LUXE: A NEW EXPERIMENT TO STUDY NON-PERTURBATIVE QED

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IJCLAB SEMINAR

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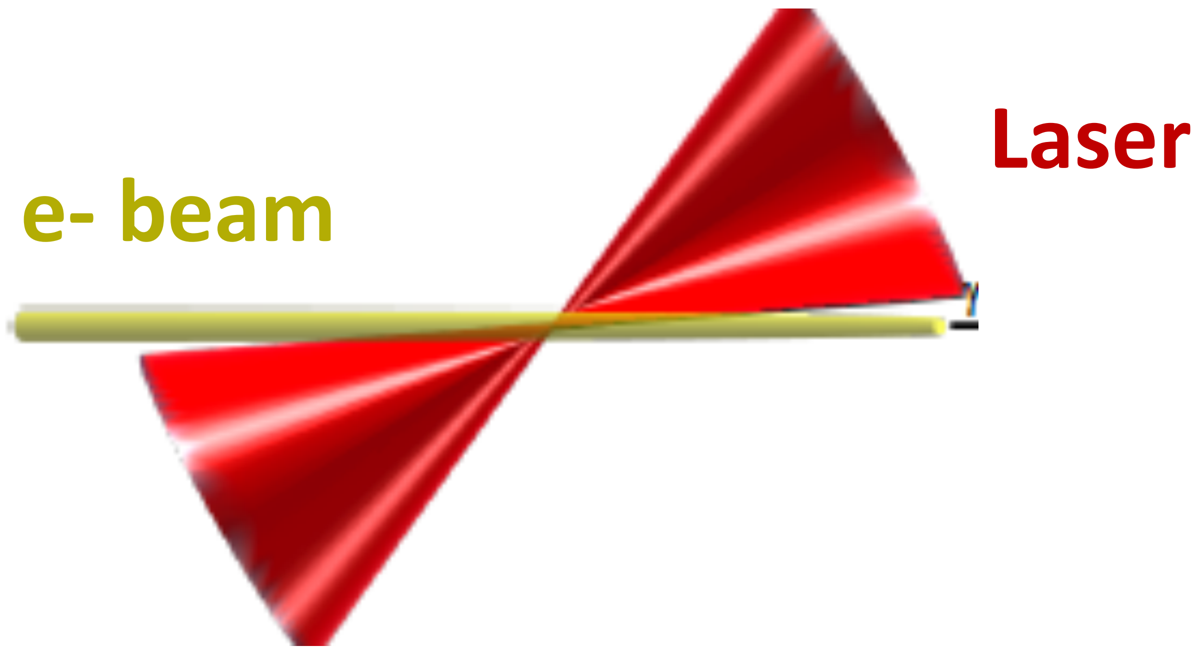
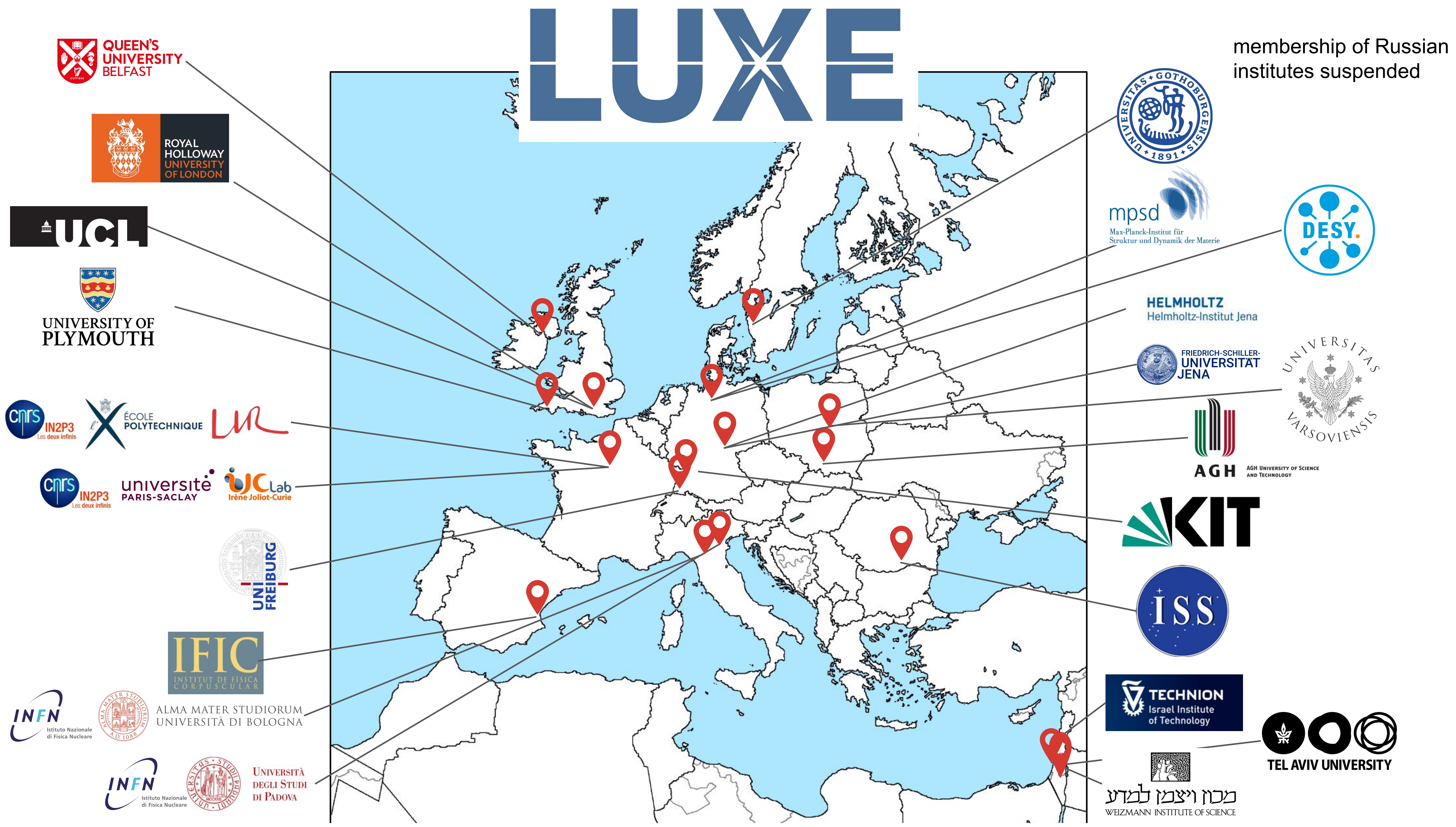
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

INTRODUCTION: WHAT IS LUXE AND WHAT ARE WE GOING TO DISCUSS TODAY?

- Luxe: **L**aser **U**nd **X**FEL **E**xperiment
  - New experiment planned in Hamburg using
    - European XFEL electrons accelerator
    - High-intensity laser
  - Synergy between particle physics and laser physics!



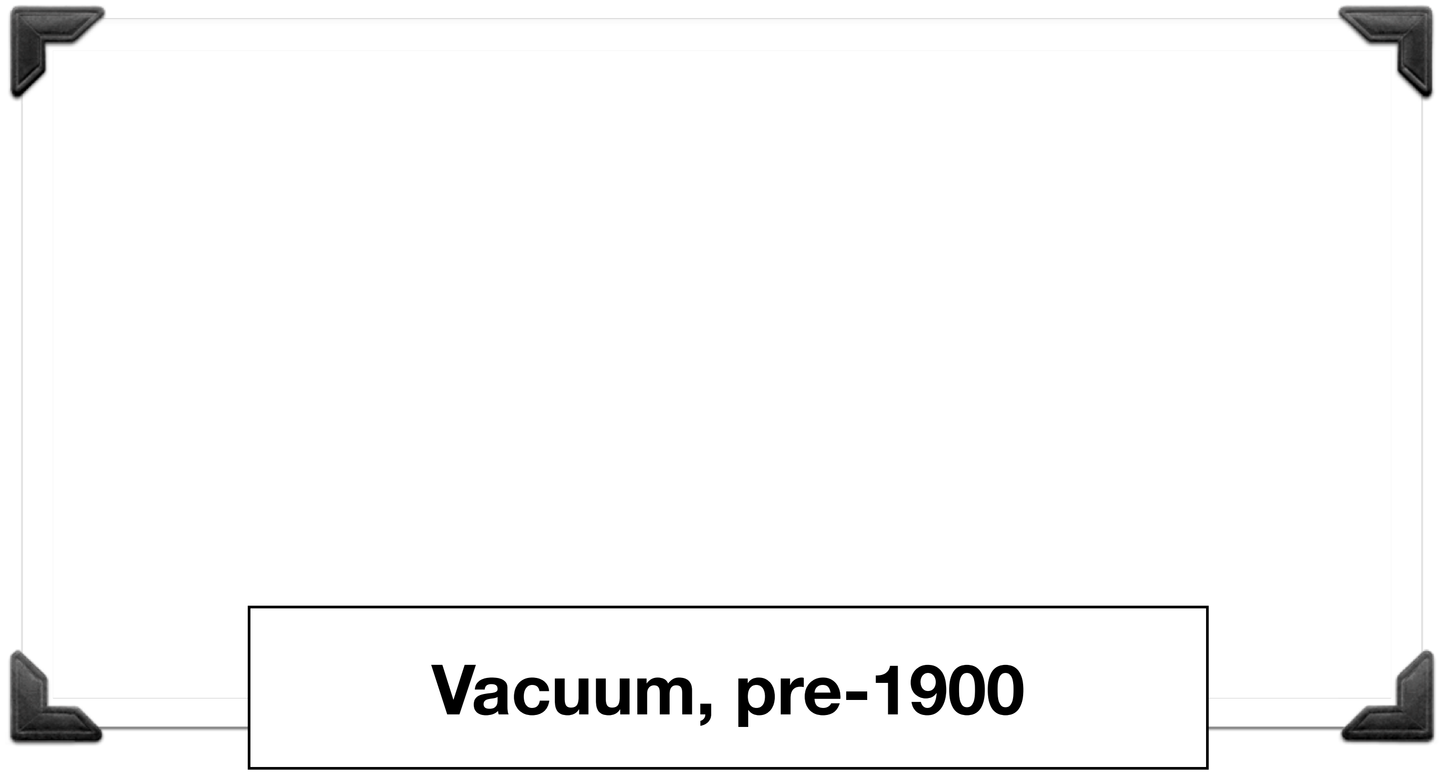
- Main documents describing the experiment:
  - LOI (2019): https://arxiv.org/abs/1909.00860
  - CDR (2021): published by EPJST: https://arxiv.org/abs/2102.02032
- Collaboration ~100 authors 22 institutes, from experimental and theory community!
  - France participation: IJCLAB, LLR.
- Discussed in the following:
  - What is strong-field QED and why is it interesting?
  - What does LUXE add compared to previous SF-QED experiments?
  - What are the key technologies to obtain LUXE's measurement goals?

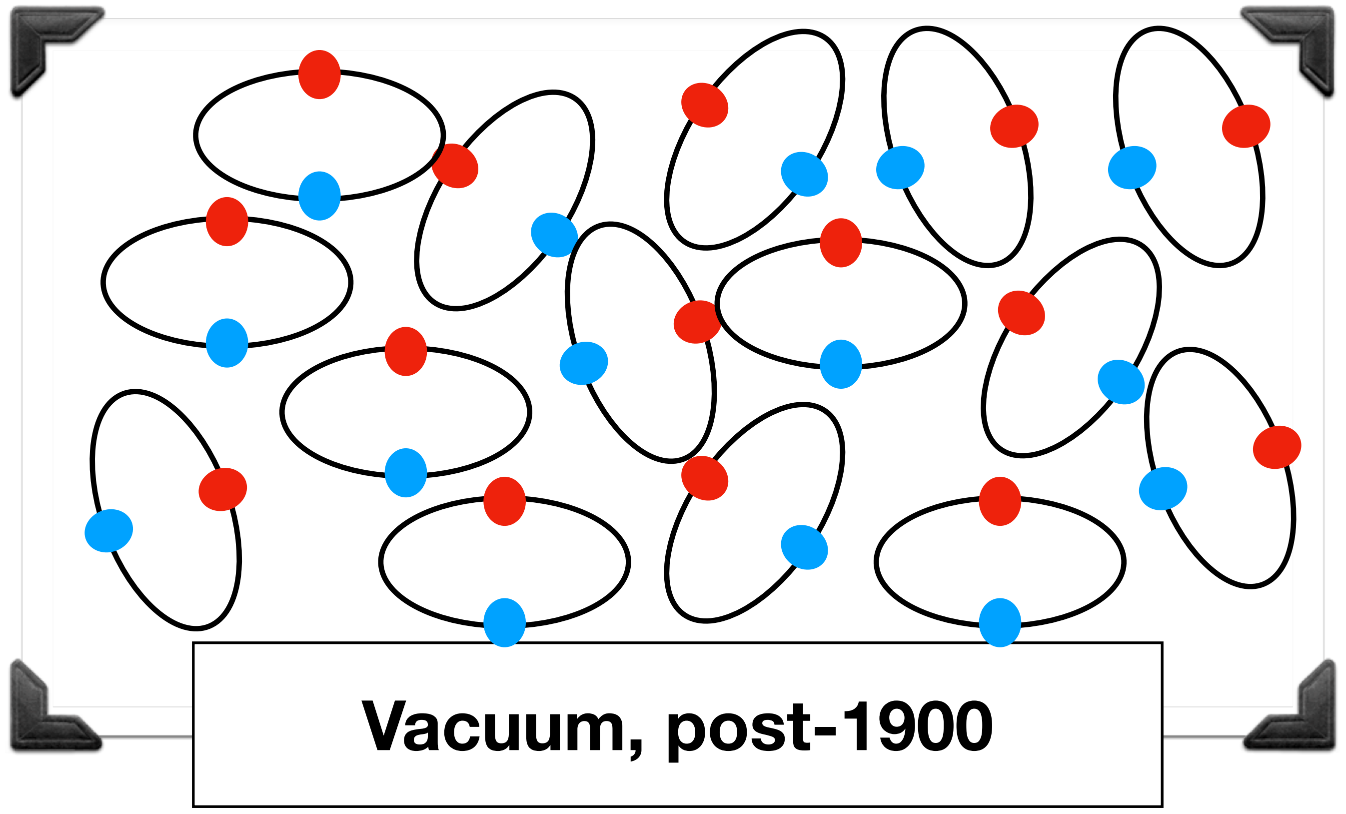


- Quantum Electro Dynamics: One of the most well-tested physics theory!
  - Calculation in QED based on perturbative theory of α_{EM}.
    - Anomalous moment of electron (g-2) as a precision better than 1 part in a trillion and data in agreement with theory.

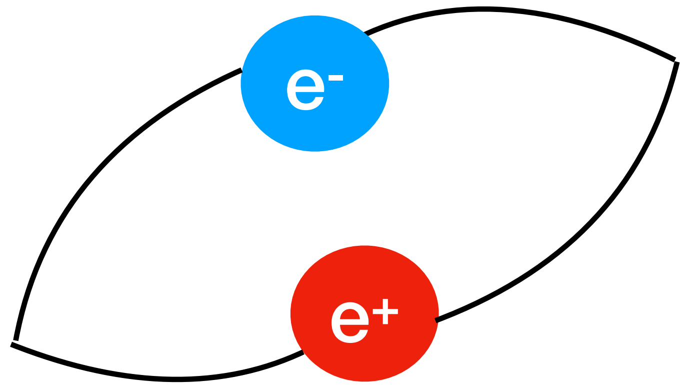
Nobel prize 1965

- The vacuum:
  - State with the lowest energy.
  - Vacuum consists of virtual particles that can be charged and couple to fields.
  - Quantum fields: average is zero, but variance is not!
  - Coupling to virtual particles affects physical particle processes

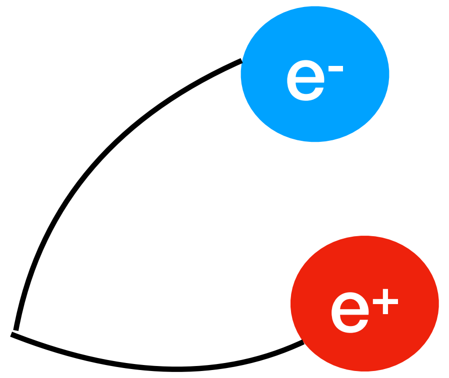




- If one apply a strong electromagnetic field on a vacuum:
  - $W_{field} < 2\,m_e$



$W_{field} > 2m_e$



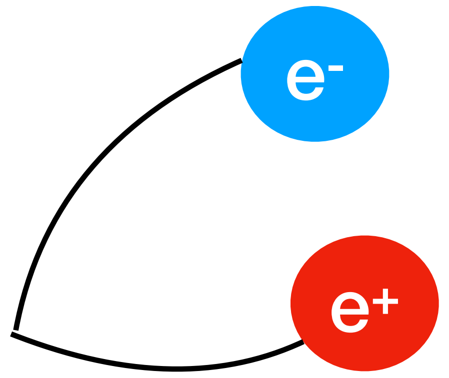
$$W_{field} = \frac{\varepsilon e}{m_e}$$


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

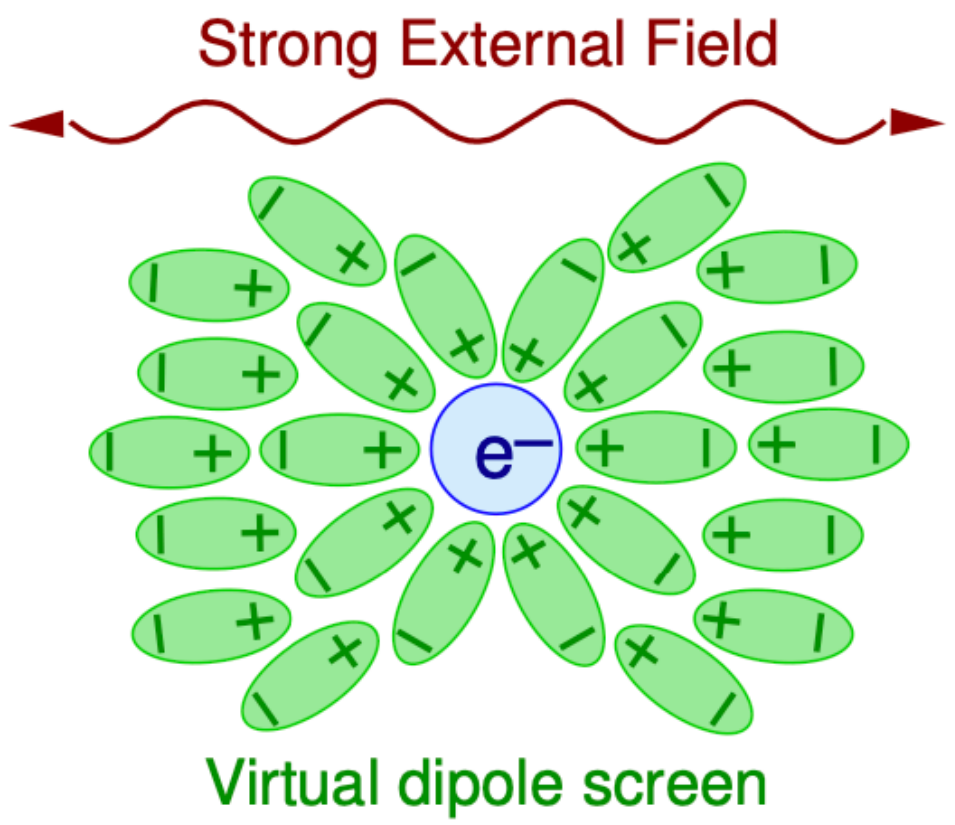
Schwinger
Phys. Rev. 82 (1951), 664

- Vacuum boils if field large enough to create real pairs:
  - "critical field" → Schwinger-Limit: $\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \mathrm{V/m}$
  - QED becomes non perturbative above Schwinger-limit → Strong field QED (SFQED)!

- Experimental consequences:
  - **Field-induced ("Breit-Wheeler") Pair Creation:**

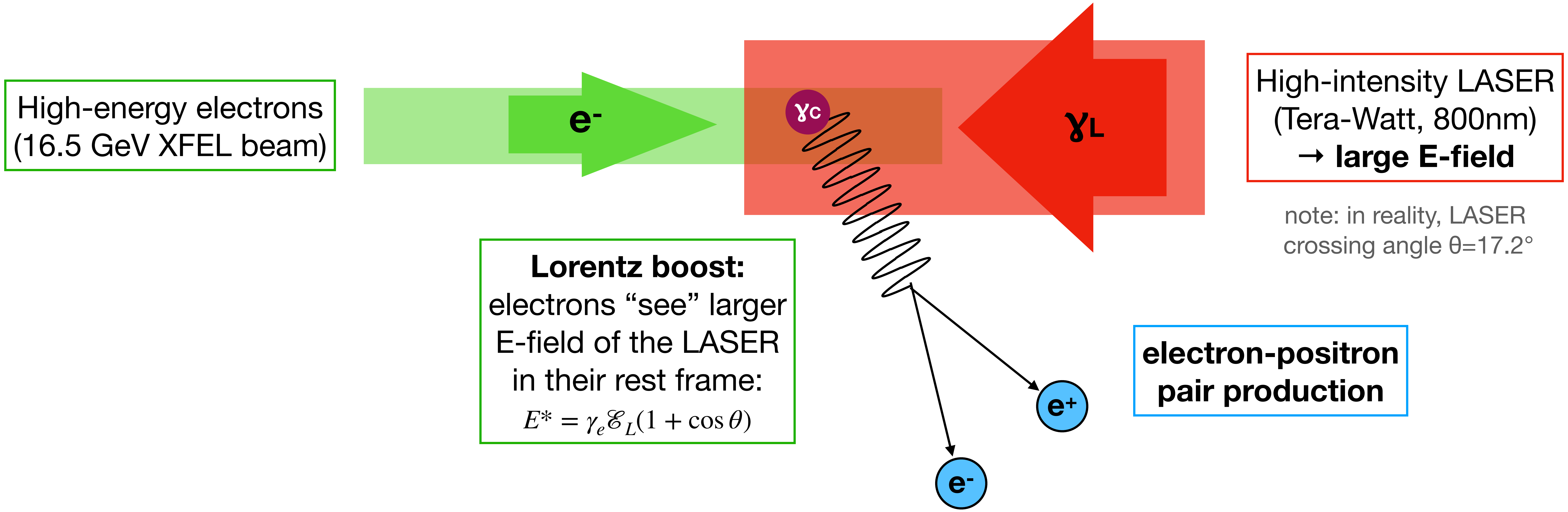


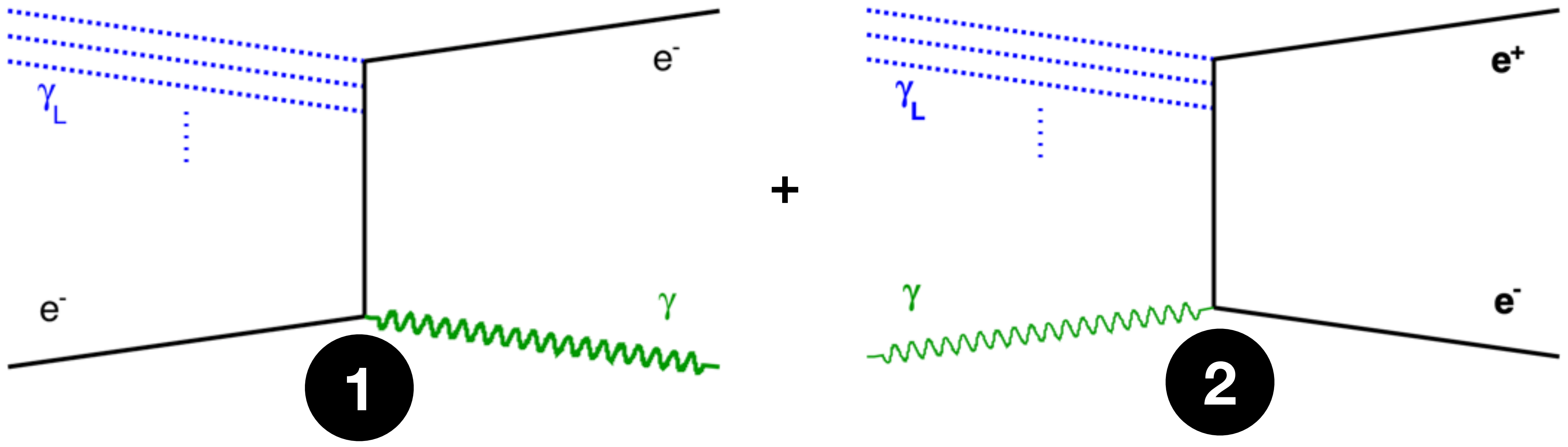
  - **Modified Compton Spectrum:**
    - Effect on Compton edges position.
    - Electrons obtains (significantly) larger effective rest mass.



- Non-perturbative and strong field QED can be probed in laboratory at LUXE!

