# LUXE: a new experiment using a laser and XFEL electrons to investigate QED in the strong-field regime

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- **Introduction**
- **Strong field QED**
- **E144 experiment at SLAC**
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- **Conclusions and outlook**

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# Introduction

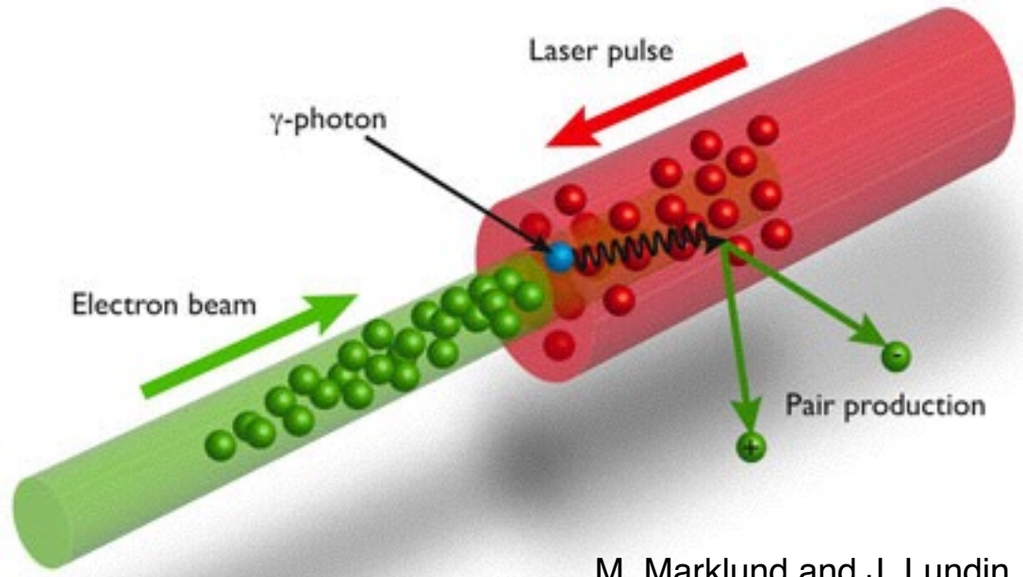
- Quantum mechanics and quantum electrodynamics has been investigated and measured with amazing precision in many experiments and high-precision predictions describe this well.
  - However the strong field regime, where QED becomes non-perturbative, has still not been measured.
- The strong field regime was already considered by Heisenberg, Euler et al. in the 1930s.
- Characterised by the Schwinger critical field (1951):

$$E_{\text{crit}} = \frac{mc^2}{e\lambda\!\!\!^{-}_C} = \frac{m^2c^3}{e\hbar} = 1.3\times10^{16}\ \text{V/cm}$$

- This has not been reached experimentally in the lab, although they are expected to exist:
  - On the surface of neutron stars.
  - In bunches of future linear $e^+e^-$ colliders.
- Can be reached by colliding photons with a high-energy electron beam
  - First experiment to try this E144 @ SLAC in 1990s.
  - Propose to do this using XFEL beam: LUXE.
- **Explore QED in an unexplored region.**

# Non-linear QED processes

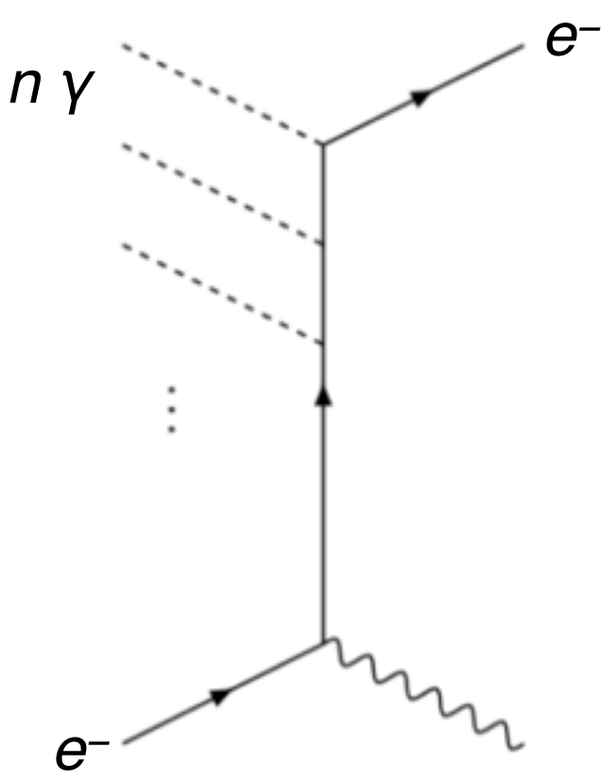
- Initial interest in two strong-field processes in the interaction of electron beam with high-power laser pulse.
  - Non-linear Compton scattering where multiple laser photons are absorbed and a single photon radiated.
  - One or more such Compton scatters happen.
  - Produced photon interacts with laser field to produce electron–positron pair (Breit–Wheeler)




