PSI2022

# LUXE - A new experiment to study non-perturbative QED in electron-laser and photon-laser collisions

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# Introduction

- Strong field quantum electrodynamics (SFQED) deals with the interaction of matter and intense electromagnetic fields
- Relatively new area of research - pioneering SLAC E-144 experiment in 1996
- Has become more accessible with developments in laser and beam technologies
- Important for understanding extreme conditions in: plasmas, magnetars, future lepton colliders...
- Standard QED is very well tested e.g. electron magnetic moment; transition and non-perturbative regimes less so
- Need experiments to help theoretical understanding and test models

# Review of SFQED

## Volkov states and the Furry picture

- QED is described by the Lagrangian density

$$\mathscr{L} = \bar{\psi}(i\gamma^\mu \mathscr{D}_\mu - m)\psi - \frac{1}{4}\mathscr{F}^{\mu\nu}\mathscr{F}_{\mu\nu}$$

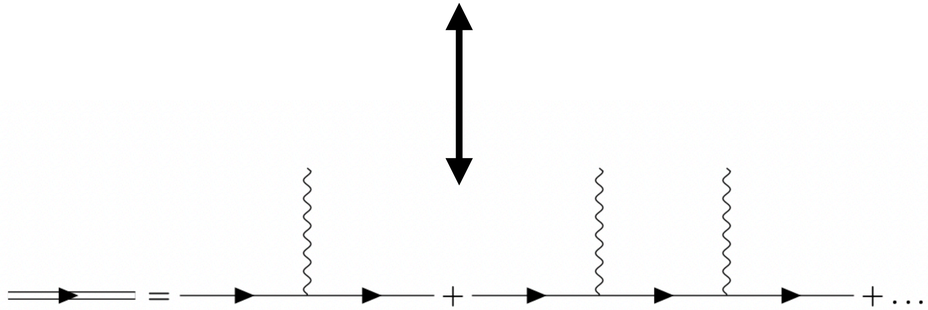
- $\mathscr{D}_\mu = \partial_\mu + ie\mathscr{A}_\mu$ is the covariant derivative; analogous to classical EM minimal coupling

- By separating the field term into background and external, the Lagrangian can be written as

$$\mathscr{L} = \underbrace{\bar{\psi}\left[i\gamma^\mu\partial_\mu - e\gamma^\mu\mathscr{A}^{(b)}_\mu - m\right]\psi}_{\text{Propagation of fermion in background field}} - \underbrace{e\bar{\psi}\gamma^\mu\mathscr{A}^{ext}_\mu\psi}_{\text{Fermion - external field interaction}} - \underbrace{\frac{1}{4}\mathscr{F}^{\mu\nu}\mathscr{F}_{\mu\nu}}_{\text{Light-light interaction}}$$

Feynman momentum propagator in Furry picture - Volkov propagator

$$S_F(p) = \frac{i}{\gamma^\mu\left[p_\mu - e\mathscr{A}^{(b)}_\mu\right] - m}$$



Representation of the Volkov propagator as a Feynman diagram

$$q^\mu = p^\mu - \frac{e^2\langle a^2\rangle}{2(k\cdot p)}k^\mu$$

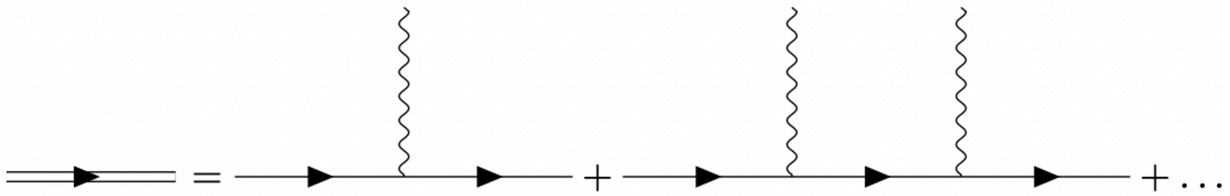
$$q^2 = m_*^2 = m^2(1+\xi^2)$$

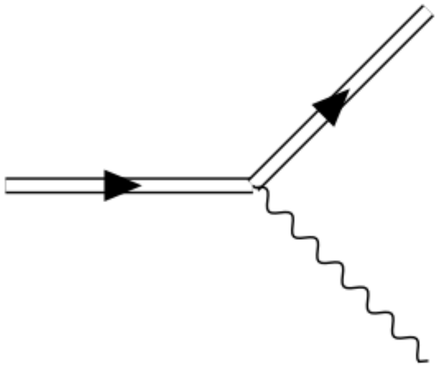
Dressed momentum (quasimomentum) and mass of the propagating fermion

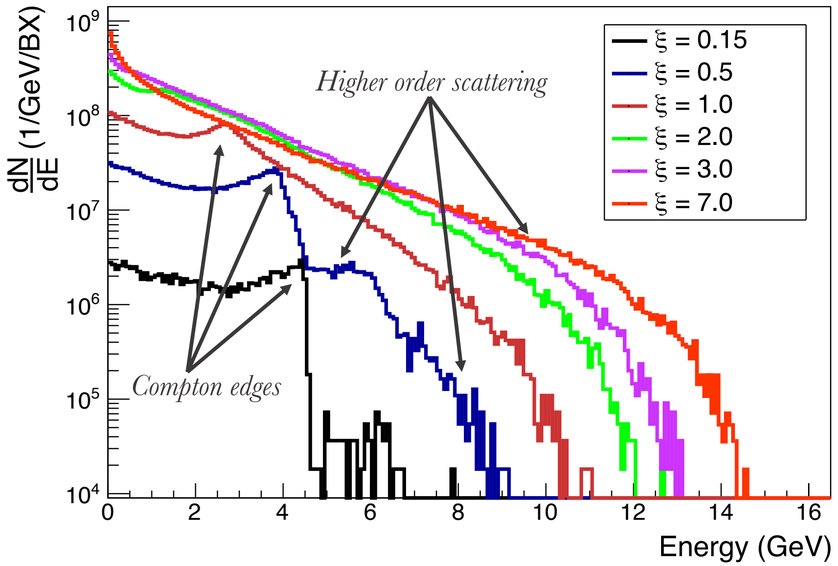
# Review of SFQED

## Perturbative, non-perturbative and inbetween

- Background field (e.g. a laser) is treated classically
- Infinite plane waves -> Volkov solutions to Dirac equation
- Exact in coupling $\alpha$, but Volkov solutions depend non-linearly on $\xi = \dfrac{e\sqrt{\langle a^2 \rangle}}{m}$
- New coupling $\xi$ introduces different regimes:
    - $\xi \ll 1$ - perturbative (standard QED)
    - $\xi \sim 1$ - transition
    - $\xi \gg 1$ - non-perturbative
- Critical field of SFQED - $\varepsilon_{cr} = 1.32 \times 10^{18}\,\mathrm{V/m}$