LUXE: ELECTRON-LASER COLLISIONS

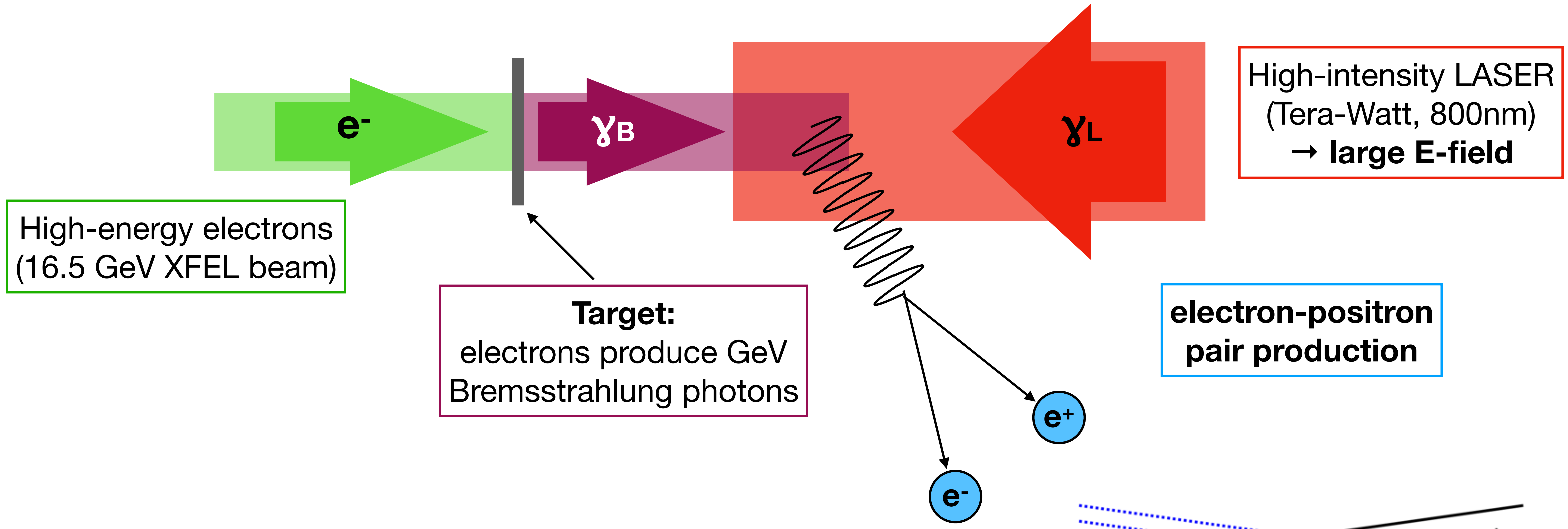


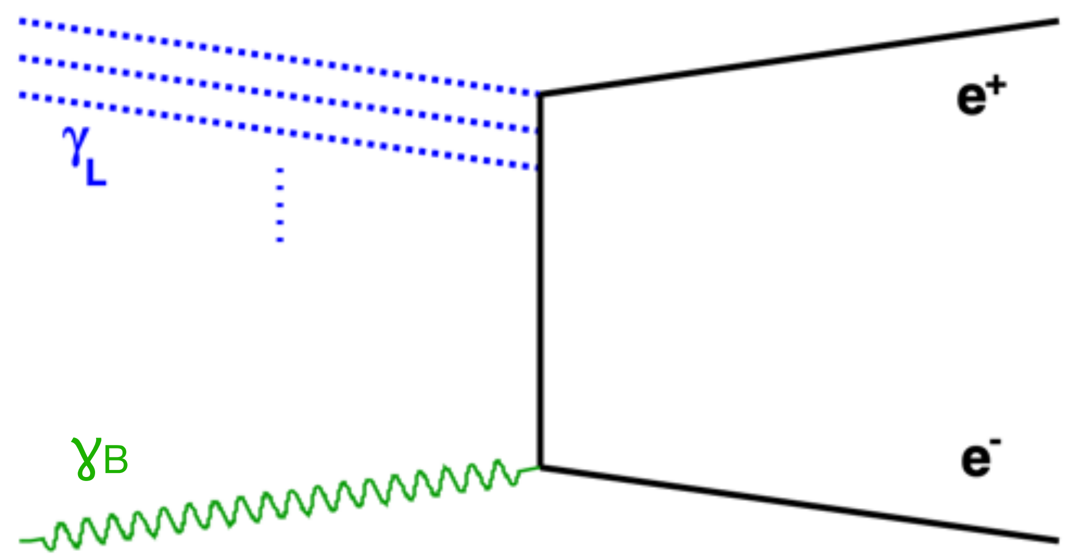


Physics processes:

1. **Non-linear Compton Scattering:** $e^- + n\gamma_L \to e^- + \gamma_C$
2. **Non-linear Breit-Wheeler pair production :** $\gamma_C + n\gamma_L \to e^+ + e^-$

LUXE main goal: Measure positron rate as function of LASER intensity





Physics process:

Non-linear Breit-Wheeler pair production : $\gamma_B + n\gamma_L \rightarrow e^+ + e^-$

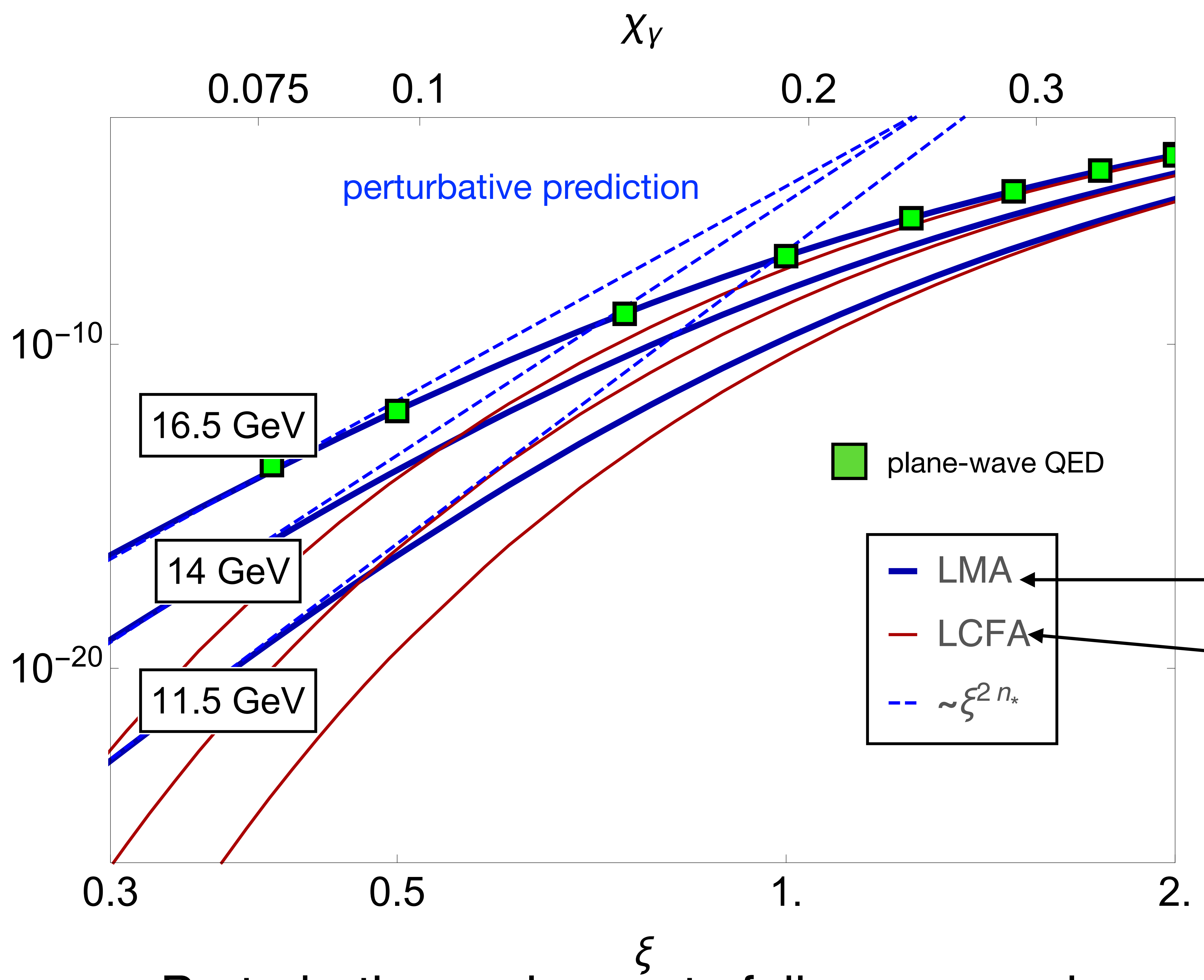
LUXE: first SF-QED experiment to probe directly photon-photon interaction

INTRODUCTION: SFQED PREDICTIONS

- Parameters used in SFQED:
  - ξ = Measure of e-Laser coupling and Laser intensity.
  - X² = fraction of Laser energy transferred to electron beam.

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

probability of Breit-Wheeler process → P



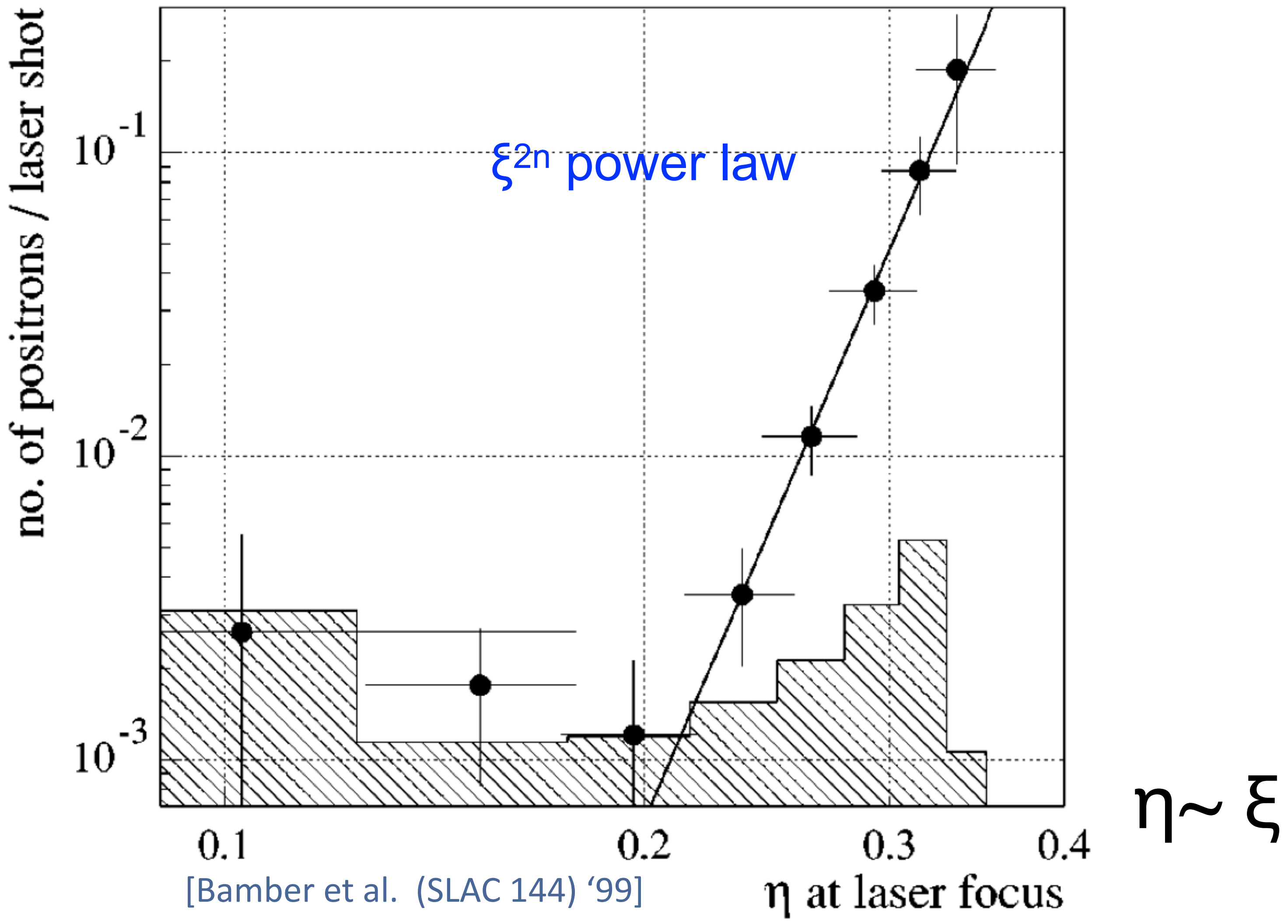
(LMA) Locally Monochromatic Approximation valid at low ξ

(LCFA) Locally Constant Field Approximation valid at high ξ

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

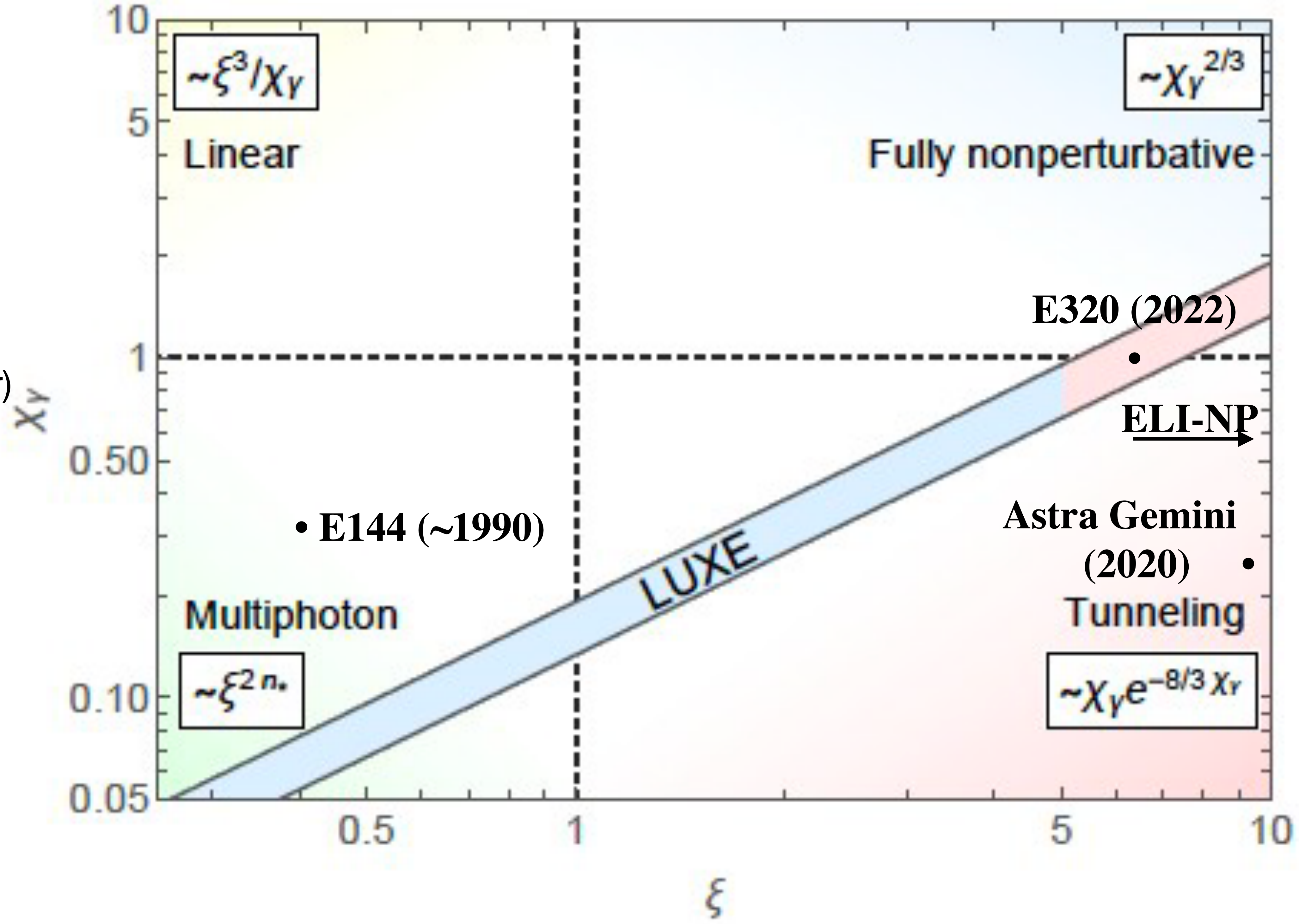
$\xi \gg 1$: $R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$ — Non-perturbative regime, departure from power law

- Historically SFQED with accelerators studied first in 1990's at SLAC E144 (experiment)
  - 1TW laser with $I_{Laser}=10^{18}$ W/cm^2
  - e- beam: 46.6 GeV
  - reached ξ<0.4, χ ≤ 0.25
  - observed multi-photon interaction: $e^- + n\gamma_L \rightarrow e^- e^+ e^-$ process
  - observed start of the ξ^{2n} power law, but not departure



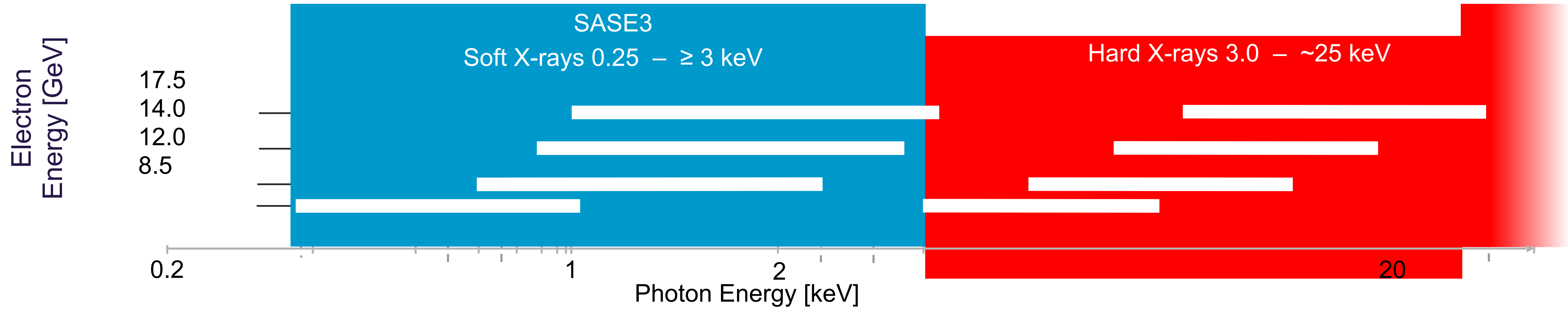
- Nowadays multiple experiments proposed worldwide:
  - SLAC-E320 (US), Astra Gemini (UK), ELI-NP (RO), LUXE (DE)
  - Summary of parameters needed to reach non-perturbative regime

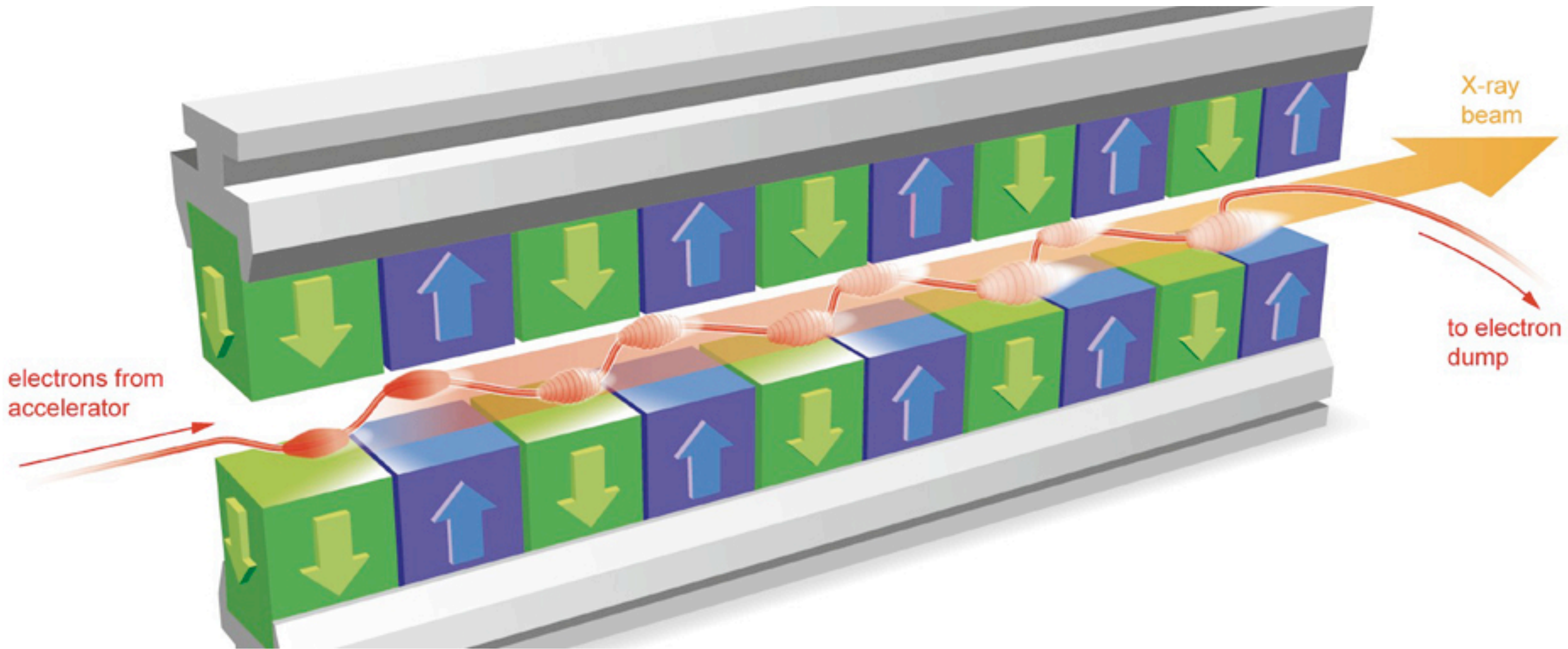
e- Beam	I_{Laser} [W/cm^2]	
1 eV	10^{29}	(Not currently achievable)
1 GeV	10^{22}	(corresponds to 10 PW laser)
10 GeV	10^{20}	(corresponds to 100 TW laser)

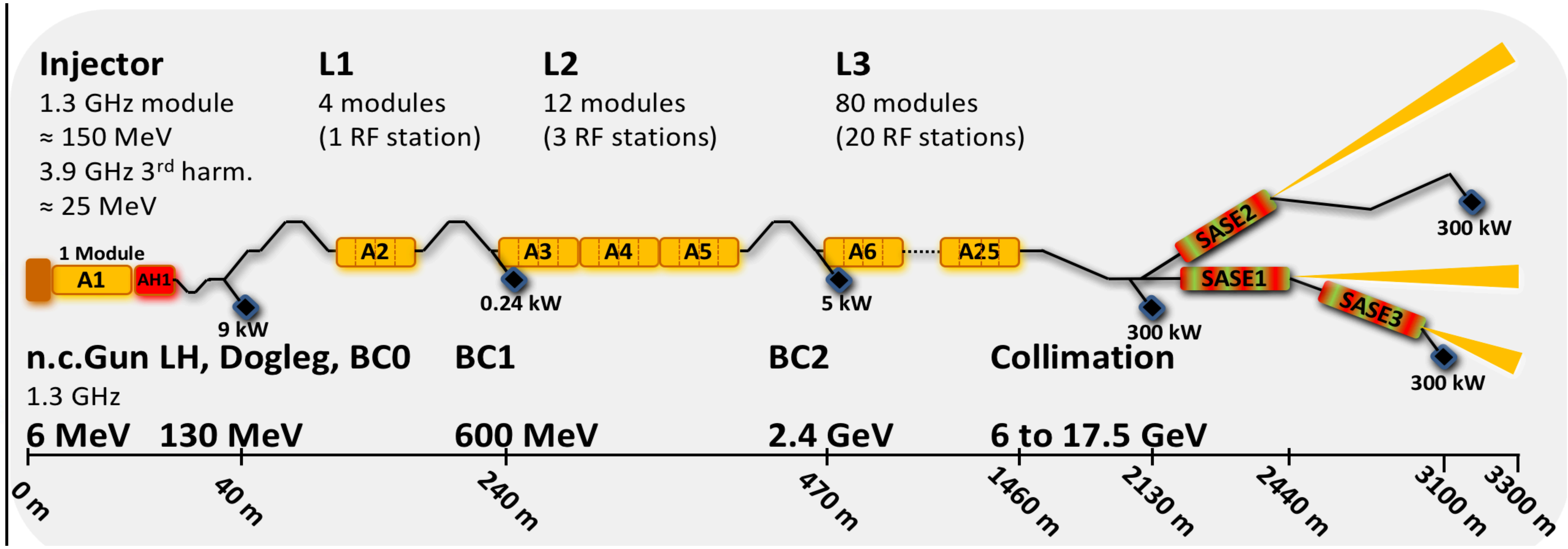


- Luxe allow to measure with precision large part of ξ vs X phase space.
  - Might be the first one to report observation of non perturbative regime.
    - Only experiment proposed to directly explore photon-laser interactions.

- European XFEL:
  - Running since 2017.
  - Linear electron accelerator.
    - 1.9 km long.
    - Up to 17.5 GeV.
    - 2700 electron bunches at 10 Hz.
  - Provide X-ray photons to 6 experiments.
    - Electron through undulator:
      - SASE (self-amplified spontaneous emission)
    - 0.25 keV to 25 keV.