M. Marklund and J. Lundin,
Eur. Phys. J. D 55 (2009) 319

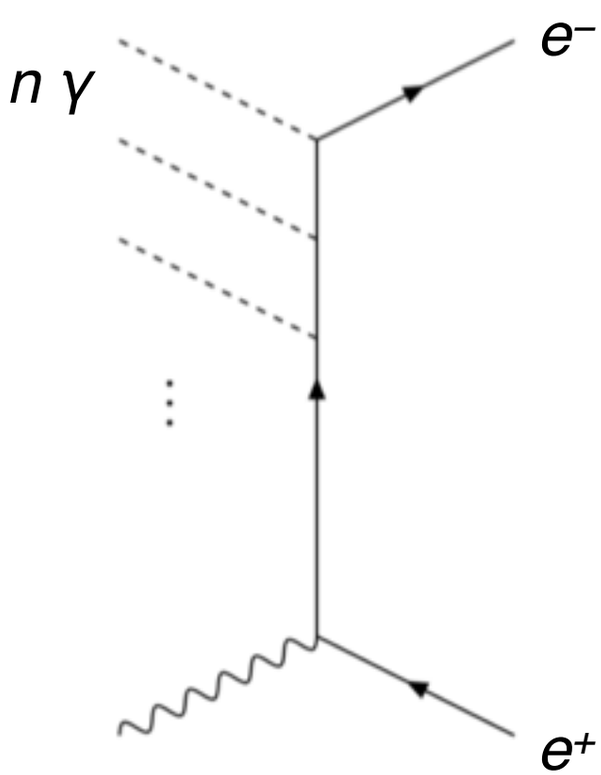
Compton

$$e^- + n\,\gamma \;\rightarrow\; e^- + \gamma$$




Pair production

$$\gamma + n\,\gamma \;\rightarrow\; e^+ + e^-$$




$$\eta = \frac{e\,E}{m_e\,\omega\,c}$$

$$\kappa = \frac{2\,E_\gamma}{m_e\,c^2}\,\frac{E}{E_{\mathrm{crit}}}$$

$$\Upsilon = \frac{E_{\mathrm{beam}}(1-\cos\alpha)}{m_e\,c^2}\,\frac{E}{E_{\mathrm{crit}}}$$

# Compton and pair-creation processes

- Pair creation predictions:

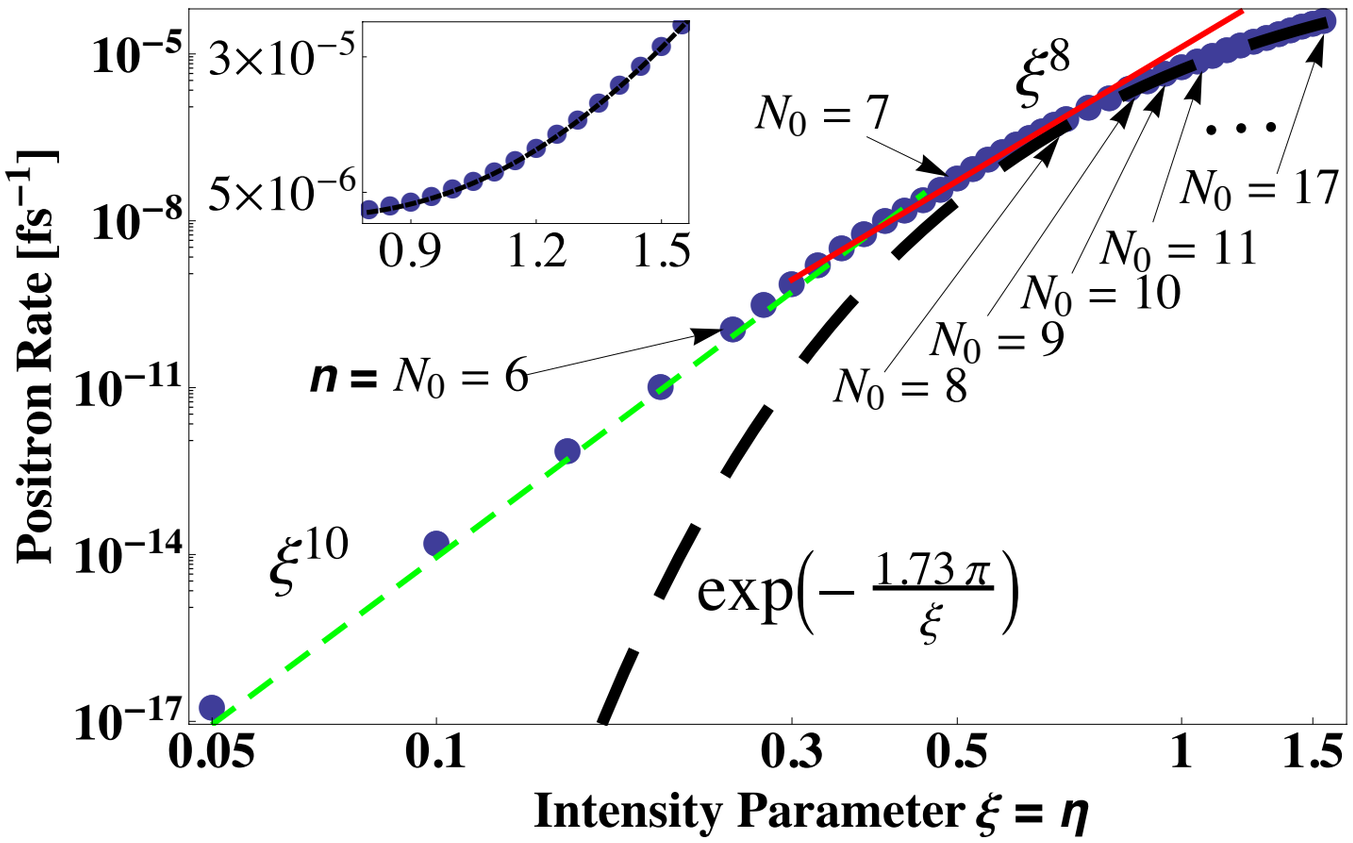
**Perturbative**

$$\eta \ll 1 \quad : \quad R_{e^+} \propto \eta^{2n} \propto I^n$$

**Non-perturbative**

$$\eta \gg 1 \quad : \quad R_{e^+} \propto \exp(-4/(3\,\kappa))$$

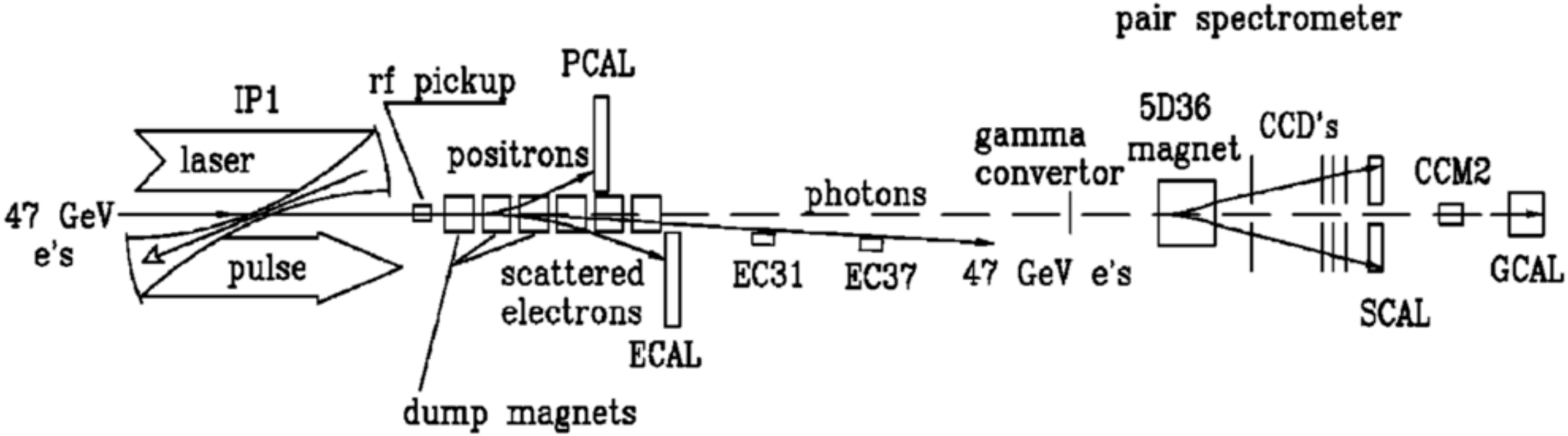
H. Hu, C. Müller and C. Keitel,
Phys. Rev. Lett. **105** (2010) 080401




