Test-beam Measurements of Instrumented Sensor Planes for a Highly Compact and Granular Electromagnetic Calorimeter

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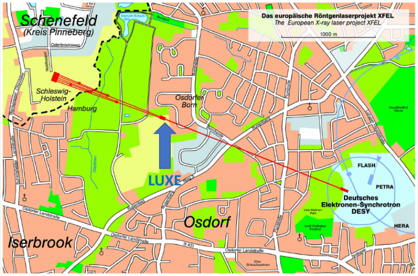
The LUXE project at DESY, Hamburg

LUXE: Laser Und XFEL Experiment



LUXE milestones documents:

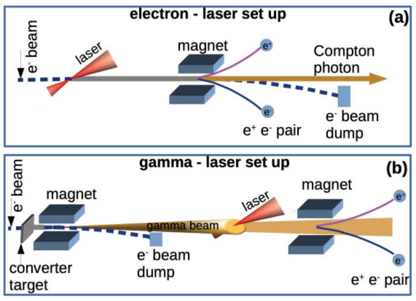
- **LOI** (2019) 1909.00860
- **CDR** (2021) EPJ ST 230, 2445 - 2560
- **TDR** (2023) 2308.00515 (EPJ ST Accepted)

LUXE Collaboration

- at DESY as the host laboratory
- at Eu.XFEL 16.5 GeV electron beam
- over 20 participating institutes
- about 130 active scientists

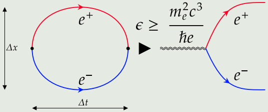
Physics Programme at LUXE: Study of QED in the strong field non-perturbative regime

LUXE: Two modes of operation



- *e*-laser: using 16.5 GeV XFEL e^- beam
- γ-laser: using bremsstrahlung γ photons
- collide them with **High Power** (40 or 350 TW) optical **Laser** (**HPL**) [phase-0 / phase-1]

non-linear and non-perturbative QED

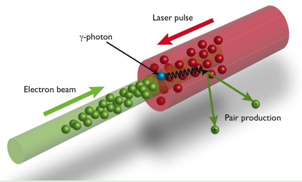


- physics at and above Schwinger limit:

$$\mathcal{E}_{cr} = \frac{m_e^2 c^3}{\hbar e} = 1.3 \times 10^{18}\ \mathrm{V/m},$$

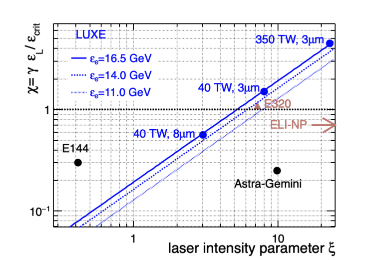
- boosted frame: $\chi = \gamma \frac{\mathcal{E}_{HPL}}{\mathcal{E}_{cr}}$

$$RMS(\mathcal{E}_{HPL}) \sim 10^{14}\ \mathrm{V/m}\ \ (\times 10^4\ \mathrm{e}^-\ \text{boost})$$

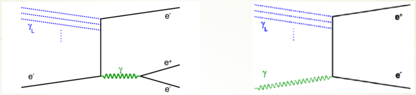


LUXE: the detectors challenge: very high rate of particles

Parameters space and e^+ rate

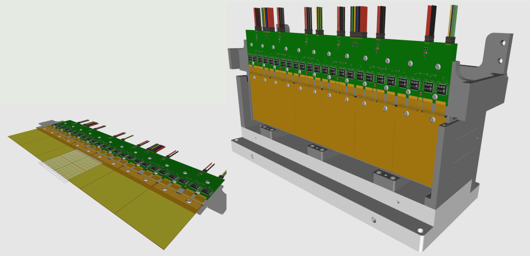


- laser intensity, dimensionless amplitude of $\mathscr{E}$ field): $\xi = \frac{m_e \mathscr{E}_L}{\omega_L \mathscr{E}_{cr}}$, ω_L - laser frequency



- **expected positron rate:** $10^{-5} - 10^{6}$ per BX, EM showers overlap at high multiplicity