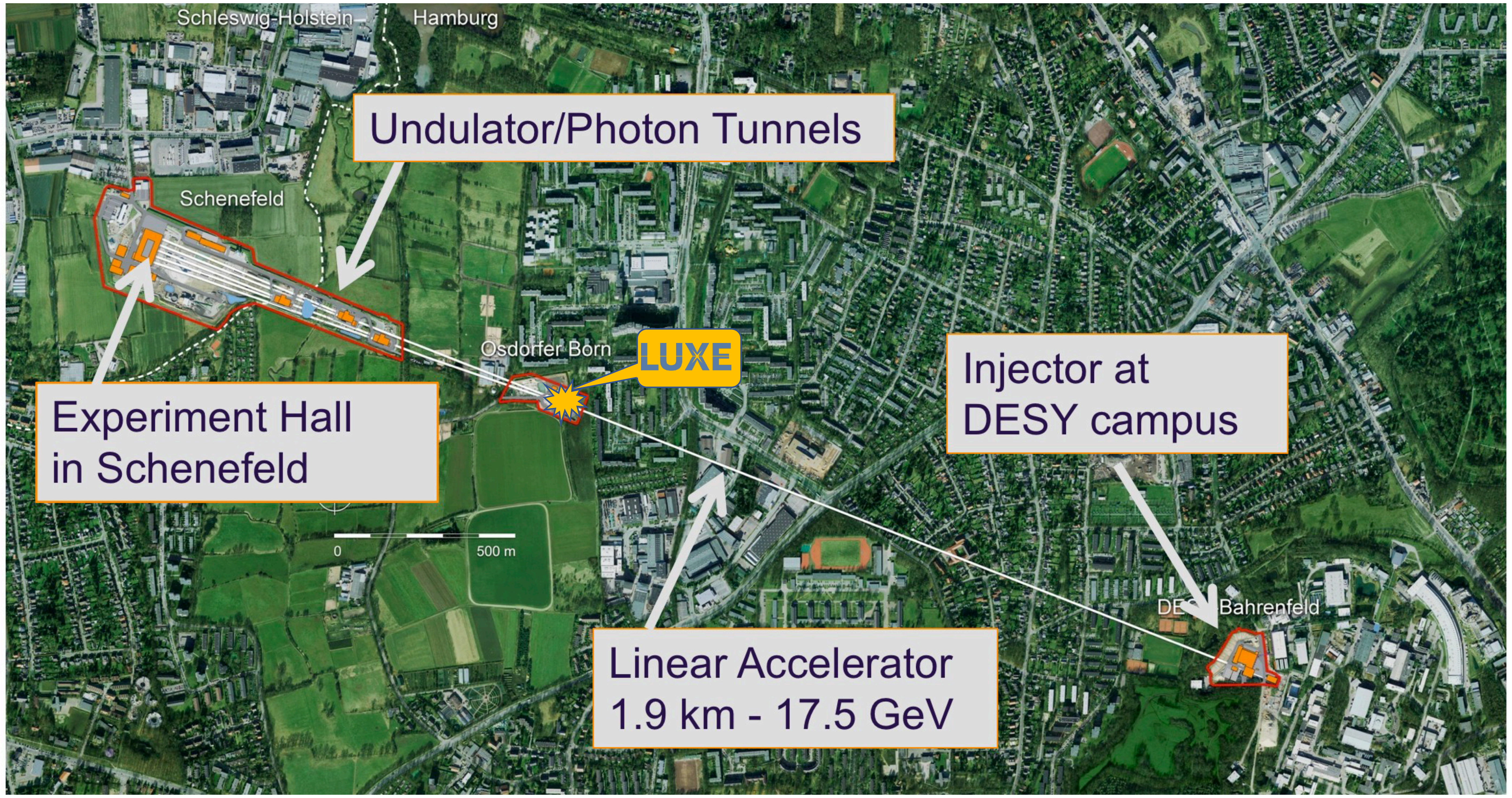


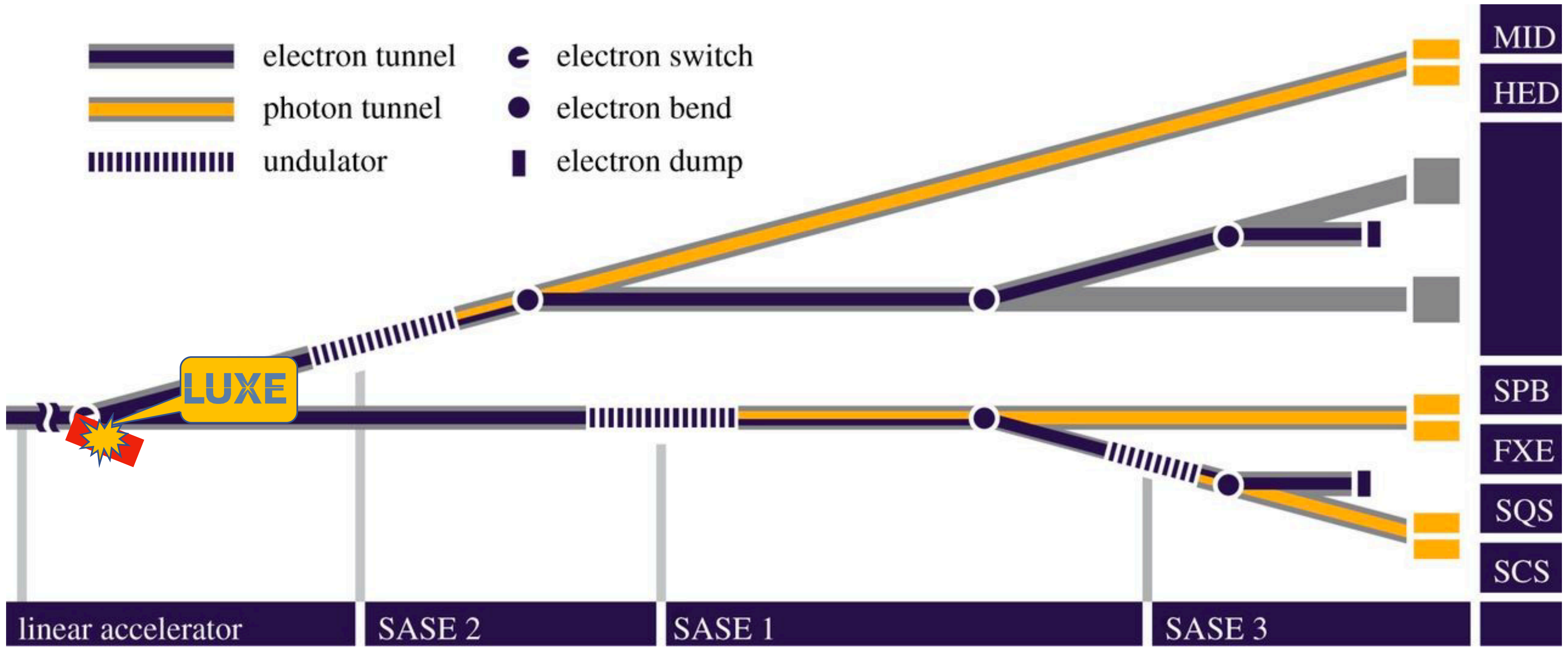




LUXE@EUROPEAN XFEL

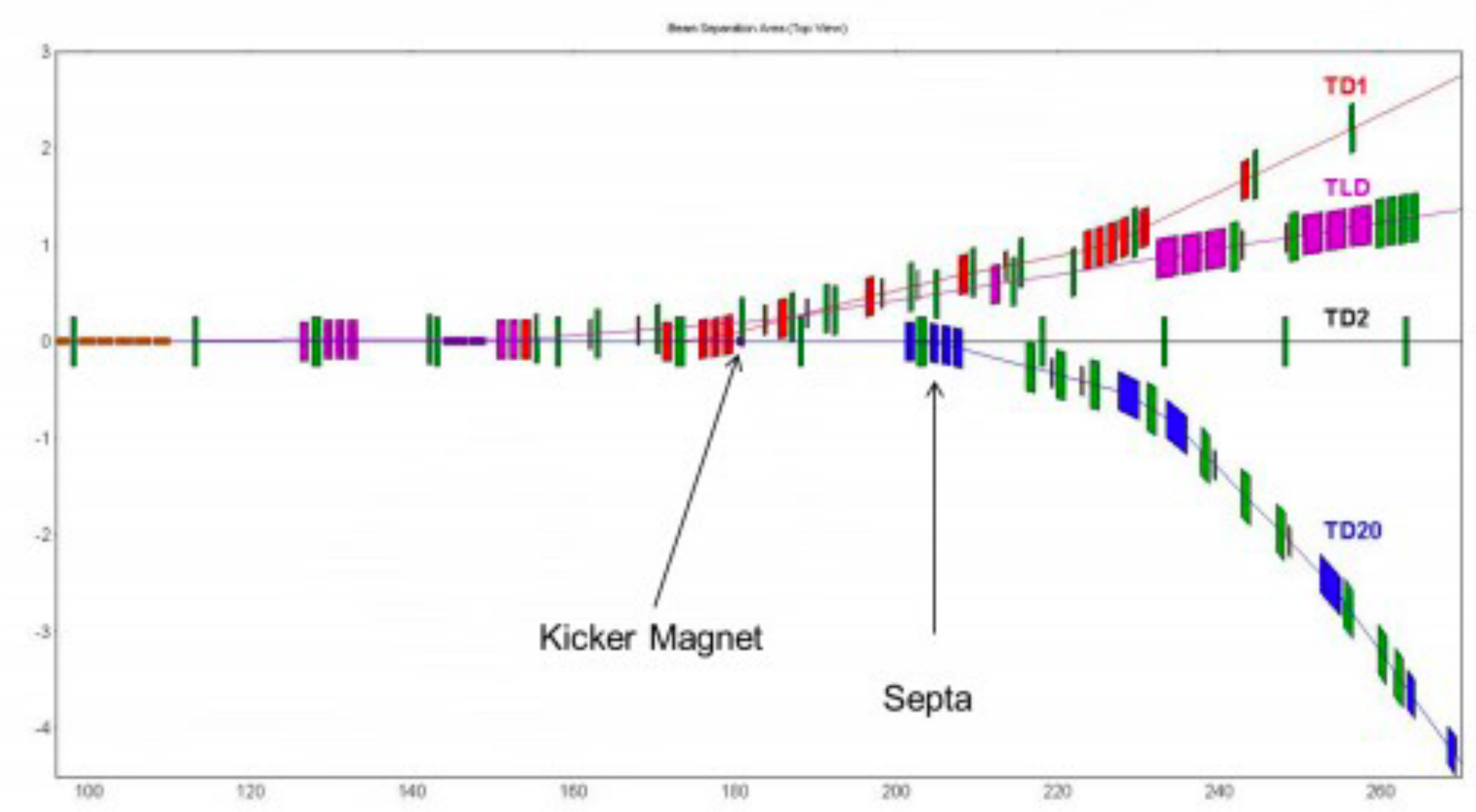
- Experiment will be located in annex of XS1 shaft building in Orsdorfer Born.
  - Built for XFEL extension (after 2030).
- Experiment will have no impact on photon science,
  - Only use 1 of the 2700 bunches.
- Physics parameters used:
  - 1 bunch at 10 Hz.
  - Aim to run @ 16.5 GeV with 1.5 10^9 electrons/bunch (0.25nC).
  - With $\sigma_x, \sigma_y = 5\mu m$.
  - Pulse 130 fs





FROM THE ACCELERATOR TO THE EXPERIMENT

- Construct dedicated new extraction line at the end of the LINAC.
  - Reusing magnet design from XFEL (or HERA for quads).
  - New fast kicker magnets (2 µs: kicks bunch at end of bunch train).
- Independent machine CDR released in 2019 (not public).
  - More information can be found in (or in our CDR): https://accelconf.web.cern.ch/ipac2019/papers/tuprb008.pdf

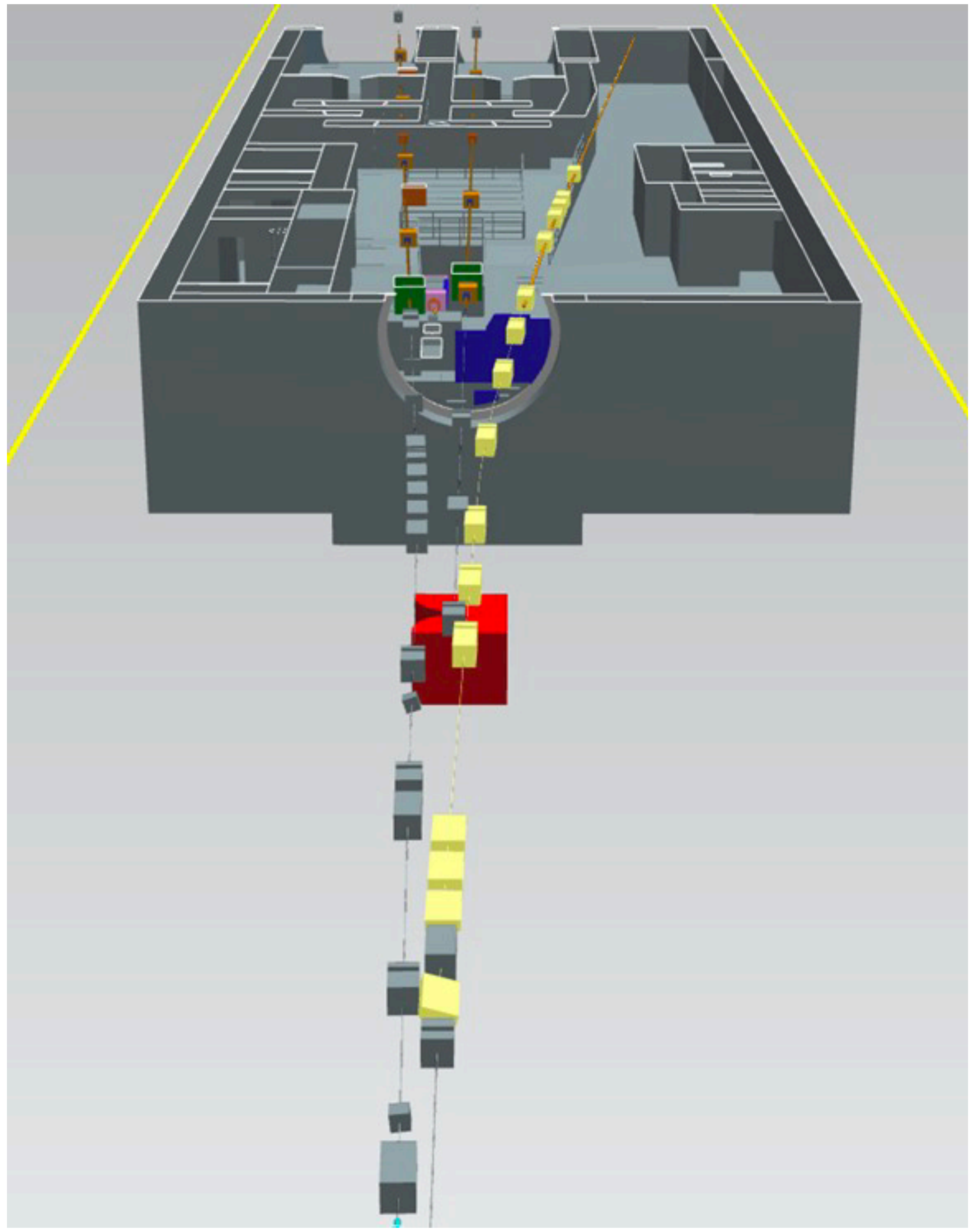


XTD20 Electron Beam Transfer Line
Conceptual Design Report

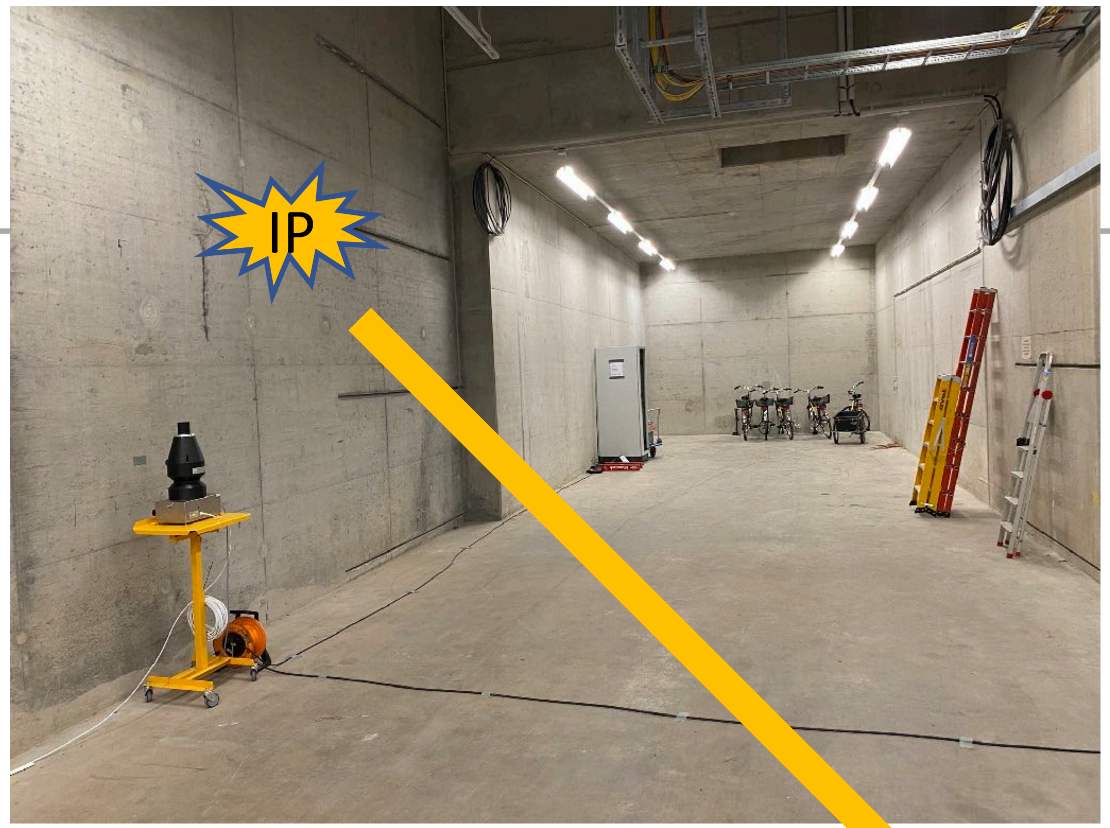
Editors: Florian Burkart, Winfried Decking

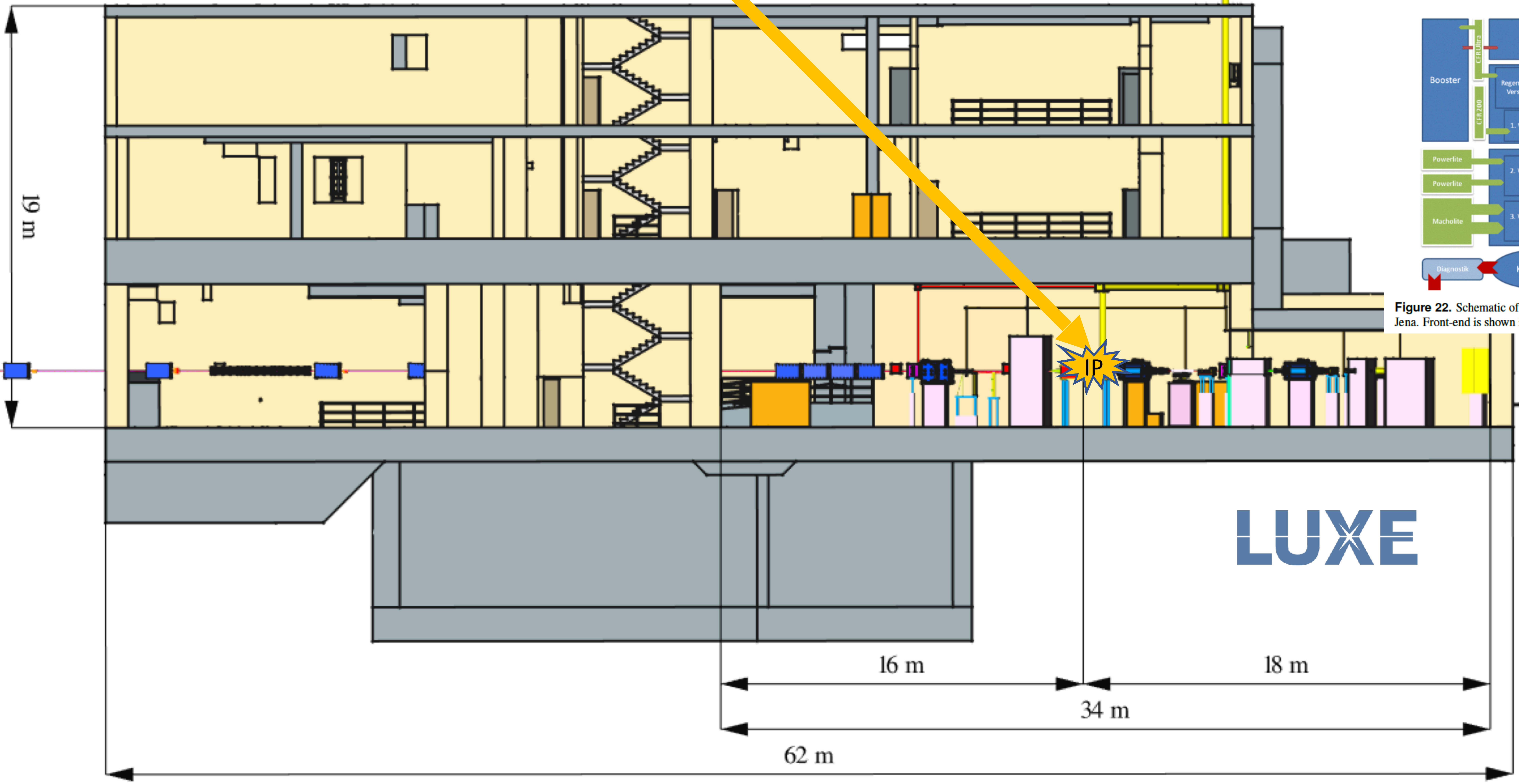
with input from: R. W. Assmann, R. Brinkmann, F. Burkart, W. Decking, H. Eckoldt, N. Golubeva, B. Heinemann, M. Huening, L. Knebel, M. Koerfer, B. Krause, D. Lenz, L. Lilje, C. Martens, M. Scheer, M. Schmitz, F. Obier, R. Platzer