**Variation of laser intensity, and hence $\eta$, is important**

# E144 experiment at SLAC

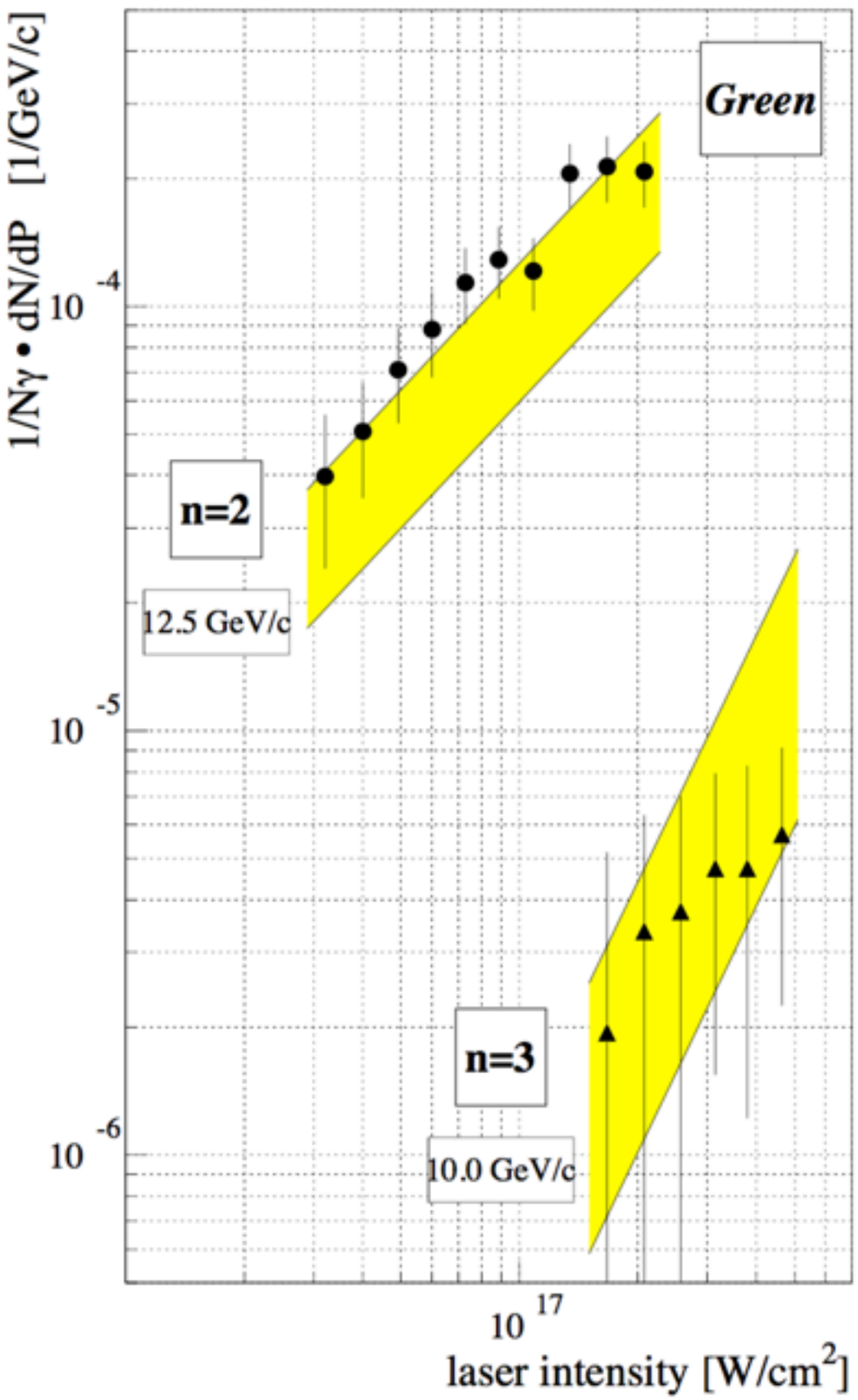
Schematic of SLAC E144 experiment

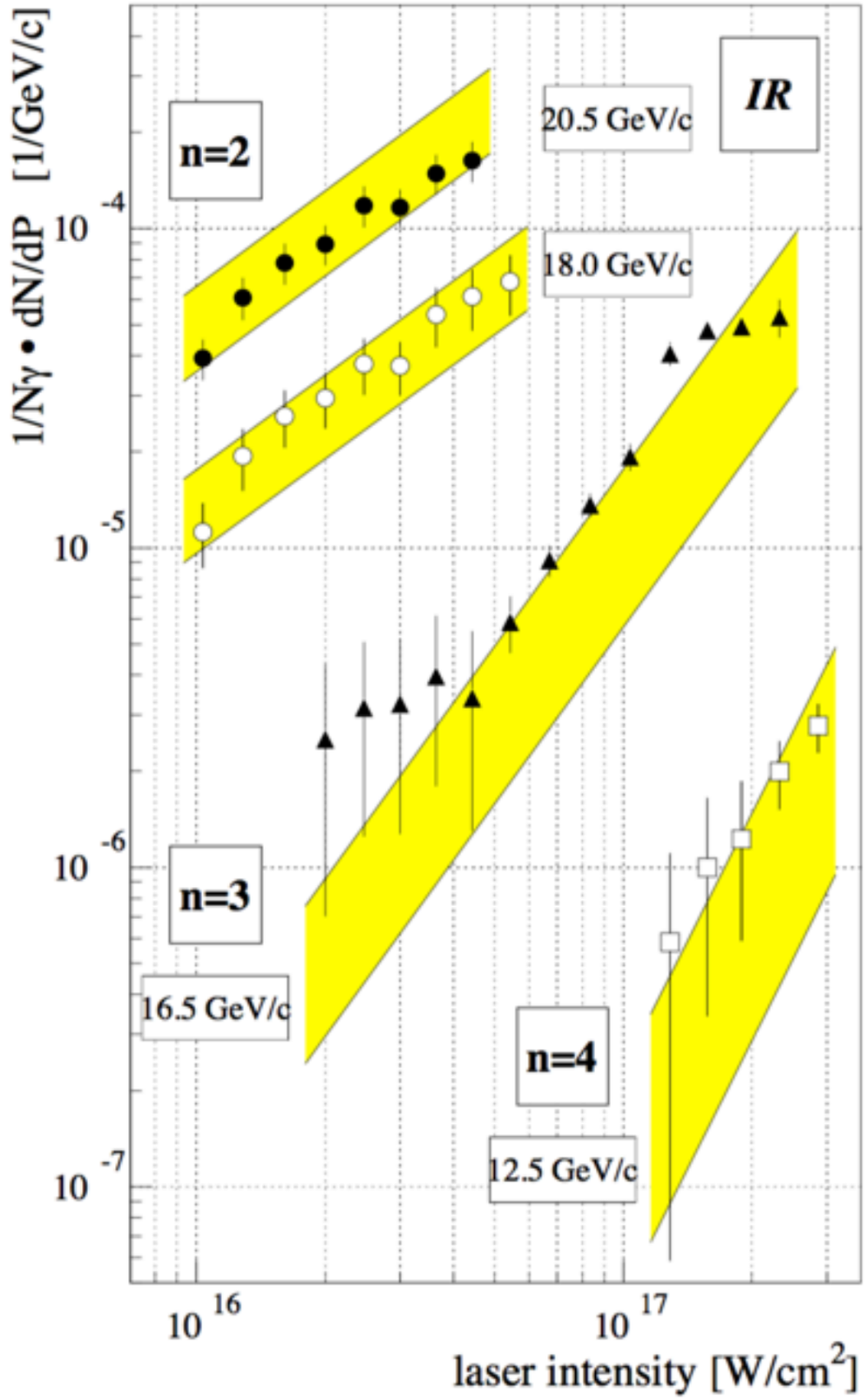



- Used 46.6 GeV electron beam (Final Focus Test Beam) with $5 \times 10^9$ electrons per bunch up to 30 Hz.
- Terawatt laser pulses with intensities of $\sim 0.5 \times 10^{18}$ W/cm$^2$ and frequency of 0.5 Hz for wavelengths 1053 nm and 527 nm.
- Electron bunch and laser collided with 17° crossing angle.

E144 Coll., C. Bamber et al., Phys. Rev. D 60 (1999) 092004;
T. Koffas, “Positron production in multiphoton light-by-light scattering”, PhD thesis, University of Rochester (1998), SLAC-R-626.