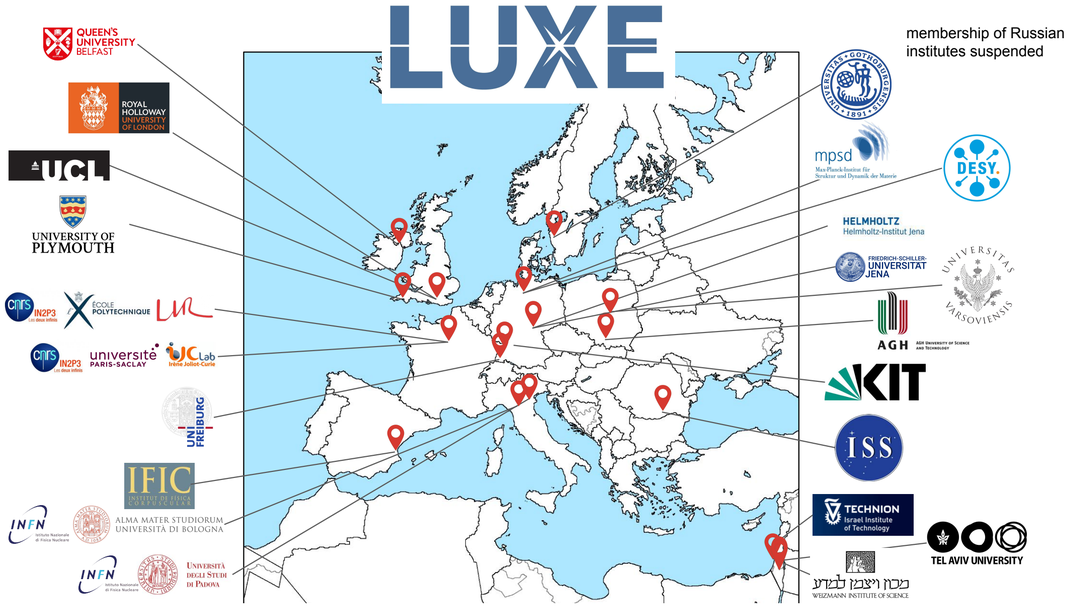


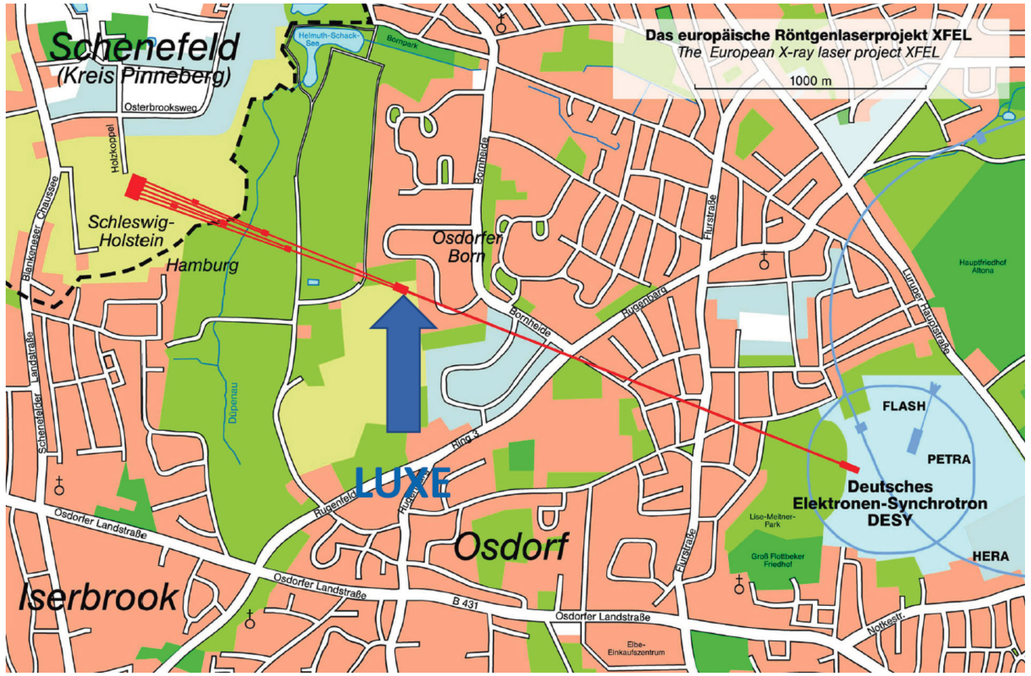




# The LUXE Collaboration

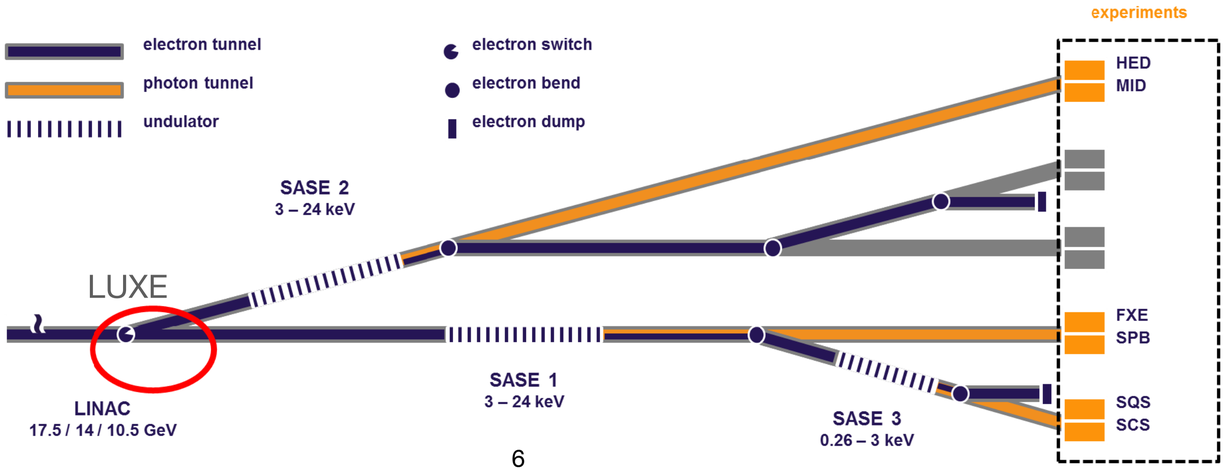
- LUXE (Laser Und XFEL Experiment) is a collaborative effort of 18 institutions
- Based at DESY and Eu-XFEL in Schenefeld and Hamburg, Germany
- Plan to use an high-intensity laser (up to 350 TW) and 16.5 GeV electron beam (Eu-XFEL) to explore less studied areas of SFQED
- CDR published in Feb 2021 and working towards TDR for late 2022
- Proposed to start data taking in 2026