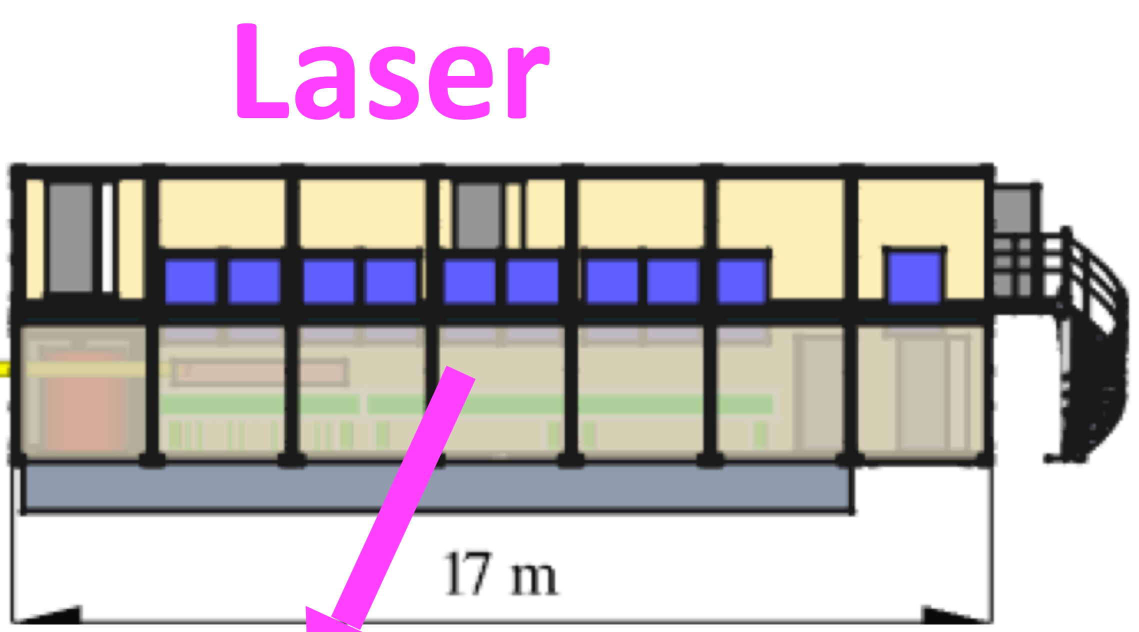
August 2019



LUXE IN XS1 BUILDING







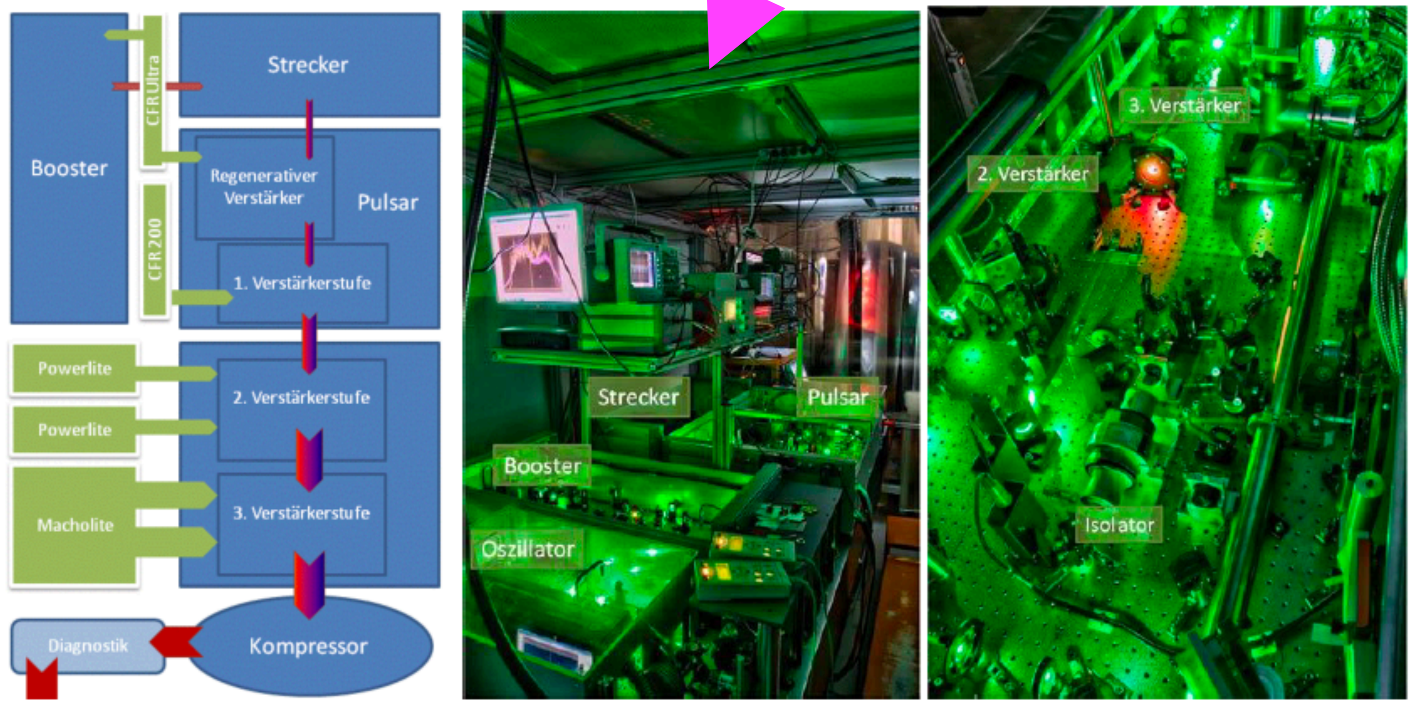
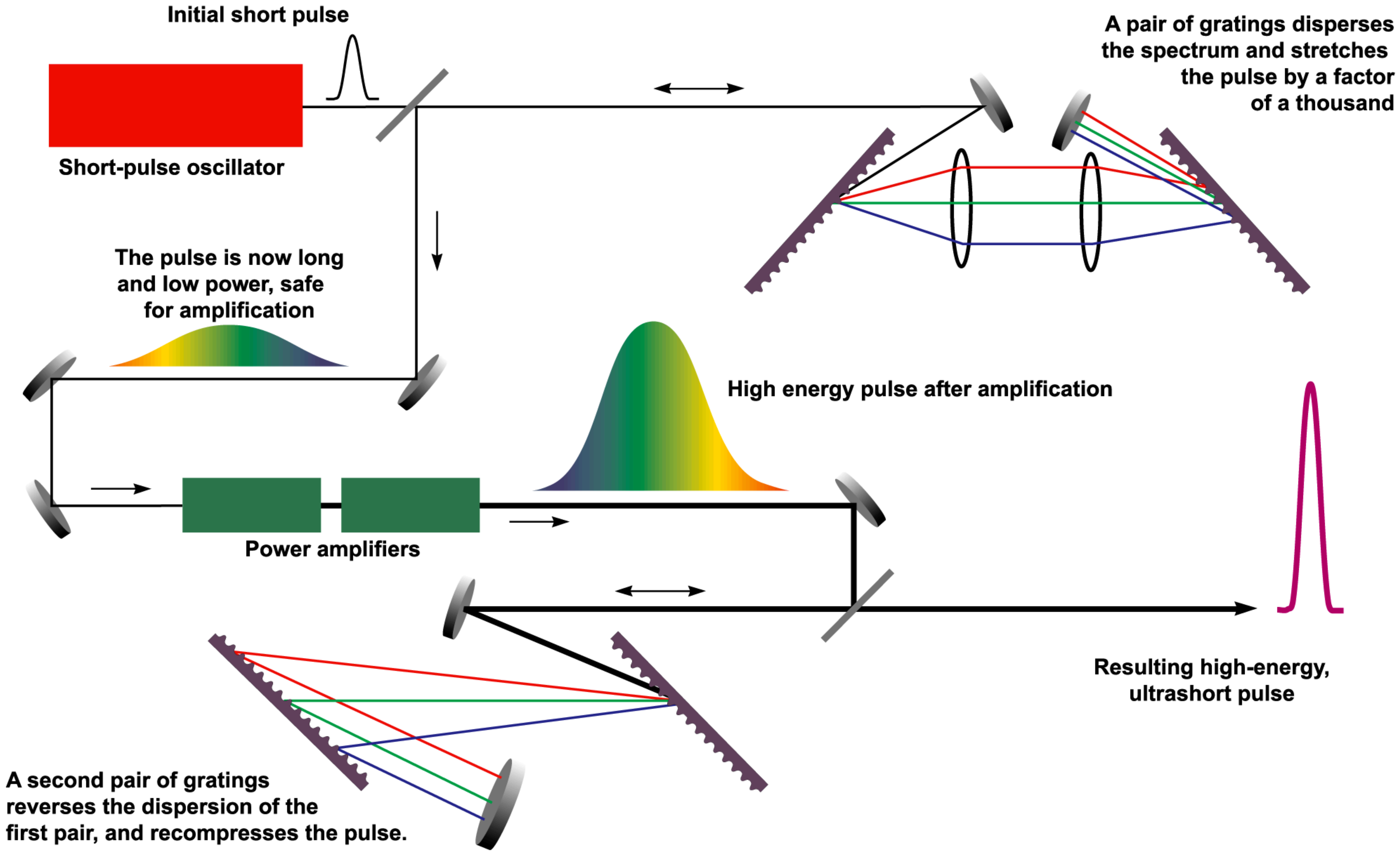
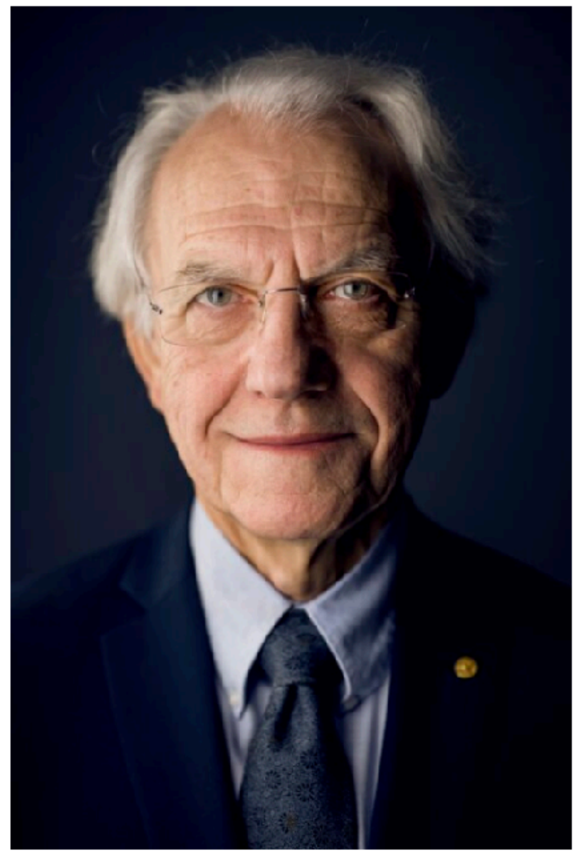


Figure 22. Schematic of the JETI system highlighting major assemblies. Current Installation of JETI-40 at the University of Jena. Front-end is shown in centre and power amplifiers right.

ULTRA INTENSE LASER - CPA TECHNIQUE



- 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.*”
  - Technological leap to reach very-high intensity with laser!



Gérard Mourou

Prize share: 1/4

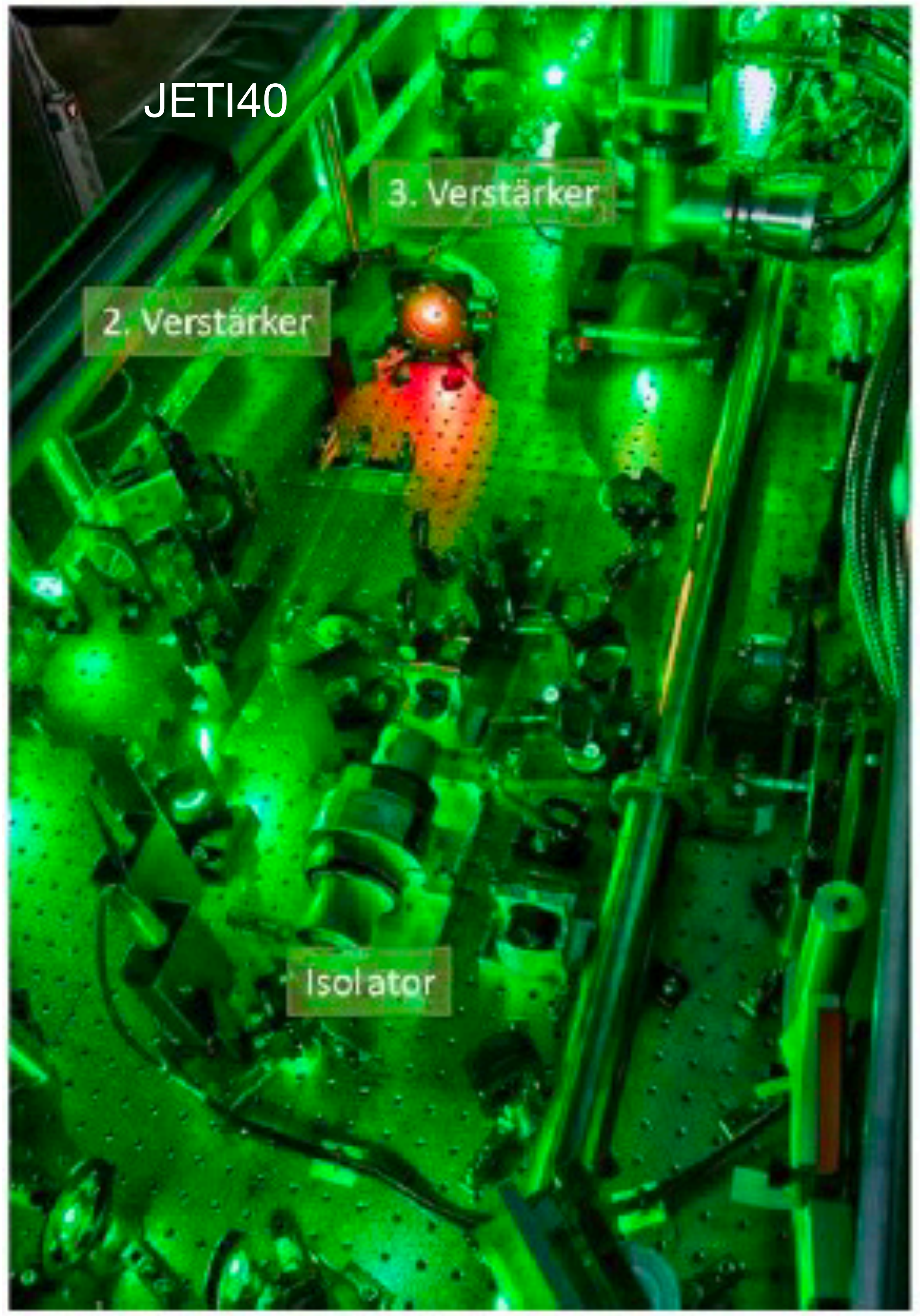
Donna Strickland

Prize share: 1/4

LASER IN LUXE

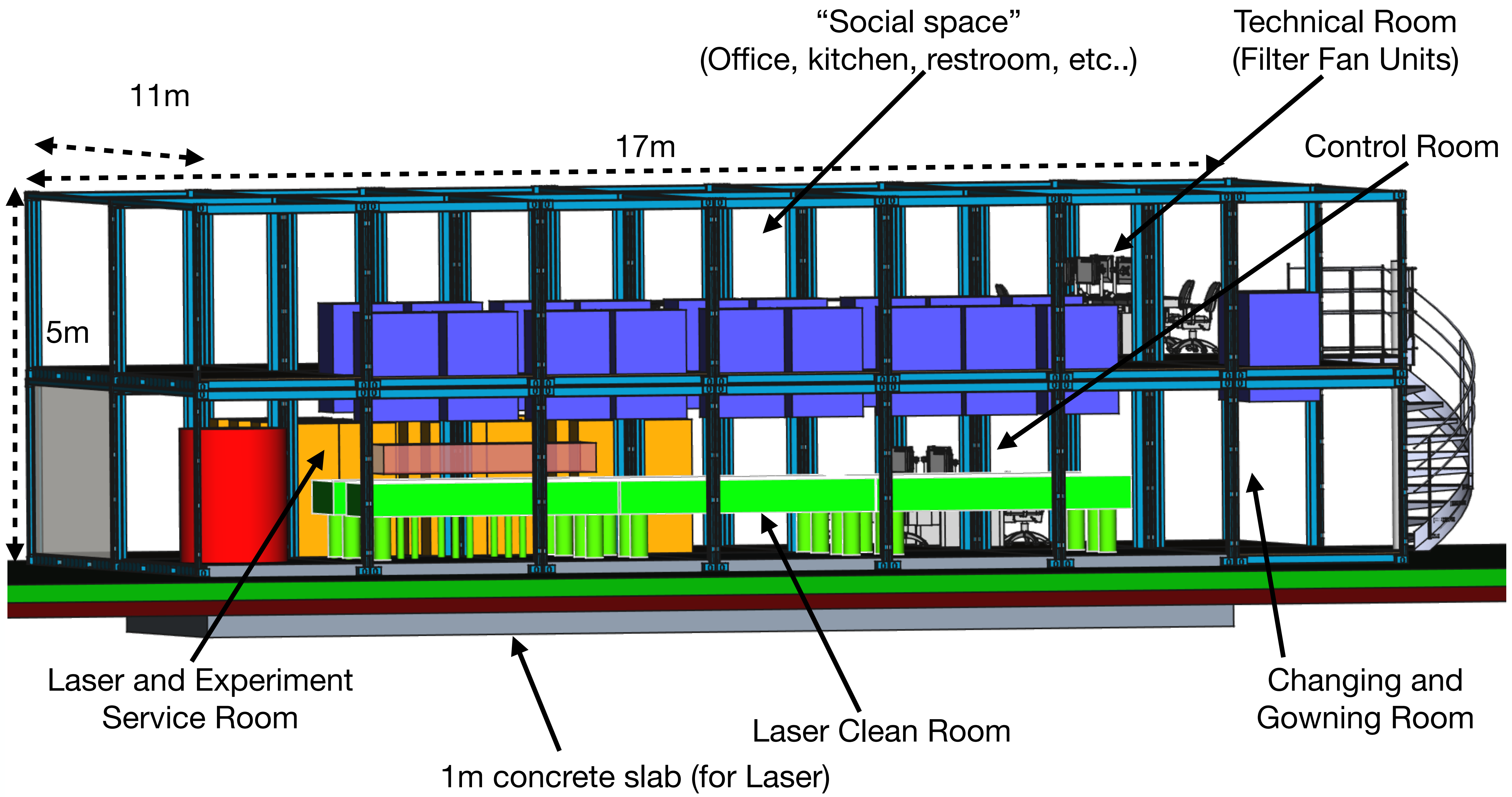
- Use Ti:Sa laser with 800 nm wavelength (E=1.55 eV).
- Energy focused strongly in both time and space to obtain high intensity.
- Two phases:
  - In phase 0 reuse JETI40 (Jena custom 40 TW laser), or new system.
  - In phase I will use commercial 350 TW laser.
- Laser parameters:
  - Repetition rate: 1Hz.
  - Pulse length 30 fs

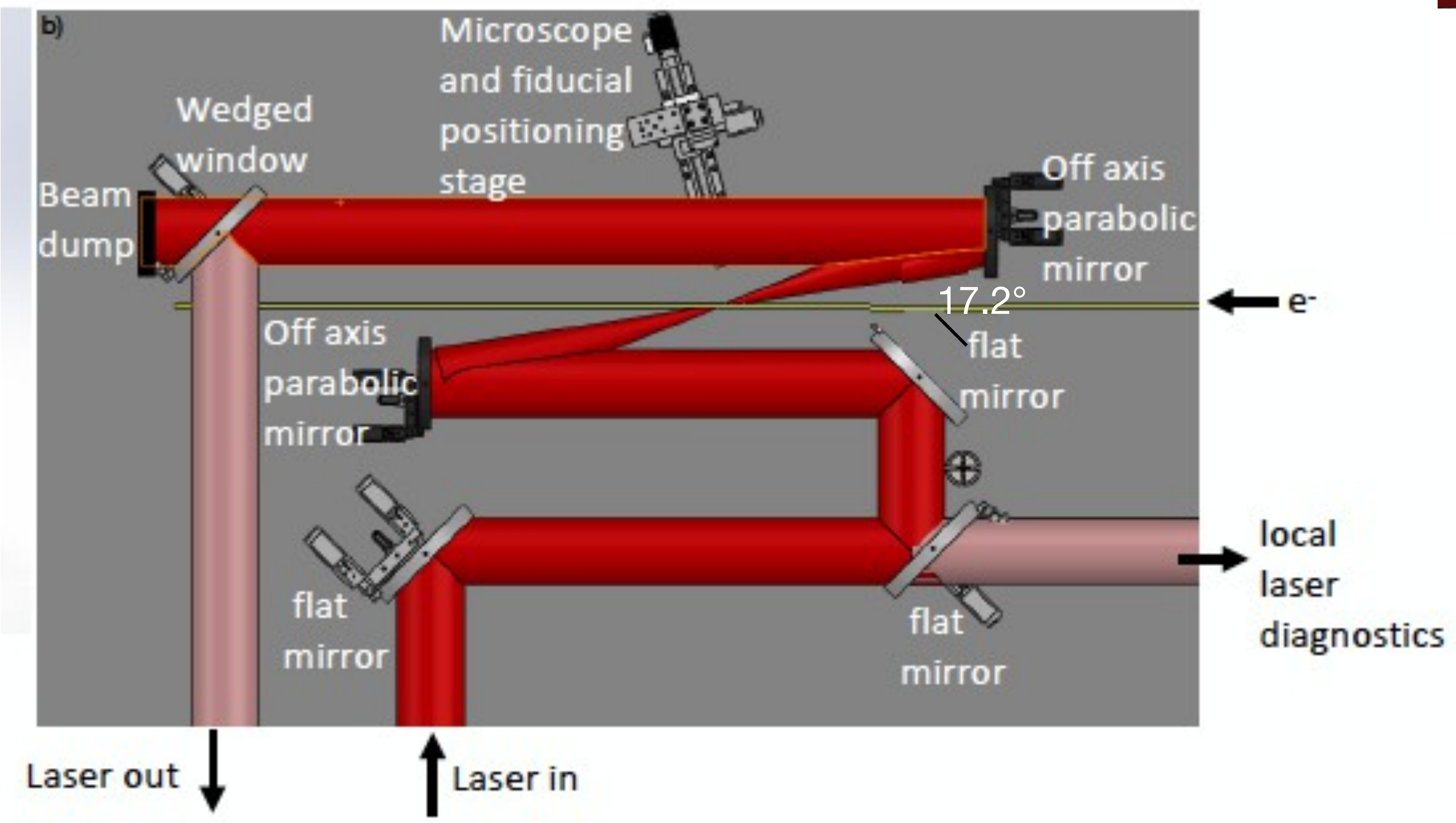
Parameter	Phase 0	Phase 0	Phase I
Laser power	40 TW		350 TW
Laser energy after compression [J]	1.2		10
Percentage of laser in focus [%]	50		
Laser focal spot size w_0 [μm]	>8	>3	>3
Peak intensity [10^{19} W/cm2]	1.9	13.3	120
Peak intensity parameter ξ	3.0	7.9	23.6
Peak quantum parameter X E_{beam}=16.5 GeV	0.56	1.5	4.5

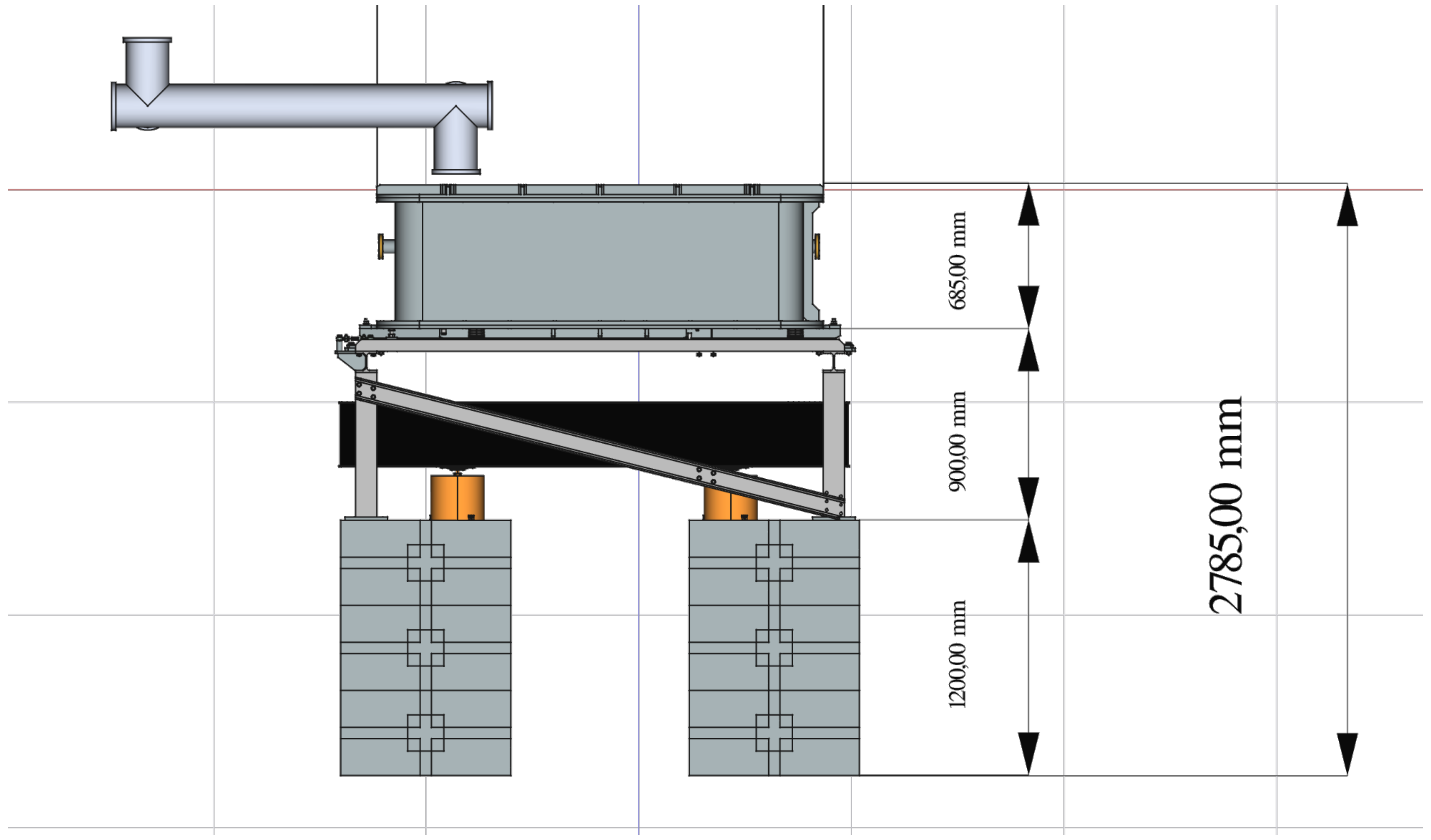


LASER BEAMLINE AND IP CHAMBER

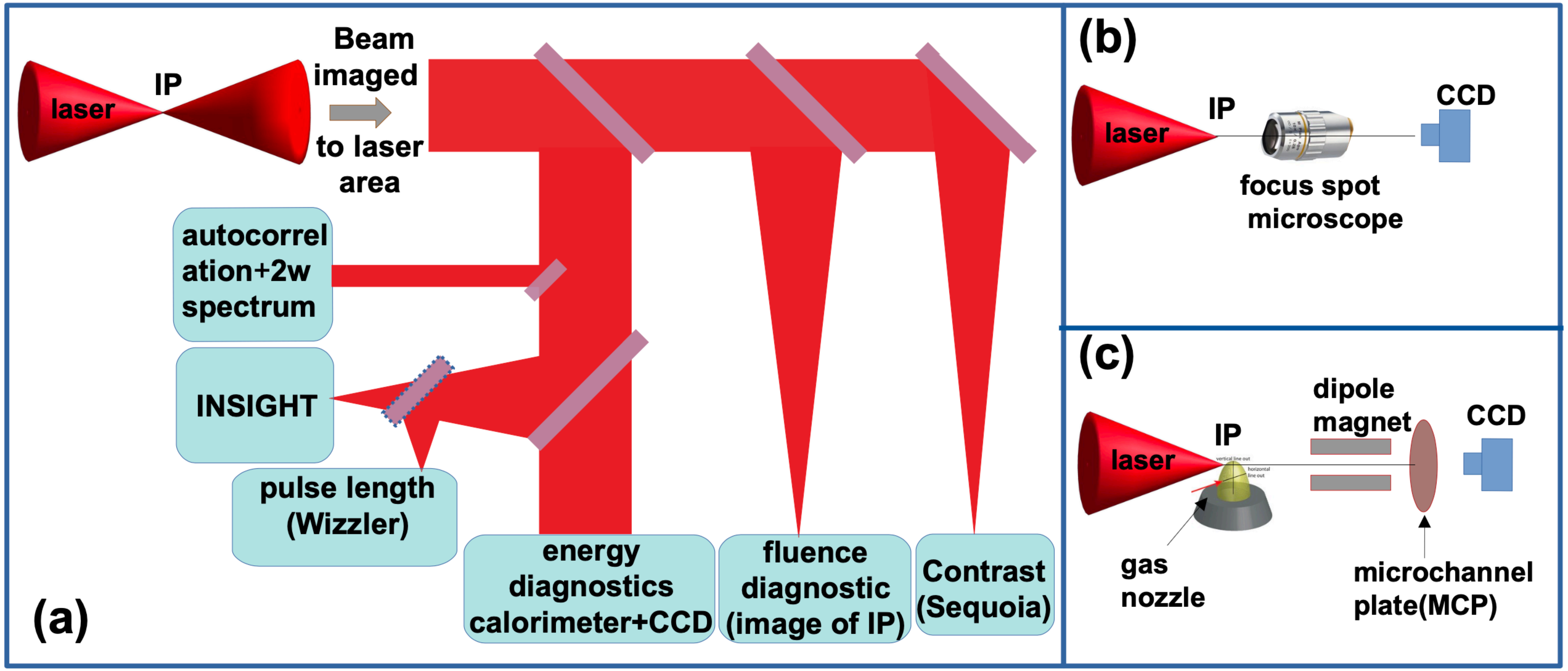
- Laser installed in new surface building.
- Guided from iso-6 clean room down to IP via ~50m beam line.
- Thick concrete slab in laser lab to allows laser stability.
- Final focusing done just before IP in dedicated chamber.
- IP chamber vacuum vessel reusing ALPS2 design.







