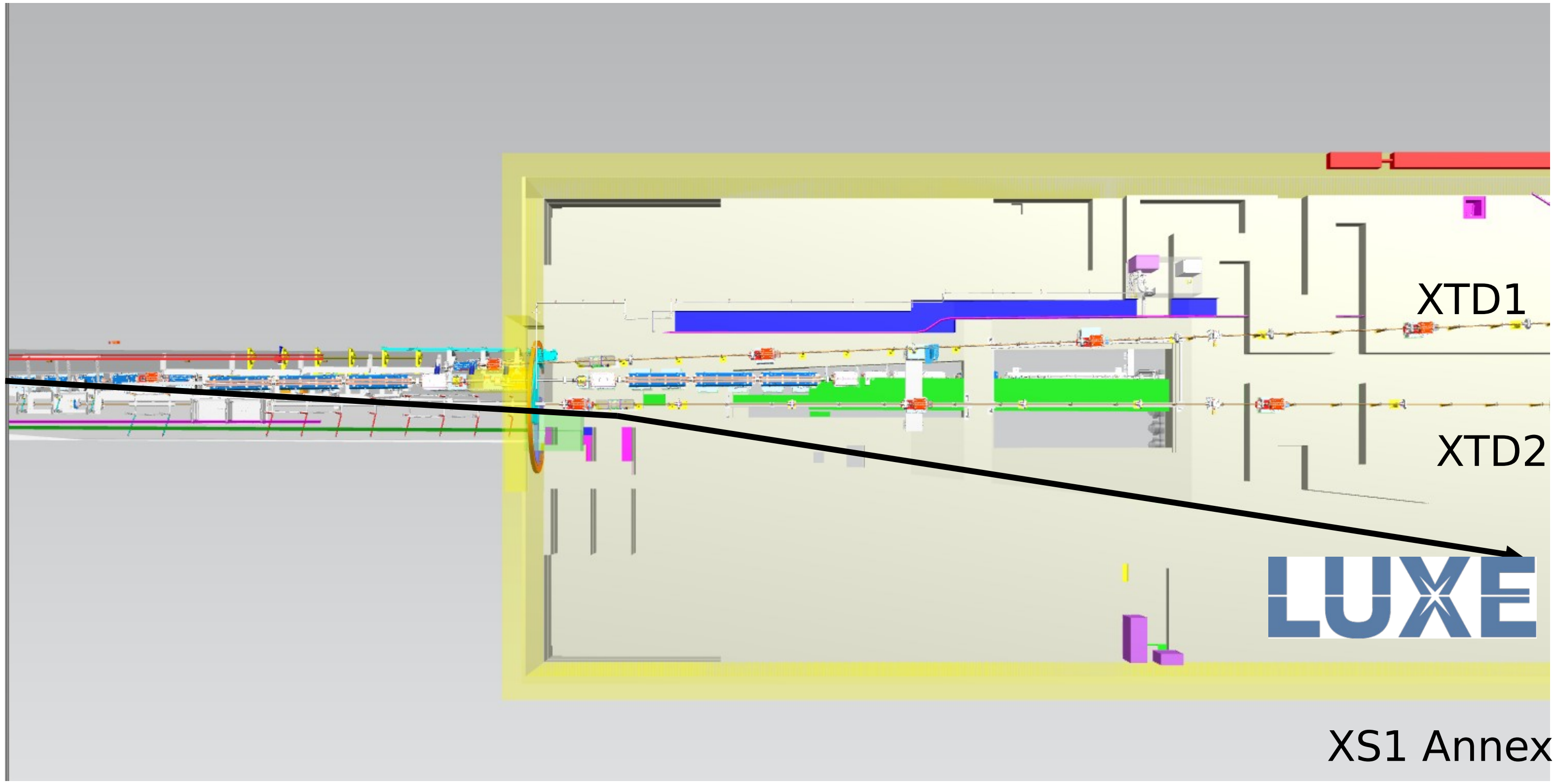
LOCATIONS IN EU.XFEL TUNNEL

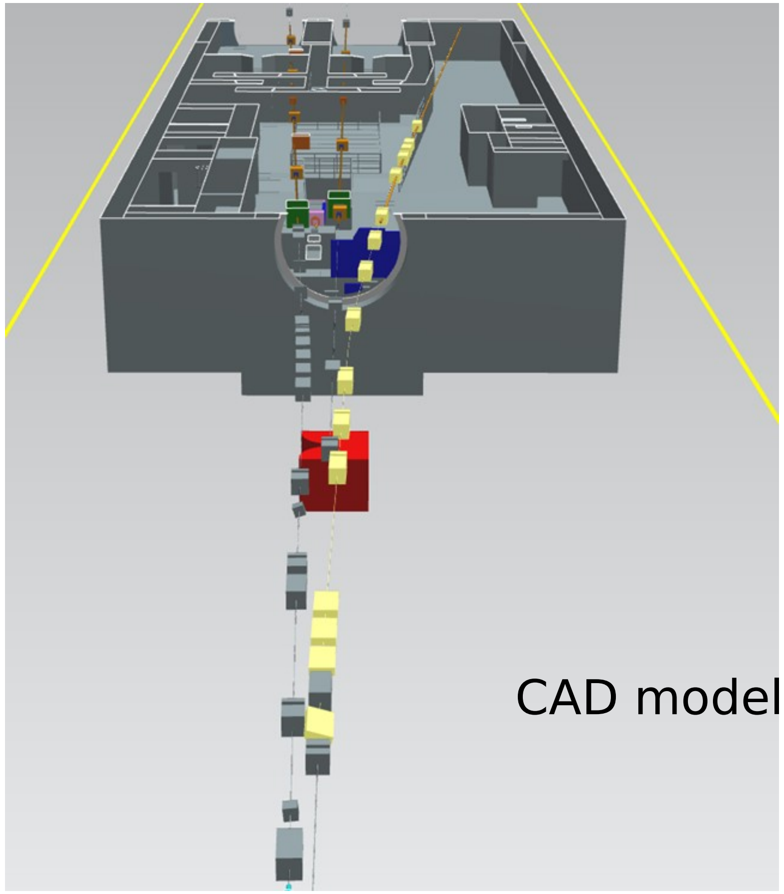
- **Location at EU.XFEL:**
  - Annex of shaft building XS1: at end of electron accelerator
  - Was build for 2nd EU.XFEL fan foreseen for later (>2029)
- **Design aims to have no impact on photon science programme**
  - Use only 1 of the 2700 bunches in bunch train (kicked out by fast kicker magnet)





SCHEMATIC VIEW: BEAM EXTRACTION AND TRANSFER



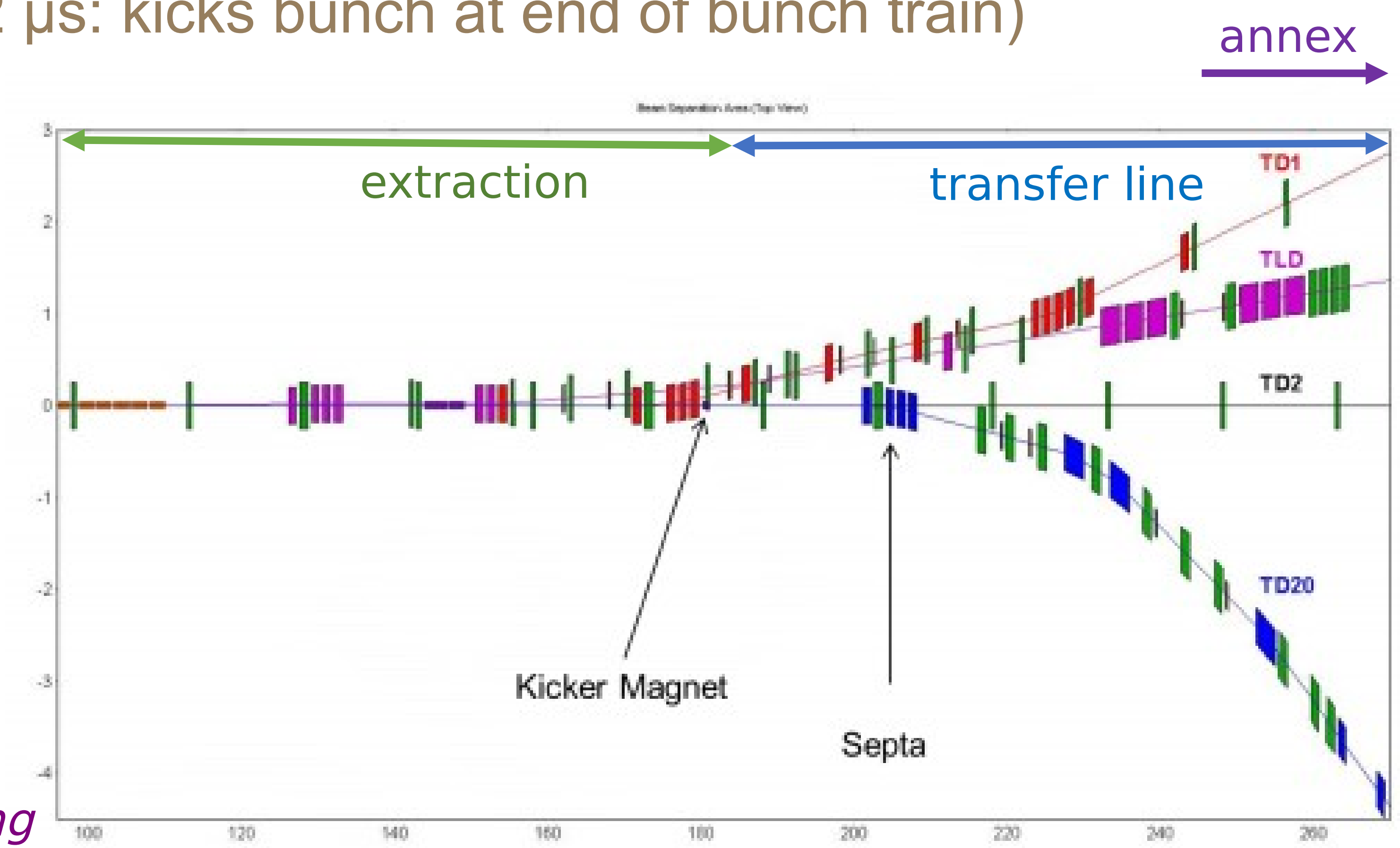


M. Huening, M. Scheer, F. Burkart, W. Deckin

BEAMLINE LAYOUT

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

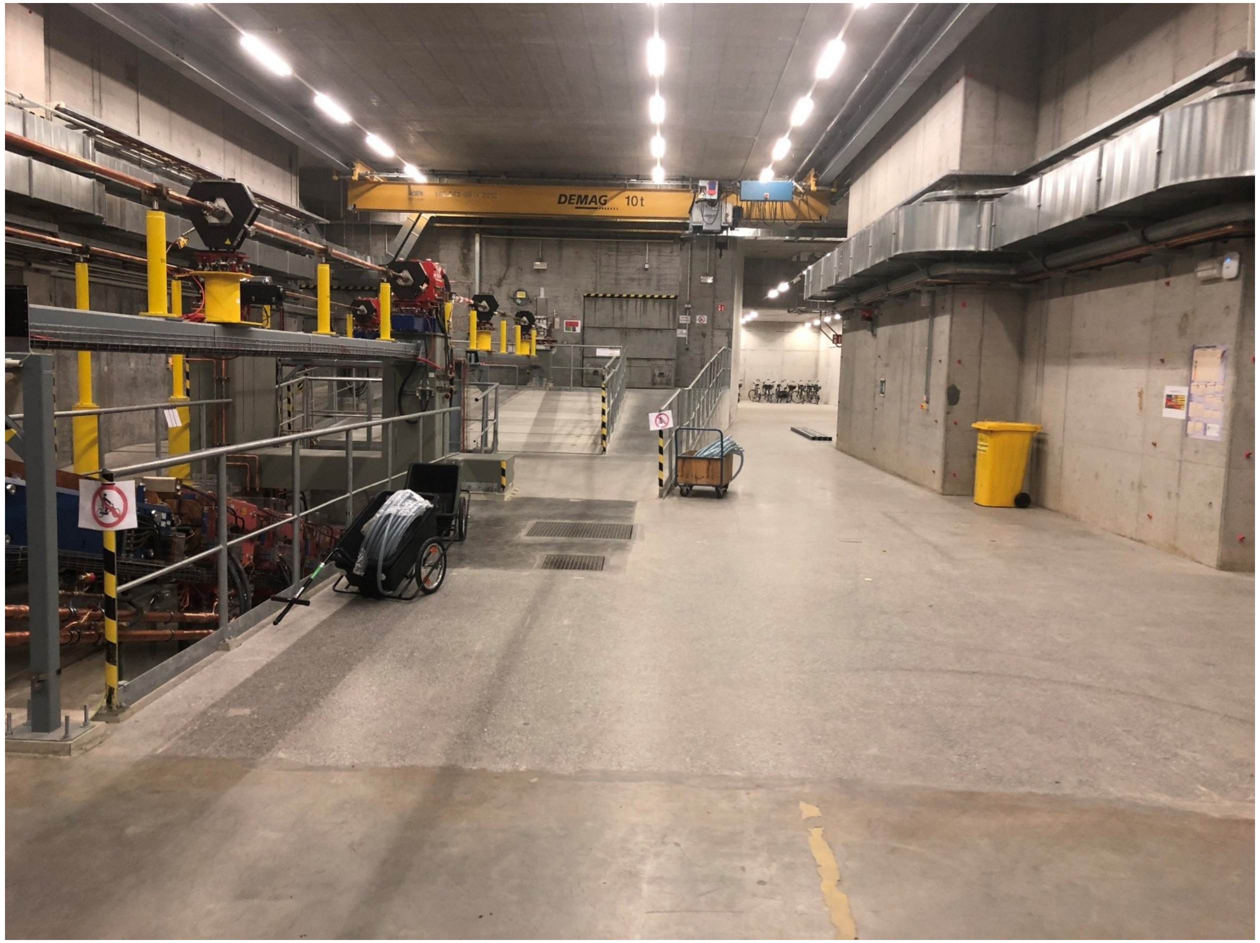
- Most magnets use design already operating today in XFEL.EU
- New fast kicker magnets (2 μs: kicks bunch at end of bunch train)



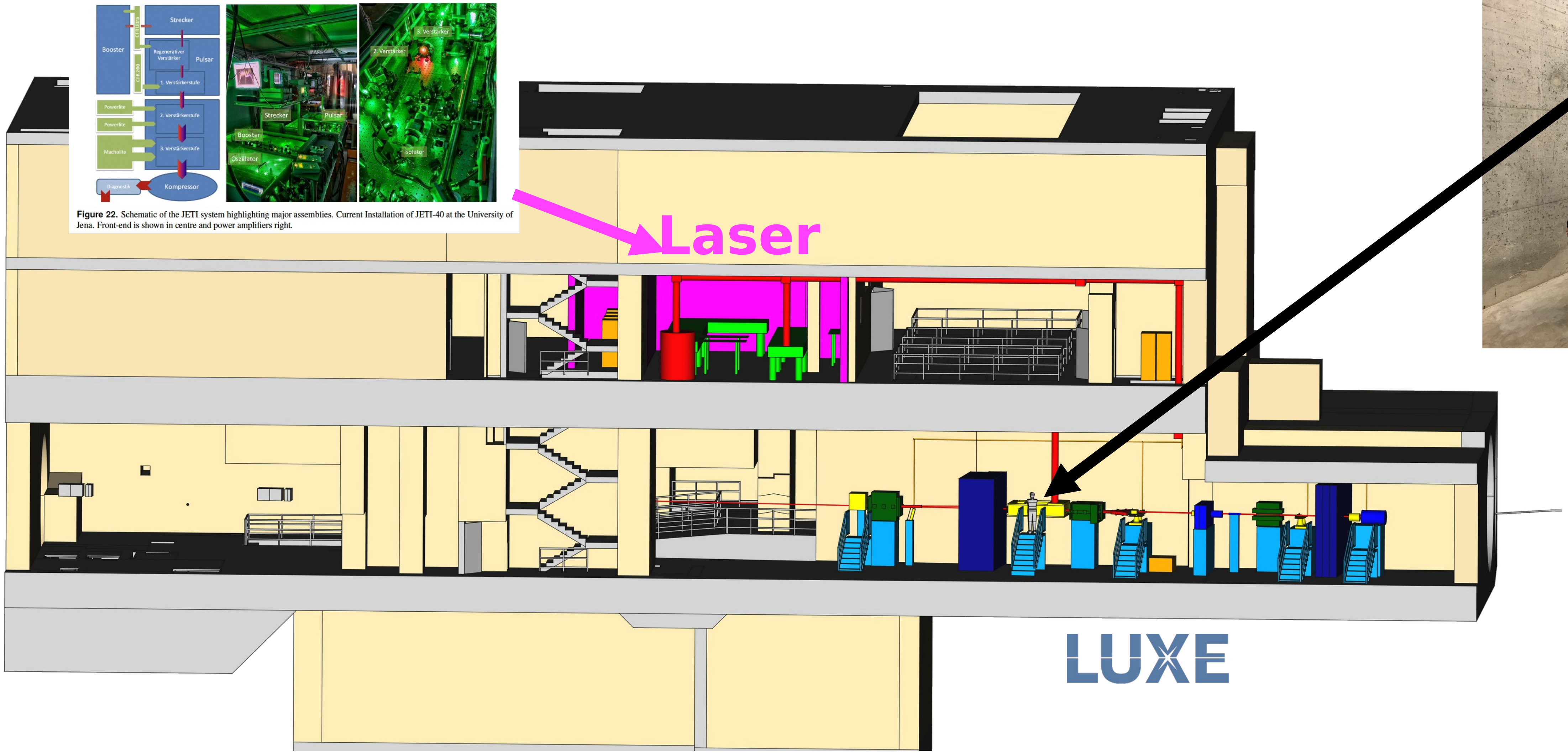
PICTURE OF TUNNEL AT XS1 ANNEX

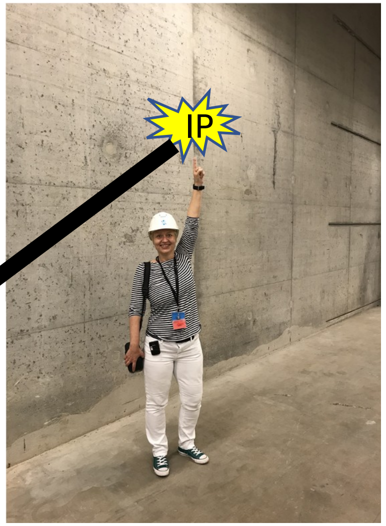
- **Shaft located at end of linear accelerator of European XFEL**

- **Dimensions of annex**
  - 60m long, 5.4m wide, 5m high



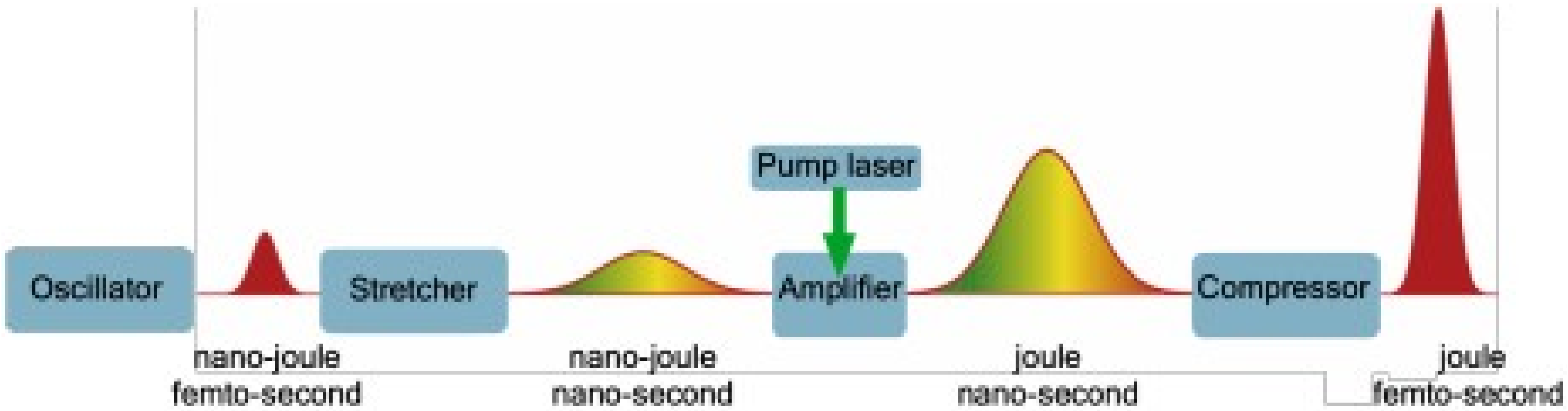
XS1 BUILDING

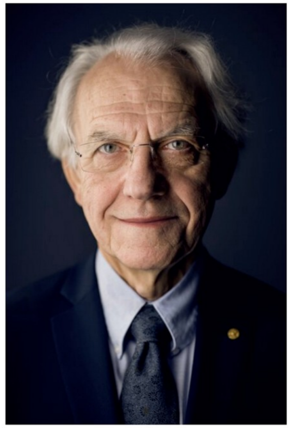




LUXE

LASER TECHNOLOGY





© Nobel Media AB. Photo: A. Mahmoud

Gérard Mourou

Prize share: 1/4

© Nobel Media AB. Photo: A. Mahmoud

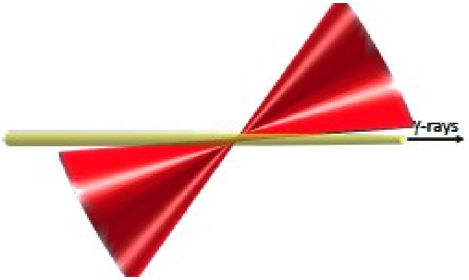
Donna Strickland

Prize share: 1/4

- **Use Chirped Pulse Amplification (CPA) technique**
  - Half of the NP 2018 shared by Gerard Mourou and Donna Strickland "*for their method of generating high-intensity, ultra-short optical pulses*."
- **Use Ti:Sa laser with 800 nm wavelength (E=1.55 eV)**
- **Energy focussed strongly in both time and space => high intensity**
- **Experiment has two phases:**
  - Initially 40 TW (phase-0), later 350 TW (phase-I)