# E144 experiment results



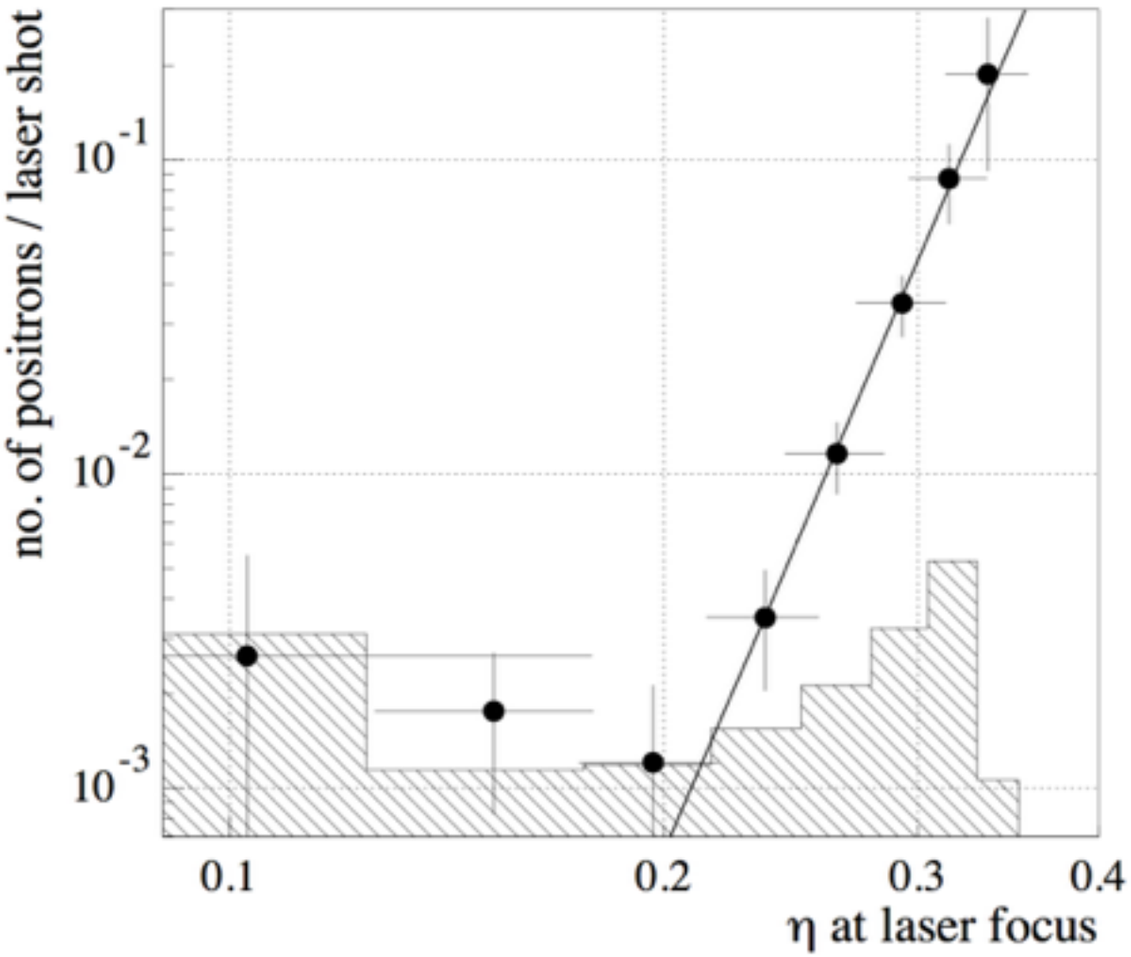




Data on non-linear Compton scattering compared to simulation

# E144 experiment results

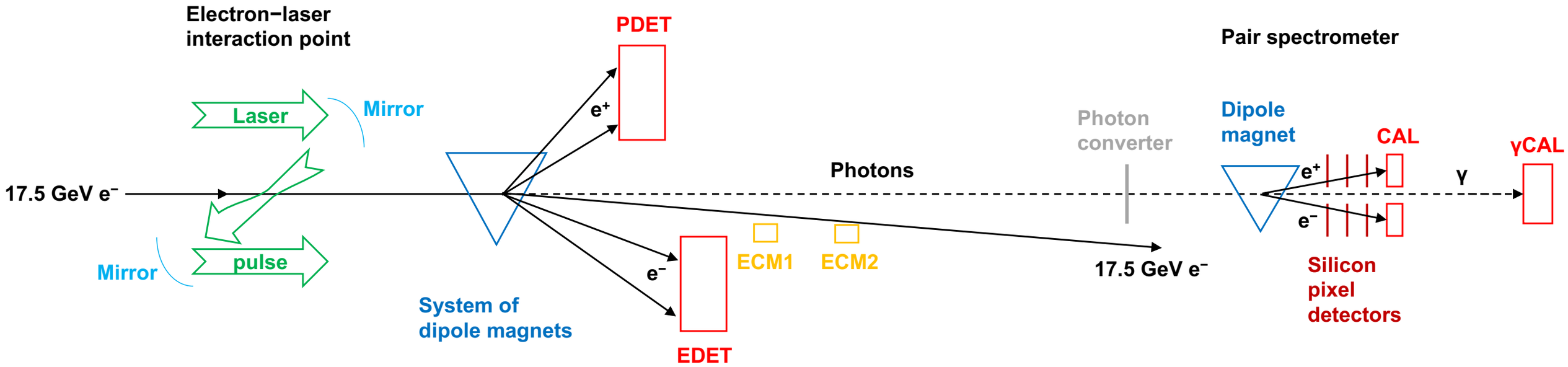
E144 achieved $\eta < 0.4$ and $\kappa < 0.25$

- Measured non-linear Compton scattering with $n = 4$ photons absorbed and pair production with $n = 5$ photons absorbed
- **Observed strong rise ~ $\eta^{2n}$ but not asymptotic limit**
- Measurements well described by theory
- Large uncertainty on the laser intensity
- **Did not achieve the critical field**