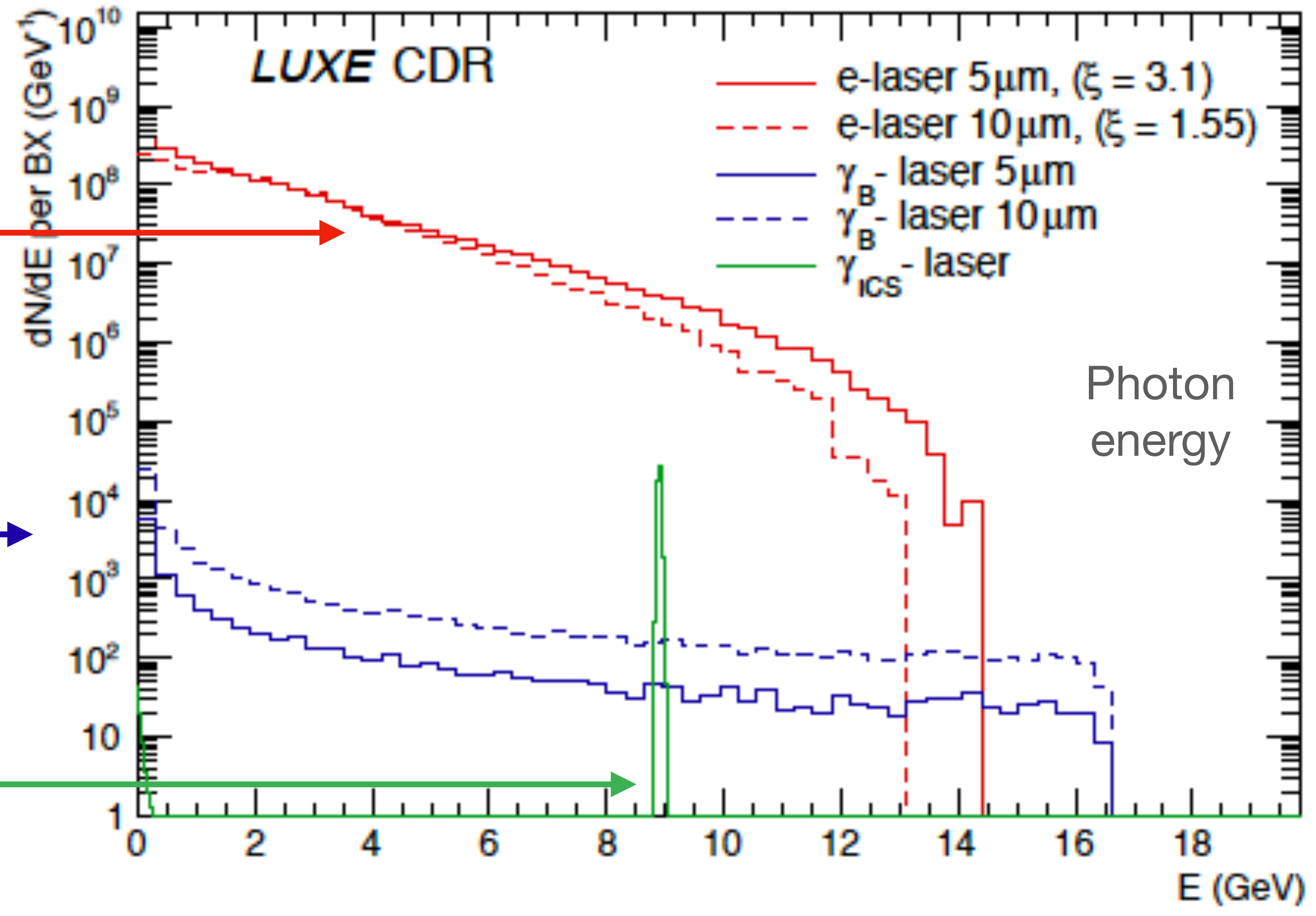
LASER DIAGNOSTICS

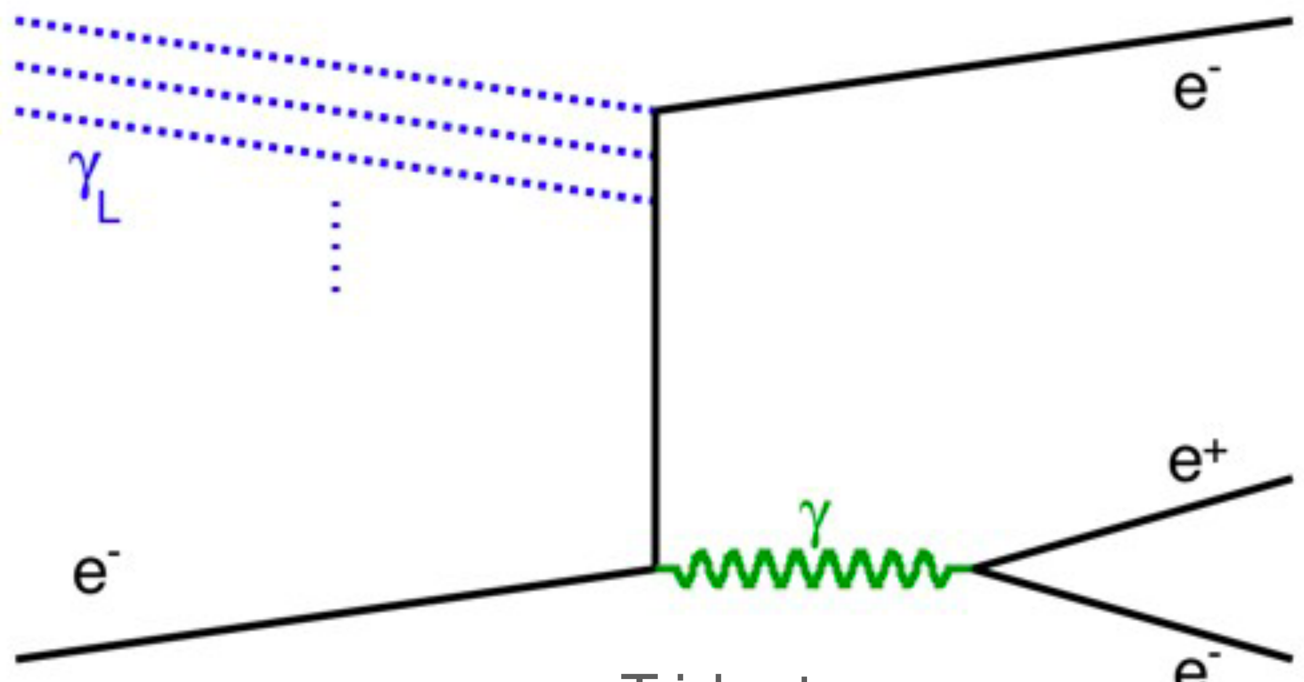


- Laser characterisation quantities: energy, pulse length, spot size
- many (partially redundant) measurements planned
  - Laser is not perturbed by e^- beam allow multiple diagnostics
    - In IP chamber and back in laser clean room.
- Laser intensity uncertainty has a large impact on sensitivity
- goal: ≤ 5% uncertainty on Laser intensity, 1% shot-to-shot uncertainty

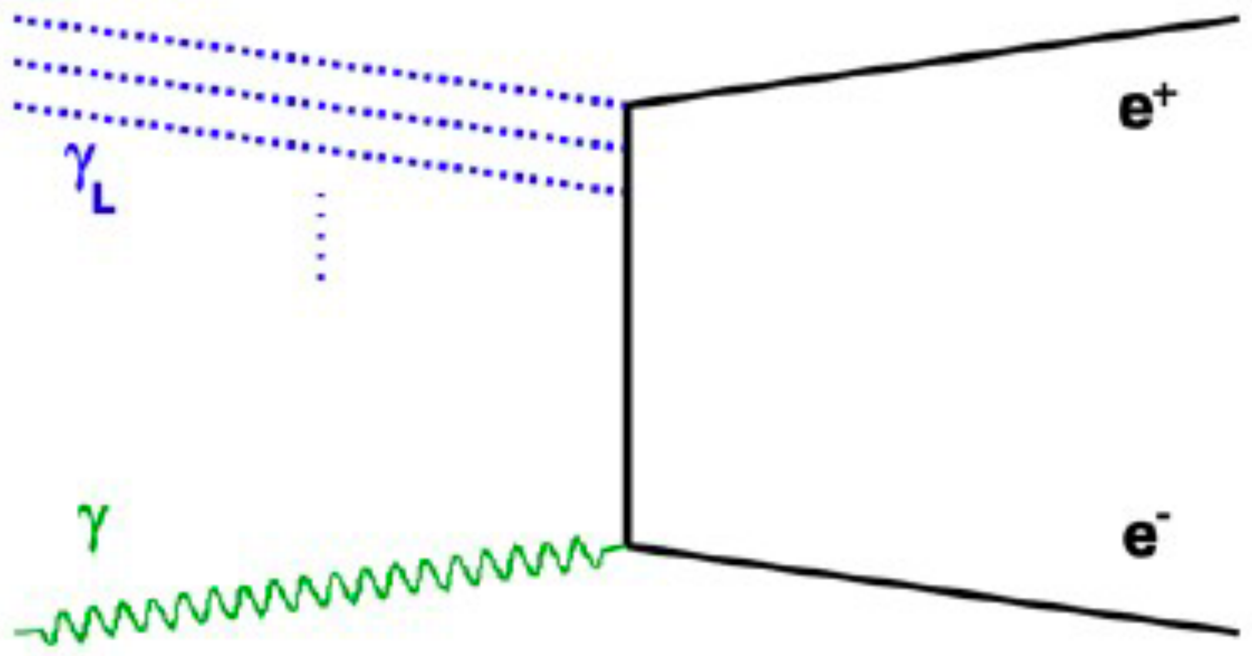
PAIR PRODUCTION MODES

- 3 methods to produce pairs, that allow to probe different energy range:
    - Compton scattering with interaction between Compton photon and laser.
        - Largest rate.
            - e-laser mode
    - Bremsstrahlung photons produced upstream (with target).
        - Highest energy available.
            - gamma-laser mode.
    - Compton photon produced upstream.
        - Monochromatic photon source: E=9 GeV.
            - gamma-laser mode via Inverse Compton Scattering

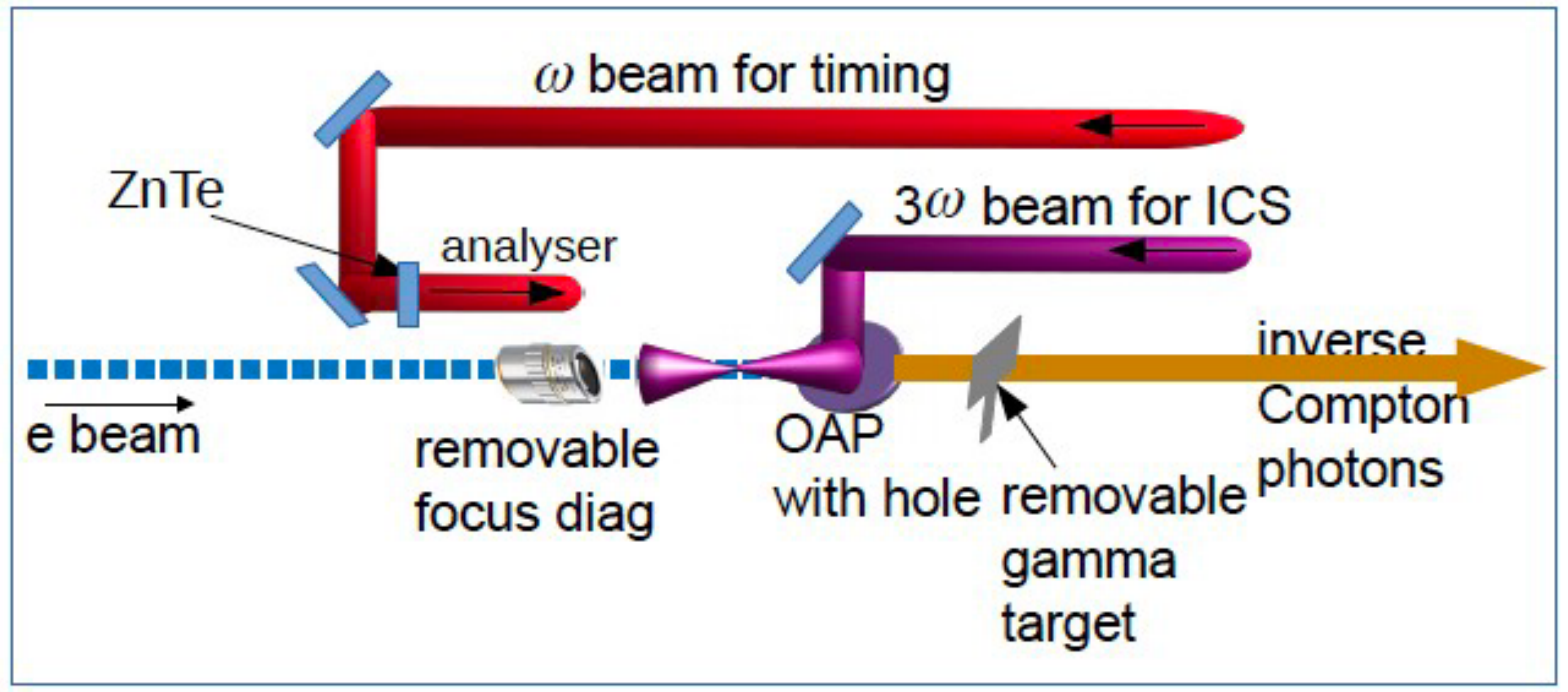


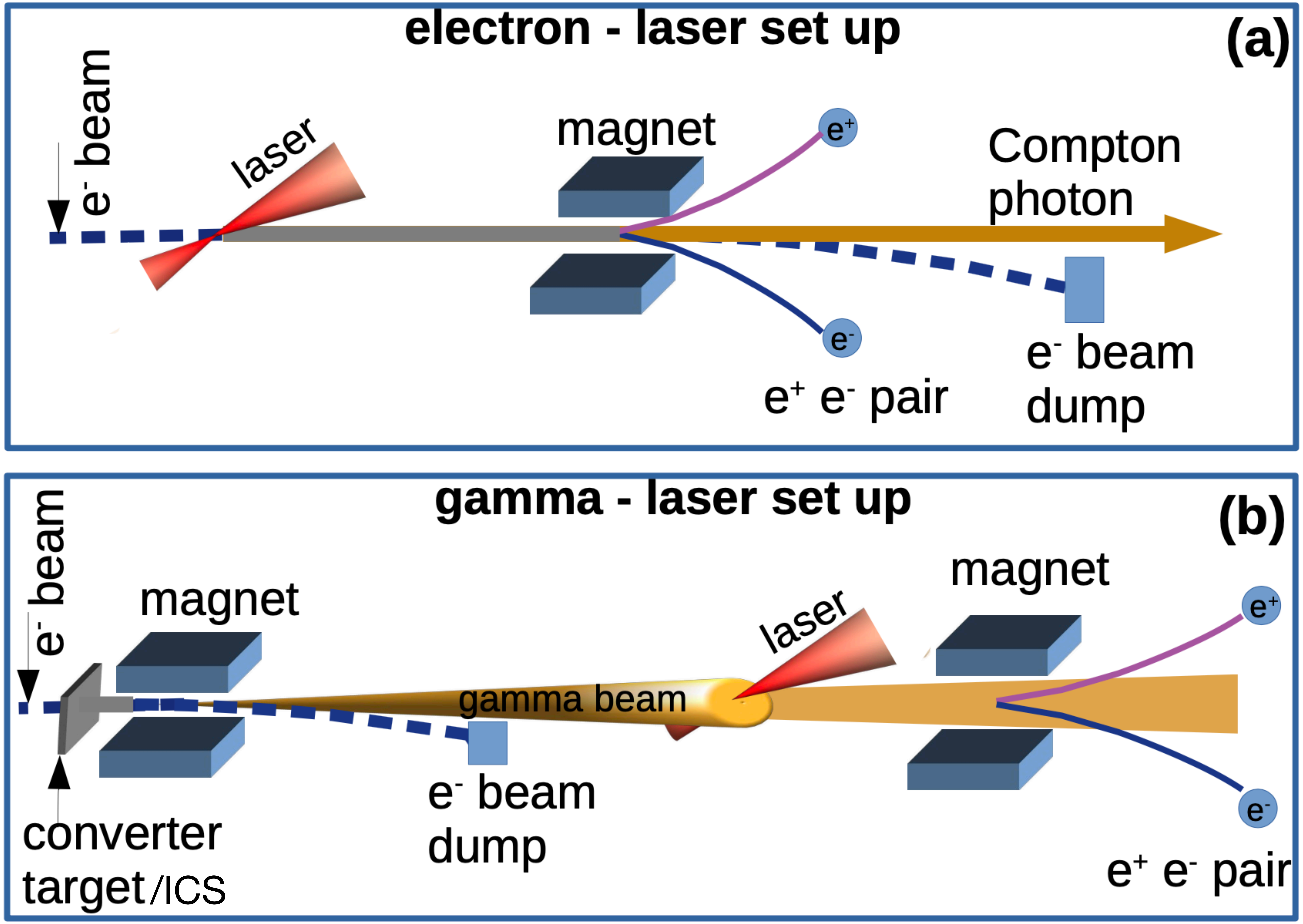


Trident



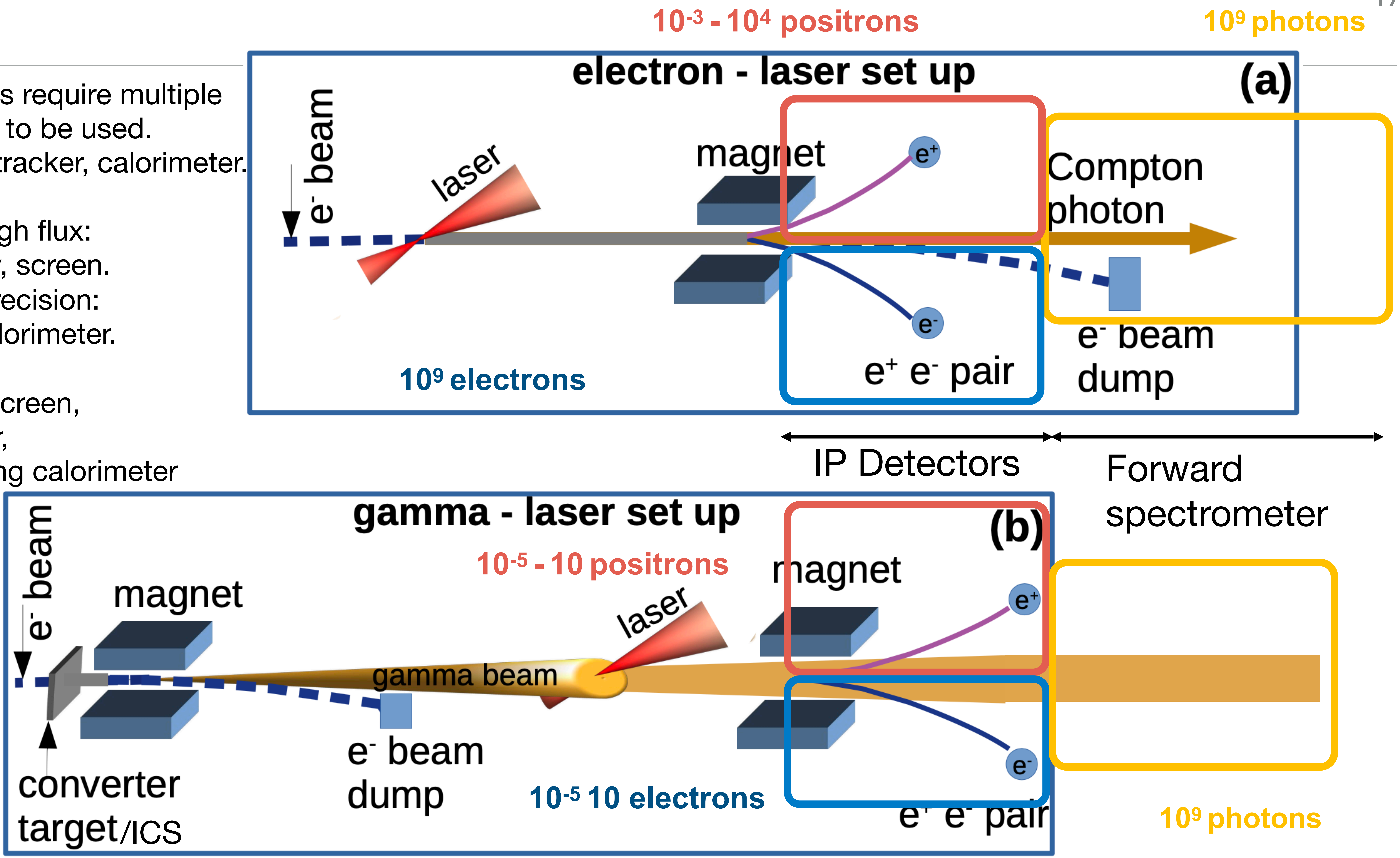
Breit-Wheeler




electron - laser set up
(a)
e- beam
laser
magnet
e+
Compton
photon
e-
e+ e- pair
e- beam
dump
gamma - laser set up
(b)
e- beam
magnet
gamma beam
laser
magnet
e+
e-
e- beam
dump
converter
target/ICS
e+ e- pair

RATES

- Different rates require multiple technologies to be used.
- e^+ precision:tracker, calorimeter.
- e-
  - (e-laser) high flux: Cherenkov, screen.
  - (ɣ-laser) precision: tracker, calorimeter.
- ɣ high flux: scintillating screen, beam profiler, backscattering calorimeter

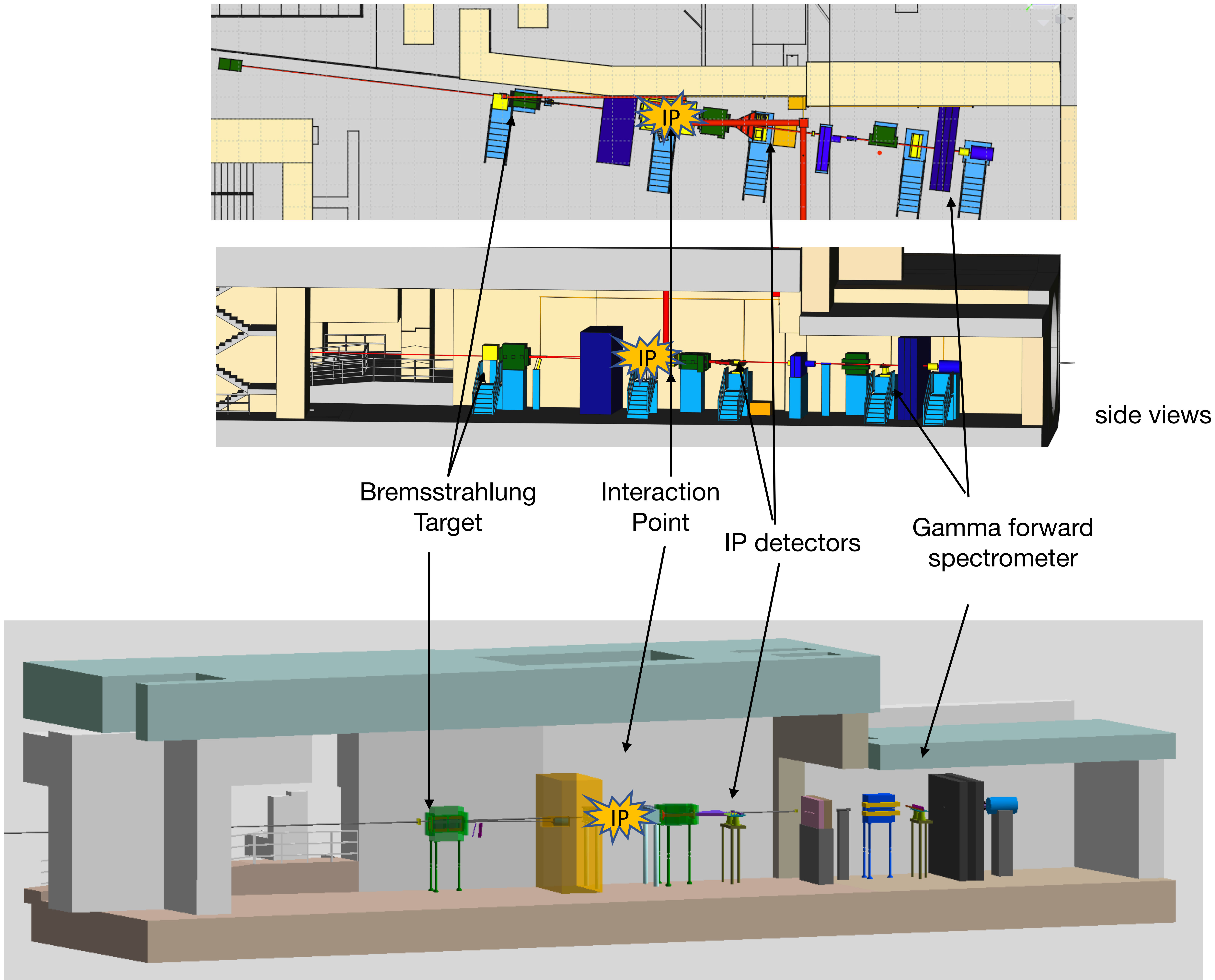


WHAT WILL IT LOOK LIKE?