LASER PARAMETERS

- Repetition rate: 1 Hz
- Pulse length 30 fs
- Collision angle: 17.2 degrees



Parameter	Phase-0	Phase-0	Phase-I
Laser energy after compression [J]	1.2		10
Percentage of laser in focus [%]	50		
Laser focal spot size w_0 [μm]	>8	>3	>3
Peak intensity [10^{19} W/cm²]	**1.9**	**13.3**	**120**
Peak intensity parameter ξ	**3.0**	**7.9**	**23.6**
Peak quantum parameter χ: E_{beam}=16.5 GeV E_{beam}=14.0 GeV	**0.56** **0.48**	**1.50** **1.28**	**4.5** **3.8**

Laser intensity:

with

E_L: energy (J)

Δt: pulse length (s)

: focus area (m²)

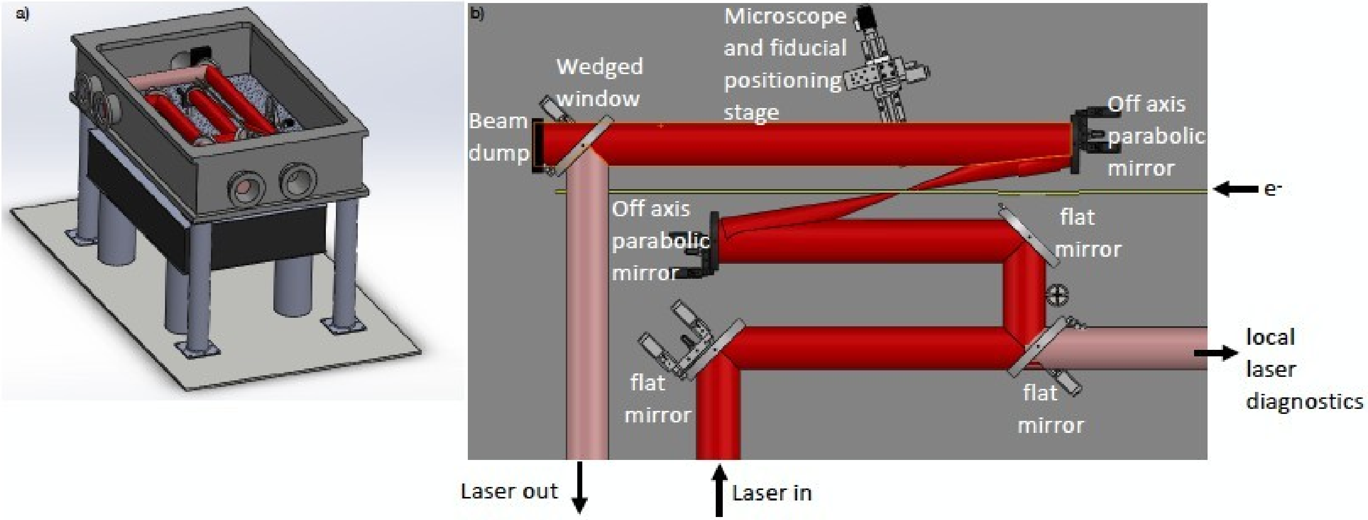
intensities achieved by de-focussing laser or stretching pulse

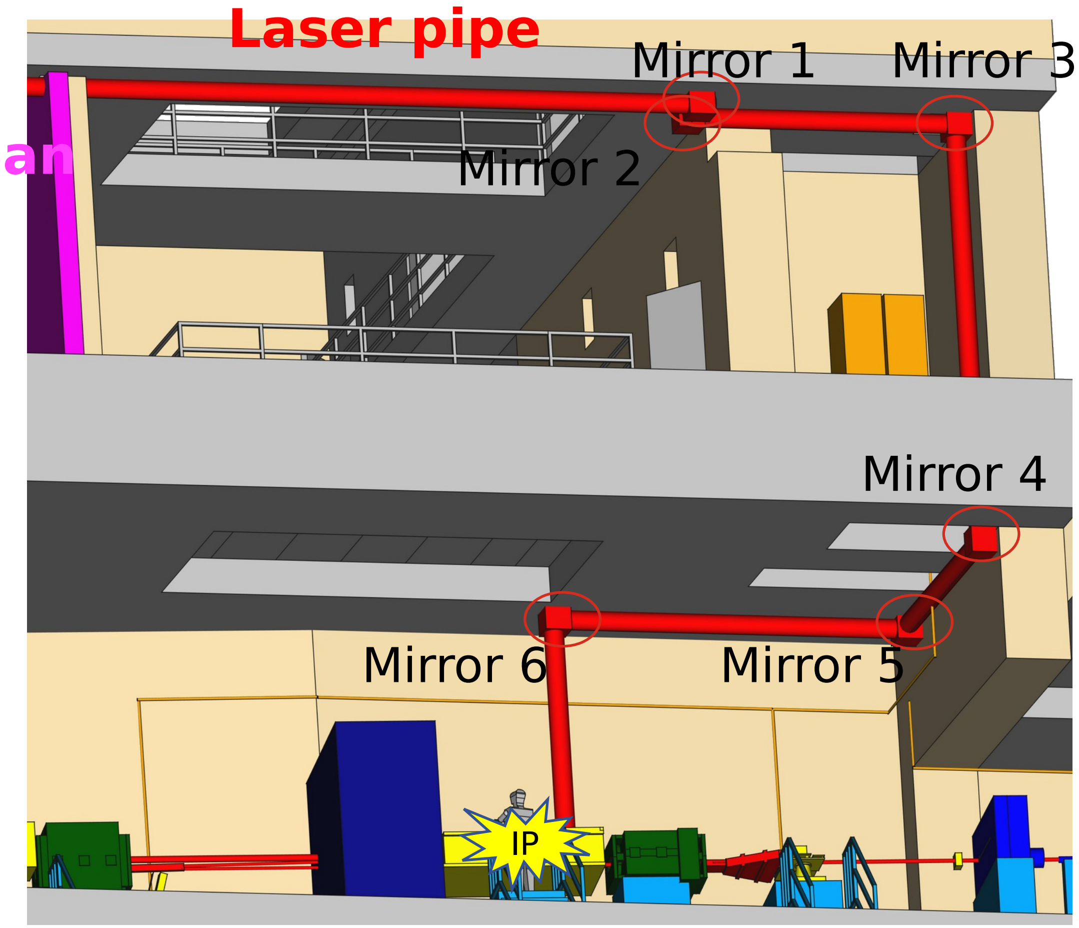
LASER BEAMLINE

Laser guided from laser clean room to IP via 40 m long pipe and six mirrors

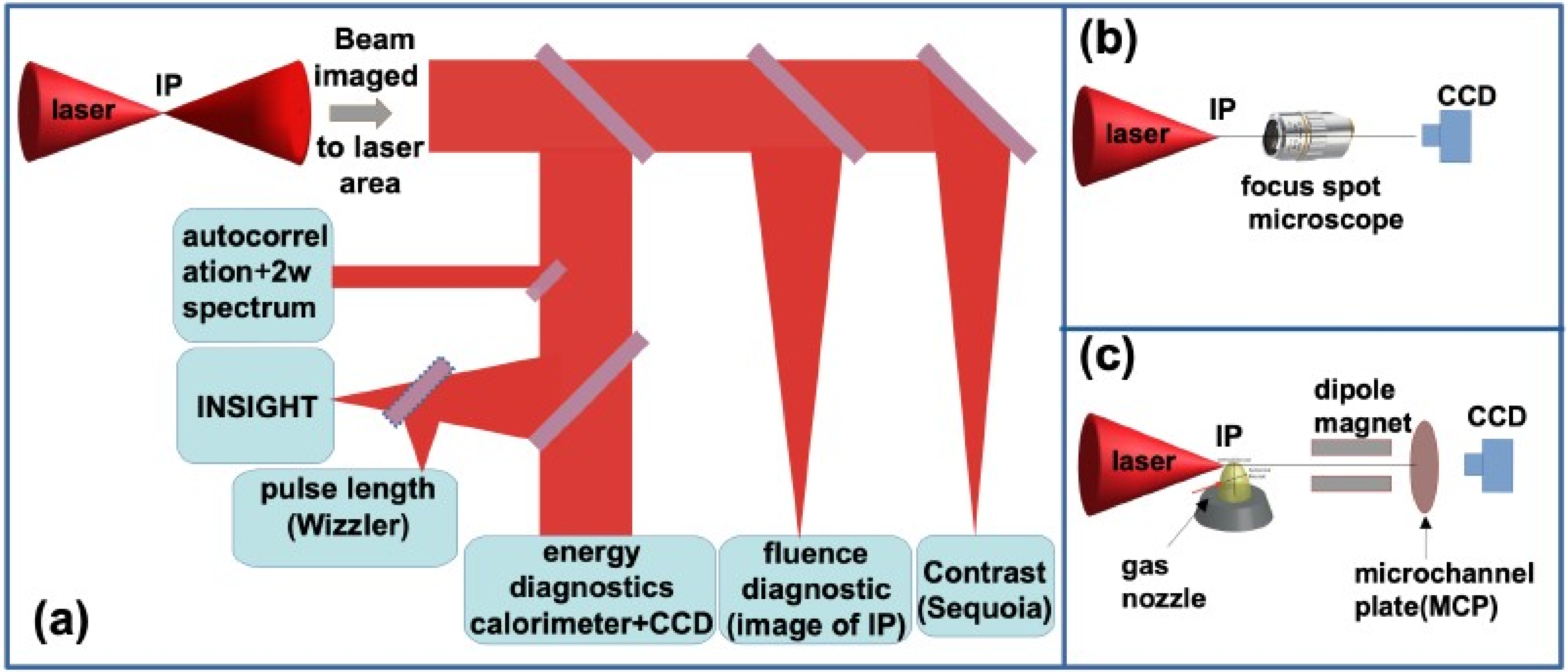
Final focusing done just before IP via dedicated chamber

Designed by I. Pomerantz (Tel Aviv U)





LASER DIAGNOSTICS

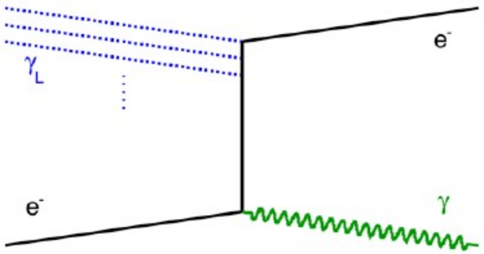


- **Need 3D characterization of laser: energy, pulse length and spot size**
  - Goal: 5% on intensity => plan many (partially redundant) measurements

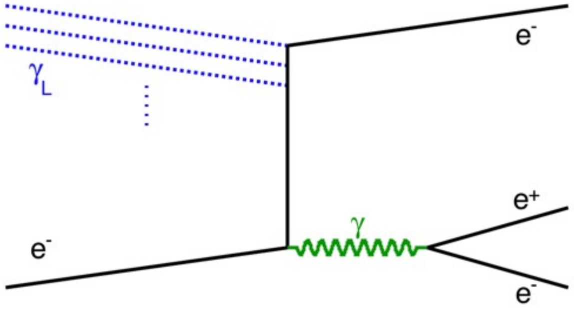
PARTICLE DETECTORS AND PHYSICS MEASUREMENTS

e-laser mode

Compton process:



Trident process:



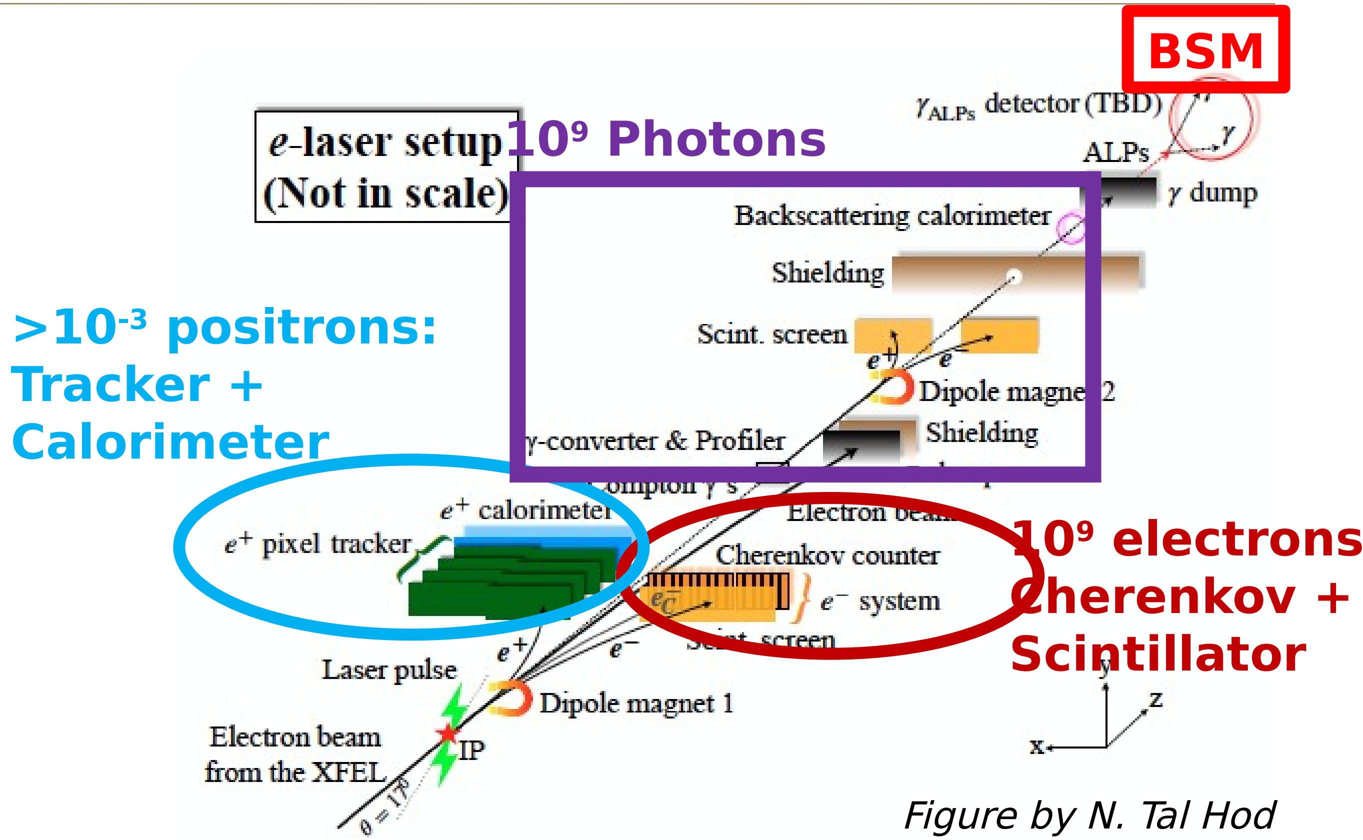


Figure by N. Tal Hod

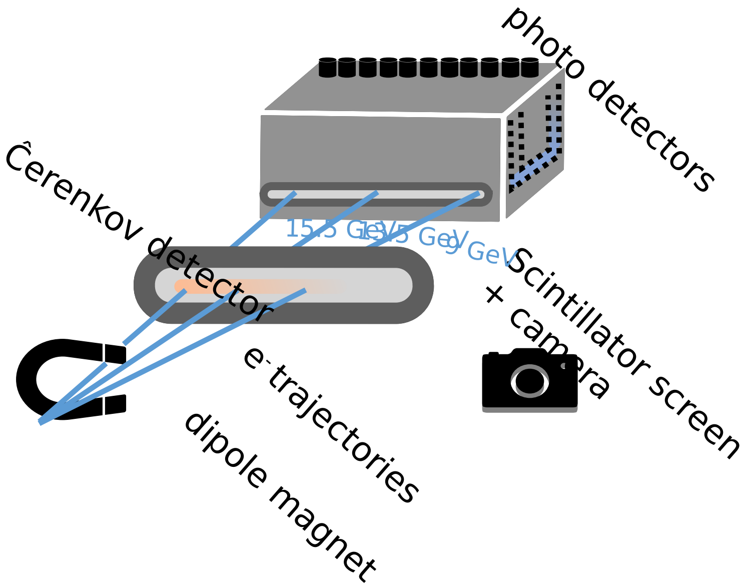
- Goal: Detection of electrons, positrons and photon fluxes and measure their energy spectra
- Particle fluxes vary between ~0.01 e^+ and 10^9 (e^- and γ) per laser shot!
- Use technologies adapted to respective fluxes of signal and background

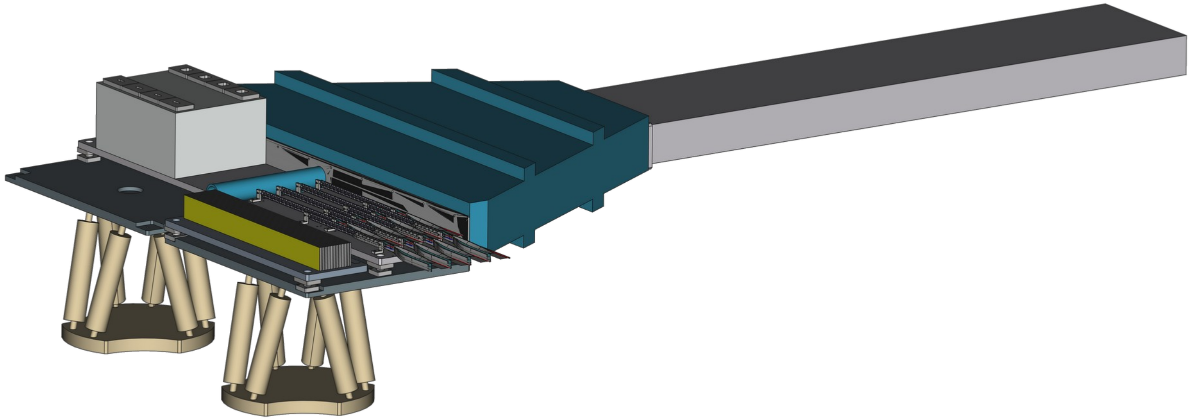
DETECTORS

- **High rate regions:**
  - Cerenkov detectors
  - Scintillator screens

- **Low rate regions**
  - Silicon pixel detectors
  - High granularity calorimeters

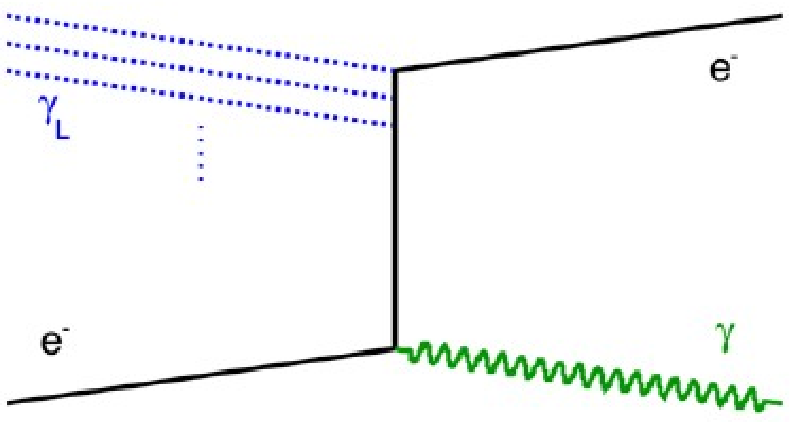
Two complementary technologies used in each case for cross-calibration, reduction of syst. uncertainties