# Eu-XFEL electron beam

- Generates x-ray photons for 6 experiments
- 1.9 km LINAC accelerates electrons to multi-GeV energies - 2700 electron bunches at 10 Hz
- LUXE is designed to be parasitic - aim to use 16.5 GeV electrons with $1.5 \times 10^9$ electrons/bunch
- Only one of the 2700 bunches will be used



# Strong-field QED processes

- Two dimensionless parameters are important for LUXE

Quantum effects

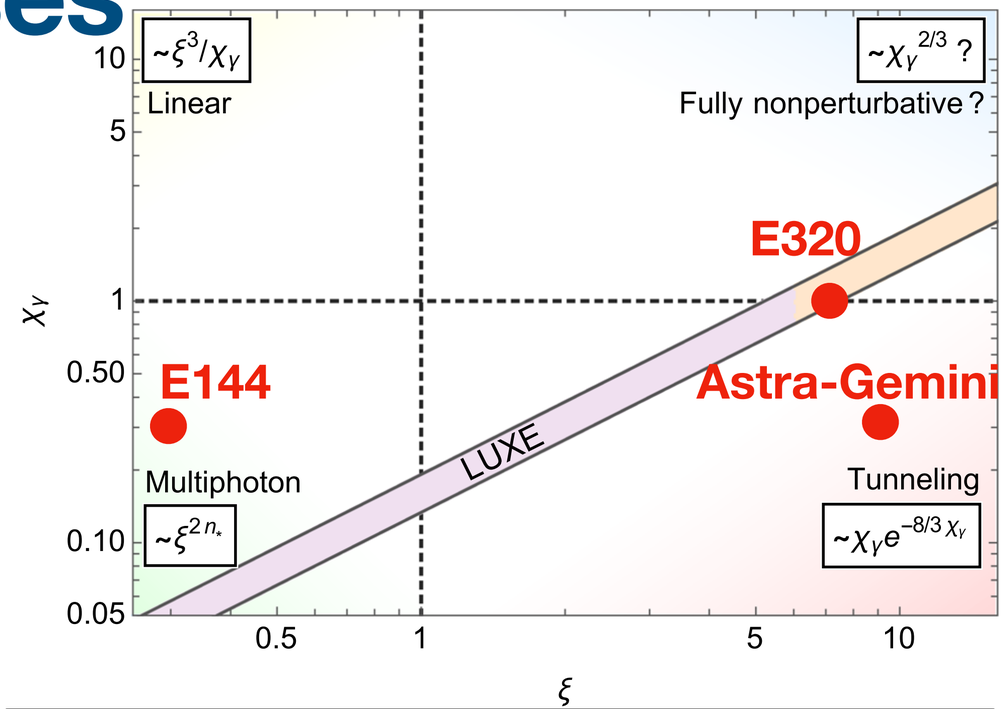
Non-linear effects

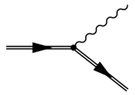
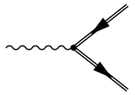
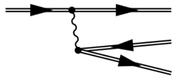
$$\chi = (1 + \cos\theta)\frac{E\omega_L}{m_e\varepsilon_{cr}} \qquad \xi = \frac{m_e\varepsilon_L}{\omega_L\varepsilon_{cr}}$$

$\theta$ = crossing angle, $E$ = particle energy, $\omega_L$ = laser energy, $\varepsilon_L$ = laser electric field

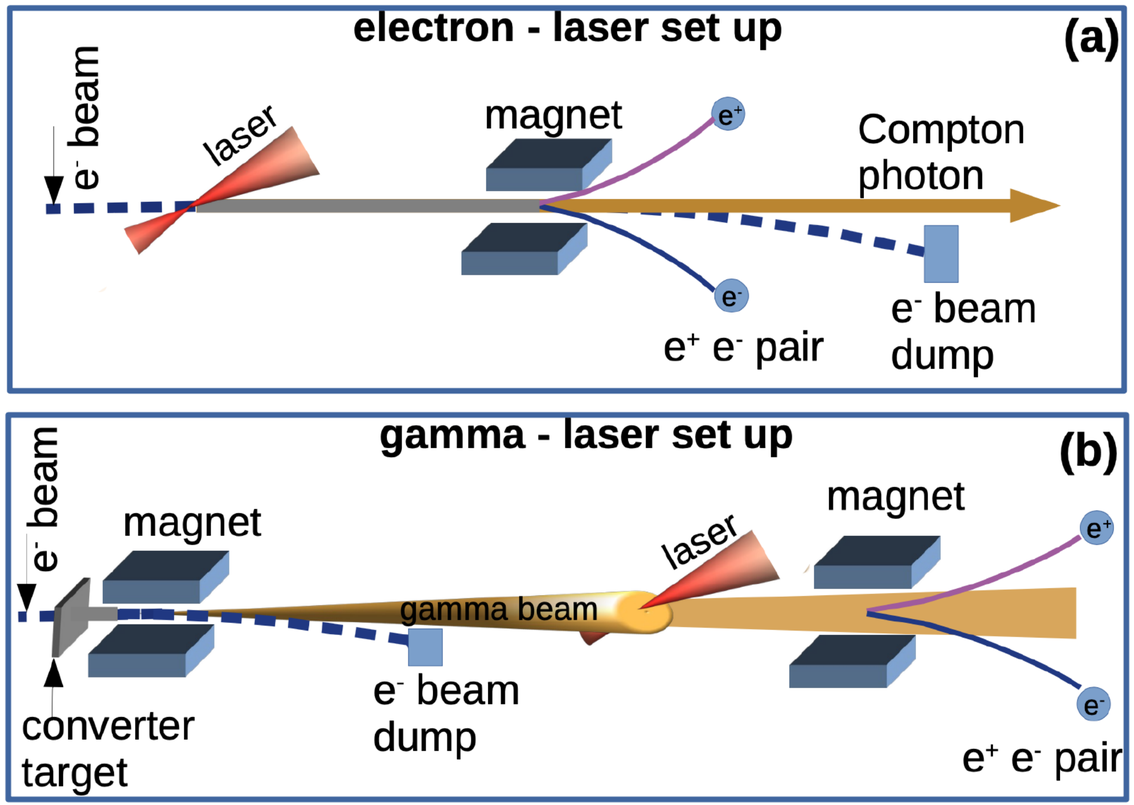
- Use Lorentz boost to exceed critical field

- LUXE to explore new areas of the $\xi, \chi$ parameter space that previous/ upcoming experiments have not




| LUXE Candidate Processes | | |
|---|---|---|
|  | Non-linear Compton | $e^{\pm} \to e^{\pm} + \gamma$ |
|  | Non-linear Breit-Wheeler | $\gamma \to e^{-}e^{+}$ |
|  | Non-linear trident | $e^{\pm} \to e^{\pm} + e^{-}e^{+}$ |