top view of experimental area

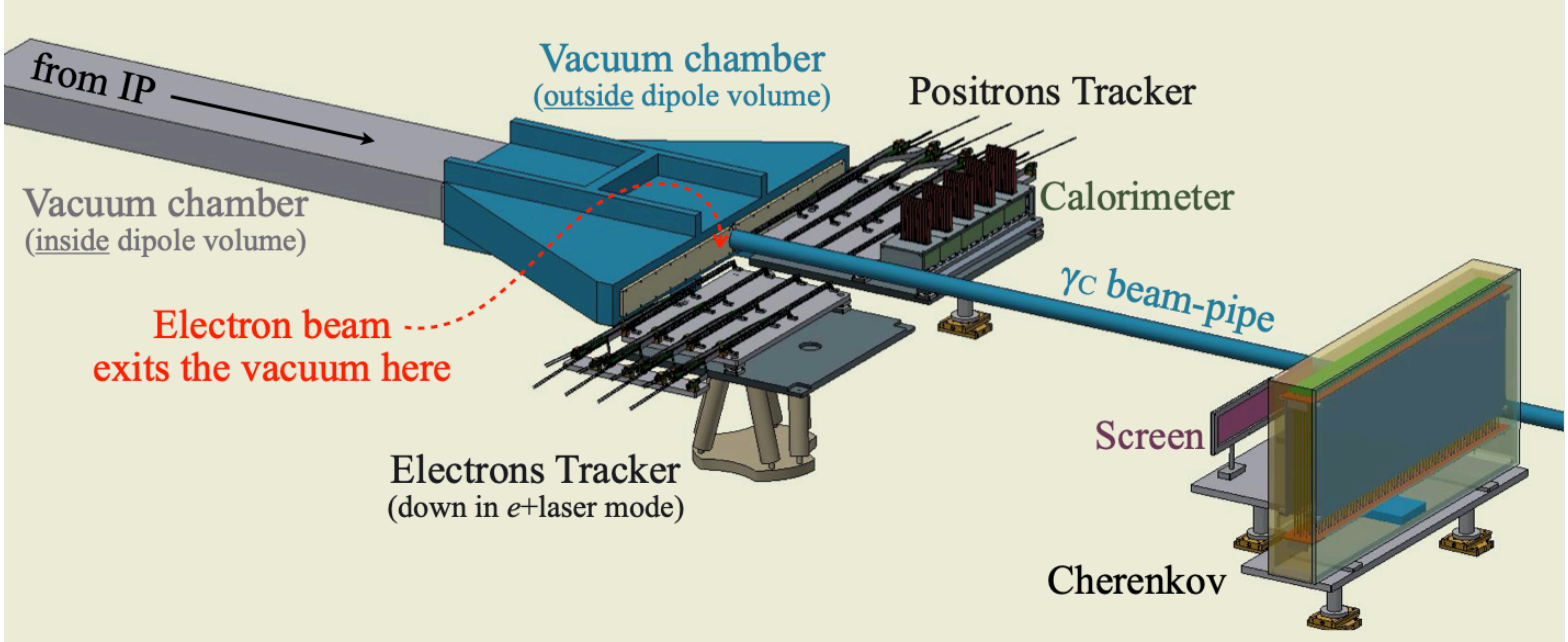
CAD:

side views of experimental area



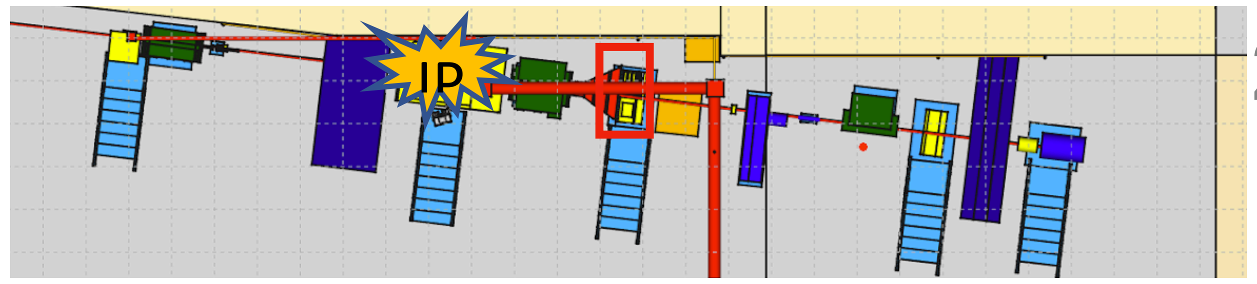
Full Geant4 simulation:

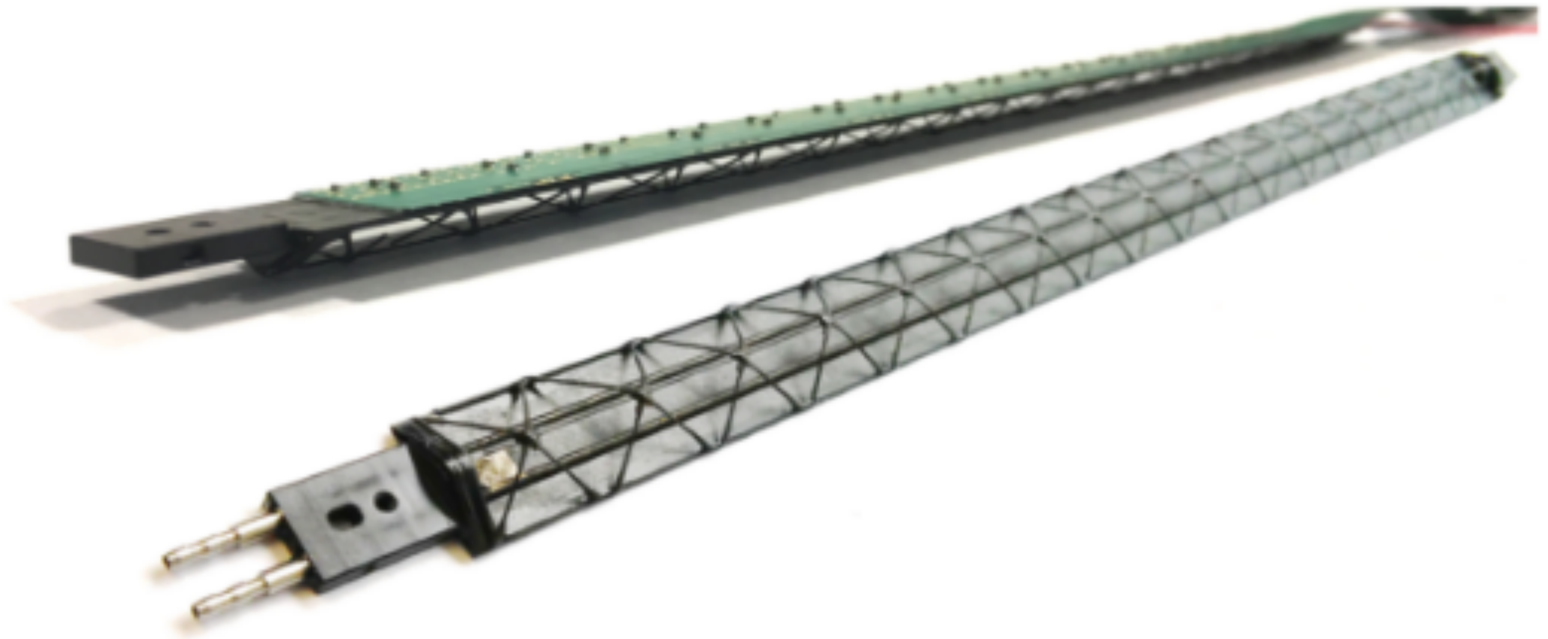
IP DETECTORS



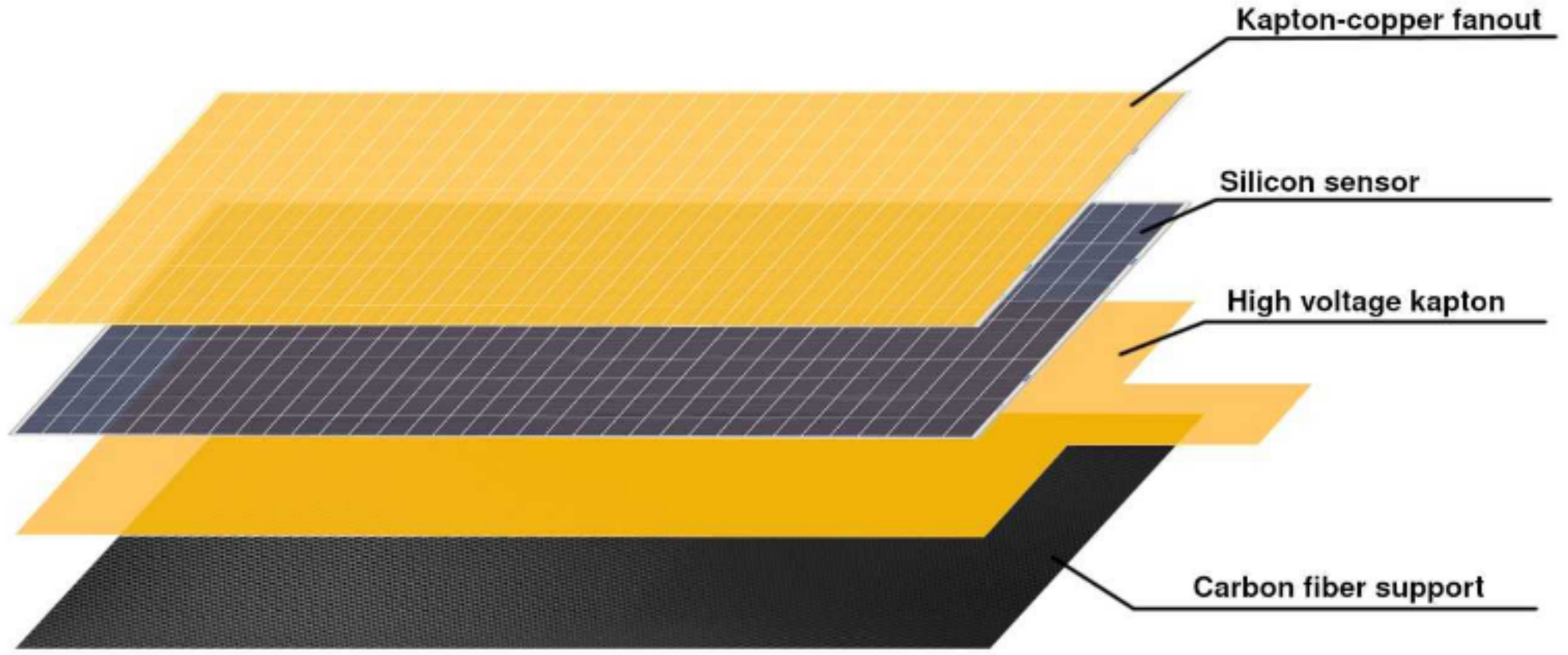
- Two complementary detector technologies per measurement:
  - Cross-calibration, reduction of systematic uncertainties.

PRECISION DETECTION SYSTEM (E-LASER: IP DETECTOR POSITRON SIDE | GAMMA-LASER: IP DETECTOR BOTH SIDES)

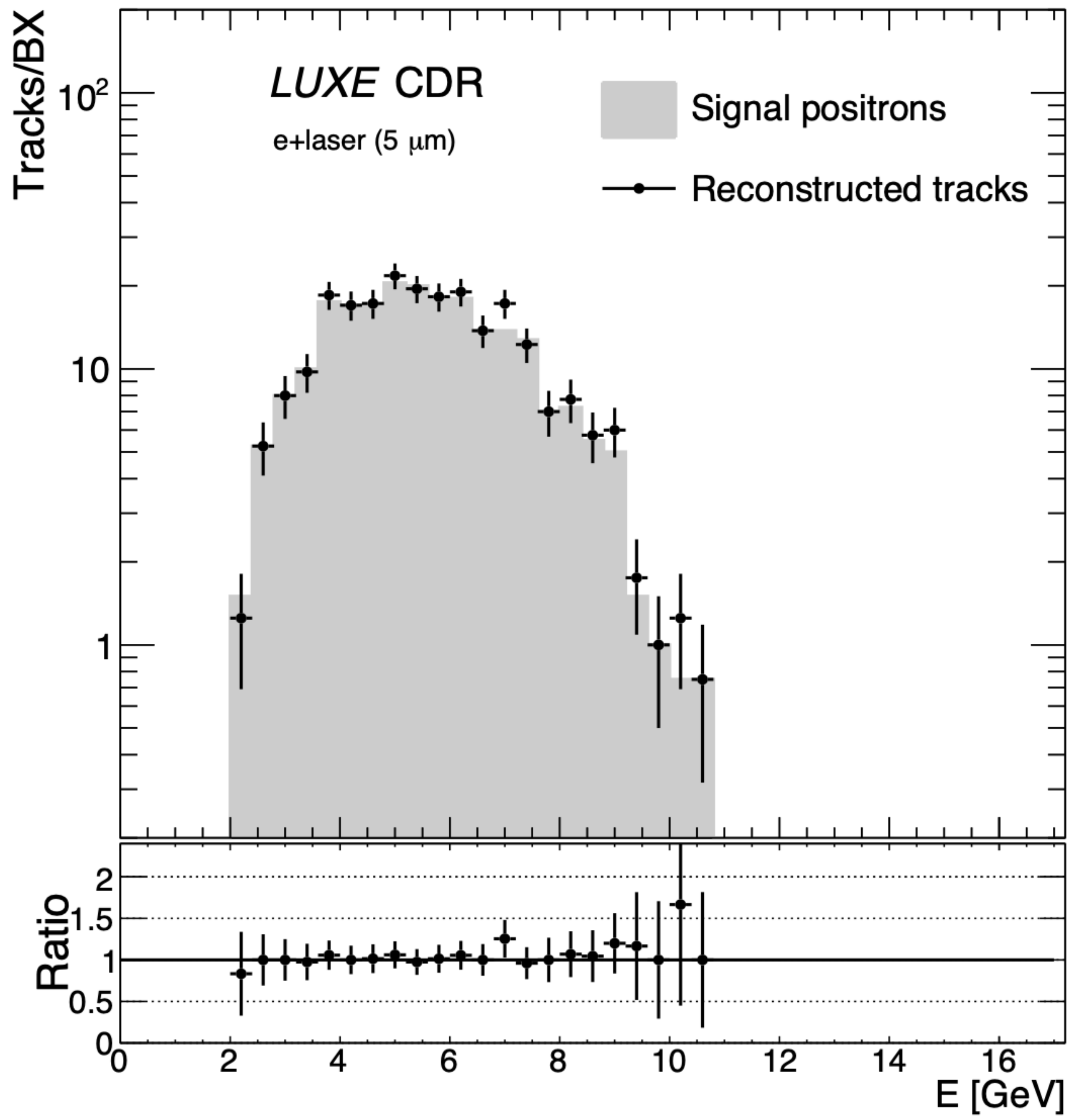




ALPIDE tracking detector stave



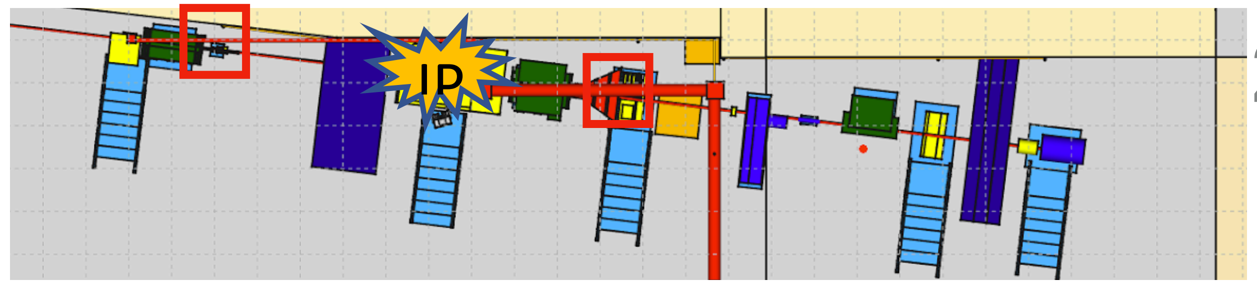
High-granularity ECAL layer

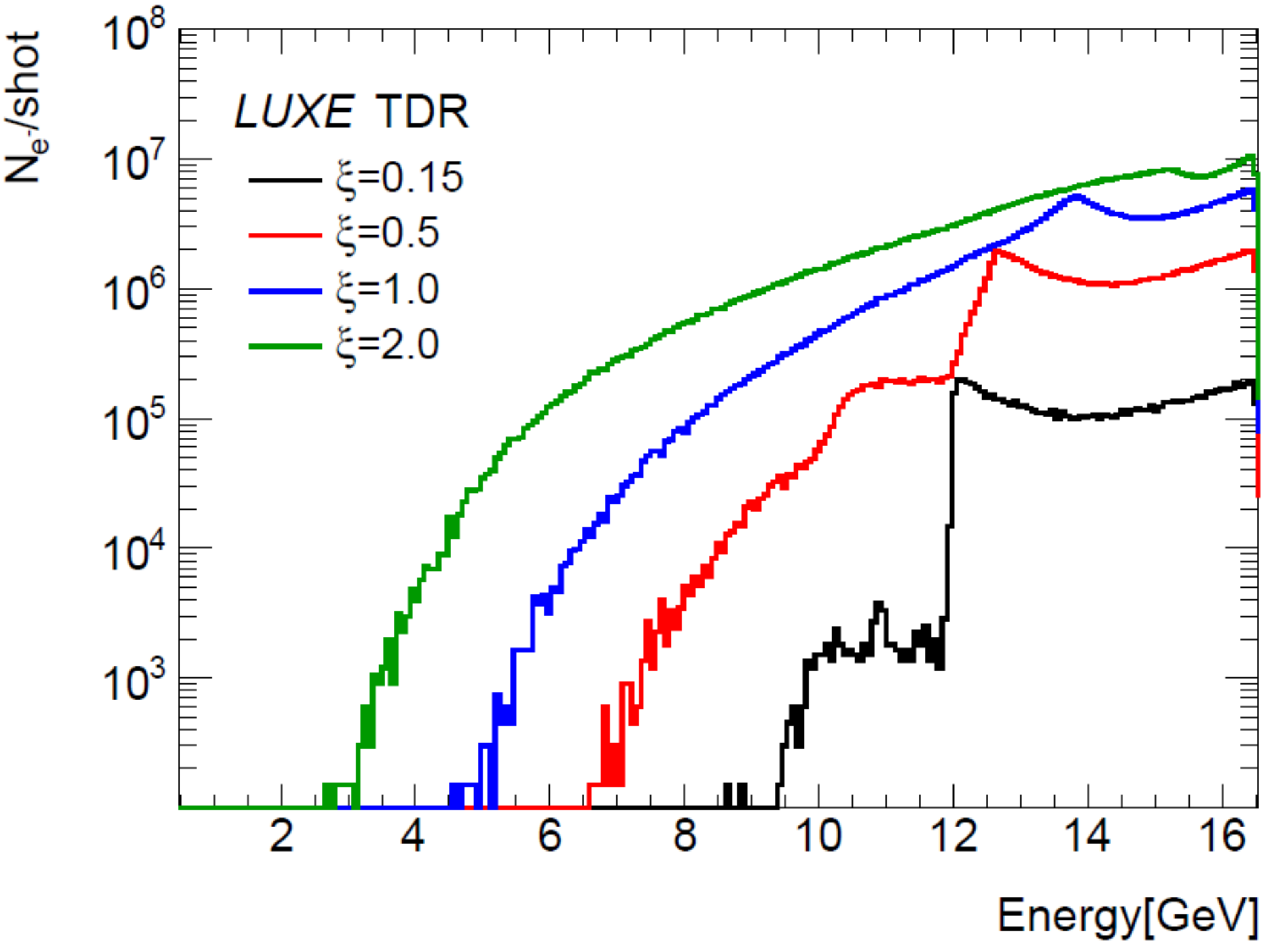


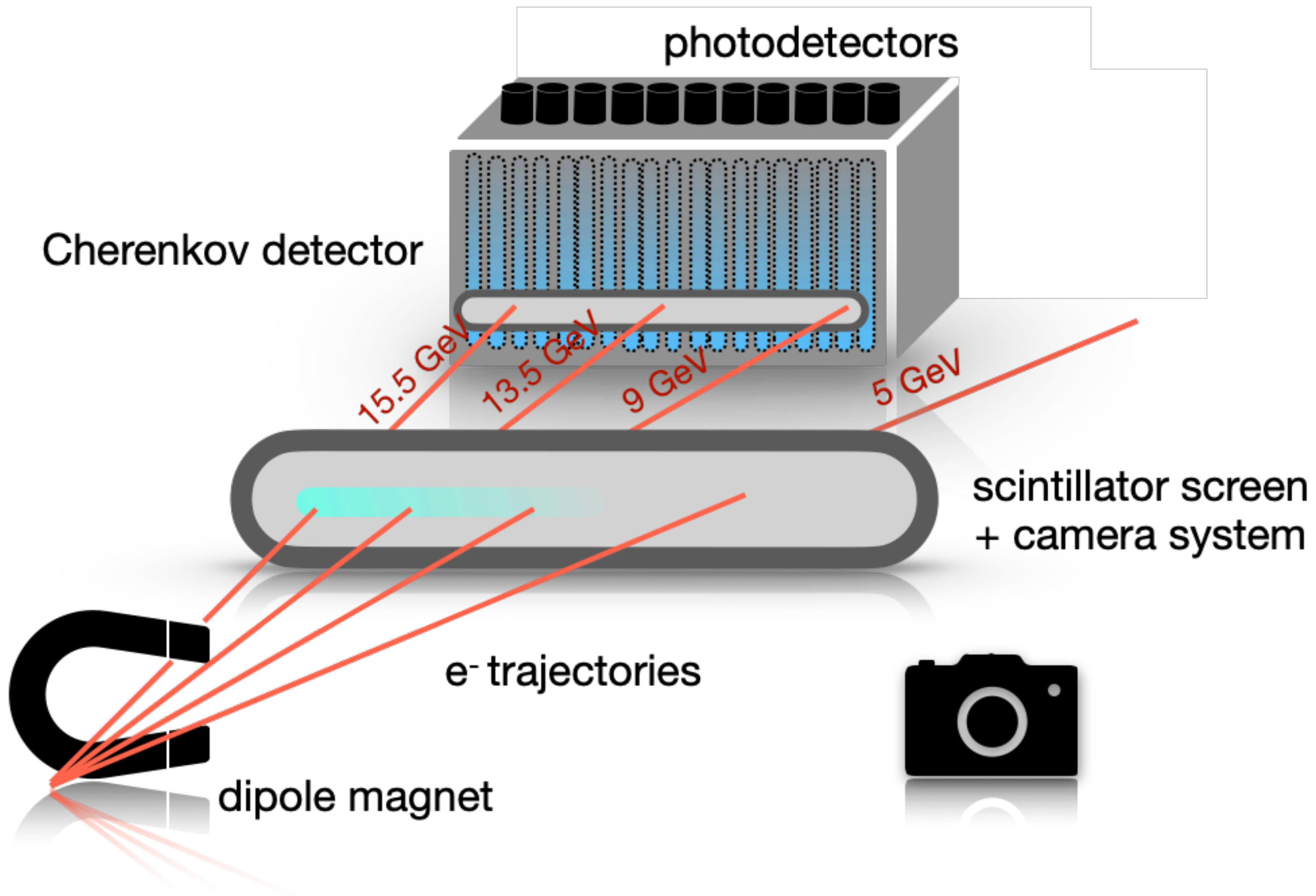
- Silicon Pixel Tracker:
  - four layers of ALPIDE silicon pixel sensors → developed for ALICE pixel tracker upgrade
  - pitch size (27 x 29 µm), 5 µm resolution
  - tracking: $\varepsilon > 98\%, \ \frac{\delta p}{p} \approx 0.3\%$
  - very small background (<0.1 event / bunch crossing)
- Si High-granularity Calorimeter: (ECAL-P - e-laser)
  - Based on Forward Calorimeter for ILC (FCAL). Read out by FLAME ASIC .
  - 20-layer sampling calorimeter – high granularity: independent energy measurement through shower and position
  - Energy $\frac{\sigma_E}{E} = \frac{19.3\%}{\sqrt{E/GeV}}$, position: $\sigma_x = 0.78\ mm$
  - shower medium: 3.5mm Tungsten plates ($1X_0$), active medium: Silicon sensors ($5x5cm^2$, 320µm thick)
- Si High-granularity Calorimeter: (ECAL-E - ɣ-laser)
  - Based on ILC ECal. Read out by SKIROC2A ASICs.
  - 15-layer sampling calorimeter – high granularity: independent energy measurement through shower and position
  - shower medium: 7*2.5mm + 8*4.2mm Tungsten plates ($15X_0$), active medium: Silicon sensors ($5x5cm^2$, 320µm thick)

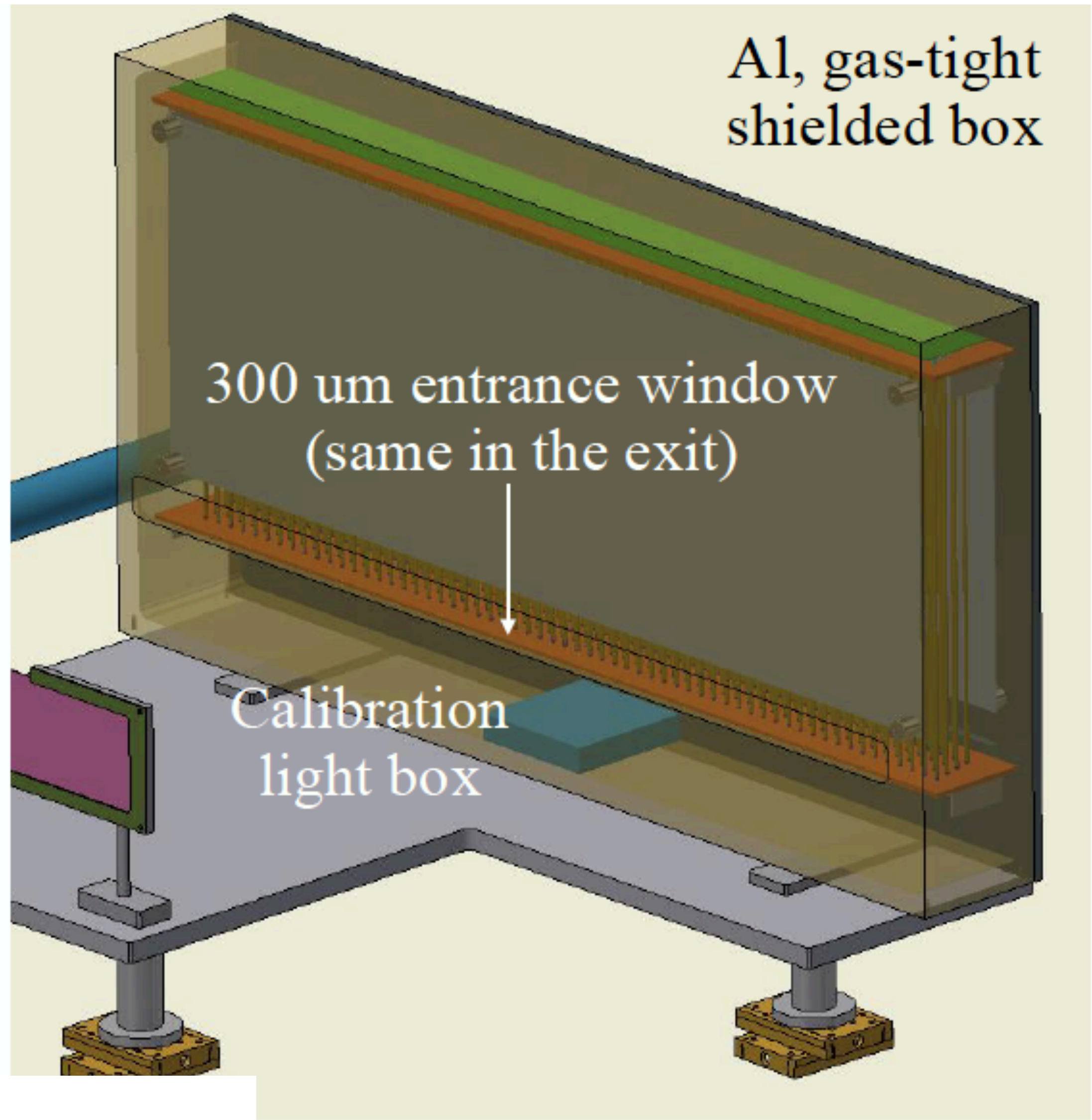
High signal efficiency, high resolution!