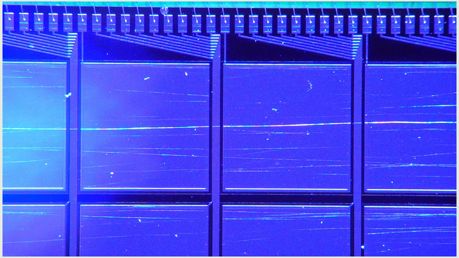
Solution for e^+ calorimetry: ECAL-p



- compact, high density sampling calorimeter
- small Moliére radius: ~ 9.3 mm
- high granularity
- 21 layers of 3.5 mm $(1X_0)$ tungsten absorber
- 1 mm gaps instrumented with active sensors

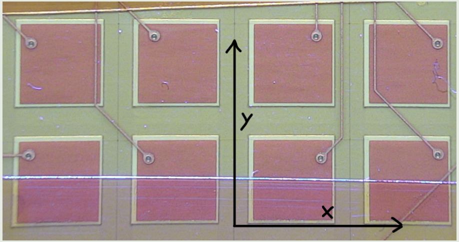
ECAL-p: semiconductor sensors investigated on the test-beam

Gallium Arsenide sensor:



- National Research Tomsk State University
- GaAs crystals compensated with chromium
- 4.7×4.7 mm^2 pads, 0.3 mm gap between pads
- pads are made of 0.05 μm vanadium layer
- sensor thickness 500 μm
- total wafer area: 51.9×75.6 mm^2
- 1 μm thick Al traces in the gaps between pads
- better radiation tolerance than silicon

Silicon sensor:



- produced by Hamamatsu (CALICE design)
- Si crystals: p+ on n substrate diodes
- 5.5×5.5 mm^2 pads, 0.01 mm gap between pads
- few nm pads Al metalization
- sensor thickness 500 μm (320 μm)
- total wafer area: 89.7×89.7 mm^2
- external kapton fan-outs with copper traces connected to the sensor pads with conductive glue

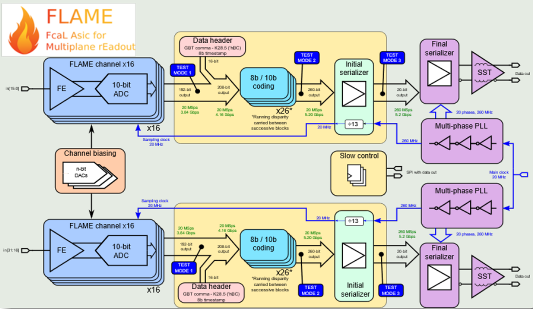
FLAME/FLAXE front-end ASIC designed by AGH University of Krakow

- FLAME (FcaL Asic for Multiplane rEadout) is a 32-channel ASIC in CMOS 130 nm
- 10-bit ADC in each channel, two fast (5.2 Gbps) serializers and data transmitters
- FLAME has been already used in several test-beams of FCAL and LUXE-ECAL collaborations
- final DAQ version will use a new front-end ASIC FLAXE, which is based on FLAME (in progress)

FLAME ASIC specification

- Analog front-end in each channel:
  - CR-RC shaping ($T_{peak} \sim 50$ ns)
  - two switched gains (high gain for MIPs, low gain for showers)
  - $C_{in} \sim 20 - 40$ pF
- 10-bit ADC per channel:
  - $f_{sample} = 20$ MHz
  - ENOB > 9.5 (effective resolution)
  - FPGA to extract amplitude and time
  - Power $< 350\ \mu$W @ 20 MHz

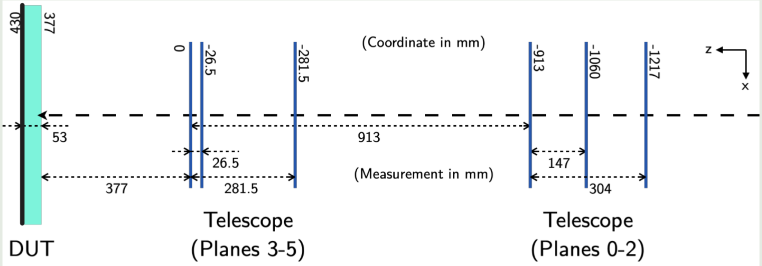
32-channel FLAME ASIC



Test beam setup, DESY, Hamburg (September 2022)