# Experimental Setup

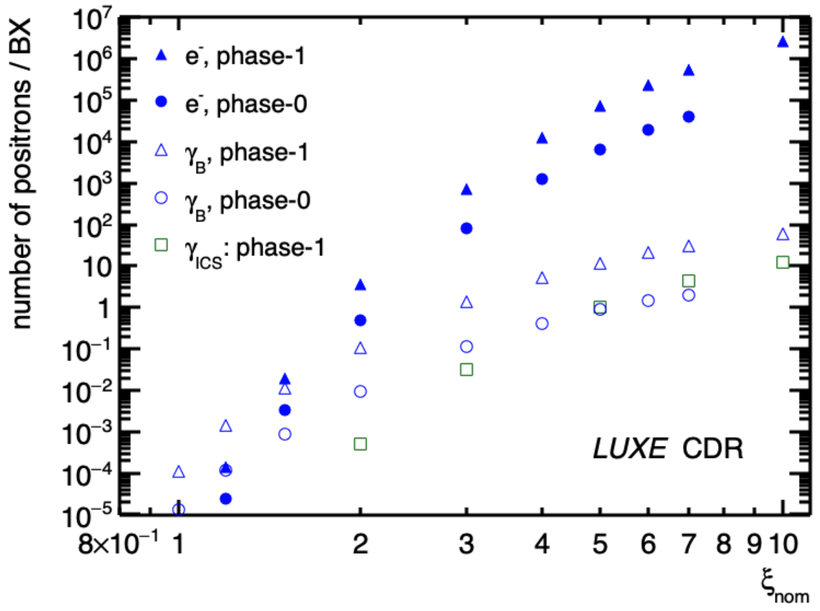


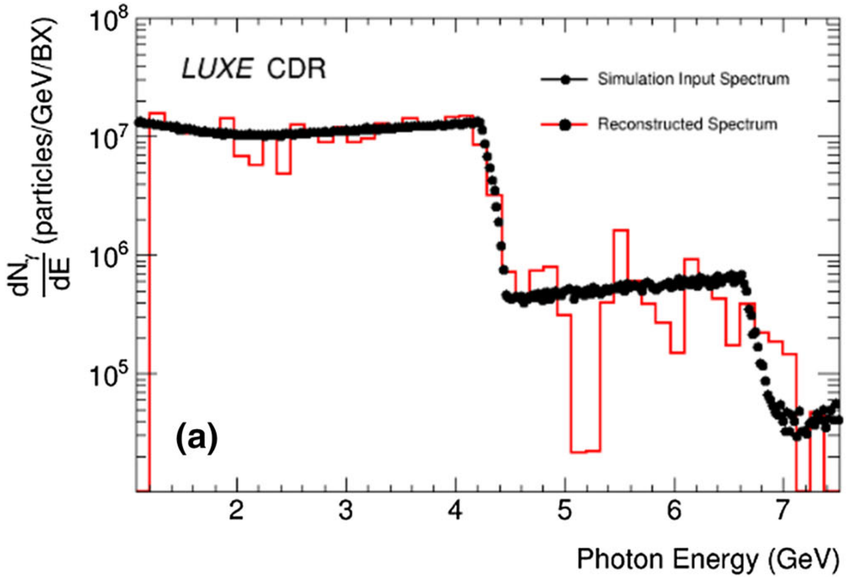

- LUXE will have two operating modes in each phase
- Electron-laser mode:
    - Electron beam interacts with laser directly at IP
    - Investigates non-linear Compton scattering and trident processes
- Gamma-laser mode:
    - Electron beam converted to bremsstrahlung by a converter target
    - Investigates non-linear Breit-Wheeler process BSM investigations are also planned

# Measurement of SFQED processes

## What to measure?

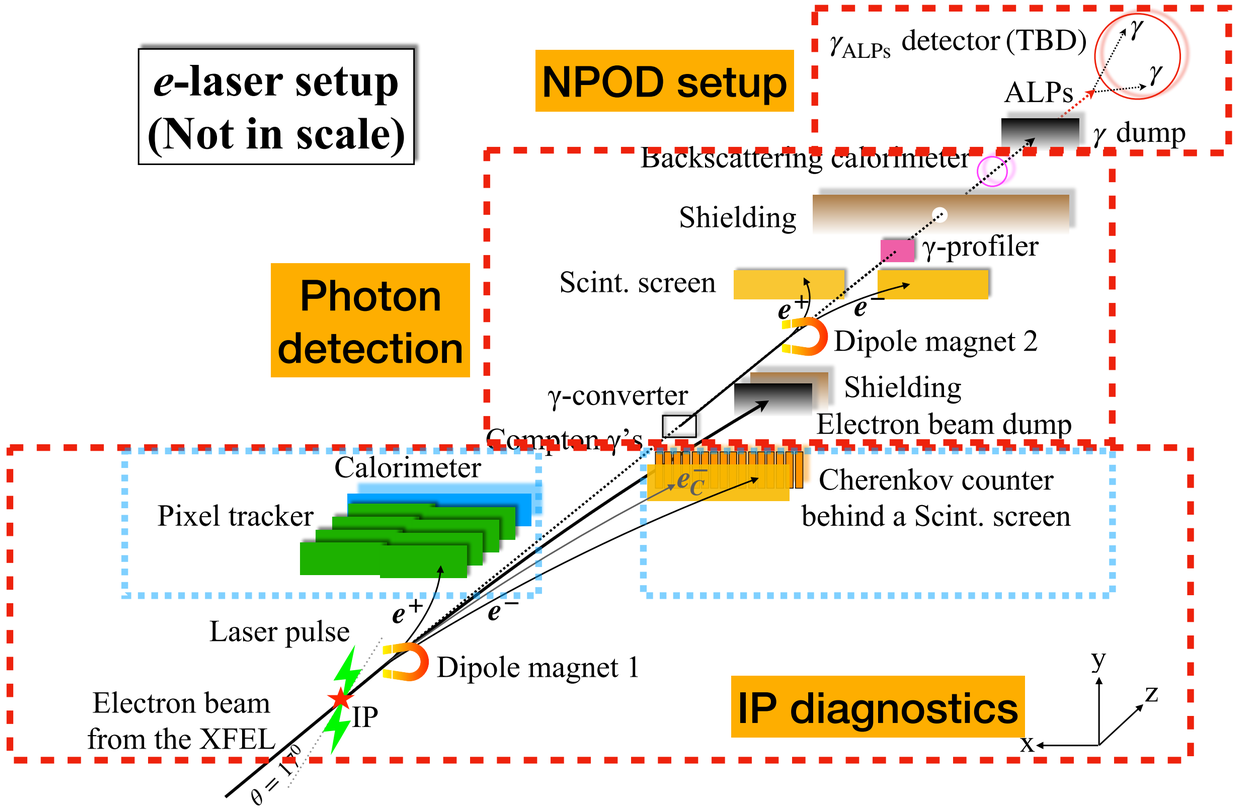
- LUXE aims to observe the characteristics of SFQED processes as a function of $\xi$
    - Rate of Breit-Wheeler positron production
    - Appearance and position of Compton edge in photon and electron spectra
    - Polarisation-dependent shape effects
- Two phases to cover large range of $\xi$
    - Phase I - 40 TW laser
    - Phase II - 350 TW laser
- Large range of particle rates expected across LUXE system, from $10^{-3}$ to $10^{9}$ per second!