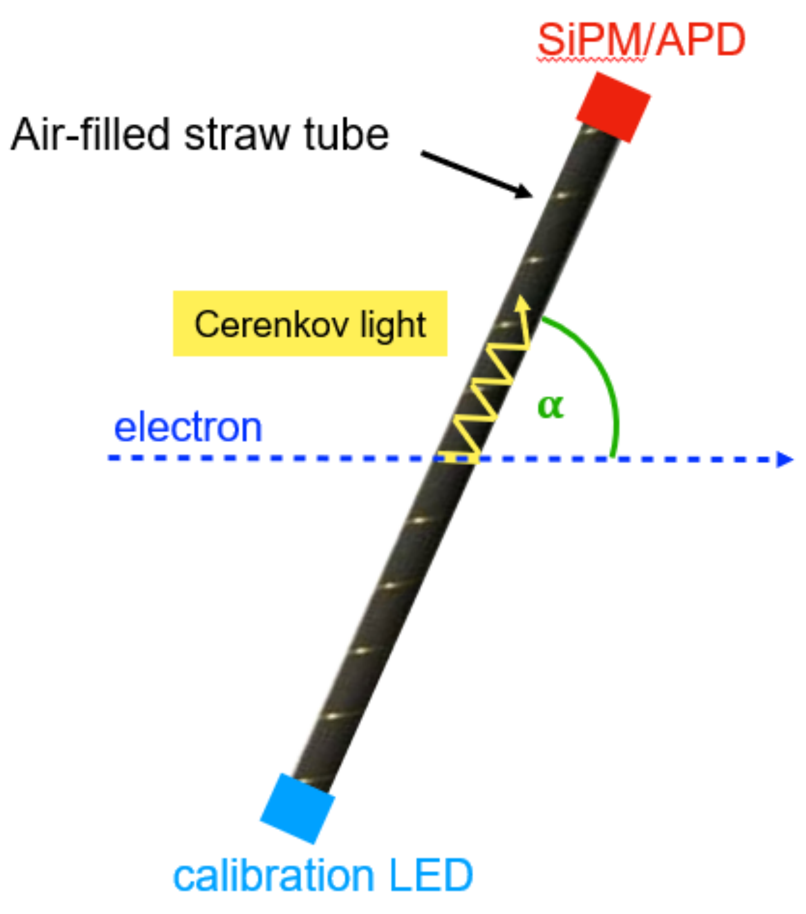
ELECTRON DETECTION SYSTEM (E-LASER: IP DETECTOR ELECTRON SIDE | GAMMA-LASER: BREM TARGET)

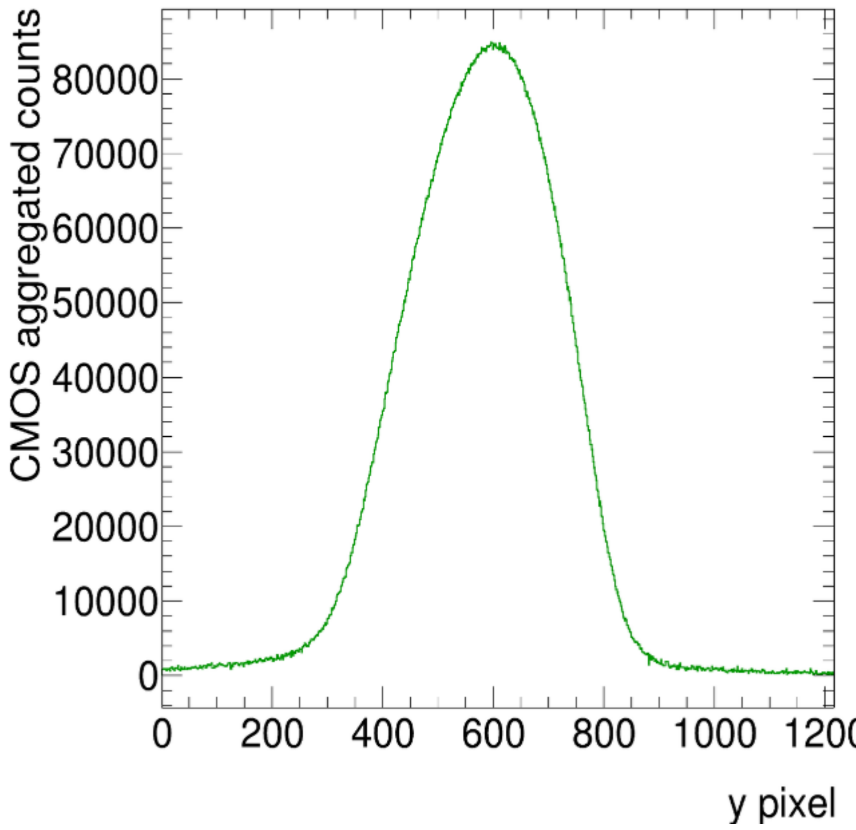


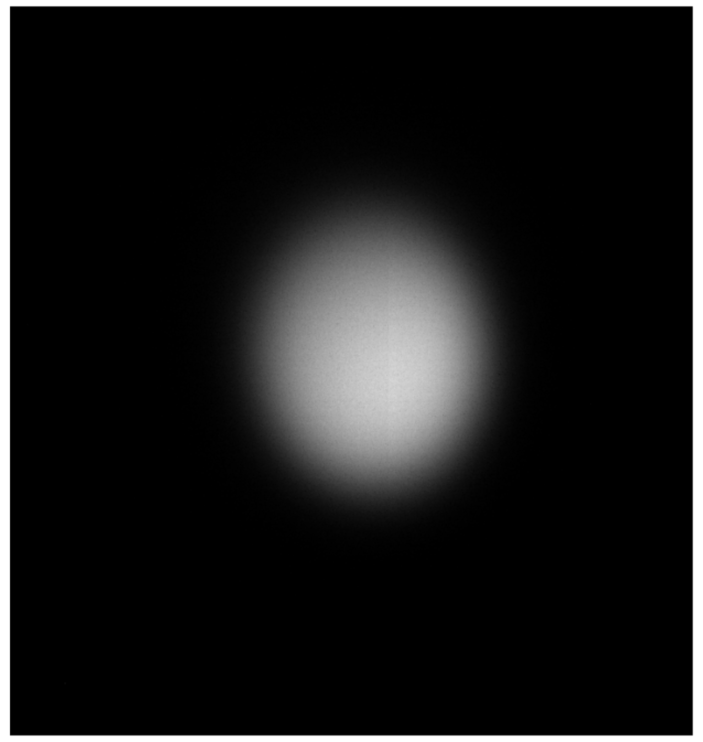












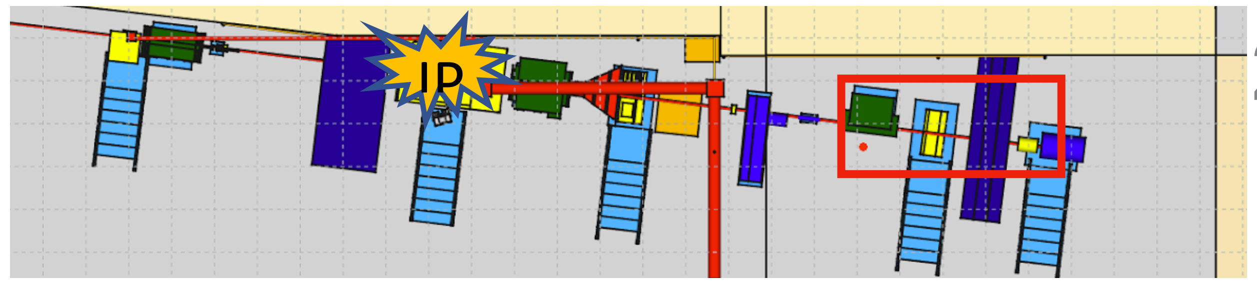
Beam spot imaged on Scint. Screen

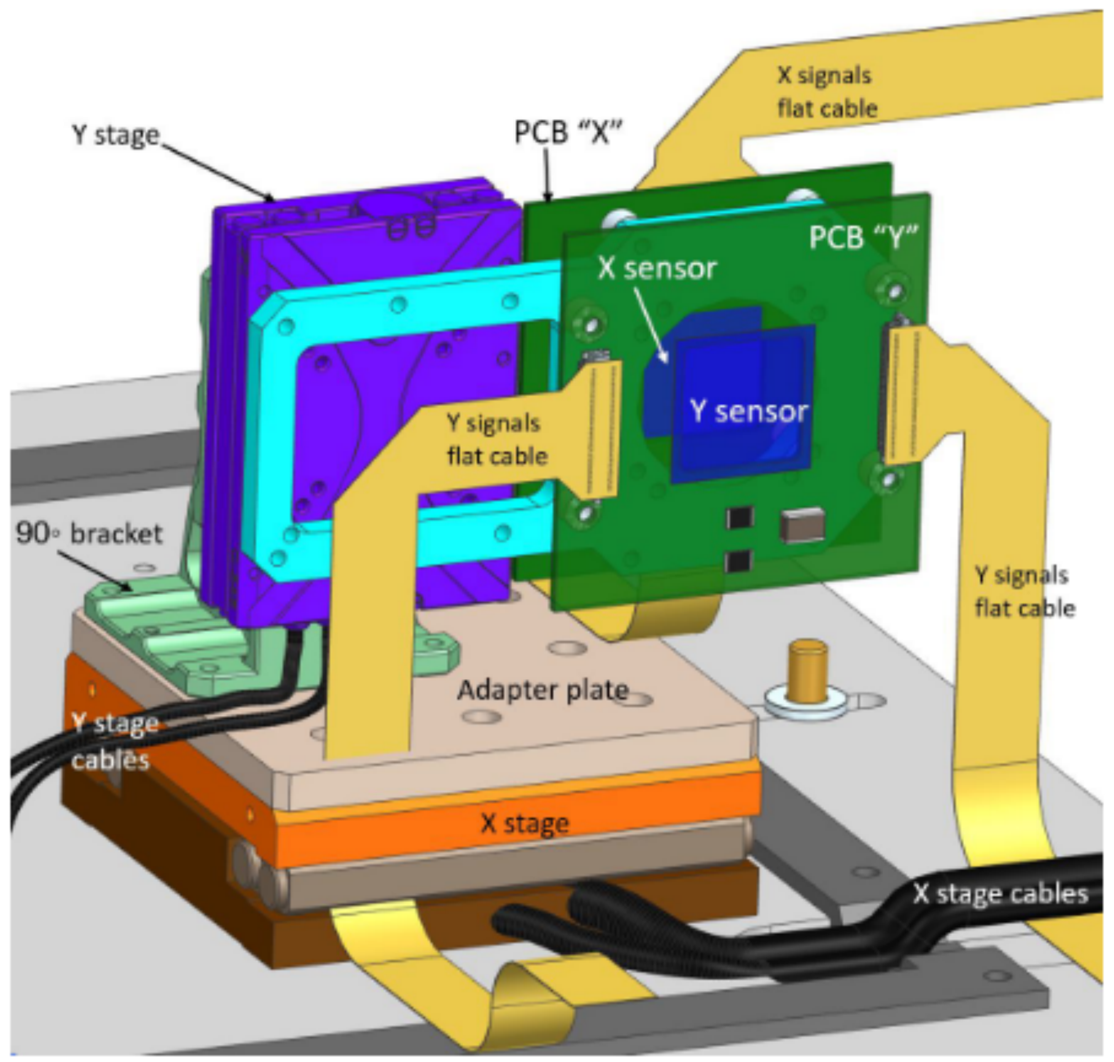
Straw prototype

- Scintillator screen (LANEX) with camera:
  - Camera takes pictures of scintillation light.
  - resolution of full system ~500µm
- Cherenkov detector:
  - Finely segmented ($\varnothing = 4mm$) Air-filled channel (reflective tubes as light guides) → charged particles create Cherenkov light
  - Active medium Air: low refractive index - reduce light yield, suppress backgrounds (Cherenkov threshold 20 MeV)

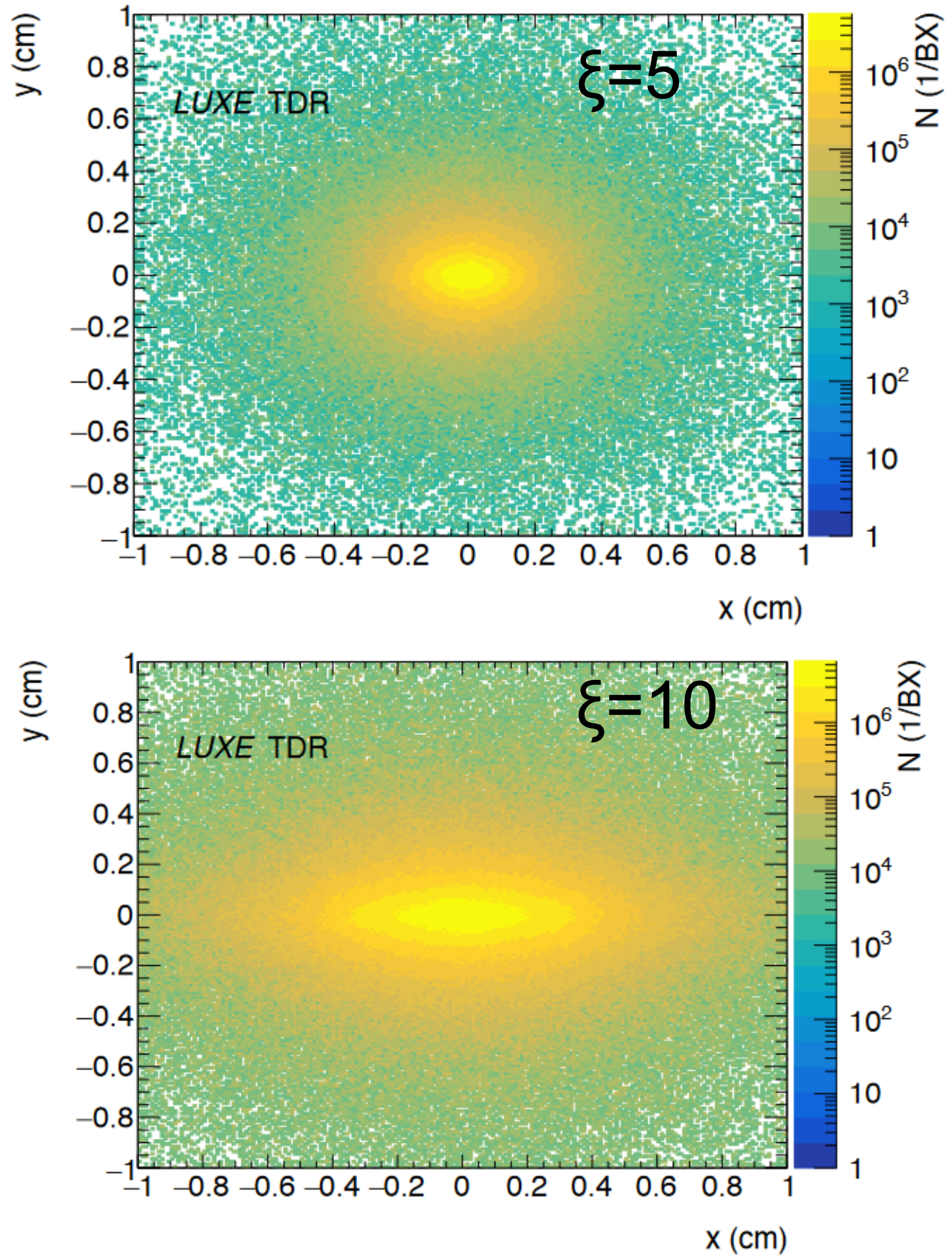
Electron detectors: High rate tolerance, large dynamic range!

PHOTON DETECTION SYSTEM (END OF BEAMLINE IN BOTH MODES)