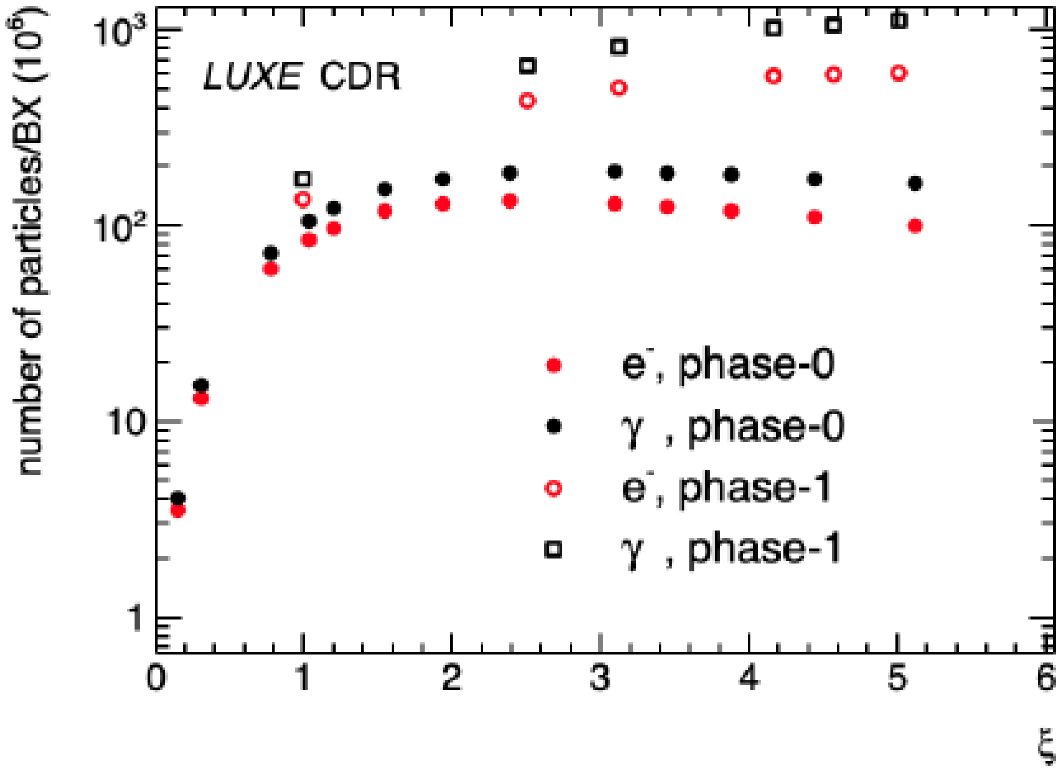


E-LASER MODE: COMPTON SCATTERING

Low-energy photons
from laser

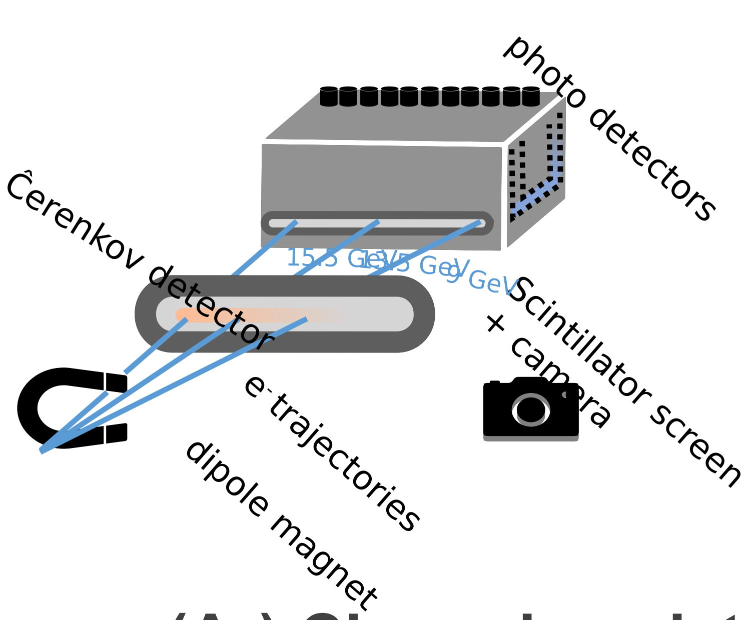


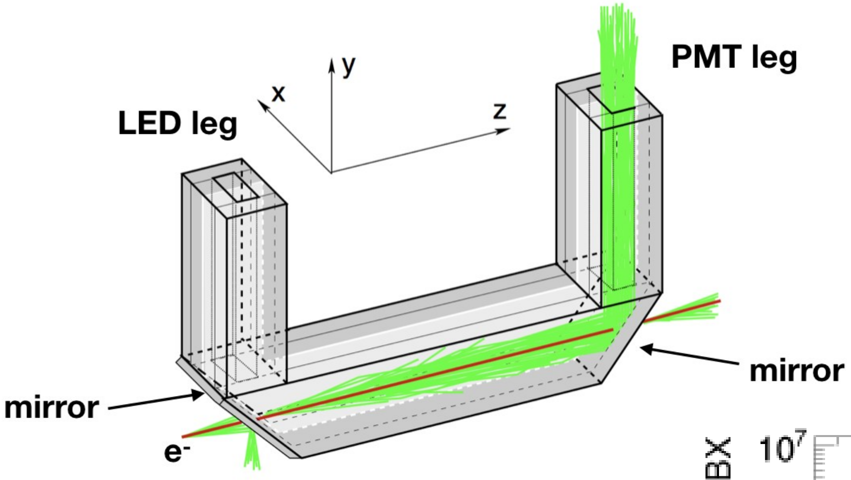
$$e^- + n\gamma_L \rightarrow e^- + \gamma$$

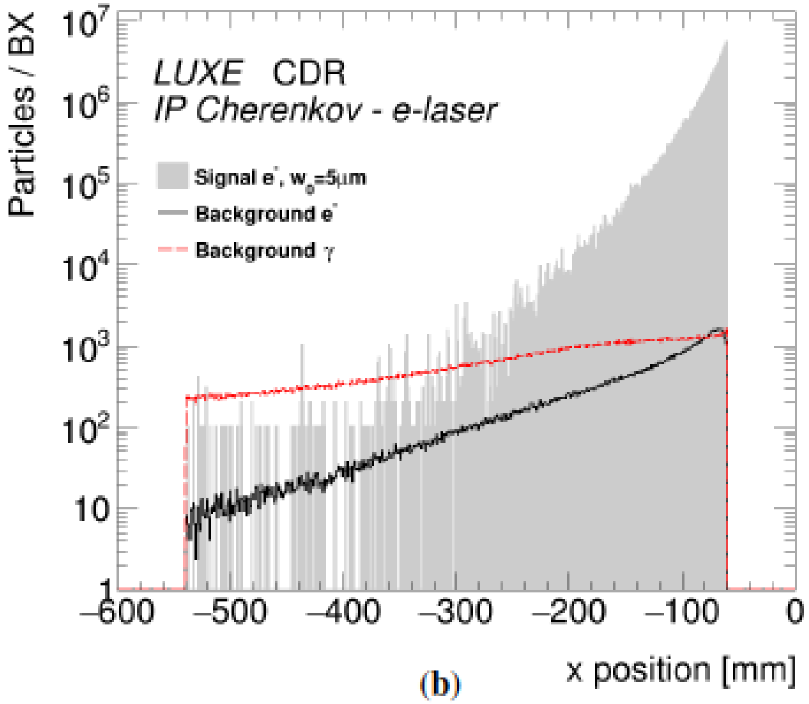


- Expect ~10^9 electrons and photons per laser shot
  - Chose detectors that can cope with this high rate => Cherenkov & Scintillator

CHERENKOV DETECTOR



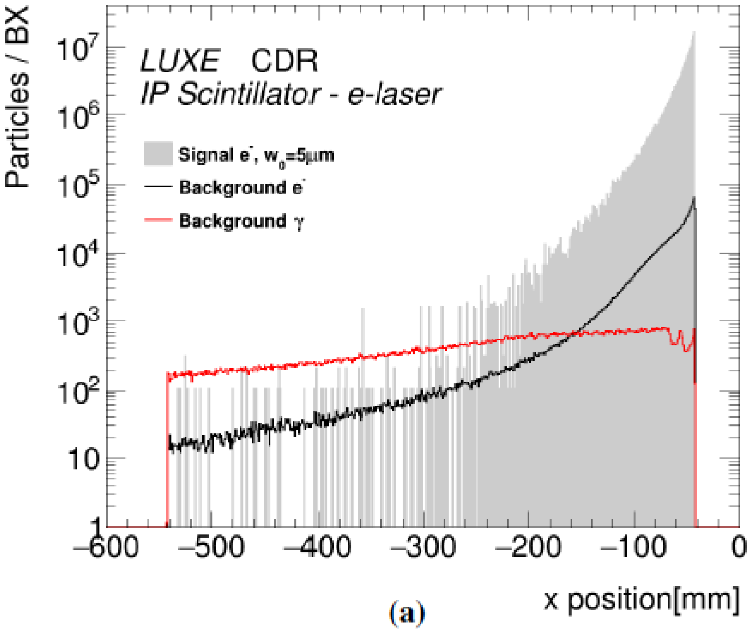


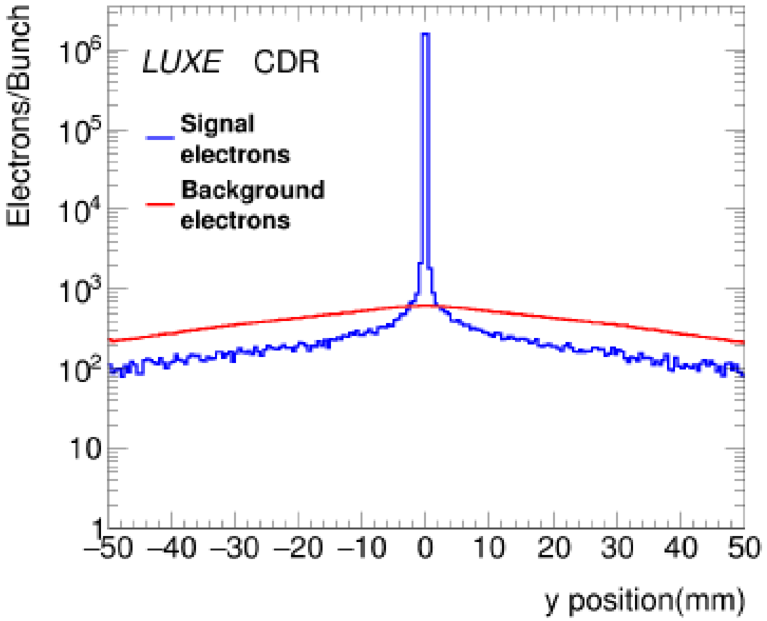


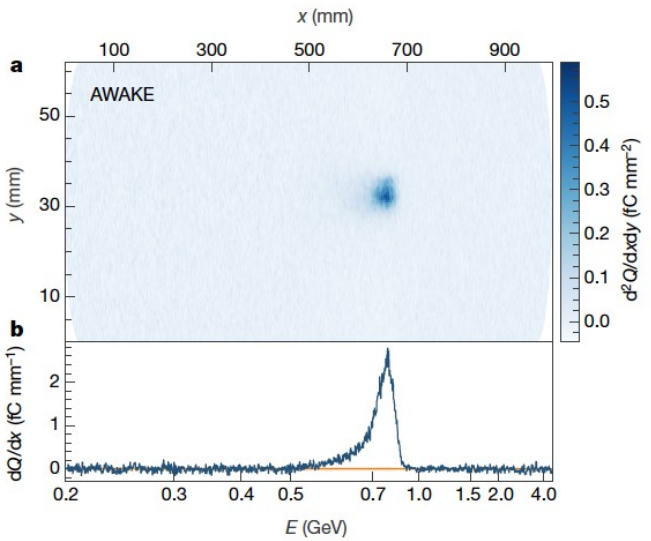
- **Gaseous (Ar) Cherenkov detectors**
  - Low refractive index gas (Ar) and optical filter to reduce light yield
  - Fine segmentation (1.5mm) to resolve Compton edges
    - See later
  - Signal/background >1000
    - Not sensitive to electrons <20 MeV
  - Initially developed for ILC polarimeter

SCINTILLATOR SCREEN

- **Basic principle**
  - Camera takes pictures of scintillation light
    - Position determines energy
  - Signal/background ~100
  - Used e.g. by AWAKE experiment at CERN





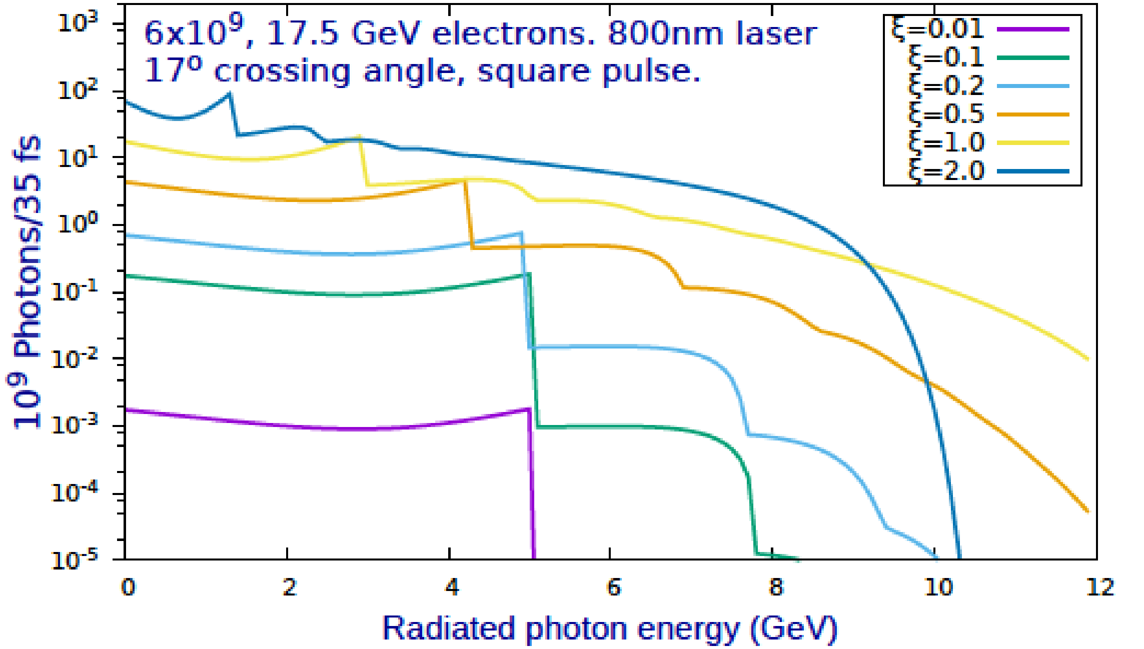


nature.com/articles/s41586-018-0485-4

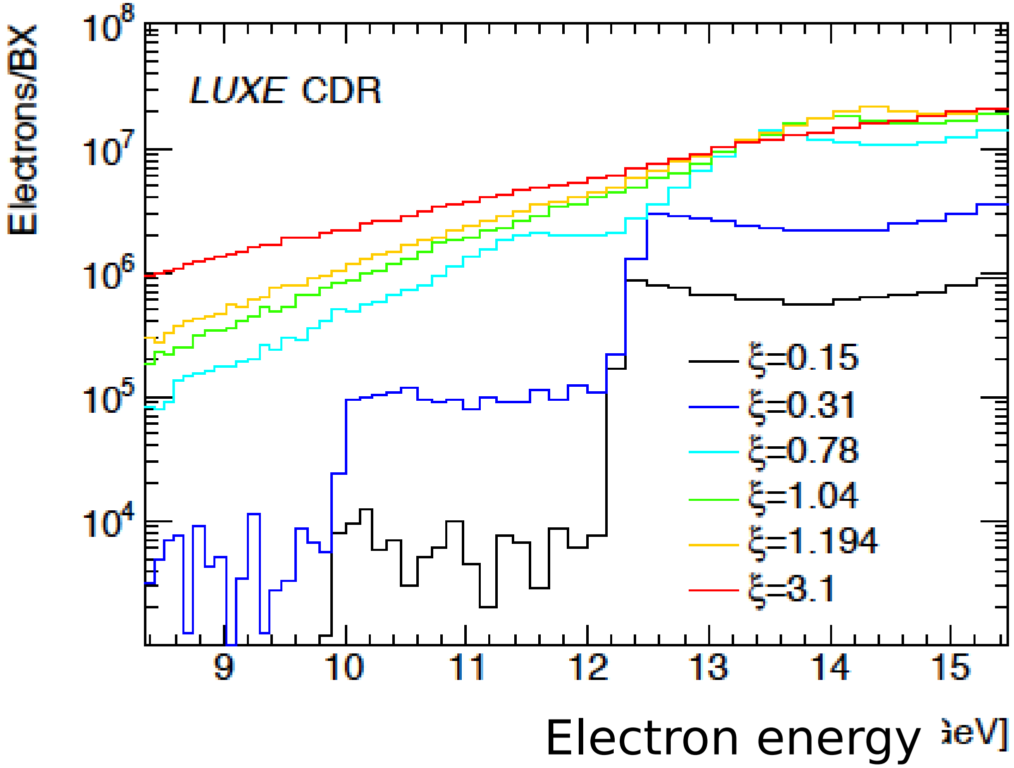
COMPTON-EDGE SHIFT

Compton energy spectrum modified:

- Compton edges shifted to lower energies as electrons acquires an effective mass:

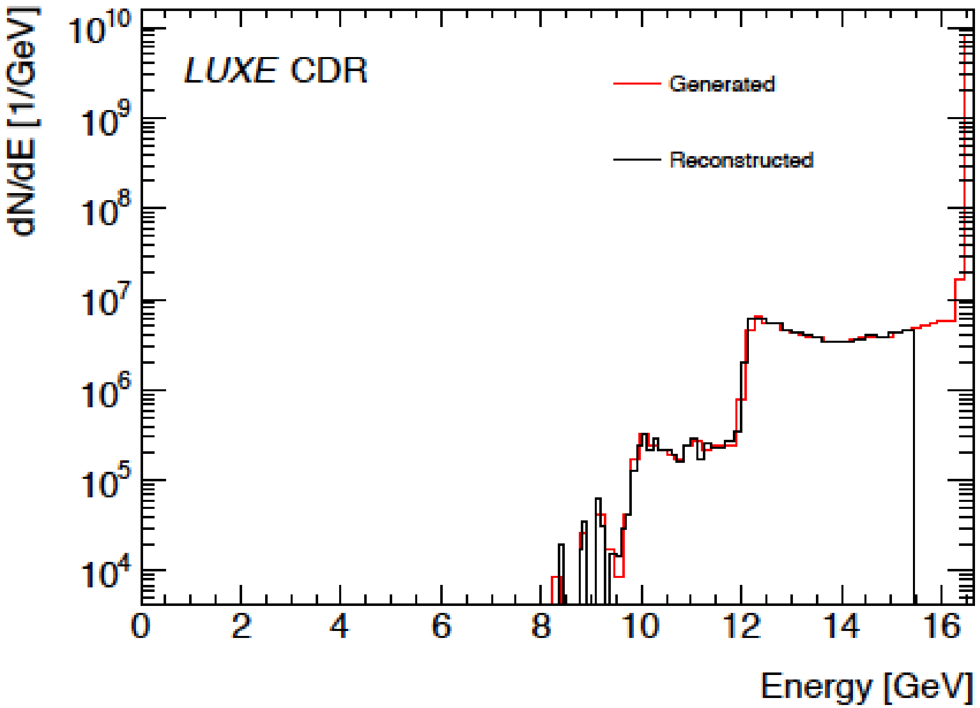


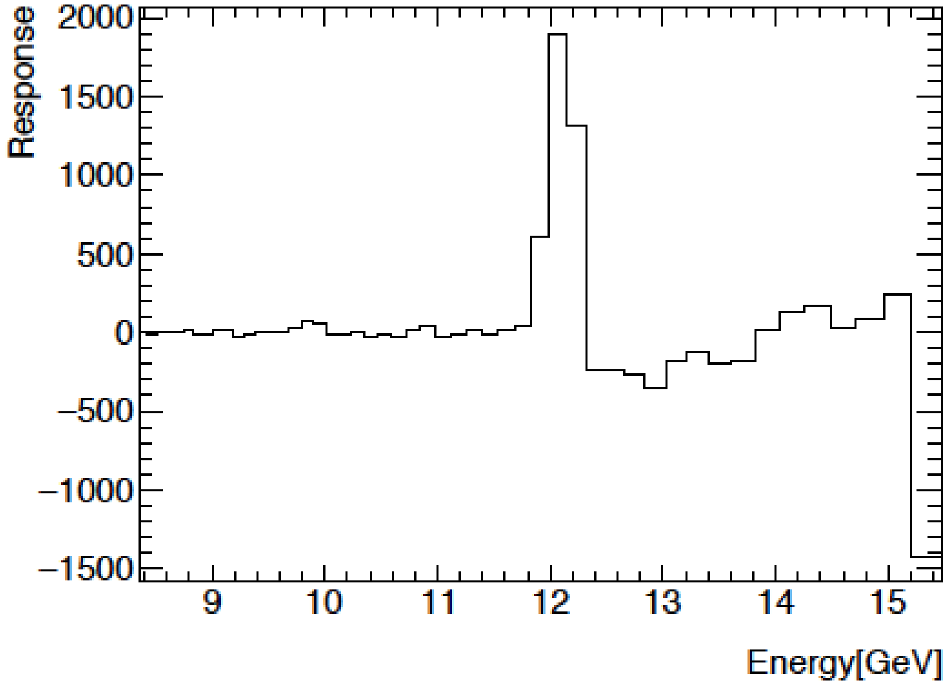
A. Hartin



=> Goal: measure these edges

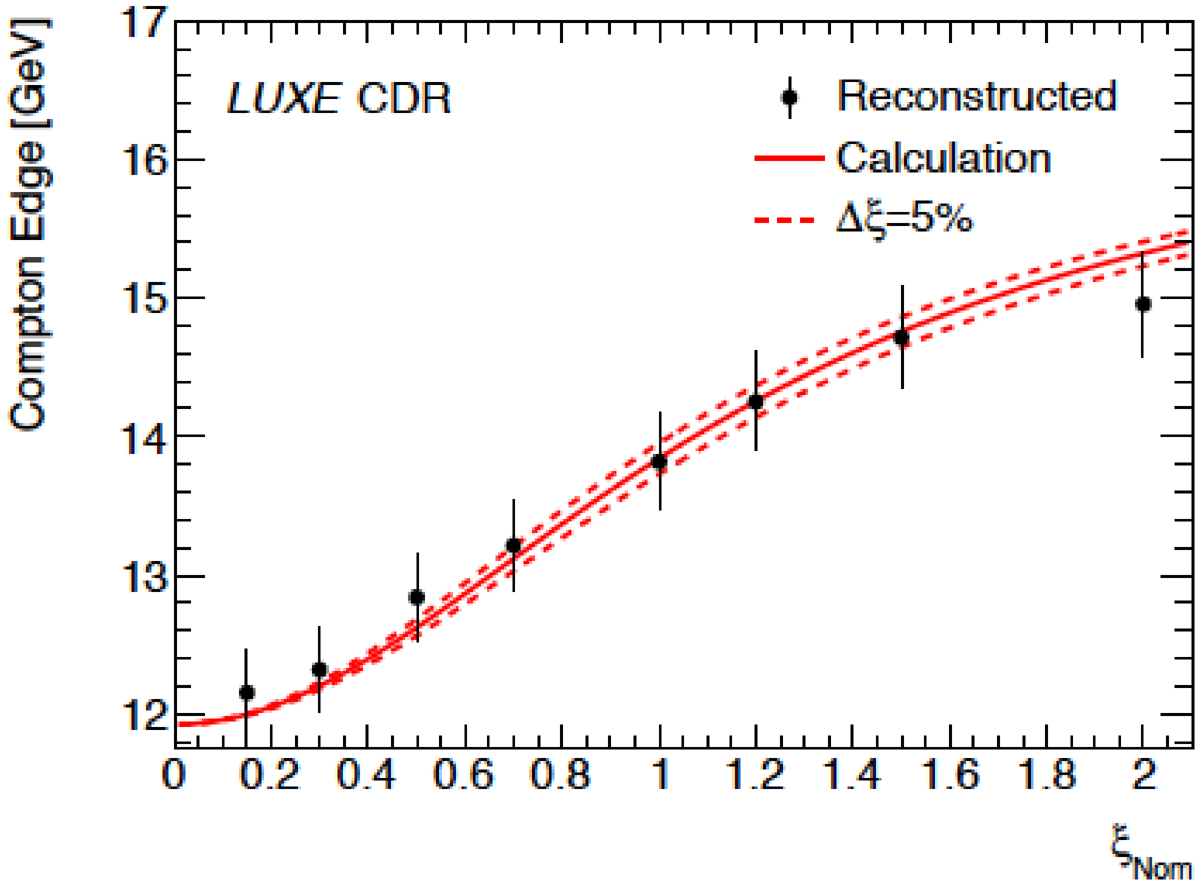
COMPTON-EDGE ANALYSIS: RECONSTRUCTION





- Gaussian laser pulse: superposition of different ξ → edges overlay in spectrum
- Position and shape of edges sensitive to dependence of nonlinear Compton cross-section on ξ
- Edge reconstruction vis Finite Impulses Response Filter (FIR) → max. in response = edge position

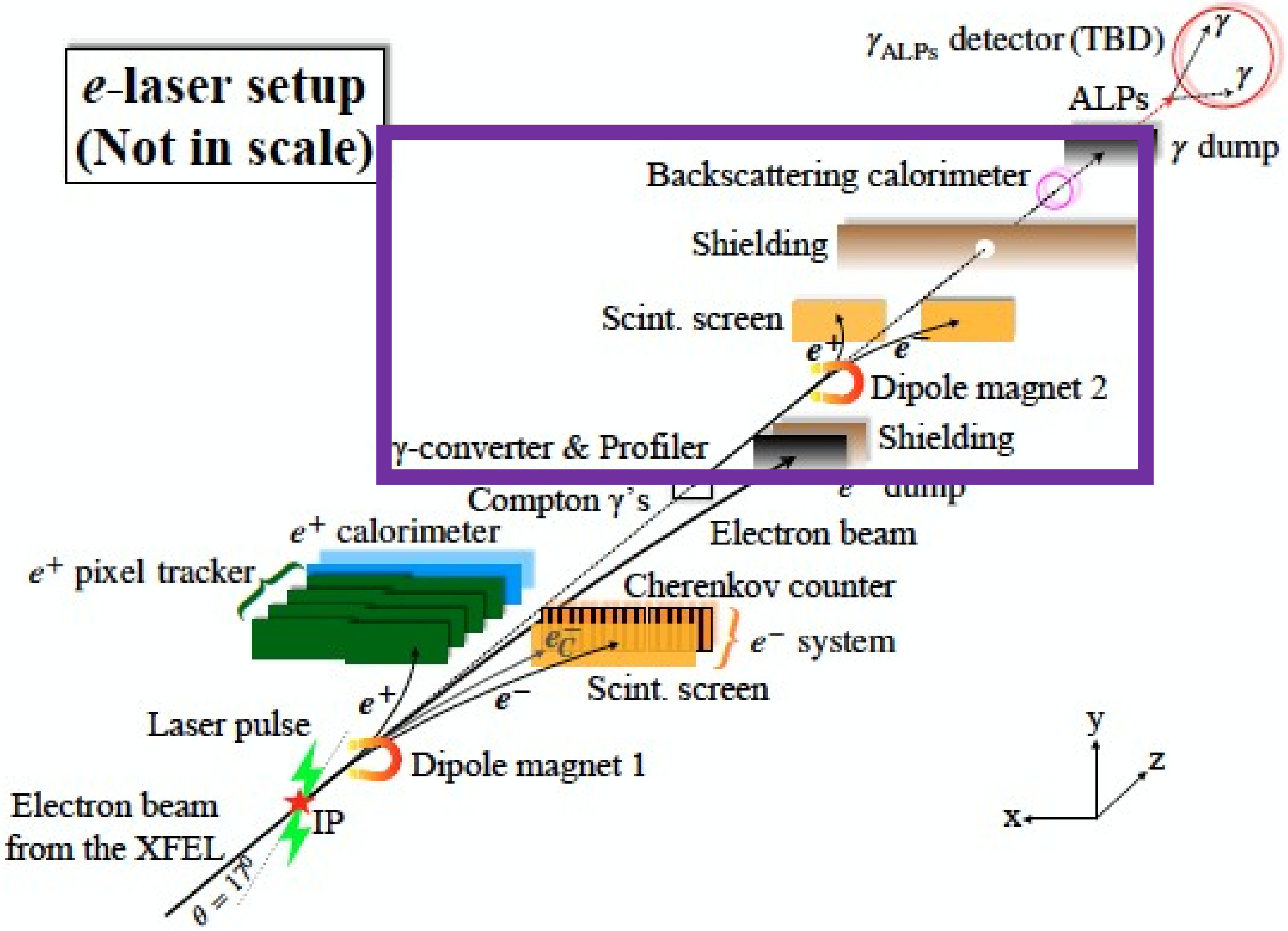
COMPTON-EDGE ANALYSIS: SIMULATED RESULT



Phase-0

- First harmonic kink position (edge of maximum ξ) as a function of ξ_{max} compared to theory prediction

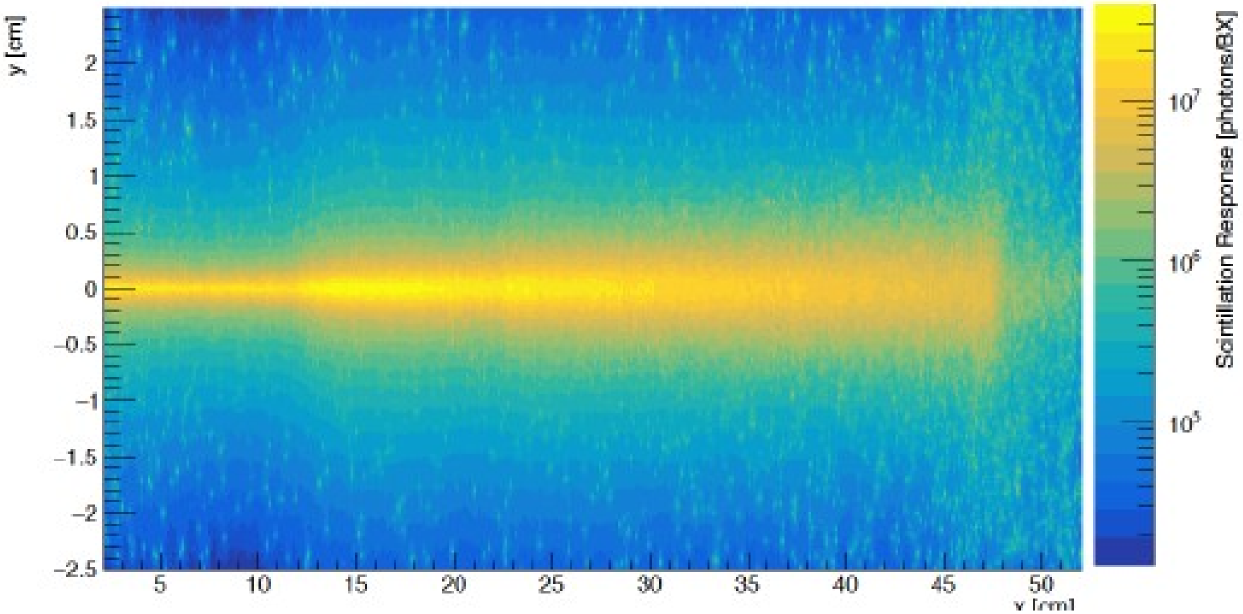
PHOTON DETECTION SYSTEM

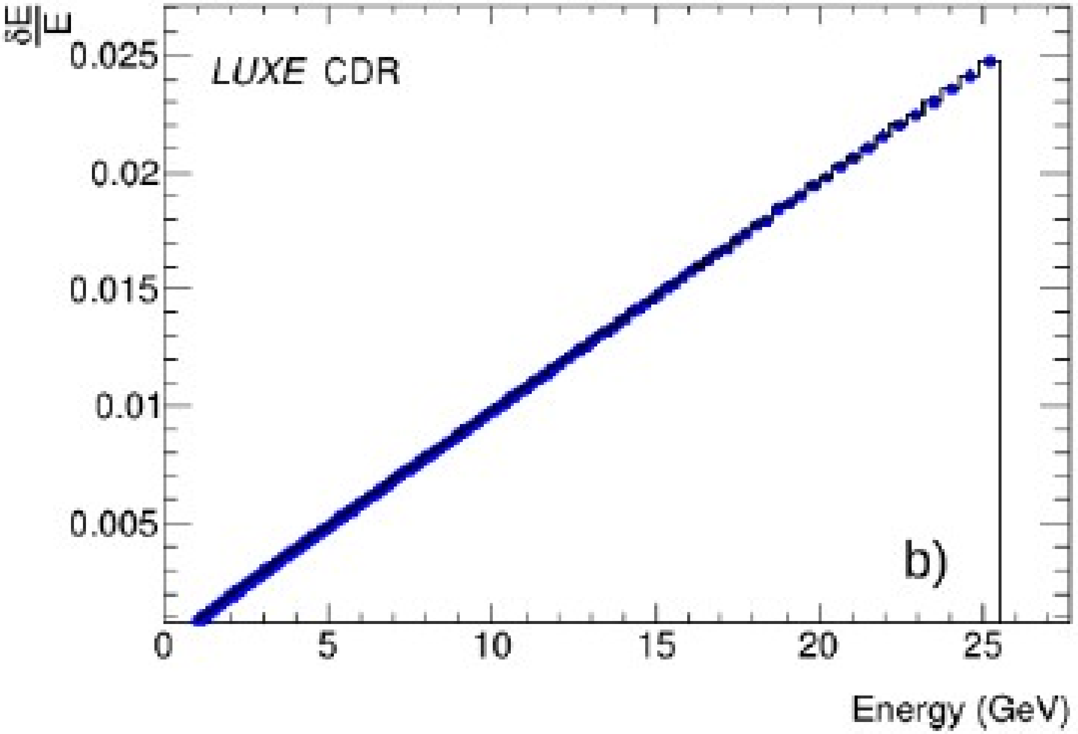


- **Three detector technologies**
  - Spectrometer with scintillator screens behind converter
    - Measure flux and energy spectrum
  - Backscattering calorimeter
    - Measure flux
  - Gamma profiler (sapphire)
    - Measure location

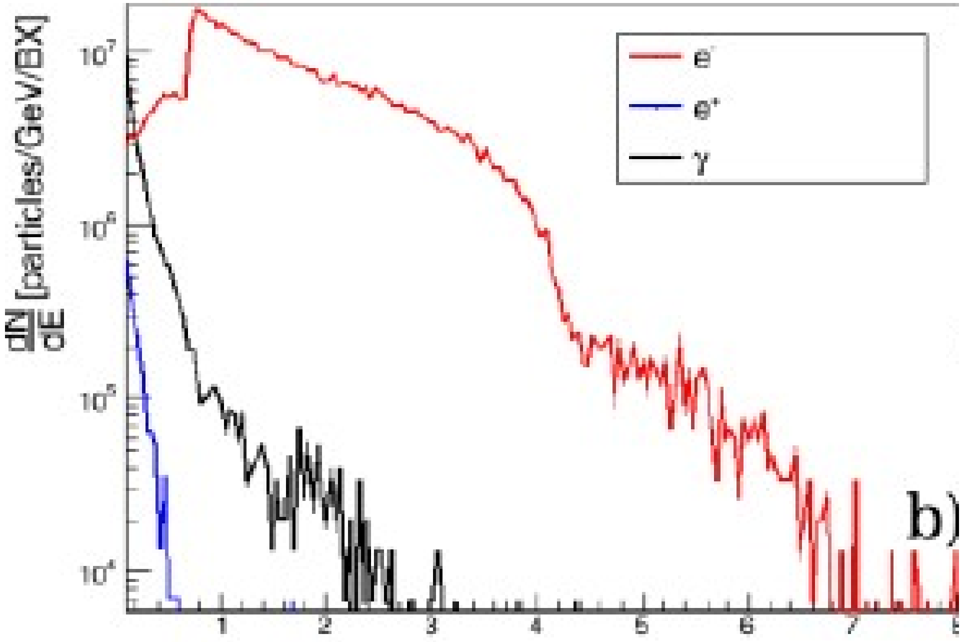
PHOTON SPECTROMETER

- **Up to 10^9 photons per bunch crossing with ~GeV energies**
- **Energy spectrum measurement**
  - Spectrometer with scintillators behind converter
  - Energy resolution <2%



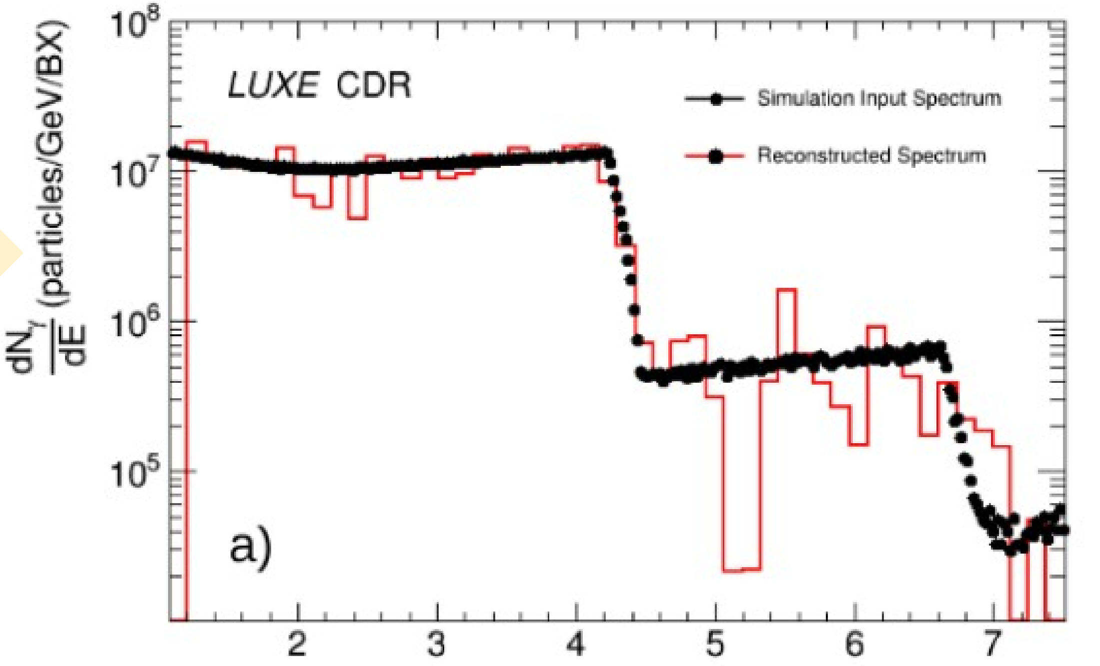


PHOTON ENERGY MEASUREMENT



Electron energy [GeV]