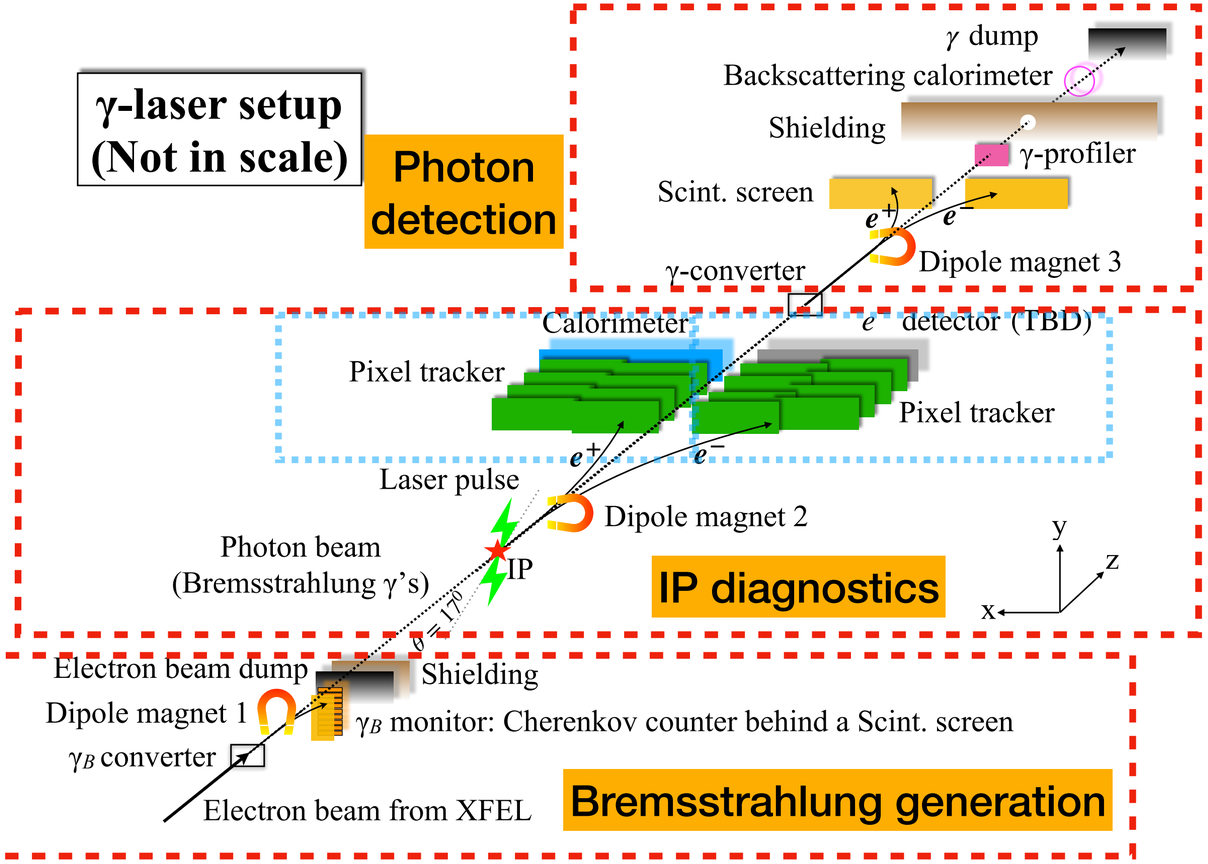


# Measurement of SFQED processes

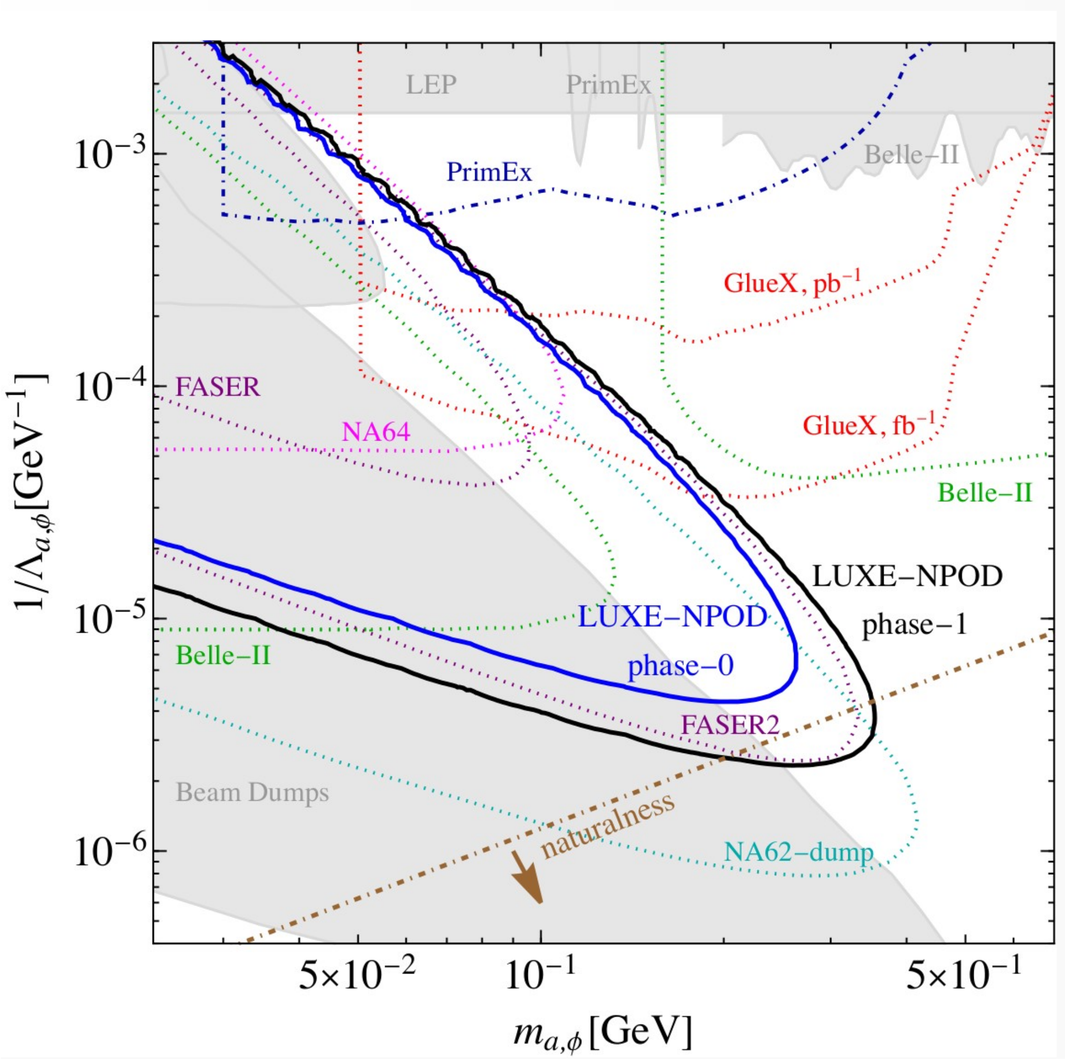
## How to measure?