Beam telescope (EUDET collaboration), scintillators and Detector Under Test (DUT)

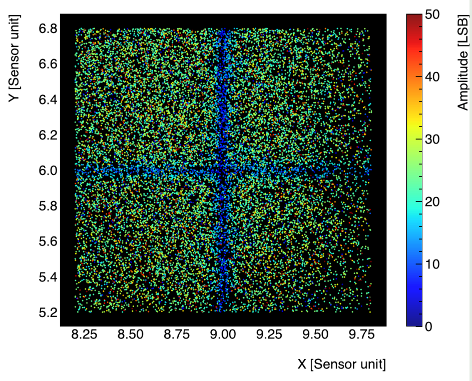
- Electrons arrive from the right, pass the first scintillator, then six ALPIDE pixel sensors, the second scintillator, and hit the sensor, denoted as DUT (Detector under Test)
  $\sim$ 35 μm resolution of the track extrapolated from the TB telescope



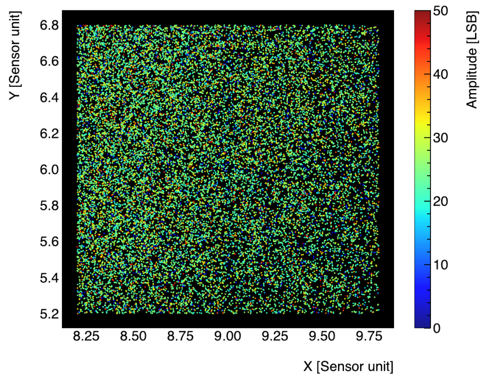
- Two 16 $\times$ 8 pad arrays of Silicon sensors and two 15 $\times$ 10 pad arrays of GaAs sensors were tested on 5 GeV electron beam at the DESY-II facility
- investigated were homogeneity of the sensor response, edge effects and signal sharing between pads
- in addition: test of the FPGA based data on-line preprocessing (amplitude and time reconstruction)

XY hits distribution

GaAs sensor (2 × 2 pads)



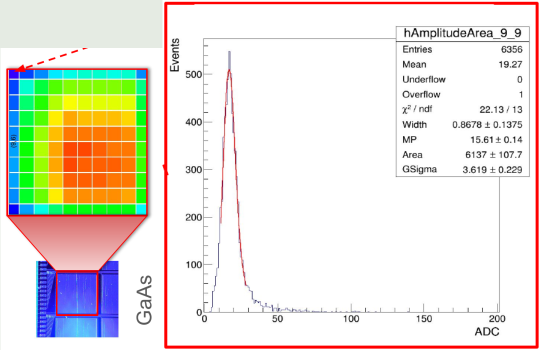
Si sensor (2 × 2 pads)



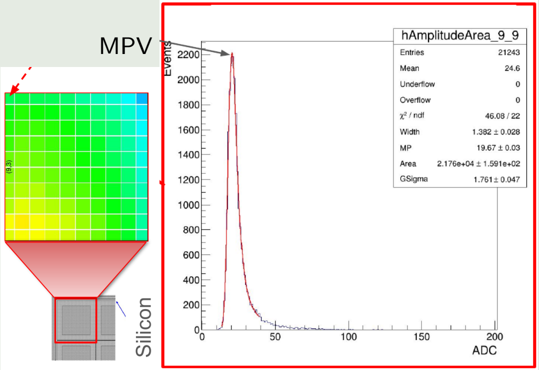
- after alignment with beam telescope ($\sim$ 35 μm resolution on DUT XY)
- color (Z scale) indicates the size of the signal
- loss of signal for GaAs sensor in the region between pads