deconvolute

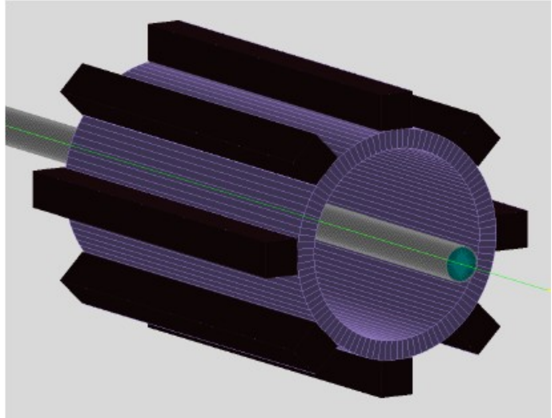


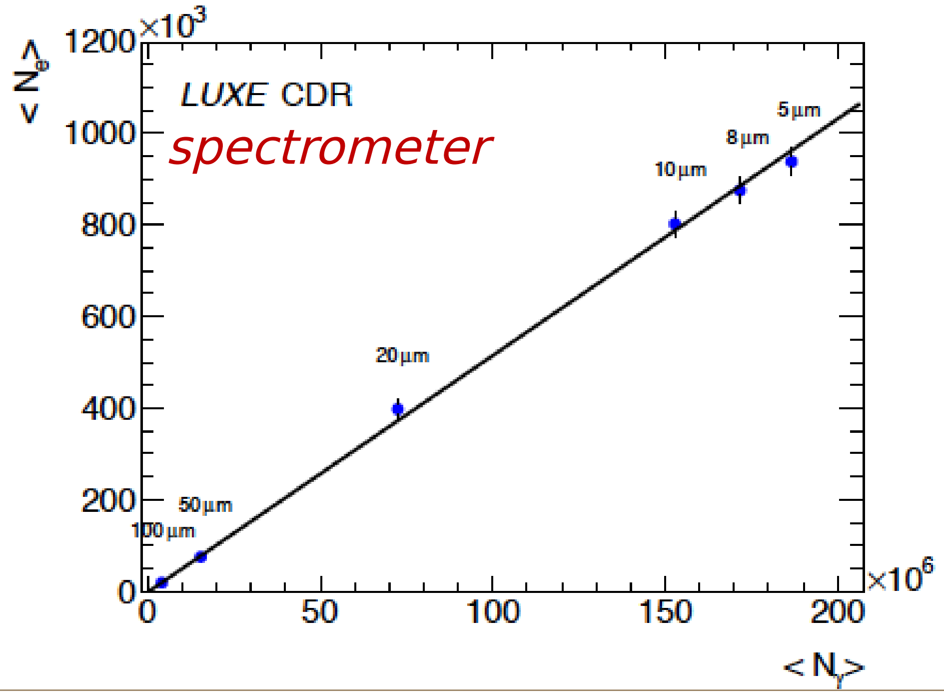
Photon energy [GeV

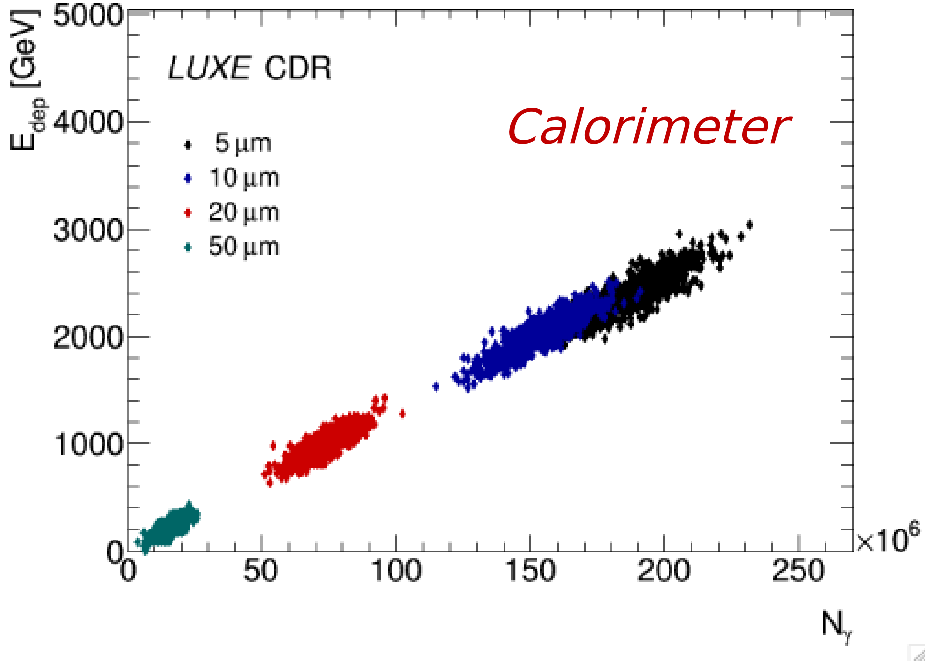
Alternative way to reconstruct Compton edges

PHOTON FLUX

- Up to 10^9 photons per bunch crossing with ~GeV energies
- Flux measured with
  - Spectrometer
  - Backscattering calorimeter (lead glass blocks)

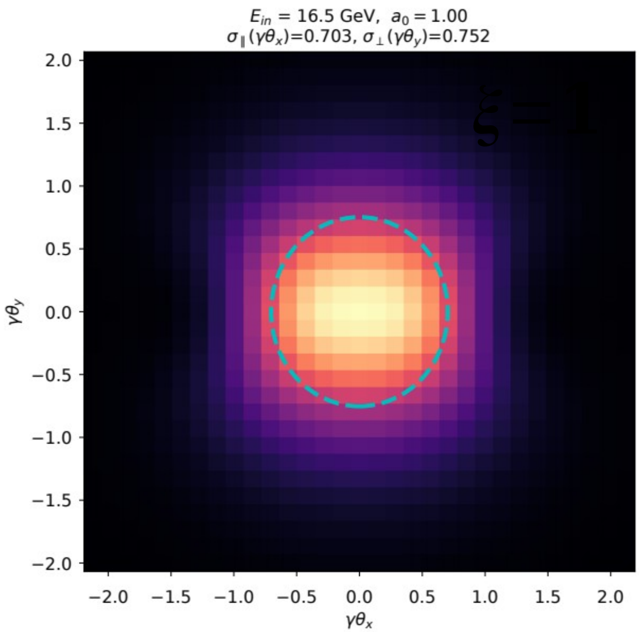


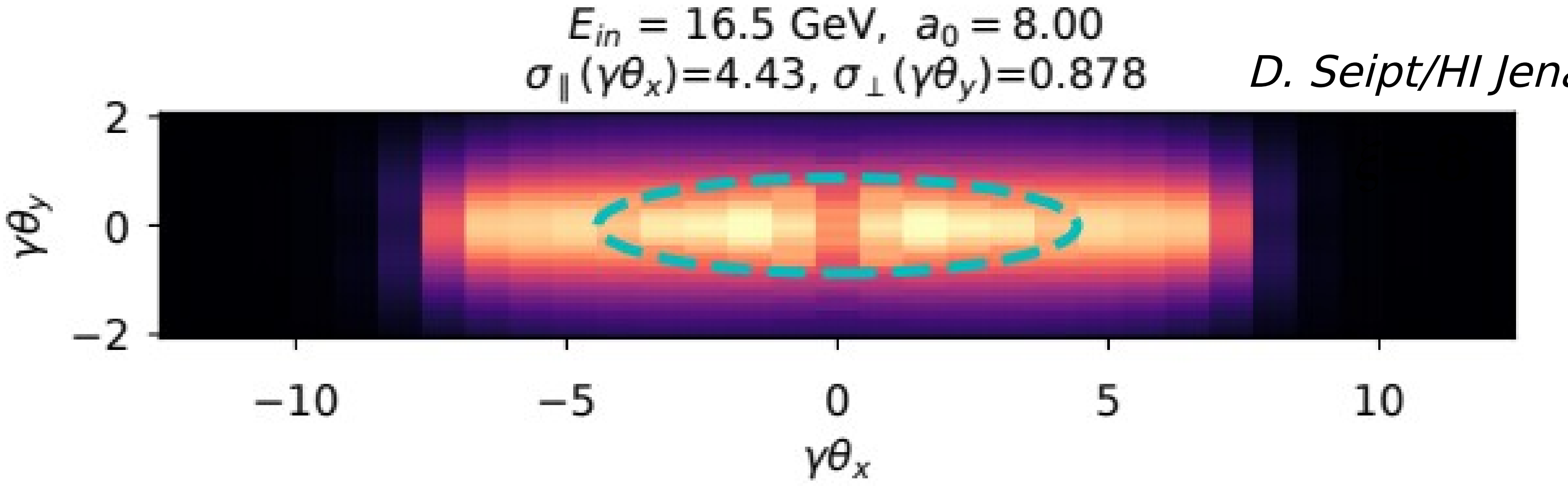




GAMMA PROFILER

- **When using polarized laser, expect angular spectrum of photons to depend on ξ for and distance from IP of 6m:**
  - Parallel: m, Perpendicular: m
  - Ellipticity is independent measure of laser intensity parameter



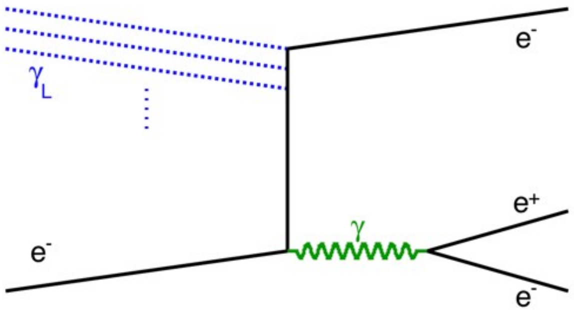


D. Seipt/HI Jena

- **Measurement of 5 m provides constraint: for ξ>2**

Positron Detection: e-laser mode

$e^{-} + n\gamma_L \rightarrow e^{-} + e^{+¿+e^{-}¿}$



>10^-3 positrons: Tracker + Calorimeter

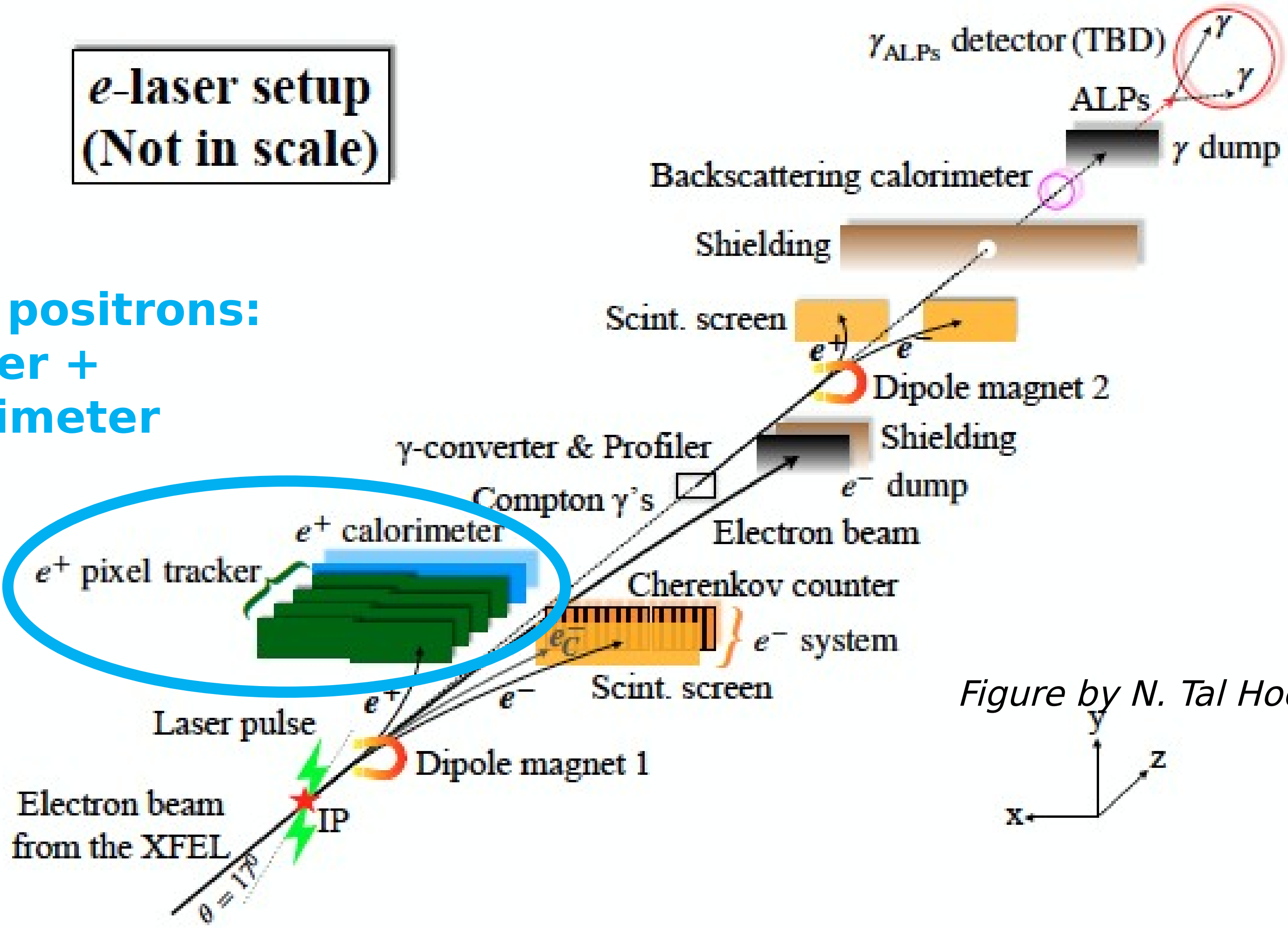
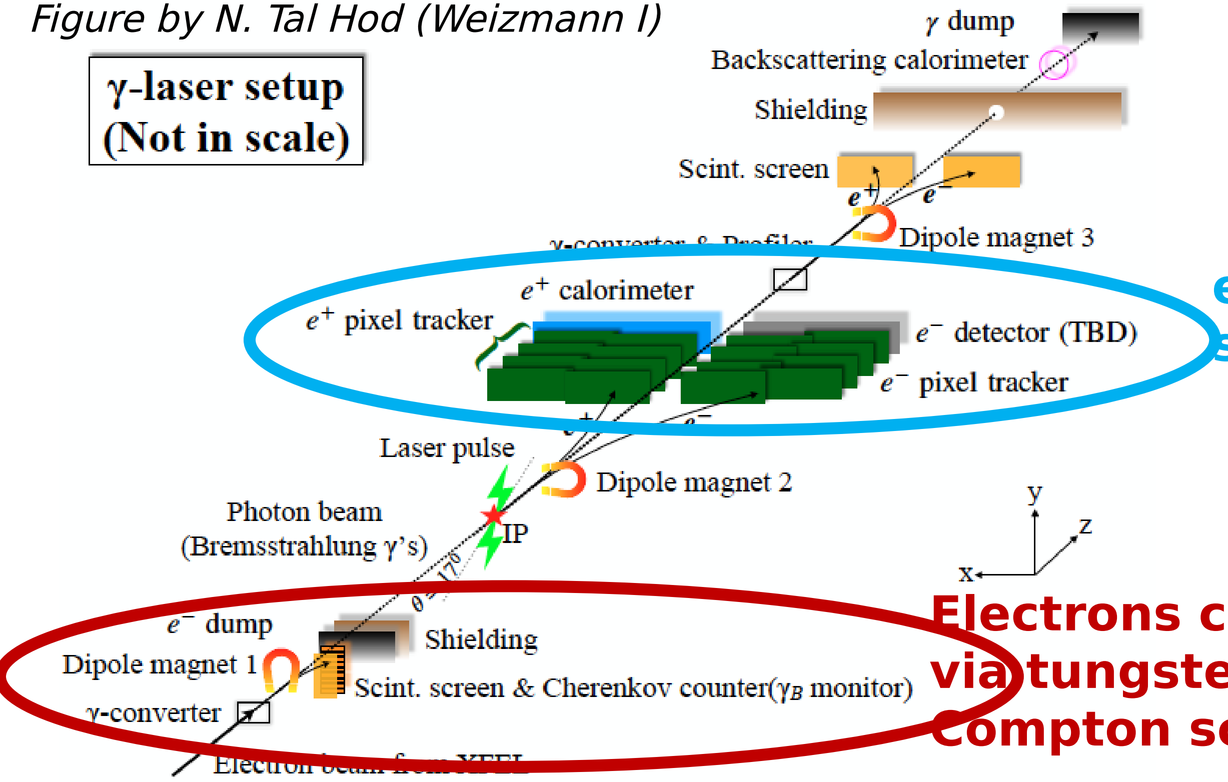


Figure by N. Tal Hod

Low e+ rate: different technology than on electron side

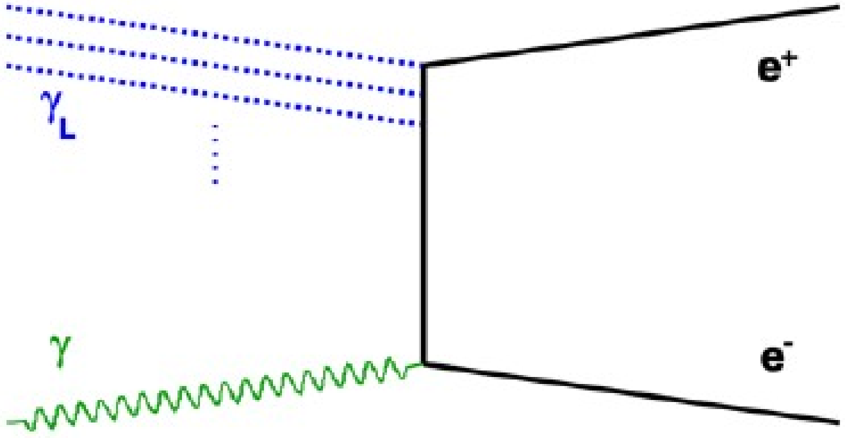
-laser mode

Figure by N. Tal Hod (Weizmann I)



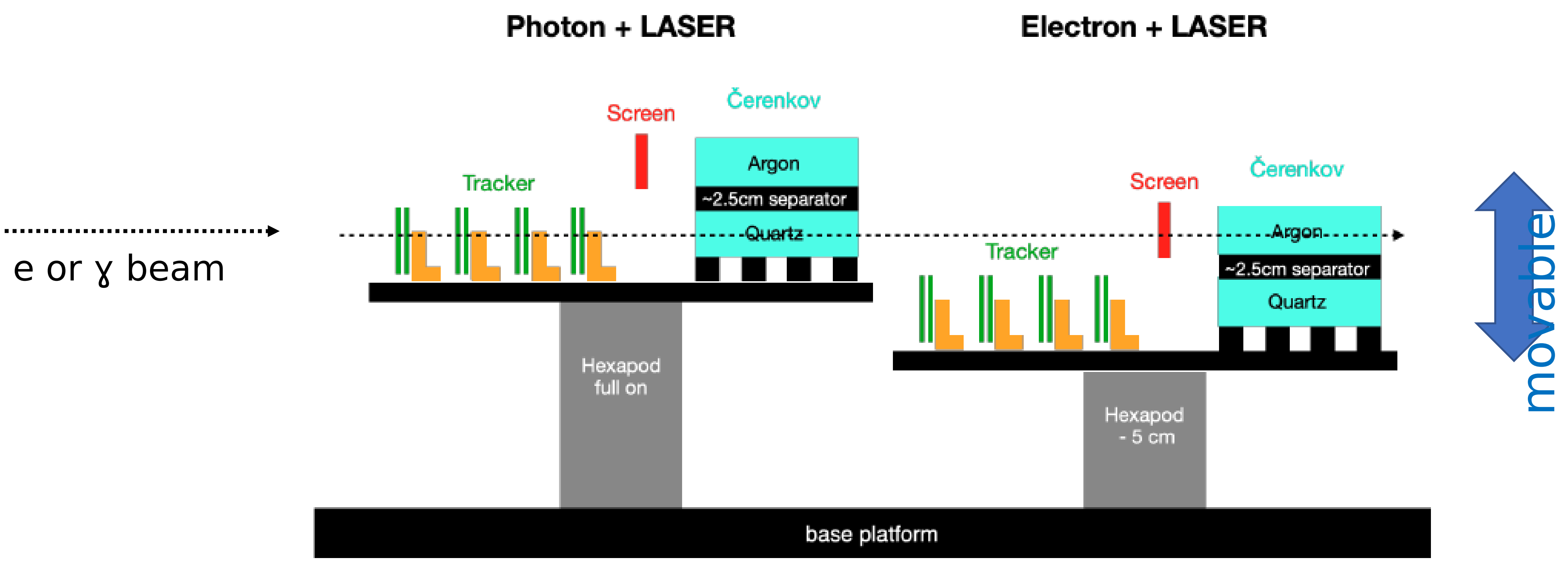
e+e- pairs: same rates

Electrons converted to photons via tungsten foil or inverse Compton scattering



Provides most direct test of Schwinger limit

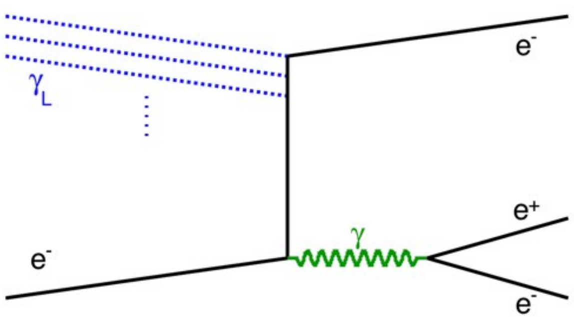
ELECTRON AND PHOTON LASER MODE



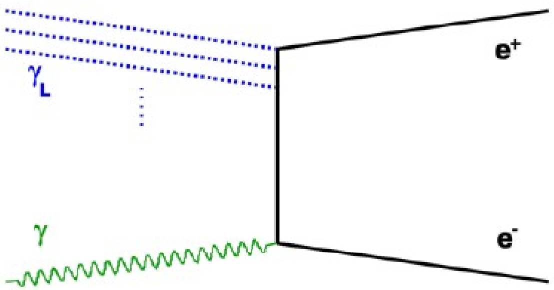
- **Very different e- rate in e-laser and photon-laser modes**
  - need to change detector technology when photon-laser run starts