# LUXE (Laser Und XFEL Experiment)

**Goal: setup experiment with electrons from the XFEL beam with real photons from a high-power laser and measure physics at the critical field**




- Experimental schematic follows ideas of E144
- To be defined in detail and optimised
- Would run parasitically, i.e. XFEL beam can still be used afterwards

# Location in XFEL tunnel


Electron beams

Photon beams

- LUXE could fit in a currently unassigned tunnel of the XFEL complex.
- Expect experiment to be ~1–2 m wide and ~50 m long.
- Final possible location depends on:
  - optimisation of experimental setup
  - infrastructure, layout requirements, e.g. position of laser
  - …

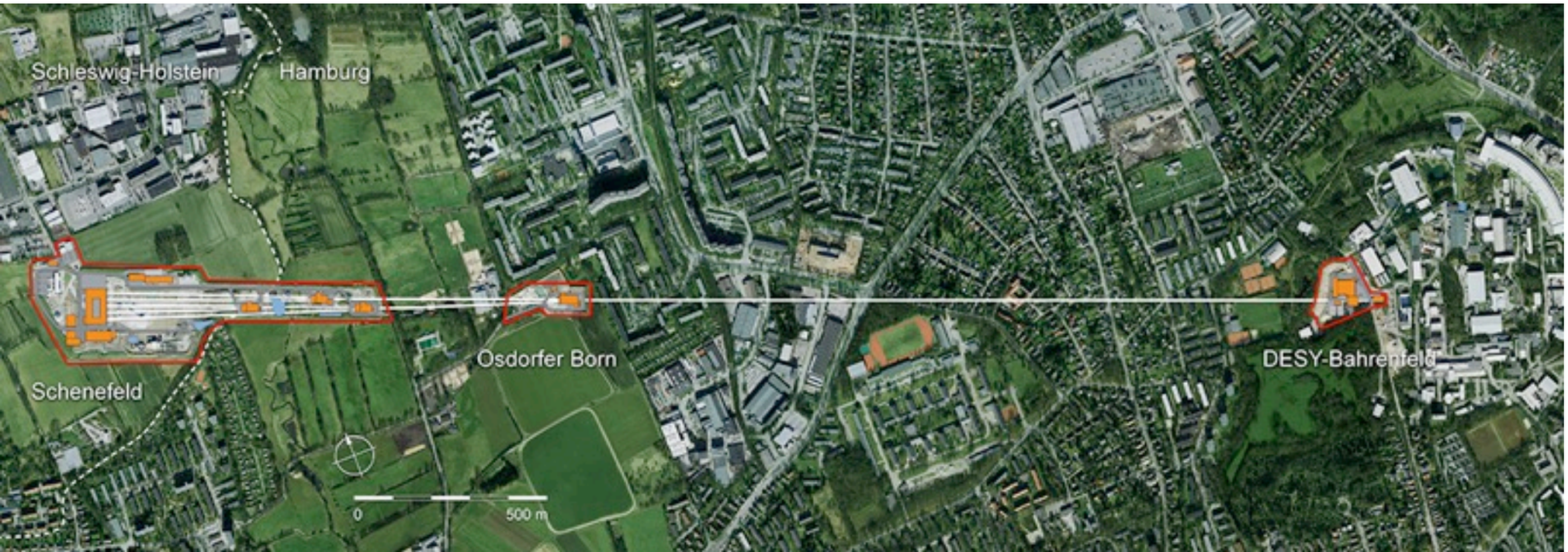
# XFEL electron beam parameters

- **XFEL electron beam parameters similar to those at SLAC.**
- **May have possibility to change some parameters?**
- Want to match electron and laser beam sizes.