Sensor homogeneity study

GaAs sensor



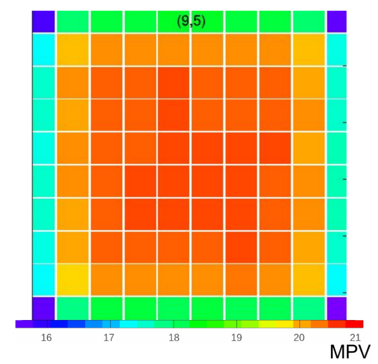
Si sensor



- Pads were subdivided into 10×10 XY sections and plotted was amplitude distribution in each section
- Fits of Landau distribution convoluted with Gaussian $\rightarrow$ Most Probable Value (MPV) on next page
- color (Z scale) encodes the statistic of hits

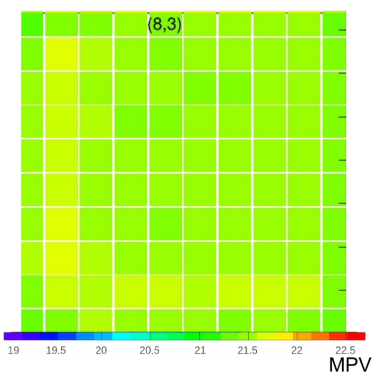
Sensor homogeneity study (cont.) : 10 × 10 pad subsections

GaAs sensor (single pad)



- GaAs: Drop in amplitude around edges and esp. in corners

Si sensor (single pad)

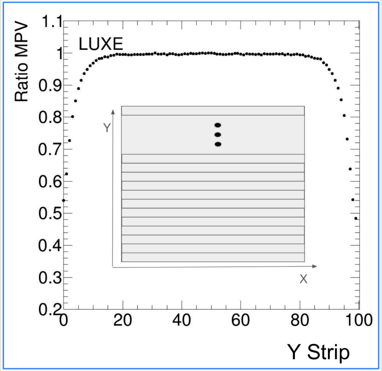


- Si: more uniform response, but...
- ... L-shaped area of a bit higher amplitude

- color (Z scale) encodes the MIP value

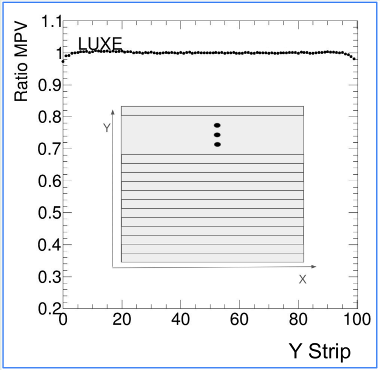
Sensor homogeneity study (cont.) : 100 vertical (Y) strips on pad

GaAs sensor (single pad)



- GaAs Y scan: **MPV drop : 50%** wrt pad center

Si sensor (single pad)

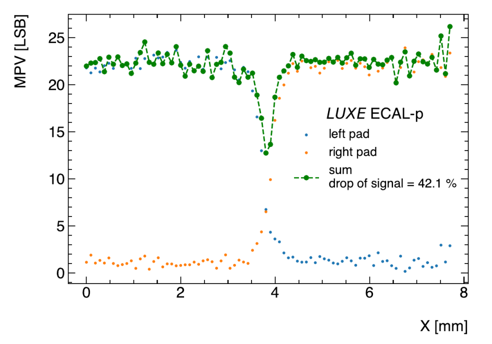


- Si Y scan: **MPV drop : 2-3%** wrt pad center

- Normalized to MPV of central strip. Similar response along X direction

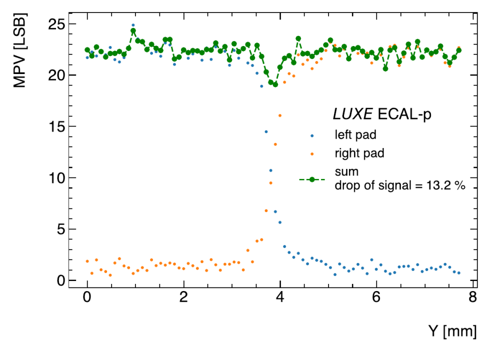
GaAs sensor: signal sharing between pads