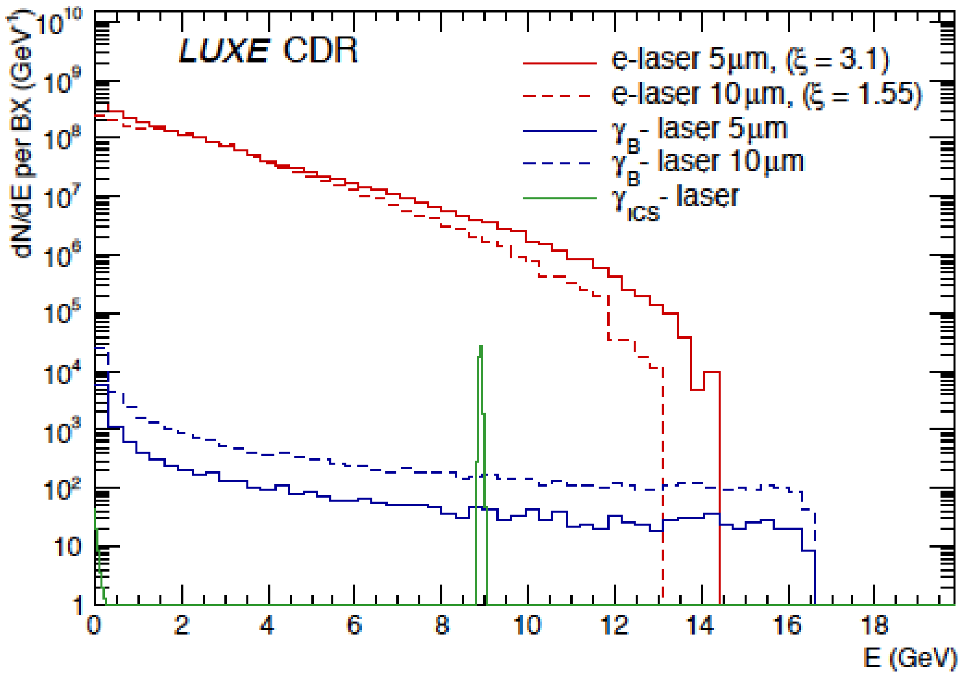
PAIR PRODUCTION

$$e^{-}+n\gamma_L \rightarrow e^{-}+e^{+¿+e^{-}¿}$$

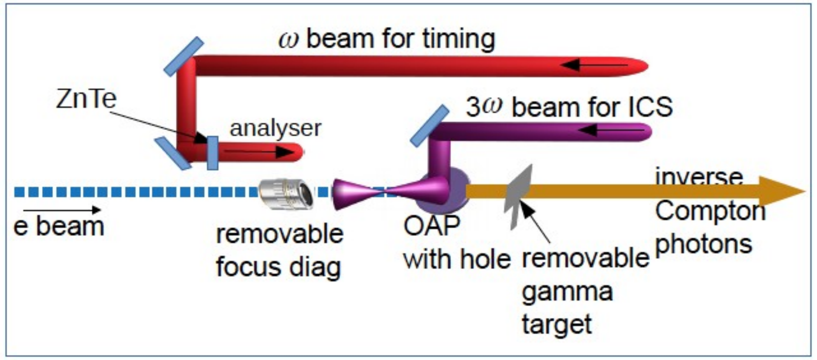


$$\gamma+n\gamma_L \rightarrow e^{-}+e^{+¿¿}$$



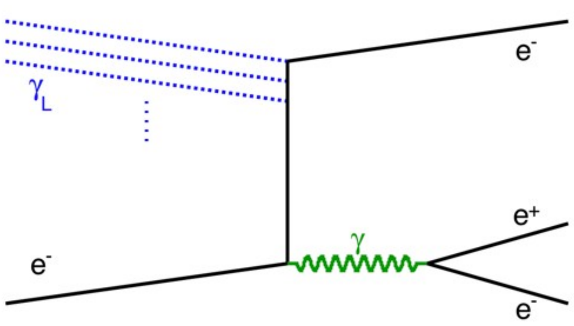


- Three methods for producing pairs
  - Compton photons inside same laser pulse => largest rate
  - Bremsstrahlung photons produced upstream => highest E
  - Compton photons produced upstream (E=9 GeV)

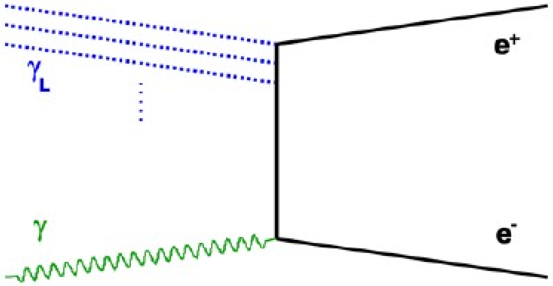


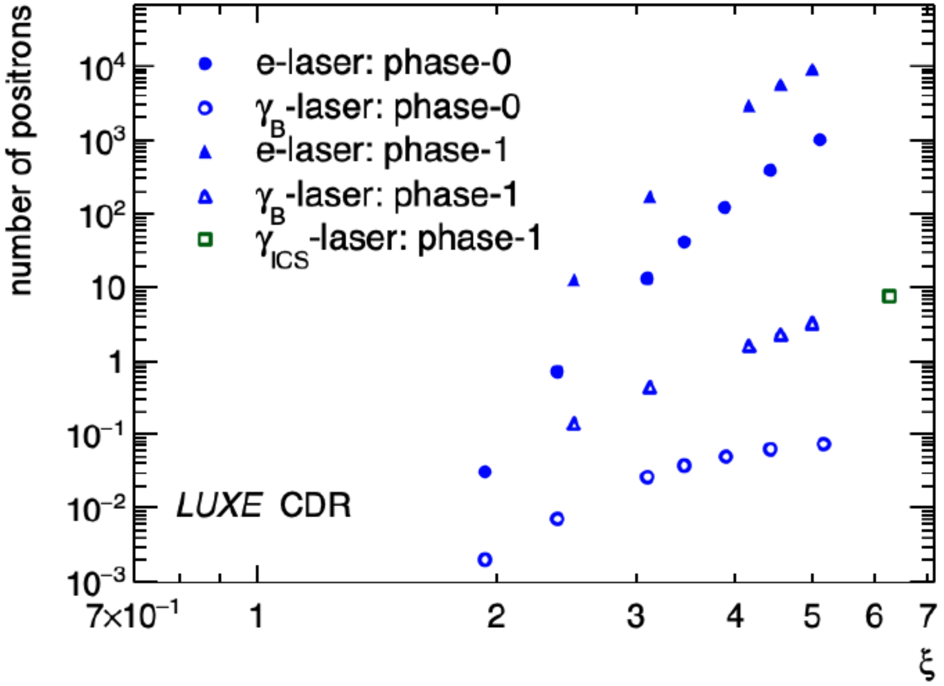
PAIR PRODUCTION

$e^{-} + n\gamma_L \rightarrow e^{-} + e^{+¿+e^{-}¿}$



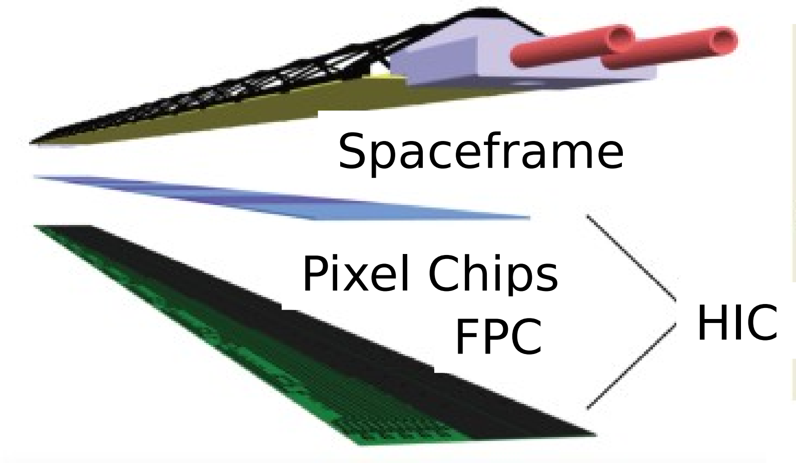
$\gamma + n\gamma_L \rightarrow e^{-} + e^{+¿¿}$

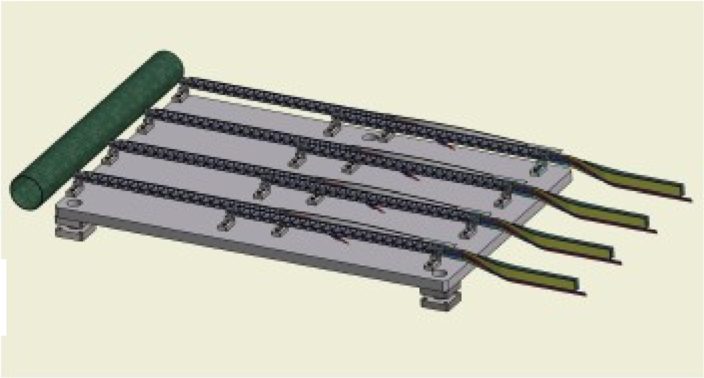


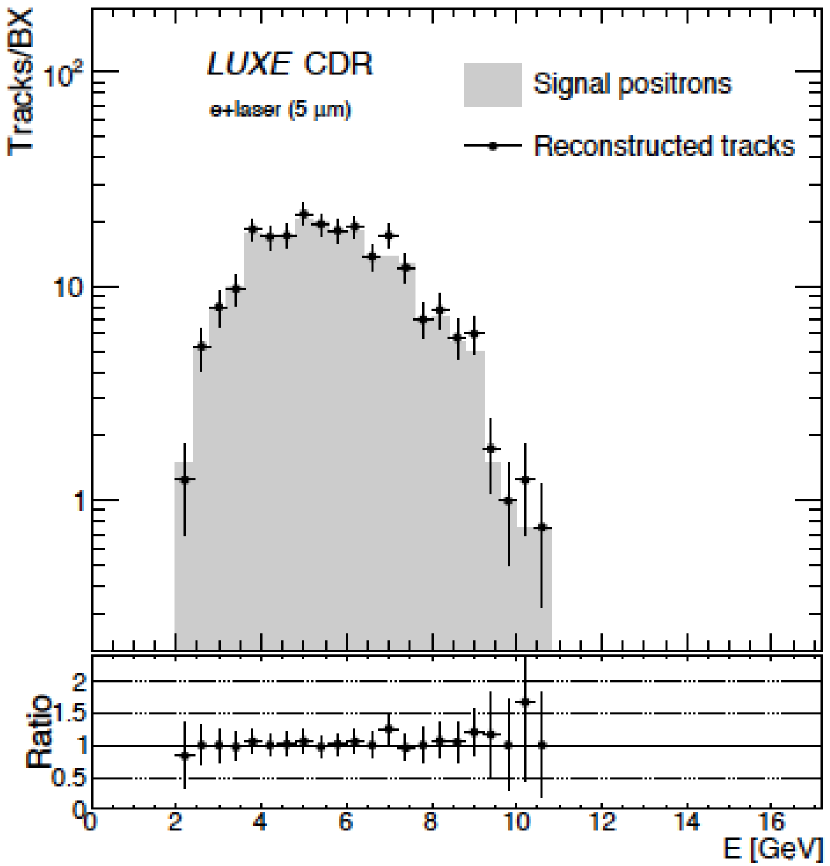


- **Expected event rates**
  - Electron-laser mode: 10^{-2}-10^{4} e^+e^- pairs
  - Photon-laser mode: 10^{-3}-1 e^+e^- pairs
- **Need good background rejection and good linearity**
  - Silicon pixel tracker and high granularity calorimeter

TRACKER



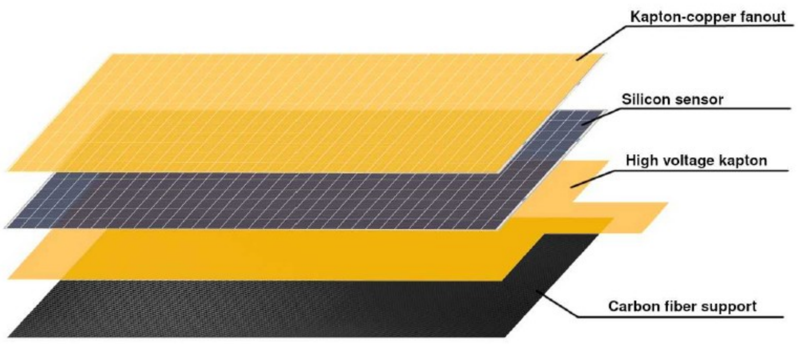


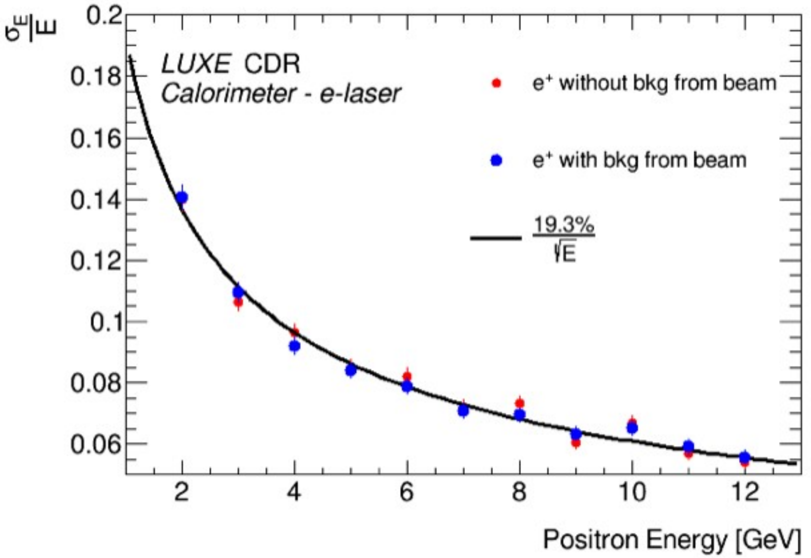


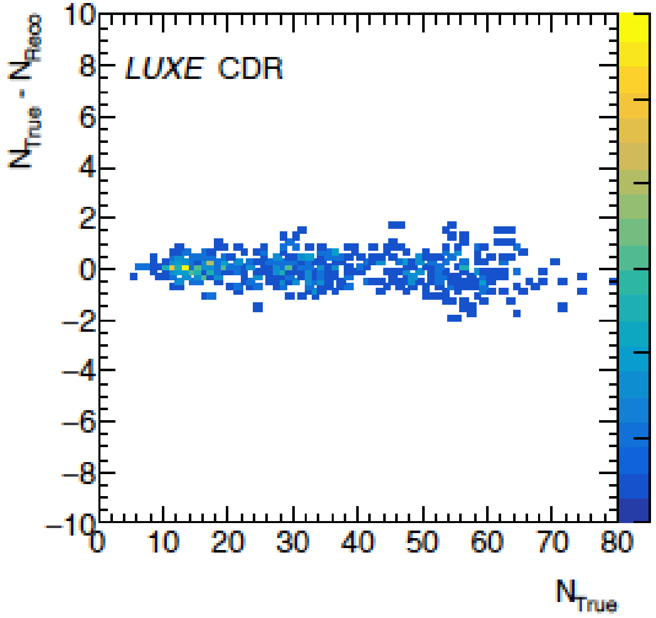
- **Four layers of ALPIDE silicon pixel sensors**
  - Sensors developed for ALICE tracker upgrade
    - Pitch size: 27 x 29 μm² => spatial resolution ~5 μm
  - With tracking:
  - Background: <0.1 event per bunch crossing

N. Tal Hod, A. Santra (Weizmann I)

HIGH GRANULARITY CALORIMETER



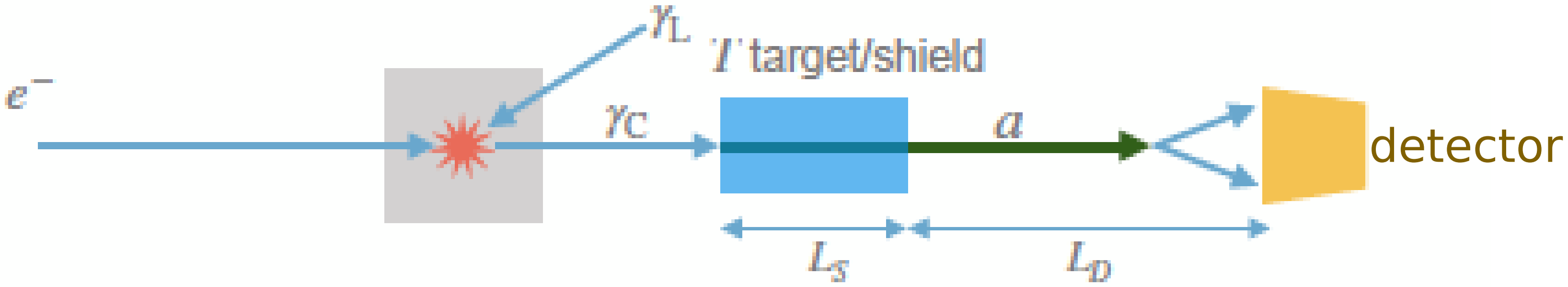




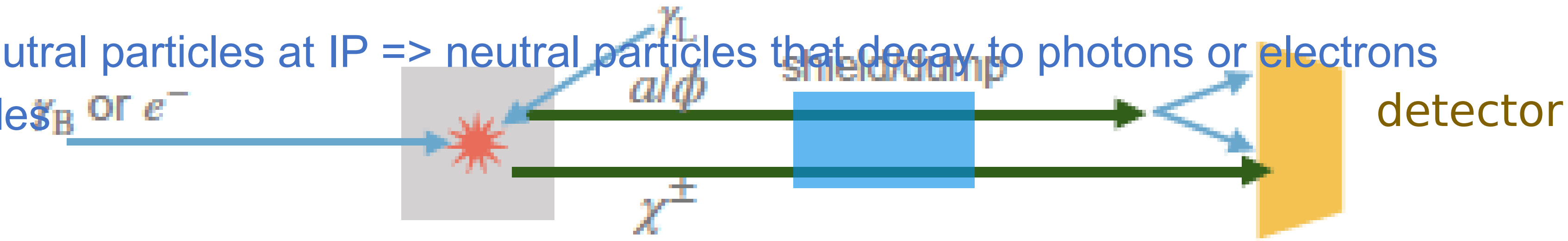
- **High granularity calorimeter**
  - 20 layers of 3.5 mm thick tungsten plates
  - Silicon or GaAs sensors (5x5 cm^2 pads, 320 µm thick), Moliére radius 8 mm
  - Readout via FLAME ASIC (developed for FCAL)
- **Resolutions: ,**
  - Independent measure of energy via position and calorimeter => $N_{particle}$

BSM PHYSICS

- Three ideas being explored at present
  1. Use high photon flux from strong-field Compton process for beam dump type experiment => neutral particles that couple to photons (axion-like particles)