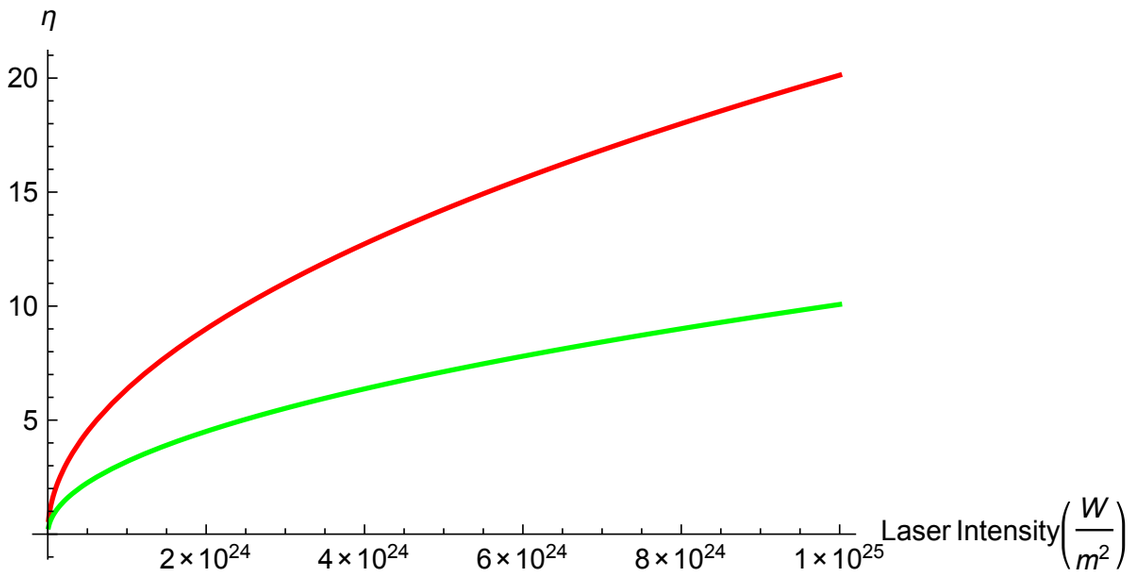
Other XFEL electron beam parameters

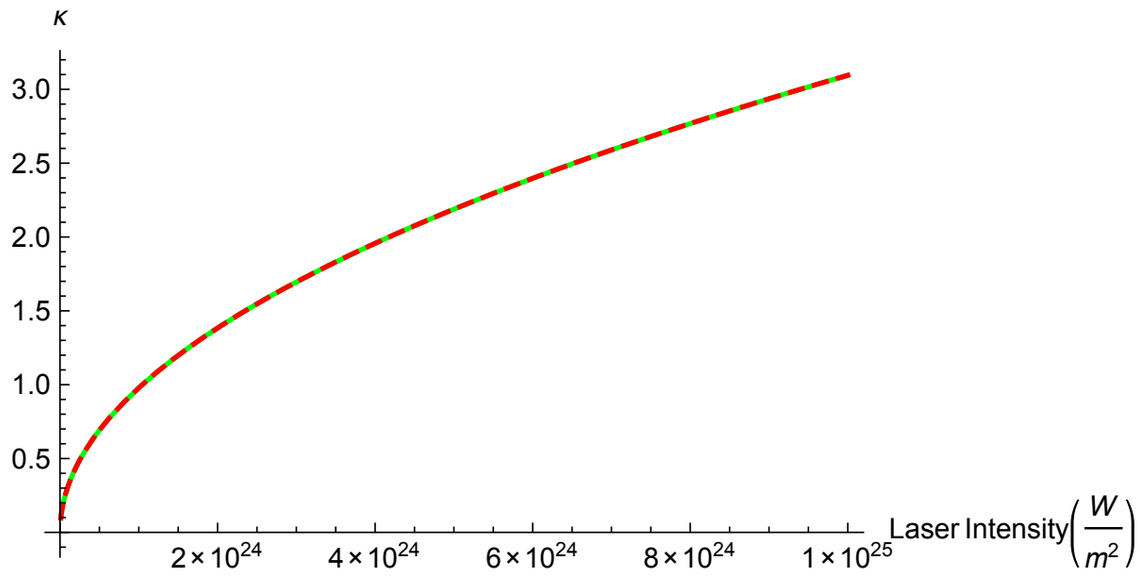
- Bunch trains of 3250 bunches with a bunch spacing of 200 ns.
- Repetition rate of 10 Hz.
- Emittance at undulator is 1.4 mm · mrad.
- Energy spread is 1 MeV.

| | XFEL | SLAC |
|---|---|---|
| Beam energy (GeV) | 17.5 | 46.6 |
| Charge ($N_{e-}$/bunch) | $6 \times 10^9$ | $5 \times 10^9$ |
| $\sigma_{x,y}$ (μm) | 30 – 60 | 60 |
| $\sigma_z$ (μm) | 20 | 500 – 1000 |



# LUXE sensitivity

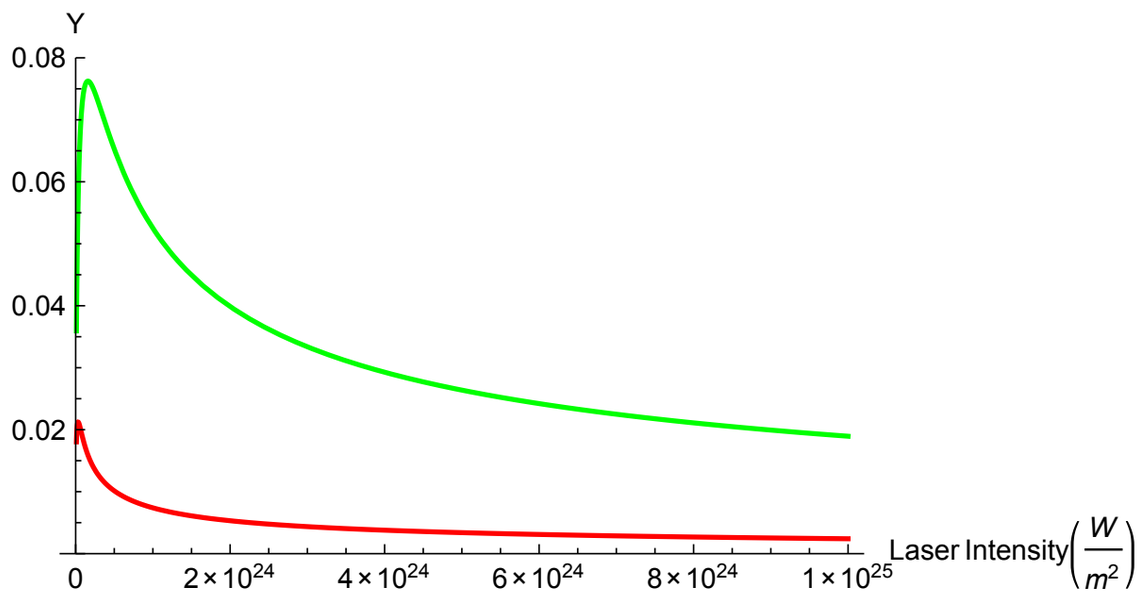



- $E_e$ = 17.5 GeV
- $\theta(e,\gamma)$ = 17°
- Laser intensity varied $10^{20}$ – $10^{21}$ W/cm$^2$
- $\lambda$ = 1053 nm, 527 nm

- **LUXE: $\eta \sim 3$, $\kappa \sim 1$ at $10^{20}$ W/cm$^2$**
- **LUXE: $\eta \sim 10$, $\kappa \sim 3$ at $10^{21}$ W/cm$^2$ for a green laser**