GaAs sensor: 2 × 1 neighbor pads: X scan



- **X scan - traces between pads**
- sum of MPV drops of 40%

GaAs sensor: 2 × 1 neighbor pads: Y scan

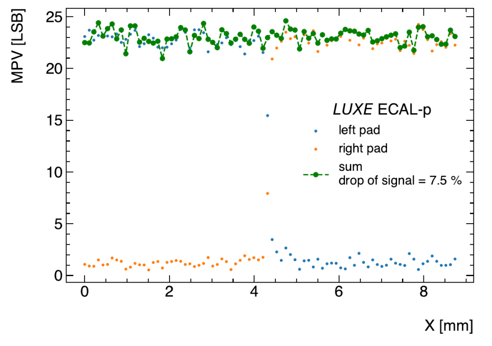


- **Y scan - without traces between pads**
- sum of MPV drops of 15%

- MPV measured as a function of x and y, crossing the area between two pads
- **gap between GaAs pads** 300 μ**m**

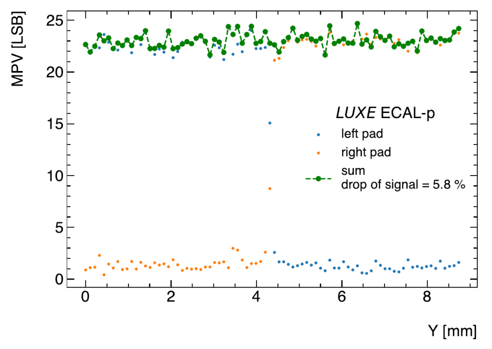
Si sensor: signal sharing between pads

Si sensor: 2 × 1 neighbor pads: X scan



- no signal drop is observed

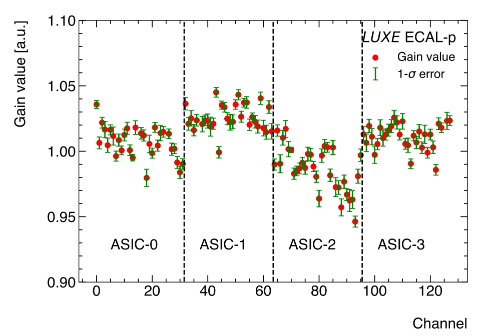
Si sensor: 2 × 1 neighbor pads: Y scan



- no signal drop is observed

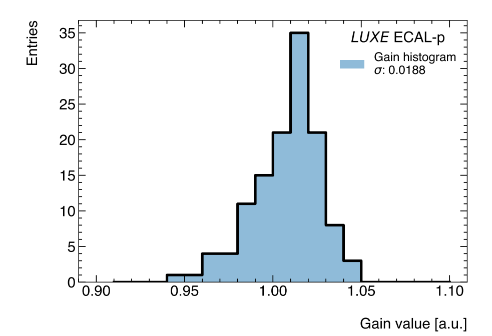
- MPV measured as a function of x and y, crossing the area between two pads
- **gap between Si pads** 10 μ**m**

Relative gain [a.u.]



- relative gain vs. chanel number for 4 ASICs
- using calibrated charge injector (2 – 12 fC for MIPs gain)

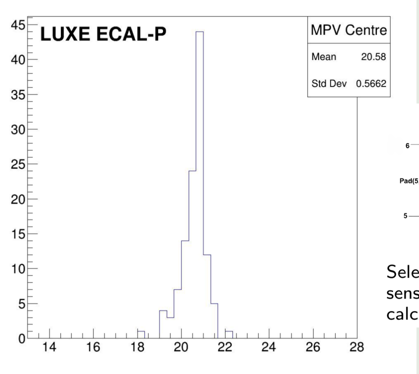
Relative gain [a.u.]