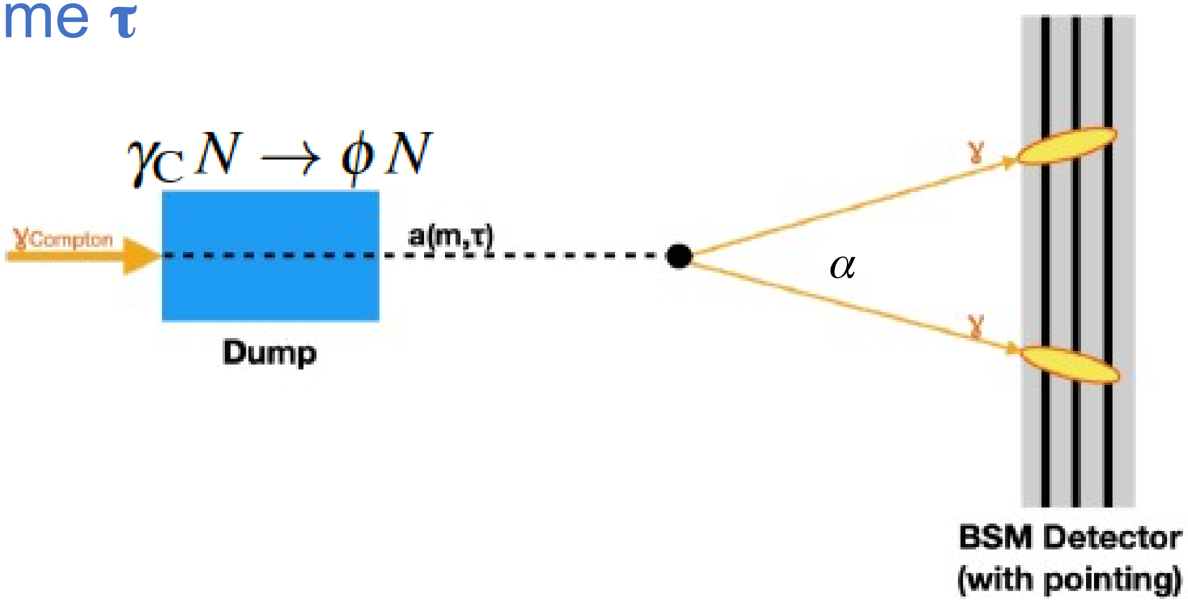
  2. Produce directly neutral particles at IP => neutral particles that decay to photons or electrons
  3. Milli-charged particles



G. Perez, Y. Soreq et al., to be published

SENSITIVITY TO AXION-LIKE PARTICLES

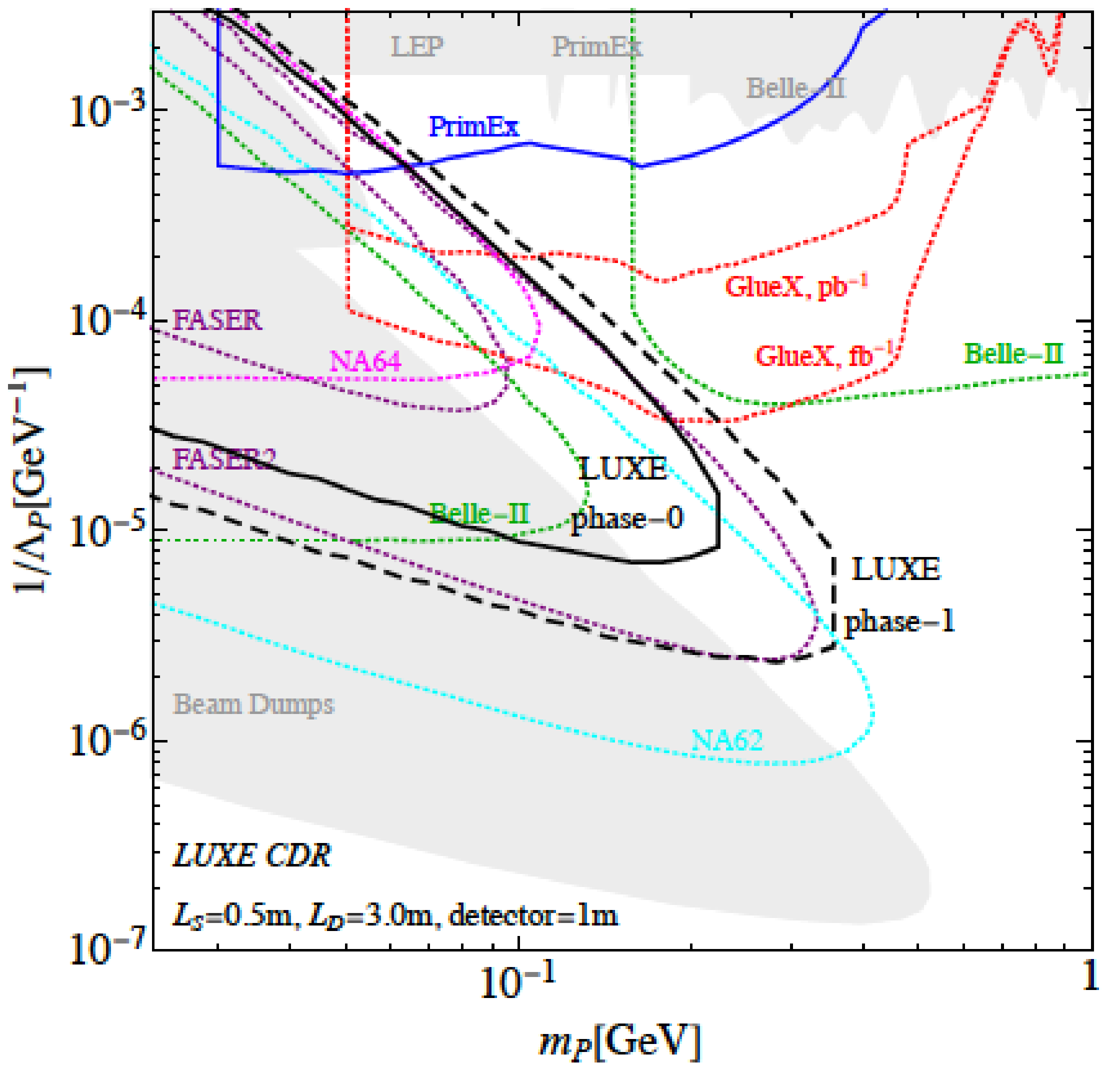
- **Photons dumped on beam dump**
  - Converted to axion-like particles (ALP,) via Primakoff effect
    - Sensitivity to masses of m(a)~100 MeV
  - ALPs decay to photons after some lifetime **τ**



- **Place detector behind dump**
  - Measure energies and angles =>
  - Also determine lifetime by reconstructing decay point
  - Could use e.g. calorimeter with good pointing resolution (tbd)
    - E.g. SplitCal by SHiP looks good (JINST 13 (2018), no. 02, C02041)

SENSITIVITY TO AXION-LIKE PARTICLES

- **Sensitivity estimated for 1 year assuming no background**
  - This still needs to be verified!!!
- **Competitive with other ongoing and planned experiments**
  - e.g. similar to FASER2



CONCLUSIONS AND OUTLOOK

- **Exciting opportunity to explore QED in new regime using European XFEL and high power laser**
  - Observe transition from perturbative to non-perturbative regime of QED
  - Parasitically use for BSM physics
- **Goal is installation in 2024 during extended shutdown planned for European XFEL**
  - Conceptual design report will be released within the next week
  - Interesting detector technologies used, optimized for physics goals
  - Reviews starting
- **We welcome new collaborators**

S. Weinberg (03/2019): "*My advice is to try crazy ideas and innovative experiments. Something will come up.*"

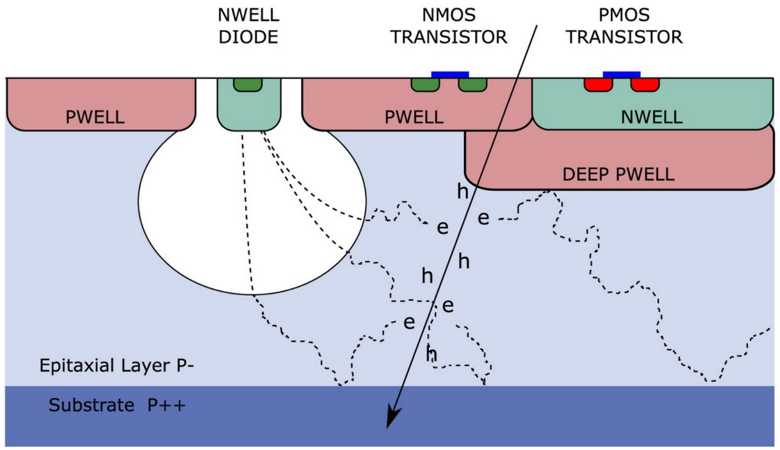
BACKUP

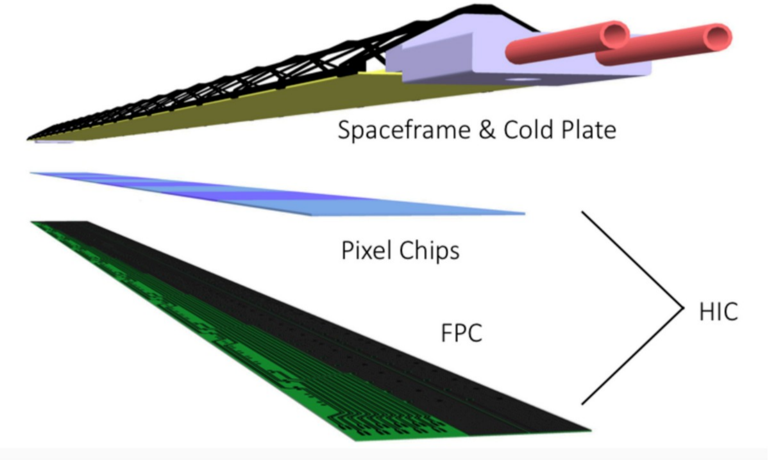
GOALS OF THE LUXE EXPERIMENT

Probe QED in a new regime

- Measure interaction of real photons with electrons and **photons at or beyond the Schwinger limit,** thereby probing a new strongly coupled regime of quantum physics
- Measure **non-perturbative production of e^+e^- pairs** from light
- Make precision measurements of eɣ and ɣɣ interactions in **a transition from the perturbative to the non-perturbative regime of QED**
- Use strong-field QED process to design **sensitive search for new particles beyond the SM** that couple to photons

SILICON DETECTORS

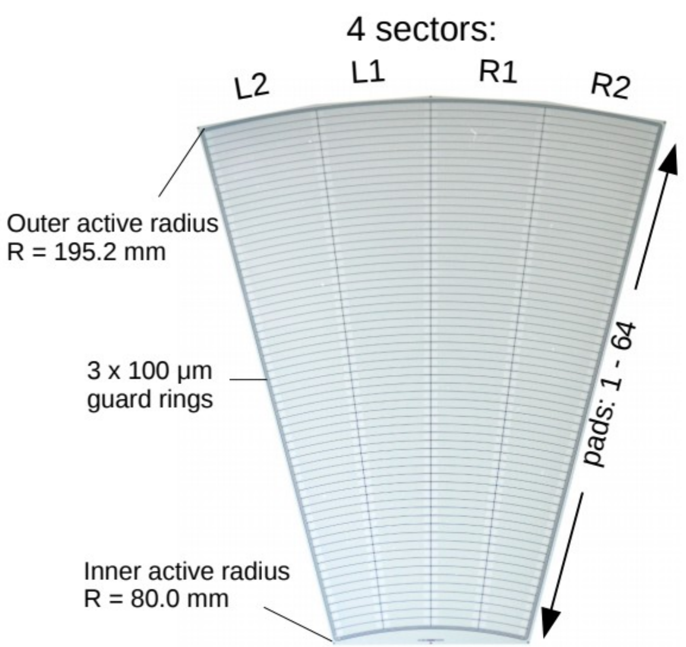


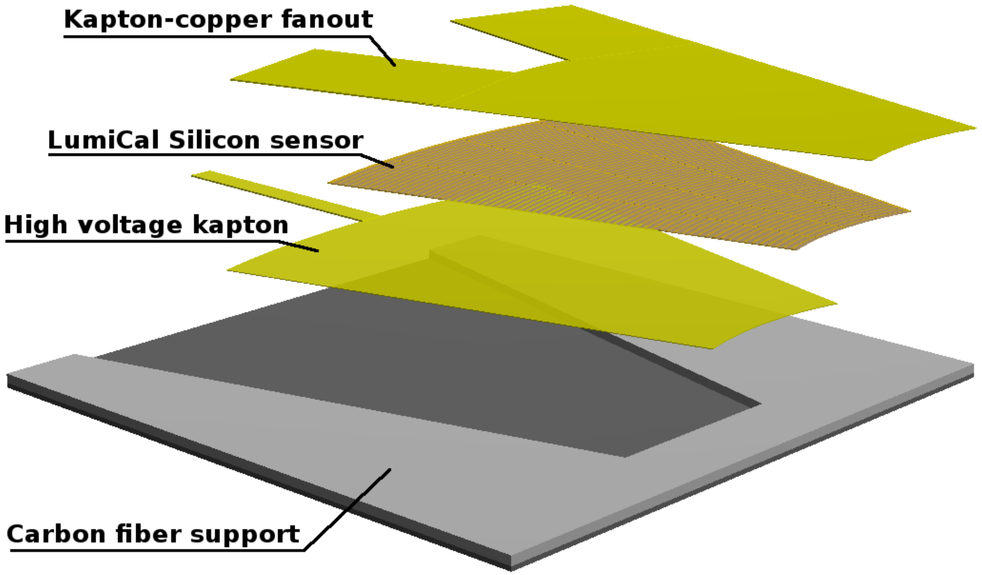


N. Hod (Weizmann Inst.)

- **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



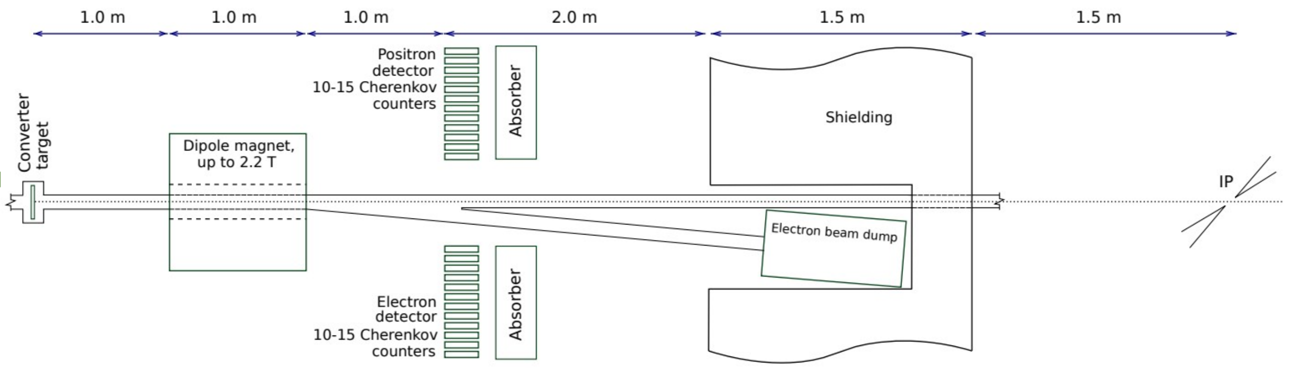


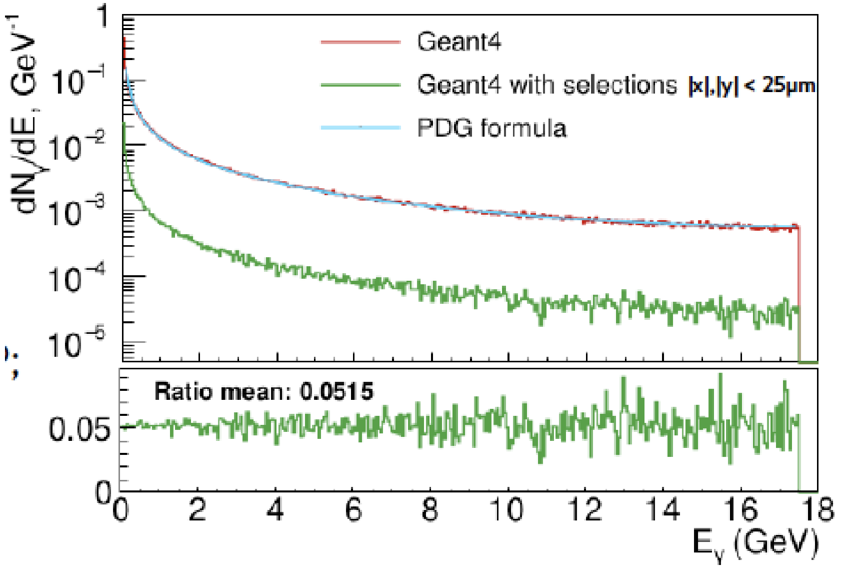
Y. Benhammou, H. Abramowicz, A. Levy (Tel Aviv

- **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

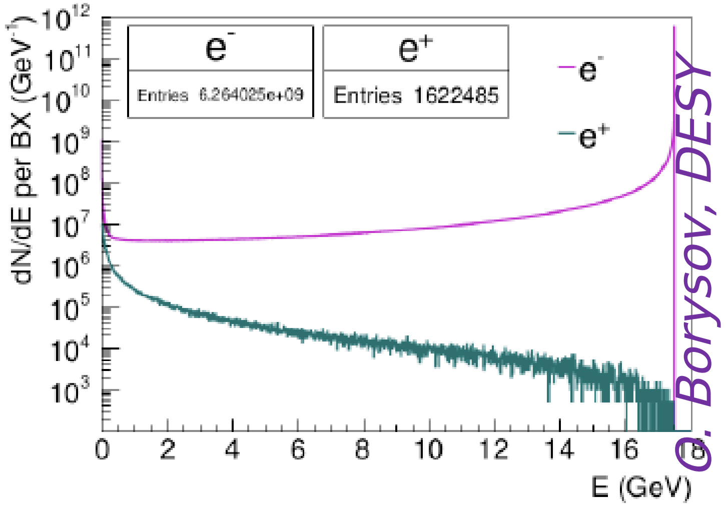
HIGH-ENERGY PHOTON FLUX

photon converter



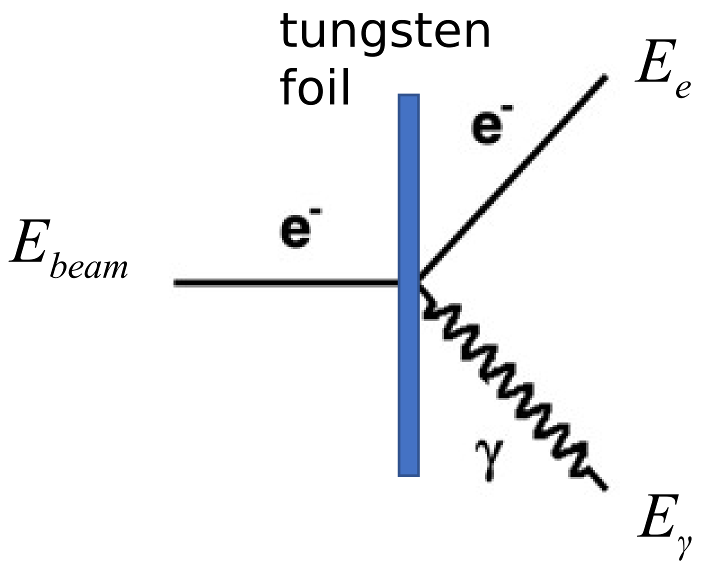


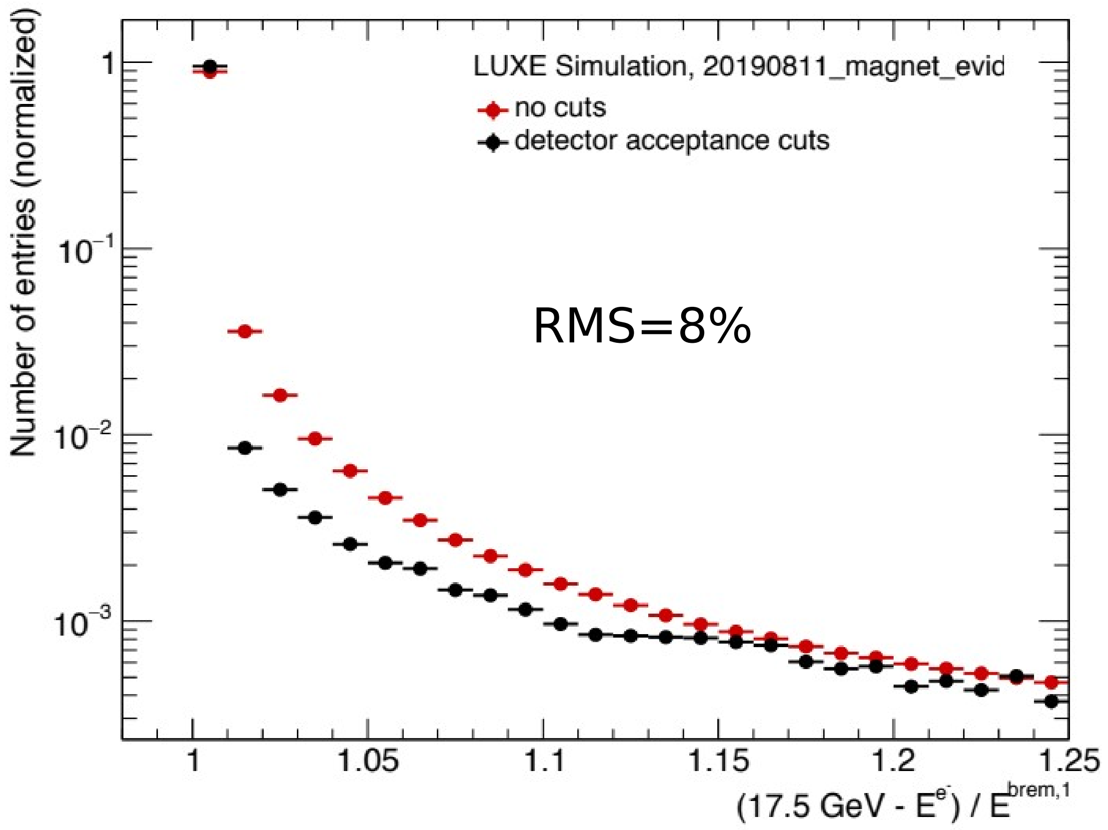
- **Simulation of converter using Geant4**
  - Tungsten Target with 0.01 X_0 (35 μm) => 1% at IP
- **Spectrum of photon energies important to know**
  - Measure by observing electrons and positrons right after dipole magnet
- **Particle detection**
  - 2T magnet followed by array of Cherenkov detectors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