- Recall, E144: $\eta \sim 0.3$, $\kappa \sim 0.2$



# LUXE physics range

- LUXE should be able to extend significantly into new regions
- **Fields at or above the critical field (for the first time !)**
- Want to run at lower last intensities to see perturbative transition
- Consider variation of other parameters, e.g. laser wavelength
- Interesting optimisation study to do

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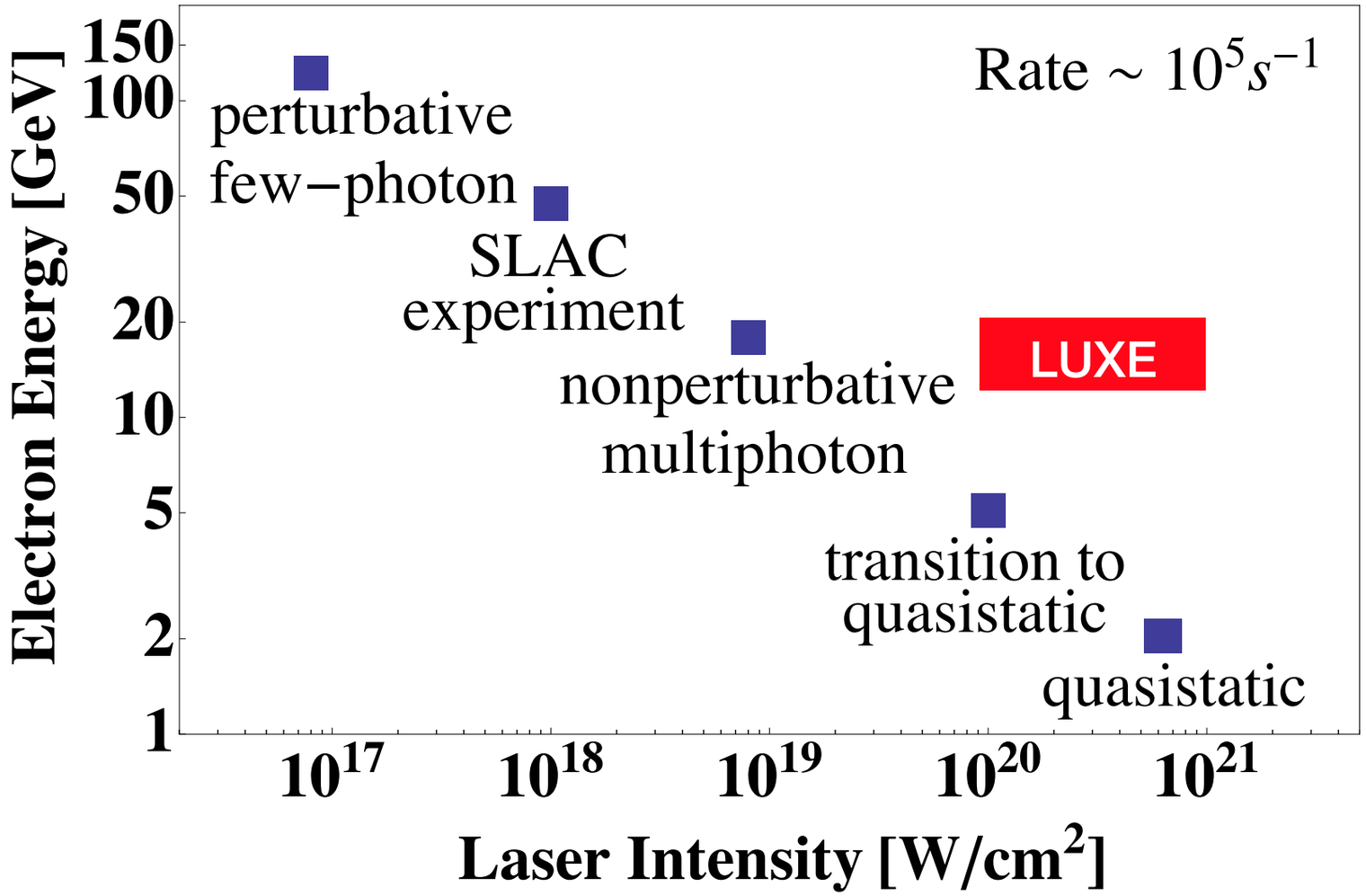

# Conclusions and outlook

- **Strong-field QED is a new physical regime which needs to be investigated.**
  - We may see something new and unexpected or
  - Confirm and understand predictions which go back ~ 80 years
  - Understand and apply knowledge to systems where this occurs, e.g. neutron stars, high energy colliders
- **Propose to set up an experiment using XFEL electron beam and measure physics above the Schwinger critical field.**
- Initial investigations and consideration of pioneering E144 experiment suggest we will be able to be well above the Schwinger field.
- **Embarking on feasibility/design study of machine, laser, experimental setup**
  - Simulation of experimental setup, optimisation, parameters, e.g. laser, beam size.
  - Spectrometer detector designs.
  - Theoretical calculations and physics simulations.
  - Evaluate that experiment is parasitic to XFEL.
- **Plan to host a workshop next spring/summer to gather interest and develop further.**
- People welcome to join.

# Additional info for FLC strategy

- **LUXE funding situation**
  - DSF application currently under evaluation (strong support also from XFEL director)
  - 1.1.2018-21.12.2019
  - 175 kEUR (1 PD + 2PhDs + travel + equipment for prototypes)
- **Design study for next two years**
  - simulations of beamline + sfQED + detectors
  - prototype detectors
  - prepare “TDR” for full experiment
- **A lot of similarities with ILC Compton polarimeters**
- **Real-life test of ILC beamstrahlung physics!**