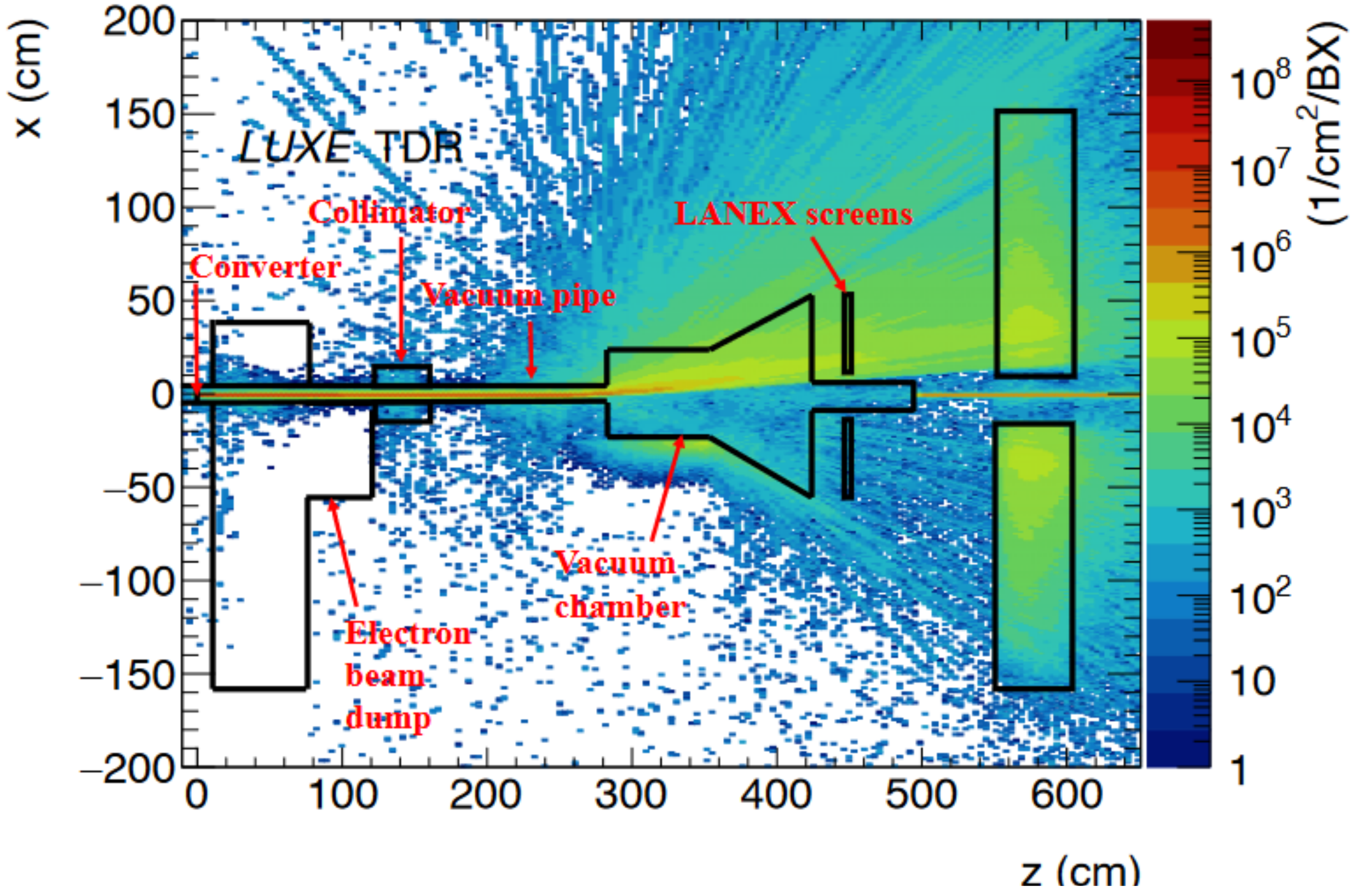




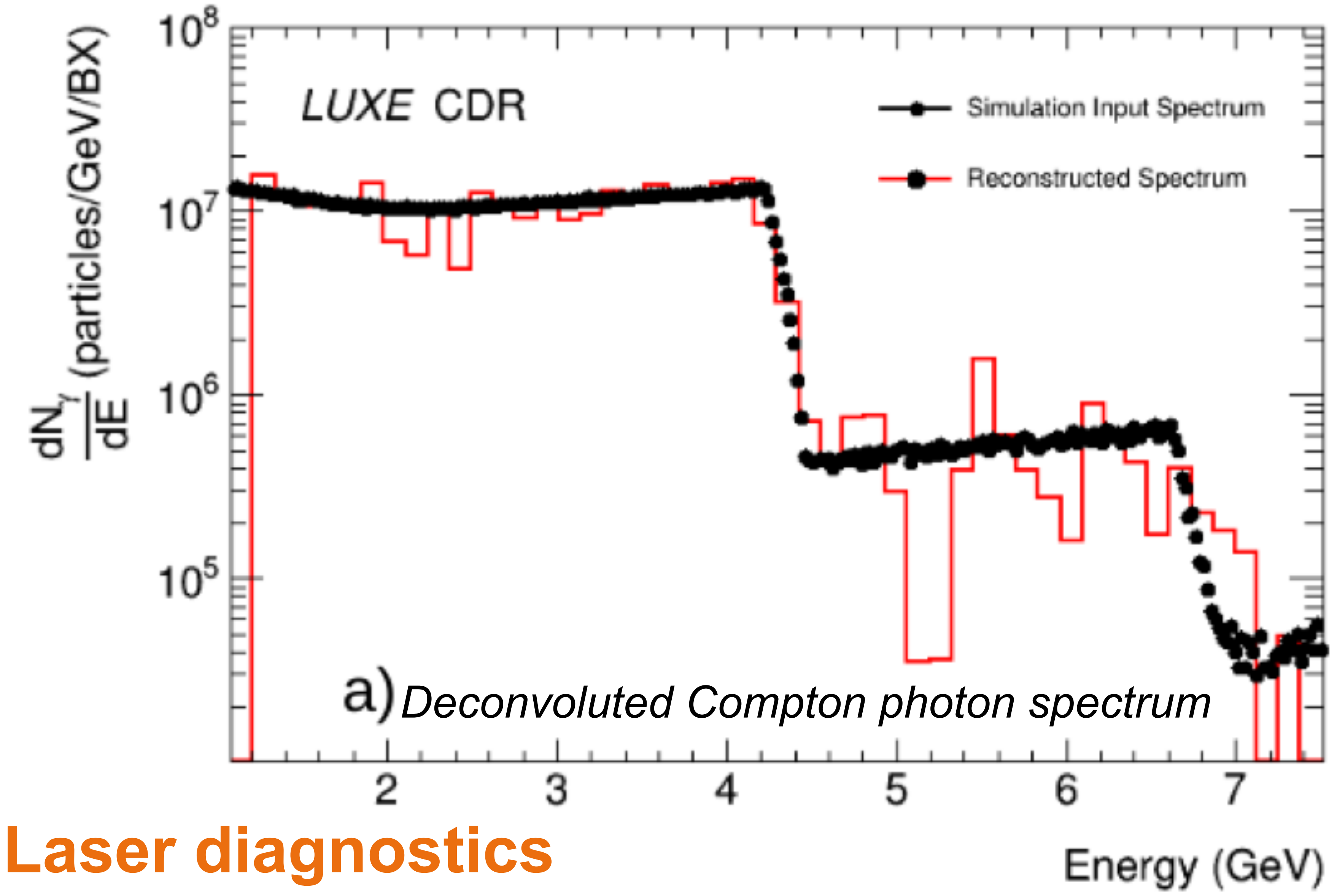
Gamma Beam Profiler



Electrons simulated in Gamma Spectrometer



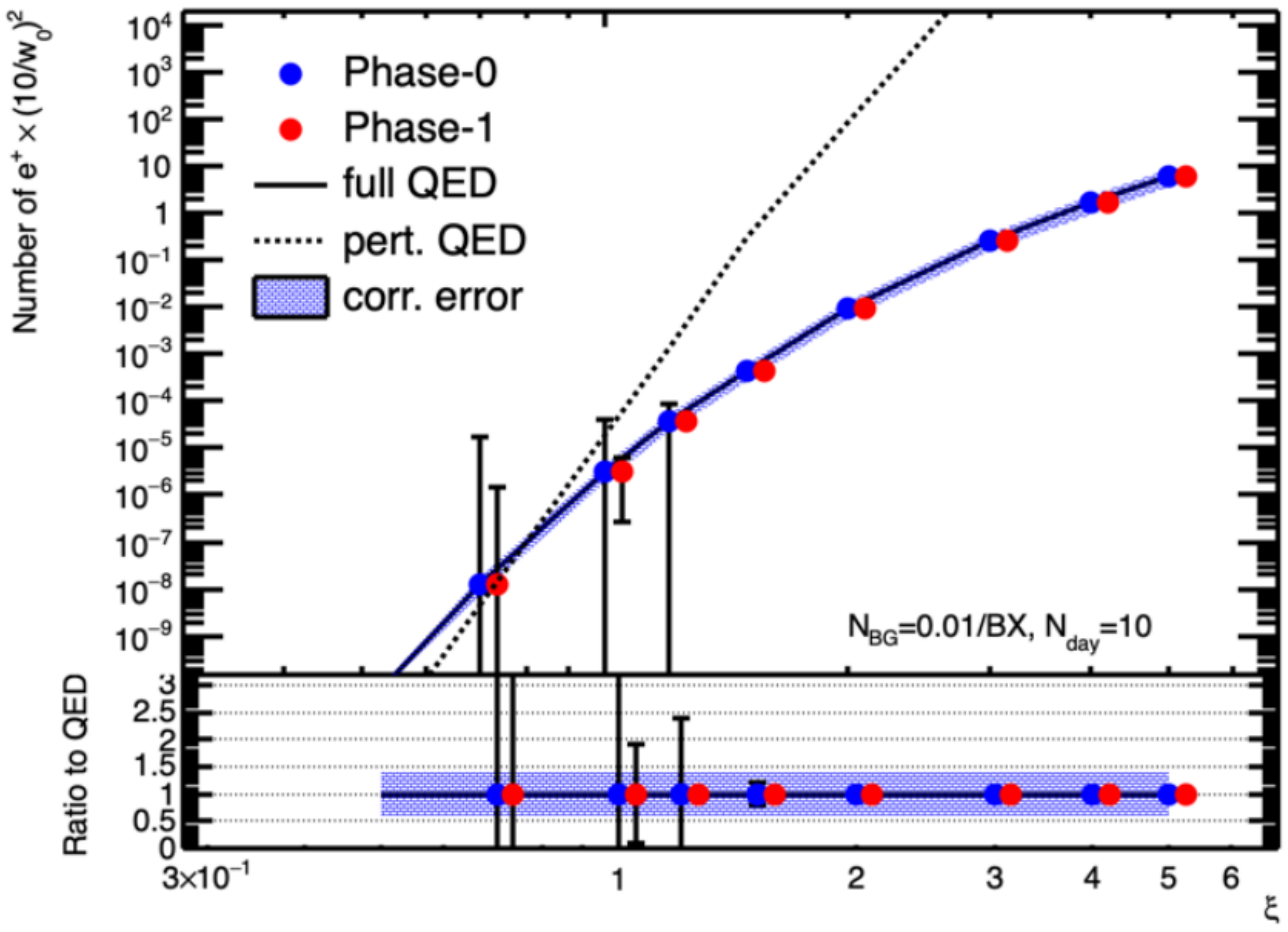
- Gamma detector technologies:
  - Gamma profiler (sapphire strips)
    - ɣ beam location and shape
    - precision measurement of Laser intensity
  - Gamma spectrometer with scintillator screens behind converter
    - Measure flux, energy spectrum ($\frac{\delta E}{E} < 2\%$)
  - Gamma dump backscattering calorimeter
    - Measure photon flux.

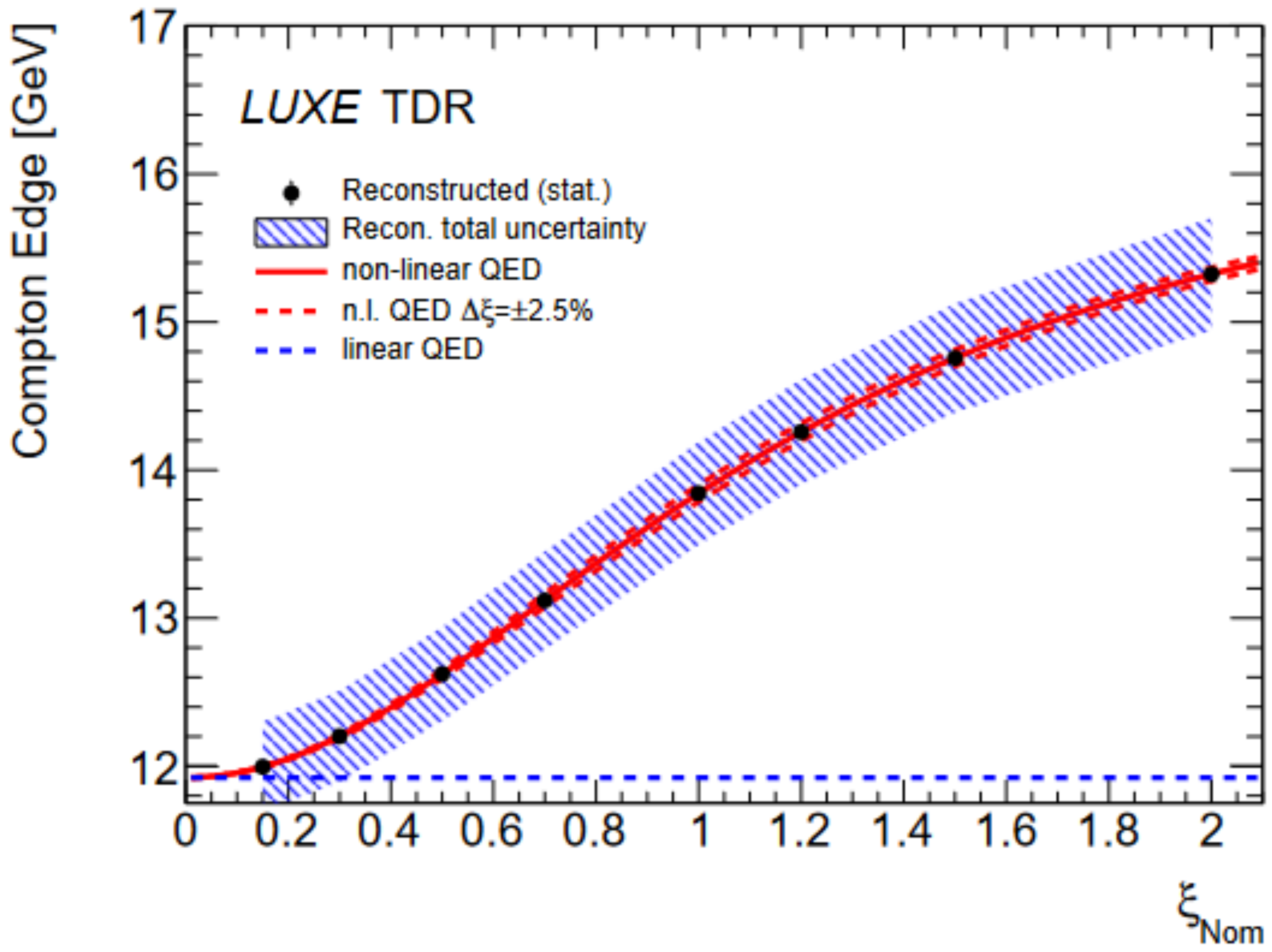


a) *Deconvoluted Compton photon spectrum*

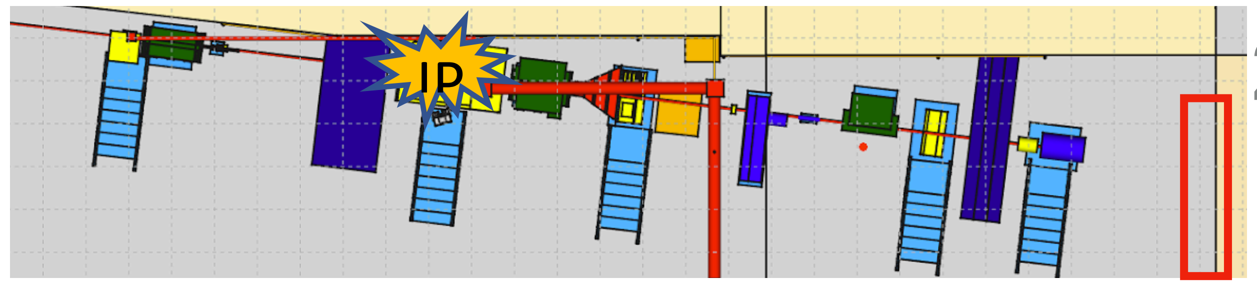
Photon detectors: Precision measurement of ξ, complementary to Laser diagnostics

EXPECTED RESULTS

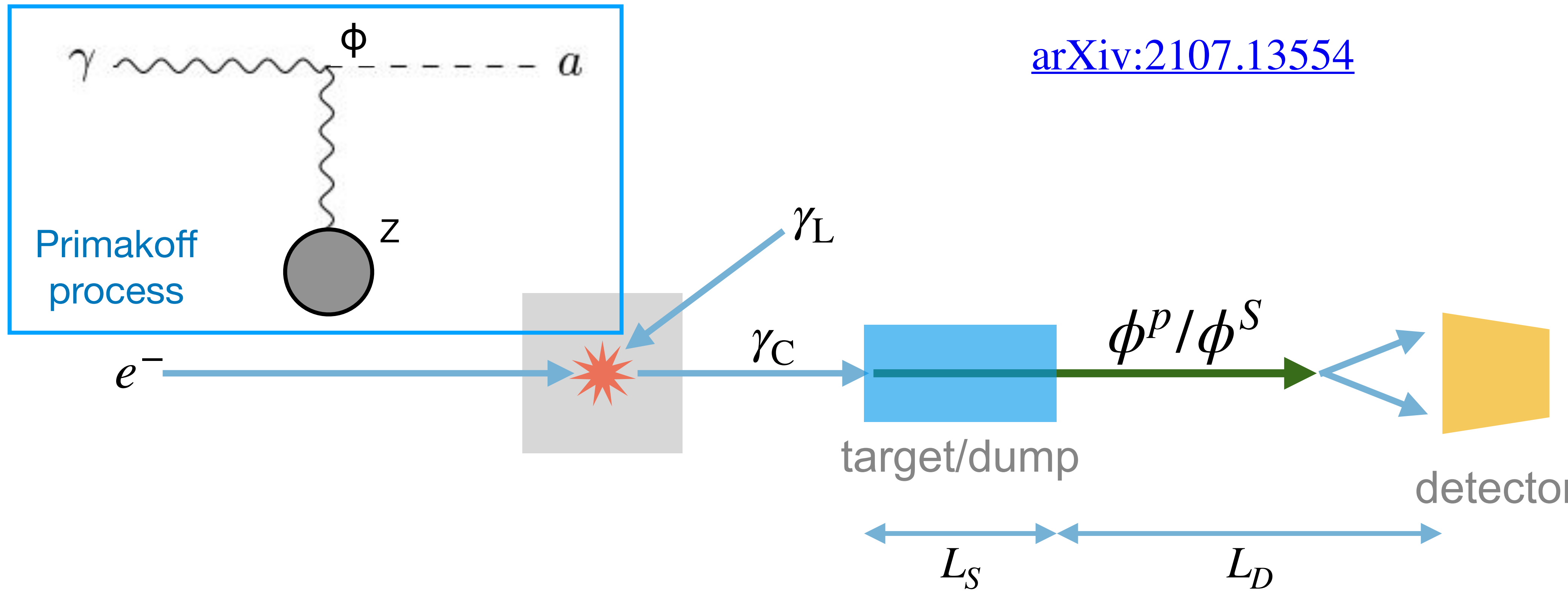




- Positrons rates
  - Number of Breit-Wheeler pairs produced in photon-Laser collisions
  - Assuming 10 days of data-taking and 0.01 background events/ bunch crossing
  - 40% correlated uncertainty to illustrate effect of uncertainty on ξ
- Compton Edges
  - Measure position as function of ξ in electron-laser collisions.
  - Assuming 1h data-taking, no background.
  - 2% energy scale uncertainty to illustrate impact



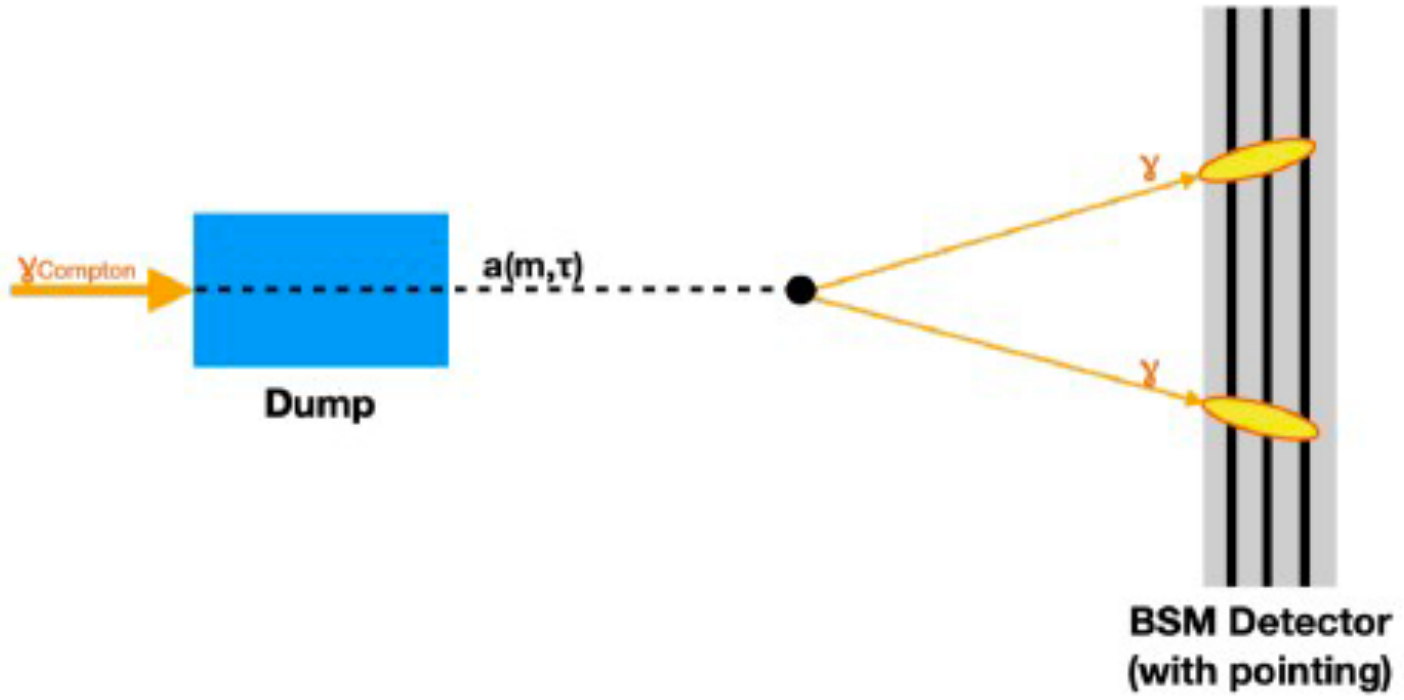
BSM PHYSICS? (DETECTOR TO BE PLACED AT THE END OF THE BEAMLINE)

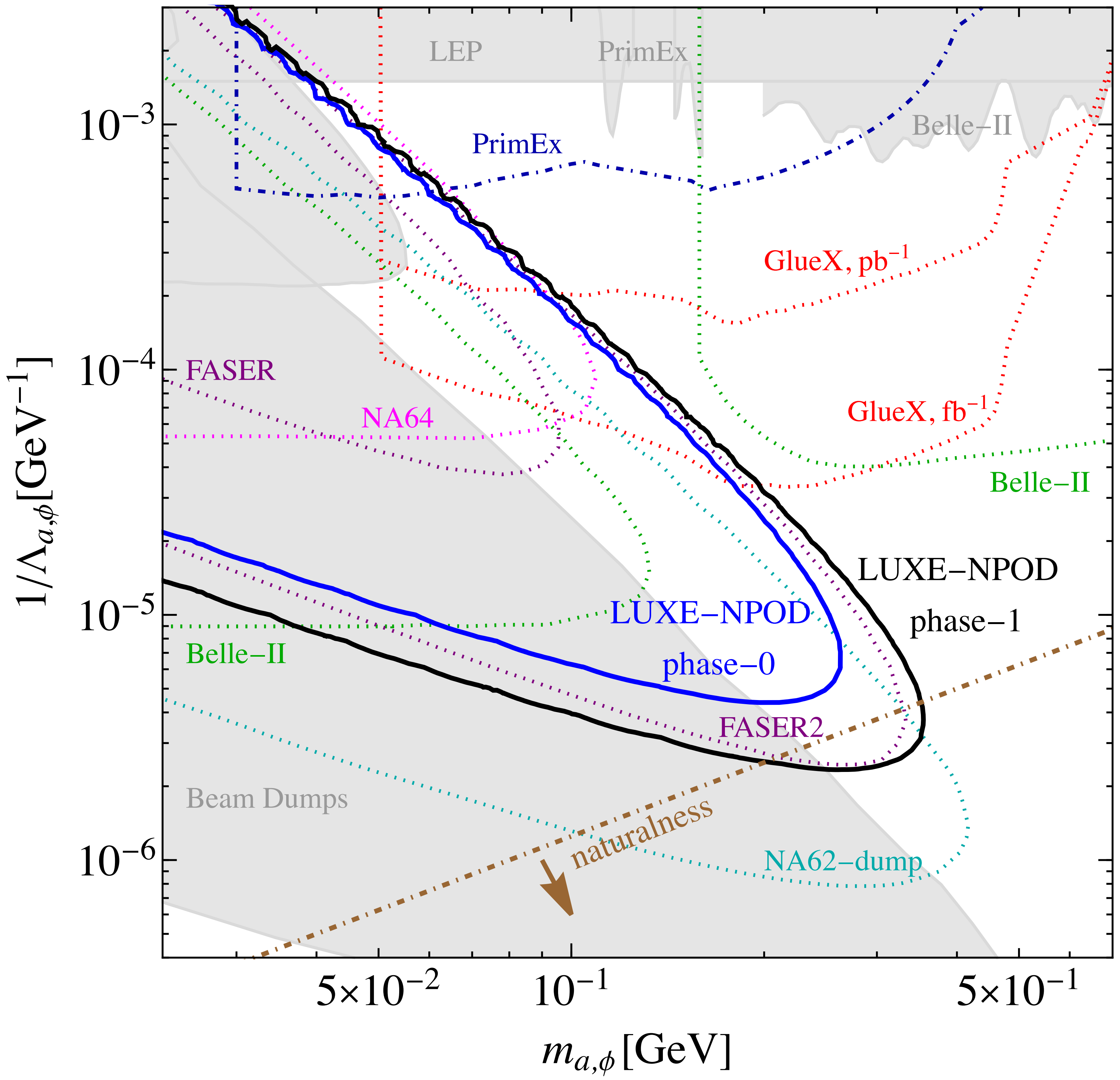


arXiv:2107.13554

- Explore sensibility to BSM theories.
  - Axion-like particles (ALPs) produced in dump.
  - New neutral particles produced at IP.
  - Milli-charged particles.

- For ALPs:
  - sensitive to masses m(a)~100 MeV.
  - decay to photons after some lifetime τ.
  - Place detector behind dump.
  - Could use calorimeter with good pointing resolution to constrain decay point.

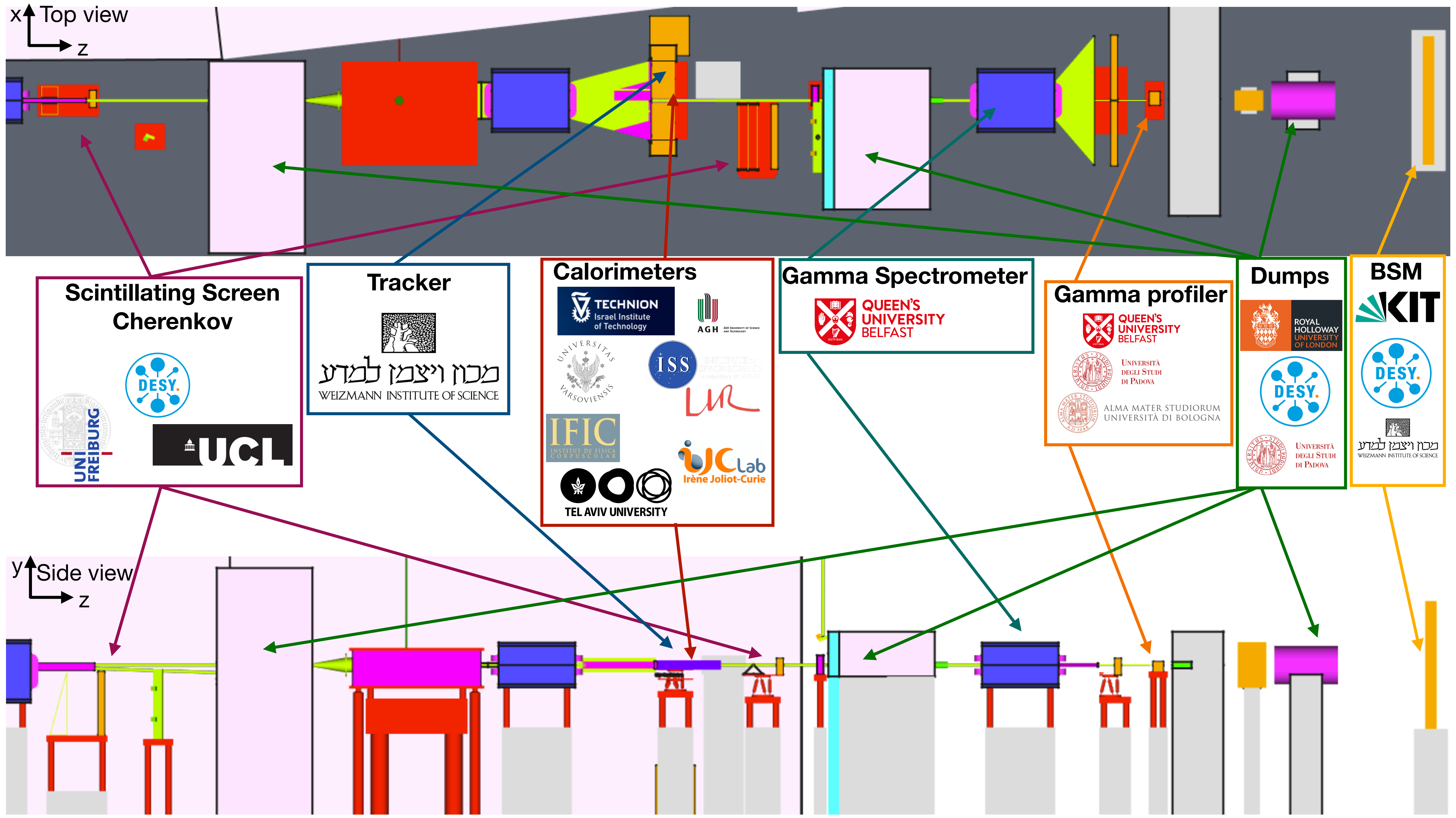




- First sensitivity show very competitive results!
  - After just 1 year of data.

ONE WORD ON THE PLANING

- LUXE initiated in 2017 (A. Ringwald, B. Heinemann)
- 2022: international collaboration with ~20 institutional members, significant contributions to the experiment by external partners envisioned.
- Nov 2022: LUXE officially recognized as a DESY experiment!
- In parallel of review continue detector R&D, and experiment planification. Foresee four-year construction period, after which data-taking could start
  - Depending on approval time-scale this could be as early as 2026
  - Use as much as possible long shutdown of EUXFEL in 2025.
- Extensive material on detailed design and planning available
  - TDR in Mid-2023



- The LUXE experiment will allow to measure QED in uncharted regime!
  - Might expect some surprises there!

- Synergy experiment between particle physics and Laser physics!
  - Experiment is planing to function on established detector technology to cope with challenging rate of particles to measure!
    - 10^{-2} to 10^{9}.
  - Innovative development for Laser control system, and Laser diagnostics underway.

- LUXE TDR should come soon (after CDR), allowing further review of this exciting experiment!
    - Still lot of works to do before the experiment can be running.

THANK YOU FOR YOUR ATTENTION!

LUXE

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UCL

UNIVERSITY OF PLYMOUTH

CNRS IN2P3 Les deux infinis

ÉCOLE POLYTECHNIQUE

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https://luxe.desy.de/