G. Borysov, DESY

PHOTON ENERGY MEASUREMENT

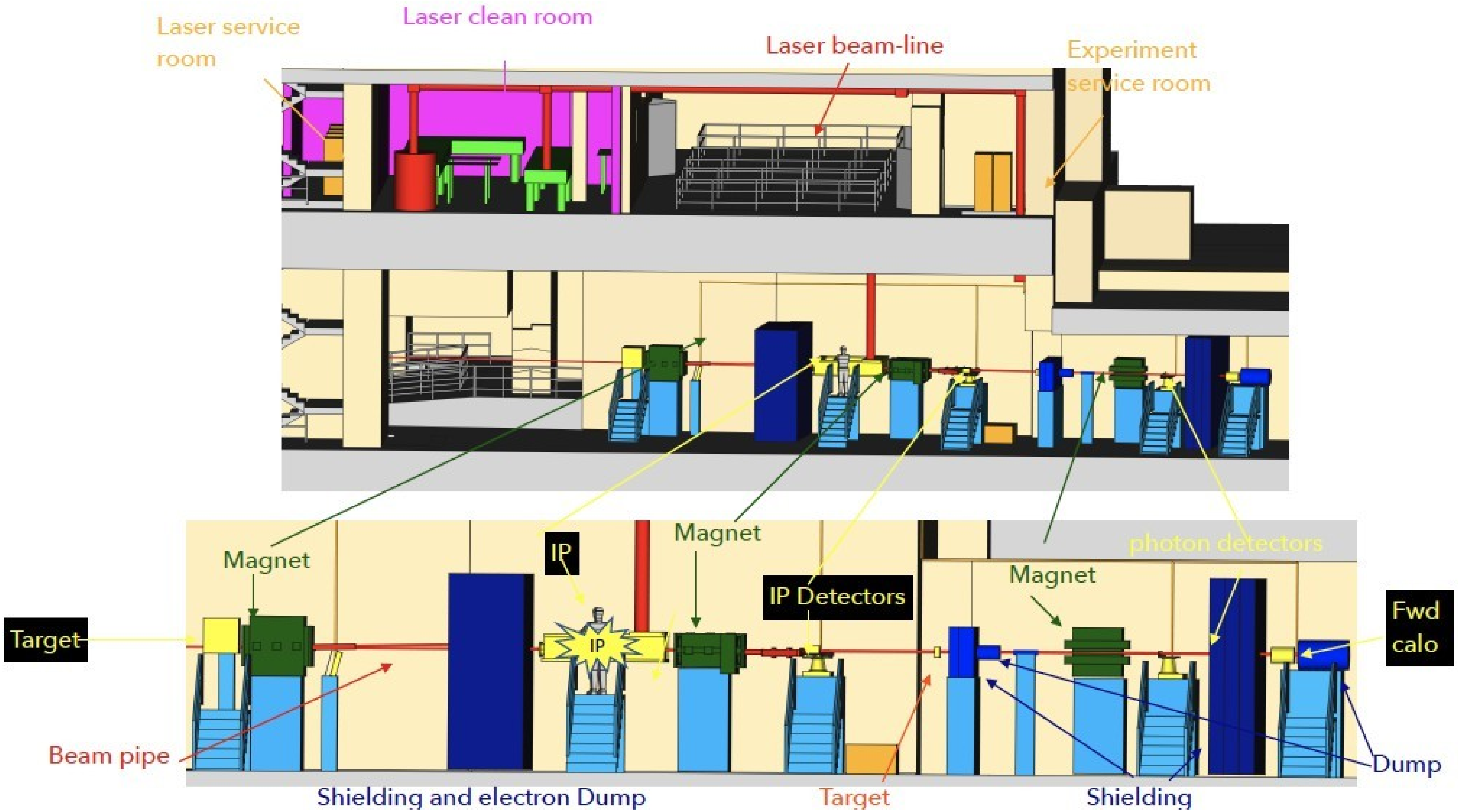




M. Saimpert, DESY

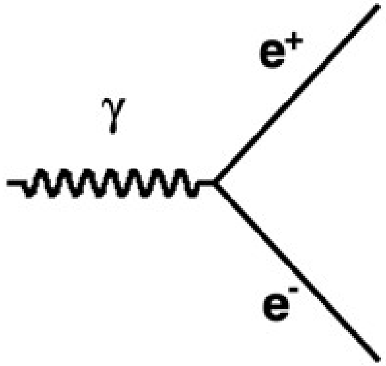
- **Photon energy determined from measured electron energy to within ~10%:**

GENERAL OVERVIEW: XS1 BUILDING



PAIR PRODUCTION PROCESS

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

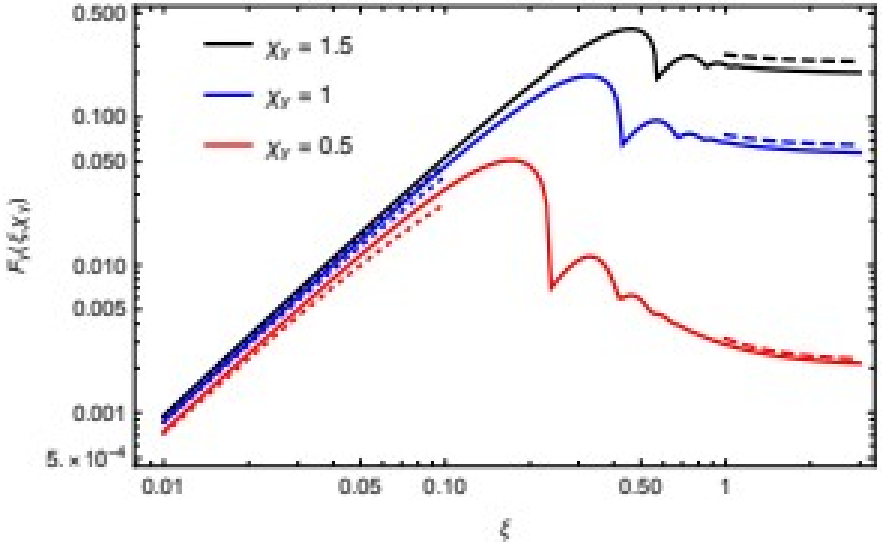


$$\frac{\Gamma_{\mathrm{SPP}}}{V} = \frac{m_e^4}{(2\pi)^3}\left(\frac{|\mathbf{E}|}{\mathrm{E_c}}\right)^2 \sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n\pi\frac{\mathrm{E_c}}{|\mathbf{E}|}\right) \qquad \propto \exp\left(-\pi\frac{E_c}{|\boldsymbol{E}|}\right)$$

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

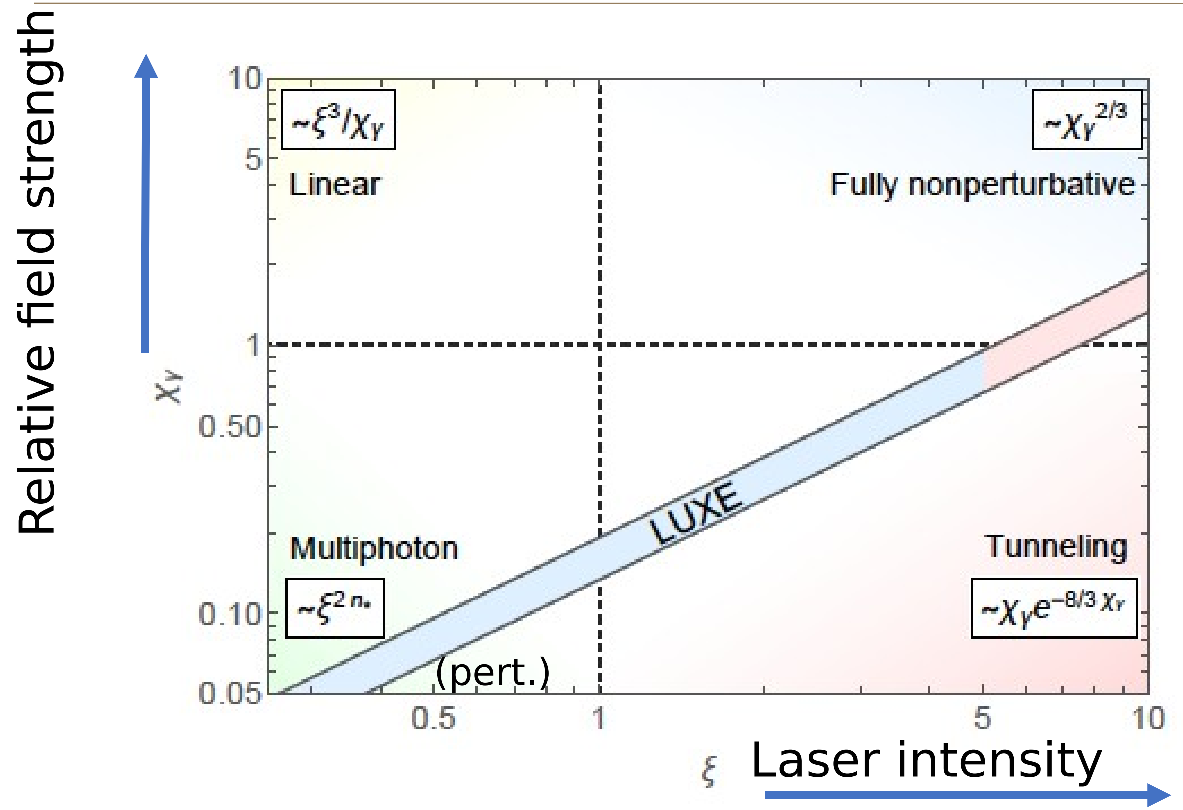
$$\Gamma_{\mathrm{OPPP}} \to \frac{3}{16}\sqrt{\frac{3}{2}}\,\alpha\, m_e\,(1+\cos\theta)\;\frac{|\mathbf{E}|}{\mathrm{E_c}}\exp\left[-\frac{8}{3}\,\frac{1}{1+\cos\theta}\,\frac{m_e}{\omega_i}\,\frac{\mathrm{E_c}}{|\mathbf{E}|}\right]$$

- **Good agreement between full calculation and asymptotic result for and**

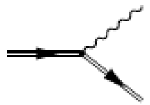
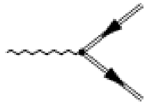
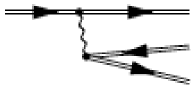


A. Hartin, A. Ringwald, N. Tapia: arXiv:1807.10

LUXE PARAMETER SPACE: THEORY VIEW

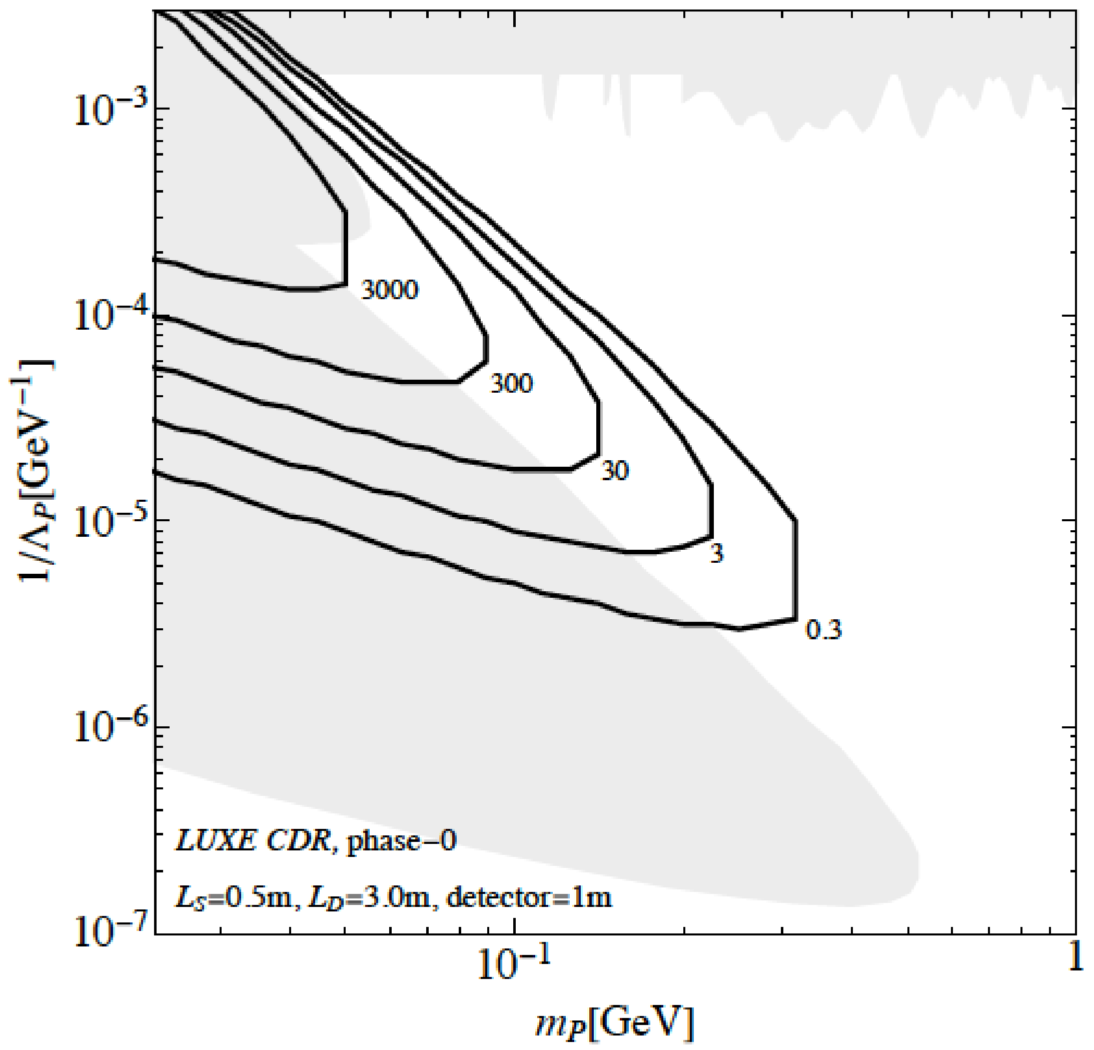


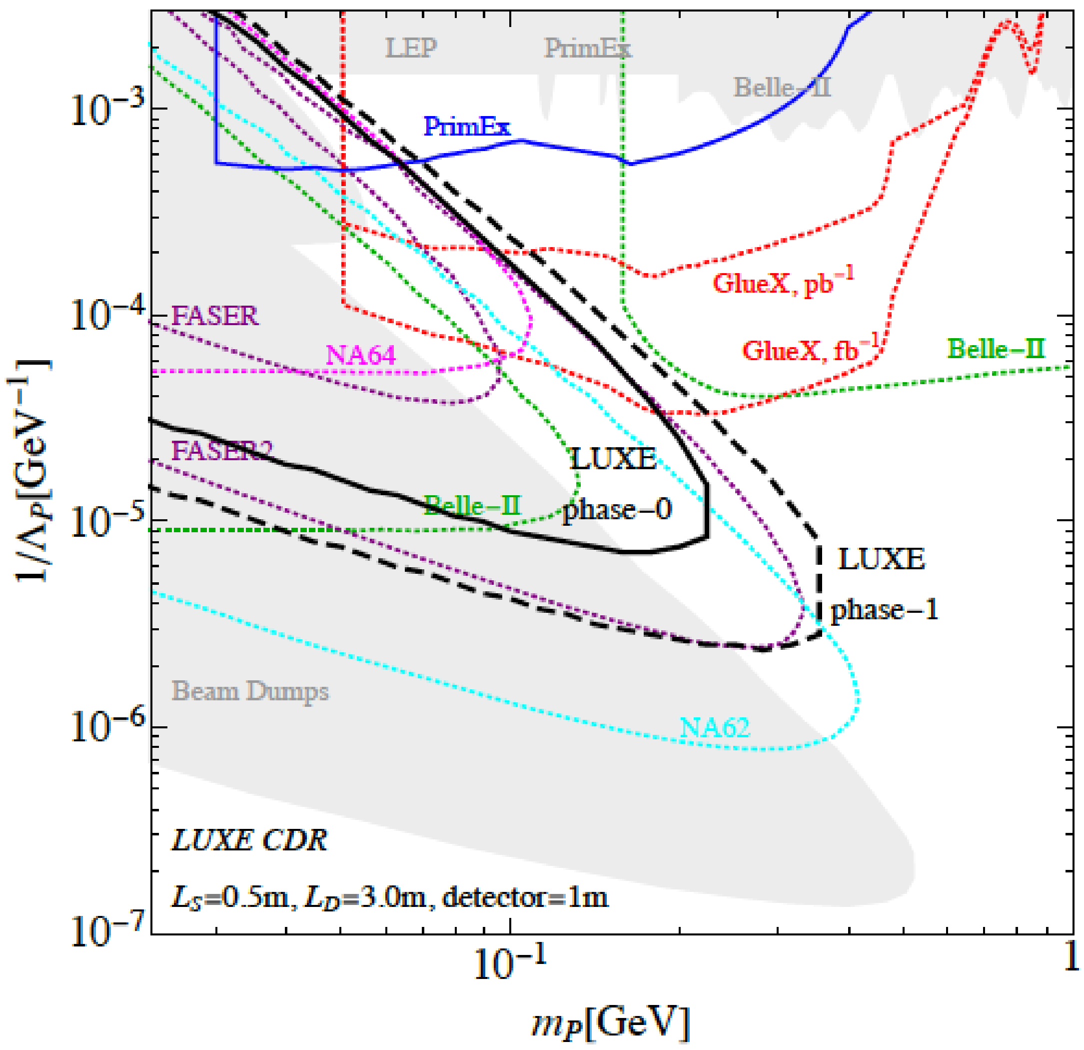
three processes at LUXE

LUXE Candidate Processes		
	Nonlinear Compton	$e^\pm \to e^\pm + \gamma$
	Nonlinear Breit-Wheeler	$\gamma \to e^- e^+$
	Nonlinear trident	$e^\pm \to e^\pm + e^- e^+$

- **LUXE will probe three different regimes as the laser intensity is varied**
  - Dedicated teams for calculations and simulations contributing to LUXE
  - All results based on custom simulations (A. Hartin, UCL)
    - Cross-checks by other theorists involved ongoing (Gothenburg, Plymouth, Skoltech, MEPHI, Jena)

BSM SENSITIVITY





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

SNOWMASS SESSION: HIGH FIELD PHYSICS WITH INTENSE ELECTRON AND LASER BEAMS

Contribution list | Timetable

Oct. 7th 2020

Wed 07/10

Print | PDF | Full screen | Detailed view | Filter

Time	Contribution	Speaker / Time
13:00	**Schwinger field physics** *Zoom 20*	*Michael Peskin* 13:00 - 13:10
	SLAC E-320 experiment *Zoom 20*	*Sebastian Meuren* 13:10 - 13:15
	LUXE experiment *Zoom 20*	*Beate Heinemann* 13:15 - 13:20
	One-sliders *Zoom 20*	13:20 - 13:23

More interesting issues concern modeling and emergent behavior:

The pairs in the e+e- plasma created by Schwinger fields are produced coherently. What is the effect of this quantum coherence ? Are there prominent plasma modes enhanced by this effect ? Is there nonlinear pattern formation ?

This is an unexplored regime, so we should expect surprises.

Fascinating nonlinear phenomena arise from coherent effects in high-harmonic X-ray generation and from spinodal decomposition in alloys and polymer solutions. Why not here?

Thus, the motivation to explore the $\chi > 1$ regime is very strong.

M. Peskin