# Beyond the Standard Model - LUXE NPOD

- High photon fluxes ( $\sim 10^9/\mathrm{s}$ ) expected
- Opportunity to perform BSM searches using the photon dump (NPOD)
- In particular, ALPs and mCPs can be investigated in a wide parameter-space range



# Summary and Outlook

- LUXE will study a previously unexplored regime of strong field QED using high intensity optical lasers and the 16.5 GeV Eu-XFEL electron beam
- Design of experiment will allow for measurement of key SFQED processes such as non-linear Compton scattering and non-linear Breit-Wheeler processes in both the transition and non-perturbative regimes
- BSM investigations are also planned, utilising the high photon fluxes anticipated

- Passed stage 0 approval by DESY directorate
- Currently preparing TDR for publication and awaiting further approval stages
- Data taking proposed to start in 2026

# Thank you for your attention!

- For more information:
  - CDR - https://doi.org/10.1140/epjs/s11734-021-00249-z

**Conceptual Design Report for the LUXE Experiment**

H. Abramowicz[1], U. Acosta[2,3], M. Altarelli[4], R. Aßmann[5], Z. Bai[6,7], T. Behnke[5], Y. Benhammou[1], T. Blackburn[8], S. Boogert[9], O. Borysov[5], M. Borysova[5,10], R. Brinkmann[5], M. Bruschi[11], F. Burkart[5], K. Büßer[5], N. Cavanagh[12], O. Davidi[6], W. Decking[5], U. Dosselli[13], N. Elkina[3], A. Fedotov[14], M. Firlej[15], T. Fiutowski[15], K. Fleck[12], M. Gostkin[16], C. Grojean[*5], J. Hallford[5,17], H. Harsh[18,19], A. Hartin[17], B. Heinemann[†5,20], T. Heinzl[21], L. Helary[5], M. Hoffmann[5,20], S. Huang[1], X. Huang[5,18,20], M. Idzik[15], A. Ilderton[21], R. Jacobs[5], B. Kämpfer[2,3], B. King[21], H. Lahno[10], A. Levanon[1], A. Levy[1], I. Levy[22], J. List[5], W. Lohmann[‡5], T. Ma[23], A.J. Macleod[21], V. Malka[6], F. Meloni[5], A. Mironov[14], M. Morandin[13], J. Moron[15], E. Negodin[5], G. Perez[6], I. Pomerantz[1], R.Pöschl[24], R. Prasad[5], F. Quéré[25], A. Ringwald[5], C. Rödel[26], S. Rykovanov[27], F. Salgado[18,19], A. Santra[6], G. Sarri[12], A. Sävert[18], A. Sbrizzi[§28], S. Schmitt[5], U. Schramm[2,3], S. Schuwalow[5], D. Seipt[18], L. Shaimerdenova[29], M. Shchedrolosiev[5], M. Skakunov[29], Y. Soreq[23], M. Streeter[12], K. Swientek[15], N. Tal Hod[6], S. Tang[21], T. Teter[18,19], D. Thoden[5], A.I. Titov[16], O. Tolbanov[29], G. Torgrimsson[3], A. Tyazhev[29], M. Wing[5,17], M. Zanetti[13], A. Zarubin[29], K. Zeil[3], M. Zepf[18,19], and A. Zhemchukov[16]

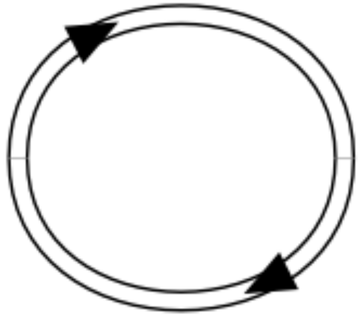
  - TDR to be published soon

# Back up

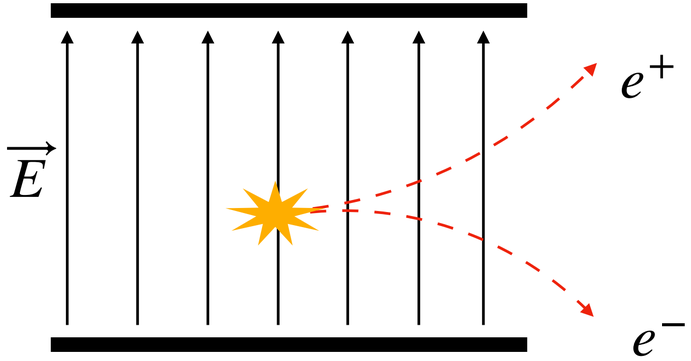
# Review of SFQED

## Sauter-Schwinger effect

- Vacuum persistence probability $|\langle 0, t = \infty | 0, t = -\infty \rangle|^2$
- In 'classical' QED, this is unity; in SFQED, it is less than one generally
- Implies there is a possibility that the presence of a strong background field can generate lepton pairs
- $N_{pairs} = 2VT \frac{e^2 E^2}{(2\pi)^3} \exp\left(-\pi \frac{m^2}{eE}\right)$ for a static electric field
- Defines the Schwinger limit: $E_S = \frac{m^2}{e} = 1.32 \times 10^{18}$ V/m
- Below $E_S$ - pair production is exponentially suppressed
- Above $E_S$ - pair production grows quadratically
- Not yet possible to reach experimentally -> Lorentz boosting techniques!