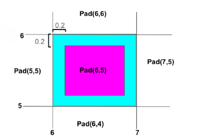
- distribution of relative gains
- RMS $\sim 2\%$

- good homogeneity of front-end preamplifiers, some dependence on ASIC fabrication

MPV: GaAs sensors

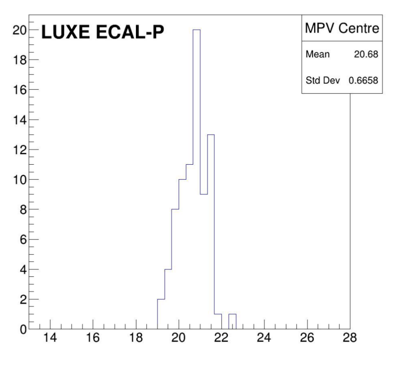


- RMS: 2.8%



Selected area of the sensor pad for MPV calculation

MPV: Si sensors



- RMS: 3.2%

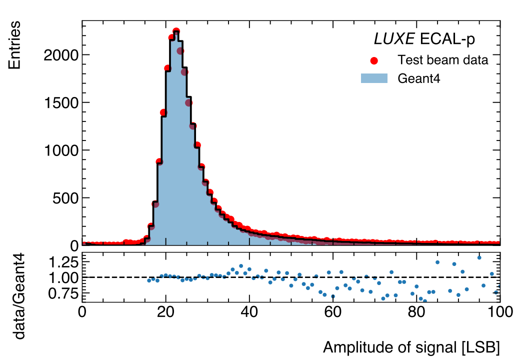
- MPV distribution after gain correction, excluding edge effect (20% margin)

Comparison with Geant4 MC simulation

response of a Si sensors to 5 GeV electrons

- energy loss dE/dx [GeV] in 500 μm Si sensor from Geant4
- energy loss converted into number of charge carriers using 3.6 eV per electron-hole pair
- gain of the read-out chain determined from charge injection: 3.45 LSB/fC
- as a cross-check 3.46 LSB/fC was obtained fitting the gain as a free parameter

response of a Si sensors to 5 GeV electrons



- good agreement DATA/MC for MIP

Summary

- **two types of semiconductor sensors (GaAs and Si)** for high density EM calorimeters **were tested** at 5 GeV electron beam at DESY
- energy losses for MIPs are well described by Landau distribution convoluted with Gaussian function
- homogeneity and signal sharing study were performed using hit position from the beam telescope
- **for GaAs sensors edge effect are observed** related to aluminum tracers and bigger gap between pads (up to 40-50% signal drop)
- **for silicon sensor edge effects are barely visible**
- after gain correction, in the central region of pads the **homogeneity** of the sensors amounts to **2.8 and 3.2 %** for the GaAs and Si sensors, respectively
- collected data are in **good agreement with** Geant4 **based MC**
- readout electronics absolute gain agrees between MC simulations and independent lab measurement (converting the energy loss into charge and using the gain of the readout chain)

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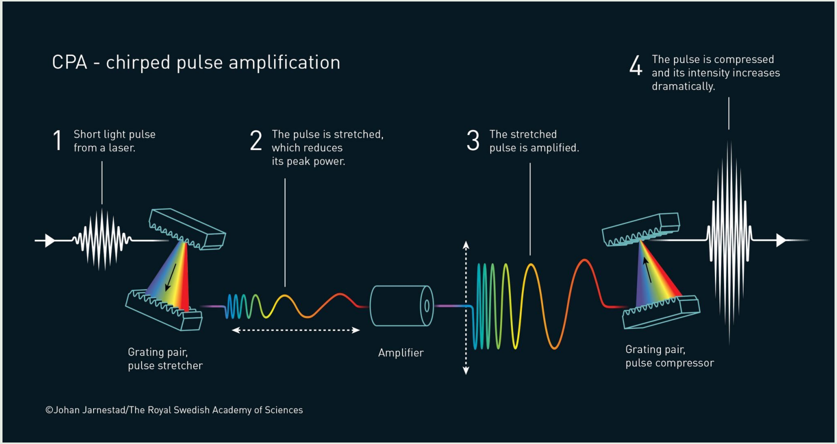
- **Thank You Very Much for Your Attention !**

BACKUP PLOTS FOLLOWS...