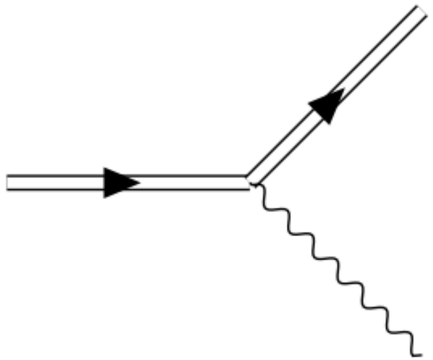


Euler-Heisenberg one-loop contribution to vacuum diagrams



# Review of SFQED

## Non-linear Compton scattering



- Matrix element for a dressed electron to emit a single photon

$$S = -ie\int d^4x\, \bar{\psi}_{p'}(x)\gamma^\mu \epsilon_\mu \psi_p(x)\frac{e^{ik\cdot x}}{\sqrt{2\omega}}$$

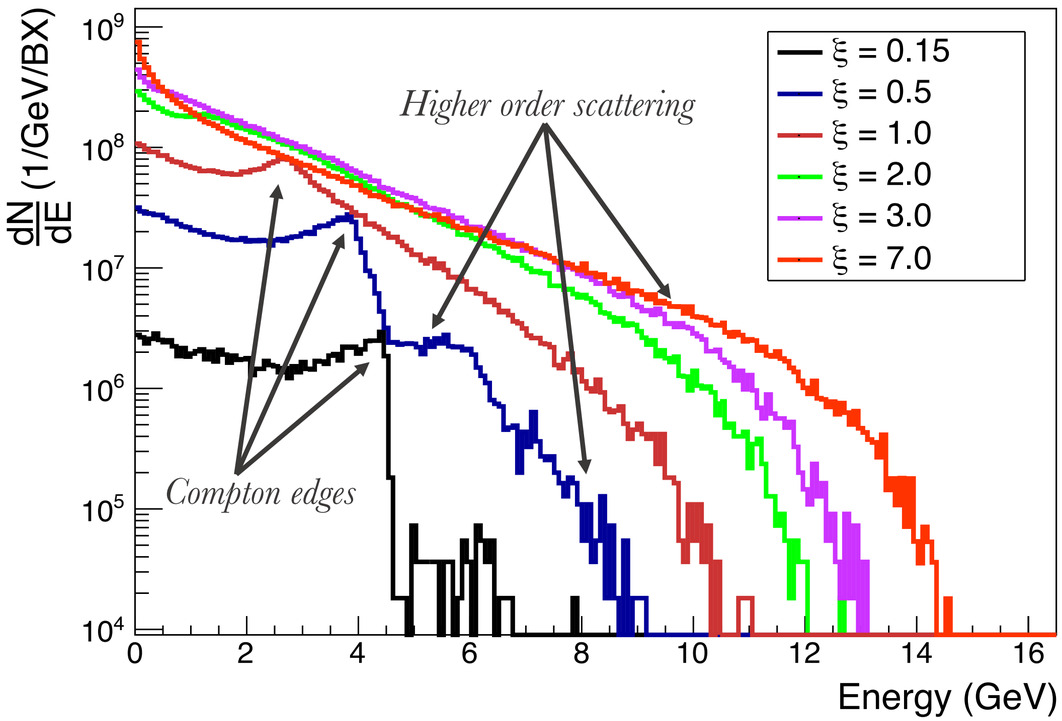
- Expansion using Bessel functions gives a set of momentum conservation equations $\{sk + q = q' + k' \,:\, s \geq 1\}$

- Effectively, electron can absorb $s$ virtual photons from the background field, then emit a photon -> total probability of emission involves a sum over $s$

- For $\xi \ll 1$, multiple Compton edges appear

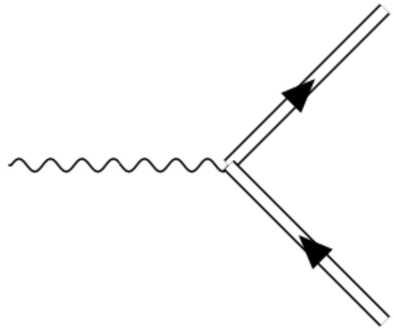
- For $\xi \gg 1$, emission becomes synchrotron-like

$$\xi = \frac{e}{m}\langle a^2 \rangle \quad \chi_e = \frac{e}{m^3}\sqrt{|\mathcal{F}_{\mu\nu}p^\nu|^2}$$



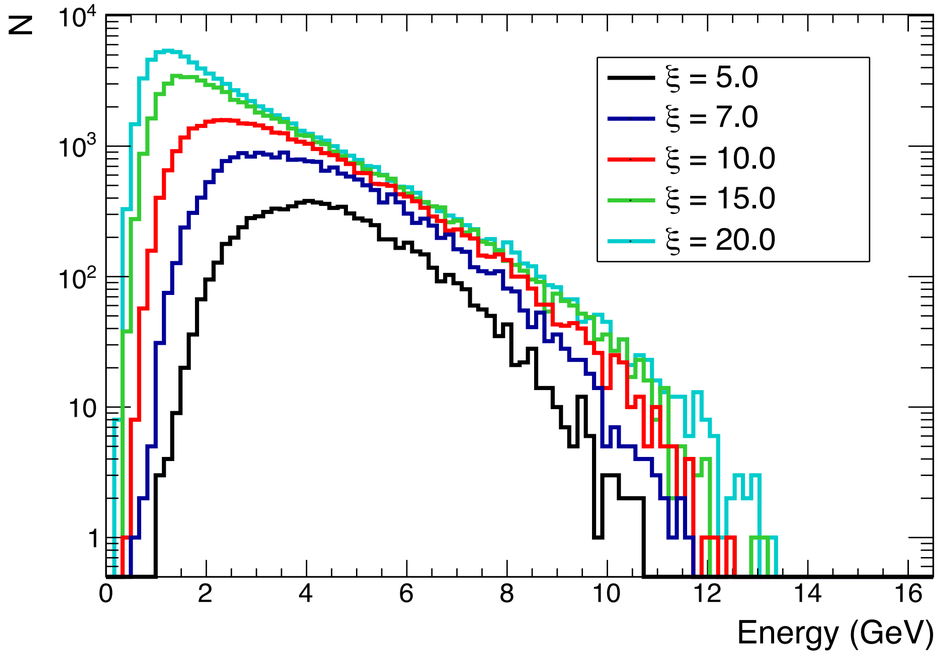
# Review of SFQED

## Non-linear Breit-Wheeler production



- Breit-Wheeler production is related to Compton scattering by crossing symmetry -> matrix element can be found by appropriate re-substitution
- Similar set of conservation equations apply $\{sk' + k = q_- + q_+ \ : \ s \geq 1\}$
- Unlike NLC scattering, NBW has an exponential suppression in the low $\chi_\gamma$ regime
- In quantum regime, scaling is the same - this leads to SFQED cascades

$$\mathscr{P}^{NBW} \sim \begin{cases} \alpha\chi_\gamma e^{-8\chi_\gamma/3} & \chi_\gamma \ll 1 \\ \alpha\chi_\gamma^{2/3} & \chi_\gamma \gg 1 \end{cases}$$

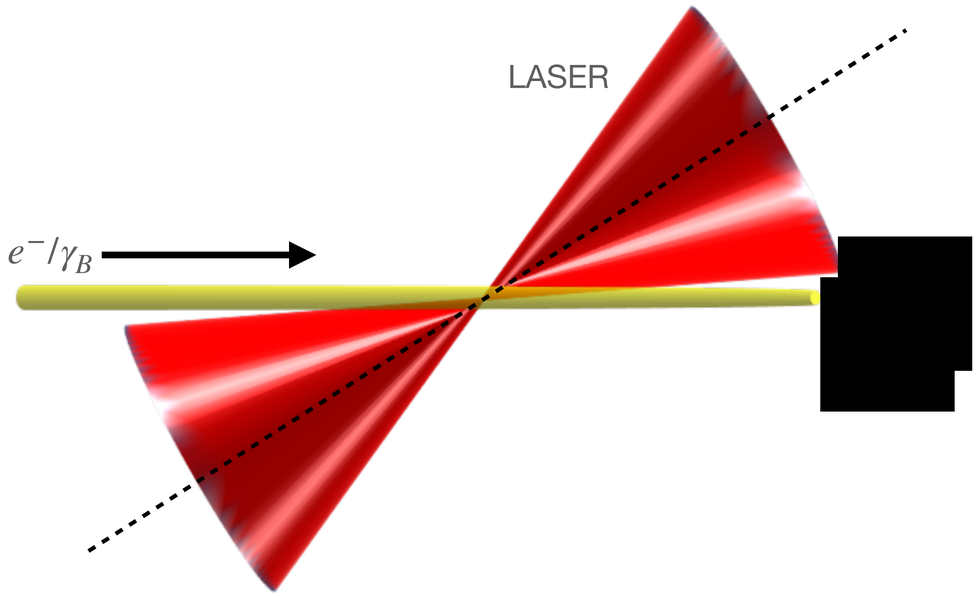


# Laser

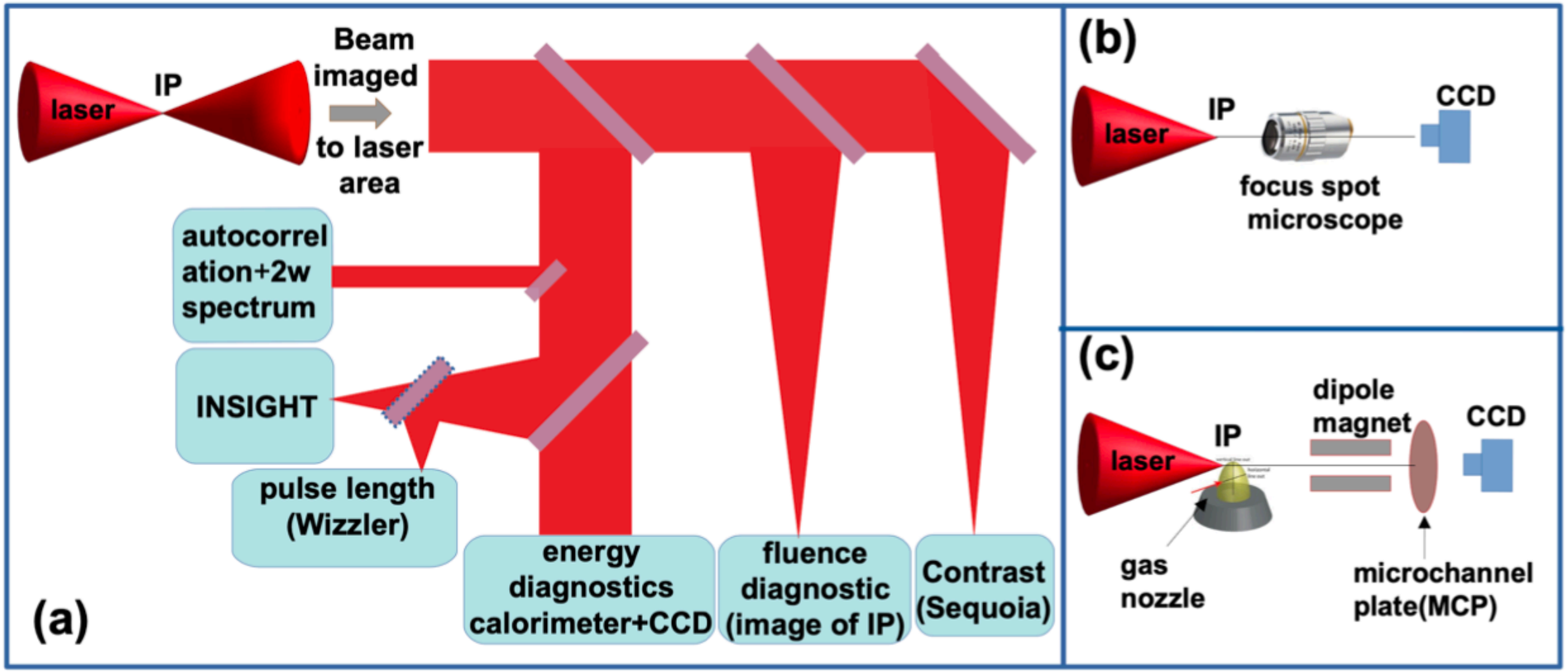
- Ti:Sa 800 nm wavelength laser to be used
- CPA technique to provide ultra-short pulse
- LUXE will have two phases:
  - Phase 0 - JETI40 (Jena's 40 TW laser)
  - Phase 1 - commercial 350 TW laser
- Key parameters summarised in table
- Laser diagnostics - energy, pulse length and spot size
- Aiming for $\leq 5\,\%$ uncertainty on intensity with $1\,\%$ shot-to-shot fluctuations

| | 40 TW, 8$\mu$m | 40 TW, 3$\mu$m | 350 TW, 3$\mu$m |
|---|---|---|---|
| **Laser energy after compression (J)** | 1.2 | 1.2 | 10 |
| **Laser pulse duration (fs)** | | 30 | |
| **Laser focal spot waist $w_0$ ($\mu$m)** | 8 | 3 | 3 |
| **Fraction of ideal Gaussian intensity in focus (%)** | | 0.5 | |
| **Peak intensity in focus ($\times 10^{20}$ Wcm$^{-2}$)** | 0.19 | 1.33 | 12 |
| **Dimensionless peak intensity, $\xi$** | 3.0 | 7.9 | 23.6 |
| **Laser repetition rate (Hz)** | | 1 | |
| **Electron-laser crossing angle (rad)** | | 0.35 | |

| **Quantum parameter** | | | |
|---|---|---|---|
| $\chi_e$ **for** $E_e = 14.0\,\mathrm{GeV}$ | 0.48 | 1.28 | 3.77 |
| $\chi_e$ **for** $E_e = 16.5\,\mathrm{GeV}$ | 0.56 | 1.50 | 4.45 |
| $\chi_e$ **for** $E_e = 17.5\,\mathrm{GeV}$ | 0.6 | 1.6 | 4.72 |



# Laser Diagnostics



# LUXE Simulations

- Programs used for simulation:
  - Ptarmigan - SFQED Monte-Carlo code -> Used to simulate the electron/photon - laser interaction at IP https://github.com/tgblackburn/ptarmigan
  - Geant4 and FLUKA - general particle tracking Monte-Carlo codes -> Used for background estimation, radiation prediction and detector performances
- SFQED simulations utilise two computational approximations
  - LMA - locally monochromatic approximation
  - LCFA - locally constant field approximation