CPA: Chirped Pulse Amplification

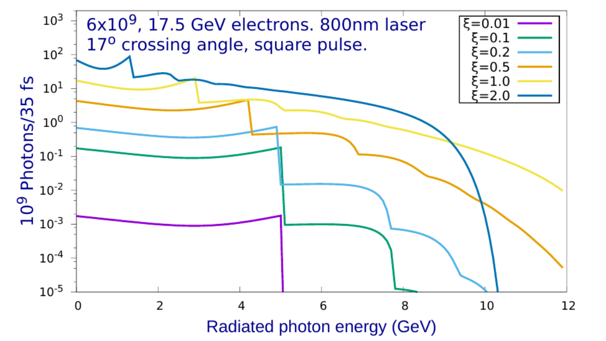


2018 Nobel Pize Donna Strickland and Gerard Mourou
"for method of generating high-intensity, ultra-short optical pulses"

dimensionless intensity parameter (filed energy density) ξ^2

- $\xi^2 = 4\pi\alpha(\frac{\mathscr{E}_L}{m_e\omega_L})^2 = (\frac{m_e\mathscr{E}_L}{\omega_L\mathscr{E}_{cr}})^2$, $\leftarrow$ "classical picture"
  ω_L - laser frequency, ξ - "dimensionless amplitude" of $\mathscr{E}$ field
- $\xi^2 = 4\pi\alpha\bar{\lambda}_L\bar{\lambda}_C^2 n_L$, $\leftarrow$ "quantum picture"
  $\bar{\lambda}_L$ and $\bar{\lambda}_C$ - reduced laser and Compton wavelengths,
  $\bar{\lambda}_L \sim 1\ \mu$m
  $\bar{\lambda}_C \sim 10^{-6}\ \mu$m
  n_L - number density of laser photons
- for low and moderate $\xi \lesssim 1$ the probability of net absorption of n laser photons $\propto (\xi^2)^n \sim \alpha^n$
  (consistent with perturbative QED vertex counting)

Non-linear Compton γ spectrum



- low laser intensity (ξ) $\rightarrow$ KleinNishina process
- $\xi \nearrow$: increasing flux of Compton photons
- $\xi \nearrow$: shift of Compton edge with laser intensity ($\rightarrow$ next page)
- additional structure due to multi-photon absorption

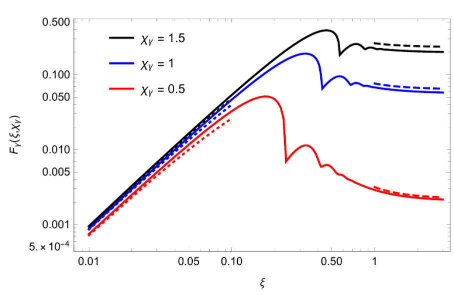
Non-linear Compton γ spectrum

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

- for monochromatic, circularly polarized laser pulse: $|\vec{\mathscr{E}}| = const$
- in transverse plane circular motion of electron with frequency ω_L
- **energy accumulated in this transverse degree of freedom can be treated as extra, effective mass of the electron**
- electron transverse momentum: $P_\perp \sim \xi m$
- $E^2 = m^2 + P_\perp^2 + P_\parallel^2 \sim (1+\xi^2)m^2 + P_\parallel^2$
- electron effective mass: $\overline{m} = m\sqrt{1+\xi^2}$
- $\rightarrow$ shift of the lowest order Compton edge (scaling as $1/\sqrt{1+\xi^2}$)
- $\rightarrow$ can be used to monitor the intensity parameter ξ

Rate of e^+e^- pair production

full calculation and asymptotic behavior (dotted-dashed)



- in a constant static field: $\propto \exp\left(-\pi \frac{\mathcal{E}_{cr}}{\mathcal{E}}\right)$ (Schwinger process)
- in plane wave laser (asymptotic): $\propto \exp\left(-\frac{8}{3}\frac{1}{1+\cos\theta}\frac{m_e}{\omega_L}\frac{\mathcal{E}_{cr}}{\mathcal{E}}\right)$
- good agreement for $\xi \ll 1$ and $\xi > 1$
- initial growth with ξ then drop due to the Compton